Soil, Water and Timber Management: Forest Engineering Solutions in Response to Forest Regulation

Proceedings

July 11-14, 2005
Fortuna, California, U.S.A

Organizers:

Department of Forestry and
Watershed Management
Humboldt State University

Department of Forest Engineering
Oregon State University

Sponsors:

Council on Forest Engineering 28th
Annual Meeting

International Union of Forestry
Research Organizations
Division 3.10.00: Forest Operations
and Techniques

Green Diamond Resource Company

Pacific Lumber Company

L.W. Schatz Demonstration

Tree Farm (Humboldt State)

HUMBOLDT STATE UNIVERSITY

OSU

International Union of Forestry Research Organizations

COFE

Proceedings of the Meeting on

Soil, Water and Timber Management: Forest Engineering Solutions in Response to Forest Regulation

Editor

Peter J. Matzka

Fortuna

California, U.S.A

July 11-14, 2005

Sponsors:

28th Annual Meeting of the Council on Forest Engineering

International Union of Forestry Research Organizations, Division 3.10.00

Green Diamond Resource Company

Pacific Lumber Company

L.W. Schatz Demonstration Tree Farm (Humboldt State)

Organized By:

Department of Forestry and Watershed Management

Humboldt State University

Department of Forest Engineering

Oregon State University

Hosted By:

Department of Forestry and Watershed Management

Humboldt State University

Acknowledgements

Thanks go out to the people involved in making this conference a success. While many individuals and organizations were involved, a few need to be recognized personally. A special thanks to:

- Green Diamond Resource Company, the Pacific Lumber Company, and our members at large for volunteering their time and efforts to plan and support the field tours
- Carl Hansen, the Director of the Extended Education Department at Humboldt State, along with his staff for coordinating registration and management of finances
- Northern California Society of American Foresters and member Brian Wing for the creation and maintenance of the conference webpage through their website and web provider
- L.W. Schatz Demonstration Tree Farm for providing computing space and resources to create the proceedings and also provided student assistance during the conference
- Jenny Matzka and Peggy Kellogg for coordinating the accompanied persons program and tours.

Organizing Committee:

The 2005 COFE meeting was organized by the Humboldt State Department of Forestry and Watershed Management and Oregon State Department of Forest Engineering and consisted of the following members:

Peter Matzka, Co-Chair (HSU)

Loren Kellogg, Co-Chair (OSU)

Otto Van Emmerick, Member at Large (Green Diamond Resource Company)

Kate Sullivan, Member at Large (Scotia Pacific/Pacific Lumber Company)

Proceedings

The proceedings are reproductions of papers submitted to the organization committee with minor editing to conform to a standard paper format. No attempt was made to review or verify results. Specific questions regarding papers should be directed to the authors.

The proceedings are available from:

Council on Forest Engineering

620 SW 4th Street

Corvallis, OR 97333-4428

Humboldt State University

Department of Forestry and Watershed Management

c/o Peter Matzka

1 Harpst Street

Arcata, CA 95521

Oregon State University

Department of Forest Engineering

Peavy Hall

Corvallis, OR 97331

Table of Contents

Plenary Session I, II, and II

BREAKOUT SESSION 1

BREAKOUT SESSION 2

BREAKOUT SESSION 3

BREAKOUT SESSION 4

POSTER ABSTRACTS

Plenary Session I

Codes of Forest Practice and Forest Certification: Complementary Efforts to Improve Timber Harvesting Practices in Tropical Forests

Dennis Dykstra

PNW Research Station, USDA Forest Service

620 SW Main Street, Suite 400

P.O. Box 3890, Portland, OR 97208-3890, USA

The politics of certification and impacts on Global markets

Eric Hansen

Department of Wood Science and Engineering

Oregon State University

Corvallis, OR 97331, USA

What the certification movement has done to forestry in the United States

Paul Harlan

Collins Pine

Lakeview, OR 97630, USA

Plenary Session II

California perspective on regulations and how they have affected the forest industry - background overview with a focus on solutions in response to regulations

Gary Rynearson

Green Diamond Resource Company

900 Riverside Road

Korbel, CA 95550, USA

BC, Canada perspective on regulation

Ron Davis

BC Ministry of Forest

P.O. Box 9510 Stn. Prov. Govt.

Victoria, BC V8W 9C2

Changes in Forest Engineering education and practices in response to environmental regulations and forest certification

Hans Heinimann

Swiss Federal Institute of Technology

ETH - Zentrum HGG23

Zurich CH-8092

Switzerland

Plenary Session III

Forest road building practices in British Columbia: Some changes in response to regulation

Doug Bennett

Forest Engineering Research Institute of Canada

2601 East Mall

Vancouver BC V6T 1Z4

CANADA

Forest harvesting practices in British Columbia: Some Changes in response to regulation

Brian Boswell

Forest Engineering Research Institute of Canada

2601 East Mall

Vancouver BC V6T 1Z4

CANADA

Retooling logging operations in response to changing forest practices

Pete Bailey

Skyline Thinning Company

3114 Industrial Ave.

Springfield, OR 97478, USA

The impacts of new road transport regulation on forest-wood sector in France

Elisabeth Le , Maryse , and François

Abstract

In France, more than 90% of the wood is transported by road, that is to say about 34 millions m^3 per year, and lorry gross weight used to be limited to 40 tons which is the general limit. Cost of transport is an important factor for the competitiveness of the wood industries (20 to 40% of the wood delivery cost at the mill), and one of the major levers left. Since the very large windstorms of 1999 (they blew down more than 3 annual cuts) and the promulgation of the new Forestry Act in 2001, the French legislation has evolved to meet expectations of wood professionals with a better recognition of the specificity of wood transport by road with a special decree dedicated to roundwood transportation: Decree n°2003-416. This decree authorizes higher gross vehicle weights (from 52 to 72 tons) than the Road Code limits. The Decree n°2003-416 dedicated to roundwood implies that each local authority has to define the road network suitable for higher gross vehicle weights, if possible with professionals. The varying involvement of the actors of the forest-wood sector and the possible disagreement with local authorities on the definition of such a network lead to discrepancies in the application of the decree in the different administrative districts (department). Therefore, in order to help some professionals to organize the wood transport, a map showing the global network dedicated to the roundwood traffic is provided on a website and is very regularly up-dated. To face the lack of coherence pointed out among the departmental road networks, a complementary approach is proposed at a larger scale and is based on the identification of "structuring roads" or "strategic roads" for wood removals from the forest to the mills. Such regional approach implies the participation of most of the stakeholders. Two regions have already developed such actions: Limousin and Burgundy. The application of transport regulation implies a new dialogue between stakeholders, based on a mutual comprehension.

Keywords: roundwood, transport, competitiveness, regulation, road networks.

---

[1] Project leader Elisabeth Le Net, AFOCEL, Domaine de l'Etançon, 77370 Nangis, France. Email:Elisabeth.lenet@afocel.fr

[2] Maryse Bigot, AFOCEL, Domaine de l'Etançon, 77370 Nangis, France.
Email: maryse.bigot@afocel.fr

[3] François Lewin, TEMBEC R&D KRAFT – GIE, BP 202, 31804 Saint-Gaudens Cedex,
Email: francois.lewin@tembec.com

Context

Road transport is the most important mode of timber transport in France. About 34 millions cubic meters over bark, that is to say more than 90% of all timber, are transported every year by lorries from the forest to various processing plants:

16 pulp mills (7 millions cubic meters over bark),

25 fibreboards and panels mills (3.5 millions cubic meters over bark),

Close to 2 500 sawmills (20 millions cubic meters over bark), most of sawmills being small firms (90% of them have less than 20 employees; 10% of them produce 50% of sawnwood).

Transportation by rail and waterways is very limited (respectively less than 2 millions cubic meters and less than 100 000 tons per year) and so far, perspectives of development for these two alternative modes of transportation seem also limited. Both modes indeed imply regular and sometimes large and steady flows of wood. It is difficult to achieve: wood lots and mills are generally very small sized and not geographically concentrated but sprayed all over the country. Moreover, the strategy of the State owned Railway company is not favorable to wood transportation (during the last 2 years, dramatic reduction of the number of wood railway stations from 200 to 40 and a 30% increase of the fees in average – more is planned; poor quality services and delays). The monopolistic situation of this historic railways operator is such that the wood market is declining sharply for this transportation mode.

In average, the procurement distance is about 100 km. Pulp mills have generally higher radius (up to 300 km), as they need large quantities of wood and a certain quality of fiber.

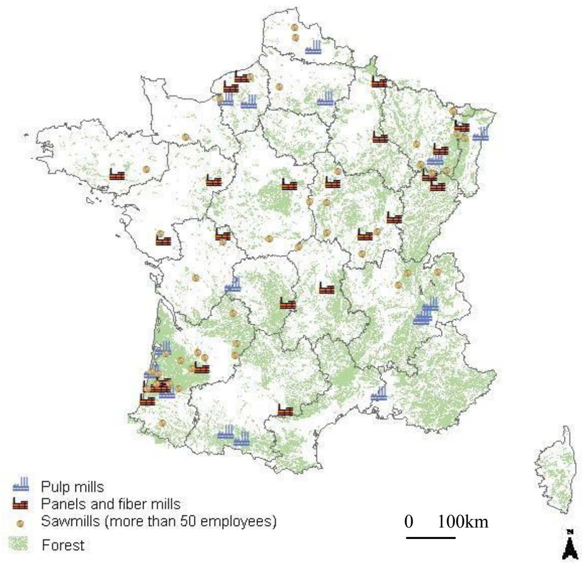


Figure 1: Forest resource in France and main consumers of roundwood

Nevertheless wood transport costs represent a substantial part of the industry's raw material cost at mill (20 to 40%) and so have a direct impact on the sector's overall competitiveness. The permanent increase of fuel price, the level of wages and taxes combined to an increasing international competition, lead to explore new solutions. Beside technology-based innovations (logistic optimization, intermodal transport…), professionals consider an evolution of the regulation as the unique other source of improvement for the competitiveness of the forest-wood sector in France.

Haulers do not have a strong lobby but wood professionals managed to make national authorities change the regulation for roundwoods transport, giving them the opportunity to load higher weights than for the transport of other goods. But evolution of regulation is a long process: started in 1997 with specific arrangement for long logs. After the 1999 windstorms, a new phase began in order to have a specific regime for the regulation of wood transportation in general. This process led to the recognition of wood transport particularities in the Forestry Orientation Act of 2001, and the publication in 2003 of the Decree n°2003-416 related to "roundwoods" transportation.

Regulation Concerning Wood Transportation in France

Basic rules for the goods transport

The basic rules concerning the transportation of goods can be found in the Road Code, among all the other rules concerning the traffic on the roads of the French territory. In this code, two main parameters are used to settle the legal limits of "conventional transport", submitted to the basic rules or the Road Code: the maximum axle weight and the maximum total weight for the loaded vehicle. Of course, these values depend on the number and type of axle (drive axle or not) and on the type of the vehicle (rigid, articulated…) but anyway, the legally permissible maximum weight of the vehicle or the combination of vehicles cannot exceed 40 tons for 5 axles and more. Cf. Tables 1 and 2. One exception to this limit of 40 tons concerns the transport to/from a maritime port or combined transport (rail/road; fluvial/road). Then, the maximum legal weight is 44 tons for 5 axles and more. The implementation of this specific regulation is far from being easy.

Table 1 : Maximum legal load capacities for transport vehicle (Road Code - R. 312-4I)

Vehicle type	Number of axles	Maximum weight (tons)
Rigid motor vehicle	2	19
	3	26
	4 or more	32
Trailer or semi-trailer	2	19
	3 or more	26

Table 2 : Maximum gross vehicle weights (Road Code - R. 312-4II)

Vehicle type	Number of axles	Maximum weight (tons)
Articulated vehicle	4 or less	38
Road train	5 or more	40

Besides this "conventional transport", is defined the "special transport"[1], restricted to the traffic of "outsize goods, machinery or vehicle that exceed legal limits of length, width or weight" (R. 433-1-l). Special transport is divided in three categories, based on length, width and weight criteria, height being not taken into account. *Cf*. Table 3. Every category of special transport is submitted to specific rules. A specific Transport Ministry service is in charge of the elaboration of road networks for the 1st category and the 2nd category taking into account the technical characteristic of roads, bridges, tunnels, supporting structures, junctions…

Table 3: Classification of special transport

Characteristics	1st category	2nd category	3rd category
Length	≤ 20m	20 < L ≤ 25	> 25
Width	≤ 3m	3 < W ≤ 4	> 4
Total Weight	≤ 48 tons	48 < W ≤ 72	> 72

[1] The first regulation document on "special transport" was published in 1975, Circular n°75-173.

Rules for wood haulage

In France, chipping in the forest is very rare. Trees are either processed in tree length (the top end diameter defining the total length of the product) or bucked into logs of various lengths, from 2m up to more than 10m (the length can be predefined or can result from quality criteria such as insertion of a big branch). Logs between 2m and 6m-8m are very common for softwoods but also for pulpwood of both conifers and broadleaves (motor-manual or fully mechanized cutting with forwarder). Longer logs and tree length are more frequent in steep terrain or mountainous areas, but also for large-sized or high quality timber (motor-manual cutting with cable or skidder).

Transportation of long logs

Long logs haulage can operate under the rules of special transport, as long logs are considered by the Road Code as an "indivisible load that cannot be transported by vehicles meeting the legal limits of the conventional transport". Since 1997, a particular place is dedicated to long logs within the "special transport" regulation. Nevertheless this haulage is submitted to authorizations geographically limited (a special journey or a network of authorized roads) and with other restrictive conditions (nominative and/or temporary authorizations).

These "authorization for long logs" were delivered by the authorities of the administrative subdivision of France called "department" – there are 96 departments in France, average size being less than 6000 km^2. Since the 2003 update of the "special transport" regulation, the authorizations are called APL and AI. The State authorities at the French department level are still the ones in charge of their delivery.

APLs (for *local range authorization*) are published to satisfy "permanent local economical needs". They define authorized and prohibited roads for special transport within the department area. *Cf.* Table 4. Continuation of transportation to a bordering department is possible only if this department has also published an APL. For vehicles exceeding the limits of APL, or in departments without APL, haulers must have an AI authorization.

Table 4: Maximum legal specifications for long log transportation with an APL authorization

Vehicle	Length (m)	Over-length at backside (m)	Width (m)	Height (m)	Total Weight
Rigid motor vehicle	15	3	2.55**	4	44 tons / 5 axles 48 tons / 6 axles
Tractor + semi-trailer (drawbar or dolly*)	25	3			
Tractor + long load dolly	25	7			

* 1 drive axle + 1 or 2 bearing axles; ** It is the normal limit defined for conventional transport by the Road Code. Maximum values for axle weights are also the conventional ones.

AI (for individual authorization) is a nominative authorization personally delivered to a hauler for a limited duration or a well-defined number of journeys, depending on the category of the special transport concerned. Some are permanent (AIP). Cf. Table 5. This authorization can be multi-department but is delivered by the authorities of the department the wood starts from, after conferring with the other departments concerned.

Table 5: Main characteristics of AIP authorizations, for any type of vehicles

Special transport 1st category	Special transport 2nd category	Special transport 3rd category
Maximum validity ≤ 5 years	Maximum validity ≤ 2 years	Well-defined period
All or part of 1st category special transport network	All or part of 2nd category special transport network	Delivered for a single journey
The highest criterion determines the category.		

Transportation of roundwoods

From the regulation point of view, roundwoods are not considered as an "indivisible load that cannot be transported by vehicles meeting the legal limits of the conventional transport". As a result, transportation of roundwoods cannot be operated under the rules of "special transport". That implies that roundwoods transportation used to be submitted to the rules of the conventional transport, so limited to a total weight of 40 tons maximum - Cf. Tables 1 and 2 - until the promulgation of the Forestry Orientation Act in 2001, that has opened a special regime for "roundwoods" transportation regulation.

Two phenomena led to the establishment of a roundwoods regulation:

The increasing need for a higher competitiveness and the will among professionals to cease being out of law. Vehicle used for the haulage of roundwoods are generally equipped with a loader that reduce the effective load capacity by 2 to 3 tons. As a result overweighing was a very common practice. Controls became more and more frequent. Haulers and mills feel now very concerned with this subject. This context and the associated control system have some impacts on the incentives to invest in new materials such as load weighing devices.

The 1999 storms. In December 99, the two large windstorms Lothar and Martin blew down close to 140 millions cubic meters, that is to say about three national annual cuts. To face efficiently this catastrophe, there was an urgent need to harvest, haul and store the wood in good conditions to prevent decay. Quite rapidly, wood transportation has been perceived as a potential bottleneck, so National authorities published in February 2000 a special circular authorizing, temporarily, the transportation of logs with special authorization (Circular n°2000-12). This action aimed at generalizing, wherever, the publication of “authorizations for long logs” was necessary. Professionals of the wood sector received this measure (Circular n°2000-12) very positively, as they were then allowed to transport 44 tons or 48 tons (respectively for 5 or 6 axle vehicles) instead of 40 tons.

In July 2001, the Forestry Orientation Act n°2001-602 was promulgated and article n°17 authorized for 5 years the use of higher weight vehicles to transport roundwoods on road networks defined at the department level and called **APR (for *prefect authorization*).**

The Decree n°2003-416 details the impacts of this Article 17:

- the maximum gross vehicle weights, Cf. Table 6,
- the duration of this temporary measure (until July 2006); this temporary measure has been extended1 in 2005, for 3 extra years (until July 2009),
- the modalities to determine APRs.

Table 6: Maximum gross vehicle weight for roundwoods

Maximum gross vehicle weight	Axles
52 tons	≥ 5 axles
57 tons	≥ 6 axles
65 tons	≥ 7 axles
72 tons	More than 7 axles

In addition to this decree, an order brings some precisions concerning vehicle specifications (weight per axle in particular) and an attestation model for vehicle constructor: constructor must indeed certify that a specific vehicle has the technical

[1] The Rural Territories Development Act, n°2005-157, 23 February 2005, Article 229.

characteristics to support the higher weights than 40 tons.

To follow the roundwoods regulation, haulers must today keep in their vehicles:

- the technical attestation for the vehicle signed by the constructor and validated by the authorities in charge of technical controls,
- the APR documents of every department concerned by the journey (departure, transit and destination department) or at least, the official departmental maps of networks authorized for roundwoods transportation.

From an operational point of view, the edge between "special transport" and roundwoods regulation is fuzzy. The main criteria are the following: the divisible/indivisible character of the logs; the length of the vehicles: 16,5m + 3m[1] for articulated vehicles; 18,75 + 3m for road trains. Most of haulers are not very well informed of the regulation and face many difficulties to obtain the certification from constructors, especially for old vehicles.

Theoretically, this evolution in the regulation cannot have anything else than a positive impact for the competitiveness of the forest-wood sector in France. Practically, not much changed for haulers.

Transportation of Roundwoods: the Implementation of the New Regulation

The principles of the implementation process

The implementation of the Decree n°2003-416 relies on the definition of one APR in each of the 96 departments of France. Elaboration of APR is a quite complex task, as it implies all the authorities in charge of the policy and the operation of the different types of roads (highways and national, departmental and local roads):

- the Prefect, the official representative of the National Government at the department level. He is also responsible for the police at the department level for national roads.
- the Transport Administration, through its regional[2] (DRE) and departmental (DDE) units. They are the operational bodies for the implementation of the Ministry of Transport and Infrastructures

---

[1] Over-length at backside.

[2] Departments are grouped into 22 regions.

missions (controls of technical specifications on roads and infrastructures such bridges, projects of construction…). They are also responsible for the maintenance and the operation of the national roads that are State property.

- the Department Council, which owns and runs (including policy) the roads belonging to the department,
- the Local Council, which owns and runs the local roads (including policy), belonging to the “Commune”,
- The Local Councils Association,
- the companies in charge of the operation of the highways (the State owns the highways but leaves the operation to private companies through a franchise),
- other companies such as EDF (national electricity operator), GDF (national gas operator), RFF (National operator in charge of railways tracks), VNF (National fluvial operator)…

Moreover, as the Transport Administration does not know much about the forest-wood sector, representatives of the Agriculture Administration through their regional and departmental units, are generally also involved.

At least, it was strongly recommended by the Ministry of Agriculture, Transport and Interior[1] that elaboration of APR should be carried out in co-operation with the professionals of the forest-wood sector. As a result, discussions concerning the definition of APR in the different departments generally involve delegates of regional or departmental associations representing all types of business within the forest-wood chain. Managers of wood transport firms, as well as large wood procurement companies or mills are sometimes also involved.

The results of the implementation process

The definition of APR as required by the Decree n°2003-416 has proved to be as a very slow process, for many reasons.

First of all, the start of the process in the 96 departments has been very much delayed. Partly because of the complexity of the process, most of the regional and departmental units of the Transport Administration were waiting for a circular from their Ministry explaining how to implement the Decree n°2003-416 (a kind of practical guidelines). Some antagonisms were also found between the different

---

[1] This Ministry is responsible for the traffic control.

Ministries concerned, and this led to a late publication of this circular, in summer 2004 only.

Besides, the time-limited validity of the Decree (even with its prolongation up to 2009) has probably negatively influenced peoples' motivation, so mobilization of professionals was sometimes unsatisfying.

Thirdly, the process of the definition of APR itself is a long process. Many and many discussions are necessary before reaching an agreement, as the objectives of the people involved are basically conflicting. For example, higher loads mean higher profitability for the transport business but potential higher costs for road maintenance. It is not surprising so that road owners and managers (Departmental Council and Local Authorities in particular) put some curbs in the process.

This explains why in June 2004, that is to say more than one year after the promulgation of the Decree n°2003-416 (April 2003), but before the publication of the multi-ministerial circular, only 4 departments had signed their APR. After the publication of the circular in summer 2004, 20 APRs were rapidly concretized. At present (statement at 31st of May 2005), 46 APRs are published and 26 are in preparation (draft). In the other 24 departments, work is in progress, but a draft is not yet elaborated.

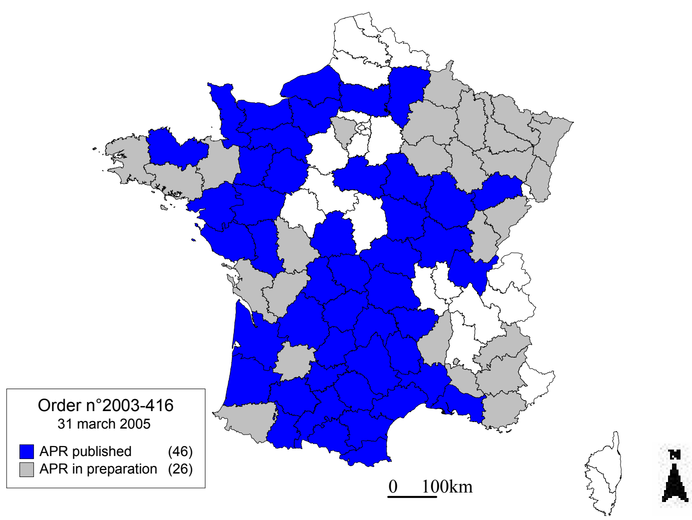


Figure 2: Departmental implementation of the Decree n°2003-416 related to roundwoods (31 March 2005)

To sum up, more than 2 years after the promulgation of the decree concerning roundwoods transportation, but nearly 4 years after the promulgation of the Forestry Orientation Act in 2001, less than 50% of the 96 departments of France have implemented the targeted measure of higher limits of gross weight for wood transportation. Among the 46 APR published, the quality and density of the roundwoods network are very different.

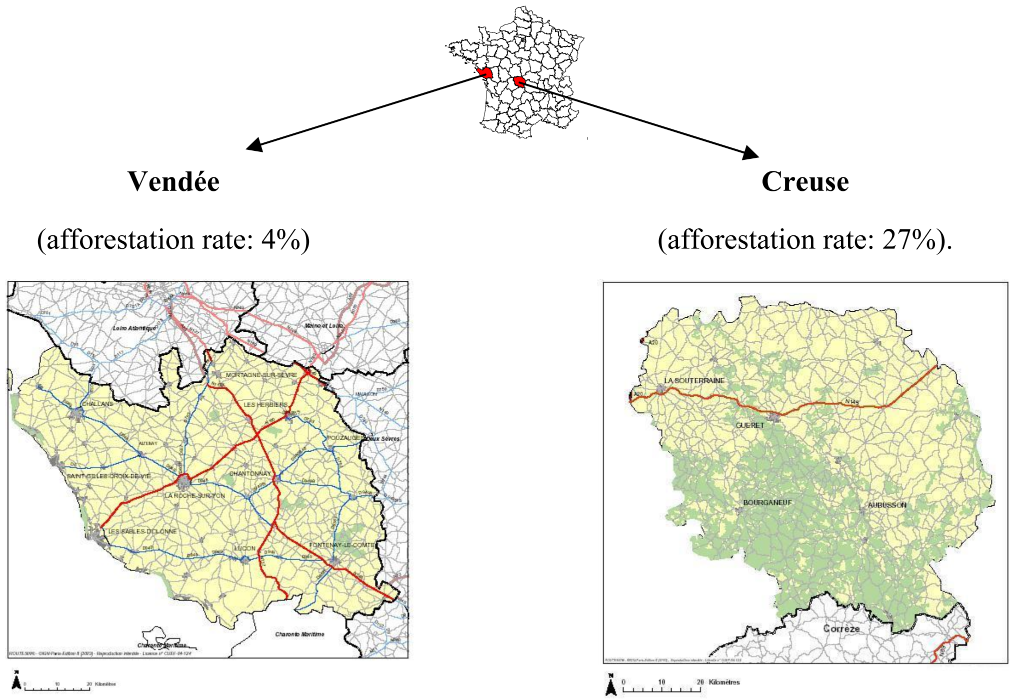
Consequences of the implementation process for haulers and wood industries

Whereas professionals of the forest-wood chain put many hopes on the Decree n°2003-416, the depth analysis of the 46 published APRs shows that only three of them can be considered as really positive for the forest-wood sector, by providing an effective and practicable road network for the traffic of vehicles weighing more than 40 tons.

On the contrary, many restrictions can be found in most of the APRs. For example, only some parts of the highways or national roads are authorized for higher weight vehicles, or authorized roads are not connected to forested areas and/or mills. This means that APRs contain implicit barriers that prevent professionals taking a real benefice from the new regulation.

It must also be highlighted that the 3 advantageous APRs are not found in forested departments. This is particularly worryingly as it points out the question of the knowledge and recognition of the importance of the forest-wood sector in France at national, regional and local levels.

Maps of Figure 3 illustrate two extreme cases: a very favorable APR in a "non-forested" department (Vendée - afforestation rate of 4%) and a very restrictive APR in a more forested department (Creuse - afforestation rate of 27%). In Creuse, the APR is limited to the tiny part of the highway and to the single national road passing through the department while in Vendée, there is a real network of authorized roads and it is also possible to use a 20 km strip from and to the roads of the network to join a forest or a mill that would not be located within the network.



Green areas are forests. Authorized roads are in red (national roads) and blue (departmental roads). Gray roads are the ones not included in the APR network (local roads are not represented).

Figure 3 : Examples of two extremely different APRs

In addition to the intrinsic restrictions of the APRs are the limitations resulting from the lack of co-operation between neighboring departments. Some departments have worked on their own, without taking into account the work of the bordering departments (especially when they were not in the same administrative region). This results in incredible situations - whereas Europe is underway- that a 5 axles lorry of 52 tons is allowed to use for instance the national road n°19 in department A but should unload a part of its logs (until 40 tons) when entering the bordering department B as this one has not included national n°19 in its APR or even does not have any APR. Of course, such a system cannot be effective and the general rule is clear: in case of mismatch between two departmental networks, the minimal value of the gross weight is the one applicable. So, in our example, as there is no continuity about the authorized gross weight between departments A and B for the national road n°19, haulers will have to stick to the limit of 40 tons both in departments A and B.

A last problem is found, related to the share of responsibility concerning safety measures and controls between the different authorities: the mayor (elected by the Local Council) has the predominant power for the policy in the built-up areas of its commune. This means that even if a national road has been identified in an APR as a part of the authorized network for roundwoods transportation by department, regional and national authorities, the part of the national road passing through the built area of a commune can be removed from the network because of the decision of the commune mayor. And there are 36 000 communes in France…

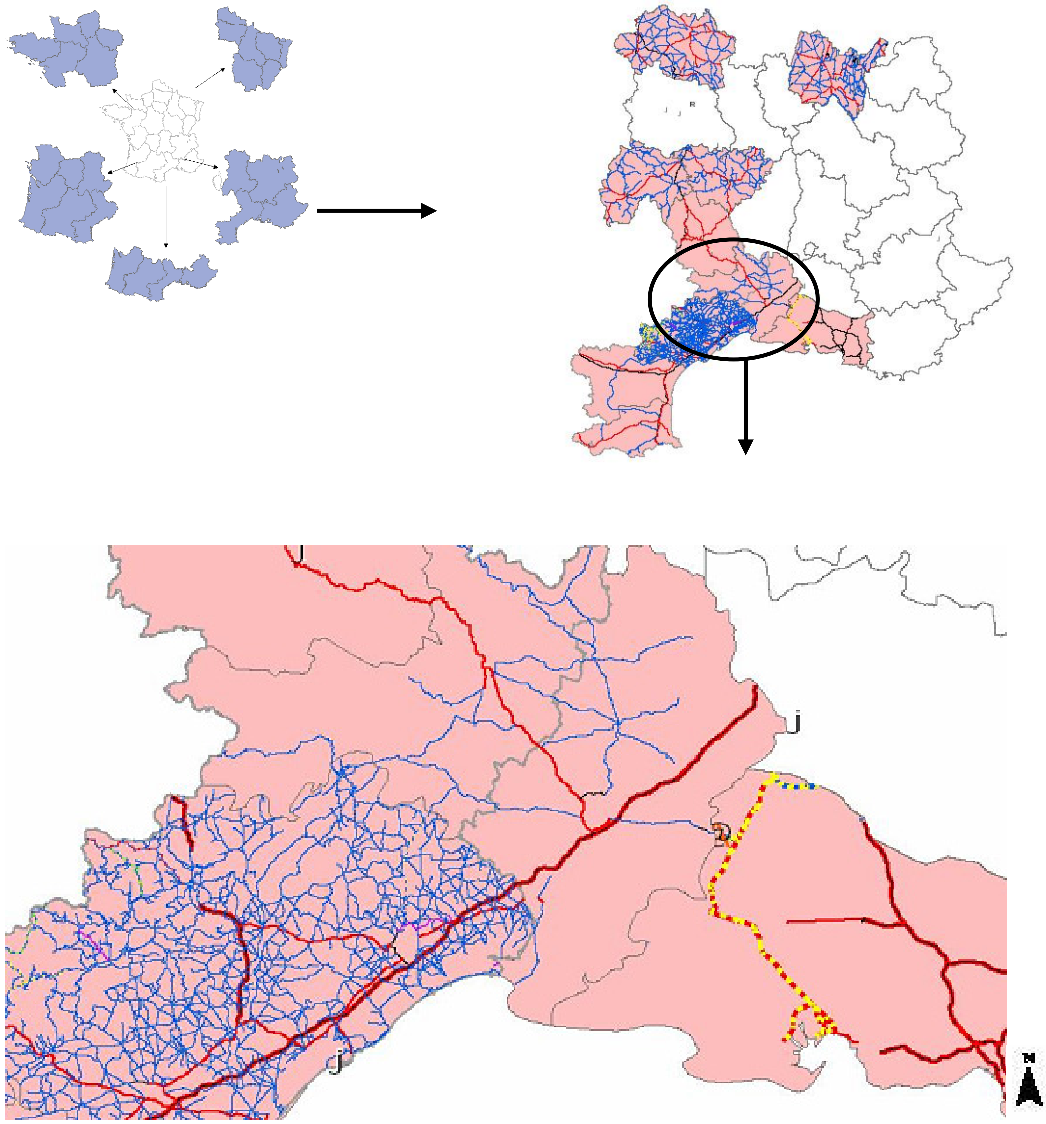
To sum up, despite the new regulation concerning roundwoods transportation, lorries have to respect the former limit of 40 tons for most of their journeys because of an uncompleted and incoherent implementation of the Decree n°2003-416… and overweight is still a reality.

Perspectives

Decree n°2003-416 should result in an increased competitiveness of the forest – wood chain. It is at least still expected. But in the current context, to achieve a successful implementation of the new regulation concerning roundwoods transportation, different actions have been undertaken[1]:

- Keeping an up-to-date survey and analysis of the whole implementation process of the new regulation at national, regional and departmental levels (APR published or in preparation…),
- Mapping all the roundwoods networks published in APR and identifying the incoherencies between departments. *Cf.* Figure 4,
- Providing professionals with these maps and analysis on a dedicated web site (restrictive use) regularly up-dated,
- Providing regional and departmental authorities or bodies with socio-economic information concerning the impact of the forest-wood-paper sector in their local economies,
- Organizing open seminars dealing with the challenges faced by the wood transport.

[1] Those actions have been done by AFOCEL thanks to financial support from some of French Pulp and Paper mils such as Tembec and the French Agriculture Ministry.



Blue: departmental roads authorized for 52 (5 axles)/57 (6 axles) tons

Red: national roads authorized for 52 (5 axles)/57 (6 axles) tons

Red-yellow: national road authorized for 72 (7 axles and more) tons

Red-blue: department road authorized for 72 (7 axles and more) tons

Gray color: the administrative borders (department)

Figure 4: Example of maps illustrating the incoherencies between different departments.

To overcome some of the identified curbs, some collaborative approaches seem interesting to identify "structuring network" or "strategic roads" for the wood removals from forests to the mills. Elaboration of codes of practices is probably another useful tool to achieve a more successful implementation of the roundwoods transportation regulation.

Complementary Approaches for Positive Impacts of the Roundwoods Regulation

From forest to wood industries: how to haul?

In some forested regions, some initiatives have been developed to improve the haulage of wood from forest to mills. Those initiatives are not directly connected to the Decree n°2003-416 on roundwoods.

Two regions have engaged such a work: Limousin started in 2004 and Burgundy in 1991.

The "structuring network" in Limousin

The 3 Departmental Councils of the region Limousin and the regional representatives of the Agriculture Ministry (DRAF) and Transport Ministry (DRE) engaged a study to:

1. determine a road networks to haul wood from forest to mills, wood railway stations and wood platforms,
2. make work together all the stakeholders: wood industries, loggers, haulers, bodies in charge of the operation of roads (the 3 levels presented above), the people's representatives…

This work is constraint by the following rules:

- All mills, wood railway stations and wood platforms must be integrated in the network.
- At least 80% of the forest resource have to be served.
- Less than 50% of the existing road system can be selected.
- Open meetings must be organized to reach global agreement.

To do so, a pilot study has been launched in a specific Limousin area for 19 months. This step-by-step approach has implied to start by collecting information from professionals and operational actors: Which roads are traditionally used to supply the local mills? What are the bottlenecks?

The working meetings are organized at local level with all the stakeholders. During a first meeting, an external consultant presents a draft for the network; it is discussed and a collective proposition is prepared. During a second meeting, the “structuring network” is validated.

Contrary to the “roundwoods network”, this approach is far more collaborative, much more time consuming, does not focus on higher weight vehicles, and aims at tackling with the haulage of domestic forest resource. This experience also proves that actors of the forest-wood chain can find agreement with authorities without clashes. Last but not least, the “structuring network” can be used to identify where to target the costly road investments (particularly the European structural funds to regions).

The “strategic roads” in Burgundy

The “strategic roads” objective is very close to the one proposed in Limousin. Its specificities come from the method used: it is a less open process than in Limousin and more forest-oriented:

1. The first step is to map the forest resource, forest roads and forest facilities (landing at road side) and road networks in connection with forest areas (a focus has been done on local roads).
2. Information comes from official data bases.
3. A Committee composed of experts (administration, private actors-mainly haulers, authorities) is charged of selecting the most pertinent local roads.
4. Some adjustments are made by haulers and bodies in charge of road operation (DDE and Department Council) to identify the departmental roads.

Burgundy has been divided in 3 forest areas. For the first area studied, 36% of the local road identified as of interest for forest (step n°3) have been declared as “strategic roads”. The work on the third area began in 2005.

The “strategic roads” approach is considered as the best tool for the stakeholders of the forest-wood sector in Burgundy and is used for APR discussions.

Local Codes of Practice

In tools such as Codes of Practice, the responsibilities and duties of each actor of the wood extraction and transportation are identified: forest owners, loggers, haulers, mills, local Councils.

Out of 4 codes of practice identified, two are regional and two have been elaborated at the departmental level. *Cf.* Figure 5.

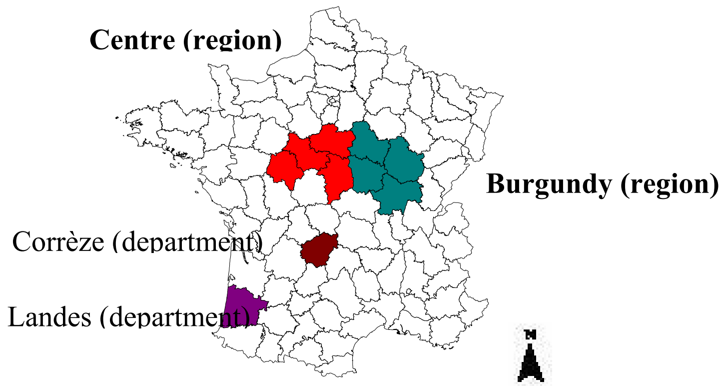


Figure 5: Codes of Practice for wood haulage in France

In Burgundy, the Code of Practice has been made in relationship with the “strategic roads” work. In this region, the forest-wood sector is traditionally important and it explains the long collaborative process engaged. In the Centre Region and in the Landes department, the elaboration of the code is connected to the Decree n°2003-416 and the publication of APR. It is a proof of the professionals’ goodwill towards bodies in charge of road operation. In Corrèze (Limousin), the code has been promulgated in 1996 but is more oriented as a code of practice for wood storage.

The Code of Practice of Landes published in 2004 is of particular interest. As other codes, it has been elaborated in a collaborative way. Moreover, a working group has been set-up with representatives of the stakeholders to control its implementation. Regularly, the group points out the different available statistics: number of traffic controls and fines in comparison, quantities of wood deliveries at mills… In this department, the Code of Practice was a prerequisite for the “roundwood network” of the APR. Even if this APR is limited to 5 axles lorries of 44 tons and 6 axles lorries of 48 tons, professionals find it satisfying due to the favorable local haulage conditions (short procurement radius, flat terrain…). Moreover, the APR network is very large: it is possible to join it from any point after having notified this journey to the local Council and/or Department Council.

Conclusion

The impacts of the favorable new road transport regulation on forest-wood sector in France are not the ones expected. For instance, the favorable roundwood networks are not found in traditionally "forest and/or wood departments". The departmental application of the national roundwood regulation has highlighted that the consensus is not a French tradition, but also that forest-wood sector has a recognition difficulty at local, departmental, regional and national level. Some ideas could be certainly pick up from the agricultural sector concerning rural lobby. One of the problem faced is communication: many haulers are not very well informed of the regulation and are not enough well-organized to improve this knowledge.

The implementation history of the Order n°2003-416 presented in this article demonstrates that some work has already been done. Local initiatives such as Code of Practices, "structuring roads" or "strategic roads" are positive and should be developed. Landes and Limousin actions, emphasized co-operation approach, provide evidence that the application of transport regulation implies a new dialogue between stakeholders based on a respective comprehension.

The next phase is to engage a national coherent and satisfying roundwood network for the traffic of roundwood lorries over 40 tons all over the country. Why not relying on efficient experiences to elaborate for example a national Code of Practice of wood haulage? Why not engaging an analysis including wood chips transportation (from 40 to 44 tons for 5 axles, this idea is examined at present for all goods in France) and opportunities of wood logistic platforms?

By now, wood transportation in France is on the edge. All the difficulties and curbs identified in this article, as well as the positive approaches, give experience to go ahead. Work is still in progress.

Research and Policies to Address Concerns about Soil Compaction from Ground-Based Timber Harvest in the Pacific Northwest: Evolving Knowledge and Needed Refinements[1]

Paul W. Adams[2]

Abstract

The Pacific Northwest has a relatively long and substantial history of research and policies to address questions and concerns about forest soil compaction from logging operations. Observations of broad, deep, and persistent levels of soil compaction after timber harvest, combined with documented growth impacts to Douglas-fir, Ponderosa Pine and other important species, helped fuel this interest and activity. Although general concerns about the negative effects of compaction seem justified, more recent research findings as well as changes in harvest systems and forest conditions have been inconsistently integrated into current practices and policies. Among the areas of greatest need for refinement are a more site-specific understanding and identification/prediction of tree and plant growth and hydrologic impacts, and of cost-effective policies and prescriptions to address these concerns.

Key words: forest soils, site productivity, skidding, soil disturbance, watershed hydrology

---

[1]Paper presented at Council on Forest Engineering Conference on Soil, Water, and Timber Management: Forest Engineering Solutions in Response to Forest Regulation, July 11-14, 2005, Fortuna, CA.

[2]Professor and Extension Specialist, Oregon St. Univ., Forest Engineering Dept., 204 Peavy, Corvallis, OR 97331-5706. E-mail: paul.adams@oregonstate.edu

Introduction

For several decades, forest soil compaction from ground-based timber harvest has been the focus of considerable research in the Pacific Northwest. And as negative impacts of compaction were documented or raised as management concerns, various policies and practices were developed to avoid, reduce or mitigate compaction. More recently, research on the effects of compaction has revealed some relatively complex and equivocal results, and the array of harvest systems and equipment options has expanded significantly. However, recognition of these key developments related to the issue of compaction and its management has been spotty, and many regulations and other policies continue to reflect a relatively dated understanding of both problems and solutions.

In this paper I will review and discuss both historical and contemporary research, regulations, and practices on the impacts and management of soil compaction in the Pacific Northwest. This discussion will present a case for a need and some desirable directions for refining our views and policies on ground-based timber harvest, in order that forest managers and operators can more consistently achieve resource conservation objectives in a cost-effective manner.

Early Research

Because of the strong historical connection of soil science to agriculture, much of the early research on forest soils in the U.S. was patterned after concerns and methods that emerged from farming and grazing. With the increase of both mechanized agriculture and intensive grazing, soil compaction and related problems were widely observed and studied, and this experience and research literature provided the foundation for the first comprehensive review of forest soil compaction nearly 50 years ago (Lull 1959). Researchers in the Pacific Northwest were among the first to study the nature and impacts of forest soil compaction, including negative effects on seedling growth (e.g., Pearse 1958; Steinbrenner and Gessel 1955; Youngberg 1959).

Expanded Studies & Outreach

After a relative lull in compaction research in the region in the 1960's, Dr. Henry A. Froehlich reviewed and again called attention to the issue (e.g., Froehlich 1973), which prompted nearly two decades of expanded research by him, his students and other investigators. Much of this work is summarized in two comprehensive review papers (Froehlich and McNabb 1984; Cafferata 1992). Key findings included many examples of soil compaction from skidding with both tracked and wheeled logging vehicles over a wide range of soil types, and multiple observations of related growth reductions in seedlings of several commercial tree species.

As the scope of both the occurrence and the negative impacts of compaction became clearer, a pointed effort was made by Oregon State University to inform forestry professionals, loggers and landowners about the problem as well as solutions such as designated skid trails and tillage. Key activities included seminars, short courses, field training, publications, and audio-visual programs (Adams and others 1985). Between 1981-90, over 2,200 individuals attended these programs and thousands more acquired or viewed the publications and audio-visual programs (Adams 1994).

Policies & Practices Adopted

As research and awareness about soil compaction began to grow significantly in the 1970s, federal managers and resource specialists in the Pacific Northwest became concerned that logging-related soil impacts could conflict with the resource protection mandates of laws such as the National Forest Management Act of 1976. Thus, they initiated their own reviews of potential soil compaction problems and solutions. Among the key documents that emerged was a "Soil Compaction Study Task Force" report (Cornell and others 1977), which pointedly concluded: "we believe prudent land management should limit the extent and degree of compacted soil."

Soon after, specific soil protection guidelines were developed (e.g., Boyer 1979) and some were codified in administrative handbooks and manuals (e.g., USDA Forest Service 1983). Formal policies to manage soil compaction on state and private lands initially were much more limited, but the substantial research and extension activities of the 1970s and 80s combined with the widely visible federal policies stimulated broad interest, leading to less formal efforts among many forest managers, landowners and operators. By the late 1980s, for example, the use of designated skid trails was a relatively common practice in the region, regardless of ownership.

Because of the scope and duration of their application and influence, the 1983 Region 6, USDA Forest Service standards for defining and managing soil compaction are briefly highlighted here:

> *"The total acreage of all detrimental soil conditions [e.g., compaction] should not exceed 20% of the total acreage within the activity area." Detrimental compaction is defined primarily as "an increase in soil bulk density of 15% or more over the undisturbed level…"*

This area limitation for soil compaction prompted the use of not only designated skid trails, but also soil tillage as means for mitigation in situations where such trails were less practical or where previous harvest entries had created significant existing areas of compacted soil.

Some Changes & Surprises

Soil moisture – Early knowledge gained from engineering studies and soil testing had a direct influence on some of the initial directives for the management of soil compaction from logging operations. Specifically, the "Proctor Test" showed that soil moisture was an important variable in the degree of compaction that resulted from heavy loads, which suggested that compaction could be significantly reduced by restricting operations to periods of lower soil moisture levels. As a result, directives such as the following were adopted by some managers (BLM 1976), along with the "Speedy Moisture Testers" that were often used to monitor moisture in the field:

"A. Tractors – Limit operation to the period when soil moisture is below 25%."

However, the relationship between moisture and compaction can vary greatly with soil type and with the amount and type of applied energy. And further studies of these relationships specifically for forest soils and loads from logging vehicles strongly suggested that soil moisture limits were a relatively inconsistent or ineffective policy for controlling the degree of soil compaction (Froehlich and Robbins 1983; Froehlich and others 1983). Whether or not these particular studies were influential, the use of specific moisture limits to manage compaction declined significantly in the 1980s.

Soil tillage – The agricultural roots of concern and knowledge about soil compaction extended to one of the key approaches for its mitigation on forest lands, i.e., tillage. However, initially both the terminology and tools for tilling compacted forest soils focused on what was most familiar and readily available, and thus "ripping" with crawler tractors normally used for logging and forest road and skid trail construction became more common. In some cases, front-mounted brush blades with tines were used on compacted soils in a manner similar to scarification for site preparation for reforestation. Likewise, a tool designed for another purpose, i.e., the rear-mounted rock ripper, was often used to loosen compacted forest soils.

But as research began to better clarify the degree and depth of forest soil compaction from logging vehicles, important questions arose about the efficacy of rippers and brush blades for mitigating compaction problems. In the early 1980s an important study (Andrus and Froehlich 1983) compared the relative effectiveness and costs of various tools for treating compaction over a range of forest soil types and site conditions. Among the key findings was that in operational treatments a "winged subsoiler" with three long (36 in.) shanks loosened over 80 percent of the compacted soil in skid trails. This was 2-4x greater than the volume loosened by conventional rock rippers and brush blades, an observation that helped lead to relatively common policies and contract language for tillage specifically with winged subsoilers (e.g., BLM 1995).

Timber & machines – The initial concerns and reactions regarding forest soil compaction in the region emerged at a time when larger timber and yarding vehicles were still relatively common. Even in the 1970s, the potential for reducing soil compaction through logging vehicle design and selection was studied (Froehlich 1978) and recognized through operational guidelines (e.g., BLM 1976). Since the 1970s, however, changing policies and timber availability on both public and private lands led to a significant trend towards operations in smaller, denser timber and more mechanized and sophisticated ground-based logging systems.

Perhaps because of the scattered and gradual nature of the shift in operations and equipment over the past three decades, the questions and concerns about soil compaction under these newer conditions received somewhat less attention and focus. Nonetheless, research and monitoring confirmed that despite their unique design and use, highly mechanized systems (e.g., harvesters and forwarders) for logging younger and smaller timber have the potential to produce significant soil compaction (Allen and others 1999; Cafferata 1992; Powers and others 1999).

Other notable findings – Although most research in the region has confirmed that forest soil compaction should remain an important concern for resource managers, with time and more refined investigation a growing number of studies have shown results that vary from common expectations and reveal the inherent complexity of the issue. For example, Miller and others (1996) showed that although soil compaction was evident 8 years after tractor harvest of sites in coastal Washington, average height and volume of trees planted on skid trails differed initially from uncompacted areas but then recovered and became comparable. A similar study in the Oregon Cascades also showed a trend of growth recovery over time, although after 10 years planted trees in skid trail ruts remained smaller than in uncompacted areas (Heninger and others 2002). Although growth effects were not examined, Craigg (2000) found little or no difference in soil strength in skid trails on coarse pumice soils in central Oregon.

A study of trees planted on a range of soil types in northern California (Gomez and others 2002) showed a comparably wide array of growth responses to compaction, from negative to positive. The positive response occurred in a sandy soil, whose available water holding capacity increased with compaction. In a study of 7-years of post-thinning growth in second-growth Douglas-fir in western Oregon (Martinez-Ben and others 2000), trees next to designated skid trails grew better than trees between the trails, presumably because of better release and the limited area of compacted soil. Similar findings have been observed in thinned stands with planned skid trails elsewhere in the region (R.E. Miller, personal communication).

Current Issues & Needs

The changes and more recent findings described above strongly suggest that the effects and management of soil compaction are not as simple as initially believed, and yet many perceptions, practices and policies continue to reflect historical rather than contemporary knowledge and operating realities. I will conclude with a brief discussion of some areas where I believe further work is needed to adequately refine our understanding and management of forest soil compaction, i.e., bring them into the 21st century.

Tree & plant responses – Central to ongoing concerns about forest soil compaction are potential growth impacts to trees and other vegetation. Yet when questions are asked about what impacts can be expected for a specific forest site and harvest situation, reliable answers become elusive. Thus, Miller and Anderson (2002) state: "uncertainty about the consequences of soil compaction …will remain until tree performance is reliably measured over a wide range of regional soils and climatic conditions, and over a long period of time." The phrase "reliably measured" is notable because accurate interpretation of growth effects must account for confounding influences such as competing vegetation (Powers and others 1998).

Hydrologic effects – Research has shown the importance of changes in hydrologic properties of compacted forest soils in explaining growth effects (e.g., Gomez and others 2002), yet data on these changes remain uncommon. Not only have changes in plant-moisture availability from compaction been infrequently documented, so too have effects on infiltration and drainage. While some reduction in infiltration from compaction is a reasonable expectation, the scope of this change (both degree and area) is key to whether surface runoff becomes a management concern. And without such data, it is difficult to directly address an administrative appeal that states: "there is no baseline against which to gage the [hydrologic] effects of the proposed [federal forest management] project (League of Wilderness Defenders – Blue Mountains Biodiversity Project vs. Leslie Weldon, 2003)."

Management measures – The current array of management prescriptions, harvest systems and machine types creates a much greater number of potential combinations than existed 2-3 decades ago. Although research has examined some of these pieces, the picture of the specific or relative costs (including resource impacts) and benefits of the various options remains incomplete due to some key gaps and a lack of a problem-solving analytical approach. For example, although they are widely considered beneficial, I am aware of only two case studies in the region that have documented the resource benefits of designated skid trails (Martinez-Ben and others 2000) and of slash accumulation on skid trails by harvesters (Allen and others 1997).

And with the exception of a recent general discussion (Murphy and Adams 2005), the only economic analyses of soil compaction or its management, date back to the 1980s (Andrus and Froehlich 1983; Stewart and others 1988).

Policy refinement – The aforementioned Forest Service Region 6 regulation for managing soil compaction (USDA Forest Service 1983) has been virtually unchanged for nearly a quarter-century. Although time passage alone does not justify policy changes, the effectiveness of this policy has never been fully validated nor does it account for the evolution in harvest systems and management objectives (e.g., fuel reduction, wildlife habitat). Powers and others (1998) also note limitations of such a bulk density-based standard, which led to a soil-specific, porosity-based standard in Region 5. Efforts are underway to assess and refine the Region 6 standard, at least for eastside forests (R.E. Miller, personal communication), and such renewed attention seems well deserved. For example, even in the absence of formal directives, budget constraints are forcing resource managers to prioritize practices such as soil tillage based on local experience (e.g., Craigg 2000). Perhaps this review and discussion can help stimulate further efforts to refine our understanding and management of forest soil compaction in the Pacific Northwest.

Acknowledgements

This paper would not have been possible without the knowledge and inspiration provided by Hank Froehlich, Jim Boyle, Dick Miller, and Bob Powers, as well as the questions, support and experience of countless graduate students, research assistants, and forest managers and operators.

Literature Cited

Adams, P.W. 1994. Extension education programs on the impacts and management of forest soil compaction in the PNW, U.S.A. In: Proc. Soil, tree, machine interactions in forest operations, FAO/ECE/ILO Forsitrisk Working Group and IUFRO Working Group P3.08.00, Feldafing, Germany.

Adams, P.W., Garland, J.J. and Froehlich, H.A. 1985. Research and extension programs lead to effective management of forest soil compaction in the Pacific Northwest. p. 121-124 in: Proc. Soc. Am. Foresters National Conf., Ft. Collins, CO.

Allen, M.M., Taratoot, M. and Adams, P.W. 1999. Soil compaction and disturbance from skyline and mechanized partial cuttings for multiple resource objectives in western and northeastern Oregon, U.S.A. p. 107-117 in: Proc. Intl. Mountain Logging and 10th Pacific Northwest Skyline Symp., Forest Engr. Dept. Oregon St. Univ., Corvallis.

Allen, M.M., Adams, P.W. and Kellogg, L.D. 1997. Soil bulk density and cone index after harvester and penetrometer cone index after harvester and forwarder traffic over different slash depths in the Oregon Cascades. Project completion report, Weyerhaeuser Foundation. Forest Engineering Dept., Oregon State Univ., Corvallis. 42 p.

Andrus, C.W. and Froehlich, H.A. 1983. An evaluation of four implements used to till compacted forest soils in the Pacific Northwest. Research Bull. 45., For. Res. Lab, College of Forestry, Oregon State Univ., Corvallis. 12 p.

BLM. 1995. Record of decision and resource management plan – Eugene District. USDI Bureau of Land Management. Eugene, OR.

BLM. 1976. Guidelines to minimize soil compaction. Roseburg District, USDI Bureau of Land Management, Roseburg, OR. 5 p.

Boyer, D. 1979. Guidelines for soil resource protection and restoration for timber harvest and post-harvest activities. Watershed Management, Pacific Northwest Region, U.S. Forest Service, Portland, OR. 43 p. plus appendices.

Cafferata, P. 1992. Soil compaction research. P. 8-22 in: Skaugset, A., ed., Forest soils and riparian zone management: The contributions of Dr. Henry A. Froehlich to forestry. College of Forestry, Oregon State Univ., Corvallis.

Cornell, B., Davies, G., Lanspa, K., Rowe, B., Sherell, A., Studier, D., Wickman, B., Roy, D. and Meurisse, R. 1977. Report on the findings of the Soil Compaction Study Task Force, Regions 5 and 6 and PSW Station. USDA Forest Service. 61 p. plus appendices.

Craigg, T. 2000. Subsoiling to restore compacted soils. In: Proc. 21st Ann. Forest Vegetation Mgmt. Conf., Redding, CA.

Froehlich, H. A. 1978. Soil compaction from low-ground pressure torsion-suspension logging vehicles on three forest soils. Res. Paper 36, For. Res. Lab., Oregon State Univ., Corvallis.

Froehlich, H.A. and McNabb, D.H. 1984. Minimizing soil compaction in Pacific Northwest forests. P. 159-192 in: Proc. Sixth N. Am. Forest Soils Conf. Univ. Tennessee, Knoxville.

Froehlich, H.A. and Robbins, R.W. 1983. The influence of soil compaction on young tree growth on the Yakima Indian Reservation. Final report to the Confederated Tribes and Banks of the Yakima Nation. Contract T82-6745. School of Forestry, Oregon St. Univ., Corvallis. 83 p.

Froehlich, H.A., Robbins, R.W., Miles, D.W.R. and J.K. Lyons. 1983. Monitoring recovery of compacted skidtrails in central Idaho. Soil monitoring project report on Payette National Forest and Boise Cascade lands, Contract 43-0256-2-543. Oregon State Univ., Corvallis. 58 p.

Gomez, A., Powers, R.F., Singer, M.J. and Horwath, W.R. 2002. Soil compaction effects on growth of young ponderosa pine following litter removal in California's Sierra Nevada. Soil Sci. Soc. Am. Jour. 66:1334-1343.

Heninger, R., Scott, W., Dobkowski, A., Miller, R., Anderson, H. and Duke, S. 2002. Soil disturbance and 10-year growth response of coast Douglas-fir on nontilled and tilled skid trails in the Oregon Cascades. Canadian Jour. Forest Research 32:233-246.

Lull, H.W. 1959. Soil compaction on forest and range lands. Misc. Pub. 768. USDA Forest Service, Washington, DC.

Martinez-Ben, J., Hogervorst, J. and Adams, P.W. 2000. Soil density and tree growth several years after thinning and tillage in a Douglas-fir stand in western Oregon, U.S.A. Poster paper, Intl. Symp. Managing Forest Soils for Sustainable Productivity, Sept. 2000, Vila Real Portugal.

Miller, D. and Anderson, H. 2002. Soil compaction: concerns, claims, and evidence. P. 97-106 in: Baumgartner, D.M. and others, eds., Proc. Conf. Small Diameter Timber. Washington St. Univ. Coop. Ext., Pullman.

Miller, R.E., Scott, W. and Hazard, J.W. 1996. Soil disturbance and conifer growth after tractor yarding at three coastal Washington locations. Can. Jour. For. Res. 26:225-236.

Murphy, G. and Adams, P.W. 2005. Harvest planning to sustain value along the forest-to-mill supply chain. P. 17-23 in: Proc. Conf. on Productivity of Western Forests: a Forest Products Focus, Sept. 2004, Olympia, WA. (in press)

Pearse, P.H. 1958. A study of the effects of soil compaction on the early development of seedlings of Douglas-fir and western hemlock. Res. Note 16. Univ. British Columbia, Vancouver.

Powers, R.F., Alves, T.M. and Spear, T.H. 1999. Soil compaction: can it be mitigated? Reporting a work in progress. P. 47-56 in: Proc. 20th Ann. Forest Vegetation Mgmt. Conf., Redding, CA.

Powers, R.F., Tiarks, A.E. and Boyle, J.R. 1998. Assessing soil quality: Practicable standards for sustainable forest productivity in the United States. p. 53-80 in: E. Davidson and others (eds.), The contribution of soil science to sustainable forest management. SSSA Special Pub No. 53. Soil Sci. Society of America, Madison, WI.

Steinbrenner, E.C. and Gessel, S.P. 1955. The effect of tractor logging on physical properties of some forest soils in southwestern Washington. Soil Sci. Soc. Am. Proc. 19:372-376.

Stewart, R., Froehlich, H. and Olsen, E. 1988. Soil compaction: an economic model. W. Jour. Appl. For. 3(1):20-22.

USDA Forest Service. 1983. Title 2500 – Watershed Management, Region 6 Supplement No. 45. Forest Service Manual. Portland, OR.

Youngberg, C.T. 1959. The influence of soil conditions following tractor logging on the growth of planted Douglas-fir seedlings. Soil Sci. Soc. Am. Proc. 23:76-87.

STREAM-CROSSING-STRUCTURES IN FOREST ROAD CONSTRUCTION: CLASSIFICATION OF EXISTING CONSTRUCTION SOLUTIONS AND THEIR INFLUENCE ON THE CONTINUUM FLOW OF RUNNING WATERS[1]

Thomas Steinmüller[2] and Andreas Pichler[3]

Abstract

The consideration of ecological needs in planning and/or maintaining of forest roads will be intensified with the "EU-Water Framework Directive (WFD)", which became effective in Austria in December 2000. The WFD prescribes to obtain a "good ecological state" through 2015 with regards to feasibility of the migration of aquatic organisms in torrents and rivers. Therefore stream crossing structures and migration facilities must, in theory, be adapted to maintain migration of all aquatic organisms, including small and young fish as well as macrozoobenthos.

The range of construction possibilities for stream crossing structures in alpine torrents and rivers is limited, due to Austrian conditions. Culverts, bridges and fords – with an extended variation of model type, geometry and building material – are used in forest road construction. In some cases, creative and individual solutions have been developed to overcome the migrational obstacles.

After a detailed literature review, it becomes evident, that a continuous classification of stream crossing structures in forest road construction is missing. Both terminological as well as function-oriented uncertainties exist in the use of such construction solutions. Therefore, there is a need for revision and systemization. Through an extensive evaluation (in the field

---

[1] This paper was presented at the 28th Annual COFE Meeting: Soil, Water and Timber Management: Forest Engineering Solutions in Response to Forest Regulation. July 11-14, 2005, Scotia and Fortuna, California.

[2] University of Natural Resources and Applied Life Sciences Vienna, Institute of Forest Engineering, 1190 Vienna, Peter-Jordan-Str. 82, email: thomas.steinmueller@boku.ac.at

[3] University of Natural Resources and Applied Life Sciences Vienna, Institute of Mountain Risk Engineering, 1190 Vienna, Peter-Jordan-Str. 82, email: andreas.pichler@boku.ac.at

and technical documents) of culverts used in Austrian forests, this paper gives a preview to a developed classification system and hints to the culvert´s potential to impair and/or modify ecological operability. As a result of this classification, an assessment of the "Constructive Functionality" of the selected design type will be achieved. This "Constructive Functionality" should be seen as part of a total functionality assessment, which will offer the chance to reduce the costs of later expensive modifications already during the planning phase.

Keywords: Classification system, Fish migration impediment, Forest road construction, Stream crossing structures

Introduction

Forest road construction in Austria

More than 47% of Austria's federal territory is covered with forests. Due to the great variety of landscapes in Austria, a multitude of different growth conditions exists. Differences in sites, over rather small-scale areas, characterize these forests. Twenty-five percent of Austria's forests are considered protected forests of which the majority (64%) have slopes steeper than 60% (BMLFUW 2005).

Of the many factors influencing the Austrian forests today, the most important is the intensification of forestry and changing public interests and demands. Human influence is reflected in the changing species composition of forests, introduction of alien species, air pollution, fast erosion in areas disturbed by human activities, fires started by humans (voluntary or involuntary) and forest road construction.

A dense forest road network was constructed in Austria after the Second World War. The mean road density is 48 m/ha in commercial forests and 45 m/ha in protected forests, including effective public roads. In total, there are about 150,300 km of forest roads (this figure does not including skyline or skid-trails) in Austria (BFW, 2005). Figure 1 provides a description of forest roads in Austria by ownership type, usage rights and road surface material. The majority of Austrian forest roads (92,600 km) are owned by small-scale forest owners, who own approximately half of the forested land.

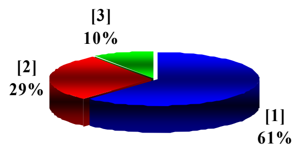
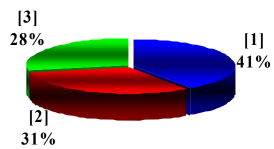
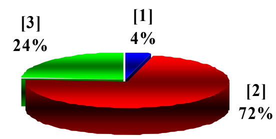
Ownership type	Usage rights	Road surface material
Small-Scale Forest Owners: 92,600 km [1] **Forest Enterprises > 200 ha: 42,900 km [2]** **Austrian Federal Forests: 14,800 km [3]**	**Private Roads (single ownership): 61,100 km [1]** **Private Roads (shared ownership): 46,900 km [2]** **Public Roads: 42,300 km [3]**	**Dirt: 6,200 km [1]** **Gravel: 107,700 km [2]** **Asphalt: 36,400 km [3]**
		

Figure 1: Description of forest roads in Austria by ownership type, usage rights and road surface material.

Forest road construction is examined through various lenses. On the one hand, it represents the precondition for ensuring the recovery, use, protection, and welfare function of forests and forest resources (see WUETHERICH 1992). On the other hand, it represents impacts on ecological systems, the landscape, and landscape experiences which, in some cases, are judged unfavourable (e.g. OLSCHOWY 1975). Because a comprehensive systemization of the various impacts does not exist, due to missing or insufficient approaches in their description, stream crossings are not compatible with state-of-the-art design (see GUNDERMAN 1978).

In Austria, a great potential still exists for forest road construction. This has been particularly clarified by the growing availability for European Union subsidies in the last years (STEINMÜLLER and STAMPFER 2004). In the next 10 years, new forest roads will be necessary to fulfil all the various public interests and demands of the Austrian forests. Along with this realization, it is of the utmost importance to consider forest protection through the careful development of roads especially in the mountainous landscapes inherent to Austria. The consideration of technical, socio-economic, and ecological concerns for planning purposes is due to the sensitive and diverse range of demands that exist today. The straightforward, increased dissemination of general knowledge and information has lead to an increased sensitivity of society in relation to the negative effects of implemented measures and determine, thereby also, the acceptance level for the implementation of new planning projects (e.g. USDA Forest service 1999). Finally, the consideration of ecological needs in planning and/or maintaining of both existing and future planned forest roads will be intensified with the "EU-Water Framework Directive".

The European Water Framework Directive (WFD)

The Directive 2000/60/EC of the European Parliament and of the European Council of 23th October 2000 established a framework for community action in the area of water policy. This framework is called the Water Framework Directive or WFD and represents a completely new orientation and organisation of European water policy, moving clearly away from merely a use-oriented approach to a more ecological consideration of waters. The central aim, as stated before, is to achieve a “good status” for all European water bodies by the deadlines set. A “good status” is mainly defined by biological parameters with consideration for the specific water type. It also suggests that there should be as little as possible anthropogenic modification from the water body’s natural state.

In Austria, the EU Directive 2000/60/EC (WFD) was incorporated into national legislation by an amendment of the Water Rights Act 1959 in December 2003. A central element of the "new" Water Rights Act (WRA) is the preparation, evaluation, and further development of water management planning (National Water Management Plans and others) to reach and retain the environmental objectives set forth by the WFD for all waters. Accordingly, the amendment contains changes, primarily, in the articles referencing the protection and keeping clean of waters ("objectives"), amendments of the provisions on water management planning and – in the new Article 7 of the WRA – the integration of the monitoring provisions formerly regulated under a special hydrology act. The interaction of the provisions on water management planning with those on the protection and the keeping clean of waters are now ruled by the principle of sustainability (i.e. the management of waters in terms of the social, economic, and ecological needs for present and future generations).

The deterioration ban, now explicitly laid down in the law, does not permit any deterioration from the water body’s current state. This means that e.g. a surface water body, which has a “very good status”, must not be downgraded to a “good status”. An absolute deterioration ban would prohibit any human interference with waters, which cannot be seriously expected from anyone. Currently, deviations from purely ecological objectives are allowed under the WFD and WRA 1959. For this to happen, an assessment is conducted in proceedings by the water management planning body in the framework of an examination of public interests. Deviations are only possible if projects do not downgrade the hydromorphology of a water body or change the discharge of pollutants from, for example, “very good” to “good”. Only within this restrictive framework can authorities approve deviations. Finally, authorized deviations are to be included in the Nation Water Management Plan (NWMP), which is prepared with public cooperation.

Austria's water bodies have been examined to see whether or not they would meet compliance requirements of the WFD by 2015. Seventeen percent of the running waters were assigned to a category of "no risk" for non-compliance and 41% to a category of "safe risk" for non-compliance. For 42% of the running waters, a risk classification was not possible. They were assigned to a third category ("risk not classifiable").

In this first examination of Austria's water bodies, it was found that there was a relatively high share of water bodies that could be considered "candidates for heavily modified water bodies". Two primary causes for this were identified as intensive use of water power and intensive use of flood control measures, including stream crossing structures of public and forest road networks required in alpine areas. Stream crossing structures cut torrents and rivers into sections and diminish the potential for migration of aquatic organisms. Traversing of water channels (e.g. stream crossing structures) leads to a potential interruption of the river/brook continuum (VANNOTE et al. 1980), whereby the type of construction has a substantial influence on the migration for macrozoobenthos and fish fauna (see BRUNKE et al. 1994). Stream crossing structures also impact water temperature, oxygen content, hydraulic characteristics (discharge depth, flow velocity of flow etc.), and substrate characteristics (e.g. NEUMANN 1979; MUHAR et al. 1986).

Stream crossing structures and migration facilities must, in theory, be adapted to maintain migration of all aquatic organisms, including small and young fish as well as macrozoobenthos. In Austria, forest road construction, usually stream crossing structures like fords, culverts or bridges are used, with variation of type, geometry and building material. Their potential influence on the river continuum and thus the maintenance of the migration facility for macrozoobenthos and fish fauna is more or less unexplained. Because of this, suitable action strategies are greatly needed for Austrian forestry. With these action strategies, fulfilment of criteria set forth by the WFD can be achieved.

Derivation of Classification Attributes

After a detailed literature review it becomes evident, that a continuous classification of stream crossing structures in the field of forest road construction is missing. Both terminological as well as function-oriented uncertainties exist in the use of such construction solutions. Therefore, there is a need for revision and systemization.

It is necessary to develop a comprehensive system of definitions which includes the entire range of existing stream crossing structure solutions and puts them in a logical order. Beyond that, possible conceivable future construction solutions must be integrated into such a typology. Based on the idea that the function of the stream crossing structure does not characterize the definition system; rather its constructional arrangement does, clear characteristics must be found which can be divided into a hierarchical pattern. By the combination of such characteristics, a multipart nomenclature can be composed.

A basic condition for setting up a multipart nomenclature is conceptual exactness. To do this, the definition should be standardized (OENORM, DIN, EN) in metrics. The first important attribute to consider is the definition of the constructional partitions of stream crossing structures.

The second attribute to consider is "levels of stream crossings". Crossing of a water channel with a barrier (e.g. forest road) can result in different water heights levels. Also, the change of the altitude of the barrier must be considered with the choice of an adapted stream crossing structure (see DIN 19661, sheet 1).

The last attribute to consider is "limitation of the river bed". Currently ecological operability of these structures is not or is only weakly considered by such an identifier. This attribute implies, at the same time, the potential degree of the impairment and/or modification of the ecological operability of the channel section which will be caused by the extension of the stream crossing structure. Figure 2 gives a preliminary overview of existing stream crossing structures in connection with level of crossings and limitation of the river bed; expansions and modifications will be necessary.

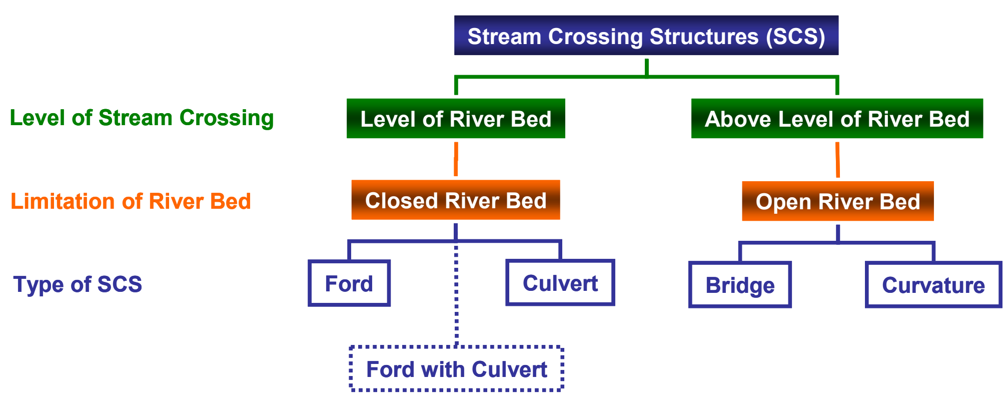


Figure 2: Stream crossing structures – construction possibilities due to Austrian conditions.

Evaluation of Stream Crossing Structures in Forest Road Construction (field study)

The evaluation of stream crossing structures took place in summer 2004 in the Forest Demonstration Centre of the University of Natural Resources and Applied Life Sciences, Vienna, which is located in the eastern part of the country in the federal state of Lower Austria. Table 1 provides important characteristics (climate, forest area, slope, elevation, standing volume etc.) of the Forest Demonstration Centre.

Table 1: Forest Demonstration Centre – characteristics.

	Value	Unit
Climate		
Annual average temperature	6.5	°C
Annual average rainfall	796	mm/y
Forest		
Forest Area	930	ha
Elevation	300-750	m
Terrain Slope	0-60	%
Standing volume	330	m^3/ha
Main Tree Species	Spruce, Larch, Pine, Beech, Oak	-
Average road density	56	m/ha

Culverts and bridges are the primary stream crossing structures in this region. A database was created in order to classify these existing stream crossing structures. The criteria have been subdivided into culvert data, stream data and data of ecological functionality.

In this evaluation only culverts were considered as stream crossing structures. In total, 35 culverts were analyzed. Thirty-two of all culverts were circular in shape and made out of concrete. The shape, material, number of cells, dimensions (width, height, length, and wall thickness), inclination, deviation and coverage of all 35 culverts are shown in Table 2.

Table 2: Culvert Data.

Data	Description	Value	Unit
Shape	Circlular	32	[n Culverts]
	Eg	2	
	Elliptical	1	
	Total	*35*	
Material	Concrete	35	[n Culverts]
Cells	Number of cells	1/2/1	[n Cells] (min/max/average)
Dimensions	Width	0.30/1.20/0.58	[m] (min/max/average)
	Height	0.30/1.20/0.59	
	Length	6.10/16.90/9.62	
	Wall thickness	0.04/0.15/0.07	
Inclination	Inclination of culverts	0/17/7	[%] (min/max/average)
Deviation	Deviation in relation to the forest road	0/46/11	[gon] (min/max/average)
Coverage	Maximum depth of coverage	0.20/2.50/0.97	[m] (min/max/average)

The average culvert in the Forest Demonstration Centre has one cell with a width and height of approximately 0.6 m, a length of 9.6 m and a wall thickness of 0.07 m. The inclination ranges from 0 to 17% (average value: 7%). There is great variation with the deviation in relation to the forest road. This ranged from 0 to 46 gon (average value: 11 gon). Depending on the situation of terrain conditions, the maximum depth of coverage has an average value of approximately 1 m.

The second part of the analysis is a description of the streams and deals mainly with the type of aquifer system, inclination of river bed, grain diameter and roughness (Table 3).

Table 3: Stream Data.

Data	Description	Value	Unit
Aquifer system	Perennial	24	[n Streams]
	Episodical	11	
Inclination of river bed	Upside of the structure	0/35/10	[%] (min/max/average)
	Downriver of the structure	0/70/19	
Grain diameter	-	0.01/0.05/0.01	[m] [%] (min/max/average)
Roughness	-	10/30/18	[kst] (min/max/average)

About two thirds of all streams have a perennial aquifer system, one third an episodical one. There is a great variance in the inclination of river beds with average values of 10% (upside) and 19% (downriver). The medium grain diameter is about 0.01 m, and roughness ranges from 10 to 30 kst (average value: 18 kst).

The last part of the analysis answers describes ecological functionality. The most important parameters within this part of the study are the barricade form, height of fall and ascendancy, and pool dimension (Table 4).

Table 4: Data on Ecological Functionality.

Data	Description	Value	Unit
Form of barricade	11 definite types	-	-
Height of fall	-	0.00/60.00/1.83	[m] (min/max/average)
Height of ascendancy	-	0.00/0.50/0.04	[m] (min/max/average)
Pool – dimension	Running in	0.00/0.36/0.04	[m²] (min/max/average)
	Runout	0.00/0.50/0.04	

Fish passage is highly correlated with height of fall, height of ascendancy, and the dimensions of existing pools. The results show a wide range exists among these parameters.

Form of barricade has been classified into 11 types (4 basic- and 7 subtypes). Type A has no pool or ramp, B has one of them only at runout, C at running in and D uses pools and ramps on both sides of the culvert (Figure 3).

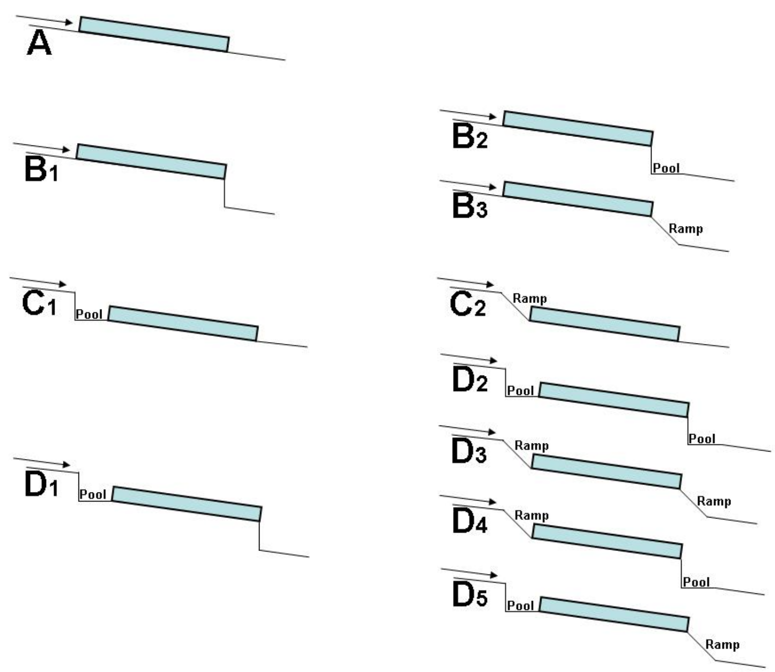


Figure 3: Form of barricade in stream crossing structures.

At 18 stream crossings (A) there is neither a pool nor a ramp connected with the culvert; in these cases the migration for fish and macrozoobenthos is guaranteed. 12 crossings (B) need a pool or ramp at runout and 5 at both sides of the culverts. C (barricade only at running in) was not observed (Figure 4).

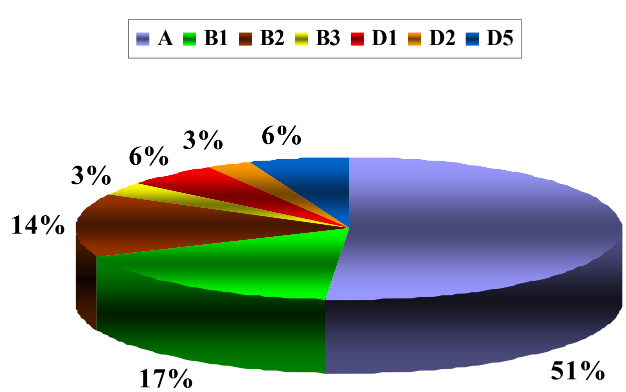


Figure 4: Percentage of various forms of barricades in stream crossing structures.

Summary

The “EU-Water Framework Directive” became effective in Austria in December 2000 and prescribes to obtain a “good ecological state” through 2015. For forest road construction this means mainly that stream crossing structures can not cut torrents and rivers into sections and can not disturb the migration of all aquatic organisms, including small and young fish as well as macrozoobenthos.

While migration should be an important consideration for those responsible for forest road construction, currently, it is not. The culverts examined in the study are representative of the stream crossing structures in much of Austria, especially in the east. The results show that there is no variance in material and only little in dimension. Also, the condition of culverts, in many cases, is poor, due to blockage and broken material. Approximately 50% of culverts limit migration as a result of barricades. Expert recommendations to improve ecological operability would be the use of different materials (e.g. corrugated plastic culverts) and more customized dimensions to suit the particular type of stream.

This study shows only a preview to a developed classification system and hints to the culvert´s potential to impair and/or modify ecological operability. Further studies will be necessary to classify other types of stream crossing structures, mainly fords and bridges. This project was only the first step in a total functionality assessment. A complete assessment will offer the chance to reduce the costs of later expensive modifications.

References

Forest Service Serial Publications (Washington Office)

USDA Forest Service (1999): Roads Analysis: Informing Decisions about Managing the National Forest Transportation System. Misc. Rep. FS-643; 222 p; Washington, D.C.

Journal Articles

BRUNKE, M.; SCHWOERBEL, J.; WENDLING, K. (1994): Die Auswirkung eines Flusstunnels auf die Fließgewässerbiozönose: Makrozoobenthon und Fischfauna. Limnologica 24(4): 297-322.

NEUMANN, H. (1979): Auswirkungen wasserbaulicher Maßnahmen auf die aquatischen Lebensgemeinschaften und das Selbstreinigungsvermögen von Fließgewässern. – Osnabrücker naturw. Mitt. 6:123-161.

OLSCHOWY, G. (1975): Straße und Umwelt. Natur und Landschaft, 50. Jg., Heft 12: 337-343.

VANNOTE, R.L.; MINSHALL, G.W.; CUMMINGS, K.W.; SEDELL, J.R.; CUSHING, C.E. (1980): The river continuum concept. Can. J. Fish. Aquat. Sci. 37: 130-137.

WÜTHERICH, W. (1992): Die Feinerschließung von Waldbeständen – Planung, Anlage und Benützung. Berichte der Eidgenössischen Forschungsanstalt für Wald, Schnee und Landschaft, 332, 91 S., Flück-Wirth, Birmensdorf.

Serial Reports

GUNDERMANN, E. (1978): Die Beurteilung der Umwelteinwirkungen von Forststraßen im Hochgebirge: Eine Delphi-Studie. Forschungsbericht FFA München, Nr. 41, 453 S., München.

Nonserial Reports

BFW (2005): Stand der Walderschließung in Österreich – Ergebnisse der Waldinventur 1992/96. Electronic document: http://www.bfw.ac.at

BMLFUW (2005): Nachhaltige Waldwirtschaft in Österreich. Österreichischer Waldbericht – Datensammlung 2002. Electronic document: http://www.lebensministerium.at

MUHAR, S., KAINZ, M., KAUFMANN, M.; SCHWARZ, M. (1986): Ausgewählte Parameter zur Erfassung und Bewertung von Fließgewässerlebensräume und ihre biozönotische Relevanz. In: Ausweisung flusstypspezifisch erhaltener Fließgewässerabschnitte in Österreich. BMLF (Hrsg.), 1996.

STEINMÜLLER, TH.; STAMPFER, K. (2004): ROADEVAL – Evaluierung der waldbaulichen, forsttechnischen und sozioökonomischen Effekte forstlicher Erschließungsmaßnahmen. Eigenverlag des Institutes für Forsttechnik der Universität für Bodenkultur Wien. 32 S.

Books or Monographs

DIN (1995): Wasserbau 1 – Stauanlagen, Stahlwasserbau, Wasserkraftanlagen, Wasserbauwerke, Schöpfwerke. DIN-Taschenbuch 179. 560 S.

Effectiveness monitoring for culverts as fish passage structures at road crossings: a surrogate measurements approach

E. George Robison[1]

Abstract

Traditionally, best management practice (BMP) monitoring approaches have been distinguished as either being compliance based (i.e., was the practice successfully done according to plan or regulation guidelines) versus effectiveness based (i.e. is the practice itself effective in achieving the stated objectives of the practice). For effectiveness monitoring of fish passage structures at road crossings, a hybrid of the two approaches may be one of the most efficient ways to do effectiveness monitoring. The ultimate measure of effectiveness for fish passage would be to track fish moving through the structure. However, many streams have so few fish remaining that this approach would be nearly impossible. In other cases, the trapping and tagging of rare fish species may cause unnecessary harm. Since fish species have known performance criteria in terms of swimming speed and jumping ability, surrogate measures such as culvert slope, bed roughness, and drops in and around the culvert can be measured to determine if an installed culvert can provide fish passage. In this paper, the advantages and disadvantages of this approach will be contrasted with direct effectiveness monitoring. It will also list some of the supporting research that ensures these surrogate measures line up with actual effectiveness. In addition, key components of a surrogate measurements effectiveness monitoring approach will be given, that not only measure criteria such as stream slope and drops in and around culvert, but also diagnose why problems areas develop because of failures in design or installation. This approach can be critical to conducting adaptive management to improve policy, regulatory guidelines, or to improve design and installation practice.

Introduction

The lack of fish passage at road crossings has been identified as a major issue that may be restricting the recovery of salmonid species in several reports. Barriers at road crossings occur on federal (GAO 2001) as well as state and private land (Conroy, 1997). There is currently much activity in replacing culverts and in

---

[1] Assistant Professor Forest and Watershed Management Department, College of Natural Resources and Sciences; Humboldt State University; 1 Harpst Street Arcata CA 95521; Phone: 707-826-3258; Fax: 425-491-2815; email: egr2@humboldt.edu

assessing and prioritizing which ones need replacing. There is a need to have tools to monitor these activities to indicate their effectiveness. However, direct measurement of success by measuring actual fish passage at each crossing can be expensive and nearly impossible due to lack of fish. Using surrogate measurements indicative of culverts that can provide successful fish passage is widely used. Using surrogate measurements to measure "aquatic quality" or health for target species or ecosystems is not new. Attempts have been made to link the stream channel morphology, chemistry or other factors to key managed species or ecosystems as a whole (Hughes 1993, Kaufmann and Robison, 1998). In these cases, measures of channel complexity such as variation in stream depths or amount of large wood in streams is used sometimes as a surrogate of a healthy ecosystem. In some cases, different entities have even created targets to decide if a stream or riparian area is "properly functioning" based on more easily measurable habitat features (Prichard et al. 1993). The degree of success that these methods have had largely depends on how much the indicators used actually influence the survival and heath of the target species, community, or ecosystem. Where knowledge is poor in regards to what makes the system work the indicator will probably be a poor reflection of what is really happening. Compared with general habitat issues, fish passage at road crossings is a simpler process and has more direct study and the key issues have been narrowed. For this reason, a surrogate measurements approach will more likely be successful in being an indicator of fish passage success or failure than general habitat indicators are in determining ecosystem function. This paper outlines the critical issues regarding fish passage and how easily measured characteristics of culverts can be tightly aligned with fish passage. The paper also compares and contrasts various surrogate measurements approaches with direct measurement of fish passage success and failure. Finally several recommendations are given regarding research questions that need to be addressed to assure that surrogate measurements and fish passage criteria are adequately indicating fish passage success or failure.

Fish Passage Issues

Fish passage can be hindered at road crossings by excessive velocity inside the culvert, by excessive elevation drops in and around the culvert or by inadequate depth inside the culvert (Bell, 1986). The degree of velocity inside a culvert that a fish can overcome is dependent on the species and size (age) of the fish along with the general health of the fish as it approaches a culvert. Likewise the ability to jump over an obstacle is dependent on the same factors. The needed water depth is largely a function of fish size. For this reason many jurisdictions have created velocity, depth and jump guidelines (for example see ODFW, 1997)

Generally speaking, these guidelines call for average water velocities of two feet per second for juvenile fish (anadromous fish before going to sea) and drops of no more than six inches to a foot. Depth guidelines vary from four inches for juvenile fish up to a foot for adult fish. These guidelines are based on laboratory studies of the performance of fish in flume like structures (Bell 1986, Powers 1997). Studies that have been done in natural situations may find the fish able to overcome greater velocities and jumps (Kane et al. 2000). Adult fish can also overcome greater velocities and obstacle heights in some cases overcoming velocities greater than 10 feet per second and scaling obstacles up to five to six feet.

While velocity as an indicator may be easier to measure than actual fish passage, it has its own set of problems. One problem is velocity is flow related that is as discharge increases so does velocity. A velocity measurement taken during low flow conditions is essentially a snapshot in time and not indicative of fish passage over a range of conditions. Deciding which day to measure this in regards to an elevated "design flow" to get an adequate velocity measurement as an overall monitoring or assessment strategy would be nearly impossible because there are limited times when the culvert will have that discharge flowing through it. It would also be difficult to predict the timing and deploy crews at the proper times. Water depth has similar issues to velocity. For this reason, most surrogate method approaches have retreated into measuring culvert slope, roughness, and degree of backwatering instead of measuring velocity and depth directly.

Water velocity in culverts is controlled by the degree of energy available through the culvert and how that energy is dissipated. Steep culverts have a large amount of potential energy due to elevation loss in the culvert. One way of reducing energy is to make the culvert flat or decrease its potential energy. Another way of reducing velocity is to create roughness in the culvert (i.e. boulders or drops in culvert) to dissipate energy via heightened turbulence rather than velocity. Yet another way is to create backwatering from a downstream weir or dam to slow water through the culvert. Any surrogate method must include accurate measures of the culvert slope, characterize it roughness and also evaluate the degree of backwatering that is in the culvert. Several culvert design strategies have been developed to deal with velocity in culverts that include open bottomed culverts that have natural bed material, closed bottom culverts oversized and embedded with large boulders and other bed material, culverts placed nearly flat with backwatering to slow water velocity and add depth, and culverts with baffles and weirs to slow water velocity (Robison et al. 1999).

Critical Components of a Surrogate Measures Protocol

The critical components of a surrogate measures protocol include measures of the culverts characteristics that are relevant to fish passage and these include:

- Culvert slope and length
- Culvert width vs. stream width (measure culvert size – diameter and length)
- Height of drops at culvert outlet, inlet or even inside culverts (also characteristics of downstream pools as a platform for jumping into the culvert)
- Existence and characteristics of roughness inside the culverts
- Degree of backwatering from a downstream structure and the characteristics of that structure

Culvert slope is crucial and can be used along with roughness and discharge in modeling exercises to estimate water velocity. Many jurisdictions set maximums for culvert slopes such as less than 0.5% for bare bottom culverts (Robison et al. 1999, Paul et al. 2002) or less than six percent for embedded culverts (BC Ministry of Forests 2002). Culvert length is crucial because fish have a burst vs. sustained speed (Bell 1986) and very short culverts with excessive velocities may be passable because fish are using burst speed to overcome the velocity. Culvert width vs. stream width can be an indicator of velocity constriction at the inlet and an area of high velocity. Height of drops in excess of the fish's jumping ability would indicate an non passable culvert and thresholds regarding fish passage range from six inches for juveniles to up to four feet for adult anadromous fish. Many culverts are now being designed to retain or trap sediment and have a bottom that simulates the natural streambed. It is critical to monitor this factor if this design is used. What is necessary is a continuous bed of material that is interlinking and stable so it will not become washed out during subsequent high flow events. For this design, the width of the stream vs. culvert width is also important in that if there is flow constriction at the inlet there may be excessive scour at that point that removes the bed material (see White 1997 for a discussion of this potential problem). The crucial issue regarding backwatering is the elevation of the downstream riffle, weir, or other structure that is backing water into the culvert vs. the elevation of the culvert. Is it high enough relative to the culvert to really backwater in at a variety of higher flows? The use of backwatering equations or modeling software such as Fish-Xing (Love et al. 1998) can also be used with these measurements.

Another aspect that can be overlooked is the long-term stability of fish passage structures. A structure may appear to be successful after installation and then fail soon thereafter. Some of the main issues are:

- The loss of bottom material inside the culvert if designed to be embedded
- The emergence of a downstream drop due to channel degradation
- The loss of a downstream weir that was used for backwatering or for stability of channel profile

One reason that culverts fail is they are often put at a higher elevation than the natural channel profile. Over time the channel degrades back to its natural position but the culvert remains higher with a drop at the outlet side of the culvert and often all the bed material erodes out of the culvert. One requirement in recent design guidance documents (i.e. BC Ministry of Forests 2002) is to include a channel longitudinal profile in with the design and place the culvert low enough in elevation that the channel will not degrade below the culverts bottom. In doing effectiveness monitoring to determine if a culvert will have long-term stability an elevation profile is essential to determine if the culvert was placed at a reasonable elevation. Another step is to conduct monitoring not only after installation but at least for some culverts after a large storm event or season to see if they survived and if they are still effective.

Comparing Surrogate Measurements to Direct Fish Passage Monitoring

A surrogate measurements protocol such as the one used by Paul et al. 2002 or Robison and Walsh, 2003 even with the detailed longitudinal profile can usually be done at a culvert in less than 90 minutes. This means several culverts can be done in a day. A faster protocol that does not have the longitudinal profile can be done in 5-10 minutes. For this reason, a sampling of a vast number of culverts can be done quite rapidly to determine fish passage in a watershed, land ownership, or even a region. Measurements of direct fish passage would consist of marking and recapturing fish or using "pit tags" (i.e. radio tracers placed on the fish to track them) and may consist of days at a given site. The cost of doing this would be much higher as well as the degree of training needed so only a few sites can be done. The advantage of direct measurement is the certainty that you get. The disadvantage is the time and cost and the necessarily smaller sample size. In between this is a protocol that uses direct measurements of velocity as a surrogate along with other surrogate measures. It is faster than direct determination but does lack the certainty of direct sampling. In addition whatever velocities taken are only relevant for that flow condition so to conduct a velocity method may require repeat visits greatly reducing the efficiency and sample size that can be attained with this method.

Linking Surrogate Measures to Fish Passage

Many of the critical surrogate measurements also double as design guidelines for culverts. For instance, in design and installation, the slope the culvert is to be put in at should be specified. Thus when doing follow-up monitoring, measuring the slope that the culvert was put in at can be thought of as implementation monitoring (i.e. was the culvert put in correctly as specified). However since slope is so tightly coupled with velocity it also can be thought of a surrogate method for effectiveness monitoring in this case. The key issue is: does culvert slope correspond to velocity which in turn corresponds to fish passage success or failure? Our degree of certainty will be based on how well the culvert slope (and the other surrogates in combination) reflects on actual fish passage. Our current knowledge is largely based on flume studies in which fish are stressed under different velocities to indicate what velocities they can overcome (Bell, 1986). One shortcoming on many of these studies is they are done in laboratory situations with hatchery fish which may not be indicative to what fish in natural situations can do (see Kane et al. 2000 for example). The link between surrogates and actual fish passage is also based on many flume studies that have modeled slope and roughness versus velocity at different discharges (Thorne and Zevenbergen 1985 and many other studies).

In essence the surrogates of culvert slope, roughness, drops, backwatering, relative culvert size to stream size will be given thresholds under which partial or complete fish passage blockage will be deemed to occur. The setting of these criteria can be somewhat arbitrary because of some of the uncertainties in these linkages. As knowledge increases, these thresholds may need to be adjusted. However the key issues of culvert slope, roughness, drops etc. will remain constant as viable indicators of fish passage. Therefore, the chronicling of the raw numbers in culvert monitoring surveys along with the overall determinations of fish passage blockage will be useful.

An obvious recommendation is to research natural fish passage at existing culverts under different conditions of slope and roughness etc. to confirm how relevant the laboratory studies of fish passage are (such as Kane et al. 2000). Another area regards monitoring the long-term stability of structures and what factors such as culvert width versus stream width are associated with culvert effectiveness (i.e. studies like White 1997). A final study area regards better understanding the velocity distributions in embedded culverts and fish behavior in terms of how they move through culverts (i.e. House et al. 2005). Most if not all of the criteria used today are based on overall average cross-sectional velocity not the extent and velocity of areas actually occupied by fish scaling a culvert.

References

BC Ministry of Forest. 2002. Fish-stream crossing guidebook, For. Prac. Br., Min. For., Victoria, B.C. Forest Practices Code of British Columbia Guidebook. http://www.for.gov.bc.ca/tasb/legsregs/fpc/fpcguide/FishStreamCrossing/FSCGdBk.pdf

Bell, M. C. 1986. Fisheries handbook of engineering requirements and biological criteria. Fish passage development and evaluation program, Corps of Engineers, North Pacific Division, Portland, Oregon. 290 p

Conroy, S.C. 1997. Habitat lost and found. Washington Trout Report. Vol. 7:1

Government Accounting Office (GAO). Report to the Ranking Minority Member, Subcommittee on Interior and Related Agencies, Committee on Appropriations, House of Representatives: Restoring Fish Passage Through Culverts on Forest Service and BLM Lands in Oregon and Washington Could Take Decades. GAO-02-136

House M.R., M.R. Pyles, and D. White. 2005. Velocity Distribution in Streambed Simulation Culverts Used for Fish Passage. Jour. AWRA. Vol. 41(1) p. 209-217

Hughes, R.M. (ed.). 1993. Stream Indicator and Design Workshop. EPA/600/R-93/138. U.S. Environmental Protection Agency, Corvallis, Oregon.

Kane, D.L., C.E. Behlke, R.E. Gieck, and R.F. Mclean. 2000. Juvenile fish passage thorugh culverts in Alaska: a field study. Water and Environmental Research Center. University of Alaska, Fairbanks, AK. 57 p.

Kaufmann, P.R. and E.G. Robison. 1998. Physical Habitat Assessment. pp 77-118 In: Lazorchak, J.L., Klemm, D.J., and D.V. Peck (editors)., Environmental Monitoring and Assessment Program - Surface Waters: Field Operations and Methods for Measuring the Ecological Condition of Wadeable Streams. EPA/620/R-94/004F. U.S. Environmental Protection Agency, Washington D.C.

Love, M., S. Firor, M. Furniss, and 5 others. 1998. Fish Crossing Software. Developed by U.S. Forest Service and several other cooperators. Available at: http://www.stream.fs.fed.us/fishxing/

Oregon Department of Fish and Wildlife. 1997. Guidelines and Criteria for Stream-Road Crossings. October 23, 1997. 7p. (Appendix A in Robison et al. 1999 referenced in note #6)

Paul J.P., L. Dent and M. Allen. 2002. ODF Compliance With Fish Passage and Peak Flow Requirements at Stream Crossings: Final Study Results. FP Technical Report 14. Available from Oregon Department of Forestry, Salem Oregon. http://www.odf.state.or.us/DIVISIONS/protection/forest_practices/fpmp/Projects/Stream_Crossing/FishPassFinalRpt.doc

Powers, Patrick D. 1997. Culvert Hydraulics Related to Upstream Juvenile Salmon Passage. Washington Department of Fish and Wildlife. 20p. Available on internet at: http://www.wa.gov/wdfw/hab/engineer/habeng.htm

Prichard, D., H. Barrett, J. Cagney, R. Clark, J.Fogg, K. Gebhardt, P. Hansen, B. Mitchell, and D. Tippy, 1993. Riparian area management: process for assessing proper functioning condition. TR 1737-9. Bureau of Land Management, BLM/SC/ST-93/003+1737, Service Center, CO.

Robison, E.G., A. Mirati, and M. Allen. 1999. Oregon Road/Stream Crossing Restoration Guide. Available from the Oregon Department of Forestry. 2600 State Street, Salem Oregon or http://www.4sos.org/wssupport/ws_rest/OregonRestGuide/index.html. 86 p.

Thorne, C.R. and L.W. Zevenbergen. 1985. Estimating mean velocity in mountain rivers. J. Hydraul. Eng. (ASCE) 111(4): 612-624.

White, D. 1997. Hydraulic performance of countersunk culverts in Oregon. Oregon State University, Masters Thesis.

Water Quality Impacts from an ORV Trail Stream Crossing in the Talladega National Forest, Alabama, USA[1]

Renee´ D. Ayala[2], Puneet Srivastava[2], Christian J. Brodbeck[2], Emily A. Carter[3], and Timothy P. McDonald [2]

Abstract

Off-Road Vehicles (ORVs) are one of the most damaging forms of recreation utilized in our National Forests. Erosion from ORV trails can be a major source of water quality impact. In 2003, a study was initiated in the Talladega National Forest to quantify water quality impacts of an ORV trail crossing a local stream. Automated samplers were installed upstream and downstream from an ORV trail stream crossing to collect suspended sediment (SS) samples. Storm-event SS samples were collected over a 9-month period and trail conditions were monitored. Three different operational conditions - closed, maintenance, and open - were observed during the sampling period. During the trail closed condition, four storm events, which included a 49 mm storm, contributed a total of 109.3 kg of SS load. Subsequent to this, two storm events during the trail maintenance period contributed a total of 4.1kg of SS to the stream. The trail was then opened to ORV traffic. During the trail open period, eight storms contributed a SS load of 6.5 kg. Since most of the observed storms had return periods of less than one year, the SS loads contributed by the ORV stream crossing were small. The measured data and the observations, however, suggest that the ORV stream crossing can contribute large SS loads during storm events with return periods of one year or more.

Key words: erosion, Off-Road Vehicles, ORV, runoff, stream crossing, suspended sediment, water quality

---

[1] This paper was presented at the Annual COFE Meeting: Soil, Water, and Timber Management: Forest Engineering Solutions in Response to Forest Regulation. July 11-14, 2005, Arcata, California.

[2]Undergraduate Student (ayalard@auburn.edu), Assistant Professor (srivapu@auburn.edu), Graduate Student (brodbcj@auburn.edu), Associate Professor (mcdontp@eng.auburn.edu), Biosystems Engineering Department, 200 Tom Corely Building, Auburn University, Auburn, AL. 36849-5417.

[3]Research Soil Scientist, USDA Forest Service, 520 DeVall Drive, Auburn, AL. 36849. email: eacarter@fs.fed.us

Introduction

Water quality is a major concern for many countries around the world. Research has been conducted in many areas to assess impairment of waterways by agriculture, urban development, wildlife, and recreational activities. Water is a finite resource that needs to be monitored and protected to ensure its longevity. In the United States, legislation has been enacted for the protection of water quality. In response to the Clean Water Act of 1977, and the Water Quality Act of 1987, improved guidelines and management practices have been implemented in each state.

Sources of pollution originally defined as "point" and "non-point" sources have more recently been viewed as encompassing too narrow a spectrum. Non-point sources are now more commonly referred to as "diffuse sources" and include the characterization "discharges [that] enter the receiving surface waters in a diffuse manner at intermittent intervals that are related mostly to the occurrence of meteorological events" (Novotny and Olem, 1993). Diffuse sources are a rising concern and are addressed by several agencies in Alabama.

Alabama Forestry Best Management Practices (BMPs) published by the Alabama Forestry Commission list sediment as "one of the most important considerations related to silvicultural activity" (Alabama, 1990). It also acknowledges that "many operations have the potential to increase sediment rates" (Alabama, 1990). Federal and state BMPs have been established and implemented to address the problem of increased sediment loads in waterways due to stream and wetland crossings.

The threat of sedimentation created by ORV trails is a growing concern for many recreational areas including our National Forests. The trail systems set up for ORVs contain steep climbs, banked turns, and ruts or crevices that sustain high volumes of riders. The nature of ORV use for recreation includes quick stops, fast accelerations, and high speed turns. This type of activity leads to miles of exposed soil surfaces. During storm events, these trail systems become a contributor of sediment into the nearby streams.

Objective

The impact of ORV use on nearby streams is a new area of interest and limited scientific data are available to address the growing concern. The objective of this study was to quantify sediment loads generated by an ORV trail stream crossing under three different trail operational conditions (closed, maintenance, and open).

Methods

Site description

The study area was located in the Talladega National Forest, Talladega County, Alabama within the Alabama Valley and Ridge Province. Elevation in the vicinity of the study site ranges between 300 and 580 m. Average annual precipitation is approximately 1330 mm while average annual temperatures range between 7.2 in January and 26 degrees C in August. Topography features of this area include short, steep slopes, narrow ridge tops, and rock and shale outcrops with slopes that range between 15 and 45 percent. Soils within this area have been identified as belonging to the Tallapoosa-Tatum association that developed from weathered slate or phyllite. Surface soil layers are composed of silt loam underlain by silty clay loam (Cotton et al.).

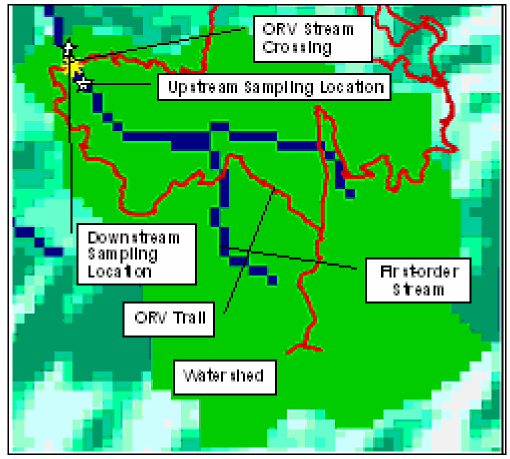


Figure 1 - Kentuck ORV trail and stream crossings. Spatial representation of the 113 ha

Permission was granted by the United States Department of Agriculture (USDA) Forest Service, Talladega Ranger District to conduct this study on their trail system. While the entire trail system is 30 miles long, a 2-mile looped portion of the trail was selected for this study. Before the data collection process could begin, certain criteria were established for selecting a suitable stream crossing to sample for SS loads: it had to be perennial, it needed to intersect the trail system, an ORV with a trailer had to be able to access it, it needed to have high enough flow rates to meet the data logger requirements, and there needed to be a sufficient stream bank for the installation of the data collection equipment. After this was completed, both a Geographic Information System (GIS) and a Global Positioning System (GPS) were used to identify and locate several streams within the trail system. The streams were assessed according to the set criteria, and a suitable stream was selected that had a bridge. The watershed area (113 ha) upstream from the stream crossing was delineated using GIS (Figure 1). The slopes of the trail approaching the stream from the left decreased from 18 percent to 1 percent slope and increased to 3 percent on the right side of the stream (Figure 2).

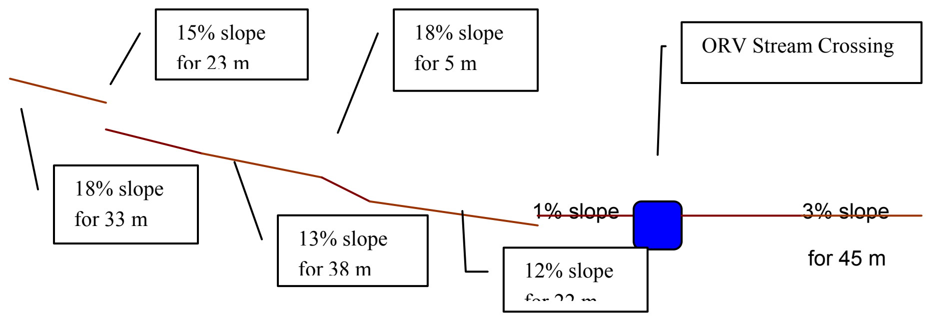


Figure 2 – Profile view of the ORV stream crossing

During the maintenance period (March 1, 2004 – March 16, 2004), a crawler tractor was used to remediate trail areas that contained standing water. The trail was then allowed to dry for several days. A crawler tractor was then used to smooth the trail. All of the soil that was removed from the trail surface during the "smoothing/blading" process was pushed to the center of the trail and compacted with repeated passes of the tractor. This process took approximately two weeks to complete and was dependent upon the weather.

Data collection

The equipment utilized for this study consisted of an 6700 water sampler, two ISCO tipping bucket rain gauges, and a StarFlow ultra sonic doppler flow meter. The upstream sampler was placed in the stream far enough above the stream crossing so that any runoff from the trail into the stream would not be sampled by the intake hose. The distance from the stream crossing to the upstream sampler was approximately 60 m. The location of the downstream sampler was selected by following the sediment plumes that were being deposited into the stream from the ORV trail turnouts. The sampler was installed just downstream from the sediment plume entry point - at approximately 16 m from the stream crossing. Both the upstream and downstream samplers were connected to their own ISCO tipping bucket rain gauge.

Several parameters and procedures were set and followed for the collection of the field data. When rainfall intensity reached 2.6 mm/hr, both the upstream and downstream samplers started collecting water samples from the stream at a rate of 250 ml every fifteen minutes. Four samples were composited into each bottle. Each 1000-ml collection bottle inside the ISCO water sampler represented one hour of a storm event. Data were collected for a full 24-hour period after the sampling began.

---

[4] Reference herein to any specific commercial products, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government.

Laboratory analysis of the water samples was conducted to determine the amount of suspended sediment (SS) in each 1000-mL collection bottle. These measurements were obtained by following standardized procedures (APHA – AWWA – WPCF, 1958), and the SS loads were calculated.

Results

Rainfall intensity and quantity has a direct affect on sediment loads contributed by ORV trail and stream crossings. The amount of exposed soil and the condition of the trail are also key factors that influence soil loss and resulting impairment of receiving streams. The following section presents sediment load contributed by the OVR trail stream crossing from the storm events that occurred during three trail conditions: closed, maintenance, and open. Sediment loads were calculated for both the upstream and downstream collection points using suspended sediment (SS) concentrations and stream flow rates.

When the data collection began (December 16, 2003) the trail was open for a short time. Soon after that, the trail was closed due to a highly degraded state. The trail remained closed until the end of February 2004. The trail had areas of exposed soil that had accumulated when the trail was open to ORV traffic. During trail closure, four storm events were recorded. These storm events included a 49 mm storm that occurred on February 6, 2004 (Figure 3).

