PRE- AND POST-FOREST MANAGEMENT INVESTIGATIONS OF FACTORS AFFECTING SEDIMENT MOVEMENT IN RIPARIAN AREAS IN NORTHWESTERN ONTARIO

by

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ABSTRACT

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The principal objectives of this study were to measure the impacts of timber harvesting on sediment transport rates (mineral and organic) associated with two clearcut areas in northwestern Ontario and to evaluate the sediment controlling effectiveness of 30 m wide riparian reserves that were prescribed in accordance with Ontario's Timber Management Guidelines For The Protection Of Fish Habitat Guidelines (OMNR, 1988). A goal of this study was to provide a practical means for assessing potential changes to sediment transport rates resulting from impacts of forest management activities in Ontario. Prior to road building and full tree logging with feller bunchers and grapple skidders, a sediment sampler was installed in each of 16 sub-catchments. Samplers were situated at a distance of either 0, 10, 20, or 30 m, measured into the reserve areas from the boundaries of planned clearcuts. Mineral and organic sediment collected in the samplers were monitored for one year (late spring to late fall) before, and two years (late spring to late fall) after impacts, and data were standardized with the amount of precipitation that fell during the respective sampling year. Indices of change were calculated to quantify differences in mineral and organic collection rates for each sampler in the first or second post-impact year compared to those in the pre-impact year. Field and GIS data (including: sampler position in the reserve, sub-catchment area, distance from road, presence of surface runoff, occurrence of trees thrown by wind, crown closure, thickness of soil organic layers (LFH), terrain slope, and a topographic index (TI) derived from GIS data describing upstream contributing area and slope) were collected in an attempt to quantify the capacity of the reserve areas to impede (or encourage) sediment collection in each sampler. The results clearly demonstrate that sediment movement in riparian reserve areas does not increase universally following forest management. Sediment attenuation through the reserve areas was variable, indicating that factors in addition to the width of a filter strip can function to control the distance to which eroded sediment is transported. Catchment area was not related to the rates that sediment was collected in samplers. Sediment collection rates were higher in samplers located closer to the road; however, the results can not be used to support categorically the accepted model whereby areas closer to roads are subject to higher erosion rates than areas further away from roads. The occurrence of surface runoff and windthrow, especially when combined, were predominant factors that contributed to increased sediment collection rates in samplers. The amount of crown closure and the thickness of LFH layers influenced rates of erosion, but the magnitudes of their influences were marginal compared to those of flow and windthrow. Steeper slopes did not consistently generate higher sediment transport rates, but the evaluation of the

effects of slope on sediment transport rates was limited by the narrow range of slope conditions that were evaluated by this study.

The results of this study indicate that slope dependent riparian reserves specified by Ontario's current timber management guidelines are sufficient to protect fish habitat from sediment transported from clearcut areas (in locations where shorelands are similar to those investigated by this study). However, the results clearly demonstrate that sediment movement in riparian reserve areas does not increase universally following forest management. Post-impact sediment transport rates were greater in areas where surface runoff flowed compared to areas where surface runoff did not flow. This study used digital elevation models (DEMs) and a GIS to map pre-impact and post-impact flow accumulations, and these data illustrated how roads can effectively re-route the natural flow paths of surface runoff. Within the study area, topographic convergences were reliably located by the application of a spatially explicit TI, and the same index was effective at identifying areas that may be subject to increased risk of erosion following forest management. The generation and evaluation of flow accumulation and TI raster data may provide useful information for evaluating potential impacts of activities that are proposed during forest management planning efforts.

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1.0 INTRODUCTION

Land use can cause rates of erosion to become accelerated above what would occur naturally (Waters 1995; Walling 1999), and sediment is believed to be the principal non-point pollutant from forestry (Swift 1988). Forest management activities, for example, can contribute to cause an increase in the volume of sediment that is deposited within river systems (Meehan 1991). Miller (1984) reported that the average rate of erosion from three small watersheds during the first year after clearcutting, site preparation, and burning was 282 kg/ha, while the average rate from three control watersheds was 36 kg/ha.

Forest management involves a variety of activities including: clearcutting, skidding, yarding, site preparation for replanting, and road construction and maintenance. Sediment generation from each of these forestry practices has been extensively researched (Waters 1995). On a relative scale, sediment generation appears to be moderate from clearcutting, although this practice appears to generate more sediment than both selective and patch cutting (Waters 1995). Comparatively, sediment generation is moderately high from skid trails, minimal from yarding, and moderate from site preparation (Waters 1995). Logging roads are by far the source of most sediment generated from forestry related activities, especially when they are built close to streams (Megahan and Kidd 1972). Conditions that accelerate erosion due to land use disturbance are intensified on steeper slopes (Waters 1995; Meehan 1991).

Most research projects investigating forestry land use relationships with fish resources have been conducted on streams in the mountainous regions of the northwestern United States, western Canada, and the southern Appalachians (Waters 1995), and most of the studies that investigated the biological effects of erosion have focused on salmonid streams. In contrast with the forest industry, research conducted by the agriculture industry is driven primarily by concern for crop productivity losses rather than pollution by sediment transported to streams (Waters 1995). In Canada, during the period 1985 – 1998, forest harvesting impact studies on stream sedimentation and morphology, and on the sustainability of fish habitat, were more prevalent than work associated with agricultural impacts (Ashmore *et al.* 2000).

The effects of sediment entering aquatic systems can combine to exert stress on fish, and these can cause populations to be reduced or changed (Ritchie 1972). Among effects of sediment were: 1) reduced light penetration through the water column which can inhibit photosynthesis and cause a decline in primary production, ultimately limiting the system's productive capacity; 2) reduced dissolved oxygen concentration due to the decomposition of organic matter that is transported with the sediment; 3) reduced survival of fish eggs and alevin; 4) reduced shellfish abundance and species richness; 5) reduced insect fauna that live on the bottom of streams and bottom-growing plants; 6) reduced ability of fish to forage caused by increased turbidity (however, this may also help young fish avoid predation); 7) reduced depth and duration of stream flow; 8) reduced abundance of suitable habitat for fish; 9) reduced amount of shelter in trout streams; 10) change in water temperature; and 11) change in water quality (Ritchie 1972). These general results are supported by more recent reviews investigating the relationships among forest practices, sediment, and salmonid reproduction (Meehan 1991; Waters 1995).

In Canada, the Federal Fisheries Act makes it illegal for any person to perform work that results in the harmful alteration, disruption or destruction of fish habitat, and states that no person shall deposit or permit the deposit of a deleterious substance of any type in water frequented by fish or allow such a substance to enter any such water (Fisheries Act 1985). Erosion rate increases resulting from forestry land uses will not harm aquatic habitat unless eroded material reaches the aquatic system (Ketcheson and Megahan 1996). Soil erosion is usually localised; however, depending at what scale soil losses are reported, they may be less than natural rates of renewal and still cause damage to local resources (Carling *et al.* 2001). If sustainable land management strategies are a goal, an emphasis should be placed on both the significance of impacts and the development of practical solutions to problems rather than reporting overall magnitude (Carling *et al.* 2001). To minimize land use impacts and afford protection to aquatic systems, many management agencies have implemented legislation and/or guidelines that prescribe best management practices for operations that will occur within their jurisdictions (Blinn and Kilgore 2001; Young 2000).

The Ontario Ministry of Natural Resources (OMNR) has developed the Timber Management Guidelines for the Protection of Fish Habitat (hereafter Fish Habitat Guidelines) to protect fish habitat from forest management impacts (OMNR 1988). The guidelines direct forest managers to designate 'Areas of Concern' (AOCs) around lakes and streams, and to reduce the risk of impacting fish habitat, forest management operations are limited or even restricted in these areas. One of the primary concerns is that sediment generated by forest management activities will move into aquatic systems and it is generally assumed that the intact shoreline forest will function as a sediment sink (Dillaha and Inamdar 1997).

Ontario's Fish Habitat Guidelines prescribe AOCs, commonly referred to as 'buffers', that increase in width from 30 to 90 m as shoreline slope increases from 0 to 60 percent (OMNR 1988, (Appendix I)). The widths are based on recommendations from a study that examined the association between sediment movement from forest roads and slope of the forest floor in New Hampshire's Hubbard Brook Experimental Forest (Trimble and Sartz 1957). To date, there has been little research to evaluate the transferability of these recommendations to other forest types, specifically the Boreal forest. In addition, there are many factors other than slope, such as soil type and local hydrologic characteristics, which may influence sediment movement.

Significant economic pressures fuel the debate between forest companies that want access to wood volume and government agencies that establish guidelines to protect forest resources. An analysis of the effect of buffer width on loggable land and commercial value of timber in southern Australia revealed that prescribing 90 metre buffers around streams can remove 50 percent of the land area from harvesting, and that more valuable forest units tend to be spatially distributed closer to streams (Bren 1997). In fact, that study demonstrated that 50 percent of the commercial value of timber volume was located within 85 metres of streams (Bren 1997). Forest companies further their argument by pointing out that natural disturbance patterns do not preserve residual mature forest along lakes and rivers, and suggest that prescribing buffer zones around these features interrupts natural successional pathways and compromises the health and integrity of shoreline forests (Buttle 2002). Additionally, riparian vegetation and landforms along the valley floor function to create a diverse set of habitats within both floodplains and active channels, and these in turn determine the abundance and quality of nutritional resources available in stream ecosystems (Gregory *et al.* 1991; Vanotte *et al.* 1980; Frissell *et al.* 1986).

Initially, when surface runoff begins to move across the land surface, it is widespread and in a thin sheet. This type of runoff is known as sheetwash or sheet flow (Briggs and Smithson 1985). Obstacles such as stones and depressions can concentrate sheet flow and cause turbulence and localized erosion. This process causes micro-channels (or rills) to develop, and as the volume of water and turbulence increase, the erosive capacity of the water increases, causing the rills to get larger (Smithson and Briggs 1985). When the sediment transport capacity of flowing water is insufficient to move particles, deposition can occur (Chang 2003). The impact of raindrops hitting exposed soil can break up soil aggregates, and the splash that results after the impact of raindrops can detach and displace soil particles (Chang 2003). The concept of soil detachment by raindrop impact and the dissipation of kinetic energy potential in raindrops is a critical component of erosion and conservation (Singer and Blackard 1978). Erosion by water involves detachment, transport, and deposition of soil particles (Chang 2003). When quantifying the total amount of material eroded from an area, it is the influence of the effects caused by these three types of erosion in combination of that is of greatest significance (Toy 1977).

The path water takes to reach a stream is controlled by climate, geology, topography, soils, vegetation and land use (Freeze and Cherry 1979). For example, the infiltration capacity of a soil influences the amount of water available for surface runoff (Briggs and Smithson 1985), and the infiltration capacity of a soil is highly correlated with the structural stability of that soil (Brady 1984). Of all soil characteristics, infiltration capacity and structural stability have the greatest influence upon erosion (Brady 1984). Where infiltration capacity is high, little overland flow occurs, and where infiltration capacity is low, more water will run off as overland flow in rills, gullies, and streams (Briggs and Smithson 1985). In addition, soil texture, organic content, the amount and properties of the clay content, the soil depth, and the presence of impervious layers also affect infiltration capacity (Brady 1984). Ground cover, which includes live vegetation and forest litter, can have a high absorptive capacity (Naslas *et al.* 1994), and the amount of ground cover has been shown to be the single most important factor influencing erosion rates (Clayton and Megahan 1997). The climate, topography, soils, and vegetation in Northwestern Ontario (NWO) are distinct compared those in areas where most forestry related erosion studies have occurred, and little research has been conducted to investigate the impact of forestry practices on erosion rates, fish habitat, or fisheries resources in NWO.

Significant effort has gone into the development of sediment transport models, especially within agricultural settings where soils tend to be deep and homogeneous, and many of these models have grown in complexity along with the power of computing technology. However, models such as the Modified Soil Loss Equation (MSLE), do not work well where surface conditions are not homogenous, and this limits or restricts their application in some areas (Elliot *et al.* 1999). Many management agencies are not able to apply sediment transport models at an operational level because of the level of complexity built into them. For example, the Water Erosion Prediction Program (WEPP) requires more than 400 input variables, and although application templates have been developed to apply the model in general land use scenarios (agriculture, range, forest), users face significant challenges while trying to determine and adjust critical values for specific sites (Elliot *et al.* 1999). Challenges can also be encountered by users who attempt to apply less complex models. For example, the type and depth of surficial geology can affect the infiltration rate of precipitation that falls on the land surface. Infiltration rates in turn affect surface run-off and sediment transport. In Ontario, the retreat of the Wisconsinin glaciers left a complex distribution of surficial geology deposits across the Province (Zoltai 1965). Currently, the best surficial geology maps available for

Ontario are at scales of 1:1,000,000 (digital) and 1:100,000 (hardcopy). These maps were created primarily from stereoscopic interpretation of airphotos at scales that ranged from 1:38 000 to 1:70 000 (Gartner *et al.* 1981). Given the complex distribution of surficial geology deposits across Ontario, it would be difficult to prescribe effective and efficient buffer strip widths based on the results of a sediment transport model generated from data at either of these scales. Hurdles that need to be overcome before many erosional models can be applied include both the labour and costs to collect data at a scale more appropriate to fulfill model input requirements, to convert new and existing hard copy data into compatible digital formats, and to validate models after data input requirements were fulfilled.

Many jurisdictions are recognizing the benefits of applying Geographic Information System (GIS) procedures to manage their natural resources (Wilson and Gallant 2000). As time and money permit, many agencies are developing GIS data sets for their landbase, including hydrologically correct rasterized digital elevation models (DEMs) (Wilson and Gallant 2000). DEMs can be used to generate secondary grid data sets that model the flow direction and flow accumulation for each cell within the extent of the DEM (Wilson and Gallant 2000). These data can be used to automate the delineation of watershed boundaries, that in turn can be used to quantify the catchment characteristics from other data layers (Wilson and Gallant 2000). Rasterized derivatives of a DEM can be used as data inputs for applying various hydrologic models across a landscape (Wilson and Gallant 2000). For example, a topographic index (TI) developed by Beven and Kirkby (1979) provides a measure that describes the relative likelihood of saturation of the overburden at a given location by subsurface flow from further upslope and the occurrence of subsurface flow exfiltration (Buttle 2002). In short, this model predicts the relative potential for groundwater discharge along the land-water interface (Buttle 2002). Beven and Kirkby's TI is derived by equation (1).

$$TI = \ln (a/\tan \beta) \qquad (1)$$

Where:

a = upstream contributing area per unit contour length (m^2)

ß = slope (in degrees)

The upstream contributing area per unit contour length is equal to the resolution of the grid squares (or length of the grid cells) when applying a single flow path algorithm such as the D8 (Beven *et al.* 1991). A different procedure is applied to calculate the upstream contributing area per unit contour length if a distributed, multi-flow direction algorithm is used (Quinn *et al.* 1995). Application of this model assumes that the top of the water table follows the surface topography. This assumption was shown to be invalid in areas of the Canadian Shield with glacial till overburden (Hinton *et al.* 1993); however, the TI may yet have relevant application in areas where soils are not uniform.

In Canada, an extensive network of sediment monitoring stations was established during the 1960s and 1970s, from which an understanding of basin-scale sediment fluxes was derived (Ashmore *et al.* 2000). Two approaches, one analysing sediment load data and the other evaluating the characteristics of sediment particles, have been used to show that in the glaciated landscape of Canada, riparian sources contribute the dominant fraction of sediment carried by rivers and that upland sources contribute little sediment (Ashmore and Day 1988; Church *et al.* 1989; Ashmore 1993). Compared to the results of erosion plot and catchment experiments, sediment yield data of rivers provide evidence that is less clear at identifying land use impacts. The high variability that can exist in sediment yield data from rivers can be affected by the buffering capacity of many river basins, whereby mobilised sediment is stored within the system on lower slopes, in small tributary streams, and in riparian areas, and may never reach the river outlet. Investigations of land use impacts using sediment yields should consider the complete sediment budget of a catchment rather than sediment output at the outlet alone (Walling 1999).

It could be argued that data from sediment monitoring networks, especially those from large rivers, facilitate only the reporting of the magnitude of erosion problems. With such data it would be difficult to isolate local erosion issues and test experimental hypotheses within an adaptive management framework, especially within relatively short periods of time. Stream bank erosion often erodes floodplains, which are composed of sediment previously deposited by natural processes and anthropogenic activities (Waters 1995). Results from erosion plot experiments and experimental catchment studies conducted around the world have provided clear evidence of the sensitivity of erosion rates to land use change (Walling 1999). Data generated from research of terrestrial erosion at the hillslope scale could be much more useful for both identifying local erosional issues and for testing hypotheses during the development of solutions to local problems.

1.1 RESEARCH OBJECTIVES / HYPOTHESES

Physical process models designed to predict down slope sediment movement may offer utilities for designing buffers to control sediment movement; however, many of these types of models are still in the developmental stage (Megahan and Ketcheson 1996). Work that expands on the development of empirical models could satisfy a current need for assessing erosion risks until the development of process based models is complete, or for future applications when data intensive process models may not be practical (Megahan and Ketcheson 1996).

In addition to slope and reserve width, this study examined factors that affect sediment production that are easily measured in the field or with a GIS, using available data. An ultimate goal of this study is to provide a practical means for assessing possible changes to sediment transport rates from forest management in Ontario, a goal not unlike that of Megahan and Ketcheson (1996).

The overall objectives of this study were to measure the impact of forest management activities on sediment transport rates (mineral and organic) associated with two clearcut areas in NWO, and to evaluate the sediment controlling effectiveness of 30 m wide riparian reserves that were prescribed in accordance with Ontario's Fish Habitat Guidelines.

Specific objectives of this study included:

1. Determine the variability in sediment attenuation (mineral and organic) as it is distributed both longitudinally along and laterally through two riparian reserve areas adjacent to clearcut areas. This was accomplished by monitoring the attenuation of sediments eroded out of sub-catchments that drained through two 30 m wide riparian reserves that had sediment traps installed at clearcut / reserve boundaries (0 metres), or 10, 20, or 30 m into the reserves.
2. Evaluate the condition of specific characteristics of riparian areas (in addition to slope) and determine how each affects the capacity of reserve areas to impede (or encourage) sediment movement. The suite of characteristics considered was selected after reviewing the scientific literature to identify critical factors that affect soil erosion that can be quickly and easily measured using either field techniques or a GIS. The collection of variables considered included: 1) catchment area; 2) distance from road; 3) presence/absence of surficial runoff; 4) amount of crown closure; and 5) thickness of the organic horizons covering mineral soil.
3. Evaluate the efficacy of using a topographic index (TI) value, derived using a GIS, from data describing upstream contributing area and slope to identify areas within the study area that have a high relative potential for

the generation of overland flow relative to other locations within the study area.

In addition to these stated objectives, this study made opportunistic use of unanticipated, naturally occurring events (windthrowing of trees within reserve areas adjacent to clearcuts) to quantify the impact of this phenomenon on sediment transport rates through reserve areas.

1.2 LITERATURE REVIEW

The following section is a literature review of factors that affect fluvial erosion rates. Processes of the hydrologic cycle provide the energy required for fluvial erosion. The material that follows explains the influence of several factors that affect erosion. The collection of factors has been limited to include those that are easily measured either through field techniques or using a GIS with data commonly available to natural resource management agencies.

Hydrologic Cycle

The circulation of water through the atmosphere, land, and waterbodies within Earth's ecosystem is described by the hydrologic cycle. The main components of this cycle are precipitation, runoff, and evapotranspiration (Chang 2003). The hydrologic cycle outlined in Figure 1.1 traces the movement of water through a forested ecosystem and illustrates how water links the atmosphere, soil, plant community, and streams within

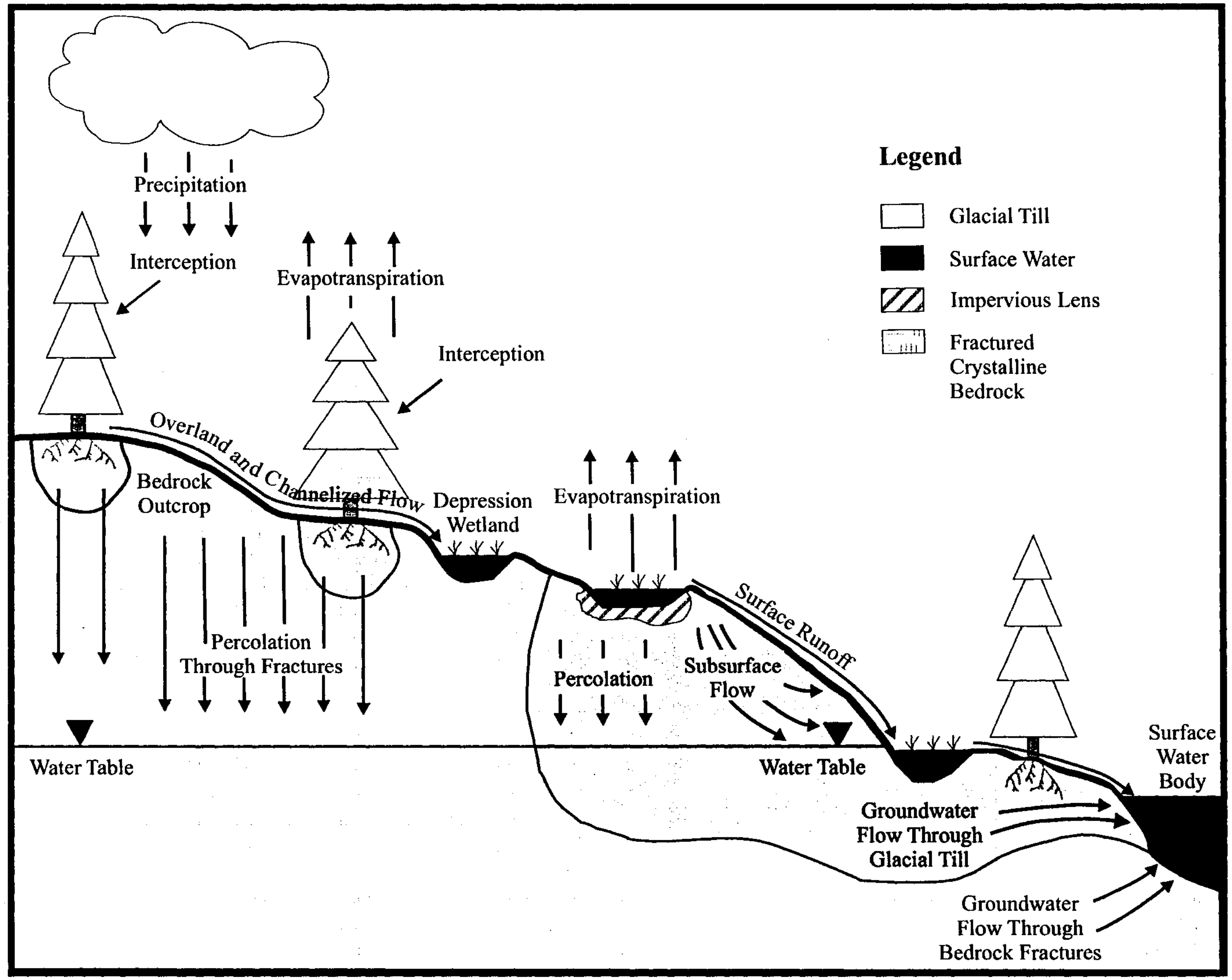


Figure 1.1 Hydrologic cycle and hydrologic pathways on the Precambrian Shield (modified from Grey 1970 and Steedman et al. 2004).

this system. While moving through the hydrologic cycle, water has the capacity to carry materials and energy between the atmospheric and terrestrial components of the forested ecosystem and streams. The transport capacity of water can cause the erosion of soil particles and the leaching of soil nutrients, fertilizers, and pesticides to forest streams (Brown 1983).

Forests affect both water quality and quantity. Forest vegetation can intercept precipitation thereby reducing the amount of moisture that reaches the forest floor. Transpiration processes of forest plants move large volumes of water from the soil to the atmosphere. Root systems, soil organic matter, and forest litter increase soil infiltration rates and moisture holding capacities. These processes may reduce the volume of water available for surface runoff, extend the duration of runoff, and/or lower water yield from forested watersheds compared to those that are non-forested; hence, the hydrologic effects of forest vegetation function to limit the transport capacity of runoff (Chang 2003). Along with these hydrologic controls, forested catchments have: a) canopies that shield and shade, b) roots that bind soil, and c) floors covered by forest litter material that has filtering-like functionality. These features can allow streams draining forested catchments to have a lower concentration of sediment, lower dissolved elements, cooler temperatures, and higher dissolved oxygen concentrations (Chang 2003).

Field and GIS data attributes were selected from among a suite of variables identified during a review of the scientific literature covering research and modelling of sediment transport generated by overland flow (Trimble and Sartz 1957; Toy 1977; Hadley 1977;

Belt *et al.* 1992; Elliot *et al.* 1999; Costantini *et al.* 1999; Wischmeier 1977; Bryan 1977; Brady 1984; Clayton and Megahan 1997; Phillips 1989; Beven and Kirkby 1979; Moore *et al.* 1988). Ultimately, these variables were selected for their influence on erosion rates and the relative ease at which they can be surveyed in the field or derived from GIS data that were readily available and distributed in Ontario. Variables rejected were: 1) time consuming and/or difficult to collect in the field, 2) difficult to quantify because they required expensive or specialized field equipment, 3) not mapped, or 4) mapped, but at a scale that was inappropriate for application in this study.

Catchment Area

The total amount of sediment flowing out of a drainage basin (total eroded less deposition) is referred to as sediment yield. It is measured at a particular point for a specified period of time and is often expressed as a ratio of mass per unit area per unit time. Generally, sediment yield decreases as drainage basin area increases (Toy 1977; Hadley 1977) because downstream reaches tend to have gentler hillslope gradients and higher sediment storage capacity compared to upstream reaches (Walling and Webb 1983). However, for drainages greater than 1 000 sq km, the same trend may not exist because of the arrangement of source and sink areas (Ashmore and Day 1988).

Distance From Road

Roads are areas of high risk for increased sediment transport compared to other areas (Belt *et al.* 1992; Elliot *et al.* 1999; Costantini *et al.*1999, Trimble and Sartz 1957). At a local scale, roads can affect the hydrologic response of soils by changing soil properties, which in turn can alter catchment scale sediment budgets (Luce and Black 2001). Reid and Dunne (1984) reported the results of a survey that quantified sediment production from roads that were surfaced with gravel or paving. In that study, sediment yields from gravel roads with heavy traffic produced 100 times more sediment compared to paved roads. Heavily used roads produced 130 times more sediment compared to an abandoned road. In a study conducted in northern Ontario, it was shown that road related erosion and deposition most often occurs within the road right-of-way, and that sediment movement extending beyond the right-of-way was the result of high runoff (Mattice 1977). Several researchers have suggested that roads should be located away from rivers and streams to allow sediment carrying runoff to be dissipated before it reaches channels (Trimble and Sartz 1957; Haupt 1959).

In their review of riparian buffer strip design, Belt *et al.* (1992) cautioned that channelized flow can transport material for thousands of feet. The capacity for channelized flow to transport material is limited by the frequency and amount of flow (Belt *et al.* 1992). When roads disrupt the natural pathways of flowing water, road cross-drain culverts can be installed to provide routes for water to flow down a hillslope. Poorly designed cross-drain systems can create particularly high risk areas for the transport of sediment by channelized flow (Belt *et al.* 1992). Ketcheson and Megahan (1996) reported that erosion from road fill slopes was diffuse and short travelled, and resulted in elongated deposits oriented laterally along their bases. Among 335 road erosional sites in southwestern Idaho that were evaluated over a four year period, mean sediment travel distance and the range in travel distance among sites with culverts were greater than those for other road erosional sites (Ketcheson and Megahan 1996). Also, sediment travel distance from culverts significantly increased during the second year of the study while this was not the case for other areas (Ketcheson and Megahan 1996).

Flow

Fluvial erosion is the entrainment and transport of material by water in the liquid phase, including that induced by raindrop splash, or through overland sheet, rill, and distinctly channelized flow. Concern for fluvial erosion dominates that for any other form of erosion and the combination of all of these types of fluvial erosion is of greatest significance (Toy 1977). Raindrops that fall on bare mineral soil can shatter aggregates, and raindrop splash can transport individual soil particles short distances. When the intensity of rainfall exceeds the capacity for infiltration, ponding will occur and Hortonian overland flow may begin (Freeze and Cherry 1979; Wischmeier 1977). When soil becomes saturated from the infiltration of rainfall and sub-surface water flow, additional precipitation can not infiltrate the soil and saturation overland flow can result (Briggs and Smithson 1985). Overland flow can move detached particles further than splash alone (Wischmeier 1977). Also, when soil becomes saturated, infiltration capacity is zero and shallow overland flow can develop to carry detached particles (Bryan 1977). Saturation overland flow is most prevalent at the base of slopes or bottom-lands where slopes are low, the soil is commonly wet, and runoff is received from further upslope (Briggs and Smithson 1985). Where shallow overland flow is concentrated, transport capacity is greater and rills can develop. This can build to a situation where attached soil particles can be sheared loose by flowing water and by slumping of undercut sidewalls and small headcuts (Wischmeier 1977).

Toy (1977) explained how vegetation can inhibit erosion in a variety of ways. If present, foliage can intercept the kinetic energy in falling raindrops and protect soil aggregates from being dislodged. Plants transpire, and in the simplest sense this dehydrates the soil and reduces antecedent moisture conditions. When antecedent moisture conditions are not lowered by transpiration, surface runoff may be more likely to occur because less rain would be required to generate saturation overland flow. When mobilised by high flow, debris from buffer strips can load stream channels and deflect flow into banks, causing erosion (Steinblums *et al.* 1984).

Mature vegetation and grasses in riparian strips can filter sediment carried in overland flow before it is transported to streams. This filtering is possible when runoff is in the form of sheet flow, which allows sediment to be deposited and prevents channelized erosion of accumulated sediments (Naiman and Decamps 1997). A review of riparian buffer strip design by Belt *et al.* (1992) reported that non-channelized transport distances have a positive relationship with slope and that the number of obstructions within the filter strip can decrease transport distance. This review went further to say that reserves that are 61 - 91 m wide are generally effective at controlling sediment that is transported in non-channelized flow. The authors caution that channelized flow can transport material for hundreds of metres and is limited by the frequency and amount of flow. Road cross-drains were noted as being areas particularly prone to this type of risk.

Headcutting processes can facilitate the advance of ephemeral gullies in an uphill direction. Most often, this requires an active seepage face with saturated soil conditions, concentrated surface flow, or both. Whether seepage or surface runoff generate the formation of ephemeral gullies, surface flow concentrations can facilitate the transport of soil and increase the volumetric dimensions of channels (Moore *et al.* 1988). Some experts believe that the prevention of sediment entering streams is dependent on the protection of ephemeral elements of stream systems (Clinnick 1985).

Windthrow

Riparian reserves are established to mitigate the effects of forest management land uses on aquatic systems. The occurrence of windthrown trees in reserves could reduce the ability of these areas to control the transport of sediment from harvested areas to streams. When hydrologic pathways link reserve areas affected by windthrow to lotic or lentic systems, it is possible that areas affected by windthrow will function as a source of sediment to aquatic systems. Wind is the primary cause of buffer strip failure (Steinblums *et al.* 1984). A number of research projects have been done to evaluate the effects of wind exposure on the amount of windthrow after logging (Hairston-Strang and Adams 1998; Heifetz *et al.* 1986; Ruel *et al.* 2001; Tang *et al.* 1997; Gordon 1973; Steinblums *et al.* 1984; Stephenson 1988). It appears that most research on windthrow was done in relation to the recruitment of large woody debris to aquatic systems, or wood fibre production. However, when standing trees are fallen (thrown) by wind, their overturned root mats can expose mineral soil to the erosive processes of raindrop splash and flowing water and these processes may also impact aquatic habitat.

Alexander (1964) reported that more trees blow down on lower slopes than on middle and upper slopes. Several researchers reported that poor drainage conditions increase the chance of wood volume losses from windthrow (Alexander 1964; Steinblum *et al.* 1984). Slow drainage conditions are encountered along stream bottoms and stream overflow areas, and at higher elevations in the bottoms of draws and on flats at the base of slopes (Alexander 1964). Work in northwestern Ontario by Stephenson (1988) did not find a significant relationship between wood volume losses from windthrow and wetter soils. However, the distribution of sites in Stephenson's study, with only one very wet, three wet, seven fresh, and no dry sites, was not well suited to detect such a relationship. The risk of windthrow is higher in areas with wetter soils, and these areas are often located along streams and at the bottoms of draws (Alexander 1988), and compared to other locations across a landscape, these areas are at greater risk of fluvial erosion because this is where shallow sheet flow and channelized flow paths are focused.

Factors other than soil drainage conditions can affect risk of windthrow. These include: 1) distance from the buffer strip to uncut timber in the direction of damaging winds; 2) distance and elevation difference between a buffer strip and the nearest ridge in the direction of damaging winds; 3) azimuthal orientation of stream flow; 4) elevation of the buffer strip; 5) stability rating of the buffer (visually estimated, based on indicators such as stream bank cutting, jackstrawed trees, debris dams, swampy areas, and landslides); and 6) original timber volumes. Trees along edges are more prone to windthrow than those away from edges (Gordon 1973; Gratkowski 1956). Buffer width did not affect windthrow risk (Steinblums *et al.* 1984), but some species are more prone to windthrow

(Steinblums *et al.* 1984; Ruel *et al.* 2001; Stephenson 1988). Topography can be a dominating factor affecting windthrow (Ruel *et al.* 2001; Tang *et al.* 1997). In his study, Stephenson (1988) found that windthrow risk was related to only one variable, a soil stability categorical index he estimated in the field. With that system, Stephenson classified a buffer as stable, moderately stable, or unstable based on the condition of tree root systems.

A significant challenge to land managers is created by the apparent complexity inherent among the suite of factors that affect windthrow risk in buffer strips. However, the risk of windthrow (and erosion) may be reduced by considering these factors singly as some may be more easily managed than others. For example, Stephenson (1988) suggested that with a single-tree selection method, large trees presenting high windfall risk could be harvested to eliminate that risk, and the risk of windthrow may be reduced by designing clearcut areas with low perimeter to area ratios to minimize the amount of edge (Gordon 1973; Stephenson 1988).

Crown Closure And Thickness of Organic Horizons Covering Mineral Soils

Vegetation cover functions to retard soil erosion (Toy 1977). Forests and grass offer the best natural protection against erosion (Brady 1984). Dense understory vegetation and a thick litter layer are largely responsible for the effectiveness of a buffer (Borg *et al.* 1988). When raindrops are intercepted by vegetation, the kinetic energy of the raindrops is expended on the vegetation rather than on the soil surface, and this reduces the potential for erosion (Toy 1977). Canopy and mulch cover both intercept rainfall;

however, mulch also functions to reduce runoff velocity. When falling raindrops intercept canopy cover, kinetic energy is dissipated; however, if intercepted precipitation drips off vegetation, fall velocity can be regained. This process causes canopy cover to be less effective at mitigating the impacts of raindrop splash compared to mulch. The combined benefits of mulch over canopy cover make mulch more effective at controlling erosion than an equivalent amount of canopy cover (Wischmeier 1977). Of all the factors that control erosion rates, ground cover has the greatest influence (Clayton and Megahan 1997). Ground cover is the crucial component of a buffer strip that allows it to function as a bio-mechanical filter of shallow overland flow (Norris 1993). Ground cover type affects sediment loss in runoff under simulated rainfall (Singer and Blackard 1978). Forest floor material can function as ground cover and can influence surface runoff, percolation, and evaporation from the soil (Rowe 1955; Grace 2002). Overall, the forest floor material would likely control erosion more like mulch than canopy cover because it is distributed over the surface of the ground. In a simulated rainfall study, Naslas *et al.* (1994) found that the absorptive capacity of litter and the water repellency of duff (decomposing organic matter) influenced the infiltration and runoff properties of their erosion plots; less sediment was discharged from plots that had litter and duff compared to plots that had litter and duff removed. Furthermore, stems of plants can obstruct linear pathways of flow and force meandering courses. This increases friction and reduces both velocity and erosive capacity (Toy 1977).

In a simulated rainfall experiment in NWO, France *et al.* (1998) showed that soil erosion was dependent on the differing amount and composition of litterfall. Results suggest that average litter production in NWO riparian areas (at the western edge of the Great Lakes / St Lawrence mixed forest region) is substantially lower than averages recorded for all other forests at the same latitude, other temperate coniferous forests, and other Great Lakes/St. Lawrence coniferous-mixed forests, but were more comparable to more northern boreal forests and other Great Lakes/St. Lawrence riparian zones. Data from France *et al.* (1998) supported the global trend whereby litter production in areas adjacent to water bodies is lower than that in upland forests. France *et al.* (1998) speculated that since litter production in NWO riparian areas is lower than once assumed, the soil entrapment capability of these areas may also be lower than once thought, and they postulated that if this is true, the sediment filtering effectiveness of buffer widths, such as those prescribed by Trimble and Sartz (1957) would be less than expected and adequate protection to aquatic systems may be absent.

<u>Slope</u>

Much work has been done that illustrates the positive relationship between slope and sediment yield and/or transport distance (Trimble and Sartz 1957; Naslas *et al.* 1994; Phillips 1989). Phillips (1989) found that slope gradient was the most critical factor affecting the effectiveness of water quality buffer zones at controlling pollutants in a solid phase (buffer width was most important for dissolved sediments). The influence of topography on erosion rates is affected primarily by slope angle and slope length. As the angle of slope increases there is a greater force of acceleration in a down slope direction. With steeper slopes, water is more likely to flow across a surface and it is less likely to infiltrate the soil. Longer slope lengths can impede or enhance erosion rates, depending on rainfall intensity. Longer slopes provide a greater opportunity for infiltration during low intensity storms, but during high intensity storms there can be a progressive increase in runoff and erosion as flow runs down slope (Toy 1977). Short slopes will produce runoff with small volumes and slow velocities. Long slopes will produce runoff with larger volumes and higher velocities that are often channelized. For these reasons, sediment transported by runoff from longer slopes can be more difficult to control with a buffer (Norris 1993).

Moore *et al.* (1988) suggested that the length slope topographic approach to modeling erosion, as applied with the Universal Soil Loss Equation (USLE), should be avoided when trying to model erosion associated with ephemeral gullies. This recommendation was based on field observations reported in that publication and the demonstration in Moore and Burch (1986) showing that the length slope factor applied in the USLE is proportional to a topographic variable, A_p. The A_p variable was derived by considering the sheet flow process. Sheet flow is the predominant erosion mechanism in agricultural fields (Brown 1983). The A_p variable is calculated by applying equation (2).

$$A_p = (A/b)^{0.4} S^{1.3} \tag{2}$$

Where:

A/b = upslope contributing area per unit contour length (units m^2/m)

S = slope (units are m/m)

The upslope contributing area per unit contour length integrates the effects of contributing area and catchment convergence and divergence, and is an indirect measure of surface and subsurface runoff at a location in a catchment (Moore *et al.* 1988). Most forested watersheds have highly dissected topography and the rough surface precludes sheet flow so water quickly runs into rills or channels (Brown 1983). Moore *et al.* (1988) attempted to use A_p to locate ephemeral gullies, but they had little success. They suggested that alternative approaches were needed to model erosion associated with ephemeral gullies.

Topographic Index (TI)

The topographic index (TI) developed by Beven and Kirkby (1979) is a function of upstream contributing area and local terrain slope. TI values represent the relative likelihood of saturation of the overburden at a given location by subsurface flow from further upslope and the occurrence of subsurface flow exfiltration (Buttle 2002). The TI predicts the relative potential for groundwater discharge along the land-water interface (Buttle 2002).

Researchers studying erosion associated with agricultural land uses have postulated that if ephemeral gully erosion could easily be prediced, then areas where conservation practices were needed would also be identified (Watson *et al.* 1986). This could also be true of areas where forestry is the principal land use. The development of ephemeral gullies is defined by topographic features of the landscape (Thorne *et al.* 1986). In a field study, Anderson and Burt (1978) demonstrated that areas of topographic convergence are locations where surface saturation is facilitated, and where groundwater flow converges. They also demonstrated that areas with convergent topography produced greater stream discharge per unit catchment area compared to areas with divergent topography or straight slopes. Beven and Kirkby (1979) suggested that topography affects surface runoff, subsurface flow, and consequently the location of zones of surface saturation and the distribution of soil water content across a catchment. Their TI relates the topographic structure of a catchment and the distribution of soil water and the potential for saturation across a catchment.

Moore *et al.* (1988) calculated a TI to model the distribution of surface soil water and the location of ephemeral gullies by applying equation (3)

$$\ln(A_s) = \ln((A_b) / S) \qquad (3)$$

Where:

A_b = upslope contributing area per unit contour length (units = m^2 / m)

S = slope (units m / m)

Prosser and Dietrich (1995) reported a difference in the relationship between upstream contributing area per unit contour width and Tan(slope) among channelized and convergent flow elements. It could be interpreted that this also demonstrates differences in erosion potential associated with these types of features. There are a range of topographic indices that calculate an erosion hazard rating from a combination of upstream contributing area and slope. These are based on arguments of erosion controlled by shear stress and unit stream power; however, most of the available data on these are for degraded grasslands and tilled cropland with few examples from forested environments (Prosser and Abernethy 1999). Secondary attributes (e.g., TI) computed from two or more primary attributes (e.g., upslope area, slope) are important because they offer an opportunity to describe pattern as a function of process (Wilson and Gallant 2000). By applying the $\ln(A_s)$ index, Moore *et al.* (1988) were able to predict the distribution of ephemeral gullies within an Australian catchment.

