University of Southern Queensland

Faculty of Engineering and Surveying

Forest Road Decommissioning: Modelling the Effect on Hydrological Connectivity

A dissertation submitted by

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ABSTRACT

The decommissioning of forest roads is occurring in many forest environments, with the aim of reducing the negative impacts of road runoff on water quality and aquatic habitat. Prioritisation of decommissioning options is however problematic, as the relative merits of competing options are difficult to assess. This dissertation presents a method of quantifying the degree to which a road is hydrologically connected to the stream network and the uncertainty associated with this. The method permits comparisons between different roads network management options and is useful for assessing the likely result of decommissioning works. To demonstrate its utility, the model was applied to an actual road decommissioning and replacement project in south-eastern Australia.

Road areas and drainage outlets were surveyed in the field and flow path lengths to streams derived from a 1 metre resolution LIDAR based digital elevation model (DEM). The results of the case study demonstrate that the road decommissioning was not effective in reducing runoff to the stream network and that the overall result of the works was counterproductive.

The procedures developed in this dissertation are an extension of the 'volume to breakthrough' model presented by Hairsine et al. (2002) and allow the quantification of road/stream connectivity without the need for extensive parameterisation. Comparisons with empirical road-derived sediment deposition models developed in the US suggest that the methodology used here may readily translate beyond its original geographical context.

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LIMITATIONS OF USE

CERTIFICATION

I certify that the ideas, designs and experimental work, results, analyses and conclusions set out in this dissertation are entirely my own effort, except where otherwise indicated and acknowledged.

I further certify that the work is original and has not been previously submitted for assessment in any other course or institution, except where specifically stated.

Christopher Stuart Eastaugh

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Signature

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Date

PUBLICATION

Some of the material in this manuscript has been submitted for publication to the *Transactions of the American Society of Agricultural and Biological Engineers* and if successful is expected to appear later in 2006 or in early 2007.

The paper has been referenced in this dissertation as:

Eastaugh, CS, Rustomji, PK & Hairsine, PB 2006, 'Quantifying the altered hydrologic connectivity of forest roads resulting from decommissioning and relocation', *Trans. ASABE (in review).*

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CONTENTS:

LIST OF FIGURES

CHAPTER 1 INTRODUCTION

1.1 CASE STUDY BACKGROUND

Following the 2002/2003 alpine bushfires in Southeastern Australia, greatly accelerated soil erosion, water turbidity and stream sediment accumulation was noted across the affected areas (White et al. 2005). These areas included a large part of the water supply catchment for the city of Canberra, leading to concerns that continued supplies of potable water may not be available without extensive treatment (ACT Government 2003).

Much of this catchment had previously been managed as a government owned commercial pine plantation, the pines having been planted from the 1920s onwards to help control soil erosion on overgrazed and rabbit-damaged cleared land (Environment ACT 2006).

In an effort to reduce the amount of sediment entering the waterways, the catchment managers (ACT Forests) commenced decommissioning approximately 100 kilometers of roads in the burnt areas (Environment ACT 2006). One of these roads was Pipeline Road, in the Lower Cotter Catchment. This road was originally constructed for plantation management purposes and for access to the nearby Namadji National Park. This road had a historic problem with erosion, and for much of its length ran very close to Pierces Creek.

The road was decommissioned by cross-barring and surface ripping, and a replacement road (New Pipeline Road) constructed on the hillslope approximately 500 m from the stream. An initial inspection suggested that the net result of the decommissioning and new road construction works may in fact have been a negative effect on water quality in Pierces Creek. This study attempts to quantify the relative water quality impacts of the different road management scenarios.

1.2 SIGNIFICANCE OF THE STUDY

Growing demands for clean water have increased pressures on catchment managers, particularly in areas where the needs of commercial and recreational users of the catchment must also be addressed. In forested catchments the higher road densities associated with industrial and vehicle-based recreational use are coming under increased scrutiny (Croke 2004), and attempts made to reconcile these uses with the need to ensure water quality goals are met.

A recognition of the negative effects of forest roads had led to a push in many jurisdictions for the roading densities to be reduced (Switalski et al. 2003). Road decommissioning may involve simply removing the road from maps and databases to allow it to naturally regenerate, surface ripping, cross-barring or revegetation, or a full recontour of the road prism. Regardless of the methods, the aim is to return catchment areas to a more natural state.

Road decommissioning can be an expensive operation, and has ramifications for commercial and recreational users and for management access. To effectively prioritise road decommissioning works and develop cost-benefit analyses of decommissioning proposals a management tool is needed to evaluate the likely effectiveness of decommissioning works.

1.3 AIMS AND OBJECTIVES

The aim of this project is to assess the effectiveness of recent road decommissioning and relocation works in Canberra's water catchment, in terms of the amount of runoff water generated on the road surface that reaches the stream network.

In order to achieve this a formal definition of hydrological connectivity is developed. A methodology is formulated for assessing the connectivity of roads of different drainage configurations or in different hillslope locations. This methodology will be able to be used to give a quantified hydrological connectivity value to any constructed or proposed forest road.

CHAPTER 2 LITERATURE REVIEW

2.1 WATER QUALITY AND SEDIMENTATION

Water quality may be adversely affected by pollutants in a number of ways. The negative consequences of water pollution are now quite well established and it is well accepted that such pollution must be minimized wherever possible. Anderson (1996) summarised the many ways that increased sediment can affect aquatic organisms, which include behavioral and physiological effects on fish, increased mortality in fish eggs, juveniles and adults, habitat alteration due to changes in stream morphology and bed form, and a reduction in food supply. In North America, fine sediment collection in gravel river beds is of concern because of its negative effects on the growth and survival of endangered native salmonid species (Suttle et al. 2004).

Jowett (2003) examined the influence of fine sediment particles on small aquatic fauna in Australian streams, and found a significant negative correlation between the accumulation of fine particles in the river bed and benthic invertebrate abundance. Jones et al. (2000) outlined the negative effects of changes to stream bed form, with particular reference to changes due to increased peak flows and the attendant increase in debris movement. An Australian study presently underway by Thompson et al. (n.d.) is looking at how coarse sediment can alter the form of the stream bed, which has ramifications for aquatic habitats.

In addition to particulate sediment, chemical pollutants and nutrients may also alter stream habitats. Abdullah et al. (2005) and DiStephano et al. (2005) linked catchment erosion rates with in-stream nutrient levels in southeast Asia and southern Italy, respectively.

Currently in the United States, water quality monitoring is centered on Total Maximum Daily Loads (TMDLs). The TMDL represents the maximum pollutant that a particular waterbody can assimilate while remaining within environmental standards. If the TMDL is exceeded, the responsible authority is required to identify the point and non-point sources of the pollutants and develop strategies for the improvement of water quality (Federal Register 2000, Elliot 2002).

2.2 EFFECTS OF ROADS

Roads have long been recognised as one of the most significant contributing factors in sediment delivery to streams in forestry environments. This was demonstrated by Megahan and Kidd (1972) in their study of forest operations on the Idaho batholith, which found that sediment production from the road prism was 770 times that from an equivalent unroaded area. A similar increase was reported by Reid and Dunne (1984), showing that heavily used roads had an increased sediment production of almost 1000 times over that of abandoned roads.

The negative effects of sediment in water supplies were demonstrated by Cornish (1989), as part of a review into the water quality ramifications of commercial pine plantations in Australia. Grayson et al. (1993) showed the connection between roads and increased sediment loads in Australian forested catchments, Anderson and MacDonald (1998) demonstrated the linkages between roading density and sediment concentrations in the Canary Islands and Pruitt et al. (2001) showed that the amount of suspended solids in streams could be correlated to the road density within a catchment. Appelboom et al. (2002) developed management practices for the reduction of sediment production from forest roads, formalizing some of the methods followed by forest services for a number of years. Recent work by Simon et al. (2002) and Dent et al. (2003) attempts to quantify sediment runoff from forest roads for use in calculations of Total Maximum Daily Loads.

Apart from the increased sediment production from the road surface, roads may also be responsible for increased stream sediment loads in other ways. Compacted road surfaces promote lower rainfall infiltration and hence greater runoff (Luce 1997). In some mountainous areas the increased likelihood of mass failure (landslides) is of concern, with Larson and Parks (1996) finding that the chance of landslides was five to eight times greater within a 170 metre wide roadside zone than in other areas. The hard, compacted road surface generally has a much lower rainfall infiltration rate than undisturbed areas, leading to increased peak flows. Croke et al. (1999) found that forest snig tracks generate six to nine times the surface runoff of undisturbed areas.

Roads also have a number of hydrological effects on water catchments, which may include subsurface flow interception, flow rerouting and the concentration of runoff flows from drainage structures. Wemple et al. (1996) introduced the concept of 'hydrologic connectivity' as an indication of how efficiently surface flows are routed from the road surface to the stream network via incised gullies or at stream crossings. Croke and Mockler (1999) extended the concept (but used the term 'linkage' rather than 'connectivity') by including consideration of partial connectivity, whereby gullying from road drainage exits that did not extend all the way to the stream were considered 'partially linked'. The concept was further developed by Bracken et al. (2004), defining connectivity as "…the volume of water necessary to breakthrough [to the stream] and result in connected flow within a catchment".

In these previous studies no attempt was made to estimate the volume of runoff that would reach the stream, only the possibility that some may.

2.3 ROAD REMOVAL

In recognition of the negative effect of forest roads on water quality, a number of government agencies (particularly in the United States) are actively decommissioning parts of their road network. Switalski et al. (2004) discuss decommissioning methods, which may range from simply blocking the ends of the road and removing it from forest service databases through to extensive road works and revegetation programs to restore the pre-disturbance topography. Schaffer (2003) outlined the current state of the road decommissioning program in the US, and concluded that significantly more research is needed to determine the effectiveness of the works and ensure that value for money is being maximised. Luce et al. (2001) suggested that road decommissioning proposals be prioritised based on their benefit to aquatic habitats, balanced against the costs of the works. As a rule of thumb, forest managers seem to consider that roads near streams should be prioritised for decommissioning, which may be a simplistic interpretation.

The effectiveness of road decommissioning works is not always guaranteed at a physical level. In a study of abandoned and decommissioned roads in California, Madej (2001) found that decommissioned roads produced one quarter of the sediment as untreated roads, but this sediment was produced from only 20 percent of the treated roads.

The disturbance created by the decommissioning works is also of concern. In a biological study into tailed frogs in Californian parks, Currens and Madej (n.d.) found that frog numbers were significantly lower in streams where road crossings had been rehabilitated, compared to those in pristine or recovering watersheds.

2.4 MODELLING

Numerous authors have developed empirical models relating sediment plume lengths emanating from road drainage outlets to road and topographical conditions (Swift, 1986; Ketcheson and Megahan, 1996; Grace, 2005) but these relate to observed sediment deposition only and so do not include consideration of fine particles that may be carried in suspension. There are also a number of different physically-based models concerning road sediment production and delivery to streams, summarised by Merritt et al. (2003), but these suffer the practical disadvantage of being highly parameterized, requiring a large amount of input data which is often difficult to obtain or accurately estimate (CRC for Catchment Hydrology, n.d.). The level of geometric detail used in these models is also of concern, with Rhee et al. (2004) finding that the widely used Water Erosion Prediction Project model (WEPP) showed variability of up to 67% in predicted sediment delivery to streams depending on relatively small changes in the resolution of input data.

Wemple et al. (1996) outlined the three ways in which surface flows leaving a road may reach streams: directly at stream crossings, via incised gullies or concentrated pathways or through a diffuse connection where some of the flow will infiltrate into the soil. While the first two pathways are relatively straightforward, the third is dependant on a raft of factors including slope, distance to stream, surface roughness and soil infiltration characteristics.

Hairsine et al. (2002) introduced a probabilistic model to estimate the amount of surface flow leaving a drainage exit that could be expected to reach the stream network in a given rain event. Based on data collected by Croke et al. (1999), Hairsine's 'volume to breakthrough (vbt5)' model estimates the volume of water that must exit a road drainage outlet in order for some surface flow to extend a distance of five metres. Experimental findings across nine sites in three forested catchments in the Eden Forest Management Area of Southeastern NSW using a range of rainfall intensities gave a mean volume to breakthrough at five metres as 336 litres, with a variance of 35600 l^2. A later independent study by Lane et al. (2006) obtained very similar values in Victoria's Upper Tyres Catchment. The vbt5 model also allows a probabilistic prediction of the length that surface flows will travel from a drainage exit under given rainfalls. The advantage of this model is that the various surface and soil characteristics are accounted for in the uncertainty ranges of the predictions, and so these parameters need not be measured or estimated.

This approach allowed Takken and Croke (2004) to estimate how many drainage exits on a particular road would be hydrologically connected in a given rain event, thus allowing different road management options to be compared. Takken et al. (2006) use this methodology to estimate the hydrological connectivity of park and plantation roads in southern Victoria, using the mean value of the vbt5 prediction as an indication of whether a section of road was 'connected' or 'unconnected' to the stream network, thus giving an estimate of what percentage of a particular road could be described as fully or partially connected to the stream network. This methodology however does not give a direct indication of how much sediment-bearing runoff water will reach the stream, nor does it permit the comparison between a given length of fully connected road and a different length of partially connected road. Much of the detail from the vbt5 model is lost through simply using the mean, without consideration of the uncertainty.

CHAPTER 3 THE STUDY AREA

The study site is situated in the Lower Cotter catchment, part of the water supply catchment area for the city of Canberra (fig. 1). Prior to European settlement the area was mixed species eucalypt forest, up until it was cleared for pasture establishment in the 1920s. Many of the steeper cleared areas showed a high propensity to soil erosion, so some of the catchment became part of a government owned *Pinus radiata* plantation forestry development, managed by ACT Forests. Severe bushfires in January 2003 destroyed much of the pine plantation and currently the vegetation consists of three year old post-fire regrowth following salvage logging of the burnt forest.

Soils are predominantly highly erosive sandy yellow podzols overlying an adamellite geology (Talsma 1983). Average annual rainfall is approximately 820 mm. Road density in the plantation estate is approximately 100 metres per hectare (S. Rymer, personal communication, 21 December, 2005).

The study site is roughly rectangular in shape, 2000 by 500 m in size, with a south-easterly aspect along the long dimension. The area is bounded on its north-westerly edge by a ridge-top fire trail and on the south-easterly edge by Pierces Creek and one of its unnamed tributaries. Elevation at the top of the ridge is 964 metres and at Concrete Crossing 592 metres (fig. 1). The two roads assessed are on the north side of a small permanent watercourse (Pierces Creek), upstream of Concrete Crossing.

