Risk Based Approach Using Terrain Attributes to Control Water Quality Impacts Caused by Forest Roads

Houshang Farabi

The Australian National University, SRES and CSIRO, Forestry and Forest Products

Abstract: Forest catchments have long been recognised as a source of high quality water. Within forested areas the unsealed forest roads are the main sources of soil erosion and there is increasing concern on the impacts about water quality caused by forest road systems. This problem has been well documented in the research-based literature in the last three decades. The primary objectives of this study are, first, to develop a risk-based approach to predict, control and minimise soil erosion and water quality impacts. Secondly, to assist in the development of more effective management systems to maintain forest roads by assessing maintenance priorities for protection of water quality. This research is being carried out in Stromlo Forest, ACT, where roads were built more than 30 years ago. Surveys have been conducted on the existing roads (and transportation system) focussing on their impacts on soil and water quality. Elements at risk (soil erosion and water quality) were identified using field survey, Digital Elevation Models (DEMs) and Terrain Analysis. The results show that a significant number of rills and gullies were initiated and expanded at locations that had a high CTI value or had a high CTI value in the neighbouring pixel. A threshold based on slope and contributing area did not predict accuracy gully location on the surface of road.

Keywords: *Forest road; water quality impacts; soil erosion; risk assessment; GIS; DEM; terrain*

1. Introduction

Areas covered by any kind of vegetation in general, and forest catchment areas in particular, have long been recognised as a source of high quality water. Water quality impacts caused by forestry activities like timber harvesting and road construction have been a major concern for forest management systems in the last three decades. The issues of soil erosion and water quality impacts affected by timber harvesting and forest roads have long interested both foresters and the public (Adams, 1994). Forest roads, including main roads, logging roads and skid trails concentrate water and increase the risk of sediments being delivered to the streams, with consequences for water quality.

The potential risk of forest roads impacting on water quality mostly depends on the location of the road and terrain attributes such as slope, contribution area, the characteristics of cut and fill batters and technical issues of road construction. Croke and Mockler (2001) showed that contributing length and slope gradient of the hillslope are two main factors of concern for channel initiation and road-to-stream linkage. Moore *et al.* (1988) argued that there is a strong relationship between the distribution of surface soil water content and independent topographic variable aspect and the compound variable $\ln(A_s)$ where $A_s = A_b / S$. They also stated that the lack of topographic uniformity like CTI (soil wetness index or soil water content) (A_s) and SPI (the erosive power of concentrated surface runoff) ($A_b * S$) are the two most important factors in determining the location of ephemeral gullies (Moore *et al.* 1988). The processes of surface erosion of forest roads that cause huge problems for water quality are: surface washing by runoff, ephemeral rills or gullies and finally gully erosion caused by water. Terrain attributes like slope, contributing area, flow pathways, curvature (plan, profile, tangential), compound topographic index (CTI), and stream power index (SPI) derived from digital elevation models (DEMs) have been used in this research to identify elements at risk (soil erosion and water quality).

The overall objective of this ongoing research is to provide a risk assessment methodology using the forest road network of Stromlo Forest (as a test area). The aim of this paper is to look at gully erosion risk in the road surface whereby a series of variables are proposed to include in statistical analysis. This paper presents preliminary results from the analysis of data collected so far.

2. Study Area

The study has been conducted in the Stromlo Forest ACT (Australian Capital Territory). The study sites are located approximately 10 km west of Canberra and cover 2182 hectares in area. Elevation in the study area ranges from 432 meters above sea level to 864 meters asl., with an average of 606 meters asl. Most of the study area has been managed for timber harvesting activities over the last 30-40 years. Rainfall in the region is around 629 mm per annum (Commonwealth Bureau of Meteorology, 2002). Stromlo Forest Managed area is serviced by approximately 264 km of unsealed forest roads excluding skid trails and snig tracks. These roads were built more than 30 years ago, which means that they were not built according to the present code of practice. In addition, the area is connected to Canberra by sealed public roads.