The distribution of water within a catchment and the development of ephemeral gullies can be affected by factors other than those accounted for in the TI. These factors can be spatially variable and can include soil hydraulic properties and vegetation (Moore *et al.* 1988). Overburden on the Precambrian Shield can vary in thickness (Hinton *et al.* 1993), and the overburden strongly affects runoff processes on the Precambrian Shield (Buttle *et al.* 2000). More complex indices that include additional variables such as climate and surficial geology may improve prediction efficiencies of these models, especially when working at regional scales (Wilson and Gallant 2000).

Upstream contributing area is affected by the flow direction algorithm that is used; hence, careful consideration must be given when deriving TIs from DEMs (Quinn *et al.* 1991). Where topography is divergent, application of a single flow path algorithm can cause local inaccuracies in calculated flow accumulations, and in such areas it would be better to apply a multiple flow direction algorithm that distributes flow out of a cell among several adjacent cells. The inaccuracy associated with use of a single flow direction algorithm is most prevalent when working with grids that have resolutions of 50 metres or more, and as finer resolution grids are used the inaccuracy assymptotically becomes less (Quinn *et al.* 1991).

2.0 METHODS

2.1 SITE LOCATION

Two adjacent blocks of land scheduled for clearcut harvesting were identified approximately 30 kilometres north of Thunder Bay in the Mackenzie River Watershed (Figure 2.1). The 19.7 ha North Block is situated along the bottom end of the north branch of the West Walkinshaw River. The 44.7 ha South Block is situated along the bottom end of the south branch of the West Walkinshaw River. As the North and South Blocks were adjacent to streams, AOCs were prescribed in the forest management plan between each of the blocks and adjacent reaches of the West Walkinshaw. The AOCs were designated in the plan to be left undisturbed to function as buffer strips.

2.2 DESCRIPTION OF STUDY AREA

2.2.1 Natural History

The north and south branches of the West Walkinshaw join to flow eastward between the North and South Blocks, and eventually join the Mackenzie River to flow into Lake Superior. Immediately upstream of the point where they join, the North and South Branches respectively drain 11.63 and 13.35 square kilometers.

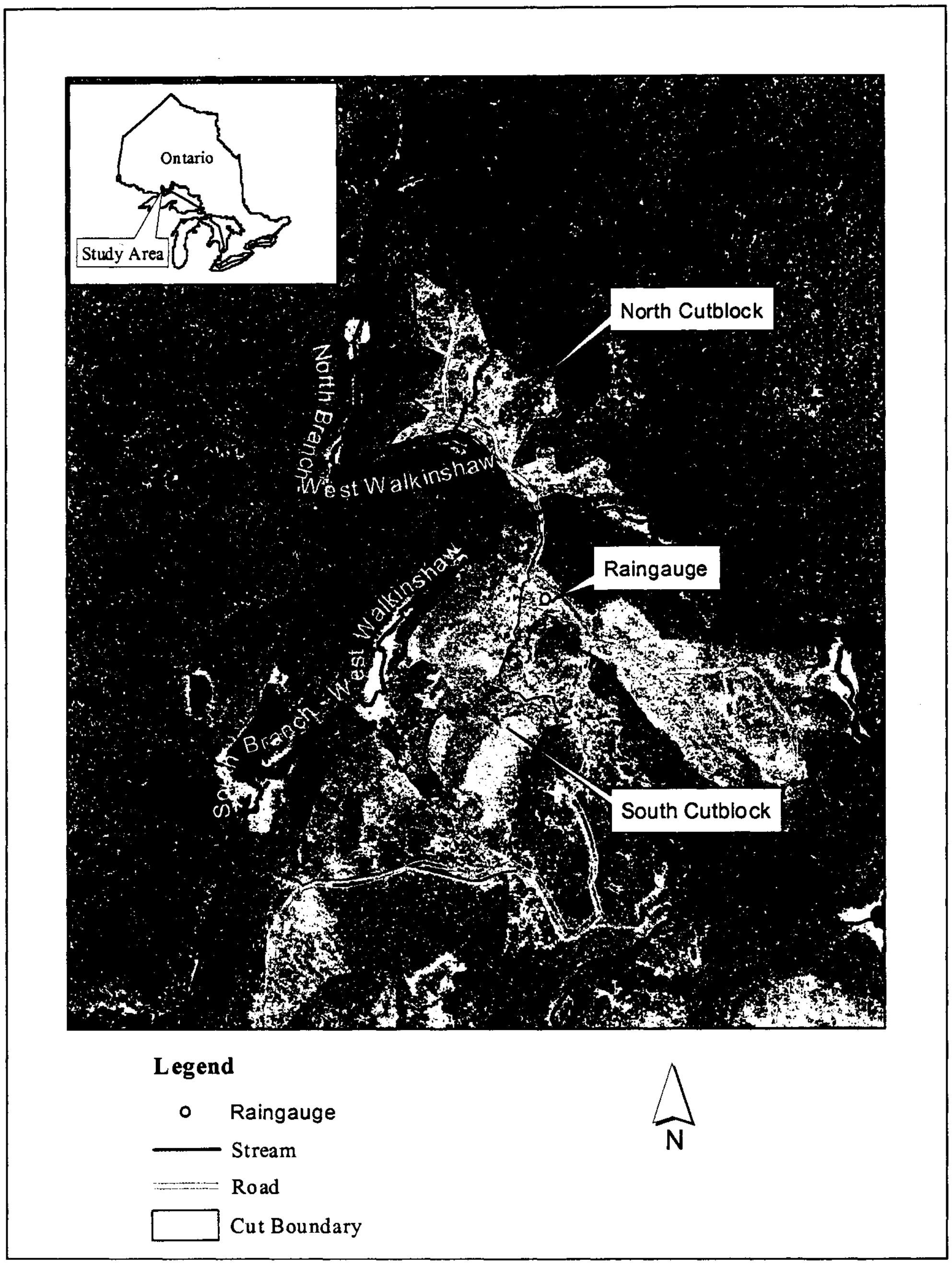


Figure 2.1. North and South cutblocks and their locations along the north and south branches of the West Walkinshaw River. GIS data are displayed over an IKONOS image (May of 2001) collected after trees on the North and South Blocks were harvested.

The study area is within the Port Arthur Hills physiographic unit, in the James Region of the Precambrian Shield (Bostock 1970). Granitic Archaean bedrock is predominant in this area, and it often breaks the surface. A complex glacial history that includes several ice margin advance/retreat cycles left morainal, glaciofluvial, glaciolacustrine, and aeolian deposits scattered across the region in which the study area lies. Across the region, the glacial events have produced a scattering of deeper glacial deposits, including morainic ridges, eskers, and drumlinoid features (Mollard and Mollard 1981). The study area is within a complex landform unit that is dominated by a till and sand veneer of ground moraine that covers a bedrock plain; however, in some areas the bedrock plain is exposed (Mollard and Mollard 1981). In this area the patchy ground moraine can vary in thickness both locally and regionally (Zoltai 1965). The moderate surface relief is largely dictated by the topography of the bedrock (Mollard and Mollard 1981). Surface water features with self sustaining brook trout populations are scattered throughout the area where groundwater inputs maintain tolerable thermal conditions for this species (Picard 1995).

The Terrestrial and Wetland Ecosite Classification for Northwestern Ontario (T&WC) is an ecological classification system that is used to describe ecosites in NWO (Racey *et al.* 1996). Ecosites range in size from 10 – 100 ha, so the T&WC was an appropriate system to classify the North and South Blocks. The Forest Ecosystem Classification for Northwestern Ontario (FEC) is used to describe ecoelements in NWO (Sims *et al.* 1997). Ecoelements range in size from 0.01 – 10 ha (Racey *et al.* 1996), so the FEC was used to classify the soils and vegetation in the vicinity of each sampler.

Table 2.1 reports the FEC classifications for soils in the vicinity of each sampler. The sampler sites were located within topographic draws that ran through the riparian reserve areas where runoff from the hillslopes above would converge. Soils in the majority of pits in the North Block reserve had imperfect or very poor drainage, and subsurface flow was encountered in seven of them (Table 2.1). An Ah layer was observed in all of the north reserve pits, and mottling was common among them. Evidence of eluviation was absent in all of the pits in the North Block reserve. Soils in two pits in the South Block reserve had poor drainage, while drainage in the remaining six South Block pits ranged from well to very rapid (Table 2.1). Sub-surface flow was encountered in only two of the pits in the South Block reserve. Five of the eight pits in the South Block reserve had an Ae layer but no Ah. The remaining three southern reserve pits had an Ah layer but no Ae. Soils were classified as Brunisols (Canadian Agricultural Services Coordinating Committee 1998). Some gleying was evident, but not enough to classify the soils as Gleysols.

Table 2.2 reports the T&WC ecosite classification for the North and South Blocks, and FEC ecoelement classifications for the vegetation community in the vicinity of each sampler. The North Block was within a spruce-pine/ledum/feathermoss ecosite with moist, sandy-coarse loamy soil (Racey *et al.* 1996) (Table 2.2). The composition of the stand on the North Block was 90 % black spruce (*Picea mariana* Lamb.) and 10 % jack pine (*Pinus banksiana* (Mill.) B.S.P.) (OMNR 1997a). The average age of the overstory

Table 2.1. Forest ecosystem classification for soils in the vicinity of each sampler (Sims *et al.* 1997).

Sampler	Soil Drainage Class	Soil Moisture Regime	Soil Type
NR-00	Imperfect	Moist	Moist / Coarse Loamy (S8)
NR-10	Imperfect	Very Moist	Moist / Coarse Loamy (S8)
NR-20	Very Poor	Very Moist	Moist / Sandy (S7)
NR-30	Imperfect	Moist	Moist / Fine Loamy – Clayey (S10)
NM-00	Rapid	Fresh	Dry / Coarse Sandy (S1)
NM-10	Imperfect	Very Moist	Moist / Sandy (S7)
NM-20	Poor	Moist	Moist / Coarse Loamy (S8)
NM-30	Very Rapid	Moderately Fresh	Dry / Coarse Sandy (S1)
SR-00	Well	Dry	Dry / Coarse Loamy
SR-10	Moderately Well	Moderately Moist	Moist / Coarse Loamy
SR-20	Well	Dry	Fresh / Fine Sandy
SR-30	Poor	Very Moist	Moist / Coarse Loamy
SM-00	Poor	Very Moist	Moist / Fine Loamy - Clayey
SM-10	Rapid	Fresh	Dry / Coarse Loamy
SM-20	Very Rapid	Moderately Fresh	Dry / Coarse Sandy
SM-30	Well	Moderately Fresh	Dry / Coarse Sandy

Table 2.2. Forest ecosite classification (Racey *et al.* 1996) for the North and South Blocks and forest ecosystem classification (FEC) (Sims *et al.* 1997) for vegetation in the vicinity of each sampler.

Sampler	Ecosite	FEC Vegetation Type
NR-00	Spruce-Pine/Ledum/Feathermoss: moist, sandy-coarse loamy soil (ES22)	Black Spruce Mixedwood / Herb Rich (V19)
NR-10		Black Spruce Mixedwood / Herb Rich (V19)
NR-20		Black Spruce Mixedwood / Herb Rich (V19)
NR-30		Trembling Aspen - Black Spruce - Jack Pine / Low Shrub (V10)
NM-00		Black Spruce / Jack Pine / Tall Shrub / Feather Moss (V31)
NM-10		Black Spruce / Speckled Alder / Sphagnum (V35)
NM-20		Black Spruce Mixedwood / Herb Rich (V19)
NM-30		Black Spruce / Labrador Tea / Feather Moss (Sphagnum) (V34)

Table 2.2. (Continued)

Sampler	Ecosite	FEC Vegetation Type
SR-00	Hardwood-Fir-Spruce Mixedwood: fresh, sandy-coarse loamy soil (ES19)	Black Spruce Mixedwood / Feathermoss (V31)
SR-10		Black Spruce / Feathermoss (V33)
SR-20		White Spruce / Balsam Fir / Feather Moss (V25)
SR-30		Jack Pine Mixedwood / Shrub Rich (V17)
SM-00		Black Spruce / Feathermoss (V33)
SM-10		Black Spruce / Feathermoss (V33)
SM-20		Trembling Aspen - Black Spruce - Jack Pine / Low Shrub (V10)
SM-30		Black Spruce Mixedwood / Herb Rich (V19)

trees was approximately 100 years, average height was 12.2 m, and stocking was 50 % (OMNR 1997a). Generally, the soils and plant community growing within the reserve area along the north branch of the West Walkinshaw River was typical of a herb rich Black Spruce Mixedwood vegetation type (Sims *et al.* 1997) (Table 2.2). However, the wettest areas within the reserve were more typical of black spruce/labrador tea/feathermoss or black spruce/speckled alder/sphagnum vegetation types. Typical ground cover for a herb rich Black Spruce Mixedwood ecoelement is 49 % moss, 33 % broad leaf litter, and 12 % conifer litter; however, spruce/labrador tea/feathermoss can have 80 % or more moss ground cover (Sims *et al.* 1997). At most of the sampler locations, the LFH layer covering the soil ranged between 0.5 and 2 cm thickness; however, in the wetter areas it was up to 16 cm thick.

The extent of the South Block covered several forest stands; however, the study area was confined to the northern most of these. This stand was situated within a hardwood-fir-spruce mixedwood ecosite with sandy to coarse loamy soil (Racey *et al.* 1996) (Table 2.2). The composition of the forest stand was 50 % white birch (*Betula papyrifera* Marsh.), 30 % black spruce (*Picea mariana* Lamb.), and 20 % jack pine (*Pinus banksiana* (Mill.) B.S.P.) (OMNR 1997b). The average age of the overstory trees was approximately 70 years, average height was 12.2 m, and stocking was 100 % (OMNR 1997b). The riparian vegetation community and soil at the South Block reserve were more heterogeneous compared to those of the North Block (Table 2.2).

The wettest portion of the southern reserve was typical of a black spruce/feathermoss ecoelement (Sims *et al.* 1997) (Table 2.2). Typical ground cover for this ecoelement is 90 % moss (Sims *et al.* 1997). The thickness of the LFH layer covering the soil within this area ranged between 5 and 12 cm.

Shrub rich jack pine mixedwood and black spruce mixedwood/feather moss ecoelements were scattered along the upstream portion of the reserve (Sims *et al.* 1997) (Table 2.2). Typical ground cover in jack pine mixedwood areas is 36 % broad leaf litter, 32 % conifer litter, and 27 % moss, but in areas dominated by black spruce, moss cover is approximately 80 % while conifer litter ground cover is approximately 5 % (Sims *et al.* 1997). The LFH layer in these areas was approximately 4 cm thick.

Along the downstream section of the southern reserve, trembling aspen-black spruce-jack pine/low shrub forest ecoelements were more prevalent (Sims *et al.* 1997) (Table 2.2). Typical ground cover in these areas was 73 % broad leaf litter, 1 % moss, 10 % conifer litter, and 6 % wood (Sims *et al.* 1997). Generally, the LFH layer in this area was approximately 4 cm thick.

Common shrubs that were encountered in the North and South Blocks included twinflower (*Linnaea borealis*), dwarf raspberry (*Rubus pubescens*), prickly wild rose (*Rosa acicularis*), serviceberry (*Amelanchier*), low sweet blueberry (*Vaccinium angustifolium*), velvet-leaf blueberry, (V. myrrilloides), bush honeysuckle (Diervilla lonicera), creeping snowberry (*Gaultheria hispidula*), and labrador tea (Ledum groenlandicum). Speckled alder (*Alnus rugosa*) was present in the wettest areas.

Bunchberry (*Cornus canadensis*), Canada mayflower (*Maiamthemum canadense*), blue bead lily (*Clintonia borealis*), starflower (*Trientale boreale*), wild sarsaparilla (*Aralia nudicaulis*), goldthread (*Coptis trifolia*), large leaf aster (*Aster macrophyllus*) and rose twisted-stalk (*Streptopus ro*seus) were among the common herbs.

Mosses were represented by Schreber's moss (*Pleurozium schreberi*), wavy-leaved moss (*Dicranum polysetum*), plume moss (*Ptilium crista-castrensis*), and stair-step moss (*Hylocomium splendens*).

2.2.2 Forest Management Activities

Before harvesting activities commenced, the boundaries of 30 metre wide AOCs were flagged between the high water mark along the streams and all areas prescribed for clearcutting. These AOCs would be left undisturbed to function as buffer strips to protect stream habitat from impacts generated by forest management related activities that would occur within the blocks. The width of the reserves was defined by the Timber Management Guidelines for the Protection of Fish Habitat (OMNR 1988), based on the slope of the terrain, as outlined in Appendix I.

An existing road, which ended close to where the raingauge was installed, was upgraded and extended into the North Block during August and September of 1997 (Figure 2.1). A temporary bridge was installed approximately 160 metres downstream of the confluence of the north and south branches of the West Walkinshaw River to provide a means for vehicular traffic to cross the river channel. During late November and December of 1997, merchantable timber growing on the North and South Blocks was cut using the full tree harvesting method. Feller bunchers were used to cut trees and place them in bunches. Grapple skidders transported bunches to roadside landings where the trees were then chipped. Slash was left in piles beside the landings and logging trucks hauled the chips to the mill. No site preparation or planting was done during the period of the study.

2.3 SEDIMENT SAMPLERS

2.3.1 Design

The design for the samplers used in this study was adapted from that presented by Bathke (1987), in which the sampler was described as a "semiportable multislot divisor for erosion and runoff measurements". Bathke's sampler was designed to quantify erosion from experimental erosion plots that were 4.88 m wide by 15 m long, in agricultural fields (Bathke 1987). The main components of the sampler included an entrance flume, sedimentation tank, divisor box with divisor plate, and an aliquot tank, which were all made from sheet metal. The primary difference between the samplers used for this study and those of Bathke's was that pressure treated plywood was used in place of much of the sheet metal specified by Bathke. This change was made primarily to keep material costs at a minimum; however, the use of plywood also reduced the amount of welding that was required to fabricate the samplers. As welding is a task that requires specialized equipment and skills, a reduction in the need for it was considered an additional benefit of the material change. Rust resistant stainless steel screws were used as fasteners and all seams were sealed with aquarium grade silicone sealant to make them watertight. To further waterproof the samplers, 0.15 mm thick polyethylene sheeting was used to wrap the samplers before they were buried.

A complete sampler was made up of several components, including: a flume, main box, sedimentation tank, litter screens, divisor box with 21-slot divisor plate, levelling rods, and aliquot tank, and outflow trough (Figure 2.2). The following sections describe the design characteristics of each of these components.

2.3.1.1 Main Box

The main boxes were built out of 1.91 cm thick pressure treated plywood that was supported by a dimensional lumber frame. Application of either an interior or exterior framing system were considered to support the plywood walls of the main box against the pressure of backfilled earth after the sampler was set into the ground. It was decided that an interior system would provide the best support; however, this system caused sampler cleanouts to be more difficult as twice the number of inside corners resulted with this configuration. The samplers were approximately 48 cm wide, 64 cm long, and 51 cm tall (exterior dimensions). When the depth of water collected inside the main box

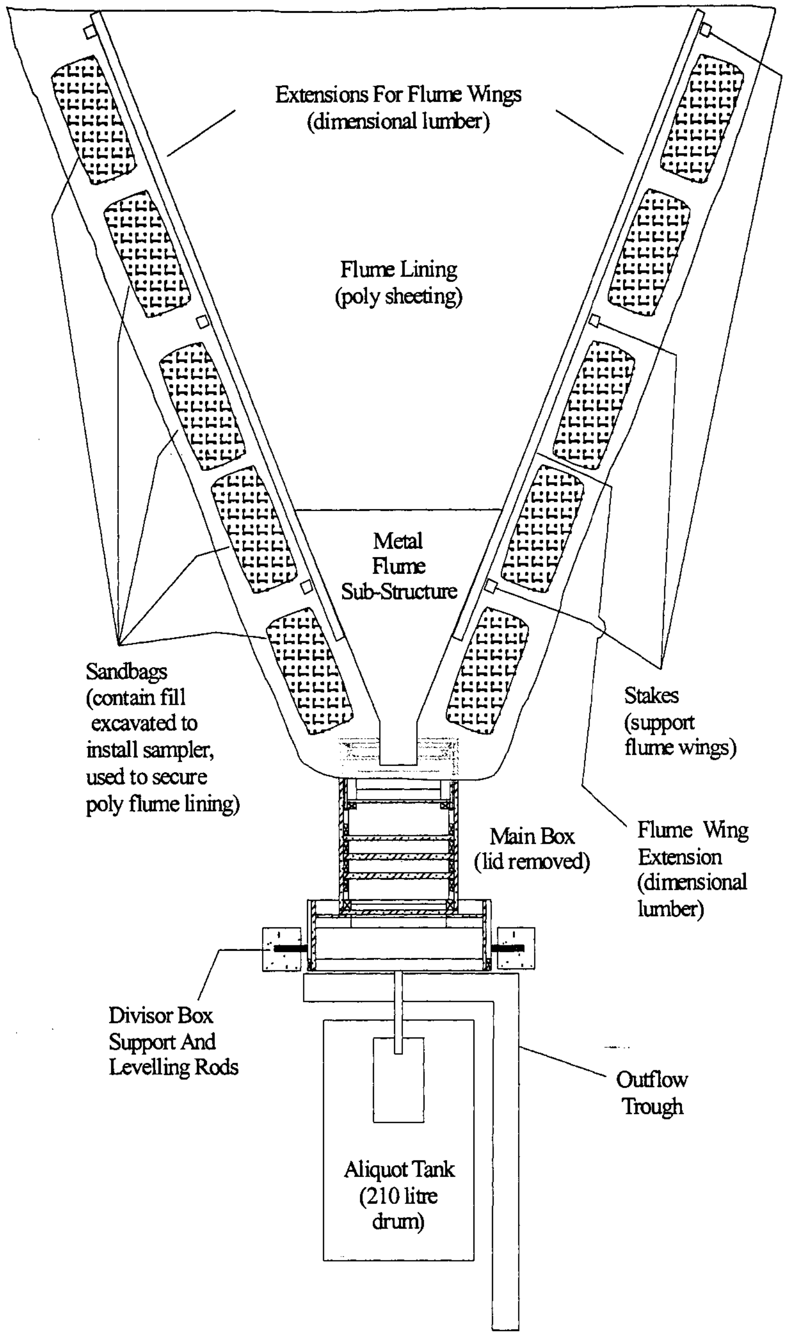


Figure 2.2 Schematic view of complete sampler installation, including flume with wing extensions and poly lining; sampler with divisor box support and levelling rods, and outflow diversion trough; and aliquot tank. The flume is situated to receive flow moving down the hillslope and the outlet of the outflow trough is placed at an elevation to allow runoff collected in the sampler to discharge through it.

reached 33.3 cm, the bottom edge of the slots in the divisor plate were breached and water would start to flow out of the sampler. At that depth, approximately 81 litres of water and sediment would have been collected.

2.3.1.2 Settling Box

A smaller box, constructed of 1.27 cm thick pressure treated plywood was constructed to set inside the main box immediately below the entrance flume (Figure 2.3). This component would function as a sedimentation tank for bedload sediment carried into the sampler (Bathke 1987). As this box would not be subjected to pressure from backfilled earth, an exterior framing system was used to facilitate easier cleaning. Bathke (1987) explained that the suspended portion of the sediment load transported into the sampler would be kept in suspension by turbulence in the sedimentation tank. These smaller particles would be carried to the larger volume contained by the main box where reduced turbulence would allow these particles to settle out of the flow.

2.3.1.3 Divisor Box And Divisor Plate

The divisor box assembly, complete with 21-slot divisor plate, was attached to the downstream end of the main box (Figures 2.3 and 2.4). The divisor box functioned to separate a 1/21 aliquot of the total volume of runoff collected by the sampler, and an extension trough attached to the divisor plate directed the aliquot into a collection tank (Figure 2.2). This design feature facilitated the calculation of the total volume of runoff that flowed through the sampler and provided a sub-sample of runoff for dissolved and suspended sediment sampling. The remaining portion of the total flow (20/21) was

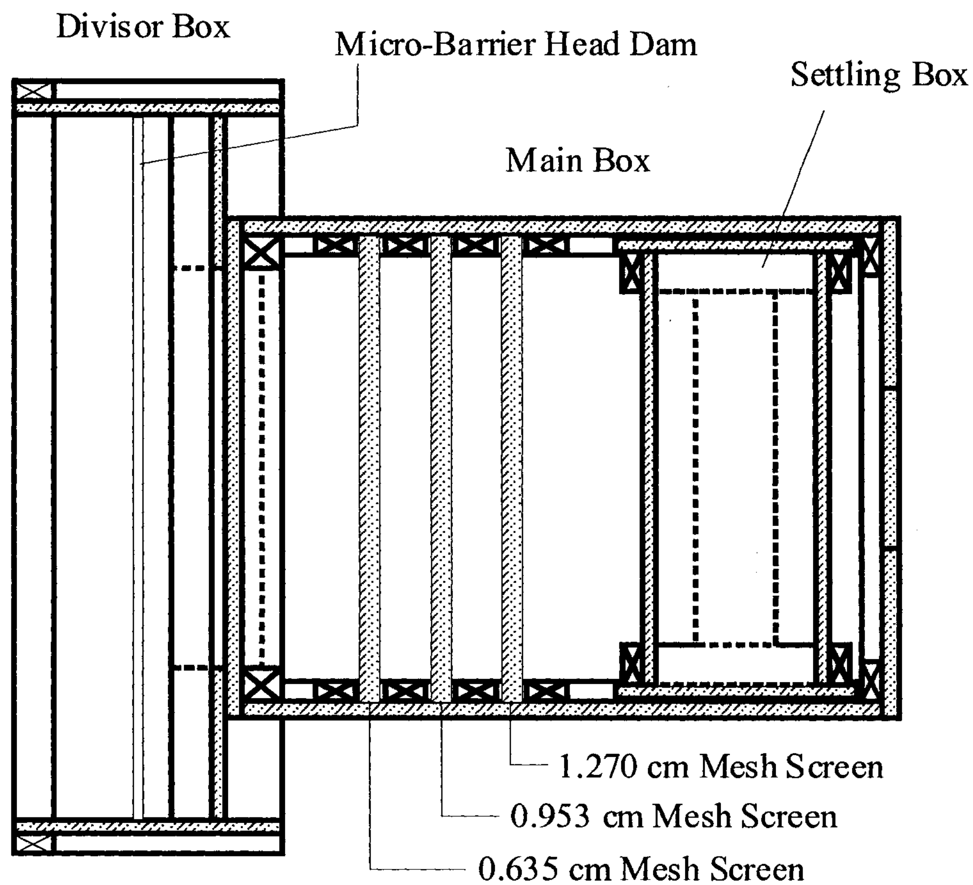


Figure 2.3 Overhead schematic view of sampler assembly with downstream end on left.

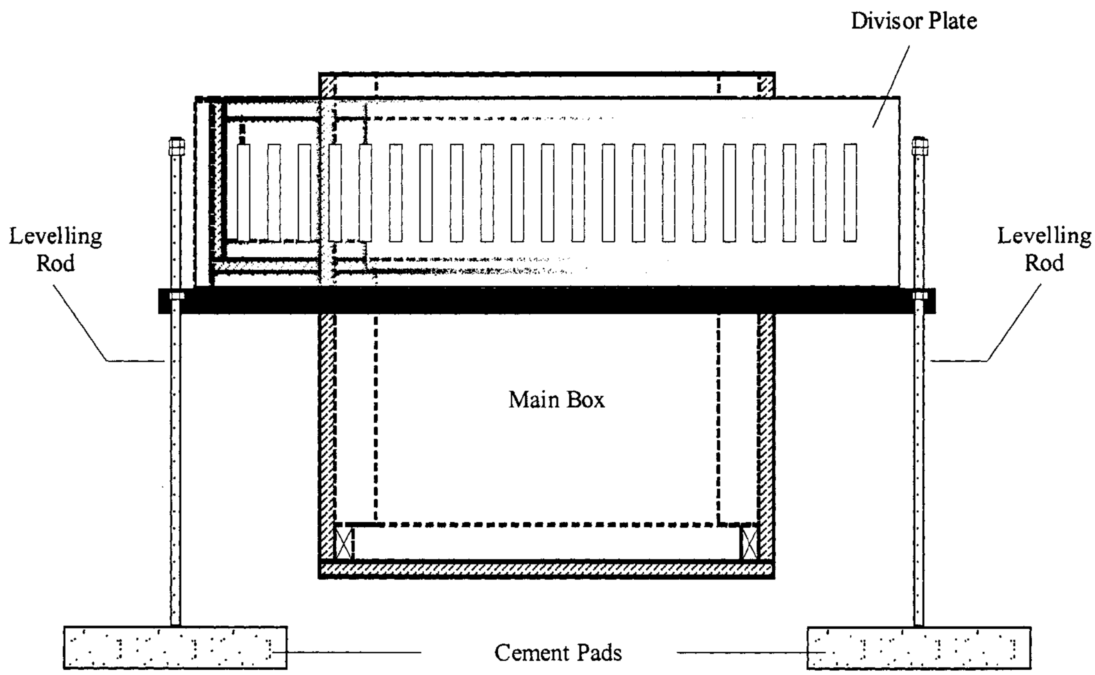


Figure 2.4 Schematic view of sampler, downstream end. Visible are: the main box, divisor plate, leveling rods, and cement pads.

directed away from the sampler assembly by a length of 10.16 cm aluminum eavestrough that was attached to the front of the divisor box, beneath the divisor plate, and it was not collected (Figure 2.2).

Accurate fractioning of the total volume of runoff that flowed though the sampler required that an equal volume of discharge flow through all slots in the divisor plate, and this required precise fabrication of the divisor plate. The divisor plate was manufactured from a 73.63 cm by 19.68 cm piece of 18 gauge sheet aluminum. The 21 slots were all precisely cut to be 10.16 cm tall and 1.27 cm wide, with a spacing of 1.91 cm (Figure 2.5). The slots were positioned on the plate so the bottom edge of each intersected a straight line. Finally, after the sampler was setup in the field, stainless steel rods threaded through a length of 2.54 cm angle iron attached to the bottom edge of the divisor box were adjusted to set the bottom edges of the slots level to a bubble in a torpedo level (Figure 2.4). Concrete pads placed beneath the rods provided a firm base for support (Figure 2.4).

To maintain the aliquot as a 1/21 fraction of the total volume of water that flowed through the sampler, it was critical that an equal volume of discharge flowed through each of the 21 slots. A set of three galvanized metal screens (0.635 cm, 0.953 cm, and 1.270 cm mesh sizes) supported by 1.91 cm thick pressure treated plywood frames were set inside the main box to filter organic material from water that flowed through the sampler and keep the divisor plate slots clear of debris. The size of mesh used was not critical; these sizes were chosen because they were locally available for purchase. The

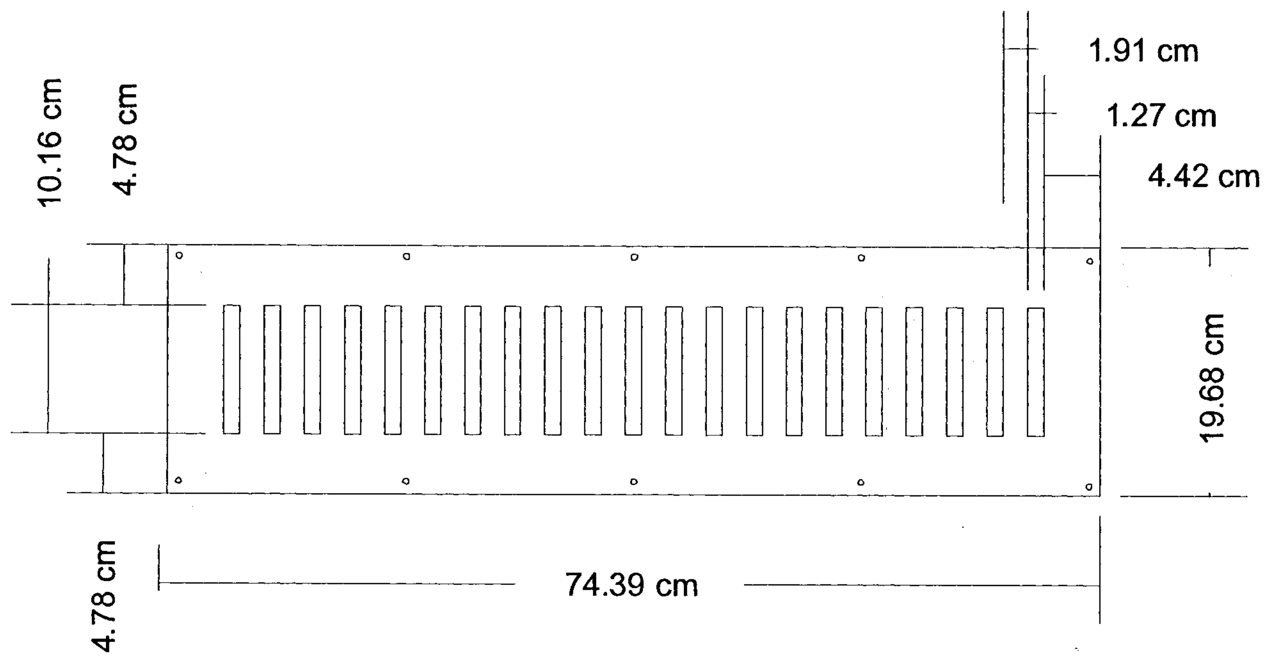


Figure 2.5 Schematic view of 21-slot divisor plate.

screens were set such that the coarsest was closest to the flume, the finest was closest to the divisor box, and the intermediate screen was set between these (Figure 2.3).

The divisor box assembly was wider than the main box, and this caused concern that the middle slots in the divisor plate, which were in line with the flume entrance-way into the main box, might be subject to faster and deeper discharge than slots situated toward the ends of the plate. This could have caused a degree of imprecision in the ratio of total discharge volume collected in the aliquot tank. To alleviate this problem, a length of one cm^2 dimensional lumber was fastened to the floor of the divisor box, across its full width. This structure functioned as a micro-barrier head dam that distributed the flow of water across the width of the divisor box and maintained an equal volume of discharge through all 21 slots in the divisor plate.

2.3.1.4 Entrance Flume

The design of the sampler incorporated an entrance flume that was lined with 0.15 mm thick polyethylene sheeting to funnel surface runoff that flowed through a topographic draw into the sampler. A flume substructure, constructed from galvanized metal, was fastened to the entrance of the main box with stainless steel screws and served several functions: 1) it supported the poly lining at the entrance to the main box and prevented water from ponding in front of the sampler; 2) it directed the flow of water into the sedimentation tank that was set inside the main box. Flume wing extensions fashioned from 3.81 cm x 13.97 cm x 2.44 m dimensional lumber were used to extend the reach of the metal flume, and they functioned to direct the complete volume of surface runoff that flowed across the width of a draw into the sampler.

2.3.2 Installation

Samplers were designed to collect sediment transported by surface runoff; hence, they were installed in locations where surface runoff was most likely to occur (Figure 2.6). A DTM point surveying of the study area did not commence until after the trees were harvested; therefore, the 5 m resolution DEM and derivatives of it were not available sources of information during the sampler site selection process. Hence, suitable installation sites, which included flow accumulation pathways in areas of topographic convergence, were identified by field inspection. Topographic divides and knoll tops were avoided as it was unlikely that surface runoff would be generated on these features. A sampler installation site was identified along each of 16 different flow accumulation paths at a distance of either 0, 10, 20, or 30 metres into the reserve areas (measured from the boundary with the clearcut). Each flow accumulation path was in a different sub-catchment. Finally, over a period of approximately six weeks during May and June of 1997, eight samplers (two at each of the four distances into the reserves) were installed within each of the two reserve areas (Figure 2.7).

Figure 2.2 is an illustration of an installed sampler, and the following text describes the process of installing a complete sediment sampling unit.

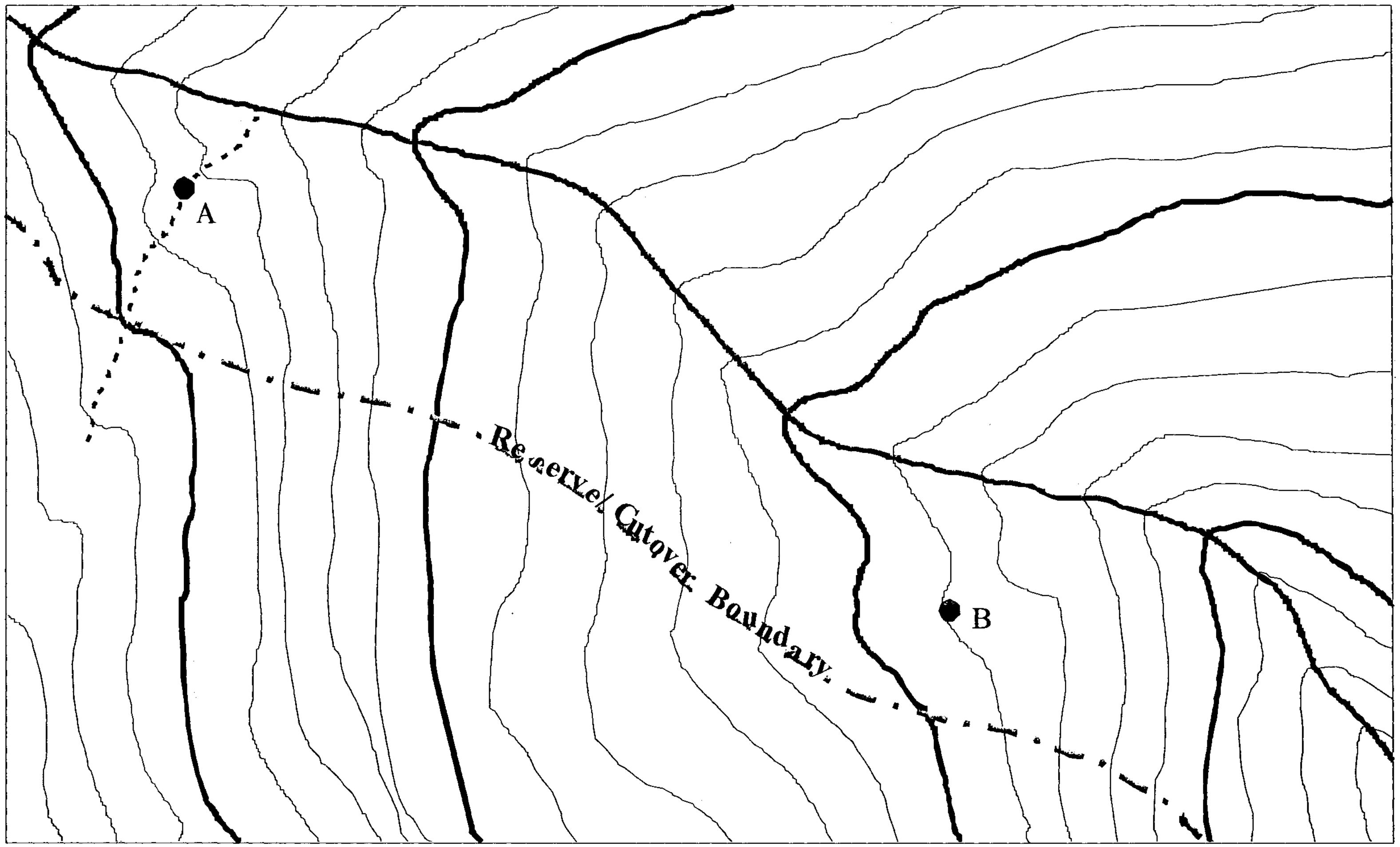


Figure 2.6. Samplers were installed 0, 10, 20, or 30 metres deep into the reserve. Precise locations were chosen by carefully examining the terrain to determine where overland flow would most likely occur given the right precipitation and soil moisture conditions. These locations included: A) intermittent channels and B) draws, as indicated above by red dots.

