The Effects of Unpaved Access Roads on Runoff and Associated Water Quality within the Seele Estate, New Hanover, South Africa

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Submitted in partial fulfilment of the academic requirements for the degree of Master of Science in the Discipline of Geography, School of Environmental Sciences, University of KwaZulu-Natal

Pietermaritzburg
2011

UNDERTAKING

The research reported in this dissertation was undertaken in the Discipline of Geography, School of Environmental Sciences, University of KwaZulu-Natal, Pietermaritzburg, KwaZulu-Natal, from 2010 to 2011, under the Supervision of Professor H. R. Beckedahl.

The work represents original work by the author and has not been submitted in any form for a degree to any other university. Where use has been made of the work of others it has been duly acknowledged in the text.

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ABSTRACT

Unpaved forestry roads can significantly affect surface runoff and sediment production, with consequential impacts for stream water quality. The potential impact of road runoff on stream water quality is mitigated by the redistribution of runoff into the forest compartments through road drains. The objective of this study was to assess runoff and the associated nutrient loads from unpaved forest access roads, and to evaluate the effectiveness of road runoff redistribution onto the forest compartments.

Unpaved road segments in Mondi Forest Plantation in Seele Estate, New Hanover, South Africa were instrumented for runoff measurement in response to natural rainfall. Two road segment classes were investigated for water quality from unbounded runoff plots: steep sloped road segments of road gradients of 9.5^{o} and 7.5^{o}, and gentle sloped road segments of road gradients of 1.6^{o} and 2.0^{o}. Water quality was also assessed by monitoring road runoff, and stream water quality was analysed for water quality parameters including; pH, Nitrates, Nitrites, Phosphates, Total dissolved Oxygen, Oxygen consumption, Ammonium and temperature upstream and downstream of the Estate. The effectiveness of road runoff redistribution into the forest compartments was evaluated through relating water distribution to tree breast height diameter. Two sets of road drains corresponding to the plots of different road gradients were selected as for runoff, and sampled, and corresponding plots or allotments were established to determine tree breast height diameter measurements.

The results of the study revealed that, as might have been expected, runoff production increases with the increasing road gradient. The quality of road runoff water was lower than the stream water. There were no significant differences observed in nutrient levels upstream and downstream of the road stream crossings. The nutrient concentrations however, were higher upstream of the estate than downstream. Significant differences in tree breast height diameter were noted between plots of different road gradients. This suggested that the gradient determines the infiltration of redistributed runoff and hence the availability of the water that can be used by the trees within a compartment. The results of the study suggest that unpaved roads are important in the generation of nutrient loads. Much of the nutrient value is redistributed within the compartment itself rather than being transferred to the stream. This suggests that, provided that road runoff can be contained within the compartments, the potentially negative impact of road runoff can be mitigated and may enhance tree growth.

ACKNOWLEDGEMENTS

This research would not have been possible without the generous help and support of the following people, to whom I would like to extend my sincere gratitude:

My supervisor Professor Heinz Beckedahl is gratefully thanked for his assistance, valuable comments and guidance throughout the research.

My appreciation to Water Research Commission (WRC) researchers (WRC Report No K5/1807/4) for use of the study site and access to runoff data.

Mondi for access to the field sites, and to the Mondi GIS Unit for provision of shape files for Seele Estate.

Ross Van Deventer, Colin Holmes, Romano Lottering, Kabir Peerbhay and Sandile Hadebe, students at University of KwaZulu-Natal for their assistance in field-work and data collection.

Mrs Ruth Howison from the University of KwaZulu-Natal (Pietermaritzburg) for assisting with transport to Seele Estate.

Dr Ramroop from the University of KwaZulu-Natal (Pietermaritzburg) for assisting with the statistical analysis of the data.

My friends and family for their support and encouragement throughout the study period, without whom this work would not have been possible.

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CHAPTER 1

Forest Access Roads in Context

1.1 The Development of Forestry in South Africa

Forestry plantations are highly significant for humankind. Siry *et al.* (2005) report that forest plantations have historically played an important role through provision of domestic products, industrial wood, energy resources, soil and water conservation and restoration of degraded land. Forests ownership varies throughout the world. In Africa, almost all forests are publicly or communally owned except for areas owned by forest product firms or private individuals especially in South Africa (Siry *et al*., 2005).

Richardson (1998) states that formal forest plantations for the production of wood products date back to approximately 255 B.C., increasing in scale and intensity through to the present. Estimates for 2003 indicated that forest plantations covered 204 million hectares of the world land area (Siry *et al*., 2005). Meadows (1999) reports that in South Africa, Forest plantations cover about 1.5 million hectares of forest plantations. *Pinus patula* and *P. ellioti* are predominant softwood species and *Eucalyptus grandis* is the main hardwood, used for pulp production (Meadows 1999). Commercial forestry plays a significant role in the economy and job creation in South Africa. Horswell and Quinn (2003) report that commercial forestry and its associated industries in South Africa accounted for 4.7% of total export earnings. Forest management activities are important for forest productive use.

World forests are actively managed (Siry *et al*., 2005). Forest management activities include; vegetation removal, logging, road building and prescribed fire. According to Amann (2004), dense road networks similar to stream drainage density are constructed in managed forest lands for timber harvesting, fire management and other forest activities. Forest roads are narrow, unpaved, lightly travelled and remote (Efta, 2006). Construction, operation and maintenance form part of the development phases of forest roads (Lugo and Gucinski, 2000). Egan (1999) states that the roads development phases, however, are controversial and periodically under scrutiny as sources of erosion. Poor planning, construction or retirement of forestry roads can have major impact on the forest environment (Egan, 1999). According to Forsyth *et al.* (2006), poor road construction, maintenance and the disturbance caused by heavy trucks transporting logs from harvested areas increases erosion rate.

Hudson (1971) states that forest roads present a considerable erosion problem for a number of reasons. First, roads are constructed on steep land and where rainfall is heavy. Second, expensive roads with careful construction are not justified as the roads are not used much. Third, the road use during harvesting operations is detrimental and is associated with a high risk of erosion. According to Lugo and Gucinski (2000) the extend of erosion, however, is determined by the intensity and the type of use. Forest roads impact on the environment and are receiving a considerable attention in research (Wemple *et al.*, 1996).

Unpaved forest roads have been cited as major sources of surface erosion that cause water quality impairment in forested areas (Sheridan and Noske, 2005; Coe, 2006). Sediment is a non-point source pollution which is the major water quality concern in relation to forest management activities (Nisbet, 2001; Brown and Binkley, 1994). Forest roads have been recognised as the primary and relatively constant source of surface erosion and water pollution in forested catchments (Forsyth *et al.*, 2006).

1.2 Runoff and Sediment Production Associated with Unpaved Forest Roads

Unpaved forest roads interact with geomorphic and hydrological processes to cause erosion (Ramos-Scharron and MacDonald, 2005. The linear nature of these roads and their tendency to run across topographic gradients and especially their concentrating effects on runoff, have a negative influence on hydrological processes (Luce and Wemple, 2001). The unpaved forest roads affect the processes which control water storage and distribution on the landscape (Ramos-Scharron and MacDonald, 2007). This not only has the potential to increase surface runoff frequency and magnitude but also to impact the dissolved mineral concentration in runoff water. Unpaved forest roads are characterised by compacted and low- permeability surfaces which decrease the hydraulic conductivity and water infiltration (Sidle *et al*., 2006). The decreased infiltration results in Horton overland flow generation, which occurs after small rainfall depths (Ziegler, *et al*., 2001). The Horton overland flow occurs as a result of the rainfall intensity greater than the soil infiltration capacity (Ziegler and Giambelluca, 1997). The infiltration capacity further decreases during a rainfall event and eventually approaches a more or less constant value thereby resulting in overland flow generation (Ziegler and Giambelluca, 1997).

Roads further affect runoff by intercepting subsurface flows and disrupting natural drainage patterns (Ramos-Scharron and MacDonald, 2005). Forest roads also intercept subsurface flow through roadcuts and the subsequent routing as surface flow (Bowling and Lettenmaier, 1997). The upslope soil properties including hydraulic conductivity, depth to the bedrock, hillslope gradient, topographic or bedrock contributing area, antecedent moisture conditions and storm precipitation determine intercepted subsurface flow volume (Coe, 2006). The runoff concentration from nearly impervious surfaces and intercepted subsurface flows effectively increase the drainage density, changing the hillslope water distribution and potentially increasing the stream peak flows (Luce and Wemple, 2001).

Surface erosion due to unpaved roads in forested areas is of particular concern worldwide (Ramos-Scharron and MacDonald, 2005). Studies have been undertaken to assess the impacts of unpaved forest roads on runoff and sediment yield (Wemple and Jones, 2003; Ramos-Scharron and MacDonald, 2007; Forsyth *et al*., 2006; Arnaez *et al*., 2004). The studies reveal the importance of unpaved forest roads in runoff and sediment yield generation. The sediment laden runoff from unpaved forest roads has been found to result in water pollution when delivered to watercourses (Fu *et al*., 2010; Forsyth *et al*., 2006).

1.3 Unpaved Forest Roads and Water Quality

Knowledge of the pollutant contribution of roads is valuable in forested catchments. The knowledge fills the gaps with respect to the absolute magnitude of nutrient loads generated from individual roads and the water quality impacts (Sheridan and Noske, 2005). The pollutant contribution of unpaved forest roads is an important concern, particularly where these roads are constructed within water gathering grounds. The uplands water source areas and forestry practices tend to place surface water at potential risk of quality degradation. To date this has, however, only been inferred on the strength of logical deduction. Almost no quantitative data are available to validate this as yet.

The expansion of upland forestry in the United Kingdom has led to increasing fears that this would lead to water quality degradation (Nisbet, 2001). In South Africa, forest expansion also has the potential to degrade water quality.

> "Commercial forestry, in South Africa, is often situated on steeper slopes in the upper areas of the catchments adjacent to first order streams. Of particular significance in South Africa is that commercial plantations are largely confined to the source areas of many of the rivers that supply the country with water" (Horswell and Quinn, 2003).

The construction of unpaved roads in commercial forests in South Africa, presents the risk of erosion and the associated delivery of sediment and nutrients to streams.

Measurement of runoff and the associated sediment and nutrient loads from unpaved forest access roads is important. Sediment production quantification and surface runoff measurement could enable modelling of the potential for runoff and sediment production from specific road segments, thereby helping to focus efforts on reducing road erosion (Amann, 2004). Understanding the processes of sediment production from unpaved forest roads will help in the achievement of more targeted and better management for the protection of stream water quality in forested watersheds (Sheridan *et al*., 2006). Best management practices are implemented by forest managers to reduce the effects of unpaved forestry roads on water quality (Forsyth *et al*., 2006; Thornton *et al*., 2000).

1.4 The Aim and Objectives of the Study

The main aim of this research is to investigate the nature of surface runoff within commercial forests, with a view to understanding nutrient loads from unpaved forest access roads impacting on stream catchments.

The objectives of this study thus are:

- to investigate the rainfall-runoff interrelationship from unpaved forest access roads,
- to assess nutrient loads associated with runoff from unpaved forest access roads,
- to evaluate the effectiveness of localised unpaved forest roads cut-off drains in terms of water, sediment and nutrient management; and
- to assess the magnitude of the impacts of road runoff on stream water quality.

In order to achieve these aims and objectives, a series of runoff plots were used in the Seele Estate (owned by Mondi), in the New Hanover district of KwaZulu-Natal to monitor the environmental impacts associated with forest roads. Before reviewing the data obtained from such monitoring, it is however necessary to contextualise the research in terms of the existing body of knowledge and the environmental setting, as well as to review the manner in which monitoring and data collection were undertaken. This forms the content of Chapters 2 and 3 respectively. The data are presented and analysed in Chapter 4. Discussions of the data analysis and conclusions that were drawn are presented in Chapters 5 and 6 respectively.

CHAPTER 2

The Impacts of Forest Access Roads on Water Quality

Unpaved forest roads have a significant impact on forest water quality. Sheridan and Noske (2005) state that these roads contribute to nutrient loads, which pollute streams and water impoundments. Road derived sediment increases suspended sediment concentrations in runoff (Coe, 2006). These views are echoed in the works of Brown and Binkley (1994), who have shown that suspended sediments transport nutrients and other potential pollutants attached to the soil particles. The impact of unpaved forest roads on water quality depends on the degree of connectivity or linkage between the roads and the receiving waters (Croke and Mockler, 2001). A number of pathways through which road produced sediments reach the streams include; diffuse, partial or fully gullied pathways and road-stream crossings (Fu *et al.*, 2010). Erosion of a hillslope by road runoff results in the formation of gullied pathways which deliver sediments to streams (Fu *et al.*, 2010). The delivery of sediment through gullied pathways is determined by factors including rainfall intensity and duration, volume of erosion, contributing road area, lower hillslope properties such as slope and vegetation cover, and the distance of the stream from the road (Fu *et al.*, 2010). Fu *et al.* (2010) however indicate that sediments are delivered more efficiently at road-stream crossings as these are the points where road runoff drains into streams preferentially.

The increased potential for water quality degradation at stream crossings is due to the combination of sediment sources with shorter pathways which decreases the ability of infiltration, trapping or diversion of sediment- rich runoff (Lane and Sheridan, 2002). Lane and Sheridan (2002) assessed the water quality upstream and downstream of the road stream crossing in Australia. The results showed suspended sediment loads were four times higher downstream of the crossing.

2.1 The Best Management Practices to Minimize the Potential Impacts of Unpaved Forest Roads on Water Quality

Minimising sediment delivery to streams is a significant objective to achieve sustainable land use in forestry (Horswell and Quinn, 2003). The best management practices (BMPs) are regularly applied as part of forest management in many countries to reduce sediment delivery to streams (Cornish, 2001). The BMPs selection depends on the resources of concern and the relative cost-benefit ratio (MacDonald and Coe, 2008) and for the present study, by the improved understanding of road surface erosion. The relatively poor understanding of erosion processes by managers is likely to lead to treatment of erosion symptoms rather than the underlying causes (MacDonald and Coe, 2008).

The understanding of all the elements that contribute to road erosion is important (Egan, 1999). The understanding can assist in the manipulation of certain factors during road building to minimise soil erosion (Egan, 1999). Sediment delivery to watercourses can be reduced through proper siting of roads away from streams and through erosion control at the source which include the prevention of sediment movement (Coe, 2006). Coe (2006) however indicates that it is difficult to totally prevent sediment movement especially on roads and hence sediment containment should be advocated. For example through judicious use of box drains.

Most BMPs are designed to minimise surface water erosive potential on unpaved forest roads (Egan, 1999) and to reduce sediment delivery to watercourses. According to Egan (1999), the erosive potential of the water is reduced by decreasing the momentum of water on the road through reducing the quantity (hence the mass) or velocity of the water. The erosive potential of water can further be minimised by increasing the road surface resistance (MacDonald and Coe, 2008). It is, however, important to recognize that there are practical limits, as the roads must still be functional in terms of providing ready access to forest compartments. Graveling the unpaved forest roads increases the road surface resistance to erosion (Forsyth *et al*., 2006) but is seldom likely to be cost effective. Under equal traffic intensities, more sediment loads will be generated from ungraveled roads than from graveled road surfaces (Forsyth *et al*., 2006). Gravelling the road can reduce sediment production by more than one order of magnitude (MacDonald and Coe, 2008).

The accumulated runoff amount and the erosive force applied to the road surface is reduced by road drainage improvement (MacDonald and Coe, 2008). The road drainage can be improved through the construction and maintenance of road drainage structures including berms and mitre drains (Ramos-Scharron and MacDonald, 2005). According to Hudson (1971), drains or ditches that are cut across the road at intervals can prevent the built-up of runoff down the road surface parallel to the slope. Drains constructed on the sides of the road can be utilised to collect road runoff which can further be disposed of by other extensions of the road drains to avoid the building up of high volumes and associated high velocities of runoff (Hudson, 1971).

Road runoff diversion by a network of road drainage into the general forest plantation reduces the potential nutrient loads that might reach watercourses (Forsyth *et al*., 2006). Undisturbed forests have surfaces with high hydraulic roughness that reduce overland flow velocities and promote deposition (Croke *et al*., 1999a). Effective uptake of extra water and nutrients by the trees could result in increased growth. In addition, the process of ground water recharge is influenced (Bromley et al., 1997). The effectiveness of this practice varies with topography, soil and vegetation characteristics, rainfall intensity and duration and the degree of disturbance within the infiltration zone (Croke *et al*., 1999a).

The effectiveness of BMPs in controlling sediment delivery can be tested (Croke *et al*., 1999b). Sheridan and Noske (2005) evaluated the effectiveness of road runoff diversion to forest floor for infiltration and sediment trapping. Their evaluation was done through modelling sediment transport across a vegetated section of forest floor. The purpose was to investigate the forest floor sediment trapping characteristics.

2.2 Water Quality Analysis in Forested Catchments

The impacts of unpaved forest roads on surface runoff, sediments and surface water quality have been assessed by researchers. The general aim of conducting such studies was the protection of water quality in forested catchments (Croke and Mockler, 2001). The impacts of forest roads on surface runoff and the associated nutrient and sediment fluxes have been investigated (Forsyth *et al*., 2006). Forsyth *et al.* (2006) however states that proper road drainage design and maintenance decreases sediment loads and runoff volume. Additionally, the potential for the nutrient loads to reach watercourses is reduced.

Important impacts of unpaved forest roads have been documented for changes in suspended sediments and nutrient loads in surface water. Forsyth *et al.* (2006) assessed the nutrient loads associated with runoff from unpaved forest roads. Subsamples of runoff were collected from the road test plots and analysed in the laboratory for nutrient concentrations. Forsyth *et al.* (2006) reported runoff nutrient concentrations higher than the concentrations observed in the stream adjacent to the road plots. Lane and Sheridan (2002) measured turbidity and total suspended solids concentration upstream and downstream of the unsealed road stream crossing. Additionally, Lane and Sheridan (2002) assessed the nutrient content of forest roads runoff. Water samples were collected from a range of natural rainfall events. Water samples were analysed by taking a 100ml runoff subsamples for phosphorus and nitrogen analysis in the laboratory. Lane and Sheridan (2002) reported significant nutrient concentrations from the roads.

Seele Estate was identified in the current study for assessment of the impacts of unpaved roads on runoff and water quality. The environmental setting of the study area is put into perspective in the next section.

2.3 Environmental Setting of the Study Area

2.3.1 Location

The Seele Estate forest plantation is located in S29^{o}23$^{/}$04$^{//}$ and E30^{o}53$^{/}$10$^{//}$ in the uMshwathi Municipality near the town of New Hanover, 60 km North northeast of Pietermaritzburg, KwaZulu- Natal (Figure 2.1). The Seele Estate was identified as a suitable research site as it satisfied the selection criteria, namely: a relatively uniform rainfall, a dense road network of variable gradient, and uniformity in age and species of forest.

2.3.2 Landuse

The New Hanover district is part of the uMshwathi Municipality. It consists of 0.9% urban, 17.0% rural, 31.8% agriculture, 10.0% natural vegetation, 0.3% water, and 40% forest (Kieker *et al.*, 2006). The Seele Estate commercial forest plantation forms part of the 40% forest cover in New Hanover District. The tree species grown include; Eucalyptus (*Eucalyptus grandis*), Black wattle (*Acacia mearnsii*) and Pine (*Pinus patula*). The plantation is served by a network of unpaved roads (Figure 2.1). These roads are classified into A, B and C- class. A-class roads are main access roads into the forest. The B- class roads provide access into the forest area itself, while the C- class roads provide access routes for individual forest compartments.

The roads have high traffic intensities during the harvesting periods when heavy machinery gain access into the forest compartments. The A and B- class roads accommodate dual traffic flow and have coarse aggregate armour on the surface. The C-class roads are constructed as single lane roads. These roads have been formed by blading of the soil surface to form a quasi-planar surface (Moodley *et al.*, 2011). The roads are drained predominantly by berms that slow and redirect the road runoff into the adjacent forest compartments.

