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An Examination of the Hydrologic and Suspended Sediment Regime of Selected Boreal Forest Basins After Fire Disturbance.

by

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ABSTRACT

Four drainage basins were studied in the Boreal Forest region of northern Saskatchewan, Canada, from spring to fall, 1996. Two basins had up to 76% of the vegetation removed by fire; the remaining two had no fire disturbance. Comparisons were made between the two types of land treatment using infiltration, runoff, suspended sediment load and stream discharge measurements. The purpose of the study was to investigate hydrologic and suspended sediment changes as influenced by fire disturbance.

It was determined that infiltration rates were lower and suspended sediment loads higher in burned basins. Spring runoff from burned basins was advanced by two weeks in the spring, and average spring and summer discharge ratios were greater for burned basins versus non-burned. Discharge peak was increased by 10% in the burn basins, whereas total discharge remained unchanged.

The lack of protective vegetation in burned basins, and changes to physical and chemical soil properties contributed to reduced infiltration, and increased erosion, but large wetland areas and increased evaporation rates are expected to have tempered discharge volumes from burned basins during warm summer months.

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DEDICATION

This thesis is dedicated to my mum, Clare Celine Butler. A person who could have achieved much in her life, in a professional and academic sense, but who instead became a sailor's wife and the loving mother of seven children. I wish you were here to receive my achievement with me. Thank you for everything.

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CHAPTER ONE: INTRODUCTION

1.1: Rationale

The character and behavior of a fluvial system at any particular location reflects the integrated effect of a set of up-stream controls, notably climate, geology, land use and basin physiography which together determine an integral part of the hydrologic cycle. Modification of the physical landscape, whether by natural or anthropogenic means, invariably results in changes to the hydrologic regime of that same landscape. For example, the removal of a significant area of vegetation by fire over a drainage basin can result in increased annual and peak water yield and decreased base flow (Bosch and Hewlet, 1982; Jaakko Poyry, 1992). In addition to this, land use disturbance can also reduce infiltration and increase soil erosion in the upper part of the catchment. The consequence is a marked addition to the total sediment yield within the basin's streams, thereby increasing morphological activity, and altering biological patterns within the lower part of the basin. (Langbein and Schumm, 1982; Dunne and Leopold, 1978).

Forest fires are one form of land use disturbance that has received much attention in past years. However, little information is available regarding the impacts of fire on the hydrologic regime of the northern boreal forests of Canada. A great deal of fire impact studies have been conducted in British Columbia and the western and coastal areas of the United States. But, because of the very different landforms in these areas, much of the information is not applicable to the boreal forests of Canada's central provinces: Alberta, Saskatchewan, and Manitoba.

Forest fires have most likely been a common event in the northern boreal forest since the last ice age and the organisms inhabiting lakes and streams within this ecoregion have no doubt had to adapt to the changing conditions in aquatic habitat quality induced by such events (Tones, 1996). But fires in the boreal forest are becoming increasingly more common. Studies show a noticeable increase in forest fires within the mixed wood section of the boreal forest between 1945 and 1983 (see Appendix A), a large number of which have been the result of human cause. These fires remove ground cover and alter the hydrologic regime and sediment yields within the waterways of the region.

Within the central and northern portions of the boreal forest is a prolific network of lakes and streams. Many of these waterways are important habitats for aquatic life, and ideal locations for commercial fisheries and agriculture (eg., rice plantations). Research in changes to the hydrologic regime and increased levels of suspended sediments have indicated impacts on water conveyance, water treatment facilities, commercial fisheries, and irrigation systems (Kidd and Pimental, 1992). Sediment is also one of the major determents of the life spans of reservoirs, and recent research has shown that many persistent contaminants (heavy metals, pesticides, radionuclides) adhere readily to fine sediment particles in rivers (de Boer and Crosby, 1995).

The effects of altered stream flow on aquatic ecosystems are both positive and negative. Increased water yield may increase the amount of available habitat for organisms; however, higher peaks can degrade stream channels, disrupt spawning substrates or fill pools with sediment (Jaakko Poyry, 1992). Decreased base flow may reduce the amount of over-wintering or critical rearing habitats.

Small increases in suspended sediment concentrations resulting from erosion generally have low impacts on aquatic life over the short term. For example, during peak spring discharge or single storm events. Sizable, or continued sediment inputs however, may have long term impacts (Stichling, 1974; Tones, 1996). Aquatic life adapt to natural fluctuations of sediment levels in streams, but high appreciations of sedimentation over the short or long term may upset the balance of the ecosystem and have a detrimental effect on fish populations (Anderson et al., 1987; Cline et al., 1994). The most common and significant example of which is the obstruction of fish movement and the removal of available habitat.

The degradation of aquatic habitat and alteration to water supplies downstream is intuitively connected to removal of vegetation due to forest fires and the changes in that portion of the hydrologic cycle where rainfall intercepts the land and is removed from a watershed. Indeed a perpetuation of hydrologic change is noticed from the small scale of soil infiltration through to the large scale, in volumes of water exiting a drainage basin. If research is to keep pace with a growing trend in forest fires, and commercial exploitation of natural resources in the boreal forest it is essential that insight be sought on the hydrologic regime of this forest and an understanding attained on how such disturbances affect the natural balance of this regime.

1.2: Project Objective

The primary objective of this thesis is to analyze the differences in streamflow characteristics and sediment loads resulting from land use treatments. This is accomplished by comparing burn and undisturbed forest cover. For this purpose four drainage basins were selected in the southern part of the boreal forest of Saskatchewan. A recent fire destroyed significant portions of forest in two of these basins, while the other two remain relatively undisturbed from both human and natural occurrence.

To accomplish the objective the following project goals were established:

- Study the relationship between proportion of burn treatment and the physical and hydrologic characteristics within drainage basins.
- Verify the relationship between suspended sediment load and discharge with previous research and to further explore the strength of the relationship between these two variables in burned basins.
- Demonstrate that drainage basins with the same physical variables and with the same land use treatment will handle hydrological input similarly over time.
- Confirm that changes to a drainage basin's land use will be answered with a change in the basin's hydrologic outputs.

It is hoped that this project will achieve a clearer understanding of the relationships between landform characteristics and the hydrologic cycle within the context of the boreal forest. The results of the study should be available for ongoing research to be utilized as an indicator of the type and level of hydrologic response expected from a drainage basin after fire disturbance.

1.3: Previous Research.

Very few comprehensive studies of the relationships between forest fires, hydrology and suspended sediment loads in streams have been conducted in any of Canada's provinces which encompass the boreal forest. The applicability of the few studies that do exist was evaluated based on the intent of the study, the methods used in the study, and, the degree of similarity between the boreal forest and the geographical area in which the study was done. Of these, three have been selected as resource for this project.

By far one of the most extensive studies to be completed in the boreal forest ecosystem is BOREAS (Boreal Ecosystem Atmospheric Study). BOREAS was a multidisciplinary project designed to study the interaction between the boreal forest biome and the atmosphere (Sellers et al., 1994). Two study areas, one on the southern and the other on the northern fringe of the boreal forest, collected meteorological measurements (precipitation, air temperature, ground temperature, and radiation), and satellite imagery, from March 1994 to October 1996. Satellite imagery from BOREAS, 1996, was used for this research.

The most recently published study concerning the water-related environment of the boreal forest is a Twenty Year Forest Management Plan Environmental Impact Assessment (EIA) developed for Weyerhaeuser Canada, Saskatchewan Division. The hydrology section of this impact assessment examined the hydrologic impacts of timber management. Impacts on streamflow within drainage basins were drawn from modeling two different harvesting scenarios. Of particular relevance to this research, the EIA also modeled impacts from natural burn disturbance. Scenarios were simulated assuming that all harvested land cover within the basins was burned. The WATFLOOD (water flood) Model, used for this EIA, is a continuous-simulation distributed-parameter hydrologic model. The model is "applicable at a watershed scale, sensitive to land cover type, and able to predict future flows" (Kouwen, 1995). Research results, pertinent to this study, indicated high infiltration rates in most of the forested areas, but lower infiltration rates in harvested areas and burn areas due to reduced precipitation interception, and in burn locations the removal of organic soil cover. Model simulations also indicated that water yield increased by up to 40% and on average 24% after a significant (53% - 60%) burn. In addition, spring melt peak flows were advanced by up to two weeks.

The Prince Albert Model Forest (PAMF) hydrology project was initiated by the National Hydrology Research Institute (NHRI) in 1993 and aims to quantify the main parameters and variables governing the hydrologic regime in the boreal forest (Pomeroy et. al., 1996). In 1995 and 1996 when fire burned a large portion of some of the established study sites research was initiated to investigate the relationships between disturbance and hydrology. Present efforts are focusing on snow accumulation, snowmelt, infiltration, evaporation and runoff measurements, and on hydrological modeling. Applicable results (for this project) in snow accumulations to date indicate that total snow accumulation is higher in open, clear-cut and burned locations in comparison with closed forest locations. Furthermore, the timing and rate of snowmelt in harvest and burn locations is faster due to increased sensible and latent heat transfers.

CHAPTER TWO: BACKGROUND

2.1: Introduction

Hydrologic studies of watersheds invariably encompass physical properties from soil and vegetation, to basin slope and shape. This is important when looking at the passage of rainfall to the ground, through and over the solum to the basin channel. Often the changes in streamflow from basins with disturbance are the result of changes in the hydrology at different scales. The processes involved in this are strongly interrelated on the landscape. On the small, stand scale (individual or small groups of trees) disturbance on streamflow primarily results from change in the hydrologic processes taking place in the vertical direction (i.e., infiltration, evaporation). On the large scale (watershed) changes in hydrology takes place in the horizontal direction (i.e., surface runoff, interflow). When large disturbance takes place within a basin both the physical properties and hydrologic processes become unbalanced at all scales. The results of this are visualized from modifications to the hydrologic regime at the basin outlet and in the volume of suspended sediment loads carried in the streams exiting the drainage basin.

Because this research investigates hydrologic response due to land use change a description of physical properties affected and hydrologic process altered by fire disturbance will follow. This chapter outlines those properties associated with land use change in the context of this research. The first part focuses on the concepts of soil properties as related to precipitation input, then infiltration and erosional response at the small, stand scale. Because suspended sediment loads are a key indicator of measured response to land use treatment and are closely associated with stream flows background of sediment load origin, measurement, and variability of scale are covered in the second part of the chapter. The third section is an overview of studies dealing with drainage basin characteristics relating to hydrologic processes at the larger, watershed scale. The final part of this chapter is an examination of wetland hydrology. Large portions of drainage basins within the boreal forest are represented by wetland sites and hence any hydrologic study in this region would be lacking without this inclusion.

2.2: Soils, Infiltration and Erosion

2.2.1: Soil Properties

Soil properties can influence degrees of erosion on the land, and levels of suspended sediment in streams. Soil erosion is a function of two opposing forces: the resisting force of the soil and the driving force of the erosion agent. Because of the differences in their inherent properties, soils exhibit different degrees of susceptibility, or soil erodibility (Lal, 1990). Important soil properties that effect the resistance of a soil to erosion include texture and organic content (Anderson, 1954; Dunne and Leopold 1978; and Shen and Julien, 1983). Soil texture is the relative proportion of the various soil separates in a soil (sand, silt, clay and loam). Both the texture and organic matter content of the soil combine to give the soil structural stability. It is this stability that effects the extent of erosion through the resistance of surface granules to the beating action of rain. For example, Brady (1990) describes those soils with high proportions of sand and organic matter content as being less easily eroded.

The presence of decaying vegetation in the form of litter and soil organic matter has several benefits to soil texture. They help to develop an aggregated, granular soil structure that increases infiltration, as compared to bare soils. Organic matter increases cation exchange capacity, and reduces soil erosion. Litter retards the evaporation of soil moisture and reduces soil erosion by protecting soil aggregates from dispersal by rainfall impact by providing organic matter for binding soil particles together (Cooke and Doorrnkamp, 1990). Litter also stabilizes soil surface temperatures. For example, Wright and Bailey, (1982) found that when it is removed thawing of the soil is accelerated in spring. When significant proportions of organic matter are removed from the soil, for example, by fire, the soil structure becomes weakened and more susceptible to the erosional forces associated with precipitation.

2.2.2: Infiltration

Precipitation reaching the ground surface may evaporate or become either surface runoff or infiltration, depending on whether or not the rain intensity exceeds the infiltration capacity. Infiltration is referred to as the process whereby water enters the surface strata of the soil and moves downward toward the water table (Cooke and Doornkamp, 1990). During the initial period of rainfall there is little, if any, runoff. The water first replenishes the soil moisture deficiency, and thereafter any excess moves on downward and becomes ground water. The maximum rate at which a soil in any given condition is capable of absorbing water is called its infiltration capacity. Rain enters the soil at capacity rates only during and immediately following periods of rainfall excess, that is, periods during which the rainfall rate exceeds the infiltration capacity. When the rain intensity is less than the infiltration capacity, the prevailing infiltration rates are approximately equal to the rainfall rates. (Dunne and Leopold, 1978; Ward and Elliot, 1995).

The infiltration capacity of a soil is influenced greatly by its structural stability. Soils with poor structural stability will usually have low infiltration capacity. For example, Brady (1990) found that soils with high sand content will most often have high infiltration capacities as well as good structural stability, and Singh (1992) noted that for this material stream densities in drainage basins is low.

The average infiltration capacity of a drainage basin changes both annually and seasonally. Seasonal changes occur with the renewed growth of vegetation after winter dormancy, whereas annual change results from the advancing stage in the development of the perennial vegetation (Tones, 1996). Both Wisler and Brater (1959), and Bouman (1994) found that moisture content of the soil reaches a maximum in the spring, minimum in the summer, and high levels again in the fall. High moisture content means that infiltration capacity rates will be exceeded faster in the spring and fall. Newson (1994) found that this seasonal difference is most noticeable where the land is low gradient and depressional, such as in the boreal forest, where standing water is found at or near the ground surface during spring and fall. Except for major changes in land use, these variations occur slowly and their effects become discernible only after a period of years. However, when an entire basin or any large portion of it is subjected to a sudden change in land use, such, for instance, as being deforested by fire, the resulting change in infiltration capacity is more immediate. Marked divisions in infiltration rates are then more noticeable between seasons, and between land that is vegetated, and land that is burned. Further, more detailed discussion of these changes are covered in Chapter 3, Literature Review on Land Use Change.

