Using GIS, Terrain Attributes and Hydrologic Models to Predict the Risk of Soil Erosion and Stream Water Deterioration Caused by Forest Roads

[a]Farabi, H. and [b]James, R.

[a]Gorgan University (Iran) and School of Resources, Environment and Society, The Australian National University, Canberra, ACT 0200, houshang.farabi@anu.edu.au and [b]School of Resources, Environment and Society, The Australian National University, Canberra, ACT, 0200

Keywords: *Forest roads, Water quality impacts, Risk, GIS, Hydrologic connectivity*

EXTENDED ABSTRACT

Most forestry systems use extensive unsealed road networks for timber harvesting and other forest management activities. These forest roads are significant sources of runoff and sediment to streams, causing impacts on the quantity and quality of stream water.

The impact of unsealed forest road networks on stream water quality has long been recognised and documented by many researchers (e.g. Takken *et al*., 2005; Flanagan *et al*., 2003; Croke and Mockler, 2001; Megahan *et al*. 2001; Croke *et al*., 1999; Montgomery, D.R., 1994 and Anderson *et al.* 1976). However, the importance of the degree of road-to-stream connectivity has only generated a limited amount of focused research and documentation (e.g. Takken *et al*., 2005;Farabi, 2005; Hairsine *et al*., 2002 and Croke and Mockler, 2001).

To predict, control and mitigate the negative impacts to stream water quality arising from forest roads, it is necessary to understand the hydrological connection between the sediment source and the stream. Thus, knowing where flow pathways from roads will reach and affect stream water quality is important for both managers and researchers. This mostly depends on the characteristics of the road layout and of the road-to-stream hydrologic connectivity. . The problems occur when this connectivity exists and the road-derived runoff with associated sediments are delivered to the adjacent streams.

The overall approach in forest road planning and maintenance is to be able to simulate, predict, and remedy or mitigate the impacts of the forest road on the elements at risk; in an efficient way. In this study, the feasibility of predicting the likelihood of sheet erosion occurrence along the road systems and risk of this to the stream water quality were explored using selected terrain attributes as indicators.

The study investigated how the risk to soil erosion and stream water deterioration arising from unsealed forest roads can be predicted, mapped and highlighted using different GIS techniques, terrain attributes and hydrologic models. Several methods were used to carry out and evaluate the study. A 10,477 ha forested catchment in the Australian Capital Territory (ACT) was used as a case study area for collecting the necessary field data.

The results showed that a small number of variables, such as hillslope gradient, Road Contribution Length (RCL), Road Contribution Area (RCA), Compound Topographic Index (CTI), Stream Power Index (SPI), drainage area and distance were the variables most highly correlated to the probability of the erosion occurring on the surface of the roads and at the outlet of drainage structures. The results also demonstrated the usefulness of GIS in combination with mathematical (algorithm) and hydrological models as a method for determining the level of road-to-stream connectivity by calculating the flow distance between the outlet of drains and streams. A combination of derived and independent variables was used to map the final risk assessment. The occurrence of problems in the elements at risk (soil and water) was presented as a set of grid layers using GIS overlay applications. The final result of this study is an integrated methodology for “Forest Road Impact Assessment” (FRIA), which uses GIS techniques, terrain attributes and hydrologic models to identify likely sources of stream sediment from forest roads.

1. INTRODUCTION

Unsealed road networks are known to be a significant source of water pollution in forests because they increase the quantity of water and delivery of sediment to streams. The degree of risk to water quality arising from forest roads is mostly related to the characteristics of road layout as the sediment source and the degree of road-to-stream hydrologic connectivity. Predicting the risk from road networks to the quality of stream water has increasingly become a relevant research task, in order to respond to the concerns of the public, environmentalists and forest managers. In Australian forest management systems, the legacy of old, poorly designed and constructed roads are now causing water quality problems. New remedial techniques are required to identify and fix the problems (Farabi, 2005).