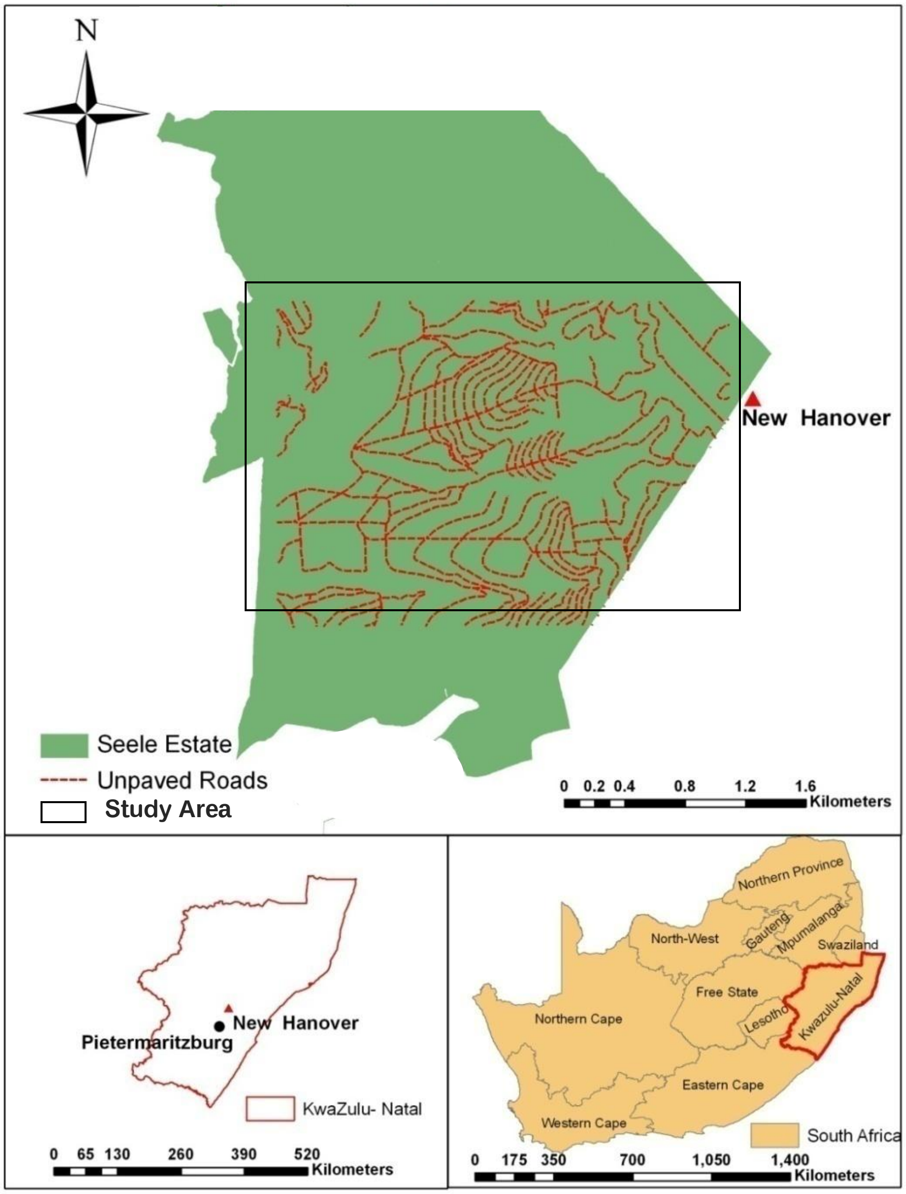


Figure 2. 1: Location of the study area (boxed) within Seele Estate (the shaded area) in New Hanover, KwaZulu-Natal, South Africa. Source: (Mondi GIS Unit, 2010).

2.3.3 Geology and Soils of the New Hanover Area

The bedrock geology of the study area consists primarily of shales of the Pietermaritzburg Formation of the Ecca Group. Pietermaritzburg formation is described as dark grey shale, carbonaceous shale, and siltstone and subordinate sandstone (Turner, 2000). They show similarities to both sedimentary rocks, particularly those of greater clay forming potential, as well as the basic igneous rocks. The soils in the study area have been divided into soil forms. The soil forms are classified according to the South African soil classification taxonomic system (Soil Classification Working Group, 1991). The main soil forms found in the study area are: Lamotte (la), Nomanci (No) and Katspruit (Ka) (Moodley *et al*., 2011) (Figure2.2).

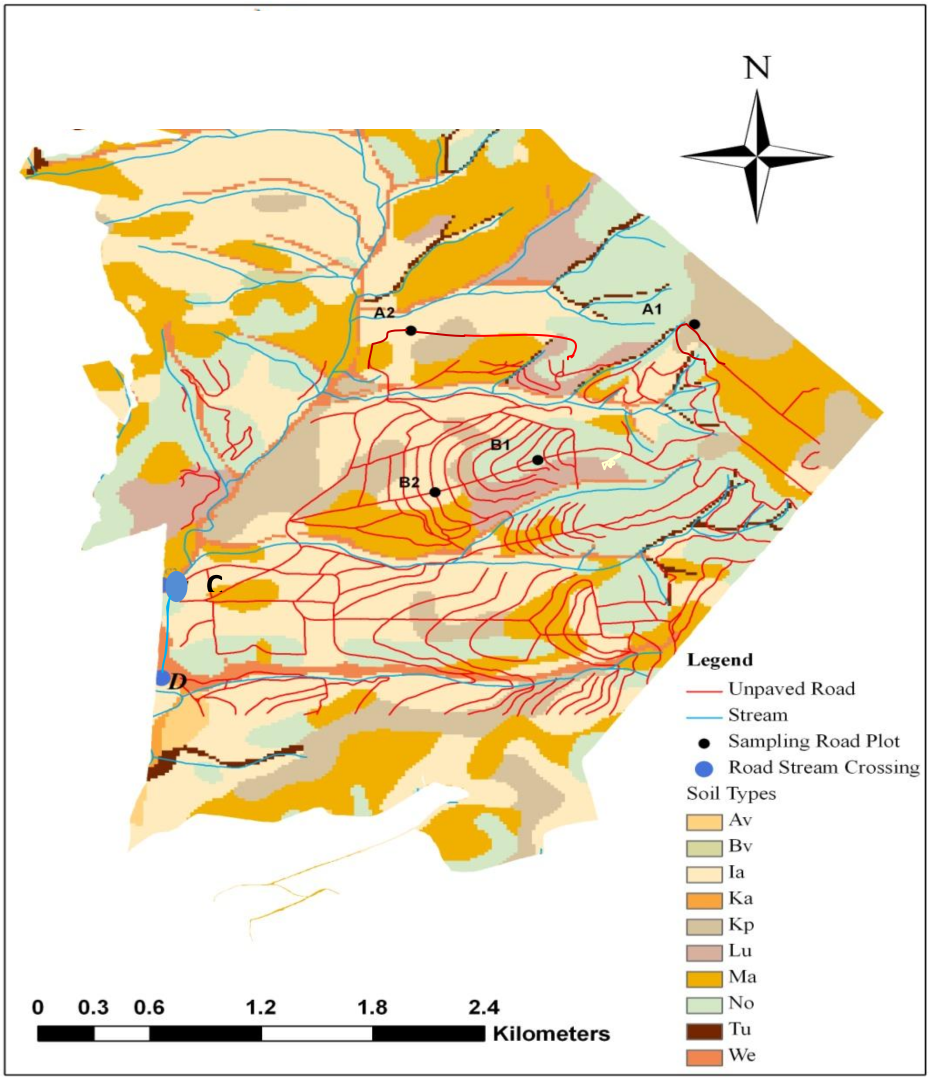


Figure 2. 2: Soils of the study area. Source: Mondi GIS Unit (2010). (For an explanation of the abbreviations used, please see text).

2.3.4 Climate

The climate of the region is characterised by warm and wet summers, cool and dry winters, and by misty conditions. The mean annual maximum temperatures vary between 26.5^{o}C and 23.8^{o}C. The mean annual minimum temperature is 5^{o}C. Much of the rainfall is received from November to May. The mean annual precipitation is 900mm.

The environmental setting of the study area has been dealt with in this section. Therefore, the methods used to collect data to meet the objectives of the study will be reviewed briefly in the next chapter.

CHAPTER 3

Research Methods and Data Collection

3.1 Introduction

The Water Research Commission (WRC) through the project (WRC Report No K5/1807/4) evaluated the contribution of unpaved forestry roads as potential sources of runoff and sediment yield in Seele Estate, New Hanover. The general aim of the WRC research was to develop an understanding of the controls on runoff and sediment production within the plantation forest. The current research was done in conjunction with the WRC project. However, the focus of this project was on the effects of the unpaved forest roads used for timber production on water quality within the estate. In order to meet the objectives of this research, necessary data was collected through utilizing a suite of field and laboratory methods. These methods are presented in this chapter.

3.2 Measurement of Runoff and Sediment Yield from Forest Roads

Measurement of runoff and sediment yield from forest roads have been based on runoff plots. Runoff plots are based on natural rainfall or on artificial rainfall through the use of rainfall simulators (Hudson, 1971). Runoff and sediment loss from unpaved forest roads have been investigated through the use of natural rain runoff plots (Forsyth *et al*., 2006; MacDonald *et al*., 2001). Runoff and erosion from unpaved roads have also been investigated through the utilization of rainfall simulators (Arnaez *et al*., 2004; Ziegler *et al*., 2001). Runoff plot design, instrumentation, and data collection vary from place to place and are determined by the objectives of the research (Sheng, 1990). Hudson (1971) states that most plots are bounded, with boundaries defining the area from which the runoff and soil are collected, and others are unbounded. The slope of the plots is determined by the terrain of the area. The plot length, width and total area are constrained by available sites (Sheng, 1990).

Runoff plots consist of collecting gutters let into the soil surface and connected to a collection container on the downstream side where the runoff is stored until it can be measured, sampled and recorded (Sheng, 1990). Automatic devices such as flumes with water level recorders and sediment samplers can be used (Hudson, 1971). Data collection from the runoff plots include measuring and recording rainfall and runoff, weighing and sampling sediment for each plot (Sheng, 1990). Sheng (1990) states that it is important to measure and collect data from plots after every runoff-producing rain. According to Sheng (1990), measurements made after several storms will not allow the identification of the results of individual storms. Runoff plots based on rainfall simulation are similar to those based on natural rainfall. The same consideration applies to plot boundaries, a collecting trough leading the runoff and sediment to containers, and recording the volume of runoff and weight of the soil (Hudson, 1971). Researchers have used rainfall simulators in most cases. Natural rainfall is unpredictable and rainfall simulators speed up the research. Additionally, the research efficiency is increased through rainfall simulators utilization since rainfall is controlled (Hudson, 1971).

Researchers and catchment managers seek information on soil erosion and the impacts on water quality. The information is required at temporal and spatial scales that reflect the timing and pattern of sediment movement due to rainfall event (Meritt *et al*., 2003). Modelling soil erosion is the processes that provide information on soil erosion. Erosion prediction models predict where and when erosion is occurring hence target efforts to reduce erosion can be implemented (Lal, 1994). A wide range of models exist for predicting soil erosion. According to Meritt *et al.,* (2003) the models differ in terms of complexity, processes considered and data required for calibration and model use. The most appropriate model depends on the intended use and the catchment characteristics in which the model is applied. The three model types that exist include the empirical, conceptual and physically-based (Lal, 1994). The empirical models predict average soil loss and sediment yield (Lal, 1994). According to Hudson (1971), empirical models are based on observation or experimental. These models allow the prediction of what will happen in certain circumstances since what has happened before in those circumstances is known. Conceptual models incorporate sediment and runoff generation transfer mechanisms in their structure (Meritt *et al.*, 2003). The flow paths in the catchment are represented as a series of storages, each requiring characterisation of its dynamic behaviour (Meritt *et al.*, 2003). Additionally, conceptual models describe the catchment processes without including the specific interactions which would require detailed catchment information (Meritt *et al.*, 2003). Physically-based models represent the individual components that control erosion together with their complex interactions, spatial and temporal variability (Lal, 1994). Lal (1994) states that these models help researchers to identify which parts of the system are most important to the overall erosion process. The most popular and widely used empirical models are: Universal Soil Loss Equation (USLE) and Revised Universal Soil Loss Equation (RUSLE) (Lane *et al.*, 1992). USLE/RUSLE is an equation that utilises the major factors affecting erosion to estimate average annual soil loss (Renard *et al.*, 1991). The major factors that affect erosion are: rainfall and runoff erosivity (R), soil erodibility (K), slope length (L), slope steepness (S), cover and management practices (C) and conservation practices (P) (Renard and Freidmund, 1994). The equation is expressed in the form

$$A= RxKxLxSxCxP$$

Where A is the estimated soil loss per unit area (Renard and Freidmund, 1994; Lane *et al.*, 1992).

The physically-based models are built in recent decades (Raclot and Albergel, 2006) in contrast to the empirical model approaches (Renschler, 2003). Water Erosion Prediction Project (WEPP) is the process- based model to predict runoff, soil erosion and sediment delivery (Lal *et al.*, 1998; Elliot and Hall, 1997). The WEPP model was developed to replace USLE (Lal *et al.*, 1998). The WEPP model is computer based and describes the physical processes that cause erosion (Elliot, 2004). The WEPP model requires large amounts of data to evaluate erosion and sediment potential (Yuksel *et al.*, 2008). The model predicts surface runoff, soil loss, deposition and sediment delivery by utilising climate, infiltration, water balance, plant growth and residue decomposition, tillage and consolidation (Renschler, 2003). Additionally, the WEPP model predicts soil erosion over a range of time scales including; individual storm events, monthly totals, yearly totals or an average annual value (Renschler, 2003; Yuksel *et al*., 2008). The WEPP model is applied to a wide range of topographies and climate. According to Elliot (2004), the model can be applied to slopes ranging from research plots 0.5m long to hillslopes longer than 500m, and to any soil, including crop-land, rangeland, forest, road, and construction sites. The model can be applied to climates with annual precipitation values ranging from below 2500mm (Elliot, 2004).

Although a range of models are available, these models were not used in the current research. The USLE and RUSLE are not applicable because they are areal and the roads are linear. The WEPP model has a complex module that does not allow effective input of South African conditions, therefore it was not pursued further.

3.3 Data collection

In order to assess runoff and the associated nutrient loads from unpaved forest access roads, road segments of different gradients were selected from the estate (Figure 3.1). The road segments were instrumented with runoff plots to collect and measure runoff. These road segments were selected to represent the road condition reflecting the steepest and the gentlest roads within the plantation. The different road gradients would allow an analysis of the relationship between road gradient, runoff and nutrient concentrations to be made. The rainfall and runoff data were collected during the 2009/2010 rainy period in the current study site, and augmented by data from the 2010/2011 rainy period. It was important to use natural rainfall because artificial rain could not be used on the extensive area.

In order to determine the nature of the water quality from the plots, water quality parameters of the runoff were analysed. Stream water quality was also assessed and compared with the road runoff. The comparisons allowed an evaluation of the potential impacts of road runoff on the local streams. According to Stevens (2001), the flow of road runoff into receiving waters may alter their water quality. The stream water sampling was undertaken upstream and downstream of the stream crossings. There were two stream crossings from the estate that could be monitored (Figure 3.1). The upstream and downstream measurements allowed the assessment of the influence of discharge emanating from the road on the water quality of the stream system.

The following water quality parameters were analysed; nitrates (NO_3^-), nitrites (NO_2^-), ammonium (NH_4^+), phosphates (PO_4^{3-}), temperature, pH, total dissolved oxygen (TDO) and oxygen consumption. Brown and Binkley (1994) state that unpaved forest roads may significantly alter the quality of water draining from forested watersheds through nitrogen (viz. nitrate, nitrite, ammonia), phosphate, dissolved solids including calcium, sodium, potassium, magnesium since they may be attached to soil particles. Additionally, environmental conditions such as temperature and pH determine the concentrations of nutrients (Redshaw *et al*., 1990). This implies that there may well be additional effects resulting from afforestation due to shade-effects.

In an attempt to control the localised effect of forest roads on streams, the impact of sediment and nutrient was reduced by leading surface runoff into cut-off drains by berms across the roadway. The hypothetical effect of this on nutrient distribution and water availability within the forest was investigated by measuring tree breast height diameter (BHD) and relating it to the water distribution since water and nutrients play a major role in tree growth (Worbes, 1999; Baker *et al*., 2003). Brienen and Zuidema (2005) performed a growth analysis for tree species and found a positive relationship between tree growth and water.

Methods utilised for data collection are described in the following sections below.

3.3.1 Details of the Runoff Plots

The four road segments instrumented to measure runoff and sediment yield are identified by codes A1 and A2, B1 and B2 (Figure 3.1).

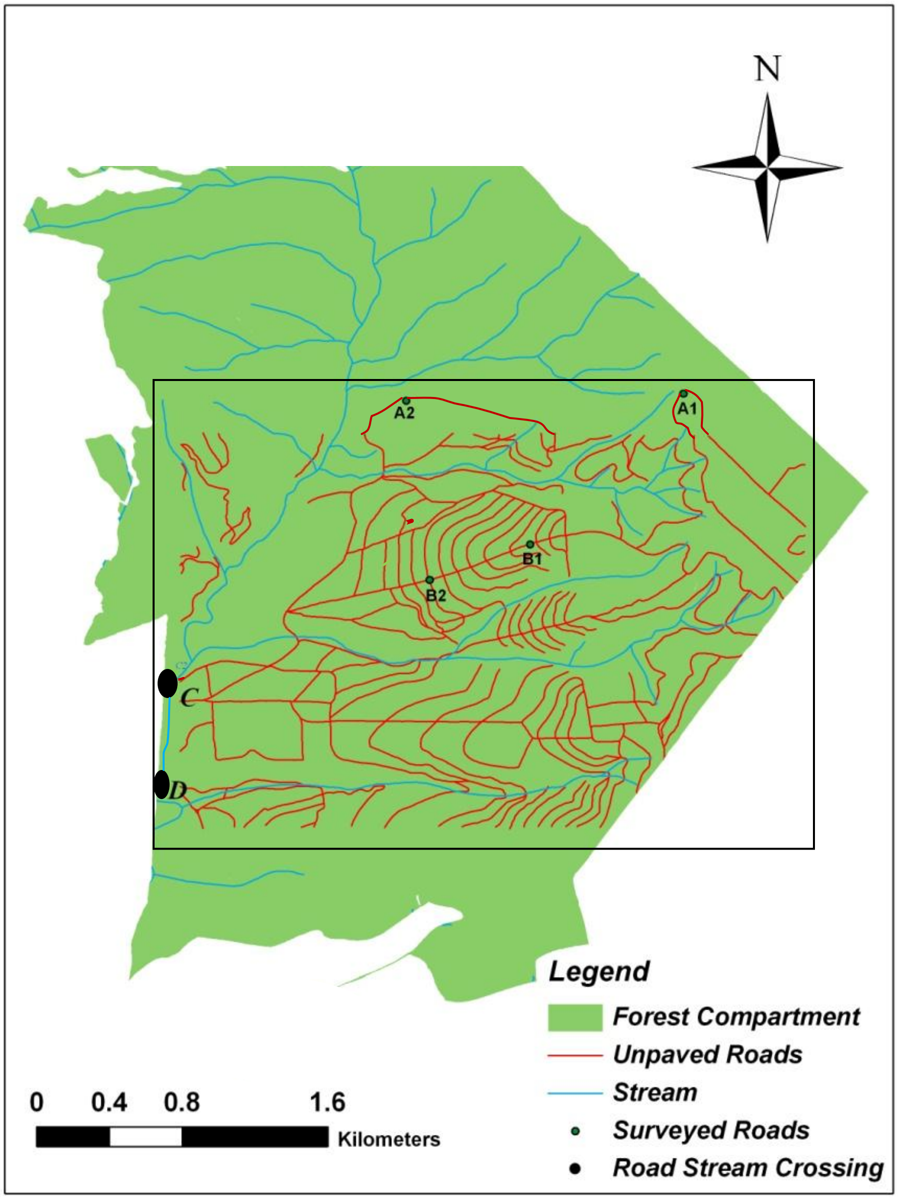


Figure 3. 1: Location of sampling sites within the study area.

The specific characteristics of the road segments are given in Table 3.1. The road segments A1 and A2 are considered a steep gradient while B1 and B2 are a gentle gradient. The road segment lengths vary between 22- 26 m and the widths vary between 4.2- 5.6m. The stream crossings are shown as C and D in Figure 3.1 (page 19).