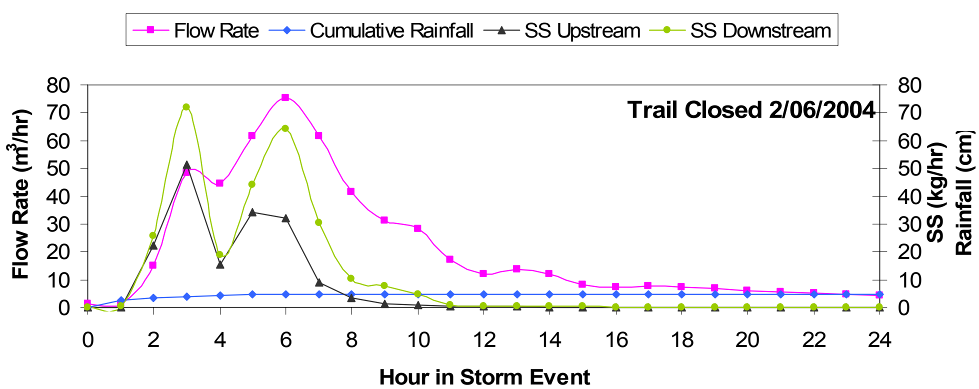


Figure 3 – Flow rate, cumulative rainfall, and suspended sediment loads from a 49 mm storm event that occurred on February 6, 2004 during trail closed condition.

The ORV trail stream crossing contributed 109 kg of sediment during this storm event, which constitutes about 39 percent of the load contributed by the 113 ha watershed (Table 1). Sediment loading to the stream reached its peak (75 kg/hr) during the 3rd hour due to the intense nature of the previous hour of rainfall. After this event, the sediment load declined both above and below the stream crossing because of the decrease in rainfall intensity. The rainfall intensity increased again during the 5th and 6th hours and contributed a large sediment load from the ORV stream crossing. The ORV trail stream crossing contributed little sediment load from other storm events that occurred during trail closed condition (Table 1). It should be noted that these storm events had a return period of less than one year.

Table 5-Individual storm events and the SS loads contributed by the ORV stream crossing.

Trail Condition	***Date***	***Cumul-ative Rainfall***	***SS Up-stream***	***SS Down-stream***	***SS Load Contrib-uted by Stream Crossing***	***% of Load Contri-buted by Stream Crossing***
		(mm)	(kg)	(kg)	(kg)	(kg)
Trail Closed	01/25/2004	22	0.8	0.9	0.1	11.1
	02/06/2004	49	171.3	280.3	109.0	38.9
	02/12/2004	20	4.8	4.9	0.1	2.0
	02/25/2004	11	0.7	0.8	0.1	12.5
Maintenance	03/06/2004	20	26.7	30.7	4.0	13.0
	03/16/2004	5	0.1	0.2	0.1	50.0
Trail Open	12/16/2003	10	0.4	0.6	0.2	33.3
	03/20/2004	9	1.3	1.7	0.4	23.5
	03/29/2004	20	2.1	2.2	0.1	4.5
	04/11/2004	13	1.2	1.7	0.5	29.4
	04/26/2004	18	0.5	0.8	0.3	37.5
	04/30/2004	22	18.2	20.4	2.2	10.8
	05/16/2004	36	7.3	9.3	2.0	21.5
	06/22/2004	10	0.3	0.9	0.6	66.7
	07/02/2004	16	1.6	1.8	0.2	11.1

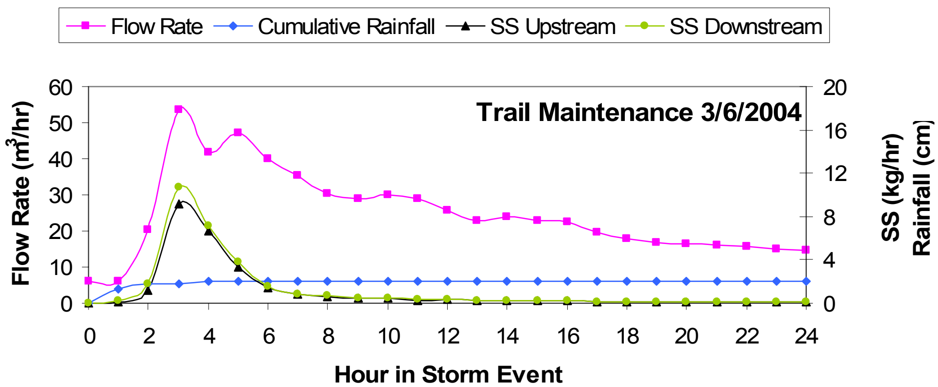


Figure 4 – Flow rate, cumulative rainfall, and suspended sediment loads from a 20 mm storm event that occurred on March 6, 2004 during trail maintenance condition.

Two similar storms, (January 25th and February 12th) which occurred during trail closure, contributed quite different sediment loads from the watershed (February 12th load being higher than the January 25th load). This could be due to a lack of rainfall prior to January 25th. While a large storm (49 mm) occurred a few days before the February 12th storm. The ground was already wet when the February 12th storm occurred resulting in more runoff and sediment load.

As mentioned earlier, during the trail maintenance period (March 1, 2004 – March 16, 2004), a crawler tractor was used to remediate trail areas that contained standing water. Even though all of the soil that was removed from the trail surface during the "smoothing/blading" process was pushed to the center of the trail and compacted with repeated passes of the tractor, this process left loose soil on the trail when a 20 mm storm occurred on March 6, 2004. During the March 6th storm event there was a steady increase in rainfall during the first few hours. As a result, stream flow rate (57 m^3/hr) and sediment load (30 kg/hr) measured by the downstream sampler reached their maximum values during the same hour (3rd), and slowly declined as the rainfall event ended (Figure 4). Two similar storm events occurring on January 25th and February 12th during the trail closed condition did not contribute nearly as much sediment as was contributed by this storm event (Table 1).

Shortly after the completion of the trail maintenance period, the trail was re-opened on March 20th to ORV use. The use of ORVs on a trail results in ruts, crevices, and the accumulation of loose soil that is spun off of the tires during fast accelerations and turns. Eight storm events after March 20, 2004 were recorded for this period. A 22 mm storm event (on April 30th) during this period resulted in 2.2 kg of sediment from the ORV trail stream crossing. The sediment load from this storm event is slightly lower than the loads generated by a similar storm event that occurred on March 6th (Table 1). This 22 mm storm occurred after an 18 mm storm on April 26th. Since the soil was already wet, this storm event contributed large runoff and sediment loads. As shown in Figure 5, the rainfall during the April 30th storm peaked during a short time (during 2nd and 3rd hour) and resulted in a high intensity storm. A larger storm (36 mm) occurred on May 16th and did not contribute nearly as much sediment load due to a lack of rainfall prior to this storm event. The ground was fairly dry and did not result in much runoff and sediment load. In general, it was observed that when storm events occurred in succession there was an increase in the SS loads contributed by the ORV stream crossing.

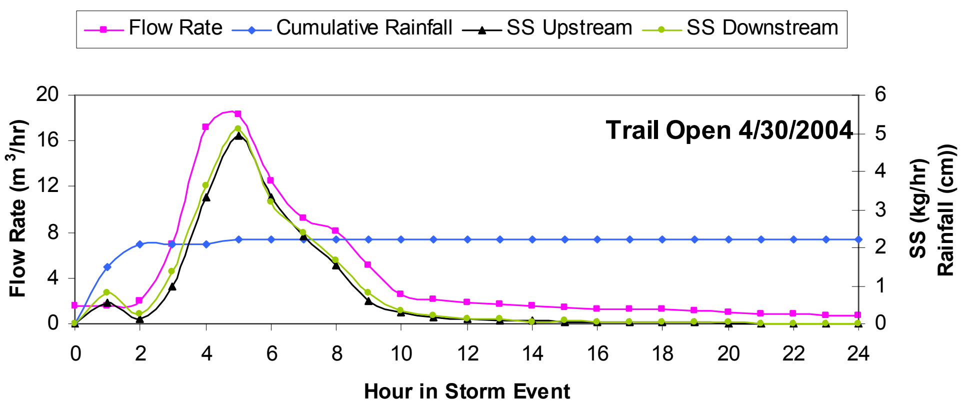


Figure 5 – Flow rate, cumulative rainfall, and suspended sediment loads from a 22 mm storm event that occurred on April 30, 2004 during trail open condition.

Conclusion

In this study, sediment loads contributed by an Off-Road-Vehicle (ORV) trail stream crossing were measured using automated samplers. Sediment loads contributed by stream crossings depend on rainfall intensity, rainfall frequency, topography, soil type, and trail condition. Data from this study suggests that back-to-back rainfall events tend to increase sediment loads from the watershed and the ORV trail stream crossing. However, isolated storm events of similar size do not contribute as much sediment load. The most significant sediment contribution into the stream occurred during an intense storm that lasted for several hours. This rainfall event had an approximate return interval of 1 year. The ORV trail did not contribute large sediment loads during other smaller events. This study suggests that ORV trail stream crossings have the potential to contribute large sediment loads from storm events that have a return interval of one year or higher. However, since data was collected for only one such event, more long-term data needs to be collected to better quantify sediment loads contributed by ORV trail stream crossings. In addition to collecting additional data from larger storms, modeling studies need to be conducted to better assess potential loads contributed by ORV trails and ORV trail stream crossings. Future plans for this study include calibrating the WEPP (Water Erosion Prediction Project) model using the collected data and quantifying long-term sediment loads contributed by ORV trails and ORV trail stream crossings. A modeling study will also help identify management practices that can be used to minimize water quality impacts of ORV trails.

References

Alabama Forestry Commission. 1990 Best Management Practices for Alabama. Alabama Forestry Commission, Montgomery, AL; 7 p.

American Public Health Association, American Water Works Association, Water Pollution Control Federation. 1985 Standard Methods for the Examination of Water and Wastewater. Sixteenth Edition. 209 C. Total Suspended Solids Dried at 103-105 Degrees Celsius. 106p.

Cotton, James L., L.A. Dungan, G.L. Hickman, and C.F. Montgomery. 1974. Soil Survey of Talladega County, Alabama. Soil Conservation Service. Washington DC.

Environmental Protection Agency. 1986 Quality Criteria for Water 1986. Office of Water Regulations and Standards. Washington DC. EPA 440/5-86-001.

Novotny, Vladimir, and Harvey Olem. 1993. Water Quality: Prevention, Identification, and Management of Diffuse Pollution. New York: Van Nostrand Reinhold; 1054 p.

A GIS-based interactive spatial decision support system for SFM-oriented timber harvest scheduling/allocation strategies in plantation forests[1]

Masami Shiba[2]

Abstract

The object of this paper was to discuss the development of a GIS-based Spatial Decision Support System (SDSS) combined with image processing facility (IDRISI 32) and a harvest schedule/allocation model for landscape perspective concerns (HARVEST). HARVEST was designed to predict changes in landscape patterns with spatial attributes resulting from the initial landscape conditions and potential timber harvest activities. Application potential was showed through examples of predicting these changes combined with technical opportunities, constrains, and trade-off. The outcome (the resulting patterns of forest openings and stand age distributions) also provided opportunities of visual feedback. This approach would enable resource managers to design and demonstrate the long-term conservation outlook of forest resources under alternative management strategies geared to multiple economic, environmental, and social objectives.

Keywords: landscape, Spatial Decision Support System (SDSS), Sustainable Forest Management (SFM), timber harvest, visual feedback

[1] This paper was presented at the 28th annual meeting of COFE- Soil, Water and Timber Management: forest Engineering Solutions in Response for Forest Regulation, July 11-14th , Fortuna, California.

[2] Associate Professor, Field Science Education and Research Center, Kyoto University, Kitashirakawa, Oiwake-cho, Sakyo-ku, 606-8502, Kyoto, Japan, e-mail: mshiba@kais.kyoto-u.ac.jp

Introduction

Dealing with the sophisticated issues of integrating forest resources management with environmental, and social values and objectives in a sustainable manner requires a more holistic and spatial approaches than has been traditionally applied to managing forest ecosystem condition at a stand level. By taking a landscape perspective, combined with improved analytical tools to support the consensus-based management decision-making, benchmarking forest management practices to meet the adequate scale or level of potential impacts caused by silvicultural and harvesting activities might be realized (Figure 1).

As for timber harvesting management tool, Harvest Scheduling Model (HSM) (e.g. FORPLAN) applied linear programming solution has been developed and put to practical use. HSM displays its great ability in leading optimum answer that maximizes timber harvesting volume by compartment or sub-compartment unit. Latest HSM gets to emphasize spatial aspects for landscape level management planning (Kurttila 2001; Murray 1999; Yoshimoto 2001). Special aspects which called adjacency constrains, limit the harvest of adjacent units. This type of approach would help to recognize the potential impact of broader regional harvest-flow constrains (Borgesa and Hoganson 2000; Hoganson and Borgesa 2000).

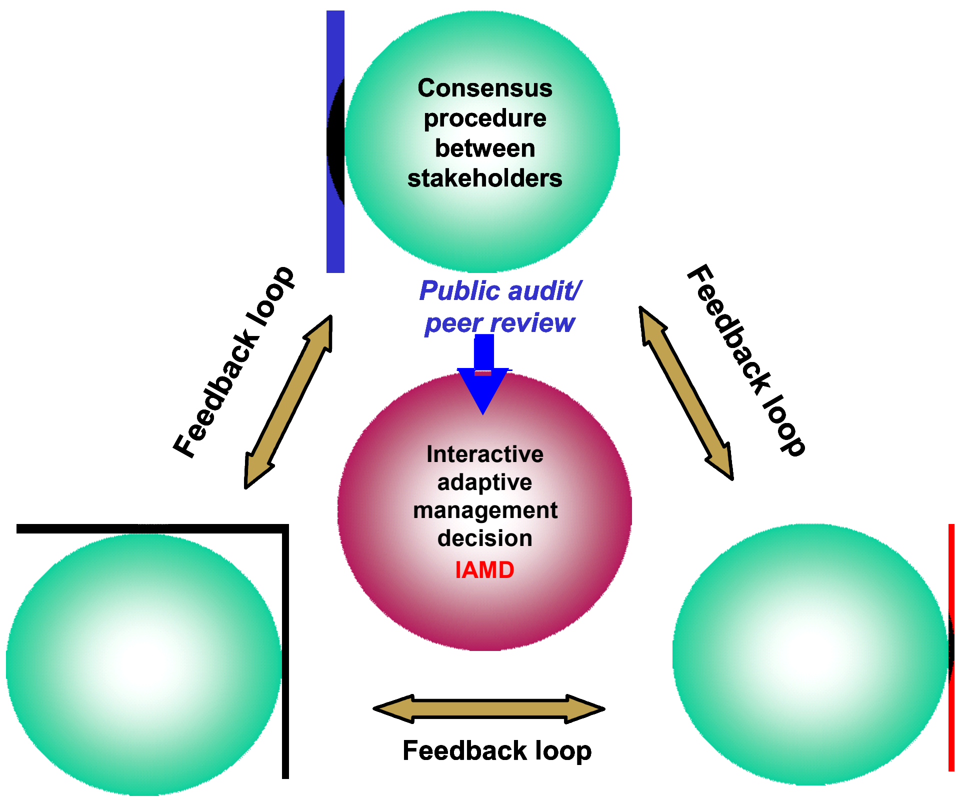


Figure 1-Concept of a proposed SDSS.

Considering a landscape perspective, however, the ability of HSM seems to be still insufficient because HSM cannot generate landscape patterns with spatial attributes resulting from the initial landscape conditions and potential timber harvest activities (Gustafson and Crow 1999). In other words, HSM cannot manage opening-up scale in both spatial and temporal context for combining each polygon's data as a minimum management unit.

GIS has now made it possible to incorporate spatial components into harvest schedule/allocation planning and simulation models. In some cases, the modeling capabilities of a particular GIS may be used directly to aid decisions about timber harvesting; in other cases, an external model is linked to a GIS database.

In this paper the author describes the development of a GIS-based timber harvest scheduling system oriented toward SFM (Sustainable Forest Management) combined with a raster GIS which offers image processing capabilities (IDRISI 32) and a harvest schedule/allocation model which allows simulation of differences in the size of timber harvest units, the total area harvested, length of harvest rotation, and the spatial distribution of harvest areas (HARVEST).

The emphasis is on provision of visual feedback on the outcome (the resulting patterns of forest openings and age class structure). Using the proposed approach, resource managers could have the flexibility to design and demonstrate the long-term conservation outlook of forest resources under alternative management strategies geared to multiple economic, environmental, and social objectives (Figure 2).

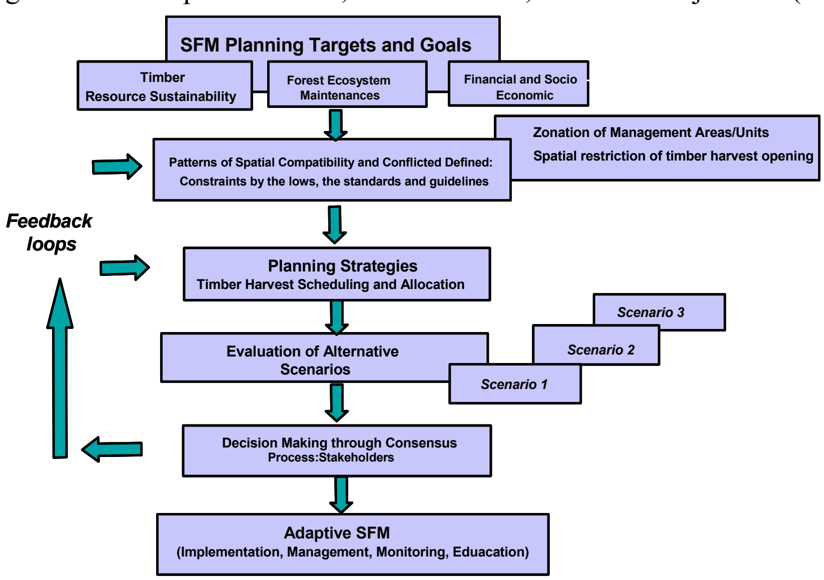


Figure 2-Framework of a SDSS for adaptive forest management.

Framework of a GIS-based timber harvest scheduling system

As has been mentioned, a GIS-based timber harvest scheduling system is characterized by the combination with a raster GIS (IDRISI 32) and a harvest schedule/allocation model (HARVEST). Processing procedures are separated functionary classification of forest management space, harvest schedule/allocation and data analysis (Figure 3).

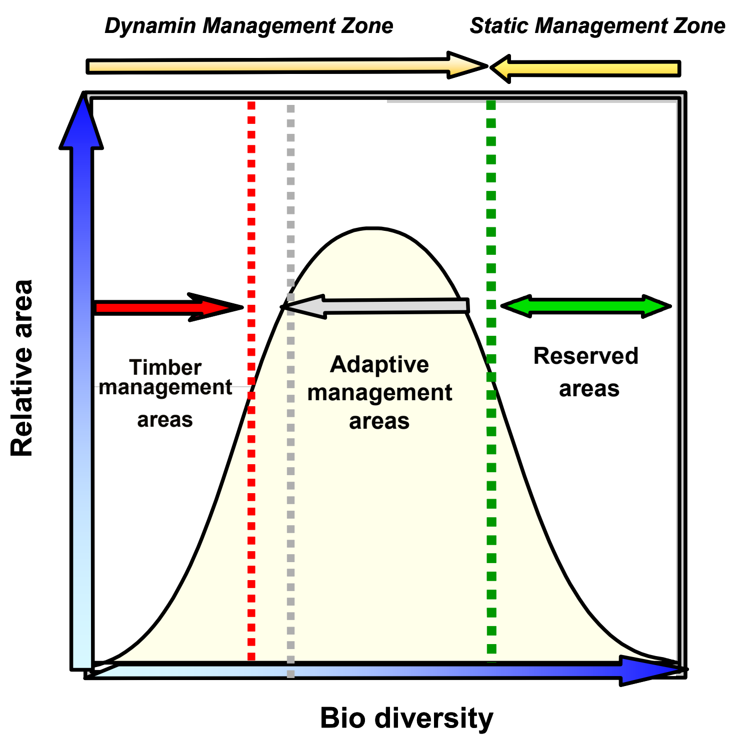


Figure 3-Zonation model to reflect differences in management approach: Bell shaped model.

Functionary classification of forest management areas

This procedure classified forest management space into functionary categories according to management plans before harvest schedule/allocation. In this paper, three categories (Static Management Zone (SMZ), Conservative Management Zone (CMZ) and Productive Management Zone (PMZ) were established (Figure 4).

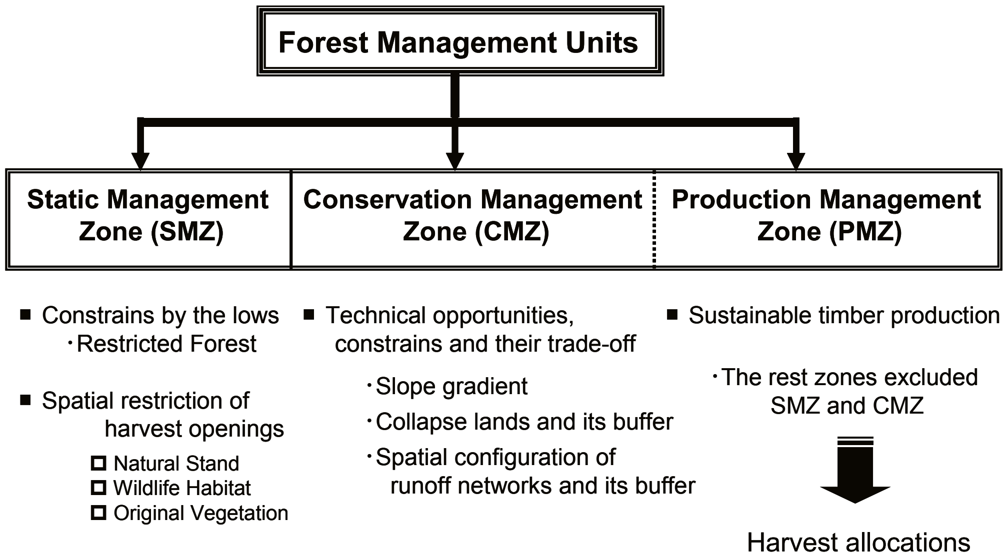


Figure 4 Adaptive standards applied to the zonation to three forest management units.

To maintain forest ecosystems, SMZ was established. SMZ was composed of natural stand, broad-leaved second growth, wildlife habitats and original vegetation. In SMZ, timber harvesting should be avoided, however, essential cares must be kept to give full play of its public benefits.

CMZ was established to maintain forestland condition over forest management operations. In CMZ, slope distribution, land collapses and mountainous river network were considered. Slope distribution limits logging operations and affects regenerated trees growth. Considering to apprehensions for spreading out of existing land collapses and for soil loss from collapses, it would be proper to arrange buffer zone. Mountainous river network should be extracted and then arranged buffer zone in order to protect riparian area. As for classification conditions about CMZ like the upper limit of slope, the width of buffer and the form of mountainous river network, various conditions in accordance with existing surveying data were supposed. CMZ should be limited for harvest method, especially avoided from clear-cutting.

PMZ was the rest zone excluded SMZ and CMZ from unrestricted forest. PMZ should be kept sustainable timber production by means of right tree on right site and positive management.

Harvest schedule/allocation

HARVEST has been developed by E. J. Gustafson at USDA Forest Service. HARVEST provides a visual and quantitative means to predict the spatial pattern of forest openings produced under alternative harvest strategies (Gustafson 1999). HARVEST approach was adopted that allowed flexible input of parameters relates to the standards and guidelines for timber harvest, and incorporated spatial information (in the form of GIS map) about the boundaries of management areas where various management goals were assigned (Gustafson and Crow 1999). HARVEST was a cell based (raster) model and produces landscape patterns that have spatial attributes resulting from initial landscape conditions and potential timber management activities (Gustafson 1999; Gustafson and Crow 1999). Inputting control parameters (Figure 5) for simulation, we are able to specify the time and place for harvest schedule/ allocation, including such conditions as forest cover types, topography, and ecology like wildlife habitats. In case of inputting strict parameters, HARVEST may not be able to find answer. Once, HARVEST finds answer, we can examine the result of simulation using outputs such as stand age map. With HARVEST, we can find a scheduling solution (i.e., determining the order in which individual stands should be harvested).

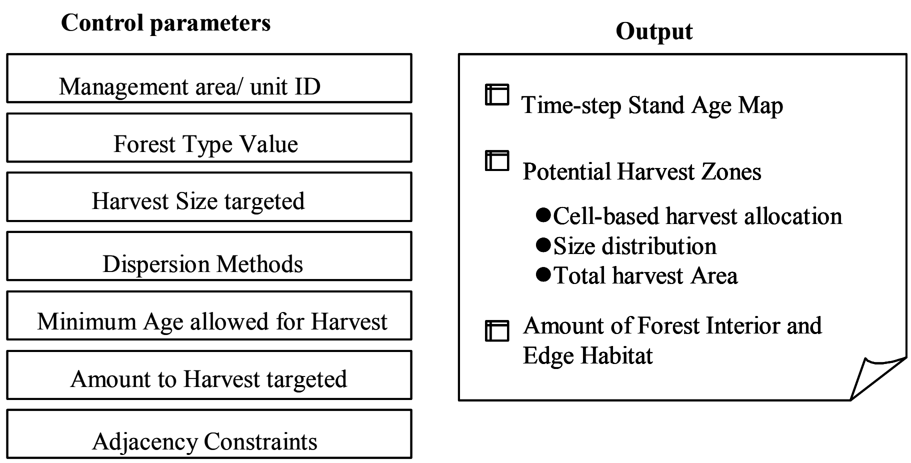


Figure 5-HARVEST parameters to simulate alternative management strategies.

Data Analysis

As mentioned above, outputs (stand age map) from HARVEST were able to visualize within IDRISI32 system so that the trend of resulting patterns and age class structure could be analyzed. The resulting patterns of forest openings would be subdivided (Forman 1995) because of the ability about opening-up scale management. In this paper, changes of the patch number and patch size were measured (Baskent and Jordan 1995; Shiba 2001).

Study Area and Methods

The study site (Miyagawa forest) located in the western part of Mie Prefecture Japan was a (JGRA). A number of planning concepts have been applied here including silvicultural treatment planning, natural resource promotion project, rural community forestry promotion program and integrated watershed management planning. The planting area of Japanese cedar amounts to 122ha (stand volume: 36,909m3) and Japanese cypress to 149ha ((stand volume: 29,601m3), respectively.

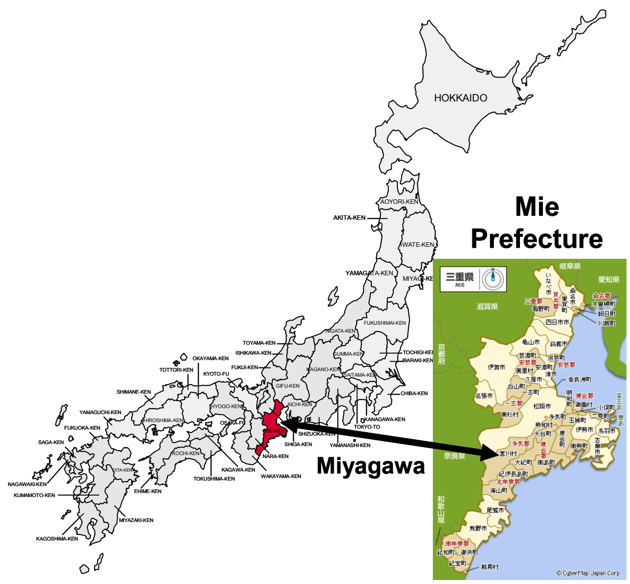


Figure 6-Location of study area.

Functionary Classification of Forest Management Space

First of all, the base map (scale 1:5,000) digitized to build the GIS database and then land collapses delineated. Raster data was prepared with 10m mesh imported from a DEM data published by the Geographical Survey Institute. While SMZ was extracted using the database, each CMZ was mapped in accordance with classification conditions. The details were as follows.

Slope distribution was mapped by 100 %, 90 % and 80 % from the point of operational limit at mountainous forest. In case of mapped by 100 %, slopes above 100 % were mapped as CMZ, and fewer than 100 % mapped as PMZ. Using “BUFFER” function, buffer zone was arranged around collapses from 10 m to 50 m with 10 m step and twice-width was arranged for over 1 ha collapses by reason of potential influence about surface soil loss, expansion of existing land collapses. In this part, collapses and buffer zone was defined as CMZ, and the rest area from CMZ was defined PMZ. Using “BUFFER” function, buffer zone was arranged around the courses of runoff from 10 m to 100 m with 10 m step. Mountainous river network and its buffer zone were mapped as CMZ, and the rest part was PMZ (Figure 7).

Harvest Schedule/Allocation

The object of harvest schedule/allocation simulation was determined that the present short-term (rotation age: 40) plantation management led to long-term (rotation age: 80). In order to realize it, age class structure must be changed gradually from concentrated 7 to 8 age class at the present (Figure 8) to almost even. Table 1 indicates HARVEST simulation model (VAR1-VAR12) parameters. Simulation period was set for 150-300 years. The objective harvesting area was decided from 20 ha (min.) to 100 ha (max.) ha within every working period. Minimum allowable cutting age was 45 year. As for each harvesting patch parameters, the mean area was set for 1.0 ha and 2.0 ha referred to private forests' working results at Shiga and Mie Prefecture (Shiba 1997; Shiba 1999), maximum patch for 2.0 ha and 5.0 ha, and minimum patch was 0.01ha (= resolution of GIS data; pixel size was 10m), 0.09 ha and 0.1 ha, respectively.

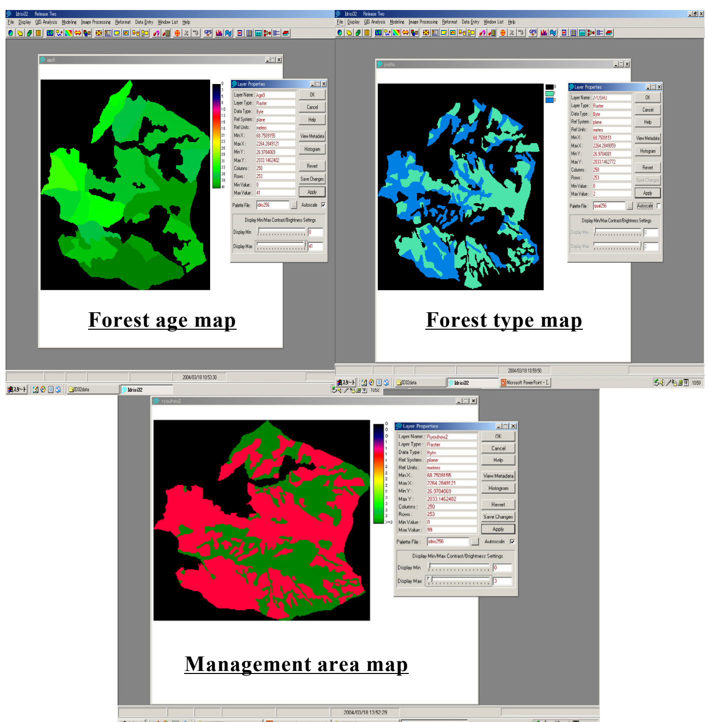


Figure 7- Input Maps required by HARVEST.

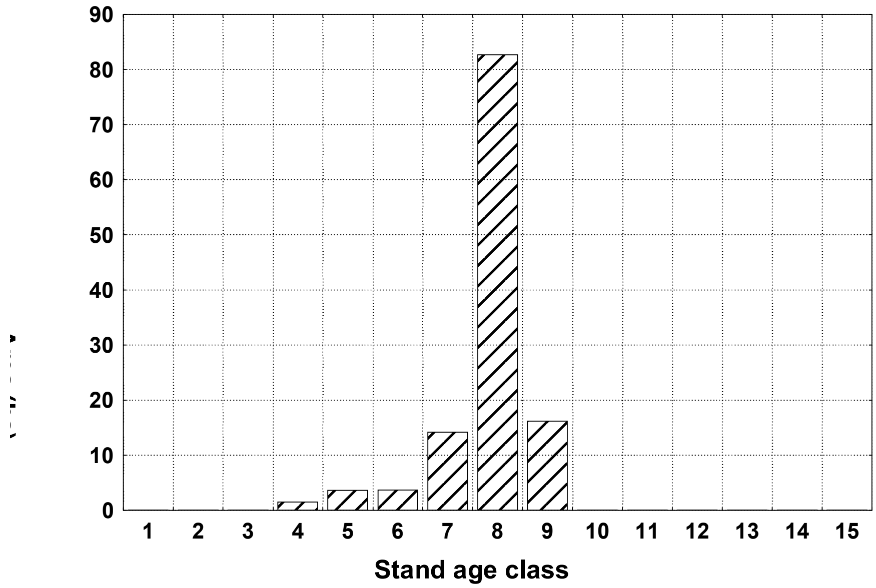


Figure 8-Stand age distribution of Japanese cedar.

Table 1 –Summary of HARVEST simulation model parameters ((VAR1-VAR12).

	Simulation models											
Harvest parameters	VAR1	VAR2	VAR3	VAR4	VAR5	VAR6	VAR7	VAR8	VAR9	VAR10	VAR11	VAR12
Time periods (yrs)	5	5	5	5	5	5	5	5	10	10	10	10
Forest type	Cedar	Cedar	Cedar	Cedar	Cedar	Cedar	Cypress	Cypress	Cypress	Cedar	Cedar	Cedar
Rotation interval (yrs)	80	80	80	80	80	80	80	80	80	80	80	80
Min. age allowed for harvest (yrs)	45	45	45	45	45	45	45	45	45	45	45	45
Amount to harvest (ha)	50	25	50	25	100	100	50	100	100	20	50	20
Avg. harvest size (ha)	1	1	1	1	2	2	2	2	2	1	1	2
Standard deviation (ha)	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
Min. harvest size (ha)	0.01	0.01	0.09	0.01	0.1	0.1	0.1	0.1	0.1	0.01	0.01	0.09
Max. harvest size (ha)	2.0	2.0	2.0	2.0	5.0	5.0	5.0	5.0	5.0	2.0	2.0	5.0
Adjacency constrains												
Green up interval (yrs)	13	13	NA*	NA	NA	13	NA	NA	13	NA	NA	NA
Buffer distance of riparian areas (m)	25	25	NA	NA	NA	25	NA	NA	50	NA	NA	NA
Simulation term (yrs)	250	300	155	150	145	155	150	305	180	300	290	200

Remark: NA* is not applicable

The Resulting Patterns of Forest Openings

The harvesting patch number was counted up all the harvesting patches during simulation. From a landscape perspective, changes of the patch number and patch size were measured within all management areas. Change of patch structure would be proved by this analysis. Comparison had made between the present and after simulation.

Results

Harvest schedule/allocation

Table 2 shows the result of predicted harvest area (ha) at each working period by 12 simulation models (VAR1-VAR12).

Table 2 Results of predicted harvest area (ha) at each working period.

Working periods	Simulation models											
	VAR1	VAR2	VAR3	VAR4	VAR5	VAR6	VAR7	VAR8	VAR9	VAR10	VAR11	VAR12
1	0.71	1.04	0.00	0.67	0.64	0.00	1.93	2.05	1.41	0.55	0.59	0.00
2	1.87	0.55	1.47	0.17	2.75	0.22	2.02	1.13	1.61	0.84	0.37	0.00
3	1.07	1.42	0.88	1.00	2.79	2.32	1.89	2.55	1.81	0.26	0.25	0.00
4	1.09	0.78	0.97	1.27	2.25	1.41	1.16	1.76	1.88	0.88	1.16	0.00
5	1.95	0.48	0.54	0.81	2.66	1.93	2.51	1.67	2.04	1.34	0.35	2.36
6	0.76	1.48	1.23	1.38	2.44	2.09	2.64	2.26	1.83	0.82	0.80	1.41
7	0.83	0.58	0.80	1.47	0.96	1.87	1.56	0.68	2.57	0.73	0.89	2.39
8	0.74	1.16	0.67	0.90	1.86	2.13	1.89	1.53	1.92	1.72	1.60	1.37
9	0.18	1.11	0.96	0.92	1.55	1.89	1.50	2.02	2.32	0.84	0.99	0.99
10	1.48	0.13	0.48	0.97	1.97	0.83	2.58	3.19	1.48	1.17	0.48	2.49
11	0.75	0.47	0.31	0.91	1.82	1.97	1.47	1.16	1.79	1.16	1.79	2.04
12	1.61	0.31	0.95	0.23	2.01	1.76	1.97	2.02	1.94	1.51	0.48	2.01
13	0.60	1.04	0.14	0.81	1.27	2.16	1.90	2.34	2.36	0.29	0.44	2.02
14	0.82	0.69	1.01	1.21	1.85	1.62	0.29	2.32	2.52	0.43	0.55	2.72
15	0.53	1.74	0.22	1.19	1.69	1.58	1.74	1.41	0.23	0.43	1.37	2.65
16	1.09	0.89	0.95	0.97	1.57	2.77	0.39	1.25	0.88	0.13	1.06	2.22
17	1.01	0.73	0.64	0.60	2.21	1.98	2.46	2.25	1.36	0.30	1.48	2.21
18	1.65	1.09	0.71	1.23	0.91	1.14	1.48	2.20	2.36	1.46	1.11	0.92
19	0.00	0.76	0.81	1.46	2.03	1.45	2.02	2.15	1.66	0.63	1.72	2.37
20	0.48	1.11	1.21	0.89	1.59	2.32	1.87	1.89	2.56	0.68	0.96	1.56
21	0.95	0.83	1.44	0.74	2.22	0.10	1.50	2.22	1.83	0.77	0.08	
22	1.65	1.27	0.83	0.44	1.27	1.73	1.11	1.24	1.09	0.10	0.76	
23	1.82	1.62	1.48	0.51	2.34	1.48	1.67	1.46	1.53	0.81	1.04	
24	0.98	1.09	1.20	0.92	1.25	1.23	2.37	0.97	1.65	1.17	0.87	
25	0.15	1.27	0.77	0.39	2.19	1.57	1.56	2.74	1.69	1.30	0.09	
26	0.57	1.11	0.53	0.84	1.92	1.97	1.72	2.74	1.96	0.92	1.46	
27	0.10	0.78	0.78	0.15	0.39	2.16	0.22	2.24	2.10	1.32	1.04	
28	0.97	1.10	0.35	0.30	1.39	2.39	1.71	0.95	1.89	1.19	0.97	
29	0.01	1.12	1.23	0.52	1.97	1.92	0.89	2.18	1.81	0.26	0.55	
30	1.35	0.51	0.39	1.05	1.70	1.88	1.55	2.70	1.95	0.18		
31	0.53	0.26	1.63					1.18	2.51	1.02		
32	1.82	1.65						1.61	1.45			
33	1.06	0.31						1.59	2.42			
34	0.57	1.34						0.22	1.52			
35	0.99	1.02						1.86	3.07			
36	1.00	0.99						1.93	0.22			
37	0.75	0.98						2.61				
38	1.30	0.78						1.83				
39	0.81	0.60						1.81				
40	0.74	0.84						1.06				
41	0.64	1.04						1.69				
42	1.29	1.00						2.11				
43	0.24	0.98						1.40				
44	0.33	0.54						1.34				
45	0.67	1.20						2.00				
46	1.04	0.64						2.04				
47	1.84	0.82						2.42				
48	0.93	1.29						2.25				
49	0.97	0.10						2.49				
50		0.61						1.80				
51		1.45						1.99				
52		0.64						1.74				
53		0.84						2.09				
54		1.32						2.09				
55		0.77						2.34				
56		1.67						1.88				
57		0.35						2.72				
58		0.08						2.60				
59		0.69						0.97				
60		0.95										

Figure 9 illustrates the stand age class after simulation by model VAR1. Age class structure changed almost even from concentrated 7 to 8 age class at the present through simulations. The target harvesting area was almost achieved through simulation periods. These results may suggest that age class structure would be smooth on the assumption of sustainable yield control.

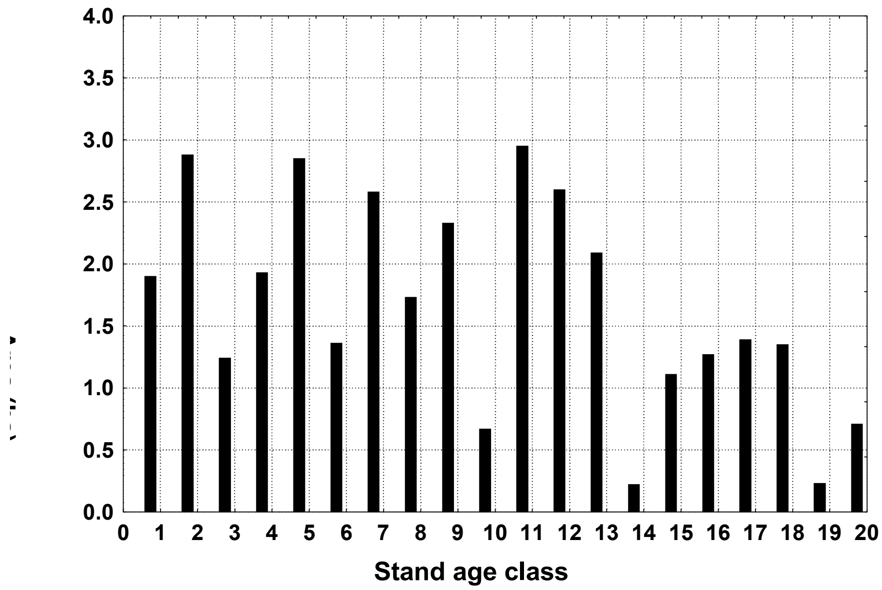


Figure 9- Stand age distributions after g HARVEST simulation: VAR1.

Table 3 is the summary of the changes of patch structures after simulations (VAR1-VAR10). The result shows that large patches at the present were subdivided into more small patches resulting from specifying harvesting patches in both spatial and temporal context through simulation.

Table 3 -The summary of the changes of patch structures.

Simulation model	Total number of patches	Average sizes for all management areas (ha)	Area of interior habitat (ha)	Area of edge habitat (ha)
1	99	2.191	24.26	130.71
2	149	1.456	26.63	129.39
3	52	4.172	29.96	125.42
4	55	3.945	28.53	128.37
5	90	2.411	27.08	125.3
6	67	3.238	20.19	130.39
7	75	2.893	31.72	123.67
8	213	1.019	25.86	122.89
9	97	2.237	16.34	134.74
10	48	4.52	No data	No data

Discussions

The development of a GIS-based timber harvest scheduling system in combination with a raster GIS which offers image processing capabilities within the same system and a harvest schedule/allocation model which allows simulation of differences in the size of timber harvest units, the total area harvested, length of harvest rotation, and the spatial distribution of harvest areas was described. GIS capabilities make it possible to produce land mosaic spatially in accordance with functionary classification strategies. HARVEST capabilities were illustrated through examples of predicting changes in landscape patterns with spatial and temporal context resulting from initial landscape conditions and potential harvesting activities. This method is not accomplished yet by traditional timber harvesting management tools. Using the proposed approach, resource managers could design and demonstrate with flexible management strategies geared to multiple economic, environmental, and social objectives. Analyses of resulting patterns would act as a factor of decision-making. Yet, above system was not considered service zone from forest roads concerning to harvesting operations. Exact figures of growing stock were not grasped either because some afforestation programs get low grades. It would be necessary to be planning harvest strategies. We are going to work out these problems and enhance this system.

References

Baskent, E. Z. and Jordan, G.A. 1995. Characterizing spatial structure of forest landscapes. Can. J. For. Res. 25: 1830-1849.

Borgesa, J. G. and Hoganson, H. M. 2000. Structuring a landscape by forestland classification and harvest scheduling spatial constrains. For. Ecol. Manage. 130: 269-275.

Forman, R. T. T. 1995. Land Mosaics. Cambridge University Press. Cambridge.; 632p.

Gustafson, E. J. 1999 HARVEST: A timber harvest allocation model for simulating management alternatives. In Landscape Ecological Analysis: Issues and Applications. Klopatek, J. M. and Gardner, R. H. (eds.). New York, Springer; 109-124.

Gustafson, E. J. and Crow, T. R.1999. HARVEST: linking timber harvesting strategies to landscape patterns. In Spatial Modeling of Forest Landscape Change: Approaches and Applications. Mladenoff, D. J. and Baker, W. L. (eds). Cambridge University Press, Cambridge; 309-332.

Hoganson, H. M. and Borgesa, J. G. 2000. Impacts of the time horizon for adjacency constrains in harvest scheduling. For. Sci. 46(2): 176-187.

Kurttila, M. 2001. The spatial structure of forests in the optimization calculations of forest planning –a landscape ecological perspective. For. Ecol. Manage. 142: 129-142.

Murray, A. 1999. Spatial restrictions in harvest scheduling. For. Sci. 45(1): 45-52.

Shiba, M. 1997. Measuring the multi-dimensional efficiency of production performances in timber harvesting operations by means of Data Envelopment Analysis (DEA). Bull. Mie Univ. For. 21: 63-100. (in Japanese with English abstract)

Shiba, M. 1999. Dateneinhüllungsanalytische Anwendungsmöglichkeiten zur Bewertung der relativen Leistungsfähigkeit von Holzerntemaßnahmen dargestellt am Beispiel des privaten Holzproduktionskörpern in der Präfektur Gifu. For. Res., Kyoto 71: 77-96. (in Japanese with Germany abstract)

Shiba, M. 2001. Quantitative analysis of fragmented landscape patterns resulting from timber harvesting practices in Kyoto University Forests. Int. J. For. Eng. 12(1): 19-27.

Yoshimoto, A., Brodie, J. D. and Sessions, J. (1994) A new heuristic to solve spatially constrained long-term harvest scheduling problems. For. Sci. 40(3): 365-396.

The Tillamook Forest Plan: Scheduling Timber Harvest, Forest Structure, and Transportation at the Landscape Scale

John Sessions, Department of Forest Engineering, College of Forestry, Oregon State University, Corvallis, Oregon 97331, USA. (E-mail: john.sessions@oregonstate.edu)

Pam Overhulser, Oregon Department of Forestry, Salem, Oregon , USA. (E-mail: poverhulser@odf.state.or.us)

ABSTRACT

To facilitate decision making by the Board of Forestry, the Oregon Department of Forestry (ODF), with support of the OSU Department of Forest Engineering, has developed a spatial harvest scheduling model to simultaneously schedule timber harvest, forest structure, and transportation at the landscape scale. A spatial model was required in order to represent ODF's planning goals that include the attainment of a distribution of floating patches of complex forest across the landscape. To prepare the data for scheduling a preliminary harvest plan over the entire forest with a supporting road network was developed. The solution algorithm uses simulated annealing to solve a Model II harvest scheduling model with spatial control. Post processing tools have been developed to verify that the scheduling model is following the rules correctly and that the results are computationally correct.

Key Words: landscape planning, transportation planning, harvest scheduling, optimization, heuristics

INTRODUCTION

To facilitate decision making by the Board of Forestry, the Oregon Department of Forestry (ODF), with support of the OSU Department of Forest Engineering, has developed a spatial harvest scheduling model to simultaneously schedule timber harvest, forest structure, and transportation at the landscape scale. This paper briefly describes the structure of the model and illustrates the output.

Known within ODF as the Harvest and Habitat (H&H) model, the model has been developed to simulate harvesting strategies for the approximately 612,000 acres of northwest forests managed under the Northwest Oregon State Forests Management

Plan by the State of Oregon including the Tillamook, Forest Grove, Astoria, Western Lane, North Cascades, and West Oregon districts.

In order to simulate the harvesting strategies, a preliminary logging plan has been prepared for the entire area; about 15,000 harvest units (Figure 1). The harvest units are subdivided into parcels that are homogeneous with respect to:

1) timber stand
2) ownership
3) riparian area
4) logging system

In addition, parcels have other attributes including various kinds of fish and wildlife designations such as owl, murrelet, and salmon protection which are used to identify various types of harvest restrictions.

A transportation tree has been developed for all districts. The transportation tree identifies the road network, existing and not yet constructed, that would be used to access each harvest unit.

GOALS AND CONSTRAINTS

The mandate for the management of Oregon State forests is to provide the greatest permanent value for the citizens of Oregon. To achieve that mandate, ODF has developed four major strategies. Each strategy uses a different approach to reach its overall goal. However, all strategies share some common subgoals including:

1) High net present value
2) Non-declining flow of timber products
3) Achievement of desired amounts of complex forest
4) Achievement of a desired distribution of complex forest structure patches on the landscape

While achieving the goals, there are also a number of constraints:

1) Limits on acres that can be cut in certain parts of the forest until the desired amount of complex forest is reached.
2) Limits on acres that can be cut in certain parts of the forest for a number of time periods.
3) Limits on the number of contiguous acres that can be clearcut in any one time period.
4) Requirements that a stand cannot have a final harvest immediately after a thinning.
5) Limits on the maximum number of regeneration acres that can be cut in a time period.
6) Although not all parcels in a harvest unit must receive the same prescription, thinnings in the upland parcels must be coordinated with

each other. Also, if a riparian parcel within a harvest unit can be thinned, its timing must coincide with either the upland thinnings, or at a minimum be coordinated with the regeneration harvest of the uplands, providing the riparian parcel does not exceed a maximum age.

7) Limits on when recently thinned parcels can be re-entered.
8) Limits on the minimum age a harvest unit can have a regeneration harvest.
9) Limits on the maximum volume that travel over a road arc during a time period.
10) Specific requirements for stands with severe Swiss Needle Cast disease
11) Requirements that stands with phellinus be assigned specific regeneration options for one rotation after the existing stand is harvested.

PRESCRIPTION DEVELOPMENT AND DECISION VARIABLES

In order to reach the goals, a number of prescriptions have been developed for each stand type. These prescriptions represent various unique thinning pathways that either an existing stand type or a regenerated stand type could grow over time. Typically each of the 300-500 coniferous strata on each district has 50 to 100 unique thinning prescriptions developed for it. Hardwood stands have fewer options. Each stand type is grown forward in the FVS growth and yield model for 150 years in 5-year steps using an initial tree list from the forest inventory. Various biological metrics, including a measure of stand structure, are evaluated at each 5-year period. The value (gross revenue without consideration of logging and transport costs) of the stand at each 5 year point in time is calculated by considering species and log diameter.

The purpose of the scheduling model is to assign a series of prescriptions and regeneration harvest times to each parcel to reach the goals while satisfying the constraints. To do this, 9 decision variables are defined for each parcel. The 9 decision variables are:

1) what prescription to assign to the existing stand
2) what period will the harvest of the existing stand take place, if at all
3) what prescription will be assigned to the regenerated stand
4) what period will the regeneration harvest take place, if at all
5) what prescription will be assigned to the second regenerated stand
6) what period will the second regeneration harvest take place, if at all
7) what prescription will be assigned to the third regenerated stand
8) what period will the third regeneration harvest take place, if at all
9) what prescription will be assigned to the fourth regenerated stand.

MODEL STRUCTURE

The structure of the harvest scheduling model would be classified as a Model II. That is, stands that are harvested can switch prescriptions at regeneration time, and that the length of the rotation can also vary from rotation to rotation. Since the decision variables are integers, the resulting problem is a large integer programming problem. The Tillamook district has the largest model consisting of about 150,000 parcels or 1.35 million integer decision variables. To solve this problem, simulated annealing, one of a family of well known modern heuristics to solve combinatorial optimization problems, is used. Simulated annealing is a stochastic, neighborhood search technique that builds up a solution incrementally by randomly selecting harvest units, prescriptions, and regeneration times for the parcels within the harvest unit. The algorithm includes rules to escape from local minima.

The multiple goals are expressed as a goal programming problem objective function structure. In order to evaluate the contribution to net present value, harvest and road costs are calculated based on the spatial location of the harvest unit and its position on the transportation tree. Roads are constructed or reconstructed as necessary to support the harvest scheduling choices. For each move, spatial feasibility, i.e., clearcut size is checked before evaluation of the objective function. If a move survives the spatial feasibility test, its contribution to the objective function is calculated. A goal unique to ODF was the goal of reaching a target distribution of patches of complex forest of differing size floating across the landscape. This accounting problem is dealt with by tracking as many as 500 patches across 30 time periods or about 15,000 patches.

Solution time depends upon the number of polygons, but a "good" solution can be achieved within one hour on a 3.4 gigahertz computer with 1 gigabyte of RAM. Usually a number of runs must be made in order to fine tune the penalty functions being used in the goal programming objective function. Since the simulated annealing heuristic is stochastic, i.e., random numbers are used during the search process, multiple runs are made to identify dominant solutions for a given set of penalty weights.

MODEL VERIFICATION

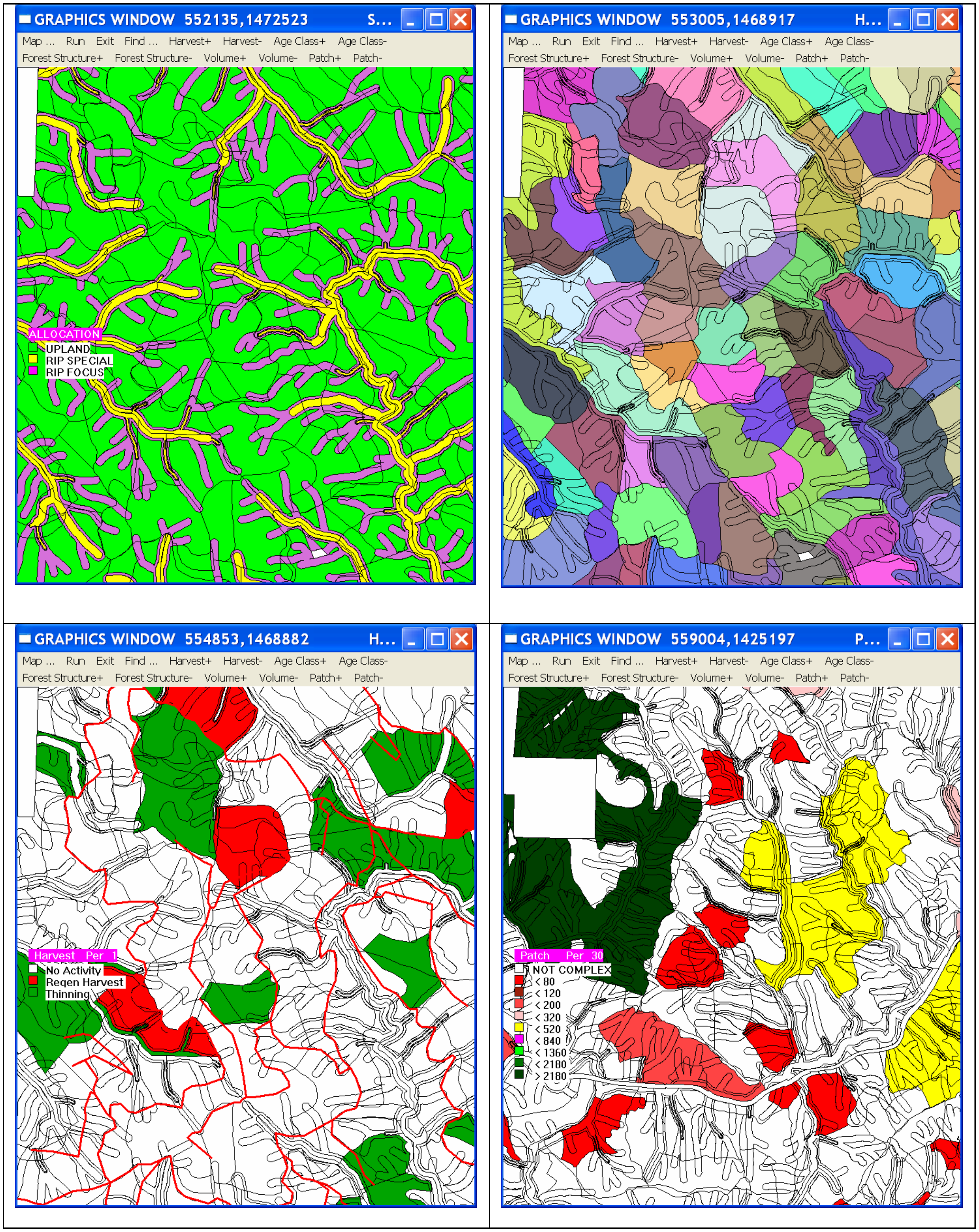
To our knowledge, the H&H project models are some of the largest, if not the largest, spatial forest models of their type. An important challenge is to understand if the model is functioning correctly. By this we mean, "Is the model following the rules and are the computations correct?" Just because a model runs, does not mean it is running correctly. There have been cases where well-known harvest scheduling models have run erroneously for several years without errors being discovered.

To help with debugging, ODF has developed two tools. The first tool is a GIS-based tool which takes the solution and verifies that it satisfies all spatial rules for the first 5 time periods. The second tool is an ACCESS-based database tool that takes the solution and independently verifies the harvest calculation for the 30-period planning horizon. After the solution passes these two tests, District teams, familiar with the ground, review the graphic and tabular output for feasibility.

GOAL ACHIEVEMENT AND IMPLEMENTATION

The H&H models use optimization techniques to identify promising solutions to represent each strategy by adjusting weights in the objective function. The Board must ultimately choose among the strategies or direct the planners to develop additional alternatives. The Board's adopted strategy will provide direction to ODF for possible adjustments to their current Forest Management Plan and ultimately the development of operational plans. As data improves, it is anticipated that the linkage between the harvest scheduling model and District operational plans will be strengthened.

Figure 1. Land classification between upland and two kinds of riparian (upper left), harvest units (upper right), first period harvest and road system (lower left), and complex forest patches (lower right).



A computerized method to find the optimal location of a centralized log landing and evaluate its influencing factors

Marco A. Contreras S.[1] and Woodam Chung[2]

Abstract

Locating a log landing is an important task in forest operations planning. Although several methods have been developed to find an optimal landing location and compute an average skidding distance (ASD), none of them simultaneously considers irregular shapes of harvest unit boundary, sloped terrain, uneven timber volume and the presence of obstacles. Skid trails are often affected by these factors, and thus they should be taken into account when a landing location is planned. In this study, we have developed a computerized method to determine the optimal landing location in a given harvest unit. Using raster-based GIS data such as a digital elevation model (DEM) and a timber volume layer, the method finds skid trails from stump to each of candidate landings and selects the least cost landing location. Unit boundary shapes, volume distribution, sloped terrain, and the presence of obstacles are analyzed in terms of how they affect economically optimal landing locations. The computerized method is briefly described, and the effects of different factors influencing landing locations are presented.

Keywords: Optimal log landing location, forest operations planning, digital elevation model, average skidding distance.

Introduction

Locating a centralized log landing for a given harvest unit is a frequent and important task in forest operations planning since landing locations largely affect logging costs as well as environmental impacts such as site disturbances. Several factors related to forest characteristics and terrain conditions are usually considered when landing locations are selected. These factors may include timber volume distribution, irregular boundaries, terrain conditions and the presence of obstacles

---

[1] Graduate Research Assistant, Department of Forest Management, College of Forestry and Conservation, University of Montana. Email: marco.contrerassalgado@umontana.edu

[2] Assistant Professor, Department of Forest Management, College of Forestry and Conservation, University of Montana. Email: woodam.chung@umontana.edu

that changes skidding directions. Although a variety of numerical procedures and computer models have been developed to identify optimal landing locations and compute average skidding distances (ASD), none of them is able to simultaneously address all the factors mentioned above.

The first widely accepted numerical procedure to estimate an ASD was introduced in Matthews's book, *Cost Control in the Logging Industry* in 1942. Based on the *centroid* and *equal area* arguments, Matthews (1942) developed formulas to calculate an ASD for a harvest unit with uniform volume in a regular shaped boundary such as squares, rectangles, wedges and circles. An improvement of Matthews's procedure was later made by Suddarth and Herrick (1964). Based on the integral formula, $ASD = \int x dA / A$, where x is the distance from a log landing to a hookup point and A is the area to be harvested, they developed mathematical equations for more accurate calculations of an ASD for the same regular geometric shapes. Furthermore, a mathematical equation for any kind of triangle was established (Peters 1978), and also several models were developed to calculate optimal road and landing spacing on unbounded tracts (Matthews 1942; Peters 1978; Thompson 1992; Liu and Corcoran 1993).

Irregular shapes of unit boundary and non-uniform volume distribution were included in numerical procedures developed in 1970s. Peters and Burke (1972) established a method to calculate an ASD on irregular shaped areas. A procedure that incorporates variable log density on irregular shapes was later built by Donnelly (1978). In addition, Perkins and Lynn (1979) developed a method that directly incorporates the roughness of the terrain into the ASD calculation. The Perkins and Lynn method also addressed the case where straight skidding is not feasible. These previous approaches used coordinate data to calculate an ASD where the data was taken from topographic maps. More recent approaches have used polygonal mesh approximations to represent the harvest area (Greulich 1989), and also considered rectilinear distances (Greulich 1994). A model that uses a DEM to calculate skidding distance and ASD was also developed (Tucek 1999). Although, this method presents a more realistic calculation of the skidding distance by calculating accumulated slope lengths from cell to cell, the 50-meter resolution used may not accurately describe the terrain configuration.

Using these previous methods to calculate an ASD, several algorithms and models were developed to find the optimal location of a centralized landing. Greulich (1991) developed an algorithm that identifies the optimal landing location on flat uniform terrain. Assuming timber is uniformly distributed across the harvest area, the algorithm finds the optimal location by minimizing a total cost function through derivatives. The most recent work by Greulich (1997) considers rectilinear skidding operations on flat and uniform terrain conditions, but it still assumes timber is distributed continuously uniform across the area.

Two main objectives of this study are 1) to develop a computerized model to find the optimal location of a centralized log landing that simultaneously considers irregular shaped unit boundaries, terrain conditions, uneven timber volume distribution and the presence of skidding obstacles, and 2) to analyze the effects of the above factors on the optimal log landing location using hypothetical harvest units with different terrain and forest attribute scenarios. Skidding obstacles are introduced in this study as an important factor influencing landing locations. When skidding across unit boundaries is not allowed due to different ownerships or riparian zones, the boundary often becomes an obstacle that changes skid trails. Small steep areas within a harvest unit where skidders cannot negotiate also become skidding obstacles. The presence of these obstacles forces the shortest skid trails to be rerouted, which results in the increase of skidding distances. In this paper, we present the computerized model developed and the effects of these influencing factors on the optimal landing location.

Computerized Model

A harvest unit is defined in this paper as an area to be harvested by ground-based systems where all logs will be brought into a single centralized log landing. Harvest units are usually delineated by forest engineers or field managers while considering forest characteristics, terrain conditions, stream locations, and existing road networks among others. It is assumed a log landing can be located anywhere within the harvest unit and will be accessed by a spur road. In this context, finding an optimal log landing location becomes a cost minimization problem that minimizes total skidding costs incurred to harvest the entire unit.

The computerized model we developed uses complete enumeration to solve these cost minimization problems. Although many optimization problems are solved using solution techniques that avoid complete enumeration (Roberts, 1984) due to its large computation time. Our model uses complete enumeration because a harvest unit constitutes a small-scale problem and it is possible to solve the problem in a reasonable amount of time.

A 10x10meter DEM representing a harvest unit is the main input data of the model along with a volume layer. A volume layer for the model can be created from a polygon-based layer by transforming it into a raster that has the same resolution as the DEM. Each grid cell in a DEM becomes a candidate log landing location in the model, while all the grid cells containing timber volume are assumed to be log pickup points.

Using the complete enumeration method, the model calculates the total skidding cost from each of candidate landing locations within a harvest unit. When calculating total skidding costs for the entire harvest unit, the model first sets one of

10x10 meter grid cells on a DEM as a candidate landing location. Then, it calculates the total skidding costs by adding up all the skidding costs from each grid cell to the candidate landing as follows:

$$TCS = \sum_{i=1}^{m} SC_i$$

where, m represents the total number of grid cells within the harvest unit, *and* SC_i represents the skidding cost from the i^th grid cell on the harvest unit to the cell representing the landing location. The skidding cost is calculated by the following equation:

$$SC_i = \left[\left(\frac{cycle\_time}{60}\right) * RR\right] * N^o turns_i$$

where, RR represents the rental rate of the skidder expressed in \$/hour, which is assumed to be \$85/hr in this study; $N° turns_i$ indicates the number of turns necessary for skidding all timber volume on the i^th grid cell to the landing, which is assumed to be an integer number. Timber volume per turn (payload capacity) is assumed to be 1.5 m^3. Lastly, *cycle_time* is a skidding cycle time in minutes for a round trip between landing and a timber location. Cycle times can be estimated using appropriate regression models. As an example, the following regression model is used in the application described in this paper.

$$cycle\_time = 3.9537 + (0.0215 * dist)$$

where, $dist_i$ represents the distance along the slope (skidding distance) from the i^th grid cell to the landing location.

Distance along the slope from cell i to cell j is calculated by adding the slope distance of adjacent grid cells along a straight line joining cell i to cell j. The black line in Figure 1 represents the direct distance along the slope from the log landing location (the cell with a circle in it) to any given cell. The red line represents how the actual distance along the slope is calculated in the model, going from the centroid of a cell to the centroid of the adjacent cell on the black line's course. The distance along the slope calculated by the model is usually greater than the direct distance along the slope. When cells i and j are on the same column or the same row, or they are located perfectly diagonal, both black and red line distances are equal. Since the distance calculated by the model follows a winding course instead of a straight line, the wander factor commonly used by other methods (Peters 1972; Donnelly 1978; Greulich 1991, Clark et al 2000) is omitted in this model.

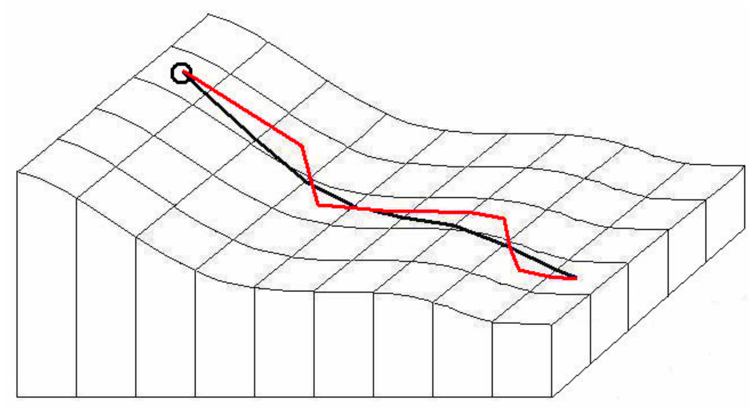


Figure 1— Calculation of the distance along a slope by the model.

The presence of obstacles that may change skidding directions is taken into consideration when the distance along a slope is calculated. One case of these obstacles would be a harvest unit with a concave-shaped unit boundary where skidding across the boundary is not allowed due to different ownerships or other natural boundaries such as streams (Figure 2a). Another case would be a small steep area where skidder cannot negotiate and have to go around it to reach the other side of the area (Figure 2b). Besides these two cases, any other zones, which cannot be crossed by heavy machinery or limit machine traffics such as wetlands, can be considered as obstacles in the model.

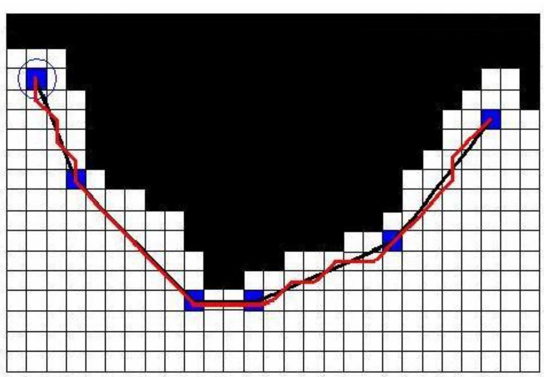


Figure 2—a) Calculation of skidding distance when the harvest unit cannot be crossed.

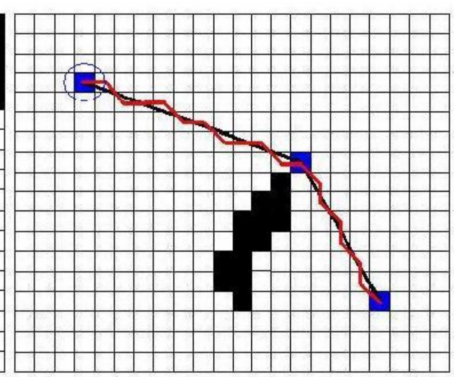
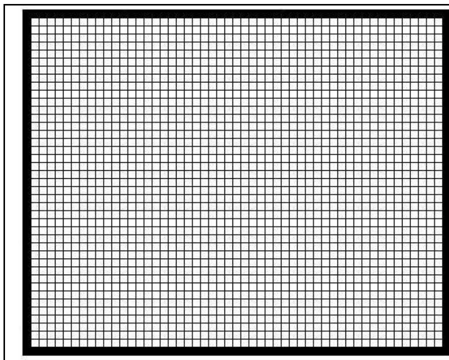


Figure 2—b)Calculation of skidding distance when steep areas exist.

Once the model calculates the total skidding costs associated with each of candidate landings (grid cells) within the harvest unit using the methods described above, it selects the least cost landing cell as the optimal location of the centralized log landing for the given harvest unit.

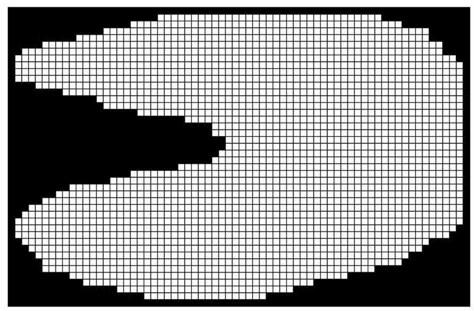
Applications

Four hypothetical harvest units were developed in order to examine the model performance and analyze the effects of timber volume distribution, sloped terrain, irregular shaped harvest units and the presence of obstacles on optimal log landing location (Figure 3). All units have the same size of 20.9 ha, and a 10x10 meter DEM was developed for each unit. Harvest unit 1 represents a regular shaped unit (Figure 3a), while units 2, 3 and 4 represent irregular shaped harvest units (Figure 3 b, c and d).



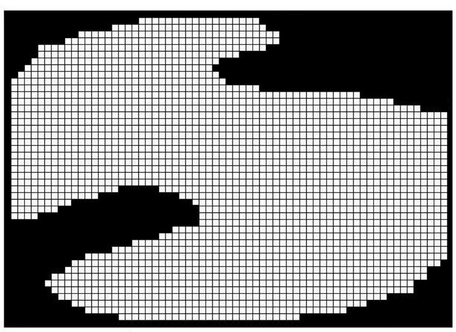
a) Regular shaped hypothetical harvest unit

1, 51columns and 41 rows



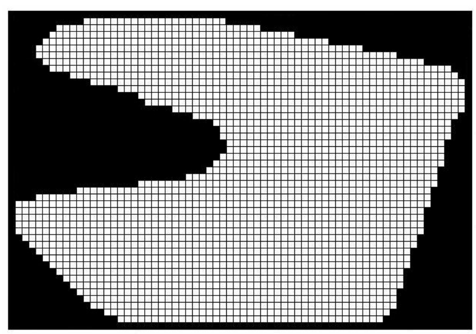
b) Irregular shaped hypothetical harvest unit 2,

65 columns and 42 rows maximum



c) Irregular shaped hypothetical harvest unit

3, 65 columns and 44 rows maximum



d) Irregular shaped hypothetical harvest unit 4,

66 columns and 45 rows maximum

Figure 3— Four different hypothetical harvest units developed for the model applications.

We ran the model on these hypothetical harvest units to find optimal landing locations under 18 different terrain and timber volume scenarios. *Cases 1* through *4* which are based on harvest units 1 through 4 respectively, evaluate the effect of the boundary shape. Those cases are examined under flat terrain, uniform timber volume distribution of 300 m^3/ha (3.0 m^3 per grid cell) and no obstacles of any kind. The effect of obstacles caused by a concave shaped harvest unit boundary (Figure 2a) is analyzed in *cases 5* through *7*, which are based on harvest units 2 through 4, respectively. To evaluate the effect of terrain condition, *cases 8* through *10* were developed using harvest unit 1 with a maximum slope inclination of 20%, 30% and 40%, respectively (Figure 4). The effect of obstacles caused by steep areas which skidders cannot pass through (Figure 2b) are analyzed in *cases 11* through *13* which present one, two and four obstacles, respectively (Figure 5). These *cases* are also based on harvest unit 1 with a maximum slope of 30%. Obstacle areas (small steep areas) were created within the unit with an average slope of 80%. The effect of timber volume distribution is evaluated in harvest unit 3 with different volume distributions. *Case 14* has an even volume distribution with an average of 300 m^3/ha (Figure 6a). *Case 15* has two volume zones of the same size with different volume distributions: 150 and 300 m^3/ha, making an overall average volume 225 m^3/ha (Figure 6b). *Case 16* has three different volume zones: 150, 300 and 450 m^3/ha with an overall average volume of 300 m^3/ha (Figure 6c).

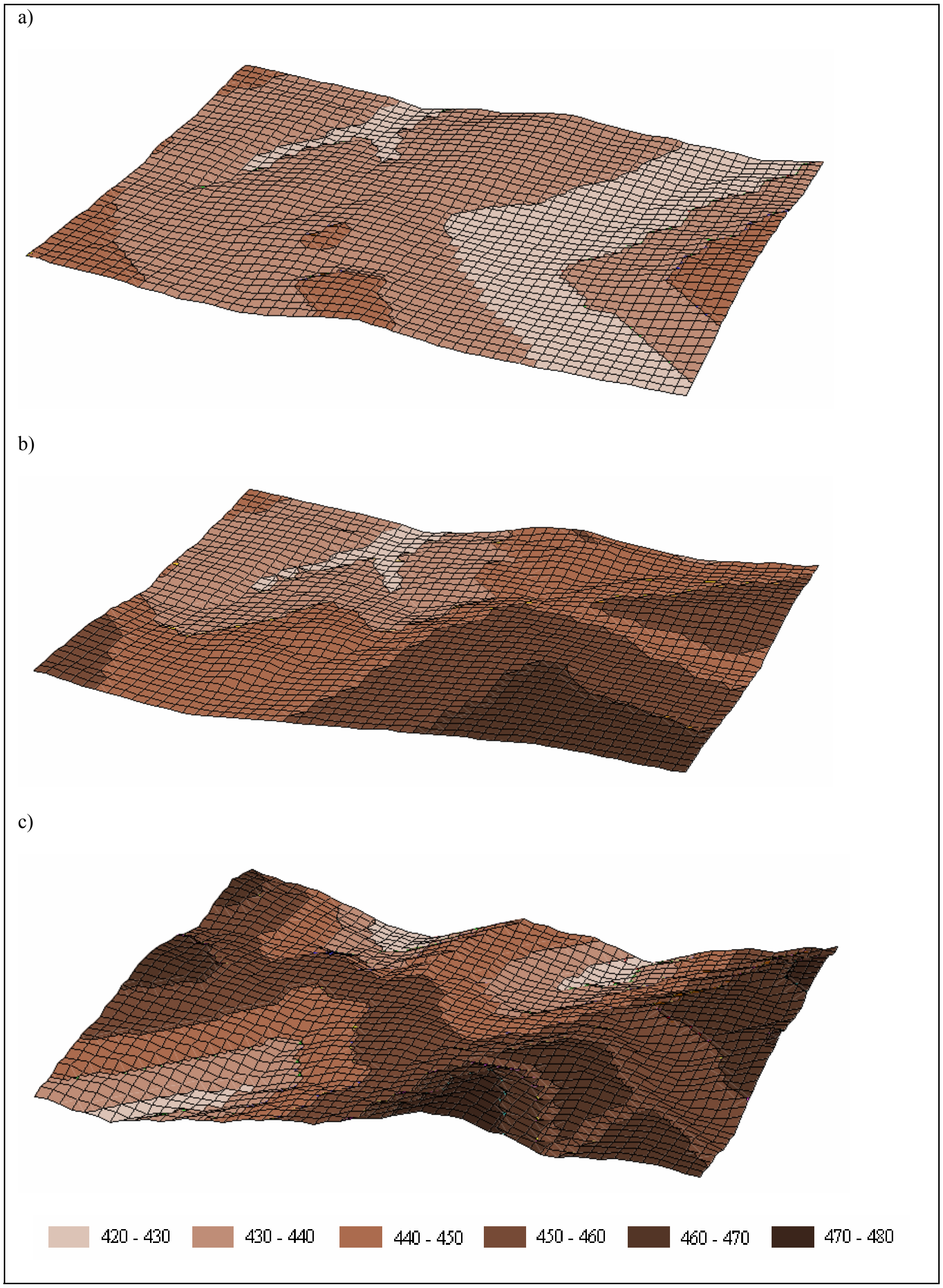


Figure 4— a) DEM of harvest unit 1 with a maximum slope of 20% for case 8, b) DEM of harvest unit 1 with a maximum slope of 30% for case 9 and, c) DEM of harvest unit 1 with a maximum slope of 40% for case 10. Elevation is expressed in meters.

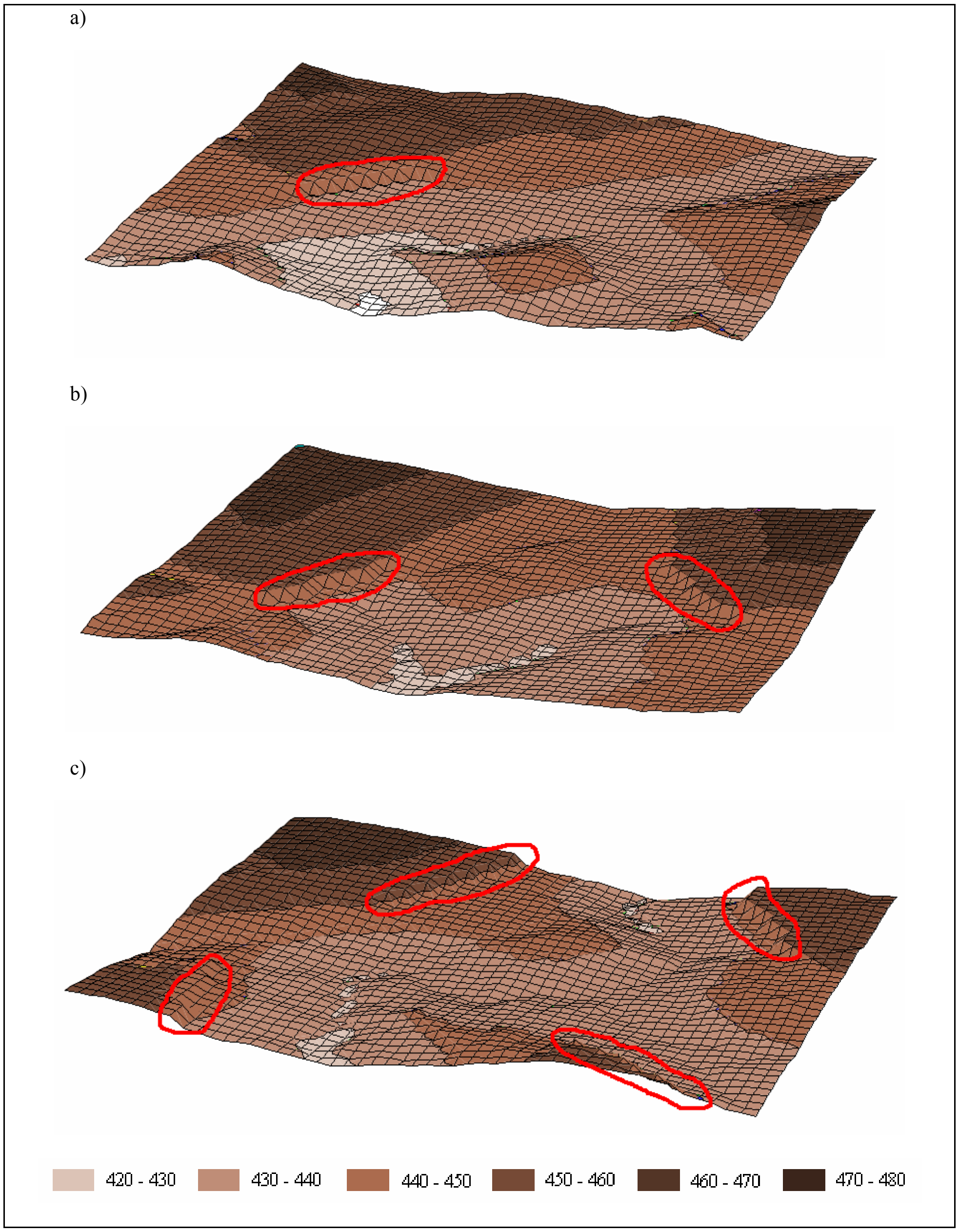


Figure 5— a) DEM of harvest unit 1 with one obstacle for case 11, b) DEM of harvest unit 1 with two obstacles for case 12 and, c) DEM of harvest unit 1 with four obstacles for case 13. Circled areas indicate the steep areas, which skidders cannot pass through.

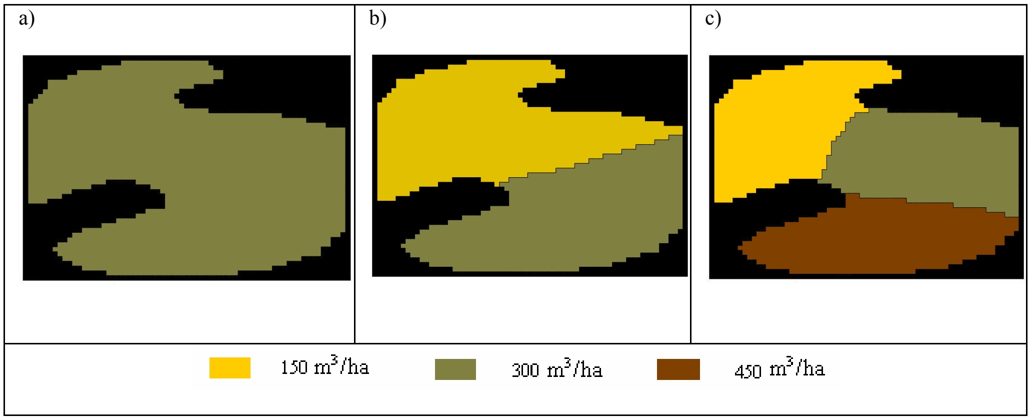


Figure 6— a) Case 14 with an even volume distribution, b) Case 15 with two different volume zones, and c) Case 16 with three different volume zones.

While *cases 1* through *16* show how each of individual factors influences optimal landing location, *cases 17* and *18* explain the effects of combined factors on landing locations. *Case 17* and *18* are based on harvest units 1 and 4 respectively, considering a DEM with a maximum slope inclination of 30%, except obstacle areas which have an average slope inclination of 80%. These steep areas were included in both cases, while obstacles caused by unit boundary were considered only in *case 18*. Uneven volume distributions with three areas are also considered on both cases (Figure 7).

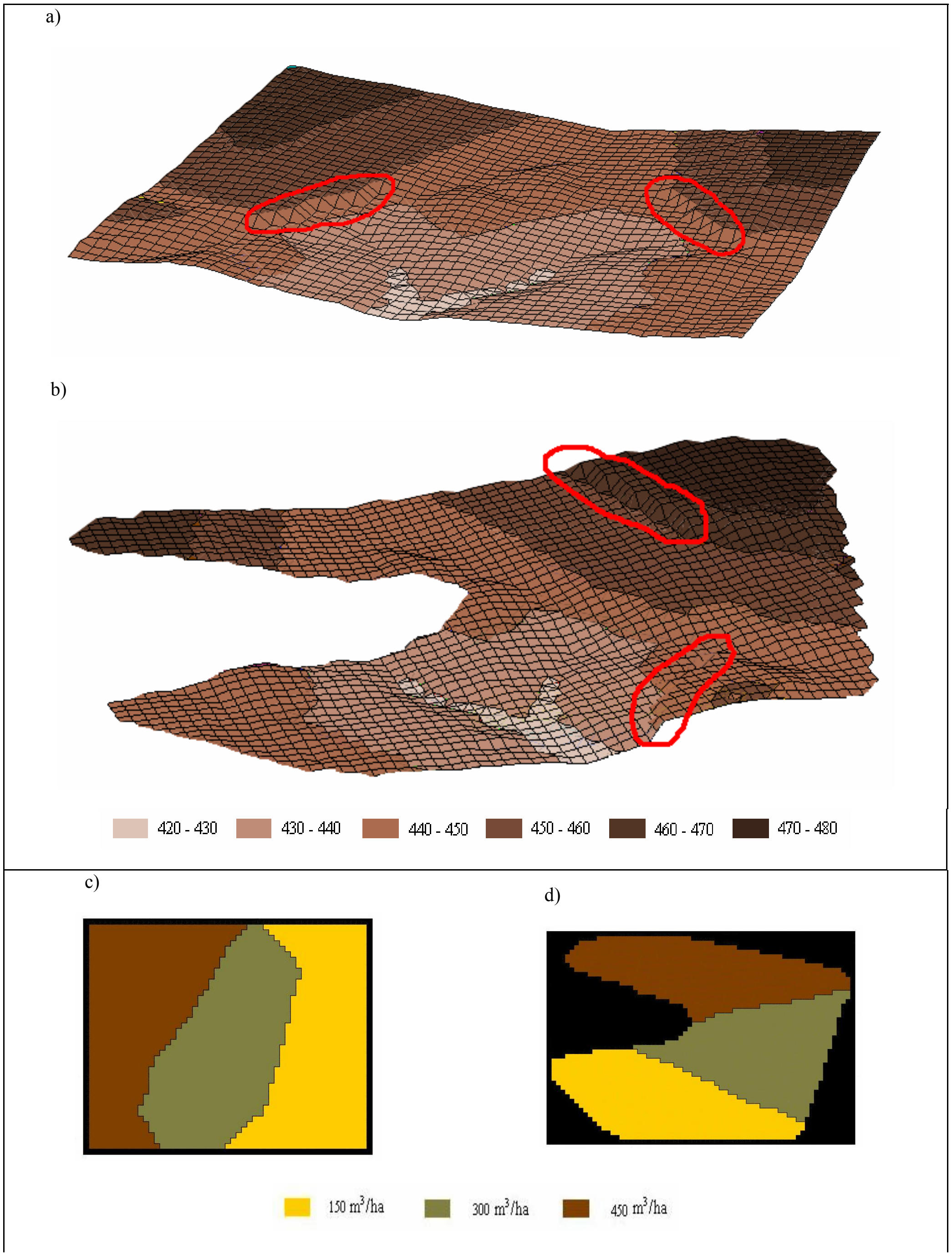


Figure 7— a) Case 17, DEM of harvest unit 1 presenting two obstacles, b) Case 18, DEM of harvest unit 4 presenting two obstacles, c) Case 17, uneven volume distribution with three zones, d) Case 18, uneven volume distribution with three zones.

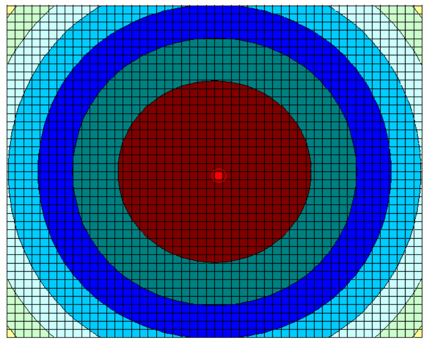
Results and Discussion

The computer model was run for all the cases described in the previous section and identified the optimal centralized landing location for each case. The landing locations are presented in a small red circle along with its row and column numbers in Figures 8 through 13. Estimated total skidding cost (TSC) associated with the optimal landing location is also presented. Each colored ring in the figures represents a range of total skidding costs, showing if a landing is located inside a ring, the total skidding costs associated with the ring would incur. For example, if a landing is located anywhere in the dark red ring in Figure 8a, the total skidding costs to harvest the entire unit using the landing would be in the range of $45,500 and $49,000.

Since *cases 1* through *4* represent flat terrain, even volume distribution and no obstacles of any kind, they are used as the baseline of comparison for other factors. Figure 8 illustrates the results for these four *cases*. The concentric circles are perfectly symmetric in *case 1* since skidding distances are straight lines (shortest distances) between two points anywhere in the unit. Colored rings around the optimal landing location show the skidding cost pattern, indicating total skidding costs increase as landing moves toward the boundary. For irregular shaped harvest unit boundaries (Figure 8 b,c, and d), the minimum TSCs slightly increase and optimal landing locations are shifted compared to the regular shape unit (Figure 8a) although all the units have the same area. This is because the geometric center of a harvest unit changes as its boundary becomes irregular shapes.

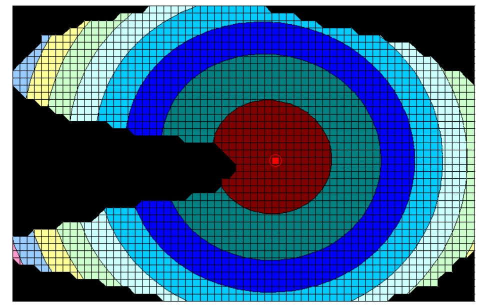
The results for *cases 5, 6* and *7,* where obstacles caused by unit boundaries were considered, show that the total skidding costs increase faster than *cases 2*, *3* and *4,* respectively, as the landing moves toward the boundary (Figure 9). This happens because skid trails have to follow the unit boundaries and if a landing is located close to the boundary, most skid trails become longer than straight lines. Interestingly, the presence of these obstacles in cases 5 and 7 does not affect the optimal landing location, but very slightly increases the minimum TSCs (Figure 9a and c). As expected, however, both cases change skidding cost patterns (shapes of rings), which indicates the increase of total skidding costs as landing moves toward the boundary. *Case 6* has an irregularity of boundary that is large enough to affect the optimal landing location. The result shows the optimal landing location is moved 42 meters southeast (3 rows down and 3 columns to the right) and the minimum TSC increases by $1,715 (Figure 9b). *Case 6* has more area where skidding along straight lines is not feasible, which explain the increase of skidding costs in the case.

a)



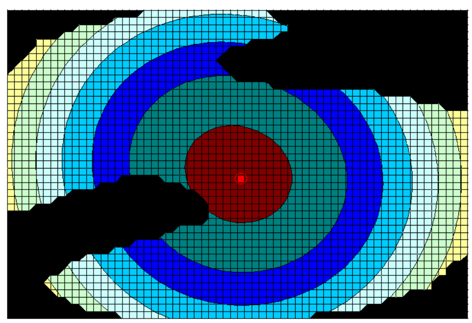
Optimal landing location at row = 21 & column = 26 with a minimum cost of $ 45,917.

b)



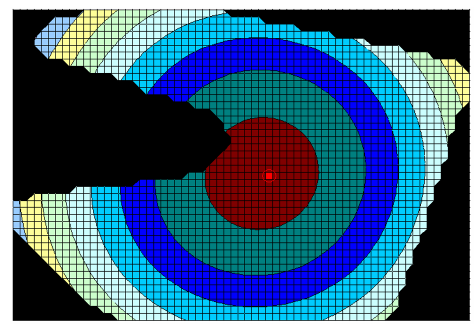
Optimal landing location at row = 22 & column = 37 with a minimum cost of $ 47,454

c)



Optimal landing location at row = 24 & column = 33 with a minimum cost of $ 47,843

d)



Optimal landing location at row = 24 & column = 37 With a minimum cost of $ 47,500

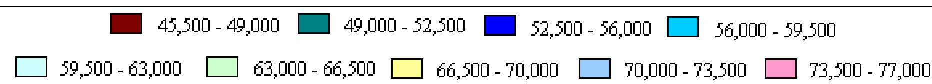


Figure 8— **a)** Model results for *case 1*, **b)** Model results for *case 2*, **c)** Model results for *case 3*, **d)** Model results for *case 4*. A red cell at the center of the circles indicates the optimal landing location. Colored rings represent different skidding cost ranges in dollars.

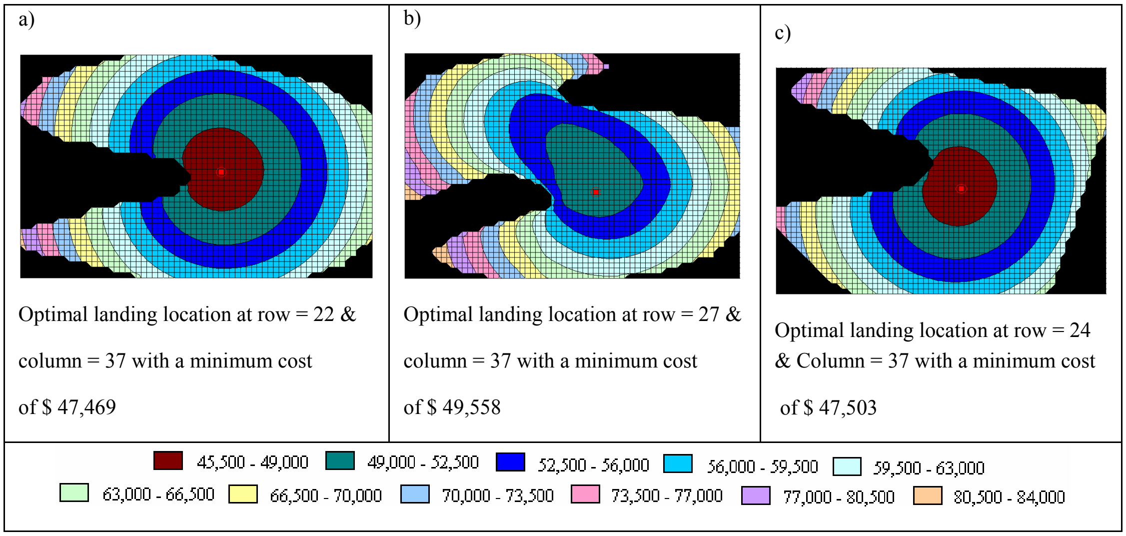


Figure 9— a) Model results for case 5, b) Model results for case 6, c) Model results for case 7.

Figure 10 illustrates the results generated by the model for *cases 8* to *10*, where different terrain slopes are considered. According to these results, the maximum slope inclination of 20%, 30% and 40% considered in *cases 8*, *9* and *10* respectively, does not affect the optimal landing location. Optimal landing locations in those cases are the same as *case 1* where the harvest unit had a flat terrain. However, the minimum TSC is increased by $1,300, $1,387 and $1,524 in *Cases 8*, *9* and *10,* respectively, compared to *case 1*. The results confirm that the skidding distance represented by a slope distance in the model increases as terrain gets steeper, but the terrain steepness does not affect the optimal landing location as long as all the skidding distances from one landing increase or decrease at a constant rate.

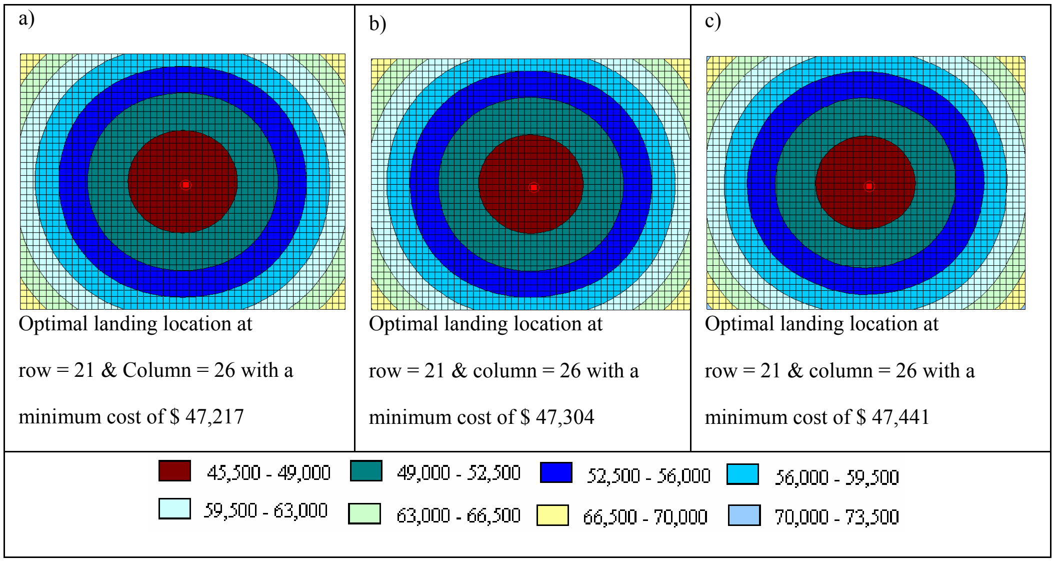
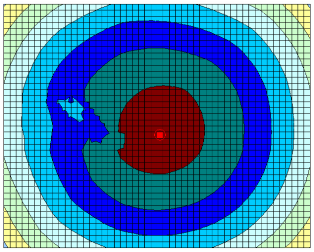


Figure 10— a) Model results for case 8, b) Model results for case 9, c) Model results for case 10.

The results from the computer model for *cases 11* to *13* are presented in Figure 11. These cases include the presence of obstacles caused by small steep areas which skidders cannot pass through. The results show that the optimal landing location is affected by the presence of those obstacles. For *case 11* which has one obstacle, the optimal landing location is moved 10 meters south(1 row down) compared to *case 1* (Figure 11a); for *case 12* with two obstacles, the landing is moved 10 meters north (1 row up, Figure 11b); and for *case 13* with three obstacles, the landing is moved 14 meters southeast (Figure 11c). The minimum TSCs also increase in the three cases by $1,573, $1,727 and $2,686 respectively, compared to *case 1*. The skidding cost pattern differs significantly when more obstacles are considered. The deformed concentric circles show how quickly the skidding cost increases if the landing is located close to the places where skidding along a straight line is not feasible.

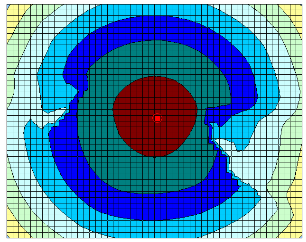
Figure 12 shows the results from *cases 14* to *16*, where different timber volume distribution is considered. Since c*ase 14* represents regular volume distribution, the result is the same as that in *case 3* (Figure 12a). In *cases 15 and 16*, however, the optimal landing location as well as concentric circles are moved towards the area with higher volume density (Figure 12b and c). As the results, the optimal landing location is moved 40 meters south (4 rows down) and 64 meters southeast (5 rows down and 4 columns to the right) in *cases 15* and *16*, respectively. Since *case 15* considers the average volume of 225 m^3/ha, which is 75 m^3/ha less than *case 14*, the minimum TSC in *case 15* decreased by $12,584. Although *case 16* considers the same volume as *case 14*, the shift of the optimal landing location toward more volume area results in reducing the minimum TSC by $1,791 (Figure 12c).

a)



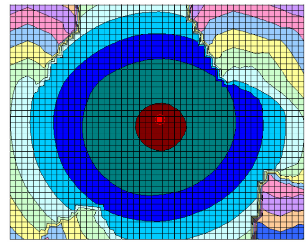
Optimal landing location at row = 22 & column = 26 with a minimum cost of $ 47,490

b)



Optimal landing location at row = 20 & column = 26 with a minimum cost of $ 47,644

c)

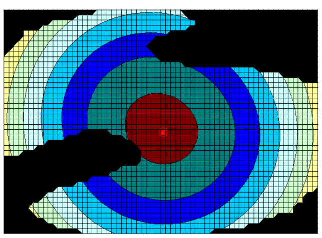


Optimal landing location at row = 22 & column = 27 with a minimum cost of $ 48,603

45,500 - 49,000 | 49,000 - 52,500 | 52,500 - 56,000 | 56,000 - 59,500 | 59,500 - 63,000 | 63,000 - 66,500
66,500 - 70,000 | 70,000 - 73,500 | 73,500 - 77,000 | 77,000 - 80,500 | 80,500 - 84,000 | 84,000 - 87,500

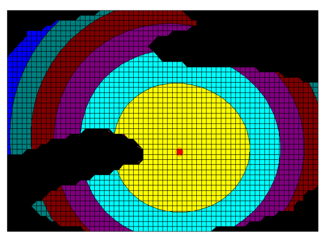
Figure 11— a) Model results for case 11, b) Model results for case 12, c) Model results for case 13.

a)



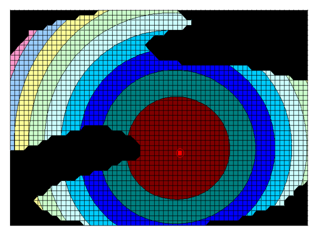
Optimal landing location at row = 24 & column = 33 with a minimum cost of $ 47,843

b)



Optimal landing location at row = 28 & column = 33 with a minimum cost of $ 35,259

c)

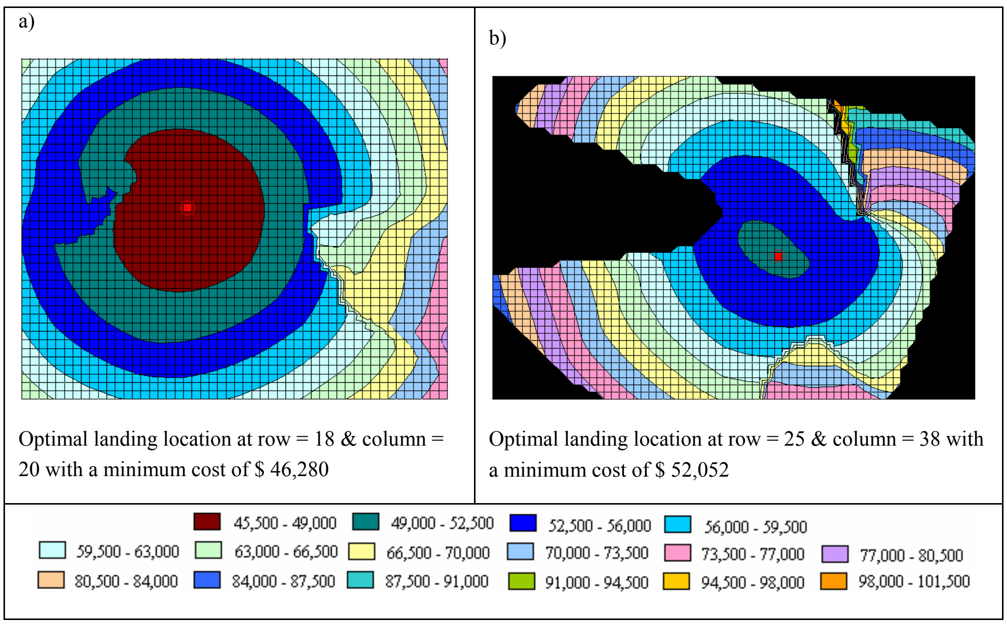


Optimal landing location at row = 29 & column = 37 with a minimum cost of $46,052

35,000 - 38,500 | 38,500 - 42,000 | 42,000 - 45,500 | 45,500 - 49,000 | 49,000 - 52,500 | 52,500 - 56,000
56,000 - 59,500 | 59,500 - 63,000 | 63,000 - 66,500 | 66,500 - 70,000 | 70,000 - 73,500 | 73,500 - 77,000

Figure 12— a) Model results for case 14, b) Model results for case 15, c) Model results for case 16.

While the results from *cases 1* through *16* show how each of individual factors influences the optimal landing location, those from *cases 17* and *18* explain the effects of combined factors on landing locations (Figure 13). Irregular harvest unit shape, different terrain condition, uneven volume distribution, and the presence of obstacles are considered in both cases. For *case 17*, the computer model found the optimal landing location to be at row 18 and column 20, with an associated minimum TSC of $46,280 (Figure 13a). The optimal location, compared to the results for *case 1*, moved 67 meters northwest (3 rows up and 6 columns to the left). This shift is mainly due to two factors: the presence of obstacles and volume distribution. The presence of obstacles makes the optimal location to move up in order to avoid increasing skidding distances as much as possible. Uneven volume distribution moved the landing location west toward a higher volume area (Figure 7). The skidding cost pattern shows that the TSC rapidly increases when the landing is located on areas with lower timber volume and/or on places where skidding along a straight line is not feasible. For *case 18*, the computer model found the optimal landing location to be at row 25 and column 38, with an associated minimum TSC of $52,052. The optimal location, compared to the results for *case 4*, moved 14 meters southeast (1 row down and 1 column to the right) (Figure 13b). In c*ase 18*, although higher volume area is located in the northern part of the unit, the optimal landing location is shifted south. This is because the presence of obstacles in the northern part of the unit (Figure 7c) holds back the shift of the optimal location towards the high volume areas. The presence of obstacles becomes the main factor that increases the minimum TSC by $4,552 in *case 18*.



Optimal landing location at row = 18 & column = 20 with a minimum cost of $ 46,280

Optimal landing location at row = 25 & column = 38 with a minimum cost of $ 52,052

Figure 13— a) Model results for case 17, b) Model results for case 18.

In summary, the results generated by the computer model for the 18 different cases show how the optimal landing location is affected by its influencing factors. Terrain conditions that are represented by a maximum slope inclination of the harvest unit do not affect the optimal landing location. Irregular harvest unit boundaries have a minor effect on optimal landing locations in the cases analyzed. However, when the harvest unit boundary becomes an obstacle, it redirects skid trails, and the landing location changes depending on the irregularity of the boundary. The presence of steep areas as well as different volume distributions are the major factors that largely affects landing locations in our applications.

Conclusion

A computerized model has been developed to determine the optimal landing location in a harvest unit under given terrain and volume conditions. Although the model can be applied only to harvest units to be harvested by ground-based systems, it is able to consider a wide range of physical and vegetation attributes of the unit that affect the optimal landing locations. The model is expected to be used to complement manual procedures in selecting economically better landing locations which has been usually done using a rule of thumb and rough approximations.

The sensitivity analyses conducted in this study confirm physical and vegetation attributes of a harvest unit need to be considered when a landing location is selected. Since all the attributes are different in individual harvest units, these landing placement problems should be considered as case specific problems, and the results presented in this paper should not be used as a general guideline in determining a landing location.

Although the model uses a complete enumeration, a landing placement problem dealing with only one harvest unit is small enough to solve quickly. The model took less than 1.5 minutes for a Pentium 4 computer to analyze the most complicated case. Data required to run the model can be easily obtained. High resolution and accuracy DEMs are more and more available, and a timber volume layer can be easily rasterized from inventory data using a GIS.

The model should be further improved to remove several assumptions made for the analysis. For example, the model currently assumes an integer number of skidding cycles per grid cell. Also, the model does not differentiate uphill from downhill skidding. Improving the model on these assumptions as well as including a more accurate cost estimate function would make the model more practically applicable. The current model does not consider any spur road construction which could be one of the major influencing factors for landing locations. Including spur road construction, landing construction and transportation costs would also enhance the model applicability. Lastly, the further improvement should include the expansion of the model's capability to consider multiple log landings in one harvest unit.

References

Clark, M.; Meller, R.; Mc Donald, T.; Ting, C. 1997. A new harvest operation cost model to evaluate forest harvest layout alternatives. Proceedings: Forest Operations for Sustainable Forest and Healthy Economies. Council of Forest Engineering (COFE). 20th Annual Meeting. Rapid City, South Dakota, USA.

Clark, M.; Meller, R.; Mc Donald, T.; Ting, C. 2000. A new harvest operation cost model to evaluate forest harvest layout alternatives. Annals of Operations Research 95: 115-129.

Donnelly, D. 1978. Computing average skidding distance for logging areas with irregular boundaries and variable log density. General Technical Report RM-58. USDA. Forest Service.

Greulich, F. 1989. The calculation of average yarding distance to a centralized landing, given a polygonal mesh approximation of the setting surface. Canadian Journal of Forest Research 19(1):141-144.

Greulich, F.E. 1991. Optimal landing location on flat, uniform terrain. Can. J. For. Res. 21(5):573-584.

Greulich, F.E. 1994. Average yarding distance for row thinning of plantations. Journal of Forest Engineering 6(1):57-60.

Greulich, F.E. 1997. An algorithm for optimal centralized landing location: rectilinear yarding operations on flat uniform terrain. Canadian Journal of Forest Research. 27(8):1192-1197.

Liu, S.; Corcoran, T. 1993. Road and landing spacing under the consideration of surface dimensions of roads and landings. Journal of Forest Engineering 5(1):49-53.

Matthews, D. 1942. Cost control in the logging industry. McGraw-Hill Book, New York. 329 p.

Neuenshwander, R.; Aedo-Ortiz, D. 1997. Dimensional variables in harvest road spacing. Planning and Control of Forest Operations for Sustainable Forest Management, IUFRO S3.04 Congress. Madrid, Spain. P 205-213.