3. Materials and Methodology

The map of the entire forest area was digitised and stored as a digital coverage in a GIS (ArcView) database. A Digital Elevation Model (DEM) initially at 40 meters resolution, which later resampled to 20 meters, was used to derive terrain attributes (such as slope, CTI, SPI, aspect). CTI a wetness index or a measure of saturation:

$$CTI = \text{In} (A_s / T^*\tan\beta)$$

Where A_s is the specific contributing area or the local upslope contributing area per unit width of contour line and T is transmissivity when the soil profile is saturated). SPI measures erosive power of flowing water based on the assumption that discharge is proportional to specific catchment area SPI= A_s * tanβ (Moore *et al*., 1993; Wilson and Gallant, 2000).

Along 35 km of unsealed forest roads, which were selected randomly, the exact locations of road lines and all road drainage structures including culverts, mitre drains, cross-banks and push-outs were mapped (Figure 1) using a Global Positioning System (GPS). Also the location of rills and gullies formed in the road surface were mapped (Figure 1). In addition data like slope, direction, contribution length and width, outlet and inlet construction, flow pathway length, distance between outlet and stream, size of culvert, whether the culvert was open or blocked and evidence of sedimentation were gathered for each individual drain, rill and gully.

For the location of the drains, rill and gullies, the attributes from the raster maps (CTI, SPI, Slope) were extracted. The data were used for identifying high-risk areas of forest roads where the road has high potential to generate sediment and deliver it to a stream.

It is assumed that CTI and SPI are the two most important factors in identifying the risk of forest roads to water quality. Therefore, it is hypothesised that the risk of negative impacts on water quality caused by forest roads will be extreme when the values of CTI and SPI are high. The relationship between contributing area and slope of travelway with gully or rill initiation on the surface of road has been examined using a threshold line.

The basic theory of risk assessment was used for assessing forest roads in order to classify, identify and analyse the impacts of forest roads on water quality. The simple representation of the risk equation is a measure of consequences (C) of water quality hazard and hazard probability (*P*) of impacts occurrence (R= C * *P*) (QAS, 2002). The below tables show the risk categories. The major problems in controlling the probability of the occurrence of risk in forest road management systems are found in levels 1 and 2 (Table1). Achieving certainty about the occurrence of risk is difficult: it needs a long investigation and acceptance of the inevitable high cost is necessary.

Table 1: Risk assessment scoring

Likelihood	Level	Consequence	Level
Almost certain	1	Catastrophic	1
Likely	2	Major	2
Possible/ Mod.	3	Moderate	3
Unlikely	4	Minor	4
Rare	5	Insignificant	5

Catastrophic events and major consequences of risk are sometimes unavoidable. Generally, risk can be ignored where the likelihood is rare or the consequence is insignificant (see Table 1 and 2). In all other situations risk should be investigated. Understanding the exact levels of likelihood and consequences where roads need to be built can help managers to make better decisions about soil erosion and water quality impacts due to the forest roads. Building forest roads where the level of likelihood is high or the consequences are serious is not acceptable (see Tables 1 and 2). Maintenance of these kinds of roads will not only need high investment but it will also be difficult to avoid impacts on water quality.

Table 2: An example of a risk matrix. E is extremely high risk, H is high, M is moderate and L is low.

Likelihood		Consequences				
		Catas.	Maj.	Mod	Min.	Insig
		1	2	3	4	5
Almost certain	1	E	E	E	H	H
Likely	2	E	E	H	H	M
Possible/ Moderate	3	E	E	H	M	L
Unlikely	4	E	H	M	L	L
Rare	5	H	H	M	L	L

In the 35 km selected road, the terrain attribute layers like CTI, SPI, slope, up-slope contributing area, forest road location and drain types are used for detailed field surveys.

Some scientists have used the same idea for catchment studies. For example, Wemple *et al.* (1996) used three classes of topographic position for their catchment study. Croke and Mockler (2001) used topographic position, road classes, drain type and period of construction in selecting road segments. Road segments for detailed survey were selected using a random sample. In the detailed survey the sample segments of roads were investigated, from which the following information was gathered:

a. Road surface and travelway situation.

b. Road's slope gradient (length and width)

c. The existence of either rill or gully on the surface of the road.

d. Any technical problems in the road drainage system and direct linkage of roads to streams.

e. Contributing areas of each individual drain.

f. Runoff delivery to the road prism from forest.

g. Soil and material types with which road has been surfaced.

h. Road-to-road linkage (runoff or sediment delivery from up-road to down-road).