Prior to the decommissioning and relocation works, roading consisted of a steep four wheel drive track along Razorback Ridge and the Pipeline Road (shown in figure 1 as ‘Old Pipeline Road), an unsealed major forestry and service road on the more level ground near the creek. The Pipeline Road was used for plantation access, as an entrance route to Namadgi National Park to the south-west and as a service road for water resources infrastructure in an adjacent catchment. Classified by ACT Forests as a 'float' road, it was expected to be of a standard suitable for use by low-loaders or multi-trailer B-double log trucks. Such carriageways are required to be gravel surfaced and approximately four metres wide (ACT Forests, 2005).

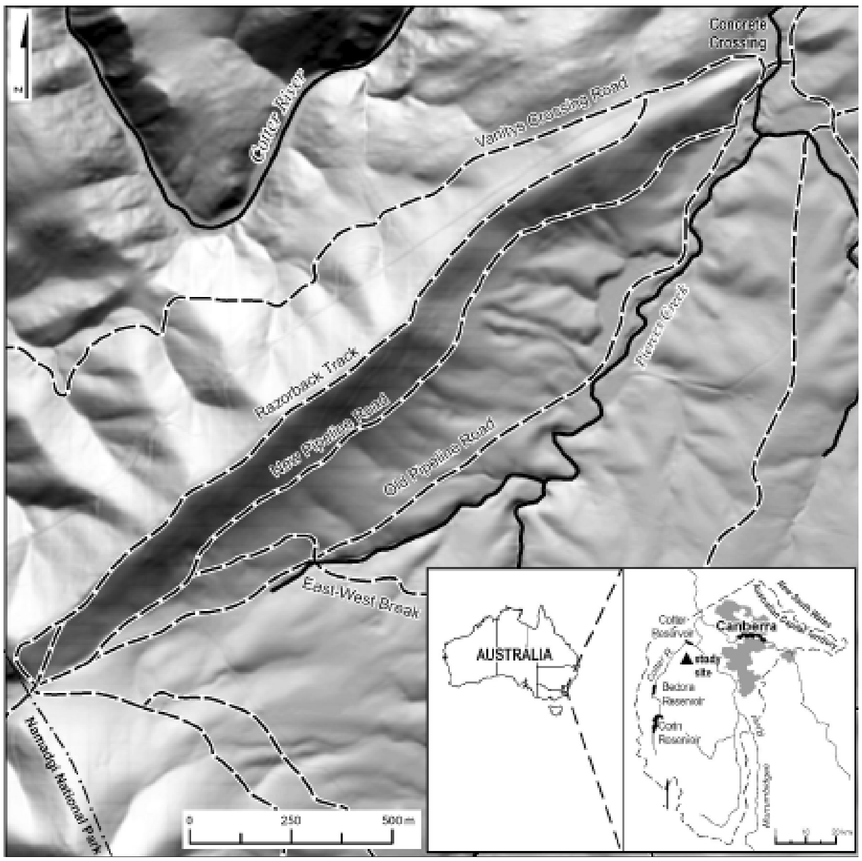

Figure 1. Site map, reproduced from Eastaugh et al. (2006).

Figure 2. Photograph taken from the northeast corner of the study area.

Following disturbance by wildfire in early 2003, elevated erosion rates and stream sediment loads were observed in the Lower Cotter catchment (White et al. 2005). Roading was identified as a major source of sediment delivered to the stream network and the decision was made by ACT Forests to remove Pipeline Road from service and replace it with a new road, parallel to the old but positioned approximately half way up the hillslope (see figure 1, 'New Pipeline Road').

The decommissioning of 2075 metres of mostly surface-level road involved culvert removal, cross barring at approximately 15 m spacing to discourage vehicle access and pavement ripping with an excavator The formal roadworks plan for these works is attached to this paper as Appendix 2, but it is important to note that the specific cross-bar construction details shown in Attachment 1 of the plan were not followed. In practice, all cross-bars were constructed the full width of the road surface (figure 3)

Figure 3. Cross-bars constructed on Old Pipeline Road

The road prism was left in place and an attempt at aerially seeding the old road surface with native grasses was not successful. The replacement road (2534 metres in length) included an extension to an intersecting road (East-West Break) and comprised 433 m of surface-level road and 2101 m sidecut road, constructed with the surface sloping inwards to a drain at the base of the embankment. Culverts were placed under the road at the distances specified in the ACT Forests roading manual to discharge water out to the hillside.

CHAPTER 4 METHODS

4.1 OVERVIEW

Four road situations are compared in this study:

1) Old Pipeline Road in its unmodified condition,
2) Old Pipeline Road in a 'best practice' modified condition where the road surface is segmented into discretely drained sections of 15 metre length,
3) Old Pipeline Road in its actual modified condition, and
4) The New Pipeline Road considered in isolation.

A comparison is also made between the original state of the old road and the combined state of the old road with decommissioning works in place and the new sidecut road. In essence this comparison will show the net result of the decommissioning and road replacement works.

Rainfall runoff from a road surface is dependent on rainfall, infiltration and the road surface area. In some environments the water flowing onto a road surface from the general forest area may be an important factor, but this study assumed such inflows to be negligible. This is consistent with the findings of Croke et al. (1999) and Motha et al. (2003), who found sediment generation from road surfaces to be 20 to 60 times that from general forest areas due to the much lower infiltration capacity of compacted road surfaces.

For simplicity, this study assumes spatially constant infiltration and rainfall, implying that the runoff volume generation from each road segment is directly proportional to the road surface area. Infiltration on the compacted road surfaces is assumed to be negligible.

4.2 DATA ACQUISITION

4.2.1 EXISTING PUBLISHED DATA

Practical work for the project commenced with a search for existing information regarding the study area. None of the publicly available maps found reflected the changed road conditions resulting from the decommissioning works, and it proved impossible to gain access to ACT Forests' GIS shapefiles. The roadworks plan map (attached to Appendix 2) does however show the old and new roads, and the distinction between 'streams' and 'drainage lines'.

Contour data on the topographical maps available was not sufficiently detailed to be of use in the study, so it was necessary to build this data from ground surveys or digital elevation models of the catchment.

To establish datum points and to ground truth the remotely sensed data, a search of the ACT Planning and Land Authority online survey control mark database (ACTPLA 2002) found several trig points near the study area. The Australian Capital Territory uses its own, ACT specific projection based on a modified version of Australian Geodetic Datum 1966 (ACTPLA 2006), labeled AGC (Adjusted Grid Coordinates). A small computer routine available from the ACTPLA website (Geomin32) was used to convert ACT grid coordinates to the more commonly used Australia wide Geodetic Datum of Australia 1994 system. This was done in an effort to keep the study based in the most up to date reference system, but later incompatibilities with remotely sensed data meant that all data had to remain on or be projected onto the AGC coordinate system.

4.2.2 *Differential GPS Survey*

An intensive field survey using a Trimble 4800 differential global positioning system receiver recorded the location of road edges, culvert locations and water runoff points from the road surface. The base station was initially located on the Mount Hardy trig point, approximately 800 metres from the southwest corner of the study area. On the AGC datum this point was at 189741.613E, 595320.754N and an elevation of 963.57 metres. Conversion to GDA94 gave a position of 672415.546E, 6085568.728N. Elevations are not expected to change appreciably in this conversion (ACTPLA 2006).

A survey peg was installed to the southeast of the study area, in a location that would allow the base station to be set up with good radio communications to the receiver. In case some areas would not have good radio reception a second survey peg was installed near the northeast corner of the study area.

Each of these new points was established by leaving the roving GPS receiver over them for several hours, with the base station set up on the Mount Hardy trig point. Data was then processed using the highest precision 'static' post-processing algorithms. This should give accuracy to within millimeters. A planned check of this accuracy using other local trig points did not eventuate due to time constraints but for the purposes of this study the accuracy of the coordinates was not particularly relevant. What was important was that the survey control points be cross-checked each day that surveying was conducted, to ensure that no errors were present in the results.

Figure 4 shows the processed output of the GPS after surveying road edges, with the location of the three control points used.

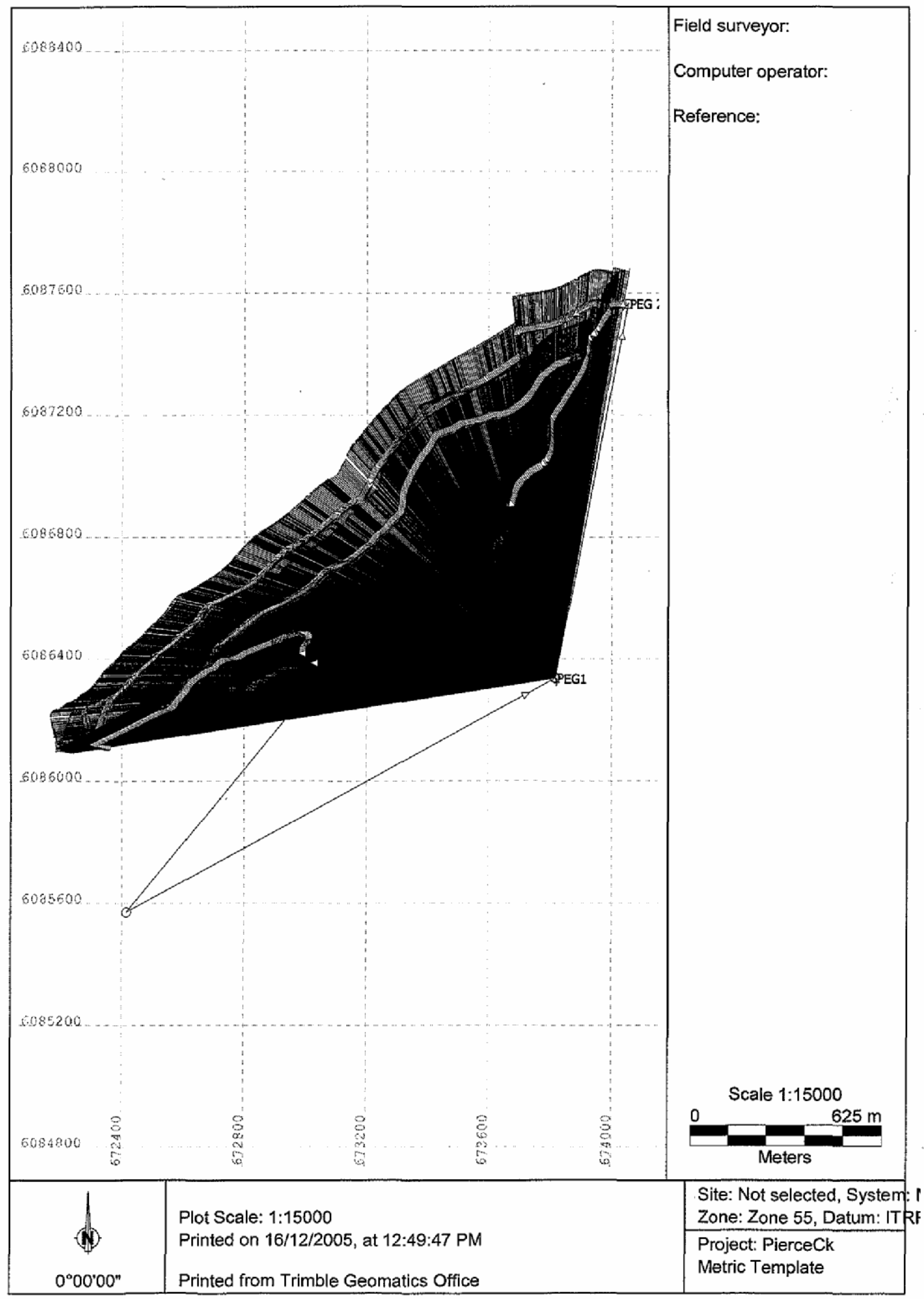

Figure 4. Output from Trimble Geomatics Office software, showing road edge locations.

The GPS receiver was set up to survey in Real Time Kinematic mode, on the GDA 94 grid. After each day's field surveying, the data was processed in Trimble Geomatics Office™ and exported in ESRI shapefile format. To simplify later processing, all of the roadside points were collected first, then streamsides and so forth. In addition to an elementary point labeling system, this prevented confusion when the final files were developed.

All roads were surveyed with points on either side at 5 metre intervals. This involved walking each side of every road, with the sampling interval of 5 metres automatically calculated by the GPS. The locations of all cross-bars on the decommissioned road were mapped and assessed as to whether or not they were effective in removing water from the road surface to the general harvest area.

Where water leaving the road had caused gullying, the gullies were surveyed to the point where flows were no longer concentrated in a defined channel. The permanent watercourses were surveyed, along with any incised gullies greater than approximately 150 mm width that entered the stream.

4.2.3 Remotely sensed data

A Digital Elevation Model of the Murrumbidgi catchment at 25 metre resolution was available through CSIRO, and this was used in the early stages of the project. Later, a more detailed 1 metre resolution DEM derived from LiDAR (Light Detection And Ranging) became available from Ecowise Pty Ltd, the ACT government's corporatised utilities service. The algorithms used in processing the LiDAR images into a DEM are unknown.

This DEM proved to be remarkably accurate when compared with GPS-derived data, and vertical errors rarely exceeded a few centimeters. This DEM was based on the AGC coordinate system.

A screenshot of a hillslope model built from the LiDAR derived DEM is presented here as figure 5.

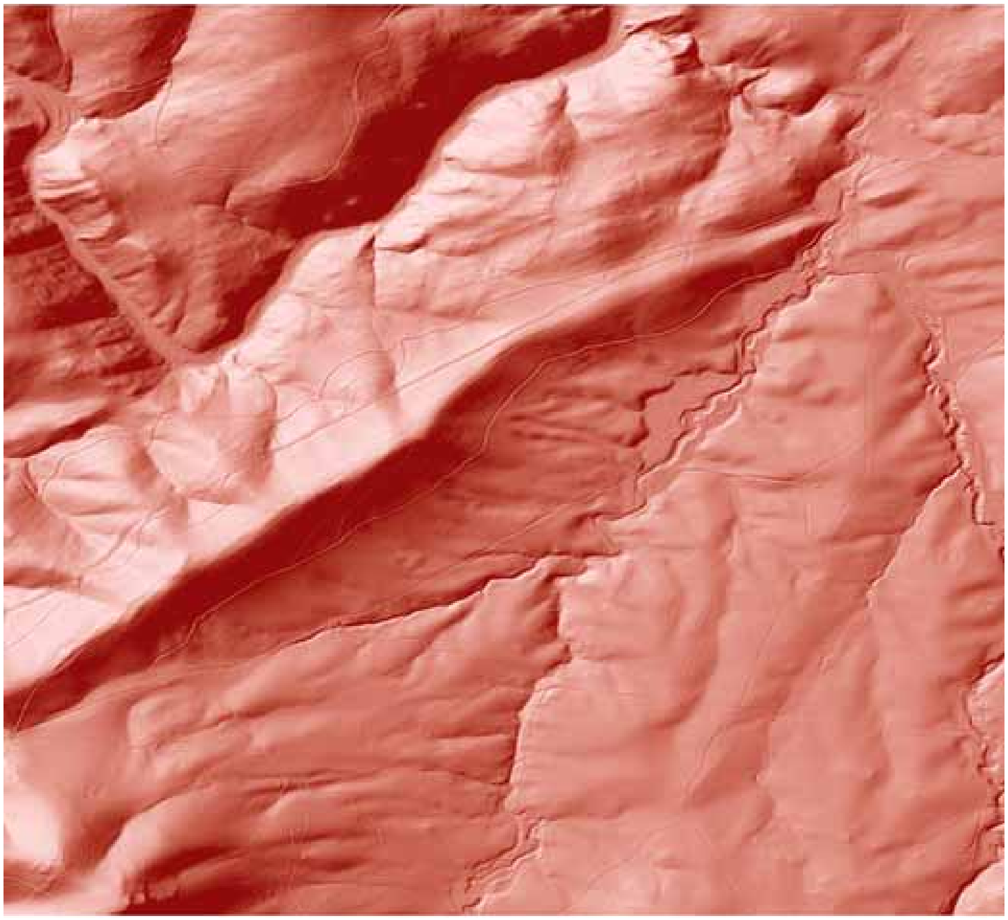

Figure 5. Hillslope model build from the 1 metre resolution LiDAR-derived DEM.