Hydrologic modelling, watershed and stream delineation play an important role in forest road management and maintenance, especially in managing the hydrologic connectivity between roads as a source of sediment and the streams. GIS-based models, Digital Terrain Modelling (DTM), Digital Terrain Analysis (DTA) and Topographic Analysis (TA) have provided essential terrain attributes layers for hydrologic modelling and Risk Evaluation Approaches (REA) used in this study.

Risk assessment has become a useful tool for management of natural and environmental systems, especially for forest road. In this research, it is argued that both the likelihood and the location of soil erosion and water quality impacts caused by forest road systems can be identified by a specific risk assessment method using GIS-based application and TA (Farabi, 2005). Forest Road Impact Assessment (FRIA) was developed and is now proposed as an integrated methodology to predict soil erosion and relate this to stream water deterioration by using GIS techniques, terrain attributes and hydrologic models.

2. METHODS

2.1. Study area description

The Stromlo Forest Management Area (SFMA) in the ACT (Australian Capital Territory) – located approximately 10km to the west of Canberra city – was selected as the case study area (Figure 1). The study area is a small catchment in the southeastern corner of the Murrumbidgee River Catchment, which drains in to the Molonglo River. The average annual rainfall of the region is about 629 mm with an average of 108 rainy days per year (Bureau of Meteorology, 2004). The major soil types or groups are *Chromosols, Sodosols and Kurosols* covering almost 98% of the study area. SFMA was first established in 1915 and the plantation continued to expand in the 1930s.

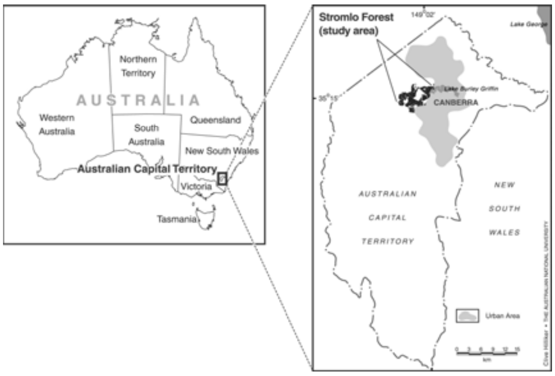

Figure 1. Location of the study area

The study area is serviced by nearly 264km of forest road networks (excluding public roads). These roads were mostly constructed in the years between 1950s and 1970s (about 62% of the total road networks). Owing to the age of the roads, they may not meet current design and construction standards and may pose increased risks to water quality (Farabi *et al*., 2003).

2.2. Data collection, road and drainage surveys

The map of the entire region, including the study area and forest road networks, has been digitised and the catchment areas have then been separated from the original map for further study using a combination of GIS software such as ArcGIS and IDRISI. The study area and road networks were classified based on landform, slope position and the age (or decade) of construction. Some road segments were then randomly selected for detailed study. A Differential Global Positioning System (DGPS) was used for gathering data from the field. A permanent base station location at the Forestry and Forest Products site (CSIRO) in Yarralumla– approximately 8 km east of the study area was used for data correction and exact positioning of the road and drainage systems.

The field data collected from the selected road segments included details of road layout, road surface, ditch, mitre drains, cross-banks, push-outs, culverts (relief and stream crossing), outlet slope (hillslope gradient), length of water flow path and also type of road-to-stream connectivity. The field survey was mostly focused on the road drainage systems because of the level of risk to water quality arising from these parts of the road segments. Therefore, an extensive dataset was collected from all drainage structures of the selected roads. Data describing the drainage systems included the exact location, road contribution width (RCW) and road contribution length (RCL) – road contribution area (RCA) was then simply calculated by multiplying of RCW and RCL, slope, direction, dimension of channel, evidence of erosion and sedimentation, evidence of channel expansion by runoff, and water flow length from outlet of drains to stream.