2.2.2.1: Measurement of Infiltration

Several methods as noted in the literature, are used for measuring soil water infiltration. Infiltrometers are the most commonly used equipment for determining infiltration rates (Linsley et al., 1982). Simulated heavy and uniform rainfall is applied to a known, sectioned area of soil, and "infiltration is computed by assuming it to equal the difference between water applied and measured surface runoff" (Linsley et al., 1982). Infiltration indexes are used where infiltrometers are not available, but rainfall and runoff time rates are known. The Phi (Ø) Index is the mean infiltration rate occurring for the duration of the storm (Singh, 1992), and is used when rainfall and runoff rates are known. The W Index is a refinement of the Ø Index because it includes interception and depression storage values. The determination of infiltration rate when using infiltration indexes involves the repetition of steps that aids in refining the period of rainfall within an event to the point where the volume of falling rainfall equals the volume of runoff (Linsley et al., 1982).

2.2.3: Erosion

Soil erosion is an important link between soil infiltration, runoff and suspended sediments in streams. It is the step where soil particles from the land are carried to the streams and removed from the drainage basin.

Soil erosion by water involves the detachment and entrainment of solid particles from the land surface or from the bed and banks of streams (Cooke and Doorrnkamp, 1990). Water is the most widespread erosion agent and can take a number of forms, including rainsplash erosion and overland flow. Rainsplash erosion takes place when raindrops striking the ground have sufficient momentum and energy to dislodge and move soil particles. Overland flow is related mostly to sloping areas (Dunne and Leopold, 1978; Brady, 1990; Shen and Julien, 1993). Once subsurface layers are saturated and depressions are filled the infiltration capacity of the soil is reached and overland flow begins (Morgan, 1979). Three types of water erosion are recognized: sheet, rill and gully erosion. Sheet erosion is responsible for removing soil uniformly across a slope, rill erosion is characterized by small irregularly dispersed channels in the soil, and gully erosion occurs when the volume of runoff water is concentrated more into larger channels and gullies (Brady, 1990). Water movement on slopes and the type of erosion that occurs is controlled by a complex set of interrelated factors. Some of these factors, for example rainfall duration, rainfall intensity, or snowmelt runoff are external to the soil-landscape system. Other factors such as soil properties, slope, and positional attributes such as relative height and distance from the slope base are integrated into the system and exert a major influence on how water will move across a surface and through it. (Dunne and Leopold, 1978; Lal, 1990; and Forester, 1995).

2.3: Suspended Sediments

2.3.1: Origin of Stream Sediment

Sediment is the major form in which material is transferred from continents to oceans. Sediment in rivers is of concern because it is a reflection of soil erosion. Most river sediment load is supplied from the erosion of cohesive river banks, and from surface and subsurface erosion in the catchment area by such processes as rainsplash, reduced infiltration capacities and surface runoff. This load can be separated into three components (Paustian and Beschta, 1979, and Roberts and Church, 1986):

1. the dissolved load, consisting of material transported in solution;
2. the wash load, comprising particles finer (<0.063 mm) than those usually found in the bed and moving readily in suspension: and
3. the bed-material load, which includes all sizes of material (>0.063 mm) found in appreciable quantity in the bed, and which is moved along the riverbed by rolling, sliding, or skipping within a few grain diameters of the bed.

The wash load moves in suspension at approximately the same speed as the flow and settles out where flow velocities are much reduced. Concentrations of suspended bed-material load are greatest near the river bed and diminish upward, whereas wash load concentrations are often uniform from the river bed to the water surface, but markedly inhomogeneous in the cross-channel. Wash load is the dominant component of the total sediment outflow from a watershed.

2.3.2: Measurement of Suspended Sediment Load

The central problem to measuring the instantaneous suspended sediment concentration is the heterogeneity of the distribution of water velocity and sediment concentration in rivers (Knighton, 1984). An accurate measurement of suspended sediment concentration requires that these heterogeneities be integrated in some way. Two approaches in suspended sediment sampling have been suggested by Guy and Norman (1970); point sampling and depth-integrated sampling. Point sampling is designed to collect continuously at given points over an interval of time. This method is generally used in deep, swift streams, where the depth-integrating sampler is unsuitable. Depth-integrated sampling provides a mechanical integration of the distributions of velocity and suspended-sediment. Most measurements of the sediment loads of the rivers of Canada and the United States are based on depth-integrated sampling. (Guy and Norman, 1970; Ashmore, 1997).

The time variability of sediment concentration measurements in natural channels depends on many factors. These are: the location of the measurement, the magnitude of the flood, the source of water and sediments, and the land use conditions within the watershed prior to the flood (Shen and Julien, 1993). According to Meade et al., (1990) suspended-load transport is easy to measure but difficult to predict because it depends to a significant degree on processes outside the river channel that are not always susceptible to accurate quantification. These processes can be categorized into four main groups: precipitation and runoff characteristics; soil resistance; basin topography; and the nature of the plant cover (Meade et al., 1990). The principal climatic factor influencing river sediment on a drainage basin scale is precipitation because it effects vegetation and runoff. "As the average vegetative cover density decreases sediment loss becomes increasingly sensitive to runoff and there appears to be a progressive increase in the rate at which sediment yield varies" (Knighton, 1984). It is important to state here that suspended sediment transport is associated with higher discharges, but the sediment supply from a drainage basin is usually not a function of the storm discharge but of precipitation (Knighton, 1984).

Suspended sediment concentration should always be measured alongside stream discharge (Guy and Norman, 1970; Paustian and Beschta, 1979). Sediment-discharge curves measure the degree of association between suspended sediment concentration and discharge (Linsley et al., 1982; Lopes and Ffolliott, 1993). These are often used when suspended sediment loads are measured intermittently over a season. They provide a single point measurement at the outlet of a drainage basin showing the collective influence of precipitation events that occurred throughout a season of measurement in that basin.

2.4: Drainage Basin Characteristics

Certain characteristics of drainage basins reflect hydrologic behaviour and are useful, when quantified, in evaluating the hydrologic response of the basins (Singh, 1992). Knighton (1984) explains that the drainage basin is typically a well-defined topographic and hydrologic entity which is regarded as a fundamental spatial unit. Streams and their tributaries within a drainage basin accommodate themselves to the local geology. The shape of the channel network reflects hydrologic processes, and also partially controls them (Mosley and McKerchar, 1993). Stream order, drainage density, bifurcation ratio, basin slope and stream profile analysis are important descriptors of basin conformity. Drainage basin network analysis allows the development of quantitative relations between geomorphic and hydrologic variables. This relationship, although variable in detail, holds true for drainage basins of any size or extent (Mosley and McKerchar, 1993). Initial study of drainage areas should include a description of these characteristics as a check that these patterns are consistent for all basins within a research project. They are also useful in identifying hydrologic regime before disturbance, so that changes experienced after disturbance can be more properly attributed to that disturbance.

2.4.1: Stream Order

Stream orders determined by Strahler (Ruhe, 1975), classify segments of stream channel according to their hierarchical position in the network. Horton's laws of drainage network composition relates stream numbers, lengths, and catchment areas to stream order. Horton predicted that in a well-developed drainage system first order streams will be more numerous than all other combined, and that each succeedingly higher order will be represented by significantly fewer streams (Knighton 1984). This is also known as the bifurcation ratio. If the number of streams is plotted against the respective stream order number, a straight line results. This orderliness is known as Horton's law of stream numbers: the number of streams of each order decreases with increasing stream order.

Other laws of drainage composition are the law of stream lengths (Horton, 1945), where an inverse linear relationship exists between number of streams of a given order and stream order number, and the law of drainage area (Schumm (1956), where mean drainage area increases with stream order number.

2.4.2: Drainage density

Drainage density is the ratio of stream length to drainage basin area; it is indicative of how frequently streams occur on the land surface of the basin (Knighton, 1984). Drainage density reflects the complex interaction of those factors which control surface runoff, and consequently varies over space, and in the long term with changes in the controlling variables. It is also causatively significant in determining the efficiency with which surface runoff is discharged from an area during individual storms.

Drainage density is strongly connected with sediment yield. Outside of periods of disturbance, high sediment yields reflect increased channel development and a more efficient drainage system. The drainage density quantifies the texture of the drainage pattern; areas with high drainage density are associated with high flood peaks, high sediment production, and steep hill slopes due to active stream incision (Dunne and Leopold, 1978). They are also a sign of such things as impervious strata, high rainfall, little vegetation. Generally, as drainage density increases, runoff increases and infiltration decreases (Chow, 1964). Low drainage density means low runoff levels and more water entering the system through infiltration (Knighton, 1984). For example, for basins within the boreal forest, which are associated with low relief and large depressional areas, drainage density and runoff levels are expected to be small, with high infiltration rates.

2.4.3: Basin Slope and Stream Profiles

Drainage basin slopes supply channels with runoff. In natural watersheds slope is spatially variable. In the upper part of the catchment the relationship between slopes and channels is immediate, but in the lower it is more subdued (Chow, 1964). Two methods used to analyze the gradient within a drainage basin are average basin slope and stream profile.

Average drainage basin slope is the mean slope value for the entire watershed. These values are obtained from determination of land area encompassed within each contour interval and the total height difference from the lowest elevation (usually the outlet of the basin) to the highest (at the watershed divide). Average slope values should be consistent between watersheds if sediment yields are being analyzed. Because the topographies in the boreal forest are smooth to rolling little variation it is expected in average slope values between drainage basins.

Ward and Elliot (1995) found that the land slope has little effect on infiltration rates or the depth of runoff, but does have significant influence on the velocity of water flow on land surfaces and in channels. This would mean that basins with steeper slopes are more likely to experience higher overland flow velocities that those basins with low slope values. Basins with low angle slopes would be expected to have low stream densities, and low flow velocities. Gloutney and Merkowsky (1995), in their project which studied the effect of forest harvesting disturbance on stream channels within the boreal forest, state that streams in Saskatchewan cannot be considered as high gradient, and therefore "it would be expected that sediment loads would not be transported downstream unless a major discharge event occurred." In addition, Saxton and Shiau (1990) observed that the influence of basin slope is most relevant to indices of peak streamflow and to the hydrograph shape. When comparing two drainage basins with the same distance from source to outlet but with different slope gradients, the basin with the highest slope average will produce a higher, and more prominent peak on the discharge hydrograph, whereas the basin with lower slope average will show a more subdued, rounded peak. Saxton and Shiau (1990) recommend where studies of hydrologic responses within drainage basins, due to disturbance, are conducted consistent slope angles should be maintained across all basins to control the influence of slope on the final hydrograph analysis.

The gradients of the main channel in a basin when linked together produce a long profile of the basin. Generally these long profiles illustrate that the lower order tributaries are steeper than those of the higher orders. The long profile of the river covers the changes in altitude from the source along its channel to its mouth. (Clowes and Comfort, 1982). These profiles give a visual outline of channel slope, and allow the researcher to identify the location of channel and section controls, when selecting appropriate sites for velocity and suspended sediment measurement.

2.5: Wetlands

Many drainage basins in the boreal forest contain wetland areas. The presence of these wetlands cannot be overlooked in this paper because of their prevalence and because they have been shown to play an important role in the hydrologic processes within watersheds. Technically wetland areas are where the groundwater table intersects the surface (Winter and Woo, 1990). Many wetlands within the boreal forest are characterized as fens and bogs which are both influenced by differing inputs of water supply. Fens are supplied by nutritionally rich seepage waters, whereas bogs are supplied only by rainfall. Both of these wetland types commonly occur in areas of impeded drainage (Price and Maloney, 1994). Many wetlands, particularly small wetlands, are connected to small perched water tables. This type of condition is common in boreal climates (Gehrels and Mulmoottil, 1990). Here compacted glacial till underlying soils once covered by continental glaciation provide shallow impermeable layers that leads to formation of seasonal wetlands.

The presence of wetlands within the study area is expected to have some effect on evapotranspiration and runoff processes taking place in the watershed. Both Gehrels and Mulamootti (1990) and Price and Maloney (1994) noted in their research that large depressions and detention storages of wetlands enhanced evapotranspiration losses during warmer summer months. In addition they found that as evapotranspiration increased in the summer months there was a corresponding decrease in discharge from surface outflows, but in the fall evapotranspiration decreased and surface water outflow increased.

Water storage in wetlands is underground or in surface depressions. The hydrological processes which characterize these systems are dominated by low slope, rough microtopography, and numerous pools which impart a large depression storage capacity (Price and Maloney, 1994). Wetlands control their own hydrological relationships by growing or declining in surface level relative to the water table. When surface depressions are full, additional water from precipitation will run off the wetland quickly. If depressions are low in water level, such as in dry summer months wetlands will act as detention areas and slow the flow of runoff (Ward and Elliot, 1995). In such cases where storage is low, or the lakes and wetlands are dispersed over widespread, gently rolling terrain these depressions will commonly retain part of the surface inflow and release the water over an extended period (Cooke and Doornkamp, 1990). The resulting outflow hydrographs are generally smooth, and the time of the peak flow lags behind the initial peak of the runoff into the lake or wetland. In general the degree of flow modification related to storage depends on the extent of the wetland, and the characteristics of flow through them. Those streams flowing on relatively impervious ground have variable discharge, whereas streams flowing on permeable ground have lower peak flows and more sustained base flow. In wetlands, surface flow may seep underground, be retained in hollows, or continue to travel across the wetlands in sheets or along channels. Where streams flow through a wetland along well-defined channels there is little exchange with the ground water, and the streamflow regime is little changed by the wetland (Cooke and Doornkamp, 1990; Winter and Woo, 1990).

CHAPTER THREE: LITERATURE REVIEW

3.1: Introduction

Because the topic of this thesis focuses on the problem of alteration in hydrologic regime due to land and vegetation disturbance by fire, it is relevant to review that literature which studies the results of that change. Chapter Three is separated into three sections. The first section reviews the literature dealing with changes in soil, infiltration and erosion associated with vegetation change at the small, stand scale. The latter two sections of this chapter focus on watershed scale response to land use change and reviews those studies pertinent to measurement of suspended sediment loads within streams, the variability associated with sediments, and discharge behaviour of streams exiting basins with and without land use treatment. Emphasis, in the last section, is placed on the development of rainfall-runoff modeling, limitations of the methods used, and various models in use today.