Perkins, R.; Lynn, K. 1979. Determining average skidding distance on rough terrain. Journal of Forestry (77) 2: 84-88.

Peters, P.; Burke, J. 1972. Average skidding distance on irregular shaped timber harvest settings. Research Note PNW-178, Portland OR: USDA. Forest Service, Pacific Northwest Research Station.

Peters, P. 1978. Spacing of roads and landings to minimize timber harvest cost. Forest Science 24 (2):209-217.

Peters, P. 1990. Optimum spur road layout near a forest boundary line. Journal of Forest Engineering 1(2):3-7.

Roberts, F. 1984. Applied combinatorics. Prentice-Hall, Inc. 606p.

Stuart, W. 2003. Checking our foundations: Matthews' least cost models revisited. Southern Journal of Applied Forestry 27(1):30-35.

Suddarth, S.; Herrick, A. 1964. Average skidding distance for theoretical analysis of logging costs. Research Bulletin 789 Purdue University AG Experiment Station.

Thompson, M. 1992. Considering overhead costs in road and landing spacing models. Journal of Forest Engineering 3(2):13-19.

Tucek, J. 1999. Algorithms for skidding distance modeling on a raster digital terrain model. Journal of Forest Engineering 10(1):67-79.

Optimally Matching Wood to Markets: Understanding Spatial Variation of Wood Density and Spiral Grain in Douglas-fir[1]

Mauricio A. Acuna[2] and Glen Murphy[3]

Abstract

In many parts of the world log markets are becoming increasingly competitive and complex. Buyers are demanding, and suppliers are offering, logs that have been cut for very specific end-uses and which may be specified in terms of internal as well as external properties. Optimally matching logs to markets requires good measurements and predictions of the wood properties in each stem. This information could be used either at the planning stage or in the on-board computers installed in harvesters to enhance bucking and sorting. To assess the geospatial and intra-tree variation in wood density and spiral grain in Douglas fir stems, over 400 wood disks were collected from 7 trees per site from a total of 17 sites in the Cascade and Coastal Ranges of Oregon. Trees at each of the sites were of a similar age and average size. Sites were selected from a range of elevations and aspects. Disks came from different vertical positions in each tree. No statistically significant relationship between wood density and either elevation or aspect was found. There was evidence of a weak negative association between the height in a tree where the samples came from and wood density. No statistically significant relationship between height, elevation or aspect was observed for spiral grain.

Key words: bucking, spiral grain, wood density, wood markets.

---

[1] Paper presented at the Council of Forest Engineering annual meeting. Soil, Water and Timber Management: Forest Engineering Solutions in Response to Forest Regulations. June 11-14, 2005. Fortuna, California.

[2] Graduate Research Assistant. Oregon State University, Forest Engineering Department. 204 Peavy Hall, Corvallis, OR 97331. email: mauricio.acuna@oregonstate.edu.

[3] Professor, Oregon State University, Forest Engineering Department. 204 Peavy Hall, Corvallis, OR 97331. email: glen.murphy@oregonstate.edu.

Introduction

Douglas fir (Psudotsuga menziesii (Mirb.) Franco) has a large economic importance, especially for the forest products industries of the United States, New Zealand, and some parts in Europe (Gartner et al., 2002), due to its primary uses as dimension lumber, piles, plywood, and pulp. Optimally matching Douglas fir wood quality to markets should lead, not only to improved product uniformity, productivity and profitability (Clarke et al. 2002), but also contribute to reduced wastage, energy consumption and environmental impacts along the seedling to customer supply chain. Wood quality can be defined in terms of attributes that make it valuable for a given end use. Quality attributes of significance include wood density, microfibril angle, fiber length, lignin content, ring width, knot size and distribution, grain angle and coarseness, color, etc. (Walker et al. 1993). It has been noted, however, that the factors controlling wood quality can be confusing and are frequently contradictory (Anon. 1965). In this paper we will focus on just two quality attributes, density and spiral grain, which can affect Douglas fir's economic value.

Wood density is a simple measure of the total amount of solid wood substance in a piece of wood. For this reason, wood density provides an excellent means of predicting end-use characteristics of wood such as strength, stiffness, hardness, heating value, machinability, pulp yield and paper making quality (Jozsa et al. 1989). It is calculated as the ratio of dry wood weight to volume and is measured in units such as kilograms per cubic meter (Hughes, 1967).

Each tree species has its own characteristic average wood density and range (O'Sullivan 1976). Some species exhibit greater variation in wood density than others. Wood density may, or may not (Yang et al. 2001), vary among provenances and is very variable among trees and within individual trees of a given provenance (Zobel and Van Buijtenen 1989). Density has been shown to be a highly heritable characteristic (Cown et al. 1992, Hanrup et al. 2004, Zobel and Jett 1995); that is, the phenotypic variation between individuals is largely due to genetic differences as opposed to environmental effects.

Cown et al. (1991) reported that wood density of radiata pine (Pinus radiata D.Don) grown in New Zealand decreases markedly with both increasing elevation and latitude. It was thought that this may be a function of temperature. Wilhelmsson (2001) developed density models for Norway spruce (Picea abies L.) and Scots pine (Pinus sylvestris) which included the diameter over and under bark at breast height, number of annual rings, latitude and elevation, and temperature as explanatory variables. These variables accounted for 50% of the total variation in the spruce density and 59% of the pine density. Harding and Copley (2000) demonstrated that density was linked to latitude in slash-Caribbean pine (Pinus elliotti Engelm. X Pinus caribbea) hybrids grown in Queensland. Elevation has also been shown to effect wood density in five species of pine grown in South Africa (Clarke et al. 2002) and in Douglas fir grown in the Pacific Northwest (Anon. 1965).

Within individual trees, density varies from early wood to late wood within rings, from pith to bark at a given height in the stem, and from stump to tip (Gartner et al. 2002, Josza et al. 1989, Kennedy 1995). Jozsa and Kellogg (1986) examined the density pattern from pith to bark at several sampling heights in Douglas-fir. Their results indicated relatively low density juvenile wood in Douglas-fir for the first 15-20 years of growth. Then a rapid increase was evident to about age 30, followed by a stable or slightly increasing density trend. This trend has also been reported by other workers (Megraw, 1986a; Gartner et al. 2002). For a tree of a given age, density usually decreases with height in the stem (e.g. as reported for radiata pine by Donaldson et al. 1995) but may be constant or even increase (e.g. as reported for spruce species by Ward 1975).

Silvicultural management (e.g. pruning and spacing) has been shown to affect density in some cases (Polge 1969, Megraw 1986a, 1986b, DiLucca 1989) but not in others (Wahlgren et al. 1968).

The distribution of Douglas-fir tree relative density from Canada, USA, Europe and New Zealand tends to be bell shaped with a mean between 0.40 and 0.50. Density for individual trees in the Western USA ranges between 0.33 and 0.57 (Anon 1965).

In 1959, Knigge (1962), cited in Anon. (1965), selected five trees from each of 51 second growth (< 100 years old) Douglas fir stands situated between the Canadian border and northern California and from the Coast Range to the western slopes of the Cascades. In general, specific gravity increased with age, improved with site class, increased with average growing season temperature and decreased with increasing growing season precipitation and increasing elevation. However, only 34% of the variation between individual trees could be accounted for.

In the early 1960's a much larger survey of wood density was carried out in the western USA for nine "high priority" species, including Douglas fir (Anon 1965). Over 9000 Douglas fir trees were sampled. A sub-sample from the western Cascade Ranges was chosen for more detailed analysis. Trees came from elevations ranging between 0 and 2400 m and from latitudes spanning 650 km. For trees between 35 and 149 years old, only two variables were significantly related to increment core specific gravity at dbh, elevation and latitude. Both of these negatively affected specific gravity, but together they only accounted for 10% of the variation in density between individual trees. The authors noted that elevation and latitude were indicators of precipitation and temperature, two of the factors that Knigge (1962) found to influence density. The authors recommended that other factors, such as aspect, site index and topography class, should be investigated.

In a standing tree which has straight-grained wood the fibers will be oriented parallel to the long axis of the stem. With little exception, fiber arrangement is at some angle, however small, to the stem axis rather than precisely parallel to it. At times this deviation is large, resulting in an obvious spiraling grain pattern. From a utilization standpoint, spiral grain is important in view of its detrimental effects on the strength, seasoning and machining properties of wood (Noskowiak 1963, Forest Products Laboratory 1999). Lumber sawn from such logs is characterized by slope of grain which causes low strength and stiffness as well as a tendency to twist as it dries. Excessive spiral grain (about 35 degrees) can severely impact log quality (Jozsa and Middleton, 2004). Noskowiak (1963) observed grain angles as high as 40 degrees in foxtail pine (Pinus balfouriana Grev. and Balf.).

Noskowiak (1963) reviewed the literature on spiral grain in trees. He noted that spiral grain is a normal phenomenon in the life span of trees and to a large extent is genetically controlled. In conifer trees there appears to be a general radial pattern. Young trees start out spiraling to the left. As the tree gets older, the magnitude of the slope gradually decreases to zero. Then the tree begins spiraling to the right, the magnitude of the spiral increasing with age (Northcott 1957, Noskowiak 1963). The magnitude of the grain deviation, and the age at which there is a change from left spiral to straight grained, and from straight grained to right spiral varies widely.

Tessier du Cros et al. (1980) found that the individual tree variation in spiral grain found in beech (Fagus sylvatica) was very large. Harris (1989) has argued that although spiral grain is largely controlled by heritability, its manifestation is partly dependent on the environment. He demonstrates this with the example of seed from trees of good form producing trees with spiral grain when grown in a different environment. Walker et al. (1993) note that, while there is considerable evidence that environmental extremes favor the development of spiral grain, this has not been formally established. Noskowiak (1963) cites conflicting evidence that aspect (Smythies 1915 [yes], Rault and Marsh 1952 [no]), elevation (Kindseth [no date] [yes], Wellner 1955 [no]), and soil type (Champion 1925 [yes], Troup 1921 [no]) affect the magnitude of spiral grain.

There is also conflicting evidence as to the effect of height in the tree on spiral grain angle. Northcott (1957) cites studies where spiral grain angle decreased with height for red alder (Alnus rubra Bong.), was not affected by height for western hemlock (Tsuga heterophylla (Raf.) Sarg.), and increased with height for both ponderosa pine (Pinus ponderosa P. & C. Lawson) and Araucaria cunninhamii.

Silviculture can also affect spiral grain. Polge (1969) reported that pruning radiata pine resulted in a reduction in spiral grain. Harris (1989) notes that economic pressures to reduce rotation ages have resulted “in a relatively higher proportion of the stem than formerly, consisting of young wood with significant spirality”.

Northcott (1957) measured the spiral grain on 140 pieces of Douglas fir from trees up to 500 years old. For cambial ages less than 100 years old the spiral grain was generally less than 4 degrees. However, some specimens ranged from 16 degrees left spiral to 19 degrees right spiral. Differences were noted between localities, individual trees and both radially and vertically within individual trees.

Optimally matching logs to markets requires good measurements and predictions of the external and internal properties of the wood in each stem (Clarke et al. 2002, Wilhelmsson 2001). These assessments could be used either at the planning stage or in the on-board computers installed in harvesters to enhance bucking and sorting. Understanding the spatial variation, within different stems and for different locations and stand characteristics, is expected to lead to improved ability to meet market requirements.

This paper summarizes the results of an investigation into modeling the effects of spatial characteristics - in particular, elevation, aspect, and height within trees - on Douglas fir wood density and spiral grain from a range of sites in western Oregon.

Material and Methods

Sites and trees selected

In mid-2003, 119 trees were felled at 17 forest sites located in the Coast Range and the Cascade Range of Oregon. The latitude and longitude of the sites ranged from 44o 13' to 45o 36' and from 122o 00' to 123o 35', respectively. The sites were chosen to cover a range of elevations (217 to 996 m) and aspects. Approximately 7 trees were felled at each site and these were selected to cover the range of diameters present. All stands contained second growth Douglas fir and were of similar age class. The characteristics of each site under study are shown in Table 1.

After felling, disks approximately 100 mm thick were cut at regular intervals up each stem: at 0, 5, 10, 20, and 30 above the base of the tree. The disks were labeled, placed in large bags, and stored in a cold room until they were ready to be used for the wood density determination. Close to 400 disks were collected.

Table 1-Characteristics of the sites under study

Site	*Elevation of the site (m)*	*Aspect**	*Average DBH of trees selected (cm)*
1	396	ENE to WNW	32.0
2	217	ENE to WNW	35.3
3	453	ESE to WSW	34.0
4	294	ENE to WNW	30.5
5	642	WSW to WNW	35.6
6	681	ENE to WNW	32.2
7	996	ENE to WNW	29.2
8	870	ENE to ESE	36.7
9	546	ENE to WNW	47.1
10	864	WSW to WNW	31.0
11	864	ESE to WSW	34.4
12	360	ESE to WSW	34.4
13	600	ESE to WSW	33.6
14	705	ESE to WSW	32.9
15	705	ESE to WSW	30.6
16	375	ENE to WNW	30.2
17	510	ENE to WNW	31.5

*ENE: East-Northeast, WNW: West-Northwest, ESE: East-Southeast, WSW: West-Southwest.

Wood density

Two wood samples were cut from each disk at about 4-5 cm from the outer edge and immediately placed in a cold store with an identification tag. The samples were later dried in an oven at 103 degrees C until their weight stabilized (24 to 72 hours). The volume of each of the samples was then measured using a water displacement method. Relative wood density (specific gravity) was then calculated.

Spiral grain angle

Each disk was cut in half and a radial line marked perpendicular to the pith. Two rings (spirals) on each side of the pith were selected; one approximately 6 cm from the outer edge and the other 5 cm from the pith. At each of the selected rings a line perpendicular to the radial line was drawn. The deviation between this perpendicular line and the direction of the spiral was taken with a protractor to obtain the spiral grain angle. An average spiral grain angle was calculated for each disk.

Two measurements of over bark diameter were made along the longest and shortest axes and averaged. In addition, measurements were made of the average diameter without bark, and the average diameter of the heart wood (recognized by a color change in the disk); these were not used in the analyses for this paper.

Data analysis

Statistical analysis of the data was undertaken following a stepwise multiple regression analysis methodology proposed by Ramsey and Schafer (2003). Briefly it included graphical analysis of the data to determine if transformations were needed, examination of the correlation matrix, fitting of the model, exploration of the residuals, checking to see if the variable added at each step was significant, and improvement of the final model. The statistical software S+ ? v. 6.0 was used for the analysis. A p-value of 0.05 was used to determine if an explanatory variable should be included in the model.

Three models were explored, one for spiral grain and two for the density. One of the density models assumed that no prior information was known about density lower down in the tree. The other assumed that a density measurement for the base of the tree was available. The potential explanatory variables included HEIGHT, the height along the tree where the disks were collected from (0 m , 5 m, 10 m or 20 m above the base), AVOB, the average diameter of each disk including the bark (mm), ASPECT, the aspect of the trees where the sample came from (1 for ENE to WNW, 2 for ENE to ESE, 3 fro ESE to WSW, and 4 for WSW to WNW), and ELEV, the elevation of the site where the samples were selected from, and DENSITY_0, the density at 0 meters above the base.

Results and Discussion

Density

Relative density for all samples had a mean value of 0.404 with a standard deviation of 0.041. The mean is lower than is usually quoted for Douglas fir; 0.45. A higher value would have been reported if the relative density had been weighted by the square of the diameter at which the sample was taken, an indicator of the volume at that point in the tree.

Examination of the scatter plots indicated that the regression assumptions of normality and specially the homogeneous variance and linearity were not met for the response variable DENSITY and the ELEV and AVOB explanatory variables. Log transformations of them were made before fitting the model. Variables HEIGHT and ASPECT were not transformed because they were nominal ones and because of their pattern observed in the scatter plots.

Potential outliers in the data were tested using Cook's distances and found to not be influential. All data points were, therefore, used in developing the regression models.

The matrix of correlations among variables is presented in Table 1. The log transformed DENSITY (ldensity) response variable had mild correlations with HEIGHT (-0.508) and log transformed AVOB (lavob) (0.423). As expected, however, there was a strong correlation between lavob and HEIGHT (-0.847).

Table 2 - Matrix of correlations among the variables considered into the study

	Height	Aspect	lavob	lavspgr	lelev	ldensity
Height	1.000					
Aspect	0.034	1.000				
lavob	-0.847	-0.024	1.000			
lavspgr	-0.087	0.105	0.110	1.000		
lelev	-0.043	0.409	-0.008	0.069	1.000	
ldensity	-0.508	0.036	0.423	0.140	0.009	1.000

When a regression model was fitted using HEIGHT, ASPECT, lavob, and lelev as the explanatory variables and ldensity as the response variable, only HEIGHT was significant ($p = 0.000$).

Not finding elevation as a significant explanatory variable for Douglas fir density runs counter to the results of the surveys by Knigge (1962) and Anon (1965). However, the later survey, in particular, found that only accounted for 6% of the variation in density even though the survey covered an elevational range that was three times that of this study. A drop in density of 0.01 was found for each 1000' increase in elevation. Not finding aspect as a significant explanatory variable for density just adds to the already conflicting literature on this topic.

The simple regression model with HEIGHT as the explanatory variable accounted for only 25.9% of the variance in ldensity. A very simple model (not log-transformed) was fitted and considered the definitive one. The results of this fit are presented in Table 3 and shown in the equation below. A box plot chart showing the average and range values in density obtained for the heights along the tree can be observed in Figure 1.

Table 3 - Results for the regression between DENSITY and the explanatory variable HEIGHT

Coefficients:	*Value*	*Standard Error*	*t value*	*Pr (>|t|)*
Intercept	0.4271	0.0027	161.0893	0.0000
Height	-0.0033	0.0003	-11.6442	0.0000

Residual standard error: 0.03533 on 390 degrees of freedom

Multiple R-squared: 0.258

F-statistic: 135.6 on 1 and 390 degrees of freedom, the p-value is 0

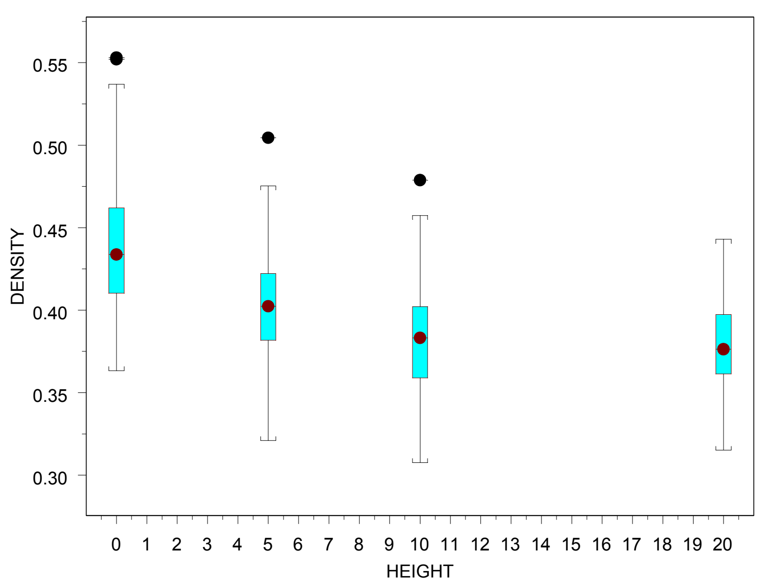


Figure 1-Box-plot chart for the variables DENSITY and HEIGHT.

From Figure 1, it is clear that there are differences in average relative density among the four heights evaluated (0.44 gr/cm3 at 0 meters, 0.40 gr/cm3 at 5 meters, 0.38 gr/cm3 at 10 meters, and 0.37 gr/cm3 at 20 meters above the base). However it is also clear that the relative density ranges significantly for each height. The minimum and maximum values of relative density are 0.36 gr/cm3 and 0.55 gr/cm3 at 0 meter, 0.32 gr/cm3 and 0.50 gr/cm3 at 5 meters, 0.30 gr/cm3 and 0.48 gr/cm3 at 10 meters, and 0.31 gr/cm3 and 0.44 gr/cm3 at 20 meters.

The clear, albeit weak, trend of wood density decreasing from the base to the top sections of the tree has been observed in other studies of Douglas fir (e.g. Megraw 1986a, Gartner et al. 2002) and for other species (e.g. for western hemlock (Jozsa et al. 1998) and for radiata pine (Donaldson et al. 1995).

When regressions models were fitted between the basic density at 0 meters (response variables) and basic density at 5 meters and 10 meters (explanatory variables), the multiple R-squared values were 0.40 and 0.35, respectively. Although the explanatory variables are statistically significant in these models, they have limited predictive capability.

Spiral grain

The mean and standard deviation for spiral grain angle for the wood disks was found to be 3.1 and 2.4 degrees respectively. This is similar to the spiral grain angle shown for Douglas fir by Northcott (1957). Regression analysis indicated that there was no statistically significant relationship between this variable and any of the explanatory variables. A model containing all four explanatory variables, HEIGHT, ASPECT, elevation and over bark diameter, accounted for less than 3% of the variation in spiral grain angle.

Finding that spiral grain angle is not affected by elevation, aspect, or height in the tree adds to the already conflicting evidence on factors affecting this wood property, although little of the evidence relates specifically to Douglas fir.

Conclusions

The objective of this study was to determine if geospatial and intra tree characteristics could be used to accurately predict density and spiral grain in second growth Douglas fir stands in Oregon. Neither wood property was related to elevation or aspect. Density was weakly related to height in the tree. Having a measure of density low down in the tree would slightly improve the predictive capability for density higher up the tree.

If density and spiral grain wood properties are to be optimally matched to markets, it is likely that tools will need to be developed to measure these properties in the forest in real time for individual logs

References

Anonymous. 1965. Western wood density survey. Report Number 1. USDA Forest Research Paper FPL-27. 58 p.

Champion, H.G. 1925. Contributions towards a knowledge of twisted fibre in trees. Indian Forestry Record (Silv. Ser.) 11 (part II): 11-80.

Clarke, C.R.E., R.D. Barnes, and A.R. Morris. 2002. Effect of environment on wood density and pulping of five pine species grown in Southern Africa. Paper presented at the 2002 Technical Association of the Pulp and Paper Industry of Southern Africa Conference, Durban, October 2002.

(http://tappsa.co.za/archive/APPW2002/Title/Effect_of_environment_on_wood_/effect_of_environment_on_wood_.html, Accessed 16 February 2005).

Cown, D.J., D.L. McConchie, and G.D. Young. 1991. Radiata pine wood properties survey. New Zealand Forest Research Institute Bulletin No. 50. 50 p.

Cown, D.J., G.D. Young, and R.D. Burdon. 1992. Variation in wood characteristics of 20 year old half-sib families of Radiata pine. New Zealand J. For. Sci. 22(1):63-76.

Donaldson, L.A., R. Evans, D.J. Cown, and M.J.F. Lausberg. 1995. Clonal variation of wood density variables in Pinus radiata. New Zealand J. For. Sci. 25(2):175-188.

DiLucca, C.M. 1989. Juvenile–mature wood transition. In Second growth Douglas-fir: its management and conversion for value: a report of the Douglas-fir task force. Edited by R.M. Kellogg. Forintek Canada Corp., Vancouver, B.C. pp. 23–38.

Forest Products Laboratory. 1999. Wood handbook: wood as an engineering material. Forest Products Laboratory, Forest Products Society, Madison, Wisconsin.

Gartner, B.L., M.N. North, G.R. Johnson, and R. Singleton. 2002. Effects of live crown on vertical patterns of wood density and growth in Douglas-fir. Can. J. For. Res. 32: 439-447.

Hanrup, B., C. Cahalan, G. Chantre, M. Grabner, B. Karlsson, I. Le Bayon, G. Llyod Jones, U. Muller, H. Pereira, J. Rodrigues, S. Rosner, P. Rozenberg, L. Wilhelmsson, and R. Wimmer. 2004. Genetic parameters of growth and wood quality traits in Picea abies. Scandinavian J. For. Res. 19(1):14-29.

Harding, K.J. and T.R. Copley. 2000. Wood property variation in Queensland grown Slash X Caribbean pine hybrids. In: "Hybrid breeding and genetics of forest trees." Proceedings of QFRI/CRC-SPF Symposium, April 2000, Noosa, Queensland, Australia. (Compiled by Dungey, H.S., M.J. Dieters, and D.G. Nikles). Department of Primary Industries, Brisbane. Pages 160-167.

Harris, J.M. 1989. Spiral Grain and Wave Phenomena in Wood Formation. Springer-Verlag, Berlin. 214 p.

Hughes, J.F. 1967. Density as an index of wood quality with special reference to the development of rapid and efficient methods of estimating density. In: Proceedings of the Tropical Forestry Meeting by Commonwealth Forestry Institution. Oxford. pp. 1-4.

Jozsa, L.A., and R.M. Kellogg. 1986. An exploratory study of the density and annual ring weigth trends in fast-growth coniferous wood in British Columbia. CFS Contract Report No. 02-80-55-017. Forintek Canada Corp., Vancouver, BC. 43 p.

Jozsa, L.A., J. Richards, and S.G. Johnson. 1989. Relative density. In Second growth Douglas-fir: its management and conversion for value: a report of the Douglas-fir task force. Edited by R.M. Kellogg. Forintek Canada Corp., Vancouver, B.C. pp. 5–22.

Jozsa, L.A., B.D. Munro, and J.R. Gordon. 1998. Basic wood properties of second-growth Western Hemlock. Forintek Canada Corp. Special Publication No. SP-38. 51pp.

Jozsa, L.A., and G.R. Middleton 2004. Discussion of wood quality attributes and their practical implications. Web page: http://www.lumber.com/products/pro_01130.asp

Kennedy, R.W. 1995. Coniferous wood quality in the future: concerns and strategies. Wood Sci. Technol. 29: 321–338.

Kindseth, P. (n.d.) Solvinn og rangvinn Skog. (Abstracted in Intern. Review Agri. 19(3):310).

Knigge, W. 1962. Untersuchungen uber die Abhagigkeit der mittleren Rohdichte nordamerikanische Douglasienstamme von untershiedlichen Wuchsbedingungen. Holz als Roh- und Werkstoff 20:352-360.

Megraw, R.A. 1986a. Douglas-fir wood properties. In Proceedings, Douglas-fir: Stand Management for the Future. Edited by C.D.O Oliver, D.P. Hanley, and J.A. Johnson. Institute of Forest Resources, University of Washington, Seattle, Wash. Contrib. 55. pp. 81–96.

Megraw, R.A. 1986b. Effect of silvicultural practices on wood quality. In Proceedings: TAPPI R&D Conference, 29 Sept. 1986, Raleigh, N.C. Technical Association of the Pulp and Paper Industry, Atlanta, Ga. pp. 27–34.

Northcott, P.L. 1957. Is spiral grain the normal growth pattern? Forestry Chronicle 33(4): 335-351.

Noskowiak, A.F. 1963. Spiral grain in trees – a review. Forest Products Journal 13(7):266-275.

O'Sullivan, P. 1976. The influence of initial espacement and thinning regime upon wood density in Sitka spruce (Picea sitchcensis [Bong] Carr.). M.Agr.Sci. thesis, University College, Dublin.

Polge, H. 1969. [Density of planting and pruning of live brnahces, or why, when and how to prune.] RFF 21 Special “Silviculture” 31:451-462.

Ramsey, F.L., and D.W. Shafer. 2002. The statistical sleuth: a course in methods of data analysis. Duxbury Press. Second Edition. 742 p.

Rault, J.P. and E.K. Marsh. 1952. The incidence and silvicultural implications of spiral grain in Pinus longifolia Roxb. in South Africa and its effect on converted timber. South African Forest Products Institute, Pretoria West, South Africa.

Smythies, E.A. 1915. Notes on the twisted fibre in chir pine. Indian Forester 41(3):69-75.

Tessier du Cros, E., J. Kleinschmit, P. Azoeuf, and R. Hoslin. 1980. Spiral grain in beech, variability and heredity. Silvae Genetica 29:5-13.

Troup, R.S. 1921. The Silviculture of Indian Trees. Oxford Press, London. pp 1056-61.

Wahlgren, H.E., G. Baker, R.R. Maeglin, and A.C. Hart. 1968. Survey of specific gravity of eight Maine conifers. USDA Forest Service, Research Paper FPL-95. 11 p.

Walker, J.C.F., B.G. Buterfield, T.A.G. Langrish, J.M. Harris, and J. M. Uprichard. 1993. Primary Wood Processing. Chapman and Hall, London. 595 p.

Ward, D. 1975. The influence of tree spacing upon tracheid length and density density in Sitka spruce (Picea sitchcensis [Bong] Carr.). M.Agr.Sci. thesis, University College, Dublin.

Wellner, C.A. 1955. Summaries of results from studies of western larch poles. Inland Empire Research Center. Intermountain Forest Range Experiment Station. Report prepared for Cooperators, Jan. 25.

Wilhemsson, L. 2001. Characterisation of wood properties for improved utilisation of Norway Spruce and Scots Pine. Doctor's dissertation. Department of Forest Management and Products Uppsala. Swedish University of Agricultural Sciences.

Yang, J-C., C-M Chiu, T-P Lin, and F-H Kung. 2001. No clinal variation in Cunninghamia lanceolata wood density sampled from thirteen Chinese provinces. Taiwan J For Sci 16(2):65-80.

Zobel, B.J. and J.P. Van Buijtenen. 1989. Wood variation, its causes and control. Springer, New York. 363 p.

Zobel, B.J. and J.B. Jett. 1995. Genetics of wood production. Springer-Verlag, Berlin. 337 p.

Meeting Total Maximum Daily Load (TMDL) Regulations through Habitat Conservation Planning for Managed Timberlands; Mendocino Redwood Company Lands, California

Christopher G. Surfleet[1]

Abstract

Total Maximum Daily Load (TMDL) regulations prescribed in Section 303(d) of the Clean Water Act affect the majority of the river systems along the North Coast of California. The regulations associated with TMDL have the potential to create adverse economic conditions for managed timber lands through increased erosion control, streamside management restrictions, monitoring, and reporting for regulation compliance. The Mendocino Redwood Company (MRC), managing approximately 232,000 acres of timberland on the North Coast of California has 70% of its ownership within watersheds requiring TMDL regulations. MRC is in the process of developing a Habitat Conservation Plan and Natural Community Conservation Plan (HCP/NCCP) to seek regulatory coverage for its timber practices for several federally and state listed species. Because of the aquatic species MRC will seek coverage for (coho salmon, Chinook salmon, steelhead trout, tailed frogs) the North Coast Regional Water Quality Control Board (NCRWQCB) suggested that MRC could seek TMDL compliance through its conservation planning efforts. MRC's aquatic conservation measures promote increased riparian protections along with sediment reduction as the main components of its management strategy. The conservation measures put forth by MRC will meet most of the requirements needed for TMDL compliance. Additional water quality objectives with timelines as well as specific water quality monitoring were needed for TMDL compliance. The additional components when included within the conservation plans create greater efficiency for managing TMDL compliance on a large land base. This efficiency provides greater flexibility in implementation of erosion control and monitoring relating to lower costs to the landowner.

Keywords: Forest planning, Habitat Conservation Plan, Total Maximum Daily Load, Water quality, Watershed management.

---

[1] Hydrologist, 2535 NW Hayes Ave., Corvallis, OR 97330; Surfleet@comcast.net

Introduction

Section 303 of the federal Clean Water Act of 1977 provides for establishment of Total Maximum Daily Loads (TMDLs) where water bodies are not meeting established water quality standards. Almost all of the large river basins in the Northern California Coast Range have been identified as being pollutant impaired by the United States Environmental Protection Agency (EPA) and the California State Water Resources Control Board (SWRCB). The primary source of the impairment, in the North Coast Region, is from increased sediment production and temperature increases occurring from forest management.

The regulatory impact from TMDLs comes when an Implementation or Action Plan is developed for the waterbody. The Action Plan, developed by the state with oversight from EPA, gets amended to the Water Quality Control Plan for the North Coast Region, the Basin Plan, and becomes a rule making or enforcement tool to meet the TMDL. One Action Plan has been developed thus far in the North Coast Region for the Garcia River (California Regional Water Quality Control Board North Coast Region, 2001). The Garcia River plan mandates: strict erosion control guidelines; inventory of all controllable erosion sites; development of a plan to repair all the controllable erosion sites within 10 years; no harvest zones along watercourses; riparian retention standards; and requires annual reporting of erosion work completed. The timelines and rigors of the Garcia River plan present significant financial burdens for landowners in the watershed. It is likely that future Action Plans, for the remaining TMDL waterbodies, will have similar requirements. For large landowners, with ownership in multiple TMDL watersheds, these Action Plans could create economic conditions that may limit competitiveness in lumber markets or potentially alter erosion control spending toward meeting TMDL needs, rather than other refuge aquatic habitat in non-TMDL watersheds.

The Mendocino Redwood Company, LLC (MRC) owns and manages approximately 232,000 acres of land for timber production. MRC is an example of a large landowner with ownership in multiple TMDL watersheds; approximately 70% of MRC's lands. Even with its best efforts company's like MRC could not implement the inventory and control of all controllable erosion and subsequent monitoring, within the timeframe shown in the Garcia River Action Plan, on such a large land base. MRC along with North Coast Regional Water Quality Control Board (NCRWQCB) staff have been seeking a solution through MRC's development of a Habitat Conservation Plan and Natural Community Conservation Plan.

Meeting TMDL Compliance through Habitat Conservation and Natural Community Conservation Planning

MRC has been developing a Habitat Conservation Plan and Natural Community Conservation Plan (HCP/NCCP) to gain Federal and State coverage for several endangered or threatened species for its timber operations. Specifically, the aquatic species that MRC seeks coverage for are coho salmon, Chinook salmon, steelhead trout, tailed frogs, red-legged frogs, and yellow-legged frogs. The habitat conservation needs of these aquatic species are consistent with goals of state water quality standards, the Clean Water Act, and the TMDLs. Because of this North Coast Regional Water Quality Control Board (NCRWQCB) suggested that MRC attempt to seek TMDL compliance through its conservation planning efforts.

HCP/NCCPs for aquatic species and TMDLs have more than just similar goals for improved water quality and habitat; they also share many of the same planning requirements. HCP/NCCP require specific quantifiable objectives to meet habitat goals, sound conservation measures to ensure habitat protection, adaptive management to ensure change occurs when needed, monitoring to inform adaptive management and compliance with goals and objectives, and reporting of progress of the plan. Similarly compliance with a TMDL Action Plan needs to demonstrate meeting specific water quality objectives, have sound management practices to limit future water quality impairment, promote adaptive management, monitor to show compliance with the targets, and reporting of pollution control efforts and monitoring results. Therefore, linking the two planning processes should not be too difficult.

Although there is much cross-over of planning requirements for HCP/NCCPs and TMDLs several additional considerations had to be addressed to meet TMDL Action Plan requirements. The water quality objectives for the Basin Plan had to be incorporated into the plan. Also, numeric targets and load allocations for TMDL watersheds had to be considered when monitoring for plan success or compliance. Finally, monitoring had to meet more than just species requirements or habitat needs, but also water quality targets.

Benefits to TMDL Compliance for a Large Land Base

The ability to achieve TMDL compliance for a large landowner, with land spanning across many watersheds, in one planning effort has many advantages. When combining TMDL regulatory compliance with an HCP/NCCP it enables efficiency for a landowner and the agencies regulating them. One major benefit is that erosion control repairs can be spread over a large land base rather than only in TMDL watersheds. MRC's approach is to repair all current and potential erosion sites on a priority basis and will be completed once the company has completed its harvest cycle across the entire land base, within approximately 30 years. The priority for erosion control would be based on such things as risk of imminent failure or significant sediment delivery, proximity to sensitive habitat, size of potential sediment delivery, adjacent harvesting, and cost effectiveness. In addition, a set amount of the high and moderate erosion sites will be repaired within a short time period ensuring the highest priority sites, in all watersheds would be addressed quickly rather than only in the TMDL watersheds.

If TMDL watersheds were the focus of sediment control efforts than many important aquatic habitat protections in other watersheds might be neglected. The priority site approach ensures the entire MRC land base is meeting or on a trajectory toward water quality objectives ensuring that other watersheds are not listed as sediment impaired. This approach takes longer than the Garcia River Action Plan timeframe of 10 years, but it ensures progress in all watersheds and when coupled with monitoring and adaptive management changes in the timeline can occur.

Another benefit is that coupling the TMDL process with other planning efforts, in this case HCP/NCCP, ensures ownership and collaboration from the SWRCB for the land management plans. This ensures that the conservation measures, monitoring and reporting meets all of the needs of the public agencies who regulate the landowner. This lowers the risk of multiple agendas by competing regulatory agencies.

The length of commitment by the landowner for an HCP/NCCP is quite long, often 50-100 years in length. This ensures that long term commitment and investment by the landowner is ensured for conservation efforts. By combining TMDL compliance with these long term plans, the public is assured of a long term commitment in not only aquatic habitat conservation but protection of all beneficial uses of water and water quality. Also, enforcement of regulations like TMDL across many watersheds is very expensive for the government authorities implementing them. Budgets for regulating the public trust and resources are only getting smaller, by promoting and giving large landowners incentives to implement water quality conservation approaches across their entire land base can, in the long run, save agencies staff time and ultimately the taxpayers' money.

Disadvantages to TMDL Compliance for a Large Land Base

A disadvantage for this large land base approach to TMDL compliance is the commitment and cost to undertaking a large planning effort for the landowner. Development of long term plans is expensive, and often requires long negotiation and development processes. The landowner must weigh the long term benefit to the short term costs of development, which is not an easy decision. Further, there are no guarantees that success can be negotiated within the development of the plan. Monitoring and adaptive management that must be incorporated into the plans could show that the landowners' best efforts may not be enough risking future regulatory surprises or costs.

Another disadvantage, and a major criticism by this author, is water quality targets that can be too rigid and often unrealistic. A range of habitat conditions are expected within undisturbed, "natural" systems. However, many of the water quality targets only strive for optimum conditions even when not physically possible. An example of a rigid water quality target is pool depths must be at least 3 feet deep. Although a 3 feet deep pool is very good pool habitat the dynamic aquatic environment cannot be expected to have deep pools in all places, especially in very small headwater streams. Water quality targets should approach a range of habitat conditions with the distribution of conditions skewed toward targeted conditions, not expecting conditions to be optimum at all places.

Discussion and Conclusions

The jury is still out on whether coupling TMDL compliance with long term conservation planning will work. MRC has engaged in the process, however, the plans are not finalized. Some legal issues remain to be addressed of being in compliance with existing TMDL Action Plans, such as the Garcia River plan. However, the advantages for both landowners and the public by this type of approach could be great. In fact, if some of the disadvantages discussed are lessened and incentives remain or are created for landowners, it may be in everyone's interest to develop these large land base plans even without an HCP or NCCP. "Stand alone" TMDL compliance plans for large land ownerships to meet the Clean Water Act and TMDL needs. The benefits could be healthier watersheds at lower costs to taxpayers and landowners and clean water for future generations of people and wildlife.

Literature Cited

California Regional Water Quality Control Board, North Coast Region. 2001. Garcia River Watershed Water Quality Attainment Action Plan for Sediment. Resolution R1-2001-72, California Regional Water Quality Control Board, North Coast Region , Santa Rosa, CA.

Monitoring: It is Our Job from Beginning to End[1]

Marvin R. Pyles, PE, PhD[2]

Abstract

Forest Engineers have a long record of informal monitoring of road construction and harvesting operations from the perspective of feasibility, productivity, and safety. Monitoring of these activities is a normal part of the engineering process since feasibility, productivity, and safety are all objectives of Forest Engineering designs. In the past decade, monitoring associated with project constraints, primarily environment constraints, has also come into being. However, much of the environmental monitoring activity that has taken place, and is currently underway, is designed by, and operationally conducted by dedicated fisheries biologists, wildlife biologists, forest hydrologists, soil scientists, etc. This monitoring activity is often viewed as a cost center in economic enterprise of forestry, with resulting lack of continuity in monitoring over normal business cycles. The result is a very well intended monitoring record that falls short of providing the information originally intended. Worse yet, most monitoring efforts do little to serve the Forest Engineer through post-operation feedback into future road and harvesting designs, and hence do not serve a role expected as a part of forest certification. This paper discusses the elements of a monitoring program for forest roads and operations in a way that is consistent with realistic expectations, and that provides performance information that directly feeds back in to future designs.

Key Words: Monitoring, Operations, Engineering, Environmental.

Introduction

The evolution of the practice of forest engineering, and forest management as a whole dictates periodic review of forest engineering practice. Forest engineers are engaged in timber harvesting design and implementation today as they have always been. But the societal climate in which the forest industry must work to maintain its

---

[1] This paper was presented at the 2005 Council on Forest Engineering meeting, July 12-14th, 2005, Fortuna, California.

[2] Consulting Engineer, Corvallis, Oregon, and Associate Professor of Forest Engineering, Oregon State University.

social license[1] to operate, is far more complicated today than just a decade or two ago. The complexity is compounded by financially driven intensive forestry in which harvesting activities must meet strict specifications in order to meet production expectations and fit within the silvicultural model developed by forest managers. Monitoring has become a default element of most forest management enterprises. Monitoring presumably provides the means of showing that the forest management enterprise and its operational elements, are meeting the expectations of society. Societal expectations take the form of the business health of private enterprise forestry, the regulatory requirements that forest operations are subject to through forest practice and environmental regulations at the state and provincial as well as national levels, and the social license granted through forest certification and the general sense of acceptability at the local community level. In order for monitoring to serve in these roles, monitoring programs must be correctly designed and implemented. It is essential that forest engineers be active participants in the design and implementation of monitoring programs.

The Engineering Method

Most of us remember something of the engineering method from our formal education. It appears in a number of texts in varying forms. It may have been presented in an introductory engineering course, or as the scientific method in an introductory forestry course. The method has always included monitoring of project results with respect to primary project objectives, but the dominance of constraints in the forest engineering projects of today and the requirements of forest certification (FSC, 2005; SFI, 2002) suggests the need for an expansion of the engineering method to include monitoring of secondary objectives and constraints as well (e.g. Figure 1).

---

[1] I was introduced to the term "social license" by the late Robert Willington, a mentor and friend, and pioneer in the business of monitoring and feedback of results to forest engineering design.

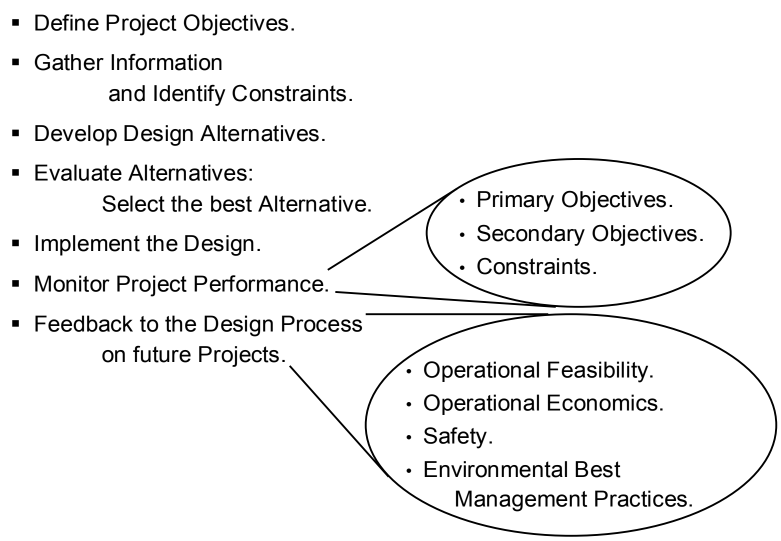


Figure 1. The Engineering Method – expanded to include monitoring in the current Forest Engineering context.

There is no absolute scale for listing project objectives as primary or secondary. I suggest that primary objectives are those which generating revenue, or are undertaken in direct support of revenue generation (e.g. road design and construction), and secondary objectives are associate with forgone gain or added cost if not achieved. The primary objective of most forest engineering projects is timber production at a cost that meets the financial objectives of the landowner or client. Worker safety, while very important, is not the reason for a harvest plan or other design, and therefore can be reasonably viewed as a secondary objective. Residual stand condition, the combination of the character of the stand (i.e. spacing and ranking of residual trees) and any damage that may have occurred during harvesting is also an example of a secondary objective.

Constraints can include many things, but the intent in this paper is to focus on the array of environmental constraints that influence forest engineering design decisions today. Typical environmental constraints include the following:

- Limiting ground disturbance.
- Machine exclusion from riparian zones.
- Limited- to no-harvest in riparian zones.
- Water-bars on skid trails.
- Road location to limit the occurrence of road associated landslides.

- Road design to limit sediment production and entry into the stream system.
- Maintaining of wildlife corridors and habitat.

Monitoring associated with project constraints is already a part of most public agency projects, and it is also a common provision in Habitat Conservation Plans. Even when a forest land owner does not operate under the authority of a habitat conservation plan, monitoring associated with project constraints is being done. However, the full enhancement that "constraint monitoring" can bring to the engineering method has not generally been developed. The key point here is the feedback from monitoring to future designs and Best Management Practices [BMPs]. This feedback is based on the professional judgment of the forest engineer, and is not generally scientifically based. In other words, a statistically based monitoring scheme is rarely if ever possible, and this precludes a scientific conclusion about feedback to the design process. Analysis of monitoring data may include statistics, but rarely will the monitoring design be robust enough to be considered general rather than a case study.

Typically, monitoring programs are developed at an ownership level, and they are developed by interested parties, e.g. fisheries biologists typically develop fish monitoring plans, and may also develop plans for monitoring water quality, although this might also be done by forest hydrologists or water quality experts. The form and detail of data collection is often focused on the discipline of the plan developer, often relies on measurements of surrogates rather than primary variables, and often will be cloaked in some form of scientifically based experimental design.

> An example is monitoring of suspended sediment in a forth order or larger stream. Fine sediments in streams have been shown by fisheries research to adversely impact the development and survival of salmonid eggs during the incubation period by reducing oxygenated water flow through the stream gravels in which the eggs are deposited (Chapman, 1988). Very low levels of suspended sediment in the stream, a surrogate for sediment deposited in the stream gravels, might be expected to indicate a healthy system, whereas high levels of suspended sediment might be expected to indicate a problem. A monitoring program based on (1) turbidity threshold sampling (Lewis, 1996) of stream water, (2) periodic grab samples of stream water, (3) pumping samples of stream water during periods of high flow, or (4) a continuous record of turbidity might be proposed to address this water quality issue.

While the data from a plan like that described above may be very fine data, that can be plotted over time, and dutifully reported in a monitoring program report, it is likely to be of little value as a part of the monitoring and feedback elements of the engineering method.

Monitoring that is part of the engineering method must have clear objectives that are linked to the engineering project design and performance, and the data collected must be specific to that design and performance. In the example above, high versus low levels of suspended sediment, while understandable as indicators of poorer versus better stream conditions from the fisheries perspective, do not allow the forest engineer to judge whether a harvesting activity and more importantly the specific design provisions of that activity were acceptable or deficient in that particular watershed. In fact, as the example is presented, which is typical of many monitoring efforts, there is no means of establishing a linkage between what is measured in the water column in a fourth order stream, and the harvesting activities at the headwaters of the watershed. It is reasonable to suggest that some linkage exists, but without knowing what it is, there is no way that the forest engineer can intelligently modify practices to improve conditions.

If BMPs or project specific forest engineering designs were incorporated in a harvesting project for the purpose of addressing constraints [e.g. downstream water quality], then the monitoring program must be specific to those designs if we are to determine their success or failure. This very strongly suggests that the forest engineer must be a central figure in the development of any monitoring program for it to be successful as a component of the engineering method, and more broadly as an indicator of the success of the forest management enterprise vis-à-vis the environment constraint system with which we currently operate.

Types of Monitoring

Before offering suggestions for monitoring of forest engineering designs, it is appropriate to review the definitions of various types of monitoring. A thorough discussion of monitoring with respect to forestry activities was presented by MacDonald, et al (EPA, 1991). The following types are often discussed with respect to forestry monitoring programs.

- Trend and baseline monitoring – measurements made at regular, well spaced intervals in order to determine the long-term trend or baseline for a particular parameter.

  Almost by definition, integrative parameters are the subject of trend or baseline monitoring. The results may be of some value to the whole forest management enterprise, and may be of interest to fisheries biologists, soil scientists, hydrologists, etc., but they are unlikely to be of much value to the forest engineer. The long time frame over which trend or baseline monitoring provides meaningful results means that those results are not likely to be available for feedback into current design methods. Further, the scale of integration in the variables, for example, turbidity in a fourth order or larger stream, is such that there may be little to no ability to link the absolute value or trend in the variable to forest engineering designs. Because short term changes in the data, which may have nothing to do with forest operations, will occur in both positive and negative directions, the results are very susceptible to misinterpretation.

- Implementation and compliance monitoring – monitoring to assess whether activities were carried out as planned, or whether specific criteria associated with a project are being met.

  Implementation monitoring can be an important element of maintaining social license for current and future forest management. If we engineer forest operations to achieve certain objectives, and to fall within the bounds of desired constraints, we can show good faith in the operational elements of forest management by documenting the degree to which we adhered to the design. The post-harvest inspection which is part of the Timber Harvest Plan administrative process in California, in effect serves the purpose of implementation monitoring of the explicit design provisions of the Timber Harvest Plan. California post-harvest inspections also can be considered compliance monitoring since they also provide a check for compliance with the more general Forest Practice Rules. There are numerous aspects of a forest operation that could be subject to implementation and/or compliance monitoring, to the benefit of the forestry enterprise. An example that has long been a part of partial-cut operations are stand damage provisions of timber harvesting designs and the specifications of partial-cut logging contracts.

- Effectiveness monitoring – monitoring to determine whether specific activities had the desired effect.

  The term effectiveness monitoring is often used in discussions of monitoring programs, but it is rarely done, usually because effectiveness monitoring is not possible in the context of most industrial forestry. A classic example exists with forest practice or water quality regulations that are written in terms of pre-management conditions. The only way to determine if the provisions of a forest engineering design achieve a particular objective with respect to natural conditions, is to have companion natural conditions for comparison. If a road design is supposed to limit turbidity increases in a watershed to 10% of the natural turbidity level, we must not only measure the level that exists after completion of the road according to the design, but we must know what the level would have been had we not built the road. This is clearly an impossible situation in the context of economically viable industrial forestry.

- Validation monitoring – monitoring for the purpose of verifying the accuracy of a predictive model.

  The use of explicit predictive models and implicit models, such as BMPs, may benefit from validation monitoring. The broader forestry enterprise usually includes the use of a model, most notably, a growth and yield model. It is common through routine inventory work to validate and update the growth and yield model as necessary. The effort required to validate a growth and yield model is illustrative of validation monitoring requirements.

In the context of some monitoring activities and requirements, the terms above may have legal meanings that should be fully understood before the term is used in reference to the objectives of a monitoring program, or in statements of project or overall management objectives.

Constraints on a Monitoring Program

Monitoring within the context of the engineering method has a set of requirements or constraints that will help guide us to the monitoring types listed above that can be reasonably done, or are likely to be beneficial from the perspective of providing helpful feedback to the design process. Requirements and constraints may vary from land owner to land owner, and depend on the nature of the land, the forests being managed and on the local or regional regulatory climate. Some possibilities are:

- Monitoring should be designed to answer a question about the performance of the engineering design [primary and secondary objectives as well as constraints can and should be considered].
- Monitoring for a single project, by definition is a case study that is not

expressly transferable to other projects or areas [transfer to other projects is a matter of professional judgment].

- BMPs are often the means of achieving project objectives and operating within the limitations of constraints, which suggests that some level of verification that BMPs do what they are intended to do is desirable.
- At the same time that verification of BMPs is desirable, the scope of monitoring that may be required to validate what is basically a model [the BMP] may be impractical, and questionable from a fiduciary perspective, given the scope of many BMPs.
- There is no inherent requirement that monitoring of all projects take place; the most effective monitoring program may be one that samples projects for a specific purpose and takes advantage of greater detail when doing so, such that a better understanding of design performance results.
- Comparison of monitoring results from current practices with either previous practices, or natural background requires a paired sampling effort that is not likely to be possible given the requirement of simultaneous application of old and new practices, or comparable unmanaged forest land from which background data can be obtained.
- The lack of a physically and statistically sound experimental design will often result in equivocal results from a monitoring program. The outgrowth of this is that professional judgment is the pathway to meaningful use of monitoring results.
- Monitoring results can be misinterpreted in ways that reflect poorly or favorably on forest management in general and forest operations in particular.

Monitoring program size is always a question. Sampling, as indicated above is a viable option that can produce the benefit of a monitoring program at a far lower cost than across the board monitoring of all projects. At the same time, there are no clear criteria for developing the sampling scheme. If there is a particularly contentious aspect of current management plans, then more intense monitoring may be required for some period of time to address the issue. A lengthy period of monitoring may be required since many of the environmental impacts of forest operations occur sporadically over time. Sediment production can be expected to be large during large storm and flood events, hence monitoring for sediment production will most likely have to be done over a lengthy enough time period to gain at least some understanding of larger storm and flood performance. At the same time, there is little point in gathered detailed data in hopes of “catching” the 50-year design event; interpretation of post-storm or flood data is far more likely to provide helpful information.

Suggested Elements of a Forest Engineering Monitoring Program

First and foremost in a Forest Engineering Monitoring program are clear objectives. Second, each objective should be linked with a specific element of the monitoring program that includes a data collection and analysis, and third, a reporting plan that is consistent with the objective, and makes the monitoring results appropriately transparent will serve to bolster and sustain social license. The fourth element is feedback to the engineering design process - failure to do this makes the whole venture a public relations scheme that will be more damaging to the forestry enterprise in the long run than if no monitoring was done.

Matching monitoring plans to objectives

In a broad sense, the objectives of monitoring are to determine the impacts of forest management activities, with an eye to reducing adverse impacts when feasible. The more specific that objectives are, the better job we can do in selecting a type of monitoring program that will meet the objectives.

Trend monitoring, although often the easiest to do, does not fit either the general objective stated above, or more detailed objectives associated with the impacts of specific engineering designs very well. There may be cases where trend monitoring is appropriate, but as a general statement it is reasonable to conclude that trend monitoring results will not usually be linked to operations in a way that provides helpful feedback to the engineering design process. Further, misinterpretation of results over a short term period can give rise to unjustified but politically powerful conclusions about the impacts of forest operations.

The results of implementation monitoring provide powerful evidence of the application of best management practices, and can serve to bolster their application as well as provide documentation of a job well done. This makes implementation monitoring an attractive element of a monitoring program. Although monitoring of all projects may have to be done if contract compliance is an issue, sampling may also be appropriate if the sampling scheme is well designed. A key to a well designed sampling scheme is random selection of sufficient projects so that a representative sample is obtained.

Effectiveness monitoring and/or validation monitoring are temptations because “effectiveness” and “validation” are at the crux of the development and application of BMPs and project specific elements of engineering designs. The key to success of effectiveness or validation monitoring is not so much in the monitoring, but in the form of the statement [hypothesis] that is in question. In general, if you cannot provide both a treatment and a control to monitor, then effectiveness or validation monitoring will not be successful. As indicated above, if the control for a treatment is to be the natural background condition, and this is interpreted to mean “unmanaged forest condition”, the effectiveness of most engineering designs or BMPs cannot be established. The challenge then is to formulate effectiveness questions in a way that monitoring can provide comparative data on both the treatment and the control, or on two treatments that are being considered. This can by done for a limited number of cases under the banner of adaptive management. For example:

> Two otherwise equal sections of new forest road could be rocked with aggregate from two different rock sources, wherein one source was suspected to provide superior performance with respect to sediment production during winter hauling. Paired sections of the road [i.e. the same traffic level, road grade, road width, subgrade soil, cut slope soil and steepness, etc.] could be reasonably expected to get similar use and winter precipitation. Hence, monitoring of sediment runoff from the road surface for both sections, could provide evidence of the superior aggregate.

If the method of obtaining sediment runoff data is physically sound, then the results will be sound for the particular case monitored, but from the broader scientific perspective, results of this type are “case study” results. None-the-less, they are valuable and can be applied to other cases on the basis of professional judgment. A monitoring program that includes some cases of this type of effectiveness monitoring can provide valuable feedback to the engineering design process, the development and application of BMPs, and can serve to maintain social license for well designed forest operations.

Data collection and analysis

A key element in any monitoring program, just like a golf swing, is “follow through”. Collecting data and analyzing data on a regular basis is necessary for an effective monitoring program. While this may seem obvious, the economic pressure of continuing both data collection and analysis throughout normal business cycles in the forest industry is challenging to say the least. Two steps are critical to maintaining a monitoring program. First, be realistic about monitoring program budgets and the correlation between budget and the amount of monitoring done. Second, design the monitoring program so that benefits are regularly derived from the program, and so that interruptions in data collection do not render the entire program ineffective. The suggestion for project level effectiveness monitoring above is an example of monitoring that can provide useful results without a continuous multi-year data record. Of course, a multi-year record may be very desirable, but even a single year of data allows for some comparative conclusions to be drawn. This is not the case with many proposed monitoring ventures.

Reporting plan

Periodic publication of monitoring results serves to bolster social license, and can be an effective means of preempting inappropriate analysis of monitoring data by detractors. In the discussion of trend monitoring above, it was noted that misinterpretation of monitoring results could be used to show that either improvement or worsening of conditions was occurring in concert with ongoing forest operations. The best means of addressing such misinterpretation is to correctly analyze monitoring data, provide a full justification and explanation of the methods of analysis as well as explanation of why other analysis methods that may produce opposite or different results are either questionable or incorrect. Correct analysis may often produce equivocal results, in which case, that is what should be reported. Monitoring results should then be published, in a refereed forum whenever possible. You can be assured that if you don't publish a correct analysis and interpretation of monitoring results, someone else will publish an analysis, and it may not be correct.

Feedback to the engineering method

Above all, don't forget that monitoring results contain information about the successes and failures of past engineering designs, and that good engineering practice requires that this be incorporated into future projects. This type of feedback is both important to improvement in engineering practice, and it is a requirement of most certification processes (e.g. Forest Stewardship Council, 2005; Sustainable Forestry Initiative, 2002). If we in the Forest Engineering community do an effective job of continuous improvement in engineering design and practice through monitoring and feedback, then it is reasonable to conclude that others less capable than we and with other agendas will be less likely to dictate engineering practice within the forest management enterprise. With this statement, no other conclusion is necessary.

References

Chapman, D.W. 1988. Critical review of variables used to define effects of fines in redds of large salmonids. Trans. Amer. Fish. Soc. 117:1-21.

EPA, 1991. Monitoring Guidelines to Evaluation Effects of Forestry Activities on Streams in the Pacific Northwest and Alaska. US Environmental Protection Agency, Region 10, Water Division, EPA/910/9-91-001. Seattle, WA. (report authored by Lee H. MacDonald, AlanW. Smart, and Robert C. Wissmar)

Forest Stewardship Council (FSC), 2005. Revised Final Pacific Coast (USA) Regional Forest Stewardship Standard. Version 9.0, May 9, 2005. 71p.

Lewis, Jack. 1996. Turbidity-controlled suspended sediment sampling for runoff event load estimation. Water Resources Research 32(7): 2299-2310.

Sustainable Forestry Initiative (SFI), 2002. Sustainable Forestry Initiative (SFI) Program. 2002-2004 Edition. American Forest & Paper Association, 1111 Nineteenth Street, NW, Suite 800, Washington, DC 20036. 44p.

Application, Effectiveness, and Compliance Assessment of Forestry Best Management Practices in West Virginia

Tony Goff, Jingxin Wang, Joe McNeel, and Shawn Grushecky[1]

Abstract
The application, effectiveness, and compliance of forestry best management practices (BMPs) were assessed based on 40 sites in two of six forest districts in West Virginia. A GPS unit was used to map the harvested tracts including landing boundaries, haul roads, SMZs, skid roads, and water bar locations. Soils and slopes were examined to determine erosion and runoff potential. By using the checklists derived from the state BMP guidelines, a total of 33 BMPs were measured at each harvest tract on haul roads, skid roads, landings, and streamside management zones (SMZs). About 10% of the haul roads measured had grades steeper than 10%. Eleven percent of the skid roads measured exceeded 15%. Of these skid roads 85% of them presented at least one or more water bar, but 11% of them had ruts greater than six inches deep. Four percent of the landings were not seeded and 34% were not mulched after the harvest was complete. The study also indicated higher levels of application and effectiveness of the BMPs. The overall BMP compliance in these two districts follows the trend in the previous assessments in the state. The results can be used to examine the interrelationship of BMP effectiveness and other site factors and to aid foresters in pre-harvesting planning. This study will be beneficial to the state long-term sediment control of forest operations.

INTRODUCTION

Timber harvesting is well-known non-point source pollution due largely to road construction and site disturbance. Roads are a major source of non-point source pollution in forest operations (Kochenderfer 1977). These are areas of high traffic and great disturbance to many layers of soil. The soil becomes compacted which makes infiltration difficult. Disturbed soil on roads also acts as a guide for water to follow after a precipitation event. When the water flows on disturbed soil it carries particles of the soil with it. The grade of the road is one factor that will determine speeds of water flow. This will directly affect the amount of runoff that results from the road construction.

[1]West Virginia University Division of Forestry Morgantown, WV 26506

BMPs have been adopted in all states to help prevent non-point source pollution. Specifically, they are developed to prevent or reduce the adverse impacts of forest management activities on water quality while permitting the intended management activities to occur (Phillips et al. 2000). The interactions between equipment, soil, and soil moisture are the primary determinants of site disturbance during timber harvesting operations (Reisinger and Aust 1990).

BMPs were initiated in West Virginia in 1972. Since this time the state BMP guidelines have been revised five times. These are voluntary guidelines, but they must be followed according to the Logging Sediment and Control Act (LSCA). This act specifically mandates logger licensing, logger certification, harvesting operation notification, and enforcement capability for activities causing erosion and sedimentation on logging sites (Wang et al. 2004).

BMP compliance has been evaluated four times in West Virginia since 1981. The last compliance study was conducted in 1996 (Egan et al. 1998). Since this time the West Virginia Division of Forestry (WVDOF) have revised the BMP guidelines three times in 1996, 2001, and 2002 (WVDOF 2002). With the modified state guidelines and the time period elapsed between compliance evaluations it seems necessary to conduct another statewide BMP assessment. This study concentrates on application, effectiveness, and compliance of BMPs and their interrelationships with other factors such as forester involvement, harvest method, and ownership.

Material and Methods

The sites were selected randomly from each of the six forest districts following a sampling protocol used by a previous assessment in the state (Egan et al. 1998). The study has been conducted since May 2004. A random sample of 30 sites were first chosen from Forest District three (Figure 1). The amount of sites studied in the other districts was based on a ratio of the number of jobs started in the same time period for this district over the number of jobs in District three. The checklists derived from the BMP guidelines were used to measure 33 BMPs in haul roads, skid roads, landings, and SMZs. Separate checklists were also used for application and effectiveness of BMPs used on sites with SMZs based on procedures developed by Schuler and Briggs (2000). This will provide feedback on how well the BMPs were constructed and how well they are working over time. The rankings for application are as follows: (1) BMP not used or poor application; (2) BMP attempted with minor deviations; (3) BMP used and correctly applied. Rankings for the overall effectiveness of the BMP applied include no effort, poor, fair, good, and excellent. The information for the checklists were gathered from the site. Tract size, forester involvement, type of harvest, and other information were also obtained from the notification forms. Each landowner was interviewed with the same questionnaire to determine satisfaction levels and other site and operation specific information.

All landings were mapped with a GPS unit. GPS points were also taken for the roads of each site and water bar placement. Once the GPS points were corrected they were overlaid on topographic maps of each site, which allows for better viewing of the slope of the sites across the entire site. The slopes of skid roads, haul roads, and SMZs were measured using a clinometer.

There are a total of 33 BMPs measured during this survey. The measurements on haul roads include length, grade, use of culverts, use of cross drainages, gravel used at public road entrances, and roads seeded and mulched. The following measurements were taken on skid roads: length, grade, water bars present and needed, length smooth, length of berm, and length outsloped. The skid roads must also be seeded and mulched. The number of approach roads diverted, landing smooth, drained, seeded, and mulched were measured at the landings. SMZ width, equipment operations, soil exposure, stabilization of soil, and existing road usage if applicable were recorded for a SMZ. The three previous categories also have fields to show if they are outside of SMZ.

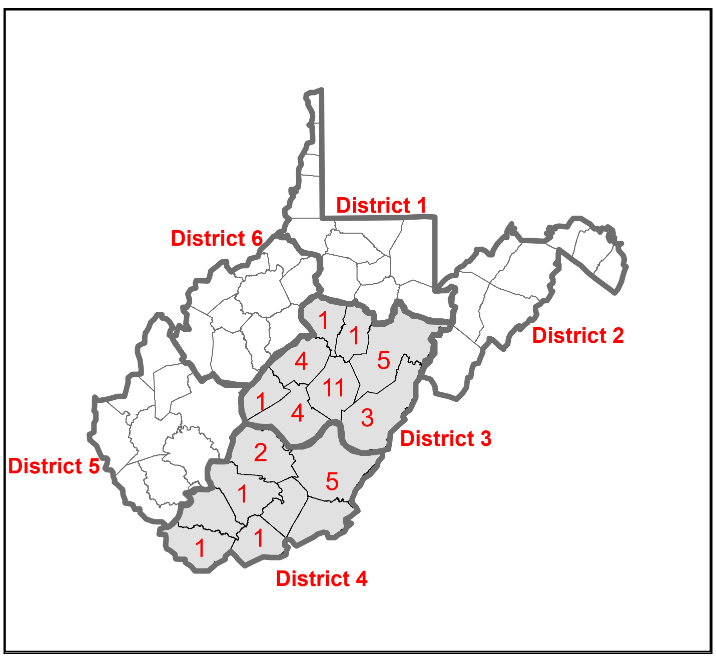


Figure 1. Sites completed in each county.

Analysis and Results

Compliance

The data was analyzed statistically to determine compliance levels with the BMP guidelines between forester involvement, harvest type, ownership, and district (Table 1). Foresters are an integral part of any harvest. When a forester is utilized in the harvest process the harvest should be planned better and more precaution is taken in erosion control. Of these forty sites 70% of them had forester involvement on either the landowner or timber owner's behalf. It should be noted that 55% of these sites are owned and managed by timber industry companies. The other 45% are owned by private individuals. Forest District 3 had 75% of the sites completed in its counties. This was based on the number of jobs started during the same time period in each district. There are three harvesting methods on the WVDOF notification forms. In these two districts 30% of the harvest types were either clearcuts or diameter limit cuts. The other 40% were selection or marked timber cuts. Tract compliance varied from 22% to 100%. Compliance of 100% was on 37.5% of the sites. Tract compliance of greater than 80% was on 47.5% of the sites. The average tract compliance is 76%. This does rate well with previous studies.

Table 1. Means and significance levels of statistics for BMP compliance rates in districts 3 and 4.

	Forester Involvement		Ownership		Harvest type			District	
	Yes	No	Private	Industry	Clearcut	Diameter limit	Selection	3	4
Haulroad	92A	92A	91A	92A	91A	93A	91A	92A	92A
Skidroad	84A	78B	80A	83A	85A	72B	88A	78B	95A
Landing	63A	58A	67A	57A	67A	42A	72A	52B	90A
SMZ	50A	100B	67A	83A		100A	50A	75A	
Tract Compliance	78A	75A	77A	77A	81A	64B	83A	71B	95A

[a] Means with the same letter in a group of a row are not significantly different at $\alpha=0.05$ (ANOVA).

The significant differences can be seen mostly among harvesting types. The diameter limit harvest type shows a significant difference from the other two types seen in this study. This could be due to a larger volume of timber being transported on the road, and also the equipment type that is used in the harvest. The harvest type also showed some significant differences in tract compliance. There was a difference between diameter limit cuts and selection cuts. This could also be explained by the equipment type used in the harvest.

The skid roads were used either more or less depending on the size of the harvest and the harvest type. There is a significant difference in districts in the skid roads and landings sections. This could be due the fact that district four had a greater percentage of industrial owned land that was surveyed. This means that a forester was involved more often than not in these sites.

Out of the 19,691 feet of haul road measured there were no segments which exceeded 15% grade. There is 49% compliance on the number of cross drainages needed on the haul road segments. Only six percent of road segments needed gravel added to them at a public road entrance. All of the haul road segments were reclaimed according to the guidelines. Only segments within the SMZ or exceeding 10% slope need to be seeded.

There were 40,296 feet of skid road measured on these sites. Of the segments measured only 2% exceeded 20% maximum grade. The compliance level in respect to water bars on these segments is 87%. 73% of the segments were outsloped. 89% of the skid roads were smooth. This means they had either no ruts or ruts that were less than six inches deep. Of the skid road segments needing to be seeded 63% of them were seeded and 9% of the segments needed mulch.

There were 52 landings examined on these sites. Fifty of these landings were outside the SMZ. There were 77 skid roads entering the landings and 94% of them had been diverted from water running onto the landing. Of the 77 landings 69% of them did not have ruts deeper than six inches and 83% of them were drained from standing water. Sixty two percent of the landings had been seeded and 58% of them had mulch applied to them.

There were 10 SMZs measured on these sites. Seventy percent of them were stabilized and 50% of them had riprap installed. The average slope of the SMZs was 5.2%. The average width of the SMZs with perennial streams was 75 feet. The average width for an intermediate stream was only 38 feet. This is one area that needs improvement since the buffer should also be 100 feet for these streams. On these forty sites there were six sites found with SMZs. The application and effectiveness checklists were filled out for each of these sites. Five of the sites were in Forest District 3 and one site in Forest District 4. Private and industrial ownership were 50% each. The average acreage was 64 acres. Foresters were involved on four out of the six sites. There were four perennial streams and two intermittent streams studied.

Application and effectiveness

The application and effectiveness of BMPs on the segments of haul road were assessed (Table 2). One site did not have any haul road so there are only five samples in this table. The "A" or "E" after each BMP stands for application and effectiveness, respectively. The grades less than 10% were ranked excellent. The width of a haul road should be a minimum of 12 feet. The third BMP is that haul roads should be constructed outside of SMZs when possible. If it is necessary to cross a stream it should be done at a right angle and gravel should be applied for 100 feet on each side of the stream. Cross drainages should be outsloped to keep water off the road. Haul roads should always be graveled for 200 feet at any public road entrance. This will help to keep mud off of main roads. Culverts and ditches were checked to see if they were clear of debris. Lastly haul roads should be constructed away from wet areas when possible. The means for the application of BMPs on haul roads ranged from 2 to 3, which indicates that the BMPs were attempted and most often applied correctly. The effectiveness levels of the BMPs applied ranged from 2.8 to 5. This should be higher to hold up effectiveness over time.

Table 2. Means and standard deviations for Application & Effectiveness

Levels for Haul roads in districts 3 and 4.

BMP	N	Mean	Std. Dev.	Min.	Max.
<10% gradeA	5	3	0	3	3
<10% gradeE	5	5	0	5	5
width=12ft.A	5	3	0	3	3
width=12ft.E	5	5	0	5	5
out of smzA	5	2.8	0.44	2	3
out of smzE	5	4.4	1.3	2	5
stream cross right angleA	4	2	1.2	1	3
stream cross right angleE	4	3	2.3	1	5
100ft. Gravel at streamA	5	2.2	1.1	1	3
100ft. Gravel at streamE	5	3.4	2.2	1	5
cross drainage outslopedA	5	2.6	0.89	1	3
cross drainage outslopedE	5	3.6	1.9	1	5
200ft. Gravel public roadA	5	3	0	3	3
200ft. Gravel public roadE	5	5	0	5	5
culverts clearA	5	2.6	0.89	1	3
culverts clearE	5	2.8	2.1	1	5
avoid wet areasA	5	2.8	0.44	2	3
avoid wet areasE	5	4.2	1.8	1	5

Skid road grade of less than 15% were applied and effectively implemented to all reads (Table 3). Steeper grades are allowed for short distances. Skid roads should also be constructed outside of SMZs whenever possible. They should be kept at least 25 feet away from streams. Skid roads should contain cross drainages every 100 feet. Water bars were assessed on the skid roads for effectiveness. Where culverts or bridges were used to cross streams they were also assessed for effectiveness. If no culvert or bridge was used or necessary then streams should be crossed at right angles. There should be no skidding directly up or down a stream channel. Skid roads should be spaced about 200 feet apart on the harvest. The roads should also be stabilized after the harvest is complete to reduce runoff and slips. The application rankings for the skid road BMPs were 2.5-3. This is a very high level of application. The effectiveness range of 3.3 to 4.7 is a ranking of fair to good.

Table 3. Means and standard deviations for Application & Effectiveness

Levels for Skid roads in districts 3 and 4.

BMP	N	Mean	Std. Dev.	Min.	Max.
<15% gradeA	6	3	0	3	3
<15% gradeE	6	4.5	1.2	2	5
out of smzA	6	2.8	0.41	2	3
out of smzE	6	4.2	1.3	2	5
25ft. From streamsA	6	2.8	0.41	2	3
25ft. From streamsE	6	4	1.6	2	5
cross drainages 100ft.A	6	3	0	3	3
cross drainages 100ft.E	6	4.7	0.52	4	5
water barsA	6	3	0	3	3
water barsE	6	4.7	0.82	3	5
culvert/bridgeA	4	2.5	1	1	3
culvert/bridgeE	4	3.3	2.1	1	5
streams crossed right anglesA	6	2.5	0.84	1	3
streams crossed right anglesE	6	3.7	1.5	2	5
no skidding in streamsA	6	2.8	0.41	2	3
no skidding in streamsE	6	4.5	1.2	2	5
road spacing 200ft.A	6	2.7	0.82	1	3
road spacing 200ft.E	6	4.2	1.3	2	5
stabilizedA	6	2.7	0.52	2	3
stabilizedE	6	3.7	1.5	2	5

The average ranking for landings constructed outside of the SMZ is 3 (Table 4). Landings should be diverted of water. This is a site of much activity and water will cause ruts to form on the landing. Landings should be at least 25 feet away from streams. They should be placed on dry, firm sites. The skid roads coming into the landings should have water diversions installed to keep water from running down the road and onto the landing site. After the harvest is complete the landing should be seeded and mulched. The last BMP states that landings should be kept to minimum size. The recommended size for a landing is a quarter of an acre. The application levels of BMPs on the landings were also high with mean ranging from 2.2 to 3. The average effectiveness levels varied from 3.3 to 4.5 for all BMPs on the landings.

This again indicates the average effectiveness of BMPs on the landings was from fair to good.

SMZ is the most sensitive area of a harvest site. If SMZ between the harvest and the stream ranked 2.8 (Table 5). Perennial and intermittent streams require a 100 foot buffer. Ephemeral streams only require a 25 foot buffer. The third BMP is whether or not there were equipment operations in the SMZ. This is permissible, but should be kept to a minimum. The landing should always be constructed outside of the SMZ. The SMZ should be smooth and not contain any ruts. This area also needs to be seeded and mulched. If there is a haul road in the SMZ it also needs to be reclaimed. When SMZs must be entered for a harvest it is recommended that they have minimum cut and fill slopes. This will limit the amount of disturbance to the area, and keep it as natural as possible. The application of BMPs in the SMZs ranged from 2 to 3 while the effectiveness levels were between 2.8 and 4.4 ranking from poor to good effectiveness. SMZs are the sensitive areas that usually require a lot of attention during operations. It is also difficult to reclaim these sites back to the levels before harvest.

Table 4. Means and standard deviations for Application & Effectiveness

Levels for Landing sites in districts 3 and 4.

BMP	N	Mean	Std. Dev.	Min.	Max.
Landing outA	6	3	0.63	2	4
Landing outE	6	4.5	1.2	2	5
Landing divertedA	6	2.8	0.41	2	3
Landing divertedE	6	4.5	1.2	2	5
25 ft. from streamA	6	2.7	0.81	1	3
25 ft. from streamE	6	4.3	1.6	1	5
dry/firm siteA	6	3	0	3	3
dry/firm siteE	6	4.3	1.2	2	5
roads divertedA	6	3	0	3	3
roads divertedE	6	4.2	1.2	2	5
seededA	6	2.2	0.98	1	3
seededE	6	3.7	1.6	1	5
mulchedA	6	2.2	0.98	1	3
mulchedE	6	3.3	1.9	1	5
min. sizeA	6	2.8	0.41	2	3
min. sizeE	6	3.5	1.4	2	5

Table 5. Means and standard deviations for Application and Effectiveness levels for SMZs in districts 3 and 4.

BMP	N	Mean	Std. Dev.	Min.	Max.
100ft. bufferA	6	2.8	0.41	2	3
100ft. bufferE	6	3.5	1.4	2	5
25ft. bufferA	5	3	0	3	3
25ft. bufferE	5	4.4	1.3	2	5
equip. ops.A	6	2.7	0.52	2	3
equip. ops.E	6	2.8	1.3	2	5
landing out of smzA	6	2.5	0.84	1	3
landing out of smzE	6	3.8	1.8	1	5
smoothA	6	2.8	0.41	2	3
smoothE	6	3.7	1.4	2	5
seededA	6	2.7	0.82	1	3
seededE	6	3.5	1.4	2	5
mulchedA	6	2.7	0.82	1	3
mulchedE	6	3.7	1.5	2	5
haul road recl.A	5	2	1	1	3
haul road recl.E	5	3	2	1	5
min. cut/fillA	5	3	0	3	3
min. cut/fillE	5	4.2	0.84	3	5

Discussion and Conclusions

In 1996 there were 95 sites observed for the survey. On these sites the overall compliance was 63%. This was a decrease in compliance after a steady increase from the three previous surveys. Surrounding states have done similar compliance studies and have found similar compliance levels to West Virginia. New York conducted a BMP compliance study in 2000 and found an overall compliance of 74%. Maine conducted a study in 1998 with a compliance of 71%. It seems that West Virginia's compliance level is following suit with surrounding states while increasing from the previous study.

Based on these 40 sites we have measured so far in Forest Districts 3 and 4 the compliance level appears to be following that in the 1996 survey. This survey shows that when foresters are involved an increase in compliance can be expected. The increases in compliance can also be related to the revisions made in the BMP guidelines by the WVDOF. The number of BMPs measured has also increased during each survey. This could mean that more guidelines are being followed. With these new compliance levels the WVDOF can again review the BMP guidelines for any further revisions based on the results. When all the WV Forest Districts are completed, WVDOF will be able to identify the potential BMP problems among districts and other operational or managerial factors. This survey will provide much needed information on the application and effectiveness of forestry BMP guidelines. The WVDOF holds many classes and seminars to better inform and educate loggers about the use of BMPs. These classes can be modified based on the results of this study to better suit the needs of the WVDOF. By completing at least 100 sites across the state, the findings from this study will help the WVDOF to loggers and landowners to conduct forest practice activities efficiently.

In these sites there were no significant differences among application and effectiveness. For the most part the BMPs were applied very well. The effectiveness of the BMPs applied also rated well. There were only a few instances where the effectiveness mean was less than 3, which is a rating of fair. If the loggers are trying to apply the BMPs then attending the classes held by the WVDOF will provide them with the proper knowledge to apply the state BPM guidelines correctly.

There will be at least 60 more sites that need to be completed in the other forest districts. The compliance data will be further analyzed. With more gathered from the field using the GPS unit, compliance, application, and effectiveness will be analyzed spatially. This spatial/graphical data along with the compliance and effectiveness results will provide useful information for WVDOF to prepare a long-term forest management and practice planning in the state.

References

Egan, A.F., R.D. Whipkey, and J.P. Rowe. 1998. Compliance with forestry best management practices in West Virginia. North. J. Appl. For. 15(40: 211-215.

Kochenderfer, J.N. 1977. Area in skidroads, truck roads, and landings in the central Appalachians. J. For. 75(8) 507-508.

Ohio Division of Forestry. 1999. Evaluation of Logging Best Management Practices on Private Forest Lands in Ohio. August 1999.

Phillips, M., L. Swift Jr., and C. Blinn. 2000. Best management practices for riparian areas. In: Verry E., J. Hornbeck, and A. Dolloff (eds), Riparian Management in Forests of the Continental Eastern United States, Lewis Publishers, Washington, D.C.

Reisinger, T. W. and W.M. Aust. 1990. Specialized equipment and techniques for logging wetlands. ASAE Paper 90-7570. American Society of Agricultural Engineers, St. Joseph, MI. 12p.

Schuler, J.L. and R.D. Briggs. 2000. Assessing application and effectiveness of forestry best management practices in New York. North. J. of Appl. For. 17(4), 125-134.

Wang, J., J. McNeel, S. Milauskas. 2004. Logging Sediment Act and Forestry Best Management Practices in West Virginia: A Review. North. J. of Appl. For. 21(2): 93-99.

WVDOF. 2002. Best management practices for controlling soil erosion and sedimentation from logging operations in West Virginia. WVDOF-TR-96-3 (August 2002), Charleston, WV. 29p.

Effect of Slash, Machine Passes, and Soil Wetness on Soil Strength in a Cut-to-length Harvesting

Han-Sup Han[1], Deborah Page-Dumroese[2], Sang-Kyun Han[1], and Joanne Tirocke[2]

Abstract

A controlled experiment on a silt loam soil was conducted to determine the effect of logging slash to buffer compaction impacts, the influence of a number of machine passes, and the contribution of soil moisture content to changes in soil strength in a cut-to-length harvest in northern Idaho. Soil strength was measured at three soil depths (10, 20, and 30 cm) for three different moisture contents (low, medium, and high) and slash amounts (none, light, and heavy) after each of 12 machine passes. At all three soil depths the main effect of moisture content and machine passes on soil strength was significant, but slash amount alone did not significantly affect soil strength. After 12 passes, we measured the highest soil strength in the medium soil moisture treatment at 5 to15 cm of soil depth. The driest soil resulted in the lowest soil strength. Slash was an important soil buffer when soil moisture was present. Soil strength did not significantly increase after the second pass of a fully-loaded forwarder (31,343 kg) at any moisture content or slash level.

Key words: soil compaction, site productivity, soil impact, mechanized harvesting

Introduction

With increased demand for fire hazard reduction and ecosystem restoration treatments in the Inland-Northwest region, multiple entries into forest stands are often considered to achieve desired objectives of managing our forest resources. This means that the impacts of harvesting operations on soils become cumulative, since those impacts tend to remain for an extended time period, perhaps up to several decades (Froehlich 1979 and Geist et al. 1989). Complete soil compaction normally

---

1 Assistant Professor and Graduate Research Assistant, Department of Forest Products, University of Idaho, Moscow, Idaho, hanh@uidaho.edu, han5939@uidaho.edu

2 Project Leader and Research Scientist, USDA Forest Service, Rocky Mountain Research Station, Moscow, Idaho, ddumroese@fs.fed.us, jtirocke@fs.fed.us

occurs in the first 10 passes of a harvesting machine (Gent et al. 1984), with the greatest increases occurring in first few passes (Froehlich 1979).

Cut-to-length (CTL) logging systems are often considered to implement fuel reduction and forest restoration treatments in the interior Northwest, USA. This logging system efficiently produces sawlog material from high density stands filled with small-diameter trees while potentially leaving low impacts on soils (Lanford and Stokes 1995, 1996, Gingras 1994). A CTL system processes trees at the stump and leaves limbs and tops in the forwarding trails that can reduce soil compaction by providing a cushioning layer from the forwarder traffic. The benefits of trafficking on logging slash have been reported in past studies (McMahon and Evanson 1994, McDonald 1997, Wood et al. 2003), but the degree of the benefit varies with soil moisture (McDonald and Seixas 1997), number of machine passes (McDonald and Seixas 1997), terrain characteristics (Wood et al. 2003), slash density (McDonald and Seixas 1997), and soil depth (Carter and McDonald 1997, McDonald and Seixas 1997, Lanford and Stokes 1995, McNeel and Ballard 1992).

Assessment of a soil's susceptibility to compaction is confounded by differences in initial conditions such as texture, soil moisture, and logging slash conditions. For example, comparisons of the amount of bulk density change among soils may be unreliable as a predictor if soil texture is not taken into consideration (Page-Dumroese et al. 1999). In addition, soil wetness will determine the magnitude of change whenever a load is applied (Terzaghi and Peck 1967) and is a serious concern for sites requiring multiple entries for ecosystem restoration (McNabb 1994). However, the compressibility of forest soils decreases at soil moisture contents drier than field capacity (McNabb and Boersma 1996). Therefore, our objective was to determine the effects that soil moisture content, slash loading, and number of CTL harvesting and forwarding cycles had on compaction in a north Idaho mixed conifer forest.

Study Method

Research plots were established on the University of Idaho Experimental Forest in northern Idaho. The University of Idaho Experimental Forest manager had previously selected these sites for summer harvesting using a CTL logging system. The harvester was Valmet 500T equipped with the Caterpillar 325 under carriage. Additional passes were made with an empty forwarder (18143 kg mass), and the same forwarder, loaded (31343 kg mass) for a total of 12 machine passes. Soils on this site are an Uvi series (fine-loamy, mixed, frigid Dystric Xerochrept). Texture changes from fine-loamy to loam at approximately 20 cm. Forest cover was predominately Douglas-fir (*Pseudotsuga menziesii* var. *glauca*) and hemlock (*Tsuga heterophylla*).

The experimental design consisted of three identical linear transects (4m x 50m) with each transect representing one of three levels of soil moisture: low, medium, and high (Fig. 1). Transects were separated by approximately 15 m to avoid any edge effect from the application of water. Each transect also had three randomly assigned replication blocks for slash treatment (none, light, and heavy). Slash blocks within a moisture treatment were separated by a 2-m buffer to allow traffic to travel on only one type of slash treatment at a time.

Soil was seasonally dry (July) prior to water application. A Freightliner FL 112 truck carrying 11,356 liters of water was used to apply water (56,781 liters total) to only the medium and high moisture transects. The water was allowed to infiltrate overnight and timber harvest began the next day. Soil moisture content samples were collected in triplicate for each transect at soil depths of 10, 20 and 30 cm before water treatment, after water treatment, and after the final machine pass. Collections were made with a bulk density sampler (5 cm diameter and 7.5 cm length). The soil samples were brought back to the laboratory, weighed, dried for 24 hrs at 105° C, and reweighed to determine moisture content.

Initial amounts of coarse woody material (> 2.54 cm in diameter) on all three transects were measured. Each transect had a minimum of 65% bare ground (visual estimate) before the harvester moved into each transect. The harvester operator was instructed to fell and process trees as a "typical" thinning operation. After the harvester moved through each of the three transects, logging slash was reorganized into the three different levels of slash:

- None: no slash (bare ground)
- Light: approximately 90 kg of slash spread on 4m x 3m block, over 75% of block covered with the materials (2.5 – 7.6 cm in diameter)
- Heavy: approximately 180 kg slash spread on 4m x 3m block, over 70% of block covered with the materials (>7.6 cm in diameter)

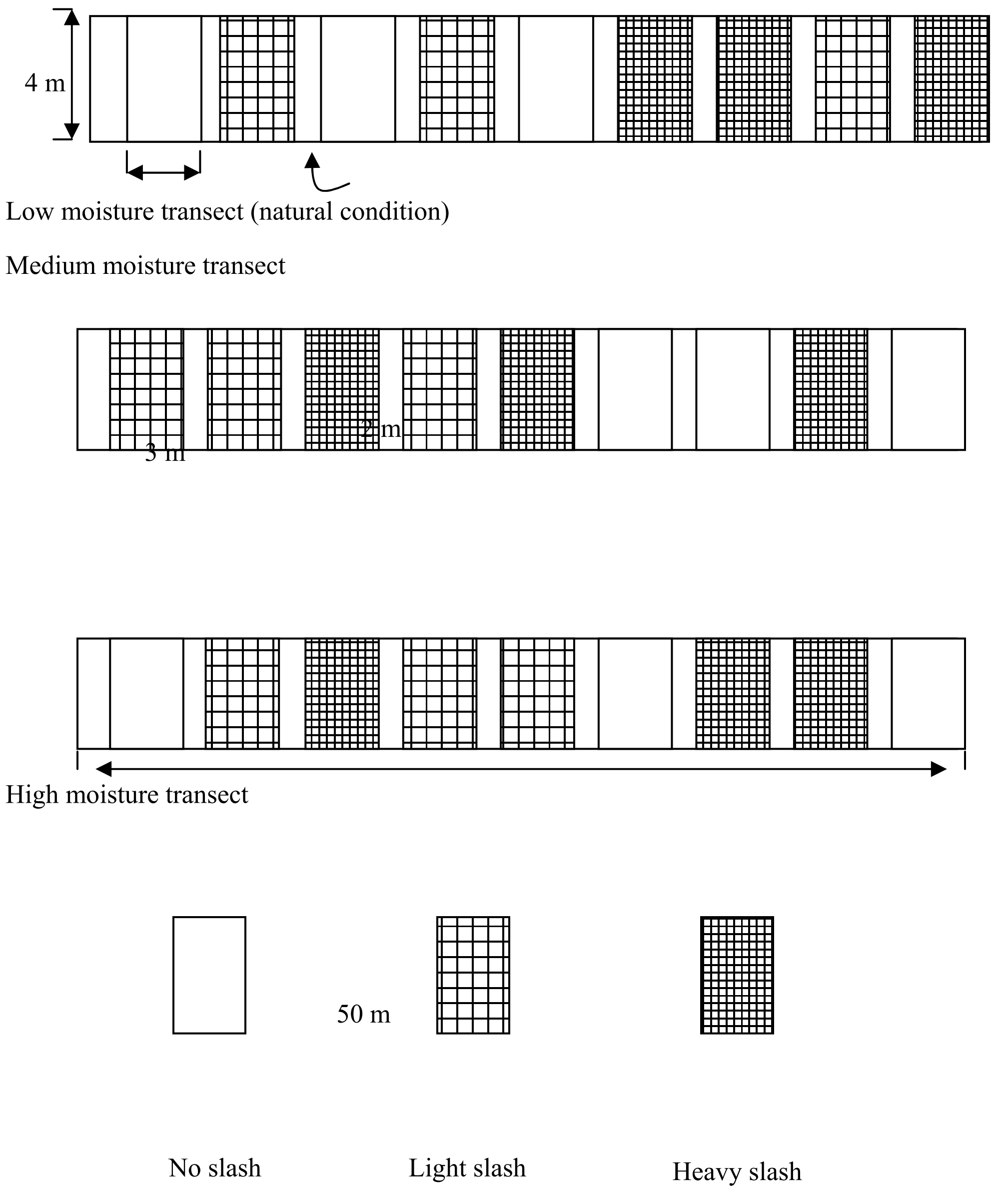


Figure 1 - Controlled experiment design containing three different levels of soil moisture content and three replications of slash treatments in each soil moisture transect (not drawn to scale)

Soil strength data were collected with an Agridry Rimik CP40 cone penetrometer after water application but before harvesting, as well as after the harvester pass, the empty forwarder pass, and each of 10 loaded forwarder passes. Three replicates of soil strength were taken at each sample point. In spring 2005, soil strength was re-measured in each transect at natural soil moisture content. Soil strength and moisture data was collected as previously described.

Rut depths were measured in the left and right wheel tracks in each moisture treatment and slash level after trafficking was complete (i.e. 10 passes of a fully-loaded forwarder). Ruts were measured in the middle point of each treatment block (i.e. 1.5 m from the edge of the treatment block). The horizontal line was drawn using a stick from outside of the skid trail as a reference for ground height. A ruler was used to measure rut depth.

Treatment effects were tested using analysis of variance (ANOVA) and post-hoc analyses (pair-wise comparison) with the number of machine passes, soil moisture, and slash level as main effects. An ANOVA test was also performed to test the effect of soil moisture and slash on rut depth.

Results and Discussion

Effect of soil moisture

Mean soil moisture was slightly higher in the top soil layers and decreased with soil depth, ranging 11.2 – 14.6% for the entire profile before water was added (low moisture, no treatment, Fig. 2). Moisture content increased to 20.9 – 29.5% for the top 30 cm soils in the medium and high soil moisture transects after the water treatment. Although we sprayed more water on the high moisture transect, both transects had similar moisture contents in the surface 30 cm of mineral soil. However, during trafficking on three transects, the high wetness treatment had more soil mixing and rutting. The additional water in the soil profile wet the profile to a greater depth and caused an unstable driving surface although moisture contents were similar for both wetness treatments

Soil conditions post-harvest (after 12 passes) at similar moisture contents revealed some differences. In general, average soil strength readings in the wheel track were much higher than those in the center line (i.e. between wheel tracks) and the undisturbed areas for all the experiment transects (Table 1). Increased soil strength was also observed in the center (between wheel tracks) in the high soil moisture transect, but to a lesser degree in the low and medium moisture transects (Table 1). In the center line, higher soil strength readings were generally found at the 20 and 30 cm soil depths for all moisture and slash treatments. These results suggest that harvesting when soils are dry limits the impact of the machinery to the wheel track but harvesting on wetter soils extends the area of influence to greater width and depth.

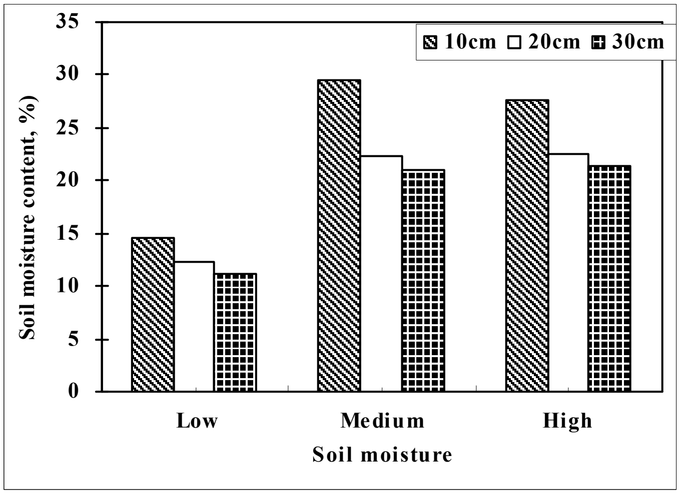


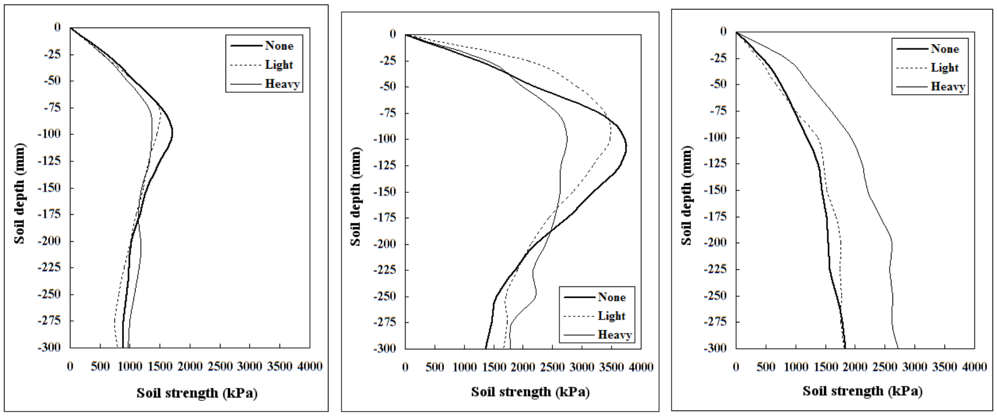
Figure 2 - Soil moisture content at three soil depths after water treatment (before harvest)

Increase of soil strength in the wheel track after harvesting varied with soil moisture condition, slash treatment, and soil depth. The largest increase in soil strength in the wheel track was observed in the medium moisture transect, up to 260% increase (exceeding 3,000 kPa with no slash, at 10 cm of soil depth) after harvesting (Table 1 and Fig. 3). Soil strength increases were also noted at the 20 and 30 cm soil depths in the medium moisture transect but were not as large as those closer to the soil surface (Fig. 3). Alexander and Poff (1985) also reported that moist soils, particularly those near field capacity, are the most prone to compaction. Although slash tended to reduce the degree of soil compaction, especially between low and medium moisture conditions, the greatest impact was still seen at soil depths of 5 to15 cm. The ANOVA analysis of soil strength data confirmed that the main effect of soil moisture on soil strength was significant at 10 and 20 cm soil depths, but was not able to be tested at 30 cm because it was confounded with transect effect.

Low moisture soils after harvesting showed a slight increase of soil strength around the 10 cm soil depth (Table 1 and Fig. 3). It was interesting to note that at 10 cm soil depth there was not much difference in soil strength between low and high moisture transects, but at the high soil moisture condition soil strength continued to increase with soil depth while soil strength decreased with soil depth under the driest soil condition (Fig. 3). This suggests that low moisture, hard soil conditions effectively limit soil impacts from logging traffic to the surface soils (<20 cm) at a minimal degree of soil compaction. In the high moisture condition, excessive moisture in the soils did not provide much support against the ground pressure and allowed the tires to penetrate into the deep soils, causing greater impacts in deep soils (>30 cm) than at low and medium soil moisture (Fig. 3).

Table 1 Average soil strength for three locations; wheel track, center line and undisturbed. The mean values are data collected at similar soil moisture conditions (31-45%) in the year (2005) after the field experiment (* Means in each row followed by the same letter are not significantly different based on one-way ANOVA at the 0.05 level).

Moisture – Slash Treatment	Soil depth (cm)	Average soil strength (kPa)					
		Wheel Track	(n)	Center Line	(n)	Undisturbed	(n)
Low – None	10	1706 a	27	930 b	27	807 b	27
	20	1022 a	27	742 b	27	720 b	27
	30	875 a	26	628 b	26	720 ab	26
Low – Light	10	1441 a	27	812 b	27	938 b	27
	20	1013 a	27	854 ab	27	720 b	27
	30	789 a	27	792 a	27	706 a	27
Low – Heavy	10	1369 a	27	872 b	27	926 b	27
	20	1184 a	27	972 ab	27	878 b	27
	30	967 a	27	957 a	27	686 b	25
Medium – None	10	3718 a	25	1225 b	27	1034 b	27
	20	2390 a	23	986 b	27	879 b	27
	30	1477 a	23	964 b	27	934 b	27
Medium – Light	10	3469 a	25	1393 b	27	1202 b	27
	20	2123 a	25	882 b	27	997 b	25
	30	1664 a	25	795 b	27	853 b	25
Medium – Heavy	10	2740 a	24	934 b	24	946 b	24
	20	2374 a	22	963 b	24	1093 b	24
	30	1776 a	21	740 b	24	830 b	24
High – None	10	1188 a	27	1174 a	27	805 b	27
	20	1550 a	24	1232 b	27	891 c	27
	30	1835 a	24	1100 b	27	789 c	26
High – Light	10	1368 a	26	1380 a	27	859 b	27
	20	1759 a	26	1400 b	27	758 c	27
	30	1810 a	26	1222 b	27	633 c	27
High – Heavy	10	1927 a	26	996 b	27	876 b	27
	20	2617 a	26	1071 b	26	692 c	27
	30	2719 a	26	915 b	26	615 c	27



Low moisture Medium moisture High moisture

Figure 3 - Soil strength changes in wheel track in relation to soil depth. The graph was based on the data collected at similar moisture contents (Spring 2005).

Effect of machine passes

Our focus on the effect of machine passes was given to the medium moisture transect because its moisture condition was believed to be the closest to field capacity for the soil studied. From pre-harvest levels soil strength increased up to the second pass of a fully-loaded forwarder (total of 4 passes): there was little increase in soil strength afterward. A single pass of the harvester on its slash mat did not increase soil strength, but forwarder traffic significantly increased soil strength at 10 cm soil depth. At 20 cm soil depth, however, both harvester and forwarder increased soil strength with their passes. At 30 cm soil depth, increases in soil strength with machine traffic were not as noticeable. ANOVA analysis showed that for all levels of soil depth, the main effect of machine passes significantly affected soil strength ($P<0.0001$). The largest increase of soil strength was observed at the first 10 cm soil depth, followed by at 20 cm soil depth, with the least increase of soil strength occurring at 30 cm soil depth.

Effect of slash

Amount of slash, soil wetness, and the number of machine passes all combined to alter soil strength and rut depth on these sites. The combined effect of these factors resulted in a mixed level of soil strength at all levels of soil depth, including interaction terms between slash and other factors (moisture and machine passes) ($P>0.05$). In soils with low moisture, bare ground (no slash) appeared to have higher soil strength at 10 cm than in the slashed replicates, but no significant effect of slash on soil strength was shown at any soil depth ($P>0.05$). However we found that slash significantly affected soil strength at 10 cm soil depth in the medium soil moisture condition (Fig. 3). This occurred only with the heavy slash treatment: light slash treatment was not sufficient enough to affect soil strength. This indicates an important note that a small amount of slash does not provide enough a cushion to absorb the ground pressure in a CTL harvesting when soils are wet. The smaller amount of slash tends to be physically broken down by the machines into pieces that no longer have the ability to distribute the machine's ground pressure and lessen its impact.

At the high moisture condition heavy slash resulted in highest soil strength (Fig. 3), which is not too unusual given the soil texture and wetness conditions. We observed that slash was broken by heavy machine traffic at high soil wetness and did not provide trafficking support. Slash was effective in absorbing equipment ground pressure until the second pass of a fully loaded forwarder, but after that the slash effect was not obvious. There was no consistent effect of slash on soil strength in the center line (between wheel tracks): soil strength changes in the center line might be influenced by other factors (e.g. water), rater than slash.

Interactions between moisture content, slash and machine passes

There were differences in the magnitude of the soil strength changes which varied with soil moisture, slash amount and the number of machine passes. This result indicated that an interaction effect between moisture content, slash and machine pass. Our ANOVA analysis on the data collected both at the time of the experiment and in the following year (at a similar soil moisture content) showed that slash alone did not significantly affect soil strength ($P>0.05$), but became significantly effective when it was combined with moisture or machine pass ($P<0.05$). The number of machine passes significantly affected soil strength for 10, 20 and 30 cm soil depths and also showed a strong effect when combined with slash and moisture content. For example, the magnitude of slash effect decreased with increase of the number of machine pass, especially after the second pass of a fully-loaded loader. Unlike the drier condition, a greater amount of slash appeared beneficial on the moist soil. This benefit was more pronounced at 10 and 20 cm soil depths: on bare ground, at 10 cm soil depth soil strength readings in the medium moisture condition were significantly different from those of the low and high moisture conditions ($P<0.05$). This was not shown in the heavy slash treatment ($P>0.05$).

Rut depth

Rut depths tended to be deeper for moist than for drier soil moisture conditions. The high moisture transect featured ruts that were significantly (13.8 – 35.3 cm) deeper than the medium soil wetness transect (8.2 - 12.0 cm) or the low moisture transect (4.5 – 8.0 cm). The main effect of soil moisture on rut depth was significant ($P<0.001$). Low moisture soils did not require heavy slash to minimize rut depth.

Ruts produced during harvesting will remain for many years, impede soil hydraulic flow, and in combination with increased compaction, likely decrease site productivity.

Conclusion and Management Implications

Forest managers need to consider soil wetness, slash, and amount of trafficking on a given site to reduce soil compaction. Scheduling harvest operation for dry periods will effectively minimize impacts on soils (e.g. soil compaction). Most site damage is likely to occur when soils are at or above field capacity. Rutting in the skid trails can be also minimized when soil are dry. Field measurement of soil water potential can provide an easy and effective method for determining when soils are susceptible to compaction by CTL logging systems.

Results from this study support the use of designated and existing skid trails. Soil strength did not significantly increased after the second pass of a fully-loaded loader although there were some variations with slash and soil moisture conditions. To minimize impacts on soils from harvesting activities, strong efforts should be given to minimize the area used for skid trails.

One of the interesting outcomes from this study was slash effect on soil strength. Slash did not provide much benefit in minimizing effects in low moisture soils: dry silt loam soils were hard enough to provide support against machine traffic regardless of the amount of slash. When soil is wet, there should be enough (i.e., heavy) slash to provide a cushion to absorb ground pressures, light slash or bare ground results in significant increases in soil strength (i.e., soil compaction). However the benefit of heavy slashing was limited to the top 10 cm soils and there were not significant differences in soil strength at 20 and 30 cm soil depths. Furthermore slash appeared to be effective in minimizing soil compaction the first 2 to 3 trips of a fully-loaded forwarder and after that slash was crushed and did not provide support.

Literature Cited:

Alexander, E.B. and R. Poff. 1985. Soil disturbance and compaction in wildland management. USDA Forest Service Pacific Southwest Region, Watershed Management Staff. Earth Resources Monograph B,158p.

Carter, E.A. and T.P. McDonald. 1997. Interaction Among Machine Traffic, Soil Physical Properties and Loblolly Pine Root Proliferation in a Piedmont Soil. Proceedings of the Ninth Biennial Southern Silvicultural Research Conference, Clemson, SC, Feb. 25-27, 1997, USDA General Technical Report SRS-20.

Froehlich, H.A. 1979. Soil compaction from logging equipment: Effects on growth young ponderosa pine. Journal of Soil and Water Conservation. Vol. 34:276-278.

Geist, J.M., J.W. Hazard and K.W. Seidel. 1989. Assessing physical conditions some Pacific Northwest volcanic ash soils after forest harvest. Soil Science Society of America Journal. Vol. 53:946-950.

Gent, J.A., R. Ballard, A.E. Hassan, and D.K. Cassel.1984. Impact of harvesting and site preparation on physical properties of Piedmont forest soils. Journal of American Society of Soil Science 48:173-177.

Gingras, J. 1994. A comparison of full-tree versus cut-to-length systems in the Manitoba Model Forest. FERIC, Special Report, SR-92. 16p.

Greacen, E.L. and R. Sands. 1980. Compaction of forest soils: a review. Aust. J. Soil Res. 18: 169-189.

Lanford, B.L. and B.J. Stokes. 1995. Comparison of two thinning systems. Part 1. stand and site impacts. For. Prod. J. 45(5):74-79.

Lanford, B.L. and B.J. Stokes. 1996. Comparison of two thinning systems. Part 2. productivity and cost. For. Prod. J. 46(11/12):47-53.

McDonald, T.P. and F. Seixas. 1997. Effect of slash on forwarder soil compaction. J. of For. Engr. Vol. 8(2): 15-26.

McMahon, S. and T. Evanson. 1994. The effect of slash cover in reducing soil compaction resulting from vehicle passage. LIRO Report 19(1): 1-9. LIRO, Rotorua, NZ.

McNabb, D.H. 1994. Tillage of compacted haul roads and landings in the boreal forests of Alberta, Canada. For. Ecol. Manage. 66: 179-194.

McNabb, D.H. and L. Boersma. 1993. Evaluation of the relationship between compressibility and sheer strength of Andisols. Soil Sci. Soc. Am. J. 57: 923-929.

McNabb, D.H. and L. Boersma. 1996. Nonlinear model for compressibility of partly saturated soils. Soil Sci. Soc. Am. J. 60: 333-341.

McNeel, J.F. and T.M. Ballard.1992. Analysis of site stand impacts from thinning with a harvester-forwarder system. J. of For. Engr. Vol. 4(1):23-29.

Page-Dumroese, D.S., Jurgensen, M.F., Brown, R.E., and Mroz, G.D. 1999. Comparison of methods for determining bulk densities of rocky forest soils. Soil Sci. Soc. Am. J. 63: 379-383.

Terzaghi, K. and R.B. Peck. 1967. Soil mechanic in engineering practice. 2nd edition. John Wiley & Sons. New York.

Wood, M.J., A.J. Moffat, and P.A. Carling. 2003. Improving the design of slash roads used to reduce soil disturbance during mechanized harvesting of coniferous forest plantation in the UK. J. of For. Engr. Vol. 4(1):11-23.

Measuring Machine Productivity with the MultiDat Datalogger: A Demonstration on Three Forest Machines

Chad T. Davis[1] and Loren D. Kellogg[2]

Abstract

Measuring productivity of forest equipment is an important aspect of managing costs in an industry consumed with operating for less. This study reports on an available option for monitoring equipment and the results and limitations a forest contractor could expect when using a datalogger to automatically gather production information. The MultiDat datalogger (engineered by FERIC) was installed on three different forest machines: 1) a Diamond 210 Cable Yarder, 2) a CAT 315C L excavator with a mulching head attachment, and 3) a CAT 518C rubber-tired grapple skidder. We observed 53:00:00 (53 hours), 75:30:00, and 7:34:00 for the three operations, respectively. Operator data entry errors impacted 1.6%, 17.1%, and 14.6% of observed time. However, operators described the datalogger as easy to use and expressed interest in knowing their results, suggesting that data entry errors may improve with comfort level. In summary, the MultiDat datalogger and software provides a good analysis tool at the contractor level for monitoring productive efficiencies and can aid in determining limiting aspects of the operation. It also seems to have applicability in long-term research studies where shift level information is part of a larger interest.