The distance from the outlet of each drain to the stream was measured in the direction of the flow pathway. As measuring the distance between roads and streams is time-consuming and expensive work, measurement of the distances was carried out for the one third of the drains only using DGPS (Farabi, 2005). Measurement of flow path and distance between road and stream was based on the topography, slope direction, depression and any other evidence that showed where water would have flowed from the outlet down to the stream.

The location and characteristics of rills and gullies on the surface of the selected road were recorded using DGPS. Data describing rill and gully erosion included the exact location, slope, dimension, RCW, RCL, RCA and other factors related to the occurrence of these types of erosion.

All field data were transferred into GIS and were stored as vector layers. A database of individual files, which contains drains and roads, were developed and complemented by adding some data extracted from the terrain attributes of the related terrain layers (Farabi, 2005).

2.3. Manipulating and modelling

A Digital Elevation Model (DEM), initially at 20 meters resolution, was created using ANUDEM and ArcInfo. The DEM was then analysed using DTM, DTA and TA in order to derive and create terrain attribute layers and maps such as slope, aspect, curvature, Compound Topographic Index (CTI), Stream Power Index (SPI), flow direction, accumulation and upslope contributing area. The terrain layers were then used for detail analyses and modelling such as: slope stability; slope and landform classification and assessment; applying the GIS-Based Revised Universal Soil Loss Equation (RUSLE); watershed and stream delineation; and predicting the distance and connectivity between road and stream.

All analysis, modelling and evaluation applications were undertaken in three different Risk Evaluation Approaches: RUSLE (REA 1), Digital Terrain Analysis (REA 2) and Design construction and hydrologic connection between roads and streams (REA 3). All factors and variables related to the soil loss equation such as rainfall erosivity (R factor), soil erodibility (K factor), topographic factors or LS factor (slope length and slope gradient), land cover management (C factor) and support practice factor (P factor) were individually calculated using ArcGIS and IDRISI. These layers were then multiplied and overlayed using different GIS techniques to predict the final index rate of soil loss from the study area and its forest road network. This layer was used as one of the risk components in mapping the final risk map for forest roads.

Slope gradient, slope length, aspect, flow direction, flow accumulation, specific catchment area and saturation zone location were derived and calculated using DTM and then were used to calculate the Stability Index (SI). The final SI risk map was created and ranked using stability class and risk criteria that were defined for each individual risk component.

The entire SFMA as a small watershed has been delineated using DTM, TA and hydrologic modelling in order to create stream networks, basins and sub-watersheds. The basins, watershed area, mean elevation, mean slope, stream flow length, high and low positions of the stream were also calculated by the delineation process. The results of the watershed and stream representation were used in road-to-stream distance and connectivity modelling.

The distance between road and streams was calculated using ArcInfo commands and algorithms to determine the road-to-stream connectivity. The stream coverage and stream grid were created from the existing stream network (from the watershed delineation process) using ArcInfo and were then used as other input layers.

Two buffer zones at 5 and 10 meters were created for the stream networks of the study area using ArcGIS; and were used as input coverage layers for different application processes in the model. The recorded field data related to the road drainage that had previously been stored as multiple files were used as drain point vector input layers. Several models and methods such as the ArcInfo *NEAR*, *FLOWLINES, FLOWPATH*, MapWin and the TauDEM extension for ArcGIS were used for predicting the distance between roads and streams. The aim of applying different models was to compare several alternative methods of predicting the distance between the outlets of the drain and the stream from a DEM. Automating the task of estimating the distance between roads and streams will reduce the cost of fieldwork dramatically.

The arc *NEAR* model determines a point-to-arc, point-to-node and point-to-point distance. The *FLOWLINES* and *FLOWPATH* programs were written based on the particle-tracking algorithm and the grid function and code (Takken, 2003). This model predicts the direction and future location of a flow, based on the local velocity field by interpolating the nearest grid (e.g. elevation grid) cell centres (Farabi, 2005). A DEM grid file was used as input file in the TauDEM and *DISTWASH* models and the distance was calculated using watershed delineation, network and DEM analysis (Farabi, 2005). The results of the applying different models were then compared with the distance measured in the field in order to find the best-predicted distance.