3.2: Land Use Change

Forest fires can destroy the forest stand, ground cover vegetation, and the forest floor. Researchers have observed that those fires with sufficient heat are capable of changing the structural and chemical makeup of the soil (Pritchett, 1979; Giovannini and Lucchieci, 1983). Others (Pritchett, 1979; Steedman and Morash, 1995) have found that as a result of the removal of undergrowth vegetation the soil surface is subject to binding, or surface sealing by raindrops. Small fines resulting from the fire fill interstitial pore spaces creating a very thin, almost impervious layer at the surface. Binding of the soil surface and increased soil moisture resulting from reduced evapotranspiration, increases overland flow, and soil erosion.

The effect of fire on chemical properties of the soil was examined by Tiedemann (1981) and Baker (1990). They pointed out that during burning certain organic constituents are vaporized, some portion of which moves downward in the soil to form a well-defined water-repellent layer within a few centimeters of the surface. This hydrophobic layer then reduces the rate at which water may move through it. In addition, Giovannini and Lucchesi's (1983) research found that coarse-textured soils can acquire a thicker and more intense water-repellent layer than finer-textured soils and that the difference may be due in part to the amount of particle surface area covered with organic substances.

The manipulation of vegetation due to land use change causes large differences in infiltration capacity under the same rainfall regime and soil. The presence of dense vegetative cover, such as grass or forest, tends to promote infiltration. This is because the vegetative cover not only provides protection from compaction due to rain, but also provides a layer of decaying organic matter which promotes the activity of burrowing insects and animals (Wisler and Brater, 1959). Bare soil surfaces, where infiltration rates diminish rapidly, have more surface runoff. This, suggests Dunne and Leopold (1978), and Ward and Elliot (1995), is because bare soils tend to have poor structure and are less permeable.

Many studies have been conducted on infiltration and erosional response after vegetation removal. DeByle and Packer (1972) studied soil losses from burned forest in the Rocky Mountain region of the United States, and Giovannini et al., (1988) looked at soil loss by erosion after burning took place in sandy loam soils in Italy. Both parties found that infiltration decreased and soil erosion increased after burning, and that erosion from summer storms was greatest the year following burning, but showed a marked reduction in the second year, and by the third and fourth years was similar to losses from the unburned forest.

The season at which the fire occurs and the weather conditions for a succeeding period during which revegetation takes place may be critical in determining whether plant regrowth is rapid or not. Armson (1979), and Wright and Bailey (1982) observed that if late summer fires occurred in areas of winter snowfall little to no revegetation may take place.

Also, the depth of snow accumulation would be greater than if forest cover were present. This finding was noted by Pomeroy et al., (1996) who found in their research on snowfall accumulations in undisturbed and burn areas of the boreal forest that snow accumulations are more predominant in exposed areas where vegetation has been removed by burning or harvesting (Appendix B, Table 1). In addition, Meng et al., (1995) investigated spring snow melt timing in central New Brunswick in response to removal of vegetation. Their findings concluded that the timing of spring melt is usually earlier, up to two weeks in areas of forest that have been disturbed by harvesting or burning.

In an earlier study on the effects of forest fire on soil properties in Northern Saskatchewan Scotter (1963) found that temperatures at the 1 inch and 3 inch depths in burned-over soils averaged higher than soil temperatures under mature forests.

The literature supported the generally held concept that removal of large areas of vegetation resulted in change to flow rates. Anderson et al., (1987); Garman and Moring, (1991); and Sahin and Hall, (1996) all observed higher flow rates from drainage basins after large areas of vegetation were removed through timber harvest disturbance. Lavabre et al., (1993), measured a 30% increase in the annual runoff yield related to the destruction of vegetation cover by fire.

3.3: Suspended Sediment

3.3.1: Overview

Very often landscape alteration can be measured by changes in suspended sediments that are carried in watershed streams because the physical constituents of a stream are intimately linked with the hydrologic regime of a watershed and with the surrounding terrestrial system. Many studies have been conducted that relate the effects of land use change within watersheds to the volumes of suspended sediment loads in streams, but, as previously mentioned most of these studies focus on changes occurring in regions outside the boreal forest. Still, similarities can be drawn from these studies because although precipitation, soil, vegetation type, and gradient may vary, parallels can be drawn from the processes involved.

3.3.2: Suspended Sediment and Discharge

Results of research investigating timing of peak sediment concentration in the stream with discharge peak are varied. Brown and Kryhier (1971), in an Oregon Coast study, found poor correlation between suspended sediment concentration and stream discharge, large variability in sediment concentrations within short time intervals, and little correlation between the sediment transport regimes of watersheds with similar characteristics. In general though, most researchers have observed that suspended load increases more rapidly than water discharge, and that most river sediment is transported at the highest water discharges (Paustian and Beschta, 1979; Meade et al., 1990).

Paustian and Beschta (1979) best describe the process of sediment entrainment with rising discharge. They explain that fine-grained sediment, which is stored on the beds or along banks of river channels during recession of floods or during low-water periods, is in plentiful supply as the river begins to rise, but the stored material is soon resuspended, and it eventually becomes depleted before the river reaches its maximum water discharge. The usual rapid increase of suspended load with discharge is interpreted as indicating that conditions of rainfall and runoff on the watershed combine to furnish to the major stream channels a large increment of debris for each increment of water. Some possible reasons why sediment increases with discharge are offered by Leopold and Maddock, (1959):

- The initial rain must fill surface detention and depression storage before surface runoff can begin. Infiltration rate decreases rapidly during the initial period of a rainstorm.
- As the soil surface becomes wetted, areas poorly protected by vegetation are subjected to the churning effect of raindrop impact which increases with rainfall intensity. Puddling of the soil surface, of it occurs, probably increases with the duration and intensity of rainfall.
- Moreover, large runoff rates imply greater depths and velocities of water flowing in eroding rills.

These factors tend toward a greater efficiency of erosion with the increase in duration and intensity of rainfall.

3.3.3: Suspended Sediment Variability

Between watersheds suspended sediment concentration varies in response to differences in streamflow, soil, topography and land use. Also, within the parts of a single watershed similar responses may be presumed to occur. Results and opinions vary on the spatial relationship between land and suspended load in streams, and on the temporal relationship between suspended load and stream discharge (Ashmore, 1996). The efficiency of stream systems in moving eroded materials from their sources to a downstream point of measurement is dependent upon a complex array of hydro-physical conditions. Saxton and Shiau, (1990) observed that the physical features which appear to be significant are size of drainage area, watershed slopes, and degree of channelization. Hydrologic characteristics include precipitation and runoff characteristics. The size of drainage area as noted by Walling (1983) is an important consideration in respect to the total yield of sediment from a watershed because the rate of sediment delivery decreases with increasing basin area. To support this finding he offers that the probability of entrapment and lodgment of a particle being transported downstream increases as the size of drainage area increases, and as such most of the soil eroded on slopes is not transported out of the basin but is deposited immediately downstream. Church et al., (1989) suggested that regional differences might also occur. Their research results disputed "'conventional wisdom' that specific sediment yield - the quantity of sediment yielded per unit of land surface - declines downstream in a drainage basin as the area drained increases" (Church et al., 1989). They observed that sediment yield from drainage basins throughout British Columbia increased downstream, except in very large drainage basins (≥1000km2).

When modeling sediment yield Pickup (1988) warns that predictive models for sediment yield from large drainage basins should be used with caution - the application of large basin sediment load values may not be applicable to small basins because of "extrinsic factors of physiography, geology and soils that deliver sediment from point sources into the system, and intrinsic unsteadiness in transport at all scales" (Pickup, 1988). Furthermore, the probability of complete coverage by a single storm event, coincident with widespread erosion and high rates of runoff per unit of drainage area, is much greater for smaller watersheds than for large ones.

3.3.4: Suspended Sediment and Fire

As mentioned, few studies exist on fire and suspended sediment loads in the boreal forest regions of Canada. Recent studies by Helvey (1980) and Ewing (1996) on postfire suspended sediment loads in Washington and Wyoming found that studies from diverse landscapes and climates generally indicate increased and widely variable erosion and sediment transport following fire. Ewing (1996) found that the "Yellowstone River had fire-related sediment increases of around 60 percent for rising and falling streamflow periods in the spring snowmelt season for the four-year peiod following the 1988 wildfires. Summer season fire-related sediments increases were less at 30 percent".

3.4: Stream Discharge

3.4.1: The Discharge Hydrograph

Of critical import to this research is the measurement and analysis of stream flow response from drainage basins. The following is a brief definition and description of the discharge hydrograph, one of the primary methods of stream flow analysis.

A hydrograph is a graph of streamflow passing a particular point on a stream, plotted as a function of time. This graph is plotted as the discharge on the ordinate and time on the abscissa (Singh, 1992). Streamflow includes rain which falls directly on the stream, surface runoff, and flow from ground water. Rain falling on the stream and surface runoff produces streamflow more rapidly than subsurface flow (interflow and baseflow), and therefore is instrumental in producing the rising limb and discharge peak, respectively. Rainfall which enters the soil but flows just below the surface (interflow) approaches the stream at a slower rate and produces the falling limb (recession flow) part of a hydrograph. Baseflow is that part of the hydrograph contributed by groundwater flow (Ward and Elliot, 1995). Figure 3.1 outlines the basic components of a discharge hydrograph.

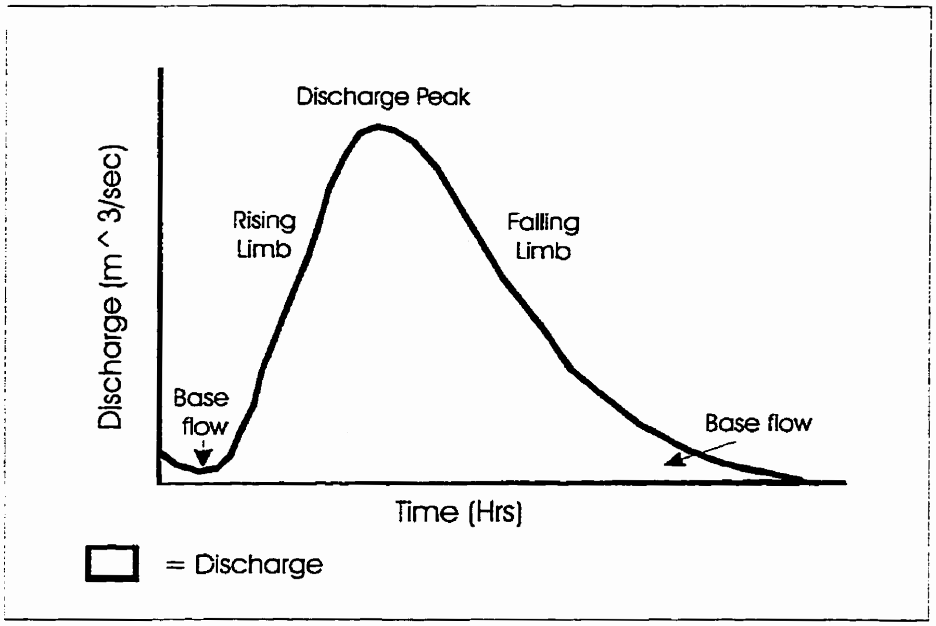


Figure 3.1: The Discharge Hydrograph.

Most researchers are interested in that part of the hydrograph contributed by surface runoff and interflow, and which is produced by individual rainfall events (Dunne and Loepold, 1978; Linsley et al., 1982; Singh, 1992;). A runoff hydrograph reflects the influence of all the physical characteristics of a drainage basin, as well as the characteristics of the storm event which causes the hydrograph.

3.4.2: The History of Rainfall-Runoff Modeling

Todini's (1988) research on the history of runoff measurement found the origins of rainfall-runoff modeling began with the need to design discharge relating to engineering problems in the urban setting (egs., sewer systems, land reclamation, and reservoir spillways). In the late 19th and early 20th centuries most engineers used empirical formulas derived from particular cases and applied them to other cases under the assumption that conditions were similar - 'the rational method' - known as the Lloyd-Davies equation

(Dooge, 1959; Hjelmfelt and Cassidy, 1975). The problem with this method says Todini (1988) was that empirical formulas could not be applied to large catchment areas where temporal and spatial variabilities were magnified. In 1932 Sherman introduced the concept of the unit hydrograph on the basis of the superposition principle. That is - "the hydrograph resulting from a given pattern of rainfall excess can be built up by superimposing the unit hydrographs due to the separate amounts of rainfall excess occurring in each unit period. This includes the principle of proportionality, by which the ordinates of the hydrograph are proportional to the volume of rainfall excess" (Dooge, 1959).

From Singh (1988) the unit hydrograph of a watershed can be defined as the hydrograph of direct runoff resulting from one unit (1 inch or 1 mm) of effective rainfall occurring uniformly over the watershed at a uniform rate during a unit period of time Development of a unit hydrograph requires gauged discharge at the basin outlet. Ward and Elliot, (1995) maintain that since the physical characteristics of the basin - shape, size, slope etc., are constant, then the shape of hydrographs from storms of similar rainfall characteristics should also be constant. This is the essence of the unit hydrograph as proposed by Sherman.

Many researchers note that Sherman's unit hydrograph was seen as a breakthrough in representing and predicting surface runoff from drainage basins (Dooge, 1959; Todini, 1988; Wilson and Brown, 1992). However, Todini (1988) adds that the unit hydrograph had a number of problems: (1) the separation of surface runoff from baseflow; (2) the effective rainfall determination; and (3) the derivation of the unit hydrograph. Solutions to these problems involved a high degree of subjectivity.