4.2.4 Other data

Data regarding drainage conditions of the Old Pipeline Road prior to decommissioning was made available by Simon Mockler (personal communication, 29th November 2005), comprising the unpublished results of ground surveys carried out by University of New South Wales / Australian Defence Force Academy cadets approximately eighteen months earlier.

4.3 DATA PROCESSING

4.3.1 FIELD SURVEY DATA PROCESSING

The point files generated by the Trimble Geomatics Office software were separated into different files according to whether they were road points, streamside points, drainage exit points, gully points or cross-bars. The freeware software tool 'ET Geowizards' was then used in conjunction with ArcGIS 9.0 to join the points on the roads, streams and gullies to create line features from these points. The road edge lines were then manually joined at the ends to create polygon features.

The drainage exit points and cross-bars were added as separate layers, and individually numbered. Stream edges and gullies remained as two layers of line features. Where a gully began at a drainage exit, the exit point was designated as being at the downstream end of the gully, on the assumption that little or no infiltration would occur along the narrow floor of an incised gully.

Road areas were then segmented according to the road surface area associated with each drainage outlet. Where water had broken through or passed around a cross-bar the road segment area was continuous until the water flowpath left the road area. Individual road segment areas were calculated with the GIS field calculator, and numbered according to the drainage outlet that they were associated with.

4.3.2 DEM PROCESSING

The DEM supplied by Ecowise was on the AGC coordinate system, and extended for several kilometers around the study area. The region shown in figure 4 was clipped from the dataset and the remainder discarded.

This DEM was on the AGC coordinate system, based on AGD66. A projection transformation in ArcGIS was performed to bring the DEM into GDA94 in line with the GPS data, but in the process of transformation errors were introduced into the dataset, creating a visibly noticeable ‘chequerboard’ effect (figure 6). This caused problems with GIS operations that used point elevations, particularly flow routing. The precise reason for the chequerboarding could not be found, so the decision was made to project all other data onto the AGC coordinate system.

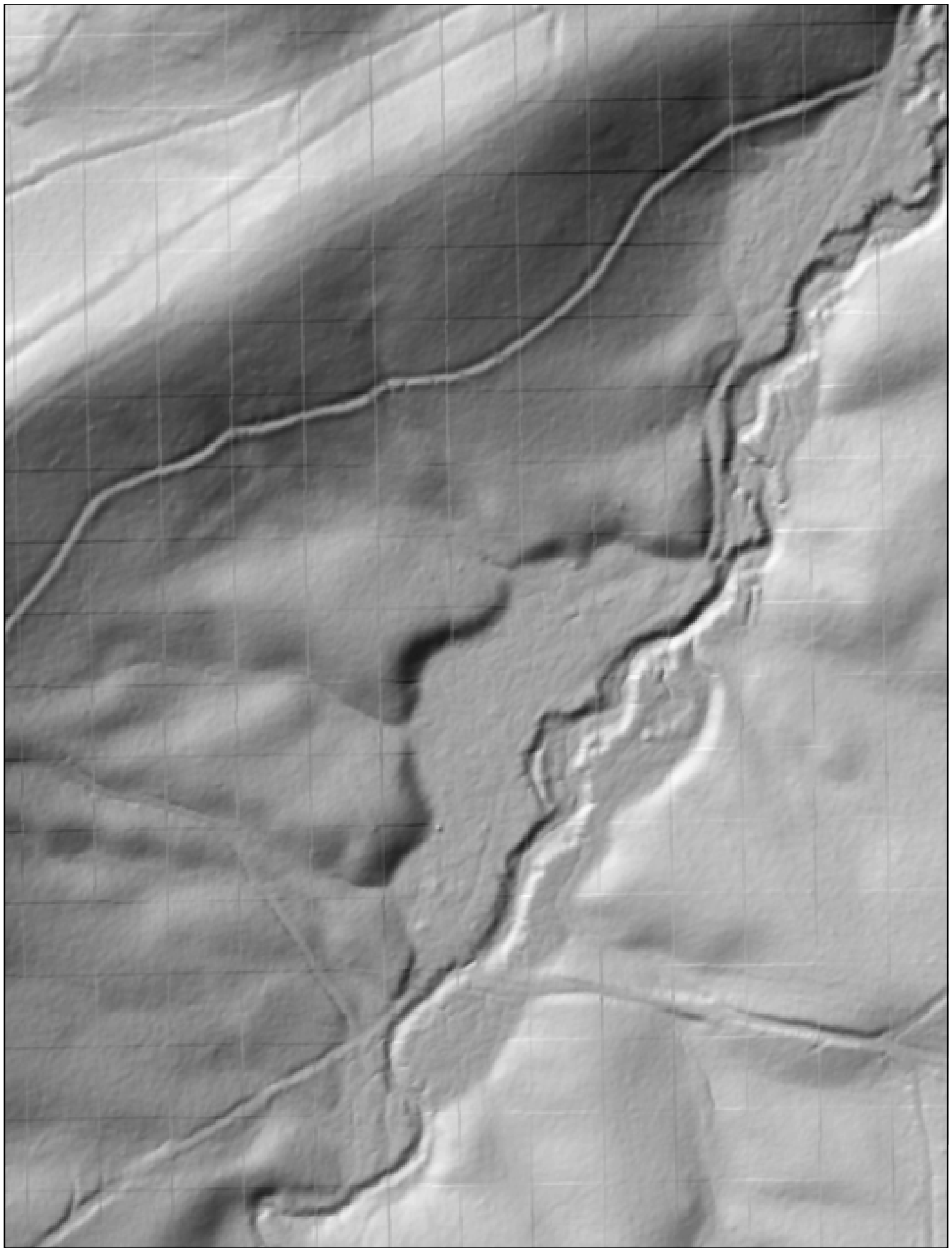

Figure 6. 'Chequerboard' effect resulting from projection transformation of the DEM

In order to determine the flow path lengths from each drainage outlet, a flowpath model was constructed from the DEM. This process involved several steps.

Firstly, the DEM needed to be ‘filled’ to remove any sinks (points not on the edge of the DEM that are lower in elevation than any of their surrounding points), and create a depressionless DEM. The ‘Flow Direction’ algorithm in the ArcGIS ‘Spatial Analyst’ extension looks at each DEM cell in turn and identifies the direction of steepest decent (O’Callaghan and Mark, 1983). The cell is then coded with a number to identify that direction, which may be into any one of the 8 surrounding cells. These numbers are shown in figure 7.

32	64	128
16	**CELL**	1
8	4	2

Figure 7. Flow direction grid assignment numbers.

The ‘Fill’ algorithm was then run on the flow direction grid, to identify cells that have no flow exit. These cells were then progressively raised in value until no sinks were left, and a depressionless DEM was created. The ‘Flow Direction’ algorithm was then run on the filled DEM.

The ‘Flow Accumulation’ algorithm was then run, looking at each cell in turn to determine how many cells would contribute flow that cell. The resultant grid can then be displayed as a series of value ranges, to give a clear visual picture of the flow accumulation characteristics of the watershed (figure 8).

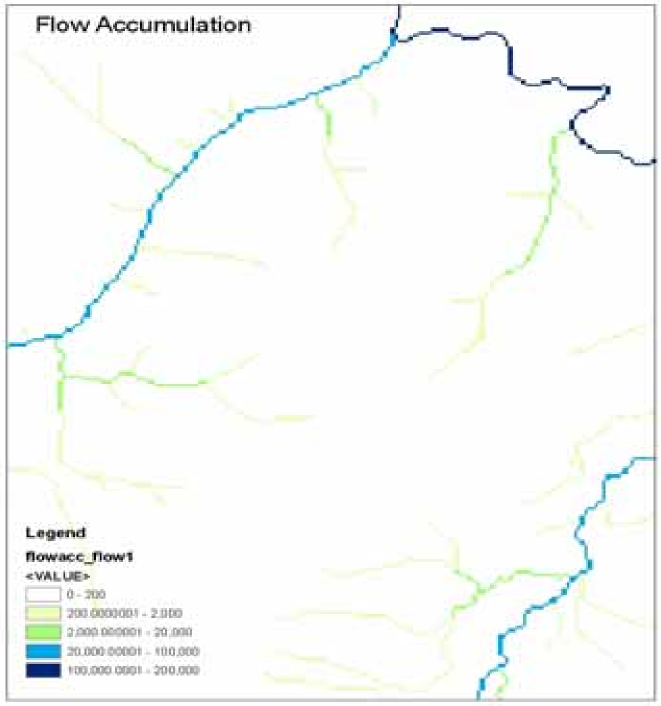

Figure 8. Flow Accumulation output grid.

This information was used in conjunction with field observations and ACT Forests' records to define the extent of the stream network. The definition of 'stream' is somewhat arbitrary, but in general if a drainage line was formally recorded as a stream by ACT Forests, or if it was directly connected to formally defined stream and showed clear evidence of an incised bed then it was defined as a stream for the purposes of this study.

The line feature of stream edges was overlaid over the DEM, and a new grid created where the cells of the DEM that lay under the streamline were given a 'null' value. The points feature of drainage exits was converted to a raster file, and the Flow Accumulation algorithm run again, but this time giving an artificially very high 'weighting' to the cells containing a drainage exit. This had the result of creating a flow accumulation grid that contained only drainage lines that began at the designated drainage exits and ended at the designated stream. This grid was then converted to a line feature, and the length of each drainage line calculated with the field calculator. A flow chart of the GIS operation is presented as figure 9.

Although the accuracy of this method of flow path calculation has been questioned when coarser scale DEMs have been used (Takken and Croke, 2004), the use of a fine resolution (1 m) DEM rather than the more common 20 m resolution produced flow paths that agreed well with field observations.

Each drainage line was associated with a drainage exit point, and hence with a road segment area (calculated with the field calculator). These features were 'joined' in ArcGIS, to give a single file containing road segment areas and the infiltration distance available for each segment's runoff water. This file was exported as a dbf. table, and opened with the spreadsheet program Excel for use in the statistical modelling developed in the next chapter.

The degree of connectivity between roads and the stream can be assessed for any given rainfall magnitude. This study used a characteristic event likely to be associated with infrequent contribution of sediment that is a large component of long term sediment loads. ACT Forests design their roads to cope with a 1 in 5 rainfall event, so this return period was selected. A two hour duration was arbitrarily chosen. At the nearby station of Canberra this design storm gives a rainfall total of 35.8mm. This rainfall depth was calculated with the software tool AusIFD, using the procedures recommended in Australian Rainfall and Runoff (Griffith University, 2004; Pilgrim, 1987).

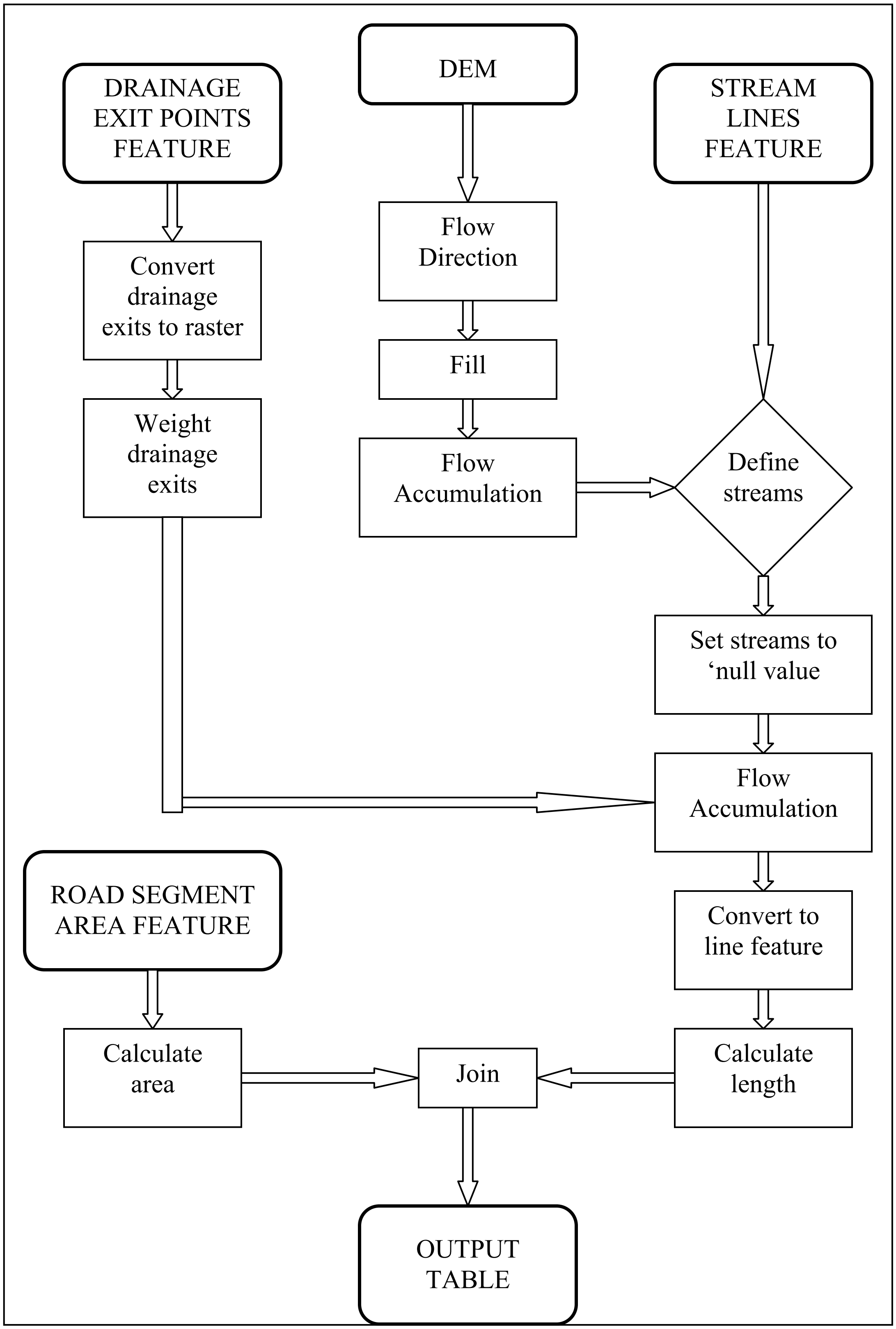

Figure 9. Flowchart of GIS operations.