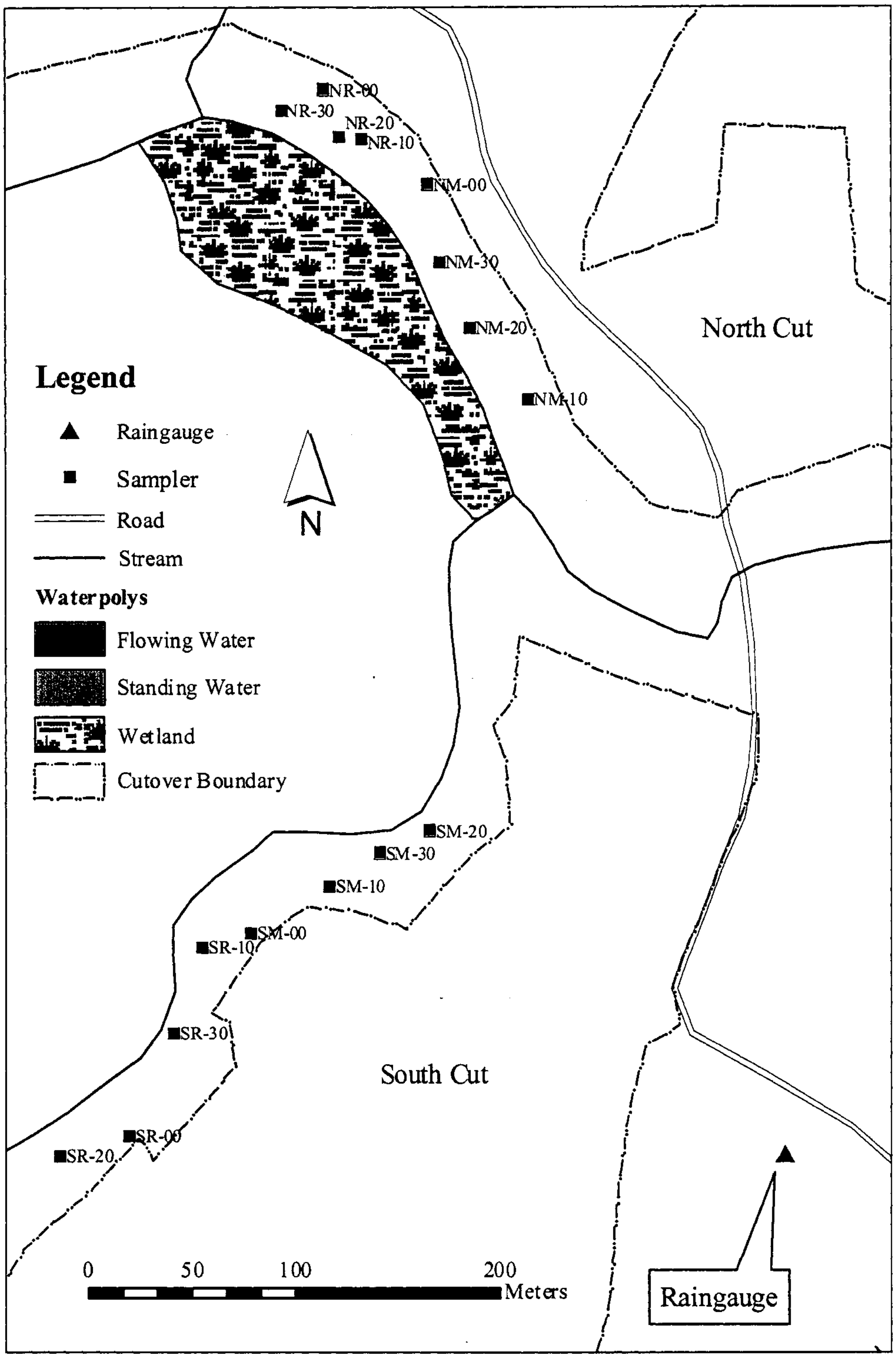


Figure 2.7. Location of samplers and raingauge

2.3.2.1 Main Box Installation

At each sampler site, a roughly cube-shaped hole of sufficient volume and depth was excavated to accommodate a sampler buried to the bottom edge of the flume entrance-way into the main box. Excavated soil was placed into nylon bags commonly used to contain livestock feed. The pit was oriented to allow the sampler to be placed with the longest axis parallel with the direction of surface water movement. The bottom of each pit was smoothed and graded so the sampler would be stable and tilted slightly downhill to ensure water would flow out the divisor plate and not back up in the flume. Care was taken to level the sampler laterally to help ensure water would flow through each slot in the divisor plate at an equal depth and volume. Small cement pads were placed beneath each level adjusting rod to provide solid bases against which the level of the divisor plate could be adjusted (Figures 2.2 and 2.4).

2.3.2.2 Entrance Flume Installation

The area immediately uphill of the main box was grubbed and smoothed to prevent water from ponding on the flume lining. To ensure a sturdy connection to the sampler, the metal flume sub-structure was attached to the sampler with stainless steel screws. Stainless steel screws were also used to fasten the flume wing extensions to both the metal sub-structure and wooden posts that were driven into the ground uphill of the metal sub-structure. Figure 2.8 illustrates the procedure used to install a polyethylene liner between the wings of the flume. A shallow trench was dug into the ground between the uphill ends of the wing extensions and one end of a sheet of 0.15 mm polyethylene sheeting was placed into it. The remaining length of the polyethylene sheet

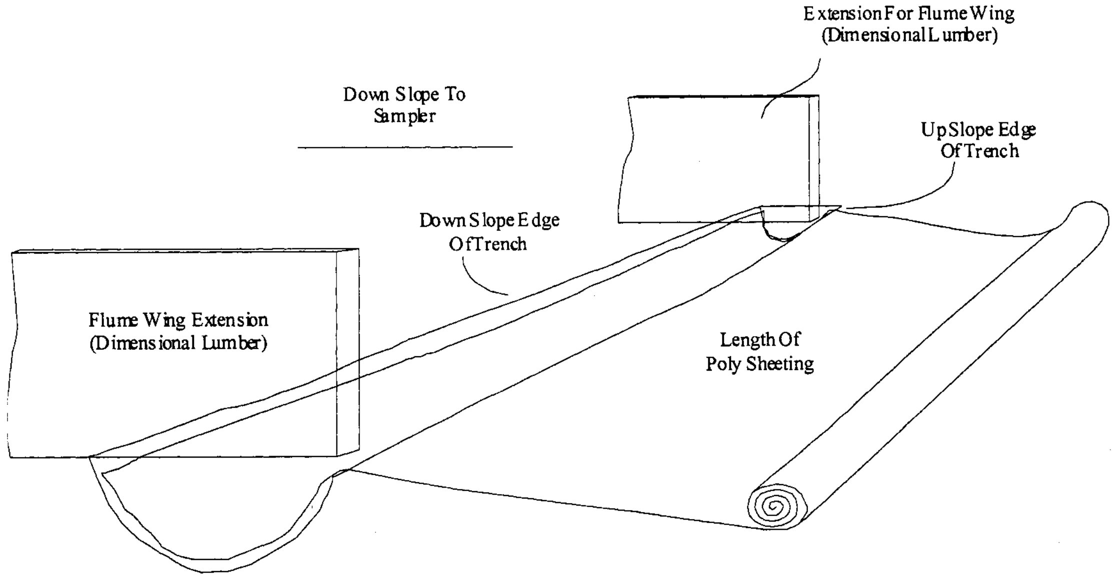


Figure 2.8 Schematic illustrating how the leading edge of the poly flume liners was installed to prevent the disturbance or exposure of soil above the entrance of the flume.

was rolled up and temporarily placed above the trench while the trench was backfilled and packed. Finally, the polyethylene was unrolled and pulled back to cover the area between the flume wings. Use of this procedure to install the polyethylene sheeting prevented the disturbance of ground cover vegetation and litter, and limited the exposure of soil above the flume opening. The sheet was then smoothed and the bottom edge was trimmed to set above the sedimentation tank inside the main box. The bags containing the soil excavated to install the main box were placed on top of the polyethylene sheeting to hold it firmly against the exterior edges of the flume wings (Figure 2.2).

2.3.2.3 Aliquot Tank Installation

Downhill of each sampler, a hole was excavated to accept either a full 225 L drum buried horizontally, or half of a 225 L drum (cut perpendicular to the longest axis) buried vertically, with the open end up. Full, rather than half barrels were used to contain the greater volumes of water that were expected at locations where surface runoff was observed (NR-10, NR-20, and NM-10). The bottom of each hole was graded flat and level to optimize the holding capacity of the drums. In locations where full barrels were used, the barrels were oriented with the longest axis parallel with the direction of flow through the samplers. Both full and half barrels were placed so the extension troughs on the divisor plates hung over them (Figure 2.2). An opening (approximately 40 cm x 25 cm) was cut into the top of each full barrel to provide an entrance-way for the aliquot sample.

2.4 DATA COLLECTION

2.4.1 Precipitation

In the spring of each year (1997, 1998, and 1999) a raingauge was installed approximately 300 m south of the stream crossing between the North and South Blocks to measure the amount of precipitation that fell between sampler cleanouts (Figure 2.1). The distance between samplers and the raingauge ranged from 234 to 354 meters for South Block samplers and 390 to 567 m` for North Block samplers. The raingauge was retrieved in the Fall of each year before it could be damaged from freezing; winter precipitation was not measured. Every two weeks, or each time a sampler was cleaned, the amount of precipitation collected in the raingauge was recorded and the collected precipitation was poured out. Where gaps in the precipitation dataset occurred after the raingauge was retrieved due to freezing temperatures, Environment Canada data collected at the Thunder Bay International Airport were used. The amount of rain collected in the raingauge between sampler cleanouts was summed to determine the amount of precipitation available to generate runoff for each sampler service period.

2.4.2 Sampler Site Description Variables

A set of local scale variables were collected to characterize conditions in the vicinity of each sampler (Table 2.3).

Table 2.3. The eight independent variables evaluated for their effects on mineral and organic sediment collection in samplers. Included are: the measurement scale of the variable; the units at which the variable was measured and reported; the variable type: (1 = Considered likely to change whether by natural processes or as a result of harvesting related activities, 2 = Considered unlikely to change by natural processes or as a result of harvesting related activities, 3 = Variables indicating the presence or absence of a condition or circumstance that may affect sediment collection rates, and 4 = Variable condition created as a result of forest management); and whether an Index of Change (IOC) value was calculated to quantify change in the condition of the variable in 1998 and/or 1999 compared to 1997.

Variable	Data Type	Units	Variable Type	IOC Calculated	Description
Reserve Width	Ratio	m	4	No	Distance from the entrance flume of each sampler to the edge of the undisturbed riparian reserve boundary at the edge of the clearcut (0, 10, 20, or 30 m).
Sub-catchment Area	Ratio	ha	1	Yes	Area contributing runoff to each sampler based on surface topography as described by the DEM.
Distance To Road	Ratio	m	4	No	Shortest distance between the entrance flume of each sampler and the road.

Table 2.3 (Continued)

Variable	Data Type	Units	Variable Type	IOC Calculated	Description
Flow	Nominal	Binary	3	No	Based on the observation of surface runoff flowing into a sampler during the period of this study: 0 = no runoff observed 1 = runoff observed
Windthrow	Nominal	Binary	3	No	Based on the occurrence, during the period of the study, of a windthrown tree within a distance of approximately five metres upstream of a sampler flume: 0 = no windthrow occurred 1 = windthrow occurred

Table 2.3 (Continued)

Variable	Data Type	Units	Variable Type	IOC Calculated	Description
Crown Closure	Ratio	Percent	1	Yes	The average of four crown closure readings (one each facing north, east, south, and west) measured late in the summer of each year with a concave spherical crown densiometer that was placed and levelled on the lid of each sampler.
LFH Thickness	Ratio	cm	2	No	Thickness of all organic layers (LFH) covering mineral soil, measured at the the pit excavated to install each sampler.
Slope	Ratio	Percent	2	No	Slope of the terrain over a distance of approximately 10 metres immediately above the entrance flume of each sampler measured with a handheld clinometer.

Table 2.3 (Continued)

Variable	Data Type	Units	Variable Type	IOC Calculated	Description
TI	Ratio	Relative	1	Yes	Topographic index (TI) value of the grid cell coincident with each sampler. The TI value describes the relative probability of subsurface flow exfiltration. Generated from the primary DEM attributes catchment area and slope using equation (1).

2.4.3 Feature Mapping And Production Of Digital Elevation Models

The following sections describe the field and office procedures that were used to survey and map features and elevations, and produce digital elevation models (DEMs) for the North and South Blocks.

2.4.3.1 Clearcut Boundary Mapping

In 1998, after the North and South Blocks had been clearcut, vertices of the cutblock boundaries were located using a Trimble Pathfinder Plus global positioning system (GPS). Each vertex was mapped by differentially correcting and averaging at least 25 GPS locations that were collected for each vertex, and OMNR base station data from Lakehead University and Trimble Pathfinder Office software were used to do this. Utilities available in the Pathfinder Office software were used to project the GPS data into the 1983 North American Datum (Nad83), Universal Transverse Mercator (UTM) projection, and Zone 16 UTM coordinate space, with metres as the units of distance measure. Boundary vertices were used to generate polygons that defined the area of each clearcut block.

2.4.3.2 Digital Terrain Model Point And Feature Surveying

A total of 505 digital terrain model (DTM) points in the North Block and 555 DTM points within the South Block were surveyed using a Sokkia total station and staff mounted reflective prism. The extents of the areas surveyed were limited to portions of the landscape that could directly contribute surface runoff (as defined by topographic divides) to sections of stream along which samplers were installed. The location of all samplers and flumes was surveyed, as were points along the road, points within the riparian reserves, points within the cuts, and points within the undisturbed forest surrounding the cuts. The location and spacing of points were determined in the field and these were guided by the objectives of accurately defining the paths of surface runoff and the boundaries of sub-catchments contributing surface runoff to the samplers. Point coordinates and elevations were recorded to the nearest centimeter. Although all DTM point data were collected post-impact, as they were surveyed each point was coded to describe whether or not the recorded elevation represented a disturbed or undisturbed elevation. Points surveyed where mineral soil was exposed, including locations on the road surface, in roadside ditches, within the road right-of-way, or on landings were coded as "disturbed". All points surveyed where mineral soil was not exposed were coded as "undisturbed".

2.4.3.3 DEM Generation, Sub-Catchment Delineation, And Feature Mapping

ArcInfo Geographic Information System (GIS) software (version 7.2, Environmental Systems Research Institute) was used to import DTM point data and feature locations into a GIS database. The ANUDEM algorithm (Hutchinson 1988), available through ArcGrid with the TOPOGRIDTOOL command, was used to generate a pre-disturbance and a post-disturbance DEM for each cutblock area. Each DEM was created at a five metre resolution. DTM points coded "undisturbed" were used to generate the pre-disturbance DEMs and those coded "undisturbed" or "disturbed" were used to generate the post-disturbance DEMs. DTM points from the OMNR's Natural Resources Values

Information System (NRVIS) data set were used to supply point elevations for areas within DEM extents that were outside the extents of the areas surveyed with the total station.

All DEMs were filled using the FILL command in ArcGrid, then a D8 flow direction grid (Jenson and Domingue 1988) and a flow accumulation grid were generated from each filled DEM using the FLOWDIRECTION and FLOWACCUMULATION commands available through ArcGrid. Flow accumulation paths were viewed by displaying all cells with accumulation $\geq$ 25 cells (equivalent to $\geq$ 0.0625 ha contributing area). Using sampler locations as pour points, pre-disturbance and post-disturbance sub-catchments were delineated using the appropriate grid data sets and the ArcGrid WATERSHED command. The results of the raster watershed delineations were used to determine pre-disturbance and post-disturbance sub-catchment areas for each sampler by multiplying the number of cells in the sub-catchments by the area of a grid cell (25 sq m). The shortest distance between each sampler and the road was measured from the GIS database using ArcView.

A secondary topographic attribute, Beven and Kirkby's (1979) topographic index (TI) was derived by applying equation (1) with the primary topographic attributes, sub-catchment area and slope that were derived from each of the filled DEMs. Sub-catchment areas were derived from the flow accumulation grid described previously. The flow accumulation algorithm assigns zero values to headwater cells located along sub-catchment boundaries and to cells that represent peaks within a catchment. To calculate TI, these zero values had to be eliminated, so ArcGrid was used to add the value "one" to each cell in the grid. As a single flow direction algorithm (the D8) was used to model the direction of flow out of each cell, the upstream contributing area per unit contour length for each cell was derived by multiplying the number of cells contributing flow to a cell (as defined in the grid with one added to the flow accumulation count) by the grid resolution (Quinn *et al.* 1991), which for this study was equal to five. The SLOPE command (with the degrees option) available in ArcGrid was used to derive a grid of slope (in degrees) for each cell in the filled DEM. Once the requisite secondary grids were generated, TI grids were derived (by applying equation (1).

2.5 SEDIMENT COLLECTION AND PROCESSING

2.5.1 Sampler Cleanout

The volume of runoff water collected in a sampler was measured (with maximum capacity = 89 L) and eliminated by bailing it out of the sampler and pouring it through a stack of brass sieves that sat over a 25 L pail. The sieve stack included 3.35 mm, 1.70 mm, 850 μm, 425 μm, and 212 μm sieves, which was a collection similar to that used to evaluate the effects of sediment on salmonid spawning redds (Chapman 1988). To sample the fraction of particles that were less than 212 μm, a 500 ml grab sample was collected through the complete depth of each full 25 L bucket, after the volume was stirred to put particles in suspension. When the volume of bailed water was sufficient to fill only a fraction of the 25 L bucket, the grab sample volume was reduced to an approximately equal fraction of 500 ml. Grab samples collected from successive 25 L pails bailed from a sampler were combined, and a single composite 500 ml grab sample was collected from that volume.

The inside surfaces of the sampler were brushed and rinsed with laboratory wash bottles filled with water that had been passed through the sieves. Mineral and organic material were then collected from the bottom of the sampler and added to the sieve stack. Finally, 20 L of filtrate that had passed through the sieve stack were poured through the sieves to rinse the material through and sort it by size. The material that had been collected on each sieve was then rinsed into separate 500 ml sample jars labeled with the appropriate sampler identification code, sieve screen size, and date. Excess water in the sample jars was decanted through the 212 μm sieve.

When the volume of the mineral and organic material was more than approximately 2 L, it was taken back to the lab in 25 L pails for sieving after most of the water was eliminated by pouring it through the 212 μm sieve that was set over a 25 L pail, and grab samples were collected by following the procedures described above. At the lab, these samples were sorted through the sieves using a hose and tap water. After sieving, these samples were rinsed into labeled 500 ml sample jars. Excess water in the sample jars was decanted through the 212 μm sieve. Grab samples were collected from the rinse water used at the lab as per the procedure used in the field, described above. This method provided a means of measuring the total volume of rinse water that was used.

This volume was needed to calculate the total mass of < 212 μm sediment from the mass determined by processing the grab sample.

2.5.2 Sample Processing

Two sets of procedures were used to process sediment samples for determining mineral and organic contents by weight. Procedure (A) was applied to all material with a particle size ≥ 212 μm. This sediment was filtered by one of the screens included in the sieve stack used to eliminate the liquid portion of the runoff collected by the samplers. Procedure (B) was applied to all material with a particle size < 212 μm. This sediment passed through all screen sizes included in the sieve stack used to eliminate the liquid portion of the runoff collected by the samplers.

The following two sections describe procedures (A) and (B), and Figure 2.9 graphically summarizes the two procedures through a flow chart.

2.5.2.1 Procedure (A): Particles > 212 μm

Water remaining in the sample jars was eliminated by vacuum filtering the contents of each jar through oven dried and pre-weighed 18.5 cm diameter, fast flowing, coarse porosity (25 μm) qualitative filters placed in Büchner-type funnels. Sieved size fractions were kept separate by using a different filter for the contents of each sample jar. All filtrate was discarded. Filters were placed on labelled foil trays that supported the filters

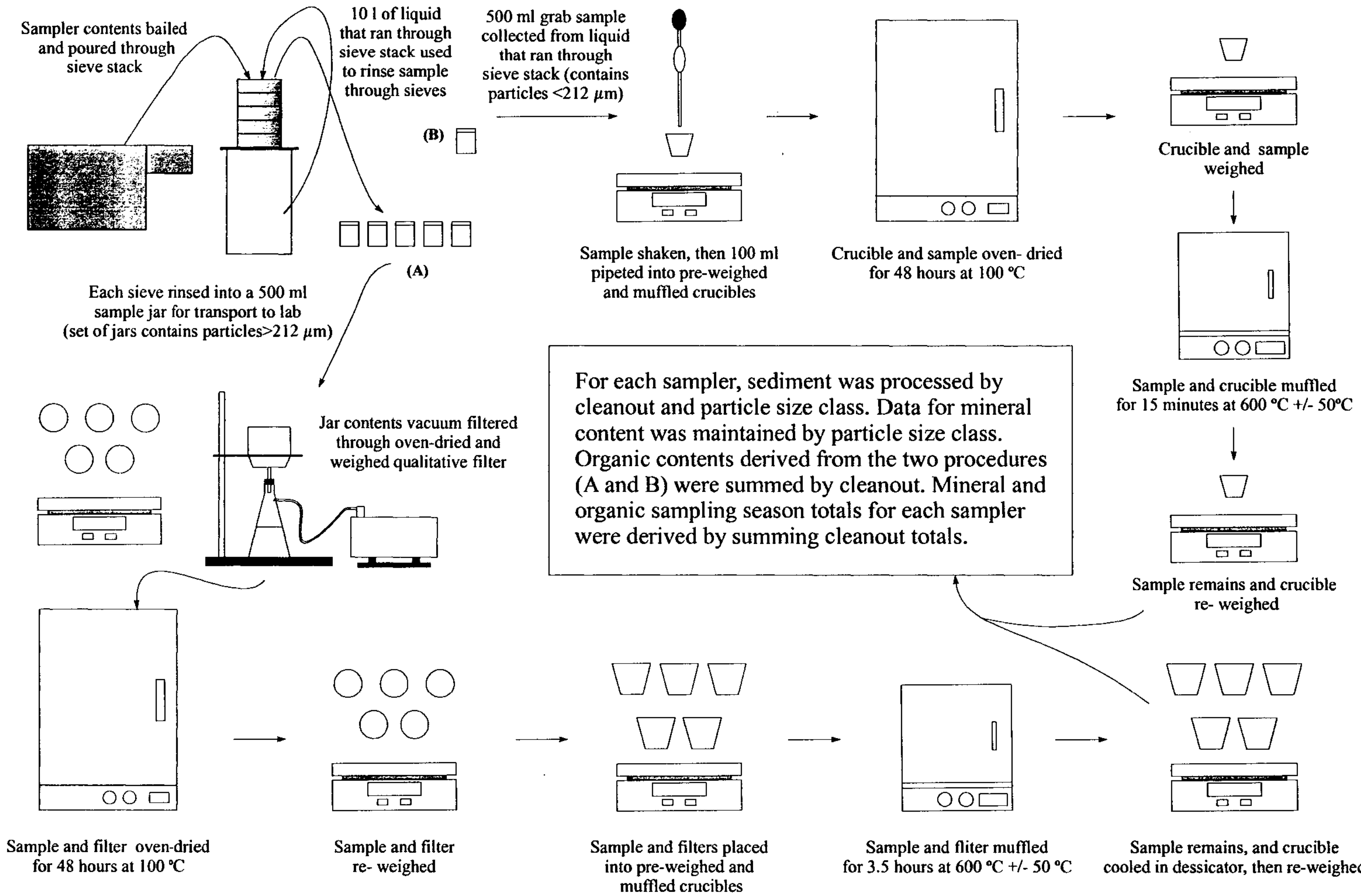


Figure 2.9 Sample collection and lab processing steps to determine mineral and organic content for sediment collected using procedure "A": sediment collected on sieves (3.35 μm, 1.70, 0.850 μm, 0.425 μm, and 0.212 μm sieves), and procedure "B": sediment <212 μm.

while they were oven dried at 100 °C for at least 48 hours. Filters and samples were weighed to the nearest gram x 10^{-3} after oven drying. An oven dried total sample weight (mineral and organic) was determined for each size fraction, for each sampler by subtracting the weights of the oven dried filters.

The samples and filters were then placed in prepared crucibles (pre-muffled and pre-weighed to the nearest gram x 10^{-3}) and were then muffled at 600° C (+/- 50° C) for 3.5 hours. After the crucibles and remaining fractions of the samples were allowed to cool in a dessicator, they were again weighed to the nearest gram x 10^{-3}.

The weight of mineral matter for each particle size fraction was determined for each sampler by subtracting the weight of the oven dried filters and prepared crucibles from the combined weight of the muffled samples, filters, and prepared crucibles together. The weight of the organic portion of all material collected on each sieve was calculated by subtracting the weight determined for the mineral matter from the oven dried total sample weights. No effort was made to report size distributions of organic material because it was subject to structural breakdown during the various steps involved with collecting and processing the samples. Total mineral and total organic weights for each sampler cleanout were determined by summing the mineral or organic weights calculated for each sieve used to process all material collected during a sampler cleanout event.

The mass of all mineral and all organic material collected in a sampling season was determined by summing cleanout totals collected over each sampling season. Totals for the 1997 season included the material from all cleanouts as all of that material was transported by runoff from precipitation. To maintain legitimate comparisons between data collected over the three years, totals for 1998 and 1999 excluded material collected during the first cleanouts as much of that material could have been transported by runoff from snowmelt rather than from runoff generated by precipitation that fell as rain.

A seasonal collection rate ($g \cdot mm^{-1}$ precipitation) was calculated for the collection of each material, mineral and organic, for each sampler. This was accomplished by dividing the seasonal total mass of material collected in a sampler (mineral or organic) by the total amount of effective precipitation the sampler was subject to during the sampling season.

2.5.2.2 Procedure (B): Particles < 212 μm

After being shaken to put particles in suspension, 100 ml of the < 212 µm sample was pipetted through the full depth of each grab sample jar. The pipetted volume was placed into a prepared 150 ml crucible (previously oven dried, placed in a muffle furnace at 550° C for 15 minutes, and weighed to the nearest milligram). The sample and crucible were put into a drying oven set at 100° C for at least 48 hours, after which time they were removed and weighed again. The sample and crucible were then placed into a muffle furnace set at 600° C (+/- 50° C) for 15 minutes. After cooling, the crucible and contents were again weighed to the nearest milligram.

The oven dried total weight of the < 212 μm sample was determined by subtracting the weight of the prepared crucible from the combined weight of the prepared crucible and sample after they were oven dried. The weight of the mineral portion of the sample was determined by subtracting the weight of the prepared crucible from the combined weight of the crucible and sample after they were muffled together. The weight of the organic portion of the sample was determined by subtracting the weight determined for the mineral material from the oven dried total weight.

Equation (3) was used to calculate the total mass of mineral and organic sediment < 212 μm that were collected by a sampler during a collection period from the mass of mineral or organic matter determined for the 100 ml pipetted sample.

$$\text{Total Mass} <212\ \mu\text{m} = V / 10 * M \quad (3)$$

Where:

V = Volume (in litres) bailed from sampler

M = Mass of mineral or organic sediment determined for 100 ml sample

2.6 DATA ANALYSES

Data were analysed by comparing descriptive statistics for mineral and organic collection rates for samplers based on groups defined by the variables described previously. Indices of change were calculated to quantify changes in mineral and organic collection rates and changes that were observed in the measured condition of the variables that were examined for their influence on sediment collection rates. Plots of the data were evaluated to determine: 1) the impact of forest management on mineral and organic sediment collection rates and 2) the influence of the factors on mineral and organic collection rates.

Sediment collection rate data for samplers were not normally distributed, and variances in sediment collection rates among groups of samplers (as defined by the variables described previously) were not equal. These conditions rendered data analysis with parametric techniques inappropriate as the assumptions (data normally distributed and with homogeneity of variance) were not met (Zar 1974). Furthermore, analysis using either parametric or non-parametric techniques would have been complicated by the repeated measuring of sediment collected in the samplers and the fact that it was not possible to replicate any of the samples (Zar 1974).

2.6.1 Index Of Change Analyses - Sediment Transport Rates

Pre- and post-harvest sediment collection rates for each sampler were compared by calculating indices of change from mineral and organic collection rates determined for each year, 1997, 1998, and 1999. Four indices were calculated for each sampler that remained in service for each of the three years: 1) 1998/97 Mineral Index of Change (98/97 MIOC) compared the mineral collection rate observed in 1998 against that observed in 1997, 2) 1998/97 Organic Index of Change (98/97 OIOC) compared the organic collection rate observed in 1998 against that observed in 1997, 3) 1999/97

Mineral Index of Change (99/97 MIOC) compared the mineral collection rate observed in 1999 against that observed in 1997, 4) 1999/97 Organic Index of Change (99/97 OIOC) compared the organic collection rate observed in 1999 against that observed in 1997. The 99/97 index of change (IOC) values could not be calculated for samplers that were not in service during the 1999 sampling season.

The IOC values were calculated by applying equation (4).

$$IOC = \ln (r_2/r_1) \qquad (4)$$

Where:

r_1 = rate (g·mm^{-1} precip) in 1997

r_2 = rate (g·mm^{-1} precip) in 1998 or 1999

Positive IOC values indicate a rate increase in 1998 or 1999 over 1997 while negative values indicate a rate decrease in 1998 or 1999 compared to 1997.

2.6.2 Index Of Change Analyses - Other Variables

Index of change values were calculated to compare 1997 (pre-disturbance) and 1998 (first post-harvest year) or 1999 (second post-harvest year) values for several local and catchment scale attributes that were measured on a ratio scale (Table 2.3). Equation (5) was applied to calculate these indices of change.

$$IOC = \ln (t_2 / t_1) \qquad (5)$$

Where:

t_1 = value of attribute as measured in 1997

t_2 = value of attribute as measured in 1998 (first year post-harvest) or 1999 (second year post-harvest)

Application of equation (5) resulted with a positive IOC value when the post-harvest measure of an attribute was greater than the pre-harvest measure. A negative IOC value resulted when the post-harvest value of an attribute was less than the pre-harvest measure of the attribute.

Only those data collected on a ratio scale were suited for this analysis. During the period of this study LFH thickness and topographic gradient were measured at each sampler only once as the conditions of these attributes were not expected to change during the period of the study. Index of change values were not calculated for the "sampler distance from road" and "sampler position within reserve" variables as these conditions could not be measured in the pre-disturbance situation.

An IOC value was calculated to quantify how the size of the sub-catchment above each sampler was affected by the construction of the road and landings. The IOC values were also calculated to quantify differences in crown closure measured in 1998 or 1999 against that measured in 1997.

The local and catchment scale IOC values were plotted as independent variables against IOC values for mineral and organic collection rates to investigate how changes in the conditions of these attributes mitigated or encouraged sediment transport into the samplers.

3.0 RESULTS

Sampling period duration and the number of sampling events (cleanouts) are presented in Table 3.1. Sampling occurred as regularly as possible given the constraints of weather and labour. In 1997 the total number of days sampled ranged from 83 to 127 days. Sampler NM-30 was taken out of service for a period of time in 1997 after sustaining flume damage from a windthrown tree. When sampler NM-30 was excluded, the sampling period duration in 1997 ranged from 119 to 127 days. In 1998 the sampling period duration ranged from 188 to 197 days, and in 1999 the sampling period duration ranged from 88 to 91 days.

3.2 PRECIPITATION

All raingauge readings for the spring through fall sampling period for the years 1997, 1998, and 1999 are plotted in Figures 3.1, 3.2, and 3.3, respectively. The amount of rainfall affecting sediment movement, totaled by sampling season for each sampler, is presented in Table 3.2. Thirty year normal precipitation data from the Thunder Bay Airport were plotted with precipitation data collected at the clearcut to determine if the pattern and amount of precipitation that fell on the study area was similar to 30 year normal data from the Thunder Bay Airport.

Table 3.1. Start and end dates of each sampling season for each of the samplers, and duration of each sampling season for each sampler. The first cleanings in 1997 removed debris collected in samplers following installation. The first cleanings in 1998 and 1999 removed sediment transported by spring runoff.

Sampler	First Clean '97	Last Clean '97	# Days '97	First Clean '98	Last Clean '98	# Days '98	First Clean '99	Last Clean '99	# Days '99
NM-00	04 Jul	31 Oct	119	20 May	26 Nov	190	11 Jun	07 Sep	88
NM-10	04 Jul	06 Nov	125	20 May	27 Nov	191	11 Jun	07 Sep	88
NM-20	04 Jul	06 Nov	125	20 May	27 Nov	191	11 Jun	07 Sep	88
NM-30	04 Jul	25 Sep	83	20 May	26 Nov	190	11 Jun	07 Sep	88
NR-00	04 Jul	31 Oct	119	19 May	23 Nov	188	10 Jun	07 Sep	89
NR-10	04 Jul	31 Oct	119	19 May	24 Nov	189	10 Jun	07 Sep	89
NR-20	04 Jul	31 Oct	119	19 May	23 Nov	188	10 Jun	07 Sep	89
NR-30	04 Jul	31 Oct	119	19 May	23 Nov	188	10 Jun	07 Sep	89
SM-00	03 Jul	07 Nov	127	12 May	18 Nov	190	09 Jun	08 Sep	91
SM-10	03 Jul	07 Nov	127	12 May	18 Nov	190	09 Jun	08 Sep	91
SM-20	03 Jul	07 Nov	127	12 May	18 Nov	190	09 Jun	08 Sep	91
SM-30	03 Jul	07 Nov	127	12 May	18 Nov	190	09 Jun	08 Sep	91
SR-00	03 Jul	05 Nov	125	12 May	17 Nov	189	09 Jun	08 Sep	91
SR-10	03 Jul	06 Nov	126	12 May	25 Nov	197	09 Jun	08 Sep	91
SR-20	03 Jul	05 Nov	125	12 May	25 Nov	197	09 Jun	08 Sep	91
SR-30	03 Jul	06 Nov	126	12 May	17 Nov	189	09 Jun	08 Sep	91

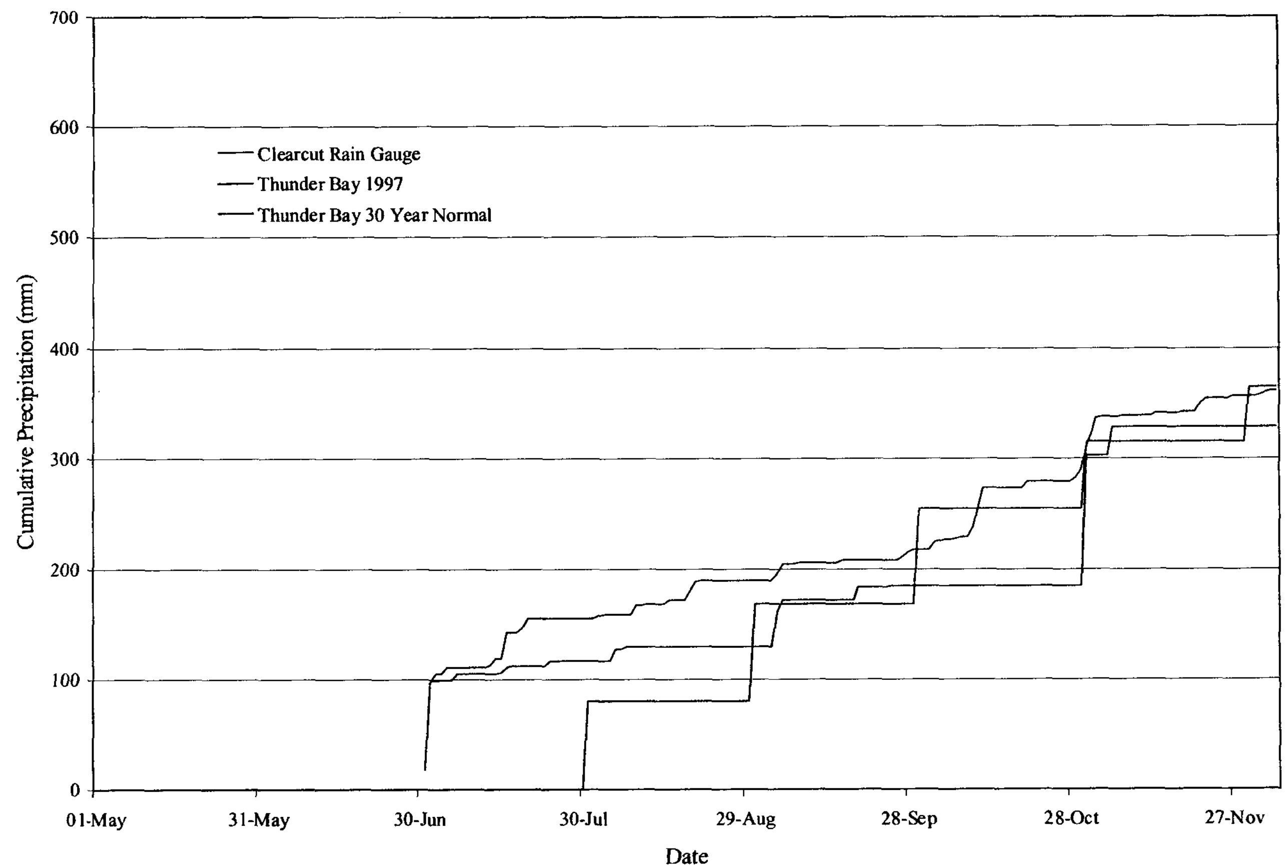
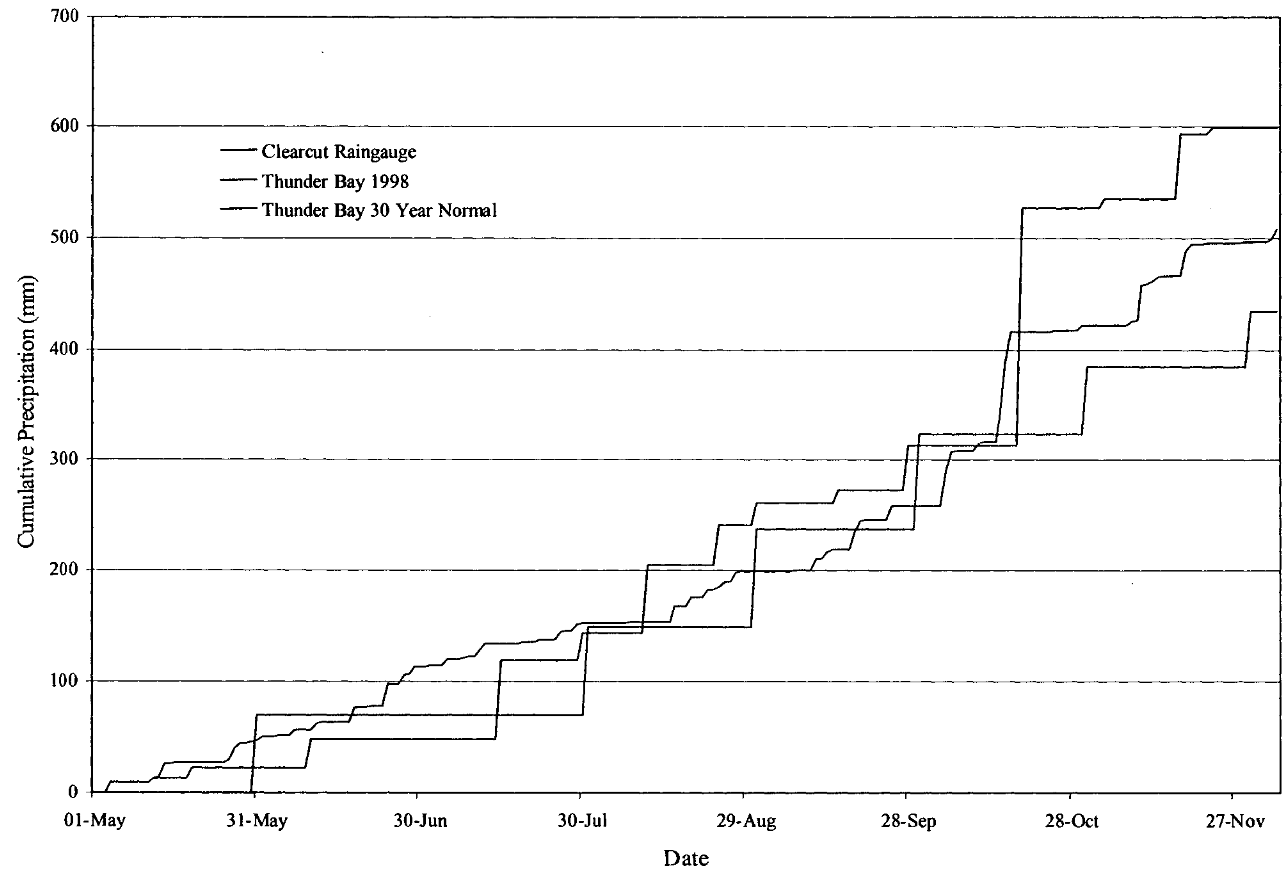


Figure 3.1 Cumulative total precipitation (mm) collected during the 1997 sampling season at the study site and Thunder Bay Airport, and normal (30 year) monthly precipitation for the Thunder Bay Airport. (Environment Canada 1997)



Data).

Figure 3.2. Cumulative total precipitation (mm) collected during the 1998 sampling season at the study site and Thunder Bay Airport, and normal (30 year) monthly precipitation for the Thunder Bay Airport (Environment Canada 1998).