Table 3.1 Details of the road segments monitored for water quality of Seele Estate

Road Plot Code	GPS Latitude (Degrees)	GPS Longitude (Degrees)	Road Gradient	Mean Elevation
			(degrees)	(m)
A1	29.23827	30.52796	7.5	969
A2	29.2442	30.53264	9.5	1019
B1	29.25429	30.52272	1.6	934
B2	29.25421	30.52459	2.0	934

3.3.2 Rainfall and Runoff

Measured data was event driven but for practical reasons could only be collected at approximately weekly intervals. Rainfall was measured by autographic raingauges at the altitudinal extremes of the catchment, and verified at each site by rainfall totalizers. The runoff was derived from unbounded runoff plots approximately 24 meters in length, 2.5 meters in width and of different gradients under natural rainfall. Unbounded runoff plots allow the lateral water movement into and out of the plots which accords with reality as opposed to bounded plots, which tend to isolate the site from the forest. Each runoff plot consisted of an upper and a lower boundary which removed the water off the road. The upper boundaries of the plots isolated the upslope contributing areas and the lower boundaries were connected to the 50l stilling wells. The runoff collected in the stilling wells was channelled into tipping buckets connected to electronic event loggers, enabling the calculation of total runoff after rainfall events. Runoff samples were collected over a five months period during the 2010/11 wet season after runoff producing rainfall events. The runoff samples were collected in 500ml polyethylene bottles that had been rinsed with runoff for water quality analysis. This was then taken to Pietermaritzburg for further analysis.

3.3.3 Water Quality

The water quality assessment involved both the on-field and off-field measurements. Manual „grab' samples of stream water and road runoff were analysed for water quality parameters by the use of the Aquamerck Compact Laboratory (product number, 1.11151.0001) produced by Merck (Germany) for water testing. The Merck method was used since it allows water quality analysis in the field, unlike conventional laboratory methods that would require transport. This is further supported by the work of (Goncharuk *et al.*, 2008) who found that analysing at the place of sample collection ensures prompt control and improves the analysis quality allowing prevention of errors relating to sample conservation and transportation. The measurements are based on colorimetric and titrimetric methods outlined in the Merck manual. Additionally, the Merck system was utilised to reduce costly laboratory analysis. The Merck system chemical test methods were based on analytical reactions and ready for use reagents. NO_3^-, NO_2^-, NH_4^+, PO_4^{3-} and pH were determined through colorimetric methods. Titrimetric methods were used for measurements of TDO and oxygen consumption. Temperature was measured with a thermometer.

The colorimetric methods involved the reagent being added to the water sample that underwent colour reactions with the substance determined. The colour intensity was proportional to the content concentration of the substance measured. The colour of the measurement solution was compared with the colour fields of the standard colour cards which corresponded to specific concentrations. Titrimetric methods involved the addition of an indicator to the water sample. The reagent solution of defined concentration was added dropwise to react with the substance being investigated. The indicator changed colour after the endpoint of titration was met. The volume of the titration solution used to bring the change in colour is proportional to the content of specific substance measured. The value determined was read off from the graduation scale on the pipette.

3.3.4 Tree Breast Height Diameter Analysis

The study plots for tree breast height diameter (BHD) measurements are shown in Table 3.2. Two classes of road drains of different road gradients, as shown in Table 3.2, were selected: one from the gentlest gradient (1.6 – 2.5^o), and the other from the steepest gradients (7.5 - 10^o) for tree BHD. The plots are located along the unpaved access roads. The study was a paired plot study where each one of the plots was at the drain outlet and the plot on the opposite side of the road (upslope) served as the control. The reason was to evaluate whether any significant differences exist in BHD between plots that received road runoff and those that did not. The classes consisted of three replications each.

Plots of 20m x 20m, as shown in Table 3.2, were established around the road drains and demarcated by the use of boundary tape. These dimensions were selected to preclude the influence from other road drains. Control plots of 20m x 20m were also established on the opposite side of the road (upslope). Plots D1 to D6 are located on one side of the roads and plots Ctr1 to Ctr6 are on the opposite side of the roads out of the possible influence of additional light and road runoff. The numbers of trees per plot varied between 36 – 57 trees but were effectively constant between individual plots and their respective control plots.

Table 3. 2: Site characteristics of tree plots monitored

Tree Plot Code		Forest Road Geographic Position		Road Gradient (^{o})
Right of road	Left of road	Latitude	Longitude	
Ctr 1	D1	29.25429	30.52272	1.6
Ctr 2	D2	29.25427	30.52407	2.5
Ctr 3	D3	29.25421	30.52459	2.0
Ctr 4	D4	29.23827	30.52796	7.5
Ctr 5	D5	29.24375	30.53156	10
Ctr 6	D6	29.24442	30.53264	9.5

Note: Plots D1 to D6 are in close proximity to the drains. Ctrl 1 to Ctrl 6 are control plots.

Plots were selected on relatively homogeneous soil conditions and all trees in the plots were similar in terms of spacing, species and age. Six transects were established in each plot: two above, two on, and two below the drain outlet. The transects ran perpendicular to the road from the forest edge into the forest interior. BHD and distance from the road edge were measured for all trees along each transect. BHD was measured by the use of a tree diameter calliper and a measuring tape was used to measure the distance from the road.

Subsamples were selected from plots at the outlets of the mitre drains. This is because water from the outlet of the drain might have not penetrated 20m into the forest compartments hence the effects of water would have been masked. A subsample was chosen such that each plot was represented by trees in close proximity to the outlet of the drain and in the direction of the flow of water. Hence, trees upslope of the outlet of the drain and beyond 10m into the forest compartments were not selected, as little or no growth impacts from road runoff were expected in that region.

3.4 Data Analysis Methods

Regression analysis was utilised to assess the relationship between rainfall and runoff from different road segments. The road plot length was not considered because it was approximately equal for all the plots. Data collected for water quality assessment was statistically analysed by the use of Statistical Package for Social Sciences (SPSS) to obtain descriptive statistics. The stream water quality and runoff quality were classified according to Aquamerck guide for grading the quality of water guidelines for fresh waters to determine the level of pollution and analysed statistically for before and after effects. Justification of this versus more empirical methods has been described in page 21. SPSS was used to perform independent t- tests. Independent t-tests at 95% confidence level ($P<0.05$) were used to test whether there were significant differences in means of water quality parameters in road runoff and stream water.

Data collected for tree BHD was statistically analysed by the use of SPSS to obtain descriptive statistics. Independent t-tests were used to compare average BHD between plots at the outlet of the mitre drains and their control plots. One-way Anova was used at 95% confidence level ($P<0.05$) to test whether there were significant differences in means of tree BHD between the six transects within each plot. The BHD measured for each tree along transects was correlated against distance from the road edge in order to investigate any change in BHD with increasing distance from the road edge to study the potential effects of road drainage on tree growth.

Chapter 3 has reviewed the methods used to obtain the data. The data obtained is presented and analysed in the next chapter.

CHAPTER 4

Results and Analysis

4.1 Introduction

The results from field and laboratory measurements are presented in this chapter. The relationship between rainfall and runoff at different road segments is analysed. The spatial and temporal variation of water quality is analysed, and the potential impacts of road runoff on the receiving stream waters are evaluated by comparing the quality of road runoff to stream water quality. Runoff redistribution onto the forest compartments was analysed by considering runoff water distribution to tree breast height diameter (BHD) in Chapter 5.

4.2 Rainfall and runoff

The monthly rainfall for the study site since the monitoring period started in November 2009 is shown in Figure 4.1.

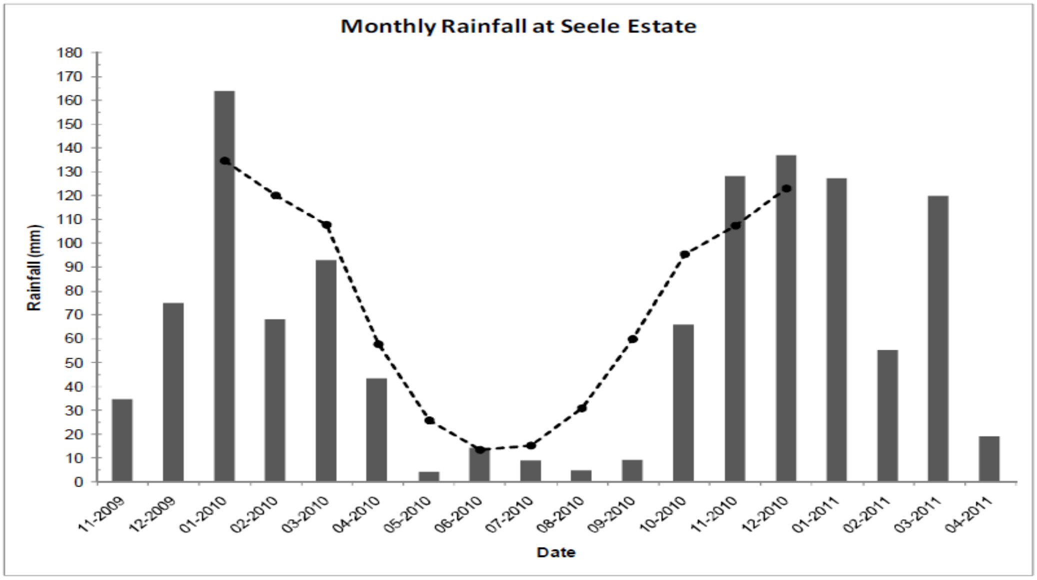


Figure 4. 1: Monthly rainfall for the study site since monitoring began in November 2009. The long term average rainfall for the region is also shown by dotted line (Moodley *et al*., 2011).

Rainfall for the sampling period (November 2010- April 2011) for the current study indicates that rainfall increased from the month of October to December. Rainfall decreased in January to April, with an exception of March where rainfall increased.

The relationship between rainfall and runoff was determined. Scatter plots for the regression of rainfall against runoff for the steep and gentle gradient road plots are shown in Figures 4.2a-d. The coefficients of determination (R^2) of the best-fit linear regression equations linking rainfall to runoff ranged from 0.14-0.32 for steep gradient road plots (Figure 4.2a) and 0.22-0.43 for gentle gradient road plots (Figure 4.2c). These results suggest that the amount of rainfall explains around 14% - 32% and 22% - 43% of the variation in runoff production for steep and gentle gradient road segments respectively.

There was a significant improvement in the R^2 of the regression by removing the outliers (Figures 4.2 b and d). The statistical F- tests at 0.05 significance level show that the regressions for rainfall and runoff are significant for all road plots (Table 4.1). This suggests that rainfall is useful in predicting runoff on these road plots.

Table 4.1: Statistical analysis using ANOVA for regression between rainfall and runoff for road plots

Plot	F	Significance F
A1	8.737	0.007
A2	24.735	0.000
B1	18.105	0.000
B2	8.321	0.015

Runoff was generated even under low rainfall events and in some instances, little or no runoff was generated under high rainfall events (Figures 4.2a-d).

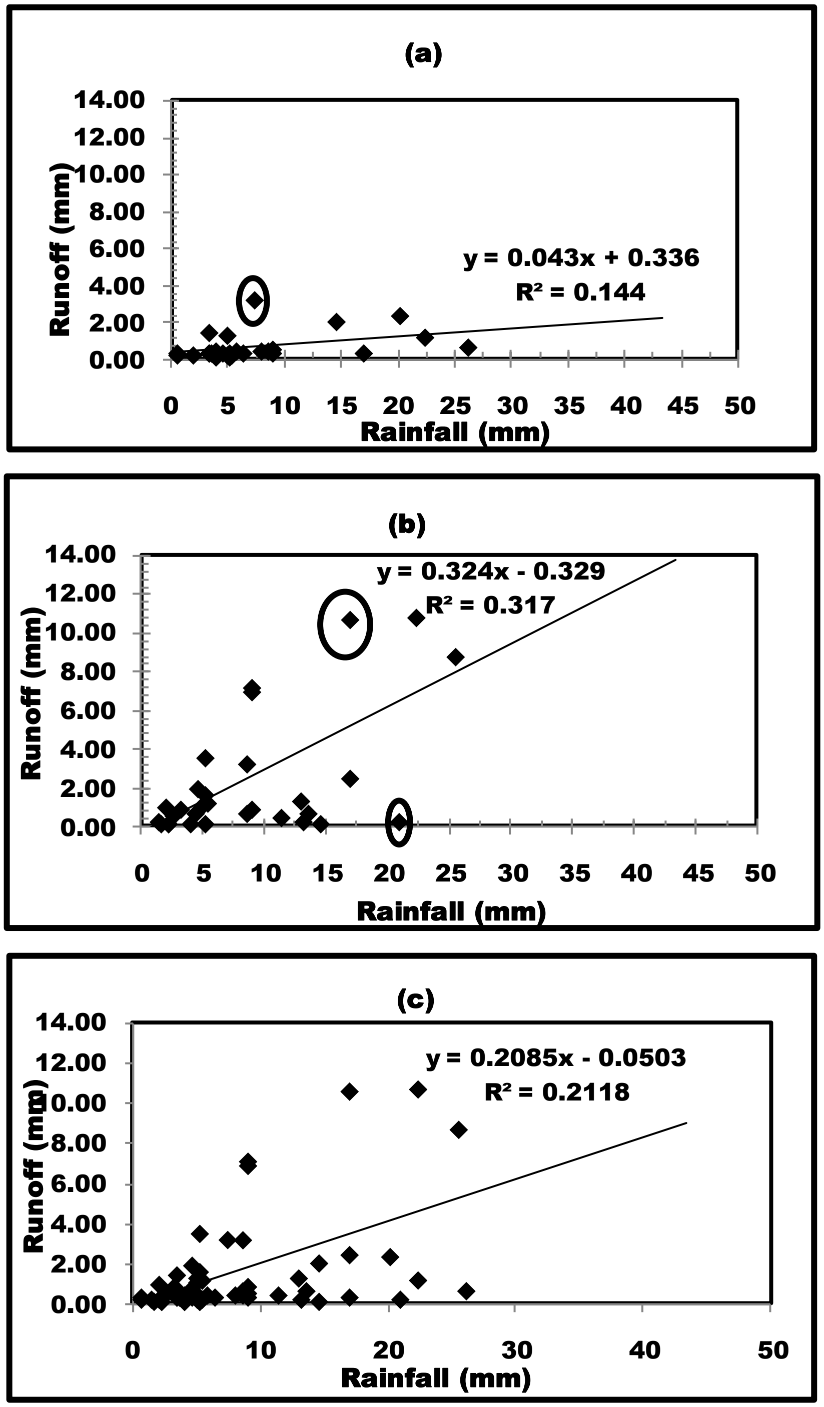


Figure 4. 2a: Relationship between event rainfall and runoff from the steep gradient road plots (a) A1, (b) A2 and (c) A1 and A2 combined. Outliers are circled and were included in the regression.

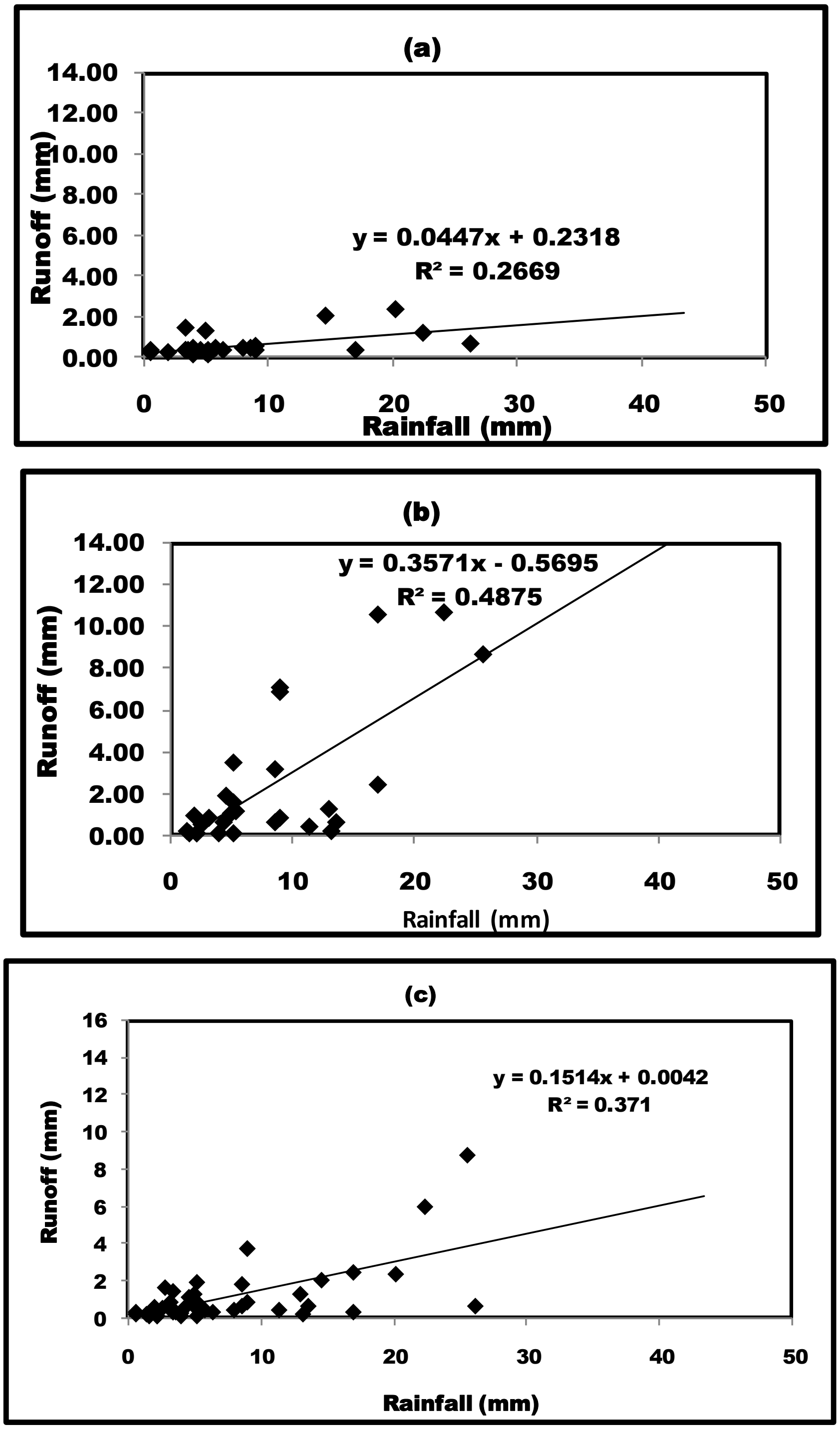


Figure 4. 2b: Relationship between event rainfall and runoff from the steep gradient road plots (a) A1, (b) A2 and (c) A1 and A2 combined. Outliers were not included in the regression.

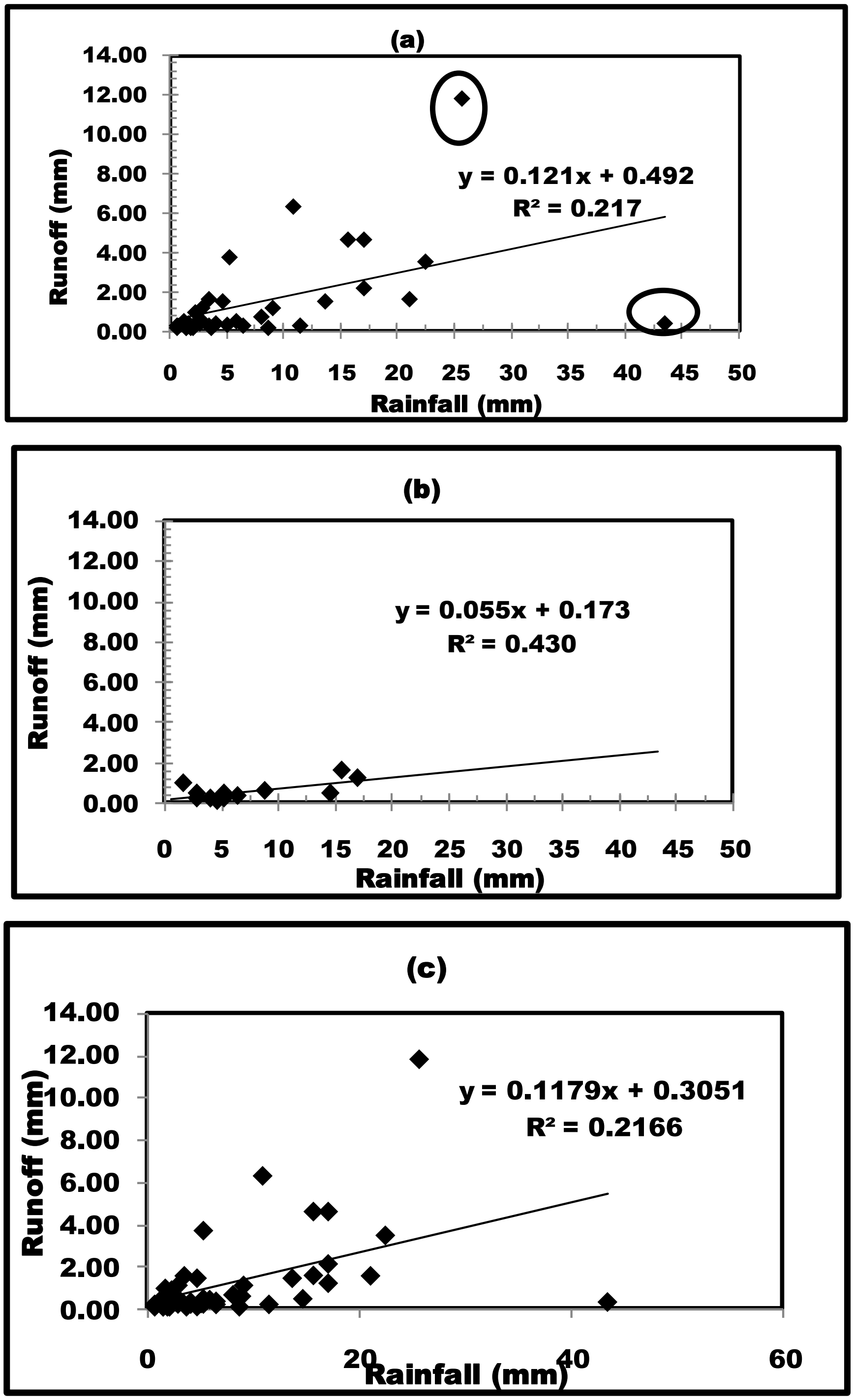


Figure 4. 2c: Relationship between event rainfall and runoff from the gentle gradient road plots (a) B1, (b) B2 and (c) B1 and B2 combined. Outliers are circled and were included in the regression.