CHAPTER 5 DEVELOPMENT OF CONNECTIVITY INDEX

5.1 ROAD MORPHOLOGY

Each road segment was classified according to whether it had a direct or diffuse flow path to a stream. The largest and third largest segments on the old road were located on alluvial flats and had no clearly defined drainage outlets, with flow leaving the road surface via indistinct pathways. These segments were excluded from the connectivity analysis. Although these road sections were quite close to the creek bank (in some cases within 5 metres), both field inspection and the DEM showed that the topography in these areas sloped away from the creek bank towards the far edge of the valley flat. This is a common occurrence in many swamp and creek environments where the channel banks can be the highest portion of a floodplain.

5.2 NOMENCLATURE

A_D	Area of road section with direct connectivity, m^2
A_{df}	Area of road section with diffuse connectivity, m^2
A_T	Total road area, m^2
N	Exceedence probability of flows over a given distance
E	Uncertainty range
C	Connectivity, m^2, expressed as the equivalent area of directly connected road segment.
CI	Connectivity Index, m
L	Length of road, m
P	Proportion of diffuse flow expected to reach stream network.
PL	Predicted sediment plume length
R_l	Road segment length
R_w	Road segment width
V_{out}	Volume of flow expected to exit road segment in a 2 hour, 1 in 5 rainfall event, m^3
X	Length of flow path from drain outlet, m
z	Statistical constant (for 90% confidence, z = 1.645).
μC	Total mean connectivity, m^2
μV_X	Mean volume of flow attaining distance X, m
$\mu vbt5$	Mean of vbt5 dataset, l
σ	Standard deviation of flows from a single segment, l
σ^2	Variance of flow volume from a single segment, l^2
$\sigma vbt5^2$	Variance of vbt5 dataset, l^2
σV_X^2	Variance of flow volume of a single segment in the vbt5 dataset, l^2

5.3 STATISTICAL MODELLING

5.3.1 Hairsine et. al.'s (2002) vbt5 model

Croke et al. (1999) conducted a series of rainfall simulation experiments over nine sites in forested catchments in southeastern Australia, covering three soil types and three vegetation age classes. Three rainfall intensities (45, 75 and 110 mm/hr) were simulated at each site. Part of the data recorded in these trials was the time taken for the drainage runoff plume to extend 5 metres from the drainage exit.

Hairsine et al. (2002) used this data to develop the 'volume to breakthrough' (vbt) model, where the vbt5 value is the volume of runoff water required for the runoff plume to extend 5 metres from the drainage exit. The mean volume determined by Hairsine et al. (2002) was 336 litres, with a variance of 35600 litres^2. Similar figures were obtained in a separate study using different methodology by Lane et al. (2006), who concluded that these figures could be used for predicting connectivity between road drains and stream networks in a range of forest environments.

This study uses the vbt5 figures of Hairsine et al. (2000) to predict the connectivity of individual road segments, and statistically sums the results to give a predicted connectivity figure for a complete stretch of road.

5.3.2 Directly Connected road segments

For a road section that has a direct connection to the stream network via a channelised flow path, the proportion of flow leaving the segment (V_{out}) and reaching the stream is assumed to be one, in that there are no infiltration losses along the flow path. This assumption is consistent with the approach of Takken et al. (2006) and is a realistic approximation in many instances because of the relatively small wetted area of gullied channels. As noted earlier, V_{out} is taken to be directly proportional to the road segment area A_D (the subscript $_D$ denoting a road segment with a direct flow path to a stream), so that ΣA_D represents the total flow reaching the stream through direct flow paths for a given rainfall amount.

5.3.3 *DIFFUSELY CONNECTED ROAD SEGMENTS*

The probabilistic model of Hairsine et al (2002) proposes that the mean volume of flow reaching a stream (μV_X) via a diffuse pathway of length X can be expressed as;

$$\mu V_X = V_{out} - \frac{X}{5}\mu vbt5 \qquad (1)$$

where $\mu vbt5$ is the mean volume to breakthrough for a 5 m hillslope segment and was found not to vary across nine forested hillslopes on three contrasting soils. This study assumes that the value of 336 litres determined by Hairsine et al. (2006) holds for the environment under consideration here, so that equation 1 becomes;

$$\mu V_X = V_{out} - 67X \qquad (2)$$

This equation represents the reduction in discharge due to infiltration of an overland flow plume as it flows across a hillslope.

μVx can be expressed as a proportion, P, of the total volume of flow leaving the segment at each drainage outlet:

$$P = \frac{\mu V_X}{V_{out}} \qquad (3)$$

Multiplying this proportion for each road segment by its diffusely connected road segment area, $A_{df,}$ represents the mean connectivity for a diffusely connected road segment. The total mean connectivity for both directly and diffusely connected road segments along a road, μC, can then be expressed as:

$$\mu C = \sum A_D + \sum A_{df_i} P_i^+ \tag{4}$$

with P^+ indicating that the summation applies to segments that are expected to contribute sediment to the stream and the subscript i denoting the individual segment.

5.3.4 UNCERTAINTY OF SEGMENTS FOR FLOWS EXPECTED TO REACH THE STREAM

Statistical relationships determined by Hairsine et al. (2002) are now used to estimate the uncertainty, E, of the proportion of flow reaching the stream where P>0. The variance of the flow volume, σV_X^2, reaching a distance X from the drain outlet is given by Hairsine et al. as:

$$\sigma V_X{}^2 = \frac{X^2}{25} \sigma_{vbt5}{}^2 \tag{5}$$

where σ_{vbt5}^2 was calculated as 35600 litres^2 across the nine sites. For an individual road section, the standard deviation σ = 38X, which can be expressed as a proportion of outflow and then multiplied by a suitable z factor to reflect a selected uncertainty. Where some proportion of the flow is expected to reach the stream (i.e. P>0),

$$E = \pm \frac{z\sigma}{V_{out}} \tag{6}$$

5.3.5 UNCERTAINTY OF SEGMENTS FOR FLOWS NOT EXPECTED TO REACH THE STREAM

Hairsine et al. (2002) did not include a consideration of the error in cases where the flow is not expected to reach the stream. In its original context this refinement was not required, but in order to determine an overall uncertainty estimate for a summation of the segments it is necessary to consider this development.

Conceptually, where a diffuse flow is not expected to reach the stream, an increased flow path distance will give greater certainty that there will be no diffuse connection (a situation not reflected in equation 5). At a certain distance (relative to V_{out}), uncertainty will be at a maximum and thereafter will reduce, eventually to the point where there is great certainty that no flow will reach the stream. This is presented graphically in figure 10.

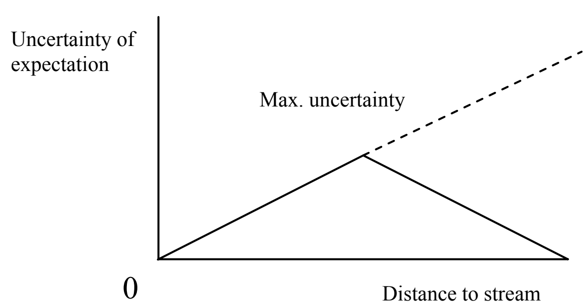

Figure 10. Conceptual representation of the changes in the uncertainty of the volume to break through flow volume predictions with distance along the flow path.

A flowpath length of zero has complete certainty of full connectivity (*P=1)*. As flow length X is increased (V_{out} being constant), the proportion of flow reaching the stream is reduced due to infiltration, and uncertainty increases in accordance with:

$$E = \pm \frac{z(38X)}{V_{out}} \text{ (from equations 5 and 6).} \quad (7)$$

Maximum uncertainty is reached when the expectation is that the flow reaching the stream is zero and increasing the flow path length beyond this will reduce the uncertainty. Equation 7 shows that uncertainty E is linearly related to distance X.

The mean proportion of flow expected to reach the stream is given by combining equations 2 and 3:

$$P = \frac{V_{out} - 67X}{V_{out}} \quad (8)$$

The flow reaching the stream could first be expected to be zero when $X = V_{out} / 67$. At this point, equation 7 gives a maximum uncertainty of $E_{max} = \pm 0.567z$, beyond this point the simplifying assumption is made that uncertainty will reduce according to the same slope as equation 7. In this case, the uncertainty when $P = 0$ can be given as;

$$E = 1.134 - \frac{z\sigma}{V_{out}} \quad (9)$$

For a single road segment then, connectivity may be described by

$C = A_D$	For a directly connected segment
$C = A_{df}P \pm (z\sigma / V_{out})A_{df}$	For a diffusely connected segment, P>0
$C = 0 + [1.134 - (z\sigma / V_{out})]A_{df}$	For a diffusely connected segment, P=0 (i.e. an unconnected segment).

It is possible for equation 8 to give negative P values. In these cases, P should be taken as zero.

5.3.6 Summations of Segment Connectivities

The connectivity of individual road segments can be summed to give a connectivity figure for a length of road. This will allow different roads or road management scenarios to be directly compared, assisting in the planning and prioritisation of decommissioning works.

While summing A_D and $A_{df}P$ for segments in a road to give an overall mean connectivity is straightforward, the treatment of the error ranges is more complex. Rather than dealing with standard deviations, it is necessary to express equations 6 and 9 in terms of variances, weighted according to the proportion of each road segment area relative to the total road area.

Standard deviations may not be summed but variances may; and then the root may be taken to determine the overall standard deviation, i.e.

$$\sigma_{A+B} = \sqrt{\sigma_A^{\ 2} + \sigma_B^{\ 2}} \qquad (10)$$

When multiplying a variance by a constant, the resulting overall variance is the original variance multiplied by the constant squared, i.e.

$$5(\sigma_A)^2 = (\sigma_{25A})^2 \tag{11}$$

Expressing equation 6 in terms of a sum of variances rather than standard deviation gives:

$$E = \pm\sqrt{\frac{z^2\sigma^2}{V_{out}^{\ 2}}} \tag{12}$$

Including a weighting factor that expresses A_{df} as a proportion of the total road area, A_T, the summation of error for segments where P>0 is most clearly arranged as:

$$E = \pm z\left[\sqrt{\sum\left(\frac{A_{df_i}}{A_T}\right)^2 \frac{\sigma_i^{\ 2}}{V_{out_i}^{\ 2}}}\right] \tag{13}$$

As shown earlier, where P=0 the point of maximum uncertainty will be where V_{out} = 67X. Our single segment error expressed in terms of variance at this point (from equations 5 and 10) is:

$$E_{\max} = \pm z\sqrt{\frac{\left(1424X^2\right)}{\left(67X\right)^2}} \approx \sqrt{\frac{1}{3}}z \tag{14}$$

The summation of errors for segments where *P*=0 is then:

$$E = \pm z\left[\sqrt{\sum\left(\frac{A_{df_i}}{A_T}\right)^2\left(\frac{4}{3}-\frac{\sigma_i^{\ 2}}{V_{out_i}^{\ 2}}\right)}\right] \tag{15}$$

Where this term results in a negative uncertainty, the uncertainty may be considered zero for that segment. This may have the effect that the uncertainty ranges are unnecessarily wide and is therefore a conservative assumption.

Combining equations for all diffuse connections, the total proportional variance in the predicted connectivity of a road length (σ_{tot}^2) then is:

$$\sigma_{tot}^2 = \sum^{P>0}\left(\frac{A_{df_i}}{A_T}\right)^2\frac{\sigma_i^2}{V_{out_i}^{\ 2}} + \sum^{P=0}\left(\frac{A_{df_i}}{A_T}\right)^2\left(\frac{4}{3}-\frac{\sigma_i^2}{V_{out_i}^{\ 2}}\right) \tag{16}$$

The total connectivity and uncertainty of a road may then be expressed as:

$$C = \sum A_D + \sum A_{df_i}P_i \pm z\sqrt{\sigma_{tot}^2}\sum A_{df_i} \tag{17}$$

Units for this index are m^2. and may be considered as an equivalent area of directly connected road surface. This then provides the formal definition of ‘hydrological connectivity’ as it is used in this study:

Hydrological connectivity (C) is a measure applied to a stretch of road that denotes how much runoff water from the road surface will enter a stream network, expressed as the equivalent area of directly connected road surface.

Dividing this figure by total road length *L* provides a connectivity index per unit length of road which is suited to comparisons between different road locations and designs, or for comparing road network connectivity across management regions.

$$CI = \frac{C = \sum A_D + \sum A_{df_i} P_i \pm z\sqrt{\sigma_{tot}^2} \sum A_{df_i}}{L} \tag{18}$$

Units for this index are metres, and may be considered as an equivalent width of directly connected road surface.

CHAPTER 6 RESULTS

The differences in road morphology and drainage characteristics between the New Pipeline Road and the Old Pipeline Road in its decommissioned condition are shown in figures 11 to 13. The new road is substantially further from the stream but has larger segment areas (fewer drains per length of road) than the Old Pipeline Road prior to decommissioning. The lengths of concentrated flows below drain outlets are greater on the new road. Although these figures are useful in describing the morphology of the two roads, they are not in themselves sufficient to describe road/stream connectivity. The greater mean distance of the new road from the stream will reduce connectivity but this improvement will be negated to a degree by the larger segment areas contributing to each drainage outlet. The statistical modelling presented above was required to objectively calculate the summed connectivity of each segment of the roads.