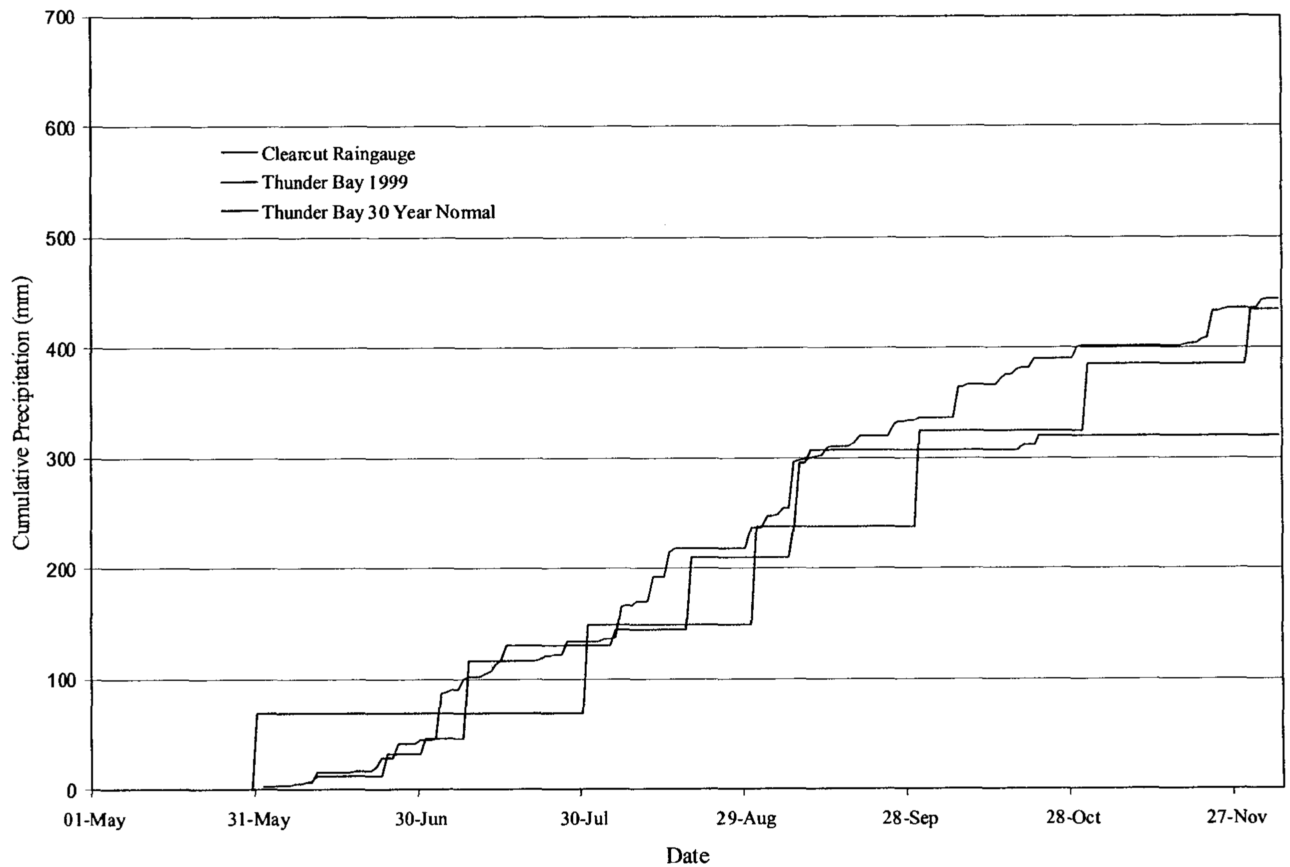


Figure 3.3. Cumulative total precipitation (mm) collected during the 1999 sampling season at the study site and Thunder Bay Airport, and normal (30 year) monthly precipitation for the Thunder Bay Airport (Environment Canada 1999).

Table 3.2 Total amount of precipitation (mm) affecting each sampler, by year.

Sampler	1997	1998	1999
NM-00	203.2	578.1	n/a
NM-10	240.4	578.1	n/a
NM-20	241.7	578.1	228.1
NM-30	85.2	578.1	n/a
NR-00	203.2	578.1	232.6
NR-10	203.2	578.1	n/a
NR-20	203.2	578.1	232.6
NR-30	203.2	578.1	232.6
SM-00	229.2	581.5	288.2
SM-10	229.2	581.5	n/a
SM-20	229.2	581.5	288.2
SM-30	229.2	581.5	n/a
SR-00	229	581.5	288.2
SR-10	229	587.3	288.2
SR-20	229	587.3	288.2
SR-30	229	581.5	288.2

The amount of precipitation that fell at the clearcut during the summer of 1997 was lower than the 30 year normal amount for the Thunder Bay Airport; however, rain events late in the fall brought the total amount of precipitation for the spring through fall period close to but slightly below the area normal (Table 3.2 and Figure 3.1). During most of the 1998 spring through fall sampling period the clearcut raingauge collected precipitation in a pattern and amount that closely matched data for the Thunder Bay Airport. Late October storm events produced precipitation in amounts sufficient to drive the 1998 sampling season total approximately 100 mm above normal amounts for the Thunder Bay Airport (Table 3.2 and Figure 3.2). The plot of the 1999 precipitation data closely matched the pattern and total amount presented by the 30 year normal data for the Thunder Bay Airport (Table 3.2 and Figure 3.3).

The amount of precipitation available to affect runoff potential varied not only among years, but also among samplers for any year (Table 3.2). In 1997 the total amount of effective precipitation among samplers ranged from 85.2 to 241.7 mm with sampler NM-30 subjected to the lowest amount of effective precipitation because flume damage from a windthrown tree caused it to be removed from service for a period of time. After excluding NM-30, the amount of effective precipitation ranged from 203.2 to 241.7 mm. The amount of effective precipitation among samplers in 1998 ranged from 578.1 to 587.3 mm. The amount of effective precipitation among samplers in 1999 ranged from 228.1 to 288.2 mm.

3.2 TRANSPORTED SEDIMENT

3.2.1 Rainfall Induced Sediment Transport

Summary statistics for mineral and organic sediment collection rates for all samplers for the years 1997, 1998, and 1999 are reported in Table 3.3. Mineral and organic sediment collection rates for each sampler are reported in Appendix II. Mineral and organic collection rates for each sampler are plotted by year in Figures 3.4 (1997), 3.5 (1998), and 3.6 (1999). The 1997 median mineral rate was almost 1.6 times greater than the 1998 median and more than 2 times greater than the 1999 median. Organic rate medians calculated for 1997 and 1998 were near identical; however, the 1999 rate was almost 75 percent lower than these. The range among samplers in the rate that organic matter was collected exceeded that for mineral matter for each of the years 1997 and 1998 (n=16), and 1999 (n=10) (Table 3.3), and each sampler always collected organic matter at a higher rate than mineral material (Figures 3.4, 3.5, 3.6, and Appendix II). In 1997 the range for organic collection was more than four times greater than the range for mineral collection. In 1998 the range for organic collection was only 1.6 times greater than the range for mineral collection. The 1998 mineral collection rate calculated for sampler NR-10 far exceeded that calculated for any other sampler, and the rate for this sampler reduced the difference between the ranges for mineral and organic collection rates that year (Table 3.3, Figure 3.5, and Appendix II). Organic collection rates calculated from 1999 data had a range that was more than 6.5 times that for mineral matter that same year.

Table 3.3 Summary statistics for mineral and organic sediment collection rates ($g \cdot mm^{-1}$ precip) for all samplers, in 1997 (pre-impact), and 1998 and 1999 (first and second years post-impact).

Year	Material	Median	Range	Maximum	Minimum
1997	Mineral	0.0014	0.0054	0.0060	0.0006
1997	Organic	0.0056	0.0239	0.0265	0.0026
1998	Mineral	0.0009	0.7650	0.7652	0.0002
1998	Organic	0.0050	1.2606	1.2625	0.0019
1999	Mineral	0.0006	0.0021	0.0024	0.0003
1999	Organic	0.0014	0.0143	0.0152	0.0009

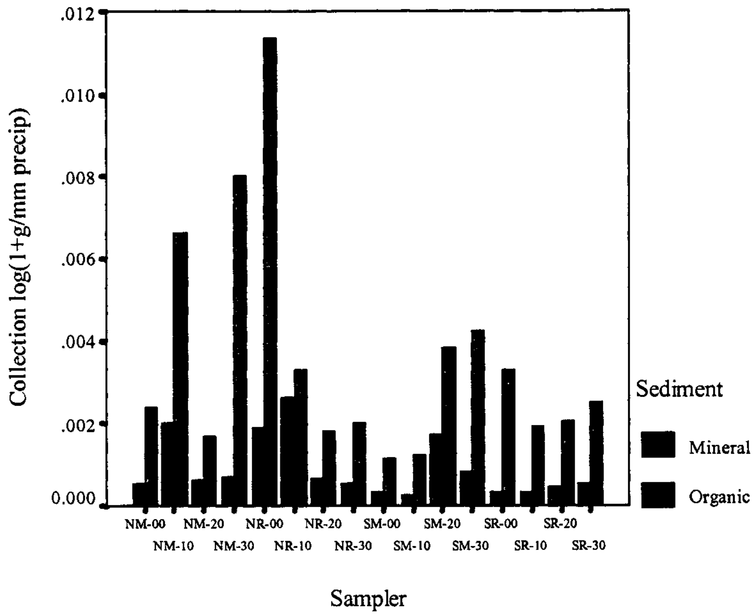


Figure 3.4 Pre-impact (1997) organic and mineral sediment collection rates ($\log(1+g{\cdot}mm^{-1}$ precip)) for each sampler.

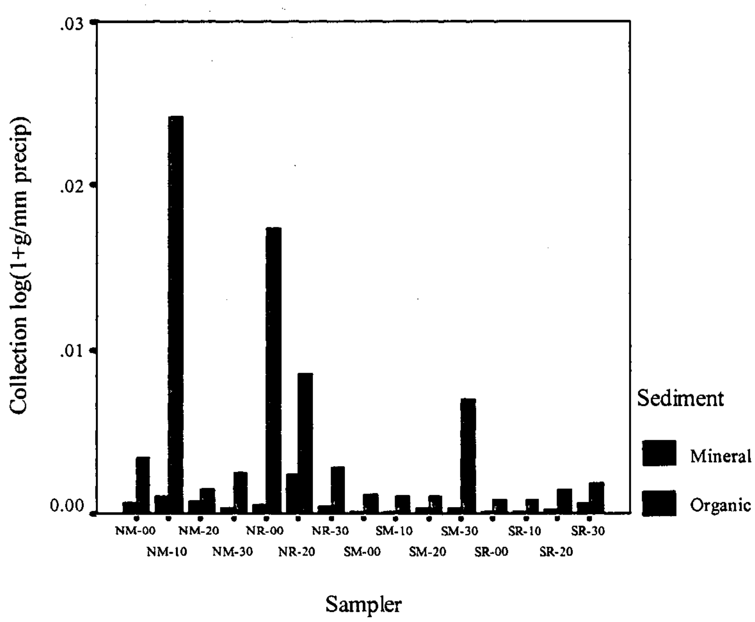


Figure 3.5 First year post-impact (1998) organic and mineral sediment collection rates ($\log(1+g{\cdot}mm^{-1}$ precip)) for each sampler (NR-10 excluded).

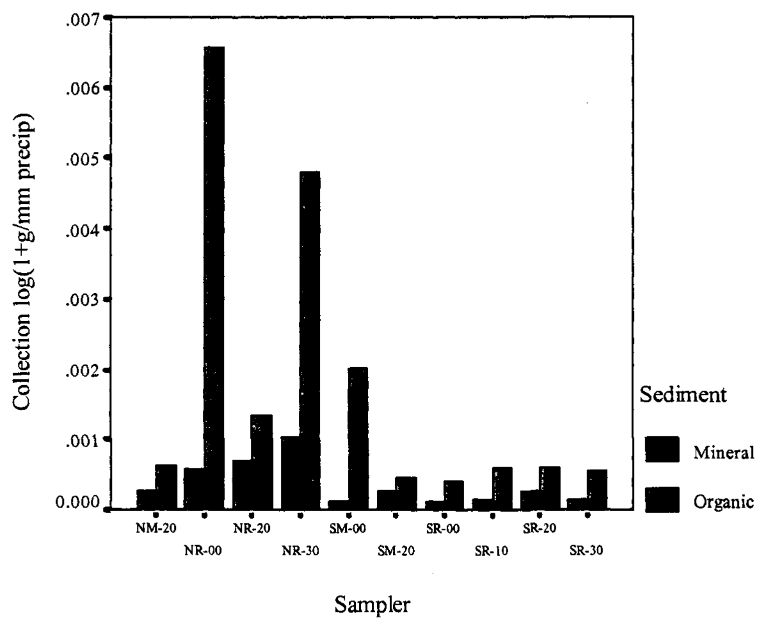


Figure 3.6 Second year post-impact (1999) organic and mineral sediment collection rates (log(1+g·mm^{-1} precip)) for each of the ten samplers remaining in service.

3.2.2 Post Impact Differences In Sediment Collection Rates

Descriptive statistics (number, median, range, maximum and minimum) for 1998/97 MIOC and OIOC and 1999/97 MIOC and OIOC values were calculated based on three different grouping structures: 1) All samplers remaining in service in the post-impact year, 2) All samplers with higher post-impact collection rates (positive IOC values), and 3) All samplers with lower post-impact collection rates (negative IOC values) (Table 3.4). Mineral and organic IOC values comparing sediment transport rates for each sampler in 1998 with those in 1997 are plotted in Figure 3.7. Mineral and organic IOC values comparing sediment transport rates for each sampler in 1999 with those in 1997 are plotted in Figure 3.8. The MIOC and OIOC values (1998/97 and 1999/97) for each sampler are reported in Appendix III.

Compared to 1997, five of 16 samplers collected mineral material at a higher rate in 1998, and the remaining 11 samplers collected mineral material at lower rates in 1998 compared to 1997. Seven samplers collected organic material at a higher rate in 1998 compared to 1997 while the remaining nine samplers collected organic material at lower rates in 1998 compared to 1997. In 1999, the second post-harvest year, only 10 samplers remained in service. During that year a pair of samplers collected mineral material at higher rates than were observed in 1997. The remaining eight samplers collected mineral material at lower rates in 1999 compared to 1997. Two samplers collected organic matter at higher rates in 1999 compared to 1997. The remaining eight samplers collected organic material at lower rates in 1999 compared to 1997.

Table 3.4 Descriptive statistics for mineral and organic indices of change (MIOC and OIOC, respectively) values. Statistics are reported by comparison grouping (1998/97 or 1999/97) and material type (mineral or organic) with samplers grouped in three different ways: 1) All samplers remaining in service in the post-impact year, 2) All samplers with higher post-impact collection rates (positive IOC values), 3) All samplers with lower post-impact collection rates (negative IOC values).

Group	Statistic	98/97 MIOC	98/97 OIOC	99/97 MIOC	99/97 OIOC
All	N	16	16	10	10
	Median	-0.7537	-0.0808	-0.8989	-1.0778
	Range	6.7267	6.4992	2.5272	2.9949
	Maximum	4.8425	5.1125	0.6476	0.8734
	Minimum	-1.8842	-1.3867	-1.8795	-2.1214
Positive	N	5	7	2	2
	Median	0.1766	0.5150	0.34286	0.7285
	Range	4.7371	4.7925	0.6096	0.2900
	Maximum	4.8425	5.1125	0.6476	0.8734
	Minimum	0.1055	0.3199	0.0381	0.5835
Negative	N	11	9	8	8
	Median	-0.8669	-0.3391	-1.0032	-1.1870
	Range	1.5947	1.3515	1.3192	1.8211
	Maximum	-0.2894	-0.0352	-0.5603	-0.3003
	Minimum	-1.8842	-1.3867	-1.8795	-2.1214

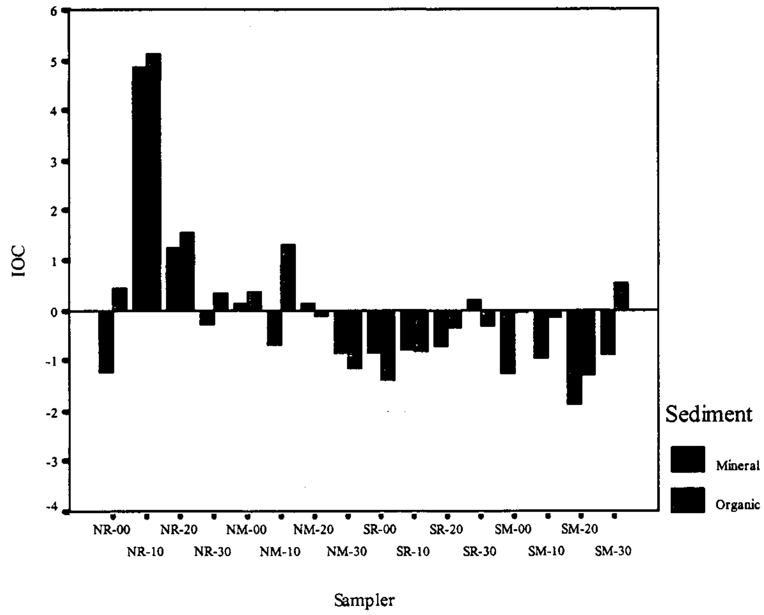


Figure 3.7 1998/97 Index of change (IOC) values for mineral and organic sediment collection rates for each sampler.

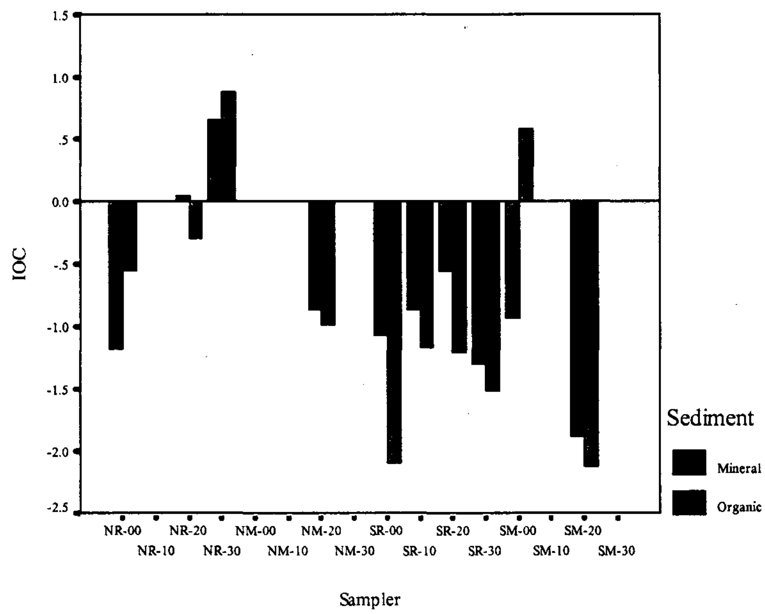


Figure 3.8 1999/97 Index of change (IOC) values for mineral and organic sediment collection rates for each sampler.

A post-harvest increase in the rate a sampler collected one material (mineral or organic) did not always coincide with an increase for the other, as is clearly demonstrated by membership differences between the two groups described above (Figures 3.7, 3.8, and Appendix II).

In general, there was only marginal change in the post- compared with pre-impact mineral or organic collection rates for each sampler; however, rate changes from 1997 to 1998 for NR-10 and NR-20 were exceptions to this (Figure 3.7 and Appendix II). Mineral and organic collection rates for all samplers generally were lower during the post harvest years; however, 1997 to 1998 rate differences for samplers NR-10 and NR-20 were prominent exceptions to this condition (Appendix 2 and Figure 3.7). The 98/97 MIOC value for sampler NR-10 was 4.8425 and far exceeded that of any other sampler. The 98/97 MIOC value for NR-20 was the second highest and was one quarter of that for NR-10. The 98/97 OIOC value for sampler NR-10 was 5.1125 and far exceeded that of any other sampler. The 98/97 OIOC value for NR-20 was the second highest and was one third of that for NR-10. The organic collection rate increase for sampler NM-10 in 1998 compared to 1997 was also prominent; however, it was about one quarter of that posted by NR-10 (Appendix 2 and Figure 3.7).

3.2.3 Reserve Width Effects On Sediment Collection Rates

Mineral and organic collection rates for each sampler position in the reserve (0, 10, 20 or 30 m) for 1997, 1998, and 1999 data are presented in Figures 3.9, 3.10, and 3.11.

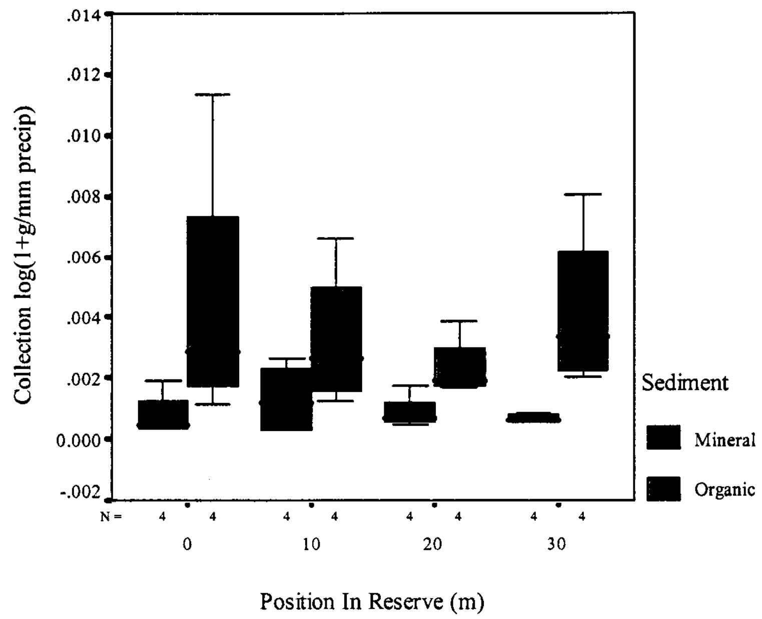


Figure 3.9 Mineral and organic sediment collection rates (log(1+g·mm^{-1} precip)) in 1997, by sampler position in the reserve (0, 10, 20, or 30 m). Boxplots show the median, 25th and 75th percentiles, and maximum and minimum values.

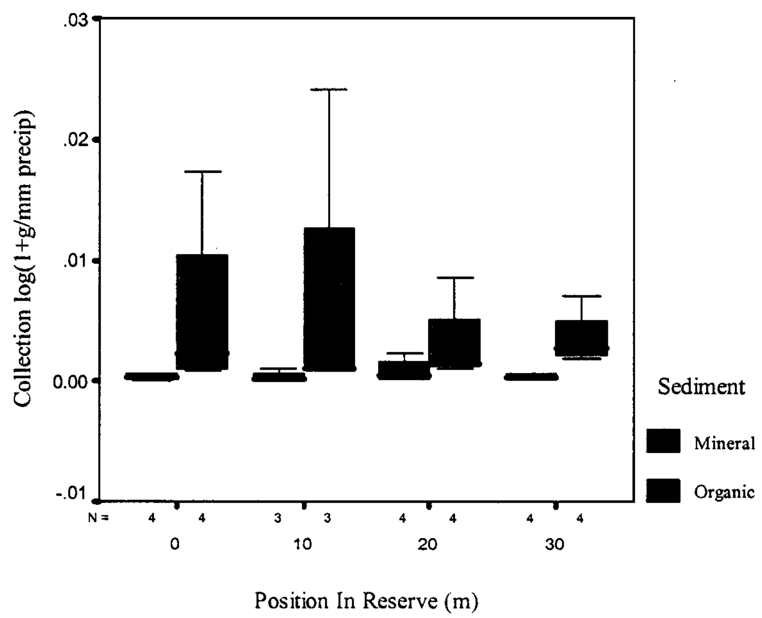


Figure 3.10 Mineral and organic sediment collection rates (log(1+g·mm^{-1} precip)) in 1998, by sampler position in the reserve (0, 10, 20, or 30 m) (data for NR-10 excluded). Boxplots show the median, 25th and 75th percentiles, and maximum and minimum values.

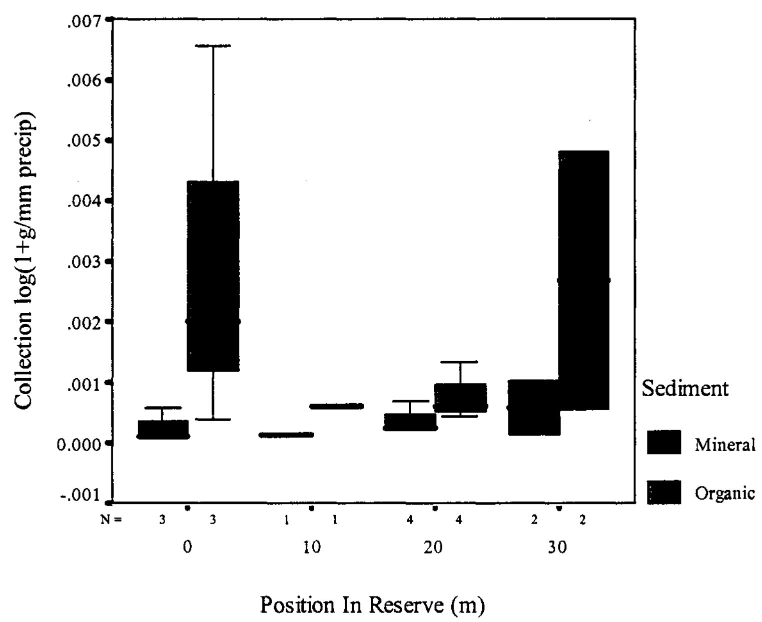


Figure 3.11 Mineral and organic sediment collection rates (log (1+g·mm^{-1} precip)) in 1999, by sampler position in the reserve (0, 10, 20, or 30 m). Boxplots show the median, 25th and 75th percentiles, and maximum and minimum values.

The 1997 data are supplied for comparison with post-harvest data and to report patterns in sediment collection rates that were observed through the stream side forest areas before forest management impacts had occurred. Descriptive statistics for mineral and organic sediment collection rates by sampler position in the reserve for each year are presented in Appendix IV.

In 1997, the median and range in mineral collection rates were similar among sampler positions in the reserve (Figure 3.9). The median rates of organic collection were similar among the four sampler positions in the reserves, but the range among samplers at a specific position in the reserve tended to decrease as distance into the reserves increased (Figure 3.9).

In 1998, the median mineral collection rates for samplers at all positions in the reserves were similar. However, the ranges in mineral collection rates were 637 and 6 times greater in the 10 and 20 m positions respectively, compared to the 0 and 30 m positions (Figure 3.10). The 1998 median organic collection rates for all positions within the reserves were similar, but samplers at 10 m positions had a range more than 104, 72, and 30 times greater than the magnitude of range among samplers located respectively at 30, 20, and 0 m positions (Figure 3.10).

In 1999, only one sampler in a 10 m position was in service, but the ranges in mineral collection rates among samplers located at the 0, 20, and 30 m positions were similar (Figure 3.11). However, at 0.001 $g{\cdot}mm^{-1}$ precip, samplers located 30 m into the reserves had the highest median mineral collection rate, and there tended to be a positive relationship between both the range and median mineral collection values and distance into the reserve. In 1999, the ranges in the organic collection rates were similar for samplers installed at the 0 and 30 m positions, and the median collection rates were 10 and 4.3 times higher, respectively, than the median rate for samplers at the 20 m positions.

To further evaluate the influence of forest management on sediment movement in the reserve, descriptive statistics (number, median, range, maximum and minimum) for 1998/97 MIOC and OIOC and 1999/97 MIOC and OIOC values were calculated for each sampler position in the reserve (m into reserve measured from the reserve/cutover boundary) (Table 3.5). The 1998/97 MIOC and OIOC values for each sampler are plotted with sampler position in the reserve in Figures 3.12 and 3.13. Most of the samplers collected mineral and organic matter at lower rates in 1998; however, samplers NR-10 and NR-20 were notable exceptions. The magnitude of reduction observed in sediment collection rates in 1998 compared to 1997 does not appear to be related to sampler position in the reserve. The 1999/97 MIOC and OIOC values for each sampler are plotted with sampler position in the reserve in Figures 3.14 and 3.15. Again, most of the samplers collected mineral and organic matter at lower rates in 1999. Sampler NR-10 was not in service during 1999, but mineral and organic collection in sampler NR-20 were less that year compared to 1997. The level of reduction observed in 1999 compared to 1997 collection rates did not appear to be related to sampler position in the reserve.

Table 3.5 Descriptive statistics for 1998/97 mineral and organic indices of change (MIOC and OIOC, respectively) and 1999/97 MIOC and OIOC values by sampler position in the reserve.

		1998/97		1999/97	
Position	Statistic	MIOC	OIOC	MIOC	OIOC
0	N	4	4	3	3
	Median	-1.0390	0.1611	-1.0737	-0.5537
	Range	1.3884	1.8163	0.2481	2.6801
	Maximum	0.1082	0.4296	-0.9328	0.5835
	Minimum	-1.2802	-1.3867	-1.1810	-2.0967
10	N	4	4	1	1
	Median	-0.7415	0.5823	-0.86184	-1.1651
	Range	5.8002	5.9513	0.0000	0.0000
	Maximum	4.8425	5.1125	-0.8618	-1.1651
	Minimum	-0.9577	-0.8389	-0.8618	-1.1651
20	N	4	4	4	4
	Median	-0.3123	-0.2328	-0.7127	-1.0996
	Range	3.1230	2.8675	1.9176	1.8211
	Maximum	1.2388	1.5562	0.0381	-0.3003
	Minimum	-1.8842	-1.3113	-1.8795	-2.1214
30	N	4	4	2	2
	Median	-0.5781	0.0075	-0.3246	-0.3231
	Range	1.0850	1.6812	1.9445	2.3931
	Maximum	0.1766	0.5150	0.6476	0.8734
	Minimum	-0.9085	-1.1662	-1.2969	-1.5197
Total	N	16	16	10	10
	Median	-0.7537	-0.0808	-0.8989	-1.0777
	Range	6.7267	6.4992	2.5272	2.9949
	Maximum	4.8425	5.1125	0.6476	0.8734
	Minimum	-1.8842	-1.3867	-1.8795	-2.1214

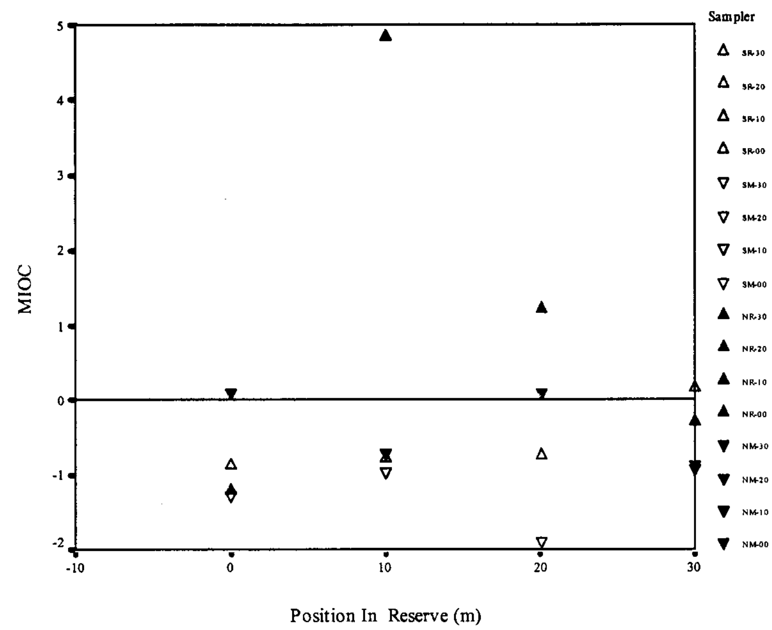


Figure 3.12 1998/97 mineral index of change (MIOC)values and sampler position within the reserve (0, 10, 20, or 30 m) for each sampler.

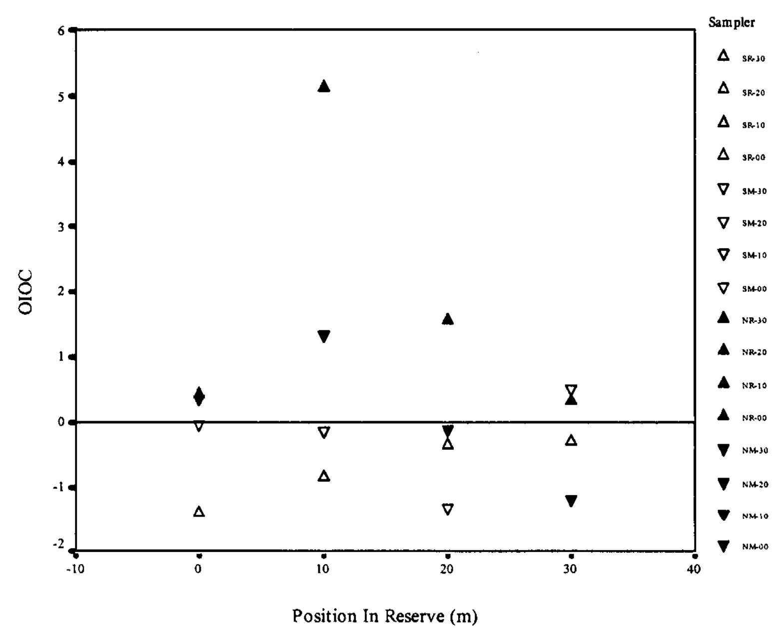


Figure 3.13 1998/97 organic index of change (OIOC) values and sampler position within the reserve (0, 10, 20, or 30 m) for each sampler.

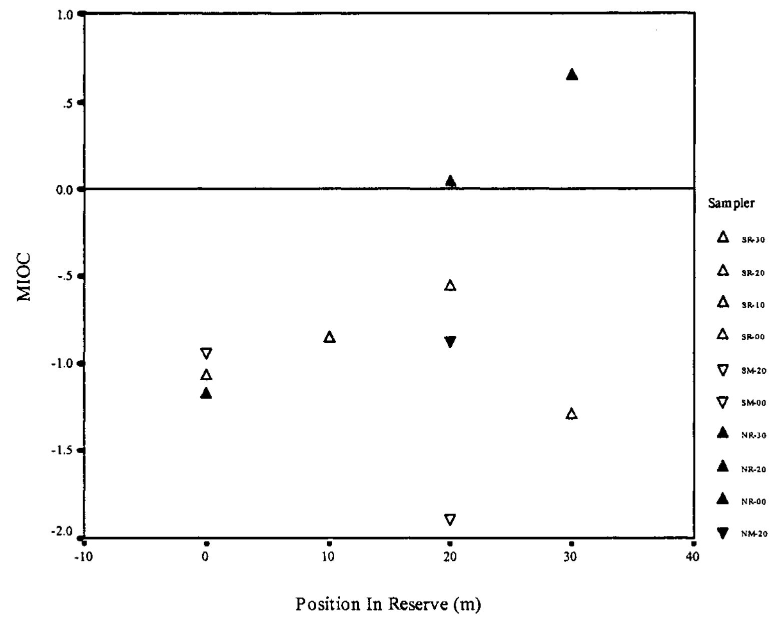


Figure 3.14 1999/97 mineral index of change (MIOC) values and sampler position within the reserve (0, 10, 20, or 30 m) for each sampler.

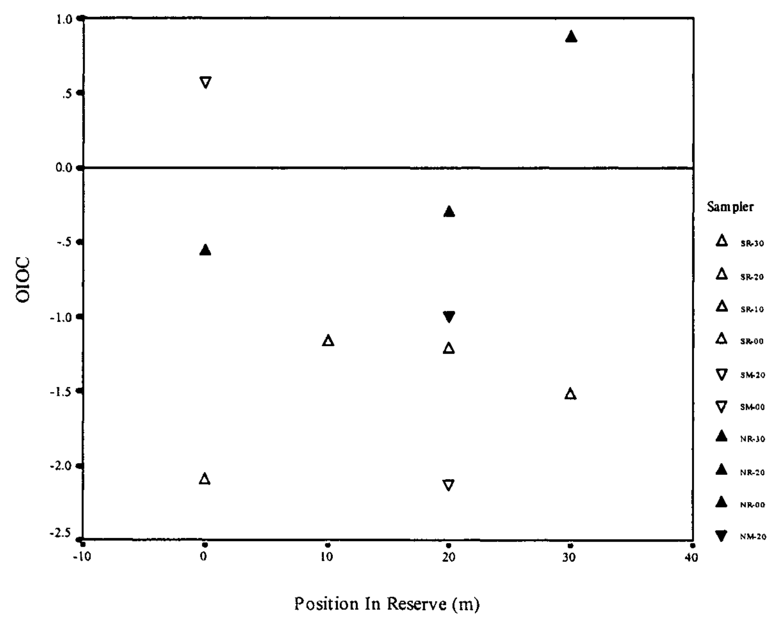


Figure 3.15 1999/97 organic index of change (OIOC) values and sampler position within the reserve (0, 10, 20, or 30 m) for each sampler.

3.2.4 Sub-Catchment Area Effects On Sediment Collection Rates

Pre- and post-impact flow accumulation paths and sub-catchment boundaries for North Block samplers are illustrated in Figure 3.16. Pre- and post-impact flow accumulation paths and sub-catchment boundaries for South Block samplers are illustrated in Figure 3.17. Comparison of pre- and post-impact flow accumulation paths reveals how design elements of roads, including the raised running surface, ditches, and placement of culverts, effectively dammed and re-routed surface run off (Figures 3.16 and 3.17). Six of the eight North Block sub-catchments delineated using the pre-disturbance DEM were dissected by the road (Figure 3.16), but none of the South Block sub-catchments were crossed by the road (Figure 3.17). A set of IOC values were calculated to quantify the effects of forest management on sub-catchment area (Table 3.6). The size of three of the sixteen sub-catchments increased, six decreased, and seven did not change (Table 3.6). The sub-catchment area IOC values ranged from –2.1263 (NR-20) to 3.6659 (NR-00) and represent considerable alteration (increase or decrease) to the sub-catchment area uphill of some samplers (Table 3.6). Most of the sub-catchment areas in the South Block did not change, but of those that did, the change was marginal compared to that which occurred in the North Block (Table 3.6).

Descriptive statistics for pre- and post-impact sub-catchment areas for all samplers in service each year are reported in Table 3.7. The range for sub-catchment area was marginally reduced by the impacts of forest management (Table 3.7). However, surface flow re-routing caused by forest management caused the median sub-catchment area for

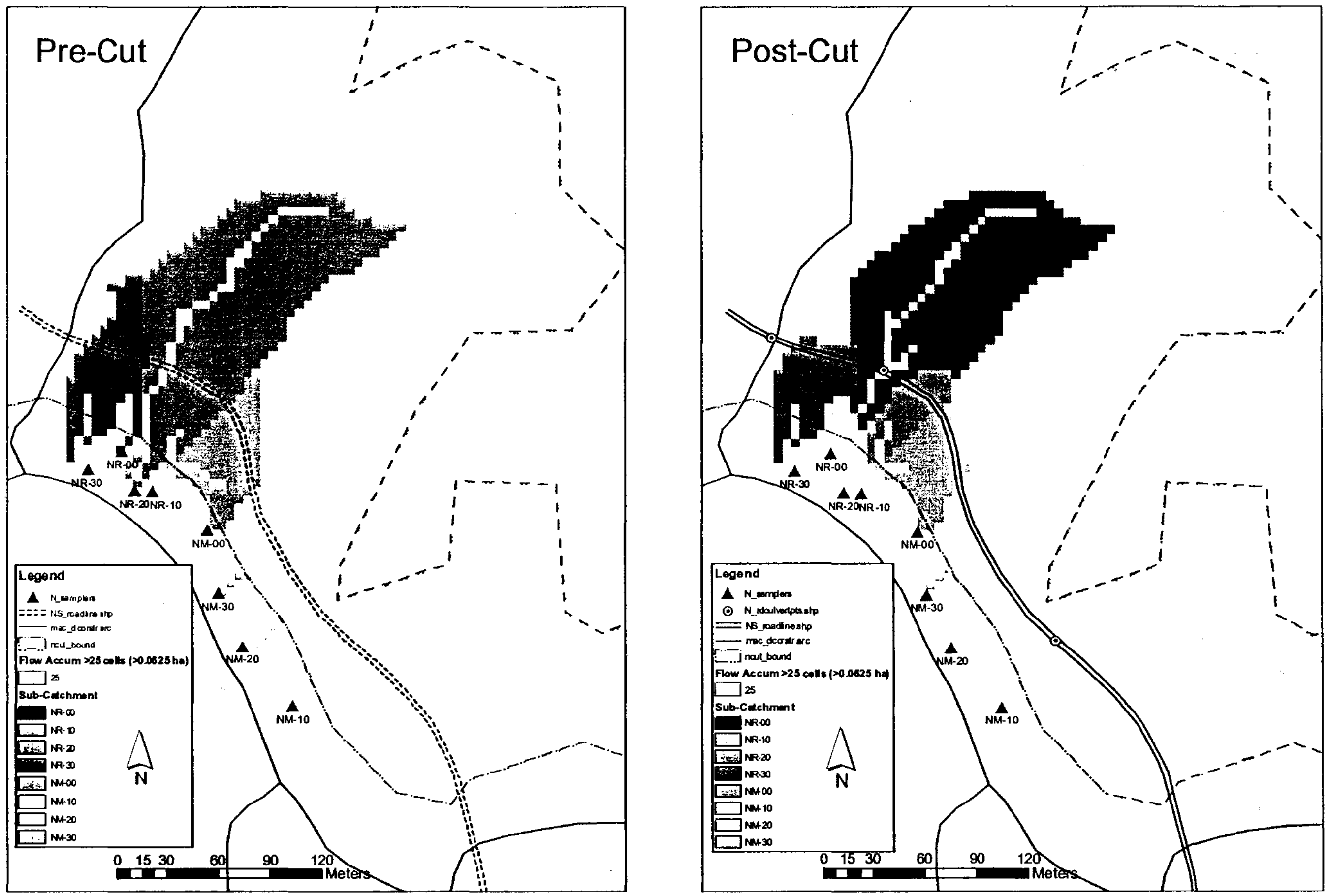


Figure 3.16. Pre- and post-impact sub-catchments and flow accumulation paths for North Block samplers.