Key words: contractor, datalogger, efficiency, forest equipment, production

Introduction

Measuring productivity of forest equipment is an important aspect for an industry consumed with increasing efficiency and lowering operating costs. Most of this data is obtainable but usually the result of complex research projects that are cost prohibitive at the contractor level. Often knowledge only exists by contractor "seat of the pants" experience. The need for accurate information on machine productivity is imperative to improve project economics for forestry managers and forest

---

[1] Faculty Research Assistant, Forest Engineering Department, Oregon State University. chad.davis@oregonstate.edu. 541.737.9926

[2] Professor, Forest Engineering Department, Oregon State University. loren.kellogg@oregonstate.edu. 541.737.2836

contractors (Brown et al., 2002).

Additionally, most forest contractors have had to diversify their abilities to become more adept at operating on sites with different harvesting characteristics. In doing so, the need for information to quickly adjust aspects of their operation has, and will, become increasingly important to maintain economical stability. With the increased focus on lowering costs abounding in the industry, a forest contractor must have the ability to continually monitor operating procedures that significantly affect production efficiencies and costs.

Forest contractors must concern themselves with the footprint they leave on a harvest site. Certification efforts are beginning to require that contractors provide proof of environmental code compliance. Percent of area covered and soil disturbance, especially for ground-based machinery, are important criteria for public lands forest managers when considering harvesting options. Use of GPS technology for general tracking of machine travel has proven sufficiently accurate. (Veal et al., 2001)

The MultiDat1, engineered by FERIC (Forest Engineering Research Institute of Canada), is a second-generation datalogger that monitors forest equipment and allows contractors to maximize machine uptime by recording and reporting activities and productive time (Brown et al., 2002). The datalogger also can be equipped with a GPS receiver to monitor machine movement and travel times. This information can be downloaded to create maps showing travel logs. This study exhibits to contractors the functionality of the MultiDat in regards to monitoring machine efficiency for harvest cost reduction and provides an example of its GPS capabilities.

Methods

The MultiDat datalogger utilizes an internal motion sensor and/or electric sensors to monitor machine motion and productivity. Only the motion sensor was used in these case studies. Use of the motion sensor required two inputs: a threshold value and a maximum time interval. The threshold value has no unit of measure and varies with each machine installation, depending on the amount of vertical and horizontal shake of the machine while idling. For each operation, the threshold value was configured to ignore a certain level of movement, ie. motor vibrations. As long as this minimum threshold value was met, the datalogger considered the machine to be in operation.

A maximum time interval was used to delineate operational delays from

[1] The Multi-Dat is manufactured by GENEQ, Inc. For more information see http://www.geneq.com.

incidental pauses or datalogger sensitivity. In combination, non-productive time was recorded only when the MultiDat detected motion below the threshold value for a sustained period exceeding the maximum time interval. The datalogger would then prompt the operator to enter a stop code as to the reason for delay. The operator had a determined amount of time to respond before the datalogger recorded a No Response for the cause of delay.

The MultiDat was evaluated in three different case studies on different machines operating with different objectives: 1) Cable Yarder Study - a Diamond 210 Cable Yarder performing a commercial thinning, 2) Mastication Machine Study - a CAT 315C L excavator with a AFE[1] Rotary Mulcher head executing a non-commercial fuels reduction operation, and 3) Grapple Skidder Study - a CAT 518C rubber-tired grapple skidder performing a commercial fuels reduction harvest. Each required a unique datalogger installation due to the configuration of the machine and work being accomplished.

The motion sensor was utilized to detect productive time and delays associated with the Diamond 210 Cable Yarder. The wiring harness of the datalogger was wired to the master switch of the yarder, thus recording data anytime the master switch was to the on position. To ignore minor vibrations, the threshold value was set to 8 and the maximum time interval was set to 2 ½ minutes. Delays not longer than 2 ½ minutes were considered part of the productive cycle. Stop code prompts lasted for 99 seconds (the maximum allowed time) and No Response was recorded if no stop code was entered. There were 10 codes that the operator had as explanation to the cause of delay (Table 1).

For the Mastication Machine Study, the datalogger was wired to the battery of the machine. The harness was connected and disconnected at the beginning and ending of each shift. The motion sensor was used to determine productive time as in the Cable Yarder Study. However, due to idling motion differences of the excavator versus the yarder, the threshold was set to a value of 6. A longer maximum time interval time of 5 minutes was used to remain consistent with another data capture portion of this machine for a different study. One of eight stop categories was used to describe the cause of each delay (Table 1).

---

[1] Advanced Forest Equipment. For more information see http://www.advancedforest.com.

Table 1—Stop and Activity Codes Used for Each Portion of the Study

CABLE YARDER	MASTICATOR	SKIDDER Delay	SKIDDER Activity
Mechanical	Machine Mechanical	Wait Processor	Outhaul
Carriage	Head/Teeth Mechanical	Wait Skidder	Grapple
Line	Discuss-Research	Wait Other	Inhaul
Crew	Planning	Mechanical	Decking
Interference	Machine Maintenance	Maintenance	Cleaning
Choker Set	Head/Teeth Maintenance	Personal	Other
Landing	Personal	Discuss-Research	
Road Change	End Day	Discuss-Crew	
Personal		Other	
End Day		End Day	

A different data collection approach was used in the Grapple Skidder study than in either of the above two, attempting to mimic a detailed time study more typical of forest equipment research. Instead of utilizing the motion sensor, the operator manually input all data through the entry of both activity and stops codes. Activity codes were summed to yield productive time. Wiring was similar to the Mastication Machine, involving only the battery. There were 6 activity codes (skid cycle elements) and 10 delay codes used to record each step in the operation (Table 1). Because the datalogger did not stop the internal clock for activity codes when the operator entered a stop code, delay times had to be subtracted from each cycle element during analysis to yield a correct productive time.

Data from each operation was downloaded from the datalogger and initially analyzed using the MultiDat software. Reports were generated and exported to Microsoft Excel. To allow for greater flexibility in data analysis, secondary reports were generated from exported raw data using a macro. This custom program allowed the researcher to amend data resulting from datalogger setup (discussed below) or varying operator shift hours that was not easily maneuverable within the MultiDat software.

Results

Results are reported for the three applications separately due to the uniqueness of data collection for each: 1) Cable Yarder, 2) AFE Mastication and 3) Grapple Skidder. These results are not intended for production rate comparisons between machines but should indicate typical expected outcomes of data collected using the MultiDat for each system when using similar datalogger setups as this study. There exists some discussion in this section that relates to the explanation of the results.

Cable yarder study

The Cable Yarder Study occurred during a thinning of a Douglas-fir (*Pseudotsuga menzeseii*) second-growth stand in western Oregon. A standing skyline shotgun with a mechanical slackpulling carriage was the harvesting system in use and employed 6 crew members. Yarding distances ranged from 200 ft. to 1000 ft., averaging roughly 350 ft for the duration of this study.

After minor amendments within the data adjusting for the continuity of road change delays, total productivity for the cable yarder operation was 52.4% of the total observed 53 hours (53:00). Percentages of daily productive time ranged from a low of 42.8% to a high of 76.5% (Table 2).

Table 2. General Breakdown of Productive Time for Cable Yarder Study

Date	Scheduled Time (hh:mm)	Productive Time	Road Change	Interference	No Response	End Day
18-Oct-04	09:00	76.5%	6.5%	13.0%	0.0%	3.1%
19-Oct-04	09:00	42.8%	42.6%	14.4%	0.0%	0.6%
20-Oct-04	09:00	46.7%	18.9%	25.9%	2.8%	6.1%
21-Oct-04	09:00	48.7%	33.7%	16.5%	0.0%	0.0%
22-Oct-04	08:00	50.6%	16.7%	19.8%	4.8%	0.6%
25-Oct-04	09:00	48.7%	44.4%	4.8%	2.2%	0.0%
Total	**53:00**	**52.4%**	**27.3%**	**15.7%**	**1.6%**	**1.8%**

After productive time, the remainder of scheduled time was broken down into four general categories. Road Changes accounted for 27.3% of scheduled time, Interference 15.7%, No Response 1.6% and End Day 1.8%.

Daily road change percentages ranged from 6.5% to 44.4% and Interference (mostly in reference to the processor/yarder interaction) ranged from 4.8% to 25.9%. The ranges for No Response and End Day were similar with both low end values at 0% and high end values around 5-6%.

Mastication machine study

The Mastication Machine study took place in a natural Ponderosa Pine (*Pinus ponderosa*) stand in central Oregon. This operation was part of a larger study conducting a non-commercial fuels reduction in which standing trees were being "thinned" to a residual spacing of 16 ft. Only trees less than 9" dbh (diameter at breast height) were considered for removal.

Results for the mastication machine are compiled from 8 days of operation totaling 75 hours and 30 minutes (75:30) of total observation (Table 3). Productive time was 65.1% of scheduled time. Start and end times for the mastication machine had to be manipulated after data export due to the randomness of operator hours. Percentages of daily productivity ranged from 0.0% to 82.2%.

Table 3. General Breakdown of Productive Time for Masticator Study

Date	Scheduled Time (hh:mm)	Productive Time	Equipment	People	No Response	End Day
28-Oct-04	6:00	68.1%	0.0%	5.6%	14.4%	11.9%
3-Nov-04	9:00	82.2%	0.0%	0.0%	0.0%	15.2%
4-Nov-04	10:30	67.3%	1.3%	8.1%	0.0%	23.5%
5-Nov-04	8:00	0.0%	100.0%	0.0%	0.0%	0.0%
8-Nov-04	11:00	74.1%	20.0%	2.1%	3.9%	0.0%
9-Nov-04	10:00	73.5%	0.0%	5.7%	21.0%	0.0%
11-Nov-04	11:00	69.8%	0.0%	4.5%	0.6%	25.2%
12-Nov-04	10:00	74.5%	0.0%	0.0%	20.8%	0.0%
Totals	**75:30**	**65.1%**	**13.7%**	**3.3%**	**7.4%**	**9.7%**

General delay categories were used at the most general level of analysis. The largest delay category was Equipment Delays, accounting for 13.7% of scheduled time. People delays accounted for 3.3% of scheduled time and ranged daily from 0.0% to 8.1%. No Response was recorded for 7.4% and ranged from 0.0% to 21.0%. Use of End Day was rather large, accounting for 9.7% of total time and ranging from 0.0% to 23.5%.

One interesting observation occurred on Nov. 5th when productive time was 00:00. This was an 8 hour shift in which an equipment delay was responsible for a total lost shift. The operator was off the job in search of a hydraulic hose for the machine. The short study period inflated the impact of this delay.

Grapple skidder study

The Grapple Skidder Study was also part of another fuels reduction project. Here, the intended goal was to reduce stocking levels in a mixed conifer stand in southern Oregon by commercial means. Stems of non-commercial size were bunched and skidded to the landing for biomass conversion. The ground-based harvesting operation employed 5 crew members – 2 skidder operators, 1 feller-buncher, 1 processor and 1 loader.

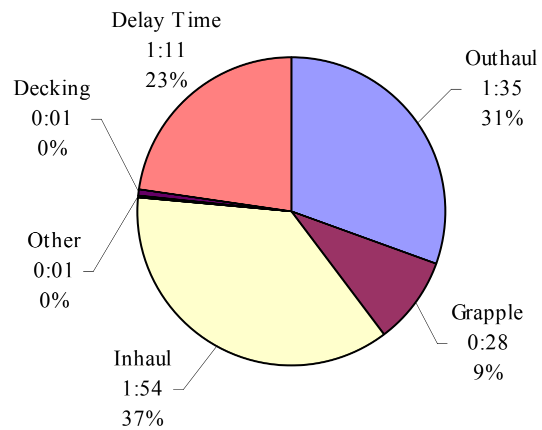
As stated earlier, the Grapple Skidder study relied on total operator input for each production and delay element of the skidding cycle. Some cycles were eliminated from analysis because of input errors. Reported results are the analysis for 11 hours, 48 minutes (11:48) of the 14 hour operation.

Cycle element analysis

One of the objectives in this study was to evaluate the automation of obtaining individual cycle time elements for skidding. This data is imperative for typical forest machine detailed time studies. If data could be obtained via the MultiDat successfully, study length could be extended for detailed time analysis of forest operations research. The Grapple Skidder Study evaluated gathering research quality cycle time element data with the datalogger. Forest contractors could also find this level of data useful when a detailed analysis is desired to adjust one facet of the operation for improved efficiency.

The average productive skid cycle time over 137 turns was 4 minutes (04:00), 77% of the average total skid cycle time of 05:11 (Figure 1). Inhaul (01:54) accounted for the most time of all skid cycle elements for the average turn. Outhaul (01:35) consumed the second most time, followed by Grapple (00:28), Decking (00:01) and Other (00:01). The low time for Decking was due to project definitions of cycle elements. The operator was only to record Decking if additional time was required to deck logs for the processor. Because the datalogger only recorded to the nearest minute, results reported to seconds are only the results of averaging.

Figure 1. ***Cycle Element Times for the Average Skid Cycle for the Grapple Skidder Study, n = 137 turns***
(time format is minutes:seconds)



Delay analysis

All delays accounted for 22.7% of scheduled time (Table 4). Individual categories of delay exhibited small percentages of scheduled time ranging from 0.0% to 9.9%. Interference is a combined delay category from three stop codes in Table 1 above; Wait Processor, Wait Skidder and Wait Other. Lumped categories were used in this general analysis in response to the short study time. Discussion, also a lumped category, consumed the second most delay time at 6.2%, of which 4.2% was Discussion-Research. Equipment delays, 2.7%, had a relatively small affect on productive time. The use of End Day and Personal were almost negligible.

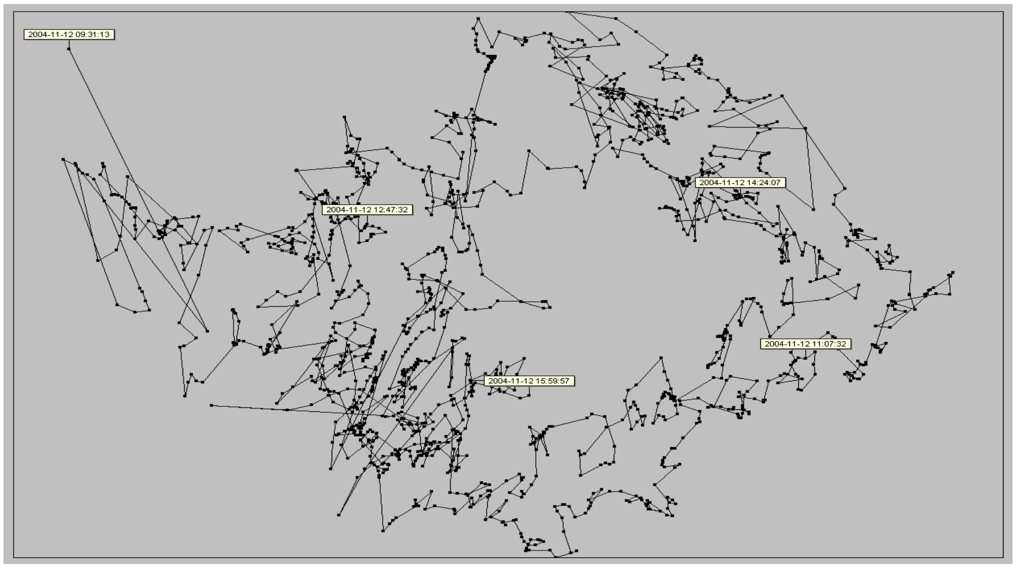
Table 4. General Breakdown of Productive Time for Grapple Skidder Study			
	12-Aug-04	13-Aug-04	TOTAL
Scheduled Time	7:34	4:14	11:48
% Productive	**79.9%**	**72.5%**	**77.3%**
Interference	9.6%	10.3%	9.9%
Discussion	4.2%	9.8%	6.2%
Equipment	2.2%	3.5%	2.7%
Other	3.1%	0.0%	2.0%
End of Day	0.9%	1.6%	1.1%
Personal	0.0%	2.4%	0.8%
Delay Total	**20.0%**	**27.6%**	**22.7%**

Delays contributed 01:11 to the average total skid cycle time (Figure 1). Delays occurred on 48.2% of observed cycles (66/137). Interference added 31 seconds (00:31) to the average skid cycle time, followed by Discussion (00:19). Other, End Day, and Personal were responsible for little of the average skid cycle time and occurred infrequently.

Use of GPS

The GPS was installed and used for the Mastication Machine study and the Grapple Skidder study. Figure 2 is an example of the typical results provided by the MultiDat software. Data points were collected at 15 second intervals or when the machine had moved 100 meters. This data can be exported to mapping software packages and overlain on maps showing unit boundaries.

Figure 2. GPS track log for Mastication Machine on 11/12/2004.



Track logs generated in both case studies resulted in some apparently erroneous data. Although the general travel pattern and location of the track log was sufficient, individual data points were notably incorrect. Some points, taken at 15 second intervals, were farther apart by more than the twice the travel distance possible at maximum vehicle speed. Possible influences on GPS signal strength include position of the machine under canopy cover and time of day. As suggested by Veal et al. 2001, the use of GPS for detailed analysis of travel patterns needs further study.

Use of GPS on forest machines, in general and more specifically with the MultiDat, need more study before claiming the widespread applicability in monitoring environmental performance. The nature of data collection, every 15 seconds for example, cannot ensure how a machine traveled from point to point or how it is sitting at the time of observation. In addition, the GPS log only provides motion data for the center of the machine, not necessarily corresponding to ground contact of the track or wheel.

Discussion

This section will focus on the applicability and the limitations of the MultiDat system and report its congruence with the chosen methodology in this study.

Road change data amendments

For the Cable Yarder study, some Road Change data was manually amended post-facto so as not to understate the impact of Road Change to productive time. During road changes, the yarder was typically left running while the operator assisted in laying out the next cable road. Among other activities, this involved moving (walking) the yarder and using the drums. Both of these actions could cause the motion sensor to jump above the threshold value, canceling any "stop code" entered and resulting in a record of productive time. When the sensor indicated motion below the threshold again, it prompted the operator for another delay code. When assisting with rigging, the operator was not tending to the MultiDat unit. After the 99 second prompt, the datalogger recorded a default stop code of No Response. Intermediary codes of productive time or No Response between the beginning and ending of a road change were amended to be analyzed as Road Change.

This must be viewed as a limitation of the datalogger in cable yarder applications. One purpose with the MultiDat is to eliminate human error by electronically controlling much of the data collection. However, this portion of the study took a lot of time to prepare the collected data for analysis. Post-facto data amendment in any situation can be cumbersome for a researcher or contractor and has the ability to impact results. Further, not all adjustments can be made with 100% certainty.

Data quality and operator cooperation

Operator cooperation is of extreme importance and was exhibited in the Cable Yarder study and the Mastication Machine study. Although in the Cable Yarder study some errors in data collection were amended, some obvious errors were not in an attempt to avoid misrepresentation of the data. The most obvious case occurs on Oct. 22nd, where No Response accounted for 4.8% of the productive time (Table 2). Looking at the daily data, this is the result of two entries totaling 23 minutes and is interspersed among Interference delays and Productive Time measurements. It is impossible to determine post-facto how this delay should have been recorded. Although for the entire observation period No Response accounted for a low percentage of scheduled time, a daily value of 4.8% can have a rather large effect in determining the causes of non-productivity for a forest contractor.

Perhaps more telling are the lessons from the Mastication Machine study. No Response accounted for 7.4% of the total scheduled time (Table 3). Adding to this effect is the probable misuse of End Day by the operator, responsible for another 9.7% of scheduled time. Together, these two categories represent 17.1% of scheduled time. Most of these instances occurred either at the beginning or ending of the shift, more than likely when the operator was greasing the equipment or fueling.

The Grapple Skidder study employed a different methodology in that the operator directly controlled the accurateness of the data. For this study, 2:12:00 (14.6% of observed time) had to be eliminated from analysis due to erroneous input. However, relative percentages of productive and delay times were similar between the included and excluded data. It is hard to predict whether this percentage of error could be expected with similar methodology over a longer term study. Here, the operator only had to cooperate for a day and a half. Daily frustration may add to operator input errors. It is also plausible that as an operator became more familiar with the MultiDat and data entry became more part of the routine such errors would decline.

Limitations for research

Production and efficiency research projects of forested machines usually occur at one of three levels: 1) activity sampling, 2) shift level studies, or 3) detailed time studies (Olsen and Kellogg, 1983).

Data collected by the MultiDat would provide a researcher with an opportunity to conduct activity sampling without being onsite. This could reduce the chance of bias on the part of the researcher or the operator. However, the research would miss observational data afforded only by being onsite during the operation.

The MultiDat also seems capable of providing reasonable shift level information with regards to productive time and delay recording. However, shift level studies often require additional information, ie. number of turns and number of pieces, that are not easily gathered with the MultiDat. These values are necessary inputs for equations in determining the cost efficiency of the machine.

Detailed time studies require intense, short duration collection of cycle time elements. Using the motion sensor methodology, the MultiDat does not afford the opportunity for research to drill down deep enough for detailed time studies. Cycle element times are only recorded to the nearest minute, generally overestimating elements less than a minute in duration. Times for delay data must be extracted from each cycle element time on an individual basis to uncover the ultimate barriers to production. One opportunity, not investigated in this study, could be to use the electric sensors to automate collection of certain cycle element times. However, with good operator cooperation, cycle time element information using only the motion sensor can be gathered rather quickly and sufficiently for most forest contractor needs.

Lastly, forest operations research, be it the result of activity sampling, shift level, or detailed time study, typically observes all the machines of an operation working in unison. Without multiple dataloggers, investigation of machine interactions in the same time frame would be impossible for an offsite analysis.

Conclusions

As for research purposes, several design features limit the applicability of the MultiDat in forest machine production and cost efficiency studies. For example in yarding/skidding studies, the inability to count number of turns and number of pieces by type make production estimates (in terms of volume or stem count) difficult by requiring a separate tabulation by the operator. Further, the non-synchronized internal clocks for activity codes and stop codes make analysis of detailed time study data problematic. Daily variations in start and stop times for shift hours, also occurring in everyday operations, make data cumbersome to analyze by requiring some manipulation.

As for forest contractor purposes, operator cooperation drives data quality results and thus, methodology should be designed to minimize the burden on machine operators. Use of the motion sensor, rather than operator input of activity codes, to determine machine production is the recommended method to gather simple efficiency data. The accompanying MultiDat software package is easy to understand and allows some flexibility for different objectives. It allows contractors to examine results generally at first and then to refocus their analysis on the areas of principal concern. The GPS tracking function provides location information that can be overlain on unit maps rather easily. Detailed analysis of travel patterns using GIS for analysis of environmental compliance requires further research.

This study tested both the intended (contractor level) and non-intended (research level and cable yarders) applications of the datalogger. The MultiDat performed sufficiently for its intended design. It provides an excellent tool for forest contractors to design and gather quick information regarding simple production figures for machines in different settings and over a range of operation types.

References

Brown, M.; Gumier, D.; Mercier, S.; Provencher, Y.; Turcotte, P. 2002. MultiDat and Opti-Grade: Two knowledge-based electronic solutions for managing forestry operations more efficiently. In Proceedings of the Woodfor Africa Forest Engineering Conference, Pietermaritzburg, South Africa, 2–3 July, 2002. Edited by L. Kellogg, B. Spong, and P. Licht. Department of Forest Engineering, Oregon State University, Corvallis, Oreg. pp. 45-49.

Olsen, E.; Kellogg, L. 1983. Comparison of time-study techniques for evaluating logging production. Transactions of the American Society of Agricultural Engineers 26(6): 1665-1668, 1672.

Veal, M.; Taylor, S.; McDonald, T.; McLemore, D.; Dunn, M. 2001. Accuracy of tracking forest machines with GPS. Transactions of the ASAE 44(6):1903-1911.

Disturbance of Soil by Skidding Operation and Its Impact on Residual Vegetation

Orhan Erdas[1], Abdullah E. Akay[1], Alaaddin Yuksel[1], Mahmut Reis[1]

Abstract

Mechanized harvesting systems provide higher quality and more consistent end products than conventional logging methods; however, they may result in a considerable amount of soil disturbance. Besides, impact of mechanized logging on physical properties of forest soil leads to damages on residual vegetation. In order to maintain the advantages of mechanized operations while overcoming the problems associated with soil disturbance, mechanized logging systems should be efficiently designed considering the importance of the physical properties of the soil for residual vegetation. Optimal soil density and soil porosity must be ensured during the operation. In this study, the effects of rubber-tired skidder on soil and their biological consequences on residual vegetation are investigated. The results indicated that defining the skidding operation in terms of physical properties of soil in the logging site and potential soil disturbance during the operation may provide environmentally friendly operations and reduce the impact on residual vegetation.

Key Words: *Skidding operation, soil disturbance, logging impact on residuals*

---

[1] Department of Forest Engineering, Faculty of Forestry, Kahramanmaras Sutcu Imam University, 46100 Kahramanmaras, Turkey. Tel: +90 (344) 223-7923, Fax: +90 (344) 221-7244, E-mail: (erdas, akay, ayuksel, mreis)@ksu.edu.tr

[2]Department of Forest Engineering, College of Forestry, Oregon State University, Corvallis, Oregon 97331, USA. Tel: (541) 737-2818, Fax: (541) 737-4316, E-mail: john.sessions@oregonstate.edu

Introduction

There is an increasing interest in mechanized ground-based harvesting systems in North America since labor productivity using conventional methods decreases as tree size decreases (Bettinger et al., 1993). Ground-based systems generally provide a safer work environment, higher quality end products, and greater labor productivity (Kellog and Bettinger, 1994). In these systems, transporting logs from the stump to a landing are usually done either by skidding or forwarding, or a combination of the two. The skidding operations are usually done with skidders and crawler tractors that transport logs by dragging them with a grapple or chokers (Figure 1). Rubber-tired skidders are lighter and less expensive than crawler tractors with similar horse-power. They have twice as much speed as tracked vehicles. Besides, skidders operate on slopes up to 45 % (Bromley, 1968).

Mechanized ground-based harvesting systems consisting of heavy-duty machines with large-size rubber-tires may cause serious impact on physical properties of forest soil which then leads to damages on residual vegetation (Erdas, 1993). Crawlers have a larger ground contact area, which leads lighter ground pressure, nearly the same as the pressure of a man's foot, and provides better traction in mud and on slippery soils (Simmons, 1979). Therefore, skidding operations should be efficiently designed to minimize the cost and to reduce the impact of the physical properties of the soil for residual vegetation. Performing ground-based operations over a slash layer can also reduce the impact (Wronski and Humpherys, 1994). In this study, the effects of rubber-tired skidder on soil and their biological consequences on residual vegetation will be investigated. The results from a previously conducted study will be also presented (Erdas, 1993).

The performance of a rubber-tired skidder is highly dependent on its drawbar horsepower, weight, and traction obtainable under the ground conditions during operation. Skid distance is generally the most important variable since it affects cycle time more than any other variables. If the skid distance increases, travel time will increase as well. In some cases where skid trail is quite straight, the longer the distance, the faster the travel speed without load.

Figure1— An example of a rubber-tired grapple skidder.

In the case where ground slope on the skid trail is steep, vehicle travels in a lower speed, which means that cycle time will be longer. Greater load weight also reduces the travel speed slightly. The load size variables such as weight, number of bunches grappled, or number of trees hooked are also important in skidding. As number of bunches grappled per turn increases, the time spent on grappling increases, which will increase the cycle time.

Methods

Interaction between soil and rubber tires

The wheel load of a skidder is transmitted to the soil surface through ground contact area of a rubber tire. The ground contact area can be computed as follows (Becker, 1960):

$$A = L \times 98.07 / IP \quad (1)$$

where

A = ground contact area (cm^2)

L = load (kg)

IP = inflation pressure (kPa)

When soil strength is high, the ground contact area increases as deformation of a rubber tire increases under wheel load (Abeels, 1983). If soil strength is low, rubber tire modifies the form of soil and generates wheel sinkage (rut depth). To predict the performance of a vehicle in relation to the various soil strengths, following equation has been suggested (Knight et al. 1962 and Turnage et al. 1972):

$$Z / d = 0\ 4.61 \times n^{0.5}(CI / NGP)^{-2.6} \quad (2)$$

where

Z = rut depth (mm)

n = number of passes of a single loaded wheel

CI = cone index of the soil, representing soil strength (kPa)

NGP = nominal ground pressure (kPa) of the tire

d = tire diameter (mm)

According to Wronski and Humpherys (1994), using a slash layer over skidding trails can increase the soil strength which leads to reduction in the rut depth (Figure 2). In this study, reduced nominal ground pressure of the tire (NGP') due to slash layer is computed using slash adjustment factor (F_S):

$$NGP' = F_S \times NGP \quad (3)$$

where Fs is estimated based on slash density, S_D (m^3/ha):

$$F_S = 1 / (0.0033 \times S_D + 0.93) \quad (4)$$

$$S_D = (p \times T \times L)/w \quad (5)$$

where

p = slash as percent of extracted timber

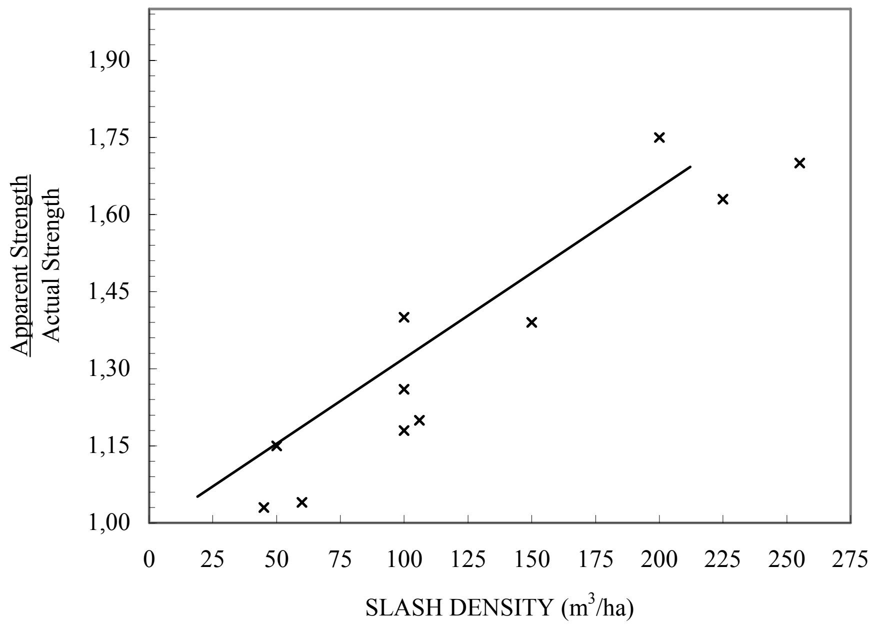


Figure 2─ The apparent increase in soil strength with increasing slash density on the trail (Wronski et al. 1990).

T = timber extracted from the unit area (m^3/ha)

S = forwarder trail spacing (m)

W = width of the forwarder trail (m)

Sample Application

The sample application is from a previously conducted study (Erdas, 1993) where the effects of various types of rubber-tired skidder on soil are investigated. Table 1 indicates the specifications of the skidders used in this study. The mechanic properties of the soil in the research area are illustrated in Table 2.

Table 1─ The specifications of the skidders.

Specification	Skidder I	Skidder II	Skidder III	Skidder IV	Skidder V
Engine Hp	80	75	65	65	60
Ground clearance (m)	0.47	0.47	0.50	0.50	0.43
Tire size	16.9-30	18.4-26	7.5-16 16.9-30	7.5-16 16.9-30	12.4-24
Tire inflation pressure	1.0	1.2	1.0-1.2	1.0-1.2	0.8-1.0
Total weight (kg)	6100	6000	3500	3500	2800
Load distribution Front Axel Rear Axel	 % 65 % 35	 % 65 % 35	 % 65 % 35	 % 65 % 35	 % 65 % 35
Load capacity (m^3)	4.0	4.0	2.0	2.0	2.0

Table 2─ Soil properties in the research area.

Soil Types	Water content (%)	Liquid Limit (%)	Plastic Limit (%)	Plasticity Index	Liquid Index
Wet clay	30.9	45.5	19.0	26.5	0.45
	247	40.6	18.3	22.3	0.29
	28.8	36.9	19.8	17.1	0.53
Sandy silt	39.6	-	-	-	-
	40.0	-	-	-	-
Wet clay-silt	28.7	24.9	19.1	5.8	1.65

In each trip, the skidders are loaded with full capacity. The rut depths are measured to investigate the correlation between soil deformation and the number of trips. Deformed soil samples are collected after the trips to indicate changes on the mechanical properties of the soil.

Results and Discussion

The results indicated that the number of trip increases as the amount of timber production increases which leads to various sizes of rut depths formations. The factors that produce various rut depths include type of the tires, structure of the tires, weight load on axels, soil capacity, number of trips, and terrain topography (Sitkei and Sohne, 1969). Figure 3 indicates the relationship between rut depths and the number of trips for sandy silt soils (Erdas, 1993). The relationship between rut depths and the number of trips are also investigated with respect to various tire inflation pressures (0.8, 1.0, and 1.2) and results are indicated in Figure 4 (Erdas, 1993).

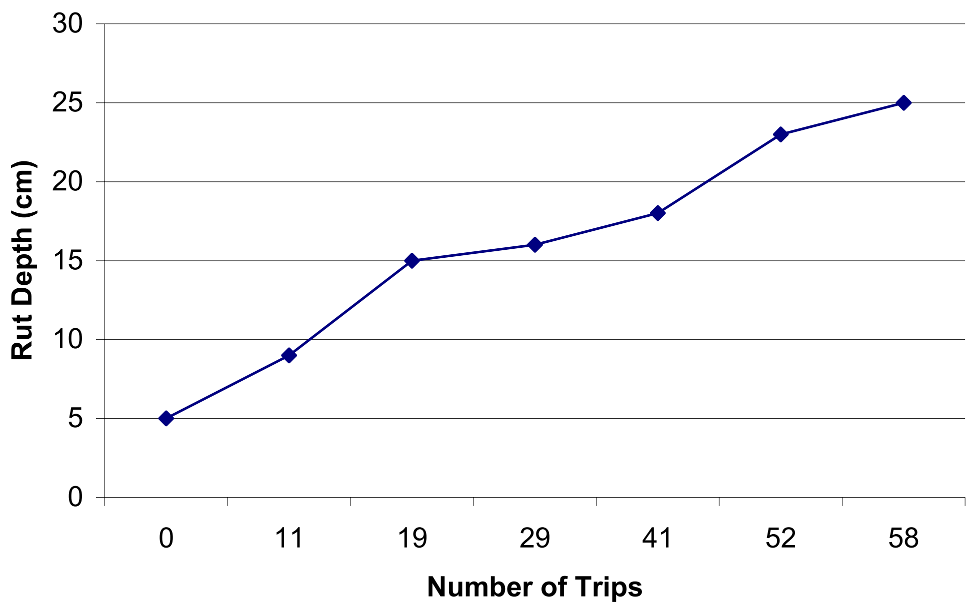


Figure 3─ Rut depths produced after number of trips along the skid trail.

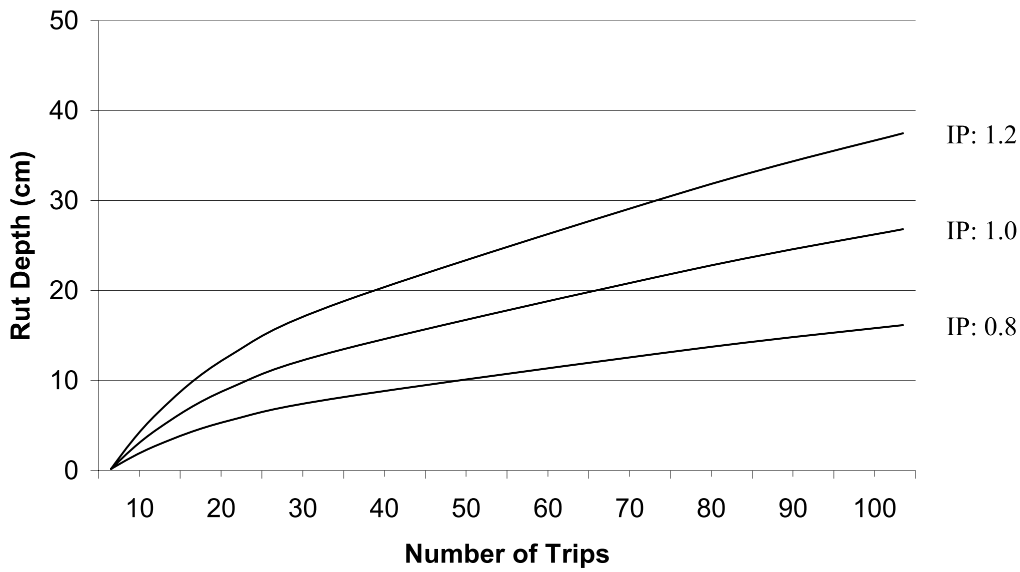


Figure 4─ Rut depths produced after number of trips with respect to inflation pressures (IP).

Soil compaction generated by the skidders, especially on soils with very low water saturation levels, reduces large-size pore in soils, decreases the soil density, prevents water transmission, disorders the soil ventilation, obstacles root development, produces erosion, reduces biological activities, and decreases growth rate (Loffler, 1985). In order to determine the changes on mechanical properties of the soil due to skidding operations, various soil samples are collected following specified number of trips and the relationship between water content, dry soil density, and water saturation are investigated with respect to the number of trips.

The results indicated that dry soil density and water saturation increases as the number of trips increase. The optimal compaction occurs when water content is also optimal. However, compaction increases as the number of trip increase till the point of optimal compaction. If the water content is greater than the optimal level, soil compaction does not increase as the number of trip increase. The results also indicated that the lower the initial water saturation level of the soil, the higher the compaction rate and with respect to the number of trips.

If the water saturation level of the soil is optimal, skidding operations does not produce any soil compaction, therefore, roots are restricted by a mechanical resistance in the soil. However, deep rut depth formations can damage the roots or break them into pieces. This may result in reduction in volume and growth rate (Bredberg and Wasterlund, 1983).

If the water saturation level is very low, soil compaction occurs after number of trips which then leads to reduction soil porosity. In general, for optimal living conditions of the plants, soil porosity should be 47%, 45%, and 40% in clay, silt, and sand, respectfully (Hildebrand, 1983). The minimum acceptable porosity level to allow normal root development in sand and clay and silt are 40% and 37-38%, respectfully (Erdas, 1993).

On the other hand, minimum dry soil density levels should be 1.55 ton/$m^3$and 1.65 ton/m^3 for clay and sand, respectfully (Hildebrand, 1983). The previous studies indicated that increasing soil density from 0.3 ton/m^3 to 1.5 ton/m^3 decreases the amount of root by 35% (Erdas, 1993). In order to analyze the effect of skidding operations, soil samples are collected from fine and rough soil classes to determine dry soil density and porosity. The results indicated that the porosity in fine soils is in the biological tolerance level (40%), while it is higher than the tolerance level. The dry soil density is found to be normal in both soil classes. In a previous study conducted in Canada (Raghavan, 1977) indicated that dry soil density increased from 1.25 ton/m^3 to 1.7 ton/m^3 after the number of trips on silt.

Conclusions

To ensure environmentally sound operations and reduce the damages on residual vegetation, the skidding operations should be well defined in terms of physical properties of soil in the logging site and potential soil disturbance during the operation. First of all, low tire inflation pressure and wide ground contact area should be retained during the skidding operation. In the logging areas with low soil strength, the skidders should not be operated with full load capacity. During the skidding operations, rut depth should be kept smaller by maintaining high soil strength and tire inflation pressure and less number of trips. Acceptable limits for soil porosity and dry soil density levels should not be exceeded on fine soils during the operation to protect root system and to ensure normal growth rate.

References

Abeels, P.F., 1983.Überlegungen zur Herstellung von Reifen für Forstwirtschaftliche Fahrzeuge, Forstwirtschaftliche Centralblatt. 102. pp: 80-86.

Becker, M.G. 1960. Off the Road Locomotion , Unişversity of Michigan Press. 160p.

Bettinger, Pete, Sessions, J., and Kellogg, L.D. 1993. Potential Timber Availability for Mechanized Harvesting in Oregon. WJAF. 8 (1) pp: 11-15

Bredberg, C.L. and I. Wasterlund. 1983. Wurzel-und Bodenschaden durch Fahrzeuge, Forstwirtschaftliche Centralblatt. 102. pp: 86-98.

Bromley W.S. 1968. *Pulpwood Production.* American Palpwood Association. New York. 213p.

Erdas, O. 1993. The effects of using skidders logging operations on mechanical properties of the soil and their biological consequences. Nature, Agriculture, and Forestry Journal. 17(1). 13p.

Hildebrand,E.E. 1983. der Einfluss der Bodenverdichtung auf die bodenfunktionen im forstlichen Standort, forstwirtsschaftliche Centralblatt. 102. pp: 111-125.

Kellogg, L.D., and P. Bettinger. 1994. Thinning productivity and cost for a mechanized cut-to-length system in the northwest coast region of the USA. J. For. Engineering, 5(2): 43-54.

Knight, S.J., and D.R. Freitag. 1962. Measurement of soil trafficability characteristics. Tran. ASAE, 5: 121-132.

Loffler,H. 1985. Bodenschaden bei der Holzernte-Bedeutung und Erfassung, Der Forst-undHolzwirt. 14(15). pp: 379-383.

Raghavan, S.V. 1977. Soil compaction in an Orchard of Southern Quebec. Journal of Terramechanics. 14(1). pp: 23-29.

Simmons, F.C. 1979. Handbook for Eastern Timber Harvesting. U.S. Department of Agriculture, Forest Service, Northeastern Area, State&Private Forestry Broomall, PA. 180p.

Sitkei , G. And W. Sohne. 1969. Beziehungen zwischen den Kenngrossen von

Ackerschlepperreifen auf fester Fahrbahn, Grundlagen der Landtechnik 19(2). pp: 29-32.

Turnage, G.W. 1972. Performance of soils under tire loads. Rep. No. 6. Application of test results to tire selection for off-road vehicles. US Army Waterways Exp. Stn. Tech. Rep. No.3-666, Vicksburg, Mississippi.

Wronski, E.B., D.M. Stodart, and N. Humphreys. 1990. Trafficability assessment as an aid to planning logging operations. APPITA, 43(1): 18-22.

Wronski, E.B., and N. Humpherys. 1994. A method for evaluating the cumulative impact of ground-based logging systems on soils. J. For. Engineering, 5(2): 920.

"Just drive right over 'em" - A Case Study of the Sensitive Plant Howell's Montia and Efforts to ensure its Persistence on Northern California Timberlands

Tony LaBanca[1] and Cheri Sanville[2]

Abstract

Prior to 2000 concern for sensitive plants was largely non-existent in the discussion between the forest products industry and state and federal regulators. In California since 2000, regulatory focus by the California Department of Fish and Game and field work conducted by industry and consulting biologists has yielded many rare plant discoveries and many logistical headaches for forestry practitioners. The annual plant Howell's montia (Montia howellii), not found in California since the 1930s, was rediscovered in 1999 and has since been found primarily on timberland and ranch roads. Initial attempts at avoidance as mitigation worked poorly. Consideration of life history and habitat characteristics has shown maintaining Howell's montia entails maintaining specific conditions that have persisted for years in an occurrence area. Road use, including passenger vehicles, log hauling, and heavy equipment, all play an important role in a prescription for local persistence. Developing a prescription for persistence for sensitive plants requires information on biology and the nature of the physical environment. This potential for communication between forest engineers and biologists is frequently ignored. Biologists realize they need a better understanding of forest management processes including planning, logistics, harvesting methods, and road maintenance to create viable and feasible sensitive species protection measures and management plans.

Keywords: sensitive plants, Montia howellii, timber harvest, road maintenance

[1] Environmental Scientist, California Department of Fish and Game, 619 Second Street, Eureka, CA 95501. Email: tlabanca@dfg.ca.gov

[2] Botanical Coordinator, Green Diamond Resource Company, P. O. Box 68, Korbel, CA 95550-0068. Email: csanville@greendiamond.com

Introduction

California is well-known for its floristic diversity and high percentage of endemic and sensitive plants, and northwestern California is especially renowned for its floristic diversity (Smith and Sawyer 1988; DellaSala et al. 1999). Historically, information on sensitive plants in conifer forests on commercial timberlands in northwestern California has been scarce because few floristic plant surveys were conducted as botanists have typically not had access. With so little information on sensitive plants in the redwoods, assessing status and distribution, analyzing potential threats from timber operations, and developing appropriate mitigation and conservation strategies is difficult.

Beginning in the late 1990s, the California Department of Forestry and Fire Protection (CDF) and the California Department of Fish and Game (DFG), in conjunction with other stakeholders, began evaluating the presence of, and impacts to, sensitive plants during the preparation of Timber Harvesting Plans (THPs). Under the THP preparation and review process, land managers began conducting surveys for sensitive plants in potential habitats, disclosing occurrences to CDF and DFG, and developing mitigation measures to avoid or minimize impacts to these occurrences. This survey, disclosure, and mitigation process was conducted pursuant to the California Forest Practice Rules, Fish and Game Code Title 14 California Code of Regulations, and the California Environmental Quality Act (CEQA). Based upon survey, mitigation, and monitoring data developed by all stakeholders in the past five years, there now exists a much greater understanding of the distribution and composition of the redwood sensitive plant flora.

Howell's Montia

The flowering plant Howell's montia (*Montia howellii*), is an inconspicuous prostrate annual of the purslane family (Portulacaceae). Stems are diminutive, branched, and often rooting from the nodes. Leaves are alternate and spoon-shaped. Flowers are not obvious and often lack petals. Pollination via insects or wind appears to be infrequent as most flowers are self-fertilizing (cleistogamous) (Kagan 1989). Each flower may produce two to three shiny black seeds, or about 27-35 seeds per plant (Guerrant 1995). Seeds are mechanically thrown within a few decimeters of the maternal plant when expelled from the fruit as it snaps open (Kaye 1992). Some seeds may be transported farther via running water (Kaye 1993).

Howell's montia germinates throughout the late fall and winter and blooms from February to June (Kaye 1993). Depending on the availability of moisture in any given year, plants tend to initiate growth and flower later in wetter sites, and may delay emergence until April (Salstrom 1992). Seeds are usually dispersed in late April through early June. The vegetative portions of the plants are often dried up and undetectable by late June. Howell's montia maintains a fairly large, but short-lived, soil seed bank with high seed viability (Kaye 1993). Ninety-eight percent of seeds germinated in germination trials under field conditions (Kaye 1992), leaving 2%, or less if some seeds are not viable, persisting in the seed bank. This lack of seedbank dormancy is consistent with winter annuals, see for example Watkinson (1981).

The species was first collected between 1882 and 1886 by Thomas Joseph Howell on Sauvies Island in the Willamette River, Oregon (Nilsson 1971). The taxon was sporadically collected or reported from British Columbia, Washington, Oregon, and northwestern California until the 1930's. In California, historic occurrences of Howell's montia were found by Eureka based botanist Joseph Tracy from 1906 to 1932 in Eureka, Phillipsville, Bridgeville, Whitethorn, and Salyer.

Since the 1930's there were few to no reports of Howell's montia and it was thought to be extirpated throughout much the historic range until 1988 when botanists from Oregon conducted field work to relocate several populations. Kaye (1993) suggests its small size and late winter/early spring phenology had caused it to be overlooked in the intervening time period. In California, no occurrences were reported since Tracy's collection from Bridgeville in 1933, and Howell's montia was presumed extinct in the state (CNPS 2001). The species was rediscovered in California in 1999 on timberlands in the Van Duzen River watershed near Carlotta.

Currently, Howell's montia has no federal or state listing (e.g. rare, threatened or endangered) in California, Oregon, Washington or British Columbia. In California, the taxon is currently inventoried by the DFG's California Natural Diversity Database and is on the Special Vascular Plants, Bryophytes, and Lichens List (CNDDB 2005). It was moved from the California Native Plant Society's Inventory of Rare and Endangered Plants of California List 1A (Presumed extinct in California) to List 2 (Rare or Endangered in California, more common elsewhere)(CNPS 2001).

Howell's montia occurs in moist to seasonally wet habitats such as the edge of ponds, rivers, dirt roads, and prairies. Summers within the range of Howell's montia are typically cool and dry, whereas the fall, winter, and spring are wet (annual precipitation 68 – 210 cm) (Kaye 1993). Vegetation in the area of occurrences is typically sparse or low growing. Topography is flat, of a low gradient, or concave. Micro-hydrologic features are more important than soil types and textures. In general, soils may be moderately to heavily compacted and are typically heavy clay with poorly drained subsoils (Salstrom 1992). The primary environmental conditions appear to be standing water for a portion of the growing season and soils derived from parent material of fine sediments.

Howell's Montia and Timberland Roads

Howell's montia exists in open, periodically disturbed habitats and completes most of its life cycle before associated species have experienced significant growth. The species appears to be sensitive to interspecific competition, requiring periodic disturbance to maintain openings in herbaceous cover of more competitive perennial species (Kaye 1993). Howell's montia often occurs at sites grazed heavily by livestock, especially cattle and sheep. Livestock reduce the biomass of competing species, provide bare, compacted soil, and create shallow depressions to collect seasonal moisture.

Periodic vehicle traffic and road maintenance appear to be an important means of maintaining the lightly vegetated character of Howell's montia occurrences. In Sauvies Island, Oregon, it was noted that a large population of Howell's montia was found with most of the plants on dirt roads that were graded three years earlier (Kaye 1993). At the Willapa National Wildlife Refuge in Washington, plants appeared to be in decline because the roadbeds on which it grows are becoming heavily vegetated with perennial grasses from the surrounding pasture (Salstrom 1992).

Since rediscovery of Howell's montia in California in 1999, approximately 60 new occurrences have been discovered (CNDDB 2005). The majority are located on seasonal roads and landings on timber and ranch lands within central Humboldt County. Although about 60 occurrences have been recorded since 1999, the actual known number of extant occurrences is likely to be fewer. This is due to changes to the habitat (vegetation succession, hydrology, road use, etc), specific aspects of Howell's montia ecology (annual plant demographics, seed dispersal, seed bank ecology, etc), and the low number of individuals in many occurrences.

In consultation with DFG, landowners with Howell's montia occurrences have employed a number of plant protection measures. These include:

- Avoiding impact to an occurrence by creating a no operations zone.
- Minimizing impacts to an occurrence by limiting the degree or magnitude of operations.
- Rectifying the impact to an occurrence by repairing, rehabilitating or restoring the impacted location after operations.

Initially, when specific information on life history and ecology of Howell's montia was limited, avoidance was the primary mitigation strategy. Over time managers learned perennial vegetation rapidly took over avoided occurrence sites. With changing available light and moisture levels Howell's montia germination and growth rates are quickly reduced. Howell's montia has been extirpated from a number of these locations. Avoidance as a plant protection measure has worked poorly and hampered Howell's montia persistence locally as high quality, occupied habitat has degraded over time with the removal of the existing disturbance regime.

A number of projects proposed to mitigate impacts by removing the top layer of soil from an occurrence site after seed set and storing the material nearby for replacement on site after the project is complete. In general, plant protection measures involving translocation and reintroduction of s3ensitive plants in California have very low success rates (Fiedler 1991). Attempts with Howell's montia have also had a low success rate. Specific information on seed bank requirements and adult plant ecology is limited. Unpredictable events, such as stream diversion and vehicle trespass may wash away or destroy redeposited material. This method of plant protection requires considerable time and effort in planning and execution. There have also been attempts to protect Howell's montia from heavy equipment use by covering small occurrences on roads after seed set with large wooden boards and geotextile fabric. This method is also labor and time intensive and does not yield better results than seasonal restrictions.

Since Howell's montia is dependent on periodic disturbance of the soil surface and it is generally found on temporary or seasonal roads, yearly road-use restrictions during the plants' growing season generally coincide with road closures developed by some landowners, and required in Section 923.4 (g) of the California Forest Practice Rules (CDF 2005) during the winter period. These closures typically do not hamper forest operations. Seasonal restriction language:

"The mitigation for Montia howellii *occurrences on seasonal roads shall be minimization through blocking road sections occupied by* Montia howellii *to all vehicle traffic and prohibiting all road use during the growing season (1 January to 1 June). After the growing season, all vehicles may operate on the roads and road surfaces occupied with* Montia howellii.*"*

Road use by heavy equipment and other vehicles after seed set removes competing vegetation, helps to compact soils, and may disperse seed to new habitat locations. Some road systems with Howell's montia were opened at the same time each year when soil moisture conditions are appropriate to perform road maintenance activities. The circumstances causing land managers to close roads during the winter period are the same conditions fostering healthy occurrences of Howell's montia.

Once larger occurrences were discovered, and land managers began to understand the activities which perpetuated the presence of these large occurrences, an effort was made to document the activities and their specific effects. DFG, working with equipment operators and forest managers, developed a grading prescription and added to the seasonal restriction language:

> *"Roads may be graded to a depth of no more than 4 inches. The soil graded from the roadbed shall be transported no further than 200 feet from the*

occurrence, and the spoils shall be deposited on a roadside berm or across the road surface."

This prescription takes into consideration the need to remove drainage structures installed the previous fall, such as critical dips and water bars, while maintaining the Howell's montia seed bank close to the surface. Frequently repeated grader passes and mixing of the graded material may bury seed too deep for germination the next season. The length of time the seed stays viable in the ground is unknown, but given the greater than 95% germination rate in the first year following dispersal (Kaye 1992) seed bank longevity is suspected to be short.

Distance and deposition recommendations are intended to keep the seed bank well distributed within the preferred habitat. This should limit the chance for an entire occurrence to be pushed away from a "good" location with appropriate light and water and into a poor shaded site without winter-period standing water. Howell's montia does well on small roadside berms of graded material and in road turn-outs where graded material is often deposited.

The timing of road work is also critical. Grading after seed set appears to improve the habitat and leads to higher plant numbers at sites the following year (GDRCO 2004), however premature grading can significantly impact a site.

Short-term monitoring in the Salmon Creek watershed, a tributary to Humboldt Bay, from 2001- 2004 (GDRCO 2004) indicates a high level of variation in the number of individuals measured from a series of monitoring points established within the occupied road system. As expected, specific locations have experienced declines of up to 60% and dramatic increases of up to 600% from year to year. All sites combined have seen an 18% increase during the monitoring period. It appears that road management is compatible and in some ways responsible for the long term persistence of Howell's montia within the Salmon Creek watershed.

Two additional considerations illustrate the often competing balance between sensitive resources. Repairing saturated road sites and rocking road systems may cause a substantial loss of habitat and extirpation of Howell's montia occurrences over time. The competing interests between sensitive aquatic resources, such as salmon and amphibians, and a sensitive plant are difficult to rectify. Some would argue that there will always be road problems associated with water in a moist climate; assuring potential habitat for Howell's montia is always being created. Additionally, recently rocked roads are improved and drained removing them as potential habitat for Howell's montia. These roads may eventually support montia as fine sediment accumulates on them periodically. But questions still remain, such as how much time is needed for fine sediments to accumulate making conditions again favorable for Howell's montia and how does this correlate with the maintenance regime required to maintain the rocked surface? As the majority of forest roads are fixed, improved, or properly maintained, Howell's montia may become less and less common.

For biologists, working with forestry and logging practitioners to understand how equipment operates, what the limitations are, and what opportunities may exist is a vital, often missing link when designing sensitive resource protection measures. In most situations there is little to no communication between biologists and practitioners actually conducting the work. Biologists generally have a poor understanding of the conditions heavy equipment work under, the wide variation of impacts possible from heavy equipment use, and the potential benefits well informed operators can provide to any resource protection design. Biologists, foresters, road managers, and equipment operators should ideally all provide input into designing sensitive plant protection measures. Biologists should be prepared to provide forestry practitioners a detailed description of habitat features they wish to maintain or create. Too often, protection measures rely upon strictly biological parameters without due consideration to the operations proposed in an area and the conditions these operations may create. Biologists should also be encouraged to experience equipment operations while designing resource protection measures to be sure the measures can be implemented appropriately and effectively. Monitoring during and after operations can assess the effectiveness of prescriptions and provide data to be used to modify specific elements of plant protection measures.

References

California Department of Fish and Game, Natural Diversity Database. April 2005. Special Vascular Plants, Bryophytes, and Lichens List. Quarterly publication, Mimeo. 88 p.

California Department of Forestry and Fire Protection. 2005. California Forest Practice Rules, 2005. Title 14, California Code of Regulations, Chapters 4, 4.5, and 10. Forest Practice Program, Sacramento, California. 285 p.

California Native Plant Society. 2001. Inventory of Rare and Endangered Plants of California (sixth edition). Rare Plant Scientific Advisory Committee, David P. Tibor, Convening Editor. California Native Plant Society. Sacramento, CA. 388p.

DellaSala, D.A., S.T. Reid, T.J. Frest, J.R. Strittholt, and D.M. Olson. 1999. A global perspective on the biodiversity of the Klamath-Siskiyou Ecoregion. Natural Areas Journal 19(4): 300-319.

Fielder, P. L. 1991. Mitigation-related Translocation, Relocation, and Reintroduction Projects Involving Endangered and Threatened, and Rare Plant Species in California.

Final Report submitted to the California Department of Fish and Game, Endangered Plant Program. 158 p.

Green Diamond Resource Company. 2004. Howell's montia (*Montia howellii*) distribution on GDRC ownership and monitoring report for the Salmon Creek Road System (2001-2004). Prepared by J. Nogueira and C. Sanville

Guerrant, E. O. and A. Raven. 1995. Patterns of Seed Production in Four Sensitive Plant Species. Unpublished report on a cooperative challenge cost share project jointly funded by Bureau of Land Management, Eugene, Burns, and Vale districts. 30 p.

Kagan, J. 1989. Final Report. 1989 *Montia howellii* inventory and monitoring. Oregon Natural Heritage Database. Unpublished report on a cooperative challenge cost share project jointly funded by Bureau of Land Management, Eugene District, and the Oregon Department of Agriculture, Plant Conservation Program. 28 p.

Kaye, T. N. 1992. Seed bank, seed germination, and fall 1991 monitoring for *Montia howellii*. A cooperative challenge cost share project on file with the Oregon Department of Agriculture and the Bureau of Land Management Eugene District. 14 p.

Kaye, T. N. 1993. Status report for *Montia howellii* Watson, with emphasis on populations in Oregon, USA. Oregon Department of Agriculture, Plant Conservation Biology Program. 54 p.

Morey, S. and D. Ikeda. 2001. Conserving plants with laws and programs under the Department of Fish and Game. In: California Native Plant Society's Inventory of Rare and Endangered Plants of California. Special Publication Number 1, Sixth Edition 2001. David Tibor convening editor.

Nilsson, O. 1971. Studies in *Montia* L., *Claytonia* L., and allied genera VI: The Limnalsine Rydb. and *Maxia* O. Nilss. Bot. Notiser. 124: 187-207.

Salstrom, D. and J. Gamon. 1992. Report on the status of *Montia howellii* Watson. Washington Natural Heritage Program, Department of Natural Resources, Olympia Washington. 49 p.

Smith, J. P. and J. O. Sawyer. 1988. Endemic vascular plants of northwestern California and southwestern Oregon. Madrono 35:54-69.

Watkinson, A. R. 1981. The population ecology of winter annuals. In: The Biological Aspects of Rare Plant Conservation. Ed. Hugh Synge. John Wiley and Sons Ltd. 253-264.

Use of Synthetic Rope as a Skidder Winchline for Designated Skid Trails

John J. Garland, PE, PhD[1] and Stephen J. Pilkerton, PE[2]

Abstract:

The use of synthetic fiber (Ultra High Molecular Weight Polyethylene, UHMWPE) rope as a replacement for steel wire rope winch line in ground skidding operations is presented. Past and ongoing research shows ergonomic gains and other operational effectiveness with synthetic skidding lines. Findings of research trials conducted in western Oregon timber types are presented. Potential economic and environmental performance for ground skidding with synthetic ropes is discussed. Addresses achieving desired environmental goals through the use of designated skid trails and synthetic rope winch lines. Potential social and environmental benefits are discussed. Benefits include tradeoffs from improved technology and planning to address operational restrictions. Research is funded by a Center for Wood Utilization Research, USDA grant to improve primary production with synthetic rope applications.

Keywords: *designated skidtrails, economic analysis, pulling winch line, soil compaction, synthetic rope*

Introduction

The goal of forest practices regulations in several states is to minimize soil damage from forest operations. The question of what constitutes "damage" varies with the regulations themselves, the organization promoting a rule or regulation, and by those doing the field enforcement. Soil disturbance is inevitable from forest operations and is not the same as damaging soil erosion, soil puddling, or soil compaction to the extent that tree growth is inhibited. Preventive measures for soil impacts have been found to be both unsuccessful (monitoring soil moisture or soil

---

[1] Professor and Timber Harvesting Extension Specialist, Oregon State University, Forest Engineering Dept., 204 Peavy, Corvallis, OR 97331. E-mail: john.garland@oregonstate.edu

[2] Research Forest Engineer, Oregon State University, Forest Engineering Dept., 204 Peavy, Corvallis, OR 97331. E-mail: steve.pilkerton@oregonstate.edu

typing) and successful (restricting the area impacted). Decisions about cost-effective preventive measures should be made by informed resource managers making tradeoffs between benefits from forest operations and some impacts modified by preventive measures. Unfortunately, organizational knowledge about these decisions is not readily passed between generations of resource managers. The use of synthetic rope as a winch line provides a new approach to the problem of minimizing soil compaction with designated skidtrails.

Prior Work

During the 1970's and 1980's, the Forest Engineering Department of Oregon State University conducted research and extension programs on the physical, biological, and engineering aspects of soil compaction from forest operations (Adams, et al, 1985). While some research continued into the present, the opportunities for improvements have been few until the availability of synthetic rope for use a winchline. With a winchline that weighs a tenth of steel, operators more easily achieve the desired skidtrail spacing.

As the basic soil processes and tree growth losses are fundamental physics, the key findings from earlier research by Froehlich and others are still relevant.

- The best approach to limiting tree growth losses from soil compaction is to limit the area in compacted soils.
- All soils compact and efforts to use soil typing are not useful
- Compacted soils inhibit seedling establishment and reduce tree growth. It does not stop established trees from growing.
- Soil compaction lasts a long time in most soils but effective soil tillage can help reduce the time to recovery
- Soil compaction is related to soil moisture but it is impossible to manage operations by soil moisture guidelines
- Productivity losses are greater for high sites than low sites
- Soil disturbance is not the same as soil "damage" or compaction
- Most of the soil compaction occurs within the first three passes (>60%).
- While there are differences between machines for compaction, the number of passes to transport the volume tends to equalize the differences.
- Frozen soil or soil covered by snow or debris/slash resists compaction.

(Froehlich and others listed in references below)

Operational and economic findings from past research are more susceptible to change over time but the findings below are likely still significant.

- Economic losses to soil compaction do not justify extraordinary measures such as cable yarding flat terrain or helicopter logging.
- Other harvest systems like shovel logging and cut-to-length have a role in minimizing soil compaction where appropriate.
- Soil compaction impacts need to be considered as tradeoffs to bring land into useful production as in the case of fire salvage/rehabilitation, brushfield

restoration, etc.

- Yarding operations should be consistent with site preparation operations for soil protection and slash treatment
- When designated skidtrails are part of the transportation system, on-site trail and road conditions should limit operations rather than some arbitrary "season" for ground-based logging

(Garland, 1983)

Economic Assessments

The economic assessment of tradeoffs between soil impacts and preventive efforts resulting in the "nearly" optimal practice can be shown in **Figure 1.** below. The y-axis is a monetary value for a given area (unit, sale, property, etc.). The x-axis can be selected depending on the variable of interest to management. One example might be the planned skidtrail spacing for similar areas. Alternatively, the percent of area in trails and landings might be of interest (the axis would not be uniformly linear but perhaps logarithmic). Another variable might be the mean winching distance pulled from the machine. The figure below shows common "index" points associated with a planned skidtrail spacing of 120 feet: ~30 feet of mean winchline pulled and ~12% of the area in skidtrails and landings.

The productivity loss curve is formed from the discounted future losses due to trees not growing in landings and skidtrails plus the expected reductions in growth in trees affected by the compacted skidtrail. At each point of the variable of interest, a value can be estimated for productivity loss. The resulting curve has an upper limit as value losses because even heavily impacted areas grow trees as the past shows. The curve cannot reach zero either as landings and transportation requirements exist for all operations.

The curve of the preventive measures starts at the origin and takes various forms. For the figure below relating costs to winch pulling at various planned skidtrail spacing, the curve becomes steep at distances in excess of 150 feet as it may become physically difficult to pull winch line (Lysne, 1980) or because the terrain/log size may result in excessive resistance from logs digging into the soil. Other curves of preventive/rehabilitation measures for shovel logging, cut-to-length, "yoader" logging, "tong tossing", or soil tillage, and so forth would have different shapes.

Optimality occurs when the total cost curve is at a minimum. Practically, the total cost curve may be rather flat along a range of skidtrail spacings. Managers will need to choose their option rationally (Garland, 1983 and Stewart, 1986).

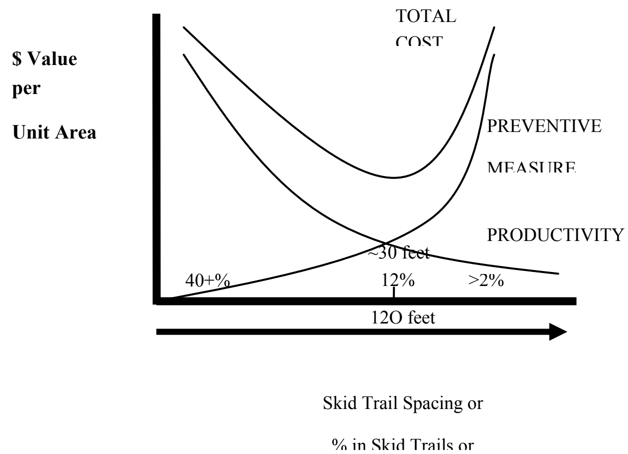


Figure 1. Relationships between soil compaction impacts and preventive measures.

Potentials with Synthetic Rope as Winchline

While it would be wonderful to conduct designed experiments combining various designated skidtrail spacings with steel versus synthetic winch lines, operational research funding has not been forthcoming. Earlier research comparing steel and synthetic winch lines during industry trials showed designed experiments would be needed as variability in operations can hide actual differences. Leonard (2003) found differences hard to isolate from studying actual operations. In one trial with a John Deere 650 tracked skidding vehicle, differences with steel versus synthetic rope were significant using regression analysis for the lateral outhaul element. Leonard states:

> At 20 feet lateral out distance, a 15% difference exists between steel wire rope and synthetic rope. When lateral out distance extends to 50 feet, a 70% difference exists. A mean distance of 22 feet equates to a 21 percent decrease in task time for synthetic rope. This time difference can result in a 0.6 minute increase at 20 turns per day (22 feet), to a 3.4 minute increase per day (50 feet). Such small time differences for part of the turn would likely be overshadowed by the operator's ability to gain more turns per day because of less fatigue when using synthetic rope.(Leonard, 2003, p. 51).

OSU student crew members were measured dragging 150 feet of 5/8" steel and synthetic rope 150 feet up a ~40% slope and a 36% reduction in time was documented (n=13). In another OSU experiment measuring ergonomic differences between steel and synthetic rope during winchline pulling, a 43 percent reduction in time was shown for pulling synthetic rope for all turns. When the data were normalized for a distance of 30 feet of winchline pulled, differences were greater (49%). **Figure 2.** below shows the difference to be even greater for uphill slopes over +20% at a 56% reduction in time. Note that for downhill pulling and moderate slopes, there is little difference between using a 9/16” swaged steel winchline and a 3/4” Amsteel Blue synthetic line. Larger steel winch lines would produce greater differences.

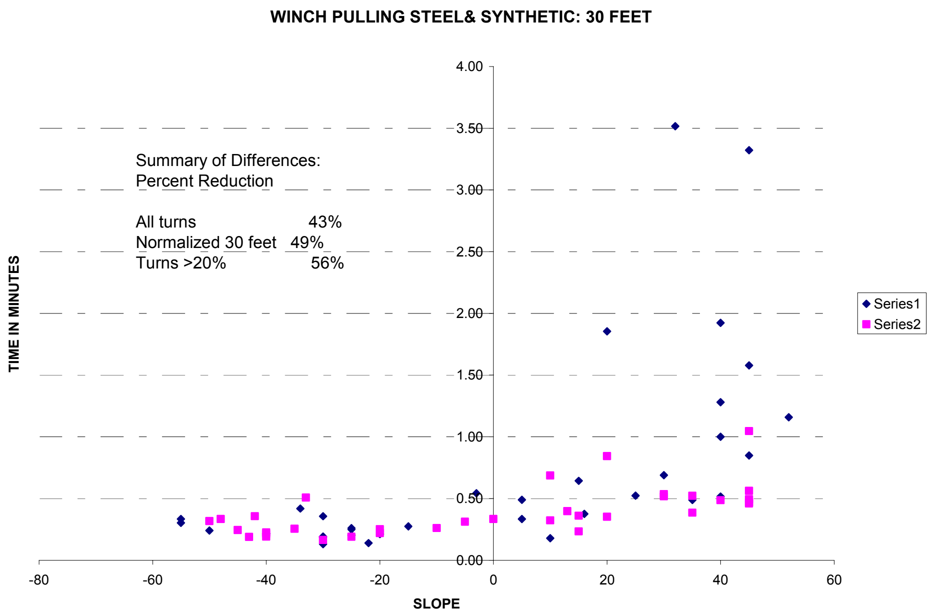


Figure 2. Comparing pulling steel and synthetic winch lines at 30 feet for various slopes.

The implications of the research for synthetic rope used as a winch line can be shown in a shift to the economic assessment curves shown earlier (**Figure 3.**).

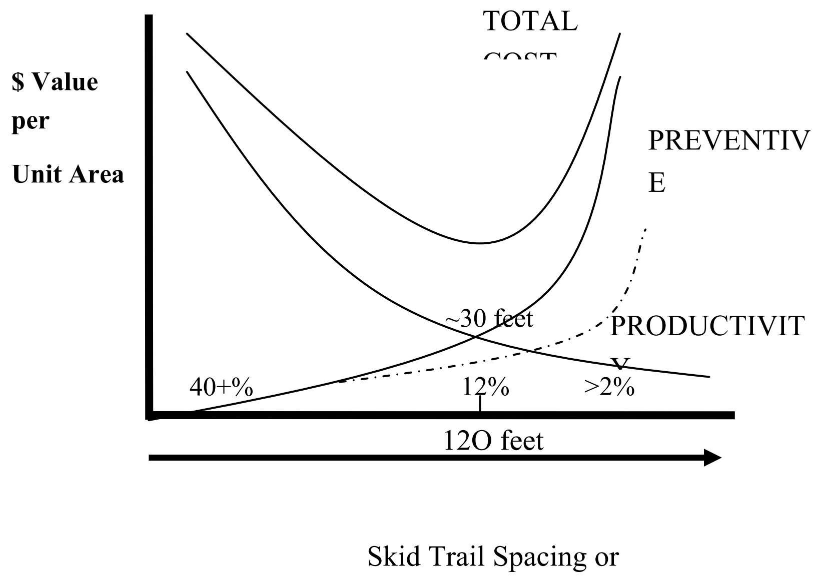


Figure 3. Shift in preventive measure curve for use of synthetic rope as winch line.

Reducing the cost of line pulling by a third in the relevant range would be a conservative starting point for assessing improvements. The shift in the preventive measure (line pulling) would likely not have much effect at lower skidtrail spacings, and for spacings greater than 150 feet, the sharp rise would again be present due to logs digging into the soil rather than human workload limits. In general, overall costs would likely be reduced and the ability to comply with a designed skidtrail spacing enhanced. Also on sloped terrain, the general scheme with steel winch lines is to minimize pulling line uphill, but synthetic rope would allow greater uphill winch pulling. Anecdotal evidence from operators shows a preference for synthetic rope leading to less fatigue at the end of the day and perhaps some additional production. One wife of a Canadian skidder operator was grateful for the use of synthetic rope stating: "You gave him back his life" (Garland, 2004). Synthetic winch lines produce significant improvements to soil protection from compaction while reducing costs compared to using a steel winch line.

References

Adams, P.W. and T. Luba. 1981. Recognizing and managing forest soil compaction problems. Slide-tape #823. Forestry Media Center http://fmc.cof.orst.edu

Adams, P.W., C. Andrus, H.A. Froehlich, J.J. Garland, and T. Luba. 1982. Soil compaction of forest lands. 16mm film or Videocassette #850. Forestry Media Center http://fmc.cof.orst.edu

Adams, P.W., H.A. Froehlich, J.J. Garland, and J. Hino. 1985. Tilling compacted forest soils. Slide-tape #876. Forestry Media Center http://fmc.cof.orst.edu

Adams, P.W., J.J. Garland, and H.A. Froehlich. 1985. Research and extension programs lead to effective management of forest soil compaction in the Pacific Northwest. pp. 121-124 IN: Proc. 1985 Soc. of Am. For. Nat. Conf., Fort Collins.

Andrus, C.W. 1982. Tilling compacted forest soils in Oregon following ground-based logging. (MS) Forest Engineering Department, Oregon State University, Corvallis, OR 97331.

Adams, P.W., J.J. Garland, and L.S. Mellem. 1987. Designated skid trails. Slide-tape #903. Forestry Media Center http://fmc.cof.orst.edu

Froehlich, H.A. 1973. The impact of even-age forest management on physical properties of soils. pp. 199-220 IN: Even-Age Management, Symp. Proc. R.K. Hermann and D.P. Lavender, eds. College of Forestry, OSU, Corvallis, OR.

Froehlich, H.A. 1978. Soil compaction from low-ground pressure, torsion-suspension logging vehicles on three forest soils. OSU For. Res. Lab. Res. Pap. 36.

Froehlich, H.A. 1979. Soil compaction from logging equipment: Effects on growth of young ponderosa pine. J. Soil Water Cons. 34:276-278.

Froehlich, H.A. 1980. Predicting soil compaction on Forested Land. USDA Forest Service, Missoula Equip. Develp. Center. Final Report Under Coop. Agreement No. 228. 120 p.

Froehlich, H.A., D.E. Aulerich, and R. Curtis. 1981. Designing skid trail systems to reduce soil impacts from tractive logging machines. OSU FRL Res. Pap. 44.

Froehlich, H.A. and D.W.R. Miles. 1984. Winged sub-soiler tills compacted forest soil. For. Ind. 2:42-43.

Froehlich, H.A. and D.H. Mcnabb. 1984. Minimizing soil compaction in Pacific Northwest forests. pp. 159-192 IN: Earl L. Stone (ed.), Forest Soils and Treatment Impacts. Proc. 6th N. Am. For. Soils Conf., Knoxville, TN.

Froehlich, H.A., D.W.R. Miles, and R.W. Robbins. 1985. Soil bulk density recovery on compacted skid trails in central Idaho. Soil Sci. Soc. Am. J. 49(4):1015-1017.

Froehlich, H.A., D.W.R. Miles, and R.W. Robbins. 1986. Growth of young Pinus ponderosa and Pinus contorta on compacted soil in central Washington. Forest Ecology and Management, 15:285-294.

Garland, John J. 1983 (1997 reprinted). Designated Skidtrails Minimize Soil Compaction. Ext. Circ. 1110. OSU Ext. Serv. 6p. Corvallis, OR.

Garland, J. 2004. Multiple Benefits of Technology Improvements: Workers, Firms and Forestry Sectors. Conference on "Of Men and Machines." Canadian Woodlands Forum and Forest Research Institute of Canada. DEMO 2004. September 14-15, 2004, Quebec, Canada. 9p.

Leonard, Jared, 2003. Applications for Synthetic Rope in Logging. (MF) Forest Engineering Department, Oregon State University, Corvallis, OR 97331.

Lysne, D.H. 1980. A study of soil disturbance and compaction resulting from the use of ground-based logging vehicles in the Sierra-Nevada. (MS) Forest Engineering Department, Oregon State University, Corvallis, OR 97331.

Stewart, R.A. 1986. An economic model of soil compaction in forestry. (MF) Forest Engineering Department, Oregon State University, Corvallis, OR 97331.

Zaborske, R.R. 1989. Soil compaction on a mechanized harvest operation in Eastern Oregon. (MF) Forest Engineering Department, Oregon State University, Corvallis, OR 97331.

Laboratory and Field Trials of Synthetic Rope for Skyline Applications in Cable Yarding[1]

Stephen J. Pilkerton[2], PE and John J. Garland[3] PE, PhD

Abstract

Evaluation of lab and field trials of synthetic fiber (Ultra High Molecular Weight Polyethylene, UHMWPE) ropes as replacements for steel wire rope running lines in skyline cable yarding applications is presented. Past and ongoing research has shown ergonomic gains and other operational effectiveness in static line applications for cable yarding. Paper presents research from laboratory loading experiments to identify load and stretch characteristics of a synthetic rope at various deflections. Results of this investigation will guide future skyline field application research and potential for incorporating synthetic ropes in payload analysis programs such as LOGGERPC. Paper also reports on actual field applications of synthetic ropes. These include the use of a 3/8-inch synthetic rope mainline on a smallwood yarder and industrial use of synthetic rope skyline extensions. Efficiencies to operations and evaluations by users are summarized. The research is funded by a Center for Wood Utilization Research grant to improve primary production with synthetic rope applications.

Keywords: *cable logging, elastic elongation, engineering strain, forest operations, skyline yarding*

---

[1] This paper was presented at the 28th Annual Council on Forest Engineering Conference; Soil, Water, and Timber Management: Forest Engineering Solutions in Response to Forest Regulations. 11 – 14 July 2005, Fortuna, California.

[2] Research Forest Engineer, Oregon State University, Forest Engineering Dept., 204 Peavy, Corvallis, OR 97331. E-mail: steve.pilkerton@oregonstate.edu

[3] Professor and Timber Harvesting Extension Specialist, Oregon State University, Forest Engineering Dept., 204 Peavy, Corvallis, OR 97331. E-mail: john.garland@oregonstate.edu

Introduction

Past and ongoing research into the use of UHMWPE (Ultra High Molecular Weight Polyethylene) synthetic ropes in place of steel wire ropes in logging applications has shown positive ergonomic and economic gains with environmental and operational effectiveness (Garland, et al, 2004; Pilkerton et al, 2004). Field applications of synthetic ropes for rigging straps, guy lines, and liftlines on cable yarding operations have been documented. Additionally, ground skidding operations are incorporating synthetic ropes for skidding winch lines to improve worker ergonomics and increase lateral reach for achieving designated skid trail spacing (Pilkerton et al, 2003; Garland and Pilkerton, 2005). Eye and long (end for end) splices as well as designed end connections achieve nearly 100 percent of rope strength (Hartter et al, 2004).

Given synthetic ropes advantage over steel wire rope with its higher strength to weight ratio, the application of using synthetic for load carrying lines such as skylines is appealing. In some circumstances, a majority of the allowable tension in a skyline is used to support the line itself. Reducing this with weight reducing synthetic ropes should result in higher payload capacity. An early estimate showed potential payload increases of 10 to 31 percent with a one-inch diameter (nominal) 12 strand single braid AmSteel® Blue[1] (ASB) rope compared to a one-inch diameter EIPS steel wire rope (Pilkerton et al, 2001). Greater improvements were associated with the smaller percent deflection of the skyline. This paper reports our initial efforts to identify the factors affecting and the relationship for stretch and tension with UHWMPE synthetic ropes. Additionally, example field trials of synthetic ropes as a smallwood yarder mainline and skyline extension are discussed.

Background

Stretch in steel wire ropes consists of two distinct types: Constructional and elastic stretch. Constructional stretch is unrecoverable, permanent stretch as the result of seating of the wires in the strands and the strands in the rope. Constructional stretch varies by rope grade, construction, core size and lay length (Wire Rope Technical Board 1993). For 6 x 19 Preformed IWRC ropes typically used in logging, constructional stretch, as a percent of length, will range from 0.33 to 0.5 percent. Elastic stretch results from the elastic deformation of the wires under load. The stretch is recoverable when the load is removed.

---

[1] Mention of trade names does not constitute an endorsement by the Forest Engineering Dept. or Oregon State University.

The elongation (stretch) of a rope as a function of an applied tensile load is the primary relationship required to model the positioning of a skyline and its resultant payload capacity. LOGGERPC 4.0, a payload analysis program (www.cof.orst.edu/cof/fe/software/logger.htm) estimates skyline systems payloads for steel wire rope. The following equation (Macwhyte 1984) is used to predict elastic stretch in steel wire ropes:

e = (P*L) / (A*E), where

e = elastic stretch, (feet)

P = load on rope, (pounds)

L = rope length under load (constructional stretch removed, in feet)

A = rope metallic area, (square inches)

E = modulus of elasticity, (pounds per square inch)

This equation applies to wire rope for which constructional stretch has been removed and for loads within the elastic limit (approximately 60 percent of nominal rope strength). A design factor of 3 is suggested for analysis in LOGGERPC and results in a design loading of 33 percent of rope breaking strength.

For purposes of this paper, we are using engineering stress and strain, as contrasted with true stress and strain. True stress uses the actual cross sectional area of the test specimen, where engineering stress uses the original cross sectional area. For steel ropes within the elastic region, the differences are small and practically indistinguishable (www.shodor.org/~jingersoll/weave/tutorial/node3.html).

The stretch relationship for steel above is problematic for use with synthetic ropes, even with ropes that have been "stabilized" (explained below). The cross sectional area of fiber in a rope of given diameter is not generally available. Strength and modulus of elasticity values are typically given in textile industry units of grams per denier—unsuitable for engineering formula. However, using the relationships for modulus of elasticity, stress, and strain one may be able to determine a stretch-tension relationship.

Using:

E = Stress / Strain,

Stress = F / A

Strain = ΔL / L

Rearranging provides:

ΔL = (F*L) / (A*E), where

ΔL = stretch (length unit)

F = Tensile force in rope (force unit)

L = unstretched rope length (length unit)

A = cross sectional area (length unit2)

E = modulus of elasticity (force unit / length unit2)

The product of A and E for steel wire rope is a constant (and hypothetically for synthetic rope) that can be empirically determined from (F * L / ΔL) for a specific synthetic rope. This product is known as axial stiffness and is a measure of the resistance to rope elongation (Banfield and Casey 1997). Thus for a known line length one can determine stretch for a given load, F. Additionally, one can determine a strain relationship (ΔL / L) for a given load. This is the percent elongation previously mentioned.

The forms above are similar to Hooke's Law where:

$$F = -k * x$$

F = Tensile force in rope (force unit)

x = ΔL displacement (length unit)

-k = Spring "constant" (force unit per length)

Thus –k is functionally equivalent to (A*E)/L. However, synthetic rope does not behave as steel wire rope in key variables. The area of material varies with tension, the modulus E is not available, and the spring "constant" may not be constant over tensions of interest. This may imply that synthetic rope could operate like a spring that deforms under use. Thus, our research effort is to investigate the value of –k for ropes of interest and the tensions and deflections in cable applications.

Elongation in Synthetic Rope

Stretch in synthetic rope is composed of end connectors (eyes), rope construction, elastic elongation, and hysteresis components. Constructional or Permanent Extension (P.E.) is that portion of extension due to construction deformation (compacting of braid and helical changes) and some plastic deformation of the yarn fibers. Elastic elongation refers to the portion of stretch that is immediately recoverable when the load is removed. Elasticity is primarily a result of fiber type. Relatively speaking, UHMWPE fiber has an extremely low elasticity compared to nylon fiber (Samson Rope Technologies 2003). There is a remaining small percentage of elastic recovery that will occur slowly and gradually over a period of hours or days. This is known as hysteresis. See Figure 1 below.

Experience has shown the elongation in new synthetic ropes will have several components. Most notable are constructional stretch and eye stretch in ropes with spliced eyes. However, rope manufacturers do not quantify these in numerical terms (i.e., as a percent of rope or eye length). They do present percent elastic elongation for loadings. AmSteel® Blue rope has an expected 0.96 percent elongation at 30 percent of break strength. This does not include eye splice stretch and is only valid for rope that has been previously loaded several times, and applies to the recoverable portion of elongation (Stenvers 2005). Comparisons of ropes typically occur after the "stabilization" of the rope (length) from a base reference load (Tension in pounds = $200D^2$, where D is rope diameter in inches) to the rated peak load (e.g., 30 percent of breaking strength) typically for 50 cycles. Thus, a new rope placed into service without "stabilization" will show larger stretch than expected until enough loadings (>50 cycles) at normal peak loads are achieved. For non-spooled ropes, which are relaxed and hand coiled between uses (e.g., lift tree guy lines) the ropes may lose their level of "stabilization" with each application.

Another type of elongation is called creep (cold flow). This refers to fiber elongation due to molecular slippage under a constant static loading. Leech et al (1993) suggest the creep of UHMWPE for long-term uses under high loads could be an issue. This elongation element may be important in guy line applications on intermediate support and tail trees. Typically these guys are tensioned to maintain a stable tree position (movement at attachment point of one tree diameter or less).

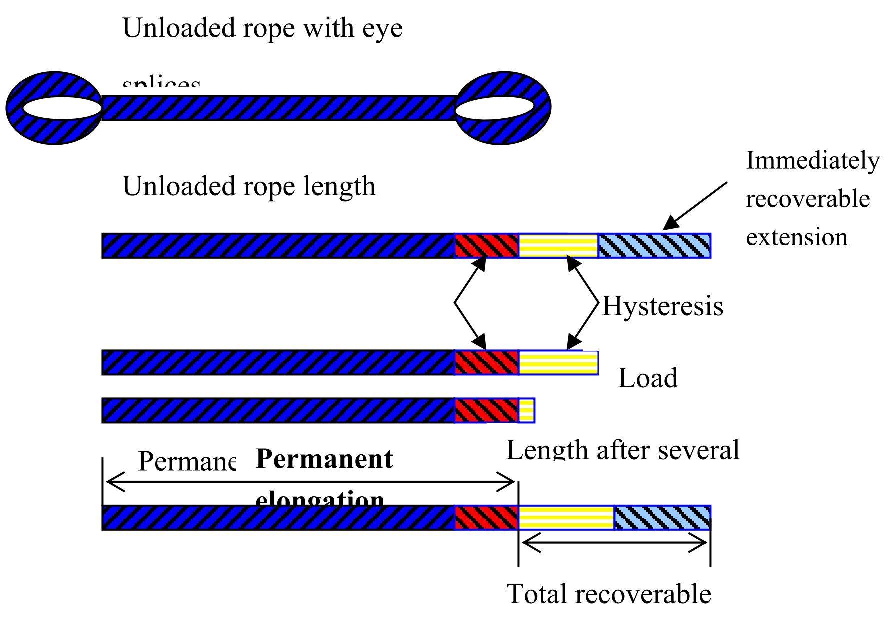


Figure 1. Elongation of synthetic ropes (after Samson Rope Technologies, 2003)

Methods

Laboratory testing

Testing was conducted in the OSU College of Forestry Knudsen Engineering Lab. A novel approach employing an inverted "V" system for loading was used to simulate a loaded skyline. The lab permitted a span distance of 50 feet between floor level endpoint anchors. A five-ton overhead hoist was utilized to create the loading force through a Skookum 10R block. Two strain gage load cells (10,000 pound rating) were installed. One was between the hoist hook and the block for quantifying the applied load. The other was between one anchor and the rope sample for the resultant rope tension. Output from the load cells was stored on a Campbell CR23X Micrologger and transferred real time to a laptop computer using Microsoft HyperTerminal 5.1. Stored data files were stripped of extraneous column numbers using DATA21.EXE. These data files were then imported into MS Excel for data analysis.

Length measurements were taken with a 75-foot Spencer steel tape incremented to one hundredth of a foot. Anchor pin diameters, length of eyes, block elevation (midspan deflection), span distance, and stretched and unstretched line lengths were recorded for each span. Sample runs were conducted to simulate loaded deflections ranging from 10 to 24 percent.

Results

Eye and constructional stretch

The new, off the reel, 3/8-inch ASB rope was 50.2 feet in length from the end of each spliced eye. Each eye was initially 32 inches in length from end of the eye to insertion point for the buried splice. The test specimen length increased in length by 0.75 feet at the base reference load of 28 pounds ($200D^2$). At the base reference load 0.11 feet of the 0.75 feet was due to eye stretch (Figure 2). The remainder 0.64 feet stretch occurred in the 44.9 feet between the insertion points (1.43 percent). After 10 cycles to 9000 pounds tension (50 percent of rated minimum breaking strength), one eye increased in length by 4.0 inches (12.5 percent) and the other eye by 5.25 inches (16.4 percent).

After the 10 cycles the test specimen had elongated to 54.3 feet or a total eye and constructional stretch of 4.1 feet. Eye stretch (both eyes) was 0.8 feet with 3.3 feet of construction stretch occurring between the eye insertion points. Thus, there was constructional stretch of 7.4 percent in this rope section.

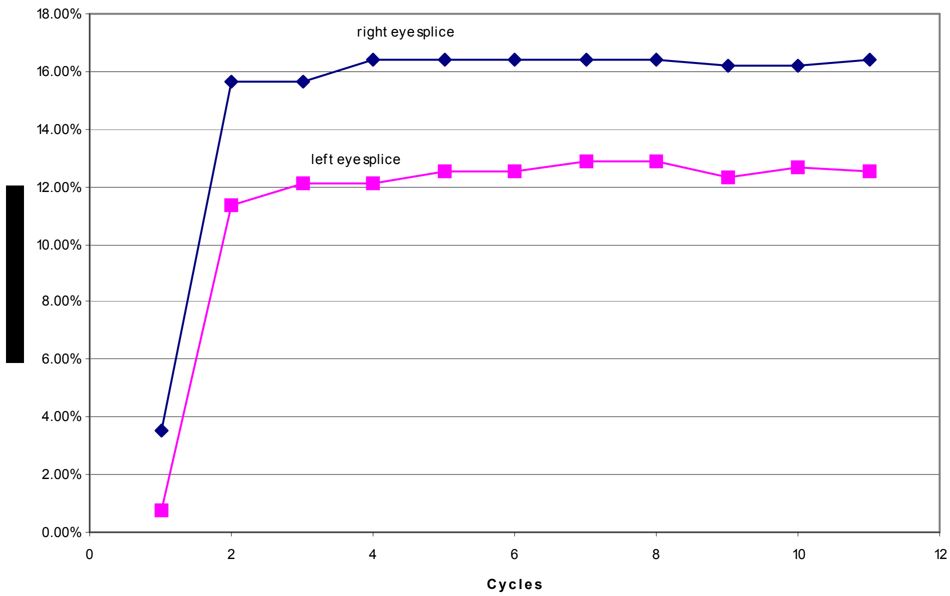


Figure 2. Elongation of eye splices (32-inch base length) in the 3/8-inch ASB rope sample tested. The first cycle loading was to a base reference tension (200D2) of 28 pounds. The remaining cycles were loadings of 9000 pounds.

Stretch – tension relationship

We expect results of stretch – tension trials at various deflections to be linear. Figure 3 shows an example for one series of loadings for an initial line length. Linear regression can be performed to model Strain (ΔL / L, unitless) as the dependent variable and tension (pounds) and deflection (percent) as the independent variables. The resulting model is:

Strain = function (tension, deflection)

If our results suggest a strong relationship between stretch and tension, they may be useful in predicting stretched line length at a given loading. We can then model synthetic rope performance similarly to that of a LOGGERPC payload analysis.

We need to continue testing with additional deflections and various rope sizes to establish relationships. In our current laboratory testing arrangements, we can only test rope up to 55 feet long. Ropes larger than 3/8-inch AmSteel® Blue need evaluations as well. From our tests at shorter lengths, the predictive model can be assessed for the longer lengths found in skyline applications.

We can also test simplifying assumptions that may make computations easier when using synthetic ropes, which may approach the straight-line geometry for rigid link analysis. It has been observed that:

“Fibre mooring lines being so much lighter have very little catenary effect and instead the compliance (to permit motion without overloading) must be provided by the elongation characteristics of the material" (www.engineeringtalk.com/news/nod/nod107.html)

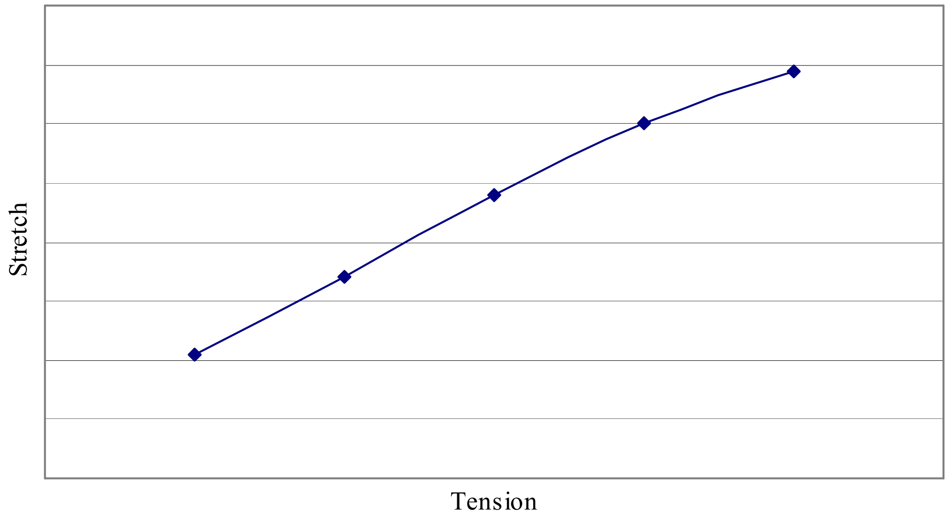


Figure 3. Stretch as a function of tensile loading for a 3/8-inch ASB rope.

Skyline extension field trials

Two operations have tried skyline extensions. One is a Southern Oregon logging contractor running a Christy HD tower yarder as a standing skyline system with a ¾-inch swaged skyline and an Eaglet carriage to thin Douglas-fir (*Pseudotsuga menziesii*). This operator purchased a 7/8-inch by 200 foot AmSteel® Blue synthetic rope with spliced eyes at the ends for the specific purpose of using it as a skyline extension. The contractor utilized both stump anchors and a mobile CAT for tailholds (Figure 4). This operator had earlier used a synthetic rope as a skidder winch line independent of the OSU-Forest Engineering synthetic rope research. Based on a positive experience, he wanted to test the extension application (again independent of OSU research efforts). The practitioners are becoming the innovators ahead of research-based knowledge. The operationally loaded 200-foot synthetic skyline extension appears to be a straight line in Figure 5.

The second operation is a large timber company crew testing synthetic rope applications with Samson Rope Technologies. The crew implemented a 1-1/8 inch by 500 foot ASB rope for a skyline extension on a Madill 172B tower yarder performing clearcut harvesting in SW Washington. Primary species harvested were Douglas-fir and western hemlock (*Tsuga heterophylla*).

The logging contractor and his rigging crew have been pleased with the rope extension. In one unit, they were logging next to a riparian buffer but needed to rig through the buffer and up the opposite slope for deflection and anchors. The 200-foot synthetic extension, weighing 40 pounds, allowed one worker to layout the extension in 10 minutes. The worker estimated it would have otherwise required 1.5 hours with significant physical effort to pull slack, then move ahead, pull slack, etc. The worker carefully avoided siwashes (zig-zags) with the layout to avoid binding and abrading the extension when raising it into the yarding position.

A comparable 7/8-inch steel wire rope extension of 200 feet in length would weigh about 370 pounds. In addition, the worker would need two coils of 3/8-inch haywire weighing 100 pounds and other rigging to make the layout to achieve the same result.

The company logging crew has encountered more operational concerns. The 1-1/8 inch, 500-foot rope segment weighs 160 pounds. This load might be reduced with two shorter extension segments (including connectors). The extension suffered partially cut strands at the stump anchor end from abrasion on a rocky surface during loading because it was not elevated from rocks at its anchor position. The damage was discovered and the damaged section removed and the eye re-spliced. The harvest manager felt this particular damage was preventable.

The company crew is operating the Madill as a live skyline system. The constant raising and lowering of the skyline may be imparting a torque to the rope extension. The twist has been estimated at 1 turn per meter. Twisting can substantially reduce the residual strength of synthetic rope. Braided ropes are reported to be torque free, but not torque tolerant. Under applied rotation, the forces are transferred to only half the strands (Pearson 2002). The situation is under review by the manufacturer. The harvest manager installed a swivel system between the skyline and the extension but was not successful because friction in the swivel was excessive and the rope lacked rotational resistance.

Mainline field trials

The Student Logging Training Program at OSU has been using a 3/8-inch AmSteel® Blue rope as a mainline on a Koller K300 2 drum tower yarder since August 2002. The mainline has functioned exceptionally well. A student worker cut several strands of the mainline with a chainsaw, which was easily repaired with an End-for-End splice (long splice). Additionally, the end of the mainline, which endures the highest loadings, has failed about a dozen times over this period. The failure always occurs near the end of the buried tail of the eye splice securing the rope to the load hook. Each failure results in the loss of approximately 10 feet of spooled length. Operators indicate this is greater to what occurred with the steel mainline, but repairs are quicker.

Figure 4. Synthetic rope skyline extension (7/8-inch by 200 foot AmSteel® Blue) laid out from the tailhold Cat into the unit.

A 100-foot section of this mainline was recently removed to test for residual strength. Four 25-foot test samples were created. Each sample was then cycled 10 times to 20 percent of initial minimum catalog breaking strength. The eleventh loading was to rope failure. The results are presented in Table 1.

Table 1. ***Residual strength for a 3/8-inch AmSteel® Blue rope used as a yarder mainline since 2002.***

Sample	Position of Rope Sample (feet from loaded end)	Residual Strength (pounds)	Percent of Minimum Break Strength
1	0 to 25	7812	42.5
2	26 to 50	11281	61.3
3	51 to 75	11448	62.2
4	76 to 100	13616	74.0

Figure 5. A raised and tightened skyline with a 7/8-inch by 200 foot AmSteel® Blue skyline extension in the foreground, viewed from the tailhold Cat. The shackle connecting the synthetic to the steel skyline is approximately positioned at the arrow in the photo.

Future Research

Preliminary results and questions generated from these investigations suggest additional research:

- Tests with V-loading (typical skyline geometry) for quantifying static loading elongation.
- Preliminary results suggest a strong relationship between stretch and tension. Developing and verifying the relationship for larger lines and deflections would allow predicting stretched line length at a given tension for modeling synthetic rope performance in LOGGERPC type payload analysis.
- Verifying tension, stretch, deflection relationships for lengths used in cable logging.
- Assess potentials for simplifying assumptions in synthetic rope analysis like the rigid link analysis.
- Alternative rope types, materials, and constructions need evaluation besides those tested.
- Modifications to carriages or new carriage designs.
- Synthetic ropes advantage over steel wire ropes for flex fatigue suggests

evaluation of a traction drive carriage such as the Woodliner (motorized carriage with skidding winch is driven along the skyline www.forsttechnik.at/woodliner-en.php). Efforts are underway to bring such a test to the Pacific Northwest.

Based on field implementation and user innovation to date, safety should be the primary concern to avoid injury and economic loss when synthetic rope is used beyond the existing research knowledge base. The following guidelines are presented:

- Recognize synthetic ropes are not a direct replacement for steel wire rope. Synthetic ropes have different cut and abrasion resistance, heat resistance, and other characteristics. Adapting field practices to reflect these differences allows for benefits from the advantages while mitigating the disadvantages.
- Use chafe protection, either used fire hose or commercially available products to create a protective layer between the synthetic rope and abrasive surfaces such as notched stumps.
- Ongoing residual strength testing suggests ropes incurring cyclic loadings may have reduced strengths during use. For some applications, increasing the rope size by 1/8-inch diameter for new synthetic ropes may be needed to approximately maintain a 1 to 1 strength ratio as the ropes become used.
- Maintain an active inspection regime for ropes in service. Apply manufacturer's replacement criteria as appropriate.

Summary

Because synthetic rope has shown promise for replacing wire rope in various logging operations, we are investigating it use for running lines and skylines in cable logging. Current uses as yarding mainlines and skyline extensions indicate potentials but concerns are evident as well. Our concern is that operational innovation may exceed the knowledge base now available from our research.

There is an approach to develop a stretch-tension relationship for use in analytical planning models for cable logging but more tests are needed. However, unique characteristics of synthetic rope require approaches different from that of wire rope. As always, research opens new questions for study and rather exciting possibilities for applications in logging. Research is continuing on this topic.

References

Banfield, S. and N. Casey. 1997. Evaluation of Fibre Rope Properties for Offshore Mooring. In Proceedings: FPS '97, 4th Annual International Conference, 1997. 15 p. http://www.tensiontech.com/papers/papers/fibre_rope_propreties/index.html

Garland, J.J., S. Pilkerton, and J. Leonard. 2004. Field testing of synthetic rope in logging applications to reduce workloads. OR-OSHA Worksite Redesign Grant Final Report. 62 p. www.cbs.state.or.us/external/osha/grants/osuforest/osuoverview.html

Garland, J.J. and S.J. Pilkerton. 2005. Use of synthetic rope as a skidder winch line for designated skid trails. In Proceedings: 2005 Annual Council on Forest Engineering Conference, 11-14 July 2005, Fortuna, CA. 8 p.

Hartter, J., J. Garland, and S. Pilkerton. 2004. Using Synthetic Rope in Forest Operations: End Connector Concepts. In Proceedings: 2004 Annual Council on Forest Engineering Conference, 27 - 30 April 2004. Hot Springs, AR. 5 p.

Leech, C.M., J.W.S. Hearle, M.S. Overington, and S.J. Banfield. 1993. Modelling Tension and Torque Properties of Fibre Ropes and Splices. In Proceedings: Third International Offshore and Polar Engineering Conference, 6 – 11 June 1993, Singapore. 7 p. www.tensiontech.com/papers/papers/model_tension_torque/index.html

Pearson, N.J. 2002. Experimental Snap Loading of Synthetic Fiber Ropes. Blacksburg, VA: Virginia Polytechnic Institute and State University; 642 p. MS thesis. http://scholar.lib.vt.edu/theses/available/etd-01132003-105300/

Pilkerton, S.J.; J.J. Garland; J. Sessions, and B. Stringham. 2001. Prospects for Using Synthetic Rope in Logging: First Look and Future Research. In Proceedings: The International Mountain Logging and 11th Pacific Northwest Skyline Symposium. 2001- A Forest Engineering Odyssey. Eds. P. Schiess and F. Krogstad, College of Forest Resources. U. Washington. Seattle, WA. Dec. 10-12, 2001. CD ROM Media. 289 p.

Pilkerton, S.J.; J.J. Garland; J. M. Leonard; and J. Sessions. 2003. Synthetic Rope Use in Logging Winching Applications. In Proceedings: 2003 Annual Council on Forest Engineering Conference, 7 – 11 SEP 2003, Bar Harbor, Maine. 6 p.

Pilkerton, S., Garland, J., and J. Hartter. 2004. Applications of synthetic rope for improved economic and environmental performance in mountainous logging. In Proceedings: 2004 International Mountain Logging Conference. Vancouver, BC, Canada. 10 p.

Macwhyte Wire Rope Company. 1984. Macwhyte Wire Rope Catalog G-18: Catalog of tables, data, and helpful information. Kenosha, Wisconsin. 260 p.

Samson Rope Technologies. 2003. Industrial Rope Catalog. Ferndale, WA. 59 p. www.samsonrope.com

Stenvers, D. [E-mail to John J. Garland]. 2005 17 June. Summary of ASTM and CI elongation procedures.

Williamsport Wirerope Works, Inc. 2000. General Purpose Catalog Bethlehem Wire Rope. Williamsport, PA. 40 p. www.wwwrope.com

Wire Rope Technical Board. 1993. Wire Rope Users Manual. Third edition. Woodstock, Maryland. 164 p.

Road Sediment Model: An Application for Modeling Sediment from Forest Roads to Streams

Carl E. Bolstad, N. Phil Peterson

Abstract

The Road Sediment Model (RSM) is a computer model that estimates the quantity of sediment that is delivered from forest roads to streams. The RSM is initially being developed for a specific industrial forest land owner (Green Diamond Resource Company), but can ultimately be adapted to other forest land owners.

Understanding the amount of sediment that enters the stream network as a result of road building and management activity is important because fine sediments are a significant source of pollution and are harmful to upland stream fish habitat. Research has also shown that forest roads are one of the primary sources of sediment; that sediment is mobilized from forest roads during periods of rainfall; and that vehicle traffic can greatly increase the quantity of sediment that runs off the road surface. The success of the forest products industry in responding to market demand while protecting the environment therefore hinges upon optimizing access to forest resources via the road network while minimizing traffic in sensitive areas during rainfall.

Other approaches to modeling road sediment use averages for rainfall, traffic and road attributes over a relatively course spatial and temporal scale. The RSM improves on other approaches by using data for actual rainfall, actual management activity, detailed road inventories, and geographic layers that spatially relate these entities. The RSM will assist forest managers by allowing them to predict sediment outputs as a consequence of management scenarios, and to compare predictions against the current estimated total of sediment delivered this year. Forest managers can then make better management decisions under current and forecasted weather conditions, which will reduce the cost of regulatory penalties as well as the cost to the environment.

This report will describe the software design project to implement the Road Sediment Model as a significant software design project. The primary challenge of this project was to integrate existing software components with custom built components to meet the following primary requirements: quickly calculate and report estimates for a large geographic area; utilize existing geographic data for roads, streams, delivery points, harvest units; and allow for future estimates based on planned harvest and projected weather.

Introduction

The Road Sediment Model (RSM) is a computer model that estimates the quantity of sediment that is delivered from forest roads to streams. The RSM was developed for Green Diamond Resource Company (GDR) in response to the need for monitoring surface erosion from roads required by a federally approved Habitat Conservation Plan (HCP) and Total Maximum Daily Load (TMDL). This model and the approach are is easily adapted to other landscapes, operating environments, and information systems.

Understanding the amount of sediment that enters the channel network as a result of forest road use is important because fine sediments are a significant source of pollution and are harmful to stream and fish habitat. Research has also shown that forest roads are one of the primary sources of fine sediment; that sediment is mobilized from forest roads during periods of rainfall; and that vehicle traffic can greatly increase the quantity of sediment that is produced from the road surface. Access to profitable short term log markets requires forest mangers to have year round access to timber harvest units and associated haul routes regardless of weather conditions.

Prudent decisions regarding wet weather hauling requires detailed and current information about delivery of fine sediment from roads. Previous approaches to modeling road sediment use averages for rainfall, traffic and road attributes over a relatively course spatial and temporal scale. The RSM improves on these approaches by using data for actual rainfall, actual management activity, detailed road inventories, and geographic layers that spatially relate these entities. The RSM assists forest managers by allowing them to predict sediment outputs as a consequence of management scenarios and to compare predictions against the current estimated total of sediment delivered for any planning period. Forest managers can then make better management decisions under current and forecasted weather conditions.

This paper describes the software design project to implement the Road Sediment Model. The primary challenge of this project was to integrate existing software components with custom built components to meet the following primary requirements: quickly calculate and report estimates for a large geographic area; utilize existing geographic data for roads, streams, delivery points, harvest units; and allow for future estimates based on planned harvest and projected weather.

Previous Work

Computer models estimating road sediment

WARSEM - SEDMODL2

SEDMODL was originally developed by Boise Cascade Corporation and has been supported by other industry and government partners. WARSEM (Washington Road Surface Erosion Model) is a new name for the latest version of SEDMODL2, which consists of an Access Database backend, an Access user interface, and various ARCINFO scripts for doing spatial operations. WARSEM first attempts to identify locations of sediment delivery by looking at intersections between roads and streams along with topography. WARSEM then estimates long-term average annual sediment yield from road segments or road systems using average annual precipitation, geologic erosion rates, road characteristics and average road use. This model has several deficiencies: 1) it tends to overestimate the quantity of road segments that deliver sediment, (2) it uses average annual precipitation, and average road use rather than actual rainfall records and management activity data at a more realistic, finer temporal scale. (3) relationships between rainfall, runoff and sediment are not calibrated to the specific land base of the user.