In 1938 Snyder generated the synthetic unit hydrograph using a set of empirical relationships for significant points on a representative unit hydrograph (Hjelmfelt and Cassidy, 1975). From Linsley et al., (1982) synthesized unit hydrographs are constructed where stream gauging records are unavailable, and do not take into account land use factors. They are a useful means of anticipating how basins will respond to rainfall without the inclusion of land use as a mitigating effect on runoff. As a baseline measure they can be effective in comparative research involving preconditioned response before treatment and modified response after. Taylor and Schwarz (1952) compared basin characteristic data for twenty basins in North and Middle Atlantic States of the US over 65 rainfall excess periods and agreed with Snyder (1938) that "the most significant basin-characteristic factors which affect the unit-hydrograph lag and peak-flow values were found to be drainage area size, length of longest watercourse, [and] length to center of area".

Conceptual models were introduced in the 1950's with mathematical techniques that were used to derive hydrograph response with the analysis of input and output data. As well, simplified differential equations were used to describe the time behaviour of water storage in a drainage basin (Todini, 1988). This period saw the introduction of unit hydrographs relating to basin size and to basin characteristic of shape. In the 1960's a more physical interpretation of the process was sought and more defined behaviour of discharge was set at the watershed scale. As Dooge notes in his paper (1959), Sherman's unit hydrograph approach still "retained an empirical character" and was "dependent on personal judgment in its practical application" (Dooge 1959). Impetus for this change arose from the need to extend flow records, to apply the model to complex watersheds with variable soils, vegetation, slopes etc., and to extend the model to other watersheds.

The resulting addition of too many parameters proved cumbersome and allowed the incorporation of errors in data and errors in basic description of the interrelations between simple process models, thereby distorting the relationship between model and reality (Todini, 1988). Coincident with the introduction of computers real time rainfall-runoff modeling was developed in the late 1970's and early 1980's. These models state Todini (1988) can be updated and recalibrated and used as a forecasting tool as conditions change over time and space.

3.4.3: Assumptions and Limitations of the Unit Hydrograph

Three independent assumptions are made in the concept of the unit hydrograph:

1. The duration of surface runoff is constant for all storms of uniform intensity and the same duration regardless of the total volume of surface runoff.

2. Two storms of uniform (uniform over an entire drainage basin) intensity and with the same duration will produce rates of surface runoff at time t in direct proportion to the total volume of surface runoff.
3. The time distribution of surface runoff from a storm period is independent of concurrent runoff from previous storm periods (Hjelmfelt and Cassidy, 1975).

Limitations of the unit hydrograph are inherent in its assumptions say Hjelmfelt and Cassidy (1975). One assumption is that a storm occurs with uniform intensity and is uniformly distributed across a drainage basin, when in actuality this does not occur very often. It has been shown that several distinct events could produce different unit hydrographs for a single watershed (Hjelmfelt and Cassidy, 1975). The most important assumption of unit hydrograph theory is that watersheds are linear. That is, the direct runoff hydrograph is derived from the effective rainfall hyetograph by a linear operation. Again, to Sherman's superposition principle; ordinates of direct runoff hydrographs are directly proportional to the total amount of direct runoff represented by each hydrograph and thus can be superimposed numerically in proportion to the total amount of direct runoff.

Khan and Ormsbee (1989) found that to remediate the problem of spatial and temporal variability in rainfall distributions a composition of storm events are collected for individual rainfall events that have similarities in rainfall volume and timing. They further suggest that this step will reduce the likelihood of the final unit hydrograph being an unrealistic representation of basin response to rainfall, and will provide a consistent mean of the parameters: discharge at peak of event, and time of initial basin response to peak of discharge.

3.4.4: Studies of Hydrologic Response

Discharge hydrographs, as previously outlined, are a visual concept of the behaviour of a basin in converting rainfall to stream flow. Because unit hydrographs are a function of several factors of a given basin: vegetation cover, land use, lithology, topography, and climate, they give a realistic interpretation of the actual hydrologic response occurring in a basin due to change. Cattanach et al., (1995) and others have found that when alterations to these characteristics take place modifications would be expected in the timing and amount of discharge exiting a basin. This modification can be measured from the discharge hydrograph.

Various methods have been used to model the response of discharge to basin change. Studies by Brandt et. al., (1990), and Lavabre et, al., (1993) focused on hydrologic outputs before and after an occurrence within the same drainage basin. They looked at the hydrological effects of disturbance by fire and clearcutting, concentrating on changes in the annual runoff response, and flood regime. Although studies such as this at first seem ideal, very often they are not environmentally or economically feasible and/or are restricting when the time frame of study is limited.

There are also situations where no data is at hand for control of the model. In such cases empirical conceptual models are used. Here the model is calibrated to many basins in the region and a standard parameter is used for ungauged basins (Bergstrom, 1991).

When environmental and time restrictions occur, historical data is unavailable, or there is no standard parameter yet developed for a region (such as at this time for the boreal forest of Saskatchewan) modeling of catchment response can be accomplished by comparing known values of rainfall and discharge with synthesized data for the same catchment (Khan and Ormsbee, 1989). Here, synthetic and unit hydrographs are compared and the magnitude of response is measured. Rogers et. al., (1985) and Bathurst (1986) both utilized comparisons between predicted and observed hydrographs in their research on modeling hydrologic response to physical change within a basin. Their argument for physically-based catchment models was that they do not require an extensive hydrological record for their calibration.

CHAPTER FOUR: REGIONAL SETTING

4.1: Introduction

The first part of this chapter is dedicated to describing the general overlay of climate, ecology, and surface geology that characterizes the greater region of study. In the second part motivation for site selection is covered, followed by pertinent physical, hydrologic and anthropogenic characteristics of each of the drainage basins. The final summary details similarities and differences between sites and their contribution to the goal of the research.

4.2: General Characteristics

The regional setting for this research was on the southern edge of the boreal forest, within the province of Saskatchewan, between the city of Prince Albert, and Lac la Ronge (Figure 4.1). Linear extent of the total study location, from north to south, is approximately 400km. The range of latitude is 53° 55' to 54° 25', and longitude 104° 40' to 105° 00'. The period of field research was from early spring to late fall of 1996.

Ecozones, Ecoregions, and Ecodistricts (in descending scale) have been used to describe regional commonality in vegetation ecology and the wildlife associated with it (Ecoregion map of Saskatchewan, 1994). Physiographic Regions, Sections, and Subsections have been similarly used to describe regional commonality in physical features and morphological character (Head et al., 1981).

A main drainage divide runs from the north, down the east side of the two northern basins (Sites 3 and 4 in Figure 4.2) then runs westward. This means that two southern basins (Sites 1 and 2 in Figure 4.2) drain to the south east while northern sites drain west, then north (Head et al., 1981, and Canada Streamflow, 1993). The two southern basins flow into the Saskatchewan River Basin, which is part of the larger Nelson Basin, which in turn flows into the Hudson Bay. The two northern basins flow into the Churchill River Basin, then into the Nelson Basin.

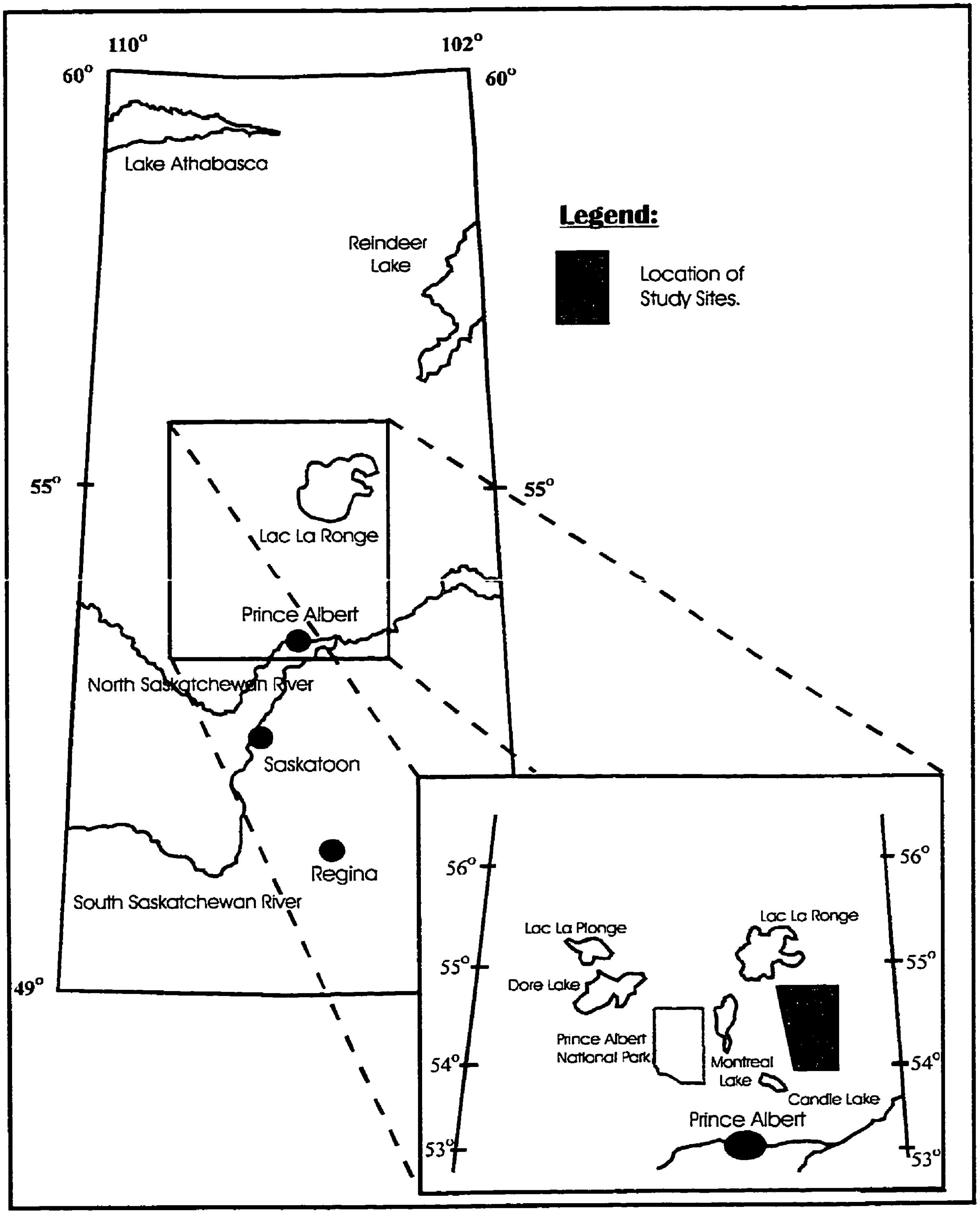
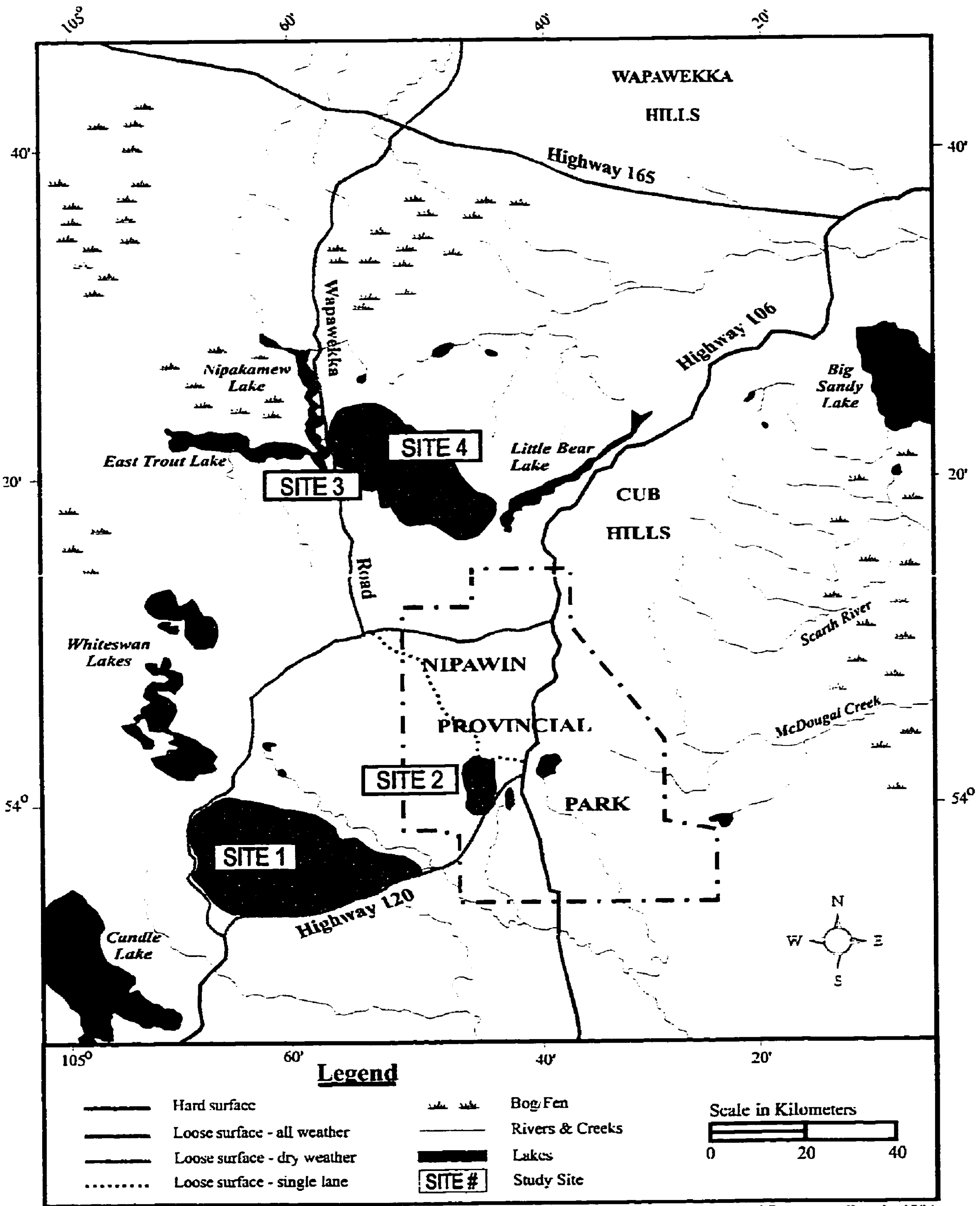


Figure 4.1: Location of Study Area Within the Province of Saskatchewan.