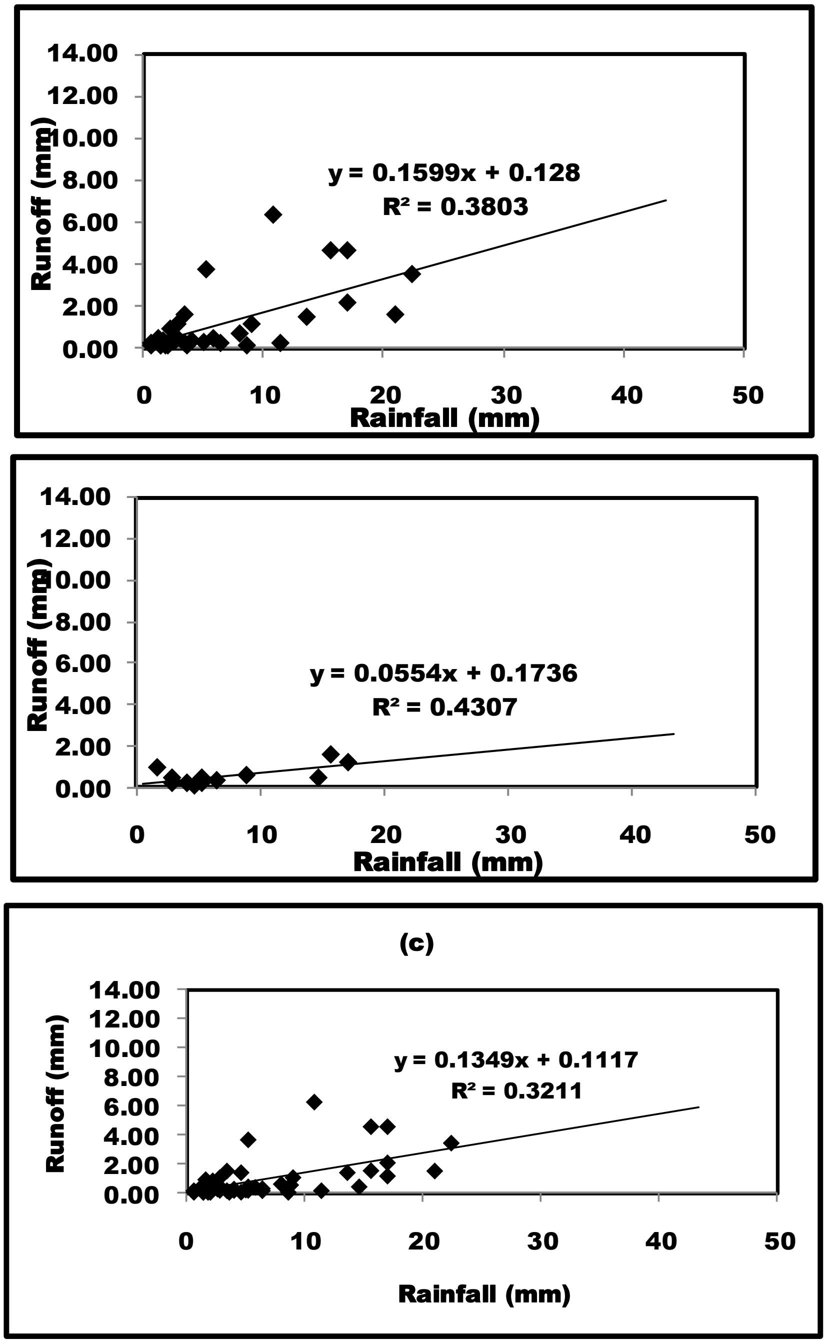


Figure 4. 2d: Relationship between event rainfall and runoff from the gentle gradient road plots (a) B1, (b) B2 and (c) B1 and B2 combined. Outliers were not included in the regression.

The relationship between runoff depth and road gradient was determined with scatter plots for the regression of road gradient for all plots (Figures 4.3). The road gradient showed poor correlation with runoff production. The coefficient of determination (R^2) was 0.143. This suggests that the road gradient explains around 14.3% of the variation in runoff production. There was a significant improvement in the coefficient of determination by excluding road plot A1 (Figure 4.3b) with R^2 increasing to 0.541. The justification for this may be sought in the complexities of the processes operating in plot A1, which will be discussed in the next sections. The linear relationship between road gradient and runoff depth suggests that runoff depths from the road plots increase with the increase in road gradient.

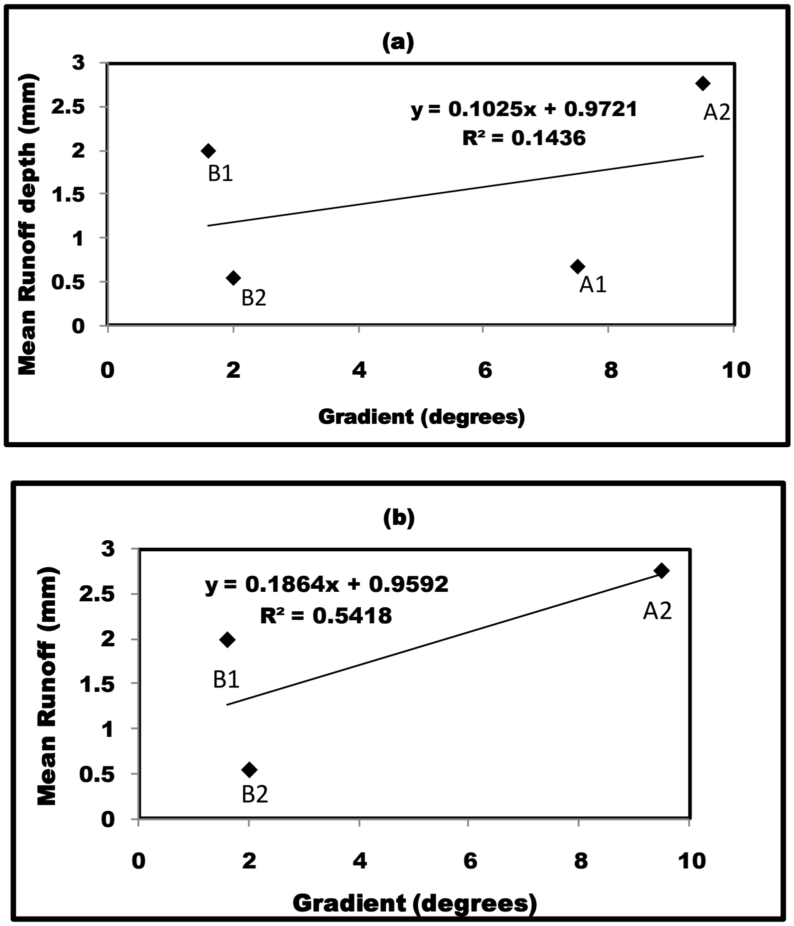


Figure 4. 3: Mean runoff depth for road plots arranged in increasing road gradient (a). In b, Plot A1 was not included based on the complexity of the site, which will be discussed at a later stage.

The mean runoff depth (mm) ranged from 0.68 to 2.77 for steep gradient road plots and from 0.55 to 2.00 for gentle gradient road plots. There was a wide variation in runoff produced from the road plots of similar gradient class suggesting differences in runoff generation.

4.3 Water Quality

The water quality data for individual sampling road plots and upstream and downstream of the road stream crossings is given in Table 4.2 and Figures 4.4a-f. The results are characterised using summary statistics for the total number of samples collected. The mean NH_4^+ concentrations for road runoff and stream water ranged from 0.1mg/l – 1.1 mg/l and 0.01mg/l - 0.04 mg/l, respectively (Table 4.2). The mean NO_2^- concentrations ranged from 0.02mg/l – 0.12 mg/l and 0.007mg/l - 0.01 mg/l for road runoff and stream water, respectively (Table 4.2). The mean NO_3^- concentrations for road runoff and stream water ranged from 7.1mg/l – 8.9mg/l and 5.4mg/l – 12.8mg/l respectively. The mean PO_4^{3-} concentrations for road runoff and stream water ranged from (0.04 – 0.08) mg/l and (0.04 – 0.07) mg/l respectively (Table 4.2). The mean TDO concentrations for the road runoff and stream water ranged from (2.6 – 4.5) mg/l and (6.6 – 6.7) mg/l respectively (Table 4.2). The road runoff and stream water mean pH values ranged from (6.6 to 6.8) units and (6.9 to 7.3) units, respectively (Table 4.2).

NH_4^+, NO_2^- and NO_3^- were commonly measured in road-runoff samples at larger concentrations than in stream water (Table 4.2 and Figures 4.4a-c). NO_2^- and NO_3^- for sampling points (C1 and C2) on the upstream crossing of the estate, however, were measured in larger concentrations (Figures 4.4b and c). Higher NH_4^+, NO_2^- and PO_4^{3-} concentrations were measured from a gentle gradient road segment B2 than other road plots (Figures 4.4a, b and d). The TDO concentration was measured in road runoff at lower concentrations than in stream water. pH values close to neutral conditions (pH=7) were observed in road runoff and stream water.

Table 4.2: The observed water quality data for road runoff and stream water samples for the sampling period November 2010 – April 2011

Sampling site	Water Quality Parameters							
	pH (units)	NO_3^- (mg/l)	NO_2^- (mg/l)	PO_4^{3-} (mg/l)	TDO (mg/l)	NH_4 (mg/l)	O_2 Consumption (mg/l)	T^o (^oC)
A1	6.8[6.0; 7.7]	8.7[2; 15]	0.05[0.0; 0.13]	0.046[0.0; 0.1]	3.1[1.2; 4.9]	0.14[0.0; 0.5]	1.8[0.7; 4.0]	23[18; 30]
A2	6.8[6.7; 7.2]	7.1[0; 15]	0.02[0.0; 0.1]	0.043[0.0; 0.1]	4.5[2.2; 9.0]	0.24[0.0; 0.5]	1.7[0.0; 4.5]	24[20; 27]
B1	6.6[6.5; 6.9]	8.0[2; 15]	0.02[0.0; 0.1]	0.04[0.0; 0.3]	2.6[1.0; 4.6]	0.4[0.0; 4.5]	0.9[0.0; 3.5]	24[18; 29]
B2	6.8[6.5; 7.5]	8.9[3; 15]	0.12[0.0; 0.5]	0.08[0.0; 0.3]	4.3[1.0; 7.5]	1.1[0.0; 5.0]	1.6[0.1; 3.8]	23[18; 29]
D1	6.9[6.7; 7.8]	5.4[2; 10]	0.007[0.0; 0.03]	0.07[0.0; 0.3]	6.6[6.0; 7.3]	0.01[0.0; 0.1]	1.8[0.1; 6.8]	23[18; 26]
D2	6.9[6.8; 7.1]	6.8[3; 20]	0.008[0.0; 0.03]	0.043[0.0; 0.3]	6.6[5.4; 7.8]	0.02[0.0; 0.2]	3.6[0.1; 6.2]	23[18; 26]
C1	7.3[6.9; 8.3]	10.7[8; 15]	0.0132[0.01; 0.03]	0.058[0.0; 0.3]	6.6[5.6; 9.0]	0.01[0.0; 0.1]	4.5[1.2; 6.9]	22[19; 26]
C2	7.2[6.9; 7.9]	12.8[6; 25]	0.014[0.01; 0.03]	0.04[0.0; 0.1]	6.7[6.0; 7.4]	0.039[0.0; 0.2]	1.9[1.0; 3.4]	22[19; 25]

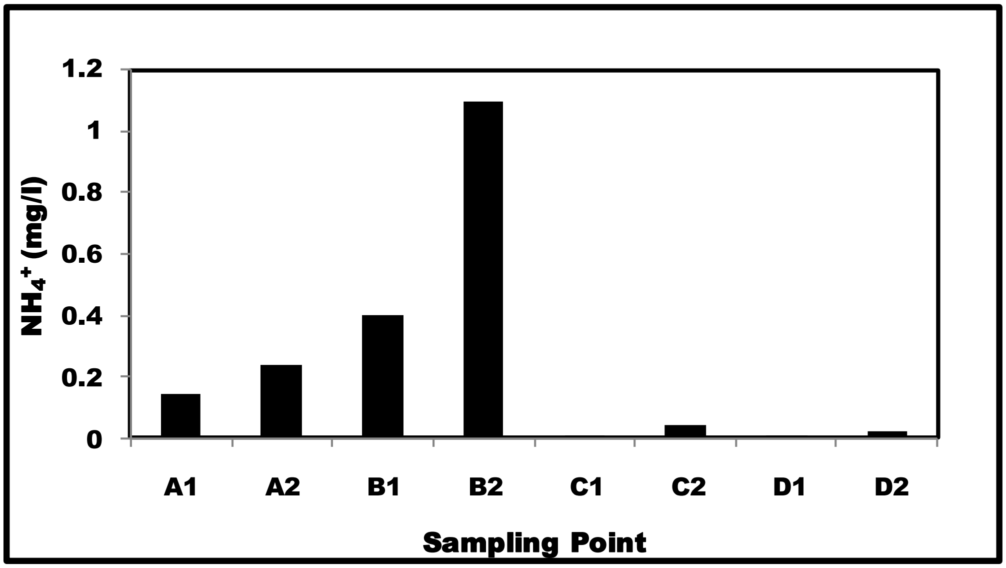


Figure 4. 4a: The mean NH_4^+ concentrations for steep (A1 and A2) and gentle (B1 and B2) gradient road runoff, and stream water upstream and downstream of the stream crossings C and D.

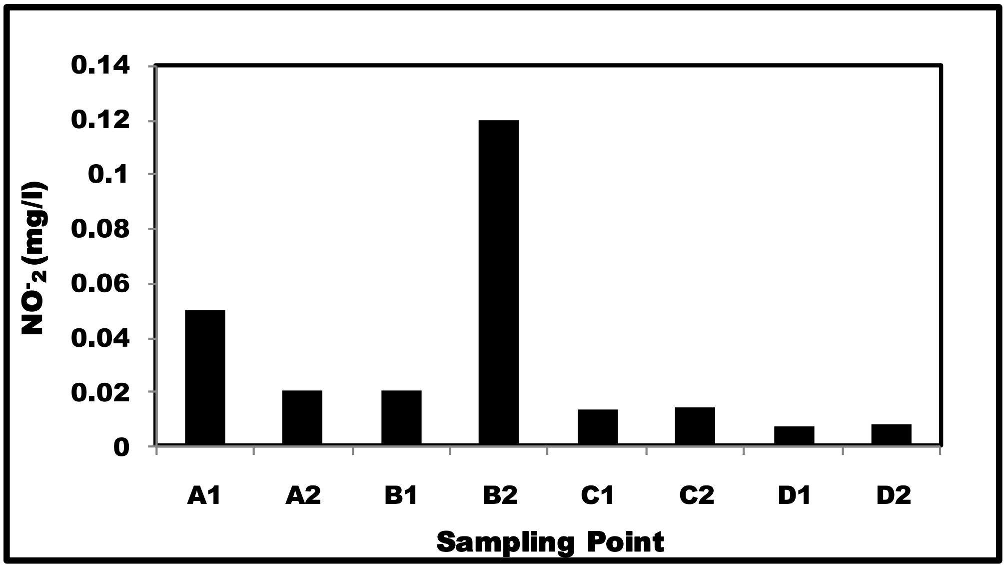


Figure 4. 4b: The mean NO_2^- concentrations for steep (A1 and A2) and gentle (B1 and B2) gradient road runoff, and stream water upstream and downstream of the stream crossings C and D.

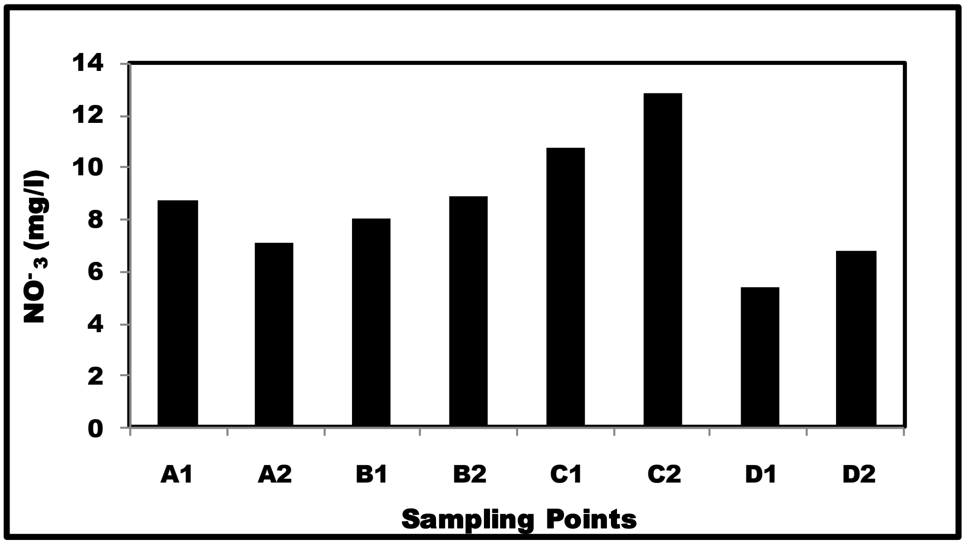


Figure 4. 4c: The mean NO_3^- concentrations for steep (A1 and A2) and gentle (B1 and B2) gradient road runoff, and stream water upstream and downstream of the stream crossings C and D.

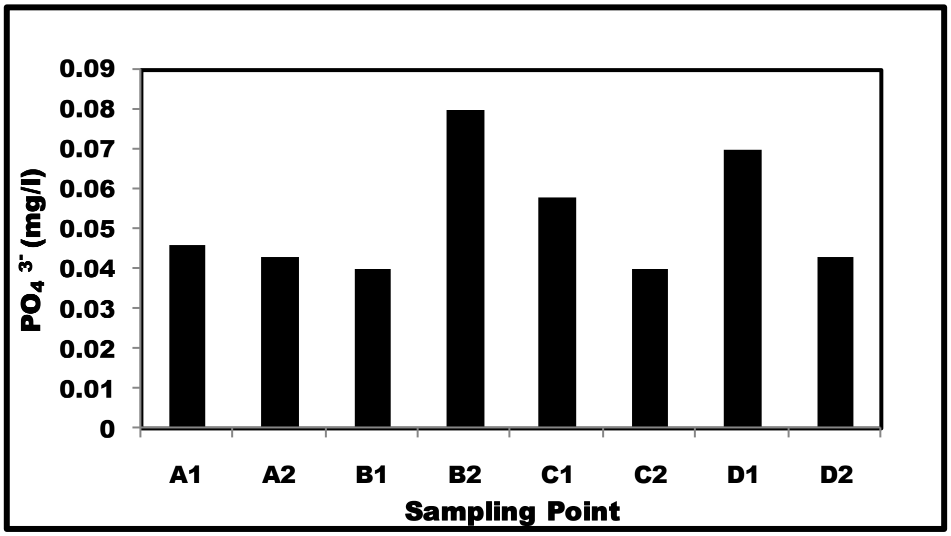


Figure 4. 4d: The mean PO_4^{3-} concentrations for steep (A1 and A2) and gentle (B1 and B2) gradient road runoff, and stream water upstream and downstream of the stream crossings C and D.