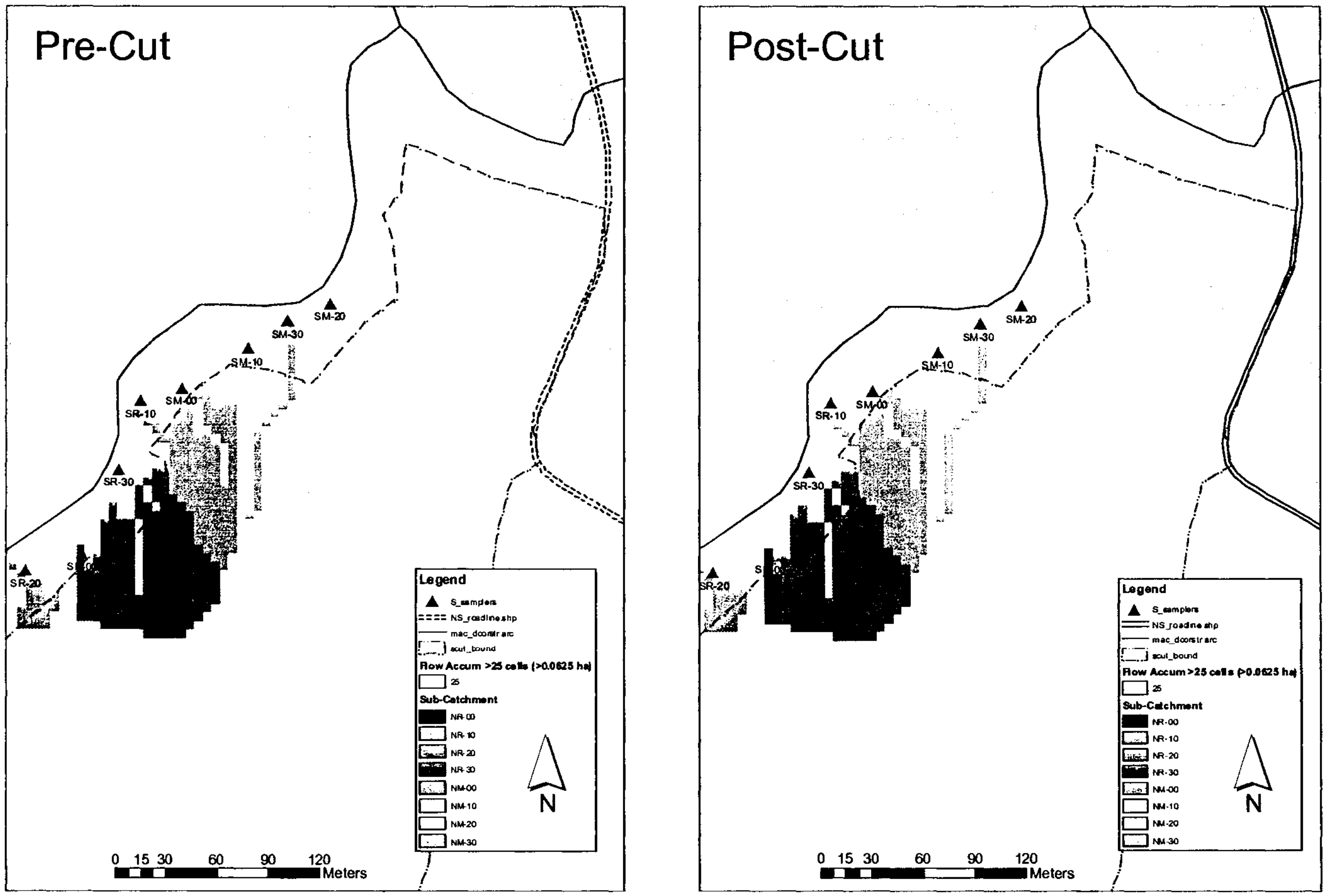


Figure 3.17. Pre-and post-impact sub-catchments and flow accumulation paths for South Block samplers.

Table 3.6 Pre- and post-impact sub-catchment areas (ha), and index of change for sub-catchment area for each sampler.

Sampler	Pre-Cut Area	Post-Cut Area	Index of Change
NR-00	0.0275	1.0750	3.6659
NR-10	0.2325	0.1750	-0.2841
NR-20	1.2575	0.1500	-2.1262
NR-30	0.2925	0.2375	-0.2083
NM-00	0.0350	0.0275	-0.2412
NM-10	4.2625	4.0575	-0.0493
NM-20	0.0275	0.1950	1.9588
NM-30	0.0100	0.0100	0.0000
SR-00	0.0375	0.0375	0.0000
SR-10	0.0175	0.0125	-0.3365
SR-20	0.0625	0.0625	0.0000
SR-30	0.5450	0.5475	0.0046
SM-00	0.3275	0.3275	0.0000
SM-10	0.0175	0.0175	0.0000
SM-20	0.0300	0.0300	0.0000
SM-30	0.0600	0.0600	0.0000

Table 3.7 Descriptive statistics for the sub-catchment areas (ha) of all samplers in service for each of the sampling years, 1997, 1998, and 1999.

Statistic	1997	1998	1999
n	16	16	10
Median	0.0488	0.1063	0.1725
Range	4.2525	4.0475	1.0625
Maximum	4.2625	4.0575	1.0750
Minimum	0.0100	0.0100	0.0125

all samplers to increase by a factor of approximately two (Table 3.7 and Figures 3.16 and 3.17).

Mineral collection rates and sub-catchment area for each sampler are plotted for the years 1997 through 1999 in Figure 3.18, and organic collection rates and sub-catchment area are plotted for the years 1997 through 1999 in Figure 3.19. A consistent relationship between mineral or organic collection rate and sub-catchment area is not presented in any of the plots.

To investigate the influence of sub-catchment area on sediment collection rates, the 1998/97 MIOC and OIOC values for each sampler were plotted with IOC values for sub-catchment area (Figures 3.20 and 3.21). Summaries of 1998/97 MIOC and OIOC values for samplers with: a) no change in sub-catchment area after forest management, b) sub-catchment areas that became smaller after forest management, and c) sub-catchment areas that became larger after forest management are presented in Table 3.8. Among the samplers that had higher mineral collection rates in 1998 compared to 1997, three had a post-impact reduction and two had a post-impact increase in sub-catchment area. The median 1998/97 MIOC among the group with smaller sub-catchment areas was more than 8.75 times greater than the group with larger sub-catchments. Among the samplers that had higher organic collection rates in 1998 compared to 1997, five had post-impact reductions and one had a post-impact increase in sub-catchment area. The median 1998/97 OIOC among the group with smaller sub-catchments was more than three times greater than the sampler with a larger sub-catchment.

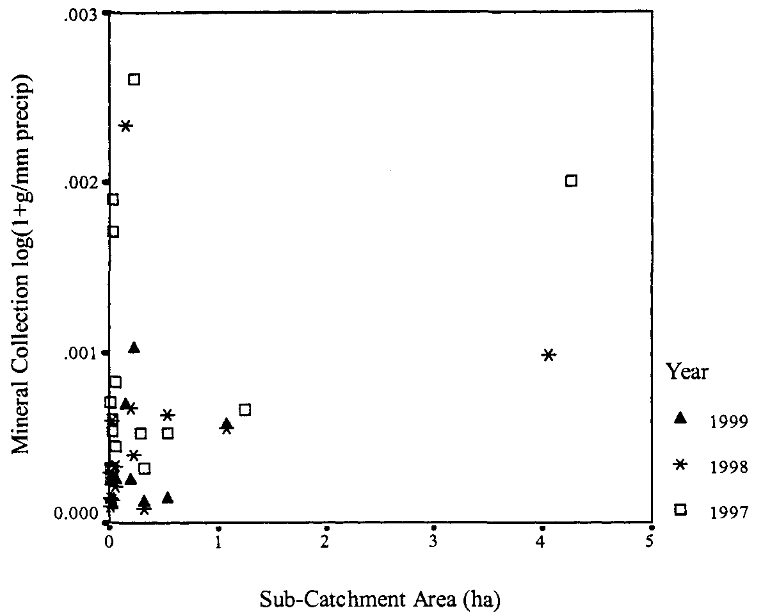


Figure 3.18 Mineral collection rates (log(1+ g·mm^{-1} precip)) plotted against sub-catchment area (ha) for each sampler (1998 NR-10 data excluded) for the years 1997, 1998, and 1999.

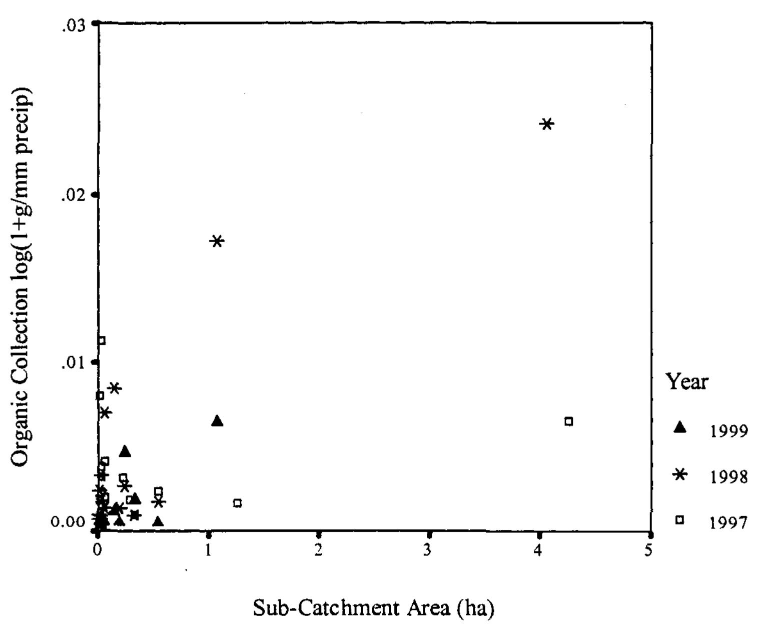


Figure 3.19 Organic collection rates (log(1+ g·mm^{-1} precip)) plotted against sub-catchment area (ha) for each sampler (1998 NR-10 data excluded) for the years 1997, 1998, and 1999.

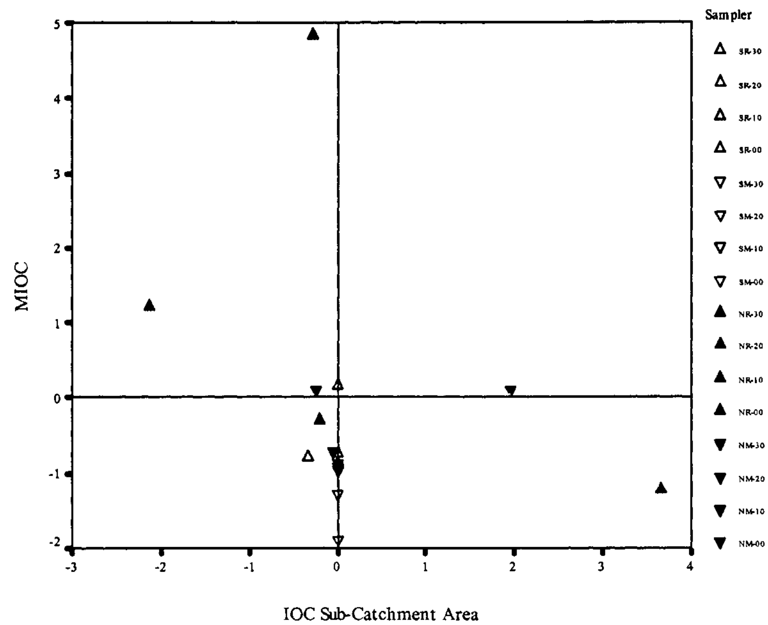


Figure 3.20 1998/97 mineral index of change (MIOC) values and index of change (IOC) values for sub-catchment area for each sampler.

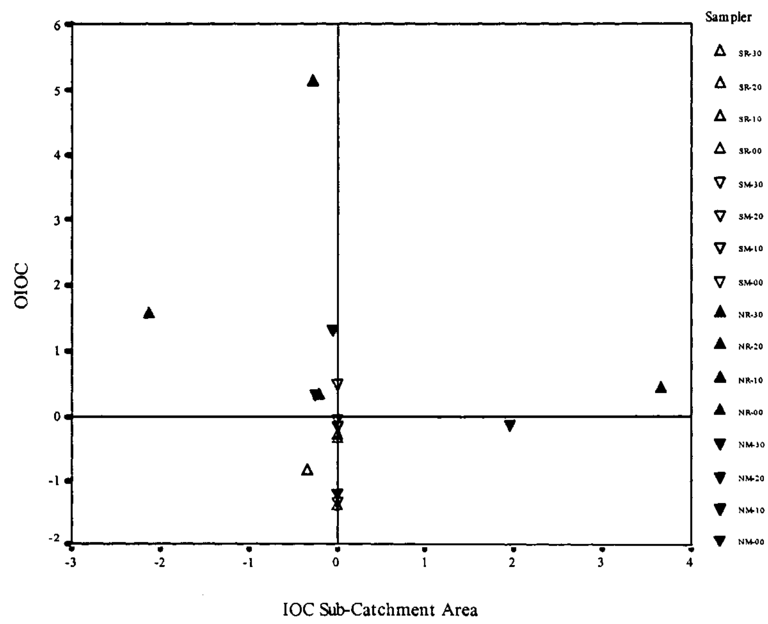


Figure 3.21 1998/97 organic index of change (OIOC) values and index of change (IOC) values for sub-catchment area for each sampler.

Table 3.8 Descriptive statistics for 1998/97 mineral and organic indices of change (MIOC and OIOC, respectively) values for samplers (n=16) with: a) no change in sub-catchment area after forest management impacts, b) sub-catchment areas that became smaller after forest management impacts, and c) sub-catchment that became larger after forest management impacts.

Material	Collection IOC >0 or <0	Area IOC = 0	Area IOC < 0	Area IOC > 0
Mineral	>0	Quad = n/a N = 0 Sampler(s) = n/a Median = n/a Range = n/a Max = n/a Min = n/a	Quad = 4 N = 3 Sampler(s) = NR-10, NR-20, NR-00 Median = 1.2388 Range = 4.7343 Max= 4.8425 Min = 0.1082	Quad = 1 N = 2 Sampler(s) = NM-20, SR-30 Median = 0.1410 Range = 0.0711 Max= 0.1766 Min = 0.1055
Mineral	<0	Quad = n/a N = 7 Sampler(s) = NM-30, SR-00, SR-20, SM-00, SM-10, SM-20, SM-30 Median = -0.9085 Range = 1.1540 Max= -0.7301 Min = -1.8842	Quad = 3 N = 3 Sampler(s) =NR-30, NM-10, SR-10 Median = -0.7058 Range = 0.4878 Max= -0.2894 Min = -0.7772	Quad = 2 N = 1 Sampler(s) = NR-00 Median = -1.2137 Range = 0 Max= -1.2137 Min = -1.2137
Organic	>0	Quad = n/a N = 1 Sampler(s) =SM-30 Median = 0.51499 Range = 0 Max= 0.5150 Min = 0.5150	Quad = 4 N = 5 Sampler(s) =NR-10, NR-20, NR-30, NM-00, NM-10 Median = 1.3167 Range = 4.7925 Max= 5.1125 Min = 0.3199	Quad = 1 N = 1 Sampler(s) = NR-00 Median = 0.4296 Range = 0 Max= 0.4296 Min = 0.4296
Organic	<0	Quad = n/a N = 6 Sampler(s) = NM-30, SR-00, SR-20, SM-00, SM-10, SM-20 Median = -0.7527 Range = 1.3515 Max= -0.0352 Min = -1.3867	Quad = 3 N = 1 Sampler(s) =SR-10 Median = -0.8389 Range = 0 Max= -0.8389 Min = -0.8389	Quad = 2 N = 2 Sampler(s) =NM-20, SR-30 Median = -0.2157 Range = 0.1783 Max= -0.1265 Min = -0.3049

To investigate the influence of sub-catchment area on sediment collection rates, the 1999/97 MIOC and OIOC values for each sampler were plotted with IOC values for sub-catchment area (Figures 3.22 and 3.23). Summaries of 1999/97 MIOC and OIOC values for samplers with: a) no change in sub-catchment area after forest management, b) sub-catchment areas that became smaller after forest management, and c) sub-catchment areas that became larger after forest management are presented in Table 3.9. Two samplers had higher mineral collection rates in 1999 compared to 1997, and both of these samplers had smaller sub-catchment areas after the impacts of forest management. Only one sampler had a higher organic collection rate in 1999 compared to 1997, and it had a smaller post-impact sub-catchment.

Overall, the examinations of Figures 3.20 through 3.23 revealed no consistent relationships between the IOC values for sub-catchment area and either MIOC or OIOC values for any of the sampling year comparisons. The greatest mineral and organic collection rate increases observed in 1998 were associated with sampler NR-10, but this sampler had a marginal reduction in sub-catchment area (Figures 3.20 and 3.21). Samplers NR-00 and NM-20 were the only samplers with considerable sub-catchment area increases after road building and harvesting; however, both samplers had mineral and organic collection rates in 1998 and 1999 that were similar to or lower than in 1997 (Figures 3.20-3.23). Sampler NR-20 had the greatest reduction in sub-catchment area, but it had the second highest rate of increases in both mineral and organic collection rates during 1998 and 1999 over 1997 (Figures 3.20-3.23).

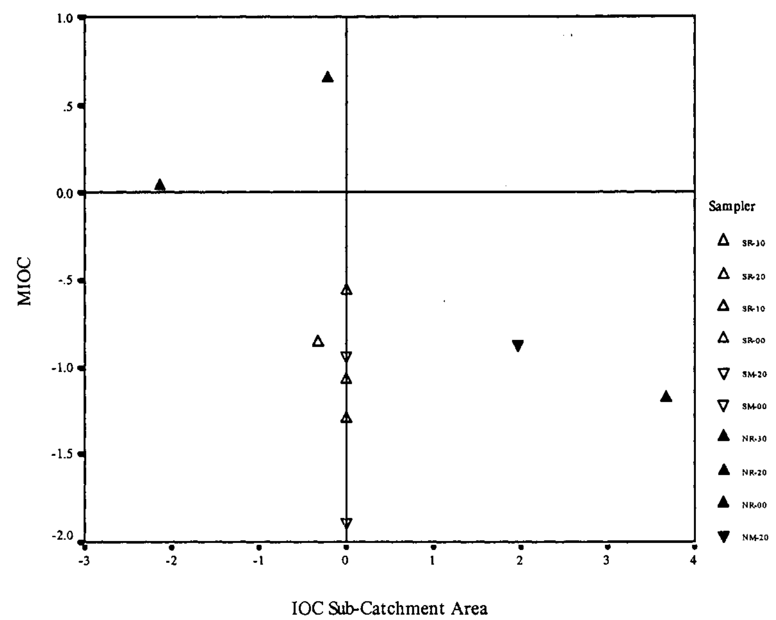


Figure 3.22 1999/97 mineral index of change (MIOC) values and index of change (IOC) values for sub-catchment area for each sampler.

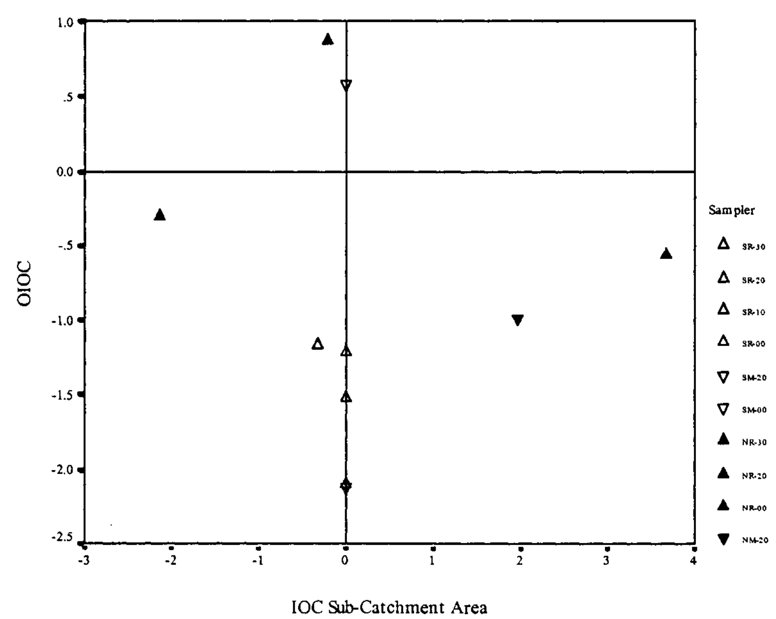


Figure 3.23 1999/97 organic index of change (OIOC) values and index of change (IOC) values for sub-catchment area for each sampler.

Table 3.9 Descriptive statistics for 1999/97 mineral and organic indices of change (MIOC and OIOC, respectively) values for samplers (n=16) with: a) no change in sub-catchment area after forest management impacts, b) sub-catchment areas that became smaller after forest management impacts, and c) sub-catchment that became larger after forest management impacts.

Material	Collection IOC >0 or <0	Area IOC = 0	Area IOC < 0	Area IOC > 0
Mineral	>0	Quad = n/a N = 0 Sampler(s) = n/a Median = n/a Range = n/a Max = n/a Min = n/a	Quad = 4 N = 2 Sampler(s) = NR-20, NR-30 Median = 0.3429 Range = 0.6096 Max= 0.6476 Min = 0.0381	Quad = 1 N =0 Sampler(s) = n/a Median = n/a Range = n/a Max = n/a Min = n/a
Mineral	<0	Quad = n/a N = 4 Sampler(s) = SR-00, SR-20, SM-00. SM-20 Median = -1.0032 Range = 1.3192 Max= -0.5603 Min = -1.8795	Quad = 3 N = 1 Sampler(s) = SR-10 Median = -0.8618 Range = 0 Max= -0.8618 Min = -0.8618	Quad = 2 N = 3 Sampler(s) = NR-00, NM-20, SR-30 Median = -1.1810 Range = 0.4319 Max= -0.8650 Min = -1.2969
Organic	>0	Quad = n/a N = 1 Sampler(s) = SM-00 Median = 0.5835 Range = 0 Max= 0.5835 Min = 0.5835	Quad = 4 N = 1 Sampler(s) = NR-30 Median = 0.8734 Range = 0 Max= 0.8734 Min = 0.8734	Quad = 1 N = 0 Sampler(s) = n/a Median = n/a Range = n/a Max = n/a Min = n/a
Organic	<0	Quad = n/a N = 3 Sampler(s) = SR-00, SR-20, SM-20 Median = -2.0967 Range = 0.9125 Max= -1.2089 Min = -2.1214	Quad = 3 N = 2 Sampler(s) = NR-20, SR-10 Median = -0.7327 Range = 0.8648 Max= -0.3003 Min = -1.1651	Quad = 2 N = 3 Sampler(s) = NR-00, NM-20, SR-30 Median = -0.9904 Range = 0.9658 Max= -0.5539 Min = -1.5197

3.2.5 Distance From Road Effects On Sediment Collection Rates

The shortest straight line distance between each sampler and the road is reported in Table 3.10. Among all sixteen samplers, this distance had a range of 275.45 m, with a maximum of 306.80 and minimum of 31.35 m. The range in distance from the road for the ten samplers that remained in service in 1999 was 258.49 m with a maximum of 306.80 and minimum of 48.31 m.

Mineral collection rates for the years 1997, 1998 and 1999 are plotted with sampler distance from the road in Figure 3.24, and organic collection rates are plotted against sampler distance from the road in Figure 3.25. The 1998 collection rates for sampler NR-10 were much higher than those for any other sampler during the period of the study; hence, excluding these data created plots at scales that better presented relationships between distance from road and the sediment collection rates associated with the majority of samplers. The road was not constructed until late in the 1997 sampling season; hence data for that year are plotted only for comparison with post-impact data. For each of the years 1998 and 1999, negative curvilinear relationships between both mineral and organic collection rates and sampler distance from the road are apparent. However, plots of the 1997 data exhibit similar relationships and the road was not constructed until the latter part of the sampling season that year.

To investigate the effects of forest management roads on changes among sediment transport rates, sampler distances from the road were plotted with 1998/97 MIOC and

Table 3.10 Shortest distance (m) between each sampler and the road.

Sampler	Distance To Road
NR-00	55.62
NR-10	57.78
NR-20	67.99
NR-30	70.87
NM-00	31.35
NM-10	50.53
NM-20	48.31
NM-30	43.47
SR-00	272.34
SR-10	231.12
SR-20	306.80
SR-30	243.54
SM-00	208.00
SM-10	173.42
SM-20	135.58
SM-30	154.92

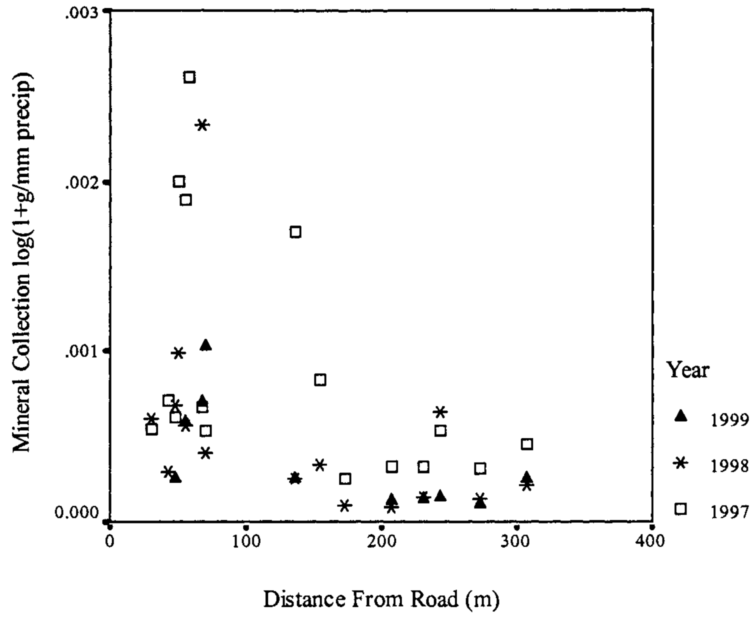


Figure 3.24 1997, 1998 and 1999 mineral collection rates (log(1+ g·mm^{-1} precip)) for each sampler (1998 NR-10 data excluded) plotted against sampler distance from road. The road was not present in 1997; hence, data for that year are plotted for comparison only.

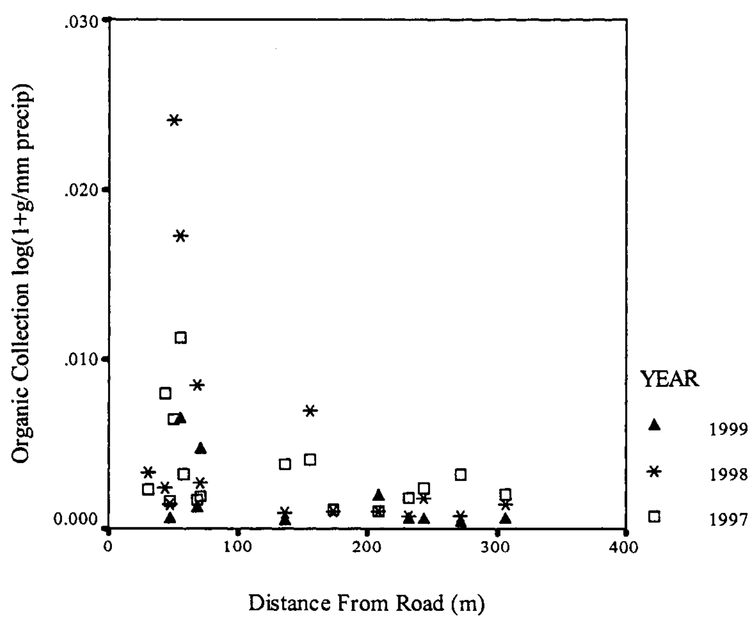


Figure 3.25 1997, 1998 and 1999 organic collection rates (log(1+ g·mm^{-1} precip)) for each sampler (1998 NR-10 data excluded) plotted against sampler distance from road. The road was not present in 1997; hence, data for that year are plotted for comparison only.

OIOC values, respectively, in Figures 3.26 and 3.27. Generally, 1998/97 MIOC and OIOC variance was higher among samplers located closer to the road compared to those located further away. Samplers NR-10 and NR-20, which had the highest 1998/97 MIOC and OIOC values, were the seventh and eighth closest to the road (Figures 3.26 and 3.27). Sampler NM-10 was the sixth closest to the road and it had the third highest 1998/97 OIOC value (Figure 3.27).

To investigate the effects of forest management roads on changes among sediment transport rates, sampler distances from the road were plotted with 1999/97 MIOC and OIOC values, respectively, in Figures 3.28 and 3.29. Generally, 1999/97 MIOC variance was higher among samplers located closer to the road compared to those located further away (Figure 3.28). Of the samplers remaining in service in 1999, NR-30 and NR-20 were the only samplers with higher mineral collection rates in 1999 compared to 1997, and of the samplers in service they were the second and third closest to the road (Figure 3.28). Sampler NR-30 also had the highest OIOC value for the 1999/97 comparison (Figure 3.29).

3.2.6 Surface Runoff Effects On Sediment Collection Rates

Samplers were classified based on the presence or absence of surface runoff or windthrow impact (Table 3.11). Samplers NR-10 and NR-20 were installed 1 - 2 m down slope of an area where emerging groundwater flow was frequently observed. Upon emerging, the water was concentrated into small channels or rills, 2 - 4 cm wide,

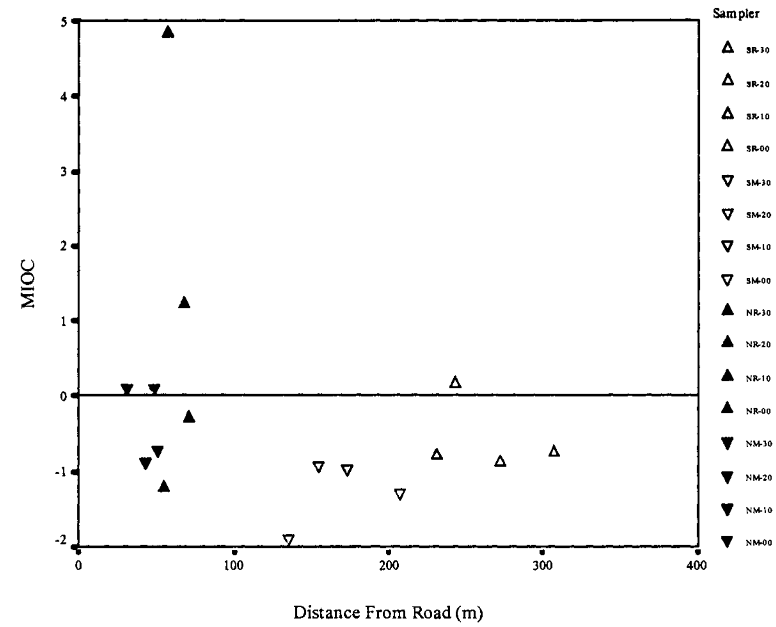


Figure 3.26 1998/97 mineral index of change (MIOC) values plotted against sampler distance from road.

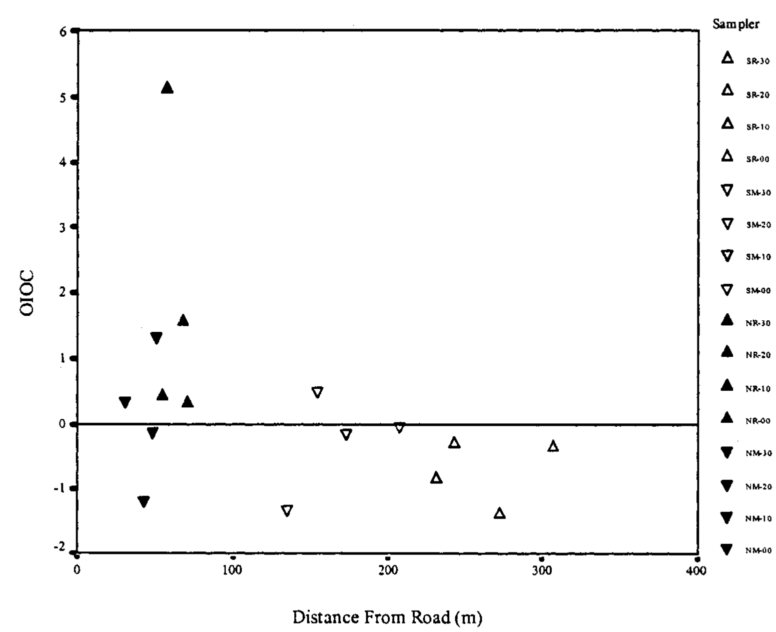


Figure 3.27 1998/97 organic index of change (OIOC) values plotted against sampler distance from road.

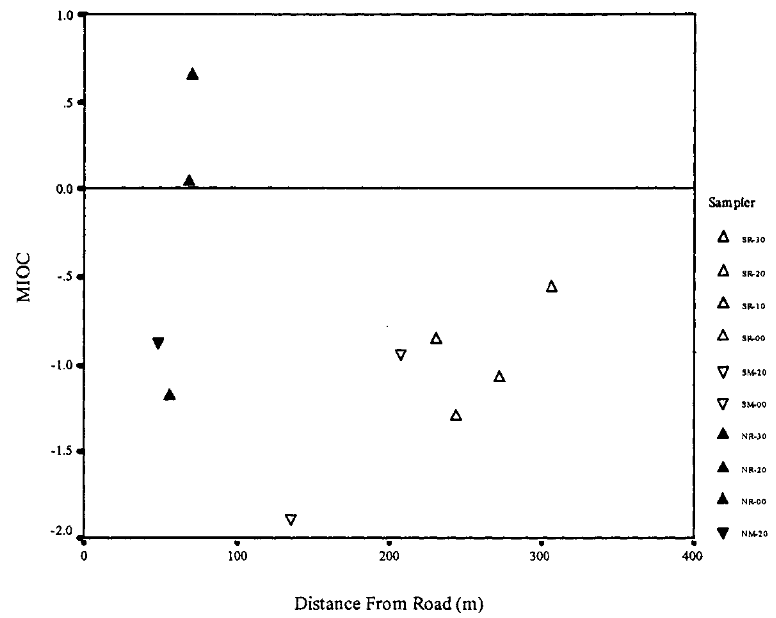


Figure 3.28 1999/97 mineral index of change (MIOC) values plotted against sampler distance from road.

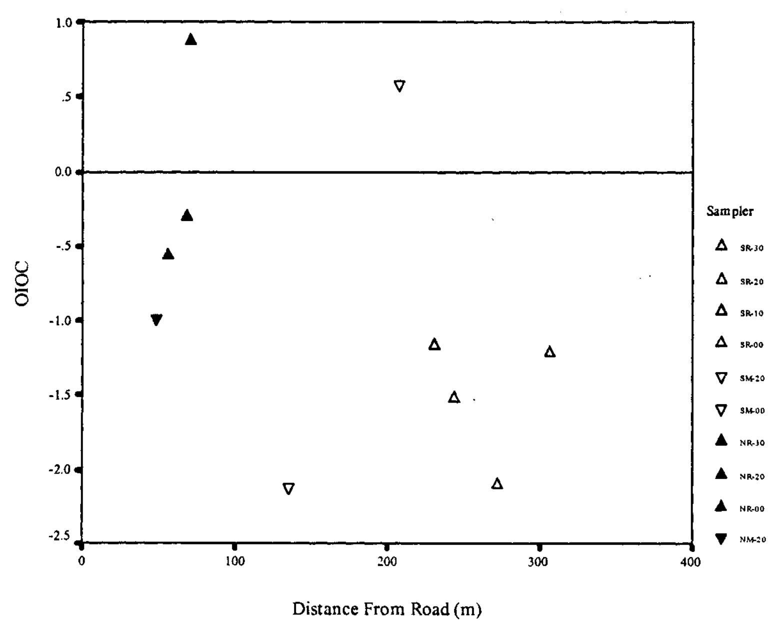


Figure 3.29 1999/97 organic index of change (OIOC) values plotted against sampler distance from road.

Table 3.11 Sampler classifications based on: 1) observations of surface runoff entering the sampler during the period of the study, and 2) the occurrence of wind thrown overstory tree(s) within approximately five m uphill of the flume during the period of the study.

Sampler	Surface Runoff Observed	Date Runoff First Noted	Windthrow Impacted	Date Windthrow First Noted
NR-00	No	n/a	No	n/a
NR-10	Yes	14 Jul 97	Yes	07 Sep 99
NR-20	Yes	14 Jul 97	No	n/a
NR-30	No	n/a	No	n/a
NM-00	Yes	31 Oct 97	No	n/a
NM-10	Yes	18 Jul 97	No	n/a
NM-20	No	n/a	No	n/a
NM-30	No	n/a	Yes	06 Nov 97
SR-00	No	n/a	No	n/a
SR-10	No	n/a	No	n/a
SR-20	No	n/a	No	n/a
SR-30	No	n/a	No	n/a
SM-00	No	n/a	No	n/a
SM-10	No	n/a	No	n/a
SM-20	No	n/a	Yes	08 Sept 99
SM-30	No	n/a	No	n/a

that ran less than 2 m before flowing into the flumes connected to the samplers. Runoff collected by sampler NM-10 was also channelized, but at 7 cm in width, this channel was slightly wider than those flowing into NR-10 and NR-20. The NM-10 channel originated more than 100 m up slope of the sampler, and flowed through a swale that was left undisturbed except for a single crossing by the road. During one field inspection of sampler NM-00, a source of sub-surface flow was observed emerging several centimetres above the leading edge of the flume, and that source of water contributed shallow sheet flow into NM-00. However, with a measured discharge of only 72 ml over a five minute period, the capacity of the flow to transport sediment was low compared to the flow observed at NR-10, NR-20, or NM-10. Runoff was never again observed at the NM-00 sampler location.

Mineral and organic collection rates, respectively, for the years 1997, 1998, and 1999 for samplers that were or were not affected by surface runoff are presented in Figures 3.30 and 3.31. Descriptive statistics for mineral and organic sediment collection rates for the group of samplers that were or were not affected by surface runoff are presented in Appendix V. Each year, mineral and organic median collection rates for samplers affected by surface runoff exceeded those for samplers that were not affected (Figures 3.30 and 3.31). Before harvesting, the flow affected samplers had median mineral and organic collection rates that were 2.5 and 1.2 times greater respectively compared to samplers not affected by flow (Figures 3.30 and 3.31). Post-impact mineral and organic collection rate medians and ranges were consistently higher among samplers that were affected by surface runoff. During 1998, the first post-impact year, when precipitation

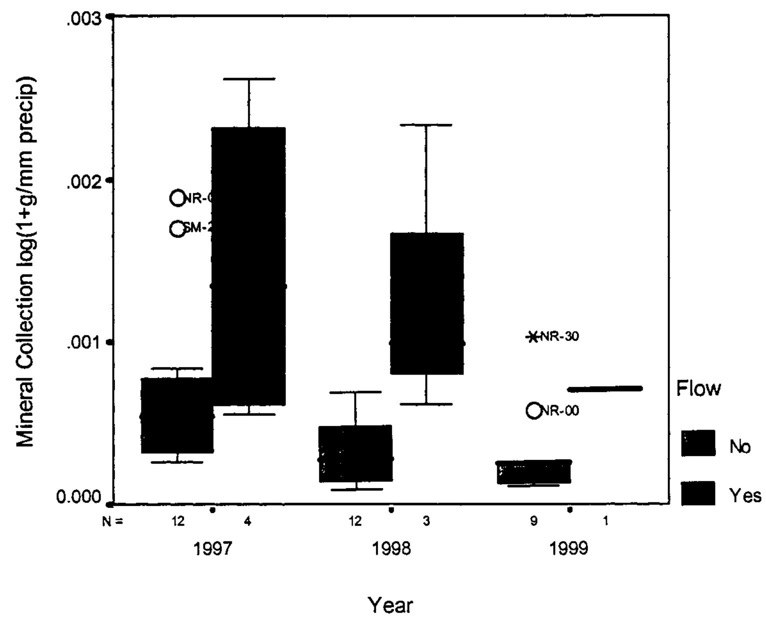


Figure 3.30 Mineral sediment collection rates (log(1+ g·mm^{-1} precip)) for all samplers (1998 NR-10 data excluded) by year and surface runoff class. Boxplots show the median, 25th and 75th percentiles, maximum and minimum values (excluding outliers), and outliers.