Source: Energy, Mines and Resources, Canada. 1994.

Figure 4.2: Location of Four Study Basins Within Central Saskatchewan.

4.3: Climate

Saskatchewan's location in interior North America at mid-northern latitudes confers on it a continental climate, with short, warm summers, and long cold winters. Seasonal weather variations are determined by three different air masses that invade the province: cold and dry air from the continental polar region especially in winter, cool and moist air from the Atlantic, and warm and moist air from the Gulf of Mexico. These move pretty much unhindered across the region without being diverted or influenced by major topographical features. The Koppen-Geiger System, which assigns class according to temperature and precipitation, classifies this region as high-latitude, boreal forest (microthermal) climate, where the coldest month average temperature is below -3°C and the average warm month temperature is above 10°C (Strahler and Strahler, 1992). The climatic region of central and northern Saskatchewan is dominated by the boreal forest. The northern limit of the boreal is the July 13^{0}C isotherm. Normally the southern boundary of the boreal region in central and eastern Canada is the position of the July 18^{0}C isotherm, but in the western provinces (including Saskatchewan) where drier conditions prevail the southern edge of the boreal forest lies to the north of this isotherm. The general area of this project is located at the southern edge of the boreal forest.

The local climate is sub-humid, with cool temperatures. Table 4.1 gives climate data for Nipawan, Saskatchewan, and Table 4.2 shows temperature and total precipitation values for the period of this research. Nipiwan is located at 53°20' latitude, 104° 0' longitude, and 372m ASL at the southern extent of the general study area. Mean temperature for January is -18.7^{0}C and for July 17.8^{0}C. Precipitation is in the form of snow during winter months and convective rainfall during warm summer months. Prevailing winds are mostly from southwest to northeast. The mean annual precipitation is 442mm while rainfall for May to September is approximately 302mm, and snowfall from November to April is 121cm. Snowfall season usually begins in the middle of October, and ends in early May. Both December and January are the coldest months, with the monthly average of degree days below zero over 500, whereas the month with highest snowfall is March (Table 4.1). Soils remain frozen from early November to late March.

Table 4.1: Average of Canadian Climate Normals for Nipiwan, Saskatchewan, 1974-1990.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Temperature (°C)	-18.7	-15.5	-8.9	2.6	10.7	15.5	17.8	15.4	9.9	3.3	-7.3	-16.6	0.8
Total Precipitation (mm)	14.2	11.9	18.5	22.6	53.6	72.5	66.2	66.1	45.6	30.0	16.5	16.4	442.3
Total Snowfall (cm)	20.3	15.9	23.3	21.1	4.1	0.1	0.0	0.0	2.5	10.3	19.8	20.6	129.0
Total Rainfall (mm)	0.2	0.8	0.3	11.6	50.9	72.7	68.8	66.2	43.0	17.6	2.4	0.4	335.0
Soil Temp 5cm below surface	-8.8	-8.1	-4.2	1.3	9.0	14.6	17.3	15.2	9.2	2.6	-2.4	-6.8	3.2
Soil Temp 20cm below surface	-7.8	-7.4	-4.0	1.4	8.9	14.5	17.8	16.8	11.4	4.7	-0.8	-5.4	4.2
Degree Days above 0°C	0.2	1.1	5.6	122.2	332.4	466.4	550.6	493.6	299.9	135.5	13.05	0.3	2425.9
Degree Days below 0°C	583.7	439.9	286.6	46.1	1.0	0.0	0.0	0.0	0.5	34.7	232.9	518.6	2118.7

Source: Canadian Climate Data, Environment Canada, 1991.

Table 4.2: Monthly Temperature and Rainfall for Research Area 1996.

	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct
Temperature (°C)	-12.1	0.2	7.2	16.0	16.2	14.8	11.0	N/A
Total Precipitation (mm)			53.3	55.3	77.5	42.2	102.1	57.5

4.4: Vegetation and Wildlife

The general study area is found located within the Boreal Plane Ecozone and the Mid-Boreal Upland Ecoregion (Ecoregion map of Saskatchewan, 1994). The Mid-Boreal

Uplands are characterized by an ascending sequence of steeply sloping, eroded escarpments, hilly glacial till plains, and level plateau-like tops. The intervening areas are comparatively level, with large, sparsely treed peatlands being common. The forests grow taller here than on the Shield and account for the bulk of the province's merchantable timber. Aspen (*Populus tremuloides*) occurs throughout the ecoregion and is dominant on the south-facing slopes of the major uplands. Where moisture conditions are favorable, white spruce (*Picea glauca*) is often mixed with aspen. Jack pine (*Pinus banksian*), in addition to its usual dominance in sandy areas, is found mixed with black spruce (*Picea mariana*) on the plateau-like tops of the uplands. Black spruce and tamarack (*Larix laricina*) dominate the low lying peatland areas. Low lying and damp locations have mostly willow (*Salix glauca*), alders (*Alnus* sp), sedge (*Carex* spp.), and spaghnum moss (*sphagnum* spp.). Figure 4.3 shows a typical black spruce community located in a low lying and subhygric location. A more permanent, hydric wetland community dominated by sedge populations can be seen in Figure 4.4.

Wildlife populations are high and diverse with moose (*Alces alces*), woodland caribou (*Rangifer tarandus caribou*), mule deer (*Odocoileus hemionus*), white-tailed deer (*Odocoileus virginiarus*), elk (*Cervus elaphus*), black bear (*Ursus americanus*), timber wolf (*Canis lupus*) and beaver (*Castor canadensis*) being the most prominent.

Fish populations include northern pike (Esox lucius); Arctic grayling (*Thymallus arcticus*), whitefish (*Coregonus clupeaformis*); white and longnose suckers (*Catostomus commersoni and C. catostomus*); trout-perch (*Percopsis omiscomaycus*); brook trout (*Salvelinus fontinalis*); pearl dace (*Semotilus margarita*); slimy sculpin (*Cottus cognatus*); burbot (*Lota lota*); fathead minnow (Pimephales promelas); longnose dace (*Rhinichthys cataractae*); finescale dace (Chrosomus neogaeus); brook sticklebacks (*Culaea inconstans*); yellow perch (Perca flavescens); and Iowa darter (Etheostoma exile). (Ecological Regions Map, Saskatchewan, 1994; Kabzems et al., 1986, Larsen, 1980).

Figure 4.3: Typical Black Spruce Community Within the Boreal Forest.

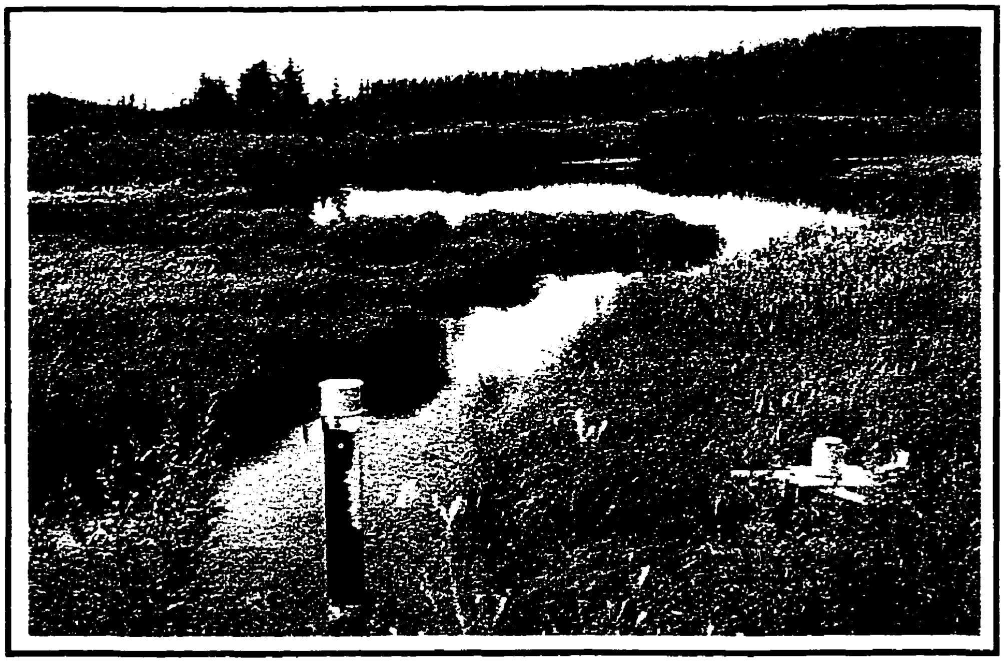


Figure 4.4: Wetland Community Within the Boreal Forest.

4.5: Geology and Soils

Three major geological formations are located in the general area of study. The Belly River Formation, consisting of sands, shales and coal, is located in the north-eastern perimeter; the Lea Park formation, consisting of light and dark gray shales, in the south-western corner, and the most dominant; the Alberta formation, consisting of dark gray shale, is situated in the greater mid-section of the general study area. Surface geology is mostly glacial moraine boulder clay and resorted till deposits. These deposits are essentially extremely variable in grade, composition and topography (Edmunds, 1947; Geologic Map of Saskatchewan, 1972).

Soil types located within the general study area consist mostly of Gray Luvisols (Gray Wooded), with some Brunisolic Gray Luvisols and Regosolic soils. On high dry areas the soil is moderately coarse textured, fine sandy loam and the surface is stoney. In low-lying areas and along streams mesic to humic conditions predominate (Geologic Map of Saskatchewan, 1972; Anderson, 1976: Head et al., 1981). Soils range from very rapidly drained to very poorly drained. Very rapidly drained soils develop in coarse textured sands (0.5 to 2 mm diameter) and gravels (greater than 2mm diameter), which are of glaciofluvial or fluvial-lacustrine origin. These soils are dry, and precipitation is absorbed almost immediately (Head et al., 1981). Figure 4.5 gives an example of these sandy soils found within the boreal forest.

Figure 4.5: Sandy Substrate and Vegetation in the Boreal Forest.

Poorly drained soils have developed under prolonged saturated or near saturated conditions. The mineral substratum which is gleyed and /or mottled is usually overlain by a shallow layer of peat which may be in various stages of decomposition. Taxonomically, these soils are usually classified within the Gleysolic Order. Generally these soils are found on level to undulating topography or in depressional areas.

Rivers and streams in this region exhibit dendritic drainage patterns. This common stream pattern is characterized by a random, tree-like branching system in which the tributaries join the gently curving mainstream at acute angles. The pattern indicates homogeneous soil or rock materials with little or no structural control. It is typified by land forms composed of soft, flat-lying sedimentary rocks, and thick glacial till. Dendritic networks reflect a relative lack of geologic control (Knighton, 1984). This pattern would be expected in this region given that the landscape is low and rolling, the soil type mostly sand and gravel, and the parent material glacial till.

4.6: Site Selection

Primary impetus for the final selection of site location of this research was the coincidence of field work and data collection for an Environmental Impact Assessment (EIA) for Weyerhaeuser Canada Ltd., in Saskatchewan. The EIA was a prerequisite for renewal of a 20 year lease of forest harvesting area covering five million square hectares in central and northern Saskatchewan. The hydrologic field work component for the EIA was to be collected by Golder Associates of Calgary during the summer of 1996. A contractual agreement with Golder Associates allowed the exchange of hydrologic and remotely sensed data for sediment data, for this research. Another consideration was that equipment, namely field measuring equipment, vehicle, and safety equipment, as well as accommodations, field help, and wages were supplied in exchange for technical field work for the EIA.

Twelve drainage basins were initially chosen as study sites for the EIA. These basins extended over a 255,000 km^2 area. Of these, 4 drainage basins were chosen for this research project: 2 burned sites, and 2 undisturbed. Because the underlying intent of this research was a comparison between basins, it was important that all sites were uniform in their morphological and meteorological characteristics. These included precipitation, temperature, soil type, vegetation type, drainage basin slope, and size of catchment area. Most of the above requisites were confirmed during a recognizance trip to the general study area in March of 1996, and from analysis of (National Topographic System) NTS topographic maps (Energy, Mines and Resources, 1973-80), GIS maps (Weyerhaeuser, 1995) and soil maps (Agriculture Canada, 1977 and 1978). Difficulty was had in locating sites with similar catchment size, that had little, or no disturbance, that were within workable travel distance, and which would have been included within the 12 sites supplied with field measuring equipment. Only two drainage basins were located completely within the Nipakamew burn, leaving the choice of burn sites limited. Also, due to the large extent of forest harvesting in the region it was difficult to locate drainage basins with no anthropogenic or burn disturbance. The sites that were eventually selected as undisturbed had the only a small of anthropogenic disturbance, were within data collection distance, and which shared similarities in temperature, vegetation and soil type. The resolution to this situation was that consistent differences in size occurred in each type of land use treatment - both the undisturbed basins and the burned basins included a large and a relatively small basin. It was hoped that this consistency would nullify any extraneous effects in hydrologic response due to basin size.

The four drainage basins (from here also known as sites) are viewed in Figure 4.2. Site numbers run in ascending order from south to north and site description follows this same order. Sites 1 and 2, and Sites 3 and 4 are closely paired geographically, and therefore share similar precipitation and temperatures, and, convenient for this study shared the same land use characteristics during the period of field research. Both Sites 3 and 4 are geographically located side by side (see Figure 4.2). Site 3 occupies a small area nestled into the southwestern corner of Site 4.

4.7: Sites 1 and 2 Biophysical Characteristics

4.7.1: Vegetation

Both Sites 1 and 2 are located slightly north of the transition between the Southern Boreal Ecoregion in the south, and Mixedwood Ecodistrict to the north. They are characterized by a larger percentage of deciduous trees, namely aspen, over the other Sites. Table 4.3 summarizes the total area of each basin and land cover percentages. Sites 1 and 2 feature a high percentage of wetlands (ranging from 19 to 28 percent). Wet coniferous is also high in these undisturbed sites.

Table 4.3: Site Area and Land Use Ratios (from Satellite Data).

