Influence of Unpaved Access Roads on Surface Runoff, Sediment Loss and Soil Water Movement within Forest Plantations

Report to the
WATER RESEARCH COMMISSION

by

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Executive Summary

1. Background

Forestry access roads are an integral component of the infrastructure needed to carry out the core functions of managing a commercial plantation. Compared to surrounding undisturbed forested land roads forestry roads are hydrologically active areas as they are compact and frequently denuded of vegetation. Road networks have frequently been cited as the leading cause of sedimentation to water courses and therefore forestry managers must continually strike a balance between limiting off-site damage caused by roads and preserving the functionality of the road network. This project concerns itself with unpaved forestry roads as the general perception is that these roads are highly vulnerable to accelerated soil loss and contribute substantially to the sedimentation of water courses. Although several studies have been presented in the literature on the impact of unpaved forestry roads on soil and water resources a large percentage of these have been conducted outside South Africa, particularly the Eastern United States and Australia. The principles and mechanism of accelerated soil loss and runoff production from forestry access roads developed in these studies are universal but the challenge remains in adopting these results to our local context given the differences in climate and geography. Furthermore, studies on forestry access roads have been often been conducted using rainfall simulators which deliver high intensity simulated rain over a small area over a short period. Local data regarding soil loss from unpaved roads (even that external to forestry) under natural rainfall is incredibly sparse and upscaling of rainfall simulation studies to larger areas and different climates frequently meet with challenges due to the absence of corroborative information against which to gauge the predictions.

As the forestry industry in South Africa increases its commitment towards self regulation and governance it becomes increasingly important that reliable and realistic estimates of surface runoff generation, erosion and transport of sediment from forestry access roads are available. This is the first and necessary step in the development of sound road management programmes and defensible policies, and forms the basis upon which this study was realized.

2. Aims and Objectives

The specific aims of the study were to:

- Evaluate the direct contribution of unpaved forestry access roads as a potentially ready source of runoff and sediment through physically based on-site measurements at the plot and road segment scale.
- Evaluate the significance of access roads in altering subsurface flow pathways within hillslopes.
- Measure off-site impacts of runoff with particular attention to erosion and sedimentation of adjacent drains.
- Based on the findings of the study, to suggest simple criteria and procedures for identifying potentially problematic segments of roads during the planning and/or development stages.
- Based upon the findings of the study, evaluate the potential for improving the current practice of redirecting road runoff to individual forestry compartments and identify critical parameters such as road, layout and geometry, soils and geology, regional rainfall intensity and frequency that could

influence the efficiency of this process.
- Investigate the applicability of current numerical models to predict runoff and sediment from forestry access roads.

3. Methods

Following a workshop with key role-players in the forestry industry, a decision was made to carry out the study within a Eucalyptus plantation. Site selection criteria were applied to Mondi's Geographic Information System (GIS) which identified the Seele Estate in the New Hanover district of KwaZulu-Natal as a potential study site which was selected after several field visits.

Rainfall was measured at two sites in the area using automatic tipping bucket raingauges. This was supported by a network of manual raingauges that were strategically positioned in the vicinity of the plots. Sixteen unbounded runoff plots, approximately 24 m in length, were constructed across a range of road gradients using customised concrete gutters for the upper and lower boundaries. Runoff and sediment from these plots were directed into a stilling well wherein the sediment was separated out and the water piped to a tipping bucket mechanism that was also customised for this study. A datalogger recorded the timing of the tipping of the bucket which when applied to a calibration relationship provided an estimate of surface runoff. Sediment from the lower gutter and stilling well was collected during each site visit. This was weighed, air dried and its particle size distribution measured.

Water that infiltrates the soil surface upslope of roadcuts has been shown in past studies to intersect the road surface and contribute to surface runoff production. This is referred to as infiltrated subsurface flow (ISSF). In order to evaluate the significance of ISSF at this estate soil water content was measured along two hillslope transects using a frequency domain reflectometry technique. One transect was isolated from road network to serve as a control while the other intersected the road network.

The movement of road runoff and sediment through mitre drains was traced by strategically positioning a network of access tubes within the compartment in order to determine the spatial distribution in water content. Measurements of the cross profile of the road network at several locations within the estate were made in 2009 and repeated in 2011 using a fixed point reference technique. This provided an indication of the change in the microtopography of the road surface between the sampling periods. The field based studies supported the assessment and testing of models in order to extend the relevance of the research beyond its site specific conditions. Following an extensive review of potential models the Water Erosion Prediction Project: Road (WEPP: ROAD) model was adopted.

4. Results and Discussion

During the first year of the study attention was focused on developing an understanding of the controls on runoff and sediment production within the estate. This was a valuable exercise as it allowed for the strategic positioning of the monitoring equipment, particularly the runoff plots. Construction of the runoff plots began in early 2009 and was completed by the start of the 2009/2010 summer season. Modifications and refinement to the experimental design took place during early summer and by November 2009 the entire monitoring network within the estate was completed. The study was originally scheduled to be completed in December 2010 but monitoring was extended until April 2011 in order to cover two full summer seasons and so strengthen the database.

Between 23 December 2009 and the 08 April 2011 there were 126 individual rainfall events in the area, which collectively produced 932 mm of rainfall. Individual rainfall events are separated from each other by a period of at least two hours of no rain using the definition of Stocking and Elwell (1976). The majority of rainstorms were of low intensity although a few intense convective thunderstorms were noted. The largest single rainstorm took place on the 26/01/2010 when 43.4 mm of rain fell within a period of 19.8 hours.

As is reported in numerous previous studies this study confirmed that relative to the surrounding undisturbed land, forestry access roads are highly compact, have high soil strength, low infiltration rates and is frequently denuded of vegetation. Infiltration rates on several road sections were found to be almost ten-fold lower than the surrounding undisturbed soil. This decreased infiltration leads to an increase in surface runoff.

The coefficient of runoff, which is the ratio of runoff to rainfall varied markedly between the different plots and ranged between 9 to 30%. Regression of this parameter with gradient showed a weak R^2 of 0.212. Surface runoff was, however, better predicted by rainfall and an R^2 of 0.416 was obtained. Sediment loss from each plot was positively related to gradient and an R^2 of 0.368 between these two parameters was obtained. Three plots which had markedly higher vegetation cover had a strong influence on this relationship. Exclusion of these plots from the analysis showed a marked in the strength of the regression relationship. This suggested and was further corroborated from field evidence, that local site conditions play an important role in the extent of soil loss from road surfaces. The effect of vegetation apart from improving infiltration rates is to mechanically anchor the soil, thus limiting the detachment and entrainment of material.

The microtopography of the road surface at the various points of measurement changed slightly between 2009 and 2011. The largest change in the road cross profile took place within the wheel tracks, as it is in this section that there is concentration of flow. The technique proved promising as a rapid low-cost method of assessing those areas within a road segment that are active erosion or depositional sites for sediment.

In the three years over which this study was carried out no evidence of ISSF within the study area was noted. Since the soil at the study site was deep and well-drained, saturated soil conditions were never achieved, nor did the roadbed intersect the bedrock surface, which are necessary conditions for ISSF. Differences in the water content of the hillslope along the control transect and that intersecting the road were difficult to detect for probably the same reasons. ISSF may, however, be an important factor that contributes to runoff from road surfaces but this may apply more to bottomland regions or close to riparian zones.

The movement of road runoff and sediment through mitre drains into the forestry compartment was tracked indirectly by measuring the soil water content distribution within the compartment. The results showed that there was a progressive increase in soil water content along the mitre drain and a marked concentration of water albeit in a small area at the drain outlet. This situation also applied to the deeper soil depths but to a marginally lesser extent than near the surface. Although this aspect will clearly need further corroboration and testing perhaps using further supporting techniques such as isotope tracer studies or electrical resistivity sounding it does suggest that sediment and runoff could be contained within compartments through appropriate location and management of mitre drains. Were this objective to be achieved it could have significant benefits in limiting the movement of sediment outside of the catchment. This investigation needs to be carried out in tandem with dedicated studies on catchment connectivity by mapping of sediment delivery pathways.

The field-based studies supported the assessment and testing of numerical models in order to extend the relevance of the research beyond its site specific conditions. Following an extensive review of potential models it became apparent that only a few could deal with spatial information. These were then tested using common datasets and either accepted for further investigation or rejected if they were found to be unsuitable to meet the objectives of the study. Through this elimination process the Water Erosion Prediction Project: ROAD (WEPP:ROAD) model was selected as perhaps the most appropriate but not ideal model of choice for testing within this study. The model performed relatively well despite its limitations of not being able to account for vegetation. Further, the model deals with individual road segments although entire road networks can be considered. The advantage of the model, however, is that it is in the public domain and can be accessed via a set of web-based interfaces. Analyzing the erosion of an entire road with these tools was complex and time consuming as segments are analyzed individually and data is entered manually. The current WEPP road erosion models have not been integrated with GIS, and therefore spatially distributed erosion simulations of road networks were not possible with these models. Therefore what is needed is an assessment of the impact of forestry road erosion for an entire watershed or a complete forest road network using established erosion prediction technology.

An attempt was made to develop a system of classifying the state of degradation of forestry access roads. As it stands this is a highly conceptual framework but has been refined to the stage where it does have some practical relevance, if only to develop a common platform against which to assess the state of individual road segments or road lengths. The potential value of fully developing such a tool cannot be underestimated as it will allow for early identification of those road segments that are at high risk for excessive sediment production and allow for timely management intervention.

5. Conclusions

The study confirmed that compared with the surrounding undisturbed areas unpaved access roads are hydrologically active areas. As roads are an important landscape element, they must be managed in a manner that limits excessive sediment loss yet preserves the functionality of the road infrastructure. A wide range of aspects related to forestry access roads have been covered during the course of the study. The data and field observations, suggest that the key to managing these road networks centers firstly upon the timely identification of potentially problematic road sections and secondly targeting these for corrective action. The conceptual forestry road degradation classification framework developed during this study may serve as a useful tool to achieve this objective.

Given that unpaved roads are usually compact bare areas and accepting that these are going to be high runoff production areas the challenge then is to manage the movement of this water in such a manner that scour and entrainment of sediment is minimised. The study showed that road drainage is an important consideration in this regard and that mitre drains are effective at removing water from the road surface. Field evidence showed that once the sediment-entrained runoff enters the forestry compartment there is a rapid decrease in energy near the exit of the mitre drain. This process is aided by the high organic matter loads on the forest floor which trap and contain the sediment. The goal thus is to manage the process such that the water and sediment is contained close to its source of origin.

6. Recommendations for Further Research

This study was aligned towards understanding the influence of forestry access roads on runoff, sediment production and soil water movement. In the presence of only a few local past studies much of the work has been exploratory in nature and strong reliance had to be made on past international studies for guidance. Techniques and systems had to be refined or adapted to local site conditions and equipment had to be customized to meet the objectives of the study, much of which has been met although perhaps not fully realized from the two years of field monitoring.

The study was conducted under natural rainfall over two full summer seasons. Although an estimate of the rate of surface runoff production and sediment loss from road sections of varying gradient has been provided, a longer monitoring period of verification may be required. Supplementary studies using rainfall simulators may also prove valuable in assessing the timing of runoff and mechanisms of soil dislodgement from the road surface. However, should this take place, it will be important to operate the rainfall simulator at rainfall intensities close to that occurring naturally.

The study showed that water flowing through the mitre drain from the road surface into the compartment may contribute to increased soil water content particularly near the drain exit. This finding is significant as it could influence the manner in which road drainage is dealt with in the future. However, this aspect needs to be further investigated perhaps using a more direct or more sensitive technique. Allied with this is the issue of catchment connectivity, i.e. the movement of water from the road surface to the stream network which has been discussed in the literature but could not be fully evaluated within the current study. Mapping of water and sediment delivery pathways, perhaps coupled with tracer studies, could aid the realization of this objective. At present riparian buffer zones within forestry areas are relied upon to contain sediment. If information on sediment delivery pathways from roads to streams are known then it may be possible to limit the travel of sediment by its management at the source of origin. Optimization of road drainage location and spacing may be a possible method to achieve this. CULSED which is a computer simulation model developed in New Zealand may have potential use in our local context and should be explored.

At present, for the South African situation, combinations of models are needed and one has to adapt the data entry to produce meaningful results. This is by no means ideal and can be a potential source of errors. It is recommended that, rather than 're-invent the wheel', close collaboration with the developers of this software take place and through the source code develop the model to allow for local data entry. In communicating with the model developers during the testing phase it was evident that strong interest in the realization of this objective exists and that they would support such an initiative. To this end the forestry industry is urged to consider this an important relationship worth expanding upon.

7. Extent to which the Contract Objectives Have Been Met

The contract guiding the scope of the scope of the investigation was drafted in principle to address several research needs with emphasis on three key objectives, namely develop an understanding of the extent to which access roads serve as a source of readily available sediment in forestry catchments, evaluate the influence of access roads in the production of surface runoff production and alteration of flow pathways in forested catchments, and test a range of numerical models that could be used by the forestry industry to predict sediment loss and runoff from forestry access roads.

The majority of past research that have quoted rates of sediment loss from forestry access roads have been based on rainfall simulation type studies. While these studies have been valuable in improving the understanding of sediment detachment and transport processes there is considerable uncertainty in extrapolating some of these findings to wider areas due to complexities of scale. Notwithstanding the technical challenges that had to be overcome in the design and operation of the custom-manufactured equipment, an estimate of soil loss and runoff production from forestry access roads under natural rainfall at the plot scale and across a range of road gradients has now been provided. The field results were used as a common dataset against which a wide range of numerical models were tested for their applicability in predicting sediment loss and runoff from forestry access roads. Although not ideal, The Water Erosion Prediction Project: Road model which is accessed via an online web-based interface, was selected as the most appropriate model of choice and provided that the source code can be modified for a wider degree of local data entry this could prove to be a valuable tool that could be adopted by foresters. The research team have been in contact with the model developers who welcome further collaboration in achieving this objective.

Although an improved understanding of the effect of roads on the subsurface movement of water in hillslopes has followed from this investigation, local site conditions precluded an in-depth analysis of the extent to which roads alter natural subsurface flowpathways. Much of the road network at the Seele estate is located on deep-well drained soils and therefore there is limited near-surface lateral movement of water. However, the study did show that runoff and sediment from roads could be managed by redirecting this via mitre drains into the forest compartments for its infiltration and filtration respectively.

Overall, the aims of the study have been achieved although some objectives have been met but perhaps not fully realised. Nevertheless, a valuable dataset has been obtained and improved insight on the influence of roads on sediment production, runoff and soil water movement in forested plantations has been achieved. The principles and techniques adopted during this study and the experience gained is readily transferable to other contexts where unpaved roads form an important and necessary component of the landscape.

8. Capacity Building and Technology Transfer

As increasing pressure is placed on the land to support an ever growing need for social and economic transformation, it is vital that management of finite resources is undertaken from an informed and responsible perspective. Whilst significant strides have been made over the years in the field of catchment management, much of the attention in South Africa, of necessity, has been directed at protecting water quantity, particularly streamflow. Arguably, lesser research attention was devoted to instream water quality as this could be managed or corrected at the point of its abstraction. However, there is increasing realization that instream water quality may be significantly influenced by land use activities. This research project was initiated to understand the impacts of forestry access roads on soil and water resources and is but an example of the multi-disciplinary approach that would be needed to fully understand the complexities of the linkages between catchment and stream. At the start of this project a team comprising personnel with a diverse range of skills and background but common interest in the effects of land use activity on soil and water resources was assembled.

A full account of the capacity building initiatives is given in Appendix 4 but three major approaches were adopted, namely formal student involvement and development, collaborative relationships with international researchers through Professor H.R. Beckedahl and technology transfer via workshops and field days. Five students based their Bachelor of Science Honours (BSc (Hons)) dissertation on selected aspects of the study. Two students registered for a Master of Science degree within the project but only one of them (Ms Kloboso Seutloali) is close to completion whilst the other (Mr Sam Smout) deregistered in favor of joining the job market. Cross-collaborative links were established with the University of Goettingen and the Martin Luther University, Halle, Germany through Professor Beckedahl and researchers from these institutions visited the site in September and November 2008. Ms Seutloali was subsequently hosted by Halle University in 2009.

The research team was fortunate to have enjoyed a good working relationship with Mondi who have shown enthusiasm and active interest in the study. Beyond the informal discussions that took place between the research team and Mondi, two workshops were held during the project namely an inception workshop in August 2008 and a report back workshop in August 2011. On 08 December 2009 the research team was asked to formally showcase the study to Mondi personnel. Representatives from their operational and environmental divisions attended the interactive meeting which was held on site. The project team was further invited during November 2010 to present the findings of the study to Mondi's environmental management forum. This forum meets regularly during the course of year to discuss environmental issues or concerns that influence the forestry industry. The meeting was held at the Seele Estate in New Hanover and was represented by Dr Moodley and Prof. Hill. Beyond this the research team has gained valuable experience and insight on the dynamics of sediment production and runoff generated by forestry access roads. During the course of the study knowledge was refined and generated, hypothesis and intuition were tested and investment in human capital promoted such that capacity was built. Hopefully, the skills developed within this research project are readily transferable to similar applications.

9. Data

All data, in both its original and processed format, and the minutes of the inception and information dissemination workshops have been stored electronically at the Department of Geography, School of Applied Environmental Sciences, University of KwaZulu-Natal, Pietermaritzburg, Private Bag X01, Scottsville, 3209.

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List of Abbreviations

AGNPS	Agricultural non-point source
AHL	Available Hillslope Length
AMC	Antecedent Moisture Condition
ANSWERS	Areal Non-point source watershed response stimulation
CLIGEN	Climate Generator
CULSED	Culvert Locator for Sediment reduction
DEAT	Department of Environmental Affairs and Tourism
DEM	Digital Elevation Model
DHSVM	Distributed Hydrology Soil Vegetation Model
DPI	Department of Primary Industries Forestry
FORECALT	Forest Road Erosion Calculation Tool
FS WEPP	Forest Service WEPP
FSC	Forestry Stewardship Council
GEOWEPP	The Geospatial Interface for the water erosion prediction project
GIS	Geographic Information System
HOF	Hortonian Overland Flow
ISSF	Infiltrated subsurface flow
LASCAM	Large Scale Catchment Model
LESAM	Landscape based Environmental Systems Analysis and Modelling
LISEM	Limburg Soil Erosion Model
MAP	Mean Annual Precipitation
MAR	Mean Annual Runoff
NCT	NCT Forestry Co-operative Limited
NFSD	National Framework for sustainable development
NSERL	National Soil Erosion Research Laboratory
OFE	Overland Flow Elements
PSS	Penetrometer Soil Strength
RI	Relative Impact Map
RMSE	Root mean square error
ROADMOD	Empirical ROAD erosion Model
RUSLE	Revised universal soil loss equation
SDR	Sediment delivery ratio
SEDMODL	Spatially Explicit Delivery MODel
SINMAP	Stability Index Mapping
SPOT	Système Pour l'Observation de la Terre
TDR	Time Domain Reflectometry
TIN	Triangular Irregular Network
TOPAZ	TOPography ParameteriZation
TSS	Total suspended solids
USA	United States of America
USFS	United States Forestry Service
USLE	Universal Soil Loss Equation
WARSEM	Washington Road Surface Erosion Model
WEPP	Water Erosion Prediction Project

Chapter One

Introduction

1.1 Scope

Commercial forests cover approximately 1.28 million hectares of South Africa's 122 million hectares of land surface area. In 2009, production from these forests amounted to more than 18.5 million m^3 of commercial roundwood, valued at R 6.7 billion (Forestry Economic Services, 2010). Together with processed wood products the total annual turnover for the forestry industry is estimated at around ZAR 20.37 billion. Approximately 170 000 people were employed by the forestry industry, of which approximately 66 500 were located directly within the plantation sector (Forestry Economic Services, 2010). Thus, there is strong potential within the forestry industry for much needed job creation and economic transformation.

Like many key industries in the country, strong importance is attached by the forestry sector to pursue a sustainable development path by addressing the interdependence between economic growth, social protection and the natural ecosystem. This embraces the main elements of the National Framework for Sustainable Development (NFSD). The country's sustainable development vision is outlined as 'South Africa aspires to be a sustainable, economically prosperous and self-reliant nation state that safeguards its democracy by meeting the fundamental human needs of its people, by managing its limited ecological resources responsibility for current and future generations and by advancing efficient and effective integrated planning and governance through national, regional and global collaboration' (DEAT, 2008).

In South Africa, the location of timber plantations, predominantly of exotic species such as *Eucalyyptus* spp., *Pinus* spp., and *Acacia mearnsii*, is guided by the rainfall distribution of the country. It is generally accepted that below a rainfall of 850 mm per annum, commercial timber production borders upon being uneconomical (Everson *et al.*, 2007). As a consequence of this much of the commercial timber plantations are located in the eastern half of the country, particularly in the KwaZulu-Natal and Mpumalanga provinces, although comparatively smaller pockets of commercial plantations (with micro-regional climates) are located in the south-eastern portion of the Western Cape Province (Table 1.1).

Table 1.1. Areal extent of commercial forests in South Africa for 2008 and 2009 (Forestry Economic Services, 2010).

Province	2009		2008	
	Afforested Area		Afforested Area	
	Hectares	%	Hectares	%
Limpopo	49 669	3.9	47 982	3.8
Mpumalanga	519 513	40.8	510 263	40.6
North West Province	304	0.0	126	0.0
Free State	----------	0.0	----------	0.0
KwaZulu-Natal	504 393	39.6	486 020	38.7
Eastern Cape	141 819	11.1	153 380	12.2
Western Cape	59 171	4.6	59 570	4.7
Total	1 274 869	100	1 257 341	100

Given that many of the plantations are situated within the major water-producing catchments in the country, it is imperative that management of these catchments ensures sustained and high quality water resources. The importance of managing forests for catchment protection is an almost universal theme and has been stressed by *inter alia* Lu *et al.* (2001) in Taiwan; Mendoza *et al*. (2005) in Mexico, Nisbet *et al.* (2001) and Carling *et al.* (2001) in the United Kingdom and Barretto *et al.* (1998) in eastern Amazonia, Brazil. The adoption of forestry best management practices by commercial foresters in South Africa has as one of its fundamental tenets the preservation of stream water quantity and quality. For this to be effectively realized it is important that sediment inputs are kept to a minimum, which is in itself a challenging task as much of the soils under forestry in South Africa are highly erodible, plantations are commonly found on steep slopes and high intensity rainfall is common during the summer months (Horsewell and Quinn, 2003).

To carry out the core functions of managing a commercial plantation such as site preparation and maintenance, timber harvesting and extraction, fire and weed control there has to be ready access via roads to the individual compartments. The density and type of roads that are constructed is often guided by the topography of the catchment and the needs of the landowner to meet the forestry operational requirements. As a general rule, forested catchments are often connected to major arterial roads via compacted, stone armoured but unsealed roads that are usually wide enough to allow for two-way traffic. Leading from these into the forestry plantation itself, is the unpaved variant where the soil surface has been graded in such a manner as to create a quasi-planar surface. Depending upon the topography the graded soil may or may not be stacked alongside the road verge. These roads are often long-term features that are usually wide enough to support heavy machinery but not long-haul timber haulage vehicles. Following from these are the minor roads that lead directly into the individual compartments and are usually formed by the repeated passage of vehicles across the same transect. No earthmoving activities are usually associated with the formation of tracks which can sometimes be temporary in response to short-term specific needs for access to the forestry compartment.

The management of forestry roads has as a core objective the limiting of sediment loss from the road surface and the preservation of the road infrastructure. The impact of forestry on soil and water resources has, in general, been the subject of much interest in the scientific literature denoted by a long and rich history. Engineering challenges related to road construction have largely been resolved and through almost 50 years of intensive research a good understanding of road design has emerged. Yet, despite roads having been recognized as one of the most hydrologically active areas within a forested catchment for the majority of moderate to low rainfall events (Ziegler and Giambelluca, 1997; Le Marche and Lettenmaier, 2001) there remains several uncertainties related to the exact functioning of the road system in the landscape (Gucinski, *et al.*, 2001).

As the forestry industry in South Africa increases its commitment towards self regulation and governance it becomes increasingly important that reliable and realistic estimates of runoff generation, erosion and transport of sediment from forestry access roads are available. This is the first and necessary step in the development of sound road management programmes and defensible policies. This project concerns itself with the latter two road types, i.e. the unpaved roads and tracks as the general perception is that it is these road types that are vulnerable to accelerated soil loss and sedimentation.

1.2 Aims and Objectives

The specific aims of the study were to:

- Evaluate the direct contribution of unpaved forestry access roads as a potentially ready source of runoff and sediment through physically based on-site measurements at the plot and road segment scale.

- Evaluate the significance of access roads in altering subsurface flow pathways within hillslopes.

- Measure off-site impacts of runoff with particular attention to erosion and sedimentation of adjacent drains.

- Based on the findings of the study, to suggest simple criteria and procedures for identifying potentially problematic segments of roads during the planning and/or development stages.

- Based upon the findings of the study, evaluate the potential for improving the current practice of redirecting road runoff to individual forestry compartments and identify critical parameters such as road, layout and geometry, soils and geology, regional rainfall intensity and frequency that could influence the efficiency of this process.

- Investigate the applicability of current numerical models to predict runoff and sediment from forestry access roads.

Chapter Two

Background and Literature Review

2.1 Introduction

Much of the early work on the environmental impact of forestry roads, especially as it relates to the impacts on water resources began in the early 1950s when commercial forestry was rapidly expanding to support a growing demand for timber and forestry related products (Beschta *et al*., 2000). These early experimental designs, which considered streamflow as the principal dependent variable, were typically of the single or paired catchment type, many of which were located in the eastern and south western regions of the United States of America (Hessburg and Agee, 2003). In a single catchment experiment, the response of the catchment is calibrated over a period of time to the climate. This may be regarded as the control situation after which the catchment is altered through some management action. The effect of the treatment is then evaluated by comparing the pre- and post-response of the catchment. One of the major criticisms leveled at this approach is that the results of the experiment are greatest in the face of a constant climate. The longer the calibration period the greater is the validity of the final results of the experiment. Several additional uncertainties arise in extrapolating the actual relationships to extraneous areas with radically different climates. To partially address the effects of climatic uncertainty, an alternative experimental approach was developed, namely paired catchment studies. In its simplest form a paired catchment study compares the hydrological (or other associated parameter) response of a catchment to a similar catchment except that in one, a deliberate treatment is imposed. For example, two similar catchments are selected, and equally gauged for streamflow response after which a deliberate treatment is imposed (e.g. clearfelling) whilst the other is left undisturbed. The latter serves as the control. The difference in streamflow response can then be reasonably ascribed to the effects of the treatment with the assumption being that all other factors are equal throughout the duration of the study.

Bosch and Hewlett (1982) produced an extensive literature review of the effect of forestry on water resources. Based on their findings, which included 94 small-scale catchment experiments distributed in different regions of the world, they concluded that forestry causes a decrease in streamflow and that the order of this effect is largest for conifers followed by deciduous hardwoods, brush and grass cover. Conversely the removal of forests through clearfelling or planting at a lower density causes an increase in streamflow and that this effect is particularly noticeable for high rainfall areas. Nevertheless in these high rainfall areas rapid recolonisation of vegetation occurs which makes the effects of clear felling much shorter-lived than in lower rainfall regions where vegetation takes longer to recolonise.

In South Africa, Lesch (1995) carried out a study to test the effects of different forestry land management practices (especially that within the riparian zone) on the water quality of six montane catchment streams. The aim was to identify which inorganic water quality variables were most affected by normal forestry management practices. It was found that of the sixteen inorganic variables studied, suspended sediment proved to be a highly sensitive indicator as it showed the level of disturbance of the upper soil layers. Although the influence of forest roads on stream water quality was not studied explicitly, it was found that bulldozing and burning of vegetation during site preparation had a much greater effect on suspended sediment concentrations than other management practices such as clearfelling and the removal of riparian vegetation.

Similarly in the USA, the effects of forest roads, although recognized as an important contributor to the amount of sediment reaching the stream network was noted in a large number of the early works but only received a stronger research focus when attention shifted towards understanding the effects of forestry on water quality According to Douglass and Hoover (1988) one of the earliest catchments established in the USA to study the effects of forestry land management on water resources was that of Coweeta, a 2270 ha catchment located in the South Western region of North Carolina. Comprising 17 subcatchments, with perennial streams that range from first to fifth order, this research station has since 1934 been subjected to an array of management interventions. Swift (1988) summarized the road-related research that was undertaken at Coweeta, which remains a benchmark publication on the subject. Since then further studies have appeared in the literature, most of which have echoed Swift (1988) that roads have three major influences on the hydrology of catchments, namely that roads may cause an increase in overland flow and sediment entrainment, that ditches, culverts and other water redistribution structures from roads alter or extend the channel network and that roads may intercept subsurface water. Each of these aspects are discussed below.

2.1.1 The Effects of Roads on Streamflow

Jones and Grant (1996) investigated the effects of roads and clear cutting on the peak flow response of small and large catchments in the Western Cascade mountains of Oregon, USA. They examined differences in paired peak discharges for 150 to 300 storm events for five basin pairs using a 34 year record. Part of the comparison was the effects of roads in both the presence and absence of clearcutting. In one of the catchments in the absence of clearfelling, peak discharge increased by 20% after 6% of the catchment was used for the construction of access roads. The begin time of storm hydrographs was calculated to have advanced by 10 hours relative to the before-treatment period. Nevertheless, they conceded that due to the high variability in the results such changes were found to be statistically non-significant.

Following clearcutting of approximately 25% of this catchment, the average peak discharge increased by 50% and the mean begin time of the storm hydrographs advanced by 6 hours. These findings were statistically significant. Re-examination of the records for the next 25 years demonstrated that although the peak discharges had declined significantly, these were still approximately 25% higher than the pre-treatment level and the storm hydrographs were still advanced by between 6 to 10 hours. For the large catchments, the extent of increase in peak discharges and advancement of the storm hydrograph was shown to depend upon the areal extent of the catchment that was cleared. The main conclusion from this study was that, in the absence of roads, clearcutting and vegetation removal affects soil water balances because of a decrease in evapotranspiration. The removal of deep rooted trees caused an increase in deep soil water storage even though the near-surface soil water content returned to near pre-treatment levels. In the presence of access roads, the soil water content distribution is different because of a change that occurs in flow pathways as subsurface flow is converted to surface flow (thus leading to shorter peakflow responses).

2.1.2 Overland Flow and Sediment Entrainment

The amount of sediment that reaches the stream network is complex, but three major phases in this process is readily recognized namely, the supply of sediment, its transport through the hillslope and its storage or attenuation before reaching the stream proper (Croke *et al*., 1999; Lugo and Gucinski, 2000 provided an interesting perspective on the ecology of roads by arguing "that the road ecosystem can be defined by the dynamics within and through a "cylinder" with changing dynamics that meanders across the landscape". They suggest that along its path the road system interacts with other systems and environmental conditions such that in vulnerable areas the extent of this hypothetical cylinder expands and contracts when conditions are more resistant to change, thus not all components of a road system erode or deliver sediment to streams at the same rate. More recently, Demir (2007) expressed similar concepts to that proposed by Lugo and Gucinski (2000) by arguing that the ecological space wherein roads function in the landscape is a combination of the geology, climate and use or function of the road system (Figure 2.1). The climatic controls are rainfall and temperature whilst the geological drivers are mainly the type of substrate and the type of topography upon which the road is constructed. The intensity of road use, its design and type influence its functioning within the landscape (Figure 2.1)

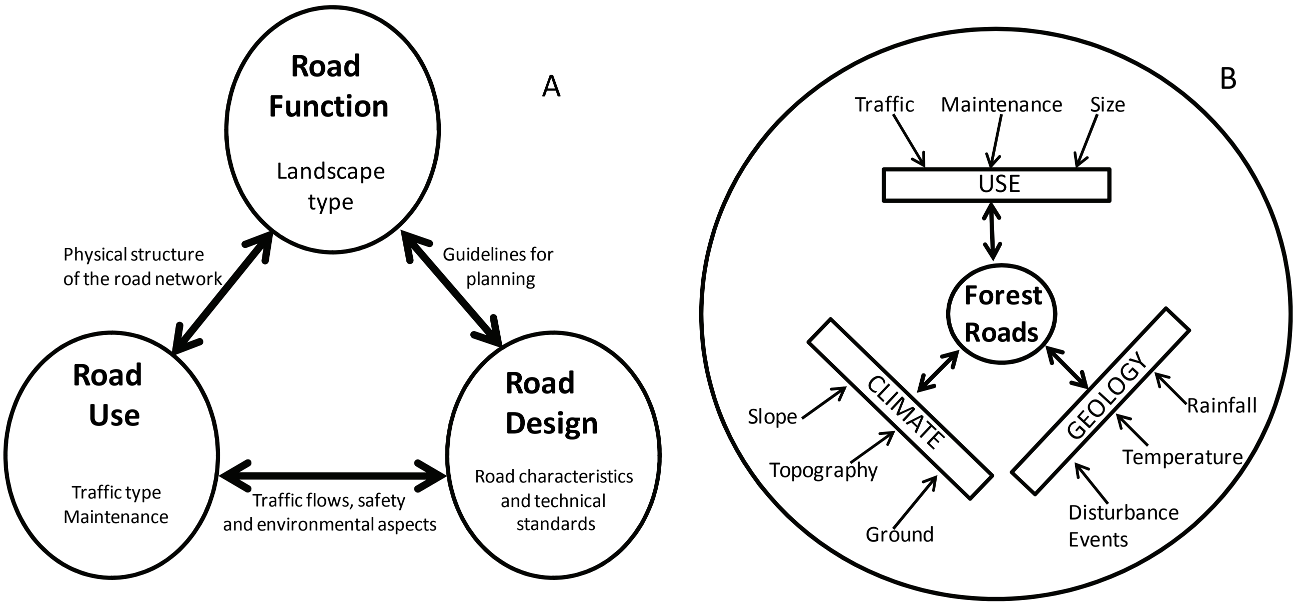


Figure 2.1. Parameters of forest road ecosystems and relationships between road function and design (redrawn *after* Demir (2007)).

Borga *et al.* (2005) found that differences in hydrologic behavior among segments of a road network are attributable to the position of each road segment relative to hydrologic flow paths. The distance between each road segment and the ridge above interacts with variations in the ratio of road cut depth to soil depth to produce predictably different responses among adjacent segments of the same road. In the absence of overland flow and mass wasting, the majority of sediment in undisturbed forestry areas is derived from channel erosion and soil creep entering the stream network along the perimeter of the channel (Anderson and Potts, 1987). In addition, forest roads provide a more impermeable layer for the initiation of surface flow than other land surfaces (Bubb and Croton, 2002). Roads are thus subject to hydraulic erosion processes and may contribute substantially to stream sedimentation, even during low magnitude rainfall events (Ziegler *et al*., 2001).

The greatest influence of roads on sediment generation has nevertheless been shown to be especially significant during the inter-rotation period, *i.e.* the period between clearfell harvesting of a compartment and establishment of the next rotation, as it is this phase that is associated with the highest level of disturbance to the forestry compartment (Ensign and Mallin, 2001). When roads cross streams, this direct connectivity of the road network can exacerbate the delivery of sediment (Wemple *et al*., 1996; Cornish, 2001). In a benchmark study Swift (1984) compared the amount of runoff generated from a forested mountainous road surface. The treatments were bare soil, grassed and 5, 15 and 20 cm gravel. It was found that the greatest amount of sediment was from the bare soil followed by the 5 cm gravel treatment. Compared to the bare soil, the grassed treatment produced 50% less sediment whilst the 15 and 20 cm treatments produced only 10% sediment. Similar studies quantifying the extent of surface runoff from access roads have been undertaken by *inter alia* Luce and Cundy (1994), Sun *et al*., (2004) and Kolka and Smidt (2004). These studies reiterated some earlier results by demonstrating that accelerated sedimentation losses from unpaved access roads can be significant and that the extent of this loss is high during times of clearfelling (Reid and Dunne, 1984; Anderson and Potts, 1987; Megahan, 1987; Fahey and Coker, 1989; Luce and Black, 1999; Constantini *et al*., 1999; Furniss *et al*., 2000; Luce and Wemple, 2001; MacDonald *et al*., 2001).

The impacts of forestry access roads on runoff and water quality has been recognised as a cause for concern in Australia. This prompted the Department of Primary Industries Forestry (DPI Forestry) to implement a range of best management practices for road design and maintenance. As with most 'best management guidelines', this is skewed towards the engineering aspects of forestry access roads, although continuous revision of these principles have emerged in the face of ongoing scientific research on runoff and sedimentation aspects. According to Forsyth *et al.* (2006) much of the early works were focused on the more temperate climatic zones of southern Australia (Grayson, *et al.*, 1993; Lane and Sheridan, 2002), although attention has now shifted towards the higher temperature, higher rainfall tropical regions of southern Queensland.

The study of Forsyth *et al.* (2006) bears resemblance to that undertaken by Swift (1984) in which graveled and ungraveled road types were compared by establishing bounded runoff plots. The soil for both plots was a highly erodible yellow podzolic loamy sand, which in the former case had been covered by a 150-200 mm layer of compacted gravel. In the two year study, contrary to the findings of Swift (1984) it was found that the graveled roads had a higher runoff coefficient (R_c) of 0.58 compared to the unpaved roads with an R_c of 0.38. The runoff coefficient is calculated as the ratio of the runoff depth to the rainfall depth. The average depth of rainfall required to initiate runoff in the graveled plot was 13.8 mm compared with 20.6 mm for the unpaved plot. The total suspended solids (TSS) loss in the graveled plots was found to be 213.9 kg km^{-1} compared with 187.8 kg km^{-1} for the unpaved treatment whilst the total sediment loss (TSS and bedload material) for the graveled and unpaved treatments (in the first year) were 3212 kg km^{-1} and 2654 kg km^{-1} respectively. In the second year of the study these rates were lower at 2509 kg m^{-1} and 1270 kg m^{-1}. These trends were conceded by the researchers to be contrary to that generally expressed in the literature, and were explained in terms of the differences in intensity of traffic between the two road systems. The graveled road received 59 times more traffic than the unpaved road, yet produced only 1.5 times more sediment, which highlights the importance of traffic intensity as a contributing factor to the amount of sediment that is generated from road surfaces.

Reid and Dunne (1984) undertook an experiment in the central Clearwater region of Western Oregon, USA to demonstrate the effect of vehicle intensity, by measuring the sediment concentration in a 200 m long road surface rut at intervals before and after the passage of a logging truck. It was found that rainfall intensity and discharge in the wheel track varied little through the period while concentration increased from 4500 mg L^{-1}, 17 min after the previous truck passed to a peak of 31000 mg L^{-1} before declining to the original level 20 min later when the next vehicle passed. They further reported that at least 1.7 kg of sediment in excess of the background level was lost from this section which equated to at least 9 kg road km^{-1} for a single truck during a rainstorm with an intensity of 1.5 mm hr^{-1}. Ziegler *et al.* (2001) undertook a similar study in Northern Thailand aimed at developing linkages between sediment production and vehicle traffic intensity. They showed that the abundance of loose road surface material at any given time is a function of vehicle traffic and other surface preparation processes occurring since the last overland flow event. In particular during the dry season, this build up of loose sediment can be extensive and relatively small overland flow volumes can transport significant sediment loads.

Sheridan *et al.* (2008) carried out a series of rainfall simulation experiments to evaluate the extent of sediment loss from unpaved roads and showed that the amount of loose sediment that is available for entrainment depends strongly upon the intensity of vehicle traffic. In a heavily trafficked site they reported a 20 mm deep layer of loose sediment on the graveled road surface compared with only 5 mm of loose material in a low trafficked site of similar condition. As reported previously by *inter alia* Reid and Dunne (1984) and Ziegler *et al.* (2001), Sheridan *et al.* (2008) also found that this loose sediment on the road surface contributes to an initially high sediment concentration, which decreases rapidly as the wet season progresses and as the erodibility of the road declines (Figure 2.2). Similar patterns of sediment entrainment were also reported in very early works that were concerned purely with the effects of clearfelling.

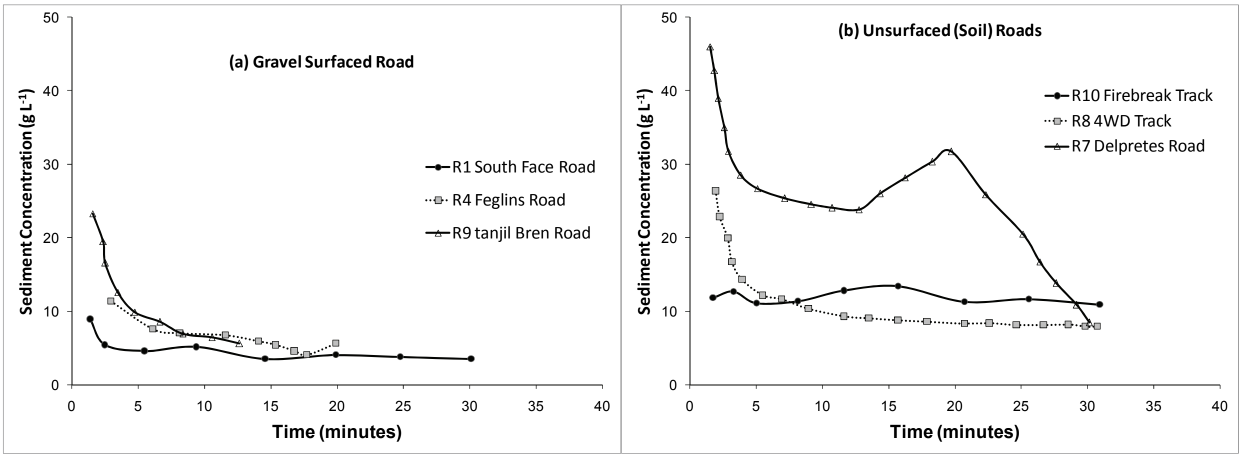


Figure 2.2. Sediment concentrations noted for gravelled and unsurfaced roads under 100 mm h^{-1} simulated rainfall. After Sheridan *et al.* (2008).

Cornish (2001) adopted a different approach by investigating the effects of road construction, harvesting and forestry regeneration on the turbidity levels of streams leaving eight small previously undisturbed eucalypt catchments near Dungog, New South Wales, Australia. Permanent forestry access roads were constructed in four of these catchments prior to harvesting. The authors found that the construction and use of access roads increased the mean turbidity levels however this effect only occurred for those catchments containing a number of stream crossings. Thus they highlighted the importance of road to stream connectivity as a critical component of sediment delivery in catchments containing access roads.

In New Zealand large tracts of land were converted to exotic *Pinus radiata* plantations in the early 1960s. Within a decade, a high incidence of fish deaths (*Salmo trutta*) were reported in the Nelson region, located in the very north of the South Island. The increase in sedimentation of rivers and streams was linked to the construction of forestry access roads (Mosley, 1980). Since the late 1970s much of the road related research in New Zealand has been undertaken in this region and is reviewed by Fransen, *et al*. (2001) (Table 2.2).

Fransen *et al*. (2001) concluded that surface erosion of new and upgraded roads at harvest times may increase sediment yield five-fold relative to pre-harvest ungraded and lightly graded roads, but further argued that much of the New Zealand studies do not offer information on either sediment delivery ratios or catchment residence time once the sediment is removed from the road surface. In many of the catchments forest road-related mass movement increased catchment sediment yields by three orders of magnitude. The general consensus from the literature suggests that the release of sediment from forest road surfaces is strongly dependent upon the type of armoring that characterizes the road segment; not all roads react in the same way as local conditions play an important role in regulating the sedimentation process. The intensity of road use influences the amount of sediment made available for potential transport and a large percentage of sediment is removed from the road surface shortly after the onset of the rainy period but the extent of this sediment loss decreases with subsequent rainstorms. Where roads connect directly with streams, this can lead to exacerbated sediment losses and high suspended sediment loads in rivers.

Table 2.1. New Zealand studies on the impacts of forestry access roads on accelerated soil erosion. Modified after Fransen *et al.* (2001).

Location	Author (s)	Erosion source and type	Type of study	Slopes	Rainfall
Glenbervie Forest, Northland	Hicks and Harmsworh (1989)	Severe gully erosion of embankment	Paired Catchment	16-28° Hillslope	1900 mm annum^{-1}
Tairua Forest Coromandel Peninsula	Pearce and Hodgkiss (1987)	Landing failure	Volumetric survey of erosion scars and sediment deposits	15-25° Hillslope 40°	Storm total 260 mm 4 days^{-1}
Kaingaroa Forest Central North Island	Smith and Fenton (1993)	Track surface runoff	Plot experiment, natural rainfall	18-23° Track	1562 mm annum^{-1}
East Coast	Phillips (1988)	Road failures	Volumetric survey of erosion scars and sediment deposits	35° Hillslope	118-265 mm h^{-1} in 24 h
Tangoio Forest Hawkes Bay	Fransen (1998)	Road fill and batter failures	Volumetric survey of erosion scars and sediment deposits	15-35° Hillslope	580-1200 mm annum^{-1}
Queen Charlotte Forest, Marlborough Sounds	Fahey and Coker (1992) Coker *et al.* (1993)	Road cutbank spoil, surface ditch runoff and sidecast Truck induced runoff	Plot experiment, simulated rainfall Volumetric survey of erosion scars and sediment deposits	25-35° Hillslope 75% of road <5°	1000-1300 mm annum^{-1}
Dart Valley, Nelson	Mosley (1980) Fahey and Coker (1989)	All road-related failures Road cutbank spoil, surface ditch runoff and sidecast	Plot experiment, simulated rainfall Volumetric survey of erosion scars and sediment deposits	35° Hillslope 3.5-7.5° Road	2000-3000 mm annum^{-1}
Tawhai Forest, North Westland	O'Loughlin *et al.* (1980)	Track Surface	Erosion pin plots, paired catchment	36° Hillslope	2600 mm annum^{-1}

2.1.3 Gullies and slope failures caused by roads

The initiation of channels, which later formed gullies because of road related runoff has been extensively reported in the literature (Megahan and Ketcheson, 1996; Rosenfeld, 1999). Montgomery (1994) demonstrated that a threshold value of surface or subsurface flow is required to overcome surface resistance to erosion and that road drainage influences this threshold. Furthermore, less drainage area appears to be required to form channels in areas receiving road runoff (Jones and Grant, 1996; Le Marche and Lettenmaier, 2001).

Rosenfeld (1999) estimated that roads accounted for as much as 42% of all slope failures in the northern Oregon Coast range due to improper road drainage or poorly managed road culverts. According to Croke and Mockler (2001) part of the reason for this is that existing guidelines for road drainage spacing are designed to prevent erosion of the road surface, with less consideration of the road drainage area and potential for gully development. The established practice within forested catchments is to divert runoff from the road surface, normally by three main mechanisms; cross culverts or drains, water bars and broad based dips. The assumption is that forest soils have good infiltration properties and high hydraulic conductivities and therefore much of the road runoff water will move to streams as subsurface flow. Notwithstanding the effects of soil hydrophobicity, this process will be supported by continual inputs of high organic matter content on the soil surface (Sidle *et al*., 1995, Bruijnzeel, 2004; Greiffenhagen *et al*., 2005). Under moderate or low rainfall intensity this assumption may be valid, however under high intensity rainfall the probability of slope disturbance or failure may be increased (Megahan *et al*., 1991). It has been demonstrated in the literature that even with well-constructed roads, too few or poorly placed drainage culverts can lead to pore water pressure accretion on downslope sites or fill material. Particular areas of concern are hillslope depressions or geomorphic hollows that have the potential to accumulate subsurface water. In steep slopes, Sidle *et al.* (2006) commented that mid-slope roads have the largest destabilizing effects by virtue of subsurface water interception and overloading and undercutting of slopes. Thus it is apparent that any road drainage that concentrates on steep slopes, in hollows or in the road prism itself will dramatically increase the probability of slope failure (Furniss *et al.*, 1998). Sidle *et al.* (1985) documented accelerated erosion rates from roads as a consequence of debris slides ranging from 30 to 300 times the forest rate.

Where subsurface water from higher upslope becomes intercepted by roads this may be diverted to surface runoff and then redirected downslope, modifying pre-existing flow pathways on the hillslope. Such influence from roads may lead to a change in hydro-geomorphic response much larger than would be expected from the small land area roads occupy (Wemple *et al*., 2001).

When roads are constructed into hillslopes the general engineering approach is to excavate the upslope section of the hillslope to create the road bed and deposit the excavated material on the downslope end. The main elements of this type of road system are given in Figure 2.3.

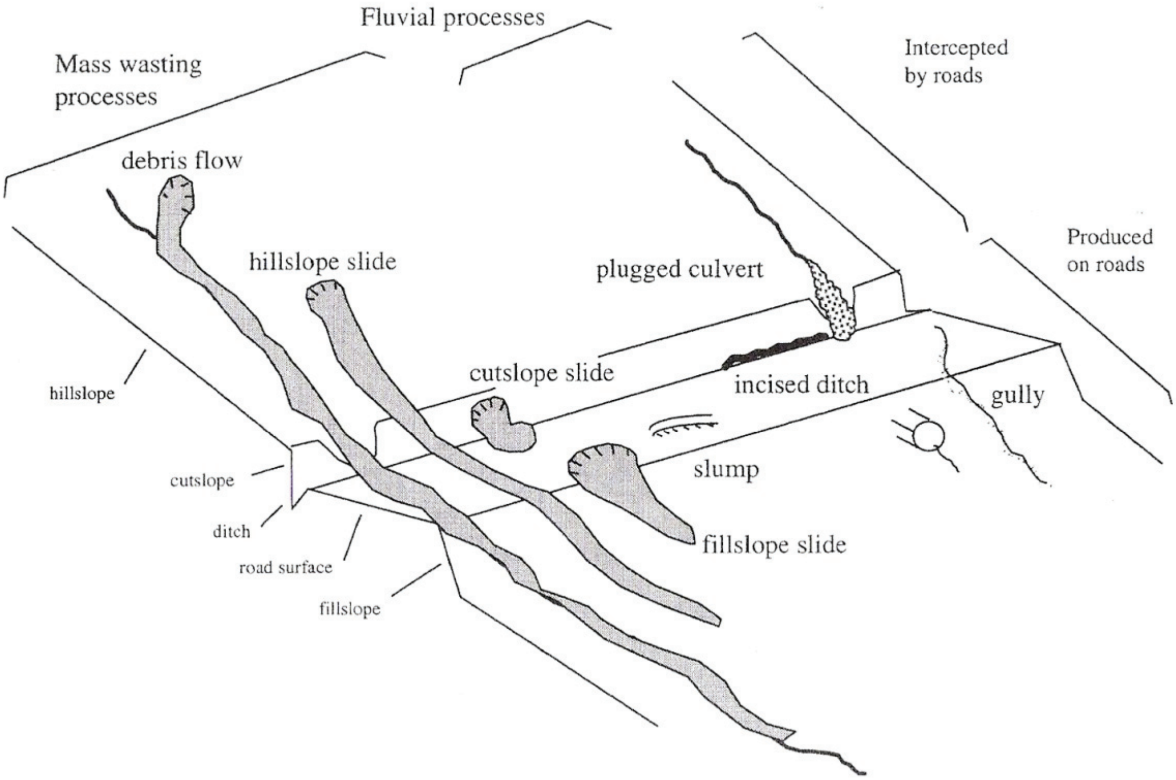


Figure 2.3. Erosional and depositional features produced by mass wasting and fluvial processes associated with forestry roads (after Wemple *et al.*, 2001).