2.4. Analysis

All terrain attributes data were extracted from GIS layers for the road and drainage positions using These data were then added into the field database file for future analysis. Field and extracted data were both used to test the usefulness of the variables (such as terrain attributes) as practical indicators of where forest road networks need interventions to manage the connection between roads and streams. The extracted terrain attribute data has been examined (comparing individuals and groups), using a threshold line and sensitivity analysis in order to identify the relationship between those variables and rill and gully initiation. Logistic regression, correlation tests and ANOVA were used for statistical analysis of the data using SPSS and STATATISCA software.

3. RESULTS

This study examined nearly 685 road drainage structures and around 120 rills or gullies on the surface of 102 km of selected roads in the SFMA. The majority of the drainage structures surveyed were mitre drains (about 82%), however, culverts dominated on steep terrain. About 5 % (33 out of 685) of the drainage structures surveyed were cross-banks installed on snig tracks on steep terrain. Only a small number of surveyed drains (1.6% or 11 out of 685) were push-out drainages.

The relationship between all independent variables such as RCL, RCA, slope, curvatures, CTI, SPI, drainage area, upslope contribution area and distance was tested for rill or gully occurrence on the surface of the road and at the outlet of the drainage systems in order to find the variables which influence the probability of the occurrence. The independent variables were identified as most important and least correlated to the elements at risk in the first stage using simple correlation and logistic regression analysis. Tables 1, 2 and 3 summarised the results of the statistical analysis for the outlet of the drains. The statistical results suggest that hillslope gradient, RCL, RCA, CTI, SPI, drainage area and distance were the variables most highly correlated to the dependent variable in the model influencing the probability of the erosion occurrence. It has found that mitre drains and culverts within greater slope and contribution area are more likely to initiate a new rill or gully or expand the existing rill and gully at the outlets.

Table 1. Summary of logistic regression of independent variables against dependent variable

Variables	**B**	**S.E.**	**Wald**	**df**	**Sig.**	**Exp (B)**
Constant	-1.45	0.20	25.3	1	0.00	0.00
Con. Length	1.5	0.71	8.27	1	0.03	0.96
Con. Area	0.12	0.03	11.34	1	0.001	1.12
Hillslope	15.8	6.26	6.33	1	0.012	1.89
Drainage area	0.25	4.26	9.33	1	0.006	1.05
CTI	-0.03	0.16	2.01	1	0.05	1.68
SPI	0.56	1.04	6.57	1	0.04	1.18
Distance	0.01	0.00	4.40	1	0.036	1.01
Plan curvature	1.58	0.99	1.99	1	0.052	1.74

Table 2. Summary of ANOVA

Model	**Sums of Squ.**	***df***	**Mean Squ.**	**F**	***p*-Level**
Regression	12.93	15	0.862	8.2	0.00
Residual	6.8	65	0.105		
Total	19.73	80			

Table 3. Model Summary of the variables in the equation and regression

Model	**r**	**r^2**	**Adjusted r^2**	**Std. Error**
1	0.83 (a)	0.69	0.65	0.270

(a) Predictors: (Constant), Hillslope, Contribution area, Contribution length, CTI, SPI, Drainage area and Distance

Table 4. Summary of the SI for the study area and its forest road networks

Stability Class Label	Condition	Area (ha)	%	Road (km)	%
Stable (1)	1.5 – 10	9483	91	242	79
Moderately Stable (2)	1.25–1.5	511	5	30	10
Quasi Stable (3)	1–1.25	290	3	19	6
Lower Threshold (4)	0.5 – 1	188	2	15	5
Upper Threshold (5)	0.001–0.5	5	0.1	0.5	0.2
Defended (6)	0	0.01	0	0.2	0

The results of the stability assessment showed that nearly 90 % of the study area and 80 % of the forest roads were stable or moderately stable (Table 4). About 90 % of the study area and 79 % of forest roads were recognised as having ‘negligible’ risk level. However, less than 5 % of the study area and more than 11 % of forest road networks were associated with ‘moderate’, ‘high’ or ‘extreme’ risk. The stability index map was later used as one of the components in creating the final risk map.