Site #	Area (km^2)	% Wet Coniferous	% Dry Coniferous	% Mixed Coniferous and Deciduous	% Disturbed and Young Growth	% Recent Burn	% Fen and Bog	% Shallow and Deep Water	Road Density km/ km^2
1	214.30	30.5	19.1	10.3	3.1	1.1	28.2	7.7	0.09
2	24.81	15.0	39.8	14.4	7.6	2.0	18.8	2.7	0.28
3	15.72	0.3	4.2	3.1	2.0	61.7	28.7	0.0	0.0
4	123.30	0.3	2.1	1.9	0.2	77.5	16.4	1.6	0.09

4.7.2: Soil and Parent Material

Sites 1 and 2 are located within the Wapawekka Hills Upland Physiographic Section, and border on the White Gull Creek Plain Physiographic Section. Both basins are found in the Physiographic Subsection of Whiteswan Upland. Their approximate distance from each other is 7.5km. Elevation ranges in this subsection range from 519 - 671m. The area is characterized by roughly undulating to steeply rolling morainic upland with local fluvial-lacustrine sands and eskers.

Here the surface geological deposits are the products of glaciation and related lacustrine and fluvial processes. The resulting deposits are glacial till, glaciolacustrine or lacustrine, and glaciofluvial or outwash materials. Glacial till occurs within the upper geological section throughout the map area. In the Whiteswan Uplands the glacial till deposits are 120m to 180m in thickness. In these regions the till occurs at or near the surface, and is generally the parent material from which the soils have developed. Glacial till deposits in this region are generally overlain by a layer of well sorted, stone-free fine sand to fine sandy loam material 15cm to 66cm ins in thickness. The origin of these materials has not been established but is probably related to fluvial-lacustrine or, perhaps aeolian deposition.

The mid and northern sections of Site 1 are dominated by Flat Bog Association characterized by extensive flat-lying lowlands and extensive depressional areas This supports black spruce, Labrador tea, and sphagnum moss vegetation. The upper peat materials are derived from the residues of that vegetation but lower strata appear to be composed of sedge peats, suggesting a colonization of sedge peat areas by mosses, then by the black spruce as the mosses build up. Small pockets of Kewanoke Association are located in the mid section of the basin. These contain degraded Eutric-Brunisol Series derived from a coarse to moderately coarse textured, weakly calcareous, gravelly glaciofluvial deposit parent material. Kewanoke soils adjacent to the White Gull Creek in the Lower Torch River Plain are capped with 6 to 12 ins of loamy sand to gravelly sandy loam textured sediments. Stones occur throughout the soil. The dominant series represented in the Site 1 basin is mainly Gleyed Orthic Luvisol, Gleysolic soils in the peaty phase. These soils occur on lower slope positions, common in complexes of Bog and Fen soils, and usually associated with the poorly drained Gleysolic soils of depressional areas. Black spruce is the usual vegetation on imperfectly and poorly drained soils (Anderson, and Ellis, 1976).

At Site 2 there is a prominent north-south orientation of Gleysolic soils and flat bog found in the south-western corner. These soils are in the peaty phase, variably textured glacial and recent deposits. They are characterized by poorly drained level and depressional areas supporting black spruce, tamarack, Labrador tea and sphagnum vegetation. The remainder of the basin is dominated by degraded Eutric Brunisol soils of sandy texture.

4.8: Site 1

4.8.1: Physical and Hydrological Characteristics

This drainage basin is the most southerly located basin in the study. It covers the largest area of all 5 sites; 214.30 km^2 (see Table 4.4). Elevation range over the basin is from 526 - 594m. White Gull Lake is one of the most prominent hydrological features within this basin. It is located in the south-western corner of the basin and covers an area of 13.42 km^2. White Gull Creek is the main tributary that flows from the lake to the basin outlet and is the stream at which all discharge and suspended sediment measurements were taken. This stream is one of the major tributaries of the Torch River, thence to the Saskatchewan River, which is part of the Saskatchewan-Nelson drainage system flowing east to Hudson Bay. Figure 4.6 shows a detailed description of the drainage basin. There are eight first order streams located in the basin, two second order, and one third order stream. Drainage density is 0.22 km/km^2.

A large proportion of land in Site 1 has standing water in depressions on the surface. Landsatt imagery (see Table 4.3 and Appendix C) indicates 28.2% of standing water in the form of fens and bogs, 7.7% in lakes. In addition to this 30.5% of the basin consists of wet coniferous stands. Much of the northern portion of the basin is covered by these low land areas.

Table 4.4: Drainage Basin Parameters.

Site #	Drainage Basin Area (km^2)	Stream Orders 1/2/3/4	Drainage Density (stream length over basin area)	Bifurcation Ratio	Total Stream Length (km)	Average Slope %
1	214.30	8/2/1	0.22	3.00	46.36	0.02
2	24.81	2/1	0.24	2.00	5.95	0.02
3	15.72	3/1	0.34	2.00	5.41	0.02
4	123.30	23/5/2/1	0.70	3.03	86.87	0.03

4.8.2: Anthropogenic Characteristics

Two roads cross through the basin. The longest, and furthest road from the basin outlet is 12.8 kms long, is single lane, has little traffic, mostly local, and crosses White Gull Creek 16.95 kms upstream from its outlet. The second road crosses White Gull Creek at the outlet. It crosses the south-western corner of the drainage basin for 5.4 kms. The portion of the road that would influence levels of suspended sediment on the stream would be that section where the road crosses White Gull Creek at the basin outlet. The road is unused except occasionally by all-terrain vehicles. It has been closed for at least fifteen years coinciding with the conclusion of timber harvesting in the basin, and from a washout of the road that occurred at the same time close to the basin outlet point. This washout occurred 8 meters to the north of the left culvert. It has rendered the roadway impassable to normal traffic use, and road barriers have been erected 50 m from road-stream intersection to prevent road usage. Two culverts channel stream flow through this road. The south culvert has a diameter of 1.2 m, and the north culvert has a diameter of 1.5 m. Both roads are constructed of local materials, mostly sand and gravel.

Highway 120 skirts the southern section of the basin. It is a two lane roadway, also constructed of local materials, sand and gravel. This highway sees heavy use by local traffic year round but is not regarded as a strong influence on the basin because it does not intersect with any tributaries within the basin. Highway 913 skirts the eastern side of the basin and sees mostly local and logging trucks through the summer months and occasionally during the winter months. Total length of roads within the basin are 12.81 kms. Road density is 0.09km/km^2. Culverts have been used for stream channeling where all streams intersect with roads in the basin.

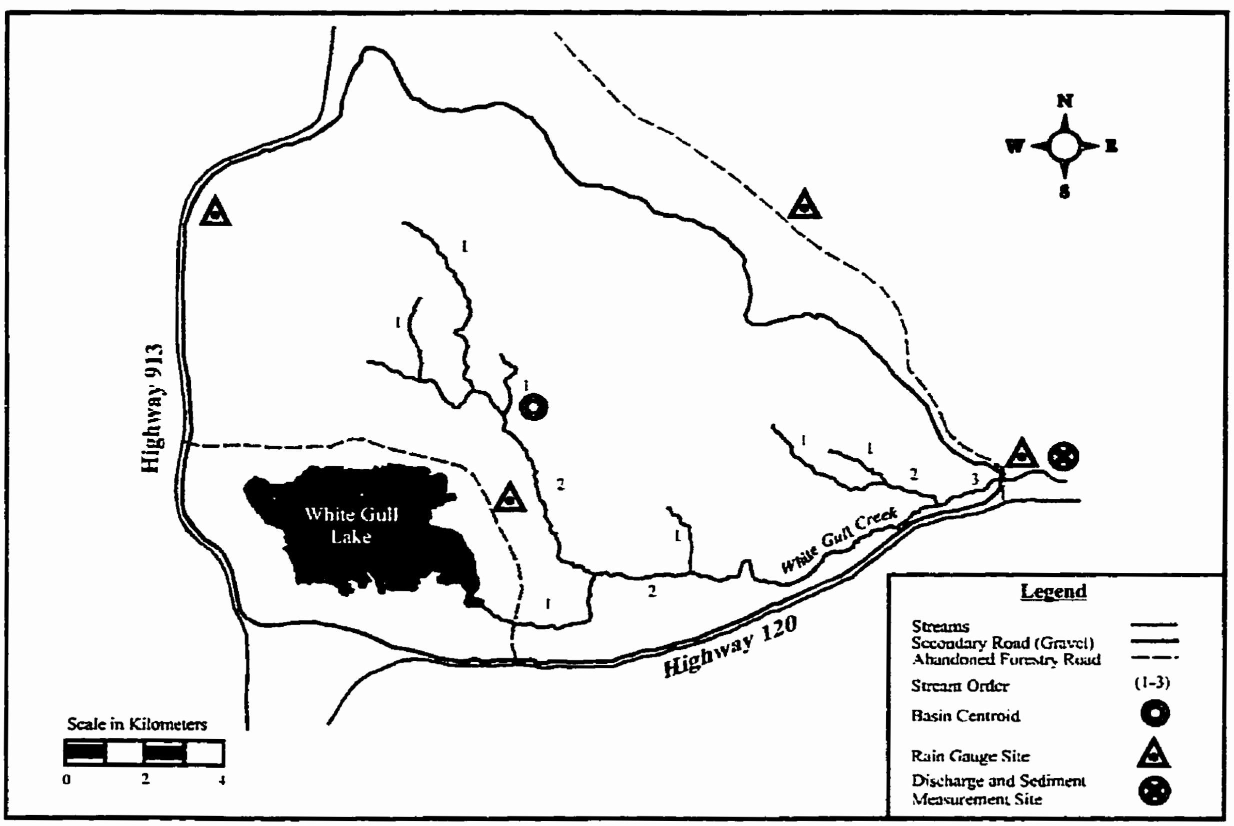


Figure 4.6: Drainage Basin Outline for Site 1.

Harvesting occurred in this basin up until approximately fifteen years ago. Spatial extent of previous harvesting is not known but regeneration areas are easily visible throughout the basin today. Table 4.3 indicates only 3.1% of Site 1 has disturbed or young vegetation. This would include regeneration from previous harvesting. At present two small contractors harvest the smaller spruce trees for fence posts in this basin. Both of these operations are small and operate only on a part time basis throughout the summer, and are not located near any of the tributaries within the basin.

Because of the time passed since major harvesting occurred in this basin, and because of the small, intermittent harvesting at the time of research, harvesting itself is not regarded as a disturbance in this basin. This is also true for road disturbance. The one road that passes through the basin does not see any heavy, continuous traffic and would not be expected to add extraneous sediment to the White Gull Creek other than by natural cause.

4.9: Site 2

4.9.1: Physical and Hydrological Characteristics

This drainage basin covers an area of 24.81 km^2. Elevation range over the basin is from 518 -572m. The basin is within the boundaries of the Nipawin Provincial Park. Figure 4.7 shows a detailed description of the drainage basin. The main stream flowing from this basin has no official name but is part of a northern tributary which feeds into White Gull Creek, which in turn feeds from Site 1. From Table 4.3 (see also Appendix C) Landsatt imagery indicates 18.8% of this basis comprises fen and bog, and 15% as wet coniferous.

As with Site 1 this basin also has a large percentage of land area where the water table is at, or close to the surface. Drainage density is 0.24 km/km^2. There are two first order streams within this basin, and one second order. The confluence of the two first order streams is located approximately 20m from the culvert which channels this stream under Highway 120.

4.9.2: Anthropogenic Characteristics

One road cuts diagonally through the basin in a south-west to north-east direction. This road crosses the upper arm of the western-most first order stream. Traffic on this road is confined to summer use only; all terrain vehicles are the main type of users during these months. Highway 120 runs along the southern perimeter of the basin. Road density at this site is 0.28km/km^2. Culverts have been used for stream channeling both at the road which crosses through the basin and at the outlet point at Highway 120. One culvert channels streamflow under Highway 120. Its diameter is 1.2 meters. As with Site 1 harvesting of this area ended approximately 15 years ago. Since that time disturbance has been from small pockets of fire. There was no evidence of recent harvesting in this basin.

As with Site 1 this site is not regarded as disturbed; no harvesting occurred in the basin at the time of research, only 2% of the basin saw fire disturbance, and the roadway that crosses the basin saw no heavy or continuous traffic.

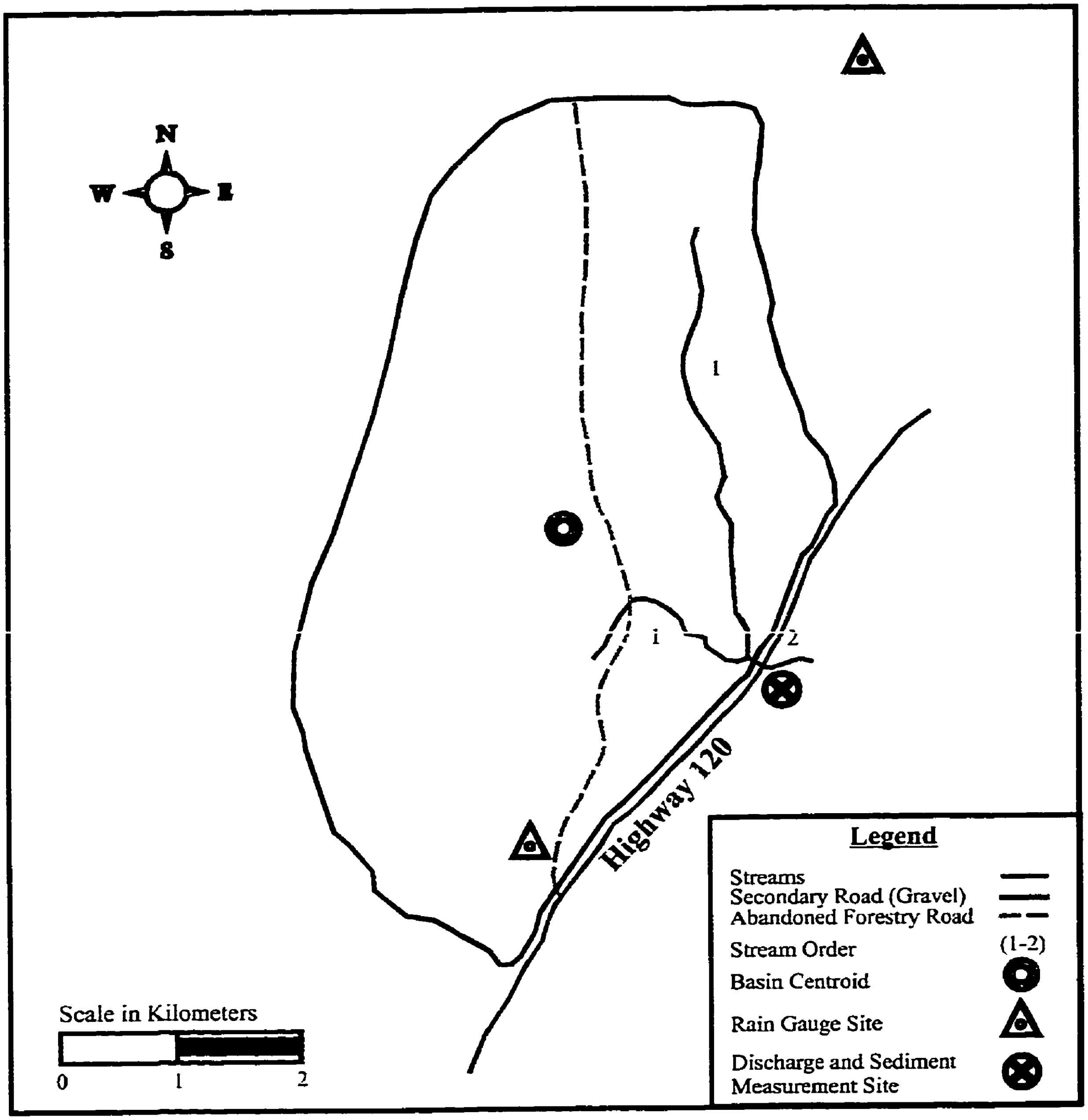


Figure 4.7: Drainage Basin Outline of Site 2.