The field data is used for testing the usefulness of terrain attributes as hands-on indicators of soil erosion and water quality impacts caused by forest road systems. Factors composed of terrain attributes, biophysical variables and forest road management issues affect water quality in areas under forest road construction. The study will reveal the contribution of different terrain attributes along biophysical variables and management issues to the water quality in the further examination. Furthermore, factors played by the terrain attributes (slope, contributing area and CTI in this paper) and technical issues of forest road construction and maintenance are assessed.

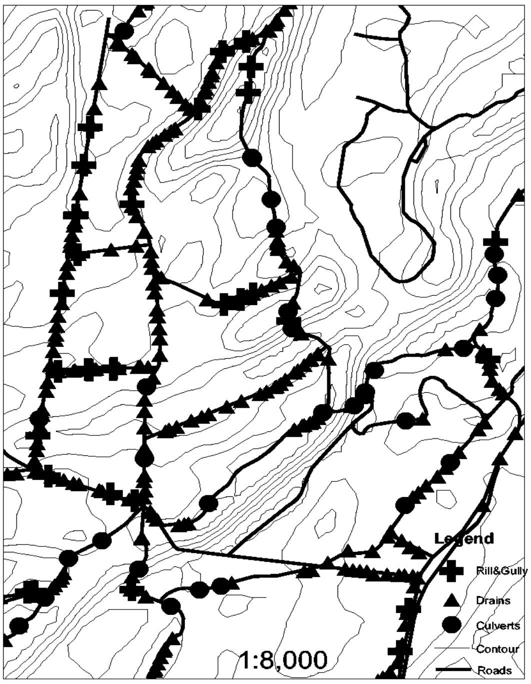

Figure 1: Study area map with road line, contour, mitre drain (triangle), culvert (circle) and rill or gully location (cross icon).

4. Results and Discussion

In Figure 2 the CTI values for the study site are shown. The location of rills and gullies on the road surface are superimposed on the map. Most rill or gully erosion has occurred where the value of CTI was larger than 7 (nearly average values at 7.8), thus supporting the preliminary hypothesis (further examination is required). Although the analysis of this relationship has not yet been finished or finally tested, it is thought that a terrain value like CTI value can play a fundamental role in water quality issues. It was also found that a significant number of rills and gullies were initiated and expanded where the value of the terrain in the neighbourhood pixel was high. For example, as can be seen from Figure 2, most rills and gullies are located very close to the pixels with high values. Extra runoff delivery from neighbouring pixels, especially from the upslope contributing area will increase the risk of rill initiation on the surface of the forest road. Note that other factors like slope, road contribution length and width, technical problems of construction and maintenance of road and drainage are very significant for soil erosion (e.g. gully erosion) and water quality problems. About 27% (26 out of 96) of rill and gully initiation was affected by lack of a proper drainage system and nearly 32% (31 out of 96) of rill and gully initiations were affected by high runoff delivery from the upslope area to the road prism. Slope gradient and slope length of upper hillslope were the two main factors in delivering runoff to the surface of the road, with other factors like contributing area also playing a main role.

Stromlo forest roads are supported mostly by mitre drain systems to control road surface runoff. About 57% (282) of mitre drains had no technical problems from building. Approximately 4% (11) of drains were blocked by stumps and nearly 51% (145) only partly worked in passing runoff out from the road prism. It has been calculated that only 37% (184) of mitre drains worked properly, 56% (277) of them working partly and 7% (33) of drains were blocked. Therefore, road surface and lower drains will be affected by extra runoff delivery from mitre drains which are blocked or are not working properly.

The culvert is another drainage system that protects roads against runoff flowing on the surface of road. Nearly 10% (5) of culverts were blocked by sediment deposition and debris and about 16% (8) of them only partly worked because of technical problems in building and sediment or debris deposition. Outlet and inlet construction is very important to avoid sediment deposition and gully initiation in the ground below where water falls from the outlets of culverts. Nearly 83% (42) of culverts did not have any kind of construction at the inlet and outlet. About 3.9% (2) of outlets and inlets were constructed of concrete and 13.7% of stone or wood. Most blocked culverts and culverts that were partly working were located where the upslope contribution length, slope and area were relatively high.