WEPP - X-DRAIN

The Water Erosion Prediction Project was developed by USDA Agricultural research service. The WEPP model is a physically based soil erosion model that can provide estimates of soil erosion and sediment yield considering specific soil, climate , ground cover, and topographic conditions. For every day being modeled, WEPP simulates vegetation, surface residue and soil water content. For each day with precipitation, WEPP determines whether the precipitation is rain or snow, and calculates the infiltration and runoff. If there is runoff, WEPP routes the runoff over the surface, calculating runoff and deposition rates for at least 100 points on the hill slope. It then calculates the average sediment yield from the hill slope. X-DRAIN is one of a series of USDA Forest Service computer programs and uses the WEPP model specifically to estimate sediment from forest roads and to determine the optimum number of cross drains needed to mitigate sediment delivery. X-DRAIN has similar deficiencies to the WARSEM-SEDMODL2 package in that it estimates sediment based on average climate and traffic conditions at a temporal scale too course to be meaningful to day to day operational management decisions.

Physical experiments in road sediment estimation

There have been numerous studies to estimate the amount of sediment that is deposited from forest roads, and to determine what the primary causal relationships are. We focus here on those that are most closely related to our geographic area of interest, and surmised to be the most comprehensive assessment of the subject.

Black and Luce

Black and Luce published several papers between 1999 and 2001 that demonstrated correlations between road length, slope, base soil type, cut slope cover, road use and road maintenance on forest roads in the Oregon Coast Range. They found that certain soil types delivered significantly more than others, and that certain road maintenance practices caused sediment production equivalent to high log truck traffic.

Megehan, Ketcheson, Monsen, Wilson, and King

These authors worked collaboratively on several papers between 1991 and 2001 studying sediment delivery from forest roads in central Idaho. These studies identified sources of sediment, deposition locations, cumulative volumes of sediment, and the ameliorative effects of road construction and erosion control practices.

Reid and Dunne

The Reid and Dunne (1984) study on the Clearwater River of the Olympic Peninsula, Washington provided the conceptual basis for the RSM, as it established a process driven approach for calculating the response of a specific road system to local environmental and operating conditions. Their method for modeling runoff and sediment yield from forest roads was based on combining results from simple unit hydrographs with sediment rating curves for road surface and traffic conditions. Actual rainfall records were used to generate response of the road surface to storms of different duration and intensity, resulting in predictions of excess runoff from the road segments. Simultaneously to development of the unit hydrographs they constructed sediment rating curves by sampling concentrations in runoff water. This system is an elegant approach because it relies on local rainfall data and the response of a specific road system to traffic to assess surface erosion thus generating a specific response to a particular operating environment.

Associated Work

Previous to model development a Total Maximum Daily Load (TMDL) had been established that is specific by land form and channel classes as defined in a federally approved Habitat Conservation Plan (HCP). Two years previous to code development for the RSM, the Reid and Dunne approach was selected and background work was initiated to determine the relationships between rainfall, excess runoff, and various factors for stratifying sediment rating curves.

Modeling excess runoff

Rain gauges were placed in the representative center of each of five areas defined to be geologically and topographically unique (“Lithotopo Units” or ”LTU’s”), within the study ownership. Beginning October 2002, capacitance rods were installed at culvert inlets to continuously record water depth in the inlet catch basins. During discrete storm events, the discharge of water from that road segment (catchment area) was recorded at the culvert outlet and related to water depth.

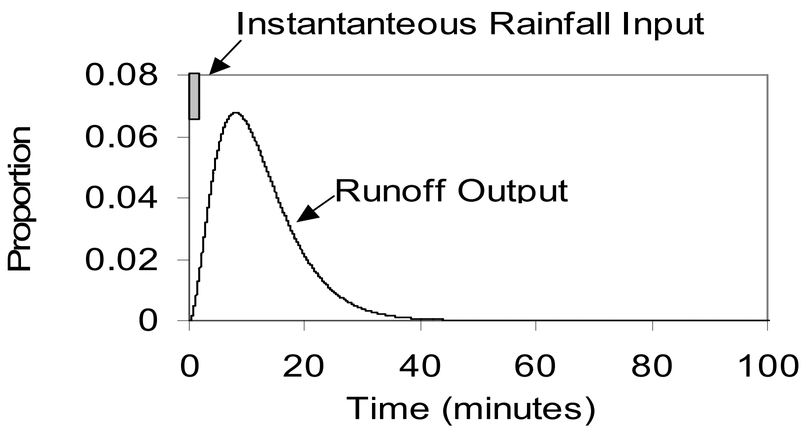


Figure 1: Instantaneous unit hydrograph. Proportion refers to the proportion of rainfall flowing from the watershed outlet at that time.

Detailed explanation of the development and parameterization of specific unit hydrographs that describe the hydrologic response of forest road segments is available in separate reports prepared for Green diamond by C. Erica Marbet.

Suspended sediment concentration

Over 450 suspended sediment samples collected between 2002 and early 2004 were processed in Green Diamond’s Dayton sediment lab according standard ASTM methods. Suspended sediment levels in these samples were highly variable ranging from more than 40 grams per liter to less than 0.01 grams per liter. The primary finding was that samples taken during times of active and heavy hauling were considerably higher than those taken during times when hauling activity had been temporarily suspended.

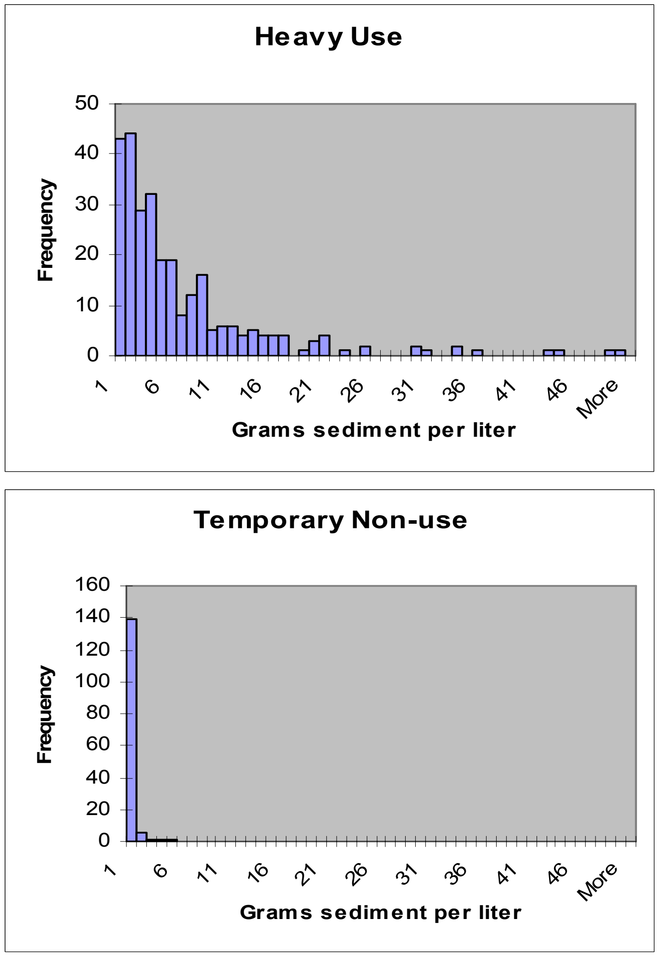


Figure 2: Frequency distribution of suspended sediment samples for heavy and temporary non-use road segments..

Based on published literature, expectations at the outset were that a rating curve could be developed relating sediment concentrations to discharge at the sample point. Conceptually this would work neatly with a scheme such as the RSM that calculates discharge at delivery points on a fine temporal scale. However, this relationship turned out to be illusive for heavy haul samples and is weak at best in data taken from temporary non-use segments. This is a result that runs counter to some published accounts and the reason may be that the sampling points in this project were all downstream of culvert catch basins and relatively short road segments. Transport of coarser particles (which add considerably to sample weight) by higher discharges may have been precluded by catch basins at culvert inlets. Similar inlet catch basins have been absent in studies for many published accounts of road surface erosion.

Sediment concentration levels in road surface runoff are not going to be easy to model but clearly there is considerable variability that can be accounted for and that is vital in helping to describe attainment of sediment load allocations for surface erosion for a particular ownership or road system. After a careful inspection of the sample analysis it was determined that the best approach at this time was to assign sediment concentrations based on sample medians for strata where data was available. Initially we were able to assign concentrations based on LTU, road type and use class for which we currently have 3 categories.

Table 6: Suspended sediment concentration values assigned various road segment strata.

AGL	Mainline	Branch	Spur
Haul	2.68	2.68	10.69
Temp. Non-haul	0.11	0.11	0.13
Non-haul	0.01	0.01	0.01

CIS	Mainline	Branch	Spur
Haul	2.68	2.68	10.69
Temp. Non-haul	0.11	0.11	0.13
Non-haul	0.01	0.01	0.01

CUP	Mainline	Branch	Spur
Haul	1.28	1.28	10.69
Temp. Non-haul	0.24	0.24	0.13
Non-haul	0.01	0.01	0.01

ROP	Mainline	Branch	Spur
Haul	2.68	2.68	10.69
Temp. Non-haul	0.11	0.11	0.13
Non-haul	0.01	0.01	0.01

SIG	Mainline	Branch	Spur
Haul	5.93	5.93	10.69
Temp. Non-haul	0.11	0.11	0.13
Non-haul	0.01	0.01	0.01

A New GIS Model

This section describes the development of the RSM. The Data Inputs section describes the conceptual model and the data inputs for the model. The requirements section further explains the requirements and the design section goes on to describe the final design and in terms of the primary components.

Data inputs

The key requirement of the RSM application was to automate the process of sediment estimation. In other words, the application must take historic and projected data for roads, rainfall and traffic and apply hydrographic and sediment data to it for automatic calculation of sediment volumes.

Early in the project, the overall objective was to use the best data available to feed into the model. For the purposes of modeling a complex spatial system such as this, the best data could be defined as being the highest temporal and spatial resolution as possible. The following sections will explain further the source and resolution of data for each of the primary inputs.

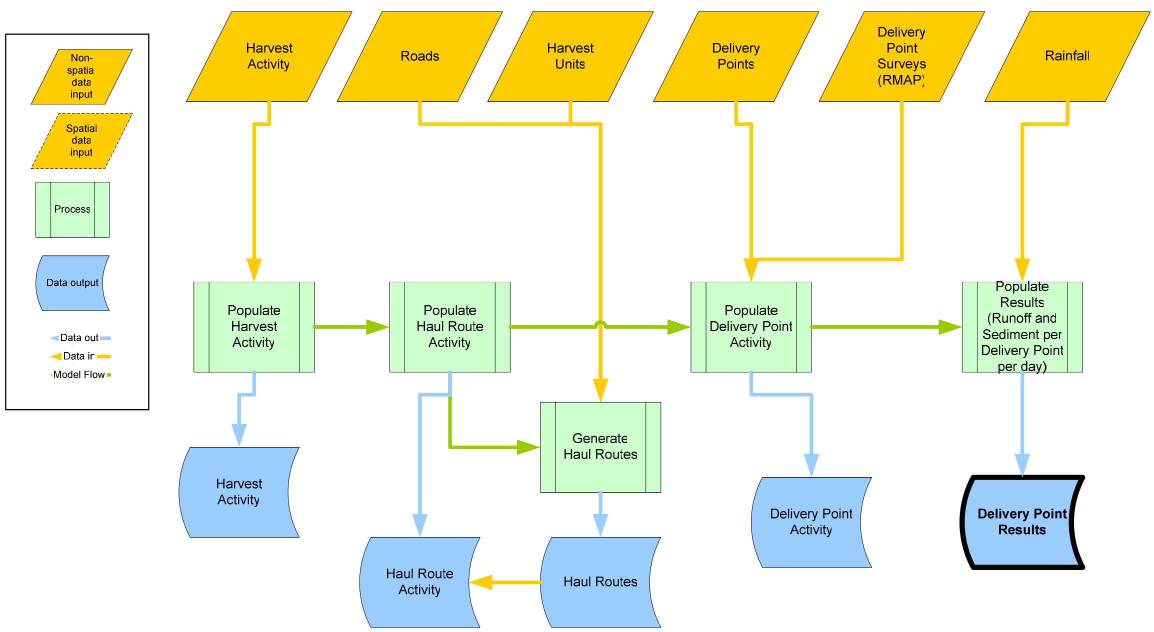


Figure 3: Data Inputs and Outputs

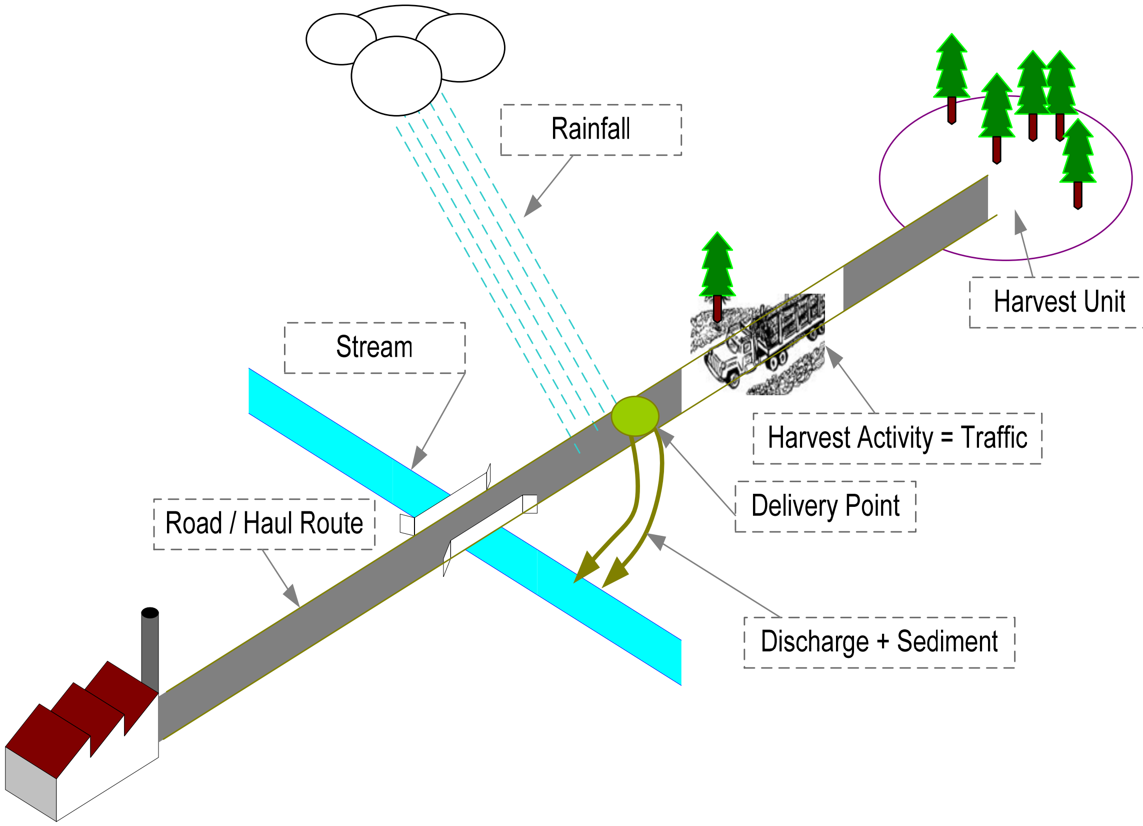


Figure 4: Conceptual Model of data inputs for the RSM

Harvest activity

This version of the RSM only explicitly examines harvest activity as an influence on traffic for the road systems. While there are certainly other types of traffic, harvest activity has the greatest impact due to the size and weight of the vehicles involved. To some extent other traffic is accounted for in the assigned sediment values as that background traffic was theoretically present during those measurements. Future versions of the RSM may include other types of traffic that are common in industrial forests.

The RSM utilizes actual harvest activity data for calculating past sediment delivery and projected harvest activity information for making future estimates. The RSM uses the harvest unit polygon layer from the GIS to determine the location of harvest activity. Non-spatial attributes include the date of harvest activity, the volume of logs transported from the unit, and the number of loads. Green diamond has two separate systems for this data. One system is used to track logs delivered to various mills. From this system we determined the volume of logs coming from each unit, and therefore the number of loads, and number of log truck trips along the haul route.

Projected harvest data comes from a similar system which is used for harvest planning.

Roads – haul aoutes

The RSM uses the vector road layer from the GIS. The road layer consists of many road segments, each with a unique id. The GIS is used to build a geometric network, which enables the use of weighted edge impedance path algorithms within the GIS software. The shortest path capability is utilized in the RSM to make an initial, automatic estimate for the haul route from each harvest unit, to the closest pavement. Users are also able to manually override the automatically generated haul routes since the automatically generated haul routes are not always the ones followed by operators. Haul routes are necessary to relate harvest activity to delivery points.

Delivery points

The RSM will access a point feature layer that represents known locations along the road network where roads periodically deliver sediment to the streams. The RSM also accesses a related database that consists of delivery point inventories, which include attributes about the length of the delivering road segment, its surface type, slope, and other attributes.

Rainfall

The RSM relies on local rain gauge data which was also used in the development of the unit hydrographs. In the present application there is a rainfall record for each terrain unit or LTU from late 2002 through present day. The unit hydrograph model requires a rainfall record at a 5 minute temporal resolution.

Requirements

Given the conceptual model and the primary data inputs as described above, the next step was to examine the requirements of the system. This section will describe the functional and non-functional requirements as developed in cooperation with Green Diamond management and user staff.

Functional requirements

Functional requirements are defined as services, tasks or functions that a system must perform. As with use-cases, it is useful to state requirements in a concise form, explicitly stating what role the system or the user is playing.

- The RSM must be able to estimate past sediment delivery quantities based on known harvest activities, recorded rainfall record, and road inventories.
- The RSM must be able to estimate future sediment delivery, based on planned harvest activities, predicted typical rainfall, and predicted road attributes (remediation work).

- The RSM will be able to save previously created “scenarios” or “runs” so that comparisons can be made between various harvest and haul scenarios.
- The RSM must be able to estimate haul routes based on a harvest unit origin and ultimate delivery location.
- The RSM must be able to store multiple haul routes for each harvest origin.
- The user will be able to edit RSM generated haul routes.
- The RSM will be able to derive the number of loads coming out of each harvest unit based on recorded harvest volumes, where load data is unavailable.
- The RSM will provide reporting that compares past and future estimates with budgets developed to comply with environmental regulations.
- The RSM must provide estimates at a daily temporal resolution in terms of cubic yards For each LTU, channel class and delivery point, as well as the percent of the annual sediment budget as defined in the TMDL.
- Allow user specified harvest units, haul routes and/or delivery points to be disabled in order to enable what if scenarios.
- Data inputs must be stored at a daily temporal resolution and m must allow for modification of data inputs for occasional cases where activity input data is incorrect, or for asking what if questions.

Non-functional requirements

Non-functional requirements are not as easily defined as either being met or not met. They are best stated and measured on a spectrum.

- Interoperability: The RSM must utilize existing data in Green Diamonds GIS and enterprise databases. Data created by the RSM must be globally shared in the company and not local to one machine. The RSM must use the same operating system, GIS Client/GIS database engine, databases, and development platforms as are currently used by Green Diamond. These platforms are Windows 2000, ESRI ArcGIS 9.0/ArcSDE, Microsoft SQL Server 2000, and Microsoft Visual Studio.NET (preferably using C#).
- Usability: The RSM will be used by forest managers and non-GIS/non-technical staff. Therefore, it must be as straightforward to use as possible. Therefore, it should be a stripped down GIS user-interface and not integrated with ESRI ArcMap, but rather a standalone application.
- Time to complete: A draft working model must be completed by the end of 2004.

Design

After defining the model requirements and data inputs we designed the RSM. The following sections explain the final functioning of the RSM in terms of the primary components.

Model run manager

The RSM generates sediment estimates by going through a multiple step process. The first step in creating sediment estimates is to create a model run, which is a persistent container in the database for data inputs and results. The model run is the parent table to all other run related tables in the database (see Appendix B). A run is defined by a temporal extent, and a specification of what channel classes to include.

Spatial preprocessor

The three primary data inputs are harvest activity, roads and rainfall. The RSM Spatial Preprocessor intersects these three inputs in a similar way for both past and future estimates. The intersection of these spatial entities is optimized by creating a logical network that relates delivery points, roads, streams, and rain gauges. The logical network is built by running a spatial intersection process periodically. This step is independent of the normal sediment estimate creation and may only be necessary when the spatial layers have changed.

Rainfall manager

The rainfall manager imports raw tipping bucket data and calculates a continuous record of rainfall intensities for 5 minute time periods. It also calculates a per unit area runoff using the unit hydrograph model we established. Earlier designs of the RSM planned to calculate discharge also as a function of road surface, slope and any other significant physical attributes, however, our initial work showed that no significant trends could be detected by road surface or slope. Therefore the same unit hydrograph model was applied to all rainfall records for all roads. A future enhancement may be to develop different unit hydrographs for different road types.

User interface

The RSM is a Windows desktop application. The interface consists of the following components: (See Appendix A for screenshots)

- a run explorer, for viewing summarized run data inputs and outputs, and navigating to other data views;
- an activity data view, for viewing and editing harvest, haul and delivery point data inputs;
- an interactive map view;
- a map table of contents for organizing map contents;
- a reporting view, for viewing and printing the sediment estimates in charts and tabular reports;

Harvest activity manager

Based on the temporal extent supplied by the user, the Harvest Activity Manager component selects harvest activity data occurring during that interval.

Haul route activity manger

The haul route activity manager first attempts to use haul routes stored in the persistent haul route library, which stores haul routes created in previously generated runs. If there is more than one route per harvest unit, then it selects the route that is marked as default. If there is no haul route available for a harvest unit, then the RSM attempts to automatically generate a route using a modified weighted edge shortest path algorithm to find the collection of road segments that represent the route from harvest unit to paved road. In some cases there may be more than one route that is used to transport logs from the harvest unit.

Delivery point activity manager

Each delivery point is associated with a receiving stream. Each stream is classified by physical response class (unique to the HCP), which is a description of the geology, slope, bedform and size of the stream. Therefore, each delivery point has a channel class, which is pre-calculated by the spatial-preprocessor. Upon definition and creation of a new run, the delivery point activity table is populated with a record for each delivery point and each day in the run interval. For each of these records, the delivery point inventory record (including the road surface and delivery length attributes) closest to the activity date is added. For each delivery point that intersects with haul route activity, the number of loads running over that delivery point is summed.

Rainfall selector

As the final step before the RSM calculates sediment volumes, the user must define what rainfall records to use. The persistent storage for rainfall is designed to store one to many records for each rain gauge. Each delivery point has a default rain gauge to which it is associated, as calculated by the spatial pre-processor as the closest rain gauge. The rainfall selector presents the user with a list of rain gauges involved in the run as defined by the delivery points. The user must then create one to many rain selection records for each rain gauge. Each rain selection record tells the RSM what rain record to use for what time period. For example: For all delivery points that are closest to rain gauge A, use the rainfall record called RainRecord102 from that records date of January 1, 2002 to June 15th 2002, and apply it to the run time interval of January 1, 2004 to June 15th 2004.

Delivery point results manager

The Delivery Point Results component incorporates the spatial and temporal data generated from the other components, and applies the sediment functions to derive a sediment concentration for each delivery point and each 5 minute time step based on the rainfall intensity, runoff volume, road type, and traffic level. Earlier designs of the RSM planned to store results at the same temporal resolution as the rainfall and runoff data, but it quickly became apparent that this would be too computationally intense to provide reasonable performance. Therefore we decided to calculate results at the 5 minute scale, but to aggregate and store results at the daily level.

Results

The draft working version of the RSM was completed on December 15th for GDR for application to their Olympic Peninsula holdings in Washington. Preliminary results for 2004 are proprietary as defined in the contract for development of the model. However, it is safe to say that operations in 2004 most likely produced sediment below the targets originally set by TMDL and HCP in 2000. Regardless of the numbers, the model worked well to evaluate fine sediment delivery to streams from the company's road system.

Further Work

Enhancements

Modules for a Harvest and Haul Activity optimizer and Relative Error Estimator are planned for the for the next version of the RSM.

Confidence estimator

The RSM should ultimately produce measures of accuracy in terms of confidence levels and confidence intervals for each of the model outputs giving the user an idea of how much confidence to place in each result.

Harvest and haul activity optimizer

The RSM should ultimately be able to run many scenarios in the background and provide the user with a solution to harvest planning and haul route selection that optimizes on delivered sediment volume.

Advanced manual haul route interface

To generate manual haul routes currently the user must select or deselect individual road segments. A highly desired enhancement would be to allow the user to define a haul route by creating a number of waypoints along the road network, and having the shortest path algorithm create a route through the waypoints.

References

Black, T. A. and C. H. Luce "Measuring Water and Sediment Discharge from a Bordered Road Plot using a Settling Basin and Tipping Bucket." Boise, Rocky Mountain Research Station. 18.

Clay, C. (2002) Technical Documentation for SEDMODL Boise Cascade Road Erosion/Delivery Model. Boise, Boise Cascade Corporation. 18.

Grace, J. M. III. (2002). "Control of sediment export from the forest road prism." Transactions of the ASAE 45(4): 1127-1132.

Greenfield, J. M. A Simple Method for Erosion and Sediment Delivery Estimation. EPA Region 4.

Grace, J. M. III, B. Rummer, et al. (1997). Sediment Production and Runoff from Forest Road Sideslopes. Minneapolis, MN, ASAE Annual International Meeting 975019: 19.

Ketcheson, G. and W. Megahan (1996). "Sediment production and downslope sediment transport from forest roads in granitic watersheds." USDA Intermountain Research Station, Research Paper: 11p.

Ketcheson, G., W. Megahan, et al. (1999). ""R1-R4" and "BOISED" sediment prediction model tests using forest roads in granitics." Journal of the American Water Resources Association 35(1): 83-98.

Luce, C. H. and T. A. Black (1999). "Sediment production from forest roads in western Oregon." Water Resources Research 35(8): 2561-2570.

Luce, C. H. and T. A. Black (2001). "Effects of traffic and ditch maintenance on forest road sediment production." Proceedings of the Seventh Federal Interagency Sedimentation Conference 2: 67-74.

Marbet, C.E. (2003) "A Unit Hydrograph Model for Runoff from Forest Roads" Simpson Resource Company Roads Project

Megahan, W.F. 1972. Logging, erosion, sedimentation: Are they dirty words? J. Forestry 70(5): 403-407.

Megahan, W. and G. Ketcheson (1996). "Predicting downslope travel of granitic sediments from forest roads in Idaho." Water Resources Bulletin 32(2): 371-382.

Megahan, W., S. Monsen, et al. (1991). "Probability of sediment yields from surface erosion on granitic roadfills in Idaho." Journal of Environmental Quality 20(1): 53-60.

Megahan, W., M. Wilson, et al. (2001). "Sediment production from granitic cutslopes on forest roads in Idaho, USA." Earth Surface Processes and Landforms 26(1): 1-11.

Peterson, N. P. and C. Bolstad (2004). Road Sediment Model Draft Model Delivery Documentation. Olympia, WA, Stillwater Sciences.

Reid, L. M. and T. Dunne (1984). "Sediment Production From Forest Road Surfaces." Water Resources Research 20(11): 1753-1761.

Savabi, M. R. (1993). "Modeling subsurface drainage and surface runoff with WEPP (water erosion prediction project)." Journal of Irrigation and Drainage Engineering 119(5): 801-814.

Sargent, Robert G. (1998) "Verification and Validation of Simulation Models" Proceedings of the 1998 Winter Simulation Conference D.J Medeiros, E.F. Watson, J.S. Carson and M.S. Manivannan, eds

Schlesinger, et al. 1979. Terminology for Model Credibility, Simulation, 32, 3, pp. 103-104.

Stefan, F. and P. Heinzelmann (2002). A modeling framework to predict relative effects of forest management strategies on coastal stream channel morphology and fish habitat. Forest Resources Management. Vancouver, University of British Columbia: 220.

Ziegler, A. D., R. A. Sutherland, et al. (2001). "Interstorm surface preparation and sediment detachment by vehicle traffic on unpaved mountain roads." Earth Surface Processes and Landforms 26(3): 235-250.

Appendix A: Screenshots

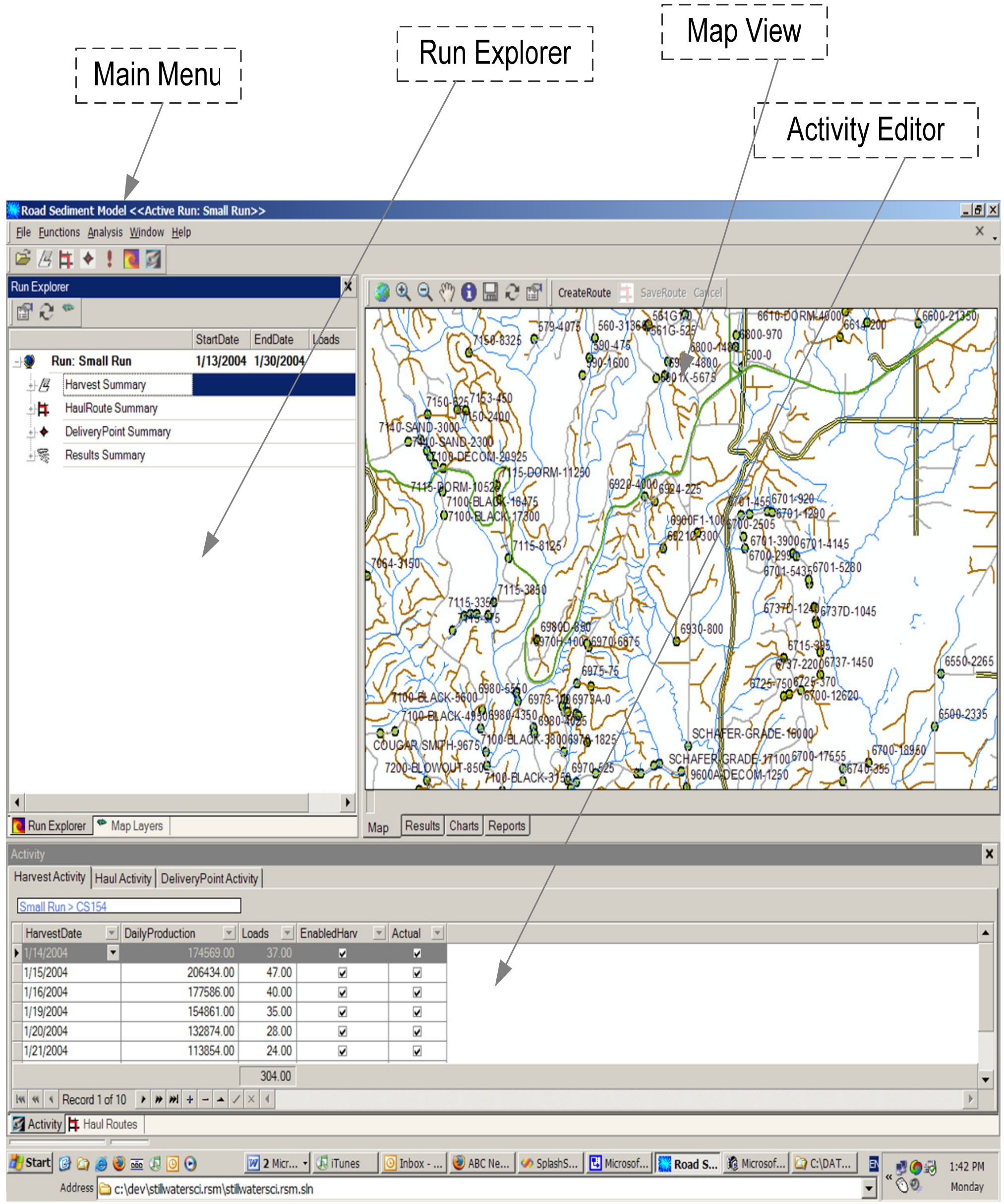


Figure 5: Overall snapshot of RSM with Run Explorer, Map View and Activity Editor showing.

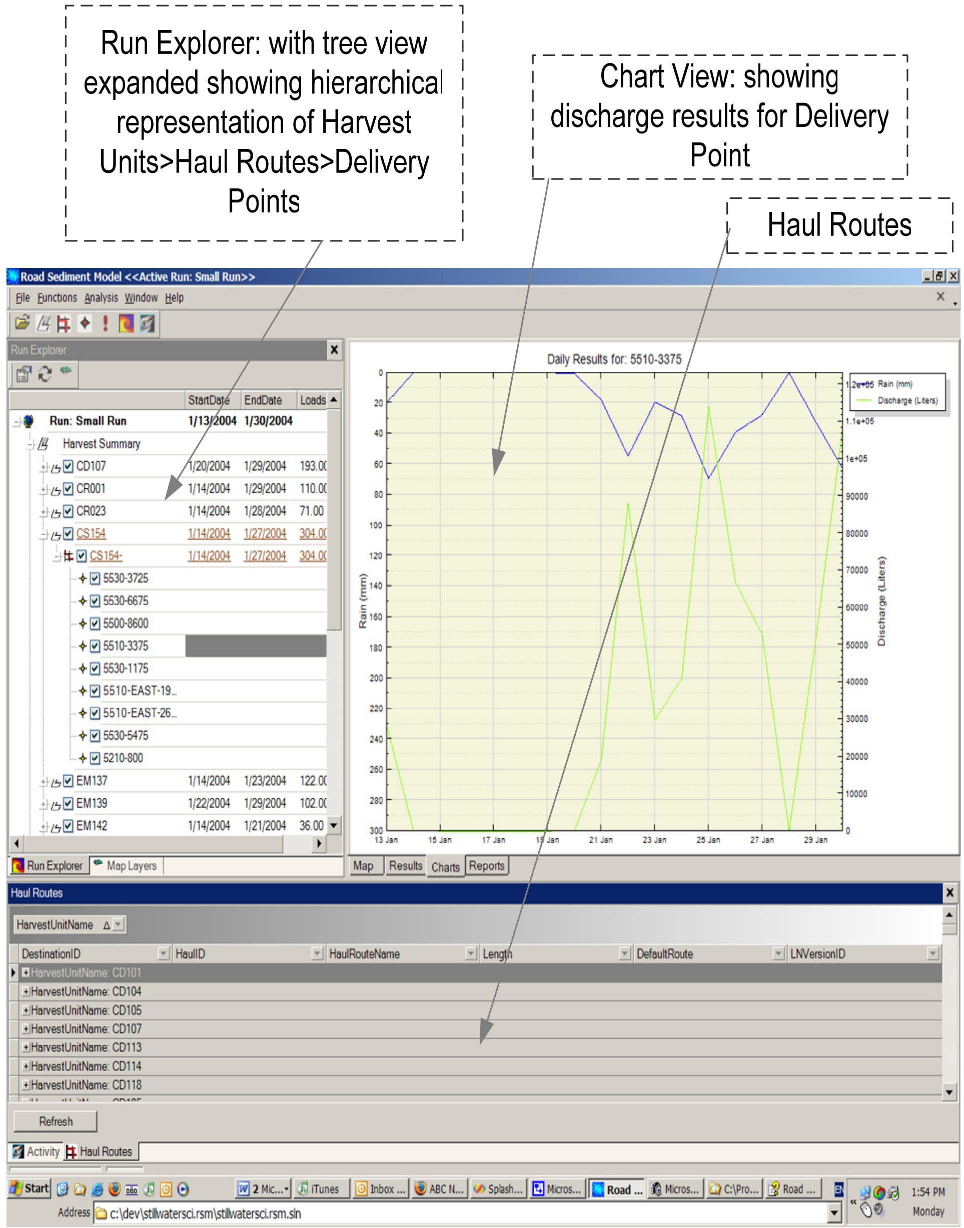


Figure 6: Overall snapshot of RSM with Run Explorer (summary nodes expanded), Chart View, and Haul Route Library.

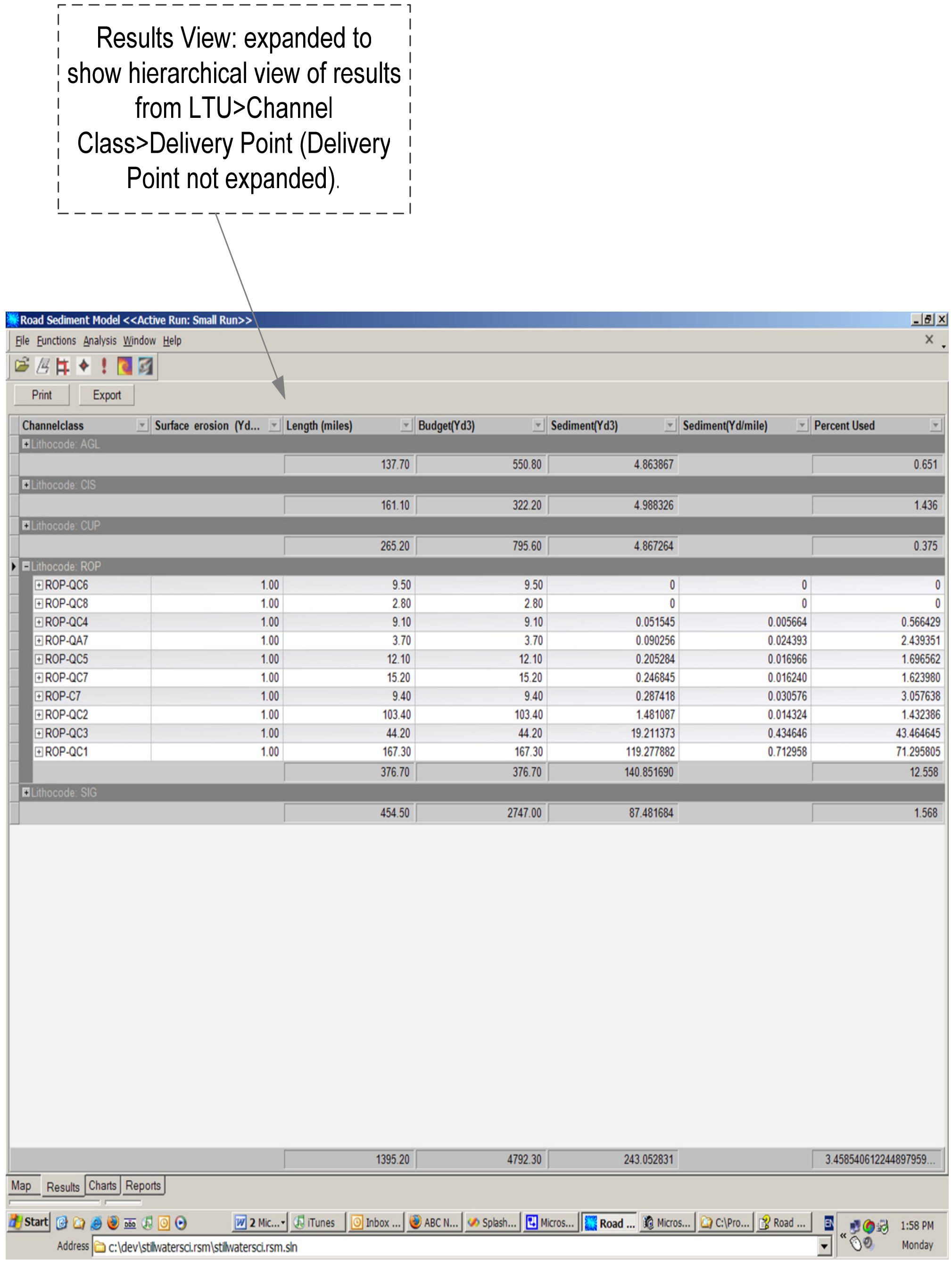


Figure7 : Close up snapshot of Results View, with results hierarchy expanded once to show channel class results within ROP LTU.

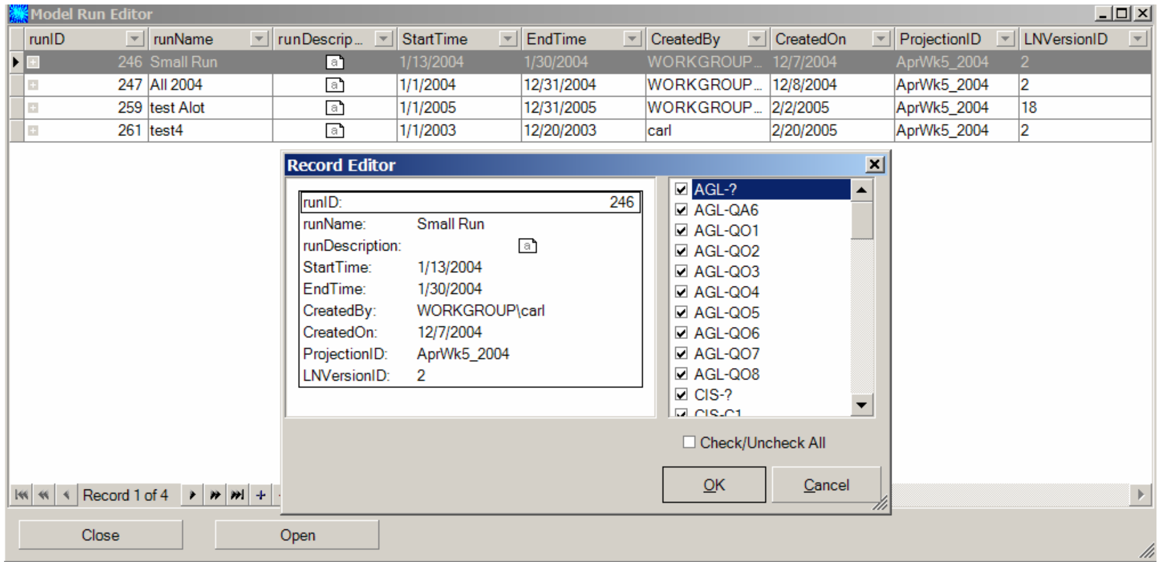


Figure 8: Close-up snapshot of Model Run Editor dialog, shows run attributes and channel class selections.

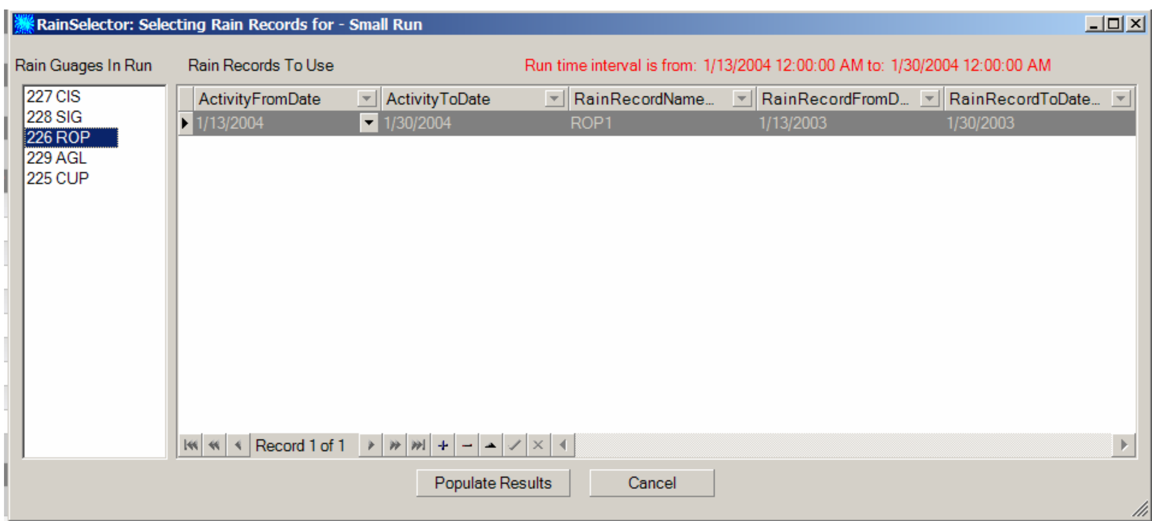


Figure 9: Close-up snapshot of Rain Selector dialog, with one rain record specified for Rain Gauge 226 ROP.

The Influence of Roads on the Hydrology of a Forested Watershed in Western Oregon

Amy Simmons[1] and Arne Skaugset III[2]

Abstract

Forest roads continue to be the focus of growing concern regarding their effect on peak flows and the delivery of chronic fine sediment in watersheds. While the effects of forest roads can be observed and quantified on the scale of an individual road segment, currently it is not possible to predict the aggregate impact of a road system on the hydrology of a watershed. The objective of this study was to determine the magnitude of surface runoff from roads in a roaded watershed.

Discharge data was collected at all road drainage culverts and the outlet of the watershed in the Oak Creek Watershed from 2002-2005. These data included peak flows for most road drainage culverts and runoff volume for a subset of culverts in the watershed. The majority of the runoff from the roads in the Oak Creek Watershed comes from a minority of the road segments. The hydrology of individual road segments can be characterized as ephemeral or intermittent. The magnitude of peak flows and the volume of runoff from the road drainage culverts are highly variable. Frequency distributions of peak flows and runoff volumes from across the watershed are extreme value distributions that are right-skewed. During the winter of 2002-2004, road runoff during storms expressed as a percent of total storm quickflow at the watershed outlet ranged from 5-25%.

Key words: peak flows, road systems, watershed hydrology

Introduction

In forested watersheds, there are many kilometers of road systems. Research results show that a hydrologic connection between streams and the road system exists and that road runoff enters streams (Wemple 1994, Toman 2004). The connectivity between streams and road systems is hypothesized to cause increases of peak flows and to deliver chronic fine sediment to streams. The impact of forest roads on

[1] Faculty Research Assistant, Department of Forest Engineering, Oregon State University, 204 Peavy Hall, Corvallis, OR 97331-5706. email: amy.simmons@oregonstate.edu

[2] Associate Professor, Department of Forest Engineering, Oregon State University, 204 Peavy Hall, Corvallis, OR 97331-5706. email: arne.skaugset@oregonstate.edu

hydrology and sediment delivery can be quantified on the scale of an individual road segment however, the cumulative effect of the road system on the hydrology and sediment yield of a complete watershed currently can not be predicted.

Concern regarding the impacts of roads on a forested watershed have prompted land managers to make decisions regarding road maintenance with little knowledge regarding how road drainage affects stream flow and sediment yield. These decisions have the potential to impact the economy in timber-producing regions by requiring potentially costly and unnecessary provisions to road and stream systems. The objective of this study was to determine the magnitude of the surface runoff from roads that might alter the hydrology of a roaded watershed.

Methods

This study was carried out in Oak Creek, an 824 hectare forested watershed in the foothills of the Oregon Coast Range in the MacDonald-Dunn Research Forest approximately 5 km west of Corvallis, Oregon (Figure 1). There are 4.6 km of road and 4.9 km of stream in the Oak Creek Watershed, which results in a drainage density of 0.64 km/km2 and a road density of 0.6 km/km2. There were 98 drainage structures on the roads in the Oak Creek Watershed during the winters of 2002 to 2005. Twenty-three of the drainage structures are stream-crossing culverts and the balance are cross-drain or drainage relief culverts.

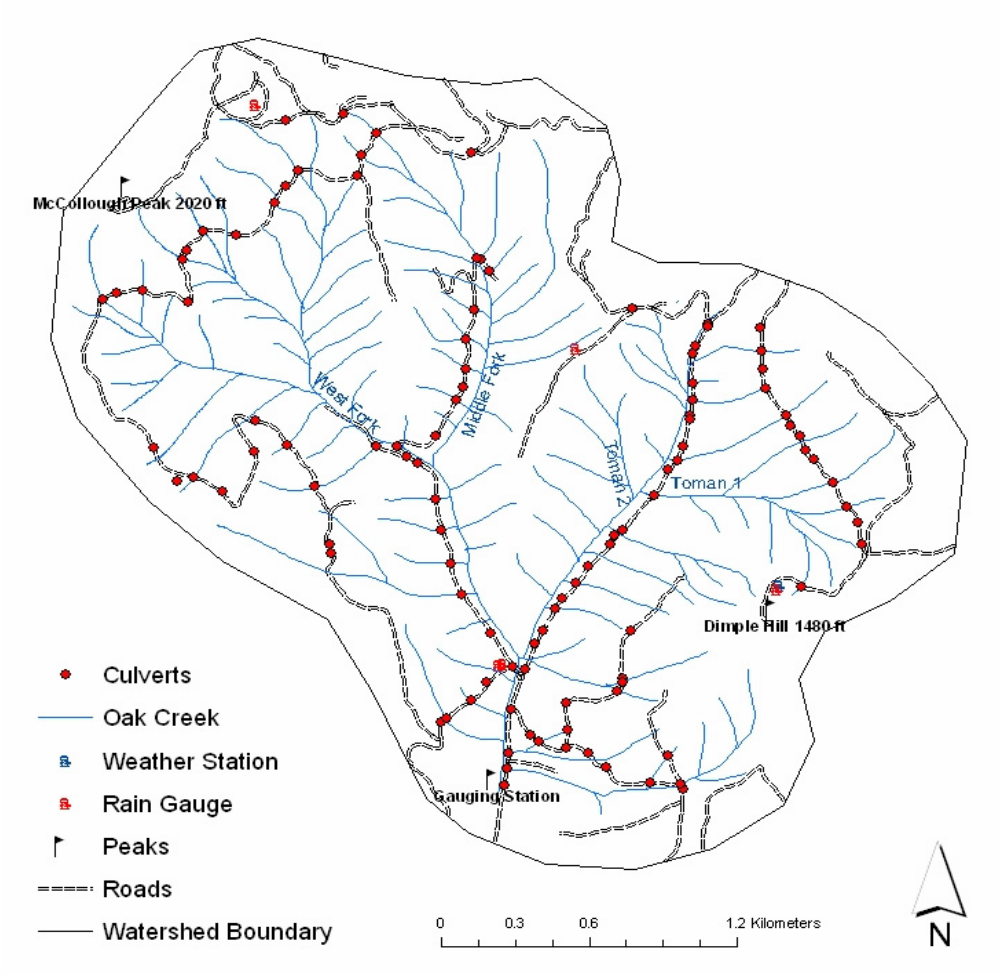


Figure 1- Map of Oak Creek Watershed located near Corvallis, Oregon.

Discharge was measured at all of the drainage structures and at the outlet of the watershed for five storms during the winter of 2002-2003 and four storms during the winter of 2003-2004 (Figure 2). Capacitance rods and crest gages were used to record water height at the drainage structures. Discharge from roadside ditches draining to stream crossing culverts was measured with trapezoidal flumes and capacitance rods. An empirical hydraulic flow equation was used to calculate discharge from the water level values collected at the inlets of the culvert (Toman 2004). Discharge at the outlet of the watershed is determined using a stage-discharge rating curve.

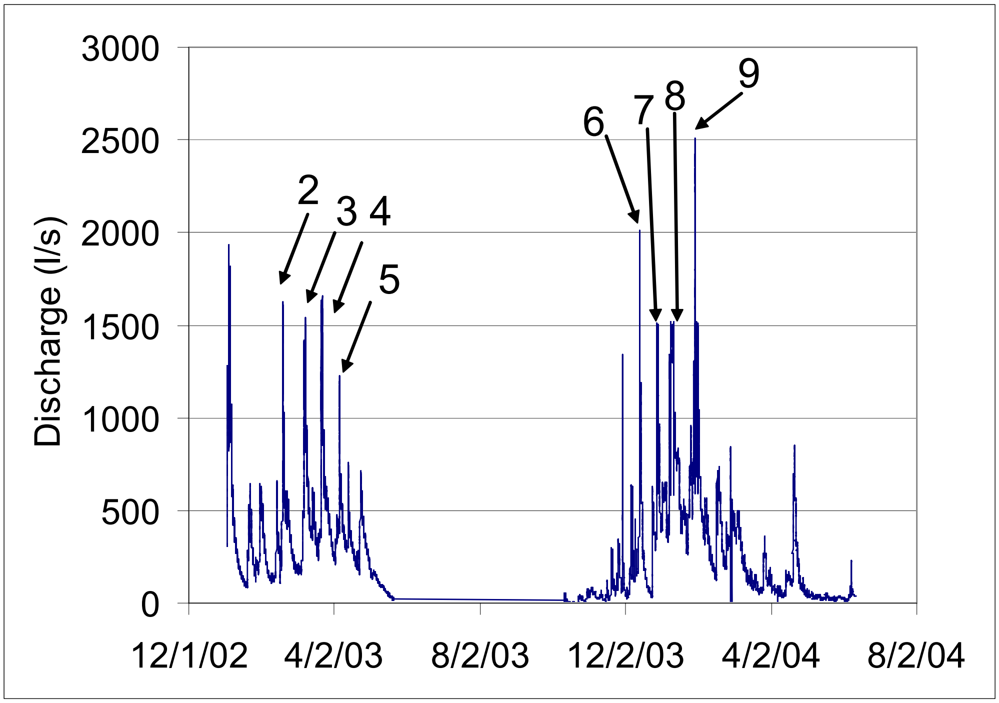


Figure 2- Discharge at the outlet of the Oak Creek Watershed. The numbered peaks, 2 through 9 correspond to storms analyzed.

For the nine storms, discharge at all cross-drain culverts, roadside ditches draining to stream crossing culverts, and the watershed outlet were separated into storm flow and delayed flow using the procedure developed by Hewlett and Hibbert (1967). Peak flows were calculated for all sites.

Results and Discussion

The hydrology observed in roadside ditches in the Oak Creek Watershed exhibits binomial behavior that has been classified as ephemeral or intermittent (Gilbert (2002), Marbet (2003), and Toman (2004)). The runoff ratio (Marbet 2003) is calculated for each storm at all cross drain culverts as a method of classifying ditch flow as ephemeral or intermittent. The runoff ratio can be used to infer the source of water contributing to ditch flow. Ditch flow classified as ephemeral most likely comes only from runoff from the road surface, while ditch flow classified as intermittent most likely comes from runoff from the road surface as well as intercepted subsurface flow.

In the Oak Creek Watershed during the winters of 2002-2004, high variability is observed in the population of peak flows at all cross drain culverts for all of the storms (n=381). The magnitude of the peak flows ranged from 0 l/s to 69 l/s. Peak flows were not recorded at all cross drains for all storms because of instrument malfunctions. Although the peak flows were highly variable, 74% of observed peak flows were less than 5 l/s.

The distribution of peak flows from cross drain culverts across the Oak Creek watershed is an extreme value distribution that is right-skewed (Figure 3). Thus, a majority of runoff from the road system comes from a minority of the road segments. This has important implications for the managers of road systems. Increased peak flows and the addition of chronic fine sediment to a stream from the road surface is an important concern in the forested watershed. The ability to identify and mitigate culverts that transmit the majority of discharge will help minimize effects of peak flow increases and sediment transport to the watershed.

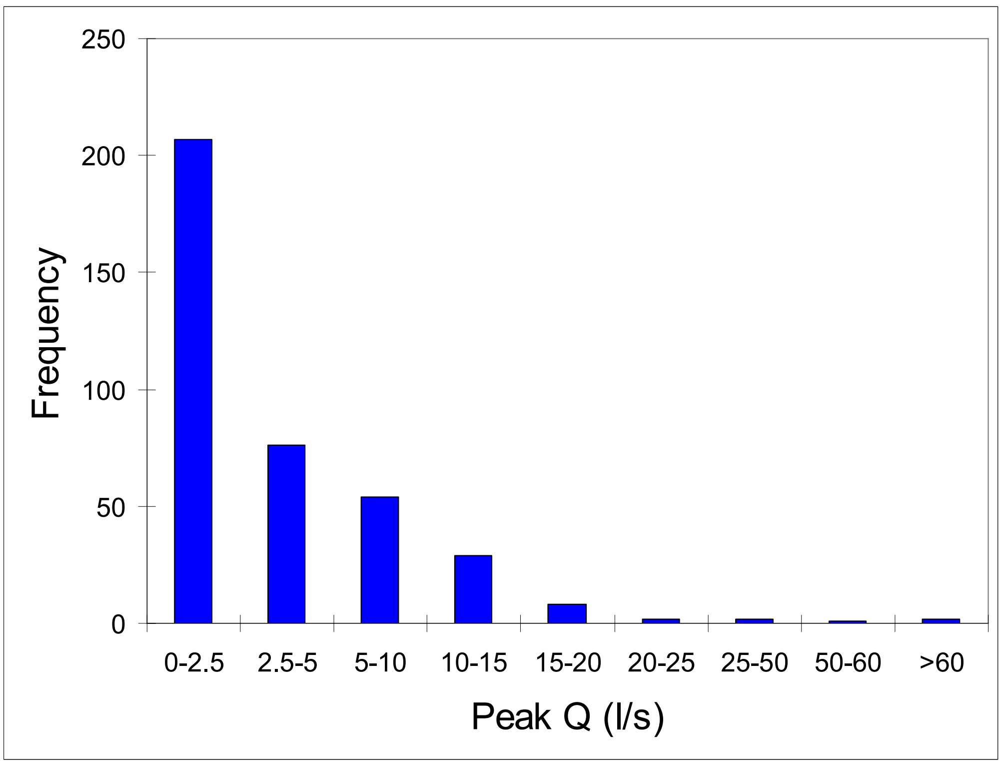


Figure 3- The frequency distribution for peak flows at the cross drain culverts for nine storms during the winters of 2002-2004.

Storm flow contributions from road surfaces at all cross drain culverts and at the watershed outlet are estimated. Road runoff generated during storms expressed as a percent of total watershed storm quickflow is estimated for each storm (Table 1) and ranges from 5 to 25%. This work continues in the Oak Creek Watershed to add more data to the relationships and provide more insight into the variability of road quickflow as a percent of the watershed quickflow from a wider cross section of storms.

Table 1- The quickflow at the watershed outlet, surface runoff from all road drainage culverts, and road runoff expressed as a per cent of watershed quickflow for eight storms in the Oak Creek watershed during 2002-2005.

Storm	Total storm quickflow from roads	Total storm quickflow at watershed outlet	Road quickflow as a percent of watershed quickflow
units	m^3	m^3	
2	27200	107060	25%
3	19804	152088	13%
4	27995	143957	19%
5	7726	56495	14%
6	11599	123620	9%
7	13721	135329	10%
8	11849	217169	5%
9	28334	186628	15%

Conclusions

During the winters of 2002 – 2004 in the Oak Creek Watershed, high variability was observed the in peak flows at the cross drain culverts. The distribution of peak flows is an extreme value distribution and is right-skewed. This means that a majority of the road runoff comes from a minority of the road segments. Identifying the road segments that contribute the largest volumes of water and potentially sediment to a watershed, is a first step that will allow land managers to minimize the impacts of roads on the watershed hydrology and sediment yield.

Management decisions are often made with little knowledge regarding how road drainage affects stream flow and sediment yield. These decisions have the potential to impact the economy in timber-producing regions by requiring potentially costly and unnecessary provisions to road and stream systems. In the Oak Creek Watershed during eight storms in 2002-2004, 5-25% of road runoff as a percent of total storm quickflow at the watershed outlet was calculated.

Continued research in the Oak Creek Watershed will increase the understanding of the influence of road systems on the hydrology of a roaded watershed. These results will provide land managers and scientists with a characterization of the hydrology and sediment yield of individual road segments and, potentially, their cumulative impact on the hydrology, which includes the magnitude and timing of peak flows, and sediment yield of storm flow at the watershed outlet.

References

Gilbert, E.H., 2002. A characterization of road hydrology in the Oregon Coast Range. M.S. Thesis, Oregon State University, Corvallis, 82 pp.

Hewlett, J.D. and Hibbert, A.R., 1967. Factors affecting the response of small watershed to precipitation in humid areas. In: W.E. Sopper and H.W. Lull (Editors), International Symposium on Forest Hydrology. Pergamon Press, NY, NY, pp. 275-290.

Marbet, C.E., 2003. Hydrology of five forest roads in the Oregon Coast Range. MS Thesis, Oregon State University, Corvallis, 94 pp.

Toman, Elizabeth M., 2004. Forest road hydrology: the influence of forest roads on stream flow at stream crossings. M.S. thesis. Forest Engineering Department, Oregon State University.

Comparison of Tabu Search and the Genetic Algorithm for Forest Road Alignment Optimization with Soil Sediment Evaluation[1]

Kazuhiro Aruga,[2] John Sessions,[3] and Edwin S. Miyata[4]

Abstract

This paper compared Tabu Search and the Genetic Algorithm for optimizing horizontal and vertical alignments of forest roads. Once a series of intersection points are manually selected, the program generates alternative horizontal and vertical alignments. The program generates ground profile and cross sections using Digital Elevation Model (DEM) and calculates earthwork volumes automatically. The program properly places and spaces drainage structures based on the Washington State Forest Practice Board Manual. Tabu Search and the Genetic Algorithm optimize forest road alignments based on the total cost of construction and maintenance. Then, the program predicts surface erosion and related sediment delivered to streams. When the horizontal alignment was fixed, the Genetic Algorithm found better solutions than Tabu Search although it took significantly longer. Tabu Search converged more rapidly to its best solution and found better solutions within less time. On the other hand, when the program simultaneously optimized horizontal and vertical alignments, Tabu Search found both better solutions and within less time than the Genetic Algorithm. Finally, we optimized horizontal and vertical alignment while limiting soil sediment to a specified maximum level. The model successfully optimized forest road alignments which reduced total road cost as well as soil sediment.

Key words: Simultaneous optimization, heuristic technique, solution quality, computational time, soil sediment

---

[1]This paper was presented at the COFE 2005: Soil, Water and Timber Management: Forest Engineering Solutions in Response to Forest Regulation. July 11-14, 2005, Fortuna, California.

[2] Kazuhiro Aruga. Utsunomiya University, Department of Forest Science, 350 Mine, Utsunomiya, Tochigi 321-8505, Japan. email:aruga@cc.utsunomiya-u.ac.jp

[3] John Sessions. Oregon State University, Department of Forest Engineering, Corvallis, OR 97331, USA. email:john.sessions@oregonstate.edu

[4] Edwin S. Miyata. University of Washington, Department of Industrial Engineering, Seattle, WA 98195, USA. email:esm@u.washington.edu

Introduction

We developed the program to simultaneously optimize horizontal and vertical alignments of forest roads based on manually selected initial alignments (Aruga et al. 2004). The program precisely generates the road prism using a high resolution Digital Elevation Model (DEM) and accurately calculates earthwork volume with the Pappus-based model (Easa 2003). The program successfully optimized the horizontal and vertical alignments simultaneously (Aruga et al. 2004). In that study, we used only Tabu Search to optimize a forest road alignment because a previous comparison of Tabu Search and the Genetic Algorithm applied to a forest road profile (vertical alignment optimization with fixed horizontal alignment) indicated that Tabu Search found a good solution in less time than the Genetic Algorithm (Aruga et al. 2005a). However, the Genetic Algorithm found slightly better solutions than Tabu Search when optimizing a forest road profile, even though it took longer. In this study, we continue to examine the relative efficiencies of Tabu Search compared to the Genetic Algorithm for solution quality and computational time for the simultaneous solution of horizontal and vertical road alignment.

Materials and Methods

Forest road design

The gradient of roads is limited by truck performance and water drainage: the maximum gradient is 18% and the minimum gradient is 2%. A vertical curve is placed to smooth out the abrupt grade change (Figure 1). A feasible curve length is determined based on Stopping Sight Distance (Mannering 1990). A simple circular horizontal curve is designed to provide a transition between two straight roadway sections (Figure 2). A feasible curve radius is determined based on stopping sight distance and the limiting speed of the vehicle around the horizontal curve. Curve widening was calculated by the off-tracking equation proposed by Cain and Langdon (1982).

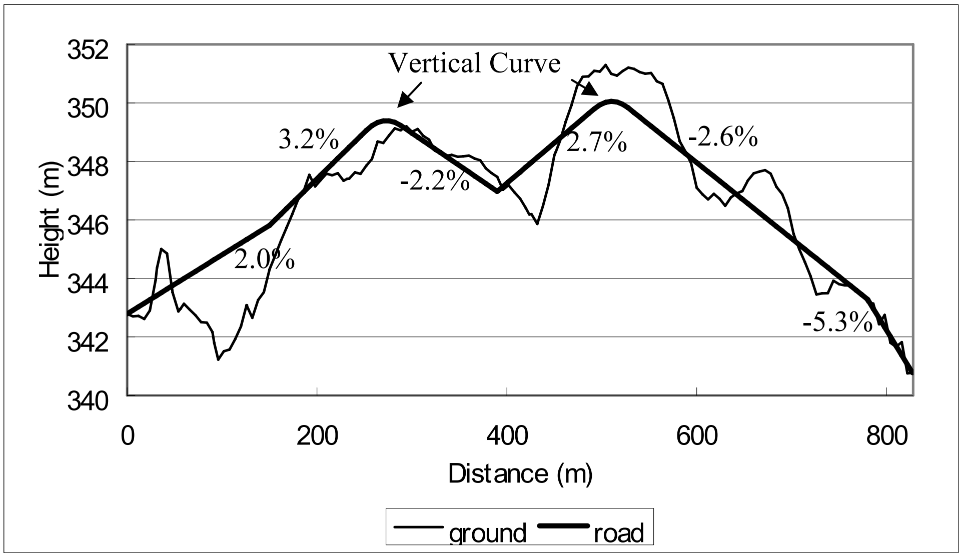


Figure 1. Forest road profile with five grade change points on the initial alignment.

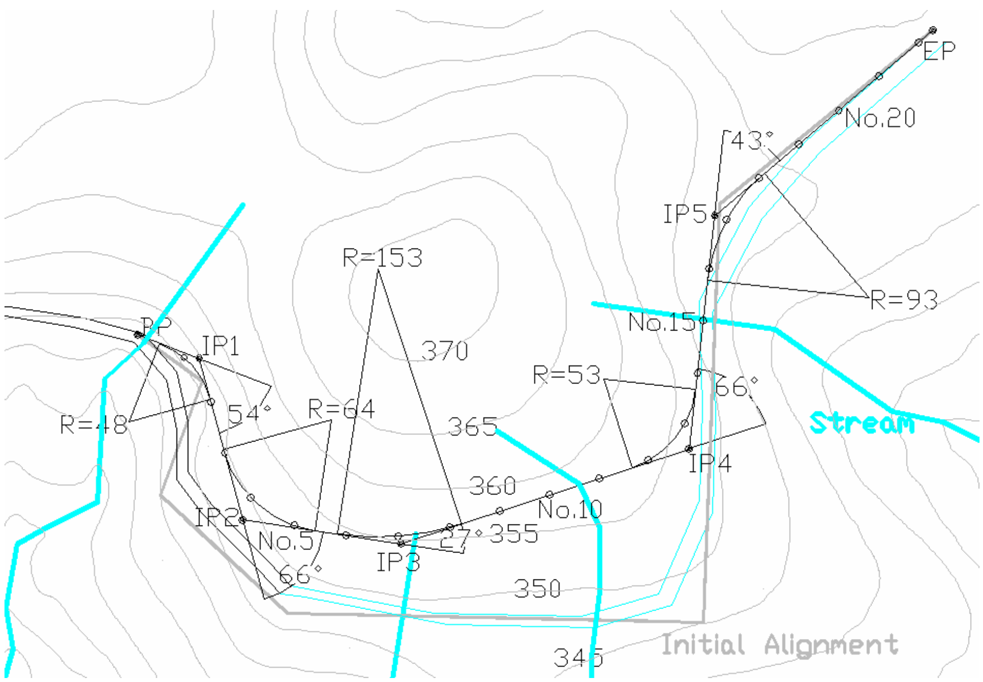


Figure 2. Forest road plane showing contour intervals, horizontal alignment, and 30-m road stations (= and = indicate an existing road and an extended road, respectively).

Cross sections are required to compute earthwork volume. In this study, the following dimensions are used to design cross sections: 4m road width, 0.8:1 cut slope, and 1:1 fill slope. The ditch relief culverts are located on the low point of vertical curves and at intervals depending on road grades based on Washington State Forest Practice Board Manual (Washington State 2001). Earthwork volume of straight roadways is computed using the average end-area method. For horizontal curve sections of the road, we use the Pappus-based method to compute earthwork volume (Easa 2003) because earthwork volume of curved roadways calculated by the average end-area method sometimes may differ from exact earthwork volume (Aruga et al. 2005b).

The total costs, including road construction and maintenance activities, are calculated using the USDA Forest Service Region 6 Cost Estimating Guide (1999). The economic distribution of cut and fill quantities is determined using the linear programming method of Mayer and Stark (1981). Finally, the program predicts surface erosion and related sediments delivered to streams based on the "Standard methodology for conducting watershed analysis" manual established by the Washington State Forest Practice Board (Washington State 1997).

Optimization of horizontal and vertical alignments

Both Tabu Search (Glover 1989) and the Genetic Algorithm (Reeves 1993) have successfully solved combinatorial optimization problems. However, those search processes are significantly different. Genetic Algorithm begins with randomly generated initial solutions and uses the mechanics of selection, crossover and mutation in which random numbers are used. On the other hand, Tabu Search is based on a gradient search and uses a Tabu list which forbids or penalizes the search for the recently visited solution to force the exploration of other areas of the solution space. Basically, random numbers are not used in Tabu Search. That is the reason why we selected Tabu Search and the Genetic Algorithm for forest road alignment optimization and compared them.

In the simultaneous optimization process, there are a number of parameters which may be either fixed or variable. For example, the locations of intersection points, the placement of grade change points, the height of grade change points, the radii of horizontal curves, and the number of intersection points and grade change points. In this study, we fixed the numbers of intersection points and grade change points manually before the analyses. In the future, the program could be extended to automatically determine an adequate numbers of intersection points and grade change points.

Tabu search

In the former study, we first generated a set of feasible solutions randomly and then the best solution was used to initiate the Tabu Search (Aruga et al. 2005a). However, solution quality of Tabu Search depends on an initial solution. Sometimes, Tabu Search could not find a good solution from the randomly generated initial solution. Therefore, we used the optimum solution with a smaller number of grade change points as an initial solution. For example, Tabu Search with four grade change points started from the optimum solution with three grade change points (Aruga et al. 2005b).

For each successive iteration of Tabu Search, a neighborhood, which is a set of new feasible solutions, is created by slightly changing the previous feasible solution. In our case, the program generates neighborhood solutions related to the location of intersection points, the heights of grade change points, and the radii of horizontal curves. Neighborhood solutions of the locations of intersections points are generated at an interval of 1-meter within 10-meter zones around manually selected intersection points. Neighborhood solutions of the heights of grade change points are generated at an interval of 1-meter within 5-meter zones around ground heights. Neighborhood solutions of the radii of horizontal curves are generated at an interval of 1 to 10 meters depending on the difference between minimum and maximum radii of horizontal curves. We also examine the placement of grade change points by selecting candidate grade change points from stations on straight roadways. Stations on curved roadways are not used as candidate grade change points because we assume that the road grade remains constant along horizontal curves. We conduct this process for 1,000 iterations.

After the best solution is found from the above procedure, the program intensifies the search in the region of the best solution. Tabu Search is again applied to the neighborhood solutions around the best solution. A neighborhood is now generated by changing vertical heights of grade change points at an interval of 0.1m within ±1 m around the selected alignment. This second search process is done while the placement of intersection points and grade change points is fixed. The objective of the second search is to refine the best solution found from the first process and provides a better solution for the final best alignment. This second search process stops after 100 iterations.

Genetic algorithm

First, we generated an initial population of 20 feasible solutions by randomly changing the locations of intersection points, the placement and the heights of grade change points, and the radii of horizontal curves. The locations of intersection points are changed within 10-meter zones around manually selected intersection points. Unlike Tabu Search process, the program used real numbers instead of integer numbers in the Genetic Algorithm process. The placements of grade change points are chosen from the stations on straight roadways. The heights of grade change points are changed within 5-meter zones around ground heights. The radii of horizontal curves are changed within minimum and maximum radii of horizontal curves. Each chromosome in the initial population is evaluated by computing the objective function value, thus each solution must be feasible with respect to the constraints.

Parent chromosomes are then selected based on fitness (the better the fitness value [objective function value], the higher the chance of it being chosen). They are then 'mated' by choosing a crossover point at random, then the crossover occurs, and two offspring chromosomes (two new solutions) result. A random mutation may then be applied to these offspring. If a random number on the range between 0 and 1 is less than the mutation probability, the current variable of a randomly chosen gene will randomly change. If offspring are feasible within these constraints, those are new chromosomes in the next generation. This process ends when 1,000 generations have passed.

Because we used randomly generated feasible solutions as an initial solution of the Genetic Algorithm, we decided to use the best of three calculations for the Genetic algorithm for the purpose of comparison with Tabu search which was started from an advanced solution.

Study site

Study site is shown in Figure 2. The elevation range is from 150 m to 400 m with ground slopes of 0% to 100%. We use a 1.52 m x 1.52 m grid DEM for forest road alignment optimization. After making DEM in 1999, new road construction was planned to extend the existing forest road in the study site. The intersection points were manually identified and the forest road design program was applied to generate an initial horizontal alignment, subject to the given geometrical design constraints (Figure 2). As a result, the total length of the extended part of the road was 827 m, which was divided into 27 of 30-meter road sections.

Results and Discussion

Optimization of vertical alignments

The model was developed with Microsoft Visual C++ under Windows XP. The program was conducted on a desktop computer which had Pentium4 2.4 GHz. We first optimized vertical alignments with the fixed horizontal alignment (Table 1). With one grade change point and two grade change points, it was practical to use complete enumeration to search for all alternatives. Neither Tabu search nor the Genetic algorithm were used for those cases. Complete enumeration found minimum costs, \$104,375/km for one grade change point and \$82,600/km for two grade change points and took about 15 seconds and 15 minutes, respectively. Then, Tabu Search and the Genetic Algorithm were used to search for the optimum vertical alignments with three to seven grade change points. Complete enumeration was not used because the calculation time was not practical. It took about 2 to 5 hours depending on the number of grade change points and generated feasible solutions during searches. Because Tabu Search was developed based on a hill-climbing procedure, Tabu Search found its best solutions quickly (within 100 iterations). An exception was the search with four grade change points which found the best solution at 400 iterations (Figure 3). This indicated that we could use a smaller number of iterations in order to reduce a computational time although solution quality was slightly reduced. Tabu Search found better solutions with larger numbers of grade change points than those with smaller numbers of grade change points. This was expected because, theoretically, the costs would be reduced as grade change points were increased.

Table 1. Costs ($/km) with different numbers of grade change points with fixed horizontal alignments (With one grade change point and two grade change points, the program searched for all alternatives).

No. grade change points	Tabu Search	Genetic Algorithm
1	104,375	104,375
2	82,600	82,600
3	80,929	72,908
4	74,727	61,922
5	75,534	60,586
6	65,821	60,041
7	60,001	60,293

On the other hand, it took 2 to 10 hours for the Genetic Algorithm to find the optimum vertical alignments with three to seven grade change points for each of the three calculations. These computational times significantly depended on the number of grade change points because the amount of time to find initial solutions increased as the number of grade change points increased. In order to find twenty initial solutions with three to seven grade change points, the program generated about 5,000, 20,000, 130,000, 800,000, and 4,000,000 infeasible solutions, respectively. In order to reduce the time to find an initial solution for the Genetic Algorithm, we should consider ways to generate feasible solutions in the future work. Chung and Sessions (2001) have used Simulated Annealing to generate initial solutions for the

Genetic Algorithm. This is expected to generate initial solutions in less time. Unlike Tabu Search, the Genetic Algorithm gradually found the optimum solution (Figure 4). This indicated that it was difficult to use fewer iterations and to shorten computational time. However, the Genetic Algorithm found better solutions using more computational time than Tabu Search except for seven grade change points. This was the similar to the former study by Aruga et al. (2005a).

Simultaneous optimization of horizontal and vertical alignments

The simultaneous optimization process of Tabu Search was able to find a better road alignment than the vertical optimization process (Table 2). It took 4 to 14 hours (Table 3). Tabu Search found the best solutions within 200 iterations which took longer than the vertical optimization process (Figure 5). However, Tabu Search still found a good solution in fewer iterations than the Genetic algorithm (Figure 6).

Table 2. Costs and lengths with different numbers of grade change points with optimized horizontal alignments (With one grade change point and two grade change points with fixed horizontal alignment, the program searched for all alternatives).

Initial solution	Fixed horizontal alignment			Horizontal alignment optimization			
		Tabu Search	Genetic Algorithm	Tabu Search		Genetic Algorithm	
No. grade change points	Length (m)	Total Cost ($)	Total Cost ($)	Length (m)	Total Cost ($)	Length (m)	Total Cost ($)
1	827	86,348	86,348	785	47,349	780	48,112
2	827	68,334	68,334	780	38,439	797	49,620
3	827	66,951	62,832	781	37,959	798	51,613
4	827	61,820	56,918	768	36,888	775	50,943
5	827	62,488	51,719	756	35,157	779	53,024
6	827	54,453	51,175	754	34,787	775	48,637
7	827	49,638	52,084	754	34,679	793	47,636

Table 3. Computing time with different numbers of grade change points

No.	Tabu Search	Genetic Algorithm
1	13 h 44 m	2 h 10 m
2	10 h 22 m	2 h 07 m
3	6 h 00 m	2 h 09 m
4	11 h 16 m	2 h 45 m
5	11 h 17 m	6 h 59 m
6	10 h 36 m	9 h 30 m
7	3 h 47 m	30 h 52 m
Total time	67 h 02 m	

The best solutions of the Genetic Algorithm with each number of grade change points were better than the results for the fixed horizontal alignment. We expected that the costs would be reduced as grade change points were increased. But, in the results using Genetic Algorithm, costs were not reduced as grade change points were increased. Sometimes, the results using the Genetic Algorithm with more grade change points were worse than those with a smaller number of grade change points or those of Tabu Search (Table 2). This was different from the former study (Aruga et al. 2005a) in the vertical alignment optimization process. According to computational time, it took 2 to 10 hours for Genetic Algorithm with one to six grade change points while it took 30 hours for Genetic Algorithm with seven grade change points because a large amount of time was required to generate twenty feasible solutions. Furthermore, it would be difficult to use fewer iterations with the Genetic Algorithm to reduce computational time because the optimum solution was found gradually (Figure 6).

Tabu Search found a better solution than the Genetic Algorithm with seven grade change points. However, Tabu Search spent a total time of 67 hours to find an optimal solution with seven grade change points, including time to find optimal solutions of smaller numbers of grade change points which were used as initial solutions (Table 3). Repeatable calculations for each number of grade change points is time consuming. Since Tabu Search found optimal solutions within 200 iterations, we could use fewer iterations, for example 200 iterations and expect a solution of reasonable quality. This could reduce computational time. In this case, computational time might be about 13.5 hours. Moreover, the process could be shortened when Tabu Search does not look at all grade change points, but a subset, ie, 1,3,5,7, etc. If this process found a good solution, Tabu Search might be more suitable for a complex problem than the Genetic Algorithm due to shorter computational time and solution quality.

Lastly, we optimized horizontal and vertical alignments considering soil sediment. In this case, we assumed that a traction surface was used on sections between the stream and the first near-stream culvert, and only pit-run was used on other sections in order to reduce soil sediment to the stream and total costs. In this analysis, we assumed that the upper acceptable limit on total sediment production delivered to streams was 0.2 tons/year. For this constraint, the model successfully optimized forest road alignment with the near-stream culverts which reduced total soil sediment delivered to streams below 0.2 tons/year. Furthermore, unit costs were almost the same and total costs were relatively smaller than that without considering soil sediment reduction (Table 4). Practically, soil sediment should be considered on a watershed basis. Future work should be combined with Geographic Information System (GIS) and will be used to consider or reduce the amount of soil sediment in a watershed.

Table 4. Costs ($/m) and total soil sediment delivered to streams (ton/year) with seven grade change points on the two optimized alignments: 1) without and 2) with a sediment constraint of 0.2 tons/year.

Element	Sub element	(1)	(2)
Staking		1.07	1.06
Clearing and Grubbing		7.68	7.60
Earthwork allocation		7.09	6.74
Surfacing	Base course	8.15	8.32
	Traction surface	2.16	2.43
Watering	Excavation	0.84	0.80
	Surfacing	2.89	2.88
Seeding and Mulching		0.67	0.66
Drainage and Riprap	Culvert	3.47	3.42
	Riprap	0.06	0.07
Maintenance		6.39	6.76
Total unit cost		40.47	40.74
Road length (m)		739	702
Total cost ($)		29,940	29,026
Total soil sediment		0.221	0.137

Conclusions

Because forest road design is a difficult task, many studies on optimization of forest roads have been done. In this paper, we compared results for simultaneous optimization of forest road alignments using Tabu Search and the Genetic Algorithm. From our previous study of vertical alignment optimization with fixed horizontal alignment, the Genetic Algorithm found better solutions than Tabu Search while Tabu Search found a good solution in less time. However, when the complexity of the problem was increased, the Genetic Algorithm could not find a better solution than Tabu Search. Although coding skill, fine-tuning of algorithms, and testing of parameters are different between the Genetic Algorithm and Tabu Search, this study indicates that our Tabu Search procedure is more suitable for forest road design than our Genetic Algorithm.

In order for the Genetic Algorithm to be more competitive, it would be necessary to develop an improved method to find initial solutions. There may be potential to do this by generating initial solutions by other methods and considering additional information such as 1) intersection points lie considering the balance between cut heights and fill heights or between cut areas and fill areas on cross sections, 2) intersection points lie so that road length is shortened.

Acknowledgements

The DEM was provided by the USDA Forest Service, PNW Research Station, Resource Management and Productivity Program. We would like to express our thanks to Mr. Steve Reutebuch, Mr. Robert McGaughey, and Dr. Ward Carson with USDA Forest Service for their willingness to provide the DEM and to help with data processing. We also express our appreciation to the Washington State Department of Natural Resources for letting us use the study site in Capitol Forest.

References

Aruga, Kazuhiro; Sessions, John; Akay, Abdullah E.; Chung, Woodam. 2004. Optimizing horizontal and vertical alignments of forest roads using a high-resolution DEM. International Mountain Logging Conference, Vancouver, British Columbia.

Aruga, Kazuhiro; Sessions, John; Akay, Abdullah E. 2005a. Heuristic techniques applied to forest road profile. Journal of Forest Research 10(2):83-92.

Aruga, Kazuhiro; Sessions, John; Akay, Abdullah E. 2005b. Application of an airborne laser scanner to forest road design with accurate earthwork volumes. Journal of Forest Research 10(2):113-123.

Cain, C.; Langdon, J.A. 1982. A guide for determining minimum road width on curves for single-lane forest roads. Engineering Field Notes, Volume 14, USDA Forest Service.

Chung, Woodam; Sessions, John. 2001. Designing a forest road network using heuristic optimization techniques. Proceedings of the Council of Forest Engineering, 21st Annual Meeting, Snowshoe, West Virginia: CD-ROM.

Easa, S.M. 2003. Estimating earthwork volumes of curved roadways: simulation model. Journal of Surveying Engineering 129(1):19-27.

Glover, F. 1989. Tabu search-Part I. ORSA J Computing 1: 190-206.

Mannering, F.L. 1990. Principles of highway engineering and traffic analysis. John Wiley & Sons, Inc, New York.

Mayer, R.; Stark, R. 1981. Earthmoving logistics. Journal of Const. Div. 107(CO2):297-312.

Reeves, C. 1993. Genetic Algorithms . In: Reeves, C. (eds)Modern heuristic techniques for combinatorial problems. Blackwell Scientific Publications, Oxford, 151-196.

USDA Forest Service. 1999. Cost Estimating Guide for Road Construction Region 6. Oregon, Portland.

Washington State Department of Natural Resources. 1997. Standard methodology for conducting watershed analysis manual, version 4.0. Olympia, Washington.

Washington State Department of Natural Resources. 2001. Forest Practice Board Manual. Olympia, Washington.

Forest Road Decommissioning Recovery Trends and Effects on Soil Characteristics at the Headwaters Forest Reserve

Peter Matzka, Matthew Bailey, Aaron Inman, and Brian Wing

Abstract

Forest restoration has become an intricate part of forest land management objectives in the recent future (Sayer 2004). A significant part of forest restoration projects along the north coast of California include the reduction of sediment inputs into nearby streams. Since forest roads are known to be a major source of sediment delivery to streams within the region, forest road removal (decommissioning) projects are of the utmost importance (Pacific Watershed Associates 2000). Forest road decommissioning projects strive to minimize the risk of future erosion problems by restoring hillside and stream channels as close to pre-road conditions as possible. Research and long-term monitoring projects have shown that road removals both reduce erosion rates and the risk of road-induced landslides (SWITALSKI ET AL 2003). To insure that the effects of road decommissioning in the Headwaters Reserve and local region are obtaining the restoration management objectives, soil and vegetation recovery trends will be measured over the first five years after treatments. It's hypothesized that the recovery trends of the soil and vegetation along the decommissioned road will become more stable with time.

Along with these measured recovery trends, possible correlations between the clegg hammer, soil penetrometer and bulk density will be identified. By creating correlations between these instruments, future road decommissioning research and monitoring projects should become more accurate. Both the clegg hammer and the penetrometer attempt to measure soil strength and compaction, thus it is believed that these two instruments will provide a correlated representation of the soils strength and compaction characteristics. More inconsistency is expected between the clegg hammer / bulk density and the penetrometer / bulk density correlations, due to the highly variable nature of soil in the region. Additionally an "observations" section will accompany this document that identifies and discusses some of the management treatment techniques observed in the field while collecting data. This section is meant to aid future road removal projects in the region and will provide the pros and cons associated with different restoration road removal treatments.

Costs and Constraints of Fuel Reduction Treatments in a Recreational Area

Jeff Halbrook[1], and Han-Sup Han[2]

Abstract

A comprehensive fuels reduction project was implemented within a highly utilized public recreation area outside Missoula, Montana to reduce the risk of catastrophic wildfire. An integrated harvest system consisting of a feller-buncher, grapple skidder, and stroke boom delimber were used to remove and process whole trees. Trees were processed into peeler logs, sawlogs, pulp logs, and hog fuel. Slash piled along the roadside was ground using a tracked horizontal grinder blowing hog fuel directly into chip vans. Elemental time and motion studies were conducted throughout the operation to record costs, productivity, delays, and limitations associated with fuel treatment within a public recreation area. Public concern over large landing areas and residual stand damage significantly impacted equipment productivity raising overall treatment costs. Skidding distances were typically long (>1000 ft) since landings were not allowed to be used within the stand. Trees were processed on narrow roads and logs were stacked between trees along the roadside. Several delays were noted where the skidder waited for the road to clear as the stroke delimber finished processing previous loads. This study provides information on innovative harvest approaches, new grinding technologies, and examines residual stand damage observed during this fuel reduction project.

Key words: costs, fuel reduction, integrated harvest, recreation, residual damage

Introduction

An increase has been seen in the population along the fringes of national forestland in the United States due in part to urban sprawl, recreational opportunities, and aesthetic ideals (U.S. General Accounting Office 1999). This area is commonly referred to as the Wildland Urban Interface (WUI). Forest management decisions directly affect these adjacent populations. Aesthetics, air quality, risks to property, ecologic effects, and economic losses are just a few concerns that need to be

---

[1] Research Forester, Department of Forest Products, University of Idaho, Moscow, Idaho 83844-1132 e-mail: halb0039@uidaho.edu (208) 885-9663

[2] Assistant Professor, Department of Forest Products, University of Idaho, Moscow, Idaho 83844-1132 e-mail: hanh@uidaho.edu (208) 885-6600

considered by forest managers (Berry and Hesseln 2004; Shindler and Reed 1996).

Western forests in the United States have become increasingly susceptible to catastrophic stand replacing wildfires. Fires which start as surface fires can quickly climb ladder fuels reaching dense canopies, often resulting in active crown fires. This is in contrast to historic forests where frequent surface fires controlled fuels and maintained an open forest canopy where heat was allowed to escape. Forests that once contained 25-35 stems per acre, now frequently hold 500 stems or more as shade tolerant species crowd the understory of the stand (Healthy Forests 2002). These forest conditions can be traced to very effective fire suppression strategies in place since the 1930's, past logging practices, and climate change (Morgan *et al.* 2003).

Prescribed fire has been used with some success in reducing ladder and surface fuels (Pollet and Omi 2002). Prescribed fire itself often does not sufficiently address the number of stems per acre or crown density issues (GFFP 2000). Prescribed burning around WUI areas also has several drawbacks. Air quality from smoke, the chance of a fire escaping, and an increased presence of wildland urban structures are just a few of the concerns associated with prescribed fire. Additionally, burning may temporarily be unsightly to some publics around recreation areas (Brunson and Reiter 1996; Scott 1996; Weldon 1996).

Mechanical fuel treatments have the potential for reducing catastrophic crown fires in dry-type ponderosa pine forests (Scott 1996; Graham *et al.* 1999; Fiedler *et al.* 2004). The effectiveness of different mechanical treatments vary with treatment prescriptions. Fiedler *et al.* (2004) modeled three widely used treatment prescriptions using the Fire and Fuels Extension (FFE) to the Forest Vegetation Simulator (FVS) model. The prescriptions favored larger diameter reserve trees and included diameter cut limits (<9 inch removal), 50% basal area removal, and a comprehensive treatment that reserved 40 to 50 ft^2/acre. The model suggested that immediately after treatment, 13%, 44%, and 90% of the stands respectively moved into the low crown fire hazard rating (Fiedler *et al.* 2004). The US Forest Service has been working with a prescription termed free thinning. Free thinning is a highly flexible prescription based on a vision of the desired residual forest. Trees are removed based on tree species, structure, spacing, and/or other requirements as a manager sees appropriate. This type of prescription allows for differing structure, composition, and diversity (Graham *et al.* 1999).

Integrated harvest systems can improve the efficiency and effectiveness of fuel reduction thinnings. Unlike cut-to-length systems, an integrated harvest system utilizes both the roundwood and biomass potential of limbs and tops. In this system, whole trees are removed and processed at a landing where roundwood logs are separated from limbs and tops. The limbs and tops are converted to hog fuel for energy by mechanically grinding or chipping. Using integrated harvest methods in WUI areas may avert air quality, risk to adjacent property, and aesthetic concerns due to burning slash.

Although effective, fuel reduction thinnings are expensive, especially on or around recreational areas in the WUI. The principles behind fuel reduction thinnings involve leaving valuable large dominant stems while removing many of the understory small diameter stems. Small diameter stems are more expensive to remove compared to larger stems due to increased cuttings needed per acre, and the value associated with these small stems (Keatley 2000). Berry and Hesseln (2004) analyzed the costs of 526 federal mechanical fuels treatment projects and found that per acre costs were around four times greater for WUI treatments. Often, the treatment costs outweigh the revenue generated by the products removed (Fiedler *et al.* 2004; Shindler and Reed 1996; Han *et al.* 2004).

Damage to residual trees left behind after thinning is a consequence of any thinning activity, and may include root abrasion and breakage, bole wounds, and broken branches and crowns. The most common injury to the bole is scarring (i.e., bark removal down to or into the cambium layer (Ostrofsky *et al*. 1986; Han and Kellogg 2000). Scars may also be gouged, thereby extending the physical damage into the wood. Damage to the remaining trees is often a concern to forest managers because it potentially results in future volume losses (Han and Kellogg 2000). In addition to this financial impact, excessive residual stand damage may cause strong negative responses from people visiting the recreational area. Residual stand damage must be minimized or avoided during fuel reduction thinning operations.

An integrated harvest system was studied to evaluate treatment costs, residual stand damage, and operational efficiencies while conducting fuel treatments in a recreation area outside Missoula, Montana.

Methods

Study area and fuel treatment

The study site encompassed 65 acres of a 119 acre fuel treatment project located 5 miles east of Missoula, Montana in the Lolo National Forest Recreation Area. The site known as the Crazy Canyon trailhead is frequently used by local residents for hiking, biking, and other recreational activities. Due to this use, constraints were placed on this fuel reduction project that would not be present during a non-recreation area treatment. Public access, aesthetics, skid trail locations, landing sites, and work schedules were just a few of these constraints. Cooperation between the forest service, the public, and the contractor allowed the project to proceed.

The integrated harvest system studied involved removing whole trees from stump to roadside where they were processed. Trees were felled using a feller-buncher with leveling cab (Timberjack 2628) equipped with a continuously rotating hotsaw. Bunches created from felling were skidded to roadside using a grapple skidder (John Deere 648E). Once at the roadside, a stroke-delimber (Daewoo DH 280) processed, decked, and sorted trees into peeler logs, sawlogs, small-diameter sawlogs, and pulp. Self-loading log trucks were used to haul these products to local mills. After harvest operations were complete, slash was ground along the roadside using a prototype tracked grinder (Vermeer HG6000TX). The grinder was assisted by a converted Timco feller-buncher used as a grapple loader. A blower attached to the outfeed conveyor on the grinder blew hog fuel directly into chip vans.

The treatment prescription was fuel reduction objective driven. This prescription therefore considered crown spacing, tree species, DBH, and ladder fuel removals in addition to treatment constraints. A free thinning approach rather than a comprehensive prescription was used to mark trees since basal area was not a determining factor for removal. Trees were marked to be cut throughout the study area during 1997, but low log market prices and a lack of contractors willing to meet the constraints of the project delayed the sale until 2004. During this delay, the marking paint faded on the trees. Though still discernable, their visibility was greatly reduced.

Plots were systematically placed throughout the study area to determine stand characteristics prior to treatment. All standing trees in these $1/10^{th}$ acre circular plots were recorded as either cut or leave trees based on marking. Diameters at breast height (DBH) were recorded for these trees as well. A diameter class distribution showing both the initial and residual stand characteristics is illustrated in Figure 1. Based on these pre-treatment measurements, there were 218 trees per acre (>4 inches) with an overall basal area of 154 ft^3. The average DBH of trees marked for removal was 10.5 inches. The treatment prescription resulted in a residual stand containing 103 trees per acre with an overall basal area of 102 ft^3. Slopes on the study site averaged 10%, but could reach 38% along draws.

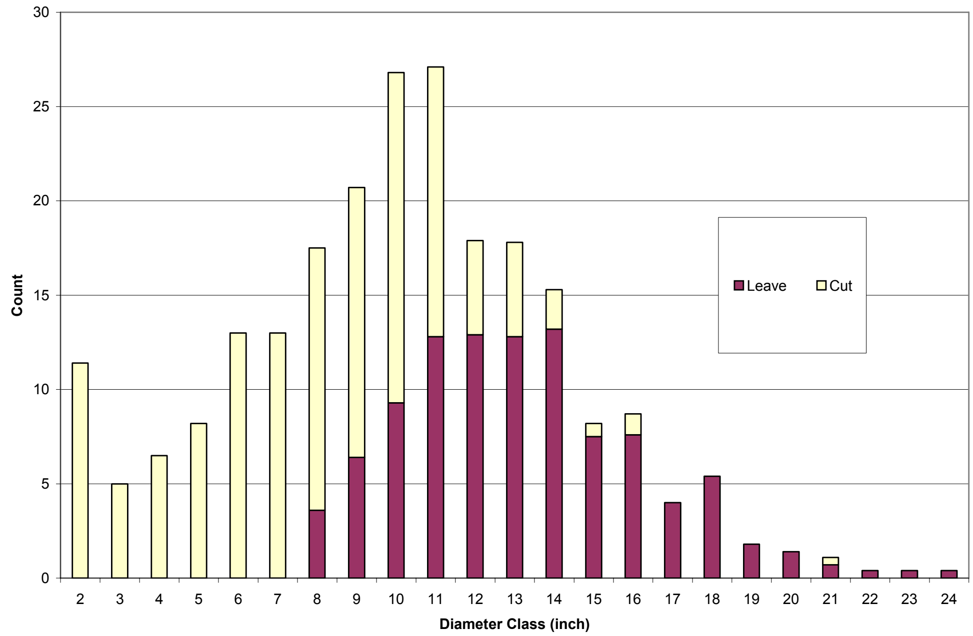


Figure 1-Estimated diameter class distribution based on marked trees

Data collection

Elemental time and motion studies were conducted on stump to deck as well as slash to loaded hog fuel operations. Individual DBH measurements were painted on standing trees and were recorded as they were felled. Travel distances for skidding were marked with ribbon every 100 feet along the roadside as well as main skid trails. Intermediate machine travel was estimated by eye. Data was manually recorded using a stopwatch in centi-minutes. Small delays (<15 minutes) were measured and categorized as operational, mechanical, personal, administrative and/or miscellaneous. Larger delays were recorded and used to assist in determining utilization rates. Scale tickets were used, in conjunction with pre-treatment stand composition information, to determine the average sawlog, pulp, and hog fuel component of the average tree removed. This information was then used to estimate hourly equipment production rates.

Recorded data were transferred to computer using the Microsoft Excel program. Stepwise regression was performed using statistical analysis software (SPSS) for each of the studied equipment to create predictive delay-free production cycle models. Independent variables were considered significant when the P-value < 0.05.

Residual stand damage data were collected from the remaining trees on 65 acres of our study site after thinning (treatment was in progress on the remaining acreage), using 33 fixed-radius plots (0.1 ac. each) that sampled 5.1% of the total area. Plots were arranged 300 ft apart in a systematic sample design with a random start. Transects were spaced at 300 ft as well. Although none of our plots were located in the center of any skid trails, 75% of the sampling plots did partially overlap them. Skid trails averaged 14.8 ft wide and were often long (>1,000 ft) because new landing construction was highly limited. The maximum off-road skidding distance was 1170 ft. The collected data included species, DBH, heights of scars from ground level, scar length and width, gouge area and depth, and distance to the nearest trail centerline. If a tree had no damage, only species was recorded.

Results

Felling

During this study, a total of 660 feller-buncher cycles were observed representing 1489 trees (Table 1). A complete cycle involved cutting and accumulating single or multiple stems and included machine travel and positioning the boom. The cycle ended when the stem(s) were placed on the ground. Productivity averaged 73 stems/scheduled machine hour (SMH), or 20.4 tons sawlogs, 1.6 tons pulp, and 5.8 tons hog fuel per SMH.

Table 1-Summary of feller-buncher cycle data

Elements	Avg.	Min.	Max.	SD	CI (+/-)
Cycle time (cmin)	1.02	0.10	4.45	0.78	0.06
Travel distance (ft)	23	0	170	31.14	2.38
# pieces	2.26	1	11	1.61	0.12

SD = standard deviation, CI = confidence interval

Regression analysis showed that a strong significance was associated with both machine travel distance and the number of stems cut when predicting delay-free cycle times. The predictive model for average felling cycle time was:

Felling (cmin) = 0.191 + 0.017*(dist) + 0.184*(#trees) + 0.269*(plots) + 0.181*(draw)

adjusted R^2 = 0.83; standard error = 0.32

where: dist = machine travel distance

pieces = number of cut trees

plots = worked adjacent to University of Montana research plots (0 or 1)

draw = worked in area where feller-buncher carried stems out of draw to reduce soil displacement from skidder (0 or 1)

Skidding

A total of 88 skidding cycles were observed throughout the study (Table 2). A complete skidding cycle involved road travel from landing to the woods, skid trail travel to bunched pile, positioning machine, grappling bunch, and travel back to the landing. A re-grappling element occurred during 19% of the skidding cycles as the operator combined two or more bunches. Productivity averaged 36 stems/SMH, or 10.1 tons sawlogs, 0.8 tons pulp, and 2.9 tons hog fuel per SMH.

Table 2-Summary of skidder cycle data

Elements	Avg.	Min.	Max.	SD	CI (+/-)
Cycle time (cmin)	9.31	5.15	19.25	2.51	0.53
Unloaded travel (ft)	1030	395	1650	307	65
Loaded travel (ft)	995	330	1700	340	71
Re-grapple dist. (ft)	9.71	0	150	24.05	5.05
Slope (%)	21	11	32	5.12	1.07
# Pieces	9.25	3	22	3.80	0.80

SD = standard deviation, CI = confidence interval

Regression analysis showed a strong delay-free cycle relationship between loaded skidtrail travel and re-grapple distances. The number of trees per bunch did not have a significant effect on delay free skidding times however. The predictive model for average skidding cycle time was:

Skidding (cmin) = 3.396 + 0.006(dist) + 0.054*(re-grapple dist) + 0.092*(slope)*

adjusted $R^2 = 0.66$; standard error = 1.46

where: dist = loaded skid trail travel distance

re-grapple dist = travel distance to re-grappled bunch

slope = % slope

Processing

During our observations, 59 skidded bunches were processed by a stroke boom delimber (Table 3). Trees were processed hot on the road after delivery by a skidder. A complete cycle involved acquiring a single unprocessed stem, delimbing, cutting one or more log combinations, and decking the products produced. Total times were recorded for processing bunches at the landing. Piling slash or adjusting logs in the deck after initial placement were considered delays. Productivity averaged 44 stems/SMH or 12.3 tons sawlogs, 1.0 tons pulp, and 3.5 tons hog fuel per SMH.

Table 3-Summary of processor cycle data

Elements	Avg.	Min.	Max.	SD	CI (+/-)
Cycle time (cmin)	6.33	1.58	13.31	2.34	0.60
# trees / bunch	9.25	3	22	3.80	0.80
# logs produced / bunch	13.08	4	26	4.70	1.20

SD = standard deviation, CI = confidence interval

Regression analysis revealed that the number of logs produced from a bunch had the greatest influence on delay-free cycle times. The predictive model for average processing cycle time was:

Processing (cmin) = 0.712 + 0.430(# logs)*

adjusted R^2 = 0.74; standard error = 1.21

where: # logs = # of logs produced per bunch

Grinding

A total of 17 chip van loads were evaluated during the study (Table 4). A prototype radio remote controlled horizontal grinder equipped with a blower attachment was used to load chip vans through the rear door. Sixty-five of the evaluated loads occurred while traveling along roadside slash piles while the remaining 35% were loaded at landing areas. A converted Timco feller-buncher equipped with a grapple loaded slash into the grinder. Productivity averaged 0.68 chip van loads per SMH or 20 tons/SMH including truck set-up and secure times.

Table 4-Summary of grinding cycle data

Elements	Avg.	Min.	Max.	SD	CI (+/-)
Cycle time (cmin)	70.08	47.30	103.50	15.56	7.40
# Grapple loads	151	113	195	18.64	8.86
Travel distance	173	0	1699	409.31	194.57

SD = standard deviation, CI = confidence interval

Regression analysis shows a strong association between travel distance and delay free cycle times. This was an important variable when moving between numerous slash piles. The number of grapple cycles needed to load a truck was included in the model, however variations between cycle volumes reduced its significance. The predictive model for grinding cycle time was:

Chip van load time (cmin) = 14.905 + 0.023(trav dist) + 0.317*(#grapple cycles)*

adjusted R^2 = 0.72; standard error = 7.24

where: trav dist = distance grinder travels throughout the loading cycle

grapple cycles = the total # of grapple cycles placed in grinder

Delay analysis

Delays were a major component of the treatment operation (Table 5). Large delays (> 15 minutes) were generally attributed to mechanical issues associated with using older equipment, and included fixing hydraulic leaks, cooling, and repairing electrical components. Several delays were noted where considerable time was spent looking for a hydraulic leak prior to it completely failing. The contractor was instructed to fix these leaks anytime oil was dripping onto the ground. Working in a recreational area also caused several smaller operational delays (< 15 minutes). We observed that each time a tree was wrapped to prevent skidder damage, cycle times increased by an average of 5.3 minutes. A lack of landing space also contributed to delays between the skidder and processor. At times, the skidder had to wait for landing space to become available while other times, longer skids caused the processor to wait for material. There was one instance where the feller-buncher was working next to a frisbee golf hole and was delayed 1.12 minutes as golfers teed off. These delays generally do not occur on non-recreation sites.

Table 5-Delays by type and duration for each machine/function

Machine/Function		Delay (%)					% of SMH
		Mech.	Oper.	Admin.	Pers.	Misc.	
Feller-buncher	(<15 min.)	3	8	1	<1	1	13.2
	(>15 min.)	36	3	1	<1	2	42.2
Skidder[a]	(<15 min.)	7	2	<1	1	<1	10.8
	(>15 min.)	0	0	0	0	0	0.0
Processor	(<15 min.)	1	22	<1	<1	<1	24.1
	(>15 min.)	36	0	0	0	0	36.5
Grinding	(<15 min.)	1	3	0	0	0	4.1
	(>15 min.)	6	21	0	0	0	27.0

[a] No major delays were noted during our observations of the skidder, however a utilization rate was used based on the contractors estimate for this project.

Detailed delay descriptions for each phase of the treatment operations were summarized as follows:

- **Felling**

Operational delays, which included cutting brush, identifying reserve trees which had been cut, and operator planning attributed 27%, 19%, and 15% respectively. Small mechanical delays included cooling hydraulics (51%), lubing machine (22%), and clearing radiators (17%). Large delays (>15 minutes) contributed 42% to the overall operation. Of these major delays, mechanical (hydraulic leaks and cooling issues) as well as operational (planning) delays attributed 64% and 27%, respectively.

- **Skidding**

Of the operational delays, wrapping leave trees to prevent damage and waiting for the processor attributed 49% and 19%, respectively. Fueling the skidder during mid-day operations attributed 98% of the mechanical delays. During the observational period, no large (> 15 minute) delays were noted.

- **Processing**

Re-piling or moving pulp logs attributed 29% to operational delays, log deck management 22%, cleaning slash off the road 21%, and waiting for the skidder 7%. Long delays (>15 minutes) contributed 37% to the overall operation. All large delays were mechanical, which included 69% electrical and 25% hydraulic (find and fix leaks).

- **Grinding**

Waiting for chip vans to arrive and widening a roadside corner attributed 67% and 31% to the operational delays, respectively. Seventy-one percent of the mechanical delays were associated with a safety switch electrical problem on the grinder. Additionally 31% of the mechanical delays involved a reoccurring blower jam that was corrected in the field by modifying the blades inside the blower.

Loading and transportation

Several products were produced from thinned material during this study. Peeler, sawlogs, and mini-sawlogs (4.5" small-end diameter) were sent to a local mill, while pulp and hog fuel went to another mill. A trucking formula is commonly used to calculate loading and hauling costs ($/ton) in the area. This formula starts with base and loading rates to which road type (gravel, paved, highway) travel mileages are added. Loading and transportation rates used for this study are shown in Table 6.

Table 6-Loading and transportation calculations

	Cost ($/green ton)					
Product	Base	Loading	Highway	Paved	Gravel	Total
Sawlogs	$2.40	$2.50	$0.00	$0.60	$1.14	$6.64
Pulp	$2.40	$2.50	$1.53	$0.28	$1.14	$7.85
Hog Fuel	$2.40	$1.50	$1.53	$0.28	$1.14	$6.85

Note: Hog fuel and pulp distances include 17 highway miles, 2.3 paved miles, and 6 gravel miles. Sawlog distances include 5 paved miles and 6 gravel miles.

Treatment costs and revenues

Hourly machine rates (Table 7) were developed using established methods and procedures for estimating owning and operating costs (Miyata 1980). Profit and risk assumptions were not included in this analysis. The low fixed costs associated with each piece of equipment (except the grinder which was new) reflected used equipment prices. The use of new equipment would raise fixed costs, but would likely increase the production rates as well. Assumptions used for these calculations include a salvage value of 20%, annual interest insurance and taxes 15%, repair and maintenance 150% of annual depreciation, and a scheduled machine working rate of 1700 hours per year. Machine lives were estimated at three-years each for the feller-buncher, skidder, and processor, 2 years for the converted loader, and 5 years for the new grinder. The labor rate used ($18.80/hr including 40% benefits) was based on the contractor's estimates for Missoula, Montana.

Table 7-Costs for individual treatment elements

Machine/ Function	Current market value ($)	Machine rate ($/SMH)	Costs ($/green ton)		
			Sawlog	Pulp	Hog fuel
Feller-buncher	70,000	63	2.27	2.27	2.27
Skidder	50,000	49	3.55	3.55	3.55
Processor	70,000	65	3.87	3.87	N/A
Loader (slash)	35,000	56	N/A	N/A	2.80
Grinder	450,000	167	N/A	N/A	8.35
Move in costs (per ton)	-	-	0.16	0.16	0.55
Loading & hauling	-	-	6.64	7.85	6.85
Total ($/green ton)	-	-	16.48	17.70	24.37

Sawlogs comprised 73% of the overall thinned material removed during this fuel treatment with pulp and hog fuel contributing an additional 6% and 21% respectively. Gross revenues ($/green ton delivered) for these products were calculated at $56 (sawlogs), $26 (pulp), and $14.50 (hog fuel). Overall treatment operations should result in a positive net revenue due to a high component of sawlogs. As seen in Table 7 however, the cost to produce hog fuel was higher than the selling price delivered. Potential per acre treatment calculations are included in Table 8 though additional costs need to be considered, which are not included in this analysis.