4.10: Sites 3 and 4 Biophysical Characteristics

4.10.1: Vegetation

The well-drained soils in this region support mixed stands of trembling aspen, white spruce and black spruce in varying proportions. Some of the well-drained upland soils in this section, particularly in the Cub Hills, support white spruce and balsam fir. Jack pine predominates on the rapidly drained soils. Imperfectly and poorly-drained soils in the section support white spruce, black spruce, and some balsam popular. Bog and fen are usually characterized by stunted black spruce with lesser amounts of tamarack. Common shrubs here are willow, swamp birch, Labrador tea. The ground is dominated by sphagnum moss.

4.10.2: Soils and Parent Material

Both sites are located within the Wapawekka Hills Upland Physiographic Section and lie across the boundary of the Dowd Lakes Upland and Cub Hills, to the south, Physiographic Subsections. The Dowd Lake Upland ranges in elevation from 519 - 549m. It has gently undulating to gently rolling morainic upland of moderately fine to moderately coarse textured till, and recent organic deposits. The Cub Hills Section has an elevation range of 549 -763m. It is gently rolling to hilly morainic upland with local gravels and fluvial-lacustrine sands. Parent materials consist of coarse textured, excessively stoney materials overlying medium textured till. This material is usually sand to sandy loam in texture and contains numerous stones and is weakly calcareous. The soils are well drained on the mid and upper slope portions of the landscape. Imperfectly to very poorly drained soils occur on the lower slope and depressional areas. Soil profile drainage is often impeded by the compact, relatively impervious upper portion of the Bt horizon, resulting in a perched water table after heavy rains. This commonly occurs in areas of low relief (Head et.al., 1981).

For both Sites 3 and 4 there is a large section of Brunisolic Gray Luvisols, and Gleysolic soils in the peaty phase. For the eastern section of Site 4 the soils tend more towards Degraded Eutric Brunisols with occasional Orthic Gray Luvisol. Soil textures throughout both basins are sandy loam containing high proportions of stones, and an overall kettle landform topography. Further to the eastern section of Site 4 the landform becomes more steeply sloped with strong rolling topography. Stream banks are steeper and most of the substrate within the stream channel are hill wash soils. In general the soils in this area are light-colored, and have developed in well to imperfectly drained sites.

4.10.3: Historical Events

In August of 1995 a large burn passed through this area, from here known as the Nipakamew Burn (see Figure 4.8). Because it occurred at the end of the growing season, very little new growth could establish before winter arrived. When thaw and runoff commenced in the spring of 1996 there was no evidence of vegetated underbrush, and small pockets of burned deadfall lay on the soil surface, as compared to unburned basins in the vicinity which had high proportions of vegetated understory. Both Site 3 and Site 4 had extensive areas of vegetation lost to fire (62% and 78% respectively)(see Table 4.3 and Appendix C). It is because of this fire's extent and its recent occurrence that these two Sites were chosen as representative burn basins for this study.

4.11: Site 3

4.11.1: Physical and Hydrological Characteristics

This drainage basin covers an area of 15.72km^2. Elevations range from 495 - 572m. The north and north-eastern boundary of this basin borders on Site 4. Figure 4.9 shows a detailed description of the drainage basin.

Figure 4.8: Typical Burn Location Beside Stream in the Boreal Forest.

There is no official name for the stream exiting this basin. Approximately three quarters of a kilometer after the stream exits the basin and passes under Wapawekka Road it enters Nipekamew Lake. There are two first order streams in this basin, and one second order stream. Drainage density is 0.34 km/km^2. The basin contains a large proportion of fen and bog (28.7%), but in comparison has only 0.3% of wet coniferous. An explanation for this would be that the burn category for land use includes wet coniferous.

4.11.2: Anthropogenic Characteristics

Satellite imagery shows that the Nipakamew Burn covered a large portion of Site 3. Table 4.3 (also see Appendix C) indicates at least 61.7% of the basin was burned during August of 1995. During spring melt the soils were noticeably saturated and 'gloppy', and the ground devoid of plant and litter material. After the snow had melted from the land in the late spring the soil surface was covered in a fine black dust and there was no visual sign of green vegetation. The landscape remained this way until late summer when low shrubs started appearing.

No roads pass through this basin, and until the Nipakamew Burn no harvesting was done in this area. During late fall and winter of 1995 and 1996 salvage of merchantable burned timber began. Access to this timber was from a small road that ran along the southern boundary of the basin, but which, at the time of study, did not cut into the basin (see Figure 4.9). Harvesting accounts for only 2.0% of this basin, and as such is not regarded in this study as a strong contributor of disturbance. Harvesting had been ongoing on the western side of Wapawekka Road between Wapawekka Road and Nipekamew Lake prior to 1995. One recent clearcut was situated on the west side of the road, and north side of the stream which exited the basin. The perimeter vegetation around this clearcut had been included in the previous summer's burn. In the spring of 1996 snow melt from this clearcut saturated the soil of the stream bank above the stilling well, resulting in erosion of top soil and mudslide of the bank onto the well. Also, during snow melt runoff in the stream exiting the basin the culvert which channeled stream flow under Wapawekka Road remained plugged with ice, prior to and during the peak stream discharge. The result of this was that the stream bypassed the culvert and ran through the road material. A 20m section of the western roadside bank eventually collapsed into the stream.

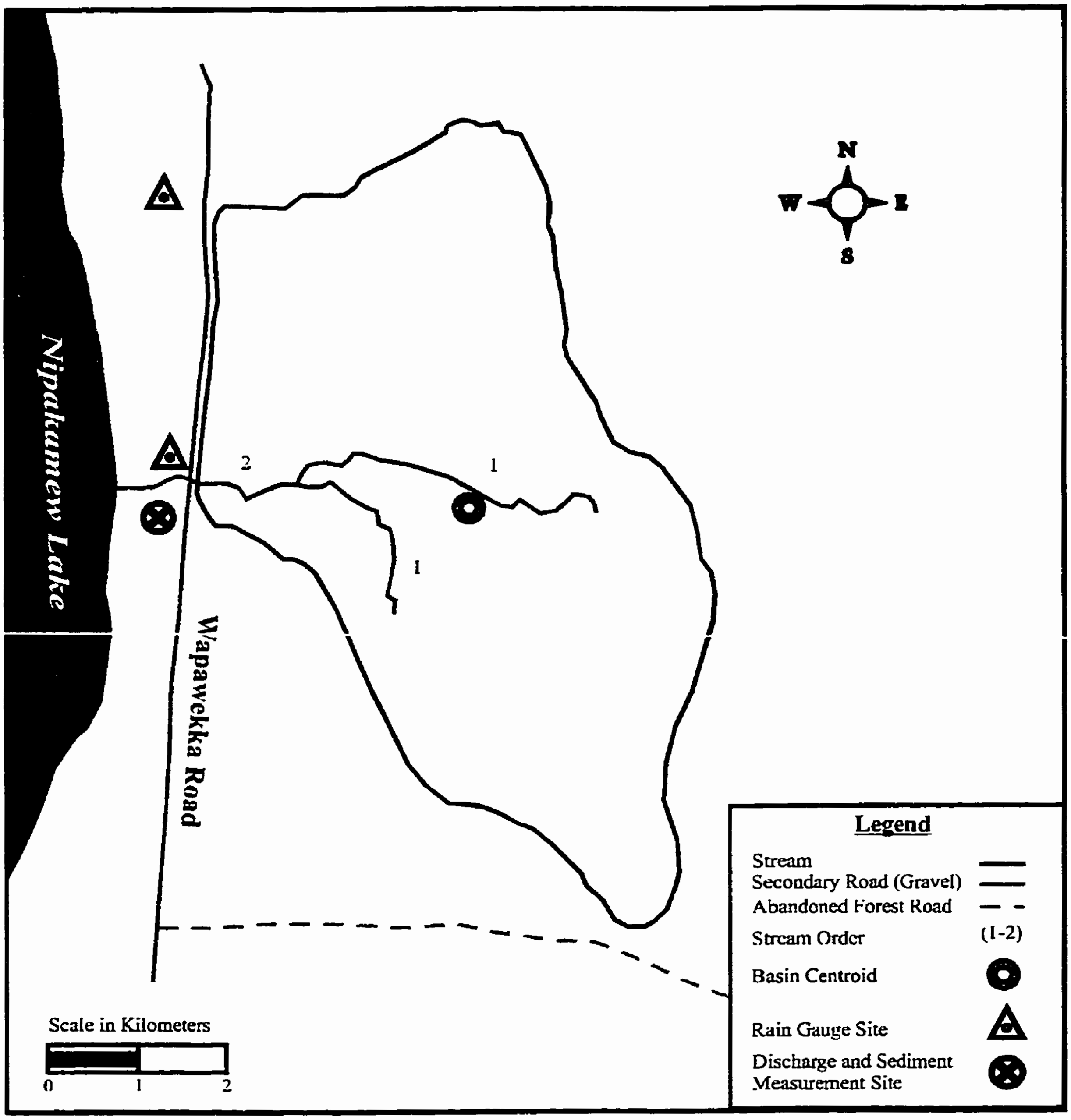


Figure 4.9: Drainage Basin Outline for Site 3.

4.12: Site 4

4.12.1: Physical and Hydrological Characteristics

This drainage basin covers an area of 123.30km^2. Elevation range within the basin is from 495 - 648m. The south western corner of this basin borders on Site 3. Figure 4.10 shows a detailed description of the drainage basin.

As with Site 3 there is no official name for the stream exiting this basin. Approximately half a kilometer after the stream exits the basin and passes under Wapawekka Road it enters Nipakamew Lake. From Table 4.3 (also see Appendix C) 16.4% of the land is covered by fen and bog, and 0.3% wet coniferous vegetation. Site 4 has the highest drainage density of all four Sites, at 0.70km/km^2. There are twenty three first order streams in this basin, five second order streams, two third order streams, and one forth order stream.

4.12.2: Anthropogenic Characteristics

Satellite imagery (see Table 4.3 and Appendix C) indicates at least 77.5% of the basin was burned during the Nipakamew Burn of 1995. As with Site 3 no harvesting was done in this basin prior to the Nipakamew Burn. Harvesting began in the late fall of 1995 and over the winter of 1995/1996. Timber harvesting was done from a small road that ran along the southern boundary of the basin. Access to the interior of this site was virtually impossible due to no roads within the basin, widespread bog along the western perimeter and indeed throughout most of the interior basin, and a large lake along the eastern perimeter. The gravel road that ran along the south side of the basin was not maintained and accessible only by all-terrain vehicle in the summer when road conditions were dry, or by larger vehicles in the winter when the ground was frozen.