The delivery of sediment, runoff from and stability of these individual road segments has been the subject of widespread interest from several authors as these factors impact on the overall management of the road system. This concept was demonstrated in a study undertaken by Wemple *et al*. (2001) who investigated the impacts of access roads on the geomorphology of a 181 km^2 catchment in the Western Cascades region of Oregon in the USA. In this study a total of 33 mass movement complexes comprising debris flows, hillslope slides, cutslope slides, fill slope slides and slumps were noted after a major rainstorm event during February 1996. This work was significant in that the researchers were able, using GIS technology, to estimate the volume of material detached, transported and deposited on a much larger scale that is ordinarily encountered at the plot-scale type of studies. They found that although roads functioned as both production and deposition sites for mass movements and fluvial processes, the net effect of roads was an increase in basin-wide sediment production. Roads intercepted almost 26 000 m^3 of sediment contributed from hillslopes and channels and stored over 19 000 m^3 of sediment. However, more than 32 000 m^3 were estimated to have been mobilized within the road prism, so roads were a net source of more than 13 000 m^3 of sediment in the catchment. Debris flows accounted for two thirds of the sediment intercepted by roads and hillslope slides and bedload trapped at stream crossings culverts accounted for the remaining one third.

Fahey and Coker (1989) found that the sediment loss from unprotected cut banks, in the Nelson region of New Zealand, was approximately nine-times the contribution from a graveled road surface and ditch. In Idaho, Burroughs *et al*. (1984) concluded that cutbanks and ditches produced 6.3 times more sediment yield than from the native road surface. Similarly Swift (1988) established that cutbanks and fill slopes are a significant source of sediment from a road prism. Jones and Grant (1996), working in the Cascades Mountains of Western Oregon, demonstrated the importance of episodic mass movements on the timing and magnitude of sediment yields in steep catchments. Six years after road construction, storm induced mass movements contributed 90% of the total sediment yield (21 000 t km^{-2}) over a 30 year period and more than 26 times the total sediment yield in a forested control catchment. Infrequent road-related mass movements are thus major sources of sediment within forests and have the greatest potential to affect stream ecosystems (Fransen *et al*., 2001).

Jordan and Martinez-Zavala (2008) undertook an investigation of the unpaved access roads servicing the Sierra de Luna Mountains in the south western region of Spain. Using rainfall simulation they established plots (10 m x 3 m) on the road bank, the sidecast fill (fill embankment) and the road bed wherein they measured both runoff and sediment loss (Figure 2.4).

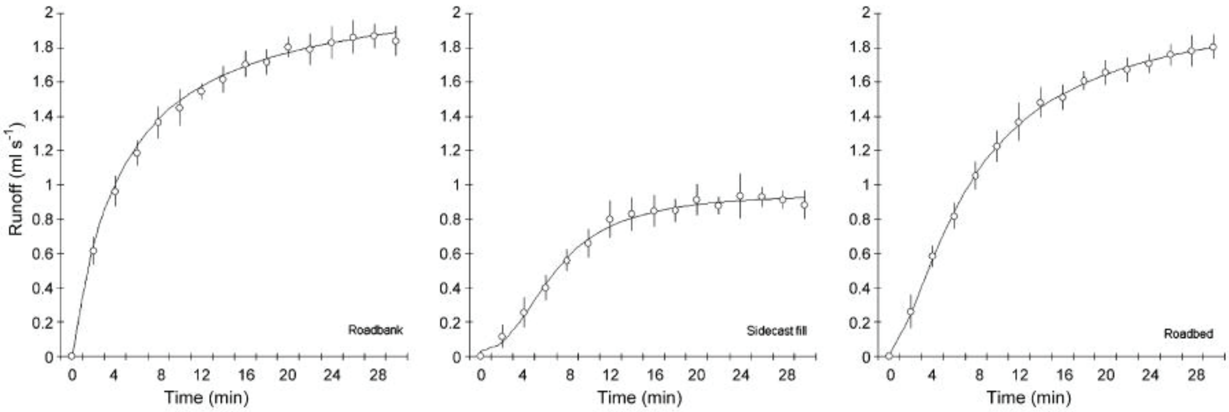


Figure 2.4. Surface runoff from rainfall simulation on different parts of unpaved forest roads (after Jordan and Martinez-Zavala, 2008).

They found that highest average runoff coefficient (R_c) was determined for the roadbank (57.84%) whereas that of the sidecast (fill embankment) were 27% and 51% respectively. The highest average runoff rate was measured on the roadbank which peaked at 1.95 ml s^{-1}. The road bank had the highest erosion with a sediment loss of 6.6 g l^{-1} and total soil loss of 105.5 g m^{-2}. The soil lost from the road bed and sidecast were 21 g m^{-2} and 17 g m^{-2} respectively. Thus, these authors concluded than runoff and sediment loss from unpaved access roads are highest from road banks and stressed the importance of good vegetation cover as a means of surface protection.

2.2 Road Linkage / Redistribution

The collective contribution of a road network to the hydrologic response of a catchment depends upon how the road segments in the catchment modify the capture and routing of flow to the stream channel (Croke and Mockler, 2001; Wemple and Jones, 2003; Jordan-Lopez, 2009). In the pre-road condition, the storm hydrograph in a catchment comprises the contributions from a set of hillslope segments draining to channels. Roads constructed parallel to the contour in midslope positions create new subcatchments with shorter hillslope lengths, and the runoff they capture may be routed directly to a stream channel. Gucinski *et al.* (2001) argued that few published studies have identified how roads in different landscape positions might influence the movement of water through a basin. Recent advances in spatial hydrological analysis and modeling have begun to address these concerns.

Croke *et al.* (2005) mapped the sediment delivery pathways in the Cuttagee Creek catchment of New South Wales, Australia using a series of data layers in a Geographic Information System (GIS). The catchment has 75 km of unpaved access roads representing 1% of the catchment area with a mean road density of 1.99 km km^{-2} and a drainage density of 4.4 km km^{-2}. A total of 14km (20%) of the road network, represented by several road segments, which was serviced by 218 drainage structures was selected for analysis. They classified the type of connectivity or linkage pathways as either dispersive or channelized (gullied). Road discharge points were referred to as gullied if the incision was greater than 0.3 m or dispersive if there was an absence of erosion. The available hillslope length (AHL), defined as the distance from the road outlet to the nearest drainage line measured in the direction of flow was calculated from the contour, drain location and stream coverage in the GIS. Using a large scale rainfall simulator two rainfall events of 30 min duration with intensities of 75 mm h^{-1} and 110 mm h^{-1} were applied at each location. Using a fluorescent dye injection at the drain outlet they were able to measure the runoff and sediment fluxes at selected distances within the downslope forested compartment. There were two significant outcomes of this research, which has made advances in developing an understanding of the manner in which roads integrate into the hydrological functioning of hillslopes. Spatially, these researchers found that the major form of road-to-stream connectivity was via gully development at road culvert outlets. According to the authors this has resulted in a 6-10% increase in catchment drainage density since the roads were constructed in the 1970s. They also found that the length of the gully defines the maximum distance that sediment is potentially transported and related the development of gullies at road outlets to the hillslope gradient and road runoff contributing area. They found a strong correlation between gully development and road drain types as culverts are used on cut and fill embankments where road contributing areas and discharge hillslope gradients are large. As was found by Megahan and Ketcheson (1996) these researchers showed that there is an exponential decrease in sediment concentration with distance downslope.

The second major finding of these authors was that in this particular catchment, a high incidence of diffuse overland flow pathways were noted at mitre drains which are more frequently used to remove water from the road surface and contained lower runoff volumes. Whilst an exponential decay relationship for the entrained sediment was found for the < 2 mm size fraction, they nevertheless showed that the clay sized fraction (< 63 µm) was not reduced but remained in suspension until the runoff had infiltrated. They conceded that diffuse overland flow pathways has less of an influence in road to stream connectivity than did the gullied pathways and stressed the importance of proper management of runoff volumes through small drain spacing.

Borga *et al.* (2005) used a GIS mapping approach to assess the impacts of forestry access roads on shallow landsliding by coupling digital topography (obtained from the GIS survey) with a simple steady state-rainfall runoff model. Using a series of numerical relationships between parameters such as drainage surface area, slope and soil properties (hydraulic conductivity, bulk density and friction angle) they calculated the saturation deficit at any point in the landscape and related this to a dimensionless relative impact score that was influenced by the degree to which the road drainage network modified the stability of the slope. For each site investigated they produced a relative impact score map that described the potential for shallow landslides due to the presence of the road network. An example of their model output is shown in Figure 2.5.

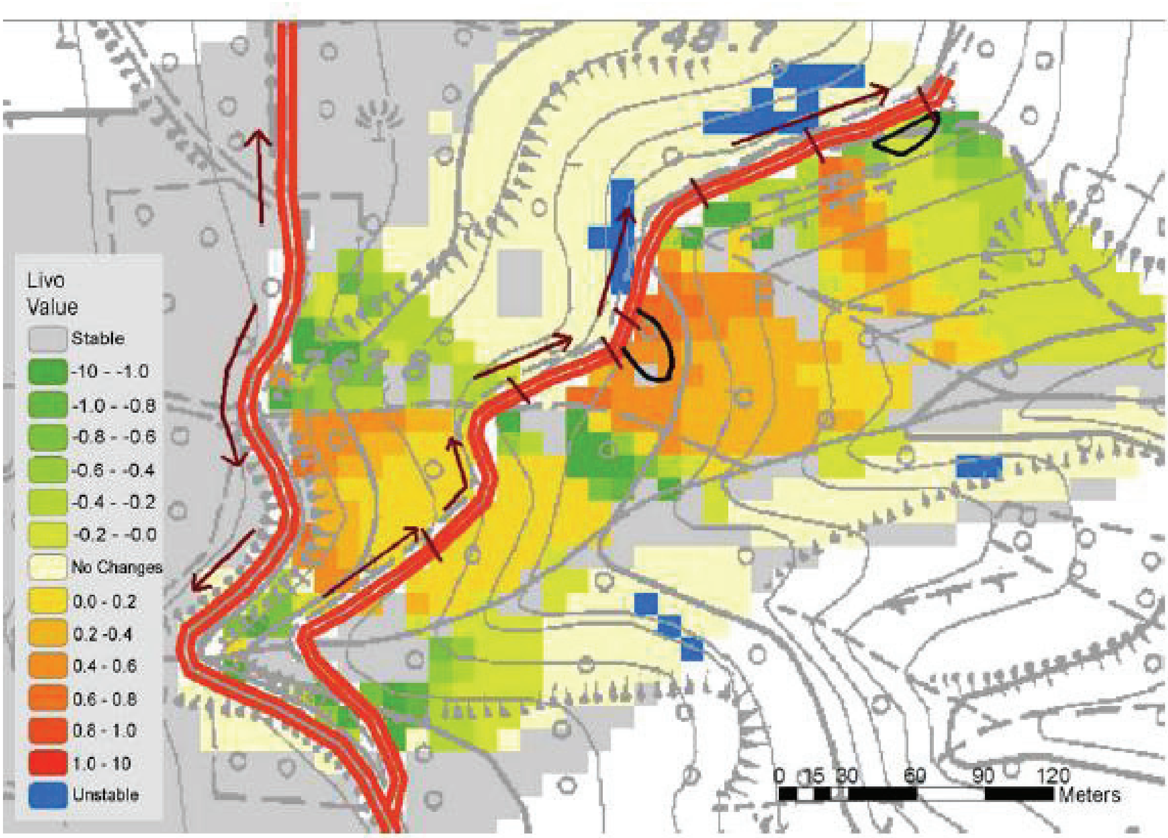


Figure 2.5. Relative Impact Map (RI) showing potential risk for shallow landsliding due to road drainage (after Borga *et al.,* 2005).

According to the authors the relative impact patterns are useful in that they show how road networks can alter pre-existing subsurface flow pathways and that roads appear to influence potential landslides downstream of runoff interception sites. Absolute values of relative impact were shown to be highest immediately below the road but extended from the area below the road to a large portion of the hillslope downslope. Despite the assumptions upon which the model is based, which is explained in detail by the authors, the value of the study was that it allowed for an integration of hillslope dynamics and road configuration aspects. In this regard the work of these researchers represents an advanced approach in investigating the impact of roads on the functioning of hillslopes.

2.3 Subsurface and Near Surface Movement of Water

Research on the impacts of roads has primarily focused on the measurement of runoff and erosion from the road surface because of the evident contrasts with surrounding forested lands. The compacted nature of road surfaces, which bring about a narrow range of hydraulic conductivities, may be regarded as ideal conditions for the generation of overland flow. This has been evaluated primarily by rainfall simulation studies (Sheridan *et al*., 2008; Foltz *et al*., 2009) or as in the current study on-site measurements under natural rainfall (Sheridan *et al*., 2006; Rijsdijk *et al*., 2007). However, less well documented is the effect of roads in altering the flow of water on hillslopes. It is often suggested that cut and fill embankments intercept water on hillslopes but few studies have conclusively demonstrated the significance of this process (Luce, 2002). Even less well understood is the mechanisms by which forest roads intercept and route water, especially given that the road occupies a very small surface area relative to the hillslope areas intercepted by the road cut on steep slopes (Wemple and Jones, 2003).

Forested soils often have high initial hydraulic conductivity due to the accumulation of organic matter on the soil surface, but this declines with depth. Thus the potential may exist for water to flow laterally along the hillslope, if there is a temporary perched water table or if an impermeable surface, such as bedrock, is encountered. Under favourable conditions the intercepted water may be transformed to surface runoff. This water, intercepted by the cutslope face, is referred to as infiltrated subsurface flow (ISSF) (Ziegler *et al*., 2001; Negishi *et al*., 2008).

A popular conceptual model to explain ISSF which has first proposed by Burroughs *et al.* (1972) is that interception occurs when a seasonally high water table flowing over an impermeable base becomes deep enough to intersect the road ditch (Figure 2.6). Thus the fraction of the permeable soil occupied by the road cut becomes a controlling factor in the amount of interception. Despite this widely accepted conceptual definition, there has been varying accounts of the contribution of ISSF to the total road runoff.

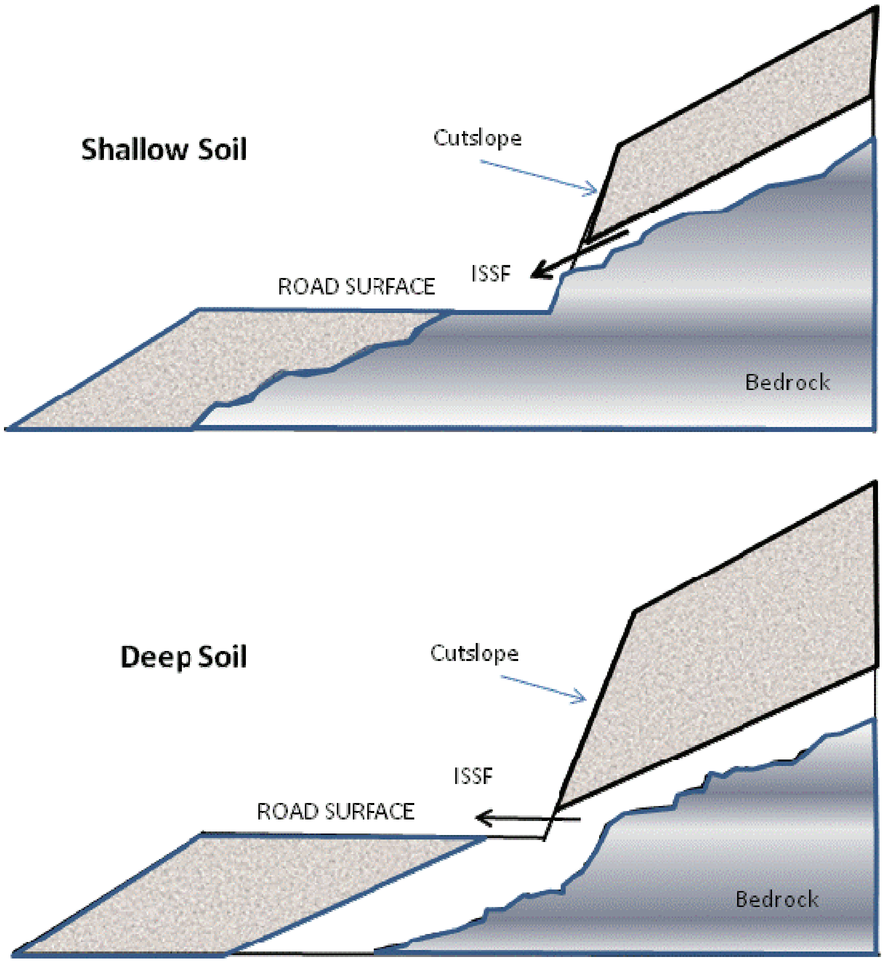


Figure 2.6. The conceptual model to explain ISSF. In a shallow soil the road surface intersects the bedrock directly and water drains onto the road surface. In a deep soil the water table is sufficiently high for flow to occur onto the road surface (redrawn after Ziegler *et al.*, 2001).

According to Inamdar and Mitchell (2007) within any particular catchment there are three important runoff contribution areas, namely the hillslope, the riparian zone and rock outcrops or similar impervious surfaces. Burns *et al.* (2001) studied the effects of these contributing areas for a small catchment in Georgia (USA) and demonstrated that rocky outcrops contributed a significant proportion of the discharge at peak flow. The contribution by the hillslope unit to total discharge at peakflow was only significant during high intensity rainfall events whereas for minor events the riparian zone regulated the catchment streamflow. Thus, road placement may be an important consideration in influencing catchment processes by modifying or intercepting subsurface flow pathways (Negishi *et al*., 2008).

Attempts at measuring and monitoring ISSF at roadcuts have been varied, both in terms of method and results. Wemple and Jones (2003) carried out a study in the western Oregon Cascades (USA) where they mapped the runoff contributing areas for each road segment within a 101 hectare catchment. Runoff (using a V-notch weir) and rainfall were measured continuously from 12 subcatchments that comprised 14% of the total catchment size during the 1996 hydrological year. Prediction of runoff for each of these road segments was made based upon a using a simple linear rainfall-runoff relationship. Estimation of interception of subsurface flow by roadcuts was made using an approach developed by Beven (1982). According to Beven (1982) the lag time between the start of rainfall and runoff represents the unsaturated zone response time for a hillslope whilst the delay between the start of runoff and the time taken to reach steady state conditions represents the saturated zone response time. Both the unsaturated and saturated response time depends upon initial soil water content, air entry potential, rate of rainfall, depth of the roadcut and gradient of the slope.

The elevation of the steady state water table at the roadcut was calculated as a function of the length between the top of the roadcut and the ridge of the hillslope, the gradient of the slope, a constant rate of input to the slope and the hydraulic conductivity of the soil. Wemple and Jones (2003) found that for roadcuts to intercept water several specific conditions must be met. First, that intensity of rainfall must be sufficiently high to cause the water table to rise above the base of the roadcut and second differences in hydrologic behaviour between different segments of a road network are attributable to the position of each road segment relative to hydrologic flowpaths. They further concluded that road segments, whose roadcuts intersected the entire soil profile were more likely to produce runoff than road segments whose roadcuts partially intersected the soil profile. Further, a road segment draining short slopes with shallow soils was more likely to produce rapid runoff response than deep soils with long slope lengths.

Negishi (2008), following a similar approach to Wemple (2003) for a catchment in Malaysia, separated event based road Hortonian Overland Flow (HOF) from ISSF by a hydrograph separation technique. HOF was estimated as rain falling on a road surface allowing for a lag time for runoff to reach the road weir whereas ISSF was the residual of total road runoff after subtracting estimated HOF. They illustrated that the response of ISSF from hillslopes was variable but depended strongly upon total storm rainfall and antecedent moisture conditions (AMC) and that when AMC was dry there was no ISSF until a critical rainfall was exceeded. This concurs with Wemple and Jones (2003) who suggested that rainfall, antecedent moisture conditions and geomorphic controls where critical in regulating ISSF.

Ziegler *et al*. (2001) adopted a somewhat different approach to investigate the contribution of ISSF to total road runoff in northern Thailand by comparing the $\delta^{18}O$ signatures of rainwater, road runoff and stream water (a proxy for soil water). They further instrumented several road cuts with soil water content sensors to assess the presence of a rising water table as this is one of the requirements for ISSF. In the three years over which this study was undertaken they were unable to detect any evidence of ISSF, citing the deep soils (> 2 m) of the study area as the main reason for their observation. They further demonstrate that immediately following rainfall, soil water content increased at shallow depths, followed progressively by the deeper layers. Based on this observation they argued that infiltration and not a rising water table (which would have caused the deeper soil layers to wet up first) was the dominant mechanism leading to an increase in the depth-specific water content in the soil profile.

Chapter Three

Experimental Design and Layout

3.1 Introduction

An important aim of the project team was to obtain early interest in this study from industry, regulators and the scientific community at large. This is crucial if the value of the research end-product is to be both informative and relevant. With these objectives in mind, invitations were sent out to several key stakeholders drawn from Government, the scientific community and industry, specifically Mondi, Sappi and NCT who collectively manage the major portion of forested regions in South Africa. At the outset of the meeting it became quite clear that the forestry industry recognized that access roads were indeed an active source of sediment within their plantations, although very little formal research to document the extent of this problem has been undertaken. There are several reasons for this; the most significant one seems to be that a large percentage of plantations were in the hands of private landowners before being incorporated into commercial operations. Thus the industry has inherited an already existing road network, with its associated challenges. According to Hurd (2007) where possible poorly sited roads are corrected when Mondi acquires a farm but this is more difficult in older plantations. The second seems to be that previously much greater emphasis was given to actual site management compared with roads as the latter was arguably of greater economic significance. In recent years there has been a change in the industry mindset as roads are now receiving far greater attention than was the case historically. This has further been motivated by the forestry certification programme that the industry has embarked upon. To this end, the research was welcome in light of its potential to inform and perhaps assist the industry to mitigate negative impacts from forestry access roads.

It was further interesting to note that the extent of road degradation seems to be compounded in Eucalyptus stands compared with Pine and Wattle. Notwithstanding the differences in interception loss caused by the differential canopy cover of pine, eucalypt and wattle the main reason cited for this is that Eucalypt leaf litter and branches has a far greater tendency to block road drains, thus leading to a compounding of the problem on the road surface itself.

Thus the recommendation was that the project team focus on Eucalypt as it is in these stands that the problem is exacerbated and could thus represent a “worst case scenario”.

Following the workshop a meeting was arranged with Mondi and through their extensive GIS database, potential study sites were identified based on rainfall, soil type and slope, with special focus on Eucalyptus plantations. Through an elimination process that also considered distance to site from the University of KwaZulu-Natal, Pietermaritzburg campus, a study site was located at Seele Estate on the periphery of New Hanover (Figure 3.1).

3.2 Site Description

The district of New Hanover is located in the midlands of KwaZulu-Natal approximately 45km north-northeast of Pietermaritzburg. The Seele Estate is situated 15 km due north of the town of New Hanover. Agriculture is the dominant land use type in the region with extensive areas under sugarcane and commercial forestry of mainly Eucalypt, Acacia and Pine species. Some maize, nuts, and vegetable is also grown in the region.

The mean annual precipitation (MAP) typically ranges between 800 and 1200 mm with much of this being received during the summer months, i.e. between late September and mid-March. The driest month is usually during June. Average midday temperatures range from 20.1^{o}C in June to 26.8^{o}C in January. The maximum daily temperature, however, can reach the mid-thirties especially when there is a hot “berg” wind blowing. The mean annual temperature is 17^{o}C. Winters can be extremely cold with occasional sub-zero temperatures. Heavy mist is also common in the area.

Two main road types service the estate, the first is type B, which have coarse aggregate armour on the road surface and is usually wide enough to accommodate the dual flow of traffic. The second class is type C which has been formed by blading the soil to form a flat surface. These are the unpaved roads that lead directly into the forestry compartments and form the subject of the current study. Although no formal drainage systems for these road types have been constructed runoff is directed from the road surface via berms into the forestry compartments. These roads do not have high traffic intensities except during the harvesting period when heavy machinery needs to gain access to the individual timber stands. These roads are generally not wide enough to support dual traffic.

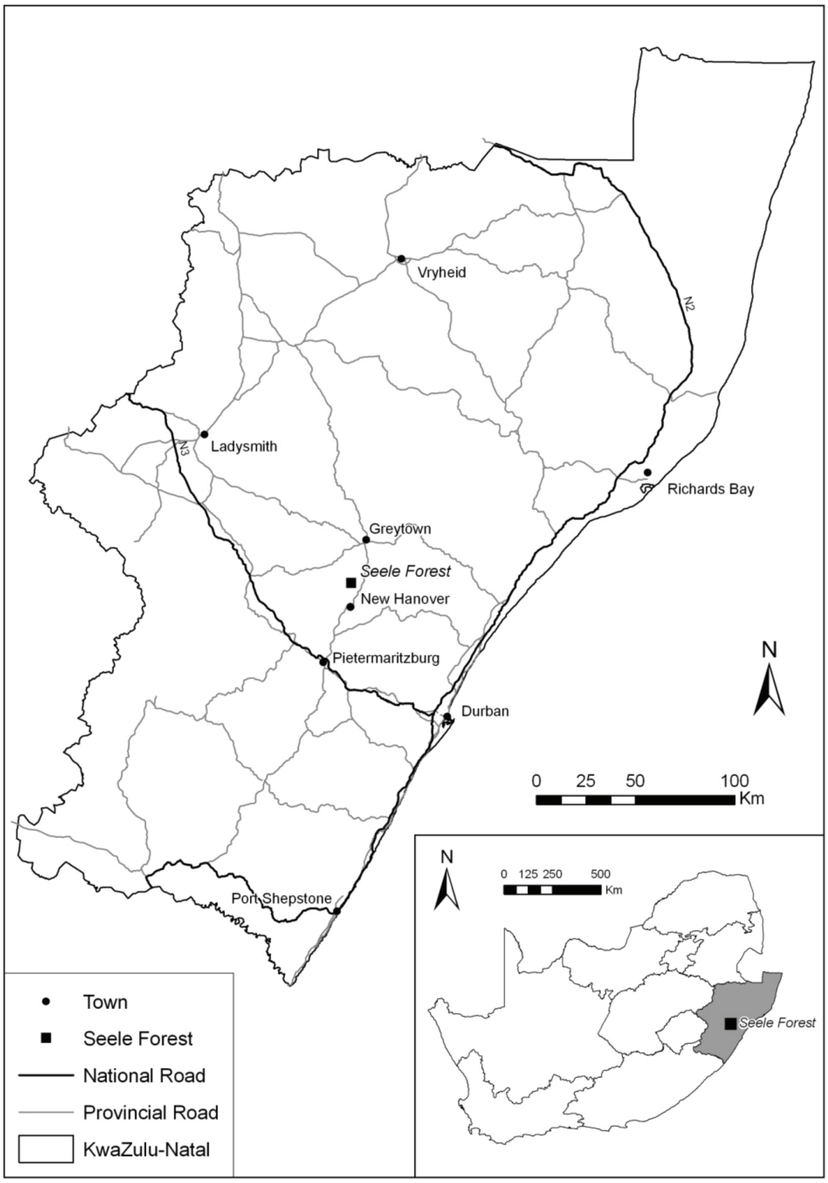


Figure 3.1. Location of the Seele Estate within the New Hanover district of KwaZulu-Natal.

Several field visits were made to the site in order to verify the information, after which a decision was taken to base the research at this locality. Once this was established, the second phase was to gather the necessary GIS vector-based data. This was obtained either from Mondi's GIS Unit or the University of KwaZulu-Natal. The following data sets were obtained:

- Coverage of road network – This was digitized from the 1:50 000 topographic sheets for the region in vector data. Data were obtained from aerial photography and SPOT imagery for the study site to include all the minor roads that did not form part of the 1:50 000 sheet because of scale.
- All the Mondi compartment names and attributes – this includes species planted, date of planting and expected date of harvesting.
- Soils data for the region – at the level of Form and family following the Soil Classification Working Group (1991).
- Slope class and aspect data – used to develop a sampling strategy in terms of road gradient.
- Further, the colour 2004 aerial photography and SPOT Imagery (2.5 m x 2.5 m pixel size) for the study site was clipped and geo-rectified.

These data have been used to create a Triangular Irregular Network (TIN) of the study area (Figure 3.2), overlay this image with SPOT imagery (Figure 3.3) and then, using 20 metre contour isolines, develop a Digital Elevation Model (DEM) to create a 3-D visualization of the study site (Figure 3.4). During field visits, using GPS, the co-ordinates for each plot and sample site were obtained – this has been 'overlain' onto the DEM and vector data (Figure 3.5). All data are stored as project files within ArcView 3.3 and ArcGIS 9.3 using WGS 84 as the standard Datum and Transverse Mercator Projection with a Central Meridian (Lo) of 31 degrees.

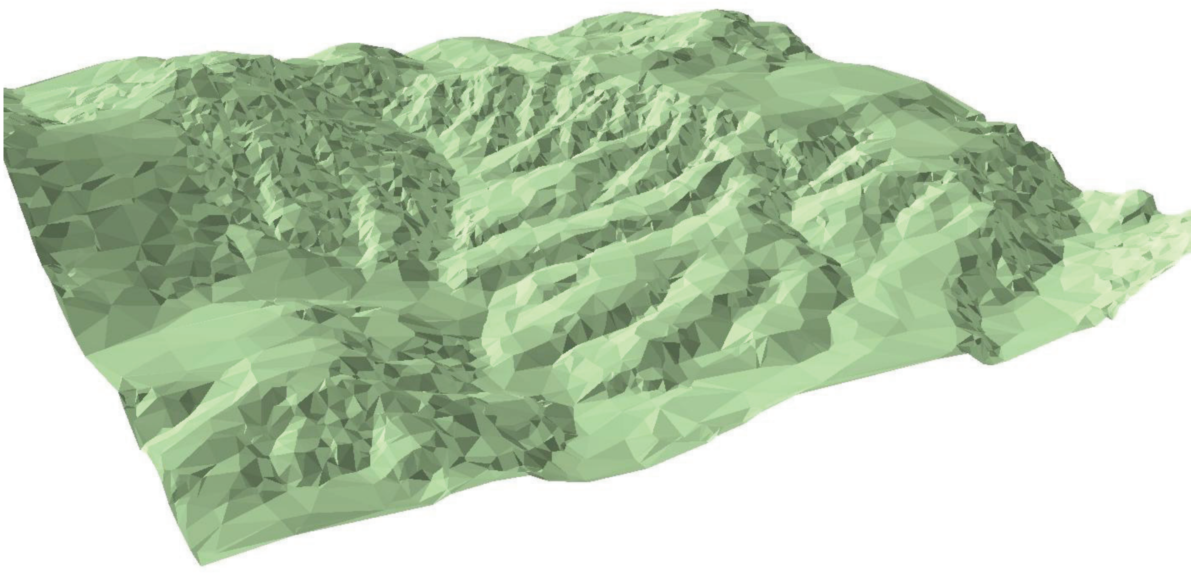


Figure 3.2. Creation of a TIN for the study area, using 20 m contour interval interpolated to 5 m. Study area has been clipped.

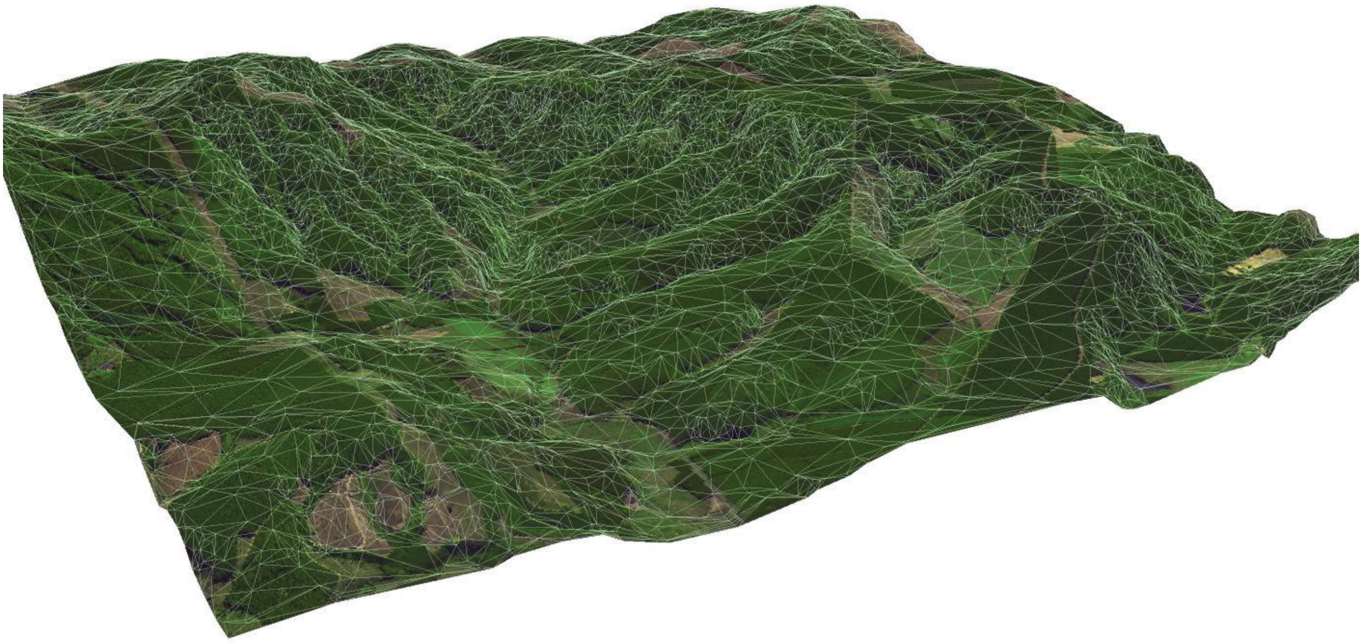


Figure 3.3. SPOT Imagery (2.5 m x 2.5 m pixel size) overlain on TIN.

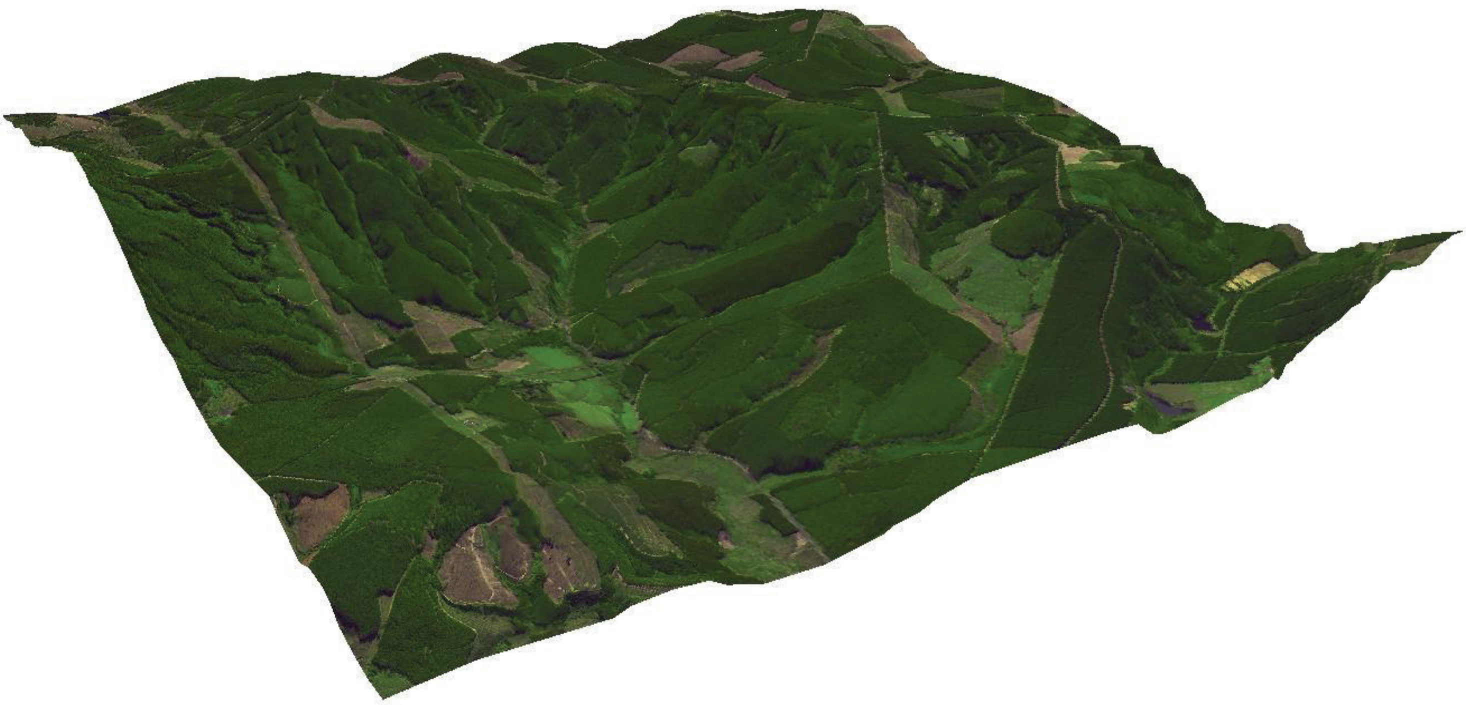


Figure 3.4. DEM created – using a 3X exaggeration. This DEM is used to develop a “fly through” – for visualization and onto which vector data are overlain.

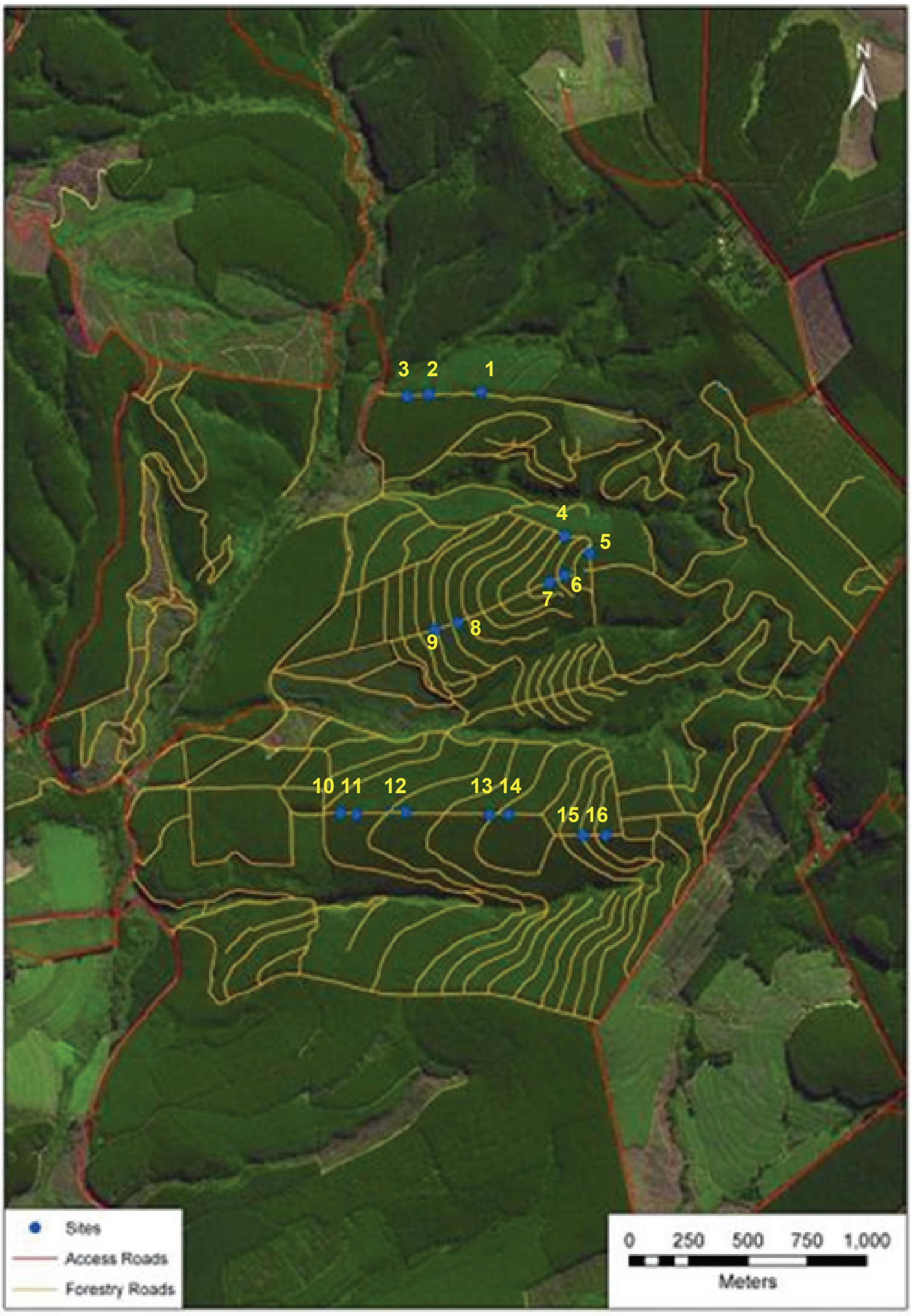


Figure 3.5. Study site on SPOT Imagery with vector data overlain and sample sites.

Once the DEM was successfully created and verified (Figure 3.4), other GIS coverages were added to the database, notably soils, slope, aspect, compartment size and species, age of compartments, road gradient, slope length. This information is shown in Figures 3.6 to 3.8.

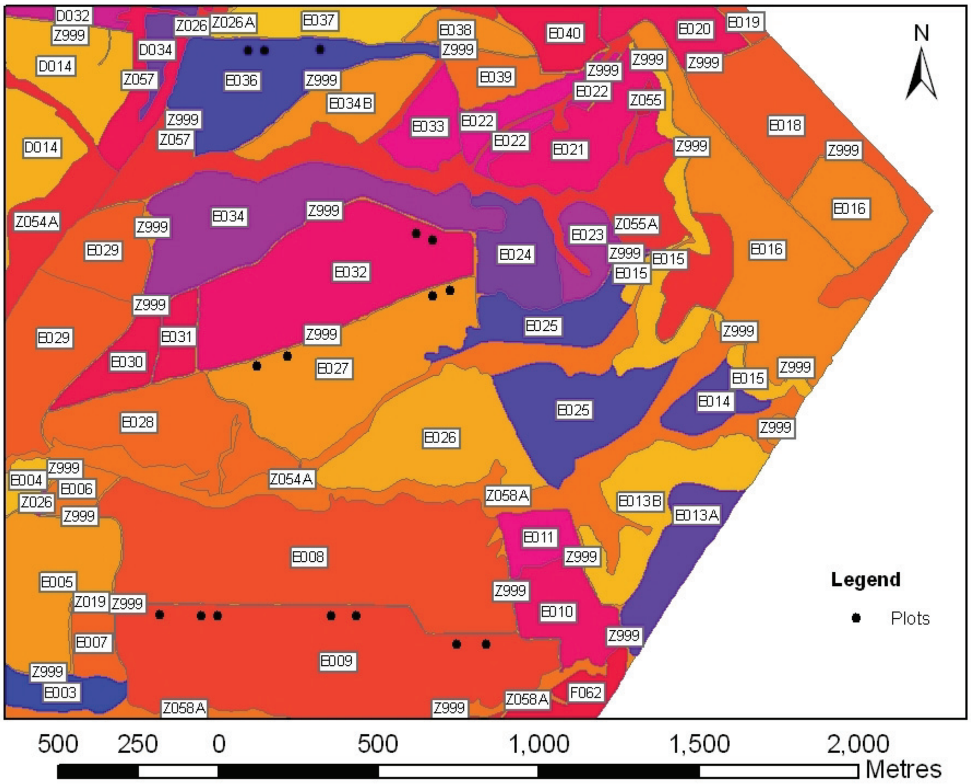


Figure 3.6. GIS coverage of the compartments showing Mondi's identification codes. The location of the sample plots is shown in black.

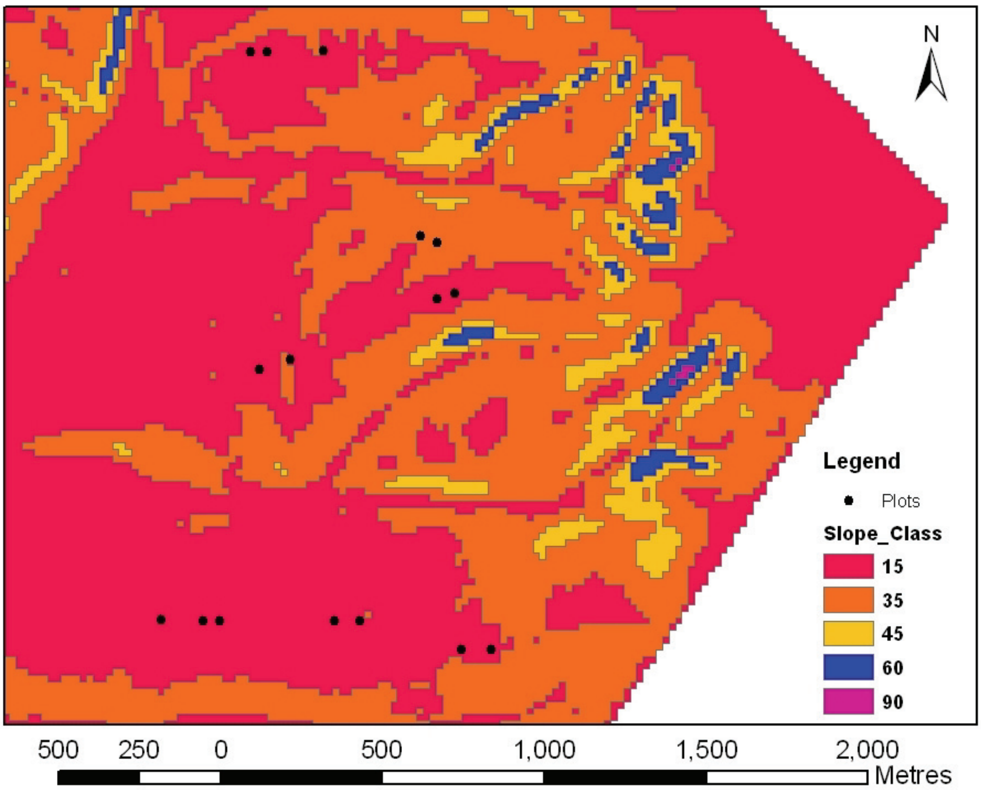


Figure 3.7. GIS coverage of the slope within the study area. The location of the sample plots is shown in black.

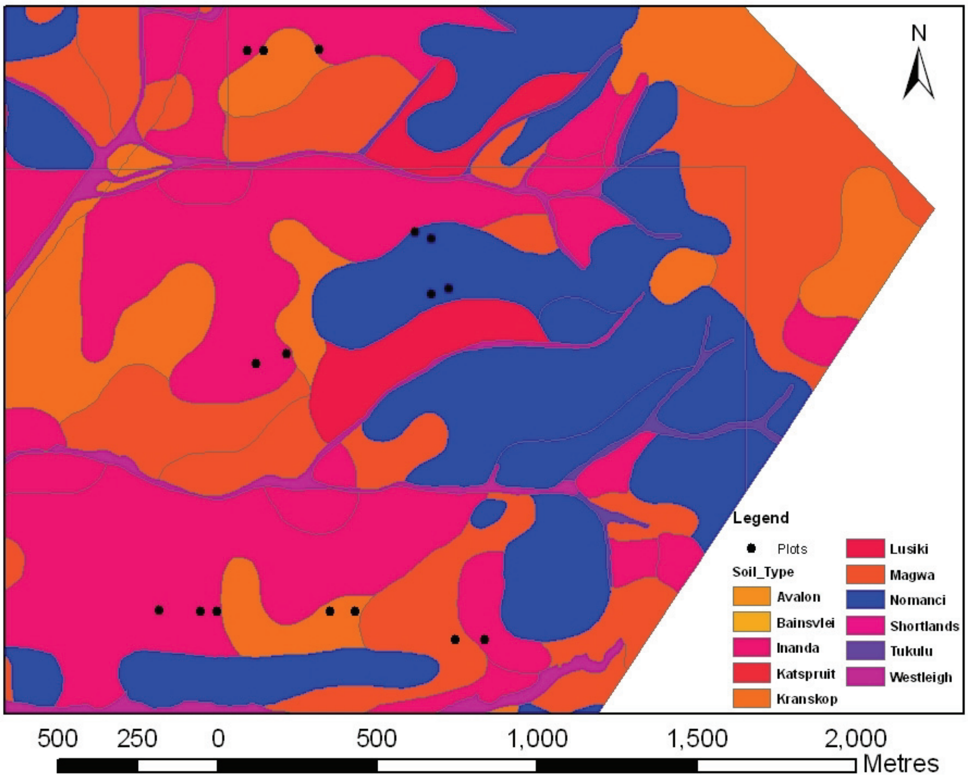


Figure 3.8. GIS coverage of the soils found within the study area. The location of the sample plots is shown in black. The soil form is shown (Soil Classification Working Group, 1991).

The majority of road networks in the region were designed and constructed to support the cultivation of sugarcane. As the frequency of access was much higher when the area was under sugarcane as compared with timber, an extensive road network exists. The general layout of the road system was the construction of a main thoroughfare along the spur of the hillslope with numerous side-roads running the length of the contour. Historically these side-roads crossed the drainage divides but this has been corrected when the area was converted to timber. Lateral roads stop just before entering the drainage divide. Nevertheless, the road network density at the Seele Estate may be higher that would normally be required to support efficient forestry operations (Hurd, 2008 pers. comm.).

All data is processed and analysed within the ARCVIEW GIS platform, although for modeling using the GEOWEPP model, it was necessary to carry out the tasks within the ARCGIS environment as this is the platform upon which the model is based. An example of the information in the database is given in Figures 3.9 and 3.10. Individual road segments were further differentiated according to gradient (Figure 3.11).