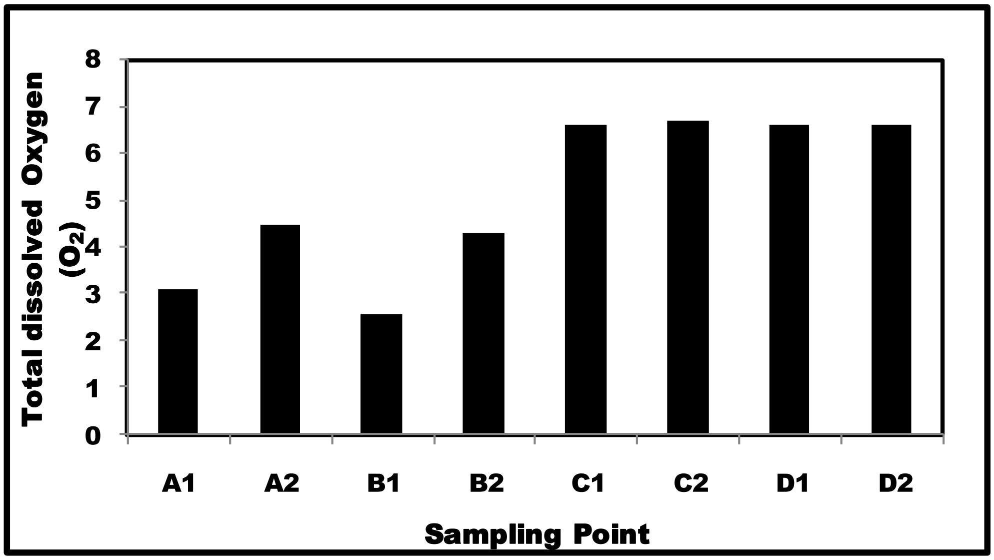


Figure 4. 4e: The mean TDO concentrations for steep (A1 and A2) and gentle (B1 and B2) gradient road runoff, and stream water upstream and downstream of the stream crossings C and D.

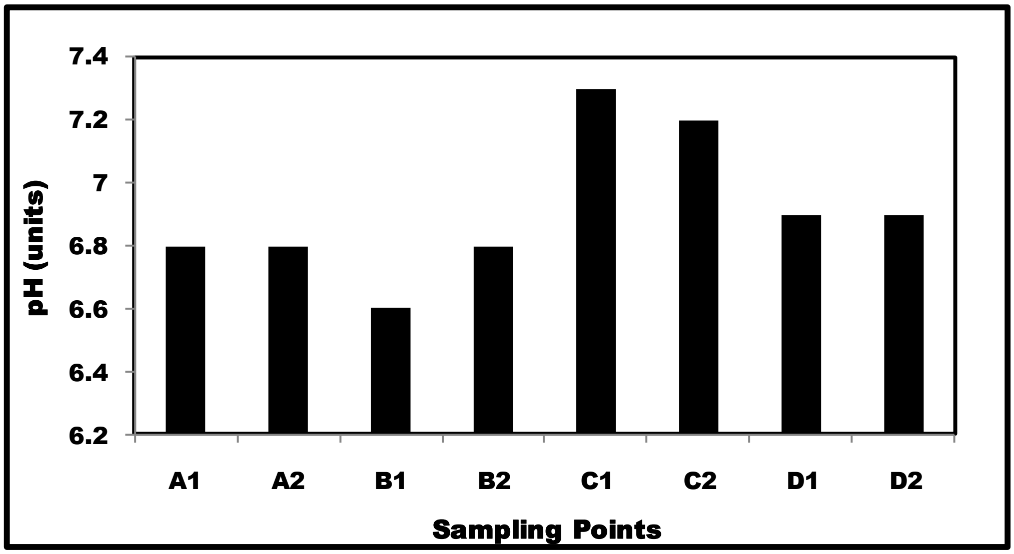


Figure 4. 4f: The mean pH levels for steep (A1 and A2) and gentle (B1 and B2) gradient road runoff, and stream water upstream and downstream of the stream crossings C and D.

Independent t- tests ($p \leq 0.05$) were used to compare road runoff quality for steep and gentle gradient roads, water quality upstream and downstream of the stream crossings (Tables 4.3 and 4.4).

Table 4.3: Independent t-tests of significant difference of water quality parameters for road runoff between steep and gentle gradient plots

Water Quality Parameter	t	df	Significance (2-tailed)	Mean Difference	Std. Error Difference
pH (Units)	0.763	34	0.451ns*	0.072	0.095
Nitrates (mg/l)	-0.405	34	0.688 ns*	-0.556	1.372
Nitrites (mg/l)	-0.939	34	0.354 ns	-0.036	0.039
Phosphates (mg/l)	-0.626	34	0.535 ns*	-0.018	0.029
Total Dissolved Oxygen (mg/l)	0.522	34	0.605 ns*	0.361	0.691
Oxygen Consumption (mg/l)	1.118	33	0.272 ns	0.558	0.499
Ammonium (mg/l)	-1.789	34	0.083 ns	-0.550	0.308
Temperature (^{o}C)	0.199	34	0.843 ns*	0.244	1.229

Note: ns, without significant difference; *highly nonsignificant

Table 4.4: Independent t-tests of significant difference of water quality parameters between upstream and downstream of stream crossings C and D

Water Quality Parameter	Stream Crossing	t	df	Significance (2-tailed)	Mean Difference	Std. Error Difference
pH (Units)	C	0.469	16	0.645 ns*	0.094	0.201
	D	0.469	16	0.645 ns*	0.094	0.201
Nitrates (mg/l)	C	-1.064	16	0.303 ns	-2.111	1.985
	D	-1.064	16	0.303 ns	-2.111	1.985
Nitrites (mg/l)	C	-0.364	16	0.721 ns*	-0.001	0.002
	D	-0.364	16	0.721 ns*	-0.001	0.002
Phosphates (mg/l)	C	0.387	16	0.704 ns*	0.013	0.036
	D	0.387	16	0.704 ns*	0.014	0.036
Total Dissolved Oxygen (mg/l)	C	-0.481	16	0.637 ns*	-0.189	0.392
	D	-0.481	16	0.637 ns*	-0.189	0.392
Oxygen Consumption (mg/l)	C	-0.722	16	0.480 ns*	-0.856	1.184
	D	-0.722	16	0.480 ns*	-0.856	1.184
Ammonium (mg/l)	C	-1.213	16	0.243 ns	-0.028	0.023
	D	-1.213	16	0.243 ns	-0.028	0.023
Temperature (^{o}C)	C	0.108	16	0.915 ns*	0.122	1.133
	D	0.108	16	0.915 ns*	0.122	1.133

Note: ns, without significant difference; *highly nonsignificant

The null hypothesis was that there is a significant difference in runoff quality between steep and gentle gradient roads, water quality upstream and downstream of the stream crossings. The concentrations of water quality parameters were not significantly different between the steep and the gentle gradient roads (Table 4.3), indicating similar nutrient concentrations from the road surfaces. The level of significance for NO_2^- , NH_4^+ and oxygen consumption, however, was low (Table 4.3). The concentrations of water quality parameters were not significantly different upstream and downstream of the stream crossings (Table 4.4), indicating no detectable increase in concentrations downstream. The level of significance for NO_3^- and NH_4^+, however, was low (Table 4.4). The concentrations of the water quality parameters were fluctuating during the observation period. This may be attributed to fluctuations in rainfall during the study period, and is discussed in the next chapter.

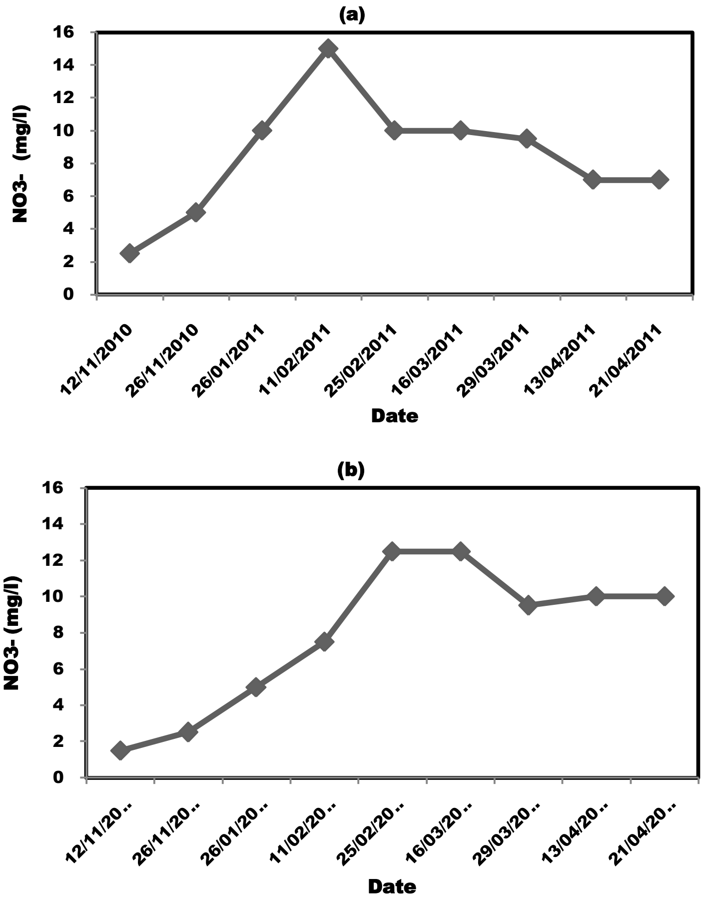


Figure 4. 5: Concentrations of NO_3^- in road runoff over the sampling period (November 2010 – April 2011) at plots of different gradient (a) gentle gradient, and (b) steep gradient.

A significant upward trend in NO_3^- concentrations was observed for road runoff during the study period (Figure 4.5). Road runoff NO_3^- concentrations followed a distinctively different pattern of trends from those of stream water (Figure 4.6). The upward trend in road runoff NO_3^- concentrations suggests an increase in NO_3^- concentrations in road runoff. A very slight downward trend suggests that the concentrations decreased slightly until reaching relatively stable conditions.

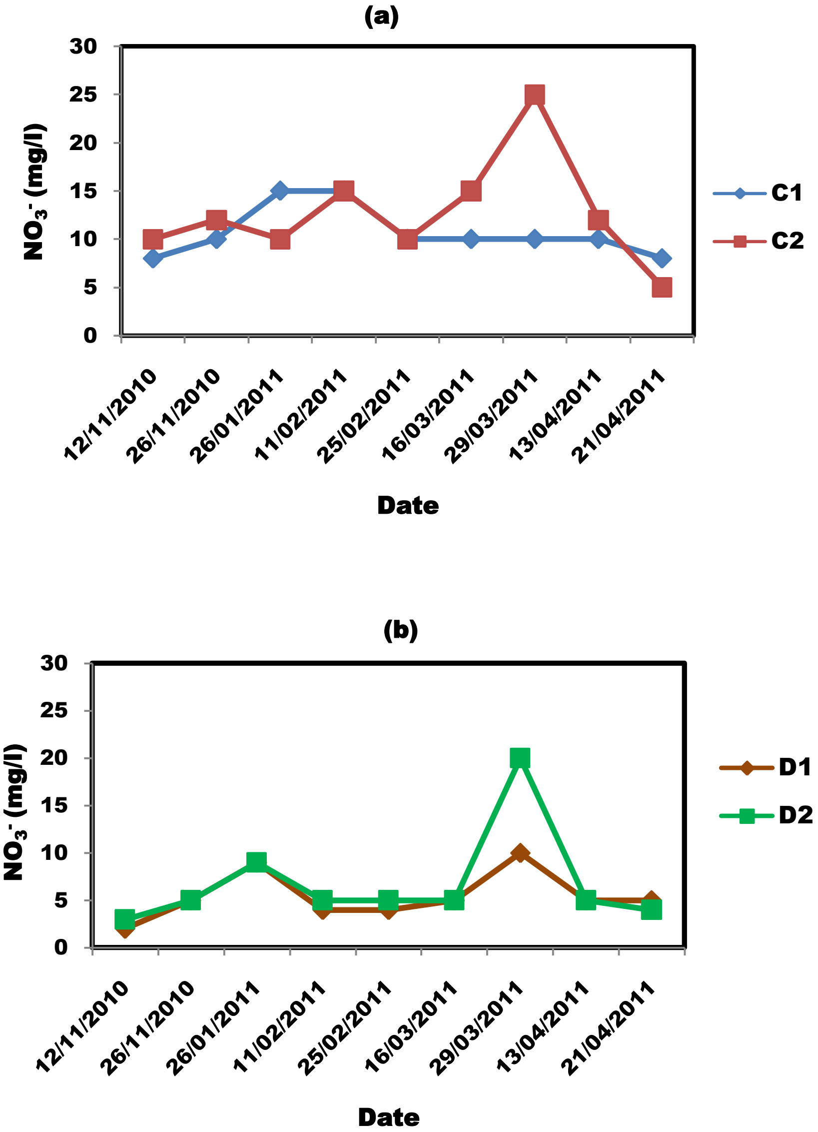


Figure 4. 6: Concentrations of NO_3^- in stream water over the sampling period (November 2010 – April 2011) at stream crossings (a) upstream of the estate (b) downstream of the estate.

The stream water did not show any significant trend in NO_3^- concentrations throughout the study period (Figure 4.6). Elevated stream water NO_3^- and NO_2^- concentrations however, were observed in the month of March, downstream of the stream crossings (Figures 4.6 and 4.7) . These concentrations decreased in April. NO_2^- concentrations at stream crossing D dropped to 0 mg/l during the sampling period. This suggests that there was no generation of NO_2^- during that period, except when the concentrations were elevated in the month of March.

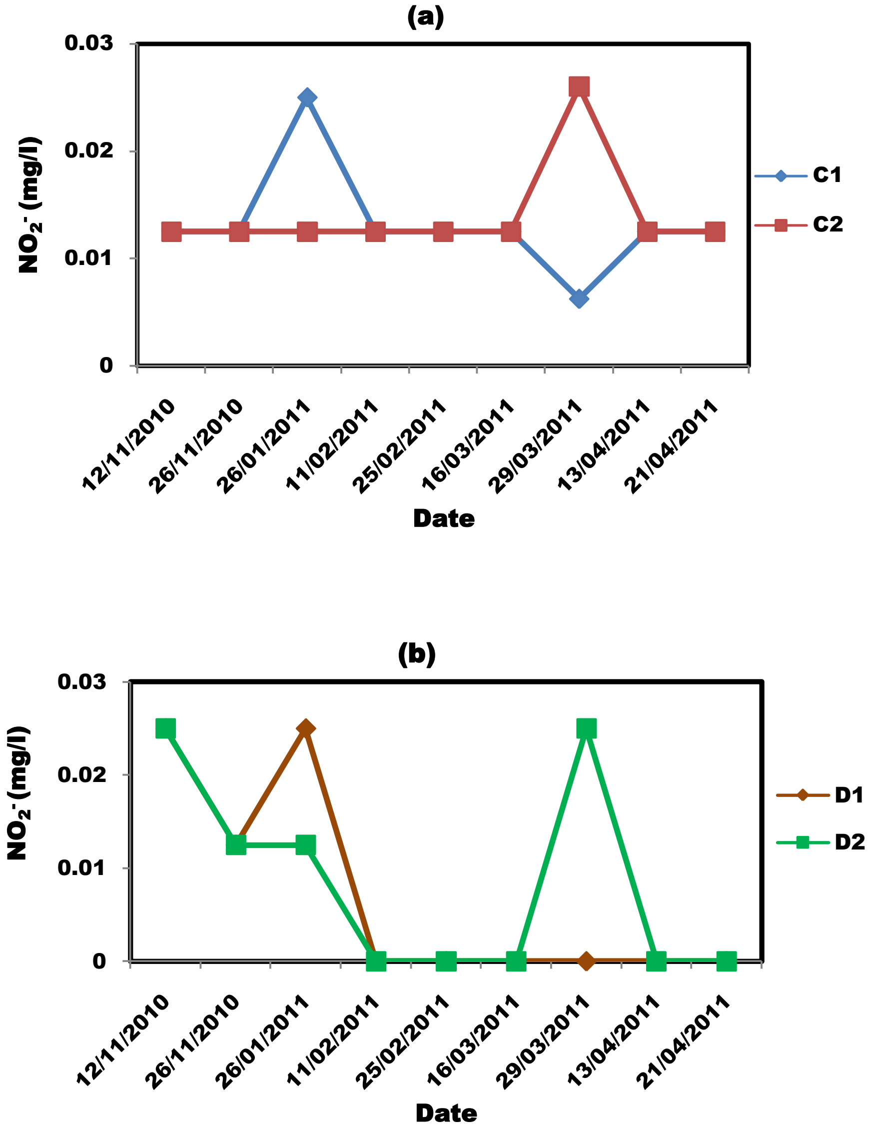
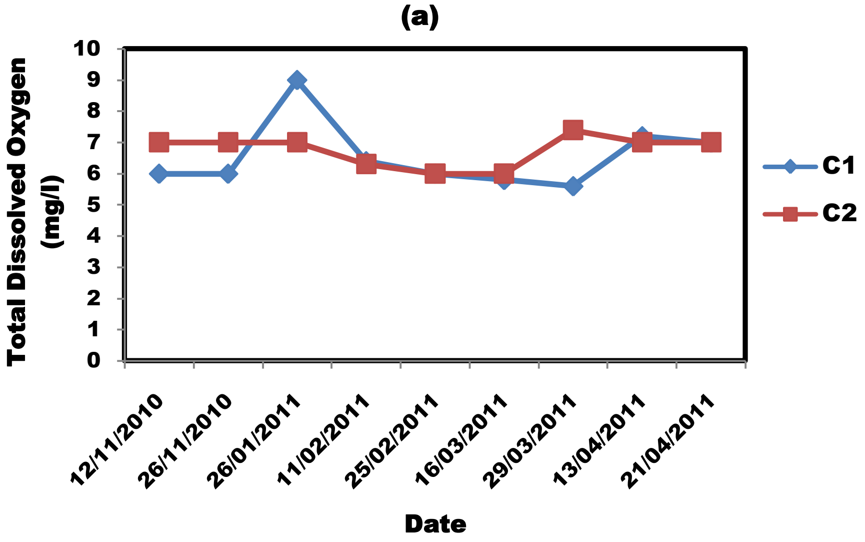


Figure 4. 7: Concentrations of NO_2^- in stream water over the sampling period (November 2010 – April 2011) at stream crossings (a) upstream of the estate (b) downstream of the estate.

Significant fluctuations were not observed for TDO concentrations upstream and downstream stream crossings during the observation period (Figure 4.8). This suggests that the TDO concentrations of stream water remained stable during the sampling period.



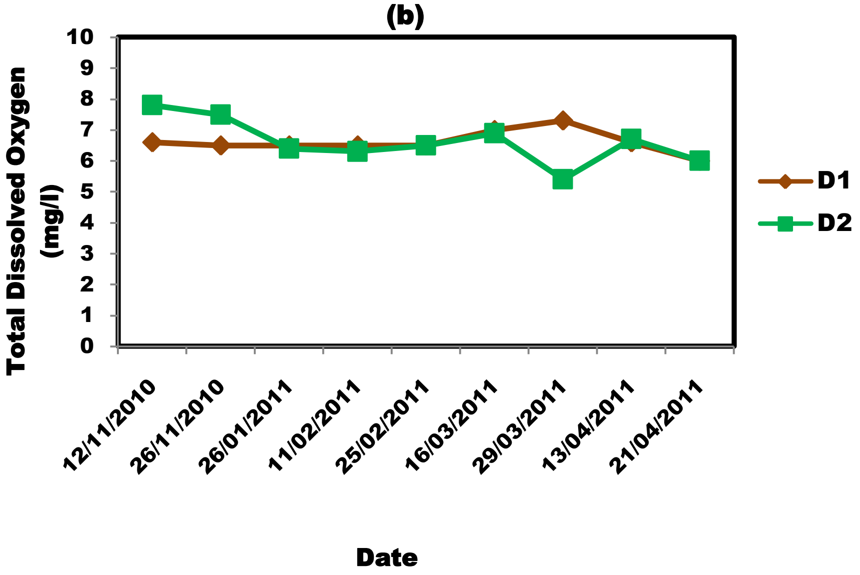
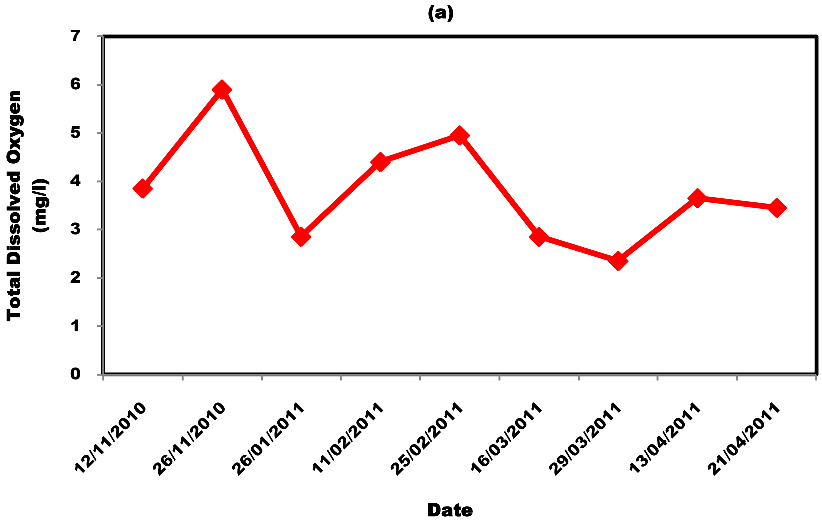


Figure 4. 8: Concentrations of TDO in stream water over the sampling period (November 2010 – April 2011) at stream crossings (a) upstream of the estate (b) downstream of the estate.