Table 5. Summary of the risk of soil loss in the study area and the forest road networks

Risk of Soil Loss	[1]N (<1)	L (1-3)	M (3-15)	H (15–25)	E (>25)
Area (ha)	1669	1745	5729	864	469
Percent	16	17	55	8	4
[2]Road (km)	37	39	180	34	17
Percent	12	13	59	11	5

[1]N= Negligible, L= Low, M= Moderate, H= High and E= Extreme (t.ha^{-1}.y^{-1}). [2]Public roads are included (about 40 km)

Table 5 summarises the results of the soil loss values and the risk of soil erosion of the entire of the study area and its forest road networks. About 12% (37 km) of the forest roads are ranked as having ‘negligible’ soil loss, 13% (39 km) of forest roads are predicted to have ‘low’ risk of soil loss. As shown in Table 4, risk of ‘moderate’ soil loss affects more than half (55 and 59%) of the study area and its forest roads, respectively. ‘High’ and ‘extreme’ risks of soil loss affect nearly 16% (51 km) of forest roads. As a result, most of the forest roads (75%) are under threat of soil loss and soil erosion, and are ranked as having ‘moderate’ ‘high’ and ‘extreme’ risk of soil loss.

The road-to-stream distance and connectivity were modelled and assessed using GIS-based hydrologic modelling in order to classify and predict the level of risk and possibility of the runoff reaching the streams. The watershed delineation results show the exact location of the streamline on the ground and the density and stream segments. The total length of the streamline of the area was 218 km, the longest and shortest streamline were 2 km and 20 m, respectively. The result of the comparison between field-measured and calculated distance has shown that two models (*FLOWPATH* and *FLOWLINES*) predicted the distance more accurately than others. The best prediction was *FLOWPATH* ($r = 0.98$, $r^2 = 0.96$ and $P < 0.00$) and *FLOWLINES* was the second-best predicted distance compared with the field-distance ($r = 0.83$, $r^2 = 0.69$ and $P < 0.00$).

The road-to-stream connectivity assessment showed that nearly 45% of the drains had no stream connection and their runoff never reached the streams directly. However, more than 30% of the drains were connected to streams by rill, gully or channel formation while 20% and 4% were by diffuse connections and stream crossings, respectively. The result has shown that the distance itself is not as important as the association with slope in road-to-stream linkage analysis.

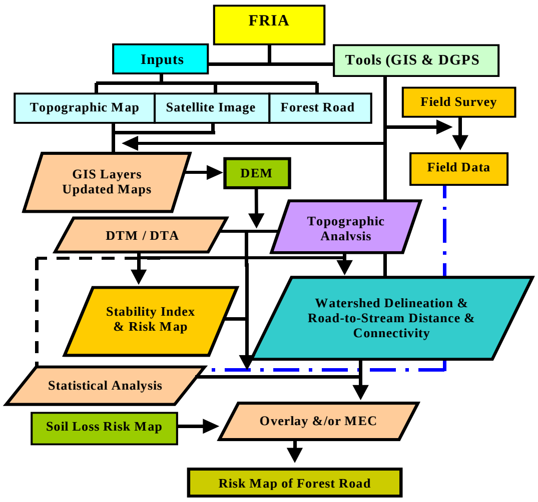

Figure 2. FRIA; A GIS-Based Method for mapping the risks to water quality arising from forest roads

The slope gradient recorded from the field was also compared with the slope gradient derived from the DEM. The comparison has shown a strong relationship (r = 0.82, R squared = 0.67 and P <0.00) between field-measured hillslope and hillslope derived from the DEM.