Table 8-Potential revenues

	Sawlog	Pulp	Hog fuel
Calculated tons/acre	32.2	2.49	9.2
Treatment costs[a] ($/acre)	531	44	224
Gross revenue ($/acre)	1803	65	133
Net revenue[a] ($/acre)	1272	21	(91)

[a]Additional costs need to be included such as road improvement, dust and weed abatement, erosion control, profit, risk, administration, as well as others not included in this analysis.

Damage to residual trees

A total of 270 trees were sampled, representing a stand composition of 45.9% ponderosa pine (n = 110), 53.7% Douglas-fir (n = 129), and 0.4% larch (n = 1) during the residual stand damage survey. After thinning, 82 stems per acre were left. The breakdown of damage by species was 47% for ponderosa pines, and 53% for Douglas-fir. In all, 30 (scarring = 26; root damage = 4) of our sampled trees (11%) showed damage if any size of scars is considered as damage. The size distribution of scarring damage found in the stand is shown in Figure 2. There was only 6.7% residual stand damage if we count scars larger than 4 in. in width plus all root damage. Root damage occurred along skid trails as a result of repeated machinery passes and accounted for 15% of the total damage. On average, 70% of the damage on a tree occurred within 3 ft of ground level. The majority of the damage (66.7%) also occurred within 10 ft of the skid trail centerline. Gouging was present in 31% (n = 8) of all scars. We observed that thick bark and summer (instead of spring) logging in addition to wrapping conveyor belts around trees that had a high likelihood of skidder damage helped minimize scarring damage.

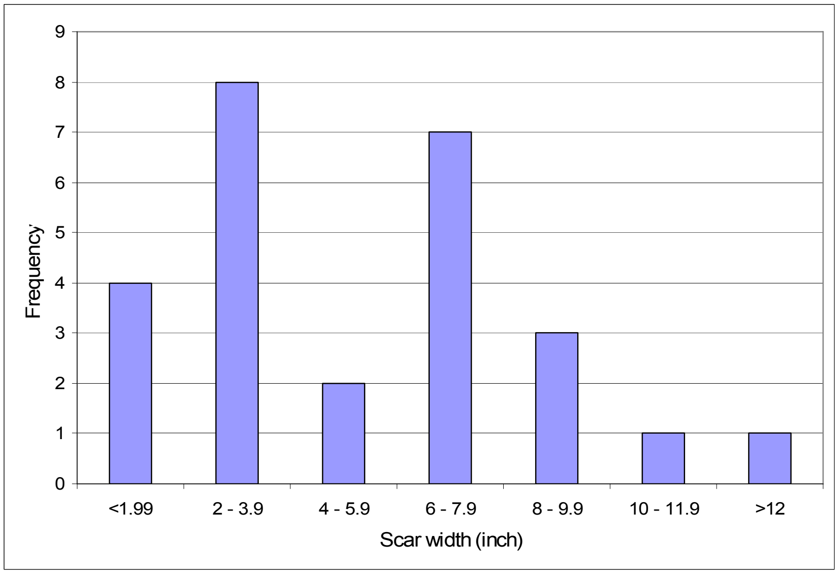


Figure 2-Frequency of scars in each scar width category

Conclusion

Fuel reduction treatments in recreational areas offer many challenges. Aesthetics, air quality, and financial considerations are important factors to consider. This integrated fuels treatment project addressed these concerns through innovative fuel treatment methods and technologies.

Landing space was highly limited in order to minimize impacts to soils and visual quality across the recreation area. Felling and skidding were carefully performed to reduce damage to residual trees. Slash created from the treatment was piled along the roadside and ground into hog fuel to avoid burning.

Treatment costs were high due to long skidding distances, delays associated with limited landing areas, and protective measures used to reduce residual stand damage. Additionally, high repair and maintenance delays associated with using older equipment decreased the machines utilization rate, which reduced production rates. A wide variety of products were produced to limit the amount of slash created from thinning (sawlogs, pulp wood, and hog fuel). Hog fuel production resulted in a net loss due to high grinding and transportation costs, and low market values. Grinding this slash did however have non-monetary values since air quality and visual aesthetics were preserved by not burning slash on site. A high sawlog component helped offset the treatment costs for this project.

The level of residual stand damage found on our research site is considered minor, with the majority of injuries being concentrated within 10 ft of the skid trail centerline, as well as along the first 3 ft of the bole up from ground level. Scarring was minor: 46% of scars were less than 4 inches in width. Low level of damage was partially due to summer logging, using protective wrapping on trees prior to skidding, and thick-barked species (ponderosa pine and Douglas-fir) that dominated the stand.

References

Berry, A.H. and H. Hesseln. 2004. The Effect of the Wildland Urban Interface on Prescribed Burning Costs in the Pacific Northwestern United States. Journal of Forestry 102(6): 33-37.

Brunson, M.W., and D.K. Reiter. 1996. Effects of Ecological Information on Judgments about Scenic Impacts of Timber Harvest. Journal of Environmental Management 46:31-41

Fiedler, C.E.; C.E. Keegan, III; C.W. Woodall; T.A. Morgan. 2004. A strategic assessment of crown fire hazard in Montana: potential effectivness and costs of hazard reduction treatments. Gen. Tech. Rep. PNW-GTR-622. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. 48 p.

Graham, R.T.; A.E. Harvey; T.B. Jain; J.R. Tonn. 1999. The effects of thinning and similar stand treatments on fire behavior in Western forests. Gen. Tech. Rep. PNW-GTR-63. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. 27 p.

GFFP 2000. Grand Canyon Forests Partnership. Flagstaff Area Fire Risk Assessment: A collaborative effort in cooperation with the Ponderosa Fire Advisory Council.

Han, H.-S., L.D. Kellogg, G.M. Filip, T.D. Brown. 2000. Scar closure and future timber value losses from thinning damage in western Oregon. Forest Products Journal 50(1):36-42.

Han, H.-S.; H.W. Lee; L.R. Johnson. 2004. Economic feasibility of an integrated harvesting system for small-diameter trees in southwest Idaho. Forest Products Journal 54(2): 21-27.

Healthy Forests 2002. Healthy Forests: An Initiative for Wildfire Prevention and Stronger Communities. As viewed and accessed October 27th 2002 on the World Wide Web at www.whitehouse.gov/infocus/healthyforests/Healthy_Forests_v2.pdf

Keatley, T.A. 2000. Harvesting Options in Small Diameter Stands Operating on Gentle Slopes. Unpublished M.S. Thesis. University of Idaho. Moscow.

Morgan, P., G.E. Defosse, and N.F. Rodriguez. 2003. Management implications of fire and climate changes in the western Americas. Chap. 15 in T.T. Veblen, W.L. Baker, G. Montenegro, and T.W. Swetnam. Fire and climatic change in temperate ecosystems of the western Americas. Ecological Studies 160. Springer. p. 413-440.

Ostrofsky, W.D., Seymour, R.S., Lemin, R.C., Jr., 1986. Damage to northern hardwoods from thinning using whole-tree harvesting technology. Can. J. For. Res. 16, 1238-1244.

Pollet, J., and P. Omi. 2002. Effect of thinning and prescribed burning on crown fire severity in ponderosa pine forests. Int. Journal of Wildland Fire 11(1): 1-10

Scott, J.H. 1996. Restoring recreational and residential forests. In: Hardy, Colin C.; Arno, Stephen F., eds. 1996. The use of fire in forest restoration: a general session at the meeting of the Society for Ecological Restoration. Gen. Tech. Rep. INT-GRT-341. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Research Station: 44-48.

Shindler, B., and M. Reed. 1996. Forest Management in the Blue Mountains: Public perspectives on prescribed fire and mechanical thinning. Corvallis, OR: Department of Forest Resources, Oregon State University. 57 p.

U.S. General Accounting Office. 1999. Western National Forests: a cohesive strategy is needed to address catastrophic wildfire threats. GAO/RCED-99-65, April 1999. A report to the Subcommittee on Forests and Forest Health, Committee on Resources, House of Representatives, U.S. Congress. 64 p.

Weldon, L. 1996. Dealing with public concerns in restoring fire to the forest. In: Hardy, Colin C.; Arno, Stephen F., eds. 1996. The use of fire in forest restoration: a general session at the meeting of the Society for Ecological Restoration. Gen. Tech. Rep. INT-GRT-341. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Research Station: 56-58.

Soil Disturbance from an Integrated Mechanical Forest Fuel Reduction Operation in Southwest Oregon[1]

M. Chad Bolding, Loren D. Kellogg, and Chad T. Davis[2]

Abstract

Most mechanical fuel reduction treatments are performed with existing or modified conventional logging equipment. These operations that harvest small, non-merchantable trees are often integrated into commercial thinning prescriptions. Little literature has quantified harvesting system effectiveness or soil disturbance concerns from such operations. This paper reports results of soil disturbance generated from an integrated forest harvesting/mechanical forest fuel reduction operation in southwest Oregon. The study was conducted in a fuel reduction thinning on a 20-acre mixed conifer stand on gentle terrain. A tracked, swing-boom feller-buncher and two rubber-tired, grapple skidders were used for felling and timber extraction. Soil characteristics were recorded pre and post treatment using both visual classification and soil strength measurements. The difference between pre and post treatment measurements determined the level of soil disturbance generated from the harvesting machines. Biological significance was based on an a priori soil strength threshold of 3000 kilopascals (kPa). Results indicate that the operation did not contribute to either statistically or biologically significant soil disturbance effects. This investigation will aid forest managers in decision making concerning expected soil disturbance generated from conventional ground-based harvesting systems on gentle terrain when employed in a fuels reduction operation.

Key words: compaction, fuel reduction, mechanical harvesting, soil strength

---

[1] This paper was presented at the 28th Annual Council on Forest Engineering Meeting, July 11-14, 2005, Fortuna, California.

[2] The authors are, respectively, Graduate Research Assistant, Professor, and Faculty Research Assistant; Department of Forest Engineering, College of Forestry, Oregon State University; 204 Peavy Hall, Corvallis, OR 97331. Email: m.chad.bolding@oregonstate.edu, loren.kellogg@oregonstate.edu, and chad.davis@oregonstate.edu

Introduction

Currently, there is a lack of information concerning mechanical forest fuel reduction systems that are integrated with commercial logging operations. Little literature is available to quantify harvesting system and silvicultural treatment effectiveness as well as residual tree and soil disturbance concerns (McIver et al. 2003). This information deficiency makes it difficult for forest managers to make sound decisions toward employing mechanical fuel reduction treatments. The additional travel required by forest machines to harvest non-merchantable trees in fuel reduction applications can contribute to increased soil disturbance; although, this assumption has not been quantified. Studies are necessary to determine the level of soil disturbance that can be expected from integrated harvesting systems. Regulatory standards established to limit the amount of area disturbed and compacted also lack this information.

This paper reports the results of soil disturbance generated from an integrated forest harvesting/mechanical forest fuel reduction operation on a 20-acre mixed conifer stand in southwest Oregon. The study attempted to detect changes in soil strength measured in kilopascals (kPa) at depths from 25-400 mm below the soil surface. The specific research questions addressed were as follows: 1) Does the use of an integrated forest harvesting/mechanical fuels reduction operation with conventional ground-based equipment on the 20-acre stand contribute to statistically and/or biologically significant changes in soil strength at various depths below the soil surface?, and 2) Are changes in soil strength related to visual soil disturbance?

Biological significance

Forest stands with long histories of intensive management tend to be characterized by numerous entries of mechanized timber harvesting systems. These entries cause the soil of many stands to become compacted to a level that inhibits future tree growth. It is unclear as to what level of compaction will consistently be detrimental to future tree growth (Landsberg et al. 2003, Miller and Anderson 2002). This value varies with tree species, soil type, and moisture. The USDA Forest Service has established a criterion based on increases in bulk density and other disturbance variables (USFS 1998). They have regulated harvesting activities to a threshold that must not exceed a 20% increase in bulk density on more than 20% of the area. Other scientists and agencies use soil strength as an indicator of detrimental compaction. It appears to be generally accepted, that for any site type, soil strength values of 3000 kilopascals (kPa) may produce a reduction in tree growth and site productivity (Powers et al. 1998, Powers and Avers 1995). The optimum approach for determining compaction effects on forested stands is to monitor tree growth as a means of "validating" predictions based on increases in soil strength or bulk density (Miller and Anderson 2002). For this study, based on the available literature and conversations with other scientists, we have a priori determined that soil strength values of 3000 kPa or greater will have a biologically meaningful effect on future site productivity.

Methods

Study site and prescription

This study was conducted in a fuel reduction thinning of a 20-acre mixed conifer stand on gentle terrain with average slopes of 12% (min 5%, max 17%) (no replication of study sites or harvesting treatments was used). The study area is located in southwest Oregon approximately 45 miles northeast of Medford and 45 miles southwest of Crater Lake National Park. Tree species consisted predominately of Douglas-fir (*Pseudotsuga menziesii*), white fir (*Abies concolor*), and incense-cedar (*Calocedrus decurrens*). The site was chosen by the landowner who was interested in gaining more information on how current mechanical fuel reduction operations affect soil strength characteristics and visual disturbance in mixed conifer forests within his ownership. Terrain, soil, and stand characteristics were considered to approximately represent other areas within the ownership. Soils in the area are well drained and are characterized as Dumont – Coyata gravelly loams (NRCS 1993).

The stand consisted of approximately 680 trees per acre with a quadratic mean diameter of 6.3-in. The unit was thinned with a 20-ft by 20-ft spacing between residual trees. Leave trees were those greater than or equal to 5-inches in diameter at 17-ft of height (approximately 7.5 inches DBH). These specifications also describe merchantable trees. Small trees greater than 3-in but less than 7.5-in DBH were considered non-merchantable. These trees were harvested and transported to landings to meet forest fuel reduction objectives. No trees less than 3-in DBH were intentionally harvested.

Experimental design and data collection

A tracked, swing-boom feller-buncher and two rubber-tired, grapple skidders were used for felling and timber extraction. Soil strength was measured pre (control) and post (response) harvest using a Rimik CP20 recording soil penetrometer. Visual soil disturbance was also measured pre and post harvest and recorded as one of twelve codes (Table 1). Pre (July) and post (September) harvest measurements were conducted during the 2004 field season to ensure that soil moisture levels were compatible.

Table 1. — Visual soil disturbance codes used during data collection. Adapted from McMahon (1995).

DISTURBANCE TYPE	CODE
Undisturbed	
No evidence of machine or log passage, litter and understory intact	1
Shallow Disturbance	
Litter still in place, evidence of minor disruption	2
Litter removed, topsoil exposed	3
Litter and topsoil mixed	4
Evidence of tire, track, or log passage (imprint < 4 inches deep)	5
Deep Disturbance	
Topsoil removed, mineral soil exposed	6
Erosion feature (rill, gully, etc.)	7
Rutted, evidence of tire, track, or log passage	
4-8 inches deep	8
> 8 inches deep	9
Clarifiers	
Skid trail	10
Haul road	11
Non-soil (stumps, rocks)	12

Within the 20-acre study site, 15 plot centers were identified from a systematic grid of the area (3-chains x 3-chains). This approach was used to establish a representative sample of the entire area. At each of the 15 plot centers, 2 random transect directions were established using a random number generator. Possible azimuths ranged from 20-360° in 20° intervals, yielding 18 possible directions. On each transect, using the point transect method (McMahon 1995), 3 soil strength profiles and 3 visual disturbance observations were recorded at 10, 20, and 30-ft from plot center in a random azimuth direction. The study yielded 87 soil strength profiles pre-treatment and 89 post-treatment or approximately 4.5 per acre. For each profile, the soil penetrometer recorded soil strength (kPa) at depth intervals of 25 mm from 25-400 mm below the soil surface. Each profile contained a total of 16 soil strength measurements. The above methods and plot locations were used both prior to any harvesting activity and after harvesting concluded. Transect directions were located randomly for both pre and post treatment measurements; therefore, sampling points were not in the same location, in most cases. Sources of variation within the data include profile to profile variation (87 units pre-treatment and 89 post-treatment), depth to depth variation (4 units), and visual disturbance class*time variation (5 units). Units of variation reflect the data structure during analysis (see below for the grouped data structures).

Data analysis

Data analysis for this study was conducted using a completely randomized design with each soil strength profile as the replicate experimental unit (repeated subject), and each of the depth classes (repeated factors) as repeatedly measured units within each profile. A repeated measures analysis of variance (ANOVA) procedure was performed with SAS v9.1 statistical software (SAS Institute 2002). The CLASS, MODEL, RANDOM, and REPEATED statements were used within the PROC MIXED procedure. A macro was used to determine the appropriate covariance structure. Akaike's Information Criterion (AIC) (Akaike 1974) values for each of 10 proposed structures were ranked and the lowest value determined the appropriate structure for the data in this investigation. The chosen structure was then used in the final model (below) to estimate means, differences among means, and their confidence limits. All statistical tests were conducted at the alpha = 0.05 significance level.

To minimize the number of repeated measures per replicate, the 16 depth intervals were grouped into 4 new depth classes: (1) 25-100 mm, (2) 125-200 mm, (3) 225-300 mm, and (4) 325-400 mm. Visual soil disturbance codes were also grouped into broader categories of (1) undisturbed — code 1, (2) shallow disturbance — codes 2-5, (3) deep disturbance — codes 6-9, and (4) skid trail — code 10. Grouped data categories consist of mean soil strength values of each of the initial broader categories. During pre-treatment measurements, only undisturbed (Pre1) and skid trail (Pre10) classifications were observed. Post harvest, observed classifications were undisturbed (Post1), shallow disturbance (Post2), and skid trail (Post10). Therefore, 5 visual soil disturbance codes were used during data analysis: (1) Pre1, (2) Pre10, (3) Post1, (4) Post2, and (5) Post10. ESTIMATE statements were used to generate estimates of pre and post treatment soil strength values at each depth class as well as the difference between these values. In this procedure, the 2 pre-treatment visual disturbance codes were averaged to generate mean soil strength values for all pre-treatment measurements. The same method was used to establish soil strength means for all post treatment measurements. The DIFF option was used to obtain estimates of differences between least square means for all pairwise comparisons.

The following ANOVA model was used to describe the relationship between soil strength, depth below the soil surface, and visual disturbance observations both pre and post harvesting.

$Y_{ijk} = \mu + V_i + \lambda_{ij} + D_k + VD_{jk} + \varepsilon_{ijk}$

where:

μ is the overall mean value of Y_{ijk} (soil strength (kPa))

V_i is the fixed effect of the i^{th} level of visual soil disturbance (i=Pre1, Pre10, Post1, Post2, or Post10)

λ_{ij} is the random effect of profile j within visual soil disturbance classification i

$\lambda_{ij} \sim N(0, \sigma^2_t)$ $j=1, 2,\ldots,n_i$, ($n_{Pre1}=70$, $n_{Pre10}=17$, $n_{Post1}=28$, $n_{Post2}=25$, $n_{Post10}=36$)

D_k is the fixed effect of the k^{th} depth class (k=1, 2, 3, or 4)

VD_{jk} is the interaction effect of the i^{th} level of visual soil disturbance and the k^{th} depth class

ε_{ijk} is the random error term that represents variability among depth classes within profiles, and ε_{ij}~Multivariate Normal($\underline{0}$,Σ) and $\Sigma=\begin{bmatrix} \sigma^2 & \sigma_1^2 & 0 & 0 \\ \sigma_1^2 & \sigma^2 & \sigma_1^2 & 0 \\ 0 & \sigma_1^2 & \sigma^2 & \sigma_1^2 \\ 0 & 0 & \sigma_1^2 & \sigma^2 \end{bmatrix}$ represents a Toeplitz (2) covariance structure among depth classes within a profile.

The model assumes that measurements recorded on different profiles are independent, observations within a profile are dependent and correlated, and that all errors are normally distributed. This analysis will determine if there are significant differences in soil strength that can be attributed to the harvesting operation. The visual soil disturbance effect will detect differences in soil strength between disturbance classes and the depth effect will detect differences between depth classes. The visual soil disturbance*depth interaction effect will detect differences in soil strength between disturbance classes at the four depth levels.

Results

Assumptions of normality were assessed and confirmed through analysis of residual plots. The sample size corrected AIC values (AICc) for each of the covariance models are given in Table 2.

Table 2. — AICc values for each covariance model. TOEP(2) had the minimum AICc value.

Model	AICc	Model	AICc
Compound Symmetry	10095.8	AR(1)	10058.2
UN(4)	N/A	TOEP(4)	10057.9
UN(3)	10058.9	TOEP(3)	10055.9
UN(2)	10057.7	**TOEP(2)**	**10053.9**
UN(1)	10094.6	TOEP(1)	10093.8

The TOEP (2) structure was selected due to its minimum AICc value and was used in the final mathematical model to estimate means, differences among means, and their confidence limits. The structure requires the estimation of 2 parameters. In this model, variance among soil strength values at each depth class was larger than among strength values between depth classes. Correlation among strength values at depth classes 1-2, 2-3, and 3-4 was estimated to be 0.37, whereas strength value correlation among depth classes 1-3, 1-4, and 2-4 was estimated to be 0.

As noted in Table 3 below, the interaction effect between visual disturbance class (VDC) and depth class was not statistically significant ($F_{12,453}=1.22$, $p=0.268$). This implies that the differences in soil strength values between visual disturbance classes do not depend on depth below the soil surface.

Table 3. — Table of F statistics for main effects and interactions.

Effect	Num DF	Den DF	F Value	Pr > F
VDC	4	171	0.46	0.7685
Depth Class	3	453	73.55	<0.0001
VDC*Depth Class	12	453	1.22	0.2684

The main effect of visual soil disturbance class was not statistically different from zero, indicating that soil strength does not depend on visual disturbance classification. As expected, the main effect of depth class was statistically significant ($F_{3,453}=73.55$, $p<0.0001$). This result implies that soil strength changes as depth below the soil surface increases.

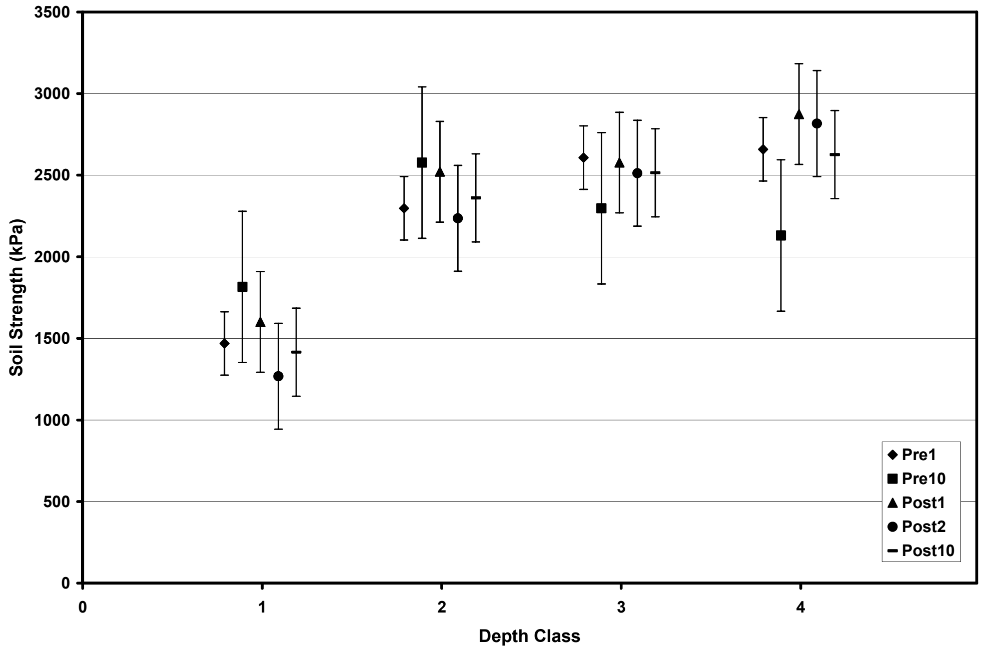


Figure 1. — Mean soil strength (kPa) with 95% confidence intervals, for the five visual soil disturbance codes within each depth class.

As indicated in Figure 1, the overlapping of confidence intervals within depth classes for each of the five analyzed visual disturbance classes implies no statistically significant difference between disturbance classes within a depth class. Soil strength values within each disturbance class tend to increase with increasing depth below the soil surface with the exception of pre-treatment skid trail measurements (Pre10). Pre10 observations show an increase in soil strength between depth classes 1 and 2, then decline at depth classes 3 and 4, although this trend is not statistically significant.

Figure 2 shows the estimated mean differences in soil strength values between pre and post treatment conditions at each depth class. Depth classes 1 and 2 show a mean decrease in soil strength following the harvesting treatment, although their confidence intervals include zero indicating no statistically significant difference. Depth classes 3 and 4 each show a mean increase in soil strength following treatment. Although the difference is only statistically different from zero for depth class 4 ($t\text{-value}_{453}=2.09$, $p=0.0367$, 95% CI=23.39, 732.41).

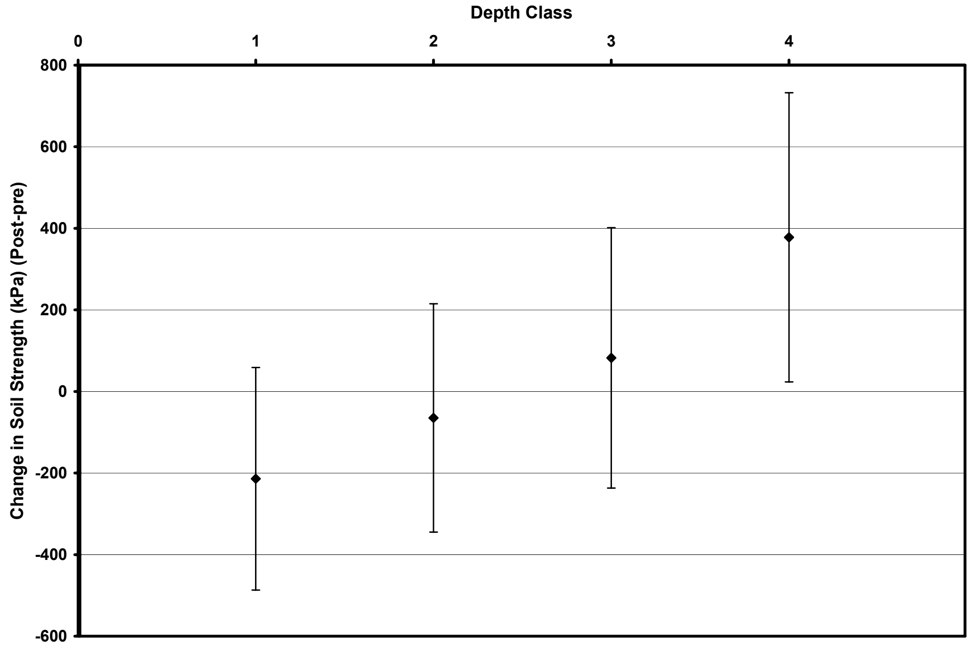


Figure 2. — Estimated difference in mean soil strength (kPa) with 95% confidence intervals between pre and post treatment measurements (post-pre) for each depth class (visual soil disturbance not considered). Note: a positive change indicates an increase in soil strength following treatment.

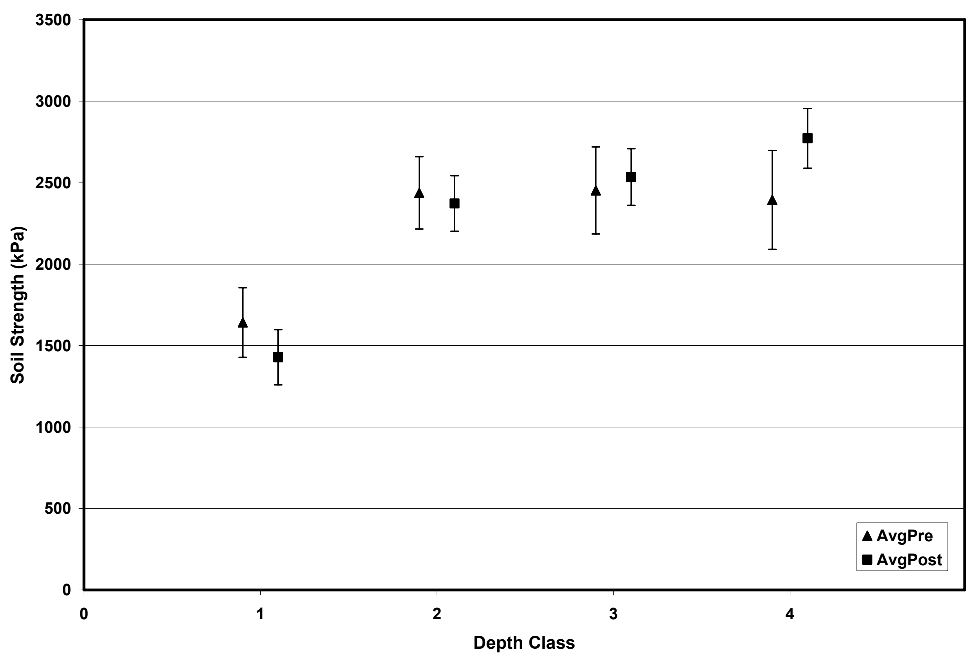


Figure 3. — Mean pre and post treatment soil strength estimates and 95% confidence intervals (averaged across visual disturbance classes) at each depth class.

Biological significance

Figure 3 shows average pre and post treatment soil strength values along with their 95% confidence intervals. The figure indicates that neither pre nor post treatment soil strength values exceeded the a priori 3000 kPa threshold for biological significance at any depth class. These results imply that the harvesting treatment did not contribute to biologically significant changes in soil strength for any depth class. Assuming that the 3000 kPa value set a priori applies to the 20-acre site, it can be concluded that the harvesting treatment did not result in detrimental soil compaction, reduced site productivity, or a reduction in tree growth.

Discussion

Based on this analysis, the following conclusions can be drawn in regards to the 2 research questions addressed in the study.

Question 1: Does the use of an integrated forest harvesting/mechanical fuels reduction operation with conventional ground-based equipment on the 20-acre stand contribute to statistically and/or biologically significant changes in soil strength at various depths below the soil surface?

Results indicate that the fuels reduction operation did not contribute to either statistically or biologically significant soil disturbance effects. The only statistically significant effect was detected at depth class 4 (325-400 mm below the soil surface). Since no deep disturbance was detected with the visual disturbance codes, this result could be due to measurement error and is unlikely the result of the harvesting operation. At increasing depth below the soil surface, the soil penetrometer often encounters tree roots and/or soil parent material. Often, these obstacles yield erroneously high soil strength values (Miller et al. 2001).

The a priori determined biologically significant soil strength value of 3000 kPa was not exceeded at any depth class. It is difficult to determine how this result applies to differing pre treatment soil strength characteristics. On the 20-acre site, the pre treatment values were below 3000 kPa for each depth class, although depth classes 2, 3, and 4 encompassed 2500 kPa within their 95% confidence intervals. This indicates that soils on the given site were already compacted to near detrimental levels (as specified by the a priori threshold). This could be a function of either past entries by mechanized harvesting operations or the inherent properties of the specific soil type characteristic to the area. The ability to increase soil strength with mechanized equipment is largely a function of the existing soil characteristics prior to harvest. Given the high soil strength values pre treatment, it is likely that the soil was already compacted to a level that inhibited further compaction. This may explain the lack of significant effects detected with this study. Had pre treatment conditions been characterized by lower soil strength, the operation may have produced a more measurable and significant effect. Further studies should investigate similar treatments in areas with differing soil conditions (low compaction – high compaction). Such studies may provide more meaningful results that could be used to establish trends in pre vs. post treatment soil strength estimates for differing levels of pre treatment compaction.

Question 2: Are changes in soil strength related to visual soil disturbance?

Visual soil disturbance classifications were not statistically significant for predicting soil strength. Confidence intervals for each of the 5 observed visual disturbance*time codes overlapped within each depth class (Figure 1). This result could be a function of study design. This study was designed to quantify soil strength and visual disturbance for the 20-acre stand as a whole. Had skid trails and feller-buncher corridors been observed separately from undisturbed areas between residual trees, for example, visual disturbance classifications may have proved more important for predicting soil strength. Although, for the forest manager, concerns regarding site productivity and tree growth are best addressed by assessing soil disturbance over the entire area since skid trails are often reused with subsequent machine entries and may be considered out of production from a tree growth stand point.

Conclusion

In conclusion, this study was successful in answering the research questions of interest. Interpretation of the results should be used cautiously and applied to similar treatment types, machine configurations, and soil characteristics. As noted earlier, the effects of such a treatment are largely unknown for differing pre treatment soil characteristics. Forest managers should carefully investigate soil conditions and the potential effects of the prescribed management action before implementation of any forest fuel reduction operation. These factors will have a significant effect on soil disturbance generated from ground-based harvesting systems. Further, it is recommended that to optimally quantify the effects of soil disturbance on site productivity, long-term studies of tree growth should be established. This quantification will serve as validation of results from studies such as this and could possibly allow for further inference to be drawn. Such an approach will allow forest managers to make informed decisions regarding possible impacts from integrated fuel reduction treatments and aid regulatory agencies in policy formulation.

References

Akaike, H. 1974. A new look at the statistical model identification. IEEE Transaction on Automatic Control, AC-19. p. 716-723.

Landsberg, J.D., R.E. Miller, H.W. Anderson, and J.S. Tepp. 2003. Bulk density and soil resistance to penetration as affected by commercial thinning in northeastern Washington. Res. Pap. PNW-RP-551. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. 35 p.

McMahon, S. 1995. Accuracy of two ground survey methods for assessing site disturbance. Journal of Forest Engineering 6(2):27-33.

McIver, J.D., P.W. Adams, J.A. Doyal, E.S. Drews, B.R. Hartsough, L.D. Kellogg, C.G. Niwa, R.D. Ottmar, R. Peck, M. Taratoot, T. Torgersen, and A. Youngblood. 2003. Environmental effects and economics of mechanized logging for fuel reduction in Northeastern Oregon mixed-conifer stands. Western Journal of Applied Forestry 18(4):238-249.

Miller, R.E., J. Hazard, and S. Howes. 2001. Precision, accuracy, and efficiency of four tools for measuring soil bulk density or strength. Res. Pap. PNW-RP-532. Portland, OR: USDA Forest Service, Pacific Northwest Research Station. 16 p.

Miller, D., and H. Anderson. 2002. Soil compaction: concerns, claims, and evidence. In: Proc. Small Diameter Timber: Resource Management, Manufacturing, and Markets. February 25-27, 2002; Spokane, Washington. Washington State University Cooperative Extension. p. 97-106.

NRCS. 1993. Soil survey of Jackson county area, Oregon. Available at: ftp://ftp-fc.sc.egov.usda.gov/MO1/text_pdf/oregon/or632_text.pdf. Last accessed: June 9, 2005. 446 p.

Powers, R.F., and P.E. Avers. 1995. Sustaining forest productivity through soil quality standards: A coordinated U.S. effort. p. 147-190. In C.B. Powter et al. (ed.) Environmental soil science: Anthropogenic chemicals and soil quality criteria. Canadian Soc. Soil Sci., Brandon, Manitoba.

Powers, R.F., A.E. Tiarks, and J.R. Boyle. 1998. Assessing soil quality: practicable standards for sustainable forest productivity in the United States. Soil Science Society of America. The contribution of soil science to the development of an implementation of criteria and indicators of sustainable forest management. SSSA special publication no. 53. p. 53-80

SAS Institute Inc. 2002. SAS OnlineDoc Version 9.1 [computer program]. SAS Institute Inc., Carey, N.C.

USFS. 1998. USDA Forest Service Manual, FSM 2520 (Watershed Protection and Management) R-6 Supplement No. 2500-98-1, Effective August 24, 1998.

Evaluation of a Harwarder in Fuel Reduction Treatments on the Lincoln National Forest in New Mexico[1]

John Klepac[2] and Bob Rummer[2]

Abstract

A TimberPro[3] TF-820E Harwarder was evaluated while applying three different fuel reduction treatments. Time-and-motion studies were carried out on the harwarder while performing felling/processing and forwarding functions. Summary results suggest a production rate of 0.27 acres/PMH (Productive Machine Hour). Hourly machine cost, including profit and overhead, is around $193/SMH (Scheduled Machine Hour).

Key words: harvesting, harwarder, productivity, costs, fuel reduction

Introduction

Cut-to-length (CTL) systems have revolutionized the practice of thinning forests. Innovations in equipment design, computer technology, and ergonomics have enabled equipment manufacturers to provide reliable, efficient and comfortable machines for contractors. Harvesters enable operators to efficiently merchandise multiple products, therefore maximizing value of harvested trees. However, these systems require a significant capital investment and must be highly utilized to cover costs. It is not uncommon for a CTL system to cost nearly $750,000.

A major challenge in implementing forest health and fuel reduction treatments is

---

[1] This paper was presented at the Annual COFE Meeting: Soil, Water, and Timber Management: Forest Engineering Solutions in Response to Forest Regulation. July 11-14, 2005, Arcata, California.

[2] Staff Engineer (jklepac@fs.fed.us) and Project Leader (rrummer@fs.fed.us), USDA Forest Service, Southern Research Station, 520 DeVall Drive, Auburn, AL 36849.

[3] Reference herein to any specific commercial products, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government, and shall not be used for advertising or product endorsement purposes.

finding harvesting systems that can work effectively with small-diameter trees. Conventional harvesting systems generally operate most economically at 200 – 300 tons per day with merchantable-sized timber. Operating in small-diameter removals, and with specialty product markets requires systems that can work effectively at lower productivity levels. Typical options have been manual systems (chainsaws and skidders) or small-scale equipment. These approaches are limited by labor availability, man-hour productivity, living wage constraints, safety issues, and other operational limitations.

In an effort to reduce the costs of first thinnings in Finland, the S. Pinomaki Ky company has developed a concept that combines the harvesting and forwarding functions on the same machine. The combination harvester-forwarder could be a viable option in commercial thinning or in the harvesting of scattered cut blocks, as well as for contractors with annual volumes too small to justify the cost of a full two-machine system (Lilleberg, 1998). TimberPro has also developed this type of combination machine.

A "harwarder" multi-function machine that combines harvesting and forwarding into a single operation offers many advantages for forest health treatments. The single operator is safely enclosed in a state-of-the-art working environment. By combining thinning functions in a single machine, the total system output is about half the productivity of a conventional 2-machine system, which may be a better match for small-scale operations in the Rocky Mountain region. Using the latest harvester head technology, the harwarder can merchandize material to create various product distributions, optimizing value recovery and utilization.

One question is whether a harwarder can economically implement forest health and fuel reduction treatments. With limitations of manual or small-scale systems on labor availability and man-hour productivity, coupled with safety issues and operational limitations, a harwarder could possibly find its niche performing these types of treatments. This study evaluated a TimberPro TF820E Harwarder while implementing fuel reduction treatments on the Lincoln National Forest in Southern New Mexico to determine the effect of tree size on costs and productivity.

Study Site

The thinning treatment was located on the Smokey Bear Ranger District of the Lincoln NF in Ruidoso, New Mexico. The project consisted of six units that ranged in size from 5 to 81 acres, totaling 221 acres. Slopes generally ranged from 9 to 23 percent on all three sites. Although, Unit 2 contained areas with slopes over 40 percent, which were not operable with the harwarder. Elevation of the study area ranged from 7500 to 8500 feet. Douglas-fir (*Pseudotsuga menziesii*) and ponderosa pine (*Pinus ponderosa*) were the dominant species, with a small component of juniper (*Juniperus* L.), and gamble oak (*Quercus gambelii* Nutt.) Data were collected on three of the six units, which will be referred to as Units 1, 2, and 3.

Unit 1 contained 55 acres and was a mixture of ponderosa pine and Douglas-fir, with a small component of juniper, cedar, and gamble oak. Unit 2 contained 48 acres and consisted mainly of Douglas-Fir, with a small component of ponderosa pine, white fir, and juniper. Unit 3 contained 81 acres and consisted of a mixture of Douglas-Fir and ponderosa pine.

System Overview

The harvest system was a single machine, a TimberPro TF820E Harwarder (Figure 1) equipped with a LogMax 7000 head. Machine specifications are listed in Table 1. Normally, the operator would work several days felling and processing. The processing head is then replaced with a grapple, allowing the operator to forward the wood to a landing. A self-loading truck was used to load and haul wood from the units to SBS Woodshavings' plant in Glenco, NM. There, the small-diameter wood was processed with a wood shaver and packaged for use as animal bedding. Logs large enough to be processed into posts and lumber were stacked in the yard.

Figure 1. TimberPro Model TF-820E Harwarder.

Table 1. Machine specifications.

Feature	Specification
Engine	John Deere 6068 250 hp
Hydraulics	Hydrostatic 2-speed transmission
Tires	Nokian 700/50-26.5
Ground Pressures (psi)	
Front wheels	11.90
Front wheels w/tracks	6.45
Rear wheels	6.25
Rear wheels w/tracks	3.75
Reach w/6-ft squirt boom (ft)	31
Payload (tons)	20
Weight (lb)	51,820

Methods

Time and motion studies were conducted on three of the six units where productivity of the machine was monitored. Two types of data were collected: gross and detailed. For gross data collection, electronic activity recorders were mounted inside the cab to monitor productive machine hours for the entire unit. MultiDat GPS units were installed to track traffic patterns of the machine. The GPS unit was set up to record a position when the machine traveled more than 26 feet or was idle for more than twenty-five minutes. Total volume hauled from each unit was obtained from load tickets at the mill. To determine operational limits and the effect of tree size on harwarder productivity, detailed time-and-motion studies were conducted for both felling/processing and forwarding functions.

Felling and processing

The harwarder processed most trees less than 5 inches Dbh (Diameter at Breast Height) into 100-inch bolts for use as woodshavings. Larger trees were cut into lengths predominately 16 or 24 feet to facilitate trucking. These were then bucked at the mill into sawlogs and vigas for decorative home building or 100-inch bolts for use as woodshavings. Volumes (outside bark) for all measured pieces were calculated using Newton's formula (Forestry Handbook, 1984). Individual pieces for each tree were summed to determine merchantable length and volume.

The harwarder was recorded on video to calculate the time to fell different-sized trees, remove limbs, and process into desired lengths. As a tree was being cut, a number was assigned to it and verbally recorded on tape. The assigned tree number was marked on the butts of each processed piece using a lumber crayon. After a number of trees had been felled and processed, detailed measurements were taken on each tree to determine volume. Measurements that were taken included Dbh, end diameters and mid-diameter (outside bark), length of each piece, and tree species. A variable radius plot using a 10 BAF prism was then installed in the area where Dbh and species of all residual trees and percent slope were recorded.

Forwarding

Forwarding productivity was measured using continuous stopwatch timing. Forwarding time elements were travel empty, load, intermediate travel, travel loaded, and unload. Travel empty was the time traveling from the deck to the first stopping point in the woods to pick up wood. Load time included reaching, grappling, and placing wood on the forwarder. Intermediate travel included the time moving in the woods between loading points. Travel loaded was the time traveling from the last loading point in the woods to the deck. Unload was the time required to transfer wood from the forwarder to a pile on the deck.

To estimate load volume, a tally of the number of pieces being loaded was recorded. To account for piece size variations, each piece was categorized into a large or small size class. A random sample of pieces was taken to measure individual pieces and volumes determined using Newton's formula. A top diameter of approximately 6 inches was used as a breakpoint to separate large and small pieces. Average volumes were determined for each piece size (large and small) and used to calculate total load volume for forwarding.

Costs

Cost to own and operate the harwarder were estimated using a machine rate analysis, which is an average annual cost spread over the life of the machine. Capital costs were calculated using a capital recovery factor (Riggs, 1977). Fuel and lube estimates were obtained from the operator and manufacturer. For comparison to other systems commonly used in the United States, cost of a typical cut-to-length (CTL) system was determined using production rates obtained from the felling and processing functions of the harwarder.

Results

Gross time study

Table 3 summarizes gross production data collected from units 1 and 2. Machine time for unit 3 was incomplete and therefore is not included.

Table 3. Gross production summary.

Study Area	Acres	Machine Hours	CCF Removed	Acres /hour	CCF /hour
Unit 1	55	200	474	0.28	2.37
Unit 2	43	175	490	0.25	2.80
Mean	49	187.5	482	0.27	2.59

Detailed data collection

Felling and processing

A cycle was defined as the time required to look for trees to cut, move to a tree, reach out to a tree, cut the tree, fell, and process. Since look and move times did not occur for each tree, these times were distributed among all trees for the analysis. A video analysis software program, was used to analyze videotapes of the harwarder performing these functions. The General Linear Models Procedure (GLM) in SAS was used to model total cycle time. Independent variables found to be significant for predicting total cycle time were dbh, dbh^2, merchantable length, and cubic foot merchantable volume.

$$Total\ cycle\ time\ (min) = 1.643 - 0.2204*Dbh + 0.0121*Dbh^2 + - 0.0148*MLen + 0.0479*MVol$$

N = 197; R2 = 0.56; C.V. = 56.01

Dbh = diameter at breast height (inches)

Mlen = Merchantable tree length (feet)

Mvol = Merchantable tree volume (cubic feet)

Other independent variables tested but not found significant included species, percent slope, and residual trees per acre. The harwarder was observed while working on slopes ranging from 9 to 23 percent, with residual stand densities ranging from 17 to 581 trees per acre. Figure 2 displays the percent of total cycle time for each of the time-study elements studied. Moving and reaching accounted for half of the total cycle time. Processing a tree accounted for almost a third of the total time, with cutting and felling consuming 18% of the total time. Summary of felling and processing functions are presented in Table 2.

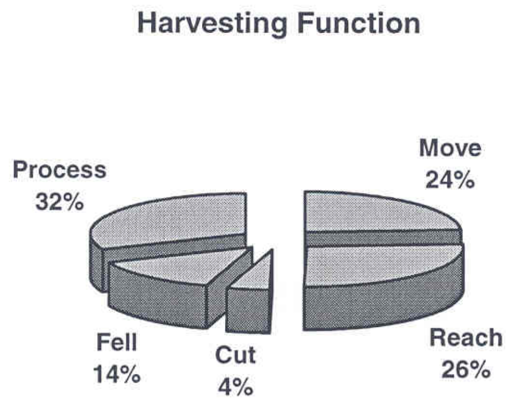


Figure 2. Percent of total cycle time for the harvesting function of the harwarder.

Table 2. Summary statistics for felling and processing.

Variable	N	Mean	Std. Dev.	Min.	Max.
Move (min)	197	0.16	0.292	0.02	3.53
Reach (min)	197	0.21	0.143	0.02	1.09
Cut (min)	197	0.03	0.045	0.01	0.50
Fell (min)	197	0.11	0.083	0.00	0.42
Process (min)	197	0.25	0.502	0.03	5.56
Total time (min)	197	0.76	0.655	0.21	6.58
Dbh (in)	197	7.8	2.98	3.1	20.0
Merch. Length (ft)	197	28.4	13.29	8.0	67.9
Merch. Volume (ft^3)	197	9.10	9.98	0.51	68.4
# Pieces	197	1.6	0.663	1.0	4.0
Trees/min	197	1.7	0.720	0.15	4.7
Productivity (ft^3/PMH)	197	748.6	593.96	29.2	3593.8

The effect of tree size on production of the harwarder is displayed in Figure 3. In this example, volumes by diameter class were calculated for ponderosa pine using a regression equation developed from measurements obtained on trees within the study areas. This diagram shows the significance tree size has on production. It took about 90 minutes to process 1 CCF while working in 4-inch Dbh trees, compared to 5 to 7 minutes while working in 8-inch and larger Dbh trees. Costs per CCF are substantially greater for the harwarder as tree size decreases.

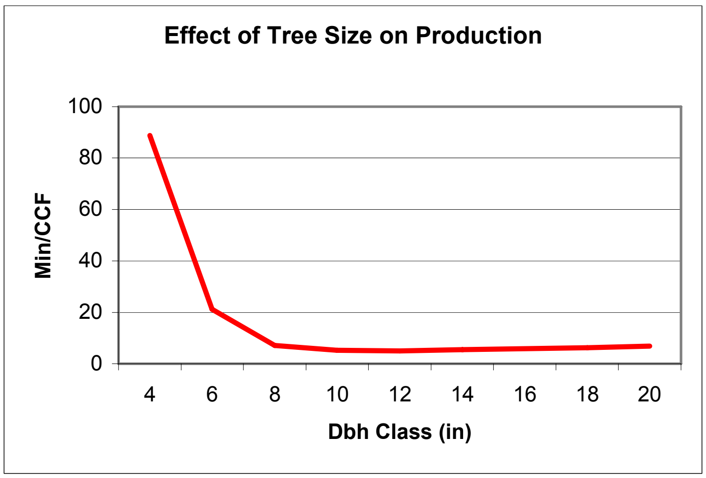


Figure 3. Time per CCF for harwarder felling and processing ponderosa pine.

Forwarding

A total of fourteen forwarder cycles were collected on the harwarder performing a forwarding function. Preparation for the harwarder to forward wood required about 15-20 minutes, which included disconnecting the harvesting head and attaching a grapple. Observations were collected from units 1 and 3. A summary of forwarding functions is shown in Table 3.

***Table 3*. Summary statistics for forwarding.**

Variable	N	Mean	Std. Dev.	Min.	Max.
Travel empty (min)	14	1.69	1.108	0.17	4.35
Load (min)	14	22.84	7.766	9.98	43.20
Int. travel (min)	14	6.28	3.355	1.55	13.17
Travel loaded (min)	14	1.71	1.243	0.33	4.98
Unload (min)	14	7.54	2.159	3.51	11.74
Total time (min)	14	40.07	10.695	17.50	58.08
# Pieces (in)	14	71.4	21.74	40.0	128.0
Volume (ccf)	14	4.11	1.264	2.80	7.30
Productivity (ccf/PMH)	14	6.48	2.107	3.38	10.29
Empty distance (ft)	14	243.9	171.13	20.0	550.0
Loaded distance (ft)	14	276.1	201.33	20.0	725.0
Total distance (ft)	14	520.0	318.46	160.0	1275.0
Load time/piece (min)	14	0.32	0.040	0.25	0.42
Unload time/piece (min)	14	0.11	0.037	0.05	0.18

Mean cycle time for forwarding was 40.1 minutes. The harwarder hauled an average of 4.1 ccf per turn, which resulted in a mean productivity of 6.5 ccf/PMH. However, as indicated in Table 3, this is at a mean total travel distance of 520 feet. Longer travel distances would decrease productivity. In some units the harwarder was required to distribute the slash on the ground to eliminate piles accumulating. Including this in the cycle time decreases productivity to 6.3 ccf/pmh. As shown in Figure 4, loading accounted for nearly 60 percent of the total cycle time, averaging 22.8 min. per turn. Unloading consumed about 20 percent of the total time and averaged 7.5 minutes. Intermediate travel, which includes moving between stops to pick up pieces, accounted for 16 percent of the total time. Traveling empty and loaded combined took 8 percent of the total time because of short travel distances observed. Load time per piece was nearly 3 times that of unload time per piece.

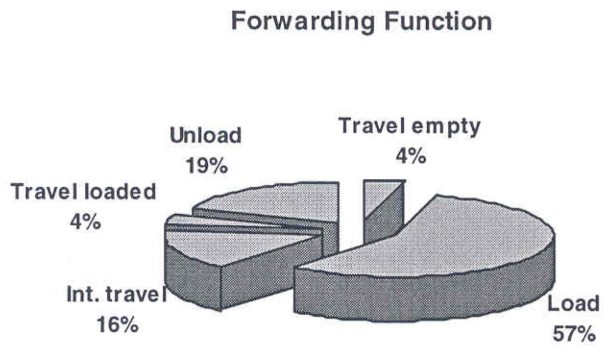


Figure 4. Percent of total cycle time for the forwarding function of the harwarder.

Costs

To calculate machine cost, parameters listed in Table 4 were used. Tire costs were subtracted from the purchase price and treated as an operating expense. A wage and benefit rate of $40/SMH was used for the harwarder. Using these parameters gives the cost estimates shown in Table 5.

Table 4. **Variables used for machine rate analysis.**

Parameter	Harwarder	Harvester	Forwarder
Purchase Price ($)	456,000	387,829	322,152
Tire cost ($)	24,000	18,000	24,000
Horsepower	300	204	168
Life (yrs)	5	5	5
Salvage value (% of PP)	20	20	20
Repair & maint. (% of Depreciation)	100	110	100
Interest rate (%)	10	10	10
Insurance (% of PP)	4	4	4
Fuel consumption (gal/hp-hr)	0.03	0.03	0.025
Lube and oil (% of fuel cost)	40	40	40
Fuel cost ($/gal)	2.00	2.00	2.00
Operator wage & benefits ($/SMH)	40	40	40
Utilization (%)	75	75	75
Scheduled Machine Hours (hrs/yr)	2000	2000	2000
Tire life (hrs)	5000	5000	5000
Profit & overhead (%)	20	20	20

Assuming the production rates of the felling/processing and forwarding functions of the harwarder are the same for a stand-alone CTL system and using the assumptions in Table 4 results in a 18 percent lower cost per ccf for the CTL system. This is because the purchase price of the harvester and forwarder were lower than the purchase price of the harwarder. Therefore, each CTL machine has a lower owning and operating cost, which leads to a lower unit cost. Using a productivity of 0.27 acres/PMH (Table 3) and a cost of $257/PMH results in a treatment cost of $952/acre for the harwarder.

***Table 5*. Cost summary for the two systems ($/SMH).**

Type of Cost	Harwarder	Harvester	Forwarder	CTL System
Ownership	59	50	42	92
Operating	62	52	39	91
Labor	40	40	40	80
Total+	193	142	121	263
$/ccf	76	32	30	62

+Includes 20% profit and overhead.

Conclusions

The hourly costs of the harwarder are lower than a two-machine CTL system. Therefore, a harwarder may have advantages where smaller tract sizes would require more frequent moves. However, because the machine cost associated with a given function (i.e. harvesting or forwarding) is higher for the harwarder than for the CTL machines, the cost per unit produced will usually be higher for a harwarder. Since the greatest difference in machine costs is associated with the forwarding function, the difference in harwarding and CTL production cost would be minimized on shorter extraction distances.

Like any CTL harvesting operation, the harwarder cost per unit produced is sensitive to tree diameter. By felling and processing single stems, costs increase significantly as Dbh drops below about six inches. This is primarily due to the effect of tree diameter on tree volume. When the harwarder is used in first thinnings or fuel reduction treatments where a significant number of small trees must be removed, the operating costs can increase dramatically. In a harwarder application it is important to consider alternative methods for treating the smallest diameter materials.

References

Forestry Handbook. 1984. 2nd Edition. John Wiley & Sons. New York. 1335 p.

Riggs, James L. 1977. Engineering Economics. New York: McGraw-Hill Book Co. 617 p.

The Variability of Construction Practices and Material Properties Found on Forest Roads in Oregon

Kevin Boston[1] and Andrea Bord[2]

Abstract

Recent rulings by Federal courts have further increased the need to improve the environmental performance of forest roads. This paper describes the first years results from a multiple year project that attempts to associate road material properties and construction practices with rut formation. The initial findings show a significant amount of variability in the soil types found on the road with 6 AASHTO soil types found within the 1-mile test section. The wet and dry unit weights are low with an average wet unit weight of 80 lb/ft^3 and an average dry unit weight of 57 lb/ft^3. The road was built during a wet period with a moisture content varying between 34 and 54 %. The resulting strength values, measured with the Clegg impact hammer, demonstrate the variability within the road as it has a coefficient of variation of approximately 35% for the subgrade, As expected higher impact values were found for aggregate road surface with a slightly smaller coefficient of variation of 26%. The durability of the rock was measured using the Micro-Deval machine and approximately 10% fines. Eighteen of the 40 segments in this road exhibited road ruts, but no statistical relationship was found, most likely due to high variability of the various properties and density. It is recommended that more direct manipulated experiments be completed to acquire the knowledge necessary to improve the understanding between forest road construction practices and material properties and environmental performance.

Introduction

Water quality regulations will continue to dominate forest operations regulations in the western United States for many years as a review of some recent Federal Court rulings will show. In the first case, Pronsolino v. Marcus (1996), 91 F. Supp. 2d 1337, first heard in the Federal District Court of Northern California and affirmed by the Ninth Appellate Court 291 F.3d 1123; 2002 U.S. App., confirmed the use of total maximum daily loads (TMDLs) to regulate nonpoint sources of water

---

[1] Assistant Professor, Department of Forest Engineering Oregon State University

[2] Graduate Research Assistant, Department of Forest Engineering, Oregon State University

pollution. In this case, TMDLs were imposed on the Garcia River in Mendocino County California, a river basin that contained only nonpoint sources of pollution from forestry and agriculture. The TMDLs required a 60% reduction in suspended sediment. This lead to additional timber harvest plan constraints that were implemented by California Department of Forestry as part of the timber harvest permit process to reduce the suspended sediment from the forest lands. Pronsolino estimated that these regulations reduced the financial returns by approximately $750,000. They challenged the authority of the Environmental Protection Agency (EPA) to set TMDLs on rivers that contained only nonpoint sources of water pollution. The district court ruled and the Appellate court confirmed that TMDLs could be set for both point and nonpoint sources of water pollution.

A more recent ruling by the Federal District Court of Northern California in EPIC v Pacific Lumber (2004), 266 F. Supp. 2d 110, in Humboldt County California challenged the EPA's definition of a nonpoint source from forestry operations. Prior to this ruling, most pollution sources in forestry were considered to be nonpoint sources and were to be controlled using best management practices. The district court ruled that many roads are now to be considered point sources of water pollution. Storm water that is collected in road-side ditches, culverts and other discrete conveyances and discharged into a river then becomes a point source pollution under the Clean Water Act and requires permits under the National Pollution Discharge Elimination System (NPDES). There is now an implied standard of pollution control that must be used on these point sources.

These rulings are from District and Appellate Courts in the Federal Court System and may be applied to other regions in the US. Rulings such as these have the potential to significantly increase the cost of forest operations. The forest industry must examine the methods used to design and construct forest roads in order to better meet society's expectations regarding environmental concerns. To improve the environmental performance of forest roads requires a greater understanding of the quality of the materials used to build forest roads and how the construction process is accomplished. Unfortunately, forest road construction differs from most other road construction projects in the lack of engineering sciences applied to the design and construction processes. Little money is spent on soil testing, and most organizations blindly use the published strength values found in soil surveys. Often times, the construction process is poorly controlled with respect to moisture content or lift thickness which leads to variable road unit weights. Construction equipment designed to produce a low ground pressure, such as dozers, are used for compaction instead of more specialized equipment. The result can be a significant amount of variability in the finished subgrade and surfacing unit weights. These factors may lead to increased environmental impacts from the forest road.

This research project has limited its focus on subgrade and surface material properties and their correlations with rut formation. Ruts were chosen as the environmental performance variable because of their ability to channel water. The ability of ruts to channel water can cause accelerated sedimentation from forest roads. Eliminating ruts may be a simple way to lower the sediment produced from forest operations instead of broader land-use restrictions. Eliminating ruts may also be helpful in avoiding a point source pollution classification and subjecting a road segment to the NPDES permit required by the Clean Water Act.

Foltz (1996) reviewed the sediment production from roads built with high and low quality aggregate rock. As expected, the low quality aggregate produced more sediment due to its inability to resist wear (Foltz 1996). However, an aggregate pavement layer's performance is not just a function of the material properties of the rock, but it is also related to the thickness and stiffness of overlying and underlying layers and the stress transferred across these layers (Dawson 1999). Dawson (1999) compared rut formation on four aggregate types with two subgrade materials. One subgrade was a resilient material (rubber on concrete) and one was a soft-clay. Only the weak aggregate material, sand and gravel, showed rutting on the resilient subgrade, while all surfacing types showed rutting on the soft-clay subgrade (Dawson 1999). This clearly shows the impact of subgrade strength on rut formation and that both surface and subsurface properties must be considered.

The results presented in this paper are from the first year of a larger study that will be completed in 2008. The project will achieve the following results:

- Quantify the various subgrade and surface strength parameters for forest roads.
- Measure the rut formation on these forest roads.
- Attempt to correlate the formation of ruts to forest road properties, traffic, and geometry.
- Determine the potential improvements in forest roads if improved construction practices were adopted.

Methods

There is little supporting information or examples in the literature that describes the optimal methods to investigate roads. Very few studies reported the variability found in the properties of road building materials. The initial decision was made to systematically divide the road into 300 foot segments with subgrade samples made at a random location within each road segment. It was hoped that this sampling intensity would capture the natural variation in soil types often found in forest roads. Clegg impact values were measured along the road in 50-foot intervals at 4 foot increments from the inside of the road. These values showed the variability along the road. The following data was collected for each segment:

- Subgrade density and moisture content using a sand-cone device.
- Clegg impact values of both subgrade and surface obtained with a 25-kg Clegg hammer.
- Approximately 200 pounds of subgrade material for various laboratory analyses.
- Approximately 1000 pounds of subsurface and surfacing rock for gradation analysis and abrasion resistance using the Micro-Deval machine.

The soils were classified in the laboratory using both the Unified and AASHTO soil classification systems. A fifteen-point strength test will be completed on each of the soil samples. This test will use three different compactive energies, standard proctor, modified proctor and one between these two, with five different water contents. These samples will be soaked for 96-hours with a surcharge weight. Following a short drainage period, the laboratory CBR test will be performed. This test drives a piston into the sample and measures the penetration resistance. From these results the required unit weights and associated moisture contents can be determined that give the desired bearing strength. This will allow for the determination of the potential strength of forest roads if construction practices were completely controlled. However, a full set of results have not been completed at this time.

Results

The soil classification shows six different AASHTO soil types and five different Unified Soil Classifications. They are distributed in a clumped distribution along the road (figure 1). The road contains some excellent subgrade materials with the A-1b soil types, but has some weak soils as well with the inclusion of an A3 soil classification. This clearly demonstrates the variability when working in a wildland environment.

The relationships seen between density and moisture confirm that the road was built when soil moisture was high. The wet unit-weights were low with values between 65 and 100 pounds per cubic foot, with moisture contents between 27 and 55 percent. The dry unit weights were considerably low with values between 45 and 78 pounds per cubic foot (figure 2).

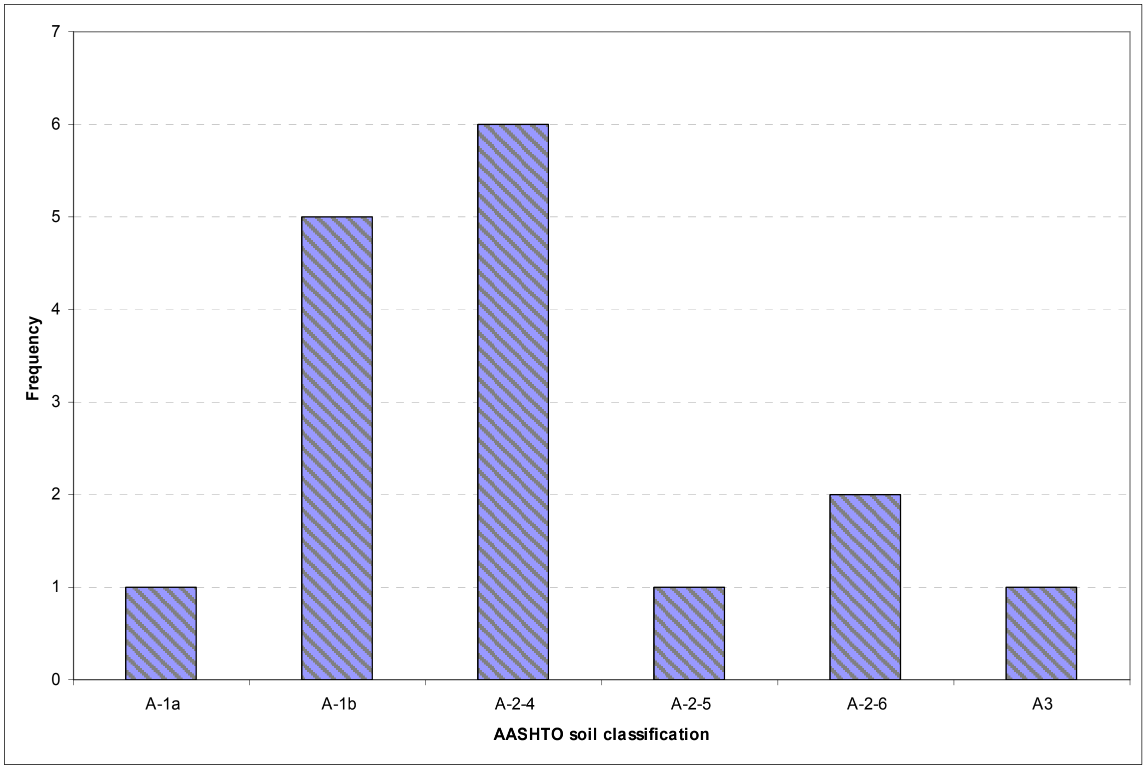


Figure 1: Occurrences of AASHTO soil types found along a forest road

Figure 2: Wet and Dry unit weights and moisture contents found along a forest road

The Clegg impact value, a strength measurement, had a significant coefficient of variability of 35 percent. Significantly lower values were found in the center of the road than the sides of the road (figure 3). This may be a result of lack of control on compaction as well as an effect of the numerous passes made by construction traffic. A lack of lift thickness control may have made compaction of the subgrade with a smooth-drum vibratory roller ineffective. The same pattern is shown with the surface rocking, but higher impact values are seen because of the stronger material (figure 4).

The coefficients of variations for these materials are shown in table 1. The wet and dry unit weights vary around 10% with a 20% coefficient of variation for the moisture content. There is a much high variability among the strength measurements with a coefficient of variations between 26 and 35%.

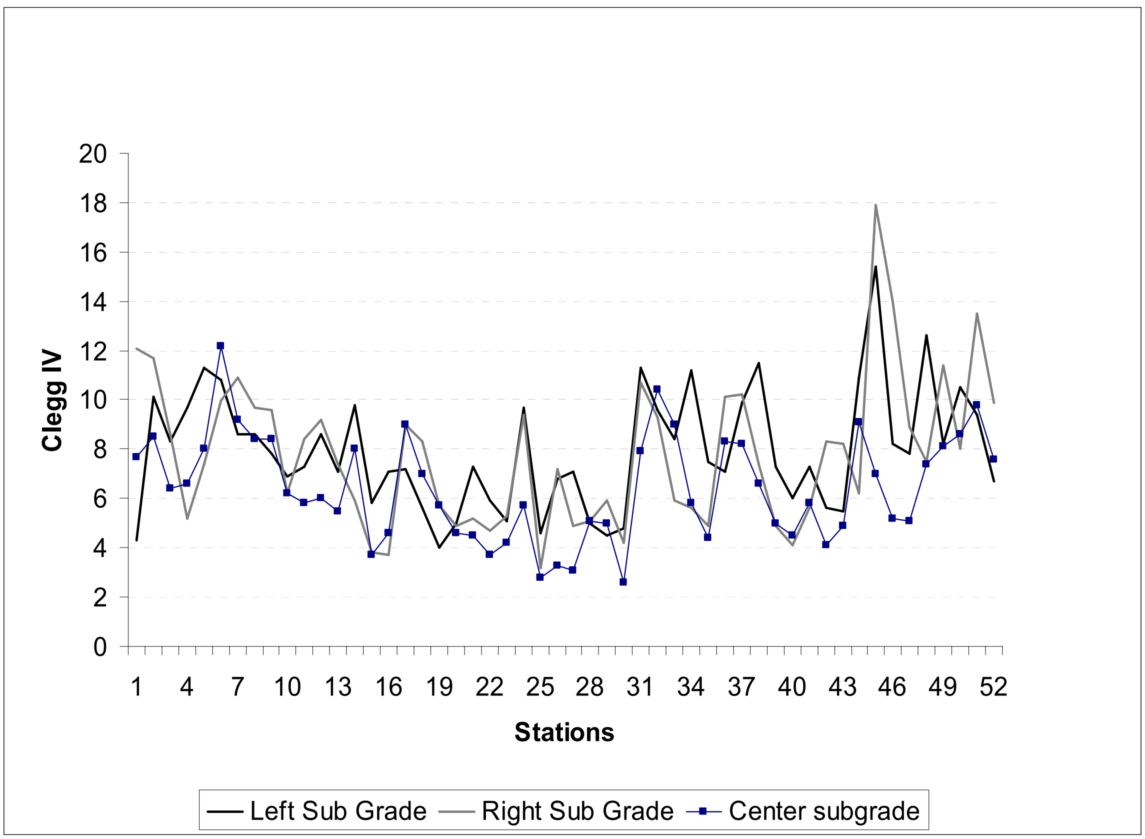


Figure 3: Comparison of Clegg Impact Values from Left, Center and Right sections of subgrade along 1 mile of forest road

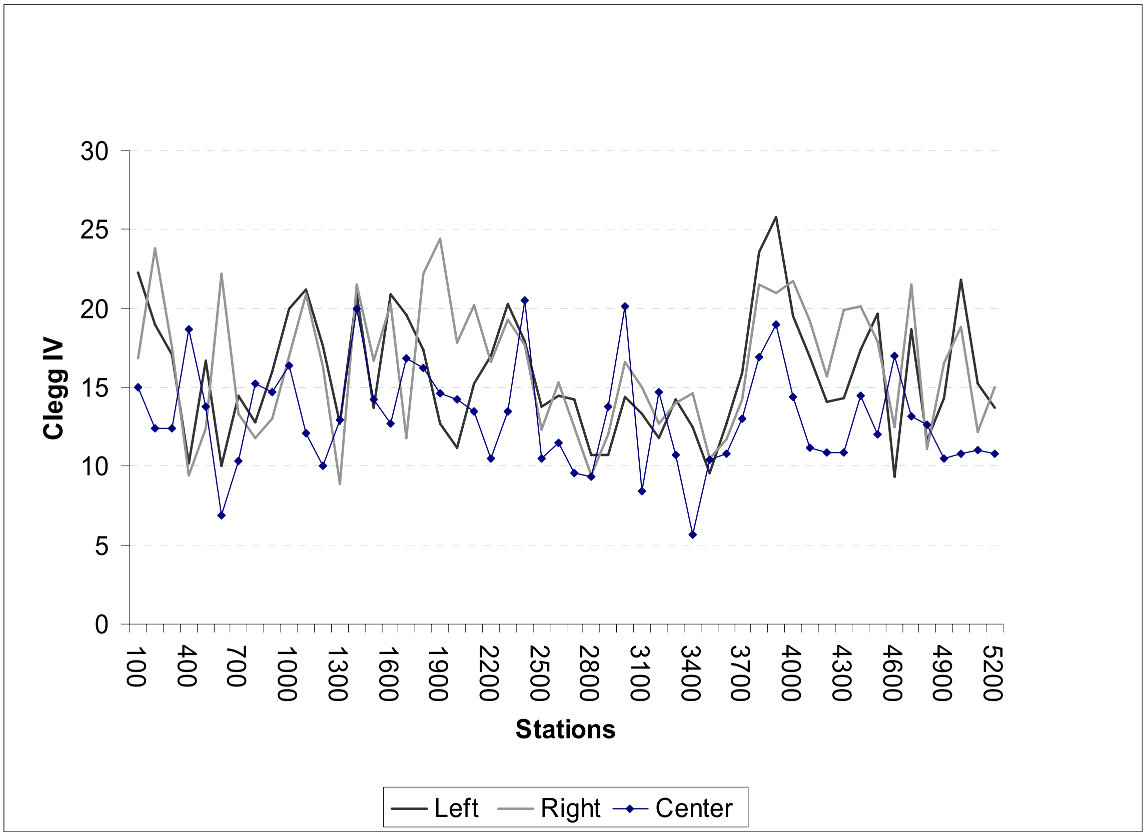


Figure 4: Comparison of Clegg Impact Values on road surface from Left, Center and Right sections along 1 mile of forest road

Table 1: Coefficient Variation of various road properties sample size from road 1

Moisture content	21.8
Wet unit weight	11.9
Dry unit weight	14.6
Subsurface Clegg Impact Value	34.5
Surface Clegg Impact Value	26.5

The last material property that is considered is the quality of the aggregate used for surfacing. The first aggregate property considered is the gradation. The gradation of the base-course and surfacing rock is shown in figure 5. These gradations may produce different environmental impacts. A densely graded aggregate with a large amount of fines may become a significant source of sediment, but because it compacts well it may resist rut development. An open graded aggregate without a large number of fines may produce limited amount of sediment, but it may not compact as well resulting in more ruts for a given traffic level.

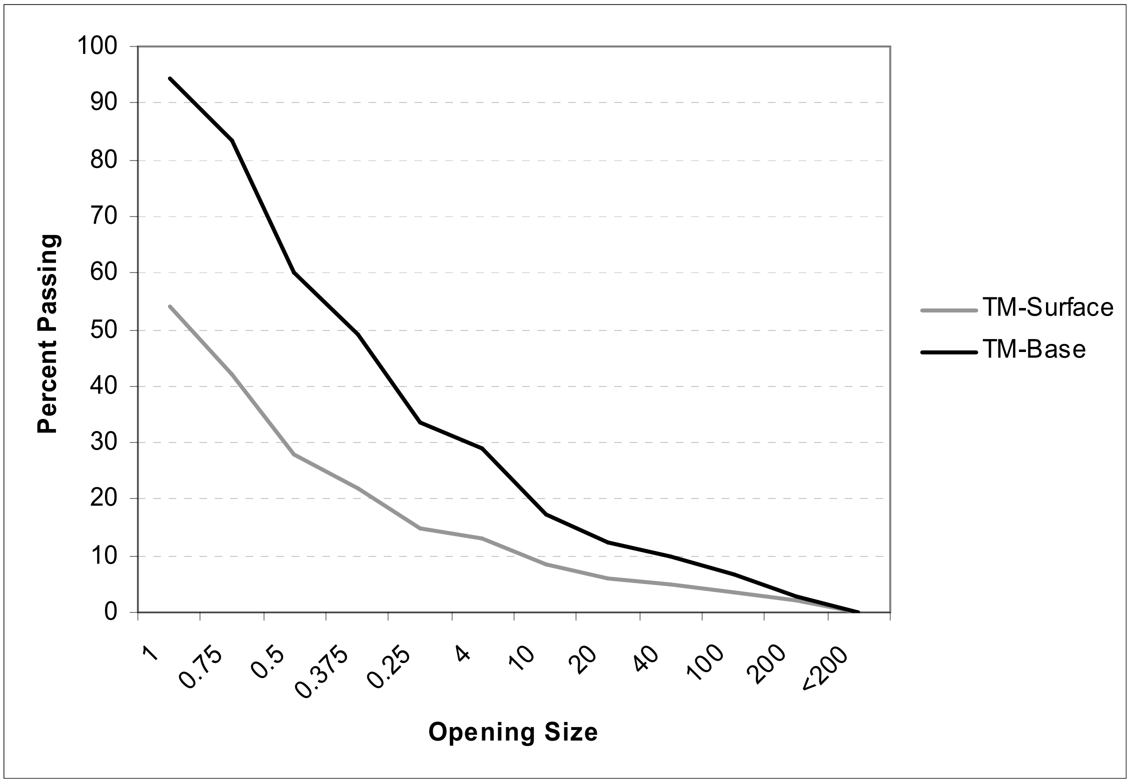


Figure 5: Needs to be replaced with a more refined work below the ¼ inch sieve

Another aspect of aggregate quality is the rock durability. There are a number of abrasion tests that have been developed in order to index rock durability. These tests create only an index and therefore cannot be directly related to field performance. This research has used the Micro-Deval test which has a smaller dead-load than the more common LA abrasion test. The Micro-Deval used a highly size-segregated aggregate sample of 1.5 kg with 2 liters of water and 5 kg of 4 mm steel balls. The sample was then tumbled for 1.5 to 2 hours depending on the rock size. The amount of fines, produced from this artificial abrasion was measured and was used to identify the durability of the aggregate. The subgrade and surfacing rock values are shown in figure 6.

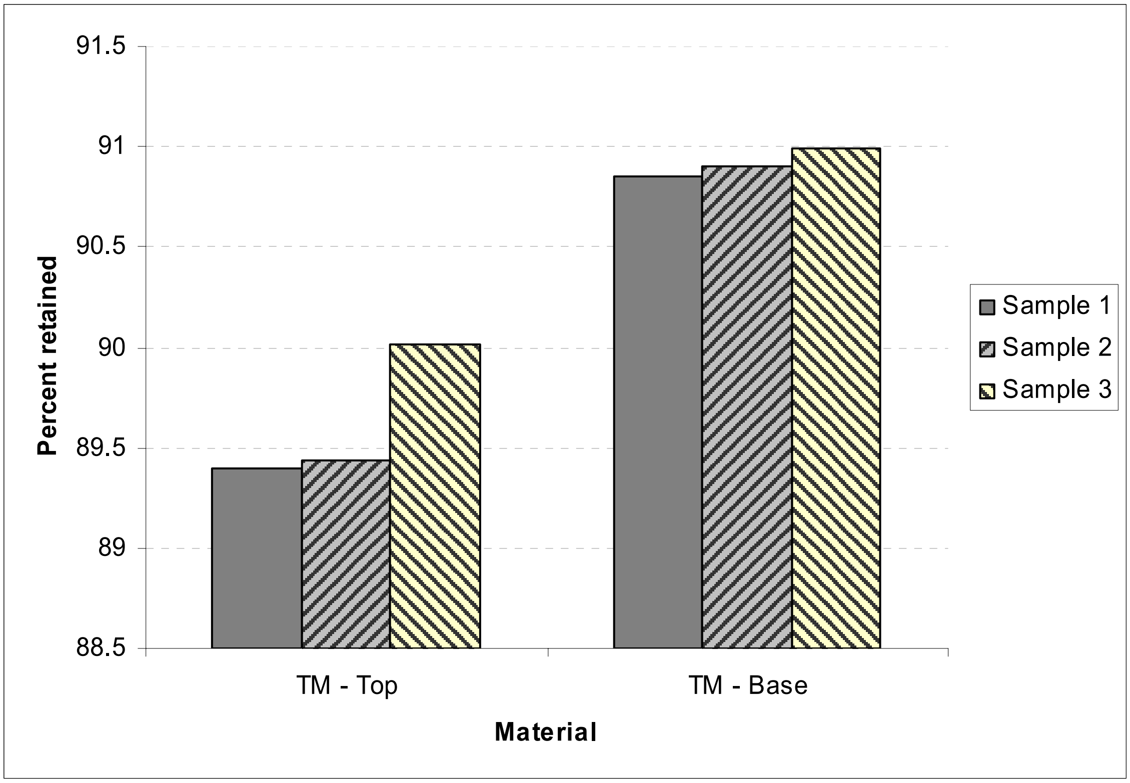


Figure 6: Micro-Deval results from surfacing and subgrade rock

This rock was of high quality with less than 10% fines being produced. Rock may be considered unsuitable for aggregate as part of an asphalt mix when the fines produced from the Micro-Deval exceed 18% of the weight (Cooley et al. 2002). No correlations have been developed at this time between Micro-Deval index values and performance in unbound-aggregate surfaced roads as far as predicting rut creation or sedimentation.

Eighteen of the 40 segments had exhibited ruts after approximately 3.5 MMbf of logs hauled. A rutting model was created using this data in a logistic regression, but no significant relationships were encountered. It could be that there is truly no significant relationship between these material properties and rut formation. The other possibility is that the variability of the system is too high and our sampling methods were unable to detect a significant difference between the combination of material properties and construction methods. Figure 7 and 8 show the incidences of ruts for two soil types, demonstrating that further information needs to be gathered.

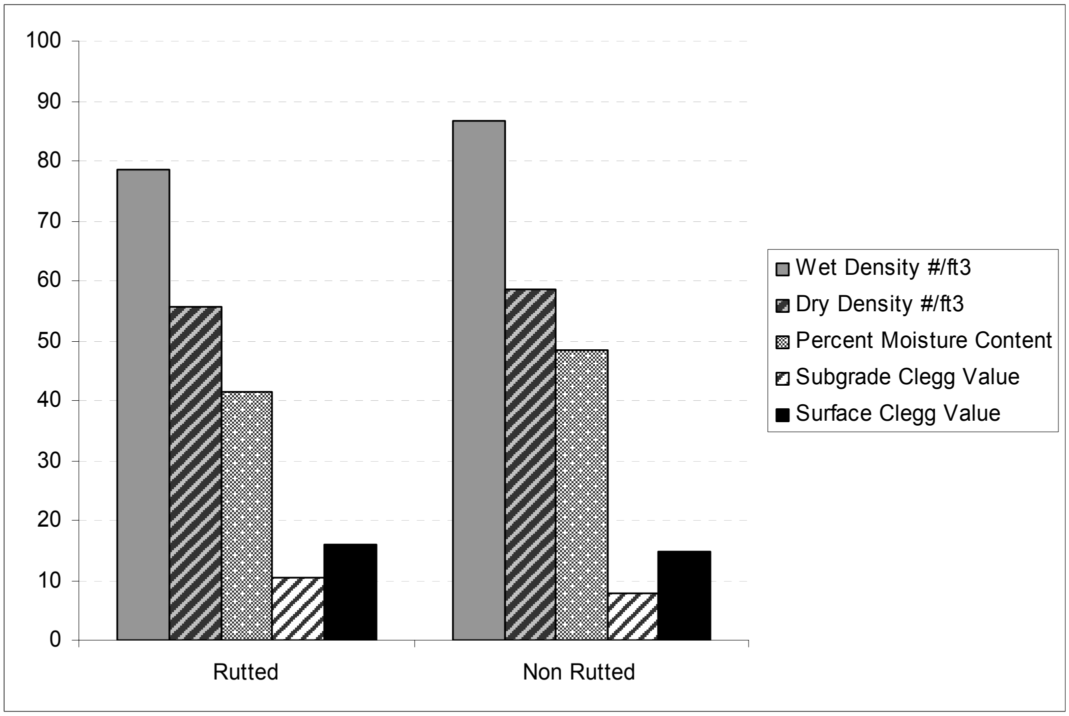


Figure 7: Comparison of rutted and non rutted sections for A-1-B AASHTO soil type

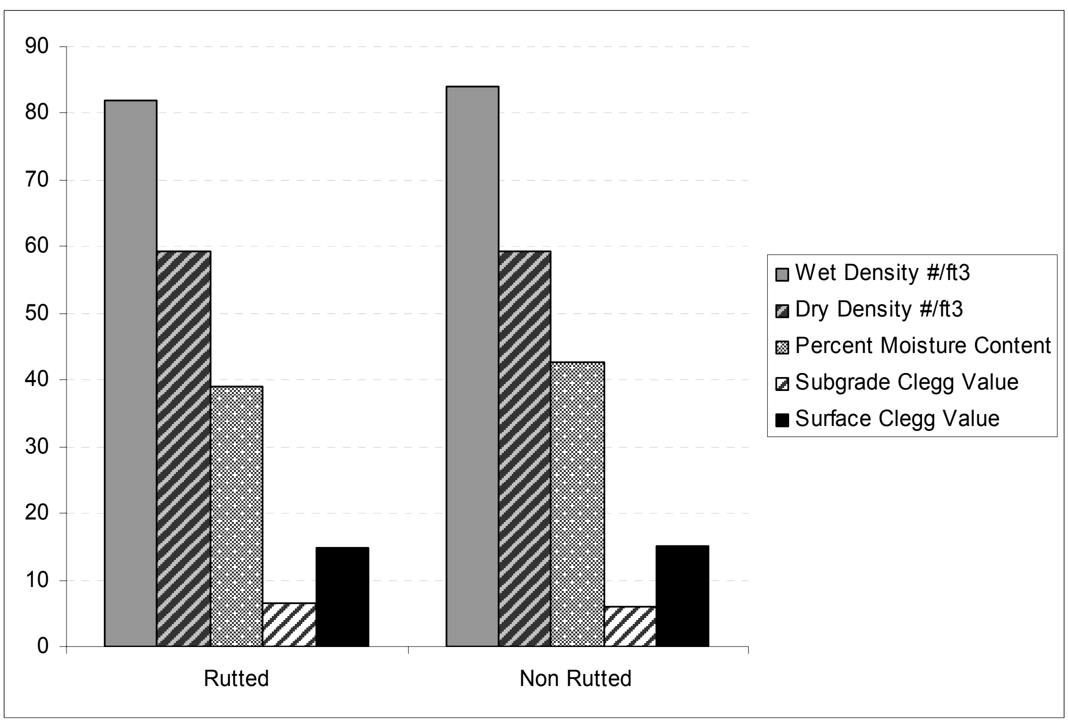


Figure 8: Comparison of rutted and non rutted sections for A-2-4 AASHTO soil type

Discussion

The variability around the parameters found in forest roads is problematic when it comes to designing road surfaces. The published values for parameters associated with the soil types encountered on this road were a dry unit weight of 100 to 140 pounds per cubic foot resulting in a CBR of 15 to 30 (Anonymous 1996) . These values are much higher than those found in the field. The dry unit weight found in the field for this soil was 45 to 78 pounds per cubic foot resulting in a CBR of 3 to 18. If the published values had been used to estimate the strength of this road without any field testing, the road would be much weaker than expected. This weaker road structure may result in increased rut formation for a given level of traffic. The results of these values can be seen more clearly by showing the impact on aggregate surfacing design. For example, if we apply "typical" published CBR strength values to an aggregate forest road assuming that we have obtained a 90% proctor compaction level, the predicted rut depth would be 1.70 inches. However, the unit weight actually achieved is much lower, only about 85% of the proctor compaction level, giving a predicted rut depth of more than 2 inches.

$$RD = 0.1741 \frac{(P_k)^{0.4704} t_p^{0.5695} R^{0.2478}}{\log(t)^{2.002} C_1^{0.9335} C_2^{0.2848}}$$

Where:

RD = rut depth in inches

P_k = equivalent single-wheel load (ESAL), kips

t_p = tire pressure, psi

R= traffic or passes

t = thickness of aggregate

C_1= CBR of top layer

C_2= CBR of subgrade layer

A five percent difference in proctor compaction level resulted in a 0.33 inch increase in rut depth. These values were obtained by assuming 25,000 ESAL's and 9 inches of surface aggregate. Typically, two-way traffic of one log truck (one pass unloaded and one pass loaded) produces 4 ESAL's. These published equations assume no variability in the material properties.

Conclusion

This project has begun to quantify the relationships between material properties and construction practices on forest roads to their environmental performance. The extreme variability found in the strength and moisture content parameters may make meeting environmental performance expectations difficult.

In the future, we need to develop a more aggressive approach to research that involves manipulative treatments instead of the passive measuring of existing practices. We will need to have the research funds and industry cooperation to allow us to monitor roads for a range of environmental values such as rutting and sedimentation as well as deliberately apply traffic to the road with the purpose of causing failure. This proposed experimental process is expected to yield the information necessary to support the road design, construction, and management practices that are required to meet the increasing environmental performance expectations for our forest roads.

References

Anonymous, 1996. Earth and Aggregate Surfacing Design Guide for Low Volume Roads. USDA Forest Service. EM-7170-16. Washington DC. p 302.

Cooley, L.A., M.S. Huner, R.H. James. 2002. Micro-Deval Testing of Aggregates in the Southeast. NCAT Report 02-09. National Center of Asphalt Technology University of Auburn.

Dawson, A. 1999. Implications of Granular Material Characteristics on the Response of Different Pavement Constructions. IN: Proceedings Symposium Modeling and Advanced Testing for Unbounded Granular Materials. Eds. Gomes, Correia, and Balkema. pp. 221-226.

Foltz, R. 1996. Traffic and No-traffic on an Aggregate Surfaced Road- Sediment Production Differences. Environmentally Sound Forest Roads and Wood Transport. FAO Seminar on Environmentally Sound Forest Roads, June 1996, Sinaia, Romania.

Selecting the Optimal Forest Road Alignment with a Maximum Sediment Production Constraint

Abdullah E. Akay[1], Alaaddin Yuksel[1], Mahmut Reis[1], Orhan Erdas[1], and John Sessions[2]

Abstract

The sum of road construction, maintenance, and transportation costs is minimized with the constraint that the average annual volume of sediment delivered to a stream from a forest road section cannot exceed a maximum level of acceptable sediment production. The sediment production is estimated using the method of a GIS based road erosion/delivery model. The model depends on the empirical relationships between road erosion factors including road surfacing, road template, road grade, vegetative cover, average precipitation, and delivery of eroded sediment to the stream channel. Road alignment with the lowest total cost is determined by a forest road alignment optimization model. Once the horizontal alignment is preselected, optimization routines are used to identify vertical alignment with the lowest total cost considering technically feasible alternatives. For each alternative vertical alignment, the model estimates the sediment delivery from a road section. The alternatives whose sediment productions exceed the acceptable limit are eliminated during the optimization process. If the total road cost without considering sediment production constraint is less than the total road cost with considering sediment production constraint, optimal forest road alignment is constrained by sediment production. In this study, the methodology and a preliminary result from a simple application is presented.

Key Words: *Forest roads, optimal alignment, sediment prediction*

---

[1] Department of Forest Engineering, Faculty of Forestry, Kahramanmaras Sutcu Imam University, 46100 Kahramanmaras, Turkey. Tel: +90 (344) 223-7923, Fax: +90 (344) 221-7244, E-mail: (akay, ayuksel, mreis, erdas)@ksu.edu.tr

[2] Department of Forest Engineering, College of Forestry, Oregon State University, Corvallis, Oregon 97331, USA. Tel: (541) 737-2818, Fax: (541) 737-4316, E-mail: john.sessions@oregonstate.edu

Introduction

Selecting optimal forest road alignment involves economic and environmental considerations. The total cost of road construction and maintenance are the most expensive activities in the process of timber production (Akay, 2003). Forest roads are the major contributors of sediment production delivered to streams from forestlands (Binkley and Brown 1993, Reid and Dunne 1984, and McClelland et al. 1999). Most of the sediment production occurs following road construction and maintenance activities (Grace et al. 1998). Potential sediment production delivered to streams from a road section increases as damages on forest cover, forest floor, and soil structure increase (Grace, 2002). Therefore, a forest road manager should evaluate sufficient number of alternative routes to select an optimal forest road alignment that minimizes the total road cost, while conforming to sediment production delivered from road sections to streams.

Forest road alignment optimization model is developed to assist a road manager in selecting an optimal path with minimized total road cost, reduced environmental impact, and improved driver safety (Akay, 2003). The model estimates the sediment production by using the method of a GIS based road erosion/delivery model. The alignment alternatives with excessive sediment productions are eliminated during the optimization process. In this paper, the road alignment optimization model is briefly described and the methodology behind the sediment prediction process is presented.

Methods

Road alignment optimization

A forest road alignment optimization model is developed to assist road managers with rapid evaluation of alternatives for the most economical path selection problem. The model selects the best path that minimizes sum of construction, maintenance and transportation costs; satisfies design specifications; considers environmental requirements; and provides driver safety.

A modern optimization technique (Simulated Annealing) is implemented to search for the best path (Reeves, 1993). Simulated annealing guides the search for the best path by using a neighborhood search. To minimize earthwork allocation cost for each alternative path, a linear programming method is used (Mayer and Stark, 1981). Linear programming method has the advantages of considering various soil characteristics along the roadway and possible borrow and landfill locations.

The model employs graphics routines (NewCyber3D, CA) to display high-resolution 2D and 3D images of the terrain in real-time, based on DEM data files. For locating initial path, intersection points are manually picked by mouse interactively on the scene. After locating the initial path, the model automatically locates cross-sections, computes earthwork, and calculates the horizontal and vertical alignment considering road design specifications (Figure 1).

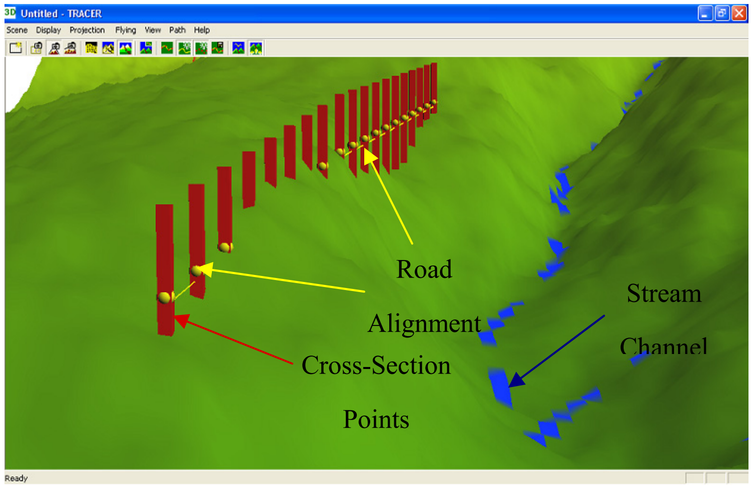


Figure 1— Optimized road alignment.

The road design specifications include geometric specifications (i.e. road gradient, curvature constraints, design speed, etc.), local site specifications (i.e. soil characteristics, stand data, etc.), and economic data (i.e. unit costs for road construction, maintenance, and transport activities). The environmental requirements include maximum sediment production, minimum allowable road grade for proper drainage, distance from streams, and maximum height of cuts and fills for soil protection. The model considers Safe Stopping Distance (SSD) on horizontal curves to ensure driver safety.

Road sediment delivery prediction

The model adopts the equations used in a GIS-based model (SEDMODL) that estimates average annual volume of sediment delivered to a stream from the road sections (Boise Cascade Corporation, 1999). In this model, the sediment delivered to a stream from each road section is estimated using the formulations developed depending on the empirical relationships between road surfacing, road use, road template, road grade, vegetative cover, and delivery of eroded sediment to the stream channel (Beschta 1978, Reid and Dunne 1984, and WDNR 1995). Total sediment delivered from each road segment (ton/yr) is predicted from two road sediment sources; road tread and cutslope:

$$Tread\ Sediment = GE_rS_fT_fG_fP_fD_fL_rRW \quad (1)$$

$$Cutslope\ Sediment = GE_rCS_fh_cD_fL_r \quad (2)$$

where,

GE_r = geological erosion rate (kg/m^3-yr)

S_f = tread surfacing factor

T_f = traffic factor

G_f = road grade factor

P_f = precipitation factor

D_f = delivery factor

L_r = length of the road segment (m)

RW = road width (m)

CS_f = cutslope cover factor

h_c = cutslope height (m)

The values for the variables used in the formulation are obtained from the previous research and listed in the data tables (Boise Cascade Corporation, 1999).

Geological erosion rate

The geological erosion rate is determined based on the geologic information such as dominant lithology and age. Table 1 indicates some of the erosion rates listed in SEDMODL documentation for 1:5000,000 scale geologic maps of Idaho, Washington, and Oregon (Bond and Wood 1978, Huntting et al. 1961, and Walker and MacLoed 1991).

Table 1─ Geologic erosion rates based on lithology and age (Boise Cascade Corp., 1999).

	Geologic Age of Formation				
Lithology	Quaternary	Tertiary	Mesozoic	Paleozoic	Precambrian
Basalt	15	15	30	30	30
Andesite	15	15	30	30	30
Ash	50	50	50	50	50
Tuff	50	50	30	30	30

Delivery factor

The sediment model computes the erosion delivery factor for each road stage based on the proximity of roads to streams (WDNR, 1995). It is assumed that a road segment that delivers directly to streams results a delivery factor of 1 (i.e. at stream crossings). A road segment within 30 meters and 60 meters of a stream results a delivery factor of 35 percent and 10 percent, respectively (i.e. at roads parallel to streams). The road segments that are located further than 60 meters do not deliver sediment to streams (i.e. sediment do not reach the stream).

The stream distance between a road stage and the closest stream point (*s*) is determined based on the stream data in attribute file. The model locates the coordinates of the middle point of the road stage under consideration. Then, it computes the horizontal distances from this point to the stream points listed on the attribute data file, and keeps the shortest distance as the stream distance. Figure 2 indicates the elements of stream distance from a road stage *r*, located between two consecutive points, *p-1* and *p*.

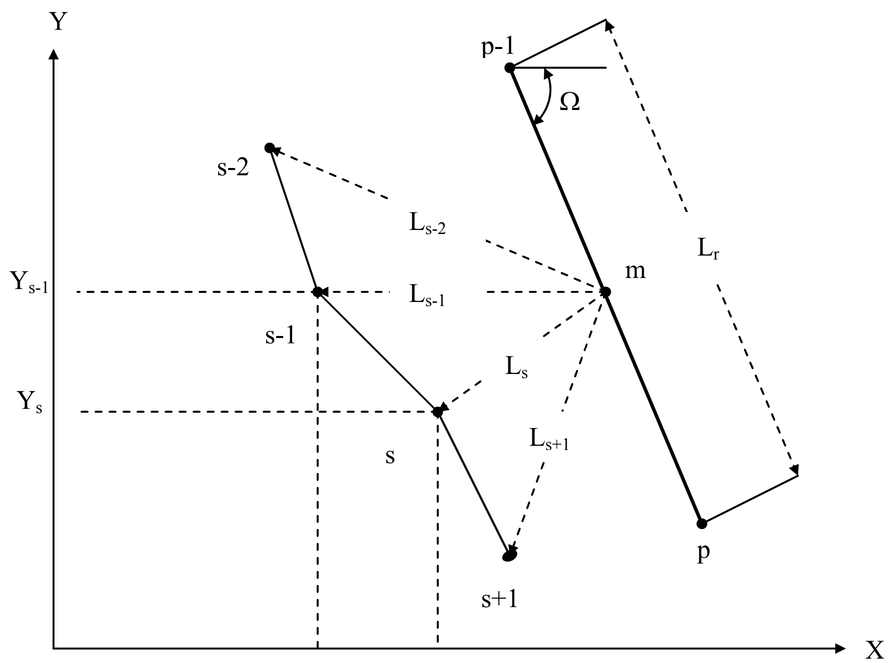


Figure 2─ Determining stream distance.

The model first computes the coordinates of the middle point of the road stage, *m*, based on angle of *Ω*, and *X* and *Y* coordinates of the station points:

$$X_m = X_{p-1} + L_r \cos(\Omega)/2 \qquad (3)$$

$$Y_m = Y_{p-1} - L_r \sin(\Omega)/2 \quad (4)$$

The distances from middle point to the stream points are computed. Following equation indicates a sample stream distance computation for stream point *s*:

$$L_s = \sqrt{(X_s - X_m)^2 (Y_s - Y_m)^2} \quad (5)$$

then, it compares all the stream distances (i.e. L_{s-2}, L_{s-1}, L_s, L_{s+1} etc.) and keeps the shortest one. In the case illustrated in Figure 1, the stream distance is L_s since it is the shortest stream distance.

Other factors

The sediment model provides the user with the surfacing factors of various surface types based on the previous research. The surfacing factors of gravel, pitrun, and native surface used in the model are 0.2, 0.5, and 1, respectively (WDNR, 1995). Traffic factors of various road classes are listed in the road class table. The data on this table are obtained from average measurements taken during road erosion inventory studies (Reid and Dunne 1984 and WDNR 1995). In this table, traffic factors of primary, secondary, and spur roads are 10, 2, and 1, respectively. The road slope factors are assigned to each road stage based on the road grade. For road stages with grade of less than 5 percent, 5 to 10 percent, and greater than 10 percent, the road grade factors are 0.2, 1, and 2.5, respectively (Reinig et al., 1991). In the model, precipitation factor is computed using the following formula based on the average annual precipitation in the basin, P_{avr} in millimeters (Reid, 1981):

$$P_f = \left(\frac{P_{avr}}{150mm} \right)^{0.8} \quad (6)$$

The cutslope cover factor as percent of vegetative or rock cover on cutslopes are also included into the sediment prediction equation based on the local conditions on the watershed (WDNR, 1995). Road width, length of the road stage, and cutslope height in the model is computed based on the road template information.

Results and Discussion

Model application

The model is applied to a simple application where a short road section (111.84 m) is located in a part of Capitol State Forest, considering road design specifications, environmental requirements, and driver safety (Kramer, 2001 and USDA Forest Service, 1999). 3D image of the terrain is generated based on DEM data from LIDAR (Aerotec, AL). Some of the constraints considered in the model are listed in Table 2.

Table 2─ Road design constraints.

Constraints	Values
Minimum curve radius	18 m
Minimum vertical curve length	15 m
Minimum gradient	± 2 %
Maximum gradient	16%
Maximum cut and fill height	2 m
Maximum sediment production	5 ton/km

After an initial path is manually generated, the model searches for the feasible alignments that satisfy all the constraints. The model evaluated 85 feasible solutions out of 1200 automatically generated vertical alignment alternatives. For each alternative alignment, the model estimates the sediment delivery from a road section.

The results from this simple application indicated that the unit road cost without considering the sediment production constraint ($34.39/m) is less than the unit road cost with considering the sediment production constraint ($46.93). Therefore, optimal forest road alignment is constrained by the sediment production. For the optimal road path without considering sediment production limit, the average annual sediment production is found to be 6.19 ton/km, which is about 24% more than acceptable sediment production.

The total cost summary for the optimal path that minimizes the total road cost and satisfies the acceptable sediment production constraint is illustrated in Table 3. According to the results, the largest cost component was total construction cost and followed by maintenance and transportation costs. For the optimal road path without considering sediment production limit, the total road cost is found to be $3847, which is about 27% less than the total road cost of the optimal road path with considering sediment production limit ($5249).

Table 3─ Total cost summary for the optimal path.

Costs	($)
Total Construction Cost	3795
Total Maintenance Cost	821
Total Transportation Cost	633
Total Road Cost	5249

Conclusions

To select an optimal forest road alignment that minimizes the total road costs and satisfies the acceptable sediment production constraint, a road manager should evaluate a number of alternative routes. An optimization model has been developed to help a road manager locating an optimal forest road alignment, while confirming specified constraints (Akay, 2003). The model also estimates average annual sediment production delivered from a road section to streams and eliminates the alternative road paths that exceed the acceptable sediment production limit. In computing sediment production, a GIS-based sediment prediction model was employed. The equations used in the sediment prediction model are easy to implement into a computer programming. However, there are number of limitations of the model that should be kept in mind when a road manager interprets the results of sediment predictions. In the model, it is assumed that all roads are in-slope with ditch, and roads are over two years old. Besides, the model tends to over-predict the sediment predictions if the attribute data (stream, soil etc.) is not accurate and road template information (road length, cut slope, etc.) are incomplete.

The results indicated that a forest road alignment optimization model can be a decision support tool that helps road managers to quickly evaluate alternative paths and to locate an optimal path, especially where sediment production delivered from a road section has high potential to exceed acceptable sediment production limit in the region. By using this optimization model, a road manager can select the optimal forest road alignment by evaluating the tradeoffs between cost components and road erosion factors.

References

Akay, A.E. 2003. Minimizing Total Cost of Construction, Maintenance, and Transportation

Costs with Computer-Aided Forest Road Design. Ph.D. Thesis, Oregon State University, Corvallis, Oregon. 229 p.

Beschta, R.L., 1978. Long-term patterns of sediment production following road constructionand logging in the Oregon Coast Range. Water Resources Research. 14:1011-1016.

Binkley, D., and T. C. Brown. 1993. Forest practices as nonpoint sources of pollution inNorth America. *Water Resources Bulletin* 29(5): 729–740.

Boise Cascade Corporation, 1999. SEDMODL-Boise Cascade road erosion delivery model.Technical documentation. 19 p.

Bond, J.G. and C.H. Wood, 1978. Geological Map of Idaho. Idaho Department of Lands,Bureau of Mines and Geology. 1:500,000 scale.

Grace, J. M., III, B. Rummer, B. J. Stokes, and J. Wilhoit. 1998. Evaluation of erosion controltechniques on forest roads. *Trans. ASAE* 41(2): 383–391.

Grace, J.M., III. 2002. Control Of Sedıment Export From The Forest Road Prısm, ASAEAnnual Meeting. Paper No. 995048. Vol. 45(4):1-6.

Mayer, R. and R. Stark. 1981. Earthmoving logistics. Journal of Const. Div. 107(CO2): 297-312.

Huntting, M.T., W.A. Bennett, V.E. Livingston Jr., and W.S. Moen, 1961. Geologic Map ofWashington Department of Conservation, Division of Mine and Geology, 1:500,000 scale.

Kramer, B.W. 2001. Forest road contracting, construction, and maintenance for small forestwoodland owners. Oregon State University, Forest Research Laboratory, Research Contribution 35. 79 p.

McClelland, D. E., R. B. Foltz, C. M. Falter, W. D. Wilson, T. Cundy, R. L. Schuster, J.

Saurbier, C. Rabe, and R. Heinemann. 1999. Relative effects on a low–volume road system of landslides resulting from episodic storms in Northern Idaho. In *Seventh International Conference on Low–Volume Roads: Vol.2. Transportation Research Record 1652*, 235–243. Washington, D.C.: National Research Council, Transportation Research Board.

Reeves, C. 1993. Modern heuristic techniques for combinatorial problems. Department ofStatistic and Operational Research School of Mathematical and Information Sciences, Coventry University. 320 p.

Reid, L. M., and T. Dunne. 1984. Sediment production from forest road surfaces. *WaterResources Research* 20(11): 1753–1761.

Reinig, L., R.L. Beveridge, J.P. Potyondy, and F.M. Hernandez, 1991. BOISED user’s guide and program documentation. USDA Forest Service, Boise National Forest. 12p.

USDA Forest Service, 1999. Cost estimate guide for road construction Region 6. Cost GuideZone 5, Davis-Bacon Area 5, Oregon. 85p.

Walker, G.W. and N.S. MacLeod. 1991. Geologic Map of Oregon. U.S. Geological Survey.1:500,000 scale.

WDNR, 1995. Standard methodology for conducting watershed analysis, Version 3.0.Washington Forest Practices Board.

Developing a Heuristic Solver for MAGIS: a Planning Tool to Integrate Resource Management and Transportation Planning on Large Forest Lands

Woodam Chung[1], Greg Jones[2], Janet Sullivan[3], and John Sessions[4]

Abstract

Forest managers have to make decisions on forest management activities and access roads when managing forest resources. Although most forest management is inevitably engaged with access roads, simultaneous planning of the resource management and transportation constantly becomes a challenge due to the increase of problem size and complexity. The Multi-resource Analysis and Geographic Information System (MAGIS) developed by the USDA Forest Service is one of few decision support systems that are able to solve the integrated tactical planning problems. However, the applications of the system have been restricted because MAGIS relies on a Mixed Integer Programming (MIP) solution technique that has substantial limitations when applied to large planning problems. In this paper, we introduce a new heuristic approach, developed to solve large, integrated tactical planning problems, and built in the current MAGIS framework as a new heuristic solver. This new solver iteratively runs a sequence of two heuristic solution techniques to simultaneously optimize management scheduling and transportation planning problems. Combining a simulated annealing solution method with a network algorithm, the solver is able to consider side constraints in a forest-level harvest scheduling problem, while building efficient road networks that make selected management activities possible. The algorithms and applications of the heuristic solver are described.

---

[1] Assistant Professor, Department of Forest Management, University of Montana, Missoula, MT 59812. Email: woodam.chung@umontana.edu

[2] Project Leader, Economics of Forest Management on Public Lands, USDA Forest Service, Rocky Mountain Research Station, Forestry Sciences Lab, P.O. Box 8089, Missoula, MT 58807. Email: jgjones@fs.fed.us

[3] Information Technology Specialist, Economics of Forest Management on Public Lands, USDA Forest Service, Rocky Mountain Research Station, Forestry Sciences Lab, P.O. Box 8089, Missoula, MT 58807. Email: jsullivan@fs.fed.us

[4] Professor, Department of Forest Engineering, Oregon State University, Corvallis, OR 97331. Email: john.sessions@oregonstate.edu

Key words: decision support system, forest tactical planning, heuristic, mixed integer programming, network analysis

Introduction

Forest managers have to make decisions on forest management activities and access roads when managing forest resources. A wide variety of optimization models have been developed to help forest managers efficiently make these decisions. Some of the models are designed to separately analyze management scheduling and transportation problems, while others try to integrate the two problems and solve them simultaneously. Although many forest managers believe that effective harvesting and transportation planning should be undertaken simultaneously, integrating two different planning problems has been a challenge due to the increase of problem size and complexity.

The most practical approach to such problems has been to solve two planning problems separately, while linking them by using the solution of one problem as given conditions of the other problem. An example of this approach is to select resource management activities using site-specific harvest scheduling tools (e.g., Stanley by Remsoft Inc.) or professional field experiences, and then identify cost effective access roads and timing of road projects using a transportation cost minimizing program, such as NETWORK2000 (Chung and Sessions 2003). Solving these planning problems in isolation is relatively simple, but generally leads to suboptimal solutions (Jones et al. 1986, Weintraub et al. 1994).