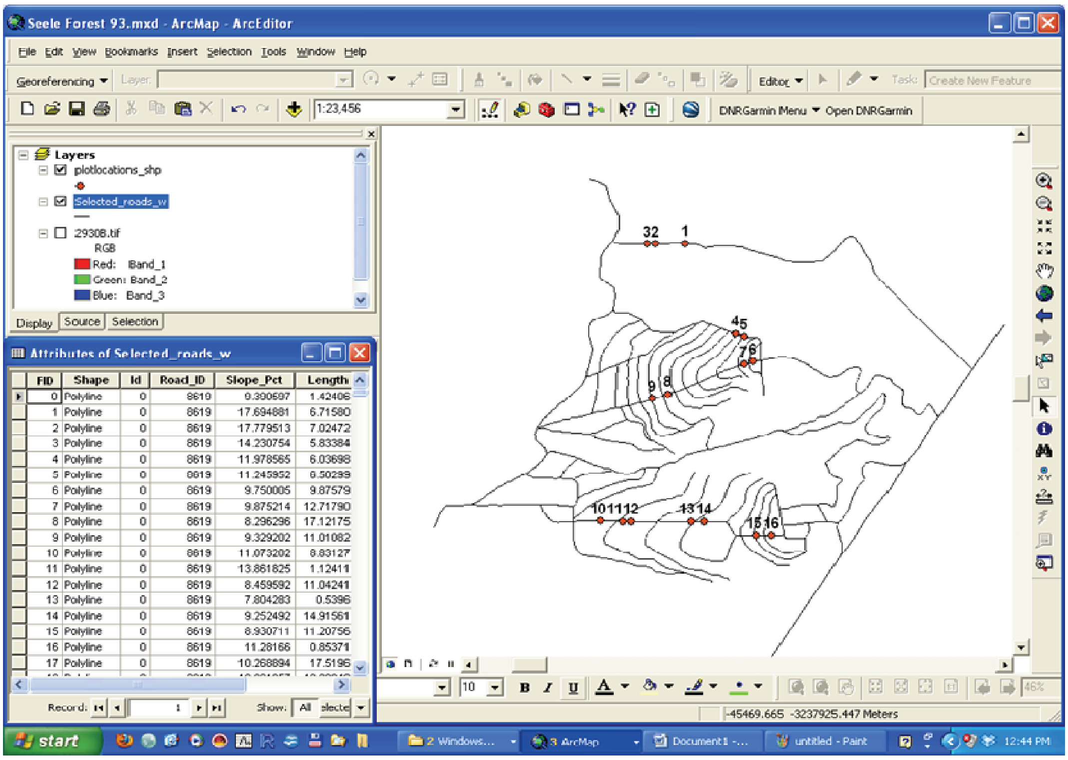


Figure 3.9. Screen shot of the ArcView 3.3 project with road network, gradient of the segment of road sampled and to be used in run-off plot investigation and attribute table with road segment length and gradient.

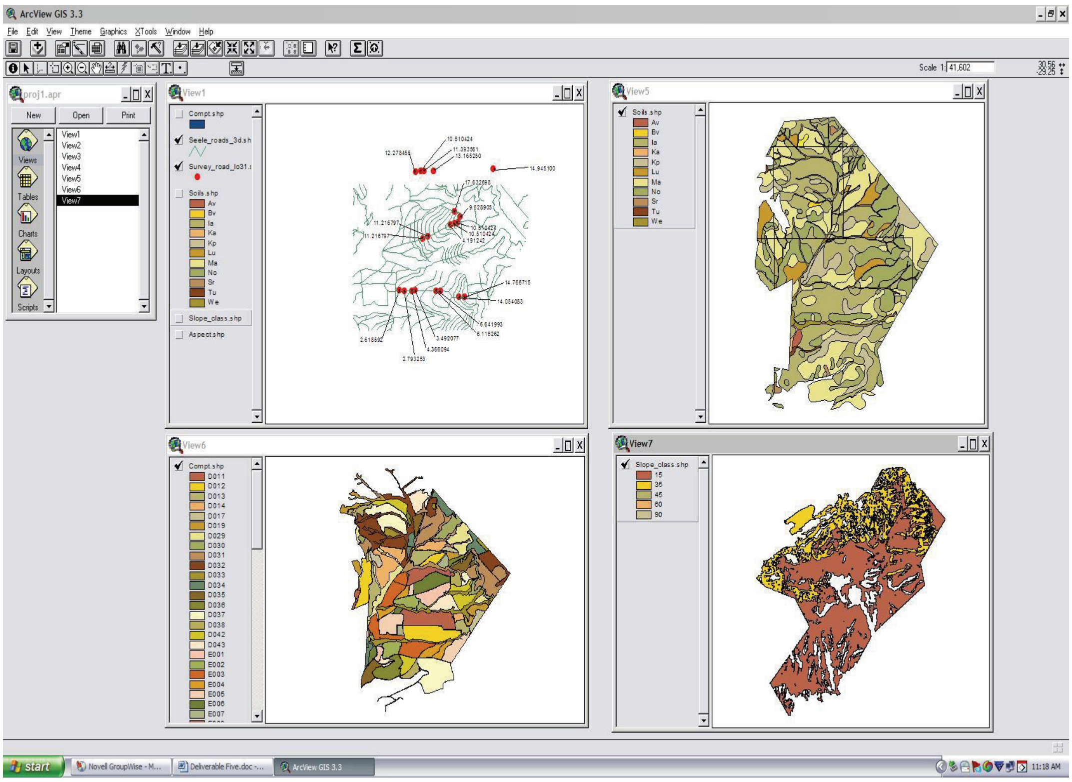


Figure 3.10. Example of ArcView 3.3 project illustrating the collected GIS vector data with attributes.

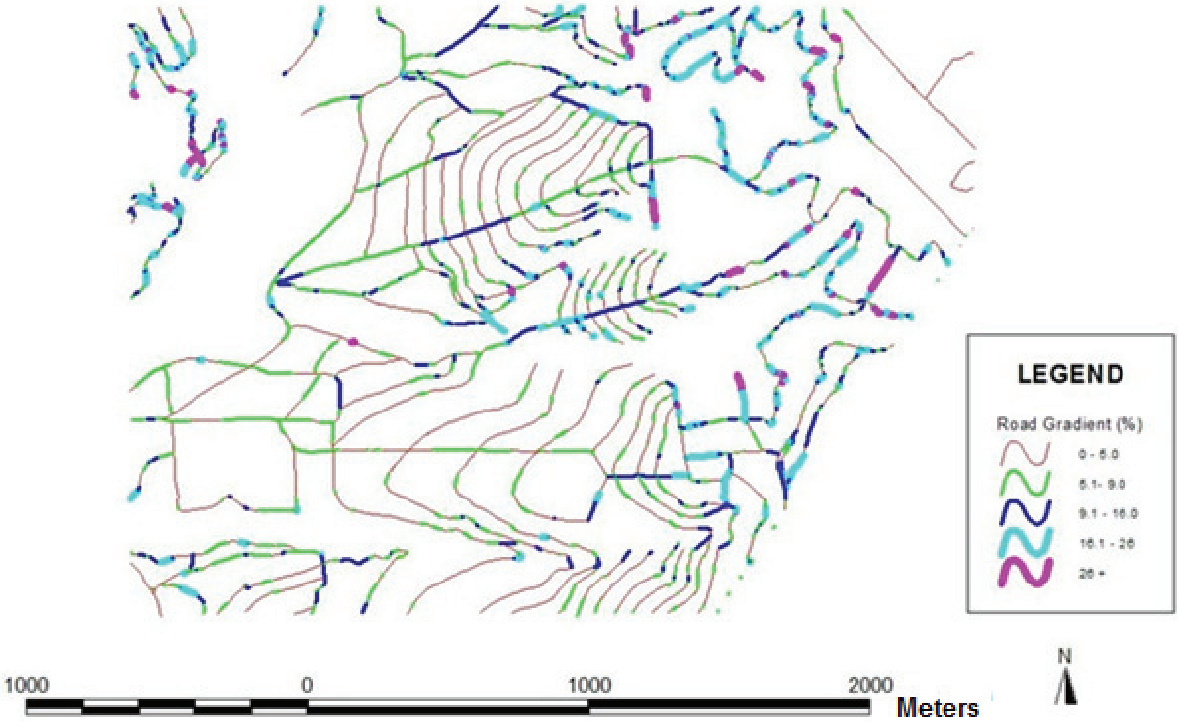


Figure 3.11. GIS coverage of the network of access roads in the study area differentiated according to road gradient. The gradient of individual road segments and its cumulative length is shown in Table 3.1.

Table 3.1. Cumulative length of individual road segments .

Percentage Gradient (%)	Road Length (km)	Percentage of Total
0-2.0	14.230	24.0
2.1-5.0	16.348	27.0
5.1-8.0	10.456	17.5
8.1-10.0	4.845	8.2
10.1-12.0	3.690	6.2
12.1-15.0	3.405	5.7
15.1+	6.948	11.7

Following from discussions at a workshop held in August 2008, a decision was taken to base the study within Eucalyptus plantations, although the Seele estate has stands of Wattle (*Acacia mearnsii*) and Pine (P*inus patula*). Consequently only those access roads serving the Eucalyptus compartments were considered further.

3.3 Measurement of Surface Runoff and Sediment Fluxes

There are two main methods that have been followed in estimating sediment production and runoff from forestry access roads. A few recent studies are provided in Table 3.2.

Table 3.2. Recent studies that have used rainfall simulation to measure runoff and sediment from forestry access roads.

Author	Experimental Approach	Plot Size	Rainfall Duration (min)	Rainfall Intensity (mm h^{-1})
Arnaez *et al.*, 2004	Rainfall Simulator	1385 cm^2	30	75
Croke *et al.*, 2005		300-600 m^2	30	75
Foltz *et al.*, 2009		1 m^2	30	100
Jordan and Martinez-Zavala, 2008		0.0625 m^2	30	72
Jordan-Lopez *et al.*, 2009		0.8 X 0.8 m	30	90
Martinez-Zavala *et al.*, 2008		0.48 X 0.48 m	30	90
Sheridan *et al.*, 2008		1.5 X 2.0 m	30	100

Rainfall simulators have been used with a measure of success to measure runoff and sediment from different parts of a road segment. In its generic form a rainfall simulator consists of a boom on the end of which is fitted spray nozzles capable of delivering water with varying velocities. The boom is connected to a pressurized water tank. The area of interest, which is usually small, is shuttered off from the surrounding environment and drained to a collection device. The experiment consists of subjecting the bounded area to simulated rainfall of a given intensity for a specified duration. Runoff and sediment is collected from this area, the results of which are then used to upscale the findings to larger areas. The main advantage of rainfall simulation studies are that they are relatively cost-effective to operate and allow for the quick collection of data. Despite this, rainfall simulation takes place at a single point in time, over a relatively small area and under a limited set of initial and instorm conditions. Notwithstanding its uncertainties in upscaling the research results to larger areas and natural conditions, this system allows for rapid measurements, especially in periods of rainfall uncertainty or drought. However, rainfall simulation studies are useful for replicated measurements on different terrains where detailed insights on the factors that regulate runoff and erosion rates are required.

The second approach has been the use of bounded or unbounded runoff plots in the presence of natural rainfall. In this system runoff and sediment is collected from a predetermined section of the road segment. In its bounded form the plot is fully isolated hydrologically from the surrounding environment whereas in its unbounded form the lateral movement of water into or out of the plot is possible. The latter unbounded design is preferred for the present study to monitor the movement of water from the forest compartments onto the road surface. A typical runoff plot consists of two main elements, namely an upper and lower boundary. The purpose of the upper boundary is to isolate upslope contributing areas (sometimes referred to as flow diversion barriers) whilst the lower boundary diverts water and runoff for collection.

In selecting the locations of the runoff plots the road network was first differentiated into gradient classes based on information obtained from the GIS roads coverage data (Figure 3.11). This was followed by field verification in which the length and gradients of the individual road segments were measured. From this population, sections of road with a uniform gradient and a length of approximately 24 m were identified and grouped into six gradient (%) classes namely 0-3; 3-6; 6-9; 9-12; 12-15 and > 15. Field inspection showed very little evidence of soil loss in the 0-3% gradient class so this was excluded from further consideration. Ten plots were chosen from this population based on gradient (2 per gradient class). The other six plots were distributed within two compartments that were due to be clearfelled. Table 3.3 shows the final plot locations.

After exploring a range of potential options for the construction of the plots, a system of preformed concrete gutters (Figure 3.12), each with a mass of approximately 80 kg, arranged end to end across the width of the road was selected. The gutters were custom manufactured for the purposes of this study. The mortar joints between adjacent gutters were sealed with a water proofing compound.

Table 3.3. Details of the sixteen road plots selected for this study. (A): Weathered bedrock exposed in places within the plot, (B) bare soil throughout the plot, (C) established grass cover.

Plot	GPS Lat	GPS Long	Elevation (m)	Slope Length (m)	Grad (%)	Width (m)	Area (m^2)	Gradient Class (%)	Road Surface Condition
1	29.23806	30.53848	1100	24.44	10.86	3.91	95.56	9-12	A
2	29.23827	30.52796	969	21.21	12.54	4.05	85.90	12-15	B
3	29.23831	30.52618	947	24.3	13.50	4.35	105.71	12-15	B
4	29.23834	30.52566	936	23.57	18.43	3.18	74.95	>15	A
5	29.23842	30.52475	927	26.65	15.96	3.6	95.94	>15	A
6	29.24375	30.53156	996	24.5	10.30	2.84	69.58	9-12	C
7	29.24442	30.53264	1019	25.1	11.55	4.1	102.91	9-12	C
8	29.24517	30.53213	1021	22.96	10.51	3.6	82.66	9-12	B
9	29.24528	30.53154	1018	24.21	10.63	3.88	93.93	9-12	B
10	29.24553	30.53089	1008	23.28	3.09	3.88	90.33	3-6	B
11	29.24703	30.5269	979	23.9	4.49	3.64	87.00	3-6	B
12	29.24729	30.52592	965	24.87	3.86	3.33	82.82	3-6	B
13	29.25424	30.52178	921	26.95	6.33	3.36	90.55	6-9	B
14	29.25429	30.52272	934	24.8	7.24	3.24	80.35	6-9	B
15	29.25427	30.52407	931	28.25	13.89	2.73	77.12	12-15	A
16	29.25421	30.52459	932	25.5	15.84	3.09	78.80	>15	A

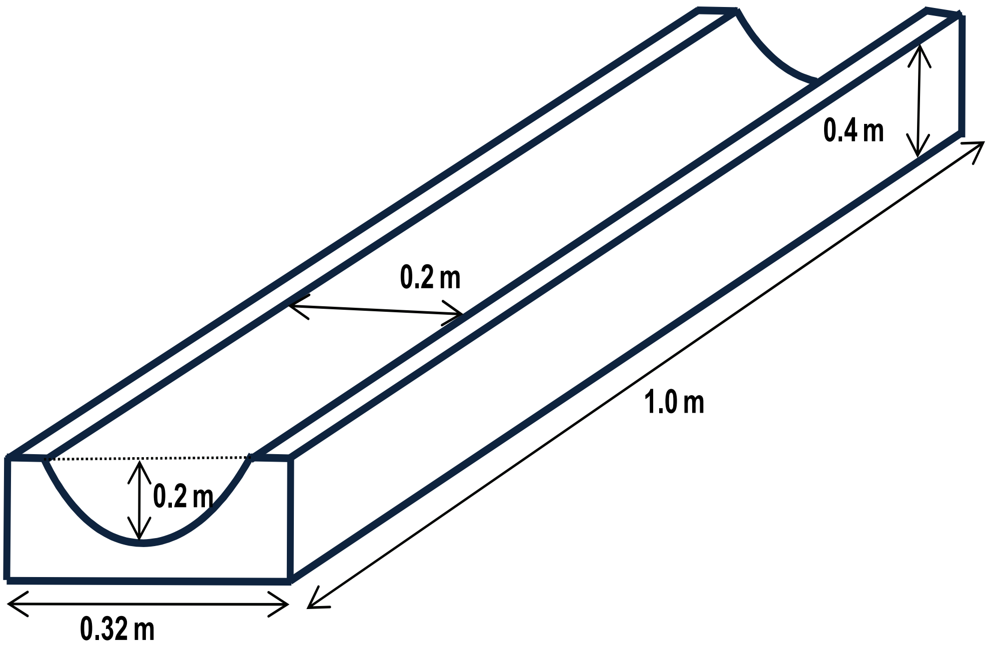


Figure 3.12. The gutters used in the construction of the runoff plots. Individual gutters were joined end to end across the width of the road.

The top of the gutter was set flush with the road surface by excavating a trench during its installation. Figure 3.13 shows the installation process for the gutters whilst Figure 3.14 shows the installed gutter across the width of the road.

Figure 3.13. A trench of was dug across the road for installation of the concrete gutters.

Figure 3.14. The completed gutter installed flush with the road surface.

The gutters were set at a slight incline to favour the gravitational flow of water. Water collecting in the upslope gutter was directed into the compartment via a V- shaped trench. Gaps between adjoining gutters were sealed with an epoxy based compound to form a water-tight seal. The plot length (distance between gutters) has been set at approximately 24 m. Due to the variable width of access roads within the catchment it was not possible to fix a specific plot width, although the width of the plots ranges from 4.2 m to 5.6 m.

Observations made during the late summer season of 2008 suggested that the gutters themselves act as efficient sediment traps. This had a bearing on the final design for the collection of runoff and sediment. A schematic representation of the complete system is given in Figure 3.15.

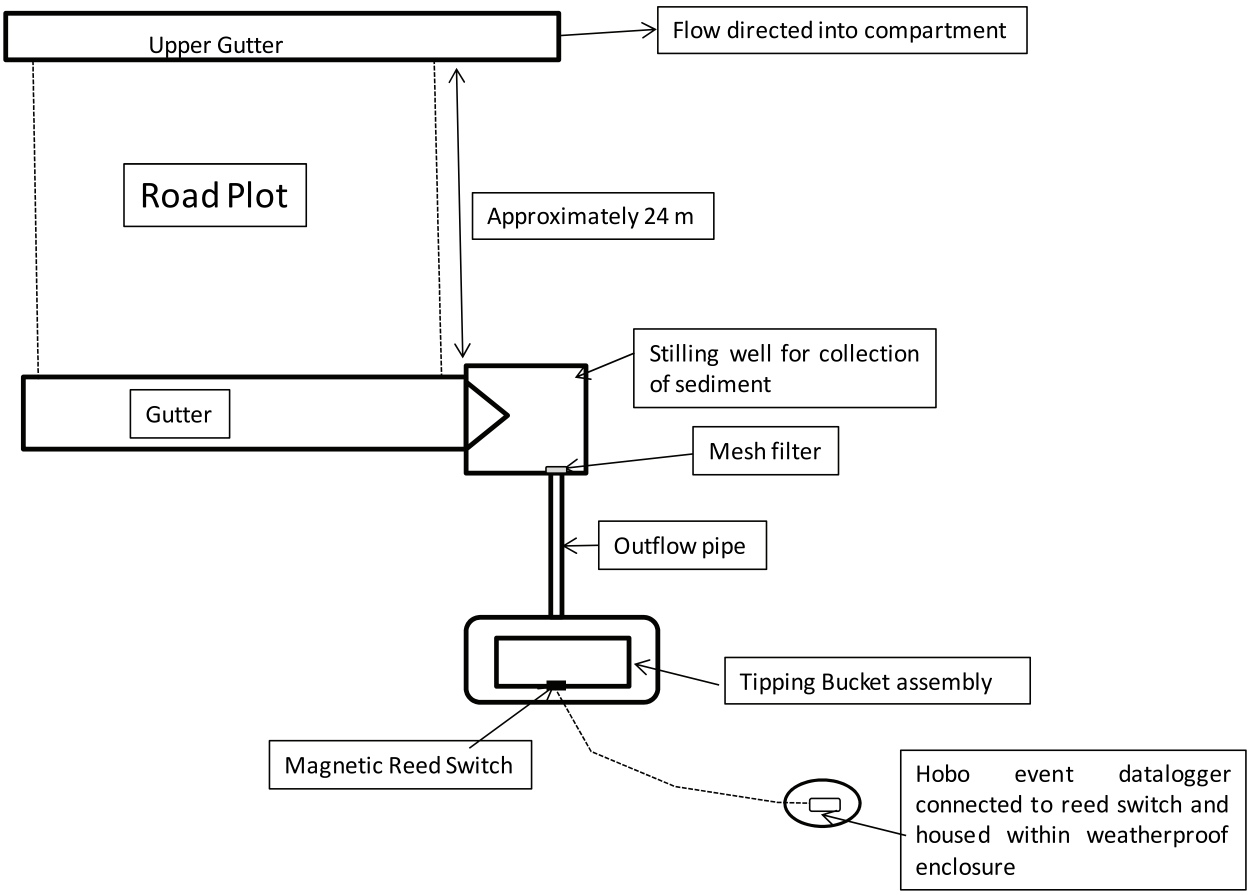


Figure 3.15. The schematic layout of the complete system used to measure runoff and sediment from the road plots.

Water flowing from the gutter is directed into a stilling well, constructed from 210L plastic drums that have been cut in half along its length. This was installed flush with the soil surface below the gutter and secured by a band of concrete along its edge (Figure 3.16).

Figure 3.16. Water flowing within the gutter is directed into a stilling well. These were constructed from 210 L plastic drums that were cut in half lengthways.

The water flowing out of the stilling well is directed through a 110 mm external diameter pipe to a tipping bucket assembly. A polyurethane mesh restricts the large particles from entering the pipe. The design of the tipping bucket is based on recommendations provided by Black and Luce (2007).

A tipping bucket consists of a container divided into two equal volumes that are balanced about an axle. Water is allowed to enter one container at a time. As the bucket fills the system becomes unstable and the heavier side tips and empties. As the bucket rotates about its axle to empty, a magnetically actuated reed switch records the passage of a magnet that is attached to the side of the bucket. The opposing side is now in position to accept the incoming water and the process repeats. This is the same principle applied in the functioning of automatic raingauges. A Hobo Event logger (Onset Corporation) records the time of closure of the reed switch. This time stamp allows for the calculation of the time that it takes to fill the bucket. The device is calibrated to determine the relationship between discharge and switch closures which, when applied to the record affords the development of a high resolution continuous hydrograph. A schematic illustration of the bucket developed by Black and Luce (2007) which has been copied for use in this study is shown in Figure 3.17. The bucket was stabilized by embedding the steel supports in 50 mm thick concrete.

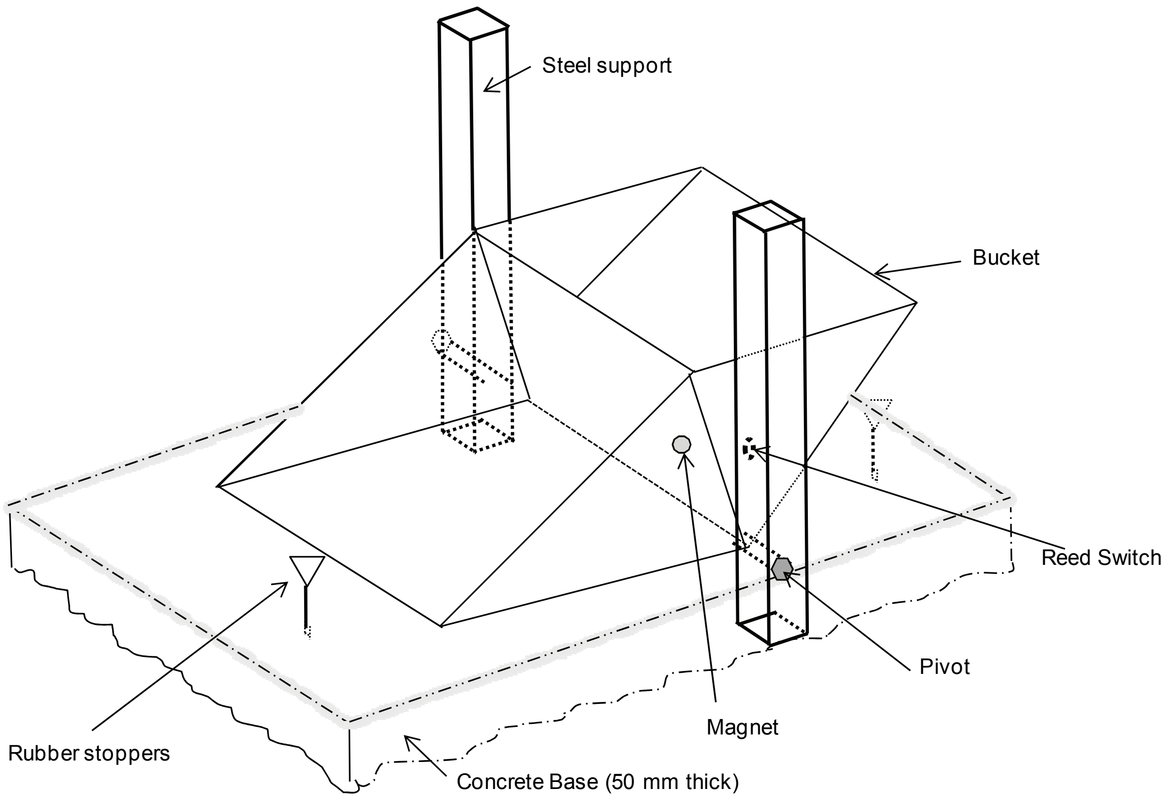


Figure 3.17. Schematic representation of the tipping bucket assembly. The bucket design was developed by Black and Luce (2007) which was duplicated for use in this study.

Since this is a gravity driven system the height of the tipping bucket had to be lower than that of the gutter exit point. On the steep slopes this was much easier to achieve but on the more gentle slopes the tipping bucket had to be installed within a pit excavated to the correct depth. Additional earthworks were necessary to drain the pit. This meant that the length of the pipe and therefore the relative position of the tipping bucket is variable between the plots. Each plot was individually calibrated by determining the volume of water and the time that it takes for the water (poured into the upper end of the upper gutter) to cause the first tip of the bucket. The data is then corrected for in calculating the rates of runoff.

Construction of the runoff plots began in April 2008 and was completed by the end of winter whilst the installations of the tipping buckets were completed in early summer. Figure 3.18 shows the completed runoff monitoring system.

Figure 3.18. Water from the stilling well is directed to the tipping bucket. A Hobo event logger records the number of tips. A: lower gutter, B: stilling well, C: 110 mm inflow pipe, D: tipping bucket, E: Hobo Event datalogger enclosure, F: drainage trench.

During the early rains of 2008 several minor modifications had to be made to the runoff plots to improve its operation notably with regards to the tipping bucket mechanism. The buckets were initially designed for the collection of runoff but it soon became apparent that the additional weight caused by the entrapment of sediment within the bucket was influencing both its calibration and its engineering tolerance as the pivots on which the buckets rotate kept snapping. This was solved by adding a finer filter mesh at the inlet of the pipe (within the stilling well) to further decrease the sediment load carried in suspension to the tipping bucket and strengthening the bucket pivots.

3.4 Collection of Sediment

During each site visit the total mass of soil collected from each plot was measured and then mixed thoroughly to ensure homogeneity in water content. A subsample of material was then taken and allowed to air dry at room temperature until there was no further significant loss of mass. This water content was then used to express the field mass on an equivalent air dry basis. A further sample of air-dry soil was then passed through a nested sieve stack consisting of sieves with an aperture opening of 4 mm, 2 mm, 1 mm, 0.5 mm, 0.125 mm and 0.063 mm in order to determine the particle size distribution of the sediment.

3.5 Cross – Profile Sampling

The processes of scour and deposition of material from the road surface will cause changes in its microtopography. By knowing the rate at which this occurs, it is possible to infer zones of active erosion and deposition. Further, albeit crude, by knowing the volumetric change that occurs and the bulk density of material of the soil it becomes possible to assess the rate of soil movement on a mass basis. There are more elegant ways of accomplishing this such as the use of sediment tracers but this technique is almost always associated with high sampling and analysis costs. A more simple and cost effective technique which has been used successfully in past studies has been the use of fixed point changes in elevation. Using this principle a further set of experiments was designed to assess the movement of sediment on the road surface.

Wooden posts were installed on either side of the width of the road (Figure 3.19). A string knotted at 100 mm intervals was stretched taught across the width of the road, leveled and secured to each post using eye nuts. The depth from this reference level to the road surface was measured in order to determine its cross-profile. The eye nuts were left permanently attached to the posts so that the measurements can be accurately repeated.

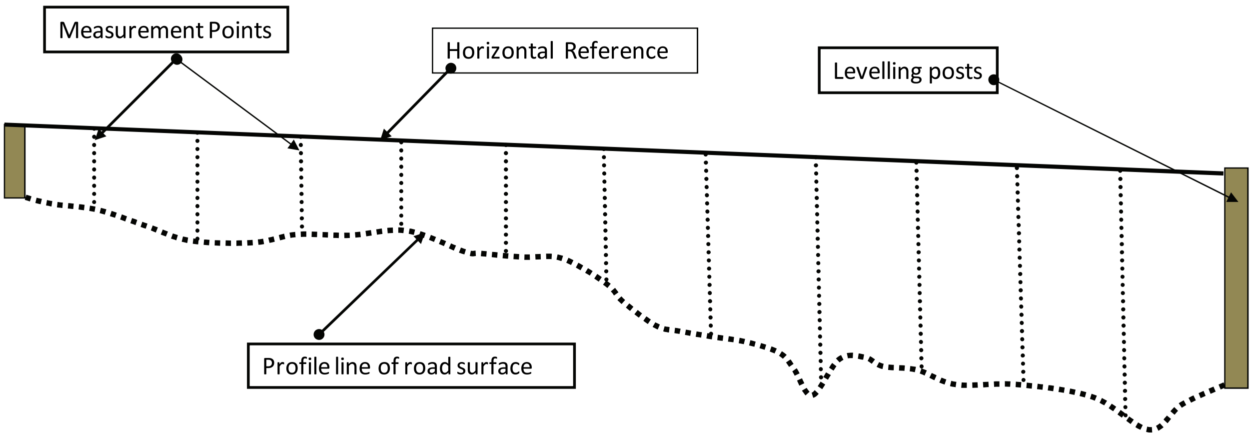


Figure 3.19. Schematic representation of the method used to measure the cross-profile of the road surface. The first measurement becomes the reference state.

Using this technique the first measurement becomes the reference state. As the road surface scours the distance from the reference level will increase whilst the opposite applies during soil deposition. Therefore over time the change in the road cross-profile can be assessed. All measurements are corrected for the distance between the reference level and the soil surface at the shorter post, to facilitate comparisons between the different measurement points in the catchment. The location of the cross-profile measurements were based on road gradient, soil type and age of compartment and are distributed throughout the catchment (Table 3.4, Figure 3.20). For selected plots three cross-profile transects were established, namely on the upper, middle and lower end of the 24 m long plot.

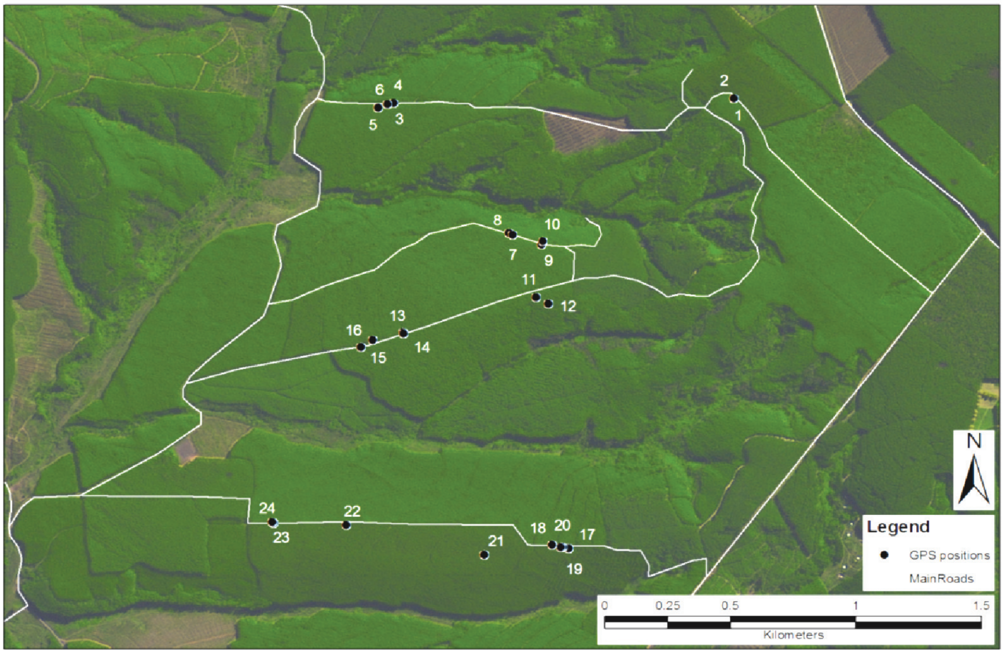


Figure 3.20. Location of road profile transects within the study area.

Table 3.4. Locations and average slope gradient of base-line profiles within Seele Estate.

Profile	GPS POINTS		Slope
	Latitude (S)	Longitude (E)	(%)
1	29.23817	30.53847	9
2	29.23817	30.53847	9
3	29.23834	30.52627	7
4	29.23838	30.52604	7
5	29.23852	30.52571	7
6	29.23852	30.52571	7
7	29.24326	30.53041	11
8	29.24331	30.53055	11
9	29.24369	30.53158	9
10	29.24357	30.53162	9
11	29.24568	30.53138	5
12	29.24592	30.53182	5
13	29.24701	30.52661	7
14	29.24706	30.52663	7
15	29.24731	30.52553	6
16	29.24757	30.52509	6
17	29.25517	30.53256	6
18	29.25512	30.53233	6
19	29.25512	30.53227	6
20	29.25504	30.53195	6
21	29.25542	30.52952	5
22	29.25429	30.52457	3
23	29.25423	30.52196	2
24	29.25418	30.52191	2

3.6 Impact of Unpaved Roads on Soil Water Movement through the Hillslope

The influence of roads on hillslope hydrology has been the subject of recent interest although there have been limited studies that have specifically focused on evaluating the extent of this interaction. To this end a further experiment was designed with the objective of evaluating the extent to which roads may intercept the movement of water within the hillslope.

In selecting a site within the estate upon which to base the study two key factors had to be met, namely the road had to be in a switchback configuration which means that it had to have sharp bend on a steep incline and secondly, the compartment had to be newly established. If the study were to be undertaken within a mature compartment then the effect of differential light penetration as a consequence of the road could have a bearing on tree growth and could mask the effects of soil water interaction. These criteria were met in selecting a site that was recently harvested and replanted to Eucalyptus. The layout of the site is shown in Figure 3.21 whilst a schematic illustration of the experimental layout is shown in Figure 3.22.

Figure 3.21. The site selected for the hillslope soil water movement study. This compartment was replanted in November 2008.

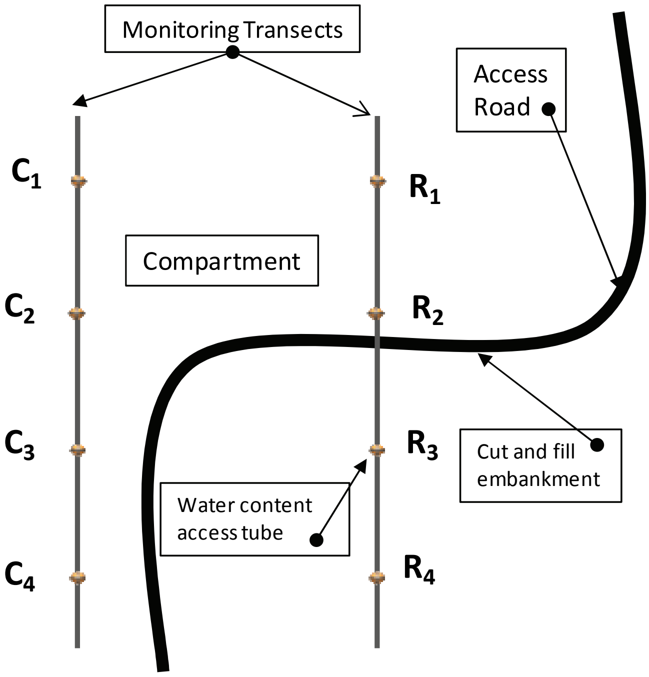


Figure 3.22. Schematic layout of the hillslope soil water movement study. The left transect serves as the control. Soil water content to a depth of 0.65 m was measured using the Diviner 2000 probe.

The bend in the road occurs approximately one third the way up the slope and extends almost the length of the contour before turning and running upslope almost parallel to the drainage divide. A cut and fill embankment has been created where the road extends along the contour. The road bed has a slight negative camber which means that the road is drained along the headwall (i.e. on the upslope side). The height of the cut embankment varies between 2 to 2.5 m. Two 150 m long transects were established. The first transect does not intersect the road and serves as the control or reference condition. The second transect has been sited such that it intersects the road and extends into the lower section of the compartment. Along each transect, soil water contents were measured.

3.7 Movement of Water into Compartments

Water flowing along access roads is periodically discharged into the adjoining compartments via drains. Berms constructed across the roads may aid this process by slowing down and redirecting the water to the drains. The hydrological significance of this practice in terms of water and sediment dynamics is lesser understood more especially when viewed against timber growth parameters. To explore this aspect, a further experiment was established within the study area. Two sites within the Seele Estate were selected for this study, namely a mature stand and a newly established stand that was planted during February 2009 (Figures 3.24 and 3.26). The latter site was burnt prior to planting and therefore had significantly less litter on the soil surface compared with the mature stand. The rainfall received at both sites is represented by the lower raingauge. It was not possible to directly measure the actual amount of surface runoff received at the road drain as installation of a tipping bucket would require that the flow of water be redirected. However, an adjacent plot with similar characteristics as the road segment had been instrumented for collection and measurement of runoff and these results provided an indicator of the range in the volume of water that could be received within the compartment. Thus, all direct measurements relied on relative changes in water content, especially its spatial distribution within the area of interest.

The objective behind the experimental design was to track the movement of both sediment and road discharge into the compartment. Diviner 2000 access tubes were installed within the compartment in an outwards radial configuration from the median of the drainage line.

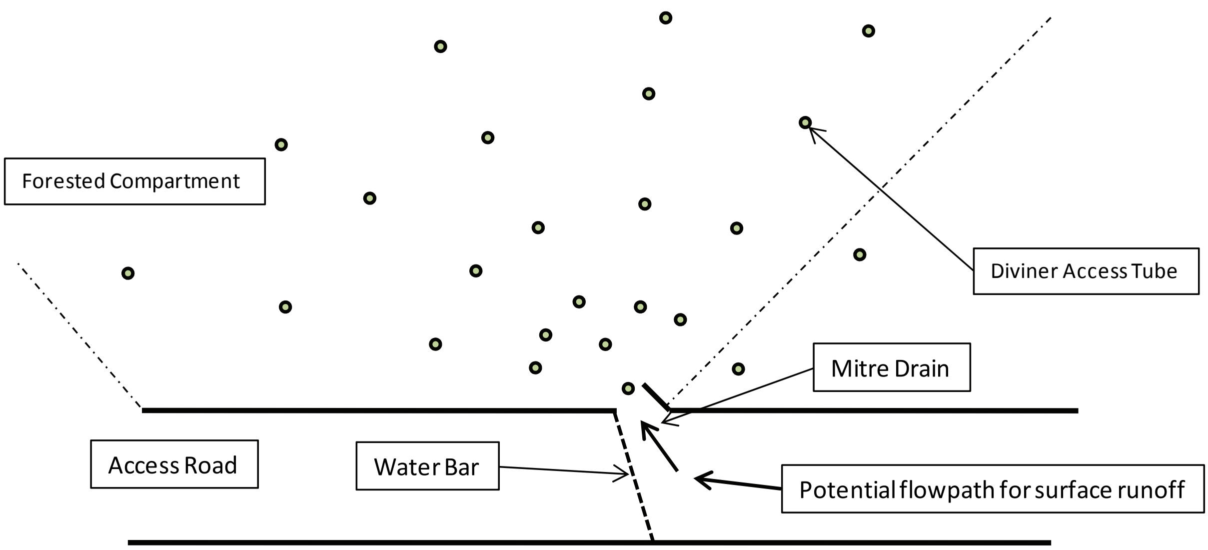


Figure 3.23. Schematic representation of the approach followed in determining the movement of water and sediment from the road into the forestry compartment.

Figure 3.24. Location of the road drainage experiment being conducted in a compartment that was replanted in November 2008.

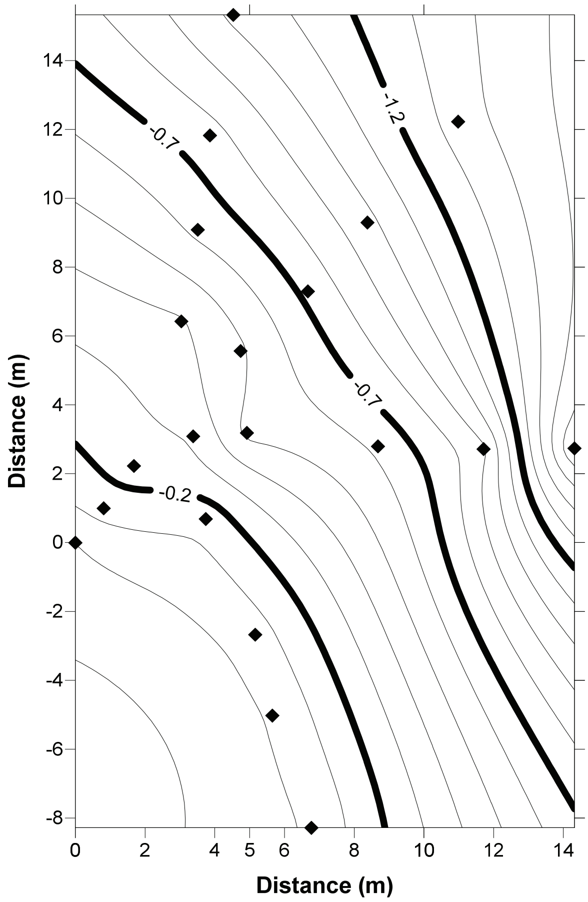


Figure 3.25. Contour map of the site that was replanted in November 2008 showing the relative position of the Diviner access tubes. The black dots represent the location of the access tubes.

Figure 3.26. Location of the road drainage experiment being conducted in a mature compartment (E008).

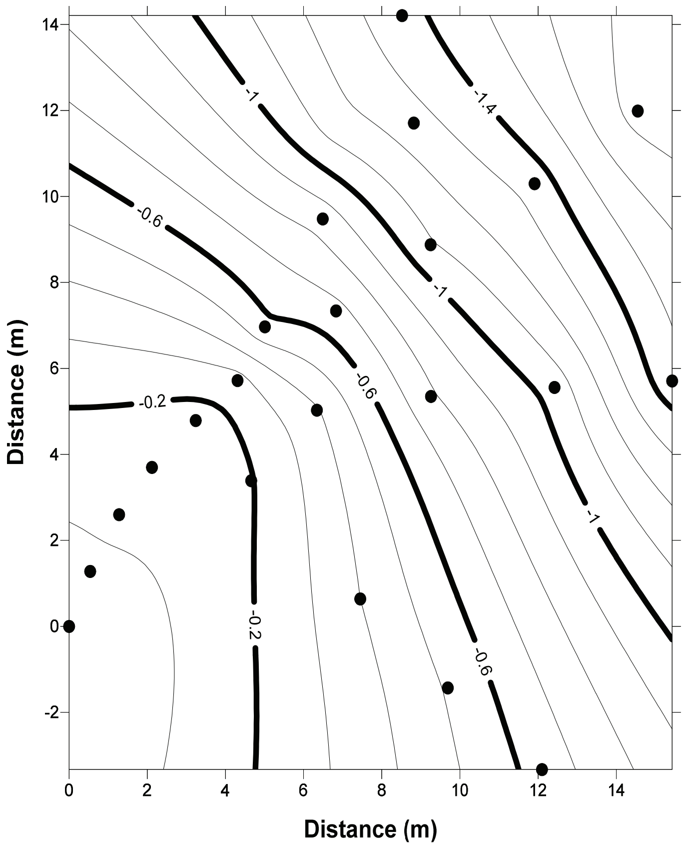


Figure 3.27. Contour map of the site under a mature canopy showing the relative position of the Diviner access tubes. The black dots represent the location of the access tubes.

3.8 Soil Water Content

Soil water content measurements were made using the Diviner 2000 capacitance probe manufactured by the Sentek Corporation in Australia (www.sentek.com.au). This system relies on the principle that the dielectric property of soil is a function of its water content. A dielectric may be regarded as a being any substance that does not conduct direct electrical current but permits the passage of lines of force associated with an electromagnetic field. Water has a relatively large dielectric constant compared with mineral soils and air. Topp *et al.* (1980) was one of the earliest researchers to show that the measurement of the time taken for an electrical impulse to traverse a transmission line which is buried in or filled with soil is uniquely related to the water content of the soil. In traditional time domain reflectometry (TDR) systems, the time taken for signal to traverse a transmission line buried in soil is measured and related via a calibration relationship to water content. In frequency domain reflectometry, upon which the Diviner system is based, the incident signal combined with the reflected signal generates a standing wave. The voltage of this standing wave acts as a simple measure of the water content of the soil. These two parameters are related via a calibration relationship.

The Diviner 2000 capacitance probe consists of a controller unit and a portable probe. To take measurements the probe is lowered into a PVC (internal diameter = 51 mm) access tube that is installed permanently in the soil at the point of measurement. The probe measures water content at depth intervals of 0.10 m to a maximum depth of 1.0 m. The advantage of the system is that measurements can be made fairly rapidly as the sensor has a fast response and all readings are stored in the memory of the controller unit for later download and interpretation.

3.9 Rainfall

Rainfall was measured using two automatic tipping bucket raingauges connected to a Hobo event logger.

Figure 3.28. The upper and lower raingauges used to record the variability in rainfall within the catchment.

The compartment wherein the lower raingauge (930 m.a.s.l) was located had been felled, burnt and replanted a month earlier whereas the upper raingauge (996 m.a.s.l) was located within a compartment roughly six months older. Thus, at the start of the experiment it is probable that the effect of canopy interception at these locations would have been limited. In addition manual type raingauges were positioned alongside plots 1,2,4,6,7,8,10,12 and 15 with the aim of measuring the cumulative rainfall received at each plot between site visits. Since these gauges were located within the mature canopy it is probable that these raingauges would have been influenced to some extent by rainfall interception losses.

3.10 Infiltration

Infiltration was measured following the double-ring infiltrometer method (Vanderlinden *et al.*, 1998). Two steel sharpened rings were gently pushed or lightly hammered into the soil just deep enough to prevent lateral leakage of water. The inner and outer rings were filled with water and the time taken for the level in the inner ring to fall by 50 mm increments was determined. The level of water in the outer ring was maintained constant with that in the inner ring. Water in the inner ring was replenished when the ponded head had disappeared. Thus the infiltration rate as a function of time was obtained. Measurements continued for an hour after steady state was obtained in order to obtain the field saturated hydraulic conductivity (K_{sf}).

3.11 Penetrometer Soil Strength

The mechanical strength of soil is a useful indictor of soil physical condition. Soil mechanical strength provides anchorage for roots and can therefore have both a direct and indirect effect on the growth of trees. The measurement of soil strength in the field is often undertaken using a choice of two types of instruments namely a torvane or a penetrometer. The torvane is specially designed to measure the shear strength of soil which relates to the frictional resistance that individual soil particles overcome when they are forced to slide over one another or move off interlocking positions. Penetrometers are instruments consisting of a conical probe (mounted on a shaft) which is usually driven into the soil at a constant rate. The penetrometer resistance is the force per unit basal area of the cone. The greater the force encountered by the probe the larger is the penetrometer soil strength (PSS).

A constant recording penetrometer manufactured and marketed by Geotron Systems, South Africa was used to conduct PSS measurements. The instrument was operated by driving a stainless steel cone (apex angle of 300^o and a basal area of 130 mm^2), mounted at the end of a 0.80 m shaft (10 mm in diameter) vertically into the soil. Insertion of the probe is aided by a chain drive gear mechanism (winding ratio 4.8:1) that is operated by turning two handles on the upper end of the instrument. A footplate ensures stability of the unit during its operation. The rate of penetration of the probe into the soil is 1 m min^{-1} at 1 second per revolution. A pressure loadcell attached to the shaft measures the resistance encountered by the probe in kilopascals at 1 mm depth intervals. The maximum pressure and depth that can be measured is 5 MPa and 0.80 m respectively. All readings are stored electronically in the memory of the controller unit which is then downloaded for interpretation. PSS is being measured at selected positions throughout the catchment. At each point of measurement readings were taken on the road surface and approximately three tree rows into the compartment on either side of the road.

Chapter Four

Measurement of Rainfall, Surface Runoff, Sediment Loss and Soil Water Movement

4.1 Rainfall

Two automatic raingauges were installed on site and a further twelve manual raingauges were located close to selected runoff plots (Figure 3.5). Figure 4.1 shows the mean monthly rainfall measured by the automatic raingauges and Figure 4.2 the daily rainfall for the region from November 2009 to April 2011. The long-term average monthly rainfall for the region as extracted from the rain atlas of South Africa is also shown (Zucchini and Nenadic, 2006). The rain atlas is a web-based interface for accessing a 16 parameter daily rainfall model that was developed by Zucchini and Adamson (1984) using daily rainfall data collected from 5070 measurement sites across Southern Africa.

In developing the model, the 16 parameters of the model were interpolated on a regular grid one minute of degree square throughout South Africa using a kriging technique that considered gradient, aspect roughness and exposure of the sites (McNeil *et al.*, 1994). This procedure provided parameter estimates for 424 624 sites, for each of which a 5000 year long artificial sequence of daily rainfall was generated. The model was run online using the exact co-ordinates (latitude and longitude) of the study area. The model outputs a wide range of rainfall statistics one of which is the mean monthly rainfall. The total rainfall measured at the Seele Estate between the 03/11/2009, when monitoring began, and the 08th April 2011 was 975 mm. The mean monthly rainfall ranged from a high of 147.6 mm in January 2010 to a low of 3.2 mm in May 2010. The distribution in monthly and daily rainfall shows seasonal trends with most of the rainfall taking place during the summer months. Summer rains lasted until the end of April. During winter, a few isolated storms occurred mostly due to the passage of cold fronts.

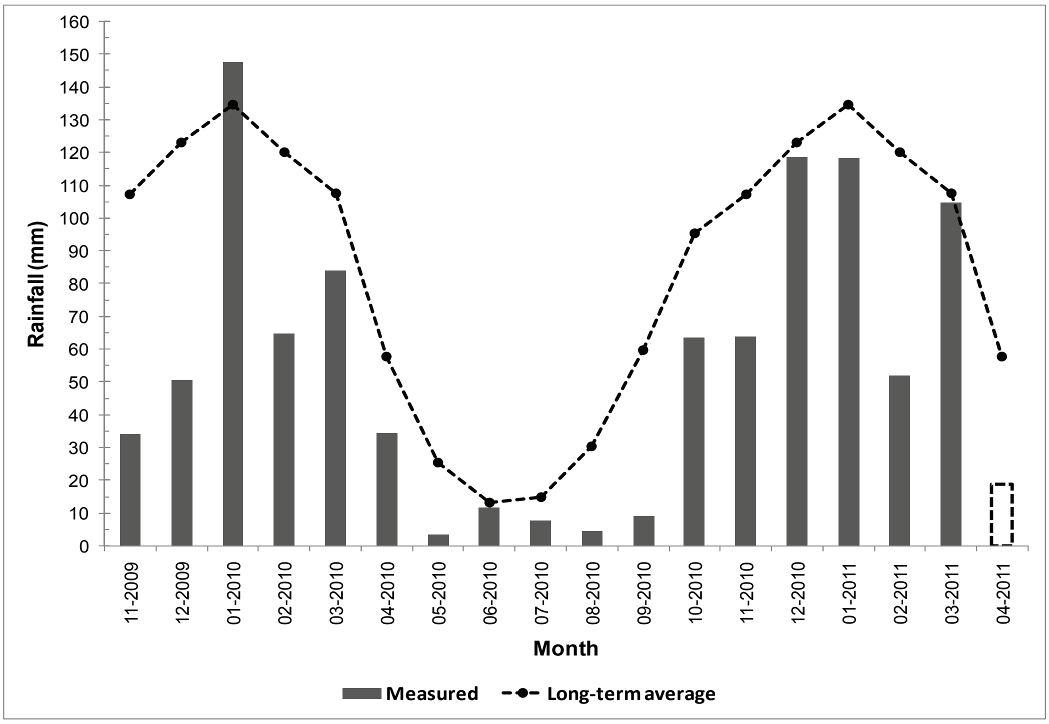


Figure 4.1. Monthly rainfall for the study site since monitoring began in November 2009. The long-term average rainfall for the region is also shown. The data for April 2011 is for the period 01^{st}-08^{th}.

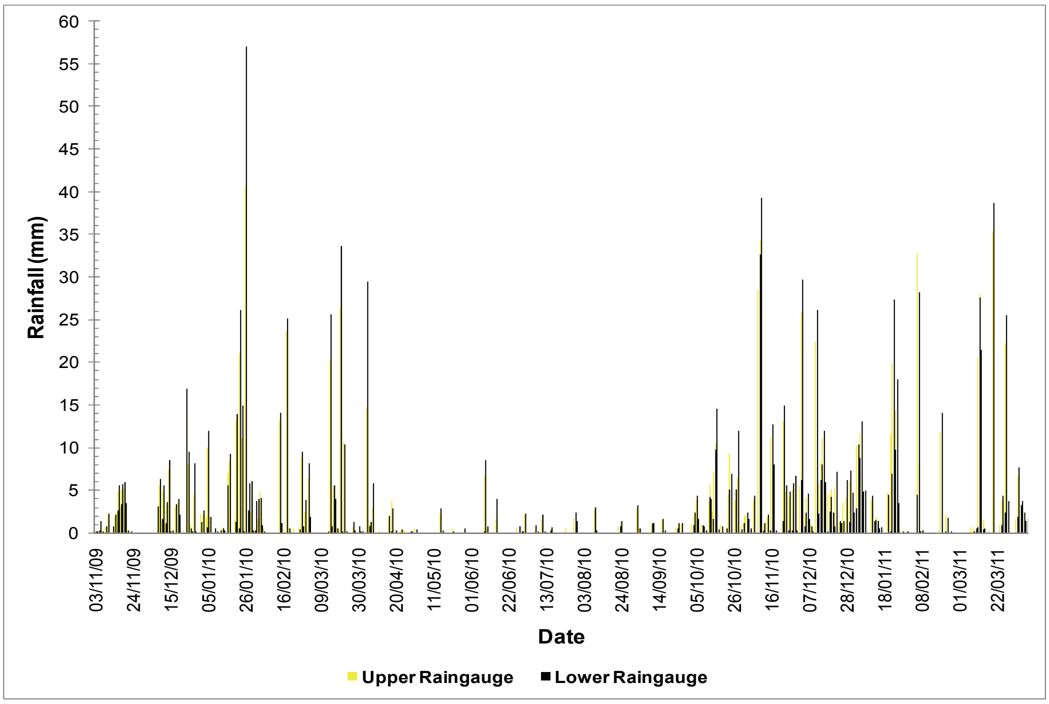


Figure 4.2. Daily rainfall received at the Seele Estate for the period 03/11/2009 until 06/04/2011.

Table 4.1. Mean monthly rainfall received at the Seele estate expressed as a percentage of the long-term average. The data for November 2009 and April 2011 does not represent a complete month.

Year	2009		2010												2011			
Month	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr
% of Monthly long-term average	*32*	41	110	54	78	60	14	89	53	15	15	67	60	96	88	43	97	*33*

With the exception of January 2010, the average monthly rainfall during the monitoring period was substantially less than the long-term average (Table 4.1). This was particularly noticeable for the normally wet month of February, when only 54% and 43% of the long-term rainfall average was received during 2010 and 2011 respectively. The winter of 2010 was also drier than normal. During August and September 2010 only 15% of the long term average rainfall for the region was received. These dry conditions are also represented in the daily rainfall record which showed only a few days that experienced rainfall greater than 20 mm.

The rainfall received at each of the two automatic raingauges showed good agreement (R^2 = 0.948) with each other, especially for rainfall events below 15 mm (Figure 4.3). Differences between the rainfall readings were found to be in the order of 5 mm larger rainfall events greater than 20 mm. Although altitude may account for such differences, the location of the gauges may have influenced the results. The upper gauge was located on a road verge adjacent to a compartment that had been replanted approximately six months earlier. The lower gauge was located on the road verge adjacent to a recently felled compartment and was in an open location. This difference in the level of canopy closure could have influenced the extent to which gross rainfall was lost through interception. There is, in general, a paucity of information regarding interception losses within eucalyptus plantations although Dye (1993) found canopy interception loss in a four year old *Eucalyptus grandis* stand to be only 4% of gross rainfall. Recently Everson *et al.* (2007) measured interception losses in a mature wattle plantation located within the New Hanover region to be approximately 45% of gross rainfall for storms < 5 mm. They further concluded that gross rainfall is reduced on average by approximately 24% for all storms.

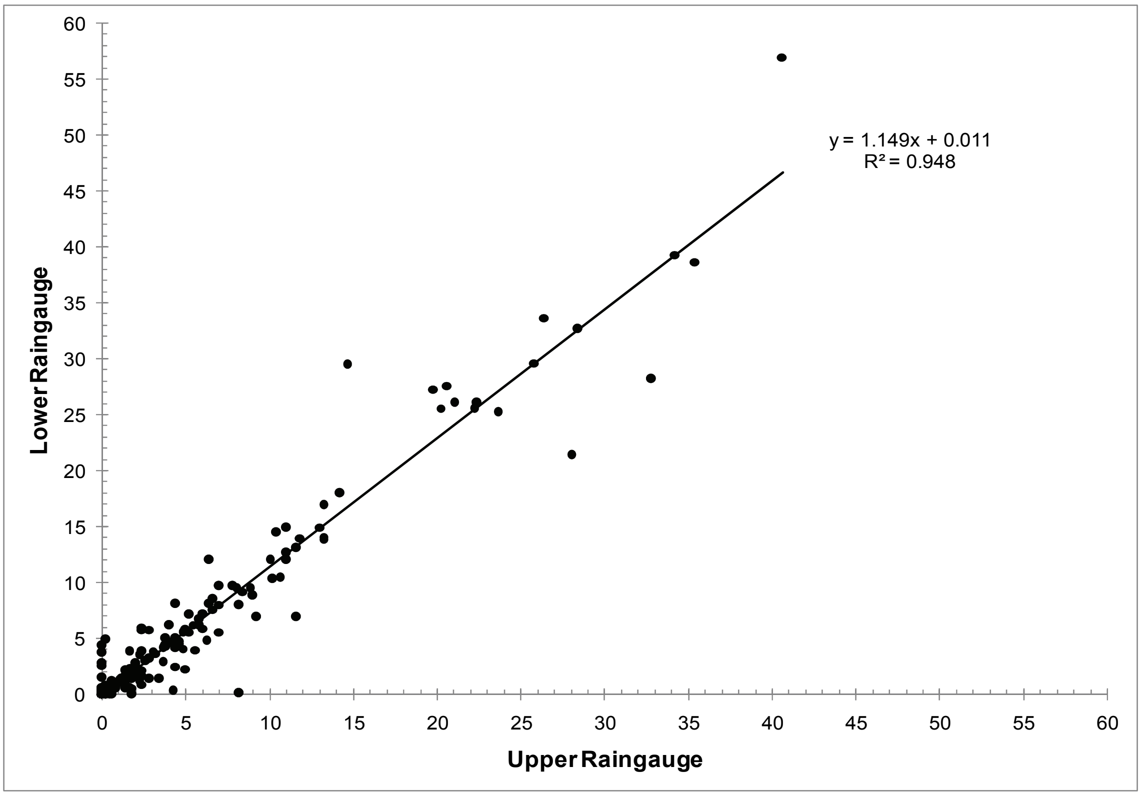


Figure 4.3. Comparison of rainfall received at the upper and lower raingauge at the Seele Estate.

Apart from the automatic raingauges a network of manual raingauges were installed adjacent to selected plots (Table 4.2).

Table 4.2. Rainfall received at the manual raingauges located near selected runoff plots.

Gauge Type	Plot	13/10 - 22/10 2010	22/10 - 03/11 2010	03/11 - 12/11 2010	12/11 - 26/11 2010	26/11 - 08/12 2010	08/12 - 21/12 2010	21/12 - 28/12 2010	28/01 - 11/02 2011
Manual Raingauge	1	-	32	78	52	70	75	>100	38
	2	-	32	95	55	65	75	>100	32
	4	30	40	85	60	74	85	>100	24
	6	30	32	70	43	55	76	>100	20
	7	28	32	80	50	58	75	>100	18
	8	30	34	60	44	60	75	>100	22
	10	32	36	75	55	55	75	>100	35
	12	32	36	80	62	62	75	>100	50
	15	30	32	75	56	55	70	>100	55
Mean		34	30	77	53	61	75	-	33
Automatic raingauge	*Upper*	*27*	*31*	*70*	*45*	*55*	*71*	*136*	*41*
	Lower	*32*	*31*	*79*	*50*	*59*	*71*	*157*	*33*

The data from the manual raingauges showed similar amounts of cumulative rainfall received at each plot for periods of low to moderate rainfall. Greater differences between these raingauges were, however, noted for the larger events due to differences in raingauge exposure which arises from the extent of canopy closure. However, the rainfall averaged across the manual gauges showed differences in the order of 2 mm when compared with the automatic raingauges.

When considering the relationship between runoff and rainfall a useful approach has been to differentiate the complete rainfall record into individual rainstorms by considering the time between the end of a rainstorm and the start of a new event. This time period is somewhat arbitrary and several time periods of no rain have been used to define individual rainstorms in previous studies. For example Ramos-Scharron and MacDonald (2007) chose an hour long period of no rain to separate rainstorms, whilst Mutchler *et al.* (1994) used a period of 6 hours of no rain to define individual rainstorms. In the current study the definition of Stocking and Elwell (1976) which was based in Zimbabwe was used where a precipitation event was separated from other events by a period of at least two hours of no rainfall. Following from this definition between the 3rd November 2009 and the 08th April 2011 there were 155 individual rain periods received in the region. The frequency distribution of these rainfall events is shown in Figure 4.4 while a list of the events is given in Appendix 1.

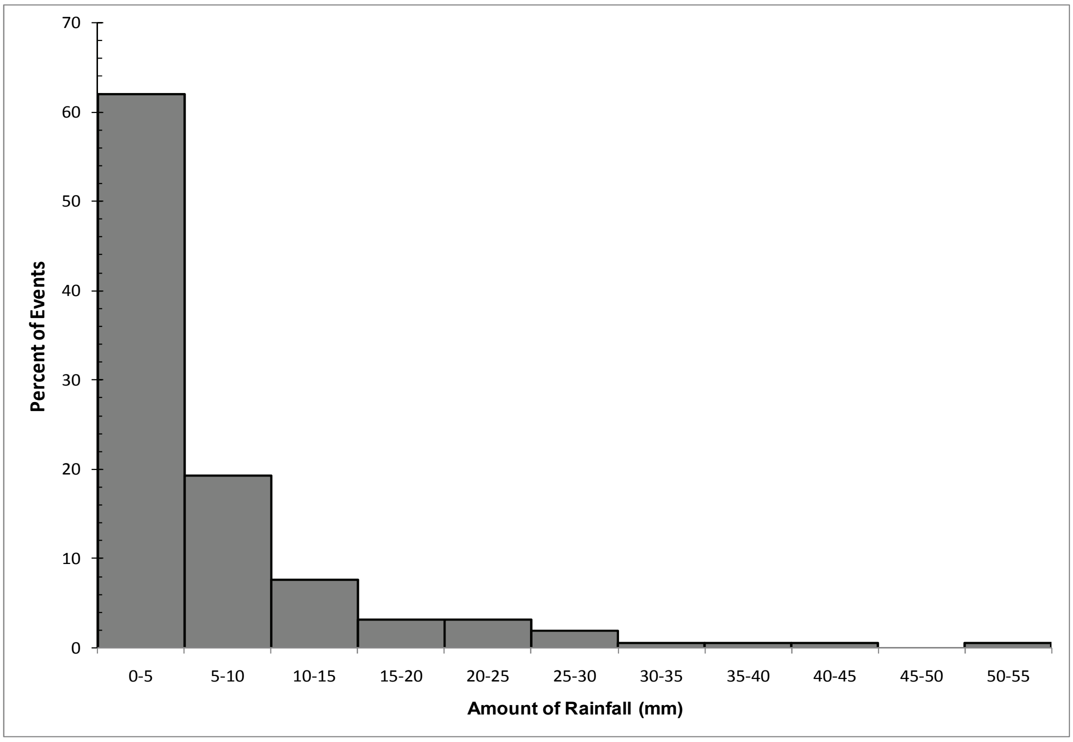


Figure 4.4. Frequency distribution of rainfall events for the Seele Estate for the period 03/12/2009-08/04/2011.

It can be seen from Figure 4.4 that the majority of individual rainfall events (62%) were within the 0-5 mm class with only a few large rainstorms having occurred during the monitoring period. Collectively, 993.7 mm of rain was received during the monitoring period. The mean duration of the 155 rainfall events was 6.88 hours and the duration of individual storms ranged from 0.2 to 21.1 hours. The largest single rain event during this period was on the 26/01/2010 when 43.4 mm was received on site within 19.81 hours at an average rainfall intensity of 2.19 mm h^{-1}.

4.2 Penetrometer Soil Strength (PSS)

The penetrometer soil strength (PSS) for the roadbed (10% slope) and for the adjoining forested compartments was found to be substantially different (Figure 4.5). Measurements were made in mid-winter when the soil was dry.

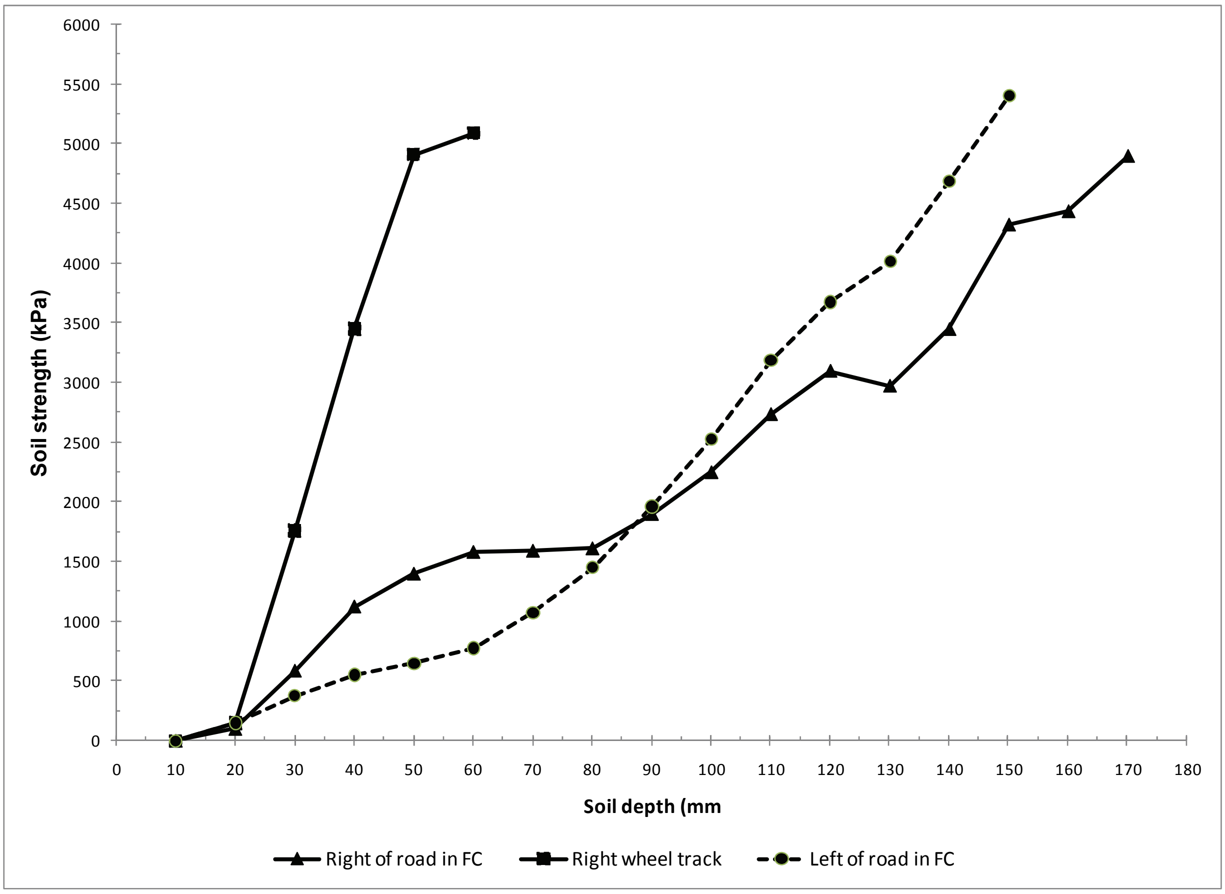


Figure 4.5. Penetrometer Soil Strength (PSS) measured within the forested compartments and the road track.

Although PSS is influenced by soil water content, relational differences showed that successive wheel traffic caused the road surface to become highly compacted. The maximum soil strength capable of being recorded by the penetrometer (5 MPa), was reached at a depth of 50 mm on the wheel track. At a soil depth of 50 mm the PSS within the compartment was 0.6 MPa and the maximum PSS within the compartment was found at a soil depth of 150 mm.

The compacted state of the road has implications for runoff generation and vegetation growth. According to Ziegler *et al.* (2001) compaction of road surfaces reduces the macroporosity of the soil surface and decreases the pore connectivity. These changes to the road surface were further shown to decrease the time between the start of rainfall and the onset of runoff. High soil strengths caused by soil compaction also limits the colonization of vegetation on the road surface, even during periods of low traffic. This causes road surfaces to remain bare for long periods of time. During rainstorms, little resistance to the flow of water may be encountered thus enhancing the transport capacity of flow to remove sediment from the road network.

4.3 Soil Infiltration

Immediately following the PSS measurements soil infiltration tests were carried out in the same vicinity using the double-ring approach. Compaction of the road surface caused a large decrease in the infiltrability of the soil compared with the soil within the forested compartment (Figure 4.6). After an elapsed time of 30 minutes, 210 mm of water had infiltrated the forested compartment compared with 12 mm on the road surface. The high infiltration rate of the soil within the compartment is due to accumulation of organic matter in the upper horizon. The presence of macropores in the forested soil could have further aided the movement of water. Very little difference was found in the infiltration properties of the soil within the forested compartments on either side of the road.

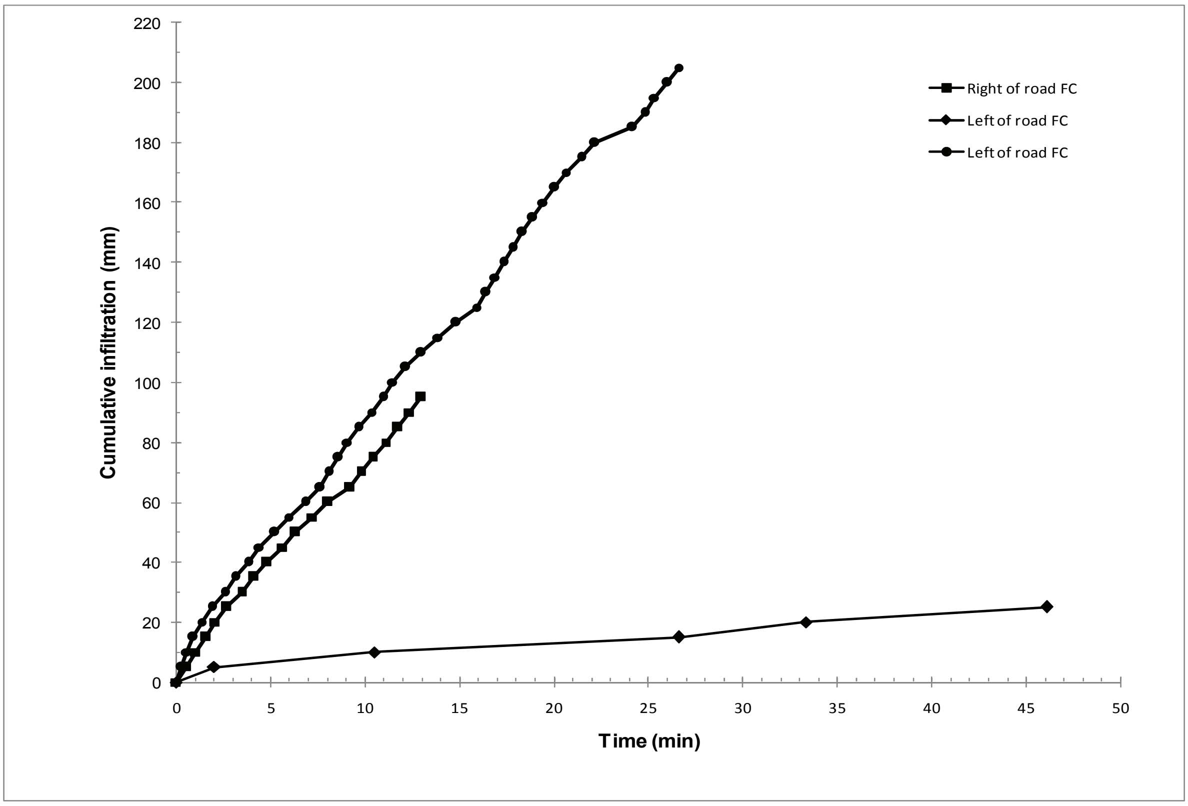


Figure 4.6. Cumulative infiltration measured on the road track and within the forested compartment.

4.4 Surface Runoff

Since unbounded plots were adopted in the experimental design, the width of the road influences the plot size. The volume of water passing through the tipping bucket was therefore normalized to the area of the plot and expressed as the depth of runoff (mm). Runoff occurred only from a few plots during winter and only in response to storms with at least 4 mm of rainfall. During summer, however, the incidence of runoff production from the plots was much higher. During the early phase of the monitoring period several technical problems with the equipment were encountered. This meant that some of the runoff events, which also contributed to the amount of sediment lost, went unrecorded. Furthermore during some intense storms leaf litter clogged the inlet to the pipe carrying water to the tipping bucket further leading to an underestimation of total runoff measured over the full duration of the monitoring period. As an example of this, the events of the 13th December 2009 at plot 10 (gradient 3.09%) are shown in Figure 4.7. Each data point on the graph is representative of a tip.

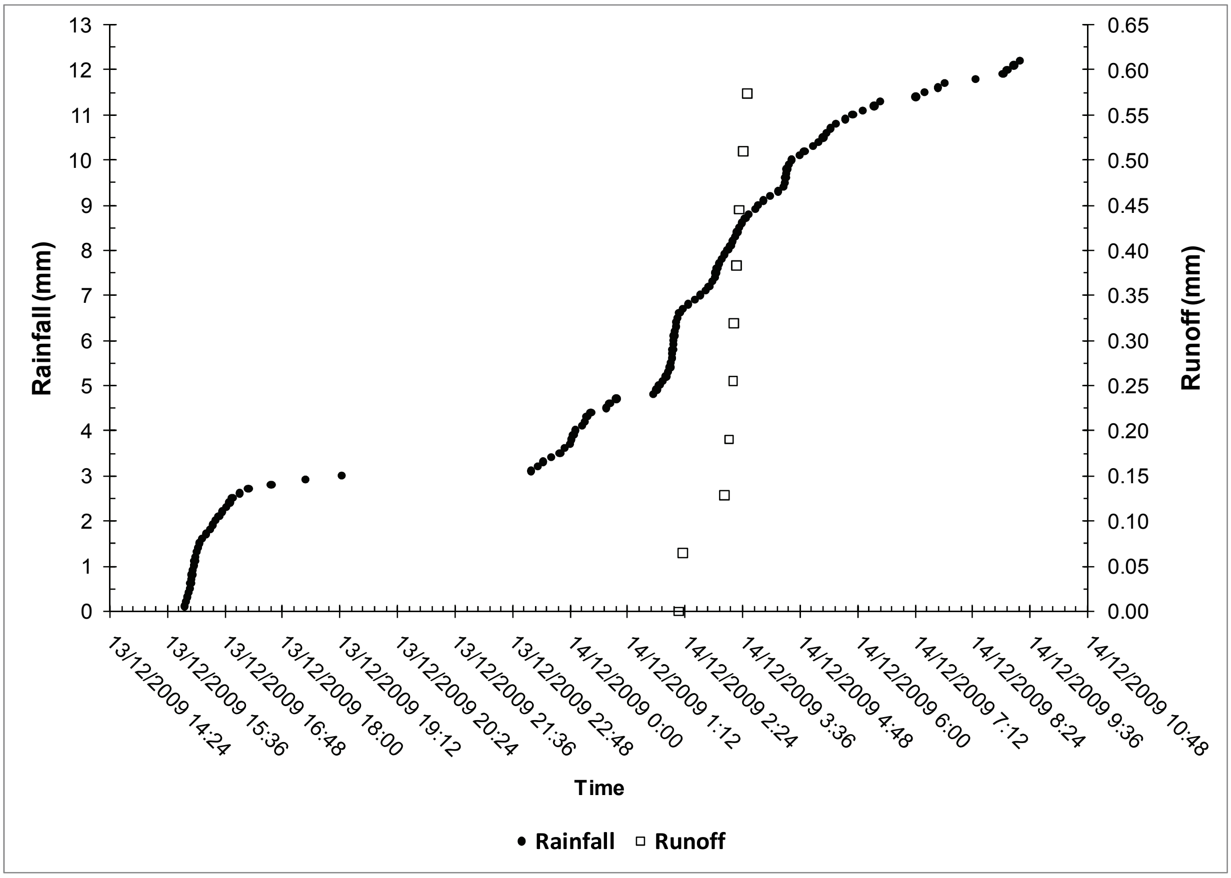


Figure 4.7. A rainfall and runoff event that occurred at plot 10 on the 13th December 2009. The volume of runoff has been normalized to the area of the plot.

At 15h00 on the 13th December 2009 a frontal system moved through the catchment. By 19h00, 3 mm of rainfall fell at the site, followed by a 4 hr period of no rain. At 23h00 the rainfall resumed, marking the start of a new rain event, and lasted until around 09h00 on the 14th December 2009, at which time a further 8.9 mm of rain was received. At 02h15, approximately two hours into the rainfall event the first tip of the runoff bucket occurred followed by a second tip ten minutes later. Within a period of 45 mins, i.e. from 03h05 to 03h50 a further 57 L of water moved through the plot, which averaged over the plot area equates to 0.50 mm m^{-2}. This was also the period with the highest rainfall intensity. Unfortunately from 04h00 onwards despite the continued rain, the logger did not record any further movement of the tipping bucket.

A site visit on the afternoon of the 15th December confirmed that whilst the logger and bucket continued to function normally the outlet of the pipe draining the stilling well was blocked by leaf litter and fine sediment thus preventing the flow of water to the tipping bucket. This occurred on several of the plots. Whilst this was unfortunate it nevertheless is an indicator that rainfall intensity is a key parameter that regulates the entrainment and movement of sediment from the road surface. This was corrected for by fitting the pipe with a larger mesh-size filter and adding a sediment sock at the inlet of the stilling well to contain the leaf litter and coarse-sized material.

Figure 4.8. Blockage of the filter mesh by leaf litter at the inlet of the 110 mm pipe prevented the movement of water to the tipping bucket. This was solved for most plots by increasing the size of the mesh.

Automated data collection of runoff was also interrupted at several plots during late December and January 2010 due to the failure of the tipping bucket pivots which had been originally under designed. Once this defect was corrected the data record was more reliable. One of the protocols adopted during each site visit to test the reliability of the instrument and thus the integrity of the information was to re-launch the logger after downloading the data, rock the tipping bucket and then re-read the logger. If the tipping action was not reflected in the test data then the runoff data collected since the previous site visit was regarded to be unreliable. Once errors in the system were fixed the logger was reset in preparation for further data collection. The area around particularly the stilling well and the lower gutter was further inspected for signs of overtopping. For mainly this reason the data for Plot 4 has been excluded from further analysis due to the very low runoff volumes recorded by the datalogger caused by frequent overtopping of the stilling well. Despite the replacement of the filter mesh with a larger size and adding a sediment sock at the exit of the gutter this was insufficient to prevent clogging of the system by sediment that came off the plot. Moreover during some intense storms runoff overtopped the lower gutter of plot 4 once this had become completely filled in with sediment.

Such challenges in the reliability of the runoff record under natural rainfall have also been reported upon in previous studies by *inter alia* Ramos-Scharron and MacDonald (2007), Sheridan *et al.* (2006) and MacDonald *et al.* (2001). A common approach in the analysis of the data is to therefore consider only those individual rainfall events where there is a corresponding measure of runoff. This approach was adopted in the current study by pairing the runoff data to the individual rainfall event but accepting only those data-pairs where one is sure that the runoff data is reliable, i.e. only that amount of rainfall contributing directly to the *reliable measured* runoff is considered further. In order to compare the response of the individual plots, the runoff times have been normalized to the start of the rainfall event.

The events arising from a 10.5 mm rain event that occurred on the 03/01/2011 beginning at 02:25 and ending at 21h35 is shown in Figure 4.9 by way of example. Only those plots considered to have reliable runoff data for this rain event are included, i.e. the equipment was considered to have been in good working order. Approximately 20 mm of rain had fallen in the area during the six days preceding the event, of which 3 mm was received between 17h00 and 19h45 the day before. A field inspection carried out during this period found ponding of water on several sections of road, some of which were impassable. Within the first two hours into the rainstorm 2.8 mm of rain had fallen, followed by a further 13 hours of light rainfall at an average of 0.25 mm hr^{-1}. Runoff began on plots 1 and 15 shortly after the rain started while a few of the plots (3,8 and10) showed a response several hours later. Compared with the rest of the plots the road section at plots 1 and 15, although different in gradient, has a high proportion of weathered bedrock occurring naturally within the topsoil. This high stone content of the soil limited the high intensity rain from fully infiltrating the road surface leading to the rapid production of runoff.

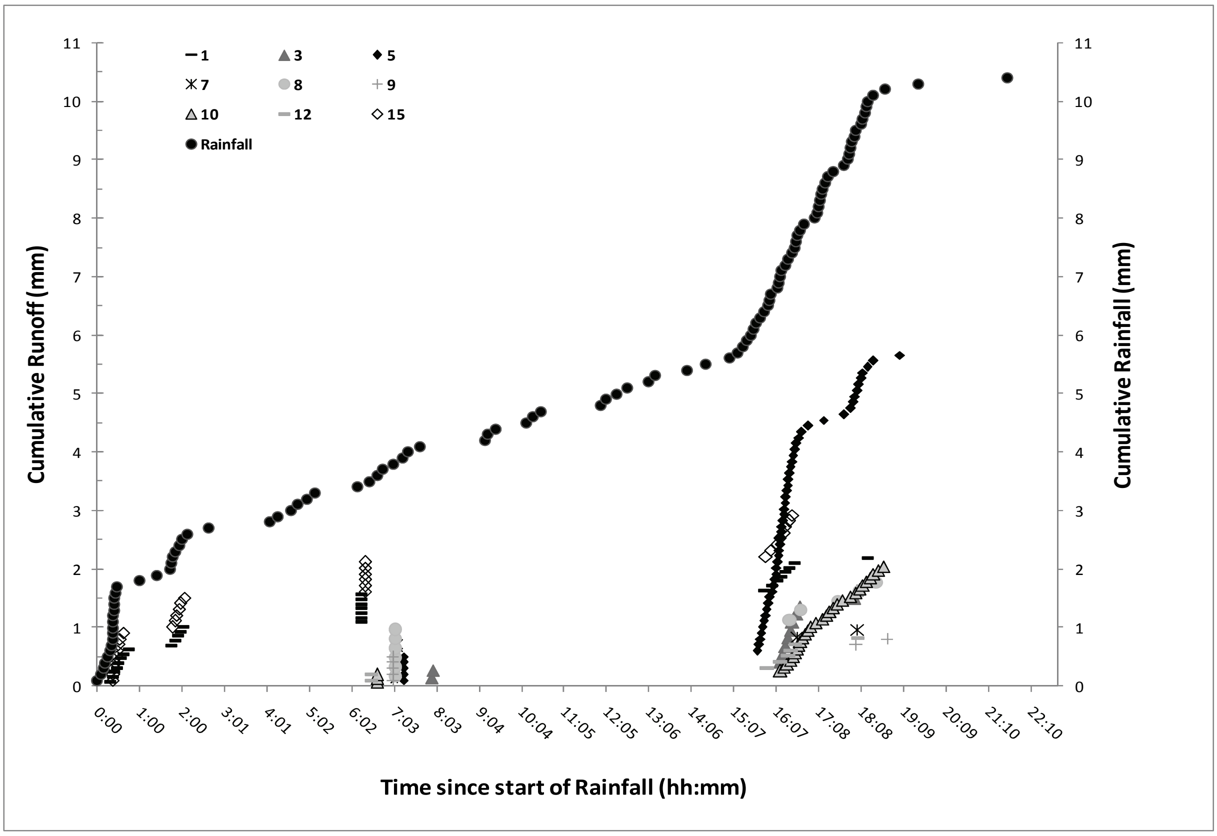


Figure 4.9. The response of the runoff plots to a 10.5 mm rainfall event that occurred on the 03/01/2011. Plots considered to have unreliable runoff data for this rain event are not included.

Given that much of the roads in the area were fairly wet, the gentle rain over the 13 hrs would have also contributed to further increase in the water content of the road surface. By mid afternoon (elapsed time of 14.5 hrs) the intensity of rainfall increased markedly and a further 5.2 mm of rain fell within the following 3 hours. This increase in rainfall intensity marked the start of runoff on several additional plots. The steep plots were more sensitive to this change in higher rainfall intensity as a major proportion of the additional rainfall was lost from plot 5 (gradient of 15.96%) as surface runoff. On the more gentle gradient plots, notably less runoff occurred leading to considerably lower coefficients of runoff. The events described in Figure 4.9 were found to be a fairly common reaction of the plots to other rainfall events (Figure 4.10).

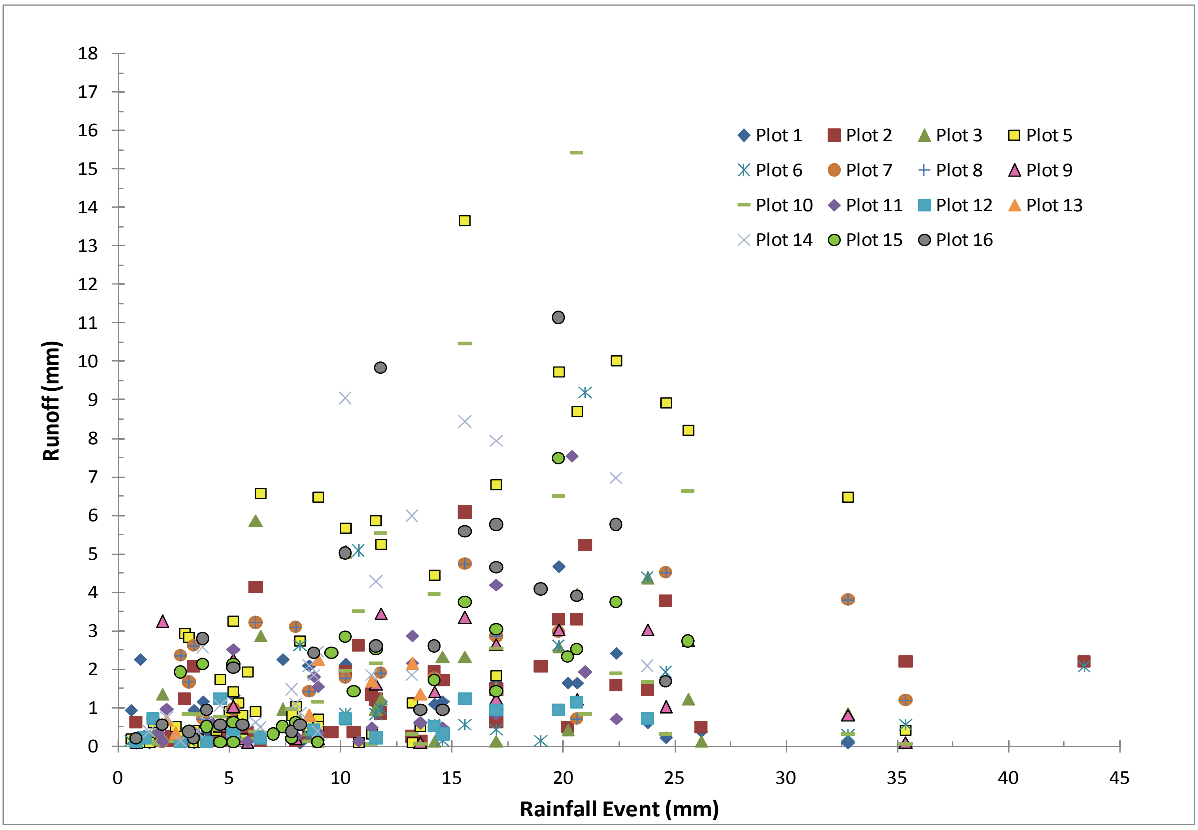


Figure 4.10 The poor relationship found between runoff and rainfall for individual events for the study site. Only those rainfall events with reliable runoff data are included.

It was difficult to draw a meaningful relationship between runoff and individual rainstorms owing to the large variability in the dataset, although regression relationships were stronger for the steep plots compared with the gentle gradient plots. These regression relationships between total rainfall and runoff for the individual plots are given in Appendix 2. Such variability was caused by some large events having produced very little runoff for the low gradient plots, despite it being established that the equipment was in good working order. A better relationship (R^2 = 0.416), however, was obtained when relating the total runoff to rainfall using paired datasets for the full monitoring period (Figure 4.11). This data was further expressed in terms of the coefficient of runoff (R_c) which is the ratio of runoff to rainfall (Figure 4.12).

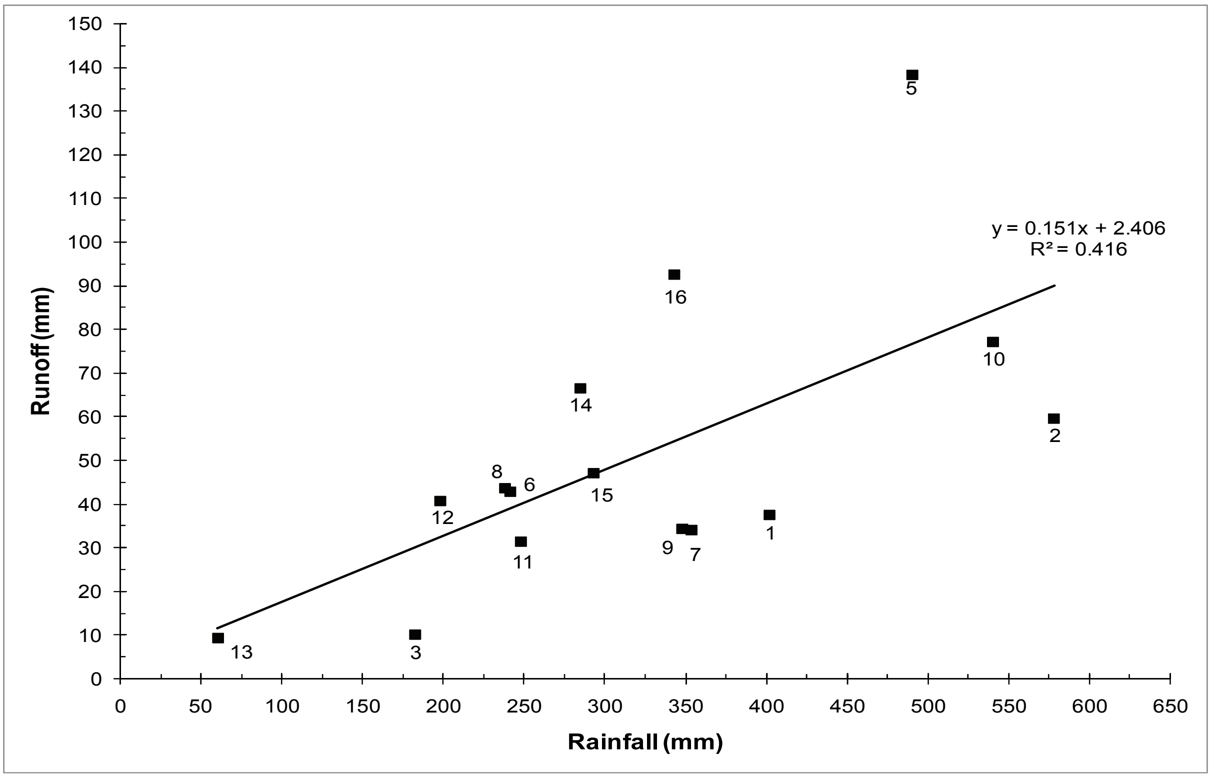


Figure 4.11 The total runoff to rainfall at each plot for the monitoring period obtained using paired datasets of reliable individual runoff – rainfall events.

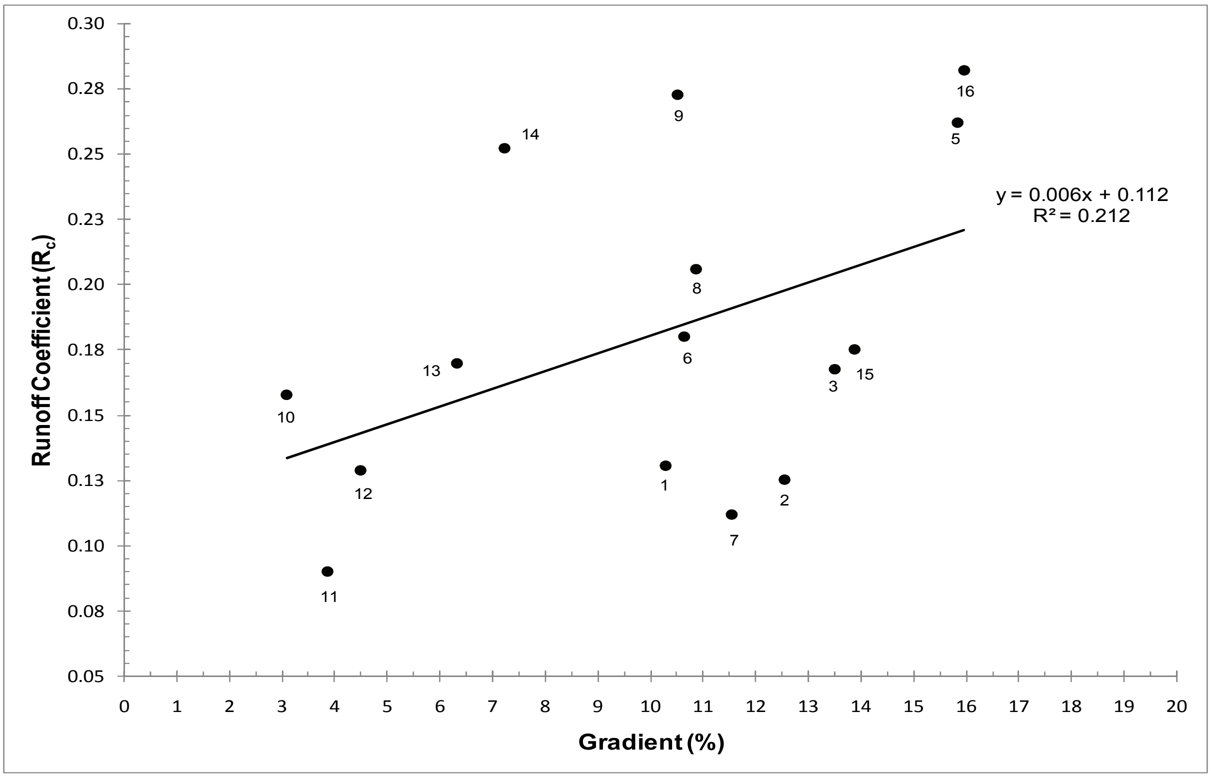


Figure 4.12. Mean runoff coefficient for the plots arranged according to increasing gradient. Plot 4 has been excluded from this analysis.

The mean runoff coefficient for the plots, however, which ranged from 0.09 to 0.30, showed poor correlation with the gradient of the plot (R^2 = 0.212) (Figure 4.12) and despite their similar gradients, plots 1, 6, 8 and 9 showed markedly different runoff coefficients. This implies that local site conditions have an important influence on the amount of runoff that is generated from a road segment. For example plots 6 and 8 which are located on a section of road that does not experience frequent traffic has a much higher vegetative cover than plot 1 and 9 which is denuded of vegetation. The higher grass cover would lower the production of runoff by increasing the infiltration capacity of the soil by their root system and ameliorating to a certain extent the compaction of the road surface (Foltz *et al.*, 2007).

The infiltration properties of the road surface are also a key factor that influences the onset of runoff, even for small events. As the antecedent water content of the road surface increases less rainfall is required to initiate runoff. The gradient of the road is important in influencing the timing of runoff which occurred earlier on the steep plots compared to the more gentle gradients. On the gentle gradient plots water was stored in surface depressions and wheel tracks which limited the extent of surface runoff. Runoff from these road sections occurred only after the depression storage of the road surface was reached. This would also explain why even some large storms did not always produce substantial runoff for the low gradient plots and accounts for the poor regression relationships that were obtained (Figure 4.10). On the steeper sections however water within the wheel tracks have a greater potential to runoff as concentrated flow, with concomitant higher erosive potential.

Much of the work reported in the literature on rainfall runoff relationships in relation to compacted road surfaces has been based on rainfall simulation studies. In this type of approach it is possible to accurately control both the runoff producing area (bordered small plots) and the rainfall intensity. By doing this the volume and timing of runoff is accurately determined which is a crucial parameter for successful numerical modeling. Also the initial antecedent moisture condition of the plot is static and known beforehand. In most cases reported in the literature a high infiltration rate of usually 75-100 mm h^{-1} is adopted in the rainfall simulation with constant application of water over a short duration, typically between 30 to 45 mins. Under these conditions the infiltration capacity of the soil is reached within a relatively short period, after which runoff begins.

The small often uniform area also ensures that surface detention storage is negligible and the short duration of the experiment facilitates the reasonable assumption that evaporation is also negligible. Runoff produced from these plots is thus due almost exclusively to precipitation excess. A typical study undertaken by Croke *et al*. (2006) in the Cuttagee Creek catchment in Eastern Australia carried out under simulated rain for 0.5h duration at intensities of 75 and 110 mm h^{-1} is shown in Figure 4.13.

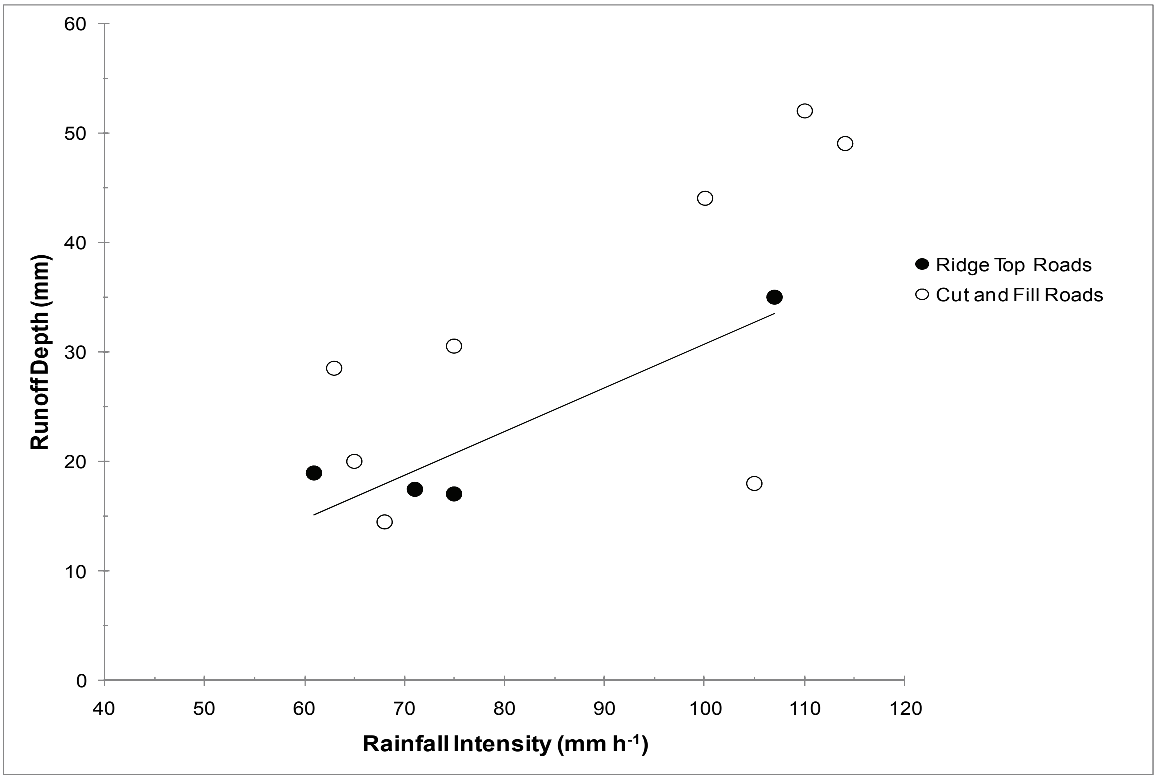


Figure 4.13. Runoff depth as a function of rainfall intensity measured under simulated rain of 30 minutes duration (redrawn after Croke *et al.*, 2006).

The plot size of 200 m^2 was large enough to be comparable with the current study. The average hydraulic conductivity of the compacted road surface at their test sites ranged between 0.42 to 22 mm h^{-1}. They found a strong positive relationships between runoff depth and rainfall intensity and that given the high intensity of the simulated rain the hydraulic conductivity of the soil was exceeded shortly after the rainfall simulator was started leading to precipitation excess runoff. Equally there was a quick recession of the runoff hydrograph shortly after turning off the simulator.

In studies such as in the current experiment, such conditions cannot be guaranteed and one must rely on a number of assumptions related to the homogeneity of the plot. Field observations coupled with measurements of runoff supports the view that besides the gradient of the road, the response of the road surface in runoff production is influenced strongly by the hydraulic properties of the soil and the surface condition of the plot. It is therefore likely that the average intensity of the rainfall event, which interestingly was consistently found to be less than the saturated hydraulic conductivity of the soil, had less of a controlling influence on the production of runoff under natural rainfall conditions. This is an important finding when viewed against previous studies in the literature that showed strong correlation between rainfall intensity and runoff and warrants further investigation.

4.5 Sediment Loss

Sediment loss is a function of the erosivity of rainfall and the erodibility of the road surface (Ziegler *et al.*, 2001, Cao *et al*., 2009). Soil eroded from the road surface can be partitioned into rainsplash erosion and hydraulic erosion. In the former case raindrops striking the soil surface will cause an ejection of sediment from the roadbed. This process will depend upon the energy of the rainfall (which in turn is related to rainfall intensity), rainfall duration, depth of rainfall and erodibility of the road surface (Renard *et al.*, 1997). Hydraulic erosion is a function of the sediment transport capacity of overland flow and is influenced by the erodibility of the road surface, the shear stress applied by overland flow and the critical hydraulic shear strength of the road surface which must be overcome to cause soil loss. The shear stress caused by overland flow is given as the product of the density of water, gravitational acceleration, depth of overland flow and slope (Govers, 1987). A simplifying assumption during this study is that plots located within the same road segment will experience similar erosive energy of rainfall during a single rain event. Where differences in sediment production exist for the same measurement period it is reasonable to infer that this is dependent upon those parameters that influence erodibility.

Sediment was collected from the plots during each site visit. In the time between site visits several individual rain events occurred, each of which would have contributed to the cumulative loss of soil from the plot. It was therefore not possible to accurately relate the amount of sediment lost to the individual rainfall event. However, the rainfall received on site since the previous site visit is known from the automated raingauge, which facilitates the development of a relationship between sediment loss and rainfall. In presenting the rainfall and runoff information in the previous section, it is also important to realise that this information represented only those runoff events that were detected by the monitoring equipment. For this reason it is difficult to relate the mass of sediment eroded to the total runoff volume within which the sediment was entrained. Many of the very small storms that occurred in winter were not enough to generate surface runoff and erosion from the roads. Nevertheless, as summer progressed larger rainfall events generated sufficient runoff to cause the movement of sediment. The early storms would have flushed much of the loose material from the road surface although this would have been somewhat delayed until the leaf litter and other protective cover on the road surface was decreased.

Figure 4.14 shows the air dry equivalent of sediment lost from each road plot between the start of the summer season in late October 2010 and the 26/02/2011. For illustrative purposes the cumulative mass of sediment lost from each plot has been normalized to the 29th October 2010 when the sediment traps were cleaned. The cumulative rainfall for this period is also shown. Sediment loss is expressed in kg m^{-2} by normalizing the mass of material collected (kg) to the plot area. It can be seen from Figure 4.14 that the extent of soil loss from the different road plots was markedly different from each other despite the erosivity of the rainfall being similar. Plots 6, 8 and 13 appear to have responded similarly to each other in terms of soil loss. Despite the differences in gradient the runoff coefficient of these plots were similar (Figure 4.12) which suggests that the surface condition of the plot is an important element that influences the erosion of sediment and its entrainment. On the other extreme, plots 2, 3, and 5 showed an almost five to six-fold increase in soil loss compared to plot 6. These plots were found to be almost denuded of vegetation with exposure of the underlying weathered bedrock in some places.

The total sediment collected during the full monitoring period, i.e. between the 22/12/2009 and the 08/02/2011 is presented in Figure 4.15. The sediment lost due to individual rain events is also shown. As would be expected, the loss of sediment was higher during the wet summer months when runoff will be higher. The total amount of sediment lost from the road surface ranged between 0.30 kg m^{-2} to 1.2 kg m^{-2}.

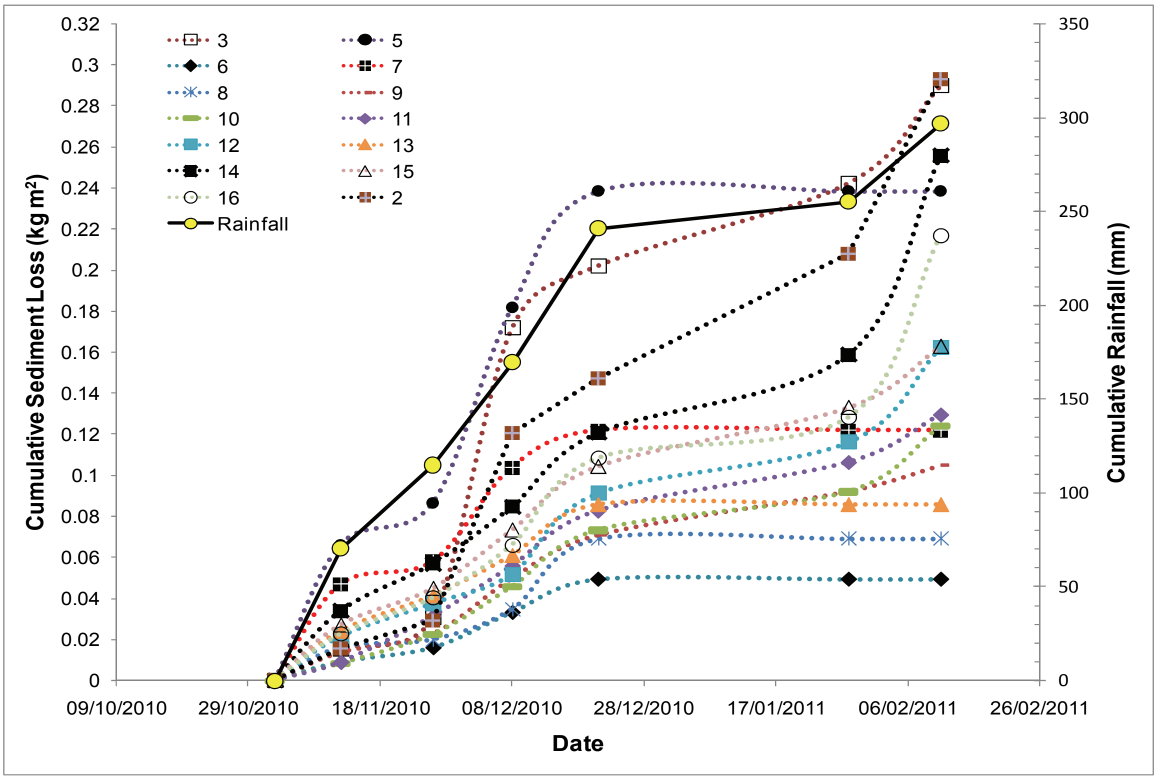


Figure 4:14. Cumulative soil loss from the runoff plots between the period 29/10/2010 and the 26/02/2011. Plot 1 and plot 4 has been excluded from the analysis due to mechanical disturbance of the plot surface during this period and overtopping of the lower gutter respectively.

Plot gradient was positively correlated with sediment loss and when measured across the full monitoring period, an approximately three fold difference in the amount of sediment lost between the steep plots and the near level plot was found. The R^2 of 0.368, however, suggests that gradient alone may not be adequate to explain the marked differences in soil loss between the plots. Of perhaps greater interest in Figure 4.15 and as alluded to earlier, was that plots located within the same road segment responded similarly. Field evidence showed that plot 6 and 8 in particular which are situated near each other have a good vegetative cover compared with the other plots as this is a section of road that is rarely used. The effect of vegetation apart from mechanically anchoring the soil together would have reduced the erosive energy of rainfall at the soil surface thus limiting the extent of soil detachment. In sharp contrast soil loss at plot 1 which is located on a gradient of 10.86% showed a total soil loss of 2.60 kg m^{-2} during this period. Between the 28/01/2011 and the 08th February 2011, 1.07 kg m^{-2} of soil was lost from the plot surface. Examination of the site, however, showed extensive wheel tracks within the plot that was caused by the passage of a heavy haulage tractor sometime during this period. This caused extensive mechanical dislodgement of the soil surface and it is for this reason the data have been excluded from a comparative assessment between plots.

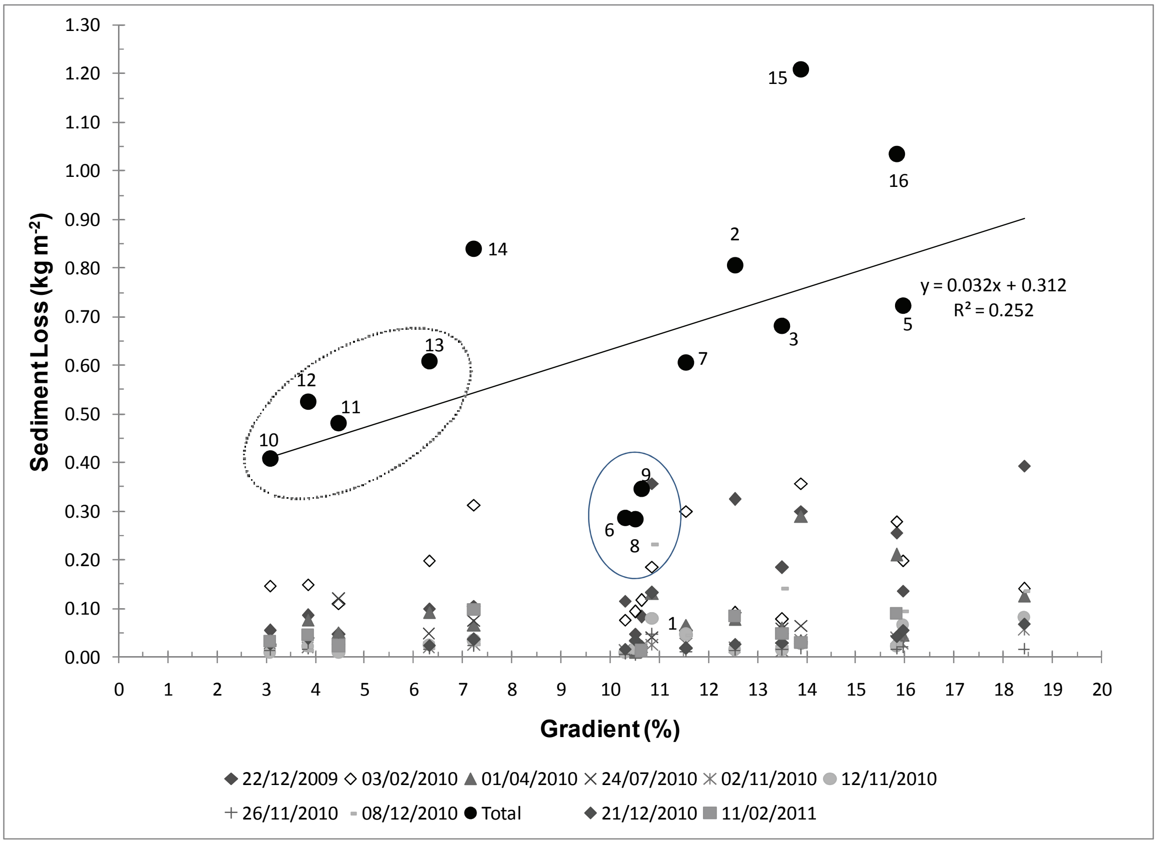


Figure 4.15. Sediment loss between the 22/12/2009 and the 08/02/2011 as a function of road plot gradient.

The effect of vehicle traffic, which has not been directly addressed within this study, has been investigated in past studies by *inter alia* Reid and Dunne (1984), Foltz and Elliott (1999) and Sheridan *et al.* (2006). The general consensus from these studies has been that traffic volume is a key parameter that influences the extent of sediment generation from unsealed roads and that the road water content at the time of trafficking has a bearing on this relationship.

4.6 Sediment Size

Since particle size diameters typically span many orders of magnitude for natural sediments, a convenient way of expressing wide ranging datasets is to use the phi scale (Dean and Dalrymple, 2002). The phi notation (Φ) is used to convert a geometric scale into an arithmetic scale and is related to the grain size diameter (d) in millimeters as $\Phi = -\log_2 d$. Using this relationship a grain size diameter of 0.5 mm will equate to a phi unit of 1 and similarly a grain size diameter of 8 mm will equal -3 Φ. The larger the grain size diameter (mm), the smaller will be the phi unit. Figures 4.16 and 4.17 show the grain size distribution for sediment collected from the plots on the 02 November 2010 (early-summer) and 21st December 2010 (mid-summer) respectively. For ease of comparison the charts are arranged according to the road segment that they occupy, although plots 4 and 5 are presented alongside plots 1, 2 and 3. The median grain size diameter (D_{50}) is the particle size corresponding to the 50th percentile of the cumulative size distribution.

The sediment eroded from plots within a common road segment showed strong similarities in their grain size distribution which suggests that the eroded sediment is closely related to the parent material characteristics. It is interesting that the median grain size of plot 1 and 4 was much coarser (0.2 Φ) compared to the rest of the plots which had a median grain size diameter in the 0.6 to 1.7 phi range. This is attributed to the high percentage of weathered coarse material that comprised the road surface at these localities. Correlation of the median grain size diameter with plot gradient showed a very weak relationship (data not shown) but this was due to the influence of the local road condition. The finer sediment size fraction of the material collected from the stilling well is, however, a conservative estimate as a portion of this size class would have been entrained in the runoff. During periodic maintenance of the equipment this size fraction was frequently noted at the base of the tipping bucket and in general, the higher the rainfall event the greater was the amount of sediment trapped.

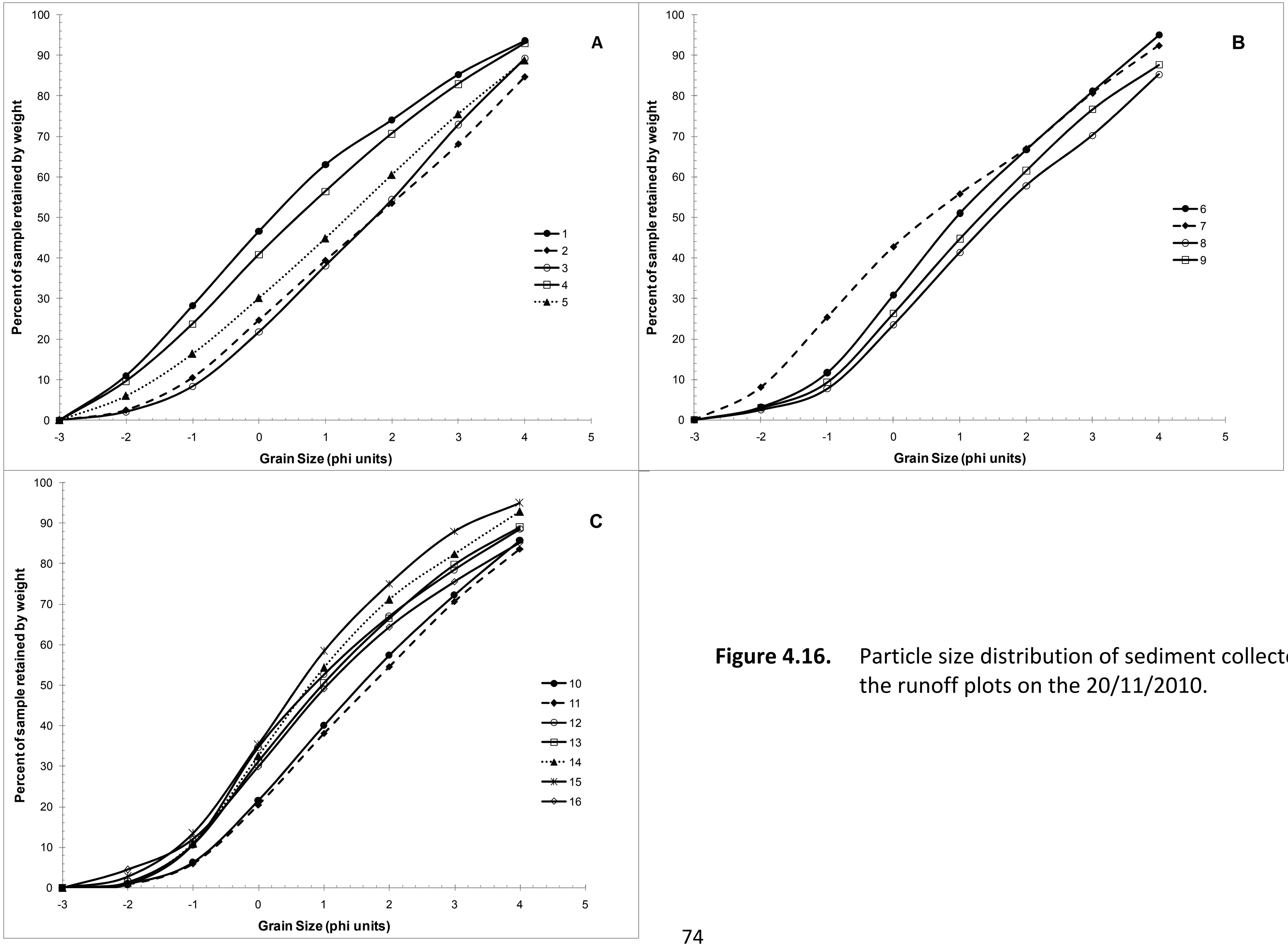


Figure 4.16. Particle size distribution of sediment collected from the runoff plots on the 20/11/2010.

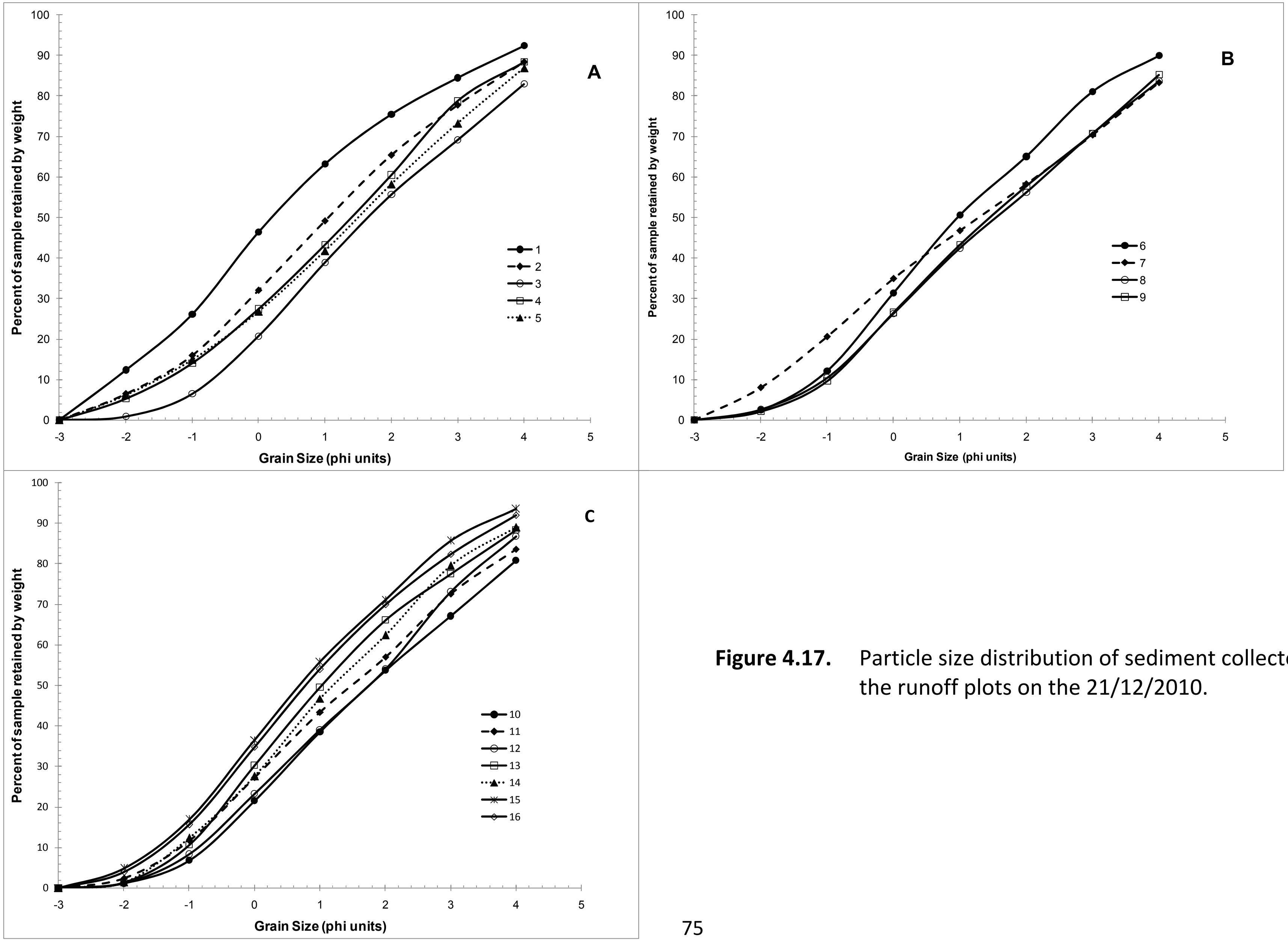


Figure 4.17. Particle size distribution of sediment collected from the runoff plots on the 21/12/2010.

4.7 Microtopographical Changes in Road Surface

The processes of erosion and deposition bring about changes in the microtopography of the road surface. When viewed against a fixed frame of reference, erosion or compaction will lower the soil surface while deposition will raise the road surface. Based on this principle, 24 locations distributed throughout the study area were surveyed during the 03/07/2009 and 2011. The procedure followed is described in Section 3.4. The results for the 24 plots are given in Appendix 3 but three cross-profiles of different road configuration are presented in Figure 4.18 as an example.

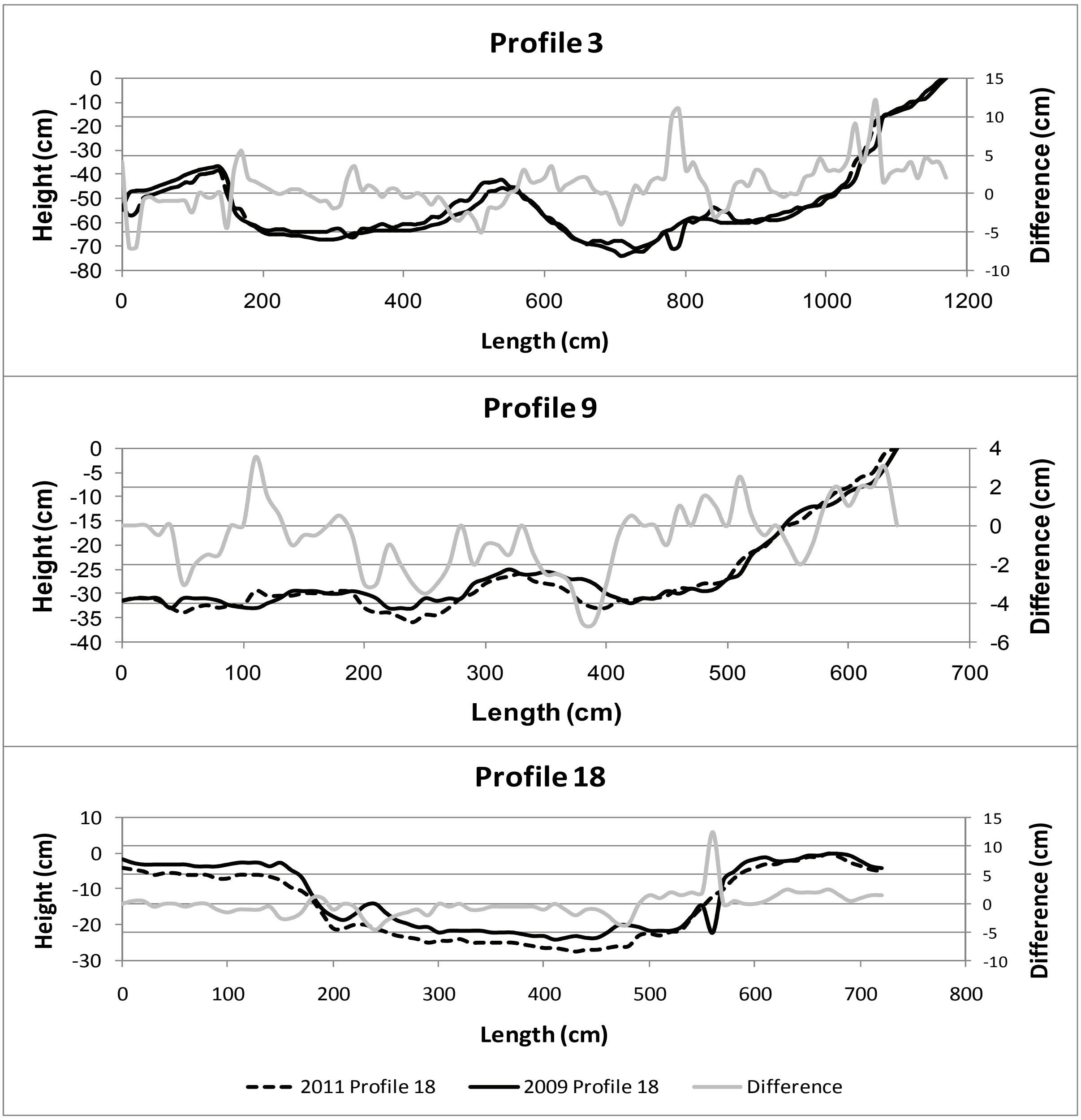


Figure 4.18. Cross profiles for road segments 3,9 and 18 measured during 2009 and 2011.

Profile 3 shows a road section with distinct rutting that has been caused by the repeated passage of wheeled traffic. Although sediment was eroded from predominantly the rutted section there was slight loss from the inter-rut area. Such differences between the 2009 and 2011 profile were in the order of 20 mm. The road side-slope which is approximately 0.5 m high showed a high level of stability over the two years. Profile 9 showed strong similarity to profile 3 in that deepening of the tracks occurred as soil was lost from this section. Compared with the previous two profiles, profile 18 showed a net loss of sediment from both the side-slopes and the road surface proper although the general shape of the 2011 profile matched that of 2009.

The value of this technique, which has proved to be remarkably accurate, is that it offers at a glance those areas within a road segment that are active erosion or depositional sites for sediment. Repetition of the measurements also allows for some understanding of the rate or soil loss

4.8 Hillslope Soil Water Content

Measurements of soil water content taken on the 01/02/2010 reflect the effect of the cumulative summer rainfall in the study area (Figure 4.19). Due to the steady rainfall in the previous week's soil water contents were relatively high and ranged between 23 to 27% by volume with uniform wetting of the entire profile to a measured depth of 0.65 mm. A large rainstorm of 59.5 mm that occurred on the 26/01/2010 beginning at 11h14 and ending at 06h01 the next morning, followed by a further 12.4 mm over the four days preceding the measurement contributed to the high water contents. Soil profile water contents for the access tubes located along the control transect and that intersecting the road is shown in Figures 4.19 and 4.20. C_1 to C_4 (control transect) and R_1 to R_4 (road transect) represent the location of the measurement points in a downslope direction. The schematic arrangement of the access tubes is given in Figure 3.23. The total soil profile water content on the 01/02/2010 was 165 mm for the control transect and 155 mm for the road transect. Profile C3 and R3, which occupied the second lowest topographic position on the control transect, showed a smaller profile water content compared with the rest of the hillslope positions. Examination of the area around the C3 access tube revealed a moderate topographic depression on the downslope portion which extended away from the transect. Thus, some of the rain received at the access tube was routed away from the point of measurement causing a lower rate of soil water recharge.

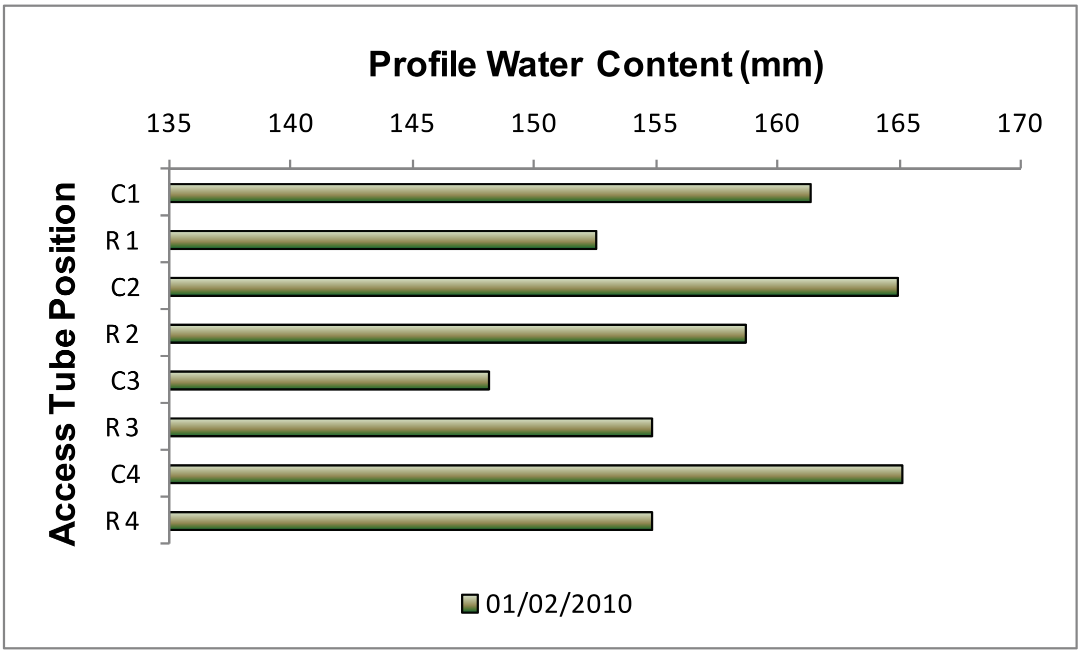


Figure 4.19. Total profile water content (mm/0.65 m) for the hillslope measured on the 01 February 2010. Numbers preceded by the letter C are the control transect and R the transect that spans the road.

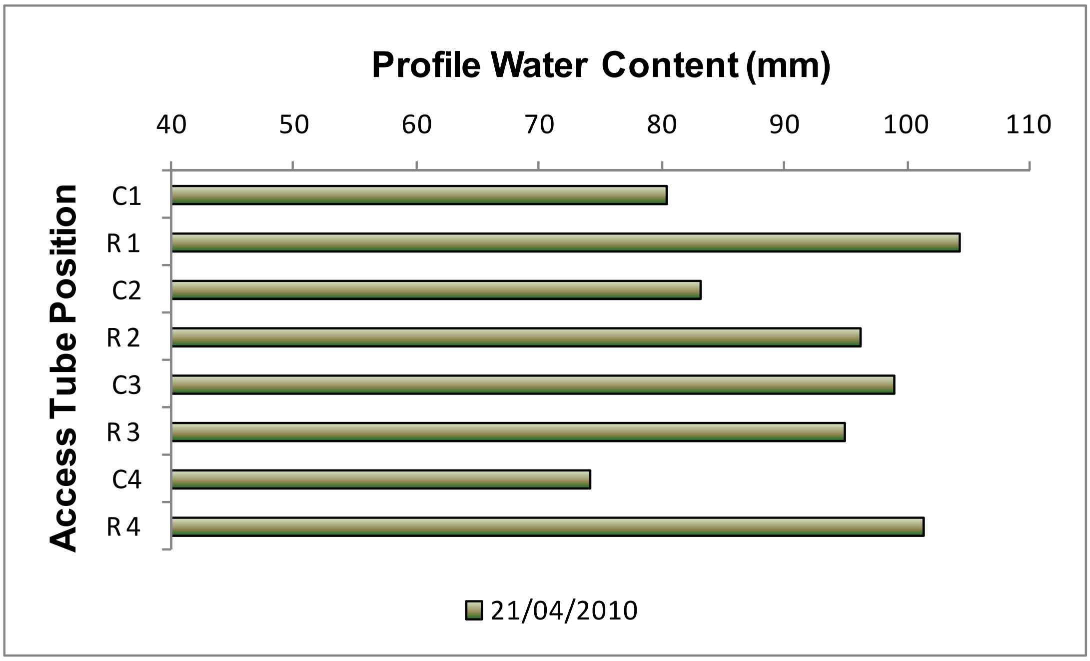


Figure 4.20. Total profile water content (mm/ 0.65 m) for the hillslope measured on the 21 April 2010. Numbers preceded by the letter C are the control transect and R the transect that spans the road.

By late summer, in the absence of further significant rainfall, a steady decrease in soil water content was observed throughout the soil profile (Figure 4.20). The topsoil dried out rapidly as water was lost through evaporation and some percolation to the deeper soil layers. Water contents ranged between 6 to 12% at a depth of 50 mm. The subsoil, which ranged between 12 and 18% by volume, was wetter than the topsoil but drier than earlier in the season. The total soil profile water content was less than was measured in February and ranged between 80-100 mm along the control transect and between 95-105 mm for the road transect. As found previously, even in late summer little difference in soil water content trends exists between the two transects or between topographic positions relative to one another.

If the general theory of ISSF generation is accepted in the current context, then for water to seep onto the roadcut from upslope contributing areas there must either be saturated conditions present or water must flow laterally along the bedrock interface. This condition has clearly not been achieved. The soil in this catchment is deep and freely drained with no evidence of perched water table conditions or exposure of bedrock at the cutslope interface (Figure 4.21).

Figure 4.21. The cut slope of the road section studied. The soil is deep and well drained with no signs of exposed bedrock at the cutslope interface.

Thus, in the absence of significant ISSF, infiltration-excess road runoff appears to be the dominant driver of sediment from forestry access roads in this catchment. The magnitude of runoff production and sediment delivery is thus controlled by interactions between rainfall and road design and placement. Cut and fill road configurations are of three types, namely insloped, outsloped and crowned. At the current study site, along the contour the roadbed is insloped and thus water will flow along the base of the cutslope. Two broad based dips have been constructed on either end of the contour road section to further drain water. Along the slope a crowned road configuration has been adopted and water is drained from the median of the road bed outwards to its margins.

Due to the compacted state of the roadbed and its substantially reduced infiltration the majority of runoff is concentrated along the road verge. The effects of concentrated flow can be seen on examination of the road verge, especially the section that runs along the slope (Figure 4.22). It is apparent that the broad-based dip has not been fully effective in shedding the excess water from the road tread and flow has continued along the road verge down the slope.

Figure 4.22. Severe gullying along the road verge at the section of the hillslope leading to the cut and fill embankment.

Several forms of active accelerated erosion processes are presented in Figure 4.22. With the increase in slope there is a corresponding increase in streampower, a parameter that relates the velocity of flow to the slope. This concentration of overland flow leads to incision of the soil surface and the development of a gully system once a critical threshold was exceeded. The critical threshold depends predominantly upon the contributing area (which in this case is the road bed), the local slope and the properties of the material being eroded.

The entrainment of sediment has resulted in the development of a series of knickpoints usually when there is a sharp increase in local gradient along the drainage line of the gully (rectangles, Figure 4.22). As the sediment is eroded the development of a well defined singular gully system along the road verge is evident with active headcut retreat and deepening of the gully floor. Widening of the gully floor has also caused some undercutting of the gully wall which in turn has led to slumping of the road bed (circled, Figure 4.22). Substantial deposition of sediment has occurred at the base of the slope in response to a loss in entrainment energy.

4.9 Movement of Water into Compartments

The distribution in volumetric water content of the soil within the mature compartment at depths of 50, 350 and 650 mm on 20/01/2010 and the 02/01/2010 is shown in Figures 4.23 and 4.24 respectively. The contour map for this site is given in Figure 3.28. The influence of the mitre drain in diverting water from the road surface into the compartment can be seen from the spatial distribution in volumetric soil water content (Figure 4.23). At the inlet of the drain, the near surface (50 mm depth) soil water content is approximately 10% but increases substantially to around 15% at the drain exit. Much of this water is, however, concentrated within a relatively small area. Field evidence indicated a high degree of soil compaction at the entrance to the mitre drain which would limit the infiltration of water. However, as the water moves further into the drain, increased surface roughness, higher organic matter loads, deposition of sediment and a change in grade would cause the flow rate to decrease and the energy of the water to be dissipated to some extent. These conditions promote infiltration which leads to an increase in soil water content. A dense accumulation of organic matter on the soil surface also serves as mulch which would aid soil water conservation. The soil upslope of the drain was found to be relatively drier at approximately 10%. The deeper region of the compartment shows much greater uniformity of wetting with an average water content of approximately 12%. Compared to the topsoil the subsoil is wetter. Although there is less spatial variation in water content of the subsoil, there is still a marked concentration of soil water in the vicinity of the mitre drain outlet. This is probably due to the receipt of water from the topsoil as internal redistribution of water and recharge occurred. Repetition of the measurements on the 01/02/2010 showed a very similar distribution in soil water content to that of the 20/01/2010. The area of high soil water concentration was, however, larger and extended approximately the entire length of the mitre drain (Figure 4.24). This was probably due to the fact that 97.4 mm of rainfall was received in the area between the two measurement periods, 40.4 mm of which was received on the 26/01/2010. The soil water content of the deep subsoil (650 mm) remained virtually unchanged.

Compared to the mature compartment the soil within the newly established compartment was wetter (Figure 4.25). Average water contents ranged between 20 to 23.5% with greater uniformity in its distribution than was noted for the mature compartment. The gradient of the mitre drain at this site is less than that at the mature compartment which may have had a bearing on the extent to which the road runoff would have been carried into the compartment. The fairly bare soil surface (the compartment was burnt before replanting) may also have contributed to increased evaporative loss of water. Despite this there does appear to be a concentration of water in the region of the drain outlet but this applied to the near surface soil. At greater soil depths much greater uniformity in the distribution of soil water content was noted with markedly wetter conditions.

These findings suggest that gravitational and local micro topographical factors are important in influencing road drainage through mitre drains. The forestry industry, particularly, road engineers have long held the view that mitre drains if properly constructed have the capacity to efficiently remove water from the road surface thus protecting the road infrastructure. What is perhaps lacking is greater attention to the fate of the water once it enters the compartment. All indications suggest that at the site studied the sediment is deposited within the compartment due to a rapid loss in the entrainment energy of the runoff. This process is further aided by a dense accumulation of organic matter on the compartment floor. Although the technique used in the current study will need further testing of its robustness, it does suggest that this is a promising approach to tracking the movement of road runoff and its redistribution within the compartment which will be a valuable exercise in evaluating flow pathways between upland sites and the stream network.

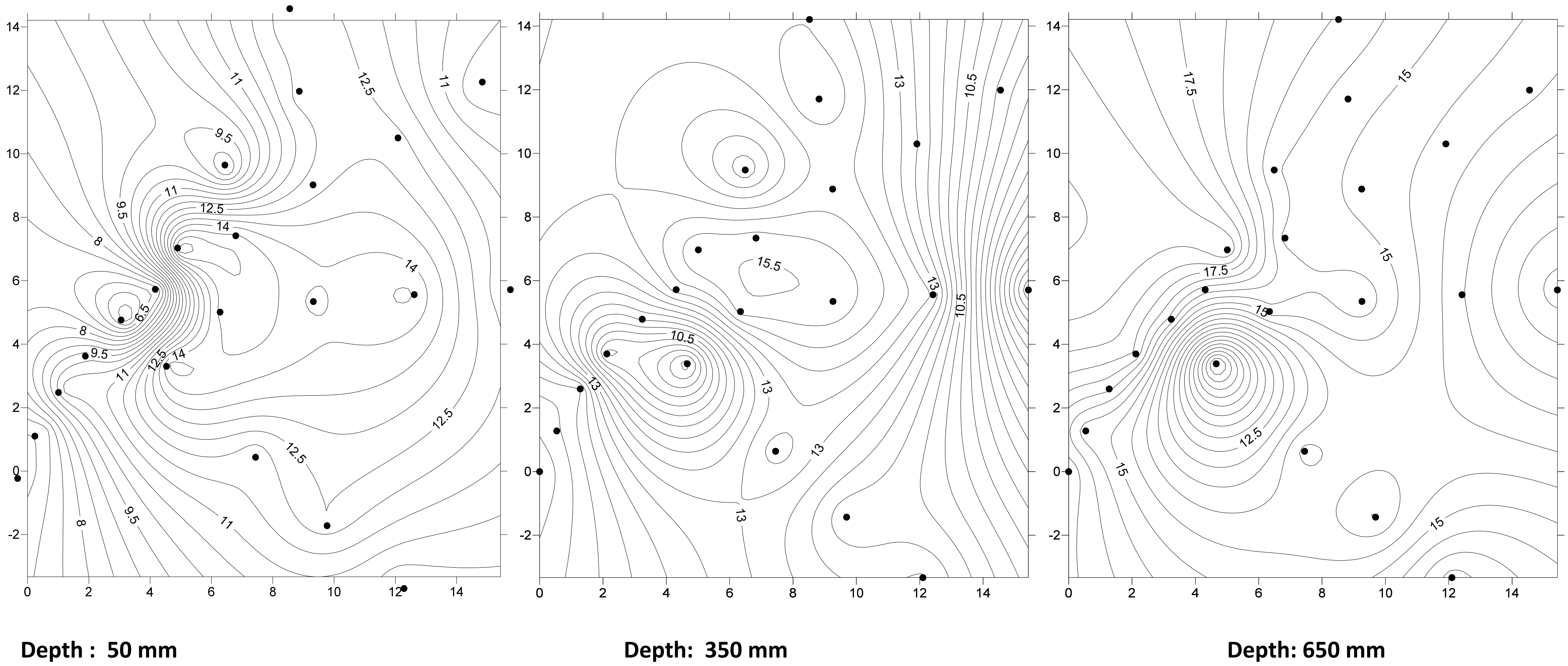
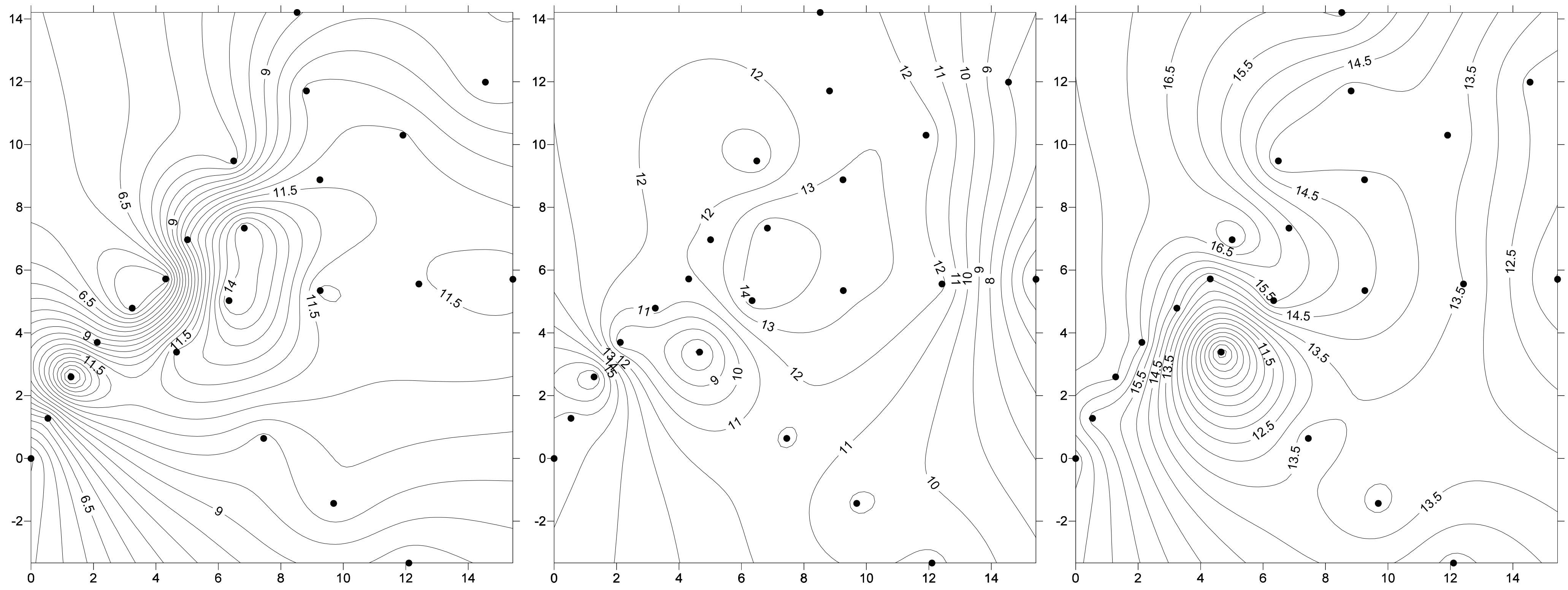


Figure 4.23. Soil water content by volume (%) in the mature compartment on the 20/01/2010 at soil depths of 50, 350 and 650 mm. The location of the access tubes within which the measurements were made is shown by the black dots. The X axis is the distance (m) into the compartment and the Y axis the distance along the fixed reference location (road).



Depth : 50 mm **Depth: 350 mm** **Depth: 650 mm**

Figure 4.24. Soil water content by volume (%) in the mature compartment on the 01/02/2010 at soil depths of 50, 350 and 650 mm. The location of the access tubes within which the measurements were made is shown by the black dots. The X axis is the distance (m) into the compartment and the Y axis the distance along the fixed reference location (road).

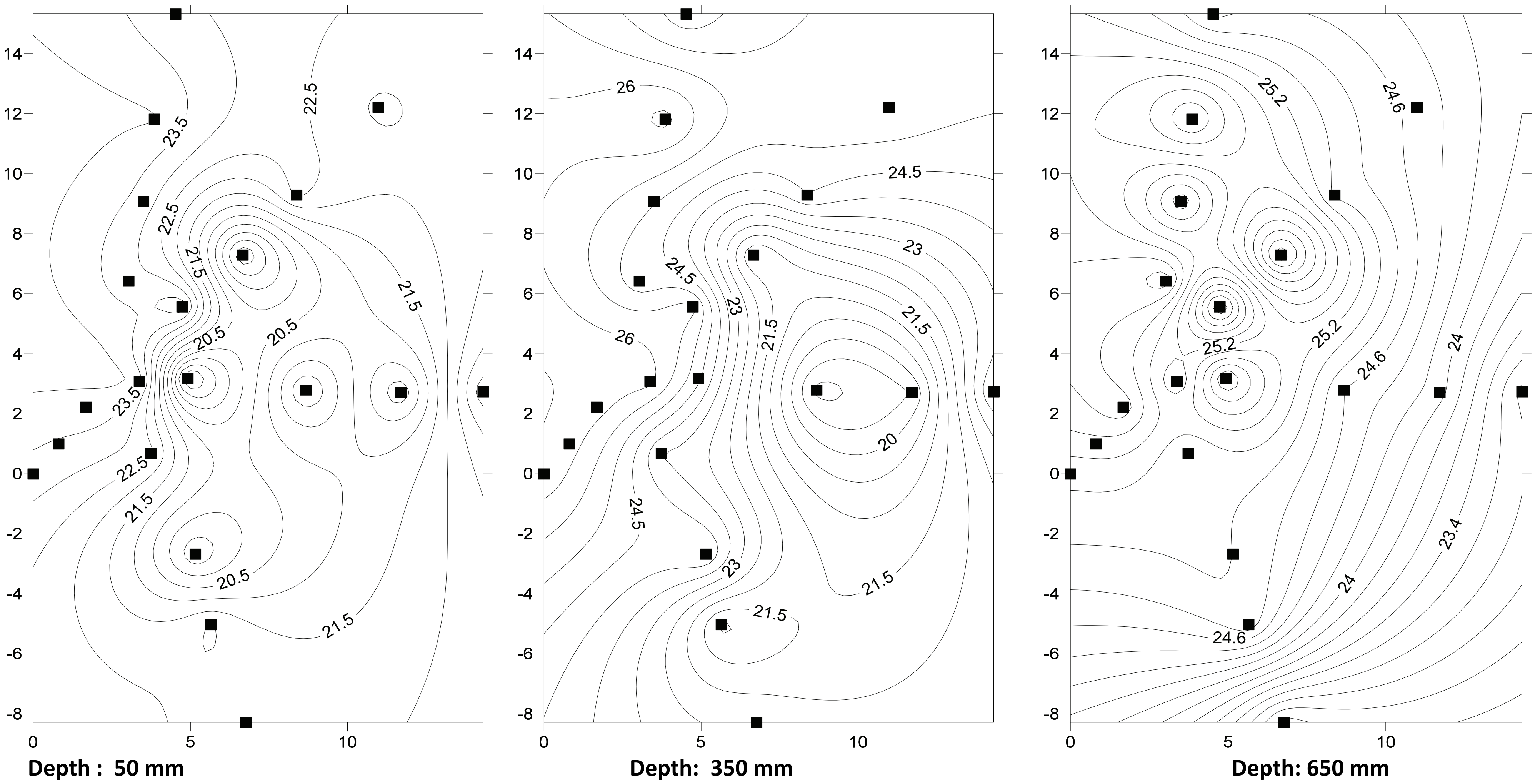


Figure 4.25. Soil water content by volume (%) in the young compartment on the 01/02/2010 at soil depths of 50, 350 and 650 mm. The location of the access tubes within which the measurements were made is shown by the black squares. The X axis is the distance (m) into the compartment and the Y axis the distance along the fixed reference location (road).

Chapter Five

Numerical Modeling of Sediment Loss in Forest Compartments

5.1 Introduction

Erosion and associated sedimentation are a major environmental issue, as landscapes become degraded, surface waters contaminated and large water bodies are unable to provide the necessary ecosystem goods and services (Akay *et al.*, 2008; Bruijnzeel, 2004; National Research Council, 2008). The use of models to predict or extrapolate sediment loss has the advantage of allowing for a catchment-scale implementation. The outputs of the model (s) can be used to recreate past disturbances and consequences as well as assess contemporary conditions or predict future scenario outcomes, in particular as a result of management practices. One can forecast outcomes prior to implementation – the wonders of hindsight! This has stemmed mainly from concurrent advances made in spatial analysis and modeling. Tools such as Geographic Information Systems have also allowed for much higher levels of data acquisition and analysis than was previously possible.

5.2 Models Used in Runoff and Sediment Loss Prediction

The variety of mathematical and statistical complexity used in contemporary hydrologic models make them difficult to neatly categorize (Singh and Frevert, 2002). Generally, models may be based on a theoretical understanding of the hydrologic cycle (physically based) or they may rely on empirically derived fits of observed data (empirical) (Table 5.1). Spatially, models may be lumped while others are distributed or semi-distributed. A lumped model uses single values of input parameters with no spatial variability and results in single outputs (Aksoy and Kavass, 2005). A distributed model, however, uses spatially distributed parameters and provides spatially distributed outputs by taking explicit account of the spatial variability of the process. Computationally, some models are deterministic while others are stochastic. A model is event based if it simulates a single event or continuous if it has the capacity to simulate many events occurring over a given season or longer time period. The data requirements of any model increases with the complexity included in the model. Distributed models, in particular, need more data than other models (Aksoy and Kavass, 2005). Model selection is thus a difficult process as it relies on the preference of the region, scientific discipline or individual for the sake of familiarity, consistency or commercial availability (Eisenbies *et al.*, 2007).

Table 5.1. Some recent models to predict runoff and sediment loss, (modified after Aksoy and Kavvas, 2005).

Model	Empirical	Conceptual	Physically Based
USLE	√		
MUSLE	√		
RUSLE	√		
SEDD	√		
AGNPS		√	
LASCAM			√
ANSWERS			√
LISEM			√
CREAMS			√
WEPP			√
EUROSEM			√
RUNOFF			√
DHSVM			√
KINEROS			√
ACRU			√
SWAT			√

In the empirical type category the Universal Soil Loss Equation USLE and Revised USLE models are probably the most widely recognized. This model, in its original form, was developed by Wischmeier and Smith (1978), primarily for agricultural catchments and later revised by Renard *et al.* (1994). Much of the model development has been based upon data from the USA. In its original form the amount of soil lost (E) expressed as tons/acre is given by the relationship E = RKSLCP, where R is the rainfall erosivity index, K is the soil erodibility factor, S is the slope, L is the length of the slope, C is the cropping factor and P is a supporting conservation practice factor. Although this model has had lesser application in forested catchments compared with agricultural catchments, the rationale behind its approach has been used with good success in the development of much more sophisticated models.

Further examples of empirical models that have been used for modeling sediment is *inter alia* the Sediment Delivery Distributed Model (which is based on the USLE (Ferro and

Porto, 2000), the event based Agricultural Non-point Source (AGNPS) which simulates runoff, sediment and nutrient losses in agricultural catchments (Young *et al.*, 1989) and LASCAM which is a conceptual sediment generation and transport algorithm (Vinay and Sivapalan, 1999). This code was originally developed to predict the effect of land use and climate change on the daily trends of water yield and quality in forested catchments in Western Australia.

5.3 Modelling Specific Road Related Runoff and Sediment

The principal approach to measure erosion and sediment loss from roads has been field-based roadside or stream monitoring, sediment tracing and the use of road erosion models. Roadside sediment traps provide information on coarse sediments (sand and gravels) but not at a finer resolution of clay and silt (Robichaud and Brown, 2002). According to Sheridan and Noske (2007) the highly variable bedload inputs and the unpredictable efficiency of sediment traps can result in uncertainty in measured sediment yields when sediment trap data is used in isolation to estimate total sediment yield. Other field-intensive techniques are available, for example the use of a bedload trap, a tipping bucket for measuring discharge and a split sampler for measuring suspended load (Sheridan *et al.,* 2006) or stream monitoring techniques. However, most of these techniques suffer from similar limitations in that, at a catchment scale, it is difficult to determine the contribution of roads *per se*, due to the mixing of sediment from multiple sources and the complexity of processes controlling sediment routing and deposition (Fu *et al.*, 2010).

The development of numerical models to assess specifically the effects of roads on the hydrology of forested hillslopes has undergone a rapid expansion since the mid-1990s. A road model comprises essentially two main components namely an erosion and delivery module. The simplest road models consider inputs from surface erosion only and models the delivery of sediment by a sediment delivery ratio (SDR) type approach. Unlike a traditional catchment-scale SDR approach, the ratio of sediment delivery to a stream to the total sediment generated from a road feature is defined as SDRR-S (Fu *et al.*, 2010). Moderately complex road models usually consider cutslopes as sediment sources. These type of models also consider features of fillslopes or lower hillslopes such as length and steepness as factors that influence the delivery of sediment to a stream. The most complex models include representation of detailed erosion processes on both cutslopes and road surfaces, and a larger number of components in sediment delivery, such as transport and deposition through ditch and fillslope, gully initiation, and sediment particle-size sorting. This increase in complexity is influenced by the level of spatial detail inherent in the application of a model.

Models are categorised on the basis of their spatial scale of application to plot, segment and catchment-scale models. Most road models are developed for their application on segment scales and include descriptive parameters that relate to evident road features. Plot-scale road models focus on detailed quantification of infiltration runoff and erosion processes on a particular road feature such as the road surface. Catchment-scale models consider roads as a component of a catchment and often involve all road features, including the upper and lower hill slopes (Fu *et al*., 2010). Depending on the capability of the model to predict sediment production rates for various size classes, road models are classified into single-size and multiple-size models. Models that do not differentiate between particle sizes are regarded as single-size models, whilst multiple-size models estimate sediment yields for a range of particle-size distributions.

The physically based models have had a much wider application than the empirical type models in evaluating the impacts of access roads on sediment and hillslope dynamics. ANSWERS (Areal Non-point Source Watershed Response Simulation), which was developed by Beasely *et al*., (1980) includes a conceptual hydrological process and a physically based erosion process. The erosion process assumes that sediment can be detached by both rainfall and runoff but can only be transported by runoff. In the model the catchment is divided into small, independent elements and within each element the runoff and erosion processes are treated as independent functions of the hydrological and erosion parameters of that element. According to the model developers, ANSWERS is especially useful as a tool to compare results for various treatment and management strategies.

The Limburg Soil Erosion model (LISEM), developed by De Roo *et al*. (1996), attempted to predict the likelihood of accelerated soil erosion through a series of empirically derived equations, although the model itself is physically based. Several indices such as *inter alia* the wetness index, stream power index are related to each other in order to derive a soil erosion hazard index. GIS is then used to develop a map of the soil erosion hazard for a particular catchment. The advancement made in this model at the time was that it was capable of accounting for roads, wheel track and channels in the soil erosion component of the source code. Road related erosion type research has predominantly been undertaken using the Water Erosion Prediction Project (WEPP), SEDMODL, Distributed Hydrology Soil Vegetation Model (DHSVM) models and GIS based analytical tools designed to calculate sediment production from road surfaces. These are briefly expanded upon here.

The Distributed Hydrologic Soil Vegetation model (DHSVM), developed by Wigamosta and Lettenmaier (1994), is a physically based spatially distributed hydrological model. This model explicitly simulates the interaction of topography, soils, vegetation, climate and water movement by representing the catchment as a collection of discrete pixels or grid cells. DHSVM routes subsurface water and surface runoff between pixels. Surface runoff is calculated via a saturation excess mechanism. This is routed to the catchment outlet using explicit information on the location of the road and stream networks. The road and stream networks are superimposed on the DEM of the catchment as GIS coverages of vectors mapped to specific pixels. The elevation of each pixel is determined and then used to calculate local slopes and flow directions and rank individual road segments for flow routing. The fraction of each pixel covered by a road or stream is prescribed along with the depth of the road cut or channel incision. Rainfall is directly intercepted while subsurface flow is discharged directly into the road or channel network according to the height of the local water table above the stream or road cut. Each pixel can have up to two vegetation layers and a user-defined number of soil layers.

Cuo *et al.* (2006) applied the DHSVM model to study the effects of roads on the Pang Kum experimental catchment in Northern Thailand. They adopted a two step approach by first calibrating and validating the model with inclusion of the road network using both streamflow and soil water content for which long-term data was available. Once the model was regarded to be performing satisfactorily, the simulation was repeated except that the roads were disregarded. All other parameters were maintained the same. The effects of the roads were then evaluated by comparing model results. Although, according to the authors mixed results were obtained the approach was useful in evaluating the effects of roads on peakflow responses. Le Marche and Lettenmaier (2001) used the model in the Deschutes River, Washington to evaluate the effects of forest roads on flood flows. They showed that forest roads alone were predicted to have increased the mean annual flood in the subcatchments from 2.2 to 9.5% and from 2.9 to 12.2 % for the ten year event. They further showed that the predicted increase in floods and harvest on peakflows at the subcatchment and catchment levels are essentially independent and the combined effects on peakflows are therefore additive. A further significant element of this study was the development of a predictive statistical model for connectivity of the road drainage to the natural channel.

As with the DHSVM model, the SEDMODL model is GIS based. The routines used in the model are based on empirical relationships between road erosion factors such as traffic intensity, road surface condition, road surface slope, vegetative cover of the road embankment and distance between the roads to the stream network. As with most GIS based models SEDMODL requires information on soils, geology, rainfall l and topography (DEM). Akay *et al*. (2008) estimated the average annual sediment delivery from road networks to steams located in the Mediterranean region of Turkey by adopting the Road Sediment Delivery Model (SEDMODL). In the model sediment is typically produced from four overland flow components namely the road surface, road embankment, fill-slope and ditch. The amount of sediment produced from the road surface is expressed in the model as a series of factors, each of which is influenced by a further set of subvariables. Briefly the total amount of sediment (t/ha) = (TS + CS) Af where TS is the sediment from the road surface, CS is the cutslope sediment and Af is the age road factor. The age road factor is based on the fact that the major loss of sediment occurs in the early years after road construction (as was reported previously). Various subvariables modify these factors. An excellent account of these is given by Akay *et al.* (2008). These authors compared the modeled effects on sediment production yield as influenced by traffic, road grade and cut-slope height for three different road sections (Figure 5.1).

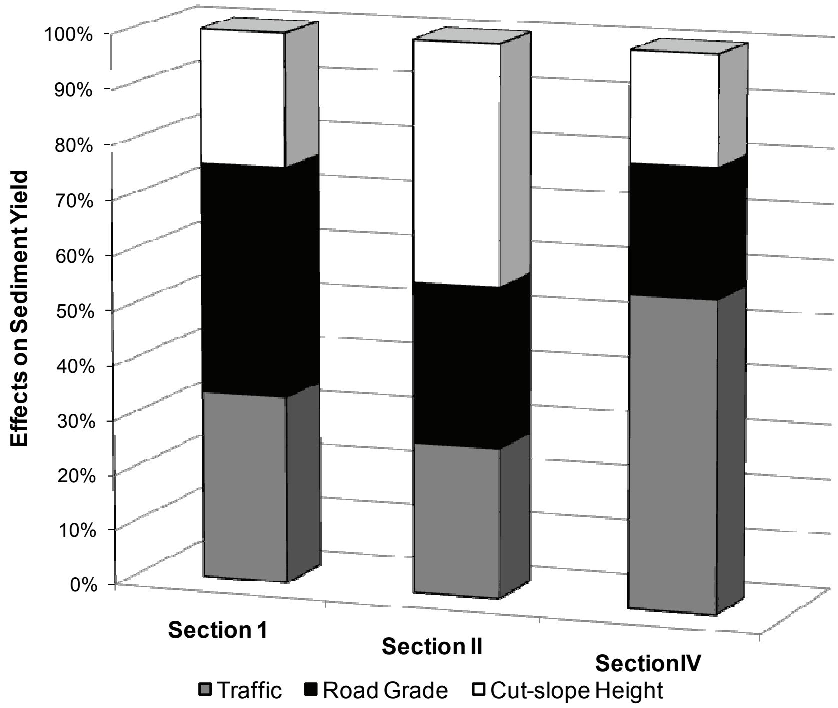


Figure 5.1. The effects of traffic, road grade and cutslope height on sediment yield (redrawn after Akay*, et al*., 2008).

They showed that the order of importance in total sediment production from roads is strongly dependent upon local conditions, but that the height of the cut-slope (road embankment) has a general positive influence on sediment production. Despite the variation in the relative significance of these variables between the different road sections these authors comment that the value of the model lies in its ability to rapidly assess the relative significance of the road erosion factors when considering road improvement techniques.

Prasad *et al.* (2005) developed a set of GIS tools to analyse the impacts of forest roads on streams considering sediment production, risks for mass movements and fish passage barriers. They calculated sediment production for each road segment based upon the slope, length, road condition and road-side drain vegetation. The road network was then overlain on a digital elevation model. Sediment production was accumulated to roadside drains by adding the sediment production of the individual road segments. These drain point sediment loadings were then used in a DEM weighted flow accumulation function to calculate sediment load inputs to streams. The conceptual framework used by these researchers is reproduced in Figure 5.2.

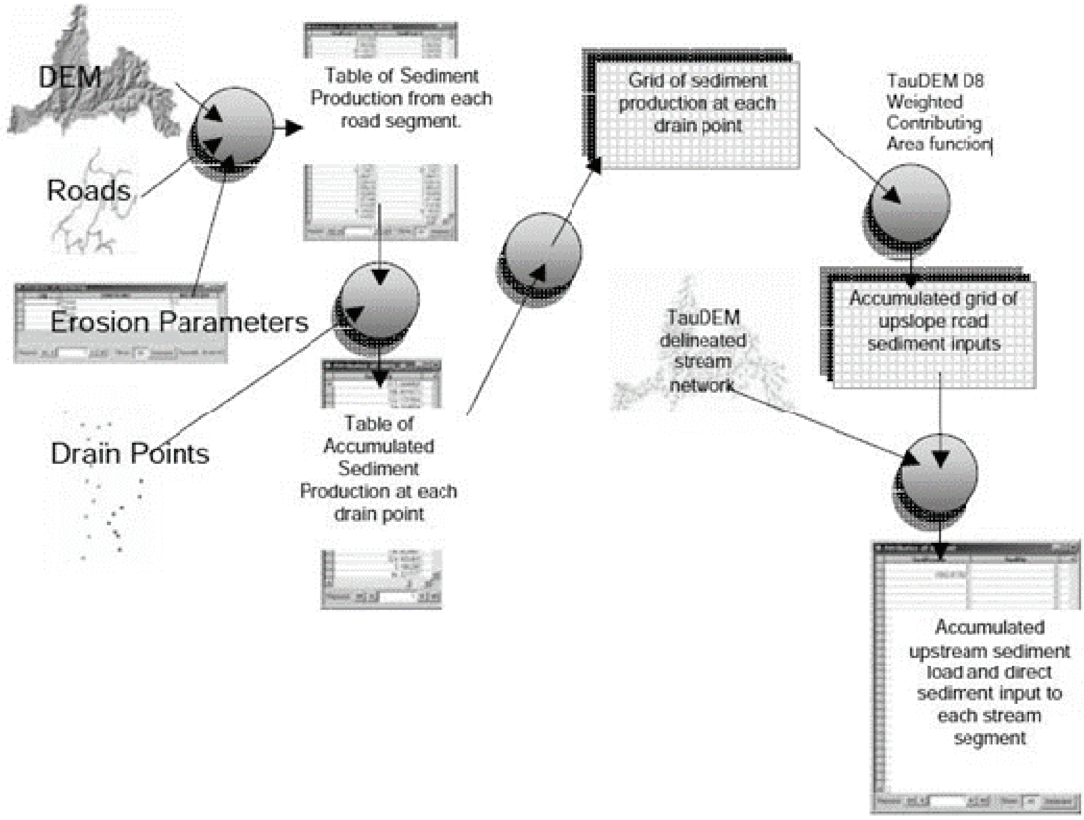


Figure 5.2. Conceptual GIS based approach used by Prasad *et al.* (2005) to evaluate sediment production from forest roads and sediment input to the stream system.

A modified form of the SINMAP model (Pack *et al.*, 1988) was used to calculate the potential for mass movements on slopes below drainpoints. According to Prasad *et al.*, (undated) the SINMAP model bases its calculation of slope stability on a relative wetness indicator evaluated from specific catchment area, slope and other hydrological variables. The effects of roads were integrated into this model by substituting road runoff from drains for the steady state recharge used in the SINMAP model.

A simple model that is applied in a highly spatially disaggregated fashion has resulting relatively high overall complexity. Thus, although a range of models are available (Beckers et *al.*, 2009), there are only a few that are really applicable. The first is the Washington Road Surface Erosion Model (WARSEM) of the Washington State Department of Natural Resources (Dube, 2004). While this model considers the erosion and sediment production of the road on the basis of the cumulative effect of the individual road segment components, it does not adequately consider the catchment context of the road. The problem is further compounded by the fact that provisional results show up to one order of magnitude variation in the range of deviation between observed and predicted results (DNR, 2004). Such variance is clearly problematic. The following models were thus identified at the onset of the study as possible models that could be used within the context of the research: ROADMOD, FORECALT and WEPP.

ROADMOD

ROADMOD is an automated model which was developed to predict average annual erosion and sediment delivery from unpaved road networks (Anderson and MacDonald, 1998). ROADMOD is imbedded within a vector-based GIS and predicts annual road derived sediment yield by an empirical relationship between road erosion rates and road surface conditions and a series of network algorithms (Anderson and MacDonald, 1998). The empirical model is a spatially distributed model (by road segment) whose outputs are annual-averaged and single-sized. This model was not chosen as the major limitation is that sediment production algorithm is determined by measuring the cross sectional area of 'missing' road surface material (including rill erosion and compaction) since construction and grading at a single location (Fu *et al*, 2010). The road erosion algorithms used in this model are based on limited data and does not include some of the key factors that control road erosion rates such as precipitation or the frequency of grading, as lacked the capacity to estimate sediment production rates from other sources (Ramos-Scharron and MacDonald, 2007). Within the context of this research, the concern was that the model assumes that sediment deposition on the road surface is negligible and that erosion rates are consistent over space and time. This may be an oversimplification of the dominant processes that occur on site.

FORECALT

Forest Road Erosion Calculation Tool (FORECALT) was developed for ArcGIS 9.1 using the Water Erosion Prediction Project (WEPP) model. The FORECALT tool uses a DEM, a GIS vector based road network map, and a series of road definition selection tools to parameterize and run the WEPP model for the combined set of all individual segments of a road network. The model is able to simulate erosion from cut slopes, road surfaces, and road drainage ditches. The model simulates both insloped and outsloped forest roads. Results of erosion and runoff per segment of forest road are displayed via the GIS interface. Outsloped forest road erosion can be displayed graphically as a map layer and total insloped forest road erosion is calculated for selected outlet points (Cochrane *et al.*, 2007). Unfortunately the FORECALT tool is presently not public domain or commercially available and thus we were unable to test the model to predict yields on the road segments.

WEPP: ROAD

WEPP, which is in the public domain, is a process-based model for simulating soil erosion by water along a hillslope or within a catchment. It was originally developed by federal agencies of the United States of America in 1985 principally between the NSERL (National Soil Erosion Research Laboratory, Purdue, USA), the USDA and the LESAM Project Group of the Department of Geography at the University of Buffalo in the State of New York. The model, which was released in 1995, considers specific erosion factors such as climate, soil type, vegetation cover percentage and topographic condition. The WEPP model calculates sediment yield, runoff, infiltration, erosion and deposition rates for everyday/single events and for multiple time periods such as monthly or annually. Being a process-based model, it requires a large amount of input data to estimate erosion and sediment yield potentials. Of major importance, however, is that unlike the USLE the WEPP model introduced the concept of separate rill and inter-rill detachment processes in an end-user computer simulation program (Flanagan and Livingstone, 1995). Since then the model has undergone constant refinement and upgrades, such that it now includes a forest applications component that considers roads explicitly (Elliot and Hall, 1997; Elliot *et al*., 1999).

The hillslope version of WEPP contains nine components, a weather generator, winter processes, irrigation, surface hydrology and water balance, subsurface hydrology, soils, plant growth, residue decomposition, overland-flow hydraulics, and erosion. WEPP can divide a hillslope into multiple overland flow elements (OFE), within which soil properties and vegetation conditions are regarded uniform and unique (Pieri *et al.*, 2006). The model uses single-event or daily climate data, and simulates runoff by calculating the difference between effective rainfall and infiltration rate, which is then routed over the land surface using the kinematic wave equation. Infiltration itself is calculated using the Green-Ampt Mein Larson model, and the simulation process is capable of considering canopy related rainfall interception, surface depression storage, deep percolation and subsurface flow. The early versions of the model tended to over predict erosion largely due to scaling problems but apparently underestimated sediment production from forested catchments with complex topography (Renschler, 2006). These have been addressed in later versions (Shuhui *et al*., 2009). The daily soil water content is simulated using a water balance equation which is linked to infiltration, runoff routing, soil evaporation, transpiration and seepage (Acharya and Cochrane, 2009).

Hillslope erosion is estimated as interrill or sheet wash and rill or micro-channel erosion. The wash erosion is treated as soil detachment due to splash and raindrop impact, with subsequent delivery taking place to the micro-channels. Detachment is seen as a function of soil type related to flow shear stressing excess of soil strength. Sediment transport and/or deposition is calculated in relation to the transport capacity of concentrated flow, compared with sediment which has already been entrained. When transport capacity within a rill or channel is exceeded due to changes in either flow rate (governed by both volume and slope gradient), deposition will occur. The model has several output options and a number of typical forest input files.

The WEPP ver. 2006.5 model which was released in 2001, further incorporated the advanced features of a GIS leading to the GeoWEPP model. The Geospatial Interface in GeoWEPP enables detailed topographic, soil and land use patterns to be taken into consideration and so to derive predicted redistribution of sediment at a variety of spatial and temporal scales. The main advantage is that GeoWEPP overcame the limitation of WEPP which required the user to manually generate the necessary data. GeoWEPP also allows a user to process digital data such as *inter alia* digital elevation models (DEM), land-use maps, orthophotos, and soil surveys. A further advance in model development occurred after the inclusion of TOPAZ (TOPography PAramateriZation), a routine that parameterises topographic data based on DEMs. TOPAZ determines the channel network based on the steepest downslope path considering eight adjacent cells of each pixel (Yuksel *et al*., 2008). After defining the watershed TOPAZ generates sub-catchments that represent the catchment. The outputs are in the form of grid layers although runoff and sediment yield for each pixel can be produced in text files. The GeoWEPP model considers the road network in the catchment as a separate coverage but does not expressly provide estimates of soil loss or runoff at the road segment level. Instead erosion potentials are determined for the entire catchment. Model performance is assessed by comparing the measured sediment concentrations at the catchment outlet with the modeled values. In validation exercises in the US, GeoWEPP was able to asses and predict short-term soil erosion at the small watershed scale within forested catchments (Renschler *et al.*, 2006). Thus, GeoWEPP could be applied to model the relative sediment and runoff production throughout the catchment but is inadequate, in terms of the purpose of this research, to provide meaningful results at the road and road segment scale.

To simplify the WEPP applications, Forest Service WEPP (FS WEPP) was developed as a set of internet-based interfaces which assists a user to rapidly predict sediment yield and runoff from forestry roads based on climate, soil texture and road design (Elliot, 2004; Cochrane *et al.*, 2007). Unlike GeoWepp, the WEPP:Road (Elliot *et al.*, 1999) module is a web-based interface for modeling individual road segments. In line with the collected parameters of this research, WEPP as a physics-based model, requires the estimation of parameters such as rainfall volume and intensity, infiltration, slope, and soil texture and erodibility parameters (Flanagan and Livingston, 1995). The WEPP:Road module (accessed from: http://forest.moscowfsl.wsu.edu/fswepp/, using WEPP: Road Batch) simplifies data input which allows users to specify selected climate, soil texture, gravel addition, road topography, drain spacing, road design and surface condition, and ditch condition (Elliot *et al.*, 1999). Rainfall is considered for generating daily weather inputs for the WEPP model if required (Elliot *et al.*, 1999).

Grace (2005) used the WEPP Roads Interface Model to evaluate the impact of both graveled and unsurfaced forestry access roads in the southern Appalachian Mountains, Alabama, USA. Field data were collected from a road sideslope over a period of 8 years. The road upon which the study was based was constructed within a mid-slope position. Selected road segments were instrumented with runoff plots which were subjected to different erosion control strategies. A full description of the study site and treatments is given by Grace (2002) but briefly an exotic mixture of grasses (vegetation level 1) and a native mixture of grasses (vegetation level 2) were tested as erosion control strategies. The model was then tested against the measured data (Figure 5.3).

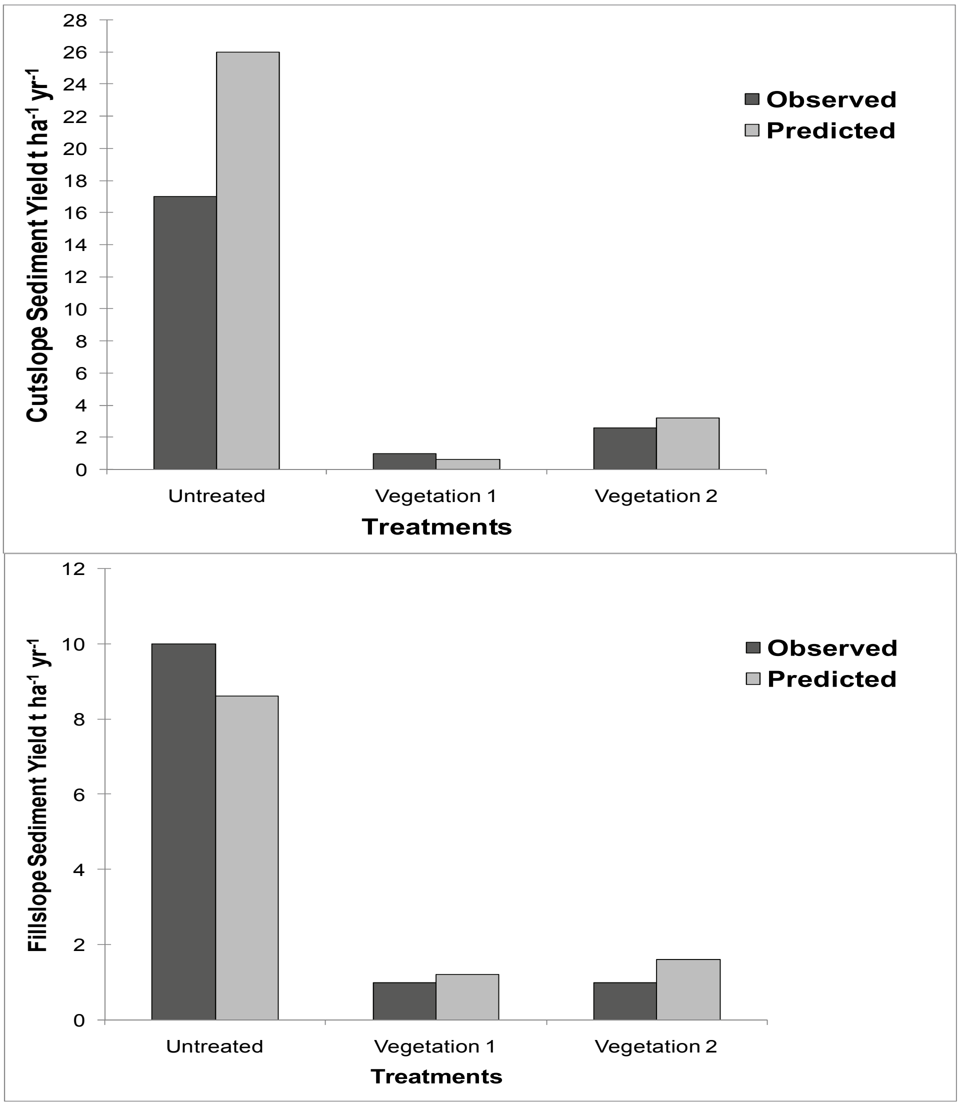


Figure 5.3. Average annual sediment yield observed and predicted by WEPP for untreated and vegetated road cutslope (top) and fillslope (bottom), after Grace (2005). Vegetation level 1 is a mixture of exotic grass and vegetation level 2 is a mixture of native grasses.

Their study found that the WEPP model was extremely successful in predicting sediment yield for both cutslopes and fillslopes although the predicted average sediment yield for the cutslope was in the order of 10 t ha^{-1} more than the observed values. They explained these differences to the availability of sediment available for erosion due to the removal of easily transported sediment from the cutslope embankment. No differences were found between the observed and simulated sediment yields for the fill-slope. They concluded that the WEPP model is adequate to describe average annual sediment yields from roads. Interestingly, Pieri *et al.* (2006) also concluded that the model displayed good agreement between observed and predicted runoff when applied to an experimental catchment in Centonara, Italy. On the contrary Gronsten and Lundekvam (2006) found that the model did not perform well when used to simulate surface runoff and erosion in southeastern Norway. They explained their results to the inability of the model to effectively deal with the high organic matter soils found in this region and recommended that the soil erosion parameters needed revision in order to improve the model's performance. Notwithstanding these comments, the general opinion regarding the WEPP model is that it is robust enough to predict road erosion in catchment management decision-making processes.

As this model is based on the principle of a continuous, physically based erosion model considering road-based erosion, sedimentation and water generation in the spatial context of small catchments, it has clear points of commonality with the objectives of the current study and was therefore selected for use on the project. A further advantage is that it provides a cost-effective means of evaluating road erosion using relatively fewer field measurement as well as being readily available and easy to access online. It also requires little training or preparation to acquire input data (Elliot *et al.*, 1999). This report therefore compares the results obtained from field-based roadside monitoring and sediment trapping to the outputs of the WEPP model. The WEPP model has two interfaces; the WEPP:Road and the WEPP:Road batch developed by USFS (United States Forestry Service). After a preliminary study and revision, the WEPP: Road interface was used as it is a simpler version adapted to simulated erosion from an individual road segment (Elliot *et al.*, 1999). The approach has been to compare the WEPP:Road model to field-based observations/ measurements to ascertain if the USA developed model is appropriate for South African conditions to determine soil erosion and sediment yield estimations.

5.4 Modelling Procedure

The following procedure was followed using WEPP online at http://forest.moscowfsl.wsu.edu/fswepp/ and the main interfaces accessed are graphically depicted below (Figure 5.4). During the process a number of limitations were identified. To begin with it is important to ensure that metric units are selected (not default option) before proceeding as this will allow for metric units in all interfaces.

Figure 5.4. The main WEPP model interface selection screen.

A climate generator (CLIGEN) generates 'typical' weather sequences for WEPP. WEPP includes a list of weather stations statistics from the USA predominately on non-mountainous terrain which are distributed on approximately a 100 km grid for the entire United States. These statistics can be modified for local climatic conditions using the CLIGEN routine (Elliot, 2004), a stochastic weather generator which produces daily estimates of rainfall, temperature, wind, radiation and dewpoint for a single geographic location using historical information (Figure 5.5). Unlike other climate generators, it produces individual storm parameter estimates such as time to peak, rainfall intensity and storm duration. These parameters are needed to run the WEPP model.

A limitation of using CLIGEN is that it is difficult to adapt to South African climate with the majority of the weather stations in the model being situated in the northern Hemisphere. The climate data for this particular project was adapted using the Melbourne, Australian option as it is situated in the southern Hemisphere and therefore the seasonal variations are similar to those of South Africa. One is able to adjust the rainfall and temperature data, however the co-ordinates and altitude data cannot be altered and saved. Thus we were able to adapt the model to run with our field and historical data but not able to store and repeat the process at a later stage. A severe limitation as it required duplication of data input to run the model. To use CLIGEN effectively one would need to have historical climate records for South Africa programmed into CLIGEN by the developers. This is all accessed through the WEPP interfaces page (Figure 5.4) by selecting Rock: Clime.

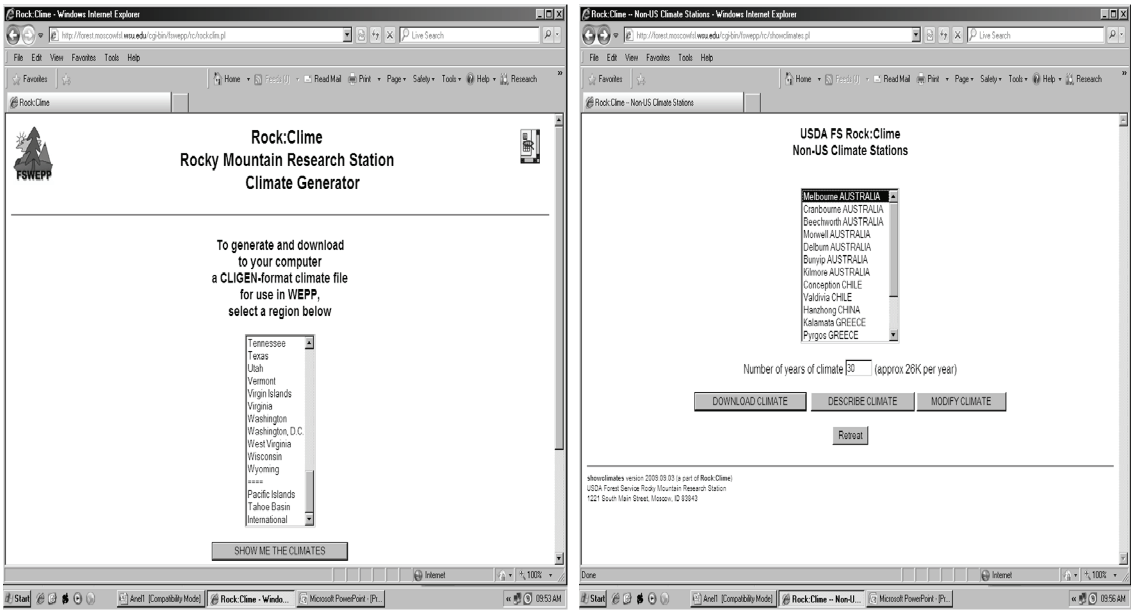
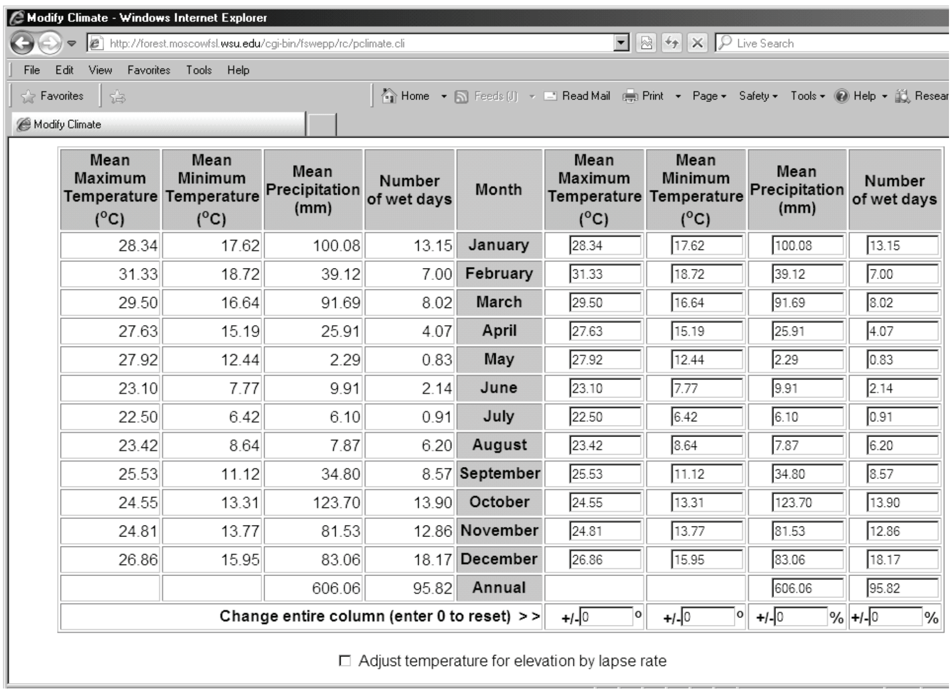


Figure 5.5. Rock: Clime weather station selection screens.



Mean Maximum Temperature (°C)	Mean Minimum Temperature (°C)	Mean Precipitation (mm)	Number of wet days	Month	Mean Maximum Temperature (°C)	Mean Minimum Temperature (°C)	Mean Precipitation (mm)	Number of wet days
28.34	17.62	100.08	13.15	January	28.34	17.62	100.08	13.15
31.33	18.72	39.12	7.00	February	31.33	18.72	39.12	7.00
29.50	16.64	91.69	8.02	March	29.50	16.64	91.69	8.02
27.63	15.19	25.91	4.07	April	27.63	15.19	25.91	4.07
27.92	12.44	2.29	0.83	May	27.92	12.44	2.29	0.83
23.10	7.77	9.91	2.14	June	23.10	7.77	9.91	2.14
22.50	6.42	6.10	0.91	July	22.50	6.42	6.10	0.91
23.42	8.64	7.87	6.20	August	23.42	8.64	7.87	6.20
25.53	11.12	34.80	8.57	September	25.53	11.12	34.80	8.57
24.55	13.31	123.70	13.90	October	24.55	13.31	123.70	13.90
24.81	13.77	81.53	12.86	November	24.81	13.77	81.53	12.86
26.86	15.95	83.06	18.17	December	26.86	15.95	83.06	18.17
		606.06	95.82	Annual			606.06	95.82
Change entire column (enter 0 to reset) > >					+/- 0 °	+/- 0 °	+/- 0 %	+/- 0 %

☐ Adjust temperature for elevation by lapse rate

Figure 5.6. Rock: Clime climate data input screen (with study site data entered).

The second step requires the user to select either an individual road segment (WEPP:Road module) or a series of connected road segments (Road:Batch module). Once selected, the user is presented with an input screen that requires climate station (as customized in Rock: Clime), soil texture and rock percentage, road design and basic road configuration information. At present the interface allows for four road design and soil texture options (Figure 5.7). The main inputs for the road segment is gradient, length and width with additional information needed for the road fill, road buffer, traffic intensity and surface condition. Four different soil types (clay loam, silt loam, sandy loam) can be chosen for the soil input. The road design is specified by defining whether the road is insloped or outsloped (Figure 5.8). Road length and gradient, fill length and gradient, buffer length and gradient, road surface (native, graveled, paved) and traffic level (high, low, none) also need to be defined. The outputs of the simulations are mean annual runoff, mean annual road erosion and mean annual sediment yield. The model is then run using the WEPP routines to estimate mean annual precipitation (30 year period) (MAP), mean annual runoff (MAR), soil loss from the road and sediment leaving the road buffer.

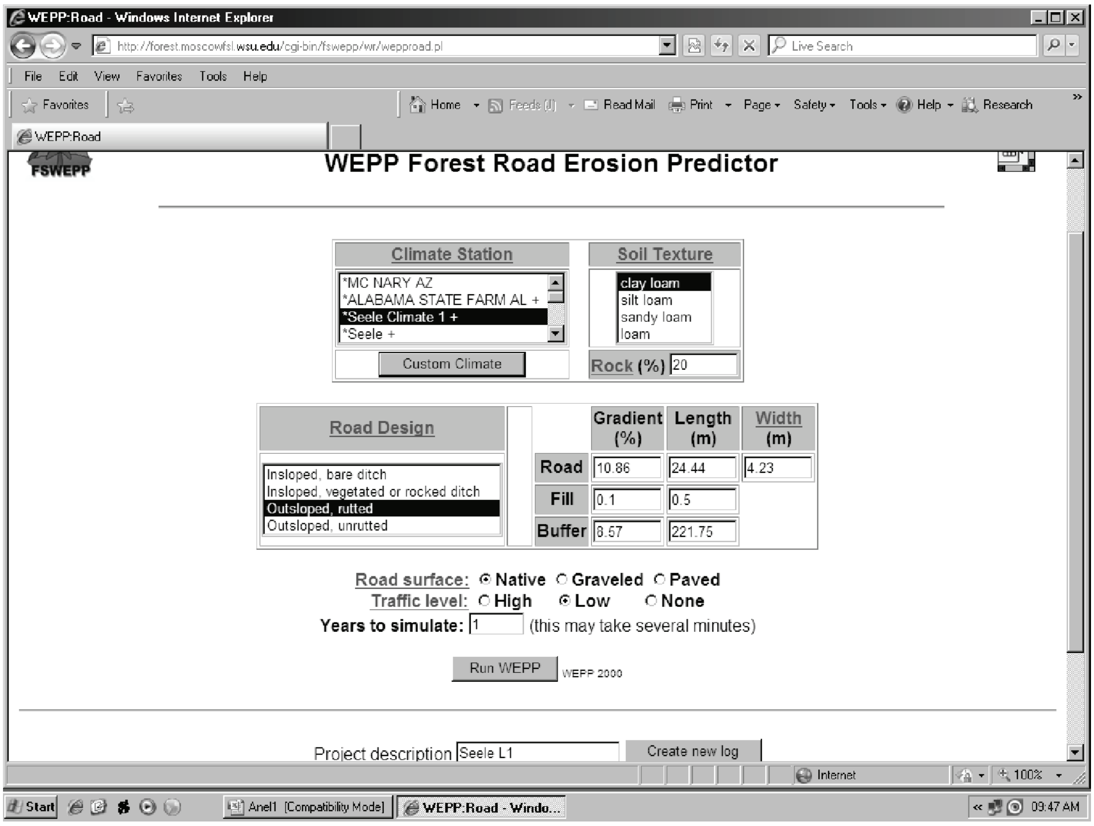


Figure 5.7. WEPP: ROAD input screen.

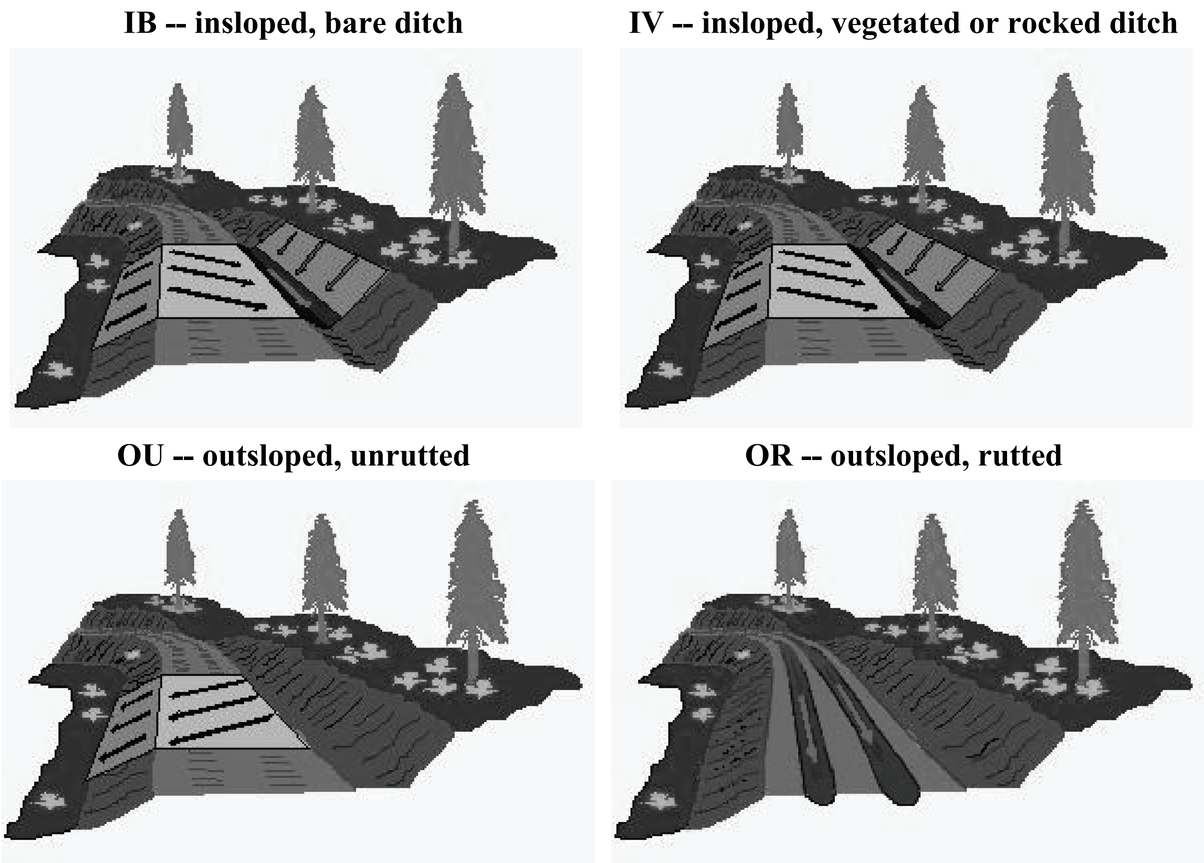


Figure 5.8. Road design options.

Once WEPP has been run, WEPP: ROAD log can be used to record each road segment run through the WEPP: ROADS model. From the WEPP: ROAD log (Figure 5.9) all parameters entered into WEPP: ROADS are displayed along with results of sediment yield (kg). Although WEPP: ROAD log is provided it needs to be backed-up immediately as it is only stored on the system temporarily.

Yrs	Climate	Soil	Rock	Surface, traffic	Design	Road grad	Road len	Road width	Fill grad	Fill len	Buff grad	Buff len	Precip	Rain runoff	Snow runoff	Sed road	Sed profile	Comment
1	Seele Climate 1 +	clay loam	10 %	native low	outsloped rutted	10.86 %	24.44 m	4.23 m	0.1 %	0.5 m	8.57 %	221.75 m	743 mm	0 mm	0 mm	76.88 kg	0.00 kg	Seele L1
1	Seele Climate 1 +	clay loam	5 %	native low	outsloped rutted	12.54 %	21.21 m	3.88 m	0.1 %	0.5 m	9.51 %	126.2 m	743 mm	0 mm	0 mm	66.97 kg	0.00 kg	Seele L2
1	Seele Climate 1 +	clay loam	5 %	native low	outsloped rutted	13.5 %	24.3 m	3.56 m	0.1 %	0.5 m	13.17 %	113.93 m	743 mm	0 mm	0 mm	87.70 kg	0.00 kg	Seele L3
1	Seele Climate 1 +	clay loam	15 %	native low	outsloped rutted	15.96 %	26.65 m	2.82 m	0.1 %	0.5 m	18.26 %	131.4 m	743 mm	0 mm	0 mm	95.22 kg	0.00 kg	Seele L4

Figure 5.9. WEPP: ROAD log file

5.5 Results

The modelled and the measured data are plotted as a function of road gradient (Figure 5.10). It is clear that at gradients greater than 9% the model under predicted the amount of sediment lost relative to the observed information. At gradients less than 9% the reverse situation applied. Spearmans rank correlation matrix between the measured data and gradient and the observed data and gradient showed a significant correlation, which as would be expected, is higher for the modelled dataset.

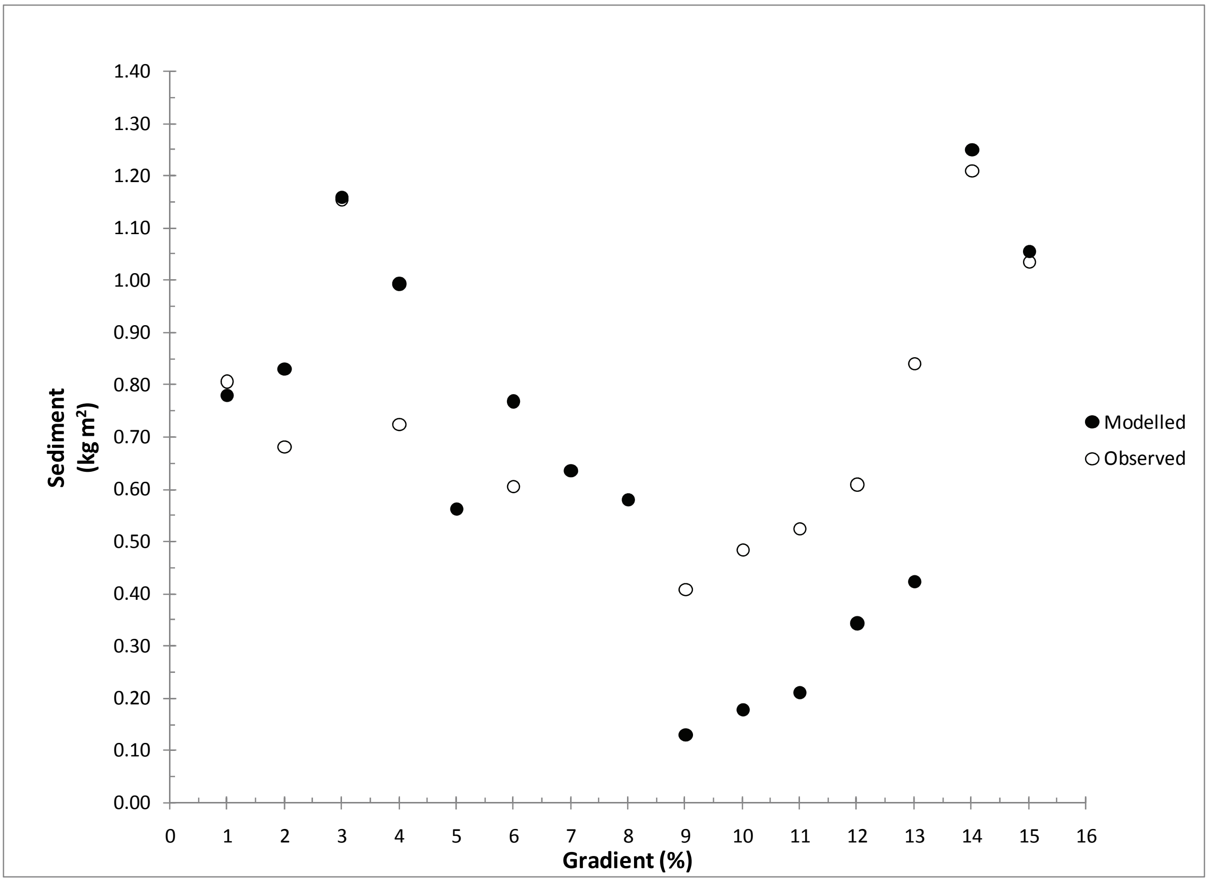
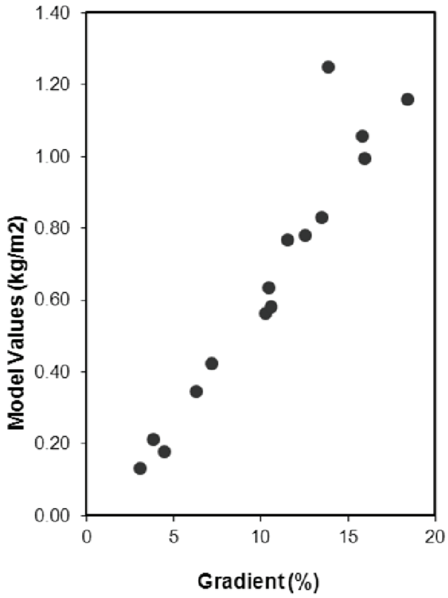


Figure 5.10. Experimental plots gradient versus observed and modeled sediment load.

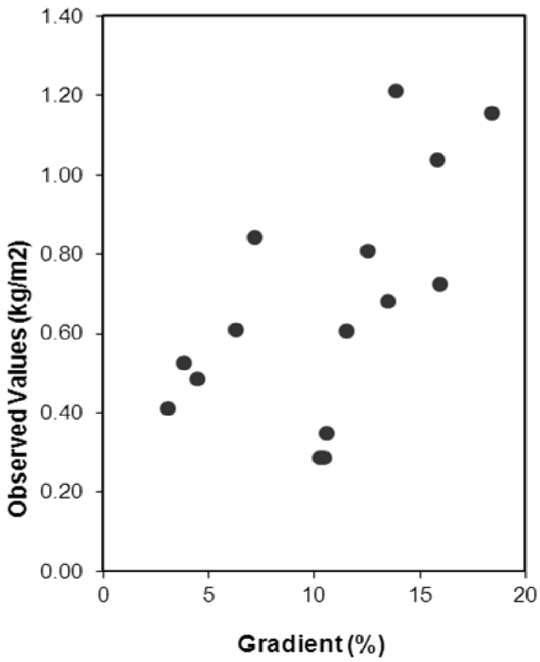
A Spearman's Rank correlation between the gradient and modeled data provides the following outcome:



Gradient	Model Values
12.54	0.779622936
13.5	0.829667471
18.43	1.157931813
15.96	0.99249531
10.3	0.562374245
11.55	0.767466718
10.51	0.634436702
10.63	0.57997675
3.09	0.129862366
4.49	0.17667479
3.86	0.210222285
6.33	0.343117767
7.24	0.422764835
13.89	1.248922169
15.84	1.055523828

Figure 5.11. Spearman's rank correlation of the modeled sediment yield (kg m^{-2}) against the road gradient (%) is significant (Spearman's rank = 0.9679, 13 d.f., P = 3.59E-09).

For the observed data the following results were achieved:



Gradient	Observed Values
12.54	0.806309971
13.5	0.680861646
18.43	1.155584552
15.96	0.72361892
10.3	0.286320703
11.55	0.605281339
10.51	0.284147485
10.63	0.345943408
3.09	0.407996858
4.49	0.482674674
3.86	0.524429079
6.33	0.608723567
7.24	0.840515269
13.89	1.209607129
15.84	1.035074456

Figure 5.12. Spearman's rank correlation of the observed sediment yield (kg m^{-2}) against the road gradient (%) is significant (Spearman's rank = 0.6324 13 d.f., P = 0.011458).

Figure 5.13 shows the regression relationship between the predicted and the observed values of sediment loss from the plots. The strength of the regression relationship is moderate with an R^2 of 0.518. For three road plots, namely 6,8 and 9 the modeled values were substantially higher than the observed. As was noted earlier these plots have a good vegetative cover which probably limited the dislodgement and entrainment of sediment. Although the WEPP model has been shown to deal with vegetative cover adequately this has not translated to the WEPP:Roads component. The user interface makes no provision for site specific vegetative cover as from the outset roads are treated as bare soil surfaces. If these plots are removed from the comparison then the R^2 increases significantly to 0.727.

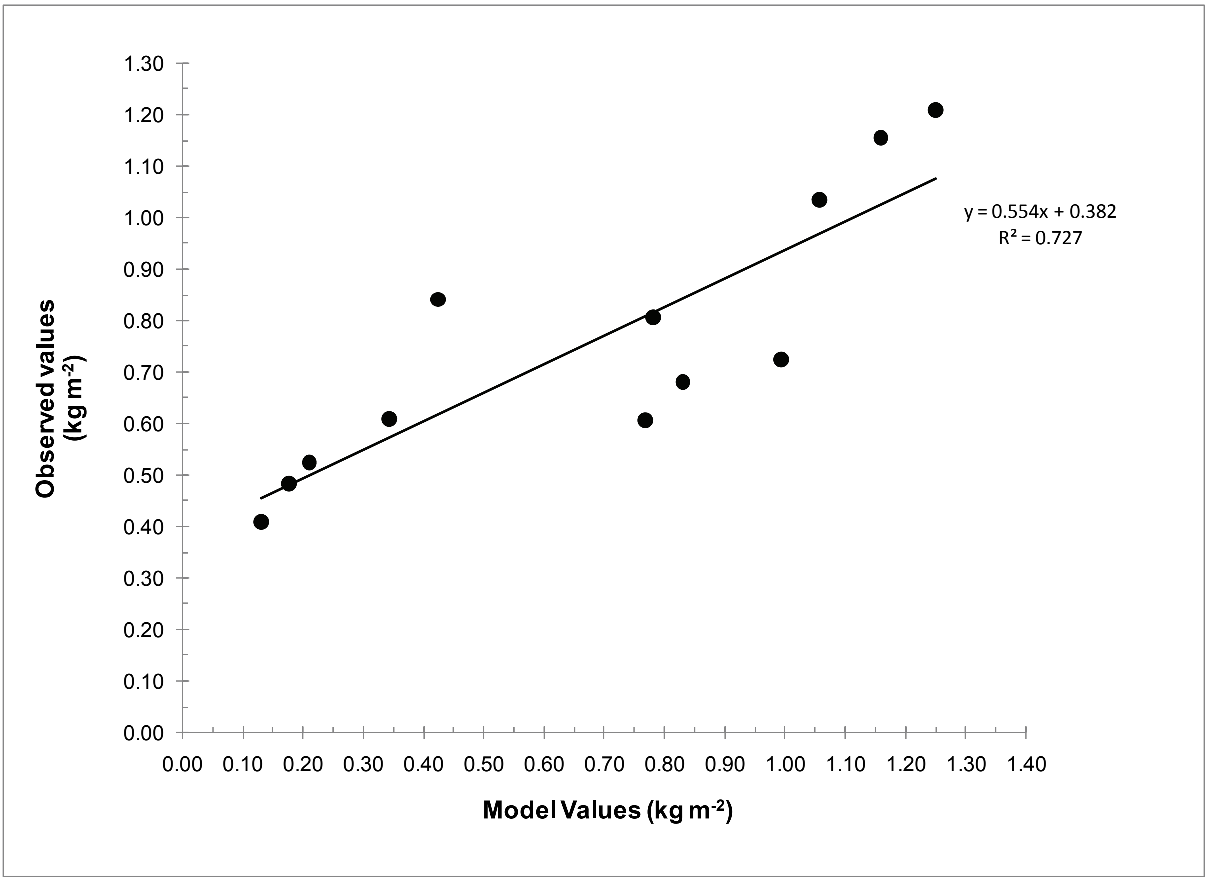


Figure 5.13. Observed versus modeled sediment loads for the experimental plots.

The root mean square error (RMSE) is a further statistic that can be used to derive useful information about the performance of the model by the nature of the difference between the observed and predicted values (Wilmott, 1981). It has the same units as the observed and predicted values and is computed based on the number of paired observations (N), predicted values and observed values. The RMSE was calculated using the formula

$$RMSE = \sqrt{\frac{\sum_{i=1}^{N}(P_i - O_i)^2}{N}}$$

Where Pi = predicted
Oi = observed
N = number of observations

The RMSE of 0.244 kg m^{-2} suggests that the model may be used to estimate sediment yield with a reasonable measure of accuracy within the estate. Further validation of the model will, however, be required in extraneous areas.

In order to obtain an approximate estimate of total sediment loss throughout the catchment based on the total road area and gradient the entire road network was classified into four gradient classes. The total road length in each gradient class was computed from the DEM and multiplied by an average road width of 3.8 m to obtain the total road area per gradient class. The mean sediment loss per gradient class (Figure 5.14) based on both the observed data and that predicted by the WEPP:Road model was used to calculate total sediment loads.

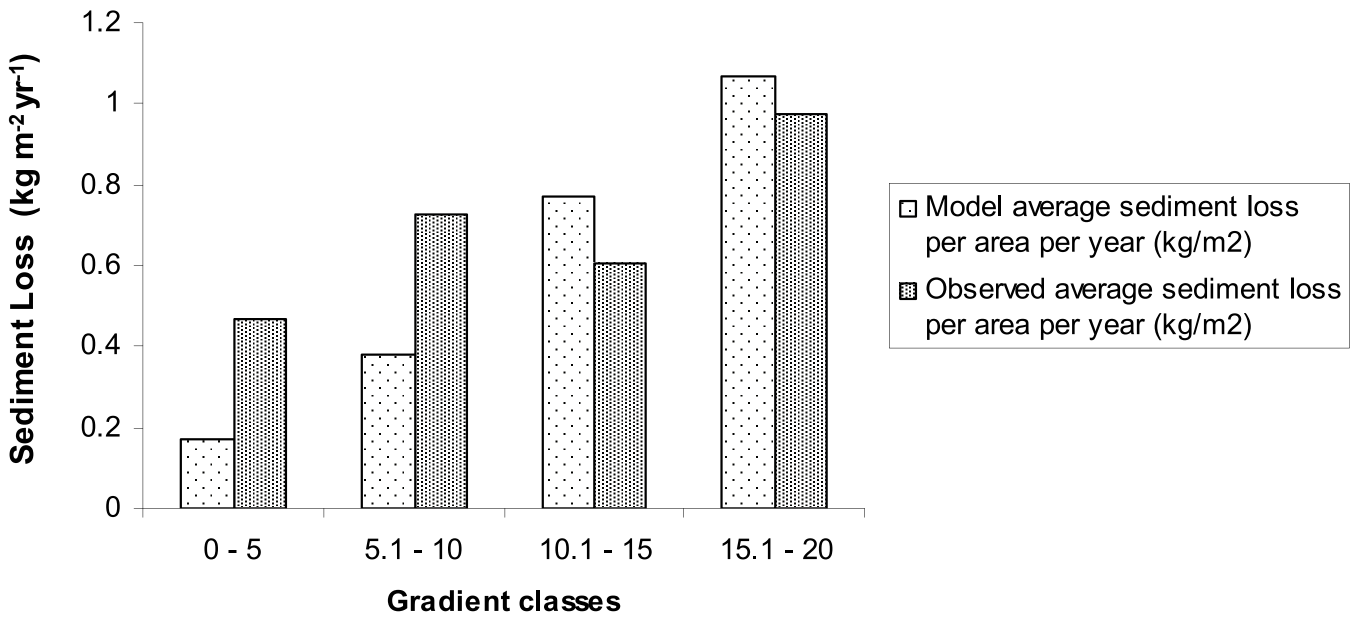


Figure 5.14. Observed sediment yield and the modeled sediment yield.

Table 5.2. Total sediment loads.

Gradient	*Road Length (m)*	*Road Area (*3.8 m) = m²*	*Model average sediment loss per area per year (kg m⁻²)*	*Observed average sediment loss per area per year (kg m⁻²)*	*Model sediment loads (kg)*	*Observed sediment loads (kg)*
0-5	30578	116196.4	0.173	0.470	20101.77	54612.31
5.1-10	15301	58143.8	0.380	0.725	22094.64	42154.26
10.1-15	7095	26961.0	0.771	0.604	20786.93	1628.38
15.1-20	6948	26402.4	1.070	0.973	28250.57	25689.54
Total Roads					**91233.92**	**124084.48**

At the outset it must be stressed that the estimates of the total sediment loads quoted in Table 5.2 represent at best a first approximation, the confidence of which will improve as field estimates of erosion rates improve or refinements in model prediction occur. Of perhaps greater significance from Table 5.2 is the realization than even small changes in the rate of soil loss from road surfaces can lead to large sediment loads that could potentially find its way to watercourses. Even on gentle gradients as much as 20 tons of soil within the study site may be mobilized. The deposition of sediment beyond the road system such as within the forestry compartment may mitigate such risks although this aspect has yet to be effectively explored.

According to Fu *et al.* (2010) despite the large number of existing physics-based erosion models for hillslope and catchment applications, the number and diversity of these models for unsealed roads is relatively small. This makes the direct adoption of a model to suit the exact nature of the study challenging. Nevertheless, the successful adaptation of selected physics-based models to road erosion and sediment delivery studies indicates the potential of incorporating roads into pre-existing hillslope models without major alterations to their structure. Most road erosion studies have been undertaken to assess offsite water quality problems. Hence, according to Fu *et al.* (2010) there is a need to consider both erosion from roads and the processes that govern sediment delivery from roads to streams. However, in most models, there is a significant bias towards the erosion process, with much less consideration given to delivery processes. This is due to the difficulty of obtaining monitoring data to quantify or test road-to-stream connectivity across a range of physical environments. Thorough evaluations of the outputs of road models, particularly in their capacity to estimate the amount of the road-derived sediment reaching a stream, are largely limited. This supports the need for the extensive on-site road sediment collection within this research. The most common, and sometimes only, variable to determine sediment delivery from road to nearest stream or outlet point is the distance between road and the point.

However, of concern is that this will ignore other important contributing factors, such as the contributing road area and rainfall intensity (Hairsine *et al*., 2002), gully initiation (Croke and Mockler, 2001), groundcover, interception, slope, and the presence or absence of runoff-detaining features along the flow path, such as raised sections of road or 'overflow' sections., as the present research can testify to.

A counter argument to the use of both erosion and delivery modeling could be made that modeling the likely locations of highest sediment generation from a road network can be effective in identifying opportunities to control erosion (Fu *et al*., 2010). What is required is field inspections which may identify whether the generated sediment is being delivered to areas of concern in problematic quantities, and whether the best solution is improved road management or improved off-road practices such as detention ponds or road berms. Similarly, modeling the sediment delivery potential of road segment is useful to identify potential road segments for further investigation or monitoring on sediment generation, and to assess alternative road or drainage locations to control road-derived sediment from entering streams (Eastaugh *et al*., 2008).

5.6 Limitations

As with any models and undertaking site specific research there are a number of limitations that are encountered with a broad, generalised model. The following have been documented with the intention of; i) ensuring people are aware of the limitations and take these into consideration when interpreting the results, and ii) to be considered if others intend to use the model.

- A limitation regarding the input of data was that WEPP: ROADS would only accept up to 300 m for the buffer length. This is impractical in many situations and it is often, from field observations, not clear where the entry point of sediment into the stream network is,
- A major limitation which was encountered was the inability to include vegetation cover which could be common on roads with low traffic intensity,
- Limitation of soil type and traffic conditions,

- Does not consider rainfall interception from overhead vegetation,
- Considers total precipitation but not runoff per plot *per se* in the model,
- The obvious issue of up-loading southern Hemisphere data sets and the limited southern Hemisphere sites,
- The personalised climate data entered is not saved permanently and is deleted in 'an undetermined time',
- Although one can choose and slightly modify the climate data from a particular site, the model uses the historical data to simulate sediment yields, and
- The model does not use surface run-off or soil porosity to calculate sediment yields.

Furthermore, in particular in terms of experimental design, one needs to consider:

- a greater variation of road gradient to determine any obvious cut-offs of gradients,
- the impact of initial sediment loss with early season 'flushing', and
- ability to highlight event-driven activity, i.e. many storm events do not produce run-off or sufficient run-off to provide sediment.

Whilst the web-based user interface to run the WEPP:Road Module allowed for the simulation of forest road erosion, runoff and sediment yield it is limited to single road segments. To evaluate a entire road network it is necessary to analyse each segment one at a time. This is time consuming and costly as the data for each segment needs to be entered manually. Although GeoWEPP has integrated GIS and the WEPP model it applies principally to erosion and runoff at the catchment scale – thus the effect of roads are assessed in an indirect manner. This limitation was recognized by Egli (2006) who developed the FORECALT (Forest Erosion Calculation Tool) routine that effectively integrated GIS and WEPP.

A possible solution could be investigating the use of FORECALT as the approach considers that road surfaces are the main source of erosion in forest areas which leads to a degradation of the aquatic system. The sedimentation in streams affects the water habitat by shortening the life of reservoirs and perturbing natural geomorphic channel processes. The idea of the model is to provide information that could provide solutions to reduce environmental impacts due to forest road erosions. It is purported that the spatial tool can be used by scientists and forest managers to analyse the erosion due to forest roads with the purpose of better forest road planning (Egli, 2006).

Road feature lines captured within the GIS and overlain on the DEM are split into individual road segments which are the fundamental elements for the road model. Egli (2006) demonstrated that road segments with a length of 80 m represents the DEM with reasonable accuracy. Each segment represents a cut and a road surface. Using the real water flow path for road elements, the effective length, width and slopes are calculated for the surface elements. The cut dimensions are estimated with the cut width calculation method based on the terrain slope. For the integration of GIS and WEPP, FORECALT creates all necessary input files for the WEPP executable programme.

5.7 Conclusions

According to Fu *et al.* (2010) access to good data is the greatest limitation to the development of sediment generation and delivery models for unsealed roads. However, one needs to be aware of the limitations when developing and applying these road models and ensure that modeling studies are supported by well-targeted monitoring. The experience gained during this study with regard to these models has been that the objectives, the anticipated modeling approach and available resources must be carefully considered when developing a monitoring program. The key guiding principle should be a clear understanding of how monitoring data will contribute to model development and testing and must respond to an *a priori* understanding of the potential factors controlling road erosion and the sediment delivery processes. Moreover, it is important to be take cognizance of the general framework and methods that will be used to generate, test, or validate a model. Thus, monitoring across the intended range of environmental conditions and road characteristics is required for confident application of a model.

The importance of unsealed roads in influencing off-site water quality is being increasingly recognised as a research priority (Fu *et al*., 2010, Ramos-Scharron and MacDonald, 2007). The identification of sediment sources and their delivery potential using mathematical models can assist in developing best management practices and/or prioritising data collection and research activities. A range of models have been developed for estimating surface erosion on unsealed roads but they are typically at earlier stages of development than corresponding models that have been applied to other land use activities. These models of surface erosion and sediment delivery from unsealed roads can be categorised as empirical and physics-based models, both of which been considered during the present investigation.

Another web-based application which has been identified within this research is the X-drain model (Elliot *et al*, 1998), which determines optimum cross drain spacing for existing or planned roads, and developing and supporting recommendations concerning road construction. The WEPP Forest Road Erosion Predictor and the X-drain model are one-dimensional applications considering only one road segment with uniform conditions at a time. However suitable and acceptable spacing of a road drainage system requires multiple simulations within a spatial network of roads. To address the problem of cross drain culvert spacing for larger forest networks, Damien (2001) developed the Culvert Locator for Sediment Reduction (CULSED). This program is an interactive design tool, implemented as an ArcGIS extension, requiring GIS road layer, a stream layer, a layer with culvert locations and a DEM. It calculates the sediment delivery at each culvert location and displays the result on the computer screen. The user can add and modify cross-drain culverts and dynamically evaluate the total sediment impact to the stream network from road systems (Schiess *et al*, 2004). CULSED models road erosion from a geo-referenced road network, however, the sediment transport and erosion calculations are a limiting factor. CULSED uses a simplified method for calculating erosion based on the Washington State Dept. of Natural Resources Manual (Damien, 2001; 2003). This model, of which an initial demonstration and preliminary data set from this research was run, could possibly be investigated for future use. However, a broad understanding of the GIS platform such as ArcGIS is required. The model is heavily reliant on well mapped roads and culverts and, as opposed to the sediment load estimation capabilities of WEPP:Roads, is designed more from a management perspective. It does include the option of delineating where and what size culverts should be positioned along a road to 'take-off' sediment at critical loads. Further detailed site surveys would be necessary to fulfill the requirements for the model.

Chapter Six

Development of Indicators of Access Road Degradation

6.1 Introduction

Criteria and indicators are rapidly developing into important and innovative tools for sustainable forestry management. The main value of criteria and indicators lies in its ability to translate often lofty principles of sustainability into measurable goals and "signposts" (Wijewardana, 2008). With the forestry certification programme, overseen by the Forestry Stewardship Council (FSC), now being widely embraced by timber producers in South Africa there is an increasing need to communicate the current "degradation" state of forests. Principle six of the FSC code of practice clearly calls for the conservation of biological diversity and its associated values, water resources, soils, unique ecosystems and the maintenance of the ecological integrity of the forest. Internationally, forests are gaining increased acceptance as ecosystems and measures are therefore being developed to promote forest health, a portion of which is dedicated to readdressing management imbalances of the past (Kappes, 2006).

Inspection and assessment of forestry access roads are crucial for the development of holistic forestry management programmes. The challenge, however, has been that much of the existing forestry road infrastructure in South Africa has been inherited from private landowners, who viewed the principal function of roads as one of purely access (Hurd, pers. Comm). Arguably, lesser attention was given to both off-site and on-site effects of road construction. For the forestry industry to institute effective road maintenance programmes and to embark on corrective action when required, there needs to be system in place to evaluate or classify either individual road segments or complete road lengths against a set of set of measurable "degradation" criteria. This process has already been initiated by the forestry industry, in part, who are in the process of compiling a rapid assessment tool to evaluate forestry access roads (Hurd, 2009). To refine this approach the physical processes and drivers that contribute to the advancement of road degradation must be incorporated into the appraisal. This can often be learnt from the specific characteristics of the access road when viewed against mechanisms governing the process of accelerated soil erosion. The availability of indicators facilitates, in part, the achievement of this objective as it allows for the effect of management interventions to be assessed within an objective framework so as to prevent or limit the negative repercussions that derive from a poor state of conservation.

Although soil and climate characteristics play an important role, soil degradation especially within forests has principally been linked to the inappropriate use of land and water resources. Much has been written on the effects of forestry in altering the physical environment and hydrology of regions. These studies have generally supported the view that in its pristine state the infiltration capacity of forest soils is usually high mainly due to the high organic matter load and litter that accumulates beneath the forest canopy. This limits the generation of infiltration-excess overland flow and allows for the replenishment of deep soil water and groundwater reserves. The construction of access roads, however, alters the overall catchment infiltration opportunities and changes the production of rapid overland flow (Waterloo *et al*., 2007). In this situation high rainfall can frequently result in high runoff. Prolonged rainfall which is greater than the infiltration capacity of the soil is likely to result in increased erosional processes.

Heavy traffic compacts roads, reducing infiltration and further increasing runoff and subsequent erosion. Consequently increased concern has been raised regarding the potential impacts that harvesting operations in plantation forestry can have on the environment (Tewari, 2001). Compaction has not only been associated with the weight of the machinery used in the industry during the harvesting phase, but also the combined forces (compaction, traction and shear) acting on the soil from the tyres or track of the vehicle and the axle load (Tewari, 2001). Further the building of roads often results in clearance of vegetation, which poses increased risks for accelerated soil loss. This can lead to the sedimentation of water courses and impact negatively on the water quality of catchments.

It is the aim of this section to investigate several of the assertions made above by investigating/assessing the condition of forestry roads and their contribution to the cycle of sediment production, runoff and, ultimately, erosion and re-sedimentation; particularly with respect to the manner in which this might ultimately affect the water quality within a given forested catchment. The potential for a soil to erode is dependent upon numerous variables such as soil type, slope gradient, slope length and the land use type. Kienholz (1977) originally produced a map of the erosion potential for East Germany based on the combined values of slope gradient, land use and soil texture into a simple "qualitative classification". A similar study was undertaken in Zimbabwe (Stocking and Murnaghan, 2001). Such work has shown the value of differentiating between erosion potential as a management tool, and the documentation of actual erosion observed on the ground. It has further illustrated that, where similar levels of erosion are found in areas of differing erosion potential, the erosion in the more susceptible area will increase in severity more rapidly than elsewhere (Cooke and Doornkamp, 1990).

6.2 Classifying Degradation on Unpaved Forestry Roads

Soil degradation represents an adverse change in soil properties over time, generally interpreted to result from human interactions that affect the equilibrium of the soil (Lal *et al.*, 2004). Blum (1998) termed soil degradation as a loss or reduction of soil energy over time, frequently set in motion by the disturbance of a 'dynamic equilibrium' of soil. From this it is then clear that any access road will, at least to some extent, represent 'soil degradation'. What is, however, of particular interest here is the *extent* of such degradation. This in turn relates to the ongoing changes that occur in the soil-water-environment continuum (i.e. the interaction between the soil, the water interacting with it in the context of the road), and the immediate surroundings.

These changes are driven by the following parameters and their interactions with one-another:

- The initial emplacement & character of the road;
- The properties of the rainfall, its conversion to surface runoff, soil water, groundwater and finally stream runoff/discharge;
- The soil character, both on the road and the adjacent environment; and
- Changes brought about by road usage, which impact both on water movement and on soil character (e.g. loss of structure through load or shear forces)

Fundamentally, the changes will ultimately revolve around erosion of soil off the road, or its corollary of sediment deposition onto or adjacent to the roadway. Taking this reasoning forward, the actual erosion (degradation) will be the combined effect of the erosion susceptibility; the usage and the preventative measures in place, and will impact on both the environment but also, ultimately, the efficient operation of the commercial forest itself. In essence then a very similar set of conditions used to postulate the original Universal Soil Loss Equation (USLE) and its current (Revised) derivative RUSLE (Renard *et al.* (1994). This then underpins the rationale used in assessing road degradation. Susceptibility and usage can be as easily (if not better) determined from company records as in the field, while the *actual state* of the road and its immediate environs can only effectively be determined by direct observation in the field. This then, together with the imperative of using as little time of the field staff as possible yet also assessing the efficient functioning of the commercial forest, (as their principal responsibilities lie elsewhere) is the reasoning behind using two tables of data which are clearly interdependent. The tables will need to be cross-referenced (for example with respect to topographic details), and will clearly need to be combined mathematically later to obtain a single value of degradation for any given road segment under consideration.

The data contained in Table 6.1 effectively represents the *potential* for degradation to occur. It therefore considers the erosivity of the dominant rainfall (measured in terms of the EI_{30} index); the erodibility of the soil (derived from the K-value nomograph of Wischmeier & Smith (1978) in the absence of more accurate data obtained from local runoff plots); the influence of topographic factors, and the nature and frequency of vehicular usage. The latter is itself classified according to vehicle type and its respective impact, with a weighting factor based on the product of 0.1 X the gross axle mass of the vehicle x ground pressure of drive tyre x gradient factor (0.1 x grad %). This is used to take cognizance of the compaction, disaggregating and shearing effect of heavy loads, aggravated by gradient which increases the shear forces acting on the soil surface.

By contrast, Table 6.2 represents the *field assessment* of the actual state of degradation on or near the road. It considers the state of the road drainage (both across the road and along it); the topographic conditions of the road segment (which should ideally match the data in Table 6.1, but may well not do so as the information for Table 6.1 is derived from scaled map interpretation rather than actual field data); the road surface condition, both when dry and when/if wet; and the nature & frequency of tracks, rills and potholes.

Table 6.1. Road Background Data.

GPS Location:							
Road Number:	**Purpose:***					**Road Segment Number:**	
1. Precipitation type:						**Comments:**	**Rating Score*:**
Type* (rate **only** the dominant rainfall)	**√ box = Yes**	**Erosivity Index* (EI $_{30}$)**				DOUBLE THE SCORE HERE:	
Frontal		A	B	C	D		
Mixed		A	B	C	D		
Convection		A	B	C	D		
2. Soil Characteristics:							
Texture (sand, silt, Clay %)							
Organic Matter %							
Erodibility* (use 'K' value from USLE nomograph) A K ≤ 0,15; B K ≤ 0,35; C K ≤ 0,5; D K > 0,5		A 15	B 30	C 55	D 100	DOUBLE THE SCORE HERE	
3. Topographic Details:(if more than 10% difference between Tables, use T2)						Match with Table 2 Section 2	
Road segment gradient. A 0 to 4%; B 5 to 8%; C 9 to 15%; D > 15%		A	B	C	D		
Road camber A slight; B noticeable; C inducing cross flow D responsible for cross-flow rills		A	B	C	D		
Straight road length for segment A up to 10 m; B 11 to 20 m; C 21 to 30 m; D more than 30 m		A	B	C	D		
Cut (or fill) embankments A up to 0.50 m height; B up to 1 m; C up to 1,5 m; D more than 1,5 m in height		A	B	C	D		
4. Road surface Properties:*							
Runoff generating road surface material A *In situ* material (soil) B Armoured – **gravel** (approx 85% water yield) C *In situ* material (rock) D Armoured – **tar** (will give almost 100% water yield)		A	B	C	D	Multiply score here by 5	

Vegetated (generally grass)	A	B	C	D	Multiply score by -1.0	
Leaf litter A slight presence; B thin but full ground cover leaf/grass; C full grass or ≈ 5cm leaf cover; D no soil visible, humus present	A A	B B	C C	D D	Multiply score by -5.0 Multiply rating based on 0.1 X gross axle mass of vehicle x ground pressure of drive tyre x gradient factor (0.1 x grad %)	
Freq of 'Water breaks' / uniform gradient A up to 1per 100 m; B to 1 per 75 m; C to 1 per 50 m; D more than 1 per 50 m	A	B	C	D		
Road drain Spacing A up to 1per 100 m; B to 1 per 75 m; C to 1 per 50 m; D more than 1 per 50 m	A	B	C	D		
5. *Dominant* Vehicle Usage: **(√ letter = Yes)** A Emergency & Management Vehicle B Forest Equipment etc C Other D Logging Trucks						
Frequency of Passage A up to 10 x per week; B up to 20 x per week: C up to 25 x per week; D up to 30 x per week	A	B	C	D	DOUBLE THE SCORE HERE	

Table 6.2. Road Field Assessment Data.

GPS Location:					**Timber Estate & Block:**	
Road Number:	**Purpose:***				**Road Segment Number:**	
1.1 Drainage Assessment Perpendicular to Road:					**Comments / Observations:**	**Rating Score*:**
Wash over surface in depression A evidence only: B obvious; C scour or sed. deposit; D > & affects use	A 15	B 30	C 55	D 100		
Wash over surface at culvert A evidence only: B obvious; C scour or sed. deposit; D > & affects use	A	B	C	D		
Culvert blocked A evidence only: B obvious; C 50%; D > 50% & impacting flow	A	B	C	D		
Rills across road* (W/D related) A up to 50 mm; B up to 100 mm W/D > 1,5; C to 200 mm W/D > 1; D depth > 20 mm and or W/D ≤ 1.0	A	B	C	D		
'washboard' problem (W/D related) A < 0,5/m; B up to 2,5/m; C up to 5/m W/D ≥ 1; D > 5/m W/D < 1	A	B	C	D		
Rill freq or extent of 'washboard' (multiply by % of segment affected) A < 0,5/ m; B up to 2,5/ m; C up to 5/ m; D > 5/ m	A	B	C	D	DOUBLE THE SCORE HERE	
Cross-drainage water flow from adjacent compartment onto road A slight; B causing shallow rills; C rills > 15cm; D severe or bank collapse	A	B	C	D		
Wash-away or scour across road A some evidence; B clearly evident; C up to 15cm; D > 15 cm	A	B	C	D	DOUBLE THE SCORE HERE	
Drain parallel & adjacent to road scoured* (W/D related) A up to 200 mm below rd (W/D> 1,5); B up to 300 mm (W/D 1-1,5) C up to 500 mm or W/D < 1; D > 50 mm or impacting track & W/D ≈ 1	A	B	C	D		
Wash parallel but on road surface & scoured* (W/D related) A rut to 20 mm; B to 100 mm; C to 200 mm; D to 350 mm (> = impassable)	A	B	C	D		
Compaction rills/tracks parallel to road & on surface* (W/D	A	B	C	D		

related) A compaction evident B moderate C severe & some wash D extreme						
Wash rills tending to gully on road surface* (W/D related) A rill to 50 mm W/D < 1,5; B rill up to 100 mm or W/D ≈ 1,2; C rill up to 200 mm or W/D ≈ 1; D rill deeper than 200 mm and W/D ≤ 1	A	B	C	D	MULTIPLY SCORE BY 1,5	
Extent of the problem (multiply by % of road segment affected) A 0 to 15%); B 16 to 25%; C 26 up to 50%; D > 50% affected	A	B	C	D	DOUBLE THE SCORE HERE	
ROAD IMPASSABLE	**REASON:**					**10000**
2. Topographic Details:					*Should* match Table 1 but might not	
Gradient of road segment A 0 to 4%; B 5 to 8%; C 9 to 12%; D > 12%	A	B	C	D		
Length of straight road segment of ≈ uniform or convex gradient A up to 10 m; B 11 to 20 m; C 21 to 30 m; D more than 30 m	A	B	C	D	IF SLIGHTLY CONVEX OR CONCAVE, MULTIPY BY 1,5 ELSE USE SHORTER SECTIONS	
Cut (OR FILL) embankments A up to 0.50 m height; B up to 1 m; C up to 1,5 m; D more than 1,5 m in height	A	B	C	D		
Is there evidence of embankment collapse / potential collapse? A potential collapse; B sediment cone exits; C cone to track; D cone affects track	A	B	C	D	DOUBLE THE SCORE HERE	
Frequency of 'Water breaks' per section of uniform gradient A up to 1 per 100 m; B to 1 per 75 m; C to 1 per 50 m; D more than 1 per 50 m	A	B	C	D	MULTIPLY SCORE BY -2	

The philosophy underpinning the rating system in the first instance is that most erosion-related process-response systems are not linear but rather power functions of some form. These processes are in part driven by self-reinforcing positive feedback mechanisms, for example, a rill will alter the micro-topography so as to effectively progressively increase its catchment area. As this increases, the discharge in the rill is likely to increase, thereby increasing the effective stream power and hence lead to further scour, which in turn increases the micro catchment. For this reason the weighting of the score on the severity indicators (A to D) is not linear but follows the slight exponential from 15 to 30 to 55 and then 100. Should a parameter or variable be absent in the sense that it does not apply, the observer would strike it through on the data sheet and record a score of zero for it.

On the other extreme, where a problem is so severe as to make the road impassable, an arbitrary score of 10 000 is suggested to highlight that there is a severe problem with that aspect of the road, and so flag it for management intervention. Factors thought to be particularly significant in furthering degradation are then weighted by a factor. The same logic applies in reverse, where factors which are particularly significant in preventing the degradation of the access road are given a negative score and, where necessarily again weighted (for example the presence of deep leaf litter on a road surface prevents degradation through surface runoff, although it may make the road segment more difficult for light motor vehicles to traverse).

Each of the factors/parameters considered to impact on road degradation will be briefly discussed in turn below:

6.3 Road Drainage

6.3.1 Cross-drainage (i.e. perpendicular to the road, although cross flow caused by road camber will also contribute).

In its most intense form this will result in water flowing over the road either in depressions at crossings of incipient streamlets, or at points where the existing culverts are blocked. A partial blockage implies that the risk of either a complete blockage happening during a discharge event, or of discharge overtopping due to insufficient through-put capacity in the culvert during a storm event is increased. The subject literature documents that the severity of rills is directly related to their depth, and that the distinction between a rill and an incipient gully is commonly based on the Width (W) to Depth (D) ratio. These values are therefore used in determining the severity indicators.

6.3.2 Drainage along the road (i.e. parallel or quasi-parallel to the roadway, both on the roadway itself and immediately adjacent to it).

The objective with most road designs is to keep the roadway as dry as possible. To this end, a drain is normally constructed parallel and adjacent to the road and the road surface either given a camber or a convex profile to shed water to its perimeter. The aim of the severity indices therefore is to again document the nature of the rills and their potential change to gullies, but their linear extent.

6.4 Topographic Character and Setting of the Road

The information here is captured in both Table 6.1 and Table 6.2 on the basis that the parameters defined here are, on the one hand critical in that they define the energy (hence flow velocity, entrainment energies and stream power of any road related runoff *cf* the rationale of the slope factor in the USLE and RUSLE) yet, as previously indicated, most of this data should be extractable from company GIS data bases and only requires field verification in order to save effort by field staff. Where there is more than a 10% discrepancy between the data in the two tables, the field values need to be used to correct Table 6.2 and the GIS data bases suitably updated.

Although there is thus a sense of 'double dipping' in considering the topographic data, this is deemed acceptable in the light of the explanation given above that Table 6.1 represents ***susceptibility*** while Table 6.2 represents the actual degradation and associated ***process***. The severity ratings for gradient are effectively capped at 12^0 as this value approaches the operational limit of most conventional forestry vehicles for unpaved roads. Relatively few road segments will have straight sections in excess of 30 m at uniform gradient. To account for this, the scored weightings for degradation should be increased on *slightly* concave or convex road segments, although in most cases the segment length should simply be adjusted accordingly. Consideration of embankments is self explanatory and attempts to take cognisance of potential ingress of sediment and/or moisture onto the road surface from the adjacent forestry compartment. Conservation measures in the form of frequent water breaks and/or drains to control discharge volume and velocity will reduce degradation, hence the negative severity weighting factors.

6.5 Road Condition

6.5.1 The dry state

The assessment in this section is designed to consider the disaggregation of the soil and its susceptibility to entrainment processes by fluids (i.e. both air and water). Both the shear forces and the compressive forces related to road usage under dry conditions will lead to disaggregation of the soil, making it available for entrainment as soon as water becomes available. This then is also the reason for considering texture, rated by the erodibility factor. Although it is questionable whether this is truly representative as clay sized material would be rated only slightly erodible, yet once disaggregated is highly mobile, it is the only index readily available at present. As before, where factors counteract degradation, such as the existence of significant leaf litter or grass, the severity score is weighted negatively to acknowledge this.

6.5.2 The wet state

The assessment here is intended to recognize both the fact that sediment is in a highly vulnerable state, and that the road condition potentially impacts on the efficient operation of that forestry compartment. Although potholes are not restricted to wet road conditions, they are increased in size very quickly under these conditions and so are listed here. The 'depth' rating of a pothole has associated with it the inherent assumption that the diameter is such that it will affect individual wheels. Once the size is such that a full axle set is affected, it becomes classified as a 'rut'. The splash and its associated cavitation processes are principally responsible for the export of sediment, whereas the shock to the vehicle under both wet and especially under dry conditions increases the vehicle maintenance requirements and hence impacts on the commercial side of the operation.

A few examples of road degradation states is presented on order to illustrate the above concepts.

Figure 6.1. Road segment in a state of good condition.

Figure 6.1 illustrates a road segment, which functionally is in good condition. The road surface is compacted, the road camber is uniform and neutral, there are no signs of loose sediment on the road surface, there is a distinct absence of depressions on the road surface and no visible signs of rill development both on the road surface proper and along the road verge. When viewed against the criteria given in Table 6.2 this road segment should achieve a low score.

As compared with the road segment shown in 6.1 that shown in Figure 6.2 represents a slightly more advanced state of degradation. Despite a similar gradient the soil type at this site is sandier and thus has a different erodibility index. There is a slight negative camber of the road bed which has led to the concentration of water along the road verge. There are visible signs of cross-flow across the road bed as water, surface depressions that lead to the accumulation of water and differential sinking of the road surface due to the plastification and shear displacement of the soil from successive traffic. Although there are distinct tracks that have formed on the road surface these have not advanced to the stage where the passage of vehicles have become severely compromised.

Figure 6.2. Road segment in moderate state of degradation.

From a sedimentation perspective this condition is significant in that there are distinct signs of the accumulation of loose sediment on the road surface, which becomes flushed out of the road system during rainfall episodes.

Figure 6.3 shows a road segment that is in a greater state of degradation than in the previous two cases. Despite much of the road surface being compacted, the cross drainage of water and run-on from the adjacent timber compartments, coupled with the strong negative camber of the road bed have led to the distinct formation of preferential flow paths on the road bed. Originally this would have started out as rills which have subsequently incised into the road bed forming a proper micro-channel. If left unattended this channel will progressively deepen and widen potentially increasing the risk for an advanced state of soil loss. Notwithstanding the current state of this road segment, it nevertheless remains functional.

Figure 6.3. Road segment in an advanced state of degradation.

6.6 Conclusion

The work reported herein has presented a conceptual framework for the rapid assessment of road segments. When coupled with an understanding of the processes of accelerated soil loss, it potentially offers a useful tool for the early detection of road management problems and the collection of information to institute corrective action. The value of this approach will be advanced when linked to rates or erosional process and other supporting quantitative information, which remains the core aims of the research.

Chapter Seven

Conclusions and Recommendations

7.1 Introduction

Forestry access roads are integral the effective functioning of management operations and are important landscape elements. Nevertheless, the very presence of a road network brings about change in the way that water is stored or distributed on the landscape. Of special interest, covered in this research, is the influence of access roads on the generation of surface runoff due to their compacted, low permeability surface relative to surrounding undisturbed regions and the increased risk for accelerated soil loss. The transport of this additional runoff and sediment into forestry compartments and its fate once in the compartment is of interest as it influences the manner in which the road network is managed. These key elements formed the basis of a dedicated research project aimed at understanding the key factors that control the production of surface runoff and accelerated soil loss from forestry access roads. At a workshop convened early on within the research project it became apparent that the forestry industry had inherited much of their road network from previous landowners who perhaps did not fully understand the impacts of road construction on the landscape. As the forestry industry embraces greater self-regulation the issue of access roads is receiving increasing attention. To manage, one must measure and take cognizance of the processes to enable the development of effective sedimentation containment strategies.

7.2 Evidence From The Literature

A survey of previous studies demonstrated that there were two main *direct* approaches to the measurement of surface runoff and sediment from forestry access roads, namely the use of sediment traps at the plot and road segment scale and rainfall simulation studies. Indirect methods have relied on field mapping exercises in which the amount of sediment lost is calculated based on changes in volume over time, for example the extent of gully widening caused by access road drainage, alteration in the physical dimensions of the road bed, or the onset of mass movement complexes caused by road construction. In rainfall simulation studies, a small bordered area within a road segment is subjected to simulated rain at a given (usually high) intensity over a relatively short period following which range of erodibility and erosivity parameters are measured. These studies provided insight into the mechanisms of accelerated soil loss from the road surface but frequently encounter difficulty in upscaling the results to the road segment or catchment scale.

7.3 Findings From This Study

Sixteen runoff plots were established on road segments of varying gradient, taking into consideration the comments of Sheridan *et al.* (2007) that the accurate measurement of soil erosion rates under natural rainfall is both costly and time consuming. The standard runoff plot, which is fully bordered and thus hydrologically isolated from the surrounding environment, could not be utilized for the purposes of the study as the plot had to offer unhindered movement of vehicular traffic. After experimenting with a range of different options for runoff plots, a final design was selected and constructed in early 2009. Each plot was bounded on two sides by custom-manufactured concrete gutters capable of withstanding the weight of vehicle traffic. The experimental design relied on natural topographic barriers to minimize the runoff into the plot from outside contributing areas. The assumption was that this component would be a negligible but untested component of the total runoff from the plot. Field observations showed that this was a reasonable assumption as little evidence of sediment washed into the plot was observed.

7.3.1 Field Measurements

Collection of both runoff and sediment occurred simultaneously by trapping and filtering the sediment within a stilling well and then piping the filtered water through to a tipping bucket mechanism equipped with a magnetic reed switch wired to a datalogger. As this is a gravity driven system this arrangement worked well on the steep road sections and only short pipe lengths were required to redirect the runoff to the tipping bucket. On the gentle road sections deep pits had to be excavated to house the tipping bucket assembly. Thus, the design of the plots had to strike a balance between the need for accurate measurement of runoff and sediment and efficient functioning of the purpose-made equipment. Technical modifications to correct design flaws in the tipping buckets and general trouble-shooting to refine the runoff plot design took place in the early parts of the summer of 2009 when monitoring began in earnest. Measurement of runoff and sediment therefore covers two full summer seasons (2009/2010 and 2010/2011).

This study confirmed that relative to the surrounding undisturbed land, road surfaces are highly compacted with markedly reduced infiltration rates. A percentage of rainfall falling on the roadbed that would have otherwise infiltrated the soil surface contributes to additional surface runoff. The dislodgement of sediment by the erosive action of raindrops striking the bare soil surface and entrainment by surface runoff leads to a net removal of soil from the roadbed.

The rainfall record for the study area showed numerous small events with a few major storms during the monitoring period. Seasonal estimates of runoff production from forestry access roads proved to be a challenging objective due to the failure of the monitoring equipment caused mainly by overtopping of the stilling well during a few high intensity summer storms. Interestingly the difficulty of acquiring *direct* seasonal or annual estimates of runoff production from forestry roads because of equipment or system failure has been alluded to in several past studies. This issue was addressed but not entirely solved by increasing the filter screen size, adding a sediment sock at the inlet to the stilling well and increasing the frequency of site maintenance in summer. Notwithstanding these challenges the general approach and one that was adopted for the current investigation is to evaluate runoff production on an event basis using only runoff and rainfall pairs that are considered reliable.

As was expected, the total runoff was moderately well correlated with rainfall. Perhaps of greater interest, however, is that the coefficient of runoff which ranged between 9 to 30% was weakly correlated with gradient. Three well vegetated plots, although steep, showed low runoff coefficients which suggest that local site condition and surface cover may have an important bearing in limiting runoff production. This has obvious implications for the management of road networks. Sediment loss varied markedly between the plots although there was a clear relationship with gradient. As was found for runoff production, the three vegetated plots decreased the level significance of this relationship which further suggests that establishing vegetation on road surfaces as an erosion control strategy warrants further investigation.

Water that infiltrates the soil surface upslope of roadcuts have been shown in past studies to intersect the road surface and contribute to runoff production. This is referred to as infiltrated subsurface flow (ISSF). In the three years over which this study was carried out no evidence of ISSF within the study area was noted. Attempts at evaluating this parameter by monitoring soil water content across two transects, one of which intersected a roadcut, met with limited success. This was due to the fact that because of the deep well drained soils at the study site saturated conditions were not achieved nor did the roadcut intersect the bedrock surface. These are necessary conditions for ISSF. Furthermore the experimental design called for a specific road configuration which could not be fully realized in the study area. From a practical perspective, however, ISSF may well be an important factor that influences runoff from road surfaces especially within bottomland regions or close to riparian zones.

The movement of road runoff and sediment through mitre drains into the forestry compartment was tracked indirectly by measuring the soil water content distribution within the compartment. The results showed that there was a progressive increase in soil water content along the mitre drain and a marked concentration of water albeit in a small area at the drain outlet. This situation applied to the deeper soil depths but to a marginally lesser extent than near the surface.

7.3.2 Modeling Framework

The field based studies supported the assessment and testing of models in order to extend the relevance of the research beyond its site specific conditions. Following an extensive review of potential models it became apparent that only a few models that could deal with spatial information were really applicable. Several models were tested using common datasets and accepted for further investigation or rejected as they were found to be unsuitable to meet the objectives of the study. Through this elimination process the WEPP: ROAD model was selected as perhaps the most appropriate but not ideal model of choice. The model performed relatively well despite its limitations in not being able to account for vegetation. Further the model deals with individual road segments although entire road networks can be considered. The advantage of the model is that it is public domain and can be accessed via a set of web based interfaces. What is needed, however, is an assessment of the impact of forestry road erosion for an entire watershed or a complete forest road network using established erosion prediction technology. The existing WEPP applications for forest road erosion prediction consider only a single road segment. Analyzing the erosion of an entire road with these tools was complex and time consuming as segments are analyzed individually and data is entered manually. The current WEPP road erosion models have not been integrated with GIS, and therefore spatially distributed erosion simulations of road networks were not possible with these models. At present, for the South African situation, combinations of models are needed and one has to adapt the data entry to produce meaningful results, this is by no means ideal and can be the source of errors. It is recommended that, rather than 're-invent the wheel', close collaboration with the developers of this software take place and through the source code, develop the model to allow for local data entry. In communicating with the model developers during the testing phase it was evident that strong interest in the realization of this objective exists and that they would support such an initiative. To this end the Forestry industry is urged to consider this an important relationship worth expanding upon.

An attempt was made to develop a system of classifying the state of degradation of forestry access roads. As it stands this is a highly conceptual framework but has been refined to the stage where it does have some practical relevance, if only to develop a common platform against which to assess the state of individual road segments or road lengths. The potential value of fully developing such a tool cannot be underestimated as it will allow for early identification of those road segments that are at high risk for excessive sediment production and allow for timely management intervention.

7.4 Recommendations for Further Research

This study has paid dedicated attention to the influence of forestry access roads on runoff, sediment production and soil water movement. In the presence of only a few local past studies much of the work has been exploratory in nature and strong reliance had to be made on past international studies for guidance. Established techniques and systems had to be refined or adapted to local site conditions or to meet the objectives of the study, much of which has been met although perhaps not fully realized from the two years of field monitoring.

7.4.1 Plot Design

The design of the runoff plot was developed specifically for the purposes of this research. Although several of the design flaws in the equipment were corrected early on in the study there remains room for improvement. The gutters, although time consuming and expensive to install has proved to be robust and capable of withstanding high axial loads while still offering uninterrupted flow of traffic. Since the gutters are by themselves efficient sediment traps it is recommended that they be retained in the plot design. As this is a gravity driven system, the sediment must be filtered out of suspension before it reaches the tipping bucket. In past studies such as that undertaken by Black and Luce (2007), sediment, organic matter and other material was transferred to huge sediment tanks where the coarse material was allowed to settle under gravity. At the end of the monitoring period the tanks were emptied using heavy lift equipment and the sediment collected. However, given that sediment loss per rainfall event was required during this study, this approach could not be adopted.

In the current study the sediment-laden water was directed through a filter mesh into a stilling well with the assumption being that the bulk of the sediment would be trapped within this well. For the most part this was achieved and the water entering the tipping bucket was fairly sediment free. However, during high intensity storms blockage of the stilling well outlet by leaves and other debris occurred, which caused the stilling well to overtop. A filter screen was added to the outlet of the lower gutter in an attempt to correct this problem but only a partial solution was achieved. An option to perhaps solve this problem may be to install a much larger mesh mid-way along the length of the stilling well (Figure 7.1). During large events, even if the debris backs up within the upper section (A) there should be sufficient space available for the movement of water. The size of this mesh may have to be determined according to the experience gained during the course of the experiment. The other components and current design details of the system can remain unchanged.

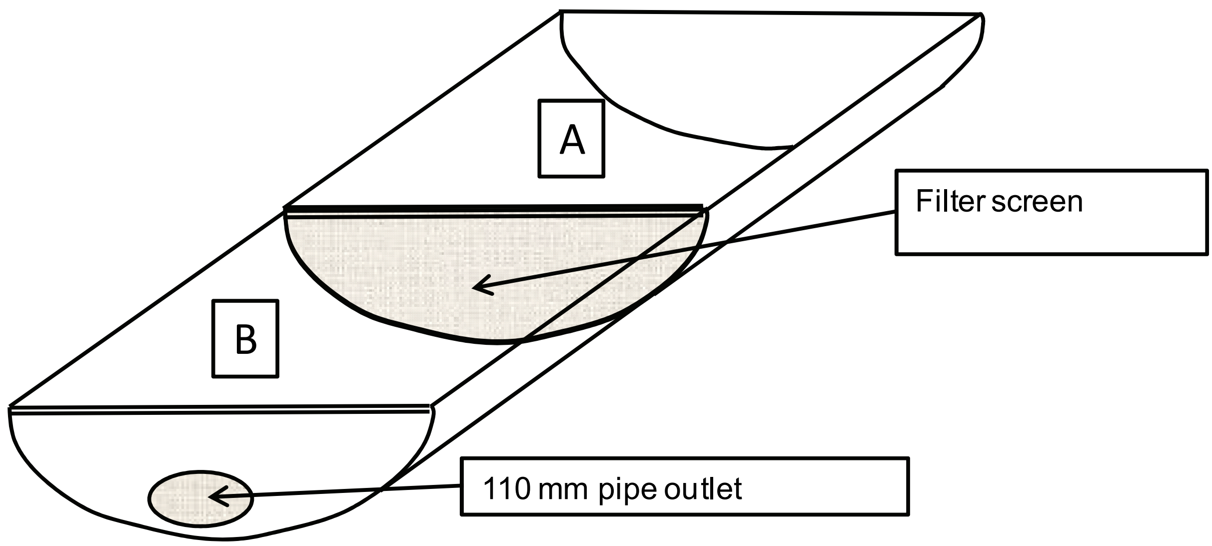


Figure 7.1 Modifications proposed to the stilling well showing the addition of a filter screen mid-way within the stilling well. The leaf litter and other debris will be retained within the upper portion (A) allowing runoff to filter through the mesh to the lower section (B).

The second design element that may require further attention is the reliability of the reed switches. These switches were found to be highly sensitive to the ingress of moisture and sediment and therefore needed replacement very often. The use of mercury switches instead of the reed type may need to be considered, bearing in mind that the power requirements will be different and that alternative dataloggers to the Hobo units may be needed.

7.4.2 Redirection of Road Runoff

This study found that unpaved access roads are a ready source of sediment within the catchment but since roads are a necessary component of the forestry infrastructure a balance must be struck between limiting the mobility of the sediment and preserving the integrity of the road network. This may be best achieved by strategically positioning the location of mitre drains and redirecting the road drainage into the forestry compartment. Although this study identified the CULSED model as a tool that could assist in this process it was not possible to fully test this in the current project. Future work should aim to do this with the objective of recommending optimum drain spacing by taking the characteristics of the road segment and local topographic factors into account.

This study showed that the forest floor within a mature compartment is efficient at trapping and filtering sediment. Although this aspect will require further corroboration and testing perhaps using additional supporting techniques such as isotope tracer studies or electrical resistivity sounding it does suggest that sediment and runoff could be contained within compartments through appropriate location and management of mitre drains. What has not been tested, however, is the relative significance of this process in recently clearfelled compartments and future studies should aim to do this. It is important that the exits of mitre drains are located away from natural watercourses or drainage divides in order to limit the direct delivery of sediment to streams. In this regard it is strongly recommended that further investigation should focus on the connectivity of the catchment by mapping of sediment delivery pathways. The direct discharge of sediment into streams at road-stream crossings has also not been covered within this investigation and monitoring programmes should also address this aspect.

The study was conducted under natural rainfall over two full summer seasons, after which an estimate of runoff production from road segments at varying gradients has been obtained. This information was used to test a range of models that could be used in extending this study beyond the study site. The WEPP: Road model showed good potential for realising this objective and further testing of the model in collaboration with the developers is encouraged. The research team have been in contact with the model developers who indicated that they will support such an initiative. Verification of the model results may require a longer monitoring period which may be further supported by supplementary studies using rainfall simulators. This type of study may prove valuable in assessing the timing of runoff and mechanisms of soil dislodgement from the road surface. However, should this take place, it will be important to operate the rainfall simulator at rainfall intensities close to that occurring naturally.

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Appendix 1

Individual Rain Events

Start of Rainstorm	End of Rainstorm	Rainfall	Hours	Average Intensity (mm hr^{-1})
3/11/2009 14:44	03/11/2009 14:44	0.1	0.00	0.00
4/11/2009 08:56	04/11/2009 08:56	0.1	0.00	0.00
5/11/2009 02:37	05/11/2009 02:37	0.1	0.00	0.00
6/11/2009 17:38	06/11/2009 18:40	0.1	1.03	0.10
9/11/2009 22:47	10/11/2009 19:19	2.4	20.54	0.12
10/11/2009 17:15	10/11/2009 18:50	0.4	1.58	0.25
13/11/2009 17:36	13/11/2009 23:43	0.7	6.11	0.11
14/11/2009 05:45	14/11/2009 06:33	0.2	0.79	0.25
14/11/2009 14:38	15/11/2009 13:42	3.2	23.06	0.14
15/11/2009 16:58	16/11/2009 12:45	3.6	19.78	0.18
16/11/2009 15:08	17/11/2009 11:58	6.2	20.83	0.30
17/11/2009 16:40	17/11/2009 18:46	0.2	2.10	0.10
18/11/2009 15:52	19/11/2009 00:53	6.4	9.01	0.71
9/12/2009 21:33	09/12/2009 23:54	6.3	2.34	2.69
10/12/2009 19:31	10/12/2009 22:12	1.6	2.69	0.60
11/12/2009 00:01	11/12/2009 05:53	2.3	5.87	0.39
11/12/2009 16:18	11/12/2009 17:20	2.4	1.04	2.30
12/12/2009 02:50	12/12/2009 14:46	1.1	11.94	0.09
13/12/2009 15:57	13/12/2009 19:14	3.0	3.29	0.91
13/12/2009 23:11	15/12/2009 08:57	9.2	9.77	0.94
16/12/2009 00:13	16/12/2009 00:16	0.1	0.06	1.65
18/12/2009 05:40	18/12/2009 06:23	0.1	0.71	0.14
18/12/2009 18:22	19/12/2009 08:30	7.1	14.13	0.50
20/12/2009 06:38	20/12/2009 20:09	0.1	13.52	0.01
23/12/2009 15:58	23/12/2009 16:59	13.6	1.01	13.45
24/12/2009 07:29	25/12/2009 04:36	8.6	21.11	0.41
27/12/2009 00:41	27/12/2009 06:23	2.8	5.68	0.49
27/12/2009 16:47	27/12/2009 22:45	1.4	5.95	0.24
31/12/2009 22:14	01/01/2010 00:13	2.4	1.99	1.21
1/1/2010 18:16	01/01/2010 21:41	1.8	3.41	0.53
3/1/2010 15:31	03/01/2010 15:42	1.8	0.19	9.42
4/1/2010 08:41	04/01/2010 17:50	9.0	9.15	0.98
15/1/2010 19:34	16/01/2010 07:50	11.4	12.28	0.93
16/1/2010 10:09	16/01/2010 13:37	2.6	3.47	0.75
16/1/2010 18:05	16/01/2010 22:45	1.4	4.67	0.30
19/1/2010 19:30	19/01/2010 22:11	1.4	2.69	0.52
20/1/2010 02:37	20/01/2010 15:49	13	13.21	0.98
22/1/2010 16:17	22/01/2010 19:56	21	3.66	5.73
23/1/2010 17:28	23/01/2010 21:30	10.8	4.03	2.68
26/1/2010 11:03	27/01/2010 06:51	43.4	19.81	2.19
28/1/2010 19:17	28/01/2010 23:40	2.2	4.37	0.50
29/1/2010 00:05	29/01/2010 21:52	4.0	21.79	0.18
1/2/2010 21:39	01/02/2010 23:50	1.0	2.18	0.46
2/2/2010 00:17	02/02/2010 03:58	3.6	3.69	0.98
13/2/2010 17:33	13/02/2010 22:54	13.2	5.35	2.47
14/2/2010 04:09	14/02/2010 08:46	1.2	4.61	0.26
17/2/2010 02:23	17/02/2010 15:45	20.4	13.36	1.53
17/2/2010 19:02	17/02/2010 23:05	3.0	4.05	0.74

Appendix 1 (continued)

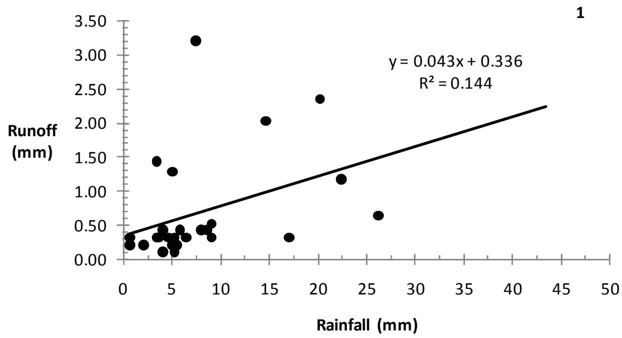
Start of Rainstorm	End of Rainstorm	Rainfall	Hours	Average Intensity (mm hr^{-1})
26/2/2010 05:02	26/02/2010 11:39	8.6	6.62	1.30
27/2/2010 21:29	28/02/2010 04:58	3.6	7.47	0.48
2/3/2010 19:05	03/03/2010 02:23	7.4	7.30	1.01
14/3/2010 05:17	14/03/2010 23:56	20.2	18.66	1.08
16/3/2010 18:28	16/03/2010 21:15	5.0	2.78	1.80
17/3/2010 13:05	17/03/2010 13:58	1.6	0.88	1.83
17/3/2010 19:15	17/03/2010 21:14	1.4	1.99	0.70
20/3/2010 16:09	20/03/2010 22:13	26.2	6.05	4.33
22/3/2010 16:00	22/03/2010 18:28	10.6	2.48	4.28
4/4/2010 17:28	04/04/2010 23:42	14.6	6.24	2.34
7/4/2010 14:45	07/04/2010 16:09	2.2	1.40	1.57
16/4/2010 21:56	16/04/2010 23:17	1.8	1.34	1.34
18/4/2010 12:31	18/04/2010 15:22	3.4	2.84	1.20
15/5/2010 08:18	15/05/2010 13:23	1.4	5.09	0.28
9/6/2010 06:54	09/06/2010 14:50	6.4	7.93	0.81
5/6/2010 09:59	15/06/2010 14:35	1.6	4.61	0.35
1/7/2010 00:52	01/07/2010 08:18	2.0	7.43	0.27
11/7/2010 20:44	12/07/2010 23:40	1.6	2.92	0.55
29/7/2010 18:35	30/07/2010 01:55	2.8	7.35	0.38
9/8/2010 17:13	09/08/2010 18:28	2.6	1.24	2.10
24/8/2010 01:13	24/08/2010 07:11	1.2	5.97	0.20
2/9/2010 16:24	03/09/2010 00:29	3.2	8.09	0.40
10/9/2010 20:32	11/09/2010 00:49	1.4	4.29	0.33
16/9/2010 17:35	16/09/2010 19:36	1.0	2.02	0.50
4/10/2010 13:46	04/10/2010 23:37	2.0	9.85	0.20
5/10/2010 22:18	06/10/2010 03:49	4.0	5.52	0.73
12/10/2010 17:03	13/10/2010 02:26	4.0	9.38	0.43
13/10/2010 13:06	13/10/2010 23:17	5.2	10.18	0.51
14/10/2010 00:12	14/10/2010 05:18	2.2	5.10	0.43
15/10/2010 17:44	15/10/2010 23:43	7.0	5.97	1.17
16/10/2010 14:16	16/10/2010 23:18	9.6	9.04	1.06
23/10/2010 14:24	23/10/2010 19:45	4.2	5.36	0.78
24/10/2010 11:08	24/10/2010 17:27	9.0	6.32	1.42
27/10/2010 18:06	27/10/2010 19:00	3.6	0.89	4.03
28/10/2010 13:34	28/10/2010 14:43	6.4	1.15	5.56
31/10/2010 20:12	01/11/2010 07:45	2.8	11.56	0.24
2/11/2010 16:53	02/11/2010 17:00	1.4	0.13	10.84
3/11/2010 19:06	03/11/2010 19:09	1.4	0.05	29.47
6/11/2010 15:20	06/11/2010 21:46	3.8	6.44	0.59
9/11/2010 11:33	09/11/2010 13:46	8.8	2.21	3.98
9/11/2010 21:51	10/11/2010 18:57	54	21.09	2.56
14/11/2010 12:39	14/11/2010 14:04	1.2	1.42	0.85
16/11/2010 13:12	17/11/2010 08:03	17	18.83	0.90
23/11/2010 15:44	24/11/2010 11:38	15.6	19.90	0.78
26/11/2010 20:30	26/11/2010 21:58	3.4	1.48	2.30
28/11/2010 17:08	29/11/2010 00:56	5.6	7.80	0.72
29/11/2010 04:13	29/11/2010 15:53	5.4	11.68	0.46
2/12/2010 15:32	02/12/2010 19:20	5.2	3.79	1.37
3/12/2010 03:23	03/12/2010 10:16	25.6	6.87	3.72
5/12/2010 20:32	06/12/2010 02:15	2.6	5.72	0.45
6/12/2010 19:21	07/12/2010 03:25	4.4	8.06	0.55
11/12/2010 13:09:14	11/12/2010 23:40:34	22.4	10.52	2.13
12/12/2010 17:45:21	12/12/2010 19:39:33	2.0	1.90	1.05

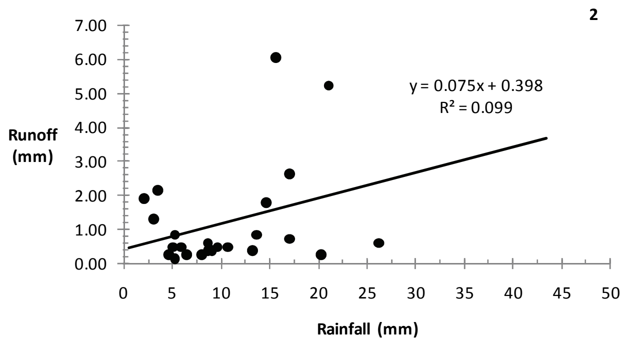
Appendix 1 (continued).

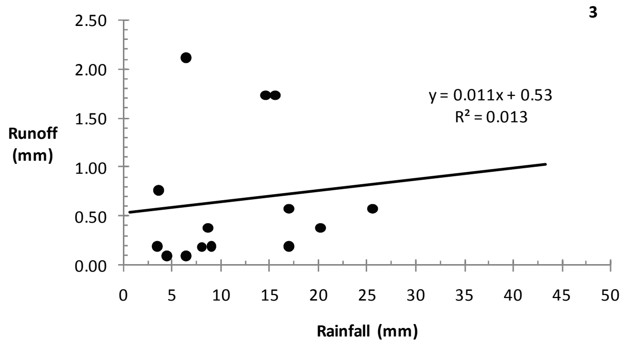
Start of Rainstorm	End of Rainstorm	Rainfall	Hours	Average Intensity (mm hr^{-1})
13/12/2010 14:56:38	13/12/2010 15:41:12	5.8	0.74	7.81
18/12/2010 22:54:12	19/12/2010 11:15:42	9	12.36	0.73
15/12/2010 05:21:35	16/12/2010 09:59:55	17	4.64	3.66
20/12/2010 08:49:53	20/12/2010 11:08:02	5	2.30	2.17
21/12/2010 04:31:02	21/12/2010 09:03:07	0.6	4.53	0.13
22/12/2010 21:09:25	22/12/2010 21:20:57	5.2	0.19	27.05
24/12/2010 19:00:12	24/12/2010 22:58:55	1.2	3.98	0.30
25/12/2010 20:57:15	25/12/2010 23:46:39	0.6	2.82	0.21
26/12/2010 02:08:04	26/12/2010 12:39:45	3.4	10.53	0.32
28/12/2010 00:34:40	28/12/2010 21:32:13	4	20.96	0.19
29/12/2010 23:58	31/12/2010 23:44	4.6	23.78	0.19
03/01/2011 02:29:46	03/01/2011 23:56:05	10.2	21.44	0.48
04/01/2011 02:30:37	04/01/2011 05:12:03	0.8	2.69	0.30
04/01/2011 15:24:46	04/01/2011 23:56:48	8	8.53	0.94
05/01/2011 00:07:04	05/01/2011 21:00:33	11.6	20.89	0.56
06/01/2011 06:19:40	06/01/2011 22:17:33	6.2	15.96	0.39
11/01/2011 04:24:03	11/01/2011 22:19:58	3.8	17.93	0.21
12/01/2011 02:03:17	12/01/2011 09:30:35	2.8	7.46	0.38
14/01/2011 21:13:26	14/01/2011 21:53:10	1.8	0.66	2.72
15/01/2011 11:30:51	15/01/2011 14:11:27	1.6	2.68	0.60
20/01/2011 12:38:42	20/01/2011 18:42:25	4.6	6.06	0.76
21/01/2011 05:35:59	21/01/2011 07:43:57	2.4	2.13	1.13
22/01/2011 18:56:41	22/01/2011 23:43:21	11.6	4.78	2.43
23/01/2011 01:54:52	23/01/2011 21:54:43	19.8	20.00	0.99
24/01/2011 01:04:57	24/01/2011 20:20:53	7.8	19.27	0.40
25/01/2011 14:32:22	25/01/2011 23:41:22	14.2	9.15	1.55
06/02/2011 16:15:09	06/02/2011 19:40:49	32.8	3.43	9.57
07/02/2011 15:47:34	07/02/2011 19:07:23	8.2	3.33	2.46
19/02/2011 04:07:06	19/02/2011 22:32:03	11.8	18.42	0.64
22/02/2011 16:00:39	22/02/2011 17:27:43	2	1.45	1.38
08/03/2011 14:05:42	08/03/2011 14:14:07	0.6	0.14	4.28
12/03/2011 18:35:28	13/03/2011 01:45:16	23.8	7.16	3.32
13/03/2011 18:50:25	13/03/2011 22:34:25	28	3.73	7.50
14/03/2011 06:16:59	14/03/2011 08:24:23	0.6	2.12	0.28
15/03/2011 01:44:13	15/03/2011 22:13:29	1.4	20.49	0.07
20/03/2011 18:07:57	20/03/2011 20:36:10	35.4	2.47	14.33
24/03/2011 20:10:13	24/03/2011 23:15:10	0.9	3.08	0.29
25/03/2011 16:14:43	25/03/2011 22:38:03	3.8	6.39	0.59
27/03/2011 06:35:06	27/03/2011 09:11:36	3.2	2.61	1.23
27/03/2011 20:34:18	27/03/2011 23:11:52	19	2.63	7.24
28/03/2011 20:56:28	28/03/2011 23:04:28	3.2	2.13	1.50
02/04/2011 18:46:03	02/04/2011 21:44:21	1.6	2.97	0.54
03/04/2011 00:49:49	03/04/2011 01:43:40	0.6	0.90	0.67
03/04/2011 16:15:06	03/04/2011 23:38:18	5.6	7.39	0.76
04/04/2011 00:05:31	04/04/2011 08:17:49	2.6	8.21	0.32
05/04/2011 12:33:41	05/04/2011 14:48:50	2.4	2.25	1.07
06/04/2011 19:22:09	06/04/2011 20:31:31	2.0	1.16	1.73
07/04/2011 21:36:56	07/04/2011 23:58:00	1.0	2.35	0.43

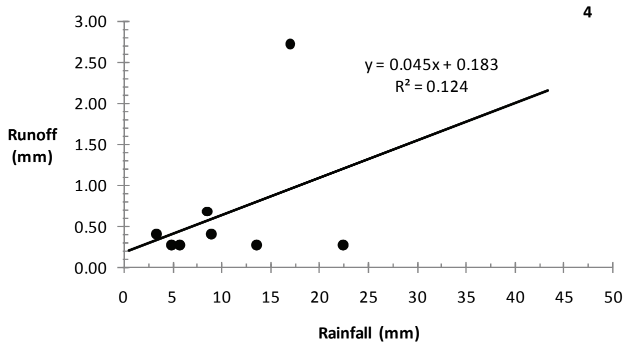
Appendix 2

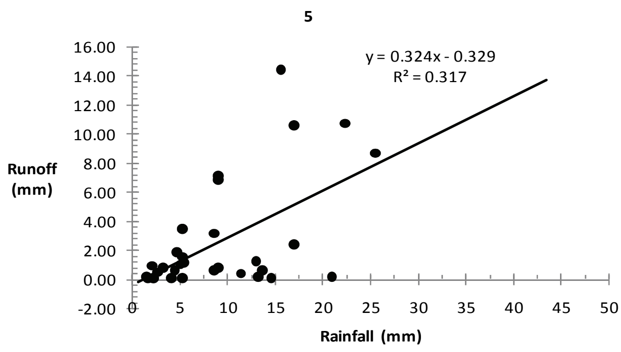
The relationship between total runoff and rainfall received at the plot. Only those rainfall events with reliable runoff data are included. Plot numbers are shown in the top right corner of the chart.

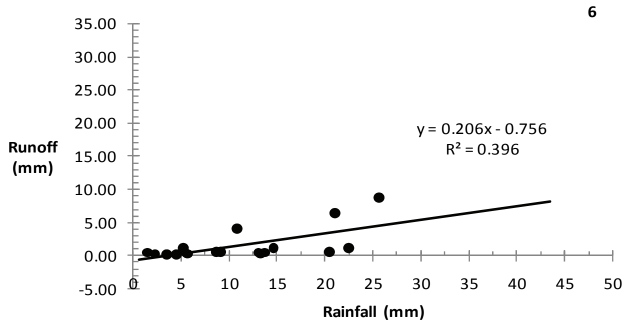


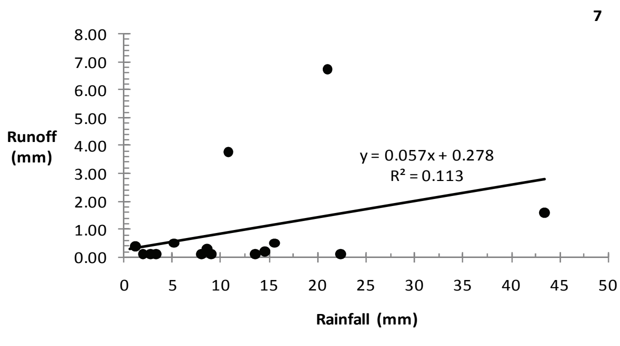


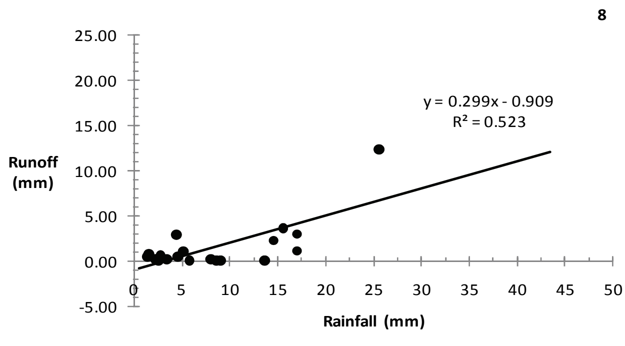




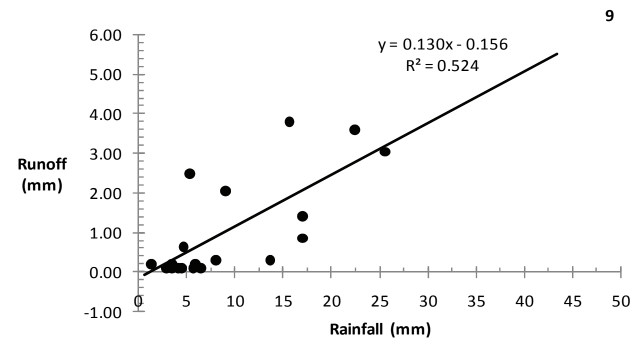


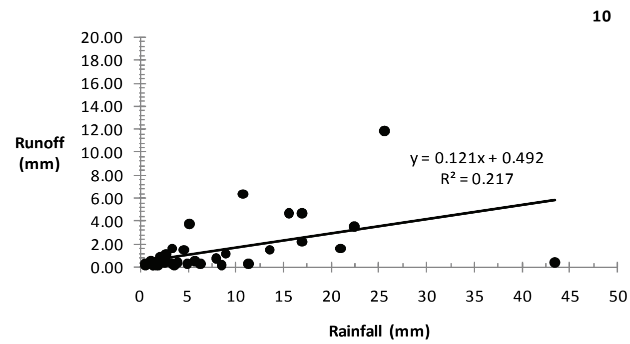


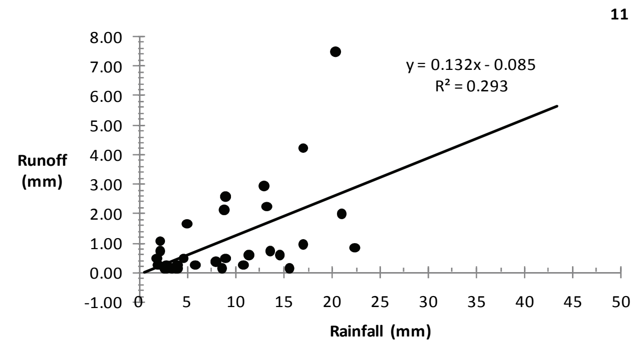


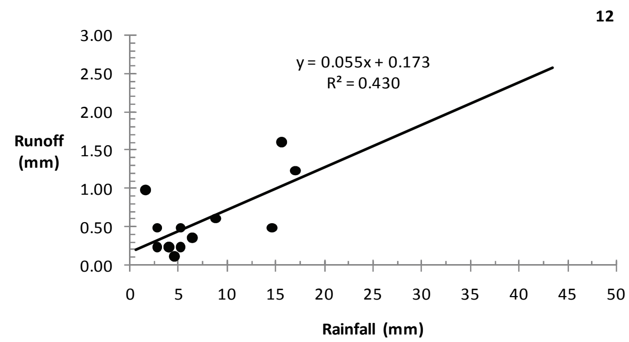


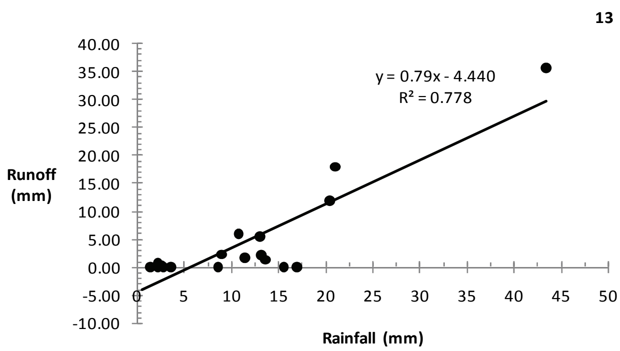
Appendix 2 (continued).

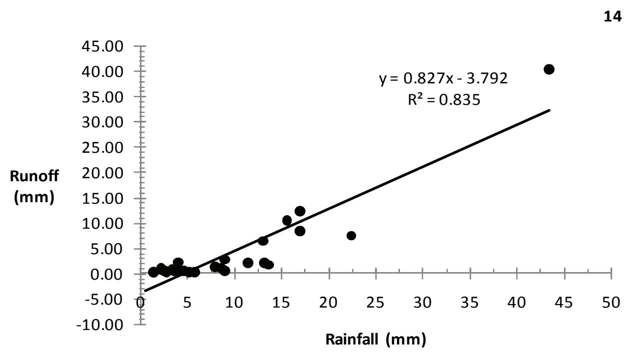


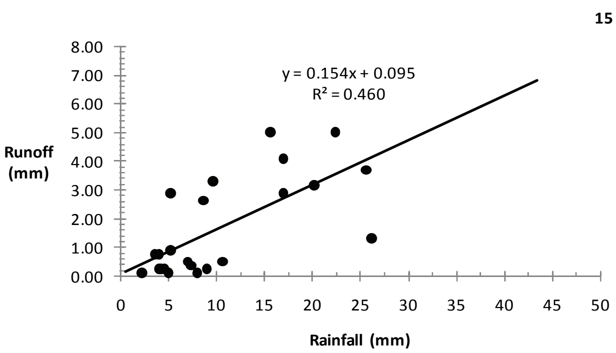


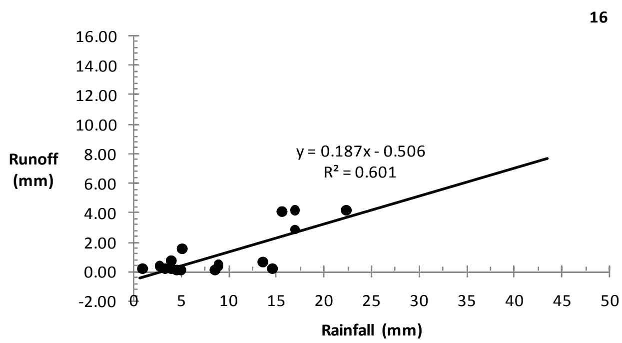






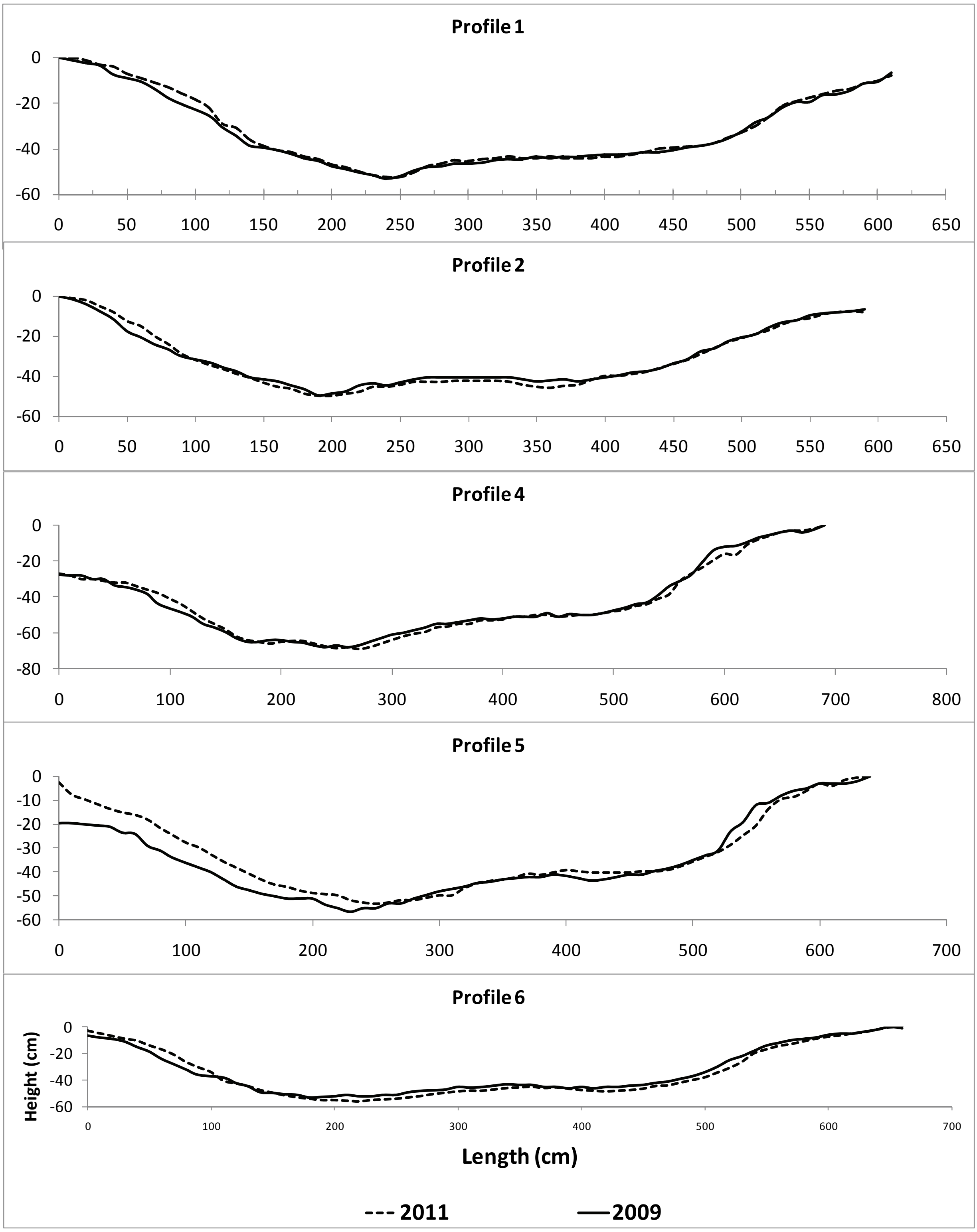




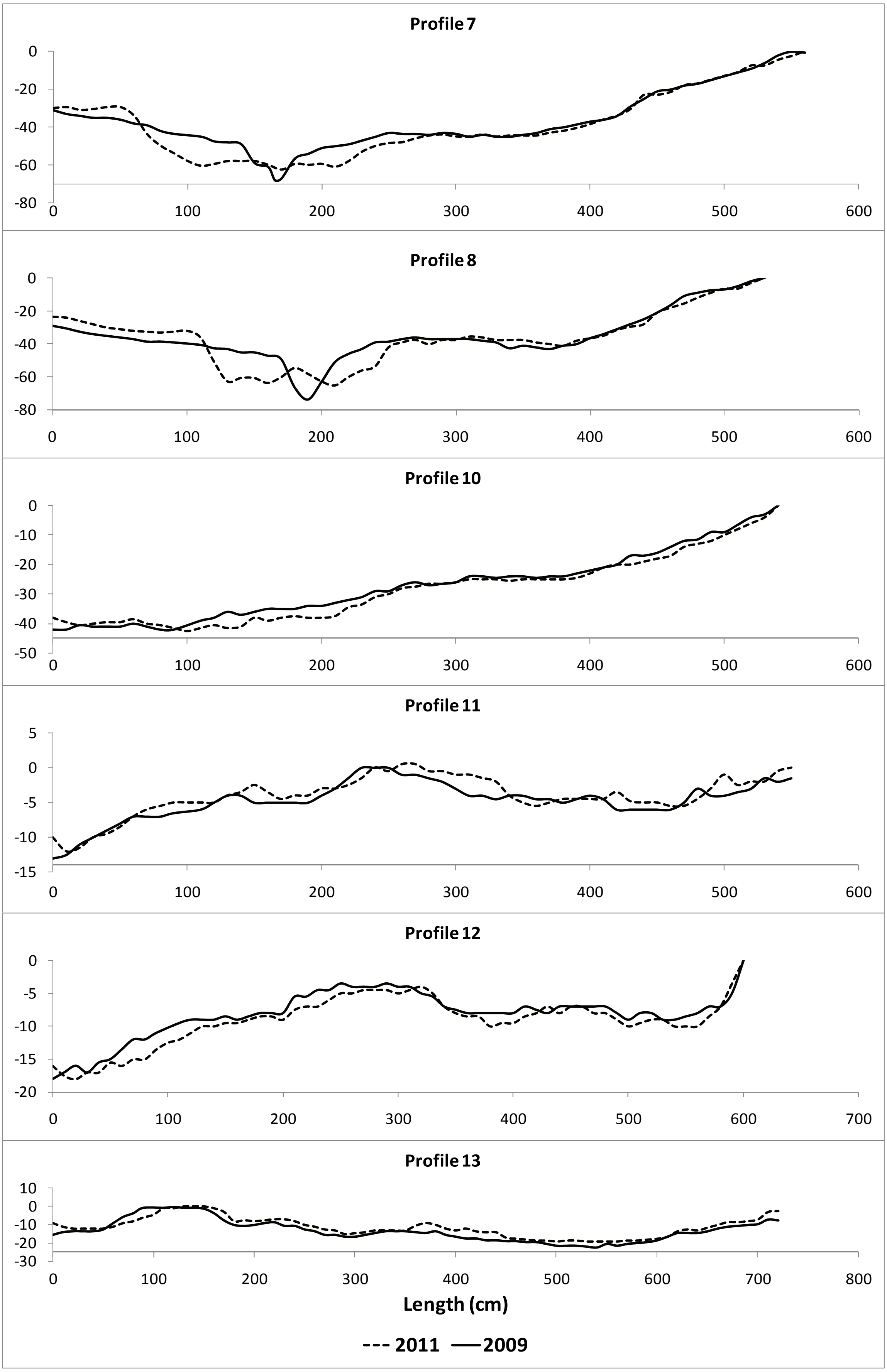


Appendix 3

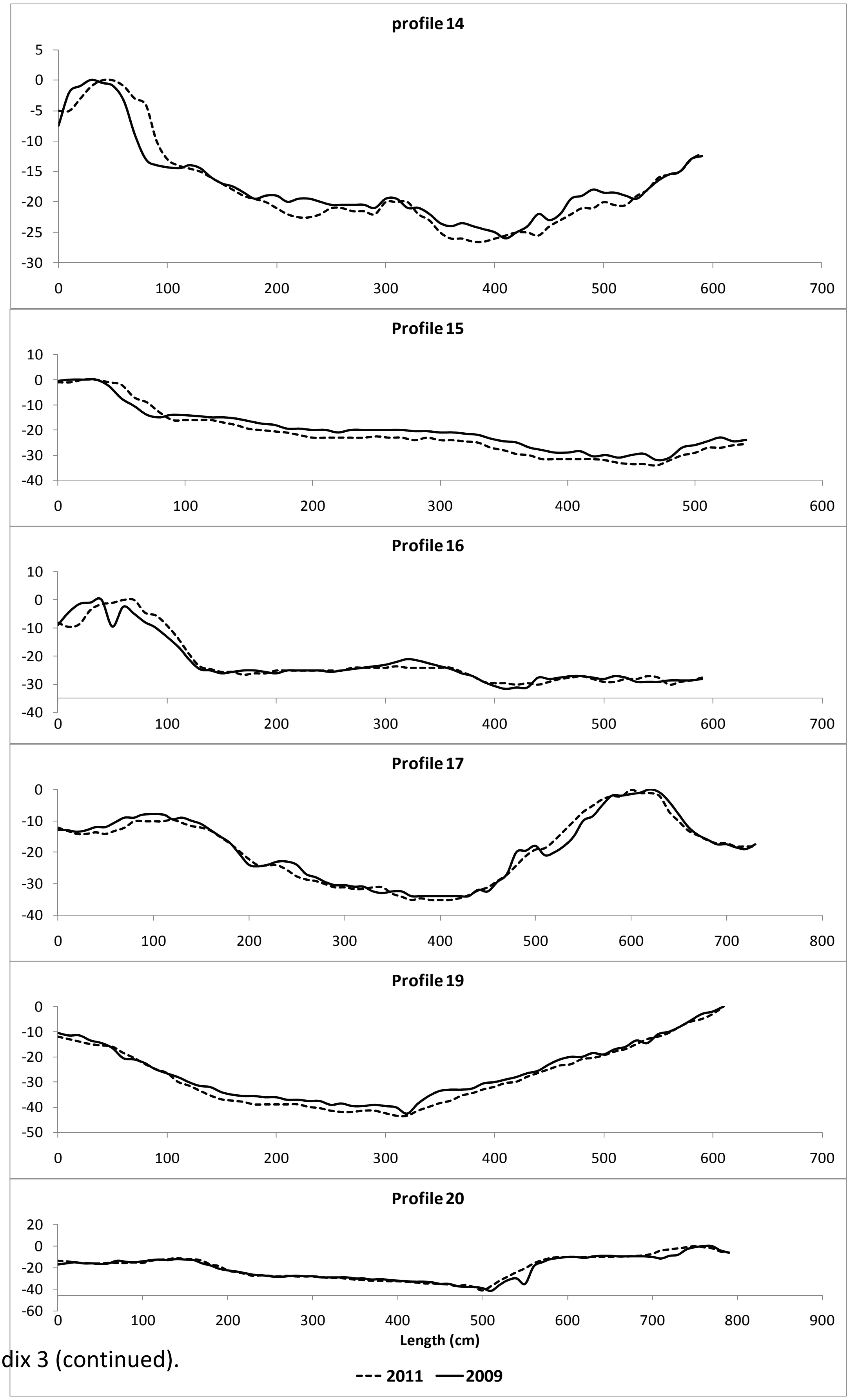
Cross Profiles



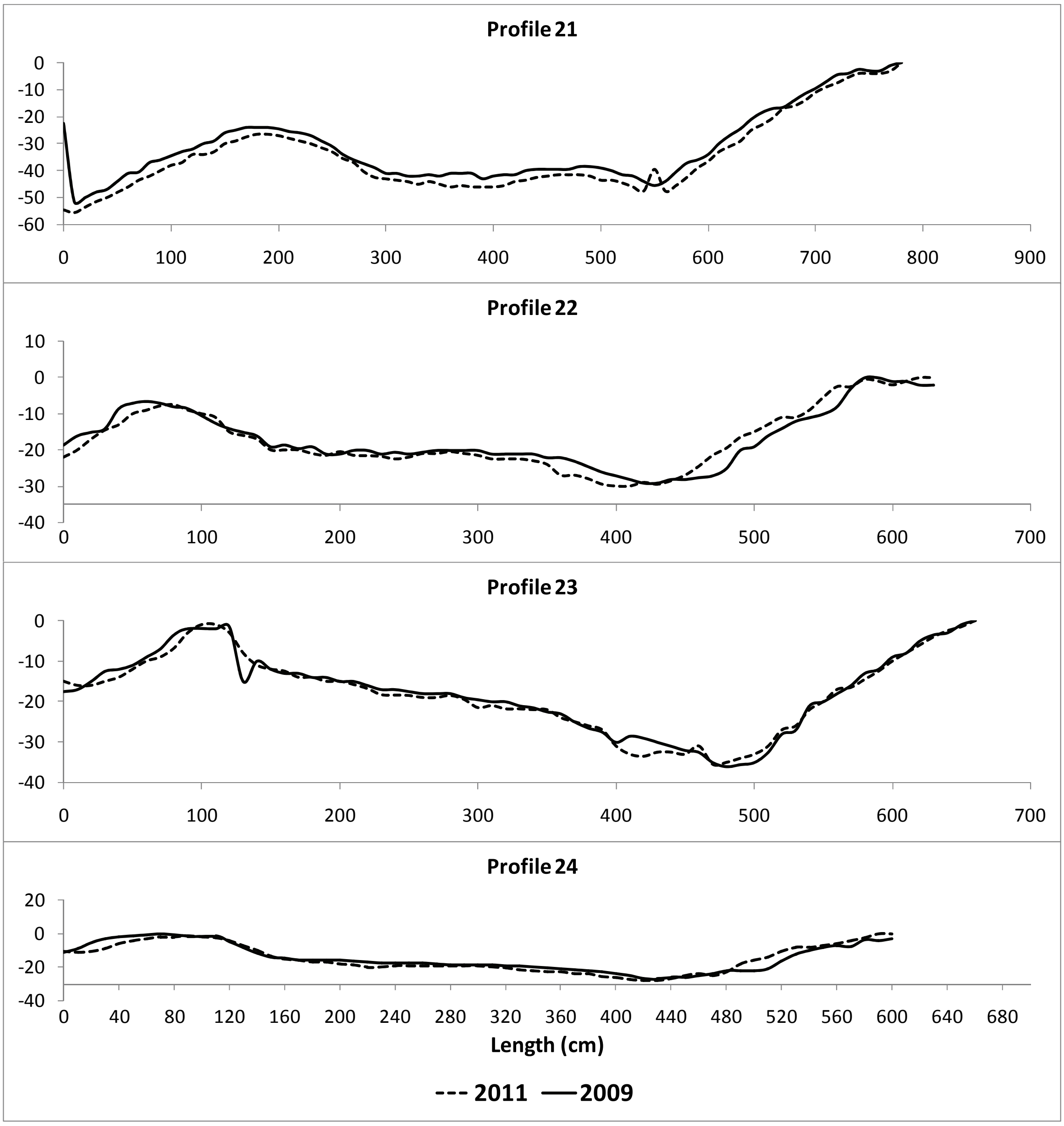
Appendix 3 (continued).



Appendix 3 (continued).



Appendix 3 (continued).


Profile 21
Profile 22
Profile 23
Profile 24
Height (cm)
Length (cm)
2011
2009

Appendix 4

Capacity Building

1. Introduction

This project was initiated in 2008. The team comprised personnel with a diverse range of skills and background but common interest in the effects of land use activity on soil and water resources. As increasing pressure is placed on the land to support an ever growing need for social and economic transformation, it is vital that management of finite resources are undertaken from an informed and responsible perspective. Whilst significant strides have been made over the years in the field of catchment management, much of the attention in South Africa has been directed at protecting water quantity, particularly streamflow. Arguably, research attention on the effect of various land use activities on water quality and its associated challenges have lagged behind. Therefore it was vital that capacity was developed in these areas in order to bridge this divide. This research project is but an example of the application of current knowledge and skills aimed at providing insight into the impacts of forestry access roads on soil and water resources. Hopefully, the skills developed within this research project are readily transferable to similar applications. During the course of the study knowledge was refined and generated, hypothesis and intuition were tested and investment in human capital promoted such that capacity was built. This report provides a synopsis of the achievements made in the latter category bearing in mind that it is sometimes difficult to differentiate between the different aspects.

2. Formal Student Involvement

During early 2008 the study was canvassed for interest amongst students in the school of Applied Environmental Sciences. Finding suitable Masters level students at that time proved difficult, so a decision was taken to split the various themes being explored in the work into mini – research projects. To test the feasibility of this approach Ms Kath de Jongh, based her BSc (Hons) dissertation entitled " Indicators of degradation on forest access roads in the New Hanover area, KwaZulu-Natal" on a component of this research. She was supervised by Prof. H.R. Beckedahl from the department of Geography at the University of KwaZulu-Natal, Pietermaritzburg and co-supervised by Dr. M. Moodley and Prof. T.R. Hill. Ms de Jongh was subsequently recruited by an environmental company and could not pursue her studies further. Ms Anel Geer registered for an Honours degree in June 2008 and began work almost immediately on aspects related to soil loss and erosion from road-cut embankments. She undertook much of the baseline road profiling and survey work reported upon in this project. Anel completed her degree in June 2009 and is now a registered Masters student with an interest in wetland mapping and function. She is being supervised by Prof. T Hill.

Mr Ernest Oakes & Mr Romano Lottering began their studies for an Honours degree in early 2009 and joined the research team first as project assistants and later as research students. Mr Oakes undertook a start as part of his Honours degree dissertation on the changes brought about in basic soil properties by forestry access roads. A comparative assessment of soil compaction, and infiltration between forestry access roads and adjoining forested compartments was made by Mr Oakes. This study was supervised jointly by Dr M. Moodley and Prof Beckedahl. Mr Lottering, under the guidance of Prof. H.R. Beckedahl based his Honours dissertation on the "development of indicators of degradation". Both Mr Oakes and Mr Lottering completed their Honours degree at the end of 2009. Mr Lottering subsequently registered for a Masters degree in the Department of Geography at the University of KwaZulu-Natal, albeit not on this project. The search for suitable MSc students continued and in 2010 two students formally registered for an MSc degree on selected aspects of the study, namely Ms Kloboso Seutloali and Mr Sam Smout. Ms Seutloali, a Lesotho National is being supervised principally by Prof H.R Beckedahl. Mr Smout was being supervised by Prof. T.R. Hill. The main focus of Ms Seutloali study was to test the relevance of the WEPP model for its applicability in the catchment considering the road network as a land use type. In addition Mr Chris Birkett based his BSc (Hons) dissertation within this project by adding to work started by Anel Geer on monitoring sedimentation rates using the cross-profile methods and relating this to the indicators of access road degradation developed by Mr Romano Lottering. The monitoring of sediment and runoff during the study is an intensive process. For this reason two additional MSc students, Mr Colin Holmes and Mr Ross van DeVenter who are engaged on separate but inter-related projects joined the research team to gain experiential learning on techniques in data collection and other technical aspects. A summary of the formal capacity building initiatives is presented in Table 1.

Table 1: Students who have participated in this research project since 2008

Year	Student Name	Race and Gender	Citizenship	Degree	Status	Where are they now?
2008	K. de Jongh	White, female	RSA	BSc (Hons)	Completed	Env.Consultancy, JHB
2009	A. Geer	White, female	RSA	BSc (Hons)	Completed	MSc
2009	E. Oakes	Coloured, male	RSA	BSc (Hons)	Completed	MSC, Hydrology Dept, UKZN
2009	R. Lottering	Coloured, male	RSA	BSc (Hons)	Completed	MSc, Geography, UKZN
2010/2011	S. Smout	White, male	RSA	MSc	Deregistered August 2011	Employed outside academia
2010/2011	K. Seutloali	Black, female	Lesotho	MSc	Active Expected completion in December 2011	Ongoing MSc study This project
2011	C. Birkett	White male	RSA	BSc (Hons)	Active	Ongoing BSc (Hons) study This project
2010/2011	C. Holmes	White, male	RSA	Technical	MSc students pursuing studies on other non-WRC related projects.	
2010/2011	R. van DeVenter	White, male	RSA	Technical		

3. Cross-Collaboration

On the 22 September, 2008, Dr Holger Vogt-Altena, Faculty of Environmental Sciences and Forestry, University of Goettingen, Germany accompanied by 12 of his students visited the study site. The aim and objectives of this study were discussed and some useful ideas were forthcoming in terms of the runoff plot designs and associated aspects. Equally, on the 7th November, 2008. Prof Fruehauf, Dr Ziert and Dr Schmidt from the Department of Geoecology, School of Geosciences, Faculty of Science, Martin Luther University, Halle, Germany visited the study site. The overarching discussion point at these site visits by foreign academics was that accelerated soil loss from access roads was an almost universal problem facing the forestry industry. These researchers expressed interest in the study and pledged their expertise to the research team if required. Ms Kloboso Seutloali subsequently travelled to Germany as part of a student exchange organized by Professor Beckedahl.

The value of any research project is increased if industry shows an active interest in research that will directly affect them. Much of the guidelines, information and regulatory framework within the forestry industry as far as access road construction and maintenance is concerned have been based on the international literature. This was clearly expressed by the forestry industry at a workshop held on the 06th August 2008 at the University of KwaZulu-Natal. The research team was fortunate to have enjoyed a good working relationship with Mondi who have shown enthusiasm and active interest in the study. Several informal discussions were held with Mondi during the course of the research and on the 08th December 2009 the research team was asked to formally showcase the study to Mondi personnel.

Representatives from their operational and environmental divisions attended the interactive meeting which was held on site. This was an extremely successful event as it allowed the industry roleplayers to increase their understanding of the soil erosion processes and runoff generation mechanisms active on forestry access roads.

Figure 1 An interactive meeting with Mondi personnel was held on site on the 08th December 2009.

The project team was further invited during November 2010 to present the findings of the study to Mondi's environmental management forum. This forum meets regularly to discuss environmental issues or concerns that influence the forestry industry. The meeting was held at the Seele Estate in New Hanover and was represented by Dr Moodley and Prof. Hill. Strong interest was again expressed in the work and valuable contacts were made during the meeting. The project team was asked by Mondi that they be kept abreast of significant outcomes from the study. To this end an information dissemination workshop was convened in August 2011. The minutes of both workshops have been included as part of the electronic data record. Beyond this the research team in its own right has significantly improved their capacity in understanding the dynamics of sediment production and runoff generated by forestry access roads.