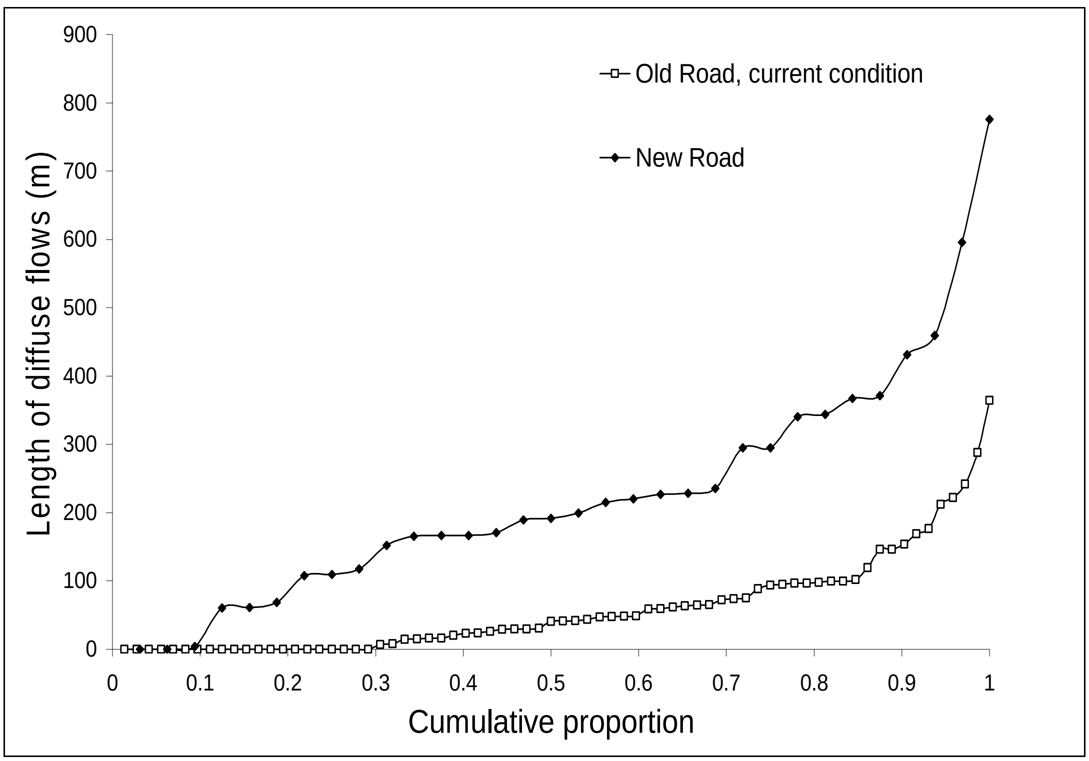

Figure 11. Length of hillslope available for flow infiltration.

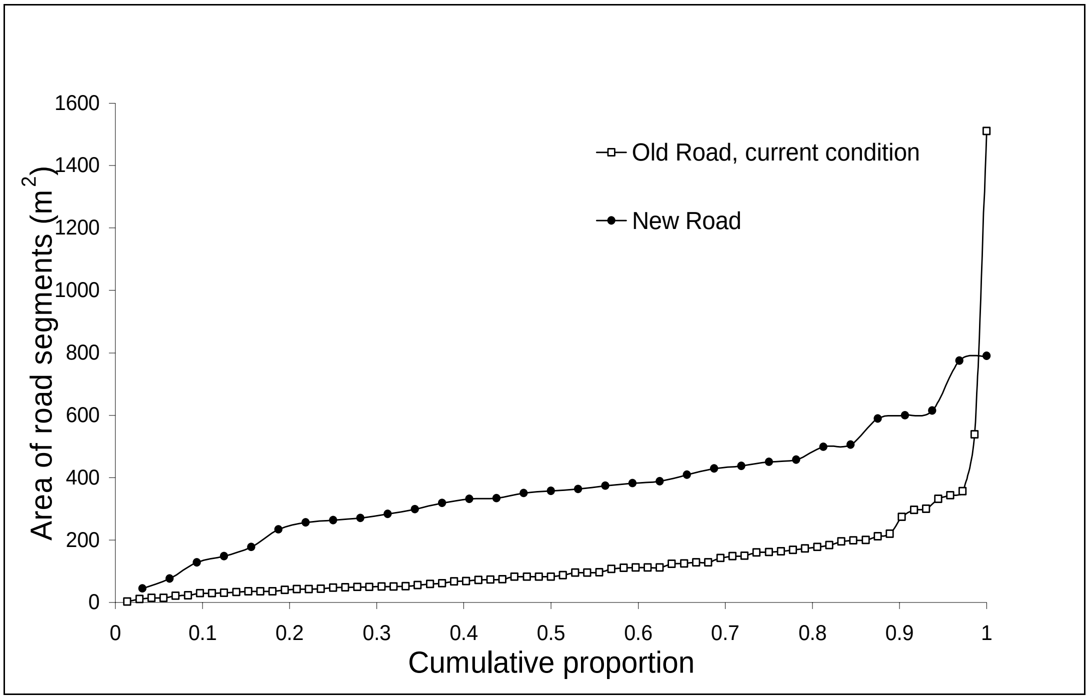

Figure 12. Cumulative frequency plot of road segment areas for the Old Pipeline Road and new sidecut road.

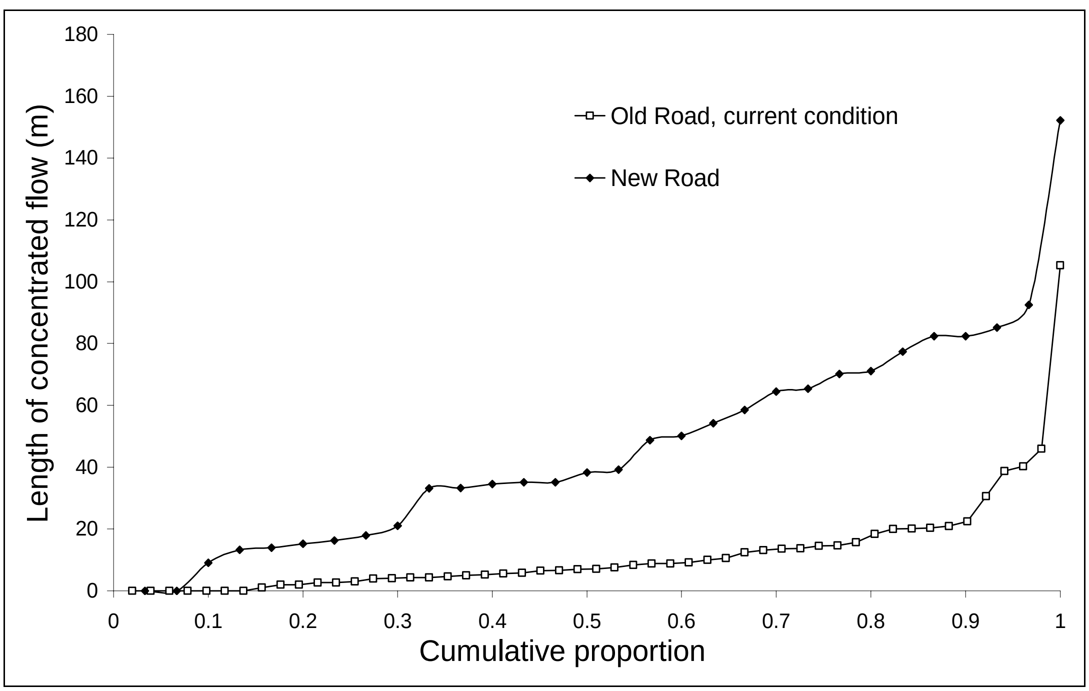

Figure 13. Length of concentrated flow (gullied or intermittently gullied) from road segment drain outlets.

The degree of connectivity between roads and the stream can be assessed for a range of rainfall magnitudes. This study used a characteristic event likely to be associated with infrequent contribution of sediment that is a large component of long term sediment loads. The arbitrary use of a two hour duration 1 in 5 year event for the nearby station of Canberra gives a rainfall total of 35.8mm (Griffith University, 2004; Pilgrim, 1987).

To illustrate the concept of connectivity, figure 14 shows the proportional connectivity of New Pipeline Road, made up of no directly connected segments, seven diffusely connected segments and fifteen unconnected segments. The width of each column represents the area of the segment as a proportion of the total road area and the column height represents the mean proportion of flow leaving the road segment that is expected to reach the stream as calculated by equation 8. The error bars show the 90% confidence limits of the prediction for that individual segment. The statistical treatment of the predictions assumes that road segments are independent. Note that some road segments have a mean connectivity of zero, but uncertainties that extend into positive values.

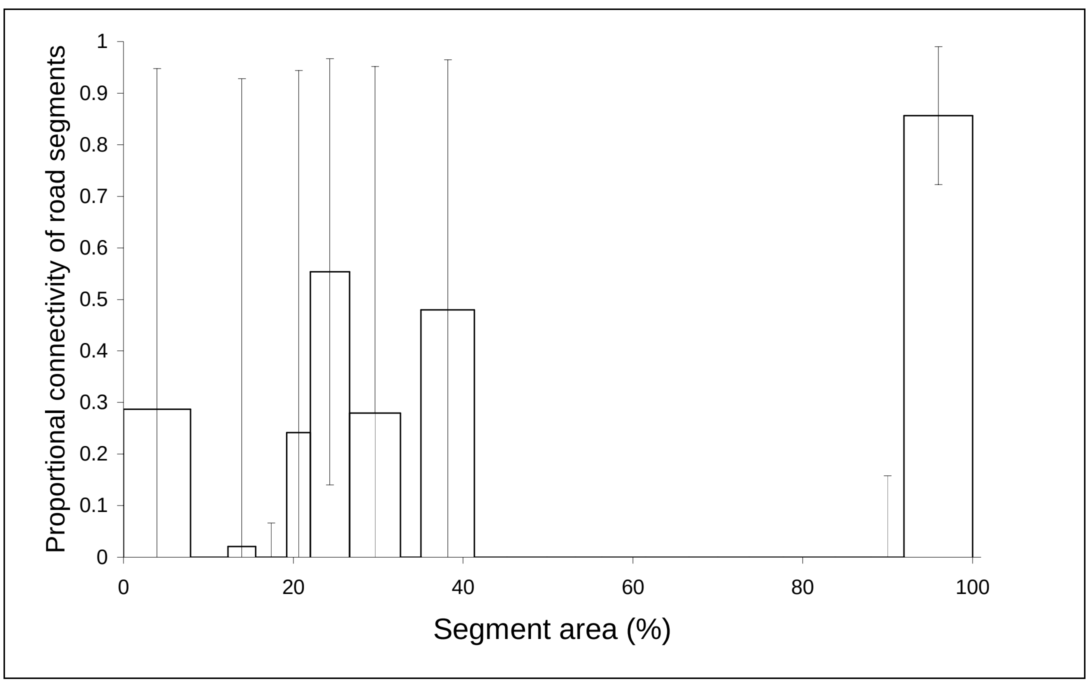

Figure 14. Connectivity of individual road segments along the New Pipeline Road

Figure 15 shows the individual connectivity of all road segments on New Pipeline Road, East West Break and the decommissioned Old Pipeline Road. The figure is presented in such a way that the graphed segments are arranged in their order along the roads and can be directly related to the road map. It can be seen that the new road (including the extension to East-West Break) contains only three directly connected segments near the intersection with Old Pipeline Road, but has several large partially connected segments at each end of New Pipeline Road. The decommissioned Old Pipeline Road however has a large number of directly connected segments where gullies have reached the stream, but the sections are less well connected at each end of the road.

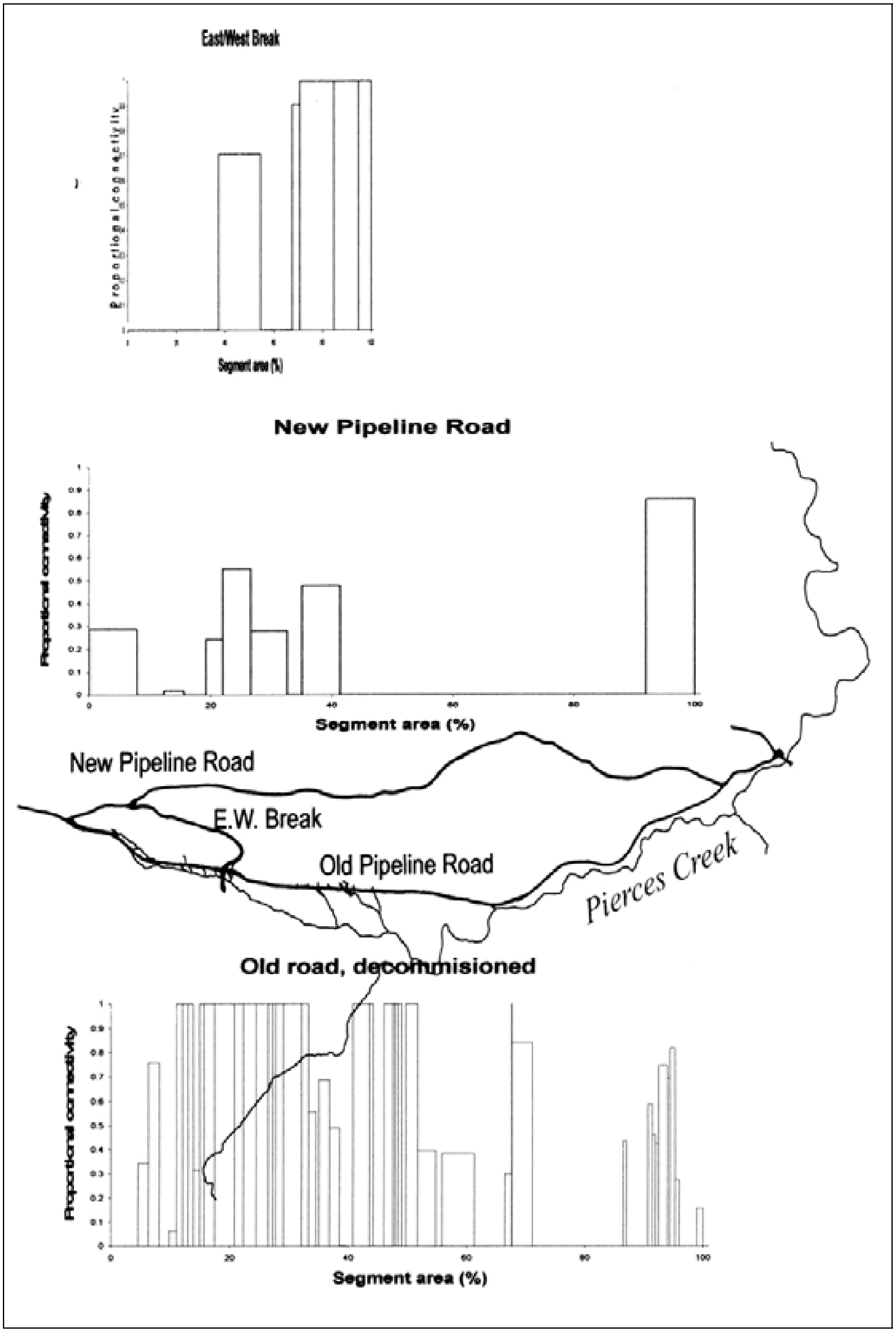

Figure 15. Road segment connectivity, related to geographic position

The mean connectivity of Old Pipeline Road is displayed in figure 16 in terms of the proportional connectivity of the cumulative road surface area. This figure shows the connectivity of the road in its pre-decommissioned state, in its current condition and in the 'best practice' design state, if the road surface had been successfully segmented at each of the cross-bars constructed. Although the mean connectivity of the decommissioned road in its current condition is slightly less than it was prior to decommissioning, the difference is not significant within a 90% confidence range. The cross-bars constructed as part of the decommissioning were built primarily to deter vehicular access, but if these had been designed to remove water from the road surface (the "potential" curve) then significant improvements in connectivity could have been attained.