The concentrations of TDO for stream water (Figure 4.8) remained higher than the concentrations for road runoff (Figure 4.9). Fluctuations of TDO concentrations of road runoff were much higher than those of stream water. This suggests unstable conditions. The road runoff TDO concentrations were lower than stream water TDO concentrations (Figure 4.9).



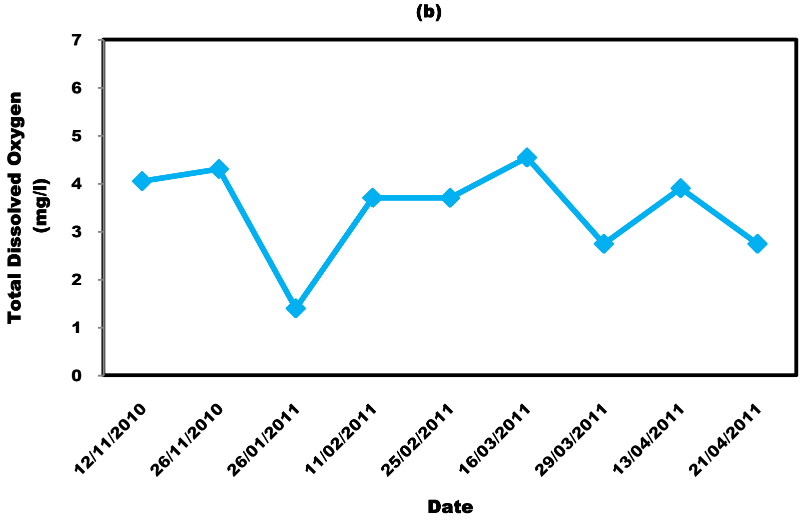


Figure 4. 9: Concentrations of TDO in road runoff over the sampling period (November 2010 – April 2011) at plots of different gradient (a) steep gradient, and (b) gentle gradient.

CHAPTER 5

Runoff from Forest Roads at Seele Estate in Context

5.1 Introduction

The individual datasets have been presented and analysed in the previous chapter. It is now possible to assess the original aims and objectives of the research again. The potential effect of the road runoff, if significant, should have an influence on the quality of the water draining the Estate. To test this, the stream runoff at road crossings above and below the Estate was analysed, as discussed in the preceding sections.

5.2 The Nature of Runoff from Forest Roads

The low R^2 values for regression of rainfall and runoff suggest that runoff generated from the road surfaces is also determined by variations in site conditions. The road gradient and plant cover influence runoff. Arnaez *et al*. (2004) reported a positive relationship between road gradient and runoff, and a negative correlation between runoff and plant cover. This suggests that runoff increases with an increase in road gradient and is reduced by a dense plant cover. Arnaez *et al*. (2004), however, found that gradient is the most sensitive site variable in the control of runoff.

Generation of runoff under low rainfall events might be the result of low infiltration rates. Croke *et al*. (1999a) have observed that forest roads have low infiltration rates which promote hortonian runoff even during low to moderate rainfall intensities. Additionally, antecedent soil moisture might have influenced infiltration. According to Zhang *et al*. (2011), soil water content preceding rainfall may be an important factor affecting the relationship between rainfall and runoff. Forsyth *et al*. (2006) states that saturated soil conditions during consecutive rainfall events result in runoff generation.

The wide variation in runoff produced from roads of similar road gradient classes may be attributed to different site conditions. In spite of their similar gradients, these roads had different vegetation cover. Thus, the mean runoff depth (mm) ranged from 0.68 to 2.77 for steep gradient road plots and from 0.55 to 2.00 for gentle gradient road plots. Nonetheless, the relatively high runoff depth from steep gradient roads may be explained by low infiltration rate that would have been possessed by these roads. According to MacDonald *et al*. (2001), low infiltration rates from steep roads may result in high surface runoff generation.

Although plot B1 and B2 were both on the gentle road gradient, a higher runoff depth of 2.00 mm was obtained from plot B1 by comparison to 0.55 mm for plot B2. This suggests that this road generated much higher amount of runoff compared to road plot B2. The infiltration capacity of this road plot is likely to have been much lower due to traffic frequencies and intensities on this road than road plot B2. Soil compaction due to traffic on the roadbed decreases the infiltration capacity and increases runoff generation (Jordan and Martinez-Zavala, 2008) a situation further complicated by the presence of some grass on the surface of plot B2. Plant cover reduces surface runoff (Arnaez *et al*., 2004).

5.3 The Impact of Forest Road Runoff on Stream Water Quality

The road runoff and stream water were classified according to Aquamerck® (Germany) guide for grading the quality of water (Table 5.1). The mean NH_4^+ concentrations suggest that the road runoff was moderately polluted and that the stream water was unpolluted. The road runoff and stream water were classified as strongly polluted and moderately polluted, respectively, in terms of TDO. The road runoff and stream water were both classified as strongly polluted and unpolluted in terms of NO_3^- and NO_2^- concentrations respectively. PO_4^{3-} mean concentrations for road runoff and stream water suggests that they were both moderately polluted.

Table 5.1: The mean values of road runoff and water quality parameters over the sampling period, November 2010 to April 2011 and the guide values for grading the quality of water (Aquamerck Compact Laboratory, 1990)

Related Organic load	Road runoff	Stream water	Quality class			
			I	II	III	IV
O_2(mg/l)	2.6-4.5	6.6-6.7	>8	>6	>2	<2
pH(acidic)	6.6-6.8	*	6.5-7.0	6.0-6.5	5.0-5.5	<5.0
pH(alkaline)	*	6.9-7.3	7.0-7.5	8.0-8.5	9.0-9.5	10
NH_4^+(mg/l)	0.1-1.1	0.001-0.04	<0.1	0.1-1	>2	>5
NO_3^-(mg/l)	7.1-8.9	5.4-12.8	<1.0	1-5	>5	*
NO_2^-(mg/l)	0.02-0.12	0.007-0.01	<0.1	0.2-0.5	4.0-6.0	8.0
PO_4^{3-}(mg/l)	0.04-0.08	0.04-0.07	<0.03	<0.5	>0.5	*

Note: I=Unpolluted to very slightly polluted; II= moderately polluted; III=strongly polluted; and IV=extremely polluted.* values not appropriate.

As expected, the concentrations of NH_4^+, NO_2^- and NO_3^- were observed to be greater in road runoff than in stream water (Table 4.1 and Figures 4.4 a-c). These high concentrations are likely to reflect the concentrations found in road runoff sediments. The road runoff was turbid for most of the sampling period and reflected the presence of suspended sediments, although it can be safely assumed that the dissolved load too would be at a maximum due to the greater surface contact with the water and suspended particles, and the turbulence associated with wash. Further, nutrients can be readily absorbed to sediment, which would further account for the concentrations observed in road runoff (Brown and Binkley, 1994). The soil forms in the road plots were predominantly *inanda, lamotte and katspruit* soil forms, which are typically humic and highly weathered (Fey *et al*., 2010). Unfortunately, soil variability is such that it could not be best constant throughout the plots.

Humic and strongly weathered soils are reservoirs (and hence sources) of nitrates, phosphates and other nutrients (Zech, 1997). Erosion of these soils could have elevated the nutrient contents. This supports the observations of Forsyth *et al.* (2006) who investigated the total iron of gravelled and ungravelled road runoff in *pinus* forest plantation and noted that erosion of sediments from exposed road surfaces elevated concentrations of water quality parameters in road runoff.

Binkley and Brown (1993) state that streams typically contain about 5 to 10mg/l of dissolved oxygen. As expected, these concentrations are lower for streams with higher organic matter. The input of fine organic debris into streams creates high biological oxygen demand resulting in high oxygen consumption (Binkley and brown, 1993). In the current study, oxygen consumption in stream water was high. Oxygen consumption in stream water was relatively high (Table 4.2) due to the contribution of water from the forest compartments themselves and the vegetation on the stream banks, although it is very difficult to measure reliably in the field. Thus the mean TDO for stream water ranged from 6.6 to 6.7 mg/l (Table 4.2). Despite the higher oxygen consumption in stream water than in road runoff water, stream water possessed high TDO (6.6mg/l – 6.7 mg/l) by comparison to road runoff water (2.6mg/l – 4.5mg/l).

Lower concentrations of TDO for road runoff than stream TDO concentrations can be attributed to a combination of factors: high temperature and turbidity. High temperatures were commonly measured for road runoff (Table 4.2) and may be attributed to light absorption by road runoff sediments (Binkley and Brown, 1993). According to Binkley and Brown (1993), high temperatures decrease oxygen solubility in water. Additionally, Cullen (2000) suggests that low concentrations of TDO correspond to turbidity of water.

Similar nutrient concentrations from the road plots of different gradients suggest that these roads produced approximately similar amounts of nutrients. Although different gradient road plots produced different amounts of runoff, little or no variation in nutrient loads from the road plots suggests a relatively constant export rate of the nutrients (Forsyth *et al.*, 2006). Higher NH_4^+, NO_2^- and PO_4^{3-} concentrations measured from a gentle gradient road segment, B2 (Table 4.2) than other road plots might be attributed to organic material within this road plot. The leaf litter might have provided the organic material which was found as organic residue layer in the stilling well. The decaying biomass might have increased nutrient concentrations in water. Forsyth *et al.* (2006) found organic residue layer in the roadside drains in the *pinus* forest plantation, and suggested that it influenced the organic carbon concentrations in surface runoff from those sites.

NO_3^- and NO_2^-concentration were higher upstream than downstream of the estate (Figures 4.4 b and c). The possible sources of high concentrations upstream of the estate might be the stream bank vegetation which was dominant upstream. The presence of nutrients in water may be the result of decaying biomass (Forsyth *et al.*, 2006). Lower NO_3^- concentrations might have been the result of downstream dilution as Binkley and Brown (1993) suggested.

The NO_3^- concentrations of road runoff increased during the study period (Figure 4.5). An increase in NO_3^- concentrations are likely related to rainfall. Given the road gradient and the exposed road surfaces, runoff erosion might be identified as the major cause of increased NO_3^- concentrations. Stevens (2001) states that the increase in nutrient concentrations of road runoff is the result of the increase in suspended sediments from erosion associated with rainfall events. NO_3^- concentrations remained high due to continuous occurrence of rainfall events. This supports Lane and Sheridan (2002) who investigated the impacts of the unsealed road stream crossings on turbidity and total dissolved solids and suggested that deterioration of water quality is triggered by rainfall events.

The downstream NO_3^- and NO_2^- concentrations (Figures 4.6 and 4.7) coincided with rainfall, that is, concentrations that increase with the increase in rainfall. Although stream runoff was not measured in the current study, these findings support de Villiers and Thiart (2007) who investigated the nutrient status of South African rivers. de Villiers and Thiart (2007) suggested that nutrient concentrations peak during high river runoff when high rainfall conditions are prevalent. This is because the diffuse sources of pollution produce seasonal concentration profiles that have direct relation to river runoff, or concentrations that peak during high runoff conditions.

High concentrations of NO_3^- and NO_2^- downstream stream crossings might have occurred as the result of fine sediment washed off from the road surface during high rainfall events, and delivered into the stream. These findings support Lane and Sheridan (2002) who investigated the impacts of an unsealed forest road stream crossing on water quality and noted that the stream crossings increased turbidity and suspended sediment.

The data presented from the analysis of road runoff has suggested that both sediment and nutrients are entrained during the runoff. The data have further suggested that the quality of road runoff water is lower than the stream water, and that the difference between the two is greater thus can generally be attributed to the dilution effects of the stream flow. This in turn suggests that the forest compartments themselves have a mitigating effect on the road runoff. In order to test this hypothesis, BHD was measured at six plots and six control plots. This is discussed in greater detail in section 5.4.

5.4 The Breast Height Diameter of Trees in Relation to Road Runoff

The mitigating effects of forest compartments on the road runoff were tested by measuring the tree BHD at six plots and six control plots as described in detail in Chapter 3. Descriptive statistics for BHD are shown in Table 5.2. The mean BHD for plots at the outlets of the road drains ranged from 133mm – 185 mm and from 138 mm – 183mm for control plots (Table 5.2). Since the size of the plots could obscure the effects of water, subsampling was done by decreasing the plot sizes at the outlet of the mitre drains. Decreasing the size of the plots increased the mean BHD (Table 5.3) as would be expected where the trees closer to the drain have a larger diameter than those further away. The mean BHD for plots at the outlet of the road drains ranged from 134mm –

192mm and from 138 mm – 183mm for control plots. The highest increase was observed from plots at gentle gradient roads.

Table 5.2: Tree BHD at road drains and control plots

Plot	N	BHD			
		Mean (mm)	Minimum (mm)	Maximum (mm)	Standard Deviation (mm)
D1	55	160	70	270	42.1
Ctr 1	56	144	80	220	29.5
D2	53	144	70	280	46.3
Ctr2	53	150	50	240	50.7
D3	46	185	60	270	47.1
Ctr3	44	183	80	310	51.5
D4	49	135	70	190	26.4
Ctr4	36	154	110	230	26.0
D5	57	136	80	190	27.6
Ctr5	56	138	70	210	30.3
D6	44	133	100	160	16.7
Ctr6	40	154	100	200	24.1

Note: N, number of trees.

The increase in mean BHD for road plots at the drain outlets after subsampling suggests that the trees in close proximity to the outlet of the road drains had high BHDs. This suggests that road runoff from the drain outlet might have been dispersed only a few metres from the drain outlet. This implies that only trees that are in close proximity to the outlet of the mitre drain received extra water and grew much better as compared to those far from the drain outlet.

Table 5.3: Tree BHD at road drains and control plots after subsampling

Plot	N	BHD			
		Mean (mm)	Minimum (mm)	Maximum (mm)	Standard Deviation
D1*	30	167	70	270	53.3
Ctr 1	56	144	80	220	29.5
D2*	28	157	80	280	54.2
Ctr2	53	150	50	240	50.7
D3*	30	192	60	250	54.7
Ctr3	44	183	80	310	51.5
D4*	30	138	70	190	32.6
Ctr4	36	154	110	230	26.0
D5*	30	140	90	180	29.9
Ctr5	56	138	70	210	30.3
D6*	26	134	100	160	17.9
Ctr6	40	154	100	200	24.1

Note:*Subsampled plots

Higher mean BHD values for plots at the road drains than control plots were recorded at gentle gradient plots (Figure 5.1). However, these were not statistically significantly different ($p < 0.05$) (Table 5.4). Based on the availability of extra water from the roads, it was expected that BHD would be higher for plots at the drains than control plots since soil moisture influences tree growth. Although the differences in BHD between plots at the outlet of the drains and their control plots were small, higher mean BHD values recorded are attributed to the alteration in water content due to runoff redistribution through mitre drains, into the forest compartments. Jalilvand *et al*., (2010) noted that the existence of a ditch or drain along the forest road caused more moisture to be fed to the cultivated trees and thus increase the tree growth. The data here supports this.

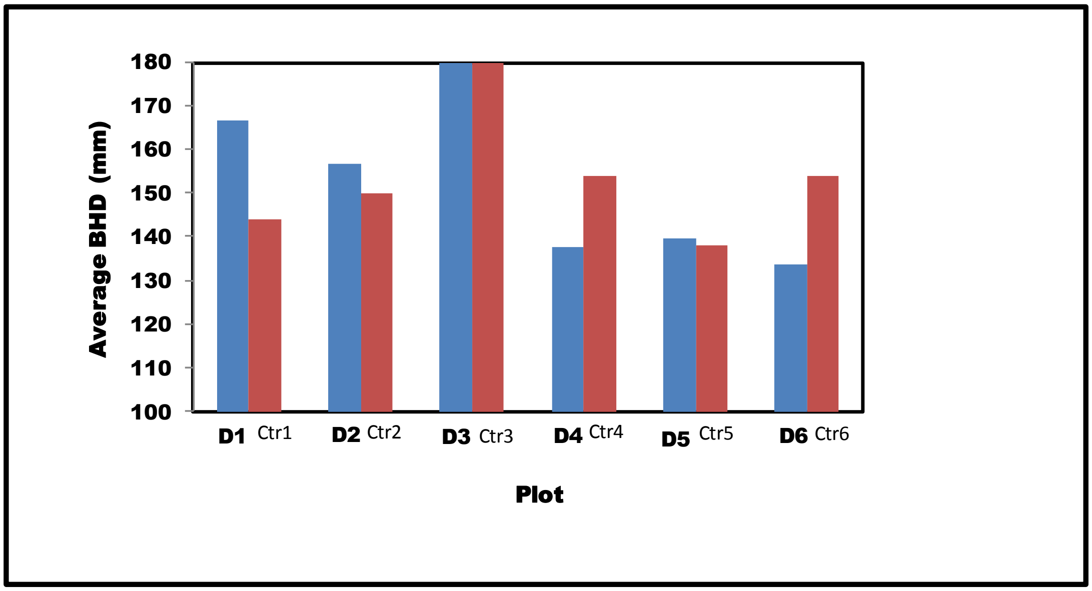


Figure 5. 1: Comparison of average Breast height Diameter of trees at road drains (D1-D6) and control plots (Ctr1-Ctrl6).

The results of independent t- tests indicate that there was no statistically significant difference, at 0.05, 0.1 and 0.25 probability levels, in mean BHD between the plots at road drains and their control plots (Table 5.4).Although the factors influencing tree growth were not measured in this study, it is likely that mean BHD was influenced by other factors such as sunlight, soil moisture and nutrients in addition to road runoff (Jalilvand *et al*., 2010). This is because the evidence that other factors including irradiance and soil nutrients are also important in determining the tree growth rates (Baker *et al*., 2003). This might have influenced the mean tree BHD values which were also not significantly different between the transects within each plot (Table 5.5).

Table 5.4: Independent t-tests of Breast Height Diameter between plots at the road drains and their control plots, and between steep and gentle gradient plots

Plots	Probability Levels					
	0.05		0.1		0.25	
	t	Significance (2-tailed)	t	Significance (2-tailed)	t	Significance(2-tailed)
Gentle gradient vs control	1.47	0.15ns	1.46	0.15ns	1.35	0.18ns
Steep gradient vs control	-2.03	0.05ns	1.89	0.06ns	4.19	0.16ns
Gentle vs steep gradient	4.97	0.00*	5.81	0.00*	6.54	0.00*

Note: ns, without significant difference; *significant

Comparisons of the average BHD for plots at road drains revealed that BHD at steep gradient plots was less than that of gentle gradient plots (Figure 5.2). This was statistically significant ($p < 0.05$) as shown in Table 5.4. This suggests that trees that received runoff from gentle gradient roads grew much better than those that received runoff from steep gradient roads. This would be expected, as where the steep sections are, water will tend to drain away rapidly and so not be accessible to the trees. Water from road runoff enhances this pattern.