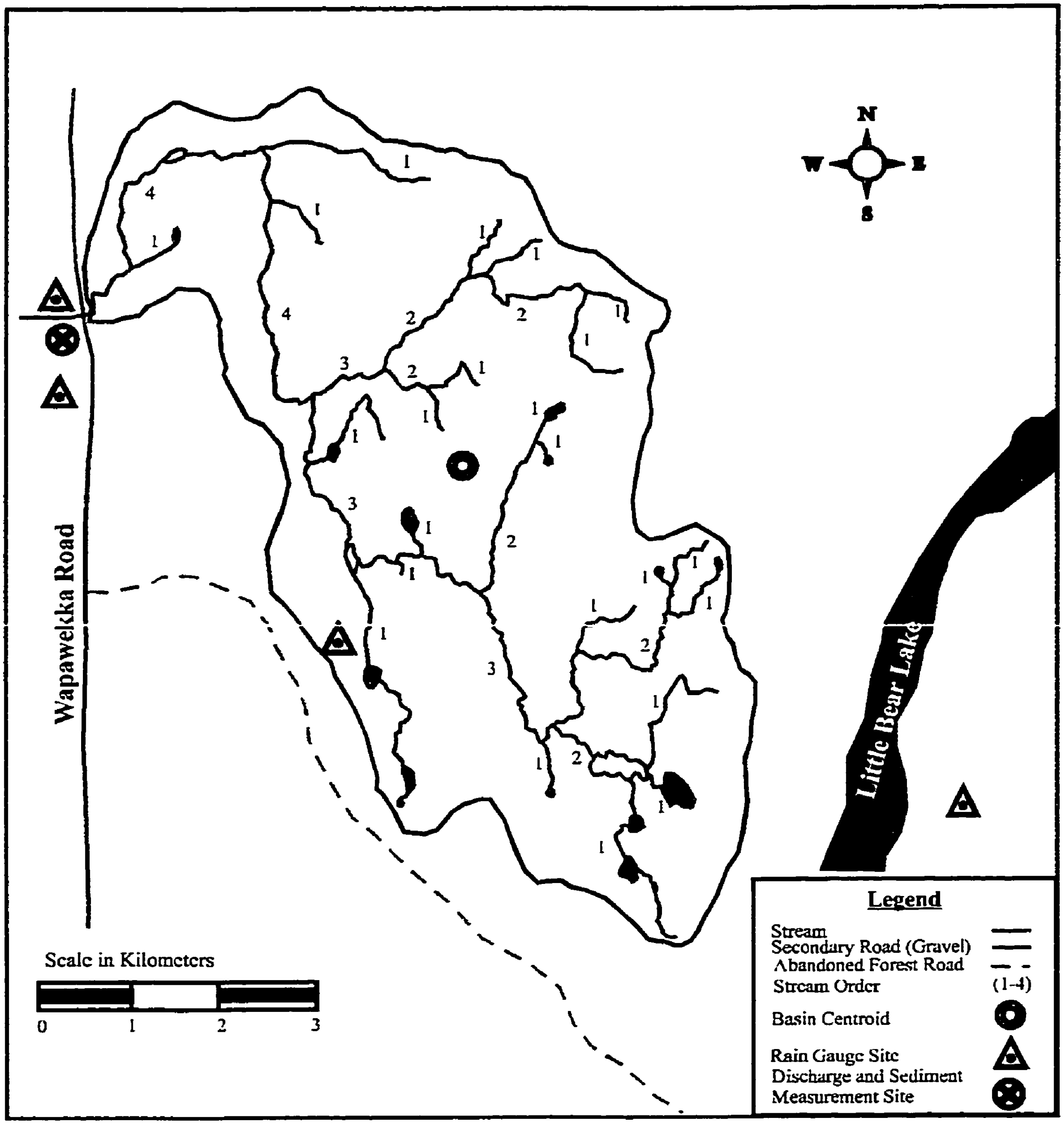


Figure 4.10: Drainage Basin Outline for Site 4.

Two culverts were used to channel stream flow from this basin under Wapawekka Road. The north culvert was 1.2m diameter, and the south culvert was 1.5m diameter. The left culvert was set at approximately 0.5m lower into the stream to allow for channeling of the stream in low flow periods and an accessible fish spawning route from Nipakamew Lake.

During spring runoff a large amount of stream flow backed up on the upstream side of Wapawekka Road. This was due to large flow volumes that the culverts were unable to handle and because a large amount of debris that blocked the upstream culvert entrances. The result of this was a rise in stage upstream of the road by approximately four meters. Metering of peak flows was done from the culverts during this time due to the high velocities and overbank flooding downstream of the road-stream intersection. Suspended sediment was collected during this time but required more care in sampling due to hazardous conditions and potential for backwash of stream bank material.

4.13: Sites Summary

Four sites were selected for the research. All sites are geographically close and share similar temperature values and hydrologic inputs. Soil and vegetation types for individual sites have been outlined and shown to be consistent across all sites. Average drainage basin slope values are shown to be relatively close (0.02 to 0.03) for the four sites (Table 4.4). It has also been established that all sites have no significant harvesting or road construction disturbance.

Two important statements are drawn for the sites:

- Prior to fire disturbance in August, 1995 all four drainage basins experienced similar climate, biophysical characteristics, and land use treatment.
- After the fire two basins had treatment by fire, the remaining two had no fire disturbance.

Since all important landscape factors are have been shown to be equally represented at all four sites differencing in hydrologic behaviour between sites should be largely attributable to the fire disturbance factor.

CHAPTER FIVE: METHODOLOGY

5.1: Introduction

The primary goal of this thesis was to quantify hydrologic and sediment change after fire treatment. This required the collection and management of data for precipitation, stage, discharge, and suspended sediment loads. Chapter Five outlines how that data was collected in the field and prepared for the final analysis in Chapter Six.

Procedures for field work preparation are covered in the first section of this chapter, in drainage basin analysis. Next, the field methodology section describes equipment and procedure requirements for hydrologic data collection at each of the four sites. The section on data treatment then outlines methods used in preparing data for analysis. The final section covers statistical analysis procedures utilized to investigate the degree of suspended sediment response resulting from fire treatment, and to develop a mathematical model that would best indicate the measure of this change.

5.2: Drainage Basin Analysis

Prior to commencement of field work each of the selected sites was examined for their individual spatial characteristics. NTS (National Topographic Series) maps with watershed perimeters outlined were scanned and imported into the MapInfo™ GIS (Geographic Information System) package. Selected projection coordinates were then input to register the images. GIS was used to determine drainage basin area, stream lengths, stream and road densities, bifurcation ratio, stream profile and average basin slope for each site.

5.2.1: Stream Orders

Systems for classifying drainage networks allow for quantitative description of channel network and length within a basin area. They are a useful means of verifying that as networks change over time within a system they still conform to the concept of constant channel maintenance (Knighton, 1984). This means that with a given set of environmental conditions (i.e., gradient, geologic control, soil texture etc.,) predictions, based on the above laws, can be made on the extent and pattern of channel network within a watershed. The purpose of drainage network analysis in this study was to show that consistent channel network patterns were consistent for all sites, and given that these characteristics were constant, comparable responses would be expected from similar precipitation inputs. Drainage network composition analysis was completed for all sites as a prerequisite for further hydrologic research in this project. Three laws of drainage network composition were first introduced in Chapter 2, Section 2.4.1: Stream Order. Equations for determining the ratio forms of these laws are taken from Horton (1945) and Schumm (1956) and are outlined in Equations 5.1, 5.2, and 5.3. Ratio forms for the law of drainage network composition are:

Law of stream numbers: $$R_B = \frac{N_n}{N_{n+1}} \qquad (5.1)$$

where R_B is the stream number ratio, or bifurcation ratio,

N_n is the number of stream segments of a given order,

N_{n+1} is the number of stream segments of the next highest order.

Law of stream lengths: $$R_L = \frac{L_{n+1}}{L_n} \quad (5.2)$$

where R_L is the stream length ratio,

L_{n+1} is the average length of streams of a higher order,

L_n is the average length of streams of a given order.

Law of drainage areas: $$R_A = \frac{A_{n+1}}{A_n} \quad (5.3)$$

where R_A is drainage area ratio

A_{n+1} is the average drainage area of streams of a higher order,

A_n is the average drainage area of streams of a given order.

Except in conditions of strong geologic control, the three ratios (R_B, R_L, and R_A) have ranges of 3-5, 1.5-3.5, and 3-6 respectively (Knighton, 1984). Ratios of each drainage composition law for each site are located in Table 5.1.

Table 5.1: Ratios for Drainage Basin Composition.

Site #	Stream Number Ratio (Bifurcation Ratio)	Stream Length Ratio	Drainage Area Ratio
Site 1	3.00	1.84	3.60
Site 2	2.00	0.02	2.00
Site 3	2.00	0.04	2.34
Site 4	3.03	1.89	3.55

Ratios for the four sites in Table 5.1 indicate that the basins with larger drainage areas conform to the three laws as stated. Values for Sites 1 and 4 are within the range expected, but at the lower end of each of those ranges. This would be expected given the depressional nature of the topography and the large percentage of wetland areas (Table 4.3). Both Sites 1 and 4 are observed as having similar ratio values for each law, once again an indication of similarity in physical and hydrologic basin characteristics.

Sites 2 and 3 have relatively small drainage areas. Ratio results for these sites are below the range expected for all drainage composition laws, once again explained by the nature of the local topography. Both sites share similar ratio values for all three basin composition laws. The above system for quantitative description of channel network, length, and area within each basin area verifies that all sites comply within acceptable range of network composition laws as outlined by Horton (1945) and Schumm (1956), and that undisturbed sites (Sites 1 and 2) compare similarly to those of disturbed sites (Site 3 and 4) in drainage behaviour and efficiency.

5.2.2: Stream Profiles

Stream profile mapping is a useful method of visualizing how water is transported out of a drainage basin. Stream profiles were constructed for each of the four sites along main channels from source to outlet. Each graph gives a distance that the channel covers through each interval of elevation, and is useful in determining where within the drainage basin varying slope gradients occur. Stream profiles for the four sites are located in Figures 5.1 through 5.4.

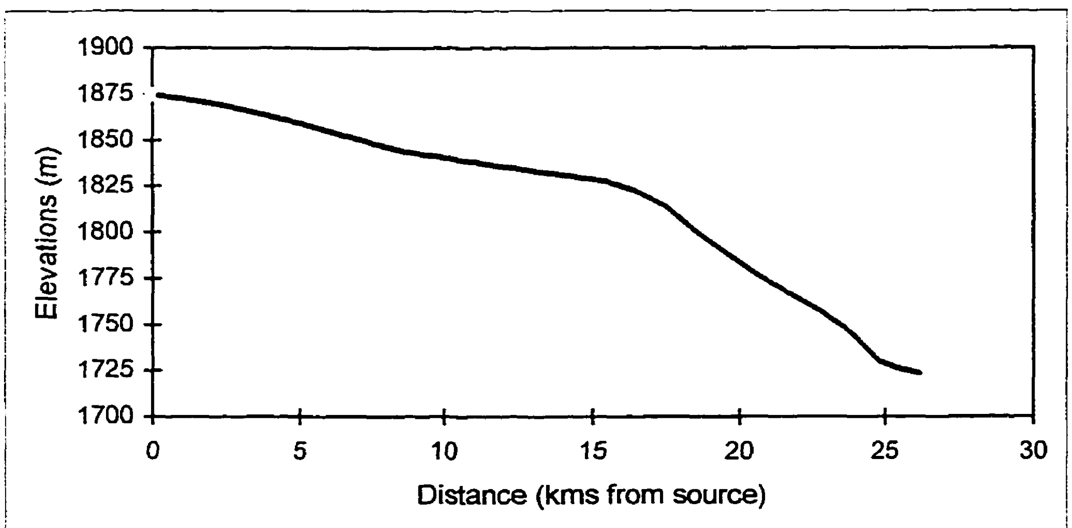


Figure 5.1: Long Profile of the Main Channel Within Site 1.

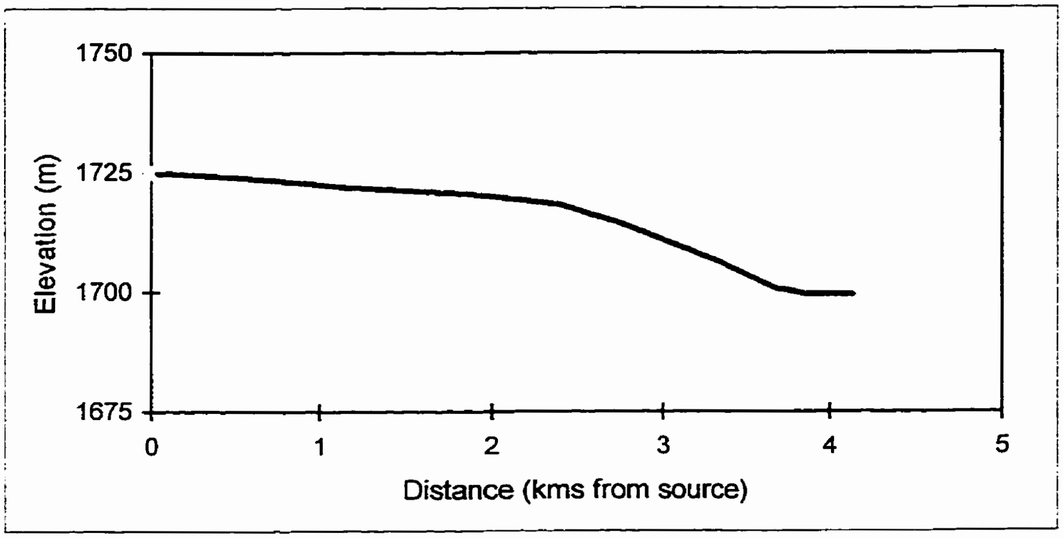


Figure 5.2: Long Profile of the Main Channel Within Site 2.

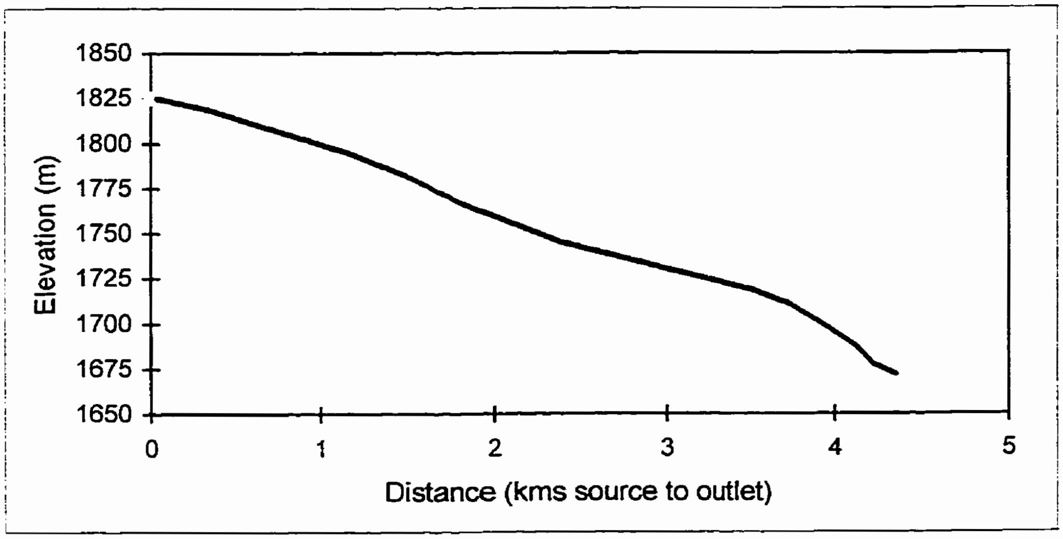


Figure 5.3: Long Profile of the Main Channel Within Site 3.