The integration of the different applications and processes presented here was used to introduce the Forest Road Impact Assessment (FRIA) method. This method is a combination of different REA including RUSLE, DTM, TA, SI, road-to-stream connectivity and variables influencing the risk based on the statistical results. Figure 2 shows a simplified FRIA as a GIS-based method that can be used to evaluate, assess and predict the harmful effects of the roads on the elements at risk.

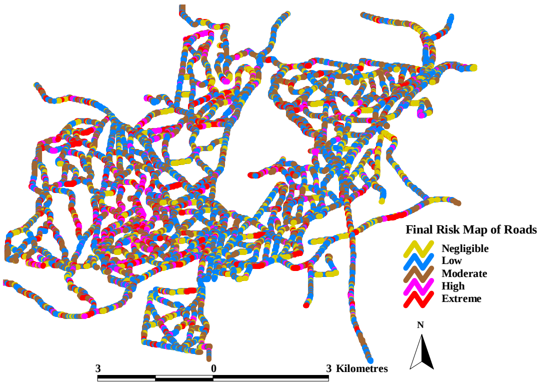

Figure 3. Final risk map for forest road network

The final risk was mapped using a combination of different components and independent variables influencing the occurrence of problems in the elements at risk (soil and water). The risk from variables on soil and water was calculated using a cell-based GIS approach. Most of the input and output layers resulting from applying the method were raster layers with 20 m resolution (20 * 20 pixel size). Therefore, the risk was ranked and mapped using an interpolation of the average pixel value of each independent variable using the risk criteria classification. The final risk map was presented as a set of grid layers using GIS overlay applications representing risk. Figure 3 is the integrated risk map for the forest road networks.

Table 6 summarises the results of mapping the risk for the forest roads. The table shows that more than 58% (172km) of the forest roads will have no significant harmful effects on the elements at risk, thus they are classified as having 'negligible' and 'low' risk. Approximately 67km (22%) of the roads have 'moderate' risk. Also, about 20% (63km) of the roads seriously affect soil and water, and they are classified as having 'high' and 'extreme' risk.

Table 6. Statistical summary of the final risk for the Stromlo forest road networks

Risk Classes		**Road Length (km)**	**%**
Negligible	**1**	55	18
Low	**2**	122	40
Moderate	**3**	67	22
High	**4**	28	9
Extreme	**5**	35	11
Total		307	100

4. DISCUSSION

DEM and terrain attribute layers, in conjunction with field data, provided the main data source used in this study. Preparation routines such as georegistration, projection, resampling (where needed), correction, and calculation of some attributes were applied to the image and terrain layers in order to prepare them for analysis. These preparations were based on the availability and usefulness of different methods such as GIS based models, especially DTM and DTA.

The results presented in this paper show that using a GIS in combination with mathematical (algorithm) and hydrological models is very useful for determining the level of road-to-stream connectivity by calculating the distance between drains and streams. As explained above, the analysis of the modelling has shown acceptable accuracy when using different GIS-based models to predict variables such as slope gradient, distance and upslope contributing area. This will reduce the amount of fieldwork and therefore reduce the cost of evaluations.

Analysis has determined that the statistically significant features, which indicate the likelihood of a hydrological connection between roads and streams include: distance between stream and road, hillslope gradient from road to stream, road contribution area, and the value of the CTI for the outlets of the drainage systems. The results of the analysis suggest that, of the many variables tested, only a small number of factors were important in determining the risk arising from forest roads in terms of soil erosion and water quality. The reasons for that were related to the multi-collinearity among some variables, some independent variables were used to create other variables and therefore they had an indirect effect when used to determine the elements at risk. Some variables play the same role on most of the road prism and finally, the result of the sensitivity analysis showed that presence or absence of some variables was not important to the final result.