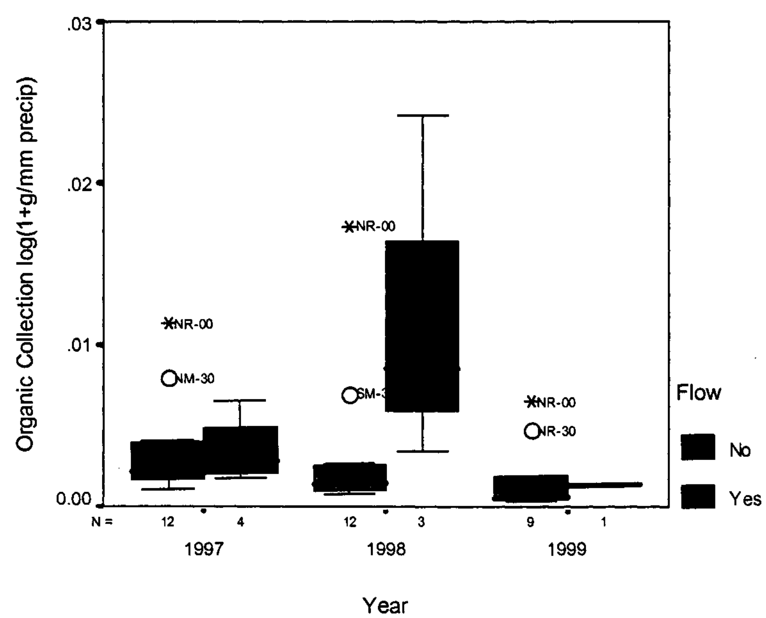


Figure 3.31 Organic sediment collection rates (log(1+ g·mm^{-1} precip)) for all samplers (1998 NR-10 data excluded) by year and surface runoff class. Boxplots show the median, 25th and 75th percentiles, maximum and minimum values (excluding outliers), and outliers.

rates were above normal, mineral collection medians and ranges, respectively, for the group of samplers that were affected by surface runoff were 5.93 and 480.99 times greater than those for samplers that were not affected by surface runoff (Figures 3.30 and 3.31). Also, in 1998 organic collection medians and ranges for the group of samplers that were affected by surface runoff were 11.38 and 32.36 times greater, respectively, than for those samplers not affected by surface runoff. In 1999 sampler NR-20, which was the only runoff affected sampler that remained in service, had mineral and organic collection rates that were 2.7 and 2.2 times greater than the group of samplers that were not affected by surface runoff (Figures 3.30 and 3.31).

To evaluate the influence of surface runoff on sediment collection rates, the 1998/97 MIOC and OIOC values for samplers that were or were not affected by surface runoff are presented in Figures 3.32 and 3.33, and 1999/97 MIOC and OIOC values for these two groups are presented in Figures 3.34 and 3.35. Collection rates among samplers affected by surface runoff and those that were not affected changed differently in the post- compared to pre-impact years. The 1998/97 rate comparisons revealed that the largest post-impact increases in collection rates were among samplers that were affected by surface runoff, and the largest post-impact decreases in collection rates were among samplers that were not affected by surface runoff (Figures 3.32 and 3.33). While there were some exceptions, samplers affected by surface runoff generally had higher mineral and organic collection rates in 1998 compared to 1997 (Figures 3.32 and 3.33). The 1998 mineral and organic collection rate increases for NR-10 were almost four and three times greater, respectively, than those for NR-20, despite the fact both samplers were

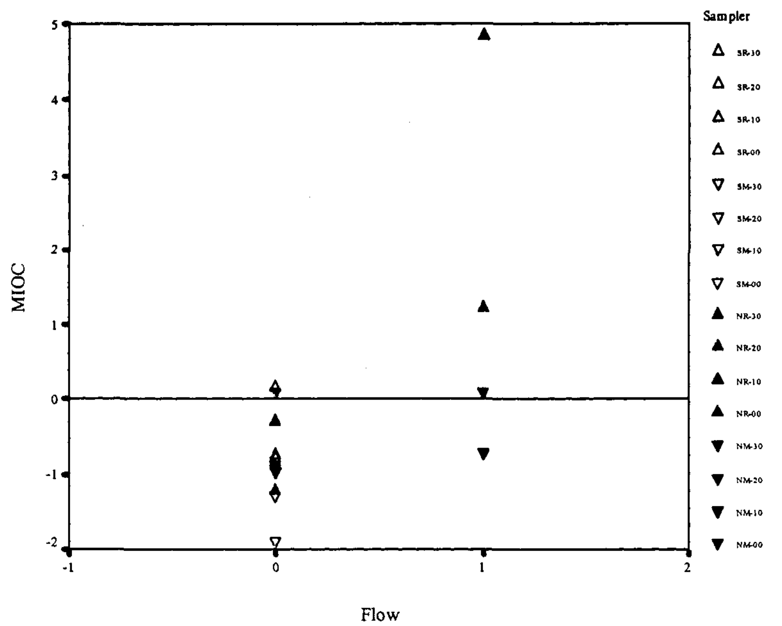


Figure 3.32 1998/97 mineral index of change (MIOC) values for samplers affected by surface runoff (1) and those not affected by surface runoff (0).

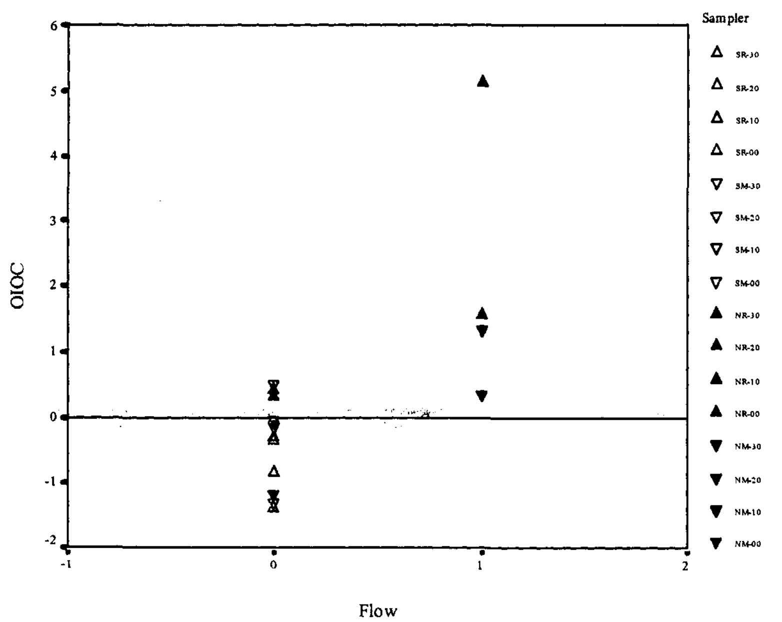


Figure 3.33 1998/97 organic index of change (OIOC) values for samplers affected by surface runoff (1) and those not affected by surface runoff (0).

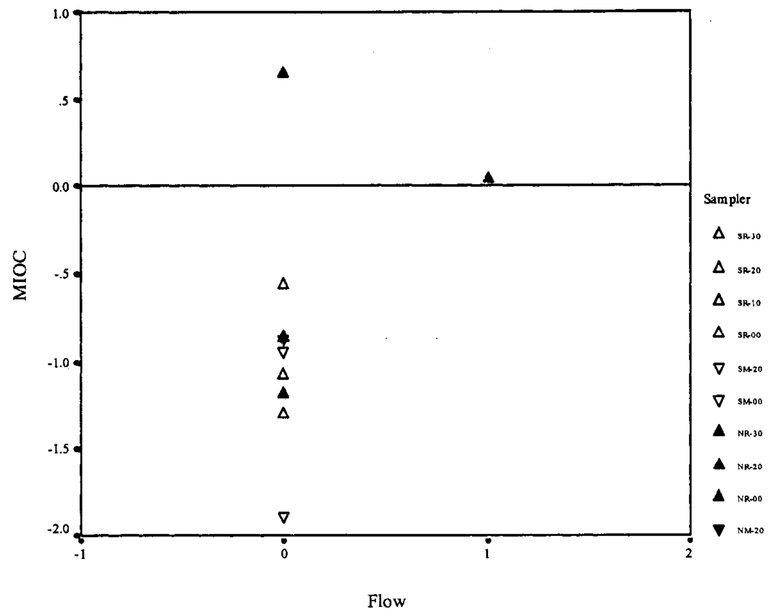


Figure 3.34 1999/97 mineral index of change (MIOC) values for samplers affected by surface runoff (1) and those not affected by surface runoff (0).

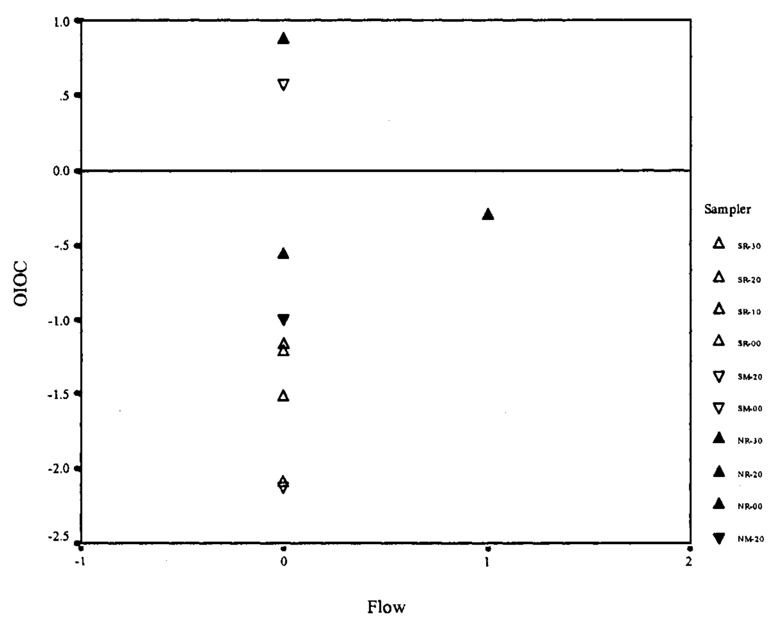


Figure 3.35 1999/97 organic index of change (OIOC) values for samplers affected by surface runoff (1) and those not affected by surface runoff (0).

affected by runoff (Figures 3.32 and 3.33) (Figures 3.32 and 3.33). In 1999, the influence of surface runoff on mineral and organic collection rates was less apparent (Figures 3.34 and 3.35).

Flow accumulation paths ($\geq$ 25 cells) generated from the DEMs for the North and South Blocks are illustrated in Figures 3.16 and 3.17, respectively. Among the most prominent pre-impact flow accumulation paths that run through the North and South Blocks are those that flow into three of the four samplers that were affected by surface runoff (NR-20, NR-10, and NM-10). Other prominent pre-impact flow accumulation paths lead to samplers NR-30, SR-30, and SM-00, all of which were not classified as samplers that received surface runoff. At the 25 cell threshold, a pre-impact flow accumulation path is not displayed for sampler NM-00, the fourth sampler classified as having received surface runoff, or any of the remaining samplers. Post-impact flow accumulation paths are similar to those for the pre-impact condition for all South Block samplers, but the road caused the paths of several North Block flow accumulations to change. Flow accumulation paths indicate that much of the area that contributed flow to sampler NR-20 during the pre-impact situation drained into sampler NR-00 after forest management impacts. Sampler NR-00 was never observed to collect surface runoff. Sampler NM-20, which also was never observed to collect surface runoff, began receiving flow from what was part of the NM-10 sub-catchment prior to forest management impacts.

3.2.7 Windthrow Effects On Sediment Collection Rates

Samplers were classified based on the presence or absence of windthrow impact (Table 3.11). Sampler NR-10 was the only sampler affected by both surface runoff and windthrown tree(s) (Table 3.11). Mineral and organic collection rates, respectively, for the years 1997, 1998, and 1999 for samplers that were and samplers that were not affected by windthrows are presented in Figures 3.36 and 3.37. Descriptive statistics for mineral and organic sediment collection rates for the groups of samplers that were and were not affected by windthrown trees are presented in Appendix V1. Median rates of mineral and organic collection for the two groups of samplers declined over the years 1997 to 1999; however, compared to the affected group, the range in mineral and organic rates for the unaffected group changed much less over the period of the study (Figures 3.36 and 3.37). In 1997 the medians for mineral and organic collection rates in samplers affected by windthrows were more than double those for samplers that were not affected (Figures 3.36 and 3.37).

To evaluate the influence of windthrow on sediment collection rates, the 1998/97 MIOC and OIOC values for samplers that either were or were not affected by windthrown trees are presented in Figures 3.38 and 3.39, and 1999/97 MIOC and OIOC values for these groups are presented in Figures 3.40 and 3.41. The range for 1998/97 MIOC and OIOC values for the affected samplers was more than 2.6 and 2.1 times greater, respectively, than the range for the unaffected group. The size of the range for the affected group was driven by values for sampler NR-10, which was the only sampler of the group to have

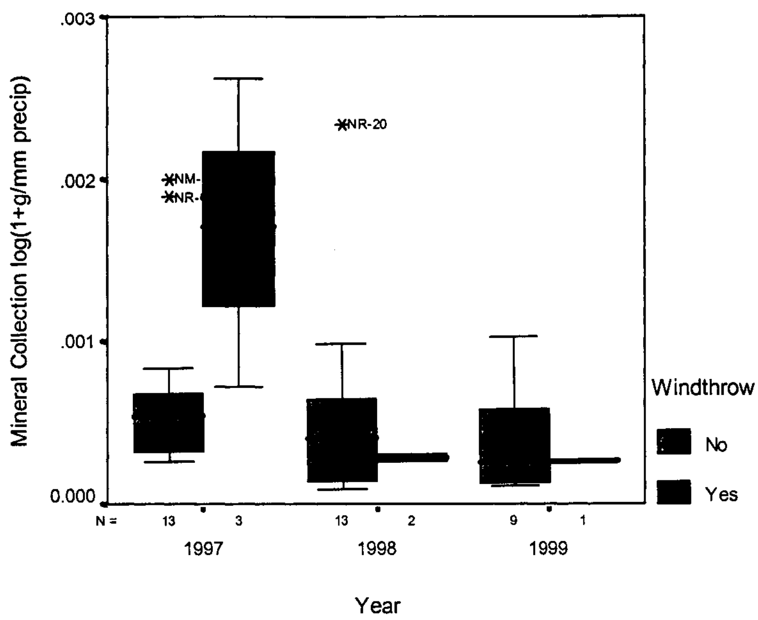


Figure 3.36 Mineral sediment collection rates (log(1+ g·mm^{-1} precip)) for all samplers (1998 NR-10 data excluded) by year and windthrow class. Boxplots show the median, 25th and 75th percentiles, maximum and minimum values (excluding outliers), and outliers.

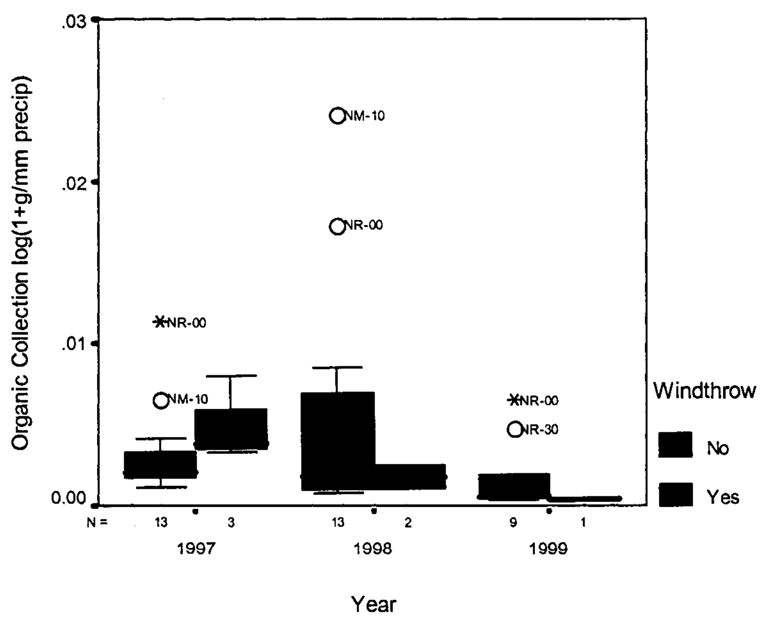


Figure 3.37 Organic sediment collection rates (log(1+ g·mm^{-1} precip)) for all samplers (1998 NR-10 data excluded) by year and surface runoff class. Boxplots show the median, 25th and 75th percentiles, maximum and minimum values (excluding outliers), and outliers.

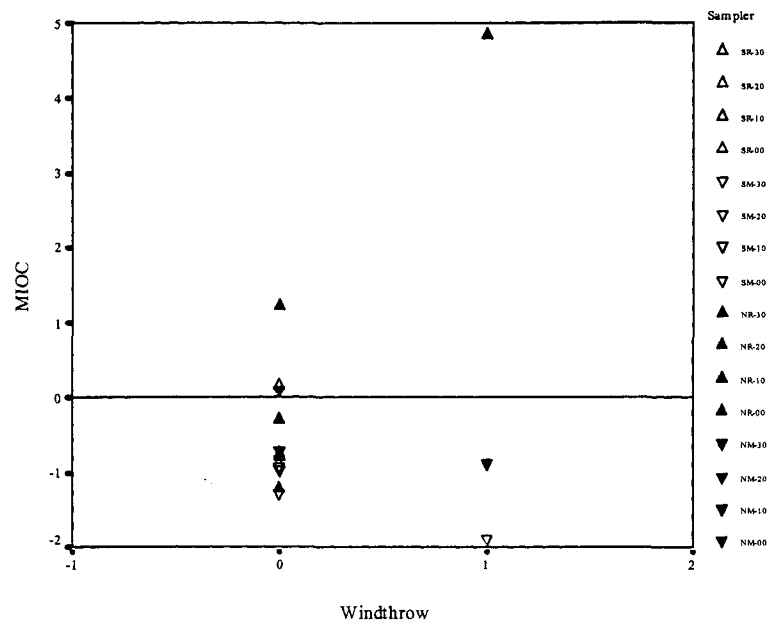


Figure 3.38 1998/97 mineral index of change (MIOC) values for samplers affected by windthrow (1) and those that were not (0).

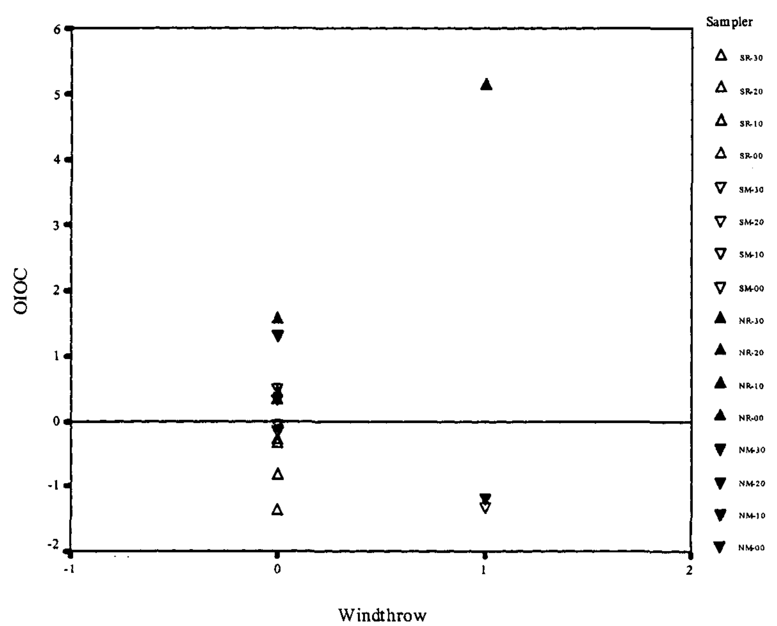


Figure 3.39 1998/97 organic index of change (OIOC) values for samplers affected by windthrow (1) and those that were not (0).

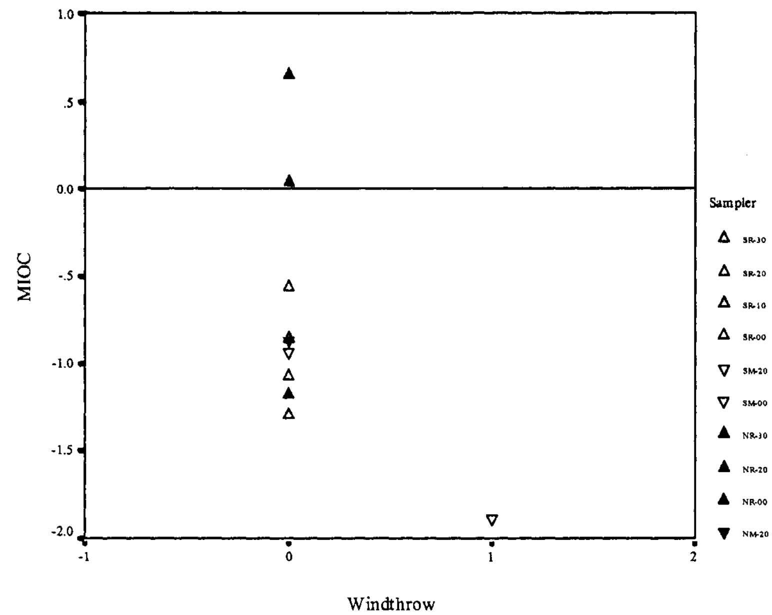


Figure 3.40 1999/97 mineral index of change (MIOC) values for samplers affected by windthrow (1) and those that were not (0).

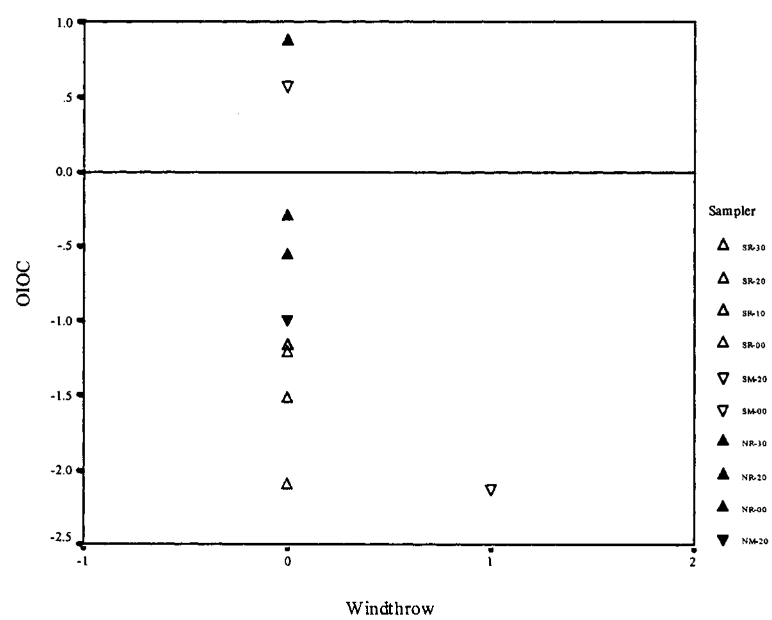


Figure 3.41 1999/97 organic index of change (OIOC) values for samplers affected by windthrow (1) and those that were not (0).

higher rates in 1998 compared to 1997. Sampler NR-20, which had the second greatest increase in 1998 compared to 1997, was not affected by windthrow (Figures 3.38 and 3.39). In 1999, only one windthrow affected sampler remained in service and it had the greatest reductions in mineral and organic collection rates in 1999 compared to 1997 (Figures 3.40 and 3.41).

3.2.8 Crown Closure Effects On Sediment Collection Rates

The average of four crown closure readings measured at each sampler in the summer of 1997, 1998, and 1999 are reported in Table 3.12. In 1997, the median crown closure for the sixteen samplers was 75.38 percent, with a range of 66.75, maximum of 91.50 and minimum of 24.75. In 1998, the median crown closure for the sixteen samplers was 66.25 percent, with a range of 55.00, maximum of 89.00 and minimum of 34.00. In 1999, the median crown closure for the ten samplers remaining in service was 80.00 percent, with a range of 52.00, maximum of 91.25 and minimum of 39.25.

The mineral and organic collection rates and percentage crown closure for each sampler for the years 1997, 1998 and 1999 are presented in Figures 3.42 and 3.43. The distribution of samplers across the range of crown closures studied was uneven, but variances for mineral and organic collection rates were generally highest among samplers with mid-range crown closure for each of the years 1997, 1998, and 1997 (Figures 3.42 and 3.43).

Table 3.12 Average of four crown closure readings (%) measured for each sampler during 1997, 1998, and 1999, and index of change values comparing crown closures measured in 1998 or 1999 with those measured in 1997.

Sampler	1997	1998	IOC 98/97	1999	IOC 99/97
NR-00	67.00	58.50	-0.1357	62.25	-0.0735
NR-10	70.25	66.00	-0.0624	n/a	n/a
NR-20	79.75	70.50	-0.1233	78.75	-0.0126
NR-30	24.75	34.00	0.3175	39.25	0.4611
NM-00	79.00	65.50	-0.1874	n/a	n/a
NM-10	72.50	57.75	-0.2275	67.50	n/a
NM-20	78.25	82.50	0.0529	91.25	0.1537
NM-30	85.25	66.50	-0.2484	n/a	n/a
SR-00	82.25	86.75	0.0533	86.00	0.0446
SR-10	88.75	89.00	0.0028	90.25	0.0168
SR-20	91.50	86.00	-0.0620	88.75	-0.0305
SR-30	46.50	49.75	0.0676	46.50	0.0000
SM-00	86.75	83.50	-0.0382	81.25	-0.0655
SM-10	71.50	58.50	-0.2007	n/a	n/a
SM-20	69.00	66.75	-0.0332	55.75	-0.2132
SM-30	46.25	46.75	0.0108	n/a	n/a

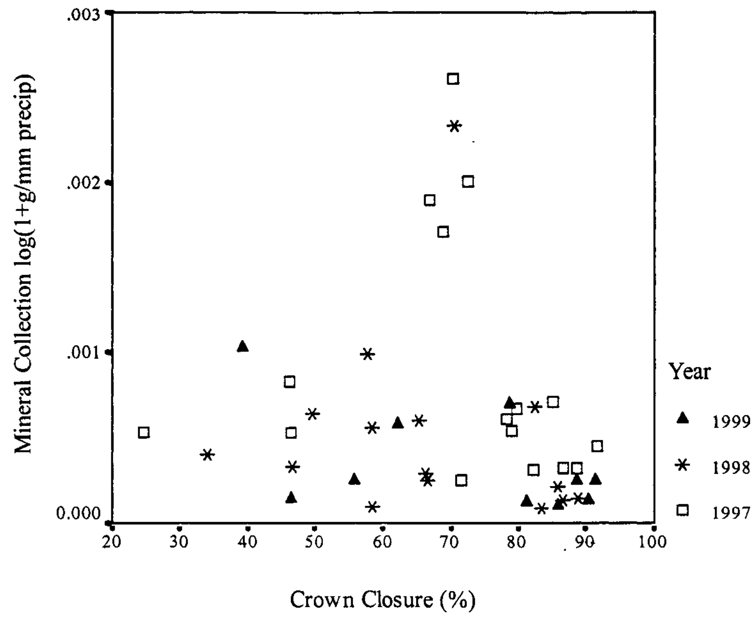


Figure 3.42 Mineral sediment collection rates (log(1+g·mm^{-1} precip)) for each sampler in 1997, 1998 and 1999 (1998 NR-10 data excluded) plotted against fall crown closure (percent).

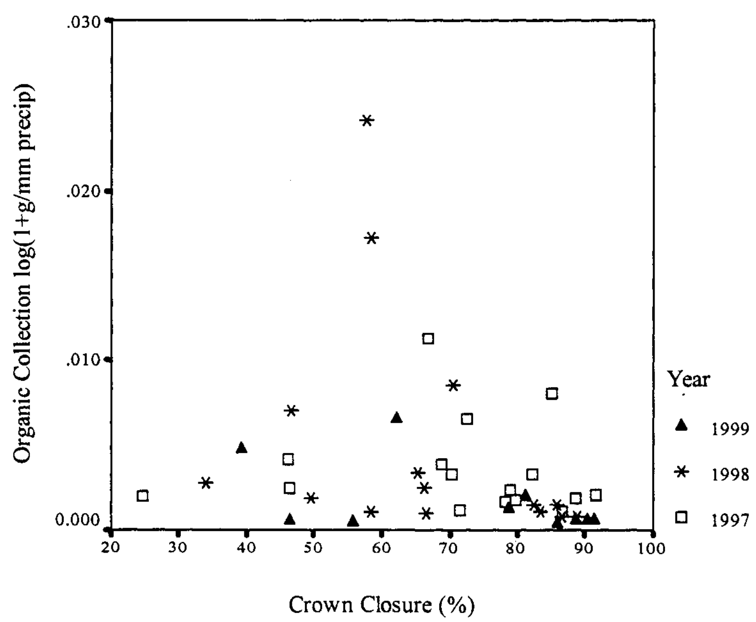


Figure 3.43 Organic sediment collection rates (log(1+g·mm^{-1} precip)) for each sampler in 1997, 1998 and 1999 (1998 NR-10 data excluded) plotted against fall crown closure (percent).

A set of IOC values were calculated to quantify changes in crown closure in 1998 or 1999 compared to 1997 (Table 3.12). Post-impact regeneration in the clearcut areas was not at a level sufficient to contribute to increasing crown closure for any of the samplers; therefore, change that occurred to the amount of crown closure at each sampler was a result of vegetation dynamics within the reserves. Compared to values in 1997, crown closure measured in 1998 was lower for 10 samplers and higher for six. In 1999, when only ten samplers remained in service, five samplers had higher and five samplers had lower crown closure compared to 1997 (Table 3.12).

To evaluate the influence of a change in crown closure on sediment collection rates, the 1998/97 MIOC and OIOC values for each sampler were plotted with the 1998/97 IOC values for crown closure for the samplers (Figures 3.44 and 3.45). There was not a consistent relationship between change in crown closure and change in mineral or organic collection rates among data collected in 1998 compared to 1997 (Figures 3.44 and 3.45). However, samplers NR-10 and NR-20, which had the greatest rate increases in 1998 compared to 1997, were among the group of 10 samplers with less crown closure in 1998 compared to 1997.

Summaries of 1998/97 MIOC and OIOC values for samplers with: a) no change in crown closure after forest management, b) crown closures that became smaller after forest management, and c) crown closures that became larger after forest management are presented in Table 3.13. Among the five samplers that had higher mineral collection rates in 1998 compared to 1997, three had post-impact reductions and two had post-

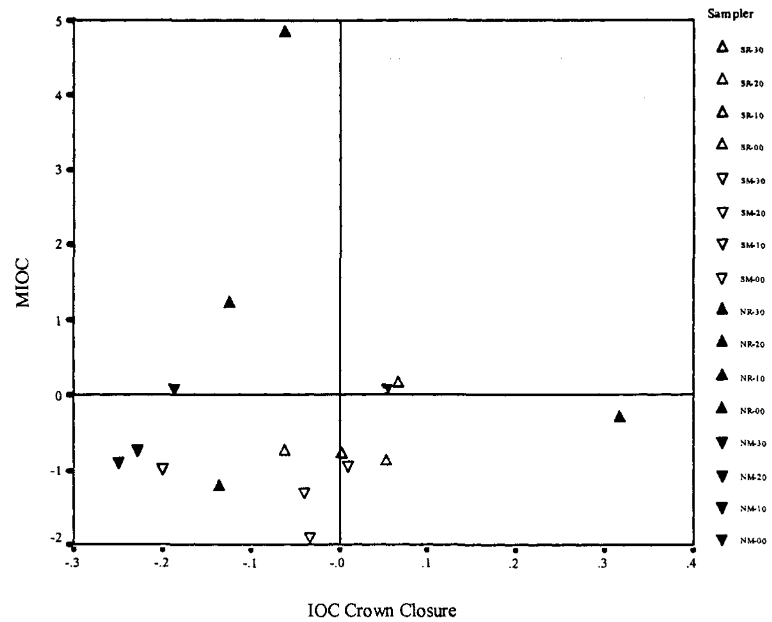


Figure 3.44 1998/97 mineral index of change (MIOC) values and 1998/97 index of change (IOC) values for crown closure for each sampler.

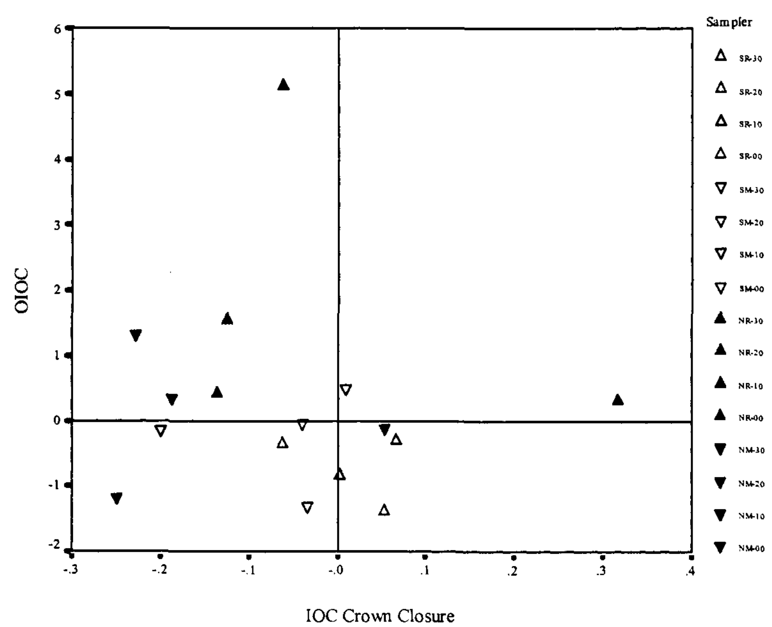


Figure 3.45 1998/97 organic index of change (OIOC) values and 1998/97 index of change (IOC) values for crown closure for each sampler.

Table 3.13 Descriptive statistics for 1998/97 mineral and organic indices of change (MIOC and OIOC, respectively) values for samplers (n=16) with: a) no change in crown closure (1998 compared to 1997), b) decreased crown closure (1998 compared to 1997), and c) increased crown closure (1998 compared to 1997).

Material	Collection IOC >0 or <0	CC IOC = 0	CC IOC < 0	CC IOC > 0
Mineral	>0	Quad = n/a N = 0 Sampler(s) = n/a Median = n/a Range = n/a Max = n/a Min = n/a	Quad = 4 N = 3 Sampler(s) = NR-10, NR-20, NM-00 Median = 1.2388 Range = 4.7343 Max= 4.8425 Min = 0.1082	Quad = 1 N = 2 Sampler(s) = NM-20, SR-30 Median = 0.1410 Range = 0.0711 Max= 0.1766 Min = 0.1055
Mineral	<0	Quad = n/a N = 0 Sampler(s) = n/a Median = n/a Range = n/a Max = n/a Min = n/a	Quad = 3 N = 7 Sampler(s) = NR-00, NM-10, NM-30, SR-20, SM-00, SM-10, SM-20 Median = -0.9577 Range = 1.1784 Max= -0.7058 Min = -1.8842	Quad = 2 N = 4 Sampler(s) = NR-30, SR-00, SR-10, SM-30 Median = -0.8208 Range = 0.6190 Max= -0.2894 Min = -0.9085
Organic	>0	Quad = n/a N = 0 Sampler(s) = n/a Median = n/a Range = n/a Max = n/a Min = n/a	Quad = 4 N = 5 Sampler(s) = NR-00, NR-10, NR-20, NM-00, NM-10 Median = 1.3167 Range = 4.7551 Max= 5.1125 Min = 0.3574	Quad = 1 N = 2 Sampler(s) = NR-30, SM-30 Median = 0.4175 Range = 0.1951 Max= 0.5150 Min = 0.3199
Organic	<0	Quad = n/a N = 0 Sampler(s) = n/a Median = n/a Range = n/a Max = n/a Min = n/a	Quad = 3 N = 5 Sampler(s) = NM-30, SR-20, SM-00, SM-10, SM-20 Median = -0.3391 Range = 1.2761 Max= -0.0351 Min = -1.3113	Quad = 2 N = 4 Sampler(s) = NM-20, SR-00, SR-10, SR-30 Median = -0.5719 Range = 1.2602 Max= -0.1265 Min = -1.3867

impact increases in crown closure. The median 1998/97 MIOC among the group with less crown closure was more than 8.75 times greater than the group with smaller sub-catchments. Among the seven samplers that had higher organic collection rates in 1998 compared to 1997, five had post-impact reductions and two had post-impact increases in crown closure. The median 1998/97 OIOC among the group with more crown closure was more than three times greater than the samplers with less crown closure.

To evaluate the influence of change in crown closure on sediment collection rates, the 1999/97 MIOC and OIOC values were plotted with 1999/97 IOC values for crown closure (Figures 3.46 and 3.47). The 1999/97 MIOC and OIOC values appear to increase with 1999/97 IOC values for crown closure (Figures 3.46 and 3.47), and these relationships indicate that increased crown closure was accompanied by increased mineral and organic collection rates in 1999 compared to 1997. However, these relationships are driven primarily by the extreme values for samplers NR-30 and SM-20. When data for NR-30 and SM-20 are excluded, relationships between MIOC or OIOC and IOC for crown closure are not apparent.

Summaries of 1999/97 MIOC and OIOC values for samplers with: a) no change in crown closure after forest management, b) crown closures that became smaller after forest management, and c) crown closures that became larger after forest management are presented in Table 3.14. Among the two samplers that had higher mineral collection rates in 1999 compared to 1997, one had a 1999 post-impact reduction and one had a 1999 post-impact increase in crown closure. The sampler with more crown closure in

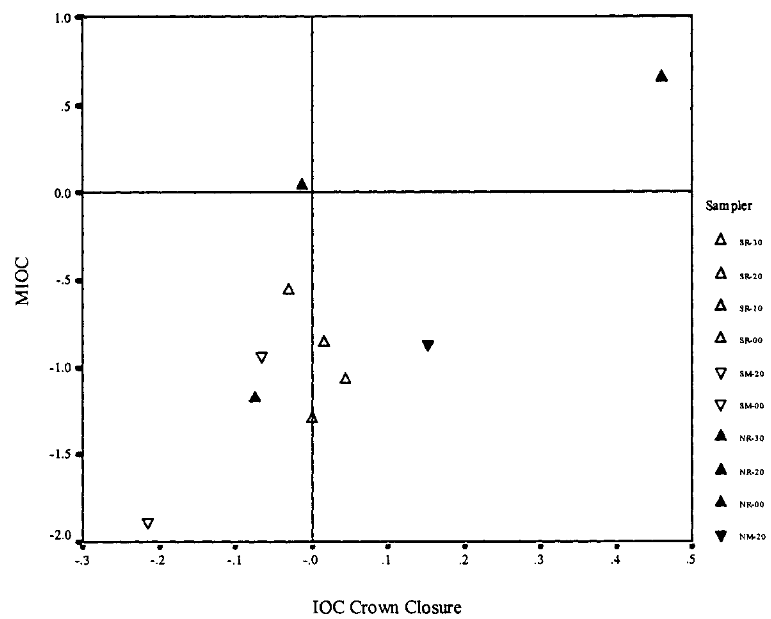


Figure 3.46 1999/97 mineral index of change (MIOC) values and 1999/97 index of change (IOC) values for crown closure for each sampler.

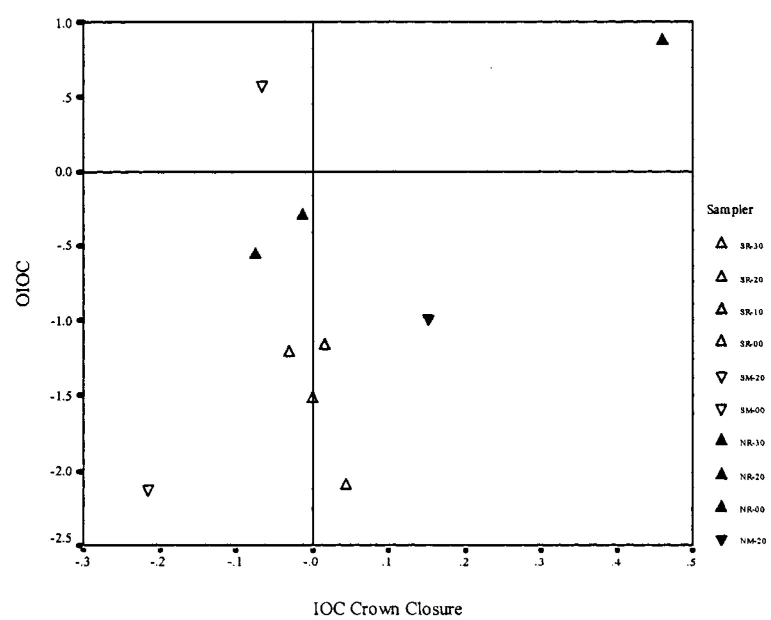


Figure 3.47 1999/97 organic index of change (OIOC) values and 1999/97 index of change (IOC) values for crown closure for each sampler.

Table 3.14 Descriptive statistics for 1999/97 mineral and organic indices of change (MIOC and OIOC, respectively) values for samplers (n=10) with: a) no change in crown closure (1999 compared to 1997), b) decreased crown closure (1999 compared to 1997), and c) increased crown closure (1999 compared to 1997).