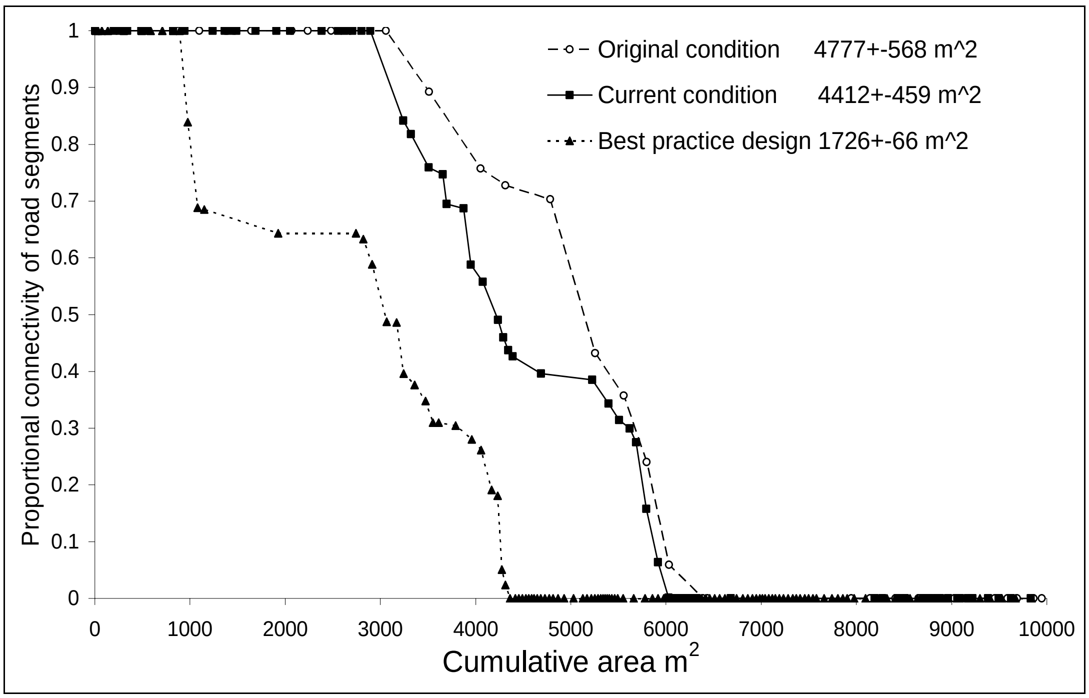

Figure 16. Cumulative road area shown in relation to mean proportional connectivity for the Old Pipeline Road under three management scenarios.

Figure 17 shows the mean connectivity of four different road scenarios:

1) The old road in its original, pre-decommissioned condition,
2) The new road alone (assuming total prism removal of the old road, reducing its connectivity to zero),
3) The combined connectivity as the old road and new road currently exist, and
4) The combined connectivity assuming effective segmentation of the old road.

The smaller area under the line representing the new road shows it to be much less connected than the pre-decommissioned old road, but even if the decommissioning had fully segmented the old road the overall improvement (comparing the two road potential with the pre- decommissioned road alone) is not significant. The combined roads as they currently exist show significantly greater connectivity than the pre-decommissioned road alone.

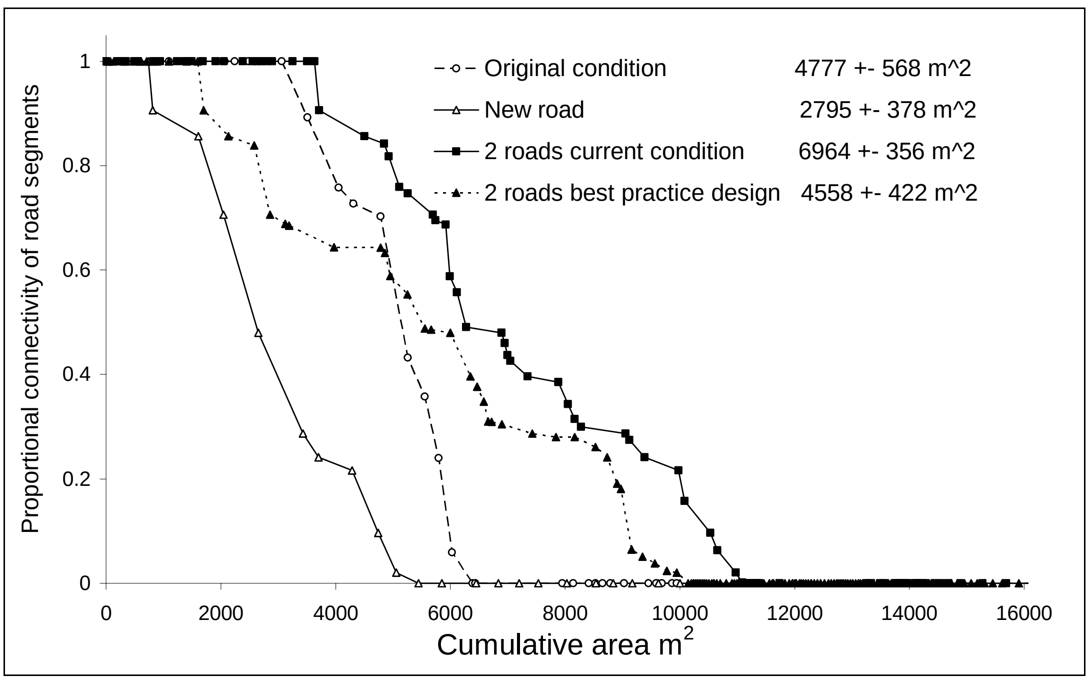

Figure 17. Cumulative road area shown in relation to mean proportional connectivity for four road management scenarios.

Connectivity results for several road situations for different rainfall events are presented in figure 18. Uncertainty ranges are for a 90% confidence interval. The results for a 35.8mm rainfall event are effectively the areas under the curves in figures 16 and 17.

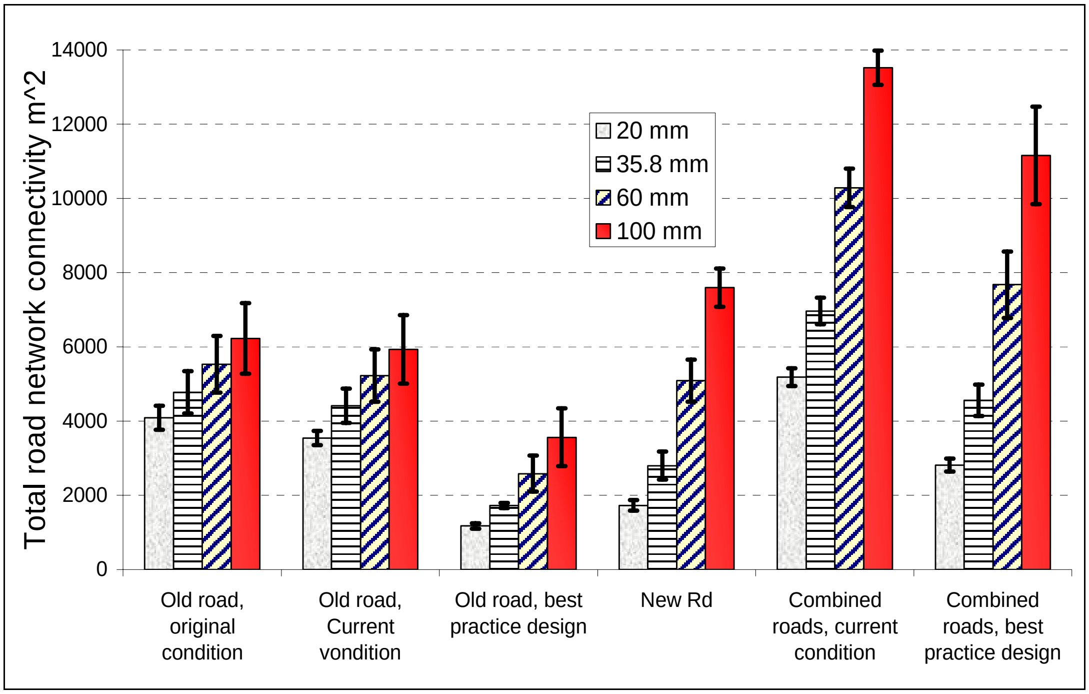

Figure 18. Summary of connectivity variations in relation to rainfall amount and road management scenarios.

For small rain events of 20mm or less, the decommissioning as it was carried out has marginally reduced the connectivity of Old Pipeline Road. Although under larger rainfall events the mean connectivity is slightly lessened, the difference is not significant within a 90% confidence interval. If the cross-bars had all been constructed to effectively shed water from the road surface rather than simply as vehicle barriers then a connectivity improvement for this road at all rainfall levels could have been achieved.

New Pipeline Road is less connected to the stream network than the original Old Pipeline Road under low rainfall events, due to its greater distance from the stream. Under greater rainfalls however, the greater length (and hence greater surface area) of the new road results in higher connectivity than the original road. This is illustrated in figure 19, showing how the gains from having less directly connected segments are offset at higher rainfalls by the increased area of diffusely connected segments.

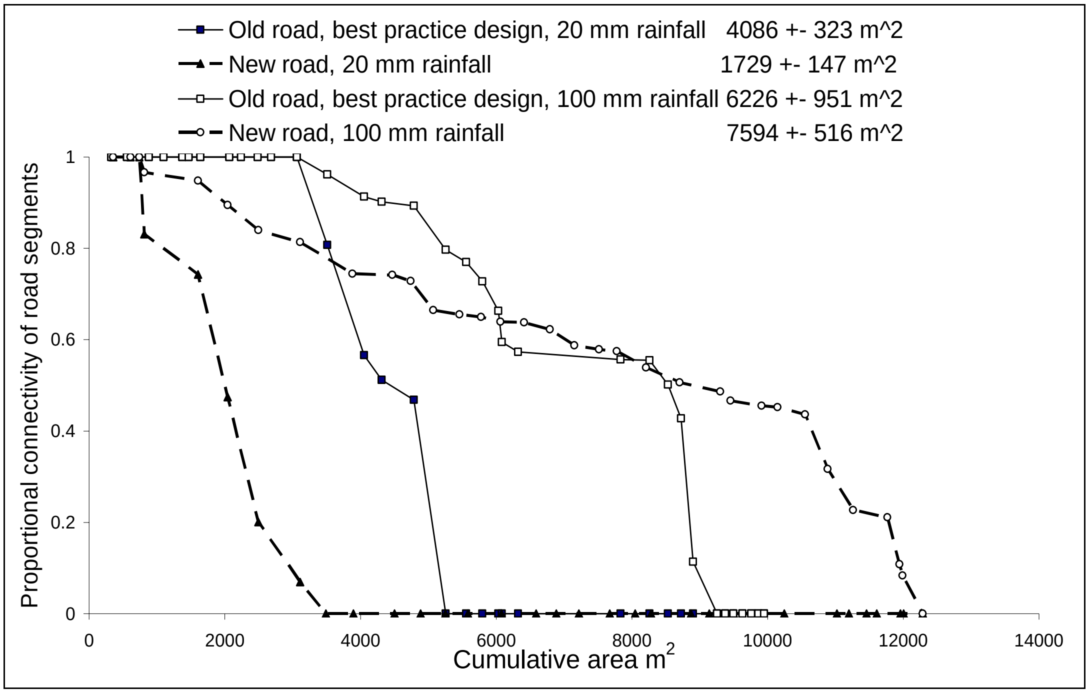

Figure 19. Variations in area of specific connectivity for two rainfall intensities.

Comparing the old road in its pre-decommissioned condition with the combined two-road situation currently present shows that connectivity is increased at all rainfall levels. Even if the old road had been fully segmented then improvements would only be apparent under low rainfall events.

CHAPTER 7 DISCUSSION

7.1 MODEL UTILITY

Although several models exist for the prediction of road-derived sediment production and delivery (Merritt et al. 2003), they suffer from the practical disadvantage of being highly parameterised, requiring a large number of input variables and parameters which are often difficult to obtain or accurately estimate (CRC for Catchment Hydrology n.d.). Sediment delivery predictions in some models have been found to be highly variable in some instances, depending on the level of geometric detail chosen in modeling roads (Rhee et al. 2004).

The probabilistic model of Hairsine et al. (2002) uses easily obtainable data to estimate the volume of road runoff delivery to streams, accounting for natural environmental variation through the calculation of uncertainty ranges around the mean results. Although for individual road segments these uncertainties are unworkably large, the results presented here show that where the individual results are summed over a road length, the uncertainty is reduced to a level sufficiently precise for evaluating different management options. This demonstrates the value of the model in dealing with the competing factors influencing road connectivity.

7.2 RAINFALL EVENT SELECTION

The selection of rainfall events in this dissertation is somewhat arbitrary, but they are within the range of flows used to develop the vbt5 dataset. The useful comparison of connectivity across different road locations or designs demands consistency and a rainfall value must be selected that is in keeping with the purpose of the connectivity assessment. Where chronic stream turbidity levels under low flows are of primary concern it would be appropriate to assess connectivity related to small rain events. Conversely, if flood-flow stream sedimentation is the major issue then connectivity should be calculated for large events. In the absence of defined concerns, this study suggests that a design rainfall event be chosen consistent with the road design parameters used by local forest services and a duration of two hours. In the Australian Capital Territory this method gives a 35.8mm event (AUS-IFD).

7.3 MODEL VALIDATION

Although the model developed here has not been validated in any formal sense (such as measured field trials), there are reasons to have confidence in its applicability across a range of environments. The vbt5 model at the heart of this study was developed across a range of hillslopes and surface conditions, and similar figures to those obtained by Hairsine et al. (2002) were found by Lane et al. (2006) using different methodology in an independent study in a different area. Lane et al. (2006) concluded that the vbt5 model is appropriate for predicting connectivity in a range of forested environments.