MIP formulations were introduced to integrate two tactical planning problems because of the binary character (1 or 0) of road projects (Kirby et al. 1986). These MIP approaches were able to simultaneous select timber management activities and road project options, but the applications are limited to small problems due to dramatic increase in computation time when solving large problems. Because of this reason, large and integrated planning problems are still difficult to solve using the MIP approach.

To overcome the limitation of MIP techniques, heuristic optimization approaches have been introduced to forest planning, aiming to quickly produce good and feasible solutions, without necessarily providing any guarantee of solution quality. Early heuristic approaches to simultaneously solve forest harvest scheduling and transportation planning problems include the Heuristic Integer Programming (HIP) procedure (Weintraub et al. 1994). This procedure solves the Integrated Resources Planning Model (IRPM, Kirby et al. 1986)-type MIP problems by introducing heuristic rules to mathematical programming techniques. Many other combinatorial optimization methods such as Interchange, Simulated Annealing, and Tabu Search, have been applied to solve integrated resource and transportation planning problems (Murray and Church 1995, Richardson and Gunn 2000, Clark et al, 2000), but most of them were used to solve particularly designed planning problems, and have not been implemented in widely applicable decision support systems.

Scheduling and Network Analysis Program (SNAP by Sessions and Sessions 1993) was an example of a user-friendly decision support system that solved integrated tactical planning problems. Using a series of heuristics, such as Random Search, a Steiner network algorithm, and a shortest path algorithm, the system solved harvest scheduling and road building problems considering harvesting costs, revenues, multiple species, alternative destinations, transportation systems, and wildlife habitat connections. Although solutions are quite reasonable, the solution approach has the drawback of not handling additional side constraints, such as budget and adjacency constraints (Weintraub et al. 2000). Developed in a DOS environment, SNAP also does not work in modern computer operating systems. Another example of the same kind of decision support system is the Multi-resource Analysis and Geographic Information System (MAGIS) developed by the USDA Forest Service (Zuuring et al. 1995). Instead of using heuristic solution techniques, MAGIS formulates management scenarios and road building options as MIP problems and solves them using a commercial mathematical programming package. Although MAGIS is public domain, applications of the system have been limited because purchase of the commercial linear programming package is required, and MIP solution techniques have substantive limitations when applied to large planning problems.

In this paper, we introduce a new heuristic approach, developed to solve large, integrated tactical planning problems, and built in the current MAGIS framework as a new heuristic solver for MAGIS. This new solver iteratively runs a sequence of two heuristic solution techniques to simultaneously optimize management scheduling and transportation planning problems. Combining a simulated annealing heuristic (Kirkpatrick et al. 1983) with a heuristic network algorithm developed by Sessions (1985), the solver is able to consider side constraints in a forest-level harvest scheduling problem, while building efficient road networks required for the selected management activities. We describe the algorithms and applications of the heuristic solver.

Problem Formulation in MAGIS

MAGIS is a microcomputer-based spatial decision support system that schedules forest resource management and road activities on both a geographic and temporal basis. The planning horizon includes five periods of length defined by the user. There are two main spatial components to a planning problem solved by

MAGIS: a treatment unit coverage and a road network coverage.

Management activities on the treatment units may involve removal of timber products, create changes to the residual vegetation, or both. Timber products are loaded on to the road network at 'loading nodes' and travel down the network until reaching an 'exit' node, which can be the mill site or represent a link to a mill (Figure 1). For each treatment unit, management regimes (schedules of activities) are assigned as options that MAGIS can choose from. Activities that remove timber products have one or more logging methods, each of which can have a different set of loading nodes. For example, treatment unit D in Figure 1 might have an option to commercial thin using skidder, and load onto the network at node 5. It might also have the option for a group selection using helicopter, and load onto the network at node 4. Thus, a single treatment unit can have one to many options, depending on the suitability of management regimes and loading nodes.

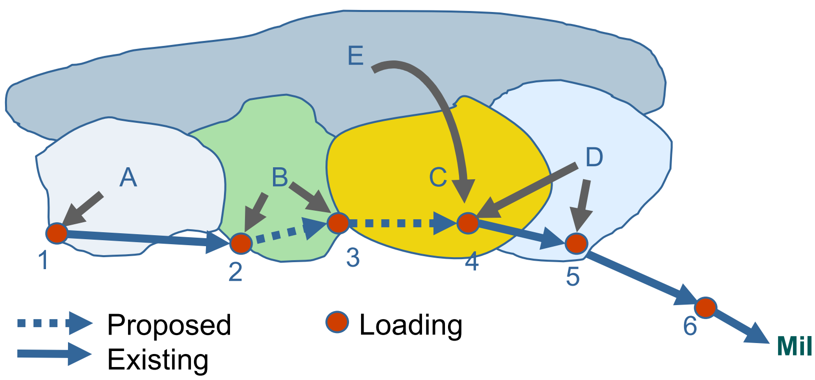


Figure 1—Treatment units and loading node options in MAGIS.

A road network coverage comprises nodes and links that represent existing and proposed road segments in a project area. Each road segment is assigned a haul cost and one or many management options called road projects. Road projects include permanent or temporary construction and reconstruction. Traffic (e.g., logging trucks) originates with a resource project and is routed through the road network to one or more user-defined final destination locations. Timber outputs are calculated as a result of management activities on a unit per unit area basis, as are costs that are linked to activities.

Once treatment unit and network coverages are established for a project area with alternative management activities, MAGIS can determine the combination and schedule of management regimes and road use to optimize a selected objective, either maximize the net present value (NPV) or minimize total costs. The following equations are used in the MAGIS heuristic solver as the objective functions:

NPV maximization problems

$$Max \quad Z = \sum_{n=1}^{N} NPV_n - \sum_{i=1}^{I}\left(\sum_{j=1}^{J} V_{ij}X_{ij} + \sum_{j=1}^{J} F_{ij}\delta_{ij}\right) - Penalty$$

$$st: \quad \delta_{ij} = 1 \quad if \quad X_{ij} > 0$$

$$\delta_{ij} = 0 \quad if \quad X_{ij} = 0$$

where,

N = number of treatment units (polygons)

NPV_n = net present value of the management regime selected for treatment unit *n*

I = number of time periods

J = number of links in the road network

V_{ij} = discounted variable costs per unit volume on link *j* at period *i*

F_{ij} = discounted fixed costs on link *j* at period *i*

X_{ij} = total volume of output products transported over link *j* at period *i*

Penalty = a user-defined penalty applied to solutions violating any of given constraints

Cost minimization problems

$$Min \quad Z = \sum_{n=1}^{N} total\cos t_n + \sum_{i=1}^{I}\left(\sum_{j=1}^{J} V_{ij}X_{ij} + \sum_{j=1}^{J} F_{ij}\delta_{ij}\right) + Penalty$$

$$st: \quad \delta_{ij} = 1 \quad if \quad X_{ij} > 0$$

$$\delta_{ij} = 0 \quad if \quad X_{ij} = 0$$

where,

$totalcost_n$ = total discounted costs of the management regime selected for treatment unit *n*

Problem Solution Techniques in the Heuristic Solver

Using Simulated Annealing to schedule resource management activities

Simulated Annealing (SA) is a heuristic search technique that has been widely used to solve large combinatorial problems in various fields (Kirkpatrick et al. 1983). The approach is a Monte Carlo method that uses a local search in which a subset of solutions is explored by moving from one solution to a neighboring solution. To avoid becoming trapped in a local optimum, the procedure provides for an occasional acceptance of an inferior solution to allow it to move away from a local optimum.

The probability of accepting inferior solutions partly depends on temperature levels. SA starts from a high temperature, which likely provides high probability to accept inferior solutions. SA explores a broad range of solution space at this high temperature stage. The temperature drops down as the solution process goes on. At a low temperature level SA intensively search a narrow solution space where good solutions are likely located. Once the pre-defined minimum temperature is met, SA stops the solution process and reports the best solution found. In forestry, SA has been investigated by a number of researchers to solve spatial harvest scheduling problems, including Lockwood and Moore (1993), Murray and Church (1995), and Öhman and Eriksson (1998).

The SA process employed in the heuristic solver is described in the following steps and Figure 2.

Step 1. Develop an initial solution by randomly assigning each treatment unit (polygon) one of the management regimes available for the unit including "No action".

Step 2. Create a new solution by slightly modifying the current solution; assign a different management regime to a randomly selected treatment unit.

Step 3. Evaluate the new solution. If the solution violates any of the side constraints (e.g., minimum volume harvested or maximum allowable acres treated in a certain period), penalize the solution.

Step 4. If this new solution is better than the current solution, accept the new solution. Otherwise, generate random x in the range (0, 1), and if x < exp{-(solution difference between new and current solutions)/temperature}, accept the new solution. If the new solution does not meet any of the above conditions, discard the solution.

Step 5. Go to Step 2 unless a user-defined stopping criterion (e.g., ending temperature) is met.

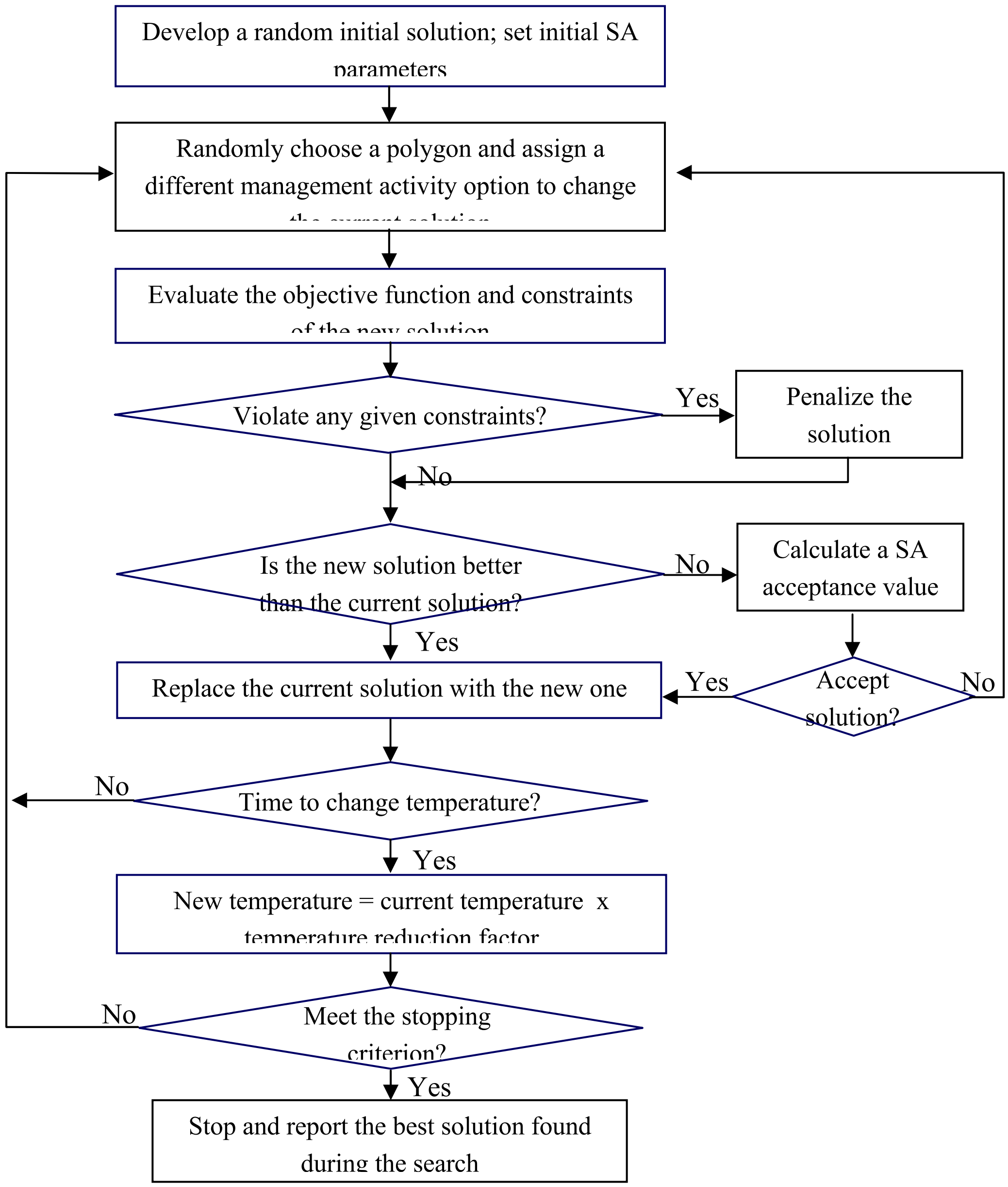


Figure 2—Flowchart of the Simulated Annealing algorithm implemented in the heuristic solver.

Using the heuristic network algorithm to identify cost effective road networks

The heuristic network algorithm developed by Sessions (1985) is employed to optimize road options that facilitate selected resource management activities. The algorithm starts with sorting loading nodes associated with the selected management regimes by time and volume (Figure 3). Then, it solves for the shortest path from each loading node to the destination while considering only variable (transportation) costs for the first iteration. After the first iteration, the algorithm adjusts variable costs to include consideration of fixed costs per link. For each link product volumes are summed across 5 planning periods (Vol_j, where, j is a link ID.) The variable costs for each link, VC_j, are then recalculated using the concept of equivalent variable costs (Schnelle 1980). Thus, revised variable cost at link j becomes $VC_j = VC_{init} + F_j/Vol_j$. The volume over all links is then reset to zero and the next iteration starts using the new set of variable costs. This process continues until the same solution is repeated for two consecutive iterations.

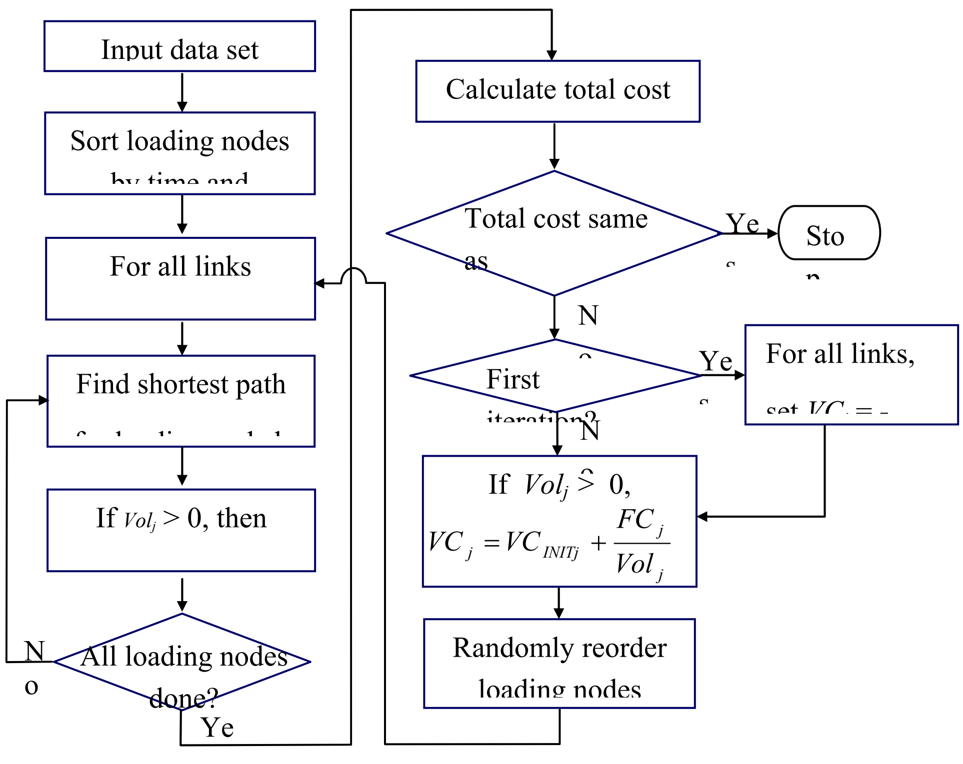


Figure 3—Flowchart of the heuristic network algorithm developed by Sessions (1985).

If a road segment is assigned two or more project options (e.g., different road standards), the heuristic solver adds extra nodes, and connects the nodes to "from"- and "to-nodes" of the road segment using dummy links that represent different options (Sessions 1985). The least-cost road option is selected by the solver during problem solution after the haul volumes over a link are determined. In the case that more than one possible destination exists in the road network, the solver adds a dummy node which acts the final destination, and connects all the actual destinations to the dummy node via one-way links. In this way, all output products from management regimes arrive at the final destination via one of the actual destination nodes. To identify the actual destination node, the solver checks the second-to-last node of the optimal path for each output product.

Integrating two solution techniques – a feedback mechanism

The heuristic solver first optimizes resource management activities by selecting the best management regime for each treatment unit without considering truck transportation (Figure 4). Then, it identifies loading nodes required for the selected management regimes and calculates timber volumes arriving at each of the loading nodes. Using these loading nodes and product volumes as the entry nodes and traffic volumes to a given road network, the solver optimizes road projects and transportation routes, which completes the first iteration. The second iteration begins with temporarily adding the road costs to the management regimes selected for the treatment unit polygons during the first iteration. If more than one management regime shares the same road links, the road costs on the links are distributed to the management regimes in proportion to the product volume that each management regime contributes. With this updated costs, the solver optimizes management regimes again for all treatment units as the first part of the second iteration. When a solution is evaluated, original costs of each management regime are restored and counted.

This feedback mechanism of the heuristic solver temporarily increases the costs of the management regimes that were ever included in the previous solutions. Since high cost management regimes are not likely selected during the solution process, this may provide a relatively higher chance for being chosen to the management regimes that are never included in the solutions. A number of repetitions of this feedback process are required to get to a steady state where the results remain the same as the previous iteration. Depending on the problem, the repetition of this process might not merge to a steady state, but keep bouncing around within a range. Setting a stopping criterion such as maximum number of repetitions (RP in Figure 4) will be necessary to terminate the algorithm in a reasonable time. The best solution is always stored over the iteration process.

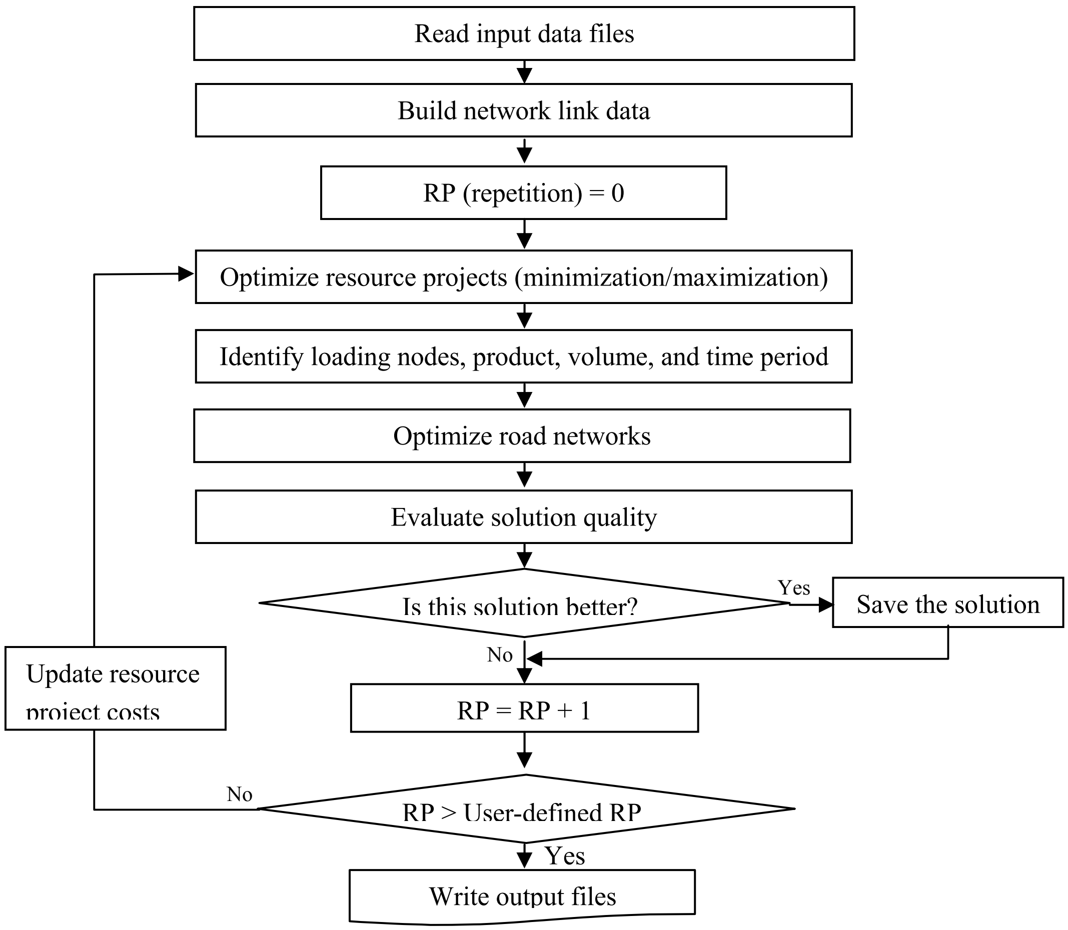
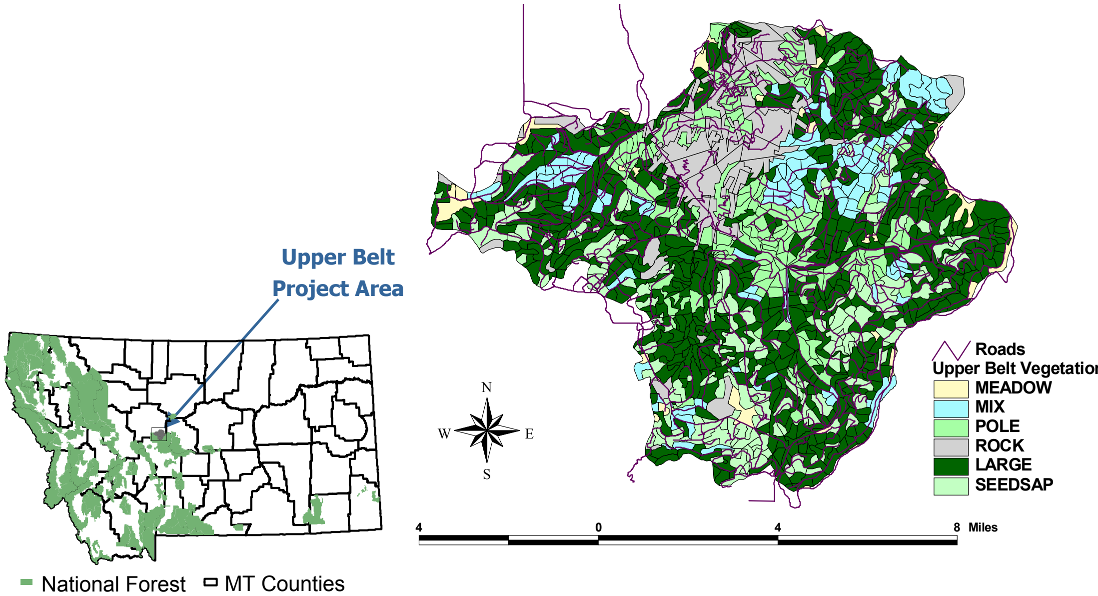


Figure 4— Integrating two optimization techniques in the heuristic solver

Applications

The heuristic solver was applied to solve a resource management and transportation planning problem developed for the Upper Belt Creek area (46,866 acres) in the Lewis and Clark National Forest in central Montana (Figure 5a). A total of 21,147 management options were developed for 999 treatment units located in the project area (Figure 5b). Proposed road segments developed by field managers were combined with existing road segments, which constructs a 926-link road network. Two different products (sawtimber and pulp) and five 10-year planning periods are considered in the sample planning problem.



(a) (b)

Figure 5—The Upper Belt project area located in the Lewis and Clark National Forest in central Montana (a) and vegetation classes in the area (b).

The results from the heuristic solver are compared with the optimal solution found by the Mixed Integer Programming solver. The following control parameters were set up for the heuristic solver to solve the sample planning problem.

- Number of repetitions (RP) = 100
- Number of iterations for SA = 100
- Initial temperature = 1/100 of the objective function value of the initial solution
- Ending temperature = 1.0
- Cooling rates = 0.999
- Penalty factor = 1,000

Sample Problem

Data descriptions

Number of polygons: 999 polygons

Number of management options: 21,147

Number of planning periods: 5 10-year periods

Output products: 2 (sawtimber and pulp)

Constraints: Acres to be treated in period 1 > 100 acres

Sawtimber product in period 1 > 400,000 ft^3

Pulp product in period 1> 100,000 ft^3

Number of road segments: 926 links

Results

Resource project costs: $28,950

Road project and traffic costs: $94,790

Overall project costs: $123,740

Best solution found at: 89th repetition

Solution time for 100 repetitions: 3 hours 49 min.

Comparison with the optimal solution found by the MIP solver

Heuristic solver	MIP solver	Difference
$123,740	$103,143	$20,597 (+20%)

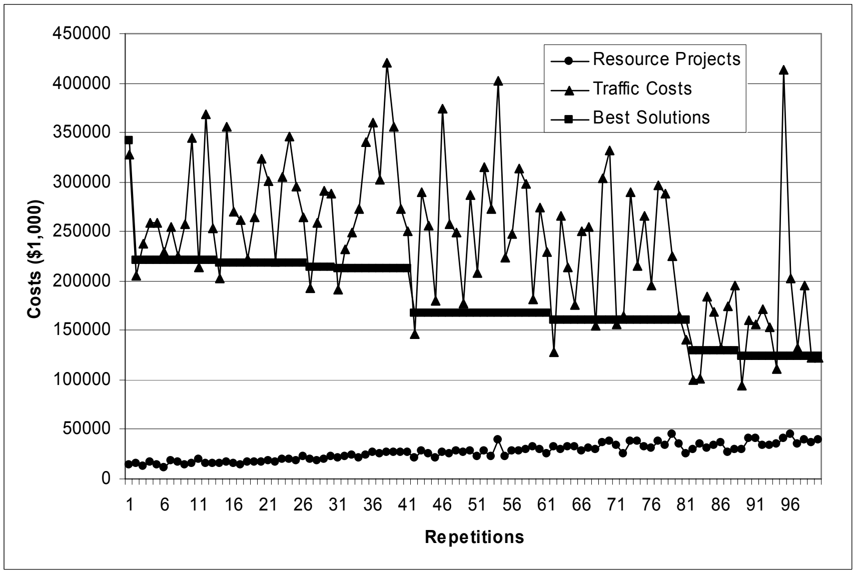


Figure 6—Performance of the heuristic solver on the sample problem.

Discussion

We have investigated an iterative, sequential use of two heuristic optimization methods in solving large, integrated, tactical forest planning problems, and developed a new heuristic solver for MAGIS by embedding the new approach into the current MAGIS framework. A simulated annealing algorithm used in the heuristic solver allows considering various constraints related to resource management projects, while the heuristic network algorithm provides the ability to solve large transportation planning problems quickly. A feedback and repetitive mechanism of the solver facilitates linking two different planning problems and exploring a variety of solution alternatives.

The heuristic solver has been applied to a sample problem and the result was compared with the optimal solution found by the MAGIS MIP solver. Although the comparison confirms that the heuristic approach does not necessarily guarantee optimality of its solutions, it shows the heuristic solver is able to find relatively good and feasible solutions. By running two heuristic solution techniques repeatedly, the heuristic solver explores a variety of solution alternatives and obtains better solutions (Figure 6). Furthermore, since the heuristic solver has virtually no limitations on problem size, it can solve very large, integrated planning problems that the MIP solver often cannot handle.

It is necessary to further validate the performance of the heuristic solver with various types and difficulty levels of problems. Besides not guaranteeing solution optimality, there are other drawbacks of the heuristic solver. Currently, it is neither able to constrain traffic amounts on specific road segments, nor able to apply different transportation costs to specific traffic types. Not considering adjacency constraints is another limitation of the current solver. Further study should investigate a modification of the problem solving techniques used in the heuristic solver to overcome these limitations.

Further study should also examine the applications of other heuristic solution techniques in order to improve solution quality and efficiency of problem solving. Other heuristic techniques may include Great Deluge (Dueck 1993), Ant Colony (Dorigo et al. 1996), and the new heuristic network algorithm (Chung and Sessions 2001) that was developed to solve multiple goal transportation planning problems.

References

Chung, W.; Sessions, J. 2003. NETWORK 2000: A Program for Optimizing Large Fixed and Variable Cost Transportation Problems. In: G.J. Arthaud and T.M. Barrett (eds.) Systems Analysis in Forest Resources, Kluwer Academic Publishers. pp. 109-120.

Chung, W.; Sessions, J. 2001. NETWORK 2001 - Transportation planning under multiple objectives. In: P. Schiess and F. Krogstad (eds.) Proceedings of the International Mountain Logging and 11th Pacific Northwest Skyline Symposium, December 10-12, Seattle, WA.

Clark, M.; Meller, R.;McDonald, T. A three-stage heuristic for harvest scheduling with access road network development. Forest Science 46(2)204-218.

Dorigo, M.; Maniezzo, V.; Colorni, A. 1996. The ant system: Optimization by a colony of cooperating agents. IEEE Transactions on Systems, Man, and Cybernetics-Part B, 26(1): 29-41.

Dueck, G. 1993. New optimization heuristics – the great deluge algorithm and the record-to-record travel. Journal of computational physics 104: 86-92.

Jones, J.G.; Hyde, F.C., III; Meacham, M.L. 1986. Four analytical approaches for integrating land management and transportation planning on forest lands. USDA For. Serv. Res. Pap. INT-361. 33p.

Kirby, M.; Hager, W.; Wong, P. 1986. Simultaneous planning of wildland management and transportation alternatives. TIMS Studies in the Management Sciences. 21:371-387.

Kirkpatrick, S.; Gelatt, C.D.; Vecchi, M.P. 1983. Optimization by simulated annealing. Science 220: 671-680.

Lockwood, C.; Moore, T. 1993. Harvest scheduling with spatial constraints: a simulated annealing approach. Canadian Journal of Forest Research 23: 468-478.

Murray, A.T.; Church, R.L. 1995. Heuristic solution to operational forest planning problems. OR Spektrum. 16pp.

Öhman, K.; Eriksson, L.O. 1998. The core area concept in forming contiguous areas for long-term forest planning. Canadian Journal of Forest Research 28: 1032-1039.

Richardson, E.; Gunn, E. 2000. A model and Tabu Search method to optimize stand harvest and road construction schedules. Forest Science 46(2)188-203.

Schnelle, B. 1980. MINCOST users instructions. USDA Forest Service Report, Northern Region, Div. of Engineering, Missoula, MT.

Sessions, J. 1985. A heuristic algorithm for the solution of the fixed and variable cost transportation problem. In Proceedings of the 1985 Symposium on Systems Analysis in Forest Resources, Society of American Foresters, Athens, GA. p. 324-336.

Sessions, J.; Sessions, J.B. 1993. SNAP II+ version 2.07 user's guide. USDA Forest Service, Washington Office, Ft. Collins, CO.

Weintraub, A.P.; Jones, G.; Magendzo, A.; Meacham, M.; Kirby, M. 1994. A heuristic system to solve mixed integer forest planning models. Operations Research 42(6): 1010-1024.

Weintraub, A.P.; Church, R.L.; Murray, A.T.; Guignard, M. 2000. Forest management models and combinatorial algorithms: analysis of state of the art. Annals of Operations Research 96: 271-285.

Zuuring, H.R.; Wood, W.L.; Jones, J.G. 1995. Overview of MAGIS: a multi-resource analysis and geographic information system. USDA Forest Service Res. Note INT-427.

Developing Road Management Alternatives[1]

Elizabeth D. Coulter[2], Dave Young[3], Dave Lysne[4], Rich Symons[5], and Tom Edwards, PE, PLS[6]

Abstract

In light of decreasing state funding for higher education, the Oregon State University College Forests are being asked to provide increasing revenue to the College of Forestry through an expanded timber sale program. This expansion means that the operating season must be extended beyond the summer dry period into spring and fall, necessitating wet-weather hauling on some roads. This change in road standard has meant a sharp increase in road expenditures. There is a need to develop road management alternatives that address a range of forest goals. Each of these alternatives comes with a range of costs, benefits, and risks. This project developed a road classification based on several criteria such as current road condition, anticipated road use, and environmental risk. This classification allows managers and decision makers to better understand and plan for seasonal harvesting restrictions.

Key Words: road classification, season of haul

---

[1] This paper was presented at Council on Forest Engineering 2005: Soil, Water, and Timber Management: Forest Engineering Solutions in Response to Forest Regulations, July 11-14, 2005, Fortuna, California

[2] This work was completed while a faculty member at Oregon State University. Currently Assistant Professor of Integrated Natural Resource Planning, College of Forestry and Conservation, The University of Montana, Missoula, MT 59812, 406-243-5529, elizabeth.coulter@umontana.edu

[3] Road and Trail Specialist, College Forests, Oregon State University, Peavy Arboretum, Corvallis, OR 97331, 541-737-6595, david.young@oregonstate.edu

[4] Director, College Forests, Oregon State University, Peavy Arboretum, Corvallis, OR 97331, 541.737.3562, dave.lysne@oregonstate.edu

[5] Timber Program Forester, College Forests, Oregon State University, Peavy Arboretum, Corvallis, OR 97331, 541-737-6460, richard.symons@oregonstate.edu

[6] Engineer, College Forests, Oregon State University, Peavy Arboretum, Corvallis, OR 97331, 541.737.6563, tom.edwards@oregonstate.edu

Introduction

Over the last decade the Oregon State University College of Forestry has increasingly come to rely on timber revenue from the OSU College Forests (CF) to fill in behind decreasing state funding for college programs. Historically, CF has offered one or two sales per year and has primarily restricted these sales to the summer months when logs can be hauled over dry roads. The expanded timber program has been accomplished by both increasing the number of sales offered each year and the volume of each sale (Figure 1). Forest roads with in the CF now need to be maintained, and in many cases upgraded, to handle larger volumes of timber across a wider range of weather and soil conditions.

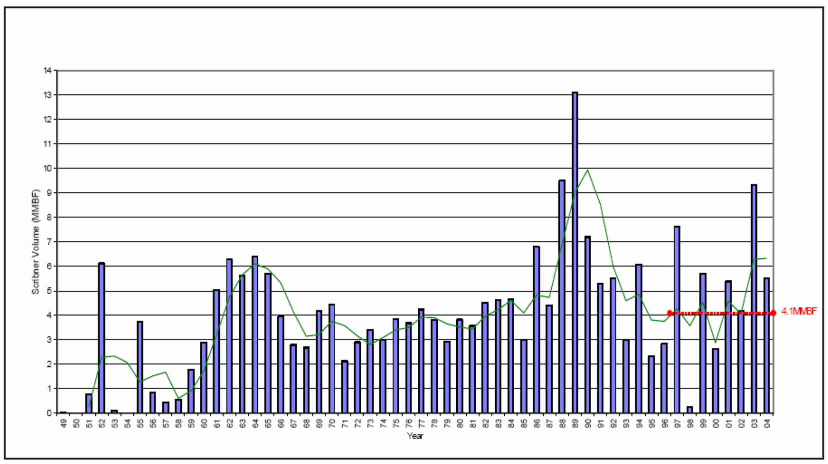


Figure 1 - Volume harvested from McDonald Dunn Research Forests from 1949-2004 in Scribner volume (MMBF) with a 3-year moving trend line shown in green and the desired harvest level from the 1993 Forest Plan (after removal of the College of Agricultural Science lands) shown in red (from http://www.cof.orst.edu/resfor/plan2004/McDonald-Dunn%20Plan.pdf).

Historically CF roads have been classified based on functional classes such as mainline, collector, and spur roads. This is the same classification used by most other forest landowners. Maintenance classes (regimes) were then assigned to each road based on classification. This classification missed several important factors that dictate the level of maintenance to be applied to each road, most importantly season of use. Therefore, a classification system is needed that recognizes both use level and the suitability of each road segment to be used at different times of year.

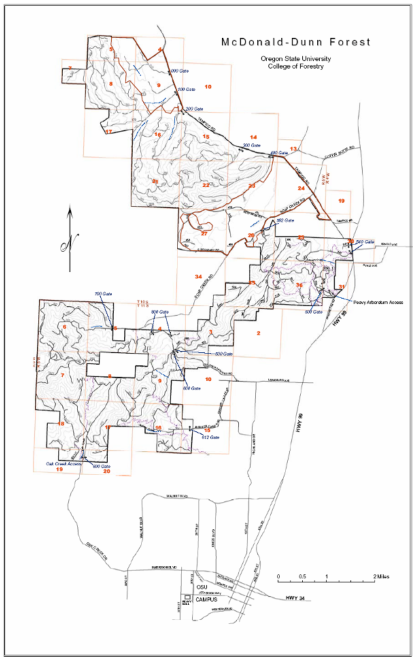


Figure 2 - McDonald-Dunn forest roads (from http://www.cof.orst.edu/resfor/plan2004/McDonald-Dunn%20Plan.pdf).

Methods

Study area

The CF maintains approximately 225 km (140 miles) of primarily gravel surfaced low-volume roads located in five separate forested tracts in Western Oregon. Most of these roads are closed to vehicular public access but are maintained for timber extraction and the support of teaching and research activities. The majority of these roads access approximately 11,000 acres in the McDonald and Dunn tracts located north of Corvallis, Oregon (Figure 2). Only the roads within these two tracts are included in this work.

Roads within the McDonald-Dunn were originally built between the 1930's and 1980's, however many have undergone significant upgrades, specifically to drainage systems. As with all road systems, road standards have varied over time with use and maintenance level.

Road management strategies

Several road management strategies were considered. These strategies ranged from upgrading all roads to three-season haul use, to requiring summer use only on all roads, to specific strategies for specific roads. Upgrading all roads to handle three-season haul would be far too expensive and clearly not needed in many areas. Restricting the hauling season to dry weather on all roads would significantly impact the ability of CF to meet target revenue levels. Therefore the decision was made to individual assign one of six haul categories to each road:

- Summer only – only dry season hauling is advised
- Three-season – the road is able to sustain three-season haul in it's current condition
- Upgrade to three-season – while the road is not currently able to sustain three-season haul, it could be upgraded to handle hauling in wet weather
- Patch-as-you-go – the road may be able to carry three-season haul in its current condition but substantial patching may be expected in some areas
- Destroy and rebuild – use the road as-is and rebuild to an appropriate standard after hauling is complete
- Abandon – the road is no longer needed to support timber extraction, teaching, research, or demonstration activities

Criteria

Six criteria were determined to be important to the assignment of the above haul categories:

- Environmental risk – specifically the risk of road-related sediment reaching waters of the state
- Volume – timber volume that is scheduled to be harvested in the current 10-year harvest period that will likely include a road in the haul route
- Seasonality – season of timber harvest, specifically taking restrictions such as threatened and endangered species requirements into consideration
- Subgrade width
- Subgrade integrity – level of subgrade compaction and consolidation
- Surface competency – the combination of rock depth, rock quality, and degree of surfacing contamination

Results

A matrix was developed to assign road management strategies (haul categories) to roads based on each road's performance on some or all of the six descriptive criteria (Table 1). The performance of each road segment on most of the criteria is relative and described by non-quantitative means. Maintenance objectives were also developed for each haul category recognizing that roads are not static entities and road conditions do change over time.

Table 1 – Road haul category assignment matrix. Stars refer to a road's performance relative to each criterion with one star being low performance and five, high performance. Blanks are used when a criterion has no bearing on the choice of the respective haul category.

Haul Category	Summer Only	Three-Season	Upgrade	Patch-as-you-go	Destroy and Rebuild	Abandon
Environmental Risk	φφφ	φφφφ	φφφφ	φφφ	φ	φφφφφ
Volume	φφ	φφφφφ	φφφφ	φφφ	φφ	None
Seasonality	Summer	Spring, summer, or fall	Summer with Spring or fall option	Spring, summer, or fall	Spring, summer, or fall	None
Subgrade width		≥16 feet	≥16 feet	≤14 feet		
Subgrade integrity	φφ	φφφφφ	φφφφ	φφφφ	φ	
Surface competency	φφ	φφφφφ	φφφ	φφφ	φφ	

Summer only

The haul category summer only was assigned to roads with incompetent surfacing that are not likely to carry a substantial volume of timber in the near future (next 10-year harvest period). This haul category was assigned to both surfaced and unsurfaced roads but was the only option for an unsurfaced road that was not scheduled to be abandoned. While it is theoretically possible to assign an unsurfaced road to the "upgrade" haul category, none of the unsurfaced roads on the CF access timber volumes significant enough to justify the cost of upgrading the road to allow for wet-weather hauling. Maintenance objectives for summer only roads focus on maintaining adequate drainage when roads are not in use.

Three-season

Three-season roads were those that are currently maintained to a standard that allows for wet-weather hauling. This category was generally synonymous with the roads that had been assigned the functional designation of mainline. This haul classification allows for the greatest flexibility in season of harvest. Because of the larger volume of timber that will be moved over the three-season roads, these roads will likely require maintenance on at least an annual basis. Additions of aggregate surfacing may be needed over time as rock is lost and worn through use and compromised through the addition of organic material through litter fall.

Upgrade

Roads selected for the upgrade designation were those that do not currently meet the standards that would allow for wet weather hauling but that could be upgraded to do so. These roads needed to have a subgrade wide enough to allow for the addition of aggregate while maintaining a running surface of at least 14 feet. The main difference between roads receiving the three-season and upgrade haul designations was the surface competency. As stated above, surface competency is a combination of rock depth, rock quality, and degree of aggregate contamination. None of these factors alone can describe the ability of a road to support wet-weather hauling and therefore must be looked at in aggregate.

Roads receiving the upgrade designation can be used in their current condition for dry season hauling. The recommended maintenance level for these roads is to retain the ability of the road to carry dry weather log traffic while maintaining the option to fortify the road for wet weather hauling. This means maintaining adequate drainage and discouraging the contamination of aggregate surfacing through periodic grading, herbicide application, and/or the removal of roadside contributors of organic material (i.e. hardwood trees that currently overtop the road).

Patch-as-you-go

The major difference between roads assigned the three-season or upgrade designations and those receive the patch-as-you-go classification was subgrade width. Many of the roads on CF lands are simply not wide enough to allow for additions of any more aggregate than what is currently on the roads. Additionally, these roads are located such that widening the subgrade is not an attractive option financially or environmentally. These roads carry the warning that yes, they can be used for three-season hauling, but managers should expect that repairs will likely be required during wet weather. These repairs have the potential to disrupt the delivery of logs, increase hauling costs, and cause environmental damage if not carefully managed. These roads receive maintenance similar to those designated as potential upgrade roads.

Destroy and rebuild

Roads assigned the destroy and rebuild haul designation were those that were formerly categorized functionally as either collector or spur roads, meaning they access small to moderate timber volume. These roads had to pose a low environmental risk, specifically in regards to sediment reaching fish-bearing streams, so that if the road were to fail during hauling operations (i.e. ruts that penetrate the subgrade develop) no significant environmental degradation would occur. In many cases these roads accessed only one upcoming timber sale area. For many of these roads the existing subgrade and surface competency is such that the cost to rebuild the road to a higher standard that would allow three-season hauling prior to timber extraction would exceed the additional hauling costs due to poor road conditions combined with the cost to return the road to a standard that allows for management access after hauling. If the road access only one sale area then there is no reason to rebuild a road to a three-season haul standard after hauling activities have ceased because this road will not be used again for timber extraction (heavy hauling) until the end of the next rotation.

Abandon

Several road segments were selected for abandonment. These roads are no longer needed to access timber and pose a high environmental risk. Abandonment will require that all vehicular access is blocked and the roads are self-draining and stable.

Discussion

This method for road classification goes beyond the functional classifications often used to describe the location of a road within a road network and recognize that not all roads with the same functional classification have the same ability to support heavy traffic, specifically during wet conditions. Functional classifications generally do not take factors such as surfacing competency or environmental risk into consideration and require managers to further explain the capability of a road to handle traffic at different times of year. These haul designations can help managers explain road needs and seasonal haul restrictions to others who do not have an intimate knowledge of an individual road's capability to support wet-weather hauling.

It is acknowledged that roads are not static entities. Road conditions change over time with use, maintenance, and natural inputs. The exact nature, extent, and rate of these changes have not been well quantified. Additional research is needed to better understand how roads behave over time.

The Opportunities to Haul Timber during Wet Weather with Forest Road Improvements

Elizabeth M. Toman[1], Arne E. Skaugset[2], Glen E. Murphy[3]

Abstract

Wet weather use on low-volume roads can be a significant source of chronic turbidity and fine sediment to streams that in turn may be detrimental to aquatic organisms including salmonids. As a result, regulations governing wet weather hauling in the western timber-producing states and British Columbia have become increasingly restrictive. A potential result of the changes in regulations is limited access to an increasing proportion of commercial forest land during the winter months. A viable option for forest managers wishing to take advantage of winter log markets is to improve road surfaces to minimize environmental problems that currently accompany wet weather hauling. The objective of this research was to investigate the opportunity costs associated with regulatory restrictions for timber hauling on a forest road during wet weather. The regulatory restrictions set forth in the California Forest Practice Rules were applied to the MacDonald-Dunn Research Forest at Oregon State University. Rainfall was applied randomly over twenty years and harvesting and hauling activities were restricted accordingly. For a twenty-year period, timber production and net revenue were reduced 15% by precipitation restrictions. The cost of restricted hauling and harvesting is potentially a resource that could be made available to improve aggregate road surfaces to minimize hauling restrictions during wet weather.

Key words: opportunity costs, low-volume roads, wet-weather hauling

[1] Graduate Research Assistant, Department of Forest Engineering, Oregon State University, 204 Peavy Hall, Corvallis, OR 97331-5706. email: elizabeth.toman@oregonstate.edu

[2] Associate Professor, Department of Forest Engineering, Oregon State University, 204 Peavy Hall, Corvallis, OR 97331-5706. email: arne.skaugset@oregonstate.edu

[3] Professor, Department of Forest Engineering, Oregon State University, 204 Peavy Hall, Corvallis, OR 97331-5706. email: glen.murphy@oregonstate.edu

Introduction

Low-volume roads produce fine sediments especially during wet weather use (Reid and Dunn 1984, Bilby et al 1989). Studies have shown that roads may be hydrologically connected to the streams and that road runoff may enter the stream network (Wemple 1994, Toman 2004). The potential for increased fine sediments and turbidity in fish-bearing streams has led to increased regulation in recent years in western states regarding harvesting and hauling activities during wet weather. For timber operations in the winter period (October 15 through May 1), the California Forest Practice Rules of 2004 require landowners to submit winter period operating plans that address erosion and road use issues. Also, hauling on forest roads during the winter months cannot occur when saturated soil conditions exist on the road. Forest owners in California have taken these regulations very seriously and some have gone an extra step to further restrict hauling during any period of precipitation. Regulations in California and other western states may become even more restrictive as technical panels review the current regulations and suggest changes.

Results of the changes in state regulations are to take an increasing proportion of commercial forest land out of production, to increase the cost of carrying out intensive forest management activities, especially timber harvesting, and to decrease the management flexibility of forest land managers and owners. Thus, forest land managers, especially the private industrial land manager, have increasingly been put at a competitive disadvantage in the domestic and international market for solid wood.

A viable option for forest managers wishing to take advantage of winter log markets is to improve road surfaces to minimize environmental problems that currently accompany wet weather hauling. This may be accomplished by the design of aggregate pavements that use geosynthetics and/or high quality aggregate. The objective of this research was to investigate the opportunity costs associated with regulatory restrictions for timber hauling on a forest road during wet weather.

Methods

The regulations set forth in the California Forest Practice Rules of 2004 were applied to the McDonald-Dunn Research Forest (Figure 1) located northwest of Corvallis, Oregon. Precipitation information for the area was used to determine when harvesting and hauling were restricted.

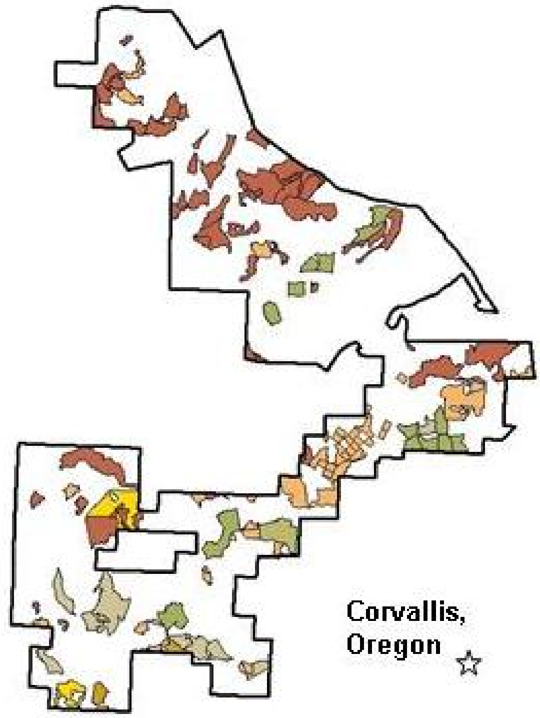


Figure 1 - McDonald-Dunn Research Forest and a possible scenario of harvest units to be cut within a future twenty-year period.

The McDonald-Dunn Research Forest is owned and managed by Oregon State University, thus a large research database is available for the forest including weather information and stand inventories. Daily precipitation values for the area are available dating from 1889 to the present. The forest plan for the McDonald-Dunn Research Forest was recently reviewed and revised for the next ten-year periods. Analysis for the forest plan revision included evaluating possible treatment types and harvest schedules for each harvest unit, and estimating production volume and projected revenue for each sale based on log grade and type. For this study, management scenarios for two, ten-year periods were used to determine harvest scheduling and annual production volumes for a future twenty-year period.

Hourly harvest costs were estimated for each scheduled unit based on production studies from the literature that were relevant to the characteristics of each harvest unit. Hourly hauling costs from the harvest units to a lumber mill located in Eugene, Oregon were estimated using Network2000®.

Winter-period precipitation data from 1889 to 2003 were randomly applied to a future twenty-year period. Through personal communication with forest land owners and analysis of the past 115 years of rainfall data, a daily precipitation value of 5.08

mm (0.20 inches) was determined to be the threshold value in which harvesting and hauling activities were stopped. Annual scheduled machine hours were reduced for the harvesting systems and hauling trucks based on the number of work days that had precipitation that exceeded 5.08 mm (0.20 inches).

Annual harvesting and hauling costs were discounted at a rate of 7% for future costs. Discounted annual costs were subtracted from annual timber revenue to calculate annual net revenue for the forest in present net worth. The estimated costs and revenue for a future twenty-year period with and without reductions in scheduled hours due to wet-weather restrictions were compared.

Results and Discussion

Over the 115-year period of precipitation record from 1889 to 2003, halting harvesting activities at a daily rainfall value of 5.08 mm would result in an average annual reduction of 36.6 work days (27% of eligible work days during the winter period of October 15 to May 1). Historical precipitation data was randomly applied to twenty future years.

Table 1 shows the reduction of work days for each year with wet weather restrictions and what these days represent as a percentage of work days lost annually. The average days lost for the hypothetical twenty-year period is similar to that estimated from 115 years of historical data.

The percentage of days lost annually was used to reduce the annual scheduled machine hours (SMH) for the harvesting systems and hauling vehicles. Although this decreased the annual operating costs, ownership costs remained the same and thus total machine costs per scheduled machine hour were increased. The reduction in annual scheduled machine hours from wet weather restrictions resulted in increases in hauling and harvesting costs per thousand board feet (MBF) as shown in Table 2.

Table 1 - Days unavailable to harvest and haul each year due to wet weather restrictions.

Year	Work days lost during winter	Percent of winter days lost	Percent of annual days lost
1	34.2	25%	14%
2	44.5	33%	18%
3	40.4	30%	16%
4	36.3	27%	15%
5	34.2	25%	14%
6	50.6	37%	20%
7	28.0	21%	11%
8	22.6	17%	9%
9	32.8	24%	13%
10	25.3	19%	10%
11	54.7	40%	22%
12	34.2	25%	14%
13	27.4	20%	11%
14	43.1	32%	17%
15	41.0	30%	16%
16	28.0	21%	11%
17	34.2	25%	14%
18	47.2	35%	19%
19	42.4	31%	17%
20	33.5	25%	13%
Avg.	36.7	27%	15%

Over the twenty-year period increases in harvesting and hauling costs per thousand board feet ranged from 1.7% (year 8) to 7.0% (year 11) and averaged 3.7%. Approximately 73% of the increased harvesting and hauling costs, was associated with the harvesting operations and 27% was associated with hauling timber from the harvest unit to the lumber mill.

Table 2 - Increases in harvesting and hauling costs per thousand board feet as a result of decreased scheduled machine hours.

Year	Increase in costs per MBF	Year	Increase in costs per MBF
1	2.5%	11	7.0%
2	4.3%	12	3.9%
3	3.6%	13	2.9%
4	3.3%	14	4.5%
5	3.4%	15	4.7%
6	4.2%	16	2.9%
7	2.5%	17	3.4%
8	1.7%	18	6.1%
9	3.0%	19	3.3%
10	2.6%	20	3.9%

The percentage of days lost annually was also used to reduce the annual timber production. An increase in machine costs and a decrease in production produced a decrease in net revenue. Over the twenty-year period this decrease ranged from 9.5% (year 8) to 22.7% (year 11) and averaged 15.4% (Figure 2).

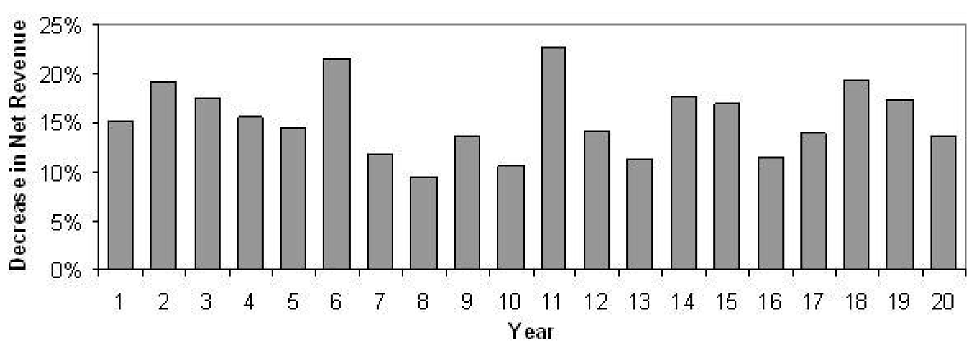


Figure 2 - Yearly decreases in net revenue from wet-weather harvesting and hauling restrictions.

In this management scenario, over 82 million board feet (MMBF) is scheduled to be harvested from the McDonald-Dunn Research Forest in the next twenty years.

With this example, production could be decreased to 70.5 MMBF with reductions in harvesting and hauling days from wet weather restrictions. Also with wet weather reductions, the total net revenue for the forest for this time period is projected to decrease from $35.5 million to $30 million (present net worth) (Table 3). The $5.5 million difference could be considered an opportunity cost and used to upgrade the road surfaces to minimize sediment production and to allow for harvesting and hauling during wet weather.

Table 3 - Harvesting results from a 20-year period in the McDonald-Dunn Research Forest

	20-year period with no reductions	20-year period with wet-weater reductions
Timber Production (MBF)	82,648	70,512
Harvesting and Hauling Costs	$7,901,719	$6,972,441
Timber Revenue	$43,390,200	$37,018,698
Total Net Revenue	$35,488,481	$30,046,257

Conclusions

The cost of restricted hauling and harvesting is potentially a resource that could be made available to improve aggregate road surfaces to minimize hauling restrictions during wet weather. In this study the opportunity costs were, on average, 15% of the total net revenue. Although 15% of the net revenue from the first year of harvesting may not be enough to improve all haul roads, over time improving the road surfaces may result in increases in production and net revenue. Also, this study did not consider the fluctuation of market log prices during the winter season. As restrictions for wet-weather hauling increase, log supply will decrease and the demand and price for logs during the winter season will increase. Forest land owners wishing to profit from the winter log market should consider the opportunity costs of upgrading their road surfaces for wet weather hauling.

REFERENCES

Bilby, R.E.; Sullivan, K.; Duncan, S.H. 1989. The generation and fate of road-surface sediment in forested watersheds in southwestern Washington. Forest Science, 35(2): 453-468.

Reid, L.M.; Dunne, T. 1984. Sediment production from forest road surfaces. Water Resources Research, 20(11): 1753-1761.

Toman, Elizabeth M. 2004. Forest road hydrology: The influence of forest roads on stream flow at stream crossings. Corvallis, Oregon: Oregon State University; 78 p. M.S. thesis.

Wemple, Beverly C. 1994. Hydrologic integration of forest roads with stream networks in two basins, Western Cascades, Oregon. Corvallis, Oregon: Oregon State University; 88 p. M.S. thesis.

AN INTEGRATED APPROACH TO MECHANICAL FOREST FUEL REDUCTION: QUANTIFYING MULTIPLE FACTORS AT THE STAND LEVEL

M. Chad Bolding [a], Loren D. Kellogg [b], and Chad T. Davis [c]

[a] Ph.D. Candidate, Forest Engineering Department, Oregon State University; M.Chad.Bolding@oregonstate.edu

[b] Professor, Forest Engineering Department, Oregon State University; Loren.Kellogg@oregonstate.edu

[c] Faculty Research Assistant, Forest Engineering Department, Oregon State University; Chad.Davis@oregonstate.edu

Abstract

Forest management practices such as fire exclusion, suppression, and reduced timber harvesting have allowed many forested stands throughout the western US to become densely overstocked with small diameter trees. This situation often leads to intensive, catastrophic, stand-replacement fires. Prescribed fire, manual removal of small diameter trees, and mechanical treatments have been used to successfully reduce forest fuels. However, there are numerous limitations and knowledge gaps for managers to select, plan, and implement appropriate technologies to meet sustainable forest management goals. Important combined factors including mechanical system cost, effectiveness, soil disturbance, and the projected fire behavior benefit must be assessed. A current Oregon State University, Department of Forest Engineering study is underway to quantify decision criteria that forest managers must consider when selecting equipment and prescribing mechanical forest fuel reduction treatments throughout Oregon. Research objectives are to compare and contrast the capabilities of various mechanical equipment configurations employed in fuel reduction treatments prescribed in differing forest and density characteristics. Conventional ground-based thinning systems as well as purpose built non-commercial harvesting machines are being investigated through an integrated approach to quantify 1) harvesting system productivity and economics, 2) soil disturbance generated from mechanical systems, and 3) system and treatment effectiveness for altering future fire behavior. This research will

supplement the small information pool for commercial forest fuel reduction and establish baseline information for non-commercial systems. This study will be the first of its kind to successfully integrate soils, harvesting, and future fire behavior into mechanical fuel reduction activities.

Keywords: fuel reduction, harvesting cost, system productivity, soil disturbance, fire behavior

Incorporating Forest Road Erosion into a Resource Transportation Planning Model

Jennifer E. Rackley and Woodam Chung

Department of Forest Management, University of Montana

Abstract:

This on-going research project incorporates an environmental impact of forest roads into an economic analysis for resource transportation planning. The Forest Service WEPP, which is a road erosion prediction model, is combined with NETWORK 2000, an extensive economic forest transportation network planning model. WEPP is used to estimate the sediment delivery from each road segment to streams. Based on the estimated sediment delivery, NETWORK2000 produces alternative road systems that minimize both transportation costs and overall sediment delivery. This methodology will be applied to the Mica Creek watershed in Idaho, the Potlatch Timber Company's experimental forest. The results are hoped to provide economically efficient and environmentally friendly alternatives for a forest road network in the watershed. The methodology and preliminary results are presented.

An Application of Ant Colony Optimization Metaheuristic to Solving Forest Transportation Planning Problems with Side Constraints

Marco A. Contreras S. and Woodam Chung

Department of Forest Management, University of Montana

Abstract

Timber transportation is one of the most expensive activities in forest operations. Traditionally, road management goals have been set to find the combination of road development and harvest equipment placement to minimize total harvesting and transportation costs. However, modern transportation planning problems are not driven only by economics of timber management, but also by multiple uses of roads and their social and ecological impacts, such as recreation, soil erosion, wildlife and fish habitats, etc. These social and environmental considerations and requirements introduce side constraints into forest transportation planning problems, which makes the problems larger and much more complex. The objective of this on-going research project is to develop a new problem-solving technique using the Ant Colony optimization metaheuristic that is able to solve large and complex transportation planning problems with side constraints. The new algorithm and sample applications are presented.

Spatial Decision Support Systems for GIS based Forest Operations Planning

Woodam Chung

Department of Forest Management, University of Montana

Abstract:

Several spatial decision-support systems developed for GIS based forest operations planning are introduced. CPLAN is a decision support system that simultaneously optimizes road locations and cable logging equipment placement using GIS data such as existing roads, streams, timber volume, and terrain information. CableAnalysis is a computer program with interactive functions designed to do payload analysis for cable logging systems using digital elevation models. The program can identify feasible cable logging areas, find efficient tower locations, estimate load carrying capacity, and determine proper intermediate support locations. NETWORK2000 is a transportation planning tool that solves large, fixed and variable cost, multiple period, multiple product transportation problems. MAGIS, a specially designed geographic information system for multiple resource analysis, is able to solve integrated harvest scheduling and road building problems considering harvesting costs, revenues, multiple products, and transportation systems.

An Ergonomic Profile of American Made Forest Machines.

Robert H. Dupré, Graduate Assistant, Louisiana Forest Products Development Center, Louisiana State University Agricultural Center, Baton Rouge, LA;

Craig Brown, Student,

Michael J. Donnelly, Student,

Fereydoun Aghazadeh, Associate Professor, Dept. of Industrial Engineering, Louisiana State University, Baton Rouge, LA; and

Cornelis F. de Hoop, Associate Professor, Louisiana Forest Products Development Center, Louisiana State University Agricultural Center, Baton Rouge, LA.

Managing author: Robert H. Dupré, Louisiana Forest Products Development Center LSU Renewable Natural Resources Bldg. Baton Rouge, LA 70803-6202.

E-mail: rdupre1@lsu.edu

Abstract

The forest products industry reports 26% more injuries than general industries making it one of the most dangerous industries in the United States. Human factors and violations of safe operating procedures are the major cause of accidents and fatalities in the forest industry. The objectives of this study were to profile American made forest machines based on the ergonomic standards given in the Swedish handbook, *Ergonomic Guidelines for Forest Machines,* and to classify each machine based on its impact to the health and wellbeing of the operator. Ergonomic measurements were taken on a Tigercat 750 feller-buncher, a Cat 550 skidder and a Tigercat 230B loader and profiled according to standards listed in the Swedish handbook, *Ergonomic Guidelines for Forest Machines*. Each machine was classed based on a set of guidelines for cab access, cab design, operator's seat and controls. The profile results show cab access to be the most limiting ergonomic feature studied on the three machines covered. The Tigercat 230B loader was classed the highest showing it had the lowest impact to the health and well being of the operator.

GuyLinePC: An Interactive Guyline Tension Analysis Program

Matthew Thompson

Department of Forest Engineering, Oregon State University

Abstract

A computer-based model for evaluating guyline tension in a tower yarding system is presented. The program calculates guyline tension according to the catenary model, utilizing combinatorial optimization heuristics and numerical iterative methods to reach equilibrium states for both the pre-tension phase and the yarding phase, respectively. Our model seeks to improve upon the usability and applicability of previously developed models (Carson, et al). The program is Windows-based (implemented in MS Visual Basic) and thus should be readily accessible to first time users. Initially our program will provide utility as an instructional tool, but we hope to develop a comprehensive decision-support useful in industry, with the potential for hand-held applications. Future research will focus on synthetic rope models and the creation of an additional heuristic to assist in deciding which stumps to utilize as anchors. Possible objectives for anchor selection include minimal tower compression, minimal maximum guyline tension, or minimal rigging cost.

References

Carson, W., Jens E Jorgensen, Stephen E Reutebuch, and William J Bramwell. A Procedure for Analysis of Guyline Tension. USFS General Technical Report PNW-142; September 1982.

Thinning Productivity and Costs using a Yoader (non-guyline yarder) in Northern Idaho.

Jeff Halbrook and Han-Sup Han

Research Forester and Assistant Professor,

Department of Forest Products,

University of Idaho

Moscow, Idaho 83844-1132

Abstract

A commercial thinning operation using a yoader (non-guyline yarder) was evaluated outside Sandpoint, Idaho to estimate production and costs. The excavator-based yarder utilizes the bucket to stabilize during operation and manages landings. These machines are relatively new, and production studies are limited. Elemental time studies were conducted during this study for both chainsaw felling and yarding operations. Trees were felled, limbed, and topped in the woods in order to leave nutrients onsite. Tree length logs were yarded using a Komatsu-based yoader and a Maki manual slackpulling carriage. This poster presents our findings and observations, including operational benefits and limitations of using a yoader for skyline thinning.

A formulation will be developed for determining the total cost associated with transporting timber over two different road standards

Henk Stander

Department of Forest Engineering, Oregon State University

Abstract

A formulation will be developed for determining the total cost associated with transporting timber over two different road standards. Through substitution and derivation this formulation will be altered to return the optimal distance that should be associated with each road standard. It will show the importance of timber volumes in determining the optimal road standard. This formulation will in turn be implemented onto spatial road data by using various GIS techniques. Timber moving along a road network will be modeled as water flowing down a stream network.

Riparian Zones, Shade, and Stream Productivity

Kim G. Mattson and Michael Newton

Ecosystems Northwest and Department of Forest Science, Oregon State University

Abstract

How does cutting the forests along streams affect the biology of the stream? We are monitoring fish, benthic invertebrates and periphyton on streams with riparian harvest treatments. The treatments reflect increasing amounts of riparian canopy removal along the stream. Our purpose is to look for biological changes in response to the canopy removal along the streams. Our work is about in the middle of a three-year program and results are just now coming in. Our initial results do not show significant effects of removing the canopy. However, the treatment means are moving in the direction to suggest that riparian forest harvests may stimulate stream productivity by increasing the sunlight to the stream.

SURVEY OF FOREST FUEL REDUCTION MANAGERS

Cornelis F. de Hoop, Amith Hanumappa-Reddy, Robert H. Dupré and W. Ramsay Smith
Associate Professor, Research Associates and Professor, respectively
Louisiana State University Agricultural Center, Baton Rouge, LA 70803
cdehoop@lsu.edu , ahanum1@lsu.edu , rdupre1@lsu.edu , wsmith@lsu.edu
Presented at the 28th Annual Council on Forest Engineering Meeting
Soil, Water and Timber Management: Forest Engineering Solutions in Response to Forest Regulation
July 11-14, 2005 Fortuna, CA

Abstract: Because of the resurging problem with wildfires, foresters and other land managers in nearly every state have begun forest operations wherein fuel reduction is a primary management objective. Literature on this wave of activity, begun mostly since 2000, is just now becoming common. To obtain a better concept of the extent and nature of forest fuel reduction activities in the nation, a survey of foresters and similar administrators was conducted. The analysis resulted in classifying mechanical and burn only operations based on the nature of projects

INTRODUCTION:

Because of the resurging problem with wildfires, foresters and other land managers in nearly every state have begun forest operations wherein fuel reduction is a primary management objective. Literature on this wave of activity, begun mostly since 2000, is just now becoming common. To obtain a better concept of the extent and nature of forest fuel reduction activities in the nation, a survey of foresters and similar administrators was conducted.

Through the results of the survey, it was anticipated that a better overview of the topic can be obtained. Currently, there are several reports on specific fuel reduction projects (Hungry Creek Project, Brown Darby Fuel Reduction Project, Applegate Fire Plan Project and others) and summary publications on commercial mechanical equipment available for fuel reduction activities (Windell and Bradshaw 2000; Ryans and Cormier 1994). There is a need for a publication that provides an overview of the localities, types and effects of recent and current fuel reduction activities. Such a publication will increase the general knowledge about fuel reduction projects, provide a basis for mutual contacts, and reduce duplication of effort.

Fuel Reduction Survey:

A survey of Forest Administrators/Fire Chiefs and other administrators who would probably over see fuel reduction projects was conducted in 2004. For each state, information was gathered to determine the best contacts for forest fuel reduction projects. The information was gathered through web sites, email, and through direct telephone contact. All persons contacted were employees of public agencies, especially the U.S. Forest Service and the state forestry agencies. Over 600 individuals were contacted.

Questionnaire: The questions were designed to address a fuel reduction project which had been completed lately or was in progress. Some questions asked about the project details such as the area treated, topography, type of machines used, and cost or revenue to treat an acre. Other questions were of a more general nature, such as fuel reduction awareness among communities and local citizens' actions. Contact information of the respondent was asked, but the information may be made available only if the respondent agrees to it. The last section of questionnaire addresses the demographics of the respondent; this information will be useful in the future in assessing demographic changes in the profession.

Verification of the Questionnaire: The questionnaire was reviewed by several personnel knowledgeable in this particular field, and changes were made accordingly. The first questionnaires were sent to a random sample of thirty addressees. They were asked to critique the questionnaires. Changes were made accordingly before the other addressees were contacted, but the changes were very minor.

Mailing: Post cards were mailed to the addressees to create awareness of the survey and its importance. A week later the survey was mailed to them. A reminder post card was mailed one week later. A second mailing was done after 3 weeks to the non-respondents. There is a body of literature that suggests that people who do not respond to survey have characteristics similar to those who respond to second mailing. Responses to the two mailings were kept segregated.

Survey Results:
Approximately 197 people responded to the survey out of the 681 mails outs. Responses to first mail out were 20 % and to the second mail out was 12%, the net response rate being 31 %. Respondents were 84% male and 16% females with age range 25-66. Among these about 20% had some college education, 57% were college graduates and 17% had graduate degrees. Their primary occupations were District Rangers, FMO, Foresters and Firefighters. Among the respondents, about 65% were employed with the USDA, 18% were with US BLM and the remaining 14% were with state forestry agencies. The results from the respondents were classified in to two groups the first being mechanical fuel reduction projects, where machinery were used to carry out the complete operation, the other was classified as prescribed burn projects only, where the entire fuel reduction was carried out with a controlled burn .

Mechanical Operations:
Approximately 151 projects were categorized as mechanical operations, as they used techniques such as hand piling, forestry mulchers or logging equipments followed by a burn. The majority of the projects were carried out on government owned lands which were in the wildland-urban interface area. The topography for the majority of the projects was moderate, which had a gradient between 10-35 %. Fig. 1 indicates the fuel conditions based on the projects, heavy ladder fuel and dense small dia conifer stands dominate the conditions in the bar chart. The number of acres for these projects ranged from a minimum of 5 acres/project to a max of 12,325 acres/project. The projected time for completion ranged from a single day to 2,555 days using a mean of 5.5 (SD =8.3) administrative personnel and a mean of 21.6(SD=31) operational personnel.

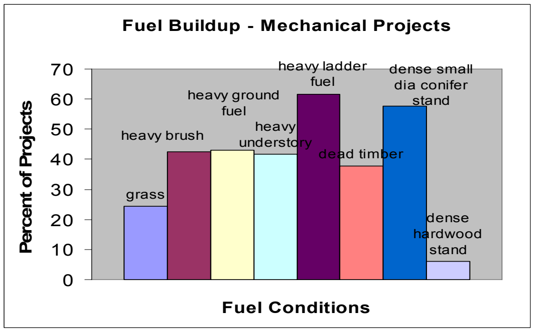


Figure 1

Cost /revenue:
Responses indicated that some projects were carried out based on the funds from grants by USFS and other agencies. Some projects cost and revenue went to the government. Other projects indicated the use of firewood to landowners. In general, the cost to land owner was $ 390 (SD=574) and the revenue to the land owner was $ 108 (SD=350). Also majority of the projects had some of the products marketed for logs, paper chips and landscape mulch (Fig 2)

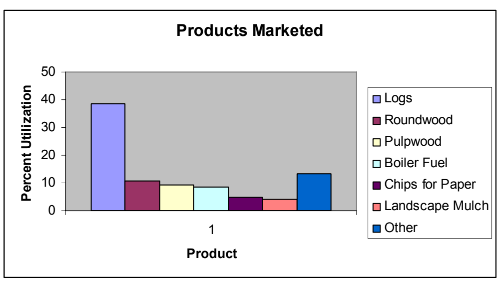


Figure 2

Fuel Reduction Machinery:
Chain saws, skidders, in-woods chippers and feller bunchers were among the popular machinery (Fig 3). The machines classified under category other were dozers, skyline cable yarders and helicopters.

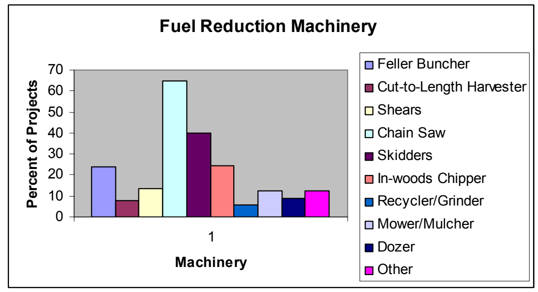


Figure 3

Time before pretreatment:
To get a concept of the perceived effectiveness of the fuel reduction treatments, we asked the respondents to estimate the amount of time until the treatment will need to be repeated. Majority of the projects carried out were estimated that it would take more than 7 years to do the same kind of fuel reduction work carried out. A few projects were classified to take about 2-7 years and less than 5% required no treatment at all.

Problems associated with operations:
Administrative, cost finding market for the materials were the top three problems which were ranked high based on the projects. Weather conditions also play an important role for any given project as illustrated (Fig 4). Some of the common problems found under the category other were related to computer problems, social acceptance, social values, limited work force, NEPA, contractors who did not assess the area's before bidding, land owner concerns, litigations environmental concerns and no funds after the site was treated.

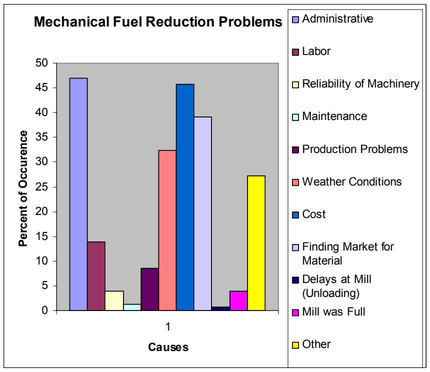


Figure 4

Burn only operations:

About 46 projects were categorized as burn only operations where prescribed burn was the major operation carried out to reduce the fuel build up.

The majority of the projects were carried out on government owned lands which were in the wildland-urban interface area. The topography for the majority of the projects was moderate, which had a gradient of 10-35 %. Fig 5 indicates the fuel conditions based on the projects, heavy ground fuel conditions with grass and heavy brush dominate the conditions in the bar chart. The number of acres for these projects ranged from a minimum of 5 acres/project to a max of 46000 acres/project. The projected time for completion ranged from a single day to 62 days with a mean of 4.13 administrative personnel and a mean of 22.95 operational personnel.

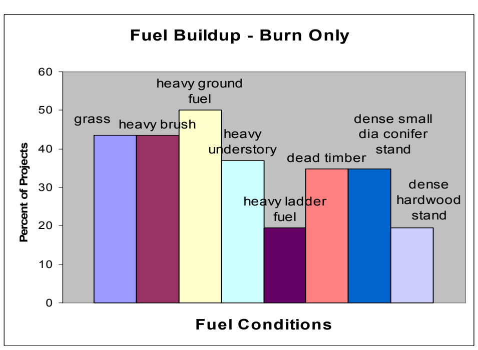


Figure 5

Cost:

The cost to run the burn operation per acre had a mean of $ 104.86 with min and max ranging from 0 to 1000 dollars per acre. 5 % reported a cost of $ 0 per acre, but no information was available whether a project was carried out free of cost to the land owner or whether some of the projects were actually funded by other agencies.

Prescribed Burn Machinery:

Chain saws were used in majority of the projects and the common equipments listed under the category other were helicopters. drip torches, trucks, ATV's and dozers.

Time before retreatment:

Majority of the projects did require to be treated again based on the geographic locations, the time frame (Fig 6) varied from 2 – 7 years before any kind of treatment was necessary. A few projects which accounted for less than 5 % required no treatment at all.

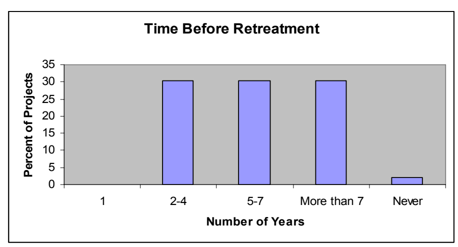


Figure 6

Problems associated with operations:

Weather conditions seemed to play a very important role which had a major effect on almost 70 % of the projects and the remaining dominating categories were due to administrative and other to name a few. Common problems under category "other" were due to smoke management, politics, funding, public understanding, tourist trade impacted and NEPA.

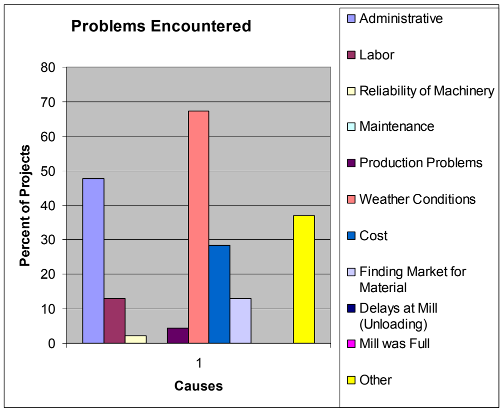


Figure 7

Combined Analysis:

This section of the survey was to seek answers to general questions whether the project was through mechanical operation or prescribed burn only operation. Typical questions included if projects can be carried out with available equipment or if there was a need to design a totally new machine, 72 % of the respondents felt that projects can be carried out with existing machines and some of the existing machines can be modified to suit the conditions. A few respondents felt newer designs were necessary as conventional machinery could not be really used in steep slopes, compact chippers which can be cabled to the work site were necessary at very steep conditions and compact machines that can keep tree spacing with out damaging them.

Educational awareness among citizens and their active involvement in fuel reduction programs play a significant role in any given situation. A few questions were targeted on awareness programs available to citizens, steps they can take to contribute to fuel reduction programs with a probable use of existing agricultural machines than investing on special machinery.

Approximately 59 % of the respondents indicated that there were educational programs, including, Firewise Programs, Firesafe council, awareness programs promoted through schools and public meetings. 55% indicated that there was substantial citizen involvement on fuel reduction projects, much of those were from land owners adjacent to forest lands.

A few comments from the forest administrators to citizens stressed on the importance of landowners to take the initiative and create defensible space around their homes and property. Possible grants through the Firewise and Fire Safe programs to execute fuel reduction around their homes and community and the advantages of state sponsored programs. Ask local firefighters or forest service personnel about what can be done to protect their homes.

About 32 % indicated that there was reluctance on the part of landowners to allow fuel reduction machinery on their property. Some comments included that they didn't want trees cut or land disturbed because of invasion of privacy, damage to residual vegetation, effects on wildlife, dust and erosion.

Approximately 33 % of the respondents had come across reports relating to fuel reduction and the most common were from National Fire Plan Operations Reporting System, NFPORS (www.NFPORS.gov), Forest Service Fuel Reduction Reports and National Fire Plan website. (NFP)

Discussion:

Although the intention of this survey was to describe mechanical fuel reduction operations, many of the respondents described fuel reduction operations wherein only prescribed burning was conducted. A comparison of the two types of operations turned out to be interesting.

A comparison of the types of fuel reduction operations by fuel buildup type revealed that the mechanical operations (Fig 1) tended to be used more where there are conditions of heavy ladder fuels and dense small-diameter conifer stands. By contrast, burn-only operations (Fig 5) tended to be used more commonly where grass and heavy ground fuels were common.
The mechanical and burn-only operations contrasted dramatically in size. Burn-only operations were three times larger, and yet they were performed in a small fraction of the time (Table 1).

Table 1

	Mechanical		Burn-Only	
	Acres	Days	Acres	Days
Mean	1,396	248	3,180	12
Min	5	1	5	1
Max	12,325	2,555	46,000	62

While mechanical operations often had a revenue stream to offset costs to landowner, the revenues were not sufficient to overcome the costs (on average Table 2). Most of the really costly mechanical operations (over $1,000 per acre) had very little offsetting revenues (often less than $100 per acre).

Table 2

	Mechanical		Burn-Only	
	Revenue	Cost	Revenue	Cost
Mean	$108 (n=28)	$390 (n=100)		$105 (n=36)
Min	0 (n=101)	0 (n=48)		0 (n=9)
Max	$3,000	$4,000		$1,000

Conclusions
This survey represents an over view of the important factors involved in carrying out a mechanical operations and burn only operations based on the type of operation which is necessary. A comparison between any mechanical operations or any burn only operations is difficult as projects are unique based on the fuel conditions, topography, man power , machinery used , funds available etc…Based on the responses it was decided to separate mechanical reductions and burn only operations to better understand these operations.

BIBLIOGRAPHY

Applegate Partnership. 2002. Applegate Fire Plan, 6941 Upper Applegate Rd, Jacksonville, OR 97530.

Brown Darby Fuel Reduction Project. 2002. Calaveras Ranger District, Stanislaus National Forest, Calaveras and Tuolumne Counties, California.

Hungry Creek Project. 2002. Michael "Mike" De Lasaux, Natural Resources Advisor, UC Cooperative Extension

Service, Plumas & Sierra Counties, 208 Fairgrounds Road Quincy, CA 95971.

Ryans, M, and D. Cormier. 1994. A Review of Mechanized Brush-Cutting Equipment for Forestry. Special Report No. SR-101. ISSN 0381-7733. Forest Engineering Research Institute of Canada. Web Site : http://www.feric.ca

Windell, K., and S. Bradshaw. 2000. Understory Biomass Reduction Methods and Equipment Catalog. Tech.Rep. 0051-2826-MTDC. USDA Forest Service Technology & Development Program, Missoula, Montana.

State of California
The Resources Agency
Department of Forestry & Fire Protection

Designing Watercourse Crossings for Passage of 100-year Flood Flows, Wood, and Sediment

Peter Cafferata, Thomas Spittler,
Michael Wopat, Greg Bundros,
and Sam Flanagan

California Forestry
Report No. 1

February 2004

Summary

Watercourse crossings associated with timber harvesting can produce substantial amounts of stream sediment. To reduce the potential for crossing failures and resulting impacts, the California Forest Practice Rules specify that all constructed or reconstructed permanent watercourse crossings must accommodate the estimated 100-year flow, including debris and sediment.

Three methods for making office-based estimates of 100-year recurrence-interval streamflows for ungaged basins are presented: (1) an analytical relationship between storm precipitation, watershed characteristics, and runoff, (2) regional regression equations based on long-term flow records, and (3) flow transference methods that adjust nearby measured discharges for differences in drainage basin size. Watershed area limitations for each method are identified. In general, flow transference methods are preferred for determining 100-year peak discharges in drainage basins where nearby long-term stream gaging station data are available, because local streamflow data are more likely to represent drainage-basin characteristics that determine peak flows than regional regression equations or analytical relationships. The estimated 100-year peak flows are then used to determine a culvert diameter large enough to handle the estimated peak flow and accommodate flood-associated wood and sediment.

Research conducted in northwestern California and the Pacific Northwest shows that culverts fail less often from flood flows alone than from accumulations of wood and sediment that commonly accompany flood flows. Foresters designing watercourse crossings are therefore required to design crossings to handle flood-associated sediment and debris in addition to the estimated peak flows. Several techniques are suggested to decrease the risk of crossing failure from culvert plugging. Other issues related to fish passage are covered elsewhere in the literature and also need to be considered in crossing design for fish-bearing streams.

Culvert diameters determined from estimated peak flows need to be checked in the field by making direct channel cross section measurements. The 3 times (3 X) bankfull stage method is suggested as one approach for field verification, but has only been validated for the rain-dominated North Coast region. Annual high flow line or active channel width measurements are alternatives for smaller or more entrenched channels where bankfull characteristics may be poorly developed.

Examples displayed in the appendix apply the watercourse crossing sizing techniques to a small tributary basin located in the Caspar Creek watershed near Fort Bragg, California. One-hundred year recurrence interval peak discharges are estimated, and wood passage concerns are addressed by sizing the culvert to fit the active channel width. Additionally, the various discharge-estimating techniques for ungaged basins are used to estimate a 10-year peak flow, and these results are compared to actual gaging station data. In this example, the direct flow transference method was found to provide the best estimate of the 10-year recurrence interval event. It is assumed that the techniques giving the best estimates for a 10-year event for this basin would also provide the best estimates of the basin's 100-year peak flow.

February 10, 2004

California Department of Forestry and Fire Protection
P.O. Box 944246
Sacramento, CA 94244-2460

Designing Watercourse Crossings for Passage of 100-year Flood Flows, Wood, and Sediment

Peter Cafferata, Thomas Spittler,
Michael Wopat, Greg Bundros,
and Sam Flanagan[1]

[1] P. Cafferata is Forest Hydrologist, California Department of Forestry and Fire Protection, Sacramento, CA. T. Spittler is Senior Engineering Geologist, California Geological Survey, Santa Rosa, CA. M. Wopat, Ph.D., is Senior Engineering Geologist, California Geological Survey, Redding, CA. G. Bundros is Geologist, Redwood National and State Parks, Arcata, CA. S. Flanagan is Fisheries Biologist, NOAA Fisheries, Arcata, CA. The cover photo was taken by Thomas Schott, District Conservationist, Natural Resources Conservation Service, Ukiah, CA.

Contents

Introduction

Timberland-owners and foresters are required by the Forest Practice Rules, as amended by the California State Board of Forestry and Fire Protection in July 2000, to design all new and reconstructed permanent watercourse crossings to accommodate an estimated 100-year flood flow, including wood and sediment loads (CDF 2003).[1] Recent hillslope monitoring work conducted throughout California has shown that problems most frequently occurred at watercourse crossings; inadequate design was cited as one of the reasons for these results (Cafferata and Munn 2002). While culverts are commonly sized to accommodate flood flows, studies in northwestern California show that flood discharge alone is usually not the primary cause of crossing failures (Furniss and others 1998; Flanagan, unpublished data, see Figure 1). To date, similar studies have not been completed outside of northwestern California to determine if these results apply elsewhere in the state. Furniss and others (1998) conclude that "because stream crossing failure in Pacific Northwest forested watersheds is caused predominantly by accumulations of sediment and debris at the inlet, hydraulic models are not reliable predictors of crossing failure."

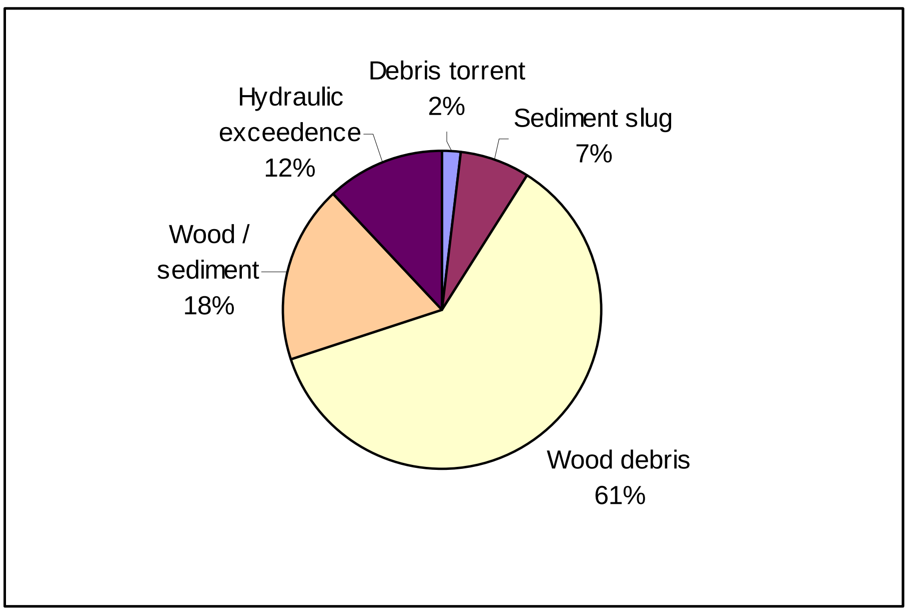


Figure 1. Failure mechanisms for culverts occurring along forest roads in northwestern California associated with storm events with recurrence intervals less than approximately 12 years (S. Flanagan, NOAA Fisheries, Arcata, CA, unpublished information; n = 57). Note that the specific distribution of failure mechanisms will vary depending on numerous factors, including storm intensity and watershed characteristics. For example, see Furniss et al. (1998) for additional information on failure mechanisms following very large floods in the Pacific Northwest.

[1] Currently the 100-year flood flow requirement is part of the Threatened and Impaired Watersheds Rule Package, which has an expiration date of December 31, 2006.

This paper presents three traditional office techniques for estimating 100-year recurrence interval water discharge: (1) the **rational method** (Chow 1964, Dunne and Leopold 1978, CDF 1983, Weaver and Hagans 1994), (2) the **USGS Magnitude and Frequency Method** (Waananen and Crippen 1977), and (3) **flow transference methods** (Waananen and Crippen 1977, Skaugset and Pyles 1991). A discussion of field techniques for evaluating proposed culvert diameters is also presented. A section on wood and sediment passage at crossings provides important information for preventing catastrophic crossing failure. Sections suggesting additional design considerations and approaches for evaluating the risk of existing crossings are also included. This report generally applies to non-fish bearing streams, since culvert sizing issues addressing fish passage are not included here. For detailed discussions of design criteria for fish passage, refer to USFS (2000), NMFS (2001), ODF (2002a), Flosi and others (2003), and WDFW (2003).

The California Forest Practice Rules specify that flood flows are to be estimated by empirical relationships between precipitation and watershed characteristics and runoff, and can be modified based on direct channel cross section measurements and local experience. The rational, USGS Magnitude and Frequency, and flow transference methods can be used to meet the first part of this requirement, while the second part can be addressed with field methods such as 3 X bankfull stage, or where bankfull stage characteristics are difficult to determine, using the annual high flow line or active channel width.

While proper crossing design is critical for passage of water, sediment, and wood, the most important method for reducing environmental impacts is to locate roads to avoid or minimize crossings. Proper location of roads, and hence crossings, reduces chronic sediment impacts as well as the potential for catastrophic failure. Higher, flatter, and drier locations require fewer and smaller watercourse crossings than sites low on hillslopes. Where there are many connections between roads and streams, impacts are inevitable, but where roads are distant from streams, their impacts are greatly reduced (M. Furniss, USFS-PNW, Corvallis, written communication, Furniss and others 2000).

Office Techniques for Determining Discharge

Rational Method

The rational method is an analytical approach for predicting peak runoff rates that has been used for engineering calculations for more than 100 years (Chow 1964, Portland Cement Association 1964, Dunne and Leopold 1978, Rossmiller 1980). Its development preceded the availability of long-term flow records that have become increasingly accessible in recent decades. The rational method equation for the 100-year flood flow is stated as follows:

$$Q_{100} = CIA$$

where:

Q_{100} = predicted peak runoff from a 100-year storm (cubic feet per second or cfs)

C = runoff coefficient[2]

I = rainfall intensity (inches per hour) for the 100-year storm

A = basin drainage area (acres)

To determine the rainfall intensity, one must: (1) determine the time of concentration for the drainage basin upstream of the watercourse crossing, (2) choose a 100-year return-period rainfall duration (e.g., 15 minutes, 30 minutes, etc.) from depth-duration-frequency (DDF) rainfall data that is similar in duration to the time of concentration, and (3) convert the 100-year return period DDF data to inches per hour for use as the rainfall intensity variable in the rational method discharge calculation. The time of concentration may be calculated using either the Kirpich Formula (Kirpich 1940, Weaver and Hagans 1994) or the Airport Drainage Formula (see Figure 7 in FAA 1970).[3] Both formulas and examples using the equations are presented in the Appendix. Based on past experience, a minimum value of 10 minutes is recommended for the time of concentration for small forested basins with both equations; smaller values tend to overestimate predicted runoff and rainfall-depth-duration data for 5 minutes are often unavailable (Yee 1994). With the Kirpich equation, the time of concentration is calculated from the channel length and elevation change from the top of the basin to the crossing, both of which can be obtained from topographic maps. The Airport Drainage equation incorporates the runoff coefficient (C), in addition to upstream watershed gradient and runoff distance, and generally produces longer estimates for the time of concentration.[4]

Short-duration rainfall-depth-duration-frequency data for 100-yr recurrence interval events (to determine rainfall intensity) are required once the time of concentration is known. Rainfall data are available for selected stations in California on microfiche cards or in tables or graphs from out-of-print California Department of Water Resources (CDWR) publications (CDWR 1976, 1981) and from the data set compiled more recently by Goodridge (2000).[5] According to

---

[2] The runoff coefficient is dimensionless because it represents the estimated proportion of rainfall that runs off. Note that no proportionality constant is needed when the rational method equation is computed using English units because one acre-inch/hour of precipitation is equal to 1.008 cfs.

[3] An improved method for determining the time of concentration has been developed by Papadakis and Kazan (1987). This approach is a kinematic wave empirical equation specifically designed to determine the time of concentration for small rural watersheds and has been adapted by several recent hydrology manuals. While it is an improved method, the equation must be iteratively solved. Dr. Wopat will attempt to develop a spreadsheet to solve this equation, so it may be more easily used by field personnel.

[4] Yee (1994) recommends the use of the Airport Drainage equation to calculate the time of concentration.

[5] Copies of the Goodridge (2000) California weather CD ROM are available from Mr. Cafferata at CDF in Sacramento or Dr. Wopat at CGS in Redding.

CDWR staff, these data will be made accessible via the Internet at CDWR's Water Data Library (http://wdl.water.ca.gov/).

Determining the appropriate runoff coefficient (C) for the crossing site is very important when using the rational method. For 100-year flood flows on California's North Coast, Buxton and others (1996) suggest that the runoff coefficient should be 0.40.[6] Experience in the Redwood Creek watershed has led to the use of runoff coefficients ranging from 0.35 to 0.45 for 100-year discharge estimates, depending on terrain type (G. Bundros, RNSP, unpublished data). Dunne and Leopold (1978) state that C values for small forested mountainous watersheds with sandy-loam soils can be 0.40 or higher for long duration storms with a recurrence interval of 100 years. Table 1 provides a general guide for rational method runoff coefficients that has often been cited. **In general, we recommend a C factor ranging from 0.30 to 0.45, depending on the specific location of the crossing.**[7]

Assumptions with the rational method include: (1) the design storm covers the entire basin with constant rainfall intensity until design discharge at the crossing site is reached (time of concentration), (2) overland flow occurs, (3) the runoff coefficient is constant across the watershed, and (4) the 100-year rainfall event produces the 100-year flood flow. In actuality, there are problems with each of these assumptions. These are minimized, however, when the basin size above the crossing site is small. Chow (1964) recommends that the rational method be limited to watersheds less than 100 acres and never used for basins larger than 200 acres. Dunne and Leopold (1978) reported that this method should only be used for catchments of less than 200 acres, but state that it frequently has been used for basins up to 640 acres. **We recommend that the rational method be limited to watersheds less than 200 acres.**

This method is easy to use, generally understood, and accounts for local conditions. Disadvantages include difficulty in obtaining rainfall intensity data for remote field sites, the assumptions listed above that are usually not met, little field validation to determine appropriate runoff coefficients for different parts of the state, and the inability of the method to account for rain-on-snow events. Detailed examples for use of the rational method (and other methods) are provided in Wopat (2003), CDF (1983), and the Appendix of this document.

[6] This report provided the results of field tests on the rational method and other techniques made in southern Humboldt County during a large runoff event.

[7] Rossmiller (1980) lists the variables that have been used by one or more investigators to estimate the runoff coefficient (C). Table 1 in the current report only takes into account one factor—soil type. Caltrans' (2001) Highway Design Manual provides a table for estimating C values that takes into account four variables: (1) differing topographic relief, (2) infiltration rates based on soil type, (3) proportion and kind of vegetal cover, and (4) degree of surface storage. Several authors have suggested that C factors should recognize that longer recurrence interval (RI) storm events (e.g., 100 yr RI) tend to have a higher proportion of runoff than shorter RI storms. Caltrans considers the C values obtained from the Caltrans table to be applicable for storms up to 5 to 10 years and suggests that such C values be multiplied by 1.25 to obtain an appropriate C value for 100-year RI storms.

Table 1. Values for rational runoff coefficients (Dunne and Leopold 1978).

Woodland Soils in Rural Areas	Runoff Coefficient (C)
Sandy and gravelly soils	0.10
Loams and similar soils without impeding horizons	0.30
Heavy clay soils or those with a shallow impeding horizon; shallow soils over bedrock	0.40

USGS Magnitude and Frequency Method

The USGS Magnitude and Frequency Method is based on a set of empirical equations derived from precipitation and runoff data collected at more than 700 stream gaging stations in California (Waananen and Crippen 1977). These records were analyzed to derive equations which were developed for 2, 5, 10, 25, 50, and 100 year recurrence intervals.[8] The equations for 100-year discharges for the six regions of California are as follows (see Figure 2 for the regional boundaries):

North Coast	$Q_{100} = 9.23\ A^{0.87}\ P^{0.97}$
Sierra	$Q_{100} = 15.7\ A^{0.77}\ P^{1.02}\ H^{-0.43}$
Northeast	$Q_{100} = 125\ A^{0.59}$
Central Coast	$Q_{100} = 19.7\ A^{0.88}\ P^{0.84}\ H^{-0.33}$
South Coast	$Q_{100} = 1.95\ A^{0.83}\ P^{1.87}$
South Lahontan-Colorado Desert	$Q_{100} = 1080\ A^{0.71}$

where:

- Q_{100} = predicted 100-year peak runoff event in cfs
- A = drainage area above the crossing in square miles
- P = mean annual precipitation in inches per year
- H = altitude index (average channel altitude) in thousands of feet (e.g., 2000 feet is 2.0)[9]

Drainage area and altitude index are reasonably easy to determine from topographic maps or newer GIS computer software tools. Mean annual precipitation is available from several sources, including: (1) isohyetal maps (such as Rantz 1972), (2) CD ROM (Goodridge 2000), (3) internet sites (Calwater planning watershed average annual precipitation is available from the

[8] Note that each equation encompasses a large, diverse geographic area (see Figure 2), and therefore is likely to overestimate discharge in some places and underestimate it in others.

[9] The altitude index should be computed as the average of the altitudes at the 10 and 85 percent points along the main channel from the crossing to its hydrologic divide, or alternately as the average altitude between the highest point in the basin and the crossing ($[H_{max} + H_{min}]/2$). However, Magnitude and Frequency discharge estimates for bridged crossings should use only the altitude index determined from the 10 and 85 percent points along the main channel because the alternative method of determining the altitude index ($[H_{max} + H_{min}]/2$) increasingly underestimates Q_{100} as the watershed area increases.

CDF FRAP site at: http://frap.cdf.ca.gov/projects/esu/esulookup.asp; additionally tabular precipitation data is available for numerous northern California stations at: http://www.wrcc.dri.edu/summary/climsmnca.html from the Western Regional Climate Center), and (4) local records.[10]

This method is easy to use, rainfall data are readily available, and flow estimates are based on measured discharge data from numerous, widely distributed locations, including rain-on-snow flow events. The primary disadvantages are that it generalizes vast regions of the state, resulting in overestimation in some areas and underestimation in other areas, and that the equations have not been updated since 1977. **The USGS Magnitude and Frequency Method is preferred over the rational method for drainage areas larger than 100 acres.** It is unvalidated for use with very small watersheds, because very small basins are outside of the range of the drainage areas used to generate the regression equations. The minimum drainage areas used to generate the regression equations, along with other information for the 100-year discharge regression equations, are displayed in Table 2.

The USGS Magnitude and Frequency Method regression equations are used for the National Flood Frequency (NFF) program in California. NFF is a widely utilized and accepted Windows-based software program, developed by the U.S. Geological Survey, that is used to estimate approximate peak discharges for ungaged basins throughout the United States (Ries and Crouse 2002; see the following websites for more information on NFF and the computer software that can be downloaded: http://water.usgs.gov/software/nff.html; http://www.fema.gov/fhm/ot_main.shtm). Use of the program allows 100-year peak flow estimates to be generated along with standard error estimates.

Table 2. USGS Magnitude and Frequency Method 100-year regression equation information (Waananen and Crippen 1977).

Region	**Minimum Drainage Area (ac)**	Maximum Drainage Area (ac)	# of Stations used in the Analysis	Std Error of Estimate ($\log_{10}$ units)[11]
North Coast	**83**	1,992,320	125	0.26
Sierra	**90**	5,772,800	212	0.37
Northeast	**38**	15,872	20	0.45
Central Coast	**109**	2,659,840	91	0.41
South Coast	**96**	412,160	137	0.39
South Lahontan-Colorado Desert	**6**	16,000	35	0.36

[10] Mean annual precipitation and rainfall-depth-duration-frequency tables for the Redwood Creek basin and a culvert sizing program are available from Redwood National and State Parks (RNSP). Contact Mr. Bundros at RNSP, Arcata, CA, for further information.
[11] To use the standard error estimate (SEE), obtain the Q_{100} discharge estimate, convert it to $\log_{10}$ units, add and subtract the SEE to get the value of 1-SEE above and below the predicted Q, then obtain the antilogs of the 1-SEE limits to find the 1-SEE range of the estimate.

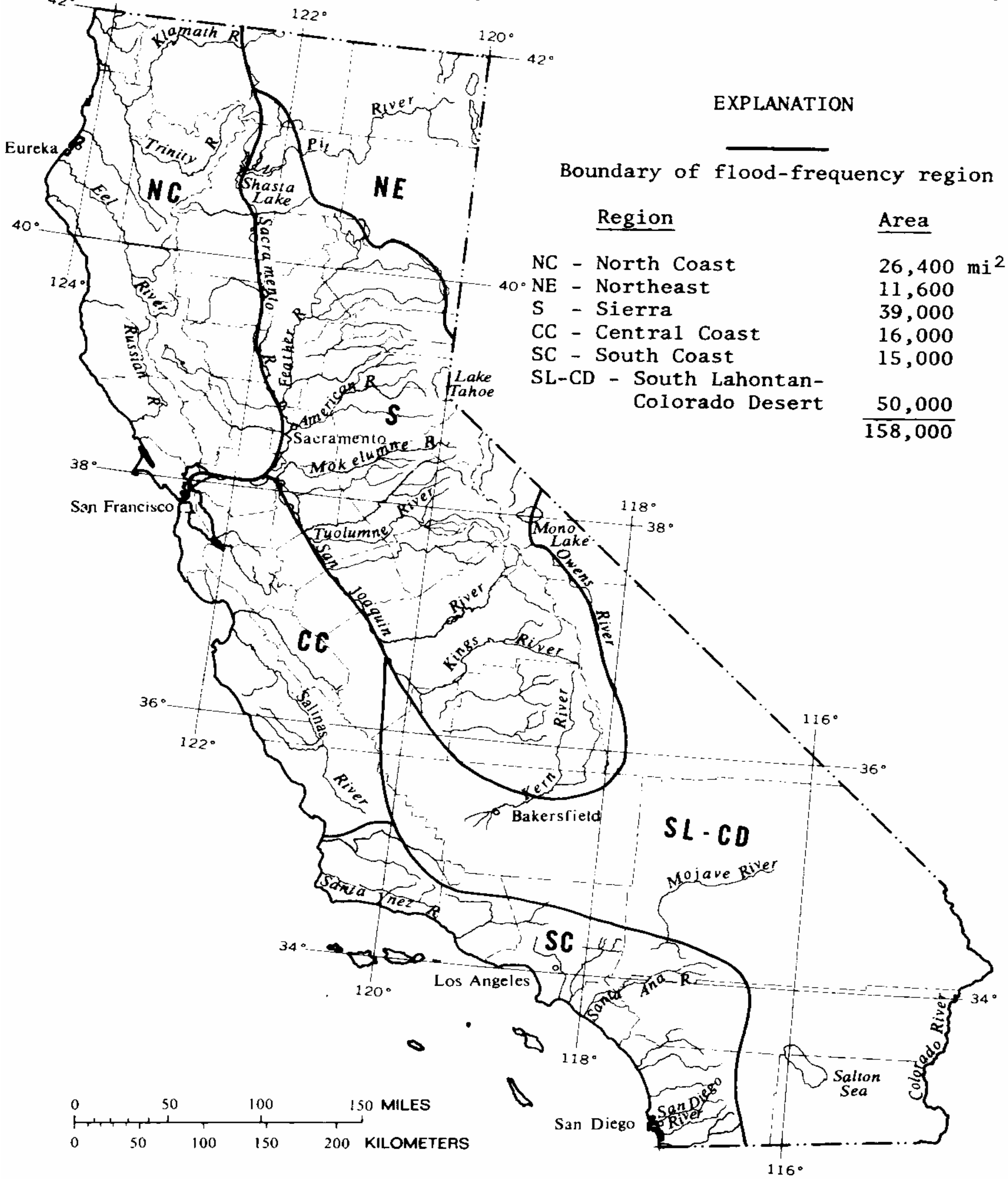


FIGURE 3.--Flood-frequency regions used in this study.

Figure 2. USGS Magnitude and Frequency Method regression equation regions (from Waananen and Crippen 1977).

Flow Transference Methods

If a stream gaging station is located on the same stream as the proposed crossing site or on a hydrologically similar nearby stream, it is possible to adjust the 100-year discharge for the difference in drainage area between the ungaged basin and the gaged basin by using the following flow transference equation (Waananen and Crippen 1977):

$$Q_{100u} = Q_{100g} (A_u/A_g)^b$$

where:

Q_{100u} = 100-year discharge at ungaged site (cfs)
Q_{100g} = 100-year discharge at gaged site (cfs)
A_u = drainage area of ungaged site (mi^2)
A_g = drainage area of gaged site (mi^2)
b = exponent for drainage area from the appropriate USGS Magnitude and Frequency equation (e.g., 0.77 for the 100-yr equation for the Sierra Region—see the equations above for the exponents for the other regions)

The downstream or nearby gaging station used with the flow transference method should have a long-term station record (suggested to be more than 20 years). Additionally, the 100-year discharge estimate for the gaged station must be known. This can be determined relatively easily for USGS gaging stations through the use of PEAKFQ, a computer software program available online that performs a flood-frequency analysis based on Bulletin 17B, which is the accepted methodology published by the Interagency Advisory Committee on Water Data (IACWD 1982), and is available from the USGS website at: http://water.usgs.gov/software/peakfq.html. Q_{100} can also be determined from Waananen and Crippen (1977) for the stations they used in their regression analysis (see Table 5 in their report), or by manually calculating Q_{100} with a flow frequency analysis [i.e., plotting discharges and recurrence intervals; see Dunne and Leopold (1978)].

Waananen and Crippen (1977) state that the flow transference method is superior to the more general USGS Magnitude and Frequency Method regional regression equations when the criteria listed above are met (i.e., the stream gaging station is nearby and the available stream gaging annual peak discharge records are adequate). **The flow transference method is preferable to the USGS regional regression equations because local data are more likely to represent the drainage-basin characteristics in terms of slopes, geology, soils, and climate when compared to the more general regional equations.**

An alternate approach to the Waananen and Crippen (1977) flow transference approach can be used if the gaged and ungaged watersheds are in close proximity, are hydrologically similar, **and are approximately the same size (within one order of magnitude)**. Skaugset and Pyles (1991) term this approach “**direct flow transference**” and state that the simplest method of direct transfer is by adjusting streamflow records by differences in watershed area:

$$Q_{100u} = Q_{100g} (A_u/A_g)$$

Field Techniques for Evaluating Proposed Culvert Diameters

Following the office calculation of 100-year flood discharges, the determination of the required pipe diameter is often made through the use of a culvert sizing nomograph (see Figure 12 or Normann and others 1985, and assume inlet control when using these nomographs).[12] It is critical to specify an appropriate headwater depth to pipe diameter ratio (HW/D) when making this calculation. The HW/D ratio used should be no more than 0.67 (previous crossing design documents usually specified a HW/D ratio of 1.0) (M. Furniss, USFS-PNW, Corvallis, written communication). A reduced HW/D ratio lowers the potential for plugging associated with pieces of wood. The proposed pipe diameter can then be field checked using either: (1) bankfull stage, (2) the annual high flow line, or (3) the width of the active stream channel in the vicinity of the crossing.