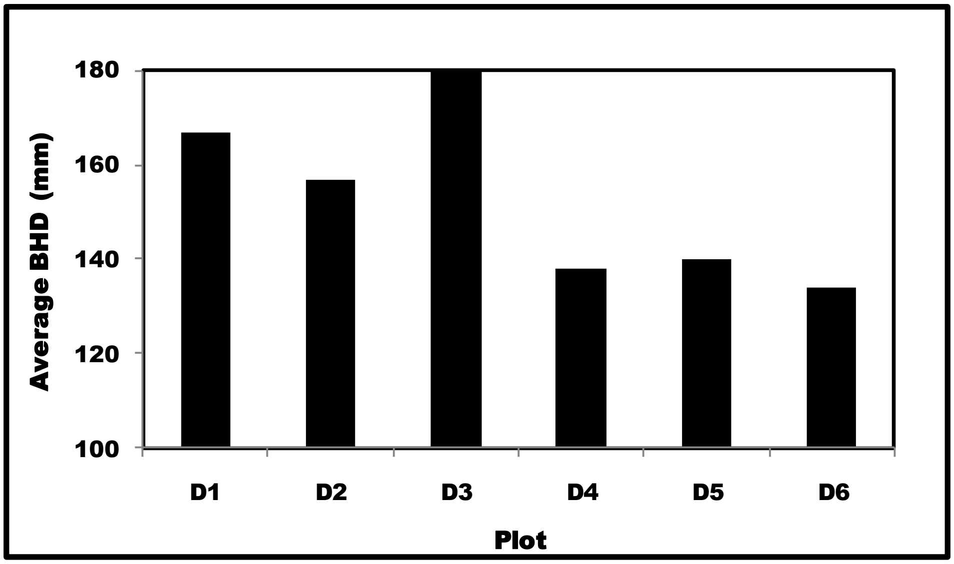


Figure 5. 2: Comparison of average Breast Height Diameter of trees at gentle (D1-D3) and steep (D4-D6) gradient road drains.

Highest mean BHD was observed in plot D3. This might have been because there is more chance for runoff to infiltrate on relatively gentle slopes (La Marchethere and Lettenmaier, 2001) to give more moisture to the trees and increase their growth. The runoff redistributed from steep gradient road might have not infiltrated in the steep gradient tree plots.

Average tree BHD comparisons of transects within plots were drawn. Six transects were measured in each plot as described in detail in Chapter 3. Figure 5.3 shows the comparison of mean BHD between transects. The results of one-way ANOVA test indicate that there was no statistically significant difference in mean BHD among the six transects in each plot (Table 5.5). This suggests that there was similar tree growths along each transect which might be explained by similar conditions such as sunlight, soil moisture and nutrients (Jalilvand *et al*., 2010).

Table 5.5: One-way ANOVA tests of significant differences ($p < 0.05$) in mean BHD between the six transects within plots D1-D6.

Plot	df	Mean Square	F	Significance
D1	17	2.732	0.808	0.674
D2	16	2.423	0.790	0.687
D3	16	3.781	1.504	0.165
D4	11	1.654	0.501	0.889
D5	11	5.225	1.964	0.066
D6	16	1.123	0.343	0.909

BHD was negatively correlated to distance from the road edge (Figure 5.4). This suggests that BHD decreased with the increase in distance from the road edge. The coefficients of determination (R^2) of the best-fit linear regression equations linking distance from the road edge into the forest interior to BHD ranged from 0.003 -0.33. The low R^2 values suggest that the distance from the road edge into the forest interior explained around 0.3% - 33% of the variation in BHD for steep and gentle gradient road plots. Scatter plots for the regression of distance from the road edge into the forest interior against BHD for plot D1 is shown in Figures 5.4.

The BHDs for transects showed poor correlation with distance from the road edge. The strength of the regression relationship (R^2) was very low (ranged from 0.0036-0.3287). While the correlations between the distance from the forest edge and BHD were very low (Figure 5.4), this relationship implies that trees far from the road edge into the forest interior had smaller BHDs. This finding is in agreement with Bowering *et al.* (2006) where a decreasing mean BHD with increase with distance from the road edge was found. It must, however, be remembered that this is not only a function of water and nutrient availability, but also of light penetration and competition factors. Oliver and Larson (1996) attributed higher BHD at the forest edge to less competition among trees at the edge. Thus, competition for water among the trees increases with the increase in distance into the forest interior resulting in lower BHD. This suggests that increasing the number of trees may facilitate more water uptake since there will be more trees to use up the water. Field observations confirm what the above data suggests.

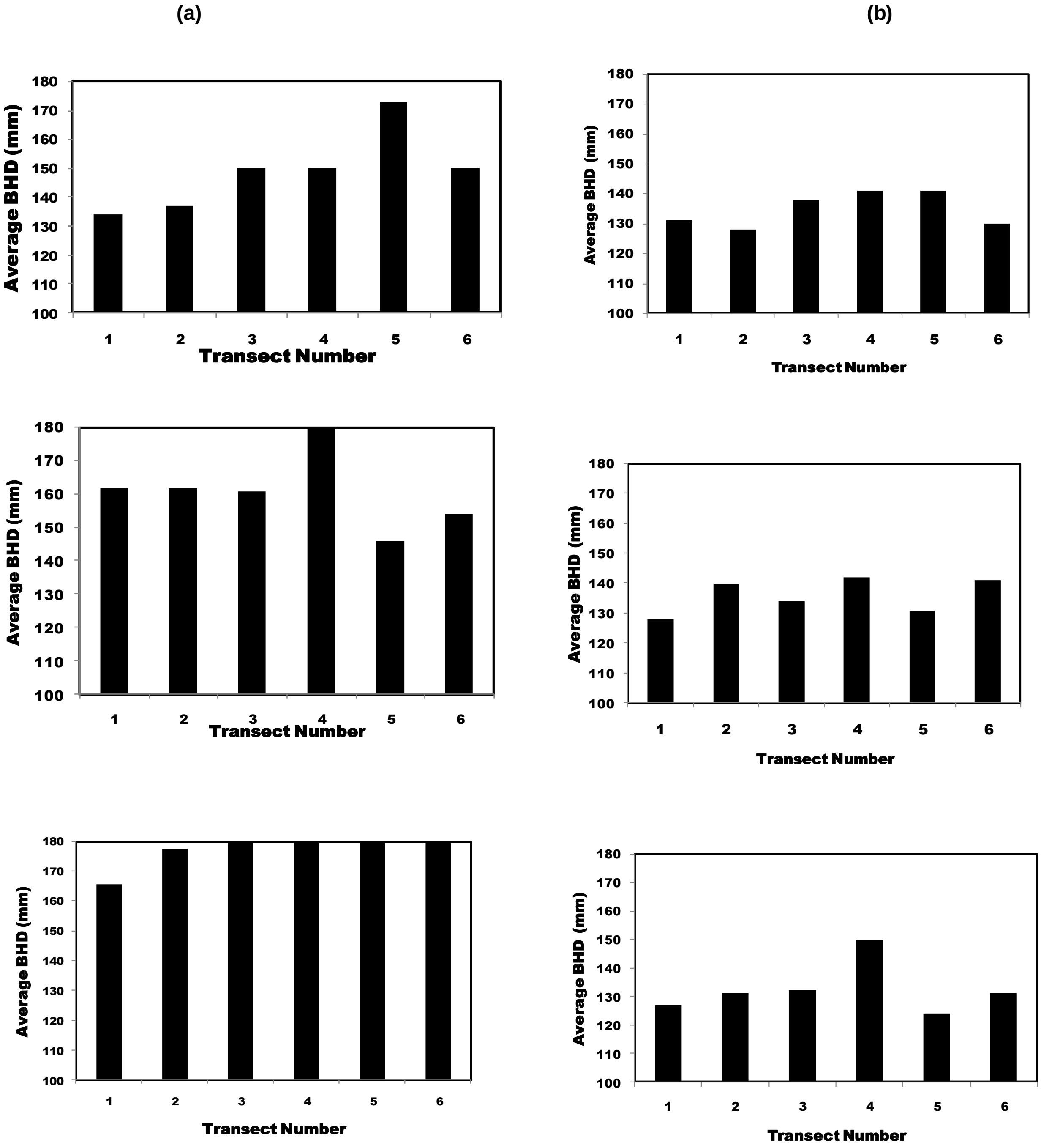
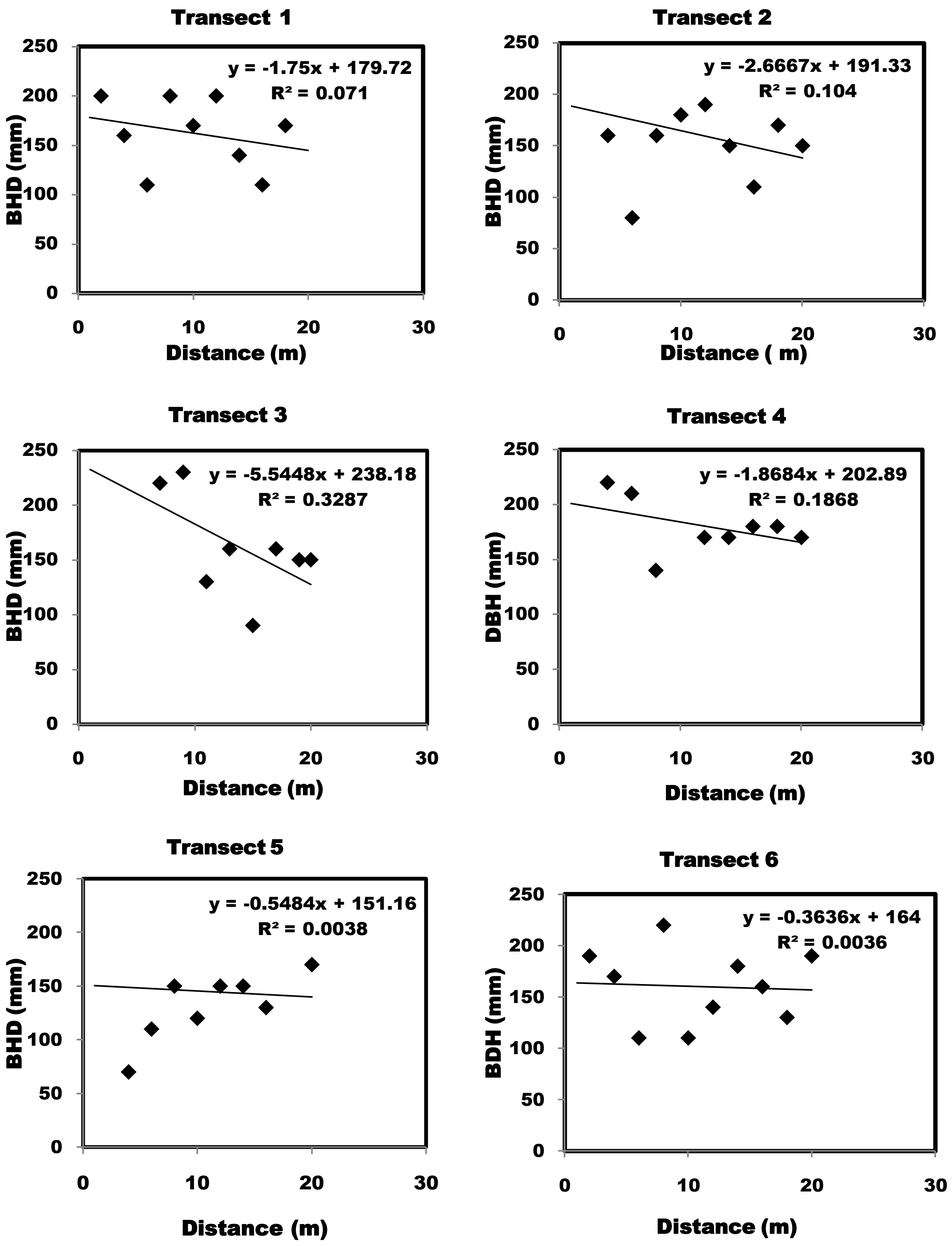


Figure 5.3: Average Breast Height Diameter for transects in gentle gradient plots (a) and steep gradient plots (b).



Transect 1

Transect 2

Transect 3

Transect 4

Transect 5

Transect 6

Figure 5.4: Relationship between distance from the forest edge into the forest interior and Breast Height Diameter for Plot D1.

The trees and the forest floor therefore take up much of the material washed off the road, preventing it from entering the stream unless there are drainage lines routing quickflow through the forest to the stream.

The runoff from the unpaved forest roads at Seele Estate has been put in context in this chapter. It is now possible to make conclusions and recommendations for future research.

CHAPTER 6

Conclusions

6.1 The Impacts of Unpaved Forest Roads on Runoff and Water Quality

The aim of this research was to investigate the nature of surface runoff within commercial forests, with a view to understanding nutrient loads from unpaved forest access roads impacting on stream catchments. The objectives developed for the achievement of the aim were to measure runoff and the associated nutrient loads from the unpaved road; evaluate the effectiveness of localised unpaved forest road cut-off drains in terms of water, sediment and nutrient management; and assess the magnitude of the impacts of road runoff on stream water quality. The results of the study suggest that unpaved forest roads generated significant volumes of surface runoff (3-166l/m^2) during the monitoring period. The amount of runoff is triggered by rainfall and the road gradient with the road gradient being the main explaining variable. The amount of runoff produced from the road plots is variable among different road gradients, increasing with the increase in road gradient. Gentle gradient road plots may generate much runoff than steep gradient road plots. This indicates that rainfall and runoff are not the only factors influencing runoff. Other site conditions such as gradient and vegetation cover on the road surface may also influence runoff production.

Nutrient concentrations of nitrates, nitrites, ammonium, and phosphates concentrations were prevalent in road runoff. pH conditions reflecting close to neutral conditions were characteristic of the road runoff. Very low total dissolved oxygen concentrations associated with high runoff temperatures were also common in road runoff. These findings are in line with work of researchers in other parts of the world (e.g. Forsyth *et al*., 2006) who suggest that unpaved forest roads generate nutrient loads. These concentrations were not significantly different between the road plots of different gradients. Elevated nutrient concentrations that occurred at the gentle gradient road plot B2 than other road plots suggest that the road surface is not the only factor that determines the concentration of nutrients in surface runoff. Conditions prevailing in the forest compartments may also have an impact on the runoff quality. The leaf litter that gets deposited and decay in the stilling wells of the runoff plots may impact on the nutrient concentrations.

Nutrient concentrations (viz. ammonium, nitrites and nitrates) were measured in road runoff in higher concentrations than in stream water for most of the sampling period. The road stream crossing (C), however, produced higher nitrates concentrations than the road runoff. This was attributed to the stream bank vegetation at this stream. These results suggest that the characteristics of the stream such as stream bank vegetation may also influence the nutrient concentrations of stream water. Unpaved forest roads produced nutrient concentrations that were higher than stream water nutrient loads during the sampling period. The road runoff nutrient concentrations that were higher than for stream water would alter the stream water quality if the runoff would flow in the stream. The elevation of other nutrient concentrations during high rainfall events suggested that rainfall affects the stream nutrient concentrations. The nutrient concentrations did not increase downstream of the road crossings.

Although the water quality for some of the road runoff was poor, using the Merck criteria, stream water draining the Estate was not seriously degraded. However higher runoff and stream water nitrate concentrations imply strongly polluted water. Deterioration of water quality as assessed by higher nitrate concentrations was triggered by decay of organic material. The principal sources of organic material were the leaf litter and the vegetation along the stream banks. This condition of elevated nitrate concentration is favourable to the development of eutrophic conditions which can be toxic to humans, and aquatic plants and animals.

There is no doubt that forest road runoff redistribution into the nearby forest compartments reduces surface water erosion and sediment delivery to watercourses. The evaluation of runoff redistribution onto the forest compartments was achieved through relating water distribution to tree growth (viz. breast height diameter). Diversion of road runoff resulted in tree breast height diameter increase for trees adjacent to gentle gradient roads and in very close proximity to the outlet of the drains. This suggested that the gradient determine the infiltration of redistributed runoff and hence the availability of the water that can be used up by the trees. Given the BHD data and that the road runoff concentrations were considerably higher than for stream water, the diversion of the road runoff into the adjacent compartments of forest plantations would reduce the potential of these loads to reach the local streams. These nutrients then become available to enhance tree growth. The lower concentrations in streams are likely to represent both a reduction due to uptake within the compartment as well as dilution effects in the stream itself.

6.2 Recommendations and the Potential for Future Research

This study has established the impacts of unpaved forest roads on runoff and water quality. It was found in the study that runoff production is the function of road gradient and rainfall. The forest plantations are located in places with steep slopes and high rainfall and the roads are prone to runoff generation. Forest managers can take measures to avoid the negative impacts of runoff generated from the unpaved access roads, on stream water quality. The current best management practise used in the estate is the discharge of the road runoff into the adjacent forest compartments. This is achieved through berms constructed across the roads, which slow down the water and redirect it into the mitre drains into the forest compartments. This is important as the amount of water from the road surface is reduced, and also tree growth is promoted, as the results of the study have suggested.

Forest managers should take into consideration the potential impacts of runoff redistribution into compartments through the forest. As previously discussed, drainage structures have the potential for incision that can lead to gully formation as runoff is discharged onto the adjacent hillslope. It is suggested that forest managers come up with measures that must be used to ensure that gullies are not formed at the outlets of the mitre drains. The results presented have supported the work of (Costantini *et al*., 1999) who recommended that the turnout drains should discharge at a stable area, have high infiltration capacities and maximize the spread of flow, in order for hillslope infiltration to be effective.

While this best management practice is being undertaken in the estate, it is important that forest managers consider other management practises especially those that are targeted at reducing nutrient generation from the roads. In the study, erosion of the road surfaces resulted in nutrient concentrations in road runoff. Gravelling the road surface has the potential to reduce road surface erosion since it reduces the erosive potential of rainsplash and overland flow, as suggested by (MacDonald and Coe, 2008).

While this study has added to the understanding of the impacts of unpaved forest roads on runoff in forested catchments, explicit investigations are required that would help maximise the quality of observations. Measurements in this study were made on the basis of record length for this research. Runoff and stream water quality measurements should be carried out on a long term basis in order to allow the determination of temporal patterns and should ideally be event driven rather than quasi-regular visits to the site. It is also important to measure the amount of runoff at the same time as runoff quality monitoring. Nevertheless, the 2009/2010 runoff and rainfall data were used in this study for regression analysis purposes.

Factors that cause runoff on unpaved roads are complex. Additional investigations that could have been undertaken during in this research to further investigate the effects of unpaved roads on runoff include analysis of factors including compaction, infiltration and traffic loads on the roads. Runoff redistribution also requires explicit investigations. The water content at the outlet of the mitre drains requires investigations. It is evident that water is not the only factor that determines tree growth. All variables that affect tree growth have to be determined and this would assist in separating the effects of water on tree growth from those of other growth determining variables.

There are certain factors that impacted on data accuracy during investigations. Equipment failure periodically hindered the proper recording of runoff data. It is suggested that runoff plots be monitored frequently to help increase the accuracy of data. Rainy conditions affected storm-event measurements of runoff and water quality since vehicles could not get access into the forest, leading to results being time based rather than event based. Stream runoff is an important variable when measuring the stream water quality, hence requires consideration.

The results of this study however, should help forest managers to understand the contributions of unpaved roads on runoff better. This will contribute to improved planning strategies for the best management practices in the future and thereby reduce surface water erosion and runoff delivery to watercourses.