Material	Collection IOC >0 or <0	CC IOC = 0	CC IOC < 0	CC IOC > 0
Mineral	>0	Quad = n/a N = 0 Sampler(s) = n/a Median = n/a Range = n/a Max = n/a Min = n/a	Quad = 4 N = 1 Sampler(s) = NR-20 Median = 0.0381 Range = 0 Max= 0.0381 Min = 0.0381	Quad = 1 N = 1 Sampler(s) = NR-30 Median = 0.6476 Range = 0 Max= 0.6476 Min = 0.6476
Mineral	<0	Quad = n/a N = 1 Sampler(s) = SR-30 Median = -1.2969 Range = 0 Max= -1.2969 Min = -1.2969	Quad = 3 N = 4 Sampler(s) = NR-00, SR-20, SM-00, SM-20 Median = -1.0569 Range = 1.3192 Max= -0.5603 Min = -1.8795	Quad = 2 N = 3 Sampler(s) = NM-20, SR-00, SR-10 Median = -0.8650 Range = 0.2118 Max= -0.8618 Min = -1.0737
Organic	>0	Quad = n/a N = 0 Sampler(s) = n/a Median = n/a Range = n/a Max = n/a Min = n/a	Quad = 4 N = 1 Sampler(s) = SM-00 Median = 0.5835 Range = 0 Max= 0.5835 Min = 0.5835	Quad = 1 N = 1 Sampler(s) = NR-30 Median = 0.8734 Range = 0 Max= 0.8734 Min = 0.8734
Organic	<0	Quad = n/a N = 1 Sampler(s) = n/a Median = -1.5197 Range = 0 Max= -1.5197 Min = -1.5197	Quad = 3 N = 4 Sampler(s) = NR-00, NR-20, SR-20, SM-00 Median = -0.8814 Range = 1.8211 Max= -0.3003 Min = -2.1214	Quad = 2 N = 3 Sampler(s) = NM-20, SR-00, SR-10 Median = -1.1651 Range = 1.1063 Max= -0.9904 Min = -2.0967

1999 compared to 1997 had a 1999/97 MIOC value that was 17 times greater than the sampler with less crown closure. Among the two samplers that had higher organic collection rates in 1998 compared to 1997, one had a 1999 post-impact reduction and one had a 1999 post-impact increase in crown closure. The 1998/97 OIOC for the sampler with more crown closure was almost 1.5 times greater than the sampler with less crown closure.

3.2.9 LFH Thickness Effects On Sediment Collection Rates

The thickness of the LFH layer at each sampler is reported in Table 3.15. In 1997 and 1998 when all 16 samplers were in service, the median LFH thickness was 5.0 cm, and the range was 15.5 cm, with a maximum of 16.0 and minimum of 0.5 cm. In 1999 when only ten samplers were in service, the median LFH thickness was 4.5 cm, and the range was 15.0 cm with a maximum of 16.0 and minimum of 1.0 cm.

Mineral and organic sediment collection rates and LFH thickness for each sampler, for the years 1997, 1998, and 1999 are presented in Figures 3.48 and 3.49. In general, there appeared to be a negative relationship between mineral and organic collection rates and LFH thickness; however, with the thickest LFH and the highest mineral and organic collection rates, samplers NR-10 and NR-20 were prominent exceptions to this trend (Figures 3.48 and 3.49).

Table 3.15 LFH thickness (cm) measured at each sampler location in 1997.

Sampler	LFH Thickness
NR-00	2.0
NR-10	15.0
NR-20	16.0
NR-30	2.0
NM-00	0.5
NM-10	2.0
NM-20	1.0
NM-30	5.0
SR-00	5.0
SR-10	12.0
SR-20	7.0
SR-30	4.0
SM-00	8.5
SM-10	5.0
SM-20	3.0
SM-30	13.0

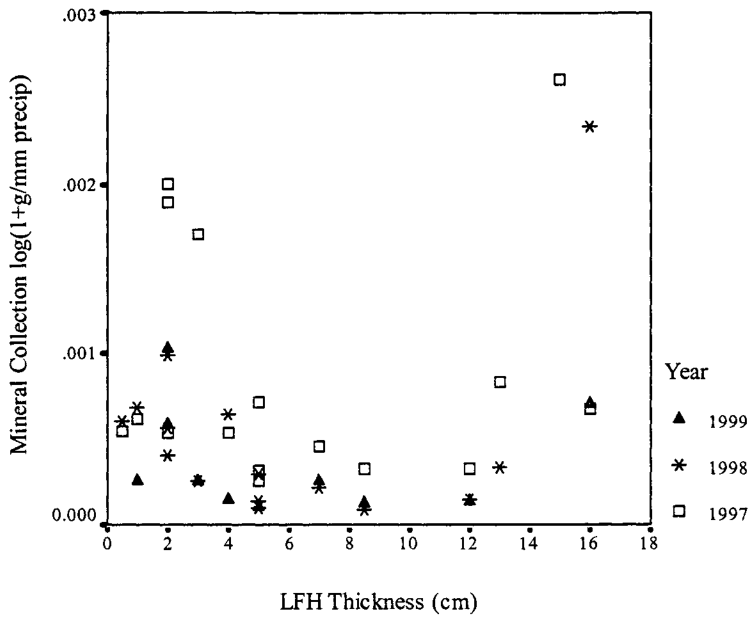


Figure 3.48 Mineral sediment collection rates (log(1+ g·mm^{-1} precip)) for each sampler in 1997, 1998 and 1999 (1998 NR-10 data excluded) plotted against LFH thickness.

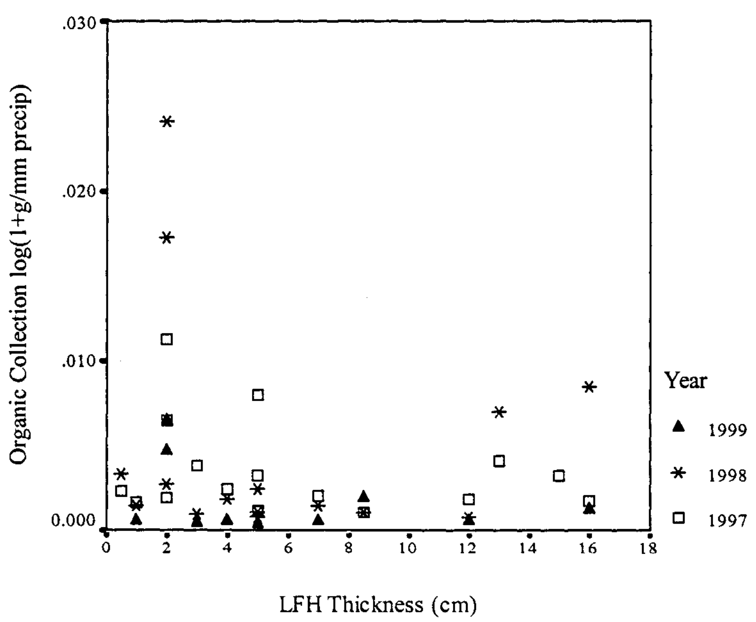


Figure 3.49 Organic sediment collection rates (log(1+ g·mm^{-1}precip)) for each sampler in 1997, 1998 and 1999 (1998 NR-10 data excluded) plotted against LFH thickness.

To evaluate the influence of LFH thickness on sediment collection rates, the 1998/97 MIOC and OIOC values for each sampler were plotted with LFH thicknesses (Figures 3.50 and 3.51). With the notable exceptions of samplers NR-10 and NR-20, both MIOC and OIOC show a general negative relationship with LFH thickness, suggesting that sub-catchments with thinner LFH layers were more susceptible to increased erosion during the first year following forest management impacts (Figures 3.52 and 3.53). However, the two samplers with the thickest LFH layers had the greatest increases in mineral and organic collection rates in 1998 compared to 1997.

To evaluate the influence of LFH thickness on sediment collection rates, the 1999/97 MIOC and OIOC values for each sampler were plotted with LFH thicknesses (Figures 3.52 and 3.53). With the exception of sampler NR-30, the 1999/97 MIOC values increased with LFH thickness (Figure 3.52). This positive relationship was contrary to what was expected as it indicates that samplers with thicker LFH layers were less able to filter increased erosion during the second year following forest management impacts. A relationship between 1999/97 OIOC values and LFH thickness is not apparent (Figure 3.53).

3.2.10 Terrain Slope Effects On Sediment Collection Rates

Terrain slope uphill of each sampler is reported in Table 3.16. In 1997 and 1998, when all sixteen samplers were in service, the median slope was 11.5 percent, and the range among samplers was 19 percent with a maximum of 26 and minimum of 7 percent. In

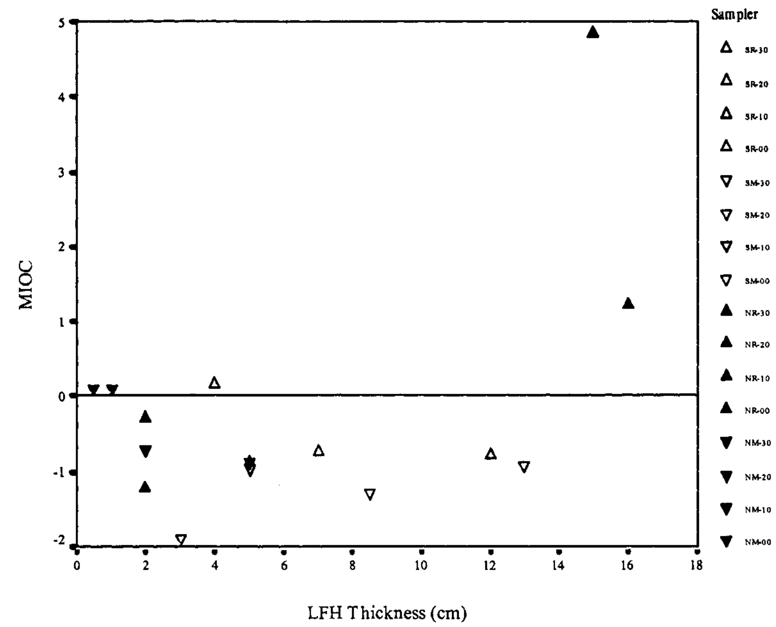


Figure 3.50 1998/97 mineral index of change (MIOC) values and LFH thickness for each sampler.

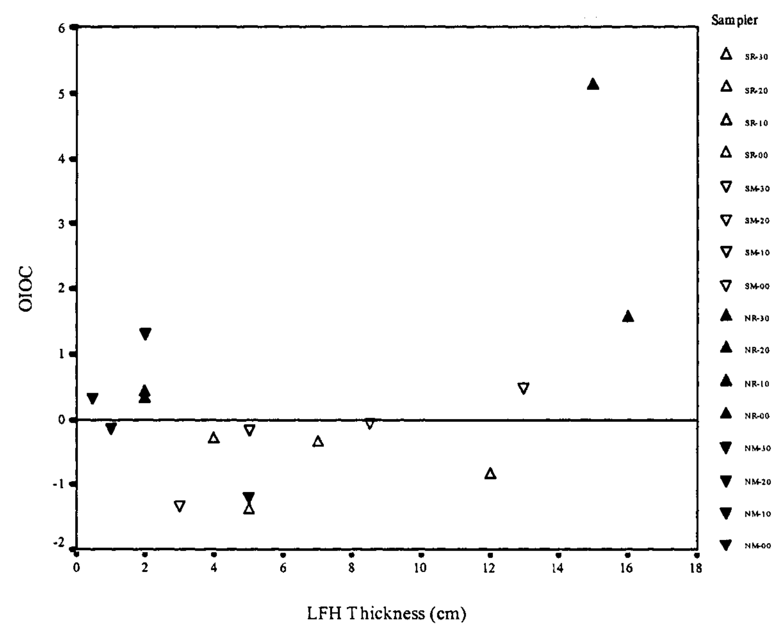


Figure 3.51 1998/97 organic index of change (OIOC) values and LFH thickness for each sampler.

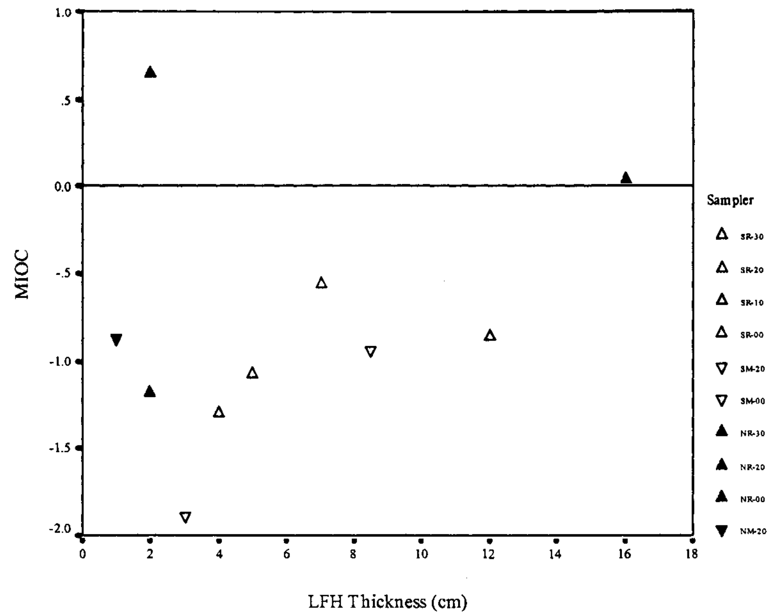


Figure 3.52 1999/97 mineral index of change (MIOC) values and LFH thickness for each sampler.

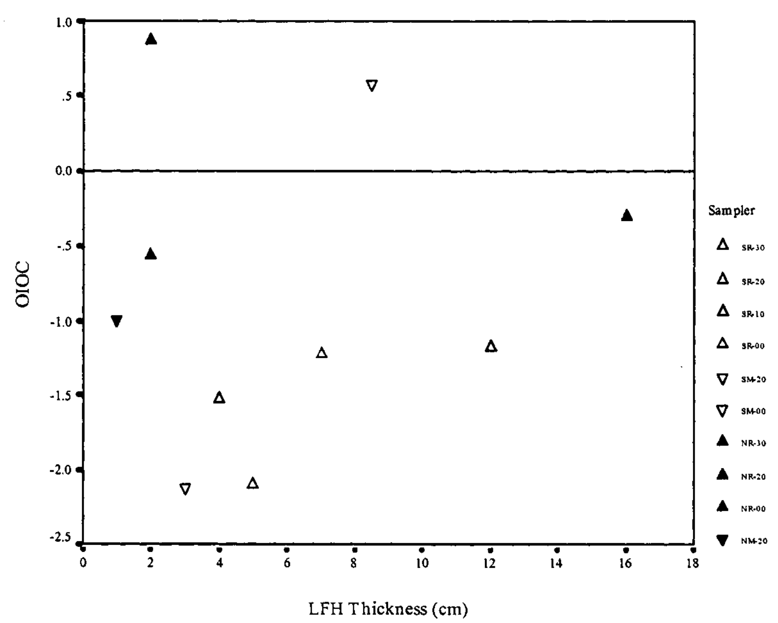


Figure 3.53 1999/97 organic index of change (OIOC) values and LFH thickness for each sampler.

Table 3.16 Slope (%) measured over a distance of approximately 10 m immediately uphill of the entrance flume for each sampler

Sampler	Slope
NR-00	8
NR-10	17
NR-20	13
NR-30	18
NM-00	9
NM-10	7
NM-20	8
NM-30	26
SR-00	9
SR-10	9
SR-20	18
SR-30	9
SM-00	14
SM-10	11
SM-20	13
SM-30	12

1999 when only ten samplers were in service, the median slope was 11.0, and the range among samplers was 10 percent with a maximum of 18 and minimum of 8 percent.

Mineral and organic collection rates, respectively, are plotted with terrain slope for each sampler, for the years 1997, 1998, and 1999 in Figures 3.54 and 3.55. No relationship between mineral or organic collection rate and slope is apparent among data for 1997, 1998, or 1999 (Figures 3.54 and 3.55).

To further evaluate the influence of terrain slope on sediment collection rates, the 1998/97 and 1999/97 MIOC and OIOC values for each sampler were plotted with terrain slopes (Figures 3.56, 3.57, 3.58, and 3.59). No apparent pattern existed between slope and 1998/97 or 1999/97 MIOC and OIOC values for each sampler (Figures 3.56, 3.57, 3.58, and 3.59).

3.2.11 Effects Of Topographic Index On Sediment Collection Rates

The spatial distributions of raw TI values derived from the North and South Block DEMs, respectively, are presented in Figures 3.60 and 3.61. With the exception of NM-30, SR-10, and SM-10, all samplers were located within a distance of about five m from a cell or zone of cells with TI values greater than or equal to eight, both before and after forest management had occurred. As samplers were installed in locations within topographic convergences, it was expected that these sites would be among the locations most likely to generate surface runoff; hence, it was also expected these sites would be

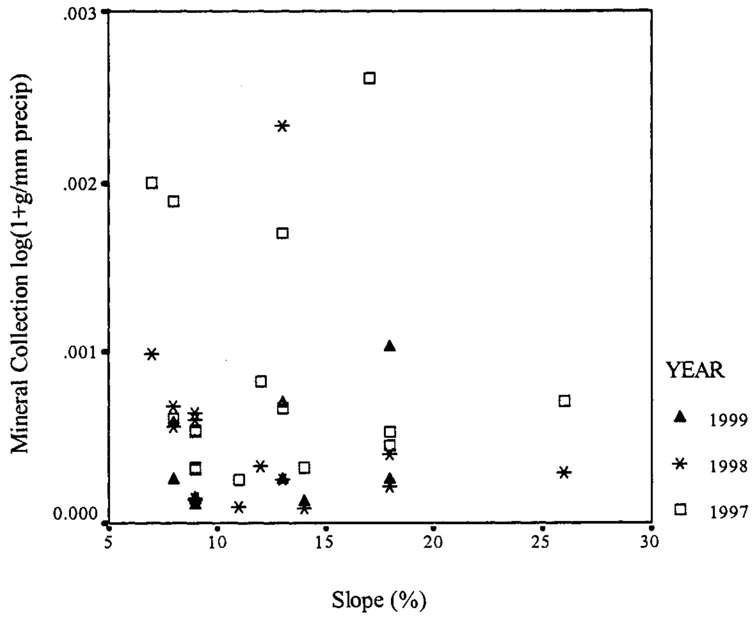


Figure 3.54 Mineral sediment collection rates (log(1+ g·mm^{-1} precip)) for each sampler in 1997, 1998 and 1999 (1998 NR-10 data excluded) plotted against slope.

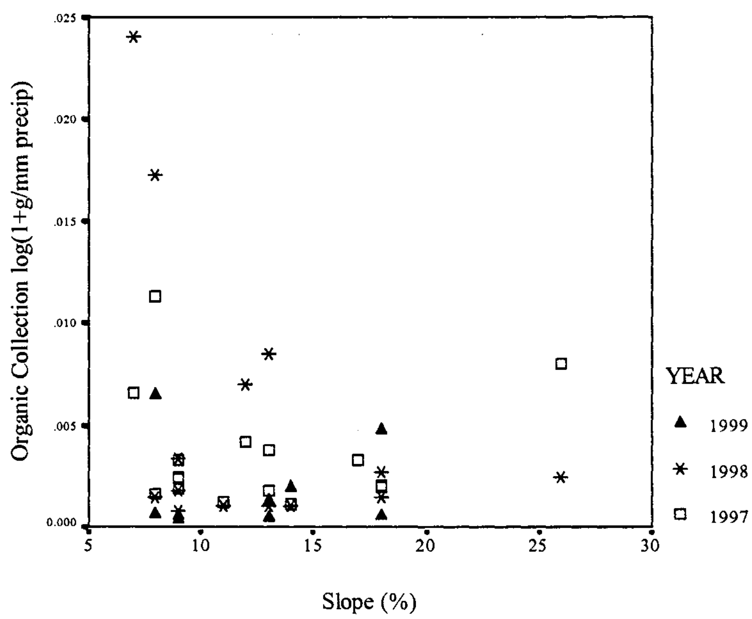


Figure 3.55 Organic sediment collection rates (log(1+ g·mm^{-1} precip)) for each sampler in 1997, 1998 and 1999 (1998 NR-10 data excluded) plotted against slope.

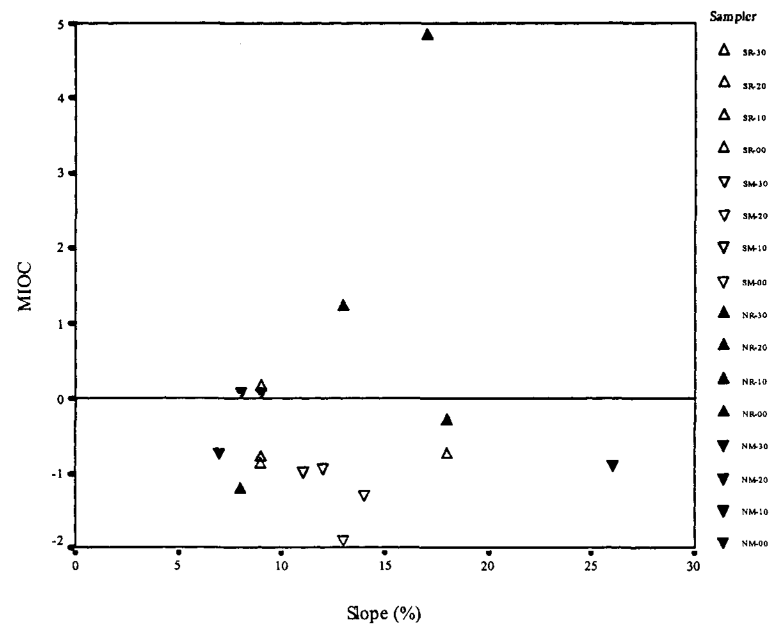


Figure 3.56 1998/97 mineral index of change (MIOC) values and slope for each sampler.

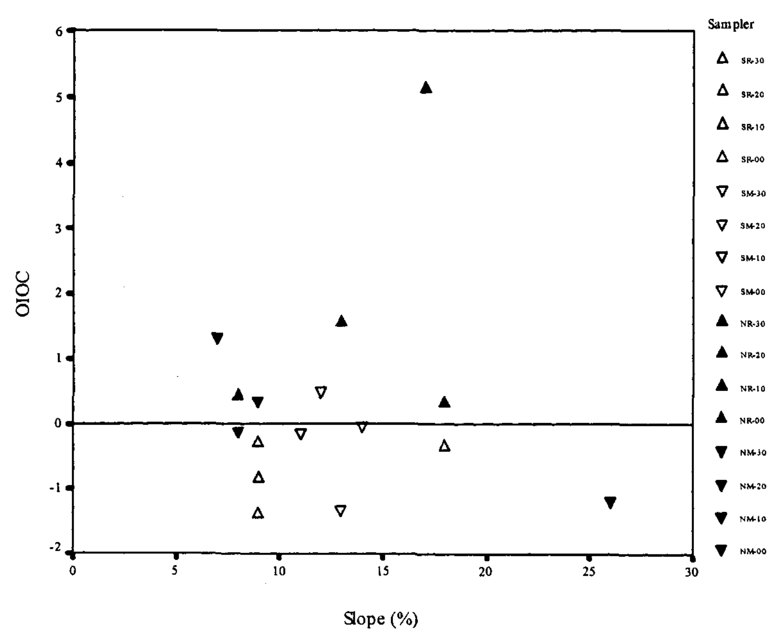


Figure 3.57 1998/97 organic index of change (OIOC) values and slope for each sampler.

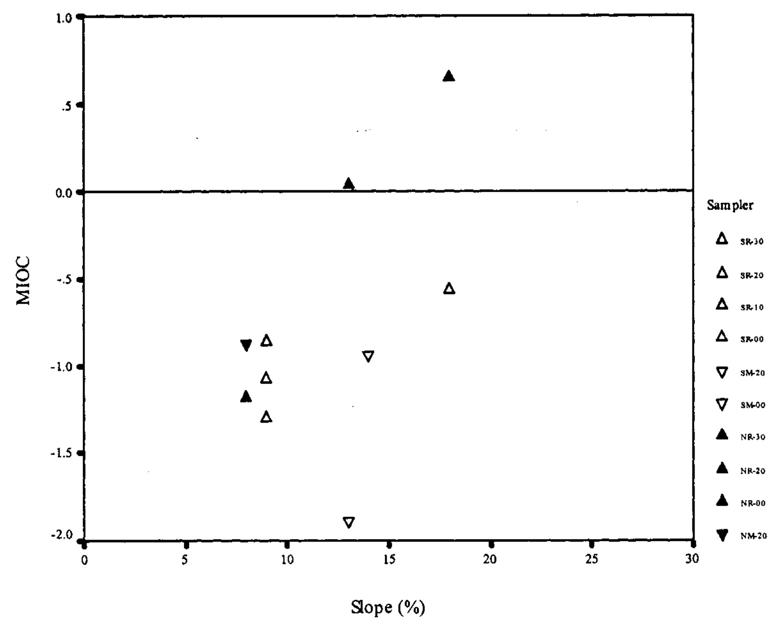


Figure 3.58 1999/97 mineral index of change (MIOC) values and slope for each sampler.

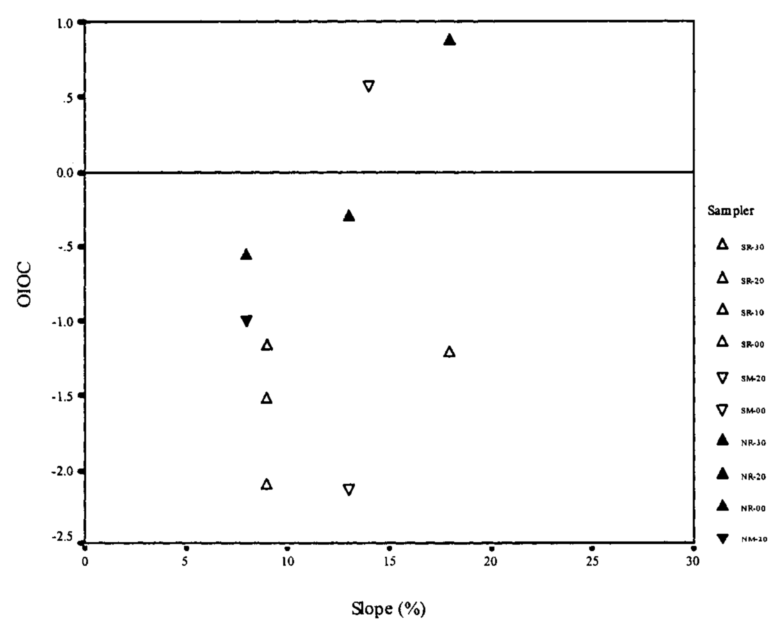


Figure 3.59 1999/97 organic index of change (OIOC) values and slope for each sampler.

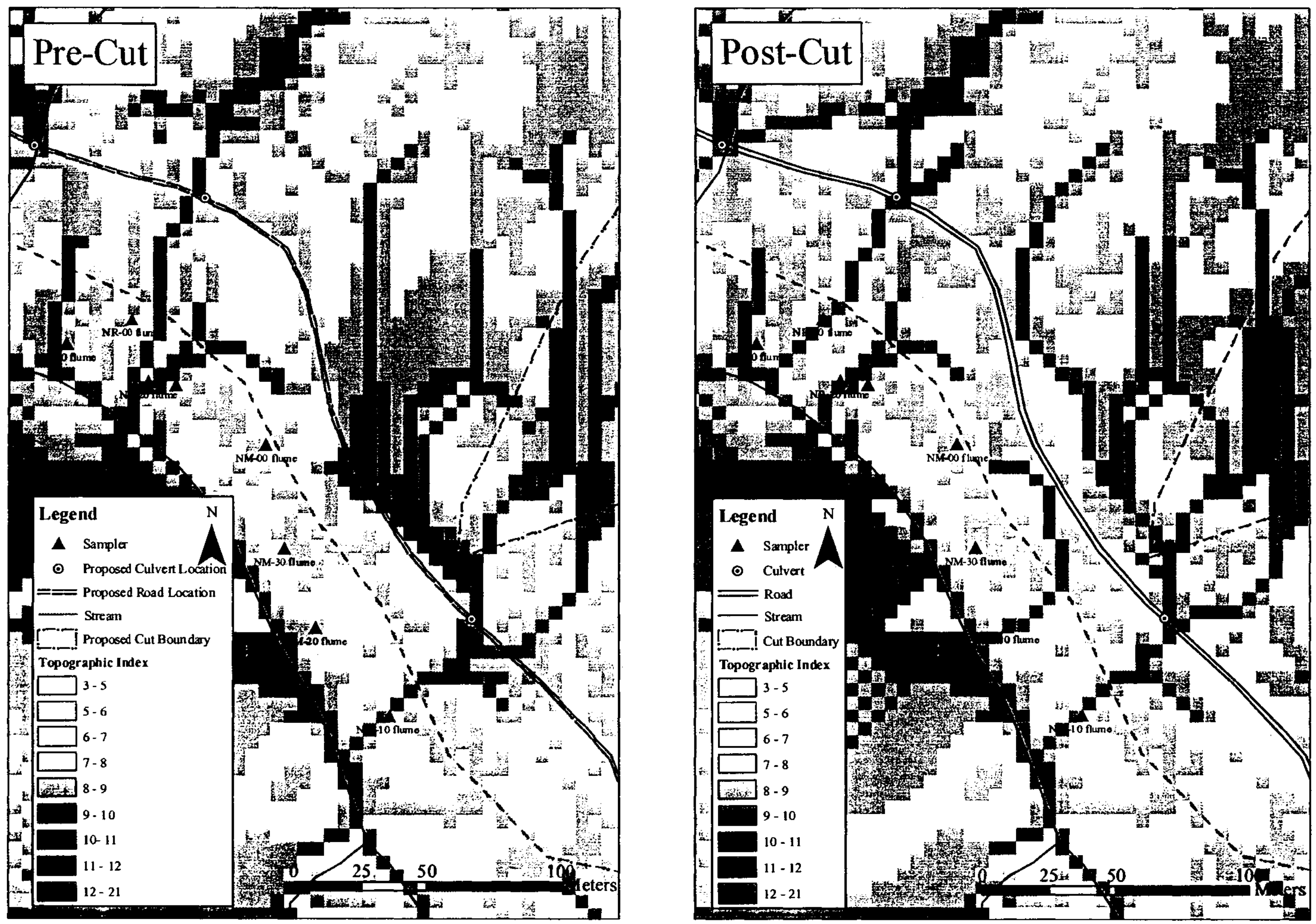


Figure 3.60. Pre-and Post-impact topographic index (TI) values (raw) for North Block samplers. Grid cell resolution is five metres.

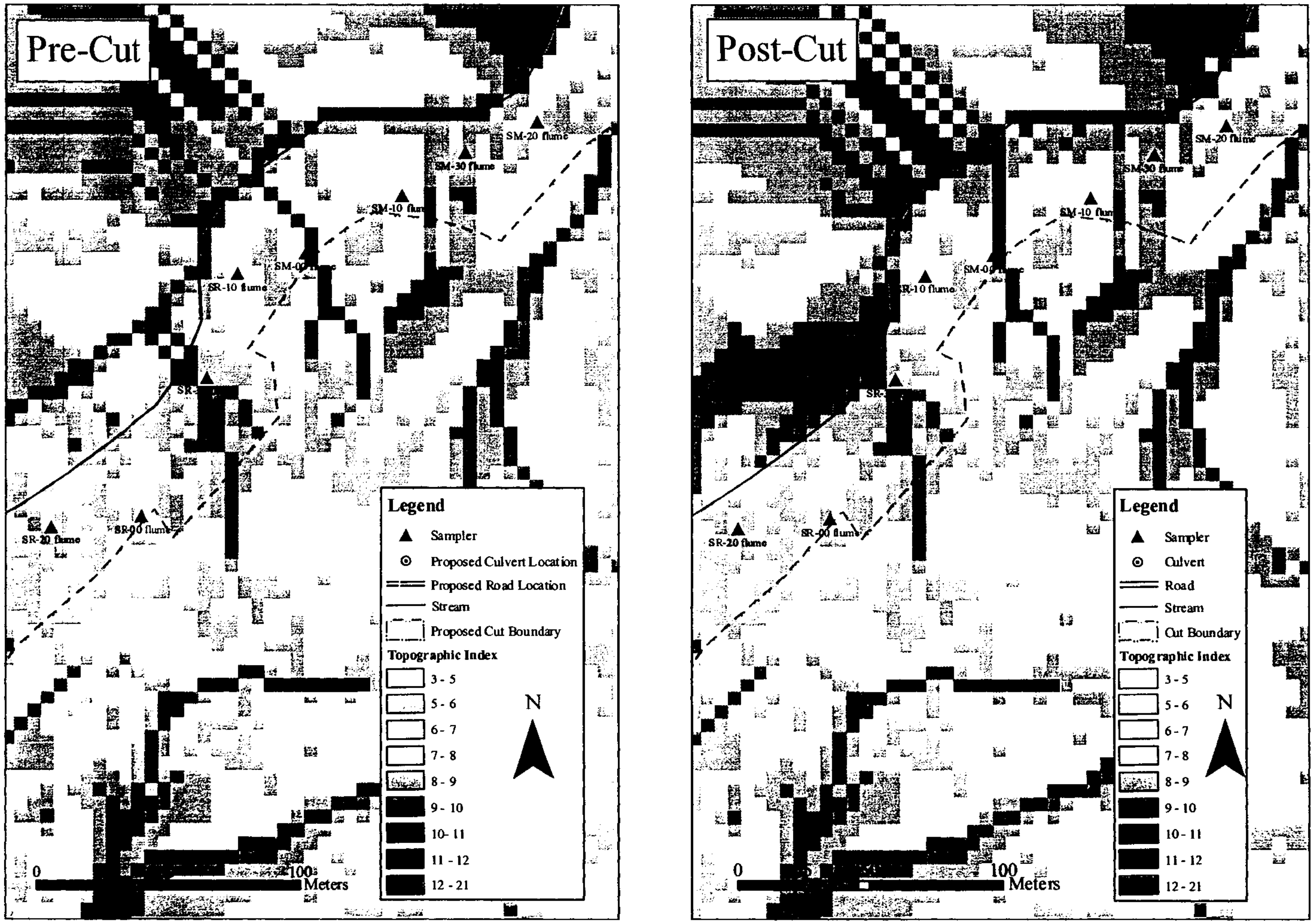


Figure 3.61. Pre-and Post-impact topographic index (TI) values (raw) for South Block samplers. Grid cell resolution is five metres.

among those with high TI values. Minor spatial deviations (+/- approximately 5 m) from an intersection between samplers and the highest TI cells reflect scale limitations of a five metre DEM.

Pre- and post forest management impact TI values for each sampler are reported in Table 3.17 and descriptive statistics of those TI values for the years 1997, 1998, and 1999 are reported in Table 3.18. In 1998, the median and range for TI values among the sixteen samplers were slightly higher compared to those in 1997. In 1999 when only ten samplers remained in service, the median was higher than in 1998 but the range fell to a value that was lower than in 1997 (Table 3.18).

Mineral sediment collection rates and TI values for each sampler are plotted for the years 1997 through 1999 in Figure 3.62, and organic sediment collection rates and TI values area are plotted for the years 1997 through 1999 in Figure 3.63. Post-impact mineral and organic collection rates appear to have a positive relationship with TI; however, data for a small number of the samplers may be driving what may otherwise be a spurious relationship (Figures 3.62 and 3.63).

A set of IOC values were calculated to quantify the difference between the pre- and post disturbance TI values for each sampler (Table 3.17). Impacts did not affect the TI value of any South Cut samplers; however, road building and harvesting effectively caused TI values for six North Block samplers to increase while those for two other North Block samplers were reduced (Table 3.17).

Table 3.17 Pre- and post-impact topographic index (TI) values for each sampler.

Sampler	Pre-Cut TI	Post-Cut TI	Index of Change
NR-00	8.5830	12.5834	0.3826
NR-10	9.9210	9.6381	-0.0289
NR-20	12.5737	11.3768	-0.1000
NR-30	10.5118	10.3184	-0.0186
NM-00	8.5486	8.3090	-0.0284
NM-10	14.0780	14.0361	-0.0030
NM-20	8.7858	10.6537	0.19277
NM-30	7.0025	6.7778	-0.0326
SR-00	8.6459	8.6459	0.0000
SR-10	7.3540	7.3540	0.0000
SR-20	8.8958	8.8958	0.0000
SR-30	11.1597	11.1597	0.0000
SM-00	10.8176	10.8176	0.0000
SM-10	7.5635	7.5635	0.0000
SM-20	7.9490	7.9490	0.0000
SM-30	8.5038	8.5038	0.0000

Table 3.18. Descriptive statistics for the topographic index (TI) values of all samplers in service for each of the sampling years, 1997, 1998, and 1999.

Statistic	1997	1998	1999
n	16	16	10
Median	8.7159	9.2670	10.4861
Range	7.0755	7.2583	5.2294
Maximum	14.0780	14.0361	12.5834
Minimum	7.0025	6.7778	7.3540

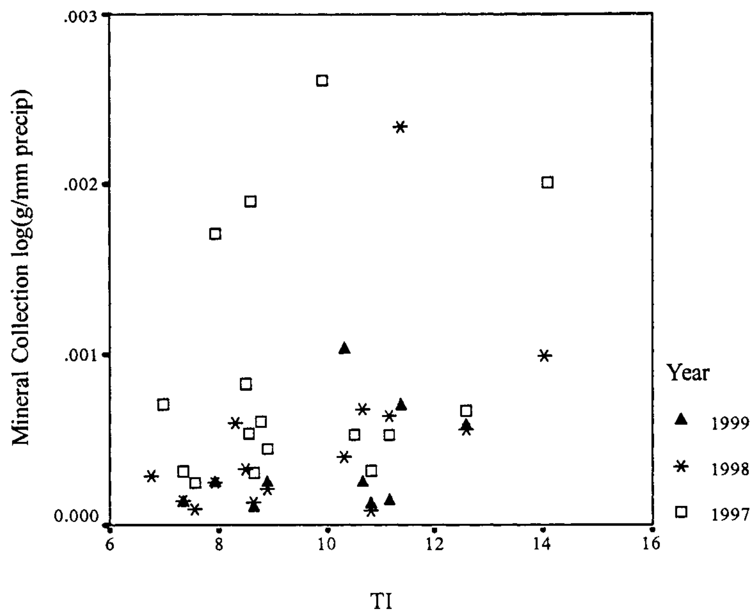


Figure 3.62 Mineral sediment collection rates (log(1+ g·mm^{-1} precip)) for each sampler in 1997, 1998 and 1999 (1998 NR-10 data excluded) plotted against maximum topographic index (TI) values (in a 3x3 cell array) for each sampler.

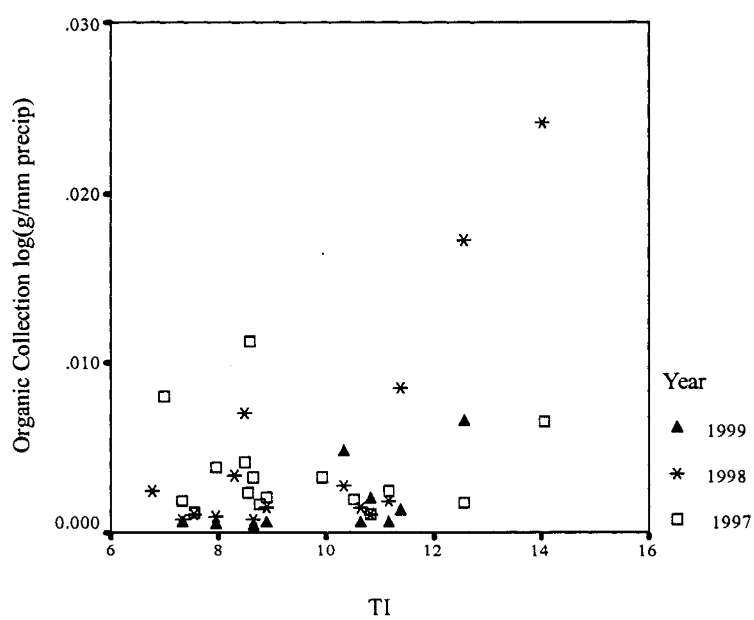


Figure 3.63 Organic sediment collection rates (log(1+ g·mm^{-1} precip)) for each sampler in 1997, 1998 and 1999 (1998 NR-10 data excluded) plotted against maximum topographic index (TI) values (in a 3x3 cell array) for each sampler.

To further evaluate the relationship between TI values and sediment collection rates, the 1998/97 MIOC and OIOC values for each sampler were plotted with IOC values for TI (Figures 3.64 and 3.65). There was no consistent relationship between change in TI value and change in mineral or organic collection rates among data collected in 1998 compared to 1997, based on 1998/97 MIOC and OIOC values and IOC values for TI (Figures 3.64 and 3.65). Samplers NR-10 and NR-20, which had the greatest collection rate increases in 1998 compared to 1997, were among a group of six samplers with lower TI values post-impact compared to pre-impact. Samplers NR-00 and NM-20 had much higher TI values post-impact compared to pre-impact; however, 1998 collection rates in both samplers were similar to those in 1997.