The vbt5 based modelling used in this paper produces results that compare well with those produced through more complicated models. Costantini et al (1999) simulated runoff plumes from two plots in south-eastern Queensland using the Areal Non-point Source Watershed Environmental Response Simulation model (ANSWERS), with an input hyetograph and surface infiltration assumption corresponding to a 30 mm rainfall. The Toolara site had a slope of 6% and the Imbil site 30%. Four simulations were run at each site, for conditions of ‘wet’ and ‘medium’ antecedent moisture and ‘rough’ and ‘smooth’ surface conditions. All of Constantini’s results fall within the 90% confidence range of the prediction produced by vbt5 modelling, as shown in figures 20 and 21.

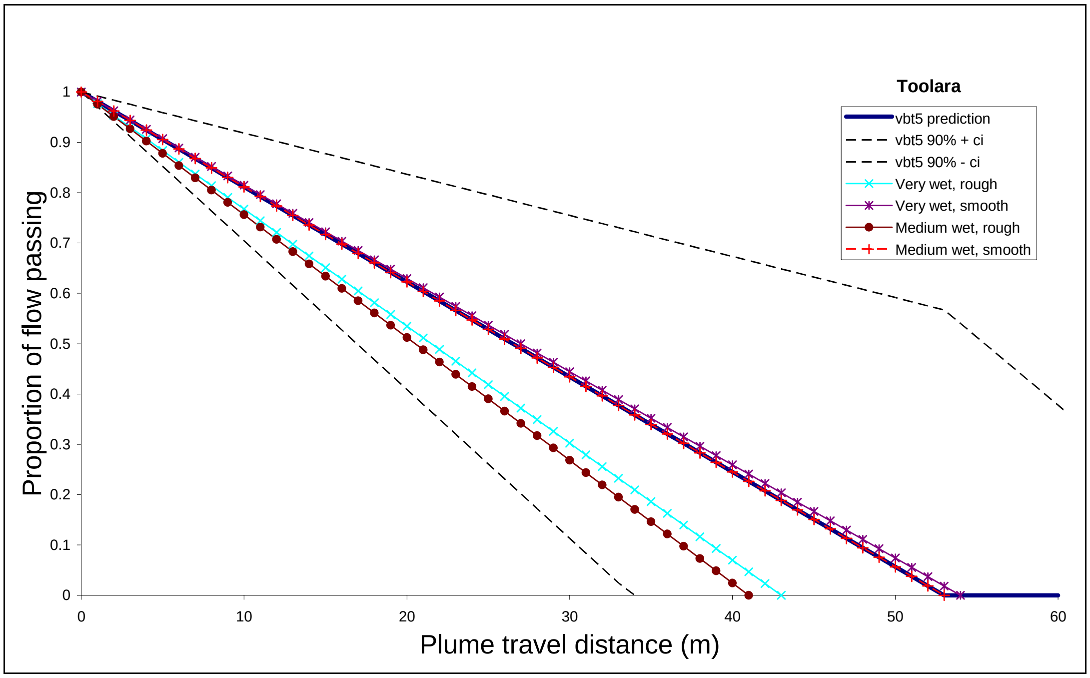

Figure 20. Comparison of vbt5 predictions to Costantini's (1999) runoff plume simulations at Toolara.

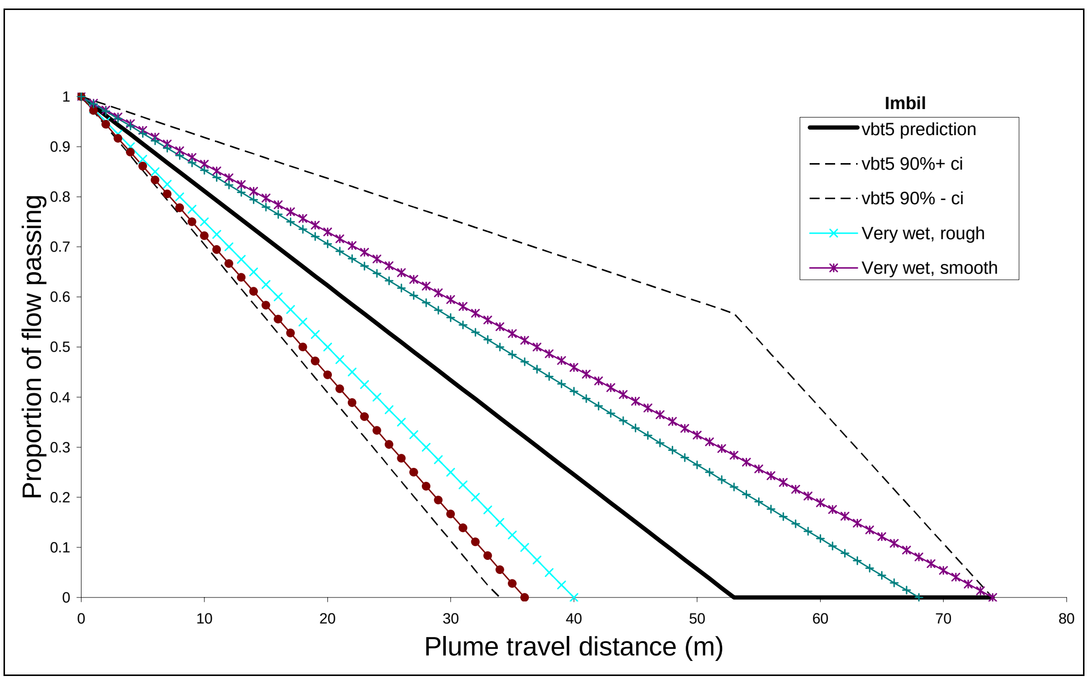

Figure 21. Comparison of vbt5 predictions to Costantini's (1999) runoff plume simulations at Imbil.

US studies into forest road drainage plumes appear to have focused on observed sediment deposition, rather than total diffuse flow distances. Those studies are certainly relevant to stream sediment delivery, but fail to pick up the finer sediments or chemical contaminants that may not be deposited. None the less, parallels may be drawn between the two approaches by assuming a linear relationship between sediment deposition distances and total flow distances, justified by the linear nature of the vbt5 model. While it is recognised that this comparing of incompatible studies is not a rigorous approach, it does however demonstrate that the vbt5 model can give results analogous to other methods.

In a study into sediment plumes from logging roads in Alabama and Georgia Grace (2005) formulated the empirical equation

$$PL = 26.9 - 0.28(R_l) + 0.16(R_l R_w) - 0.80(R_w{}^2) \qquad (19)$$

where PL is predicted length of visible deposited sediment plume (m),
R_l is road segment length (m), and
R_w is road segment width.

This formula was applied to the road segment data collected from New Pipeline Road, the decommissioned Old Pipeline Road and the Razorback Track. Figure 22 displays the results, along with a line *Lpred/5* created by dividing the total plume length predicted using the vbt5 model by 5. Visually, the fit between the two results is remarkably good, implying that a consistent relationship between observed sediment deposition distances and total plume lengths is plausible, although the assumption that that relationship is simply linear is speculative.

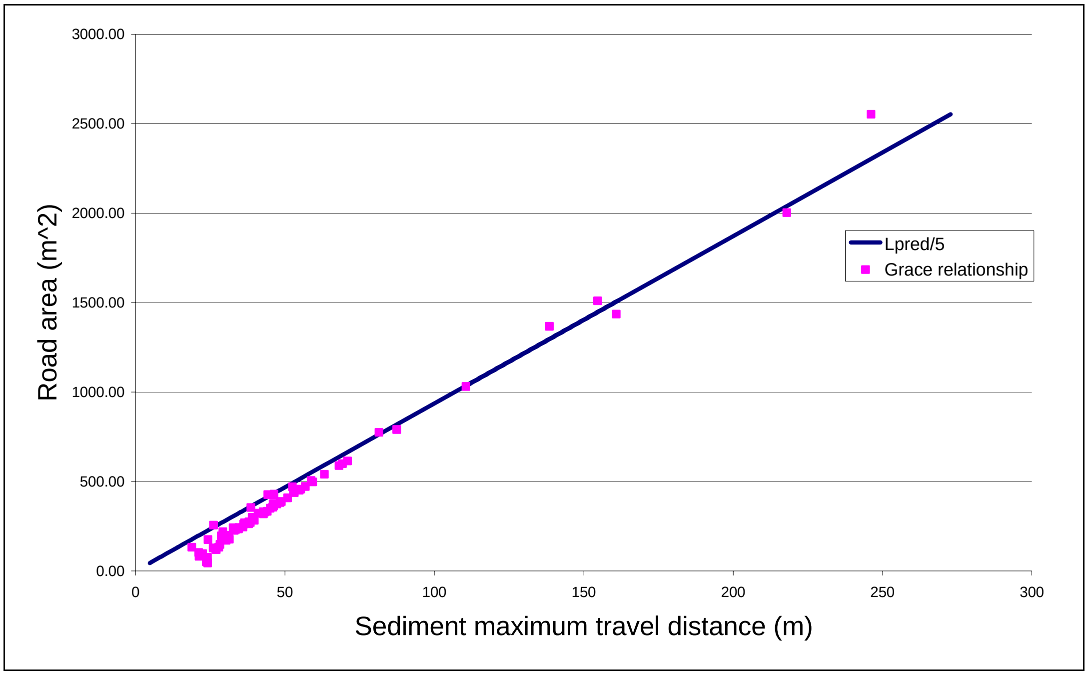

Figure 22. Comparison of vbt5 predicted plume length with sediment deposion relationships observed by Grace (2005).

Figure 23 compares the pattern of sediment deposition distance exceedence probability implied from the Pierces Creek site to that from two Idaho studies. Ketcheson and Megahan (1996) reported that sediment plume length from cross drains followed a log normal distribution and could be expressed as;

$$PL = 17.76 - 46.43\ln(N) \tag{20}$$

where N is the exceedence probability of the event.

Ketcheson and Megahan (1996) also presented the results of an earlier study by Burroughs and King (1989), but did not give the relationship.

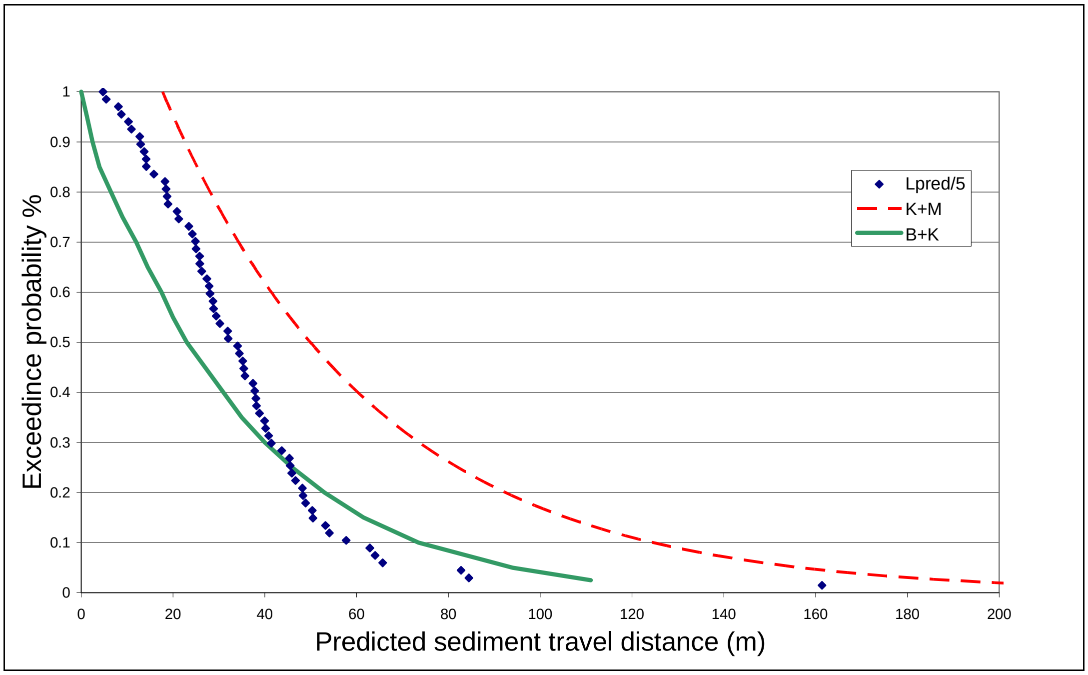

Figure 23. Comparison of vbt5 predicted plume lengths with trends of observed results from two US studies.

CHAPTER 8 FUTURE DEVELOPMENTS

8.1 MODEL VALIDATION

For a full and rigorous validation of the model, the vbt5 methodology of Hairsine et al. (2002) could be repeated at the Pierces Creek study site. A further series of similar experiments across a variety of different slopes, soil types and surface/vegetation conditions would either increase confidence in the validity of the vbt5 approximations or allow for modifications to be made to suit particular conditions.

The comparisons with other sediment plume studies in Chapter 7 are still somewhat speculative, and need a more rigorous approach. A thorough literature search may uncover further relevant studies, and approaches to the authors of the more recent papers may give access to unpublished data that would be of use. In particular, the assumption that 'observed sediment deposition' is linearly and consistently related to overall runoff plume length needs to be tested, both mathematically and physically.

8.2 STATISTICAL ASSUMPTIONS

Although the 90% uncertainty ranges developed in this paper are within workable bounds, further development of the statistical treatment of the volume to breakthrough data may allow uncertainty to be reduced. In particular, the assumption that negative probabilities be treated as zero may be provably false, thus allowing the summed uncertainties to be reduced below those presented here.

The simplifying assumption that the uncertainty associated with zero flows reduces linearly is a slight underestimation, because it cannot be stated with certainty that there will be zero flow at any given distance. As this effect will be most pronounced at very small uncertainties, in practice this assumption will have little impact on the summed results. Nevertheless, for mathematical rigour this aspect of the statistics could be improved.

8.3 TOOL CONSTRUCTION

Many of the software procedures developed in this study were labour intensive, and could be streamlined to construct a set of tools for future road/stream connectivity work. Much of the ArcGIS operation could be encoded into a set of Visual Basic scripts, and the Excel spreadsheets used could be formalized into a tool useable by future researchers or forest managers. ACT Forests and CSIRO have expressed an interest in such a tool, but time has not permitted its construction.

CHAPTER 9 CONCLUSIONS

9.1 PROJECT FINDINGS

Using the context of assessing different road decommissioning and relocation works, this dissertation has further developed the road/stream connectivity model of Hairsine et al. (2002) to permit the calculation of a road/stream connectivity index with an associated uncertainty range. Quantifying road/stream connectivity allows for comparison between different roads or road decommissioning options and also identifies individual road segments that may be of concern. The statistical treatment of the model prediction uncertainty gives a level of confidence in the predictions that is appropriate for management or design purposes, without the need for extensive model parameterisation. The natural heterogeneity of the land surface and differing soil infiltration characteristics are accounted for through the probabilistic nature of the volume to breakthrough model.