5. CONCLUSION

According to the results presented here, the major finding from this study are:

1. GIS-based application and modelling are useful tools for assessing, predicting and ranking the risk to water quality arising from unsealed forest roads. As forest road impact assessment is time consuming and expensive, these methods will reduce the amount of fieldwork and associated cost.

2. Some terrain attributes can be used as the indicator variables to predict the risk to the water quality arising from unsealed forest road networks.

3. The RUSLE can be used to map the soil loss from both the catchment area and forest roads. This map and the rate of soil loss can be used for general assessment (big picture) and the final map can be used as one of the components for detailed study.

4. The FRIA method presented here is a practical method and the outcomes of applying this method can be used directly in both designing the road layout, maintaining existing roads and also assessing, predicting and managing the risk to water quality arising from existing unsealed forest roads.

6. ACKNOWLEDGMENTS

The authors gratefully acknowledge the logistic and financial support of University of Gorgan (Iran), the ANU Forestry Program (SRES) and the division of Forestry and Forest Products of CSIRO.

7. REFERENCES

Anderson, H. W., M. D. Hoover, and K.G. Reinhart (1976), Forest and Water: Effects of forest management on floods, sedimentation, and water supply. USDA Forest Service, General Technical Report PS W-18. San Francisco, California.

Bureau of Meteorology (2004), *Climate of Canberra.* http://www.bom.gov.au/climate/ (25/07/2004).

Croke, J. and S. Mockler (2001), Gully initiation and road-to-stream linkage in a forested catchment, Southeastern Australia. *Earth Surface Processes and Landforms* 26, 205-217.

Croke, J., P. Wallbrink, P. Fogarty, P. Hairsine, S. Mockler, B. McCormack, and J. Brophy (1999), *Management Sediment Sources and Movement in Forests*: The Forest Industry and Water Quality. Canberra, CRC**:** 38.

Farabi, H., R. J. McCormack, and R. James (2003), A "Risk Management" Based Approach to Improve Management of Roads in Forest Plantation. Sweden, 2nd Forest Engineering Conference, (pp 95-99).

Farabi, H. 2005, 'Modelling the Hydrological Connection of Forest Roads as a Source of Sediment to Streams', Presented in the Simulation and Modelling (SimMod 2005) Conference in Bangkok, Thailand, 17-19 January 2005. *SimMod Conference Proceedings*, C3 03.

Flanagan, S.A., M.J. Furniss, T.S. Ledwith, S. Thiesen, M. Love, K. Moore, and J. Ory (2003), 'Methods for Inventory and Environmental Risk Assessment of Road Drainage Crossing', US Department of Agriculture (USDA), Forest Service, http://www.fs.fed.us/eng/pubs/html/wr_p/98771809/98771809.htm. (23/11/2003).

Hairsine P. B., J.C. Croke, H. Mathews, P. Fogarty, and S. P. Mockler (2002), 'Modelling plumes of overland flow from roads and logging tracks'. *Hydrological Processes* **16**, 2311-2327.

Megaham, W.F., M. Wilson, and S.B. Monsen (2001), Sediment production from granitic cuslopes on roads in Idaho." *Earth Surface Processes and Landforms* 26, 153-163.

Montgomery, D.R. (1994), Road surface drainage, channel initiation, and slope Instability. *Water Resources Research*, 30(6), 1925-1932.

Takken, I. (2003), Programming for Flowlines Calculation using Arc Macro Language. University of NSW/ADFA (unpublished).

Takken, I., J. Croke, S. Mockler, P. Hairsine, and P. Lane (2005), Delivery of Sediment from Forest Roads to Streams: A Function of Hydrologic Connectivity. In: I.D. Rutherford, I. Wiszniewski, M. Askey-Doran and R. Glazik (eds), *Fourth Australian Stream Management Conference Proceedings*, Launceston, Tasmania, pp 580-587.