Summaries of 1998/97 MIOC and OIOC values for samplers with: a) no change in TI values after forest management, b) TI values that became smaller after forest management, and c) TI values that became larger after forest management are presented in Table 3.19. Among the five samplers that had higher mineral collection rates in 1998 compared to 1997, three had a post-impact reduction and one had a post-impact increase in TI. The median 1998/97 MIOC among the group with negative IOC values for TI was approximately 11.75 times greater than the group with positive IOC values for TI. Among the seven samplers that had higher organic collection rates in 1998 compared to 1997, five had a negative IOC value for TI and one had a positive IOC value for TI. The median 1998/97 OIOC value for the group of samplers with negative IOC values for TI

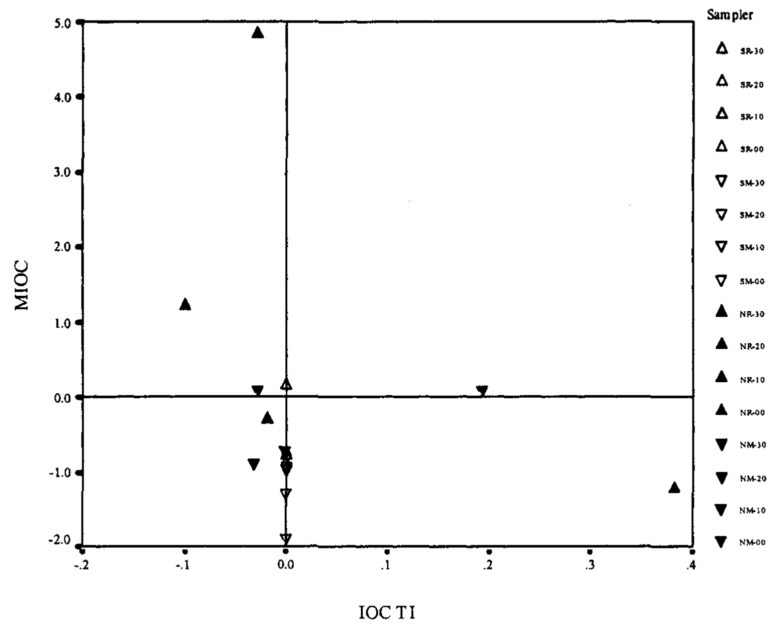


Figure 3.64 1998/97 mineral index of change (MIOC) values and index of change (IOC) for topographic index (TI) for each sampler.

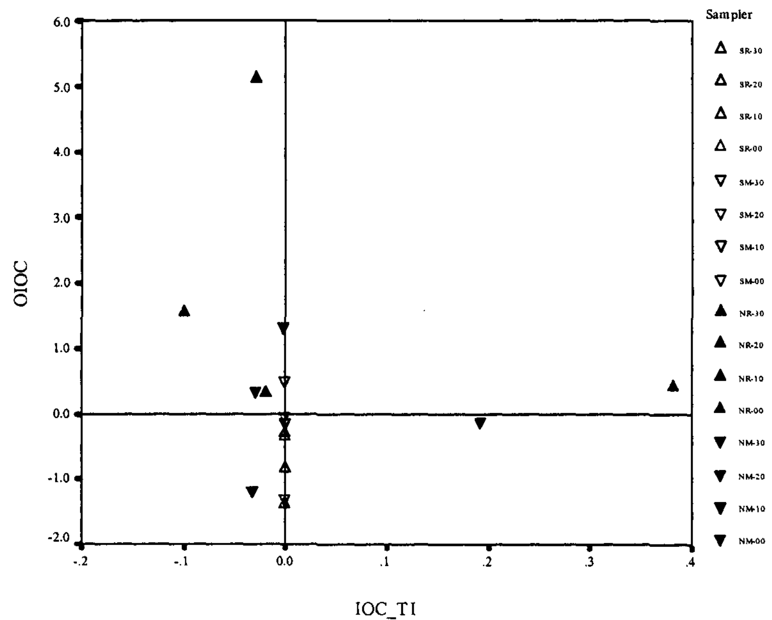


Figure 3.65 1998/97 index of change (OIOC) values and index of change (IOC) values for topographic index (TI) for each sampler.

Table 3.19 Descriptive statistics for 1998/97 mineral and organic indices of change (MIOC and OIOC, respectively) values for samplers (n=16) with: a) no change in topographic index (TI) after forest management impacts, b) smaller TI values after forest management impacts, and c) larger TI values after forest management impacts.

Material	Collection IOC >0 or <0	TI IOC = 0	TI IOC < 0	TI IOC > 0
Mineral	>0	Quad = n/a N = 1 Sampler(s) = SR-30 Median = 0.1766 Range = 0 Max= 0.1766 Min = 0.1766	Quad = 1 N = 3 Sampler(s) = NR-10, NR-20, NM-00 Median = 1.2388 Range = 4.7343 Max= 4.8425 Min = 0.1082	Quad = 2 N = 1 Sampler(s) = NM-20 Median = 0.1055 Range = 0 Max= 0.1055 Min = 0.1055
Mineral	<0	Quad = n/a N = 7 Sampler(s) = SR-00, SR-10, SR-20, SM-00, SM-10, SM-20, SM-30 Median = -0.9085 Range = 1.1540 Max= -0.7301 Min = -1.8842	Quad = 4 N = 3 Sampler(s) = NR-30, NM-10, NM-30 Median = -0.7058 Range = 0.5774 Max= -0.2894 Min = -0.8669	Quad = 3 N = 1 Sampler(s) = NR-00 Median = -1.2137 Range = 0 Max= -1.2137 Min = -1.2137
Organic	>0	Quad = n/a N = 1 Sampler(s) = SM-30 Median = 0.5150 Range = 0 Max= 0.5150 Min = 0.5150	Quad = 1 N = 5 Sampler(s) = NR-10, NR-20, NR-30, NM-00 Median = 1.3167 Range = 4.7925 Max= 5.1125 Min = 0.3199	Quad = 2 N = 1 Sampler(s) = NR-00 Median = 0.4296 Range = 0 Max= 0.4296 Min = 0.4296
Organic	<0	Quad = n/a N = 7 Sampler(s) = SR-00, SR-10, SR-20, SR-30, SM-00, SM-10, SM-20 Median = -0.3391 Range = 1.3516 Max= -0.0352 Min = -1.3867	Quad = 4 N = 1 Sampler(s) = NM-30 Median = -1.1662 Range = 0 Max= -1.1662 Min = -1.1662	Quad = 3 N = 1 Sampler(s) = NM-30 Median = -0.1265 Range = 0 Max= -0.1265 Min = -0.1265

was three times greater than the OIOC value for the sampler with a positive IOC value for TI.

To further evaluate the relationship between TI values and sediment collection rates, the 1999/97 MIOC and OIOC values for each sampler were plotted with IOC values for TI (Figures 3.66 and 3.67). There was no consistent relationship between change in TI value and change in mineral or organic collection rates among data collected in 1999 compared to 1997, based on 1999/97 MIOC and OIOC values and IOC values for TI (Figures 3.66 and 3.67). Sampler NR-30, which had the greatest collection rate increases in 1999 compared to 1997, was among a group of two samplers with lower TI values post-impact compared to pre-impact. Samplers NR-00 and NM-20 had dramatically higher post-impact TI values; however, 1999 mineral and organic collection rates in both samplers were lower than those in 1997 (Figures 3.66 and 3.67).

Table 3.20 reports descriptive statistics (number, median, range, maximum, and minimum) for 1999/97 MIOC and OIOC values for samplers with: a) no change in TI values after forest management, b) smaller TI values after forest management, and c) larger TI values after forest management. Both of the samplers that had higher mineral collection in 1999 compared to 1997 had negative IOC values for TI. Among the two samplers that had higher organic collection rates in 1999 compared to 1997, only one had a negative IOC value for TI.

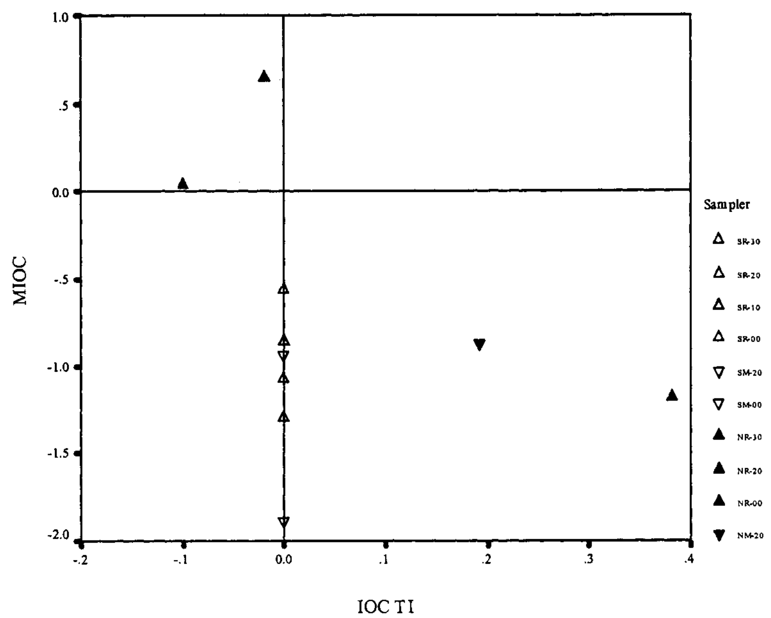


Figure 3.66 1999/97 mineral index of change (MIOC) values and index of change (IOC) values for topographic index (TI) for each sampler.

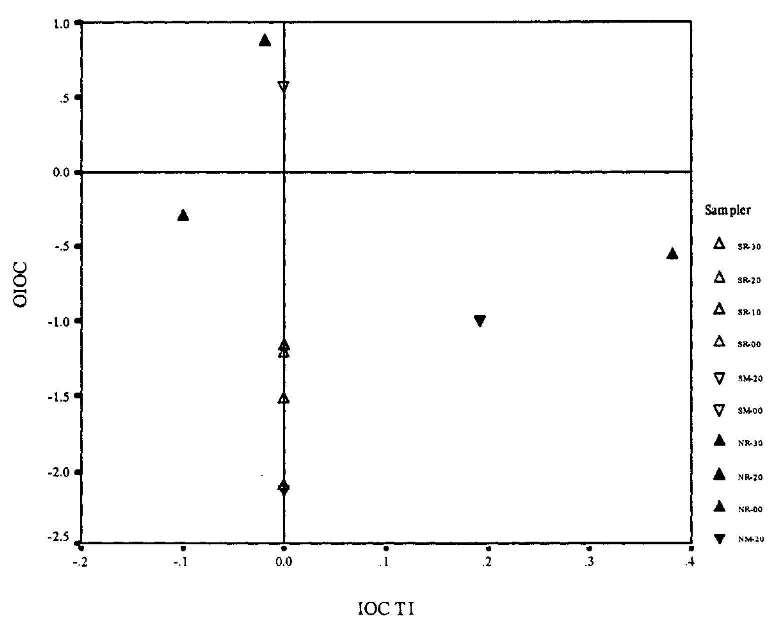


Figure 3.67 1999/97 organic index of change (OIOC) values and index of change (IOC) values for topographic index (TI) for each sampler.

Table 3.20 Descriptive statistics for 1999/97 mineral and organic indices of change (MIOC and OIOC, respectively) values for samplers (n=16) with: a) no change in topographic index (TI) after forest management impacts, b) smaller TI values after forest management impacts, and c) larger TI values after forest management impacts.

Material	Collection IOC >0 or <0	TI IOC = 0	TI IOC < 0	TI IOC > 0
Mineral	>0	Quad = n/a N = 0 Sampler(s) = n/a Median = n/a Range = n/a Max = n/a Min = n/a	Quad = 1 N = 2 Sampler(s) = NR-20, NR-30 Median = 0.3429 Range = 0.6096 Max= 0.6476 Min = 0.0381	Quad = 2 N = 0 Sampler(s) = n/a Median = n/a Range = n/a Max = n/a Min = n/a
Mineral	<0	Quad = n/a N = 6 Sampler(s) = SR-00, SR-10, SR-20, SR-30, SM-00, SM-20 Median = -1.0032 Range = 1.3192 Max= -0.5603 Min = -1.8795	Quad = 4 N = 0 Sampler(s) = n/a Median = n/a Range = n/a Max = n/a Min = n/a	Quad = 3 N = 2 Sampler(s) = NR-00, NM-20 Median = -1.0230 Range = 0.3160 Max= -0.8650 Min = -1.1810
Organic	>0	Quad = n/a N = 1 Sampler(s) = SM-00 Median = 0.5835 Range = 0 Max= 0.5835 Min = 0.5835	Quad = 1 N = 1 Sampler(s) = NR-30 Median = 0.8734 Range = 0 Max= 0.8734 Min = 0.8734	Quad = 2 N = 0 Sampler(s) = n/a Median = n/a Range = n/a Max = n/a Min = n/a
Organic	<0	Quad = n/a N = 5 Sampler(s) = SR-00, SR-10, SR-20, SR-30, SM-20 Median = -1.5197 Range = 0.9563 Max= -1.1651 Min = -2.1214	Quad = 4 N = 1 Sampler(s) = NR-20 Median = -0.3003 Range = 0 Max= -0.3003 Min = -0.3003	Quad = 3 N = 2 Sampler(s) = NR-00, NM-20 Median = -0.7721 Range = 0.4365 Max= -0.5539 Min = -0.9904

4.0 DISCUSSION

The results of this study clearly demonstrate that sediment movement in riparian reserve areas does not increase universally following forest management, and it is clear that factors in addition to terrain slope influence the rate of both organic and mineral sediment movement. In this study, sediment attenuation along lengths of undisturbed forested hillslopes situated between clearcut areas and streams was variable, indicating that factors in addition to the width of a filter strip can function to control the distance at which eroded sediment is transported. Catchment area was not related to the rates that sediment was collected in samplers.

Sediment collection rates quantified by this study were higher in samplers located closer to the road; however, data from this study can not be used to categorically support the accepted model whereby areas closer to roads are subject to higher erosion rates than areas further away from roads. This study used GIS to illustrate how roads can effectively re-route the natural flow paths of surface runoff, and this could be an effective application for forest management planning exercises. The occurrences of surface runoff and windthrow, especially when occurring in unison, were predominant factors controlling sediment collection rates in samplers. The amount of crown closure and the thickness of LFH layers influenced rates of erosion, but the magnitudes of their influences were marginal compared to those of flow and windthrow. Steeper slopes did not consistently generate higher sediment transport rates, but the evaluation of the effects of slope on sediment transport rates was limited by the narrow range of slope conditions that was evaluated by this study. Within the study area, topographic convergences were reliably located by the application of a spatially explicit TI, and the same index was effective at identifying areas that may be subject to increased risk of erosion following forest management.

Reports from other studies suggest that rates of erosion will increase following forest management related impacts (Waters 1995; Walling 1999; Meehan 1991; Miller 1984; Trimble and Sartz 1957); however, this was not a consistent result of this study. Data from the four samplers situated at the cutover/reserve boundaries were best suited to assess the impact of forest management on sediment collection rates as those samplers were in immediate proximity to these activities with no reserve area separating them from these impacts. Changes observed between post- and pre-impact sediment collection rates were not consistently higher or lower among these samplers; however, the level of change (positive or negative) among these four samplers could be considered marginal. In 1998, the first post-impact year, three of the four samplers had lower mineral sediment collection rates while one had a higher rate, and rates of organic sediment collection were lower in two of the samplers and higher in two. In 1999, the second post-impact year, only three of the four samplers situated at the cutover/reserve boundary remained in service, and mineral sediment collection rates were lower in all of them. Organic sediment collection rates in 1999 were lower in two of the samplers and higher in one. The type of change (increase or decrease) in sediment collection rate was also not consistent among the 12 samplers installed in the reserves. However, in comparison with the level of change that was observed at the cutover/reserve boundary, the changes (especially increases) observed in the reserve were of much greater magnitude. It appears therefore, that forest management activities affected the sediment collection rates of some, but not all, of the samplers.

The results of this study contradict the assumption that clearcuts are universal sources of sediment. The application of slope dependent reserve widths to protect aquatic systems from impacts of forest management implies that the spatial distribution of sediment export from clearcuts is even. The results of this study indicate that factors in addition to slope length (or reserve width) including windthrow events, the presence of surface runoff, amount of cover over soil provided by vegetation and organic layers, and topography affect sediment movement in riparian reserves. Sediment collection rates were highly variable within each distance class (0, 10, 20, or 30 m into the reserves), and a consistent negative relationship between the amount of sediment collected and distance into the reserve was not observed. Trimble and Sartz (1957) acknowledged that factors in addition to slope distance can affect sediment attenuation along a forested hillslope; however, they were unable to measure these factors. An objective of this study was to explore the effects of factors, in addition to hillslope length, for their influence on erosion rates, and the findings of these explorations are discussed below.

The processes by which eroded sediment is transported across a forest floor are not uniform, and are complicated by the heterogenous nature of the forest floor. It is believed that the suitability of wetland types for buffering aquatic systems from the effects of forest management activities by capturing moving sediment is variable (Racey 1997). Along some shorelines, the boundary between open water and dry, forested land is distinct, while other shorelines may have a non-forested wetland fringe composed of alder swale, bog, fen, or marsh vegetation communities (Racey 1997). The range in width among these features can be high (Racey 1997). In a study of 40 NWO streams with catchment area among them ranging between 1 and 100 km^2, riparian zone width ranged from 0 to 85 metres (Rankin 2000). In NWO, guidelines prescribe that the width of riparian reserve areas be measured from the high water mark of an aquatic system; however, there may be some difficulty in determining the high water mark in the field (Racey 1997). At low water levels sediment from a harvest area must be transported the width of both the reserve area and riparian forest before it reaches an aquatic system. However, water levels frequently fluctuate, occasionally inundating some wetlands or riparian communities. If sediment has been deposited along the periphery of a wetland during low water level, it can be some distance away from an aquatic system, but should the wetland become inundated by flooding, the sediment along the periphery can be introduced to an aquatic system.

The total amount of sediment flowing out of a drainage basin (total eroded less deposition) is referred to as sediment yield. It is measured at a particular point for a specified period of time and is often expressed as a ratio of mass/area/time. Generally, sediment yield decreases as drainage basin area increases because lower slopes tend to be less steep (Toy 1977; Hadley 1977).

This study showed that sediment yields from larger sub-catchments were not consistently lower than sediment yields from smaller sub-catchments because mineral and organic sediment collection rates were highly variable among the range of sub-catchment sizes that were evaluated.

A gravel surfaced forest access road was extended into the North Block during the latter part of 1997. This study found that rates of mineral and organic sediment collection in 1998 and 1999 were generally higher in samplers that were located closer to the road. This result supports those of other studies that identified negative relationships between sediment deposition and distances from roads (Trimble and Sartz 1957; Belt *et al*, 1992; Elliot *et al.* 1999; Costantini *et al.* 1999; Mattice 1977; Haupt 1959). However, 1997 collection rates were generally higher in samplers that were closer to the road, yet the road did not exist for most of the 1997 sampling season. Comparison of pre- and post-impact collection rates for individual samplers suggests that the construction of the road did not affect sediment collection rates for the majority of the sixteen samplers. Compared to samplers in the South Block, the samplers in the North Block were situated in closer proximity to the road. All of the samplers in the South Block, and six of the samplers in the North Block had lower collection rates in 1998 compared to 1997. Most of the samplers that had higher post-impact collection rates were affected only marginally.

The results of this study highlight the importance of careful consideration and planning when conducting forest management in and around flowing water courses. Furthermore, this study demonstrated how small unmapped streams can be located with flow accumulation grids generated from DEMs. This information could be useful during forest management planning exercises. Post- compared to pre-impact flow accumulation grids produced from the five metre DEMs of the study area revealed how natural flow paths were changed by forest management. In their review of riparian buffer strip design, Belt *et al.* (1992) cautioned that channelized flow can transport material for hundreds of metres and is limited by the frequency and amount of flow, and road cross-drains were noted as being areas particularly prone to this type of risk. Drainage patterns in the Pacific Northwest can be altered by forest roads (Beschta 1998), and this study demonstrated that flow paths in NWO can also be altered by roads. Culverts have been identified as locations where the risk of erosion can be high (Beschta 1998). Post-impact flow accumulation grids illustrated that NR-00 and NM-10 were the only samplers in position to receive flow from road crossings equipped with culverts. Both of these samplers collected less mineral but more organic sediments in 1998 compared to 1997. Of these two samplers, only NR-00 remained in service in 1999, and mineral and organic collection rates that year in NR-00 were lower than those in 1997.

To increase the likelihood that samplers would collect material transported by fluvial erosion, samplers were placed in areas of topographic convergence; however, during the period of this study, surface runoff was observed flowing into only four of the sixteen samplers. Samplers categorized as "flowing" were observed to collect surface runoff at least once during the period of this study, but these samplers may have collected runoff at other times as well. Flowing samplers were exposed to fluvial erosion through shallow sheet flow and channelized flow in addition to that by simple raindrop impact and splash, and this is reflected by higher sediment collection rates in these samplers. Eroded material collected by the twelve "non-flowing" samplers would have been limited to that induced by raindrop splash or isolated storm events.

Samplers NR-10 and NR-20 were installed 1 - 2 m down slope of an area where emerging groundwater flow was frequently observed. Upon emerging, the water was concentrated into small channels or rills, 2 - 4 cm wide, that ran less than 2 m before flowing into the flumes connected to the samplers. Seepages and surface run off can generate the formation of ephemeral gullies, and these surface flow concentrations can transport soil and widen and deepen channels (Moore *et al.* 1988). This may explain why collection rates in NR-10 and NR-20 were higher than rates among the non-flowing samplers. The short lengths of the channels above NR-10 and NR-20 would have limited the amount of channelized fluvial erosion that occurred above these samplers. The channel above sampler NM-10 originated approximately 100 m up hill of that sampler. Given the additional channel length, it would have been expected that collection rates in NM-10 would have exceeded those of NR-10 and NR-20, but this did not occur. Perhaps the undisturbed forest area that was left in the swale that bounded the NM-10 channel (Figures 2.1 and 3.16) helped to control the movement of sediment into the NM-10 sampler, after forest management activities had occurred.

The small streams that flowed into the samplers were not included in the digital maps that are used for forest management planning in NWO, and the small size of the channels above the samplers may be the reason for this. This study has demonstrated that forest management impacts can result in increased sediment transport rates in these streams. Modelling of stream channel networks is critical for evaluating the effects of different management scenarios on the routing of eroded sediment (Olson and Orr 1999). Flow accumulation grids have been used to demonstrate how forest management activities can re-route surface runoff (Prosser and Abernethy 1999). This study demonstrated how flow accumulation grids generated through a GIS can be used to provide this information. The DEMs generated for this study had a resolution of 5m and were generated from DTM points that were surveyed at a high density across the North and South Blocks. The generation of DEMs at a resolution as fine as 5 m is likely not practical for application at a landscape scale because of the amount of source elevation data that is required. In California, mapped drainage networks have been made more complete by supplementing stream lines with flow accumulation paths above critical, field verified thresholds (Olson and Orr 1999). Provided relevant digital elevation data are available (including DTM points, contour lines, or DEM grids), flow accumulation grids can be generated for a landscape that is much larger than the North and South Blocks evaluated by this study. Further research would be required to evaluate the application of using flow accumulation data generated at resolutions coarser than were used here.

Results of this study suggest that windthown trees can compromise reserve function by increasing sediment movement. Prior to installing samplers, no consideration was given to the wind firmness of trees that would be left standing within the reserve areas. During the study, trees were thrown by wind throughout the length of the reserve areas. However, only three samplers had a windthrown tree within five meters uphill of the flume. The group of samplers that was not affected by windthrown trees had median mineral and organic collection rates in 1997 that were much lower than the group of samplers that were affected; however, of the three samplers that were affected by windthrown trees, only one was affected in 1997 and the other two were affected in 1999. It is possible that evolving root instability and poor wind firmness associated with trees that would be thrown by wind, functioned to increase soil erodability in the vicinity of these trees, and this may have caused higher sediment collection rates in windthrow affected samplers, even before the windthrow event occurred.

In 1998, sampler NR-10 was the only windthrow affected sampler that had higher mineral and organic collection rates in 1998 compared to 1997, and the magnitudes of the rate changes for NR-10 were greater than any other observed during this study. The principal factor driving the high collection rates in sampler NR-10 was likely the combination of windthrow and surface runoff, as NR-10 was the only sampler affected by both of these factors. Sampler SM-20 was the only windthrow affected sampler that remained in service in 1999, and mineral and organic collection rates for that sampler were similar to the 1999 median collection rates for the group of nine samplers that were not affected by windthrow.

When trees are thrown by wind, their roots are often overturned, exposing soil. Soil aggregates exposed by windthrows can then be subjected to erosion by raindrop displacement. The effects caused by the three types of fluvial erosion (raindrop splash, sheet, and rill) in combination are of greatest significance to the total amount of material that is eroded (Toy 1977). Flowing water draining into sampler NR-10 could have transported the soil particles displaced by raindrop splash, and additional particles could have been sheared loose by flowing water, as described by Wischmeier (1977). Reductions in both transpiration potential and interception capacity resulting from clearcutting and windthrow events may have increased the frequency, duration, and magnitude of saturation overland flow. These conditions and related effects may explain the observed differences between sediment collection rates associated with sampler NR-10 and to those for NM-30 and SR-20, the other windthrow affected samplers.

Many land management agencies require that riparian reserve areas be left to mitigate the effects of land use on aquatic systems; however, several characteristics of riparian reserves render these areas at higher risk of windthrow compared to other areas of the forest, and these characteristics of riparian reserves include: 1) their soils tend to be wet (Steinblums *et al.* 1984; Stephenson 1988; Alexander 1964); 2) they are associated with edge (i.e. with clearcut areas) (Mitchel 2000); 3) they are often associated with clearcuts, where vegetation removal can lower frictional resistance and allow wind velocity to increase (Fons 1940; Reifsnyder 1955); and 4) they are commonly associated with waterbodies, which have lower frictional velocities than undisturbed forest cover or clearcuts, and this allows wind velocities to increase (Moore 1977). Resource managers need to consider and plan for the risk of increased erosion by windthrow. Stephenson (1988) suggested that with a single-tree selection method, large trees presenting high windthrow risk could be harvested to eliminate that risk. Black spruce is more susceptible to being blown down by wind, followed by white spruce, balsam fir, and paper birch (Stephenson 1988). To reduce windthrow risk in reserve areas, species that are susceptible to windthrow could be targeted during single tree selection logging (Stephenson 1988). Furthermore, as trees growing along edges are most susceptible to windthrow, limiting the amount of edge by designing cut blocks with low perimeter to area ratios should reduce the risk of windthrow (Alexander 1964).

Compared to trees growing in areas with drier soils, those growing in areas with wetter soils are more susceptible to windthrow. Hydrologic modeling utilities available through a GIS can be applied to identify both flow accumulation paths and areas within a landscape where the probability of encountering wet soils is high relative to other areas. This study has identified that the risk of erosion increases when windthrows occur in conjunction with surface runoff compared to erosion associated with either of these phenomenon occurring independently. Hence, conservation efforts to reduce the occurrence of windthrow, especially along flow accumulation paths that traverse through riparian reserves, could also significantly reduce the risk of erosion following forest management. Furthermore, since headwater flow accumulations are linked to those draining larger sub-catchment areas, they represent pathways that are small, and perhaps ephemeral, through which sediment can be transported from upland areas to larger perennial aquatic systems. For this reason, reducing windthrow risk in reserve areas may also assist in sparing aquatic habitat from the impacts of forest management.

Results of this study did not reveal a clear relationship between either mineral or organic collection rates in samplers and the amount of crown closure or LFH thickness. However, when data for samplers classified as being affected by windthrow or flow were excluded, a negative relationship between cover (crown closure and LFH thickness) and both mineral and organic sediment collection rates were more apparent for each of the years, 1997, 1998, and 1999. Data for sampler NR-00 were an exception to this, and this may be due to the presence of a windthrown tree located above the entrance flume of that sampler. NR-00 was not classified as being affected by windthrow, and the windthown tree above it was different from those that affected the other samplers: the NR-00 windthrow was thrown before the study commenced, and the crown-section of the NR-00 windthrow rather than the root wad was adjacent to the entrance flume. Nonetheless, this tree may have affected collection rates in NR-00.

Samplers that had dramatically higher collection rates in 1998 compared to 1997 also had lower amounts of crown closure, but not all samplers that had lower amounts of crown closure had higher rates of collection. Sampler NR-30 had the greatest crown closure increase in 1999 compared to 1997, but contrary to what one might expect, that sampler also had the greatest mineral and organic sediment collection rate increases in 1999 compared to 1997. Sampler NR-30 was not affected by windthrow or flow.

Local slope and sediment collection data from this study do not follow a positive relationship as suggested in the literature (Trimble and Sartz 1957; Phillips 1989; Naslas *et al.* 1994); however, the range in slope and maximum slope conditions evaluated by this study were much smaller than those investigated by other researchers. The slopes quantified for this study were measured over a distance of only 10 m immediately above the entrance flume of each sampler, and the influence of steeper or shallower slopes located further up the hillslopes was not accounted for in these analyses. Changes in mineral or organic sediment collection rates for 1998 or 1999 compared with those for 1997 were highly variable and do not appear to be related to local slope.

It is rare that a hillslope is uniform along its complete length, hence the degree (or percent) of slope is rarely consistent across a length of hillslope. Where slopes are steeper, the velocity of running water that might flow over it is higher, as is the capacity for sediment to be transported. Conversely, where slopes are shallower, the velocity of running water that might flow over it is lower, as is its capacity to transport sediment. These conditions create patterns of erosion and deposition along hillslopes and hint at the complexities of erosion (and depositional) processes. Consideration of factors in addition to slope (such as occurrence of windthrow events, the characteristics of surface runoff, amount of cover over soil provided by vegetation and organic layers over soil, and topography) can provide insight to designing effective and efficient buffer strips.

Beven and Kirkby (1979) suggested that topography affects surface runoff, subsurface flow, and consequently the location of zones of surface saturation and the distribution of soil water content across a catchment. This study demonstrated that Beven and Kirkby's TI can be useful for predicting areas of topographic convergence. The evidence for this was the high TI values that were coincident with sampler locations (which were situated in areas of topographic convergence). Researchers studying erosion associated with agricultural land uses have postulated that if ephemeral gully erosion could easily be predicted, then areas where conservation practices were needed would also be identified (Watson *et al.* 1986). Post-impact data showed higher variances in mineral and organic collection rates as TI values increased, and this was generally true with or without the inclusion of data for samplers affected by flow and/or windthrow. The high variance among samplers with higher TI values indicated that the TI can be used to locate areas with higher risk for erosion; however, this also indicated that some areas classified as having high risk for erosion (based on high TI values) may not actually be subject to higher rates of erosion.

Land management agencies in California have used GIS to locate areas where surface erosion hazards are high (Olson and Orr 1999). Erosion hazard ratings can be used to limit or restrict the types of operations that are allowed to occur within specific areas across a landscape (Olson and Orr 1999). The TI evaluated by this study could be used to locate areas within a management unit that may be subject to higher or lower rates of erosion after forest management impacts. However, these predictions should be field validated prior to forest management operations, at which time areas confirmed to be sensitive (wet areas, and/or areas with channelized flow) could be flagged and excluded from potentially harmful operations, or identified for careful logging.

The TI may also be useful for locating areas within reserves that may have higher relative risk for windthrow occurrence, because trees in wetter areas are at greater risk of being thrown by wind compared to trees in drier areas (Steinblums *et al.* 1984; Stephenson 1988; Alexander 1964). Trees identified to have a high risk for windthrow could be removed by selection logging (Stephenson 1988), and this could help reduce the risk for erosion.

The distribution of water within a catchment and the development of ephemeral channels can be affected by factors other than those accounted for in the TI (Moore *et al.* 1988; Hinton *et al.* 1993). These factors can be spatially variable and can include soil hydraulic properties and vegetation (Hinton *et al.* 1993). More complex indices that include additional variables such as climate and surficial geology may the improve prediction efficiencies of these models, especially when working at regional scales (Wilson and Gallant 2000).

Results of this study demonstrated that a significant portion of the risk for erosion after forest management could have been assessed using just three factors: flow accumulation, windthrow, and TI. The results of this study identified that the occurrences of surface runoff and windthrow (especially when they occur together), can increase sediment collection rates in riparian reserves, and areas with higher TI values may be subject to increased erosion compared to areas with lower TI values. Distance from roads appeared to be correlated with sediment collection rates, but these results were not totally clear. The Results of this study revealed how roads can both alter natural drainage pathways and affect the size of the contributing areas that drain through sections of riparian reserves. Consideration of the effects of forest management by applying the GIS methods used in this study may help forest managers evaluate potential impacts of various forest management scenarios, but further research into these types of applications should be conducted.

5.0 SUMMARY OF FINDINGS

The results of this study do not support the assumption that clearcut areas are universal sources of erodable sediment, and identified that areas exposed to channelized surface runoff are associated with higher risk of erosion than areas that are not exposed to channelized erosion. Analyses of sediment collection rate data have revealed two principal outcomes/results: 1) areas subject to surface runoff had higher sediment collection rates compared to areas that were not, and 2) windthrown trees can contribute to the acceleration of sediment collection rates, especially when they occur in conjunction with surface runoff. This study demonstrated that flow accumulation and topographic indices, generated with a GIS, can be used to locate areas that may be subject to increased erosion following forest management. The influence of the other factors investigated by this study (slope, distance from road, size of the sub-catchment area, amount of cover, and TI) appear to be more variable.

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APPENDICES

APPENDIX I

General guide for determining the widths of AOCs in Ontario, based on shoreland slope (OMNR, 1988).

Slope (%)	Slope (°)	Width of AOC (m)
0 – 15	0 – 8	30
16 – 30	9 – 17	50
41 – 45	18 – 24	70
46 – 60	25 – 31	90

APPENDIX II

Mineral and organic sediment collection rates (g·mm^{-1} precip) for each sampler, by year.

	1997		1998		1999	
Sampler	Mineral	Organic	Mineral	Organic	Mineral	Organic
NR-00	0.0044	0.0265	0.0013	0.0407	0.00134	0.0152
NR-10	0.0060	0.0076	0.7652	1.2625	n/a	n/a
NR-20	0.0016	0.0042	0.0054	0.0198	0.00162	0.0031
NR-30	0.0013	0.0046	0.0009	0.0064	0.0024	0.0111
NM-00	0.0013	0.0055	0.0014	0.0078	n/a	n/a
NM-10	0.0046	0.0153	0.0023	0.0571	n/a	n/a
NM-20	0.0014	0.0039	0.0016	0.0034	0.0006	0.0014
NM-30	0.0017	0.0186	0.0007	0.0058	n/a	n/a
SR-00	0.0007	0.0076	0.0003	0.0019	0.0003	0.0009
SR-10	0.0008	0.0045	0.0004	0.0019	0.0003	0.0014
SR-20	0.0010	0.0047	0.0005	0.0034	0.0006	0.0014
SR-30	0.0013	0.0058	0.0015	0.0043	0.0003	0.0013
SM-00	0.0008	0.0026	0.0002	0.0025	0.0003	0.0047
SM-10	0.0006	0.0028	0.0002	0.0024	n/a	n/a
SM-20	0.0040	0.0089	0.0006	0.0024	0.0006	0.0011
SM-30	0.0019	0.0098	0.0008	0.0163	n/a	n/a

APPENDIX III

Index of change (IOC) values quantifying changes in the rates ($g \cdot mm^{-1}$ precip) that mineral or organic sediment were collected in 1998 (first year post-impact) or 1999 (second year post-impact) compared to rates in 1997 (pre-impact).

	1998/97		1999/97	
Sampler	Mineral	Organic	Mineral	Organic
NR-00	-1.2137	0.4296	-1.1810	-0.5539
NR-10	4.8425	5.1125	n/a	n/a
NR-20	1.2388	1.5562	0.0381	-0.3003
NR-30	-0.2894	0.3199	0.6476	0.8734
NM-00	0.1082	0.3574	n/a	n/a
NM-10	-0.7058	1.3167	n/a	n/a
NM-20	0.1055	-0.1265	-0.8650	-0.9904
NM-30	-0.8669	-1.1662	n/a	n/a
SR-00	-0.8643	-1.3867	-1.0737	-2.0967
SR-10	-0.7772	-0.8389	-0.8618	-1.1651
SR-20	-0.7301	-0.3391	-0.5603	-1.2089
SR-30	0.1766	-0.3049	-1.2969	-1.5197
SM-00	-1.2802	-0.0352	-0.9328	0.5835
SM-10	-0.9577	-0.1522	n/a	n/a
SM-20	-1.8842	-1.3113	-1.8795	-2.1214
SM-30	-0.9085	0.5150	n/a	n/a

APPENDIX IV

Descriptive statistics for mineral and organic sediment collection rates ($g \cdot mm^{-1}$ precip), by sampler position in the reserve, and year.

		1997		1998		1999	
Position	Statistic	Mineral	Organic	Mineral	Organic	Mineral	Organic
0	N	4	4	4	4	3	3
	Median	0.0010	0.0066	0.0008	0.0052	0.0003	0.0047
	Range	0.0036	0.0239	0.0012	0.0388	0.0011	0.0143
	Max	0.0044	0.0265	0.0014	0.0407	0.0013	0.0152
	Min	0.0007	0.0026	0.0002	0.0019	0.0003	0.0009
10	N	4	4	4	4	1	1
	Median	0.0027	0.0060	0.0013	0.0298	0.0003	0.0014
	Range	0.0054	0.0125	0.7650	1.2606	0.0000	0.0000
	Max	0.0060	0.0153	0.7652	1.2625	0.0003	0.0014
	Min	0.0006	0.0028	0.0002	0.0019	0.0003	0.0014
20	N	4	4	4	4	4	4
	Median	0.0015	0.0044	0.0011	0.0034	0.0006	0.0014
	Range	0.0029	0.0050	0.0049	0.0174	0.0010	0.0020
	Max	0.0040	0.0089	0.0054	0.0198	0.0016	0.0031
	Min	0.0010	0.0039	0.0005	0.0024	0.0006	0.0011
30	N	4	4	4	4	2	2
	Median	0.0015	0.0078	0.0009	0.0061	0.0014	0.0062
	Range	0.0007	0.0140	0.0008	0.0121	0.0020	0.0098
	Max	0.0019	0.0186	0.0015	0.0163	0.0024	0.0111
	Min	0.0013	0.0046	0.0007	0.0043	0.0003	0.0013
Total	N	16	16	16	16	10	10
	Median	0.0014	0.0056	0.0009	0.0050	0.0006	0.0014
	Range	0.0054	0.0239	0.7650	1.2606	0.0021	0.0143
	Max	0.0060	0.0265	0.7652	1.2625	0.0024	0.0152
	Min	0.0006	0.0026	0.0002	0.0019	0.0003	0.0009

APPENDIX V

Descriptive statistics for mineral and organic collection rates (g·mm^{-1} precip) by year (1997, 1998, and 1999) for the group of samplers that were and the group of samplers that were not observed to be affected by surface run off.

		1997		1998		1999	
Flow (Y/N)	Statistic	Mineral	Organic	Mineral	Organic	Mineral	Organic
No	N	12	12	12	12	9	9
	Median	0.0012	0.0052	0.0006	0.0034	0.0006	0.0014
	Range	0.0038	0.0239	0.0014	0.0388	0.0021	0.0142
	Maximum	0.0044	0.0265	0.0016	0.0407	0.0024	0.0152
	Minimum	0.0006	0.0026	0.0002	0.0019	0.0003	0.0009
Yes	N	4	4	4	4	1	1
	Median	0.0031	0.0065	0.0038	0.0384	0.0016	0.0031
	Range	0.0048	0.0111	0.7638	1.2547	0.0000	0.0000
	Maximum	0.0060	0.0153	0.7652	1.2625	0.0016	0.0031
	Minimum	0.0013	0.0042	0.0014	0.0078	0.0016	0.0031

APPENDIX VI

Descriptive statistics for mineral and organic collection rates (g·mm^{-1} precip) by year (1997, 1998, and 1999) for the group of samplers that were and the group of samplers that were not affected by windthrow.

		1997		1998		1999	
Windthrow (Y/N)	Statistic	Mineral	Organic	Mineral	Organic	Mineral	Organic
No	N	13	13	13	13	9	9
	Median	0.0013	0.0047	0.0009	0.0043	0.0006	0.0014
	Range	0.0040	0.0239	0.0052	0.0552	0.0021	0.0143
	Maximum	0.0046	0.0265	0.0054	0.0571	0.0024	0.0152
	Minimum	0.0006	0.0026	0.0002	0.0019	0.0003	0.0009
Yes	N	3	3	3	3	1	1
	Median	0.0040	0.0089	0.0007	0.0058	0.0006	0.0011
	Range	0.0044	0.0110	0.7646	1.2601	0.0000	0.0000
	Maximum	0.0060	0.0186	0.7652	1.2625	0.0006	0.0011
	Minimum	0.0017	0.0076	0.0006	0.0024	0.0006	0.0011