This study found that the net result of the decommissioning works was a higher hydrologic connectivity between the road and stream networks at all rainfall volumes. The new road constructed in the mid-slope position was less hydrologically connected to the stream than the old valley floor road under light rainfalls, but more connected at higher rainfalls due to its greater segment lengths and greater overall road surface area. The decommissioning process was less effective than it could potentially have been, due to a less than complete segmentation of the road surface. The degree to which these conclusions transfer to other sites will depend on the morphology of the particular road network in question and the effectiveness of the decommissioning methods. Although the findings in this dissertation are site specific, mid-slope roads are quite often longer than the roads originally constructed on more level ground nearer to streams.

The procedures presented here provide a relatively simple means of analysing the likely changes in road/stream connectivity resulting from road decommissioning or relocation projects.

9.2 CONDUCT OF PROJECT

Overall, the study met the requirements set out in the Project Specification (attached as Appendix A).

1) Hydrological connectivity has been defined here as "A measure applied to a stretch of road that denotes how much runoff water from the road surface will enter a stream network, expressed as the equivalent area of directly connected road surface. (Chapter 5.3.6).

2) Hairsine et al.'s (2002) 'vbt5' model was adapted to predict the likely connectivity of road surfaces in the study area (Chapter 5).

3) Data collection and field survey details are contained in Chapter 4.2.

4) GIS procedures were developed in Chapter 4.3. Spreadsheet procedures were a straightforward application of the mathematics developed in Chapter 5 to the tables produced in the GIS.

5) Results of the study are outlined in Chapter 6, with conclusions above in Chapter 9.1

Time did not permit the development of automated software procedures, but comment is made on these in Chapter 8.3

The project was only possible due to the support and encouragement of the project sponsors, CSIRO Land and Water Division and ACT Forests. Resources utilized throughout the study are listed in Appendix C.

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APPENDIX A PROJECT SPECIFICATION

University of Southern Queensland
Faculty of Engineering and Surveying

ENG4111/4112 Research Project

PROJECT SPECIFICATION

For:	**Chris Eastaugh**, s/n 0031240008
Topic:	Forest Road Decommissioning: Modelling the Effect on Hydrological Connectivity
Supervisors:	Dr Armando Apan, USQ. Dr Peter Hairsine, CSIRO Land and Water, Canberra.
Project Aim:	To assess the effectiveness of recent road decommissioning and relocation works in Canberra's water catchment, in terms of the amount of runoff water generated on the road surface that reaches the stream network.
Sponsorship:	Commonwealth Science and Industrial Research Organisation, Land and Water Division
PROGRAMME:	**Issue B, 28 February 2006**

1) Develop a formal definition of hydrological connectivity, based on previous work and the need for quantification.
2) Research, adapt or devise a method of predicting the likely hydrological connectivity of a length of forest road.
3) Collect all relevant documentation and data available pertaining to the case study area, and carry out a comprehensive GPS field survey.
4) Research, adapt or develop GIS and spreadsheet procedures to process the GPS data.
5) Compare the connectivity of the case study roads, and assess the likely impact of the works on sediment delivery to the stream network.

As time permits: Streamline or automate procedures for rapid appraisals of prospective forest road works.

APPENDIX B DECOMMISSIONING WORKS PLAN

ACT Forests
ACT URBAN SERVICES

Site Specific Road Works Plan - ACT FORESTS No. P14/04-05

1. Location

Land tenure:	ACT Forests	**Road name:**	Old Pipeline Road
Forest:	Pierces Creek	**Section:**	
Road section: From:	New Pipeline Rd (North)	**To:**	New Pipeline Rd (South)
Crossing reference(s):	N/a		
Site description:	Old Pipeline Road runs adjacent to Pierces Creek and Dry Creek. Due to it's location adjacent to Pierces Creek it is aroad of high environmental impact. A replacement road has been constructed and the old road is now surplus to requirements and needs to be closed and rehabilitated as part of ACT Forests strategy of removing high environmental impact roads.		

2. Activity

Description of works:	Old Pipeline Road needs to be closed and rehabilitated. Generally the road needs to be breached and barred using an excavator. Specific works required at some locations are described below. During works, the excavator should ensure that it remains as far as possible from the creek. Where culverts are removed, the trench should be rounded to form a drain and rock from the headwall used to create scour protection.
Point 1	Remove culvert
Point 2	Leave culvert in place & install drop down and scour protection
Point 3	Remove 600mm dia plastic culvert
Point 4	Remove 600mm dia plastic culvert
Point 5	Bar box-cut off with herring bone bars (see Attachment One)
Point 6	Remove 600mm dia plastic culvert
Point 7	Remove 600mm dia plastic culvert
Point 8	Remove 450mm dia plastic culvert
Point 9	Remove 600mm dia plastic culvert and 300mm dia concrete culvert
Point 10	Remove 450mm dia plastic culvert
Point 11	Remove 600mm dia plastic culvert
Point 12	Remove 450mm dia plastic culvert
Point 13	Remove 450mm dia plastic culvert
Point 14	Bar box-cut off with herring bone bars (see Attachment One)

NOTE: After culverts are removed, trench left should be reshaped to approximate the shape of the natural drainage feature above the road and tie in with drainage below the road.

Length/scope of works: Approx 2.2km of road to be closed & rehabilitated

Justification for works: New Pipeline Road has been constructed to allow Old Pipeline Road, which is located close to the creek, to be closed. Rehabilitation of the road will stop traffic and allow vegetation to reestablish reducing sediment entry to Pierces Creek.

3. Site map and diagram

See attached map.

4. Site safety plan

See Attachments

5. Protection of site-specific values

Risk element	Description and Mitigation measures
Soil erosion & water pollution	No spoil resulting from this operation should be desposited in a way that would allow it to wash into Pierces Creek.
Significant threatened species, population or community	N/a
Significant cultural heritage	Cultural heritage sites are marked on the map. All are of low significance.
Other	N/a

6. Costings and materials

Item	Units	Unit cost	No. Units	Total cost	Comments
Excavator	hours	$90	50	$4,500	
Hiab Truck	hours	$70	20	$1,400	
Estimated Cost				$5,900	

8. Plan approval

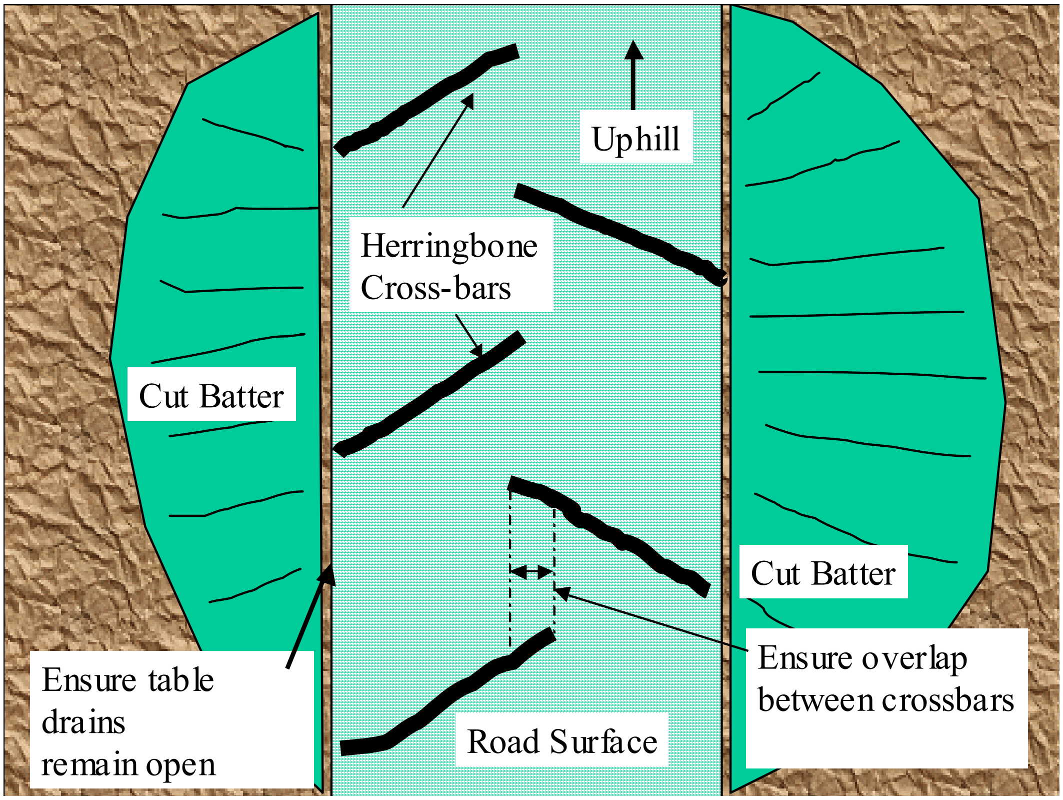
Prepared by:	Stephen Rymer		Position:	Senior Forester	Date: 3 May 2005
Approved by:			Position:		Date:
Contractor:			Compan y		Date:

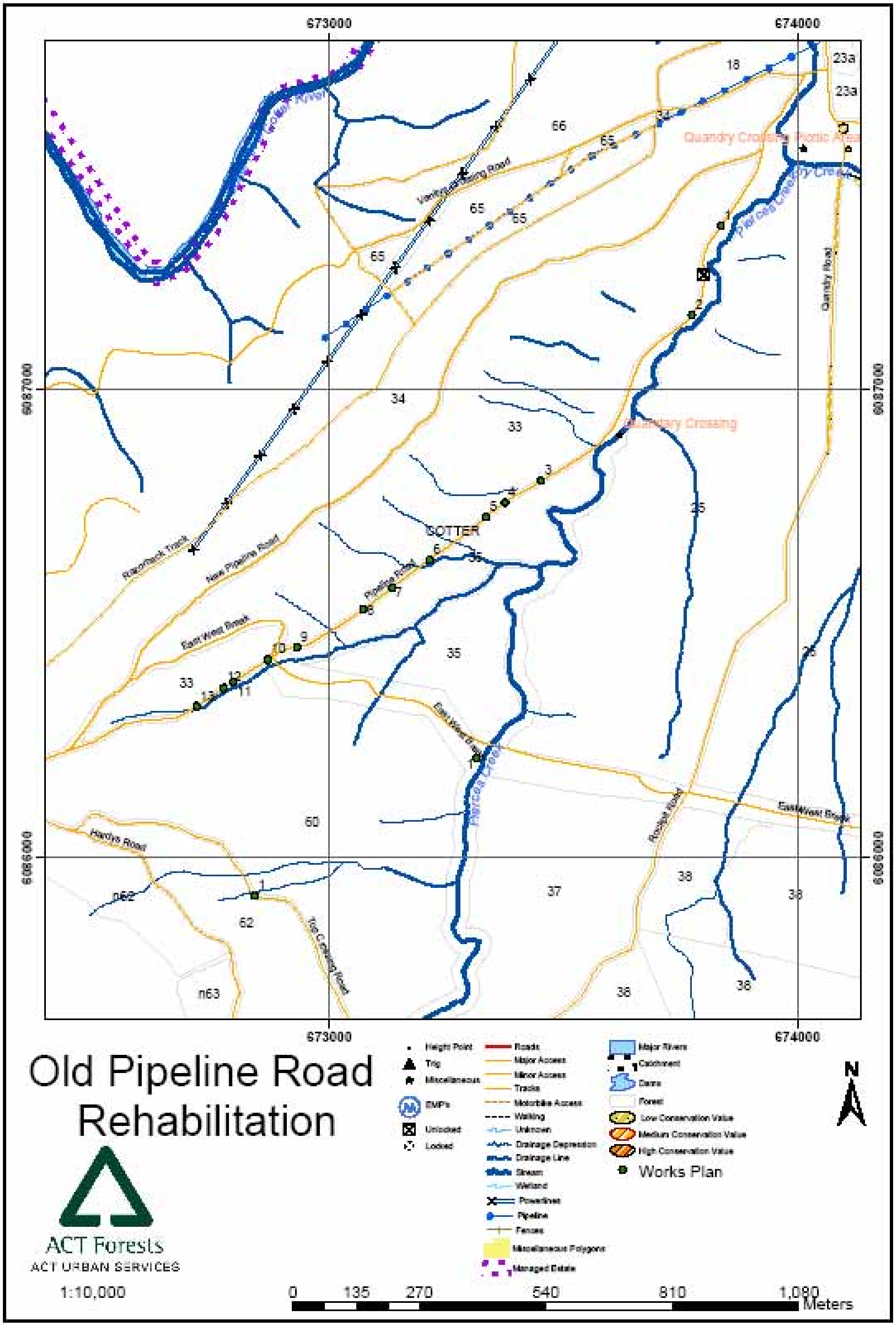
9. Changes to Plan

10. Implementation and outcome recording

1 Supervisor job diary (attachment 1)
2 Assessment of outcome
3 Assessment of effectiveness of mitigation measures
4 Pre and post works photographs

ATTACHMENT 1 – DIAGRAM OF HERRINGBONE CROSSBAR INSTALLATION




673000
674000
6087000
6086000
Quandary Crossing Picnic Area
Quandary Crossing
Pierces Creek
Quandary Road
Razorback Track
New Pipeline Road
Pipeline Road
East West Break
Hardys Road
Trig Crossing Road
Vanitys Crossing Road
COTTER
Old Pipeline Road
Rehabilitation
ACT Forests
ACT URBAN SERVICES
1:10,000
0
135
270
540
810
1,080
Meters
Height Point
Trig
Miscellaneous
BMPs
Unlocked
Locked
Roads
Major Access
Minor Access
Tracks
Motorbike Access
Walking
Unknown
Drainage Depression
Drainage Line
Stream
Wetland
Powerlines
Pipeline
Fences
Miscellaneous Polygons
Managed Estate
Major Rivers
Catchment
Dams
Forest
Low Conservation Value
Medium Conservation Value
High Conservation Value
Works Plan
N

APPENDIX C RESOURCES UTILISED

Field work required the use of a differential GPS, a works vehicle, portable communications radio, first aid kit and personal safety equipment. A CSIRO staff member assisted with field work. To analyze the data, a computer with a high level GIS package was needed. Access to a comprehensive reference library was also required

The following items were available from CSIRO, but needed to be booked in advance:

Trimble 4800 DGPS
Toyota Landcruiser troop carrier
Uniden UHF radios
First aid kit
Fieldwork partner

The following items were issued for the duration of the summer scholarship:

Dell desktop computer
ArcGIS 9.0 with '3D Analyst' and 'Spatial Analyst' extension
Access to a CSIRO Black Mountain library and electronic journal subscriptions

Personal safety equipment was issued by ACT Forests.

Further library resources were available through USQ library.