The **3 X bankfull stage method** is a potential field check (BC MOF 1995, 2002) that appears to be valid for the coastal portions of northwestern California, but may underestimate Q_{100} culvert sizes for inland areas away from the rain-dominated portion of the Coast Range. This procedure assumes that: (1) the bankfull scenario of any stream represents the mean annual flood cross-sectional flow area for the stream (Q_2)[13]; (2) that the ratio of Q_{100} culvert cross-sectional flow area to Q_2 is 3.0 or less; and (3) that the discharge cross-sectional flow areas are not sensitive to influences from pipe slope and roughness or other factors. These assumptions are not truly representative of all situations, but within the accuracy expected for establishing design discharge, this method should be acceptable for verifying proposed stream-culvert sizes smaller than 78 inches on forest roads in counties along the coast of northern California (BC MOF 1995, 2002).

To utilize the 3 X bankfull stage technique, measure the bankfull cross section allowing for scour in a representative stream reach that is not influenced by a road. In unconfined stream channels, bankfull stage is associated with the flow that just fills the channel to the top of its banks and where water begins to overflow onto a floodplain (Rosgen 1996). Specifically, measure the width of the stream at the top of the bank (W_1 = bankfull width) and at the stream bottom (W_2 = active channel width) in feet (see Figure 3). Measure the depth of the stream at several spots across the opening to obtain the average depth (D) in feet.

---

[12] A culvert that has a slope greater than 1.5% to 2% will normally exhibit inlet control (Beschta 1984, Piehl and others 1988). Normann and others (1985) provide nomographs for determining flow capacity for both round pipe culverts and other types of stream crossing structures.

[13] Q_2 is actually the median annual flood; mean annual flood is more often approximately a $Q_{2.5}$ recurrence interval event (R. Beschta, Oregon State Univ., Corvallis, written communication).

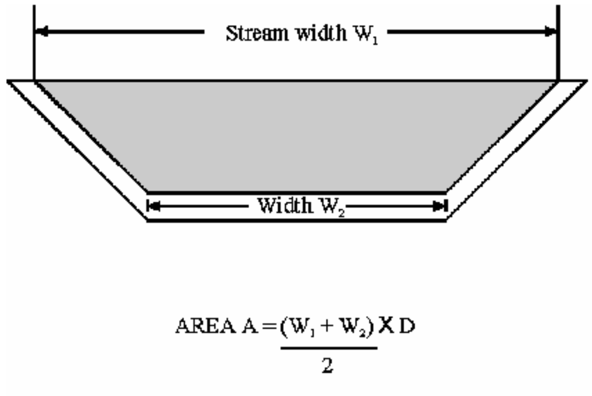


Figure 3. Diagram illustrating how to determine bankfull channel area (from BC MOF 1995).

Calculate the bankfull cross-sectional area of the stream, $A_{bf} = (W_1 + W_2)/2 \times D$. Calculate the area of the required culvert opening (A_c) as follows:

$$A_c = 3\ A_{bf}$$

Using an alternative notation where $A_c = \pi r^2$ (r = radius of the culvert opening), the diameter (d = 2r) of the culvert opening can easily be calculated as follows:

$$\pi r^2 = 3\ A_{bf}$$
$$r^2 \approx A_{bf} \quad \text{(note that this is approximate)}$$
$$r \approx (A_{bf})^{1/2}$$
$$\mathbf{d \approx 2[(A_{bf})^{1/2}]}$$

Therefore, the culvert diameter can be approximated by the simple equation: $d \approx 2[(A_{bf})^{1/2}]$. For example, a stream with a bankfull cross sectional area of three square feet would need a culvert diameter of approximately 3.5 feet (i.e., 42 inches):

$$d = 2[(3\ ft^2)^{1/2}]$$
$$d = 2(1.73\ ft)$$
$$d = 3.5\ ft = 42\ inches$$

Any evidence from major storms must be accommodated with this method. If there is a debris line along the stream channel that indicates the flood flow had a cross sectional area greater than 3 times A_{bf}, then the culvert diameter should be increased to match or exceed the flood cross-sectional area.[14] In addition to the need to accommodate streamflow, wood and sediment passage must also be considered. **The 3 X bankfull stage method works best for pipe sizes up to 48 inches (G. Bundros, RNSP, Arcata, unpublished information), and it is not applicable to culverts greater than 78 inches in diameter (BC MOF 1995, 2002).**

[14] Major storm events have a recurrence interval of 10 to greater than 100 years. If an area of a watershed had just experienced a major storm, this would likely cause an increase in culvert size relative to what the design would have been without the major storm.

The 3 X bankfull stage method uses on-site field conditions, is easy to use, provides the culvert diameter directly, and offers an easy field check of office calculations for northwestern California watersheds. There are, however, several limitations to the use of this method. **The most significant limitation is that it requires a clear indicator of bankfull stage, which can be very difficult to discern for small watersheds.[15] For intermittent or ephemeral watersheds where it is hard to determine bankfull stage and/or where longer-recurrence interval flooding has obscured bankfull indicators, it is acceptable to approximate bankfull stage with the annual high flow line (M. Furniss, USFS-PNW, Corvallis, written communication). Another approach for these types of small channels is to simply make the culvert diameter equal to the active channel width (W_2) at the crossing location.[16]**

Other limitations of the 3 X bankfull stage method include: (1) cross-sections measured should be representative of the channel in the general crossing area and not be affected by roads, (2) the identification of bankfull stages in severely impacted channels is difficult, especially when accumulations of large wood and sediment are present in the channel, and (3) while some field verification of this method has occurred in northwestern California[17] (Figure 4), virtually none has taken place in interior areas of California, so it may not be valid in inland areas away from the coast.

To illustrate the last point, Beckers and others (2002) in reviewing the 3 X bankfull stage method proposed by the BC MOF (1995, 2002) found that the ratios of 100-year stream discharge to 2-year discharge (Q_{100}/Q_2) vary substantially with basin area and climate.[18] For flood peaks generated by rainfall and rain-on-snow in coastal British Columbia, the range was 3.1 to 2.6, but for snowmelt-dominated peak flows in the Canadian Rocky Mountains, the Q_{100}/Q_2 ratio decreases with increasing drainage area from 2.3 to 1.9. Similarly, Pitlick (1994) reported that for regions where flooding is caused by large-scale frontal storms in the western U.S., 100-year floods may be 3 to 6 times the mean annual flood, but in regions dominated by snowmelt the Q_{100} is less than two times the

[15] The term “bankfull stage” is difficult to apply to small, entrenched stream channels. Bankfull stage can be determined by stage indicators situated along the boundary of the bankfull channel (Rosgen 1996). Bankfull discharge is associated with a flow which, on the average, has a recurrence interval of 1.5 years (Dunne and Leopold 1978). Field personal must be trained in identifying bankfull stages.

[16] Because the diameters of culverts sized to handle Northwestern California 100-year flood flows alone (not considering flood-associated sediment and floating debris) average approximately two-thirds the width of the active channel (W_2), a culvert sized large enough that its diameter **equals** the active channel width (W_2) should accommodate the expected 100-year flood flow and have enough additional headroom to accommodate flood-associated sediment and debris as well.

[17] The method was only field tested in coastal regions underlain by schist and mélange units of the Franciscan Complex, Central Belt terrain. The method may be more difficult to apply in harder geologic units where bankfull stages may be hard to discern. More testing of this approach is needed.

[18] There is abundant data for the two-year recurrence interval discharge (Q_2) at gaging stations, and it is the recurrence interval most similar to the 1.5 year flow commonly associated with bankfull flows.

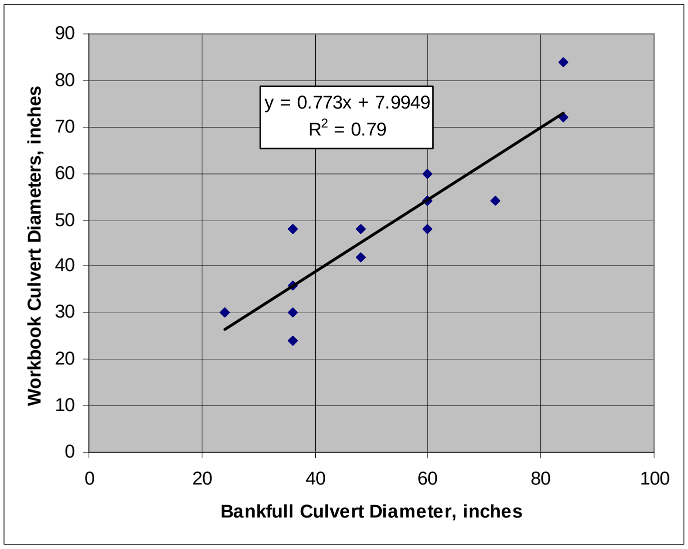


Figure 4. Plot of 3 X bankfull stage determined culvert diameters for drainage areas less than 200 acres (x axis) vs. culvert diameters determined by a workbook spreadsheet (y axis) using either the rational method (for drainage areas less than 80 acres and a runoff coefficient of 0.40) or USGS Magnitude and Frequency Method (for drainage areas greater than 80 acres and less than 200 acres) for the Redwood Creek watershed in northwestern California. Pipe diameters were determined from workbook-estimated 100-year return interval flood flows using a culvert sizing nomograph (for example, see Figure 12), and assuming a projecting pipe entrance and HW/D = 1.0 (unpublished data collected by Greg Bundros, RNSP, Arcata, CA).

mean annual flood. Rain-on-snow events greatly elevate discharge above snowmelt alone and have resulted in some of the largest floods on record in California. For example, Kattelmann (1990) found that six large floods over 60 years in the Sierra Nevada with recurrence intervals of only 10 to 20 years produced discharges that were 4 to 10 times the magnitudes of the mean annual flood. Rain-on-snow was an important mechanism in all but one of these events.

A brief review of Q_{100}/Q_2 ratios for California, using flood-flow values from 12 stations along an east-west transect approximately parallel to latitude 40°N (data from Waananen and Crippen 1977), shows average Q_{100}/Q_2 flood-flow ratios to increase eastward from the coast. Average Q_{100}/Q_2 flood-flow ratios increased eastward from the North Coast flood-frequency region (FFR) (avg. Q_{100}/Q_2 = 3.65, n = 6), through the Sierra FFR (avg. Q_{100}/Q_2 = 5.39, n = 6).[19] The increase in the Q_{100}/Q_2 ratio with distance inland from the northern California coast suggests that 100-year flood flows increase relative to 2-year bankfull flows with distance from the coast. Consequently, using the 3 X bankfull stage method to

[19] Although the average Q_{100}/Q_2 ratio for the North Coast FFR stations (= 3.65) exceeds 3.0, such flood flows can be handled by culverts with cross-sectional areas only 3 times bigger than the Q_2 bankfull watercourse cross-sectional area for two reasons: (1) the roughness of natural streambeds is greater than that of culverts, resulting in slower flow velocities and, for a given discharge, larger cross-sectional areas in a natural stream bed relative to a culvert of similar capacity, and (2) transport efficiency (Q/ft^2) increases with culvert size. For example, increasing culvert cross-sectional area 3 times increases flow capacity approximately 3.9 times.

size culverts inland from the coast should result in increasingly undersized culverts as distance from the coast (and the Q_{100}/Q_2 ratio) increases. Because of the change in the Q_{100}/Q_2 ratio with distance from the coast, we recommend that the 3 X bankfull stage method be used inland from the coast only as a field check of minimum culvert diameter. In other words, the diameter of a culvert designed to handle the 100-year flood flow and associated sediment and debris inland from the coast should be no smaller than the diameter obtained using the 3 X bankfull stage method and may be larger.

Wood and Sediment Passage at Crossings

While determination of culvert diameter based on streamflow is often the easiest aspect of crossing design, it is not the only design issue to be considered. Wood and sediment passage are often of equal or greater concern than hydraulic capacity for preventing culvert failure (Flanagan 1996, see Figure 1). Furniss and others (1998) provide advice on crossing design to accommodate wood and sediment passage. Unfortunately, it remains difficult to directly predict the loading of sediment and wood at a given crossing, but we can design crossings to better accommodate these watershed products and reduce the risk of failure.

How watershed products such as wood and sediment are processed at the pipe inlet is what determines plugging potential, and thus the actual culvert capacity. **For example, flared metal end sections are relatively inexpensive, easy to retrofit, and yield large gains in capacity for all watershed products.** Additionally, they appear to prevent the lodging of rocks and woody debris at the inlet lip (M. Furniss, USFS, Pacific Northwest Research Station, Corvallis, OR, written communication; AISI 1971).

Furniss and others (1998) describe several additional techniques for increasing the capacity of culverts for wood and sediment passage. **These include: (1) specifying a headwater depth to pipe diameter ratio (HW/D) significantly smaller than 1.0, such as 0.50 or 0.67 (i.e., at maximum flow, the pipe would be flowing one-half full to two-thirds full, respectively)[20], (2) utilizing culverts that are as wide, or nearly as wide, as the stream's active channel width (i.e., the zone of active, annual streambed scour and deposition)—particularly for small streams, (3) installing culverts at the same gradient as the natural stream channel, and (4) avoiding angular deviation by installing culverts so that they are aligned parallel to the natural channel** (Figure 5). Additionally, a single large culvert at a crossing is better for wood passage than several small ones (Furniss and others 1991). Beschta (1984) reported that: (1) various types of structures, commonly denoted as "trash racks", can be constructed upstream of the inlet to help prevent plugging by wood, but winter maintenance of these structures is critical for success; (2) organic debris can create continual maintenance problems when the culvert diameter is too small to freely pass floatable wood; and (3) culvert slopes of less than 3 percent may be prone to bedload sediment accumulation and reduced efficiency.

---

[20] Note that most previous guidelines (e.g., CDF 1983) specified a maximum HW/D ratio of 1.0.

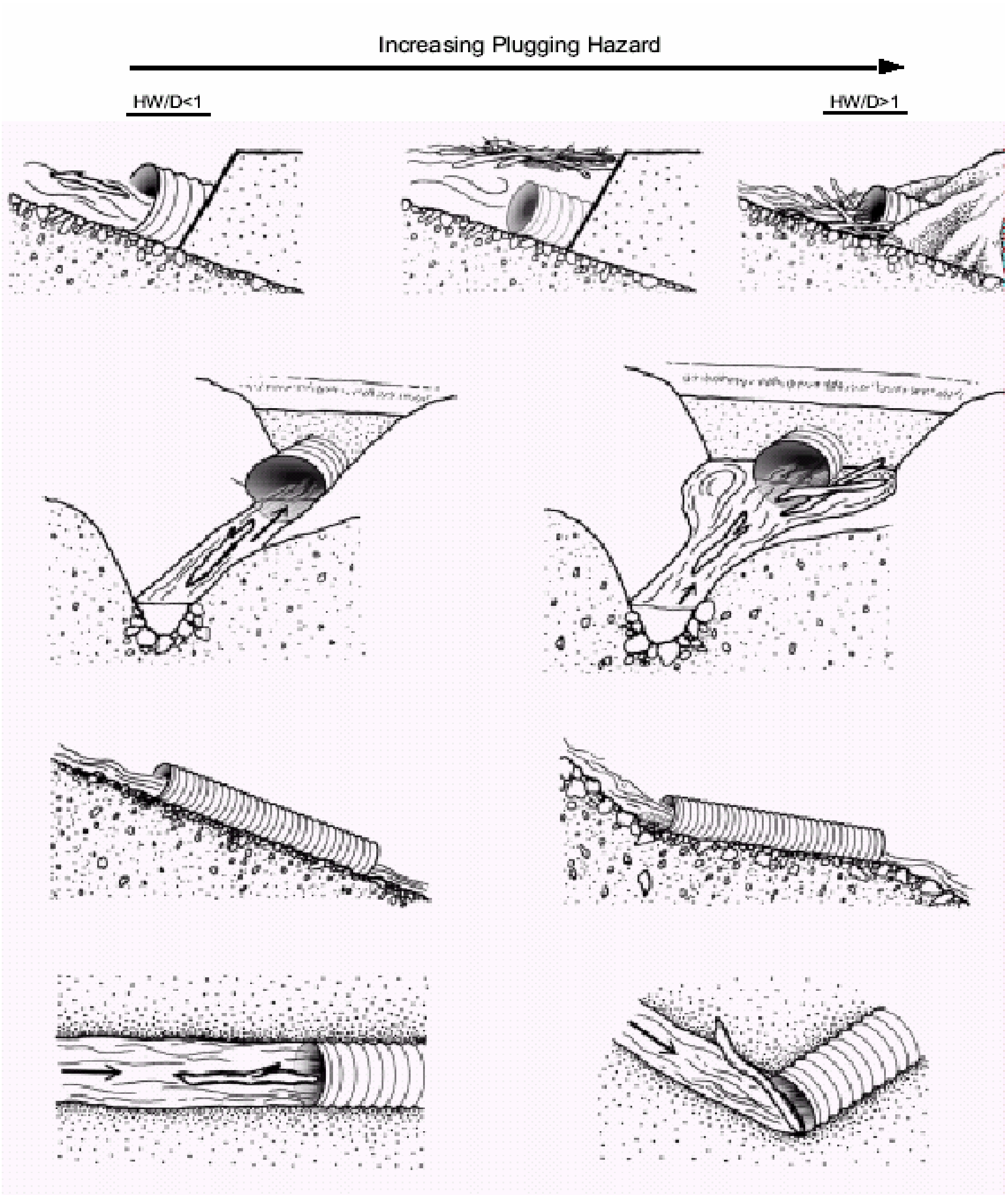


Figure 5. Reducing the probability of culvert failure due to woody debris and sediment involves not only careful consideration of culvert diameter, but configuration of the installed pipe as well. From top to bottom in the above figure, culverts should: (1) not pond water, (2) not create unusually wide areas near the inlet, (3) maintain channel grade, and (4) be placed on the same alignment as the natural stream channel (from Furniss and others 1998).

Recently conducted studies in the Pacific Northwest and northwestern California reveal that the impacts of culvert failures caused by very large, infrequent storms (e.g., greater than 20-year recurrence interval) that initiate landslides and debris flows can be reduced by minimizing the interference that the crossing presents in the path of the mass wasting feature (Furniss and others 1998). Crossing failures associated with such mass wasting processes, rather than by fluvial processes, are not the result of inadequate culvert sizing. More frequent large storms (e.g., less than 12-year recurrence interval) have been found to often cause failures by fluvial mechanisms—wood transport and fluvial sediment—and failure probability for these events can be reduced through careful culvert sizing and configuration (Flanagan 1996, Flanagan and others 1998).

For these more frequent storms, the dominant failure mechanism is wood accumulation at the inlet and typically the type of wood causing failures is small (i.e., twigs, sticks, and branches), not large logs. Pieces of wood initiating plugging are usually not much longer than the culvert diameter and often do not exceed the width of the channel (Figure 6). As stated above, culvert sizing should be driven by channel dimensions, including active channel width and channel slope. Sizing for a 100-year flood flow alone does not ensure adequate capacity for wood and sediment. For example, when a sample of culverts in northwestern California were sized for the 100-year peak flow, the resulting pipe diameters were, on average, only about two-thirds the channel width (i.e., culvert diameter/channel width ≈ 2/3). However, if the culvert is sized for wood passage (i.e., pipe is approximately equal to active channel width), it typically ensures adequate hydraulic capacity for 100-year flood flows or greater. Additionally, for wood passage it is critical to avoid culvert sizing that creates ponded conditions at the inlet (see Figure 5).

Additional Design Considerations to Reduce the Risk of Crossing Failure

Other elements can be incorporated into stream crossing design that can reduce the risk of crossing failure and potential impacts to watercourses if crossings fail. Proposed crossings should be adjusted to fit all of the field conditions present. For example, the height of fill that will exist above a culvert should be accounted for when determining the appropriate pipe diameter. As a rule of thumb, the pipe diameter should be increased by 6 inches for every 5 feet of fill above the pipe on the discharge side of the crossing.[21] For example, a pipe that is initially sized at 36 inches and would be covered by 10 feet of fill on the downstream side should be increased to 48 inches to reduce the risk of crossing failure and the potential discharge of a large amount of sediment into the stream if the culvert plugs. This approach also reduces the need for replacement of a failed crossing that would be relatively expensive compared to the cost of a slightly larger diameter pipe. It is also important to have crossing fill material adequately compacted so that overtopped pipes will have only a small part of their fill removed.

[21] This recommendation is based on the personal observations of Mr. Spittler, CGS, Santa Rosa.

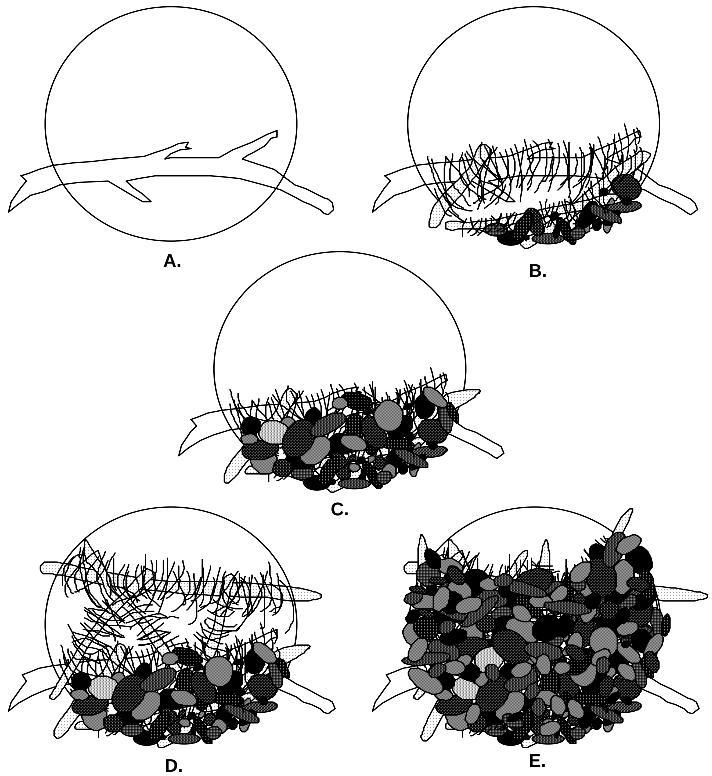


Figure 6. Plugging of culverts by wood is usually initiated by a single piece lodging across the inlet (a). This piece becomes a locus for the accumulation of detritus and sediment (b). As the plug grows, sediment and detritus seal off a portion of the inlet (c). The initiation process may be repeated with a second piece, allowing the plug to grow upwards (d and e) (Flanagan 1996).

Minimizing the amount of crossing fill and constructing a crossing without diversion potential can significantly reduce sediment impacts if a crossing were to fail (Furniss and others 1997). Constructing a crossing with no diversion potential is more cost and time effective than having to continually maintain a crossing in order to maintain flow and prevent a stream diversion. Waterbars rarely prevent stream diversions when culverts plug during a large storm and they also require long-term maintenance.

In contrast, a broad overflow dip (critical dip) at a watercourse crossing, when properly constructed, is a low-maintenance permanent structure that allows for the passage of standard log trucks at reduced speeds. The overflow dip may be constructed to discharge either at the intersection of the crossing fill with the valley wall, or over the fill face in an armored spillway. The design and construction of the critical dip discharge is important to reduce the potential for overtopping flows to erode the crossing fill (Weaver and Hagans 1994). The California Forest Practice Rules [14 CCR § 923.3(f), 943.3(f), 963.3(f); 923.4(n), 943.4(n), 963.4(n)] require that permanent watercourse crossings are constructed or maintained to prevent diversion of stream overflow down the road should the drainage structure become plugged.

Road surface runoff and surface erosion need to be considered in the crossing and approach design to minimize the potential for sediment delivery to the watercourse being crossed. Where the road surface is outsloped or flat as it approaches and crosses the crossing fill, the downslope discharge area will need to be designed for prevention of surface erosion. Where the road surface is insloped, the drainage ditch needs to be designed to avoid eroding and/or discharging fine-grained sediment into the crossing inlet. Additional erosion control structures, such as rolling dips, water bars, or cross-drains, placed close to crossing fills are useful in minimizing the amount of surface runoff from the approach and sediment delivery to the watercourse. A filter area of vegetation should be established between the ditch relief culvert outlet (or other drainage structure) and the stream channel to catch the sediment from relief-culvert discharge before the water (and entrained sediment) enters the stream channel (Kramer 2001).

When a crossing is reconstructed, crossing-induced sediment accumulations in the channel upstream of the culvert inlet should be removed before new culvert placement. This will allow the new culvert to be installed closer to the original channel grade, thereby facilitating sediment transport through the culvert (minimizing the potential for sediment accumulation at the inlet and plugging) and reducing the likelihood of post-reconstruction headcutting through the sediment that had accumulated immediately upstream of the crossing. The reconstructed channel gradient should be consistent with the natural gradient both upstream and downstream of the crossing. If a new culvert is being installed, the gradient of the culvert should be designed so that the flow velocity through the culvert does not result in inlet deposition or outlet scour. A minimum diameter of 24 inches is recommended for watercourse crossings in channels that receive flood flows (i.e., not crossings receiving discharge solely from small springs).

Rocked-lined fords are often a better replacement alternative than culverts for small headwater channels, particularly where winter maintenance is difficult and/or debris flows are likely (Spittler 1992, Warhol and Pyles 1989). Because natural stream bottoms better facilitate fish passage relative to the bare metal of culverts, bridges and other natural-bottomed watercourse crossing structures, such as arches and culverts buried with at least 20 percent of their diameter in the channel, should be installed in fish-bearing channels where standard culverts previously existed, rather than reinstalling new culverts at grade. ODF (2002b) provides guidance on how to determine the flow capacity of short and long-span bridges, as well as open-bottom pipe arch structures.

Evaluating Existing Crossings for Risk of Failure

Many of the concepts used for sizing new culverts can also be used for evaluating existing culverts to determine which ones are presently at high risk for failure. Hillslope monitoring efforts recently completed on Timber Harvesting Plans (THPs) throughout California on non-federal commercial timberlands suggest that numerous existing crossings are at high risk for failure, with frequent watercourse crossing problems documented related to culvert plugging, stream diversion potential, fill slope erosion, scour at the outlet, and ineffective road surface drainage immediately above crossings (Cafferata and Munn 2002). About five percent of the randomly selected THPs evaluated from 1996 through 2001 had one or more catastrophic crossing failures present. Similarly, Bundros and others (2003) classified 20 percent of 2,300 evaluated stream crossings in the Redwood Creek watershed as "critical crossings," which were defined as having diversion potential, an undersized culvert, and a medium or higher plugging potential.

Crossing inventories are an important component of a road management plan that aims to reduce sediment yield to watercourses, as well as prevent road damage (see Flanagan and others (1998), Flanagan and Furniss (1997) for additional information). Examples of items to consider as part of a crossing inventory include:

Crossings at high risk from wood-related plugging

- culvert diameter divided by active channel width is less than 0.7[22]
- poor pipe alignment with the stream channel
- HW/D ratio is greater than 1.0
- unusually wide areas, including sediment basins, near the inlet of the pipe

Crossings at high risk for sediment blockage

- culvert gradient is less than 3 percent
- culvert gradient is less than natural stream channel gradient

Crossings at high risk for hydraulic capacity exceedance

- existing pipe capacity has less than 100-year flow capacity
- crushing and plugging of the pipe inlet is present
- evidence of insufficient hydraulic capacity is present. Examples include:
    - floodplain-like deposits of sediment immediately upstream of the crossing
    - evidence of overtopping of the crossing by peak flows

Crossings at high risk for causing significant gullying

- diversion potential exists (the road grade through the crossing is such that a stream will flow down the road and leave its natural channel if the culvert plugs or its capacity is exceeded)

Crossings in need of replacement due to age-related deterioration

- the length of time the culvert has been installed[23]
- moderate or high degree of corrosion

[22] Research conducted in northwestern California showed that culverts sized at 0.7 times the mean stream bed width will pass, on average, 95% of fluvially transported wood greater than 12 inches long (Flanagan 1996).
[23] The service life of a culvert varies depending on local corrosion rates, but culverts generally last at least 25 years (Pyles and others 1989).

Crossing with fish passage limitations [design criteria for fish passage are described in USFS (2000), NMFS (2001), ODF (2002a), Flosi and others (2003), and WDFW (2003)]

- outlet is elevated greater than fish jumping ability
- excessive culvert gradient, resulting in water velocities that exceed fish swimming ability and endurance
- insufficient water depth in the culvert for fish passage
- the bottom 20 percent or more of the culvert is not buried in stream gravels (note that this does not ensure fish passage if present)

Following the completion of the inventory, a schedule should be developed and funding secured to make needed corrections.

Conclusions

Several office techniques, based on empirical relationships between precipitation and watershed characteristics and runoff, are available to determine an estimated 100-year discharge. However, these results should be checked against field observations. For instance, if office-based equations indicate that a 24-inch culvert would pass the 100-year flood but the bankfull cross section is more than one square foot in coastal northwestern California, the culvert may be too small for stream discharge. Wood and sediment passage requirements would likely further increase initial estimates of pipe diameter.

Culvert sizes specified as part of a permitted project in California, such as a THP, should be based on defensible, accepted methods, such as those discussed above, with documentation for the input values, appropriate maps, data sources, field observations, and calculations. Spreadsheets are available for calculating discharges for the rational and USGS Magnitude and Frequency methods which can be cited in the plan (Figure 7).[24] This level of information assists both agency review of plans and reduces the need for follow-up questions.

While we cannot completely avoid watercourse crossing failures, we can reduce failure potential through careful crossing design that accommodates water, wood, and sediment and that reduces potential erosional consequences if and when they do fail.

Acknowledgements

Dr. Robert Ziemer, Chief Research Hydrologist (retired), USDA Forest Service, Pacific Southwest Research Station, Arcata; Dr. Lee MacDonald, Professor, Department of Earth Resources, Colorado State University, Fort Collins; and Dr.

[24] Contact Dr. Wopat at CGS for a copy of the Excel spreadsheet he has developed for calculating discharge with the rational and USGS Magnitude and Frequency methods. Additionally, Moore and others (1999) provide a review of existing software tools available for culvert design and analysis.

William Trush, Adjunct Professor, Humboldt State University, and Principal, McBain and Trush, Arcata, reviewed an earlier draft and provided helpful comments. Dr. Robert Beschta, Professor Emeritus, Oregon State University, Corvallis; John Munn, Soil Erosion Studies Project Leader, California Department of Forestry and Fire Protection (CDF), Sacramento; Tim Robards, State Forests Research Coordinator, CDF, Sacramento; and Gary Rynearson, California State Board of Forestry and Fire Protection, reviewed the second draft. Michael Furniss, Hydrologist/Soil Scientist, USDA Forest Service, Pacific Northwest Research Station, Corvallis, and Dr. Carlton Yee, Emeritus Professor of Forestry at Humboldt State University, Arcata, reviewed both the first and second drafts. Clay Brandow, Watershed Specialist, CDF, Sacramento, measured the cross sectional area of North Fork Caspar Creek subwatershed HEN and offered valuable comments on the second draft. Dr. Mary Ann Madej, Adjunct Professor, Humboldt State University, and Geologist, U.S. Geological Survey, Redwood Field Station, Arcata, provided the statistical analysis for the 3 X bankfull stage analysis.

Determination of 100-Year Flood Flow

Location: Coffee Creek, Trinity County, CA

(Enter data in fields with red-colored headings. Other data fields will be calculated automatically.)

Magnitude and Frequency Method for 100-year flood flow

								100-yr flood flow Q_{100} (cfs)			
No.	Crossing	Area (acres) A	Basin maximum elevation (ft)	Crossing elevation (ft)	Area (mi^2) A	Precipitation (in/yr) P	Elevation (ft/1000) H	North Coast(1) (NC)	Sierra(2) (S)	North-east(3) (NE)	Central Coast(4) (CC)
1	*A (real)*	412.5	7215	2800	0.645	58.38	5.0075	***325.5***	***354.6***	***96.5***	***239.5***
2	*B (hypothetical)*	25	3300	3050	0.039	58.38	3.175	***28.4***	***49.8***	***18.5***	***23.6***
3					0.000		0	***0.0***	***#DIV/0!***	***0.0***	***#DIV/0!***
4					0.000		0	***0.0***	***#DIV/0!***	***0.0***	***#DIV/0!***
5					0.000		0	***0.0***	***#DIV/0!***	***0.0***	***#DIV/0!***
6					0.000		0	***0.0***	***#DIV/0!***	***0.0***	***#DIV/0!***
7					0.000		0	***0.0***	***#DIV/0!***	***0.0***	***#DIV/0!***
8					0.000		0	***0.0***	***#DIV/0!***	***0.0***	***#DIV/0!***
9					0.000		0	***0.0***	***#DIV/0!***	***0.0***	***#DIV/0!***
10					0.000		0	***0.0***	***#DIV/0!***	***0.0***	***#DIV/0!***

See below for M&F equations

Rational Method for 100-year flood flow

		$T_c = 60((11.9 X L^3)/H)$^0.385			$Q_{100} = CIA$			
No.	Crossing	Channel length (to top of basin) (mi) L	Elevation difference (ft) H	Concentration time (min) Tc	Runoff coefficient C	Precipitation (in/hr) I	Area (acres) A	100-yr flood flow (cfs) Q100
1	*A (real)*	1.97	4415	*13*	0.4	3.04	412.5	***501.6***
2	*B (hypothetical)*	0.13	250	*2*	0.4	3.04	25	***30.4***
3	*0*		0	*#DIV/0!*			0	***0.0***
4	*0*		0	*#DIV/0!*			0	***0.0***
5	*0*		0	*#DIV/0!*			0	***0.0***
6	*0*		0	*#DIV/0!*			0	***0.0***
7	*0*		0	*#DIV/0!*			0	***0.0***
8	*0*		0	*#DIV/0!*			0	***0.0***
9	*0*		0	*#DIV/0!*			0	***0.0***
10	*0*		0	*#DIV/0!*			0	***0.0***

Magnitude & Frequency Q_{100} equations

NC (1) $Q_{100} = 9.23 (A)^{0.87} (P)^{0.97}$

S (2) $Q_{100} = 15.7 (A)^{0.77} (P)^{1.02} (H)^{-0.43}$

NE (3) $Q_{100} = 125 (A)^{0.59}$

CC (4) $Q_{100} = 19.7 (A)^{0.88} (P)^{0.84} (H)^{-0.33}$

Template prepared by:
Michael Wopat
California Geological Survey
Redding, CA 96002
June 14, 2001

q100 calcs tmplt.xls, Sheet1 Page 1 of 1 2/23/2003 3:03 PM

Figure 7. Spreadsheet available for determining estimated water discharge associated with a 100-year recurrence interval event using either the rational method or the USGS Magnitude and Frequency Method (Wopat 2003; developed by and available from M. Wopat, CGS, Redding, CA).

Literature Cited

AISI (American Iron and Steel Institute). 1971. Handbook of Steel Drainage and Highway Construction Products. Washington, D.C. 348 p.

BC MOF (B.C. Ministry of Forests). 1995. Forest road engineering guidebook (First Edition). Forest Practices. Br., British Columbia Ministry of Forests., Victoria, B.C. Forest Practices Code of British Columbia Guidebook.

BC MOF (B.C. Ministry of Forests). 2002. Forest road engineering guidebook (Second Edition). Forest Practices. Br., British Columbia Ministry of Forests., Victoria, B.C. Forest Practices Code of British Columbia Guidebook. 208 p. http://www.for.gov.bc.ca/tasb/legsregs/fpc/FPCGUIDE/Road/FRE.pdf

Beckers, J., Y. Alila, and A. Mtiraoui. 2002. On the validity of the British Columbia forest practices code guidelines for stream culvert discharge design. Can. J. For. Res. 32: 684-692.

Beschta, R.L. 1984. Road drainage structures: culvert sizing at stream crossings. Paper presented at “Forest Roads Conference” in May 1984, College of Forestry, Oregon State University, Corvallis, OR. 28 p.

Bundros, G.J., D. Short, B.E. Barr, and V.C Hare. 2003. Upper Redwood Creek watershed road assessment summary report. Unpublished Redwood National and State Parks final report submitted to the Pacific Coast Fish, Wetlands and Wildlife Restoration Association. Arcata, CA. 137 p.

Buxton, T.H., W.J. Trush, and S.A. Flanagan. 1996. A comparison of empirical and regional peak discharge predictions to actual January 3, 1995 discharge at fifteen Bull Creek, Northwestern California tributary culverts. Unpubl. Rept. Prepared for the Humboldt State Univ. Institute for River Ecosystems Road Stream Crossing Project. Arcata, CA. 10 p.

Cafferata, P.H., and J.R. Munn. 2002. Hillslope monitoring program: monitoring results from 1996 through 2001. Monitoring Study Group Final Report prepared for the California State Board of Forestry and Fire Protection. Sacramento, CA. 114 p. http://www.bof.fire.ca.gov/pdfs/ComboDocument_8_.pdf

Caltrans (California Department of Transportation). 2001. Highway design manual. Chapter 810—Hydrology. Sacramento, CA. 24 p. http://www.dot.ca.gov/hq/oppd/hdm/pdf/chp0810.pdf

CDF (California Department of Forestry). 1983. Suggested culvert sizing procedures for the 50-year storm. Sacramento, CA. 31 p.

CDF (California Department of Forestry and Fire Protection). 2003. California Forest Practice Rules 2003 prepared for California Licensed Timber Operators and California Registered Professional Foresters. Sacramento, CA. http://www.fire.ca.gov/ResourceManagement/pdf/FPR200301.pdf

CDWR (California Department of Water Resources). 1976. Rainfall analysis for drainage design, Vol. I (Short-duration precipitation frequency data) and Vol. III (Intensity-duration-frequency curves). CDWR bulletin No. 195. Sacramento, CA.

CDWR (California Department of Water Resources). 1981. Rainfall depth-duration-frequency for California. Sacramento, CA. 39 p.

Chow, V.T. 1964. Handbook of applied hydrology. McGraw-Hill Book Company, New York. p. 20-8.

Dunne, T. and L.B. Leopold. 1978. Water in environmental planning. W.H. Freeman and Company. San Francisco, CA. 818 p.

FAA (Federal Aviation Administration). 1970. Airport Drainage: DOT FAA Advisory Circular, AC No: 150/5320-5B, dated July 1, 1970. Department of Transportation. 80 p. http://www1.faa.gov/arp/pdf/5320-5b.pdf

Flanagan, S.A. 1996. Woody debris transport through low order stream channels: implications for stream crossing failure. Draft Master of Science thesis, Humboldt State University, Arcata, CA. 34 p.

Flanagan, S.A. and M.J. Furniss. 1997. Field indicators of inlet controlled road stream crossing capacity. Water/Road Interaction Technology Series 9777 1807-SDTDC. San Dimas CA: U.S. Department of Agriculture, Forest Service, Technology and Development Program. 5 p. http://www.stream.fs.fed.us/water-road/w-r-pdf/fieldindicators.pdf

Flanagan, S.A., M.J. Furniss, T.S. Ledwith, S. Thiesen, M. Love, K. Moore, and J. Ory. 1998. Methods for inventory and environmental risk assessment of road drainage crossings. USDA Forest Service. Technology and Development Program. 9877--1809—SDTDC. 45 p. http://www.stream.fs.fed.us/water-road/w-r-pdf/handbook.pdf

Flosi, G., S. Downie, J. Hopelain, M. Bird, R. Coey, B. Collins, R. Taylor, and M. Love. 2003. California salmonid stream habitat restoration manual. California Department of Fish and Game. Part IX: Fish Passage Evaluation at Stream Crossings. Sacramento, CA. http://www.dfg.ca.gov/nafwb/pubs/2003/FishPassage.pdf

Furniss, M.J., T.S. Ledwith, M.A. Love, B. McFadin, S.A. Flanagan. 1998. Response of road-stream crossings to large flood events in Washington, Oregon, and Northern California. USDA Forest Service. Technology and Development Program. 9877--1806—SDTDC. 14 p. http://www.stream.fs.fed.us/water-road/w-r-pdf/floodeffects.pdf

Furniss, M.J., M. Love, and S.A. Flanagan. 1997. Diversion potential at road-stream crossings. Water/Road Interaction Technology Series 9777 1814-SDTDC. San Dimas CA: U.S. Department of Agriculture, Forest Service, Technology and Development Program. 12 p. http://www.stream.fs.fed.us/water-road/w-r-pdf/diversionpntl.pdf

Furniss, M.J., S. Flanagan, and B. McFadin. 2000. Hydrologically-connected roads: an indicator of the influence of roads on chronic sedimentation, surface water hydrology, and exposure to toxic chemicals. Stream Notes, July 2000. Stream Systems Technology Center, USDA Forest Service, Rocky Mountain Research Station, Fort Collins, CO. 4 p. http://www.stream.fs.fed.us/news/streamnt/jul00/jul00_2.htm#anchortop

Furniss, M.J. T.D. Roelofs, and C.S. Yee. 1991. Road construction and maintenance. In: W.R. Meehan, ed., Influences of forest and rangeland management on salmonid fishes and their habitats. American Fisheries Society Special Publication 19: 297-323.

Goodridge, J. 2000. California weather CD. Prepared with support from the California Department of Water Resources. Mendocino, CA.

Henry, N. 1998. Overview of the Caspar Creek watershed study. In: Ziemer, R.R., technical coordinator. Proceedings from the Conference on Coastal Watersheds: the Caspar Creek Story, May 6, 1998, Ukiah, CA. General Tech. Rep. PSW GTR–168. Albany, CA: Pacific Southwest Research Station, Forest Service, U.S. Department of Agriculture. p. 1-9. http://www.fs.fed.us/psw/publications/documents/gtr-168/01henry.pdf

IACWD (Interagency Advisory Committee on Water Data). 1982. Guidelines for determining flood flow frequency. Bulletin 17B of the Hydrology Subcommittee, Office of Water Data Coordination, U.S. Geological Survey, Reston, Virginia, 183 p.

Kattelmann, R. 1990. Floods in the high Sierra Nevada, California, USA. In: R.O. Sinniger and M. Monbaron, eds., Hydrology in Mountainous Regions II. Artificial Reservoirs, Water and Slopes. IAHS Publ. No. 194. p. 311-317.

Kirpich, Z.P. 1940. Time of concentration in small agricultural watersheds. Civil Engineering 16(6): 362.

Kramer, B.W. 2001. Forest road contracting, construction, and maintenance for small forest woodland owners. Research Contribution 35. Oregon State University, College of Forestry, Forest Research Laboratory. 79 p. http://fcg.cof.orst.edu/rc/RC35.pdf

Moore, K., M.J. Furniss, S.A. Flanagan, M.A. Love, J. Moll. 1999. A guide to computer software tools for culvert design and analysis. Water/Road Interaction Technology Series 9977 1806-SDTDC. San Dimas CA: U.S. Department of Agriculture, Forest Service, Technology and Development Program. 25 p. http://www.stream.fs.fed.us/water-road/w-r-pdf/Culvert_software_guide.pdf

NMFS (National Marine Fisheries Service). 2001. Guidelines for salmonid passage at stream crossings. Southwest Region. Long Beach, California. 14pp. http://swr.nmfs.noaa.gov/hcd/NMFSSCG.PDF

Normann, J.M., R.J. Houghtalen, and W.J. Johnston. 1985. Hydraulic design of highway culverts. Federal Highway Administration, U.S. Department of Transportation. Report No. FHWA-IP-85-15. 280 p. http://199.79.179.19/OLPFiles/FHWA/009342.pdf.

ODF (Oregon Department of Forestry). 2002a. Fish passage guidelines for new and replacement stream crossing structures. Forest Practices Technical Note Number 4. Version 1.0. Salem, OR. 14 p. http://www.odf.state.or.us/divisions/protection/forest_practices/RefLibrary/TechNote4v1.0FishPsg5-10-02.pdf

ODF (Oregon Department of Forestry). 2002b. Determining the 50-year peak flow and stream crossing structure size for new and replacement crossings. Forest Practices Technical Note Number 5. Salem, OR. 12 p. http://www.odf.state.or.us/divisions/protection/forest_practices/RefLibrary/TechNote5v1.0CrsngSizing5-10-0212.pdf

Papadakis, C.N. and M.N. Kazan, 1987. Time of concentration in small rural watersheds. Engineering Hydrology, Proceedings of the August 3-7 Symposium, Williamsburg, Virginia, ASCE, New York, NY. p.633-638.

Piehl, B.T., M.R. Pyles, and R.L. Beschta. 1988. Flow capacity of culverts on Oregon Coast Range forest roads. Water Resources Bulletin 24(3): 631-637.

Pitlick, J. 1994. Relation between peak flows, precipitation, and physiography for five mountainous regions in the western USA. Journal of Hydrology. 158: 219-240.

Portland Cement Association. 1964. Handbook of concrete culvert pipe hydraulics. Portland Cement Association. Skokie, IL. 267 p.

Pyles, M.R., A.E. Skaugset, and T. Warhol. 1989. Culvert design and performance on forest roads. Paper presented at the 12th Annual Council on Forest Engineering Meeting, Coeur d'Alene, ID, August 27-30, 1989. p. 82-87.

Rantz, S. 1972. Mean annual precipitation in the California region. U.S. Geological Survey Open-File Map. Menlo Park, CA.

Ries, K.G. and M.Y. Crouse. 2002. The national flood frequency program, version 3: a computer program for estimating magnitude and frequency of floods for ungaged sites. U.S. Geological Survey Water-Resources Investigations Report 02-4168. 42 p. http://water.usgs.gov/pubs/wri/wri024168/

Rosgen, D. 1996. Applied river morphology. Wildland Hydrology, Pagosa Springs, Colorado. p. 2-2.

Rossmiller, R.L. 1980. The rational method revisited. In: International Symposium on Urban Runoff, University of Kentucky, Lexington, Kentucky, July 28-31, 1980. p. 1-12.

Skaugset, A.E. and M.R. Pyles. 1991. Peak flow estimation and streamflow simulation for small forested watersheds. Unpublished Report prepared for a workshop titled Design and Maintenance of Forest Road Drainage, 18-20 November 1991, Oregon State University, Corvallis, OR. 19 p.

Spittler, T.E. 1992. Managing soil and water while harvesting timber in decomposed granitic terrain. In: S. Sommarstrom, ed., Decomposed Granitic Soils: Problems and Solutions. October 21-23, 1992, Redding, CA. University Extension, University of California, Davis. p. 73-83.

USFS (United States Forest Service). 2000. FishXing CD. Version 2.2. USDA Forest Service San Dimas Technology and Development Center, San Dimas, CA. http://www.stream.fs.fed.us/fishxing/index.html

Waananen, A.O. and J.R. Crippen. 1977. Magnitude and frequency of floods in California. U.S. Geological Survey. Water Resources Investigation 77-21. Menlo Park, CA. 96 p.

WDFW (Washington Department of Fish and Wildlife). 2003. Design of road culverts for fish passage. Olympia, WA. 110 p. http://wdfw.wa.gov/hab/engineer/cm/culvert_manual_final.pdf

Weaver, W.E. and D.K. Hagans. 1994. Handbook for forest and ranch roads. Final report prepared for the Mendocino County Resource Conservation District, Ukiah, CA. 161 p.

Warhol, T. and M.R. Pyles. 1989. Low water fords: an alternative to culverts on forest roads. Paper presented at the 12th Annual Council on Forest Engineering Meeting, Coeur d'Alene, ID. August 27-30, 1989. 5 p.

Wopat, M.A. 2003. Estimating 100-year flood flow and sizing crossings to handle the flood flow and associated sediment and debris. PowerPoint presentation and handout, California Licensed Foresters Association Watercourse Crossing Workshop, May 16, 2003, Redding, CA. California Geological Survey, Redding, CA.

Yee, C.S. 1994. Culvert design and installation. Unpublished paper supplied to participants at the California Licensed Foresters Association Workshop titled Road Location and Design. Redding, CA, June 9, 1995.

Appendix -- Examples of Watercourse Crossing Sizing Methods

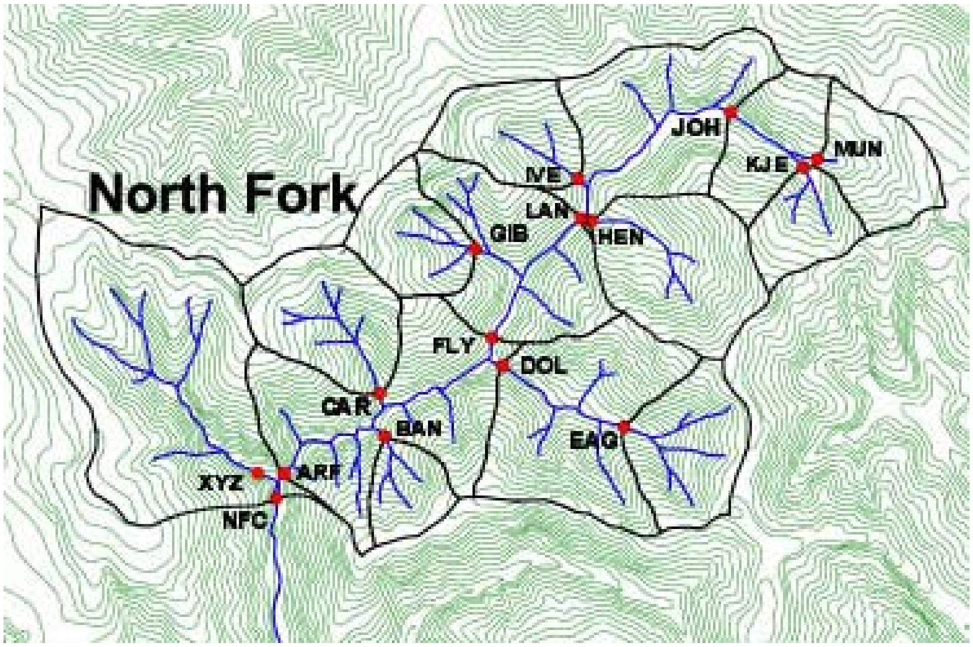


Figure 8. North Fork Caspar Creek Watershed (1168 acres), and control subwatershed HEN (96 acres) (from USFS-PSW Redwood Sciences Laboratory webpage).

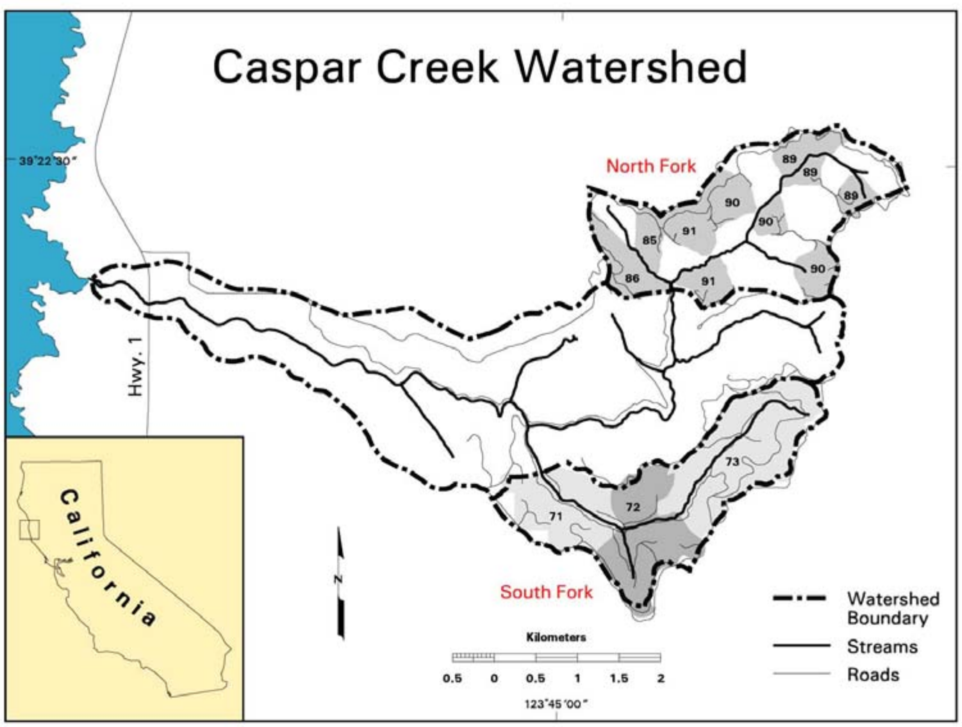


Figure 9. Location map of the entire Caspar Creek watershed (from USFS-PSW Redwood Sciences Laboratory webpage).

Part A. Predicting the 100-Year Recurrence Interval Discharge for Caspar Creek Subwatershed HEN (see Figures 8 and 9)

Rational Method

Known Information:

Drainage area (A) = 96 acres (Henry 1998) for HEN
100 yr 15 minute NF Caspar Creek rainfall = 0.76 inches/15 minutes (Goodridge 2000)
100 yr 30 minute NF Caspar Creek rainfall = 1.02 inches/30 minutes (Goodridge 2000)
Channel length = 0.5 miles from the ridge to the gaging station
Difference in elevation = 550 feet from the ridge to the gaging station
Soil type = loam

Calculate:

Q_{100} = CIA

Time of Concentration (using the Kirpich Formula):

$$T_c = \left(\frac{11.9(L)^3}{H}\right)^{0.385}$$

where:
T_c = time of concentration (hours)
L = length of the channel in miles from the head of the watershed to the crossing point
H = elevation difference between the highest point in the watershed and the crossing point (feet)

$T_c = [(11.9\ (0.5\ \text{miles})^3/550\ \text{feet})]^{0.385}$
T_c = 0.103 hours or 6 minutes
T_c = 6 minutes. 15-minute rainfall-depth-duration-frequency data from Goodridge (2000) was used because 10-minute data was not available
0.76 inches/15 minutes x 60 minutes/hour = 3.04 inches/hour
I = 3.04 inches/hour
C = 0.3 (loam soil, Table 1)
Q_{100} = 0.3 x 3.04 inches/hour x 96 acres
Q_{100} = 87.6 or 88 cfs
Pipe diameter = 54 inches (assumes HW/D = 1.0 and projecting pipe)
Pipe diameter = 69 inches (assumes HW/D = 0.67 and projecting pipe)

Time of Concentration (using the Airport Drainage Formula):

$T_c = ((1.8)\ (1.1 - C)\ (D^{0.5}))/(S^{0.33})$

where:
T_c = time of concentration in minutes
C = runoff coefficient (dimensionless, $0 < C < 1.0$)
D = distance in feet from the point of interest to the point in the watershed from which the time of flow is the greatest
S = slope in percent

$T_c = ((1.8)\ (1.1 - 0.3)\ (2640^{0.5}))/(21^{0.33})$
T_c = 27 minutes, or approximately 30 minutes
1.02 inches/30 minutes x 60 minutes/hour = 2.04 inches/hour
I = 2.04 inches/hour
C = 0.3 (loam soil, Table 1)
Q_{100} = 0.3 x 2.04 inches/hour x 96 acres
Q_{100} = 58.8 or 59 cfs
Pipe diameter = 46 inches (assumes HW/D = 1.0 and projecting pipe)
Pipe diameter = 60 inches (assumes HW/D = 0.67 and projecting pipe)

USGS Magnitude and Frequency Method[25]
Known Information:

$A = 0.15$ miles^2
$P = 46.85$ inches/year (Henry 1998)

Calculate:

$Q_{100} = 9.23\ A^{0.87}\ P^{0.97}$
$Q_{100} = 9.23\ (0.15)^{0.87}\ (46.85)^{0.97}$
$Q_{100} = 74$ cfs
Pipe diameter = 51 inches (assumes HW/D = 1.0 and projecting pipe)
Pipe diameter = 65 inches (assumes HW/D = 0.67 and projecting pipe)

Flow Transference Method (Waananen and Crippen 1977)
Known Information:

A = 96 acres (Henry 1998) for HEN; 1168 acres for the North Fork
Q_{100g} for NF Caspar Creek is 367.1 cfs (using USGS PEAKFQ program)

Calculate:

$Q_{100u} = Q_{100g}\ (A_u/A_g)^b$
$Q_{100u} = 367.1$ cfs (96 acres/1168 acres)$^{0.87}$
$Q_{100u} = 42$ cfs
Pipe diameter = 40 inches (assumes HW/D = 1.0 and projecting pipe)
Pipe diameter = 52 inches (assumes HW/D = 0.67 and projecting pipe)

Direct Flow Transference Method (Skaugset and Pyles 1991)
Known Information:

A = 96 acres (Henry 1998) for HEN; 1168 acres for the North Fork
Q_{100g} for NF Caspar Creek is 367.1 cfs

Calculate:

$Q_{100u} = Q_{100g}\ (A_u/A_g)$
$Q_{100u} = 367.1$ cfs (96 acres/1168 acres)
$Q_{100u} = 30$ cfs
Pipe diameter = 34 inches (assumes HW/D = 1.0 and projecting pipe)
Pipe diameter = 45 inches (assumes HW/D = 0.67 and projecting pipe) (see Figure 12 for an example of using the culvert sizing nomograph for a discharge of 30 cfs)

3 X Bankfull Stage Method (see Figures 3 and 11)
Known Information (based on measurements made at 3 cross-sections):

Average channel depth at HEN is 0.95 feet
Average bankfull stream channel width (W_1) at HEN is 5.6 feet
Average active stream channel width (W_2) at HEN is 4.4 feet
Combined average stream channel width at HEN is 5.0 feet
Bankfull cross-sectional area above HEN is 4.75 feet^2

Calculate:

$D \approx 2[(bfa)^{1/2}]$
$D = 2[(4.75\ \text{feet}^2)^{½}]$
Pipe diameter (D) = 4.35 feet x 12 = 52 inches

[25] The USGS National Flood Frequency Program (NFF, Version 3.2, available at http://water.usgs.gov/software/nff.html) uses the USGS Magnitude and Frequency equations to estimate flood flows in California. NFF shows there to be a standard error (SE) of 66% (= 49 cfs) for the 74-cfs Q_{100} estimate. $Q_{100} \pm 1$ SE = 74 cfs $\pm$ 49 cfs, resulting in a $\pm$ 1-SE range of 25 cfs to 123 cfs. Because the range $\pm$ 1 SE encompasses the central 68 percent of the range of the estimated discharge, there is a 68 percent chance that the true Q_{100} lies within the range defined by $Q_{100} \pm 1$ SE, that is, between 25 cfs and 123 cfs.

Active Channel Width Method

Known Information:

Average channel width above HEN is 4.4 feet (use W_2 width)

Calculate:

culvert diameter/channel width = 1.0
culvert diameter = 1.0 x channel width
culvert diameter = 1.0 x 4.4 feet
Pipe diameter (D) = 4.4 feet or 53 inches

Flow Frequency Analysis Method

Known Information:

Table 3. Annual peak discharges for station HEN from water years 1986 through 2003.

Year	Peak Q (cfs)	Rank
1986	12.8	6
1987	4.3	15
1988	7.6	11
1989	5.0	14
1990	12.3	7
1991	1.6	17
1992	4.3	15
1993	17.1	1
1994	4.1	16
1995	14.8	4
1996	11.6	8
1997	15.6	3
1998	13.0	5
1999	16.5	2
2000	6.6	12
2001	5.8	13
2002	10.1	10
2003	11.1	9

Calculate:

Table 4. Estimated discharges for various recurrence intervals (RIs), including the 10-year RI discharge (used in Appendix B) and the 100 year RI discharge (discharges estimated by the USGS PEAKFQ program).

RI (yr)	Q (cfs)	95% Confidence Limits Lower	95% Confidence Limits Upper
2	9.0	7.3	11.2
5	13.7	11.0	18.5
10	**16.8**	**13.3**	**24.0**
25	20.6	15.8	31.3
50	23.4	17.5	36.9
100	**26.0**	**19.2**	**42.6**

Q_{100} = 26 cfs
Pipe diameter = 33 inches (assumes HW/D = 1.0 and projecting pipe)
Pipe diameter = 43 inches (assumes HW/D = 0.67 and projecting pipe)

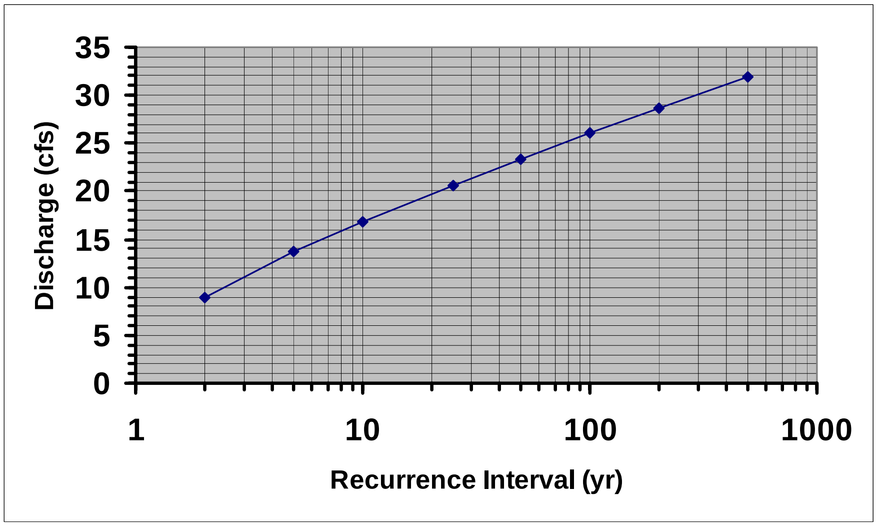


Figure 10. Plot of recurrence interval vs. discharge for Caspar Creek subwatershed HEN.

The rational method is recommended for basins less than 200 acres, while the USGS Magnitude and Frequency method is preferred over the rational method for drainage areas larger than 100 acres. Both methods are utilized for the HEN watershed for illustrative purposes. The direct flow transference method is preferred over both of these methods for HEN, however, since: (1) there are 40 years of discharge data for the downstream North Fork Caspar Creek gaging station available, (2) the subwatershed is within approximately one order of magnitude in size of the North Fork station, and (3) local data are more likely to represent the drainage-basin characteristics in terms of slopes, geology, soils, and climate than the more general regional equations or empirical relationships. Therefore, we utilized the direct flow transference method with a HW/D ratio of 0.67 and the 3 X bankfull stage method as a field check to determine the best estimate of required pipe diameter for a hypothetical crossing at the bottom of the HEN watershed. The active channel width method was used to allow for wood passage. Based on the results from these office methods and the field cross-sectional measurements, we recommend the selection of a **54 inch CMP**. The flow frequency analysis confirms that this is a reasonable estimate for this small watershed.

Table 5. Summary of the results using all the crossing sizing methods for determining the 100-year recurrence interval discharge and pipe diameters for subwatershed HEN.

Method	Predicted 100-Year Recurrence Interval Discharge (cfs)	Pipe Diameter (assuming HW/D Ratio = 0.67 for office-based methods)
Rational—Kirpich	**88**	**69**
Rational—Airport Drainage	**59**	**60**
USGS Magnitude and Frequency	**74**	**65**
Flow Transference	**42**	**52**
Direct Flow Transference	**30**	**45**
3 X Bankfull Stage	**--**	**52**
Active Channel Width	**--**	**53**
Flow Frequency Analysis	**26**	**43**

Figure 11. Clay Brandow, CDF Sacramento, measuring Caspar Creek sub-watershed HEN channel width for the 3 X bankfull stage calculation.

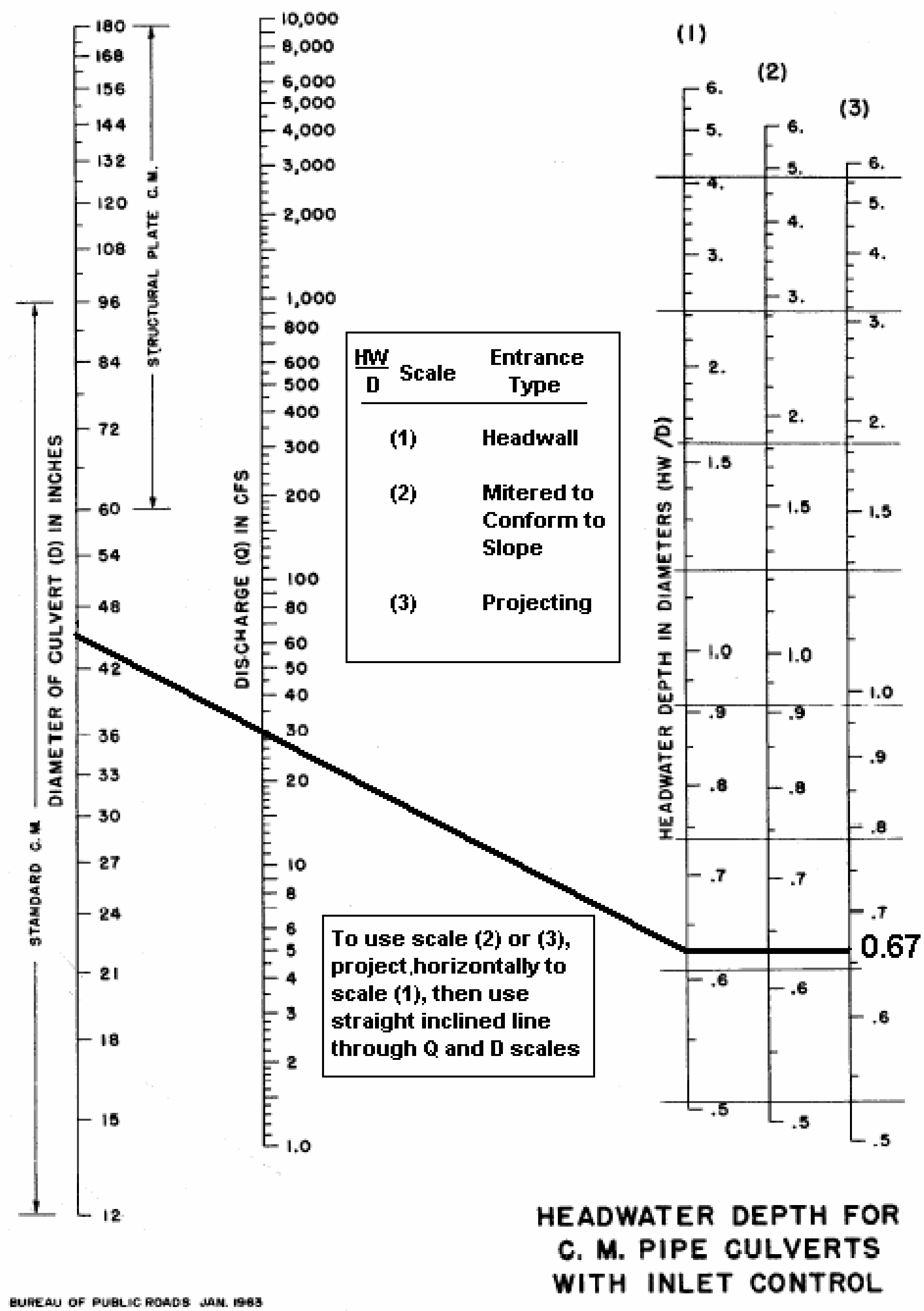


Figure 12. Normann and others (1985) culvert sizing nomograph for a round pipe with inlet control. For the watershed HEN example, using the direct transference method result of 30 cfs, a projecting pipe inlet, and a HW/D ratio of 0.67, the culvert size is 45 inches.

Part B. Predicting a 10-yr Recurrence Interval Event at Subwatershed HEN and Comparing the Results to the 10-yr Discharge Determined with the Flow Frequency Analysis

To date, the largest flow documented in the HEN subwatershed is approximately a 10-year recurrence interval event based on the flow frequency analysis presented in Part A of the Appendix (see Tables 3 and 4). **While this document was written to provide assistance in designing crossings for 100-year flood flows (including wood and sediment passage), Part B is included to provide information on how the various methods performed compared to actual gaging station data (as calculated by the 10-year flood flow using the flow frequency analysis)**. It is assumed that: (1) the 18 years of record at HEN are long enough to adequately determine a reasonable estimate of the 10-year discharge, and (2) the techniques that come the closest to predicting the 10-year event for subwatershed HEN based on the flow frequency analysis would therefore likely provide the best estimate of a 100-year event for this small basin.

Rational Method

Known Information:

Drainage area (A) = 96 acres for HEN
10-yr 15 minute NF Caspar Creek rainfall = 0.54 inches/15 minutes (Goodridge 2000)
10-yr 30 minute NF Caspar Creek rainfall = 0.73 inches/30 minutes (Goodridge 2000)
Channel length = 0.5 miles from the ridge to the gaging station
Difference in elevation = 550 feet from the ridge to the gaging station
Soil type = loam

Calculate:

$Q_{10} = CIA$

Time of Concentration (using the Kirpich Formula):

$$T_c = \left(\frac{11.9(L)^3}{H}\right)^{0.385}$$

where:
T_c = time of concentration (hours)
L = length of the channel in miles from the head of the watershed to the crossing point
H = elevation difference between the highest point in the watershed and the crossing point (feet)

$T_c = [(11.9\ (0.5\ \text{miles})^3/550\ \text{feet})]^{0.385}$
T_c = 0.103 hours or 6 minutes
T_c = 6 minutes. 15-minute rainfall-depth-duration-frequency data from Goodridge (2000) was used because 10-minute data was not available
0.54 inches/15 minutes x 60 minutes/hour = 2.16 inches/hour
I = 2.16 inches/hour
C = 0.3 (loam soil, Table 1)
Q_{10} = 0.3 x 2.16 inches/hour x 96 acres
Q_{10} = 62.2 or **62 cfs**

Time of Concentration (using the Airport Drainage Formula):

$T_c = ((1.8)\ (1.1 - C)\ (D^{0.5}))/(S^{0.33})$

where:
T_c = time of concentration in minutes
C = runoff coefficient (dimensionless, $0 < C < 1.0$)
D = distance in feet from the crossing to the point in the watershed with the greatest time of flow
S = slope in percent

$T_c = ((1.8)(1.1 – 0.3)(2640^{0.5}))/(21^{0.33})$
T_c = 27 minutes, or approximately 30 minutes
0.73 inches/30 minutes x 60 minutes/hour = 1.46 inches/hour
I = 1.46 inches/hour
C = 0.3 (loam soil, Table 1)
Q_{10} = 0.3 x 1.46 inches/hour x 96 acres
Q_{10} = 42.0 or **42 cfs**

USGS Magnitude and Frequency Method (10-yr RI Equation)
Known Information:
A = 0.15 $miles^2$
P = 46.85 inches/year (Henry 1998)
H = 1.0 (North Coast region equations use a minimum value of 1.0 for the altitude index when $(H_{max} + H_{min})/2$ is less than 1000)
Calculate:
$Q_{10} = 6.21\, A^{0.88}\, P^{0.93}\, H^{-0.27}$
$Q_{10} = 6.21\, (0.15)^{0.88}\, (46.85)^{0.93}\, (1.0)^{-0.27}$
Q_{10} = 41.9 or **42 cfs**

Flow Transference Method (Waananen and Crippen 1977)
Known Information:
A = 96 acres for HEN; 1168 acres for the North Fork
Q_{10g} (10-year RI discharge at NF Caspar Creek weir) = 232.1 cfs (USGS PEAKFQ Program)
Calculate:
$Q_{10u} = Q_{10g}\, (A_u/A_g)^b$
Q_{10u} = 232.1 cfs $(96 \text{ acres}/1168 \text{ acres})^{0.88}$
Q_{10u} = 25.7 or **26 cfs**

Direct Flow Transference Method (Skaugset and Pyles 1991)
Known Information:
A = 96 acres for HEN; 1168 acres for the North Fork
Q_{10g} (10-year RI discharge at NF Caspar Creek weir) = 232.1 cfs (USGS PEAKFQ Program)
Watershed HEN is approximately one order of magnitude smaller than watershed NF Caspar
Calculate:
$Q_{10u} = Q_{10g}\, (A_u/A_g)$
Q_{10u} = 232.1 cfs (96 acres/1168 acres)
Q_{10u} = 19.1 or **19 cfs**

Table 6. Summary of the results comparing predicted 10-year discharges at HEN.

Method	Predicted 10-yr RI Discharge (cfs)
Rational—Kirpich	**62**
Rational—Airport Drainage	**42**
USGS Magnitude and Frequency – 10-yr RI equation	**42**
Flow Transference	**26**
Direct Flow Transference	**19**
Flow Frequency Analysis – 10 yr RI (see Appendix—Part A)	**17**

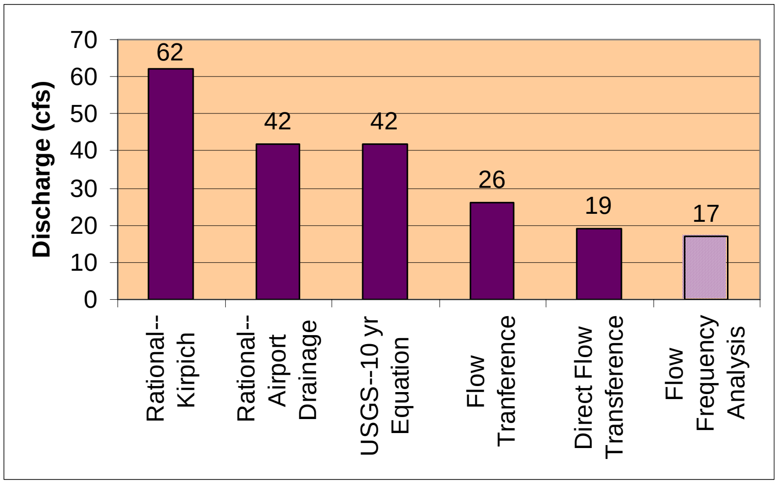


Figure 13. Predicted 10-year recurrence interval discharges and the 10-year RI event determined using flow frequency analysis (see Tables 3 and 4, Appendix—Part A).

Based on this limited comparison of the various estimated 10-year RI discharges (Q_{10}) to actual flow data from the Caspar Creek watershed, we can conclude the following:

- The Q_{10} estimate obtained for subwatershed HEN using flow frequency analysis is itself only an estimate of the actual 10-yr recurrence interval (RI) discharge and will change over time as the flow record expands. It is, however, assumed to be the best current estimate of the 10-yr RI discharge available and therefore is used as a standard against which the other discharge-estimating methods are compared.
- The direct flow transference method comes the closest to predicting the 10-year RI flow event for watershed HEN at Caspar Creek compared to the results of the flow frequency analysis obtained using the USGS PEAKFQ program.
- The direct flow transference method is preferred for predicting a peak discharge of a given RI if the gaged and ungaged watersheds are in close proximity, are hydrologically similar, and are approximately the same size (within roughly one order of magnitude)—as was the case for subwatershed HEN. Use of this method requires a nearby gaging station record of sufficient length (approximately 20 years or more). At the North Fork of Caspar Creek, this period of record is 40 years.
- Based on these results, it is concluded that the direct flow transference method likely provides the best estimate of the 100-year RI discharge for subwatershed HEN.
- If the difference in gaged and ungaged watershed areas are larger than approximately one order of magnitude, the flow transference method suggested by Waananen and Crippen (1977) is preferred.
- Most sites where crossings are proposed will not have the luxury of high quality, long-term downstream gaging station data. If this type of data exists, it should be used. Where it does not, the rational or USGS Magnitude and Frequency methods will be required, subject to the acreage limitations previously specified.

Arnold Schwarzenegger
Governor
State of California

Michael Chrisman
Secretary for Resources
The Resources Agency

Andrea E. Tuttle
Director
California Department of Forestry and Fire Protection

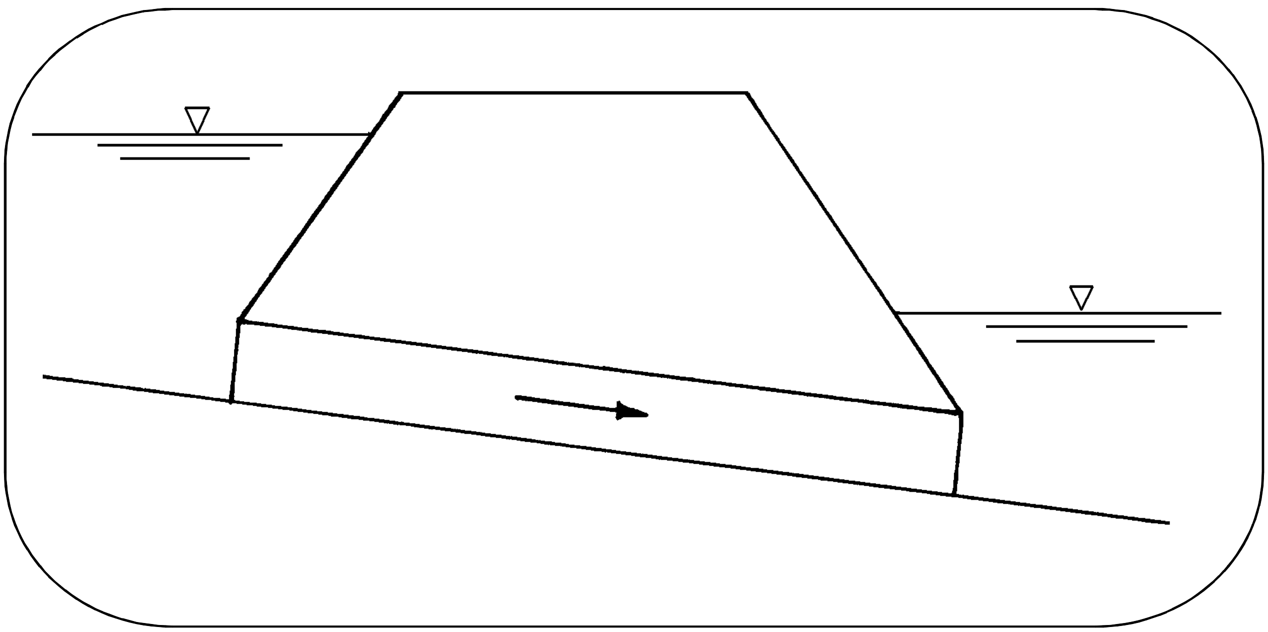
Publication No. FHWA-NHI-01-020
September 2001

U.S. Department
of Transportation

**Federal Highway
Administration**

Hydraulic Design Series Number 5

HYDRAULIC DESIGN OF HIGHWAY CULVERTS



NATIONAL HIGHWAY INSTITUTE

Training Solutions for Transportation Excellence

Technical Report Documentation Page

1. Report No FHWA-NHI-01-020 HDS No. 5	2. Governmental Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle Hydraulic Design of Highway Culverts, Second Edition		5. Report Date September 2001 6. Performing Organization Code
7. Author(s) Jerome M. Norman, Robert J. Houghtalen, and William J. Johnston		8. Performing Organization Report No.
9. Performing Organization Name and Address Ayres Associates Ft. Collins, CO		10. Work Unit No. (TRAIS) 11. Contract or Grant No. DTFH61-97-D-00025
12. Sponsoring Agency Name and Address Office of Bridge Technology, FHWA, Room 3203, 400 Seventh Street, SW, Washington, D.C. 20590 National Highway Institute, 4600 N. Fairfax Dr., Suite 800, Arlington, Virginia 22203		13. Type of Report and Period Covered 14. Sponsoring Agency Code

15. Supplementary Notes

Project Manager: Philip L. Thompson, FHWA
Editor of Second Edition: Johnny L. Morris, Ayres Associates

16. Abstract

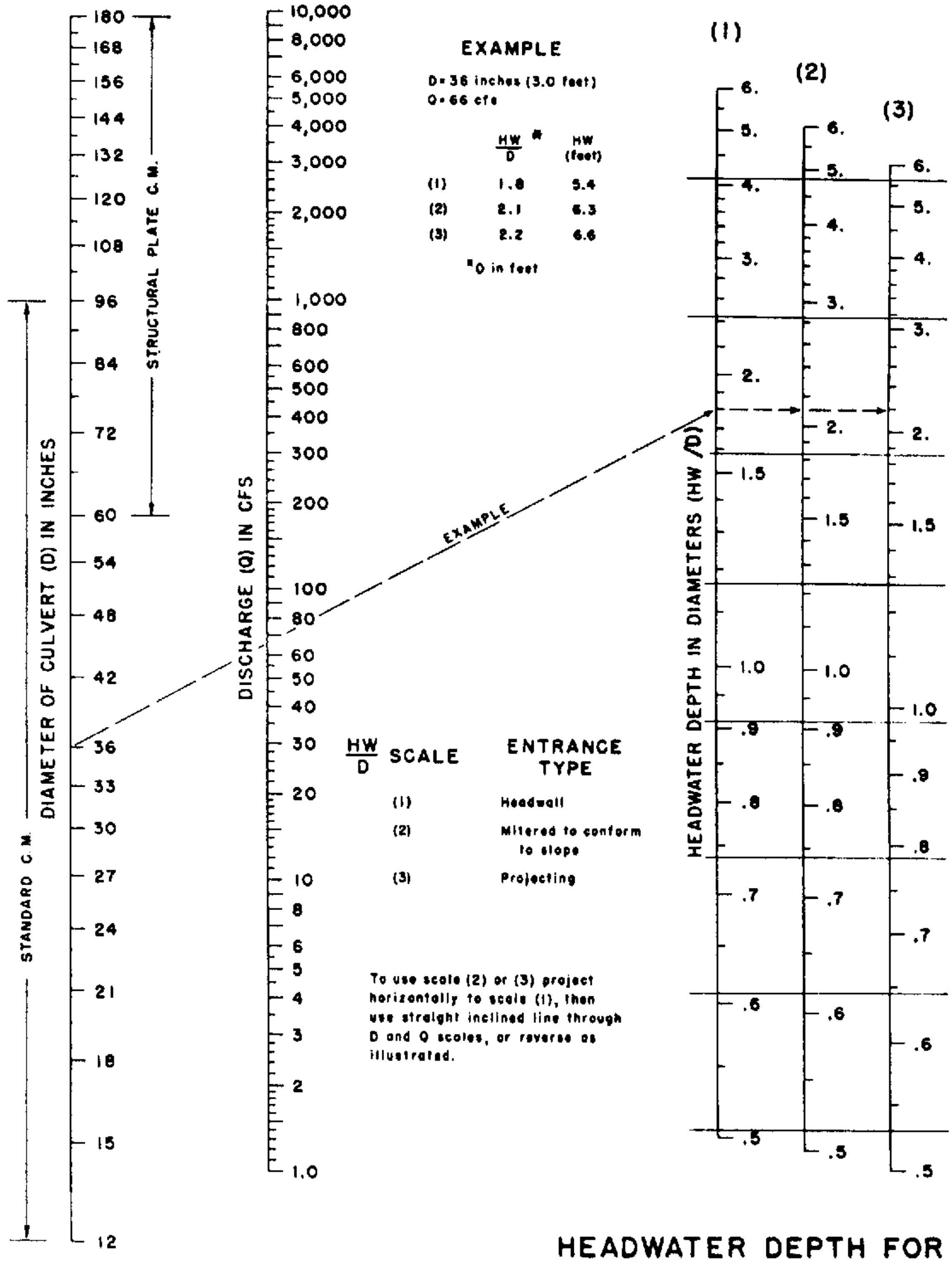
Hydraulic Design series No. 5 combines culvert design information previously contained in Hydraulic Engineering Circulars (HEC) No. 5, No. 10, and No. 13 with hydrologic, storage routing, and special culvert design information. The result is a comprehensive culvert design publication. Hydrologic analysis methods are described, and references cited. Culvert design methods are presented for both conventional culverts and culverts with inlet improvements. Storage routing techniques are included which permit the designer to account for ponding effects upstream of the culvert. Unique culvert applications, erosion and sediment control, debris control, structural aspects, and long-span culverts are discussed and references cited. Inlet control, outlet control, and critical depth design charts, many of which are newly developed, are included for a variety of culverts sizes, shapes, and materials. New dimensionless culvert design charts are provided for the design of culverts lacking conventional design nomographs and charts. The appendices of the publication contain the equations and methodology used to construct the design charts, information of the hydraulic resistance of culverts, and methods of optimizing culvert design using performance curves and inlet depression. Calculation forms are provided for most of the design methodologies in the manual.

The second edition corrected minor errors and provided both SI and English (U.S. customary) units for all equations and design charts.

17. Key Words		18. Distribution Statement	
Culverts, hydrology, storage routing, inlet control, outlet control, critical depth, tapered inlets, hydraulics		This document is available to the public from the National Technical Information Service, Springfield, Virginia 22151	
19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	376	

Form DOT F 1700.7 (8-72) Reproduction of completed page authorized

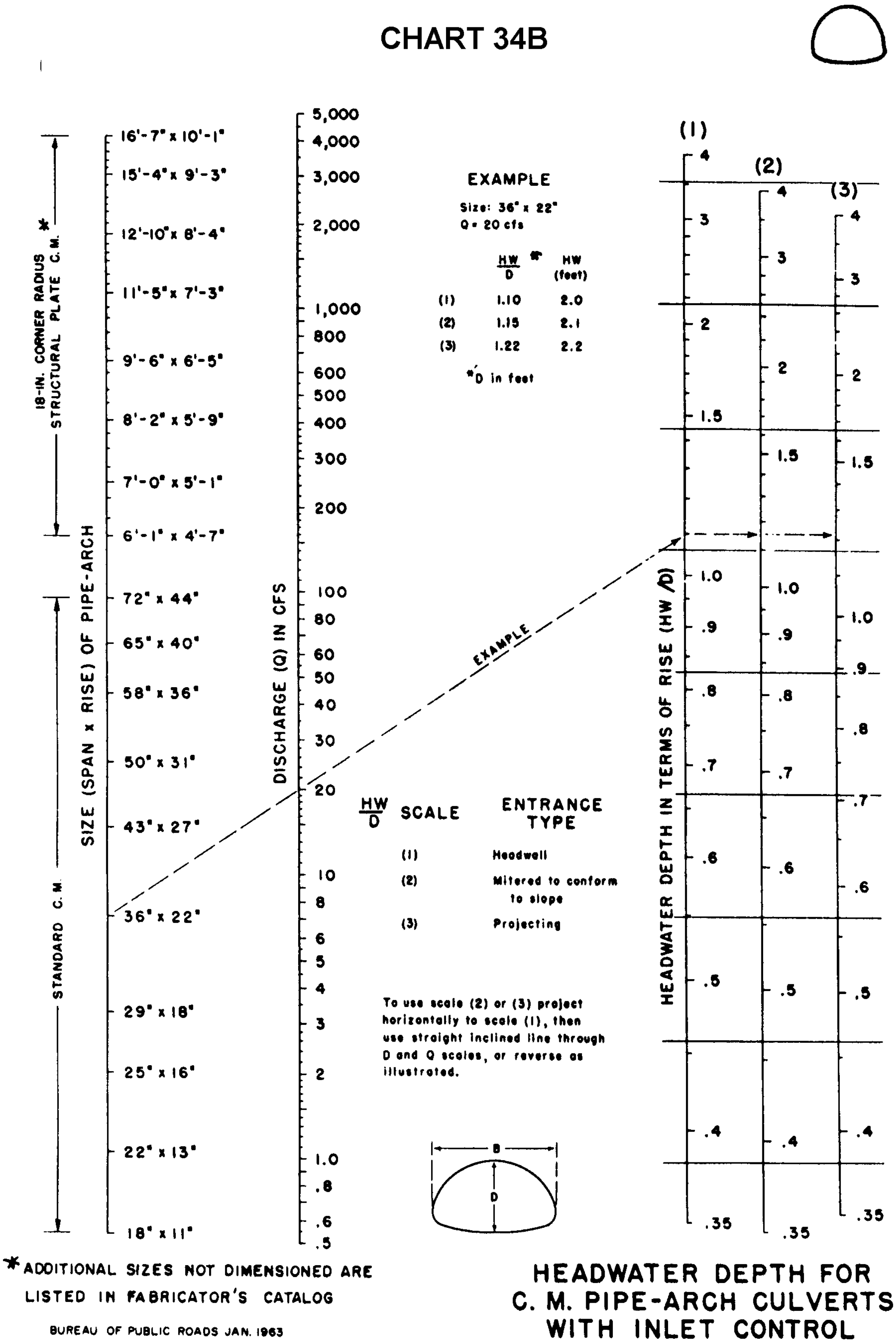
CHART 2B



HEADWATER DEPTH FOR C. M. PIPE CULVERTS WITH INLET CONTROL

BUREAU OF PUBLIC ROADS JAN. 1963

CHART 34B

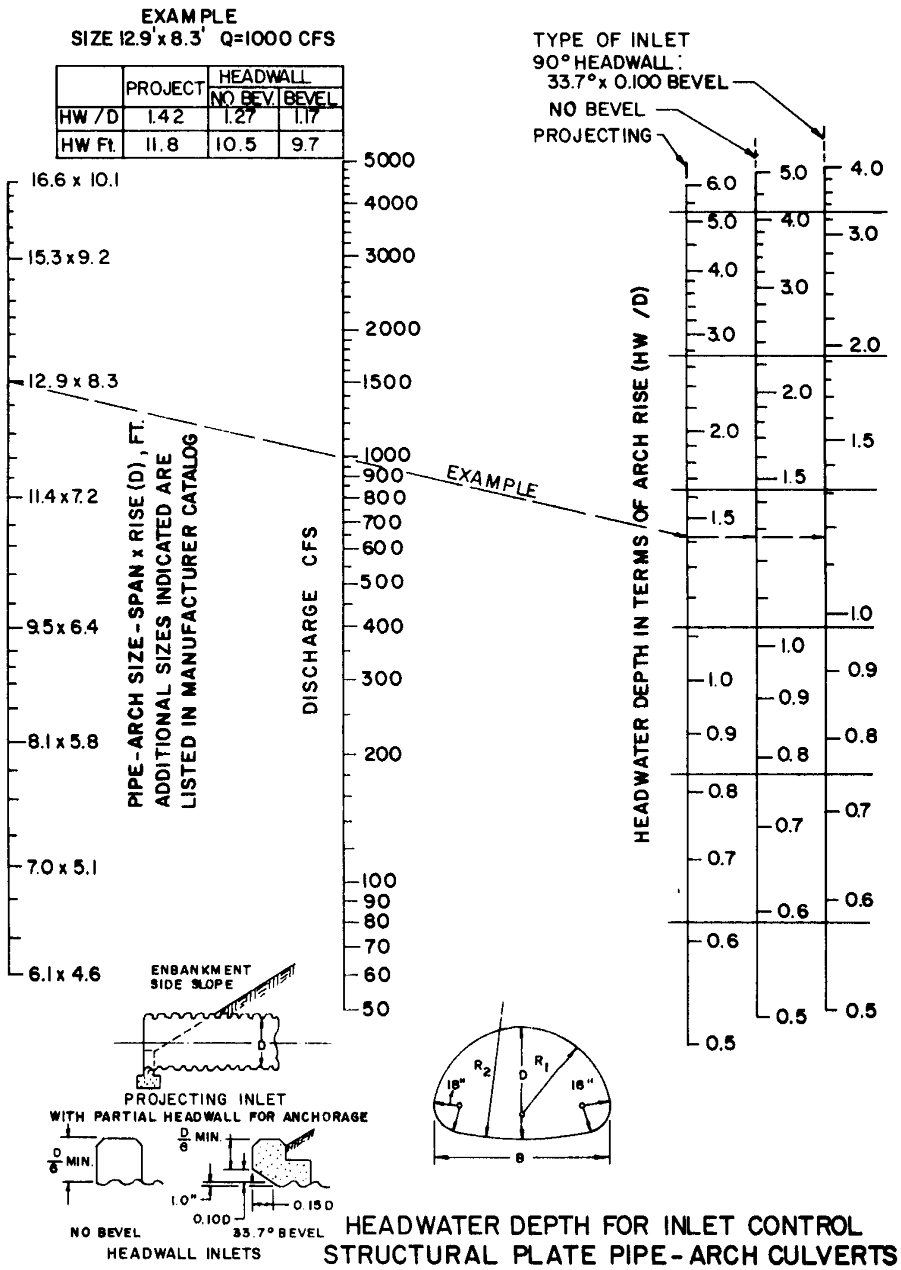


*ADDITIONAL SIZES NOT DIMENSIONED ARE LISTED IN FABRICATOR'S CATALOG

BUREAU OF PUBLIC ROADS JAN. 1963

HEADWATER DEPTH FOR C. M. PIPE-ARCH CULVERTS WITH INLET CONTROL

CHART 35B



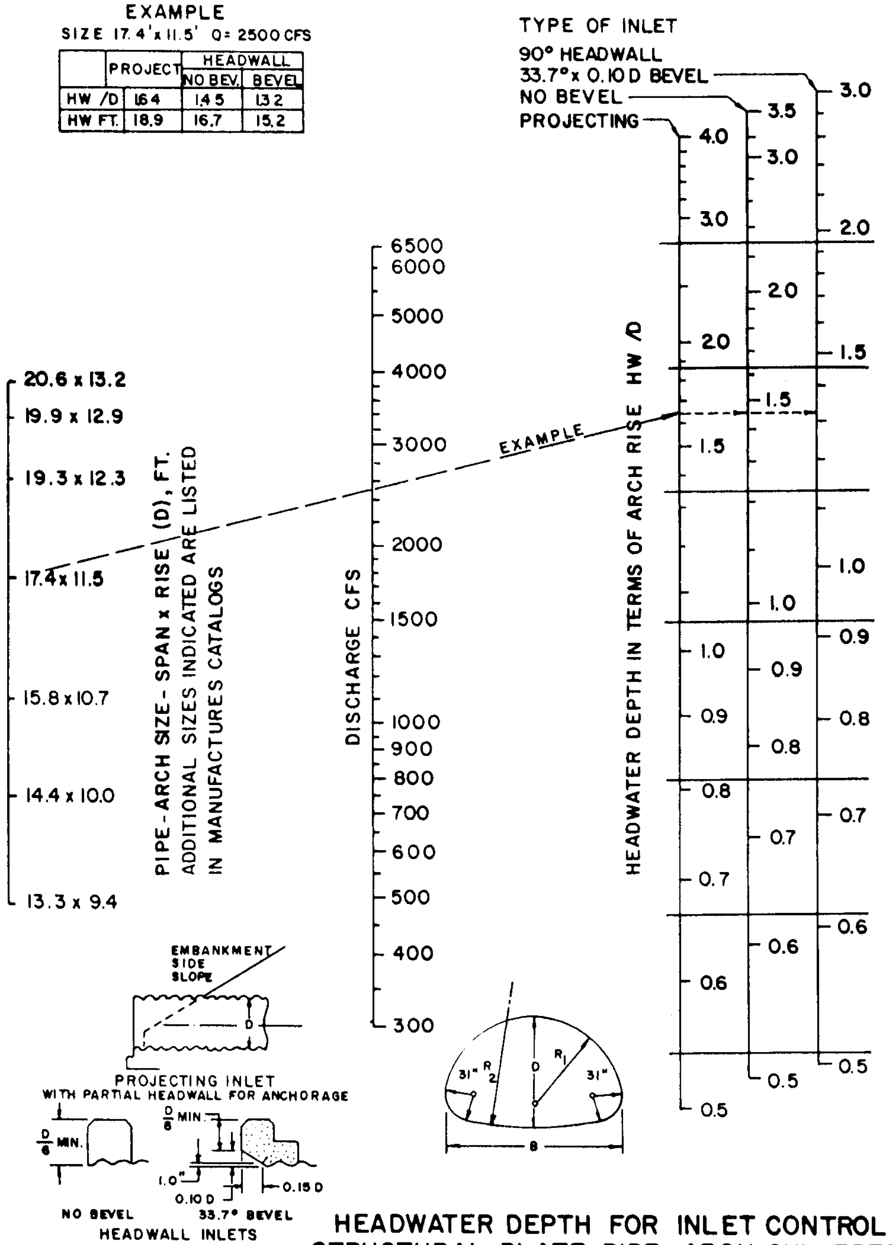
HEADWATER DEPTH FOR INLET CONTROL
STRUCTURAL PLATE PIPE-ARCH CULVERTS
18-IN. RADIUS CORNER PLATE
PROJECTING OR HEADWALL INLET
HEADWALL WITH OR WITHOUT EDGE BEVEL

BUREAU OF PUBLIC ROADS
OFFICE OF R&D JULY 1968

CHART 36B

EXAMPLE
SIZE 17.4' x 11.5' Q= 2500 CFS

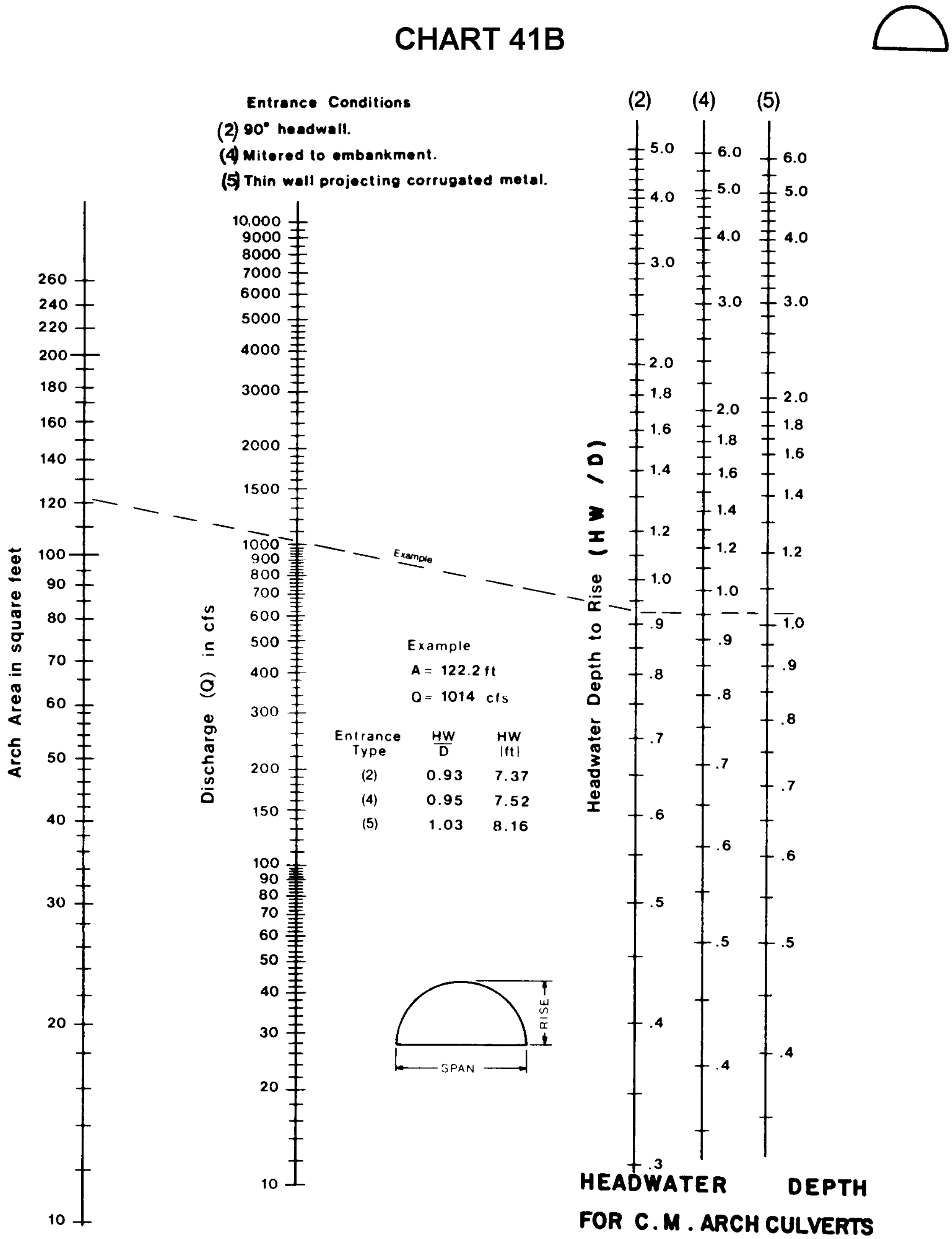
	PROJECT	HEADWALL NO BEV.	HEADWALL BEVEL
HW /D	1.64	1.45	1.32
HW FT.	18.9	16.7	15.2



BUREAU OF PUBLIC ROADS
OFFICE OF R&D JULY 1968

HEADWATER DEPTH FOR INLET CONTROL
STRUCTURAL PLATE PIPE-ARCH CULVERTS
31-IN. RADIUS CORNER PLATE
PROJECTING OR HEADWALL INLET
HEADWALL WITH OR WITHOUT EDGE BEVEL

CHART 41B

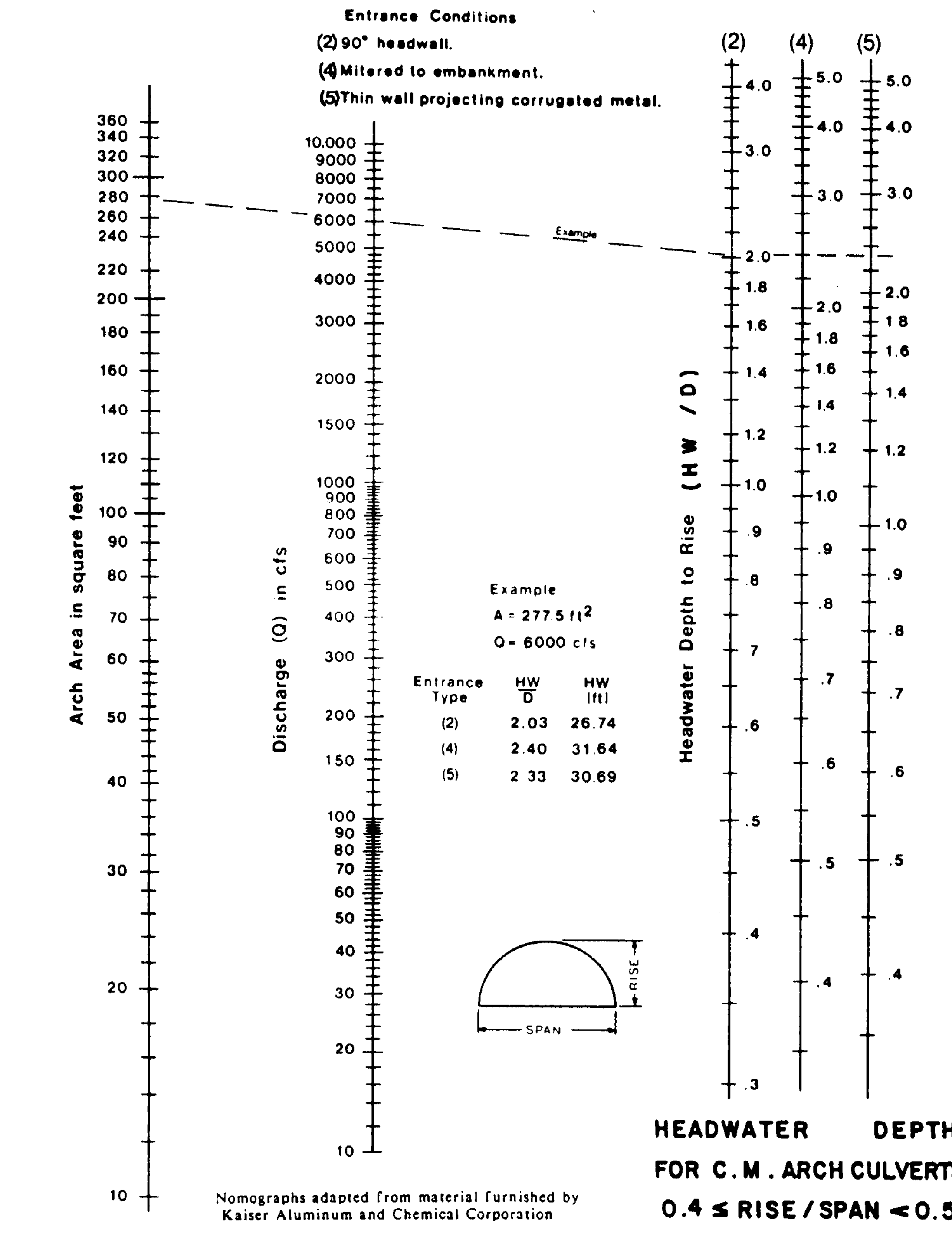


HEADWATER DEPTH
FOR C.M. ARCH CULVERTS
0.3 ≤ RISE / SPAN < 0.4
WITH INLET CONTROL

Duplication of this nomograph may distort scale

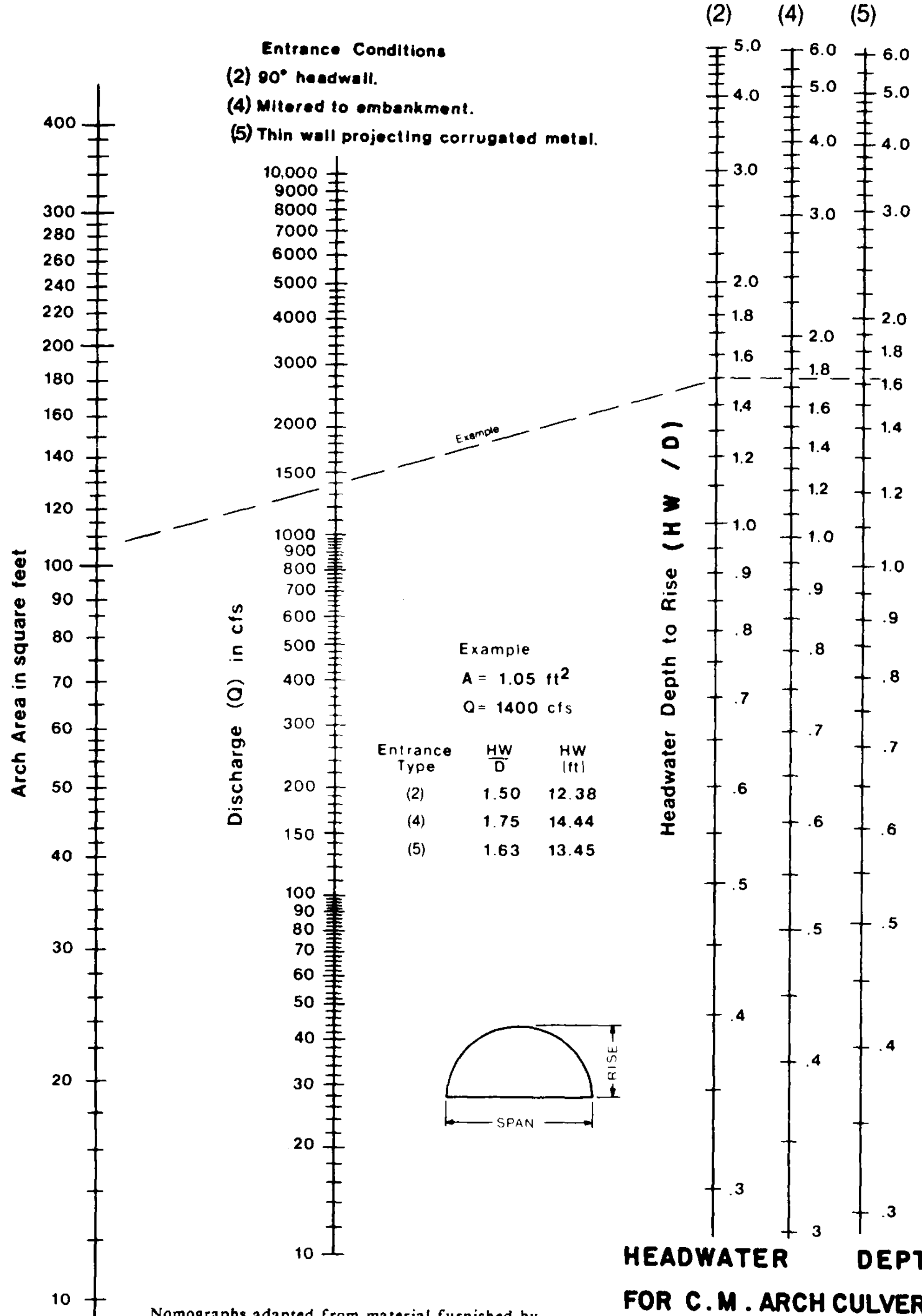
Nomographs adapted from material furnished by Kaiser Aluminum and Chemical Corporation

CHART 42B



HEADWATER DEPTH FOR C.M. ARCH CULVERTS 0.4 ≤ RISE / SPAN < 0.5 WITH INLET CONTROL

CHART 43B



Nomographs adapted from material furnished by Kaiser Aluminum and Chemical Corporation

Duplication of this nomograph may distort scale

HEADWATER DEPTH FOR C.M. ARCH CULVERTS $0.5 \leq$ RISE / SPAN WITH INLET CONTROL