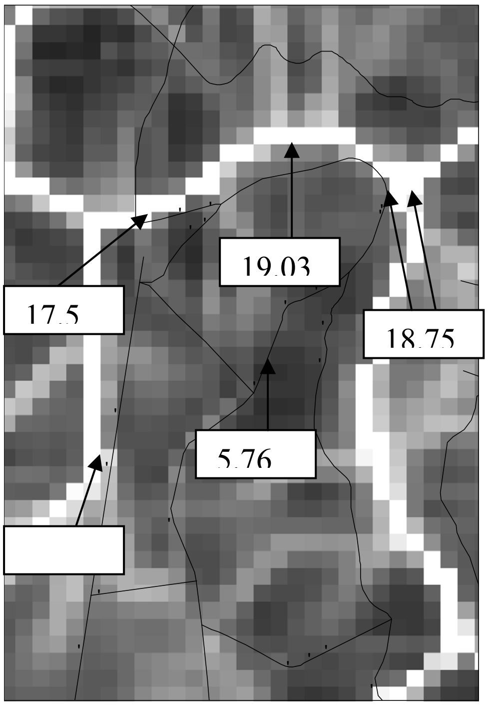

Figure 2: Compound Topographic Index of study area with the location of road layout (black line) and rill or gully location on the surface of the road (black dot icon) (Scale 1:5000)

It has been found in the preliminary analysis of the field data that there exists a strong relationship between high values of terrain attributes like CTI, SPI, slope length, upslope contributing area and curvature with rill or gully initiation on the surface of forest roads in the study area.

Therefore, a risk map of forest roads can be extrapolated by knowing the factors effecting soil erosion and water quality. Although this extrapolation results from the interaction of many factors, one causative variable can be taken at a time (Pallaris, 2000). Contribution length, contribution area, slope length, road layout location, drainage distribution, drain spacing, height and length of batters, slope of batters, road-to-road linkage, road-to-stream linkage, technical problems of road prism, type of soil and material with which the road has been surfaced, runoff delivery from upslope area to road prism and hillslope slope at the outlet of drainage systems are the main factors affecting soil erosion and water quality in forest road systems.

5. Conclusions and Further Work

This study examined 35 km of road line with 545 drainage systems and the location of 94 rills and gullies on the surface of the road and found that the majority of rill and gully erosion points had occurred where the values of terrain attributes were high. Although technical problems of drainage systems (lack of proper drain spacing and construction) also played an important role in terms of initiation of gully erosion, runoff delivery to road prism because of high values of terrain was the major cause of gully initiation. The author replicated the methodology of some previous studies such as Croke and Mockler (2001), Pallaris (2000), Wemple *et al*. (1996) and Montgomery (1994). As can be seen from Figure 3, a threshold based on slope and contribution area did not predict well gully location on the surface of road. Although gullies were initiated at most points where contribution area and slope gradient were high, this figure cannot be used as a good indicator of gully development on the surface of roads. Therefore, gully or rill initiation will be effected by other variables. The effects of other terrain attributes will be examined in further investigations in order to meet the study's objectives.

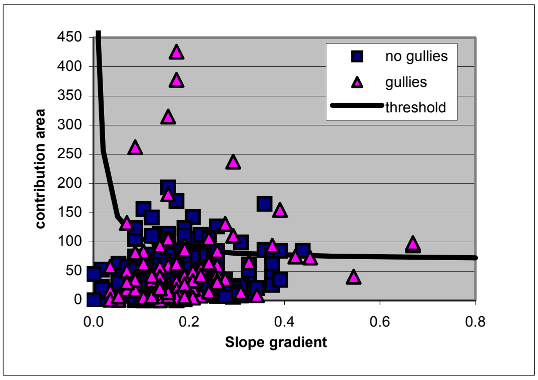

Figure 3: Fitted threshold curve separated gully and non-gully on the surface of road

The preliminary results from multiple linear regression model shown that there is no a strong linear relationship between CTI, SPI contribution area and curvatures and initiation riles and gullies on the surface of the roads because of high multi-colinearity between variables. The effects of each factor on soil erosion and water quality impacts in order to create a simple risk method and model for assessing roads will be examined using non-linear models in further investigation.

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