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APPENDICES

Water Quality Data

Sampling Site	Sampling Date		pH (Units)	Nitrates (mg/l)	Nitrites (mg/l)	Phosphates (mg/l)	Total Dissolved Oxygen (mg/l)	Oxygen Consumption (mg/l)	Ammonium (mg/l)	Temperature (^{o}C)
A1	12/11/10		6.0	2	.00	.1	2.7	1.0	.0	18
	26/11/10		6.5	2	.13	.1	2.8	2.8	.0	26
	26/01/11		6.9	10	.01	.0	3.5	1.0	.0	30
	11/02/11		7.7	10	.13	.0	4.8	.	.0	27
	25/02/11		6.8	15	.13	.0	4.9	1.1	.2	27
	16/03/11		6.9	10	.01	.1	1.2	1.2	.3	24
	29/03/11		6.8	9	.01	.0	1.2	1.2	.3	21
	13/04/11		6.8	10	.00	.0	3.3	3.3	.0	18
	21/04/11		6.8	10	.00	.0	3.4	3.4	.5	19
	Total	Mean	6.8	9	.00	.05	3.1	1.8	.1	23
		Minimum	6.0	2	.00	0.1	1.2	1.0	.0	18
		Maximum	7.7	15	.1	.1	4.9	3.4	.5	30
		Std. Deviation	.4	4.2	.1	.1	1.3	1.1	.19	4.4
A2	12/11/10		6.8	1	.00	.1	5.0	.8	.1	22
	26/11/10		6.8	3	.03	.1	9.0	.7	.1	26
	26/01/11		6.8	0	.00	.0	2.2	.7	.0	29
	11/02/11		6.7	5	.00	.0	4.0	1.0	.0	26
	25/02/11		6.7	10	.03	.0	5.0	1.0	.5	25
	16/03/11		6.8	15	.03	.1	4.5	1.0	.5	24
	29/03/11		6.7	10	.01	.0	3.7	3.7	.5	24
	13/04/11		7.2	10	.13	.0	4.0	4.0	.5	20
	21/04/11		6.9	10	.00	.0	3.5	3.5	.0	21
	Total	Mean	6.8	7	.02	.0	4.5	1.8	.2	24
		Minimum	6.7	0	.00	.0	2.2	.7	.0	20
		Maximum	7.2	15	.13	.1	9.0	4.0	.5	29
		Std. Deviation	.15	5.06	.04	.06	1.9	1.4	.2	2.7

Sampling Site	Sampling Date		pH (Units)	Nitrates (mg/l)	Nitrites (mg/l)	Phosphates (mg/l)	Total Dissolved Oxygen (mg/l)	Oxygen Consumption (mg/l	Ammonium (mg/l)	Temperature (^{o}C)
B1	12/11/10		6.5	2	.01	.0	1.0	.0	.1	26
	26/11/10		6.8	5	.13	.0	1.1	.0	.3	26
	26/01/11		6.5	10	.01	.3	1.0	.9	.0	29
	11/02/11		6.5	15	.00	.0	1.0	.0	.0	26
	25/02/11		6.5	10	.00	.1	1.2	1.2	.1	24
	16/03/11		6.5	10	.00	.0	4.6	.0	.0	23
	29/03/11		6.9	10	.01	.0	4.5	4.5	.0	21
	13/04/11		6.8	5	.01	.0	4.3	4.3	3.0	18
	21/04/11		6.8	5	.00	.0	4.5	4.5	.3	18
	Total	Mean	6.6	8	.02	.0	2.6	1.7	.423	23.5
		Minimum	6.5	2	.00	.0	1.0	.0	.0	18
		Maximum	6.9	15	.13	.3	4.6	4.5	3.0	29
		Std. Deviation	.2	4	.04	.1	1.8	2.1	1.0	3.8
B2	12/11/10		6.5	3	.03	.0	7.1	.5	.0	22
	26/11/10		6.8	5	.01	.0	7.5	.6	.0	22
	26/01/11		6.7	10	.03	.3	1.8	.7	1.0	29
	11/02/11		6.8	15	.50	.0	6.4	.0	5.0	28
	25/02/11		6.8	10	.50	.3	6.2	.0	1.0	26
	16/03/11		6.8	10	.03	.3	4.5	.5	1.0	25
	29/03/11		6.8	9	.03	.0	1.0	1.0	.4	23
	13/04/11		6.8	9	.00	.0	3.5	3.5	.8	18
	21/04/11		7.5	9	.00	.0	1.0	1.0	.4	18
	Total	Mean	6.9	8.9	.12	.08	4.3	.9	1.0	23.4
		Minimum	6.5	3	.00	.0	1.0	.0	.0	18
		Maximum	7.5	15	.50	.3	7.5	3.5	5.0	29
		Std. Deviation	.3	3.4	.21	.12	2.6	1.05	1.5	3.9

Sampling Site		Sampling Date	pH (Units)	Nitrates (mg/l)	Nitrites (mg/l)	Phosphates (mg/l)	Total Dissolved Oxygen (mg/l)	Oxygen Consumption (mg/l	Ammonium (mg/l)	Temperature (^{o}C)
C1		12/11/10	6.9	8	.01	.1	6.0	5.7	.0	20
		26/11/10	6.9	10	.01	.1	6.0	5.8	.1	21
		26/01/11	7.3	15	.03	.3	9.0	2.2	.0	25
		11/02/11	8.3	15	.01	.0	6.4	.1	.0	26
		25/02/11	8.0	10	.01	.0	6.0	5.6	.0	24
		16/03/11	6.9	10	.01	.0	5.8	5.7	.0	22
		29/03/11	7.1	10	.01	.0	5.6	1.2	.0	20
		13/04/11	7.3	10	.01	.0	7.2	.1	.0	20
		21/04/11	7.1	8	.01	.0	7.0	6.2	.0	19
	Total	Mean	7.3	10	.01	.1	6.5	3.6	.011	21.97
		Minimum	6.9	8	.01	.0	5.6	.1	.0	19
		Maximum	8.3	15	.03	.3	9.0	6.2	.1	26
		Std. Deviation	.5	2.5	.004	.08	1.1	2.7	.03	2.5
C2		12/11/10	6.9	10	.01	.1	7.0	6.8	.1	21
		26/11/10	7.2	12	.01	.1	7.0	6.9	.2	22
		26/01/11	7.4	10	.01	.1	7.0	1.6	.0	24
		11/02/11	7.3	15	.01	.0	6.3	4.4	.1	25
		25/02/11	7.9	10	.01	.0	6.0	5.0	.0	24
		16/03/11	6.9	15	.01	.0	6.0	5.6	.0	22
		29/03/11	6.9	25	.03	.0	7.4	1.2	.0	20
		13/04/11	7.3	12	.01	.0	7.0	1.9	.0	19
		21/04/11	7.1	6	.01	.0	7.0	6.9	.0	19
	Total	Mean	7.2	12.8	.01	.0	6.7	4.4	.039	21.8
		Minimum	6.9	6	.01	.0	6.0	1.2	.0	19
		Maximum	7.9	25	.03	.1	7.4	6.9	.2	25
		Std. Deviation	.3	5.4	.004	.06	.51	2.4	.1	2.2

Sampling Site	Sampling Date	pH (Units)	Nitrates (mg/l)	Nitrites (mg/l)	Phosphates (mg/l)	Total Dissolved Oxygen (mg/l)	Oxygen Consumption (mg/l	Ammonium (mg/l)	Temperature (^{o}C)
D1	12/11/10	6.7	2	.03	.3	6.6	3.8	.1	22
	26/11/10	6.8	5	.01	.1	6.5	3.8	.0	24
	26/01/11	7.8	9	.03	.3	6.5	1.5	.0	25
	11/02/11	7.2	4	.00	.0	6.5	.3	.0	26
	25/02/11	6.8	4	.00	.0	6.5	.4	.0	26
	16/03/11	6.9	5	.00	.0	7.0	1.5	.0	22
	29/03/11	6.9	10	.00	.0	7.3	3.0	.0	21
	13/04/11	6.8	5	.00	.0	6.6	.1	.0	19
	21/04/11	6.8	5	.00	.0	6.0	.1	.0	18
Total	Mean	7.0	5.	.01	.1	6.6	1.6	.01	22.6
	Minimum	6.7	2	.00	.0	6.0	.1	.0	18
	Maximum	7.8	10	.03	.3	7.3	3.8	.1	26
	Std. Deviation	.3	2.5	.01	.1	.4	1.6	.3	3.0
D2	12/11/10	6.8	3	.03	.3	7.8	5.1	.0	23
	26/11/10	6.8	5	.01	.1	7.5	6.8	.0	24
	26/01/11	6.8	9	.01	.0	6.4	1.0	.0	26
	11/02/11	7.1	5	.00	.0	6.3	.1	.2	26
	25/02/11	6.9	5	.00	.0	6.5	.9	.0	26
	16/03/11	6.9	5	.00	.0	6.9	1.5	.0	24
	29/03/11	7.1	20	.03	.0	5.4	.5	.0	22
	13/04/11	6.8	5	.00	.0	6.7	.3	.0	18
	21/04/11	6.8	4	.00	.0	6.0	.1	.0	18
Total	Mean	6.9	6.78	.01	.043	6.6	1.8	.0	22.9
	Minimum	6.8	3	.00	.0	5.4	.1	.0	18
	Maximum	7.1	20	.03	.3	7.8	6.8	.2	26
	Std. Deviation	.1	5.2	.01	.09	.7	2.4	.07	3.1

Tree Breast Height Diameter Data

Plot D1

Transect number	Tree number	Distance from road edge (m)	BHD (mm)	Transect number	Tree number	Distance from road edge (m)	BHD (mm)
1	1	2	200	4	2	6.4	210
1	2	4	160	4	3	8.4	140
1	3	6	110	4	4	12.4	170
1	4	8	200	4	5	14.4	170
1	5	10	170	4	6	16.4	180
1	6	12	200	4	7	18.4	180
1	7	14	140	4	8	20.4	170
1	8	16	110	5	1	2.4	260
1	9	18	170	5	2	4.4	70
2	1	2	270	5	3	6.4	110
2	2	4	160	5	4	8.4	150
2	3	6	80	5	5	10.4	120
2	4	8	160	5	6	12.4	150
2	5	10	180	5	7	14.4	150
2	6	12	190	5	8	16.4	130
2	7	14	150	5	9	21.4	170
2	8	16	110	6	1	2.4	190
2	9	18	170	6	2	4.4	170
2	10	20	150	6	3	6.4	110
3	1	6.7	220	6	4	8.4	220
3	2	8.7	230	6	5	10.4	110
3	3	10.7	130	6	6	12.4	140
3	4	12.7	160	6	7	14.4	180
3	5	14.7	90	6	8	16.4	160
3	6	16.7	160	6	9	20.4	130
3	7	18.7	150	6	10	22.4	190
3	8	22.7	150	6	11	24.4	90
4	1	4.4	220				

Plot D2

Transect number	Tree number	Distance from road edge (m)	BHD (mm)	Transect number	Tree number	Distance from road edge (m)	BHD (mm)
1	1	3.4	90	4	1	7.4	220
1	2	7.4	190	4	2	9.4	100
1	3	9.4	80	4	3	11.4	220
1	4	11.4	190	4	4	13.4	140
1	5	13.4	110	4	5	15.4	100
1	6	15.4	110	4	6	17.4	110
1	7	17.4	130	4	7	21.4	190
1	8	21.4	170	4	8	23.4	120
2	1	2	180	5	1	1	170
2	2	6	240	5	2	3	280
2	3	8	80	5	3	5	180
2	4	10	160	5	4	7	140
2	5	12	140	5	5	9	110
2	6	14	140	5	6	11	180
2	7	16	170	5	7	13	190
2	8	18	70	5	8	15	190
2	9	20	110	5	9	17	130
2	10	22	80	5	10	19	160
3	1	5.4	150	6	1	3	260
3	2	7.4	140	6	2	5	120
3	3	9.4	160	6	3	7	130
3	4	11.4	170	6	4	9	170
3	5	15.4	150	6	5	11	150
3	6	17.4	130	6	6	13	120
3	7	18	180	6	7	15	170
3	8	10	100	6	8	17	80
3	9	17	170				

Plot D3

Transect number	Tree number	Distance from road edge (m)	BHD (mm)	Transect number	Tree number	Distance from road edge (m)	BHD (mm)
1	1	2	230	4	2	5	230
1	2	4	200	4	3	7	240
1	3	8	140	4	4	9	100
1	4	10	170	4	5	11	230
1	5	12	200	4	6	13	160
1	6	14	150	4	7	15	270
1	7	16	140	4	8	17	140
1	8	18	130	4	9	19	150
1	9	20	130	4	10	21	180
2	1	2	230	5	1	2.3	240
2	2	4	60	5	2	4.3	130
2	3	8	220	5	3	6.3	190
2	4	14	120	5	4	8.3	200
2	5	16	240	5	5	16.3	210
2	6	18	200	5	6	18.3	150
3	1	4	240	5	7	20.3	180
3	2	8	120	6	1	2.5	250
3	3	12	230	6	2	4.4	250
3	4	14	190	6	3	10.5	230
3	5	16	130	6	4	12.5	210
3	6	18	220	6	5	16.5	180
3	7	20	180	6	6	18.5	180
4	1	3	180	6	7	20.5	150

Plot D4

Transect number	Tree number	Distance from road edge (m)	BHD (mm)	Transect number	Tree number	Distance from road edge (m)	BHD (mm)
1	1	2	140	4	1	4	110
1	2	6	160	4	2	6	150
1	3	8	70	4	3	8	190
1	4	10	120	4	4	10	180
1	5	12	160	4	5	12	140
1	6	14	140	4	6	14	110
1	7	16	130	4	7	16	140
1	8	18	130	4	8	18	110
2	1	2	140	5	1	3.5	170
2	2	4	130	5	2	5.5	160
2	3	6	160	5	3	7.5	140
2	4	8	100	5	4	9.5	160
2	5	10	150	5	5	11.5	160
2	6	12	120	5	6	13.5	100
2	7	14	120	5	7	15.5	120
2	8	16	100	5	8	17.5	120
3	1	4	170	6	1	2	160
3	2	6	70	6	2	4	100
3	3	8	160	6	3	6	90
3	4	12	150	6	4	8	140
3	5	14	130	6	5	10	150
3	6	16	140	6	6	12	140
3	7	18	140	6	7	14	130
3	8	20	140				

Plot D5

Transect number	Tree number	Distance from road edge (m)	BHD (mm)	Transect number	Tree number	Distance from road edge (m)	BHD (mm)
1	1	4.3	160	4	1	3	150
1	2	6.3	120	4	2	5	90
1	3	8.3	110	4	3	7	170
1	4	10.3	140	4	4	11	160
1	5	12.3	130	4	5	13	160
1	6	14.3	110	4	6	15	120
1	7	16.3	130	5	1	4	160
1	8	18.3	110	5	2	6	150
1	9	20.3	140	5	3	8	100
2	1	4	170	5	4	10	150
2	2	6	140	5	5	12	90
2	3	6	100	5	6	16	130
2	4	12	160	5	7	18	140
2	5	14	130	6	1	2	180
2	6	16	140	6	2	4	100
3	1	3.5	180	6	3	6	170
3	2	5.5	120	6	4	8	180
3	3	7.5	90	6	5	10	130
3	4	9.5	140	6	6	12	80
3	5	11.5	130	6	7	14	190
3	6	13.5	140	6	8	16	140
3	7	15.5	140	6	9	18	100
3	8	17.5	130				

Plot D6

Transect number	Tree number	Distance from road edge (m)	BHD (mm)	Transect number	Tree number	Distance from road edge (m)	BHD (mm)
1	1	6	140	4	3	6	140
1	2	8	130	4	4	8	160
1	3	10	100	4	5	10	140
1	4	12	140	4	6	12	140
1	5	14	130	4	7	14	160
1	6	16	120	4	8	16	160
1	7	18	130	5	1	3	140
2	1	2	120	5	2	5	120
2	2	4	160	5	3	7	110
2	3	6	140	5	4	9	110
2	4	8	140	5	5	11	120
2	5	10	110	5	6	13	130
2	6	12	130	5	7	15	140
2	7	14	120	5	8	17	120
3	1	8	150	6	1	4	150
3	2	10	160	6	2	6	120
3	3	12	150	6	3	8	120
3	4	15	120	6	4	10	130
3	5	18	100	6	5	12	130
3	6	21	110	6	6	14	140
4	1	2	160	6	7	16	130
4	2	4	140				

Plot Ctr1

Transect number	Tree number	Distance from road edge (m)	BHD (mm)	Transect number	Tree number	Distance from road edge (m)	BHD (mm)
1	1	1.3	190	4	2	4	130
1	2	3.3	100	4	3	6	130
1	3	5.3	150	4	4	8	160
1	4	9.3	170	4	5	10	110
1	5	13.3	150	4	6	12	170
1	6	15.3	160	4	7	14	110
1	7	17.3	80	4	8	16	150
1	8	19.3	130	4	9	18	150
2	1	2	100	4	10	20	110
2	2	4	180	5	1	1.3	210
2	3	6	150	5	2	3.3	170
2	4	8	180	5	3	5.3	170
2	5	10	120	5	4	7.3	160
2	6	12	120	5	5	9.3	150
2	7	16	140	5	6	11.3	150
2	8	18	110	5	7	13.3	90
3	1	1.4	150	5	8	17.3	100
3	2	3.4	150	5	9	19.3	200
3	3	5.4	140	6	1	2	140
3	4	7.4	140	6	2	4	180
3	5	9.4	150	6	3	6	110
3	6	11.4	150	6	4	8	120
3	7	13.4	130	6	5	10	140
3	8	15.4	140	6	6	12	160
3	9	17.4	140	6	7	14	160
3	10	19.4	150	6	8	18	160
3	11	21.4	120	6	9	20	110
4	1	2	220				

Plot Ctr2

Transect number	Tree number	Distance from road edge (m)	BHD (mm)	Transect number	Tree number	Distance from road edge (m)	BHD (mm)
1	1	1.2	210	3	7	12.5	150
1	2	3.2	150	3	8	14.5	230
1	3	5.2	90	3	9	18.5	210
1	4	7.2	80	3	10	19	190
1	5	13.2	80	4	1	0.3	240
1	6	15.2	200	4	2	2.3	220
1	7	13	130	4	3	4.3	120
1	8	5	50	4	4	6.3	180
1	9	8	80	4	5	8.3	110
2	1	2	190	4	6	10.3	180
2	2	4	80	4	7	12.3	170
2	3	6	140	4	8	14.3	170
2	4	8	170	4	9	16.3	130
2	5	10	190	4	10	18.3	150
2	6	12	150	5	1	4	230
2	7	14	170	5	2	6	190
2	8	16	160	5	3	10	190
2	9	18	180	5	4	12	170
2	10	20	170	5	5	14	140
3	1	0.5	190	5	6	16	130
3	2	2.5	50	5	7	18	150
3	3	4.5	190	5	8	20	50
3	4	6.5	70	6	1	4	160
3	5	8.5	150	6	2	14	60
3	6	10.5	100	6	3	20	150

Plot Ctr3

Transect number	Tree number	Distance from road edge (m)	BHD (mm)	Transect number	Tree number	Distance from road edge (m)	BHD (mm)
1	1	3.4	300	3	8	19	200
1	2	5.4	220	4	1	2	190
1	3	9.4	210	4	2	6	200
1	4	11.4	170	4	3	10	90
1	5	13.4	80	4	4	20	90
1	6	15.4	130	5	1	3	310
1	7	17.4	220	5	2	9	220
1	8	19.4	170	5	3	11	180
2	1	3	220	5	4	13	170
2	2	5	260	5	5	15	180
2	3	9	190	5	6	17	120
2	4	11	190	5	7	19	180
2	5	13	130	6	1	2.3	230
2	6	15	150	6	2	6.3	200
3	1	3	220	6	3	8.3	170
3	2	5	170	6	4	10.3	200
3	3	7	220	6	5	12.3	150
3	4	9	260	6	6	12.3	100
3	5	11	200	6	7	14.3	160
3	6	13	140	6	8	16.3	170
3	7	17	130	6	9	18.3	200

Plot Ctr4

Transect number	Tree number	Distance from road edge (m)	BHD (mm)
1	1	1.4	130
1	2	4.4	140
1	3	8.4	160
1	4	11.4	150
1	5	15.4	160
1	6	18.4	150
2	1	3	190
2	2	6	190
2	3	9	190
2	4	12	140
2	5	15	140
2	6	18	160
3	1	3	230
3	2	6	160
3	3	9	130
3	4	15	190
4	1	3.5	180
4	2	9.5	140
4	3	12.5	120
4	4	15.5	120
4	5	19.5	160
5	1	3.5	160
5	2	6.5	150
5	3	12.5	160
5	4	15.5	140
5	5	18.5	140
6	1	3	140
6	2	9	120
6	3	13	140
6	4	16	110
6	5	20	170

Plot Ctr5

Transect number	Tree number	Distance from road edge (m)	BHD (mm)
1	1	2.5	160
1	2	5.5	130
1	3	11.5	130
1	4	14.5	150
1	5	18.5	120
1	6	22.5	180
2	1	2.5	210
2	2	5.5	70
2	3	8.5	180
2	4	14.5	140
2	5	20.5	150
3	1	3	170
3	2	6	150
3	3	9	170
3	4	12	150
3	5	15	160
4	1	3	140
4	2	7	140
4	3	10	80
4	4	13	130
4	5	16	160
5	1	5	110
5	2	8	120
5	3	11	120
5	4	14	90
5	5	18	130
5	6	21	110
6	1	3	170
6	2	6	130
6	3	9	160
6	4	12	100
6	5	15	130
6	6	18	120

Plot Ctr6

Transect number	Tree number	Distance from road edge (m)	BHD (mm)
1	1	3	200
1	2	9	180
1	3	15	180
1	4	18	120
1	5	20	140
1	6	22	130
2	1	3	170
2	2	6	180
2	3	9	160
2	4	12	140
2	5	15	160
2	6	18	160
2	7	21	170
3	1	5	160
3	2	8	170
3	3	11	170
3	4	17	130
3	5	20	140
3	6	23	110
4	1	4	180
4	2	10	150
4	3	13	150
4	4	19	170
4	5	22	110
5	1	4	170
5	2	7	170
5	3	10	140
5	4	13	150
5	5	16	170
5	6	19	120
6	1	5	180
6	2	8	160
6	3	11	170
6	4	15	120
6	5	19	160
6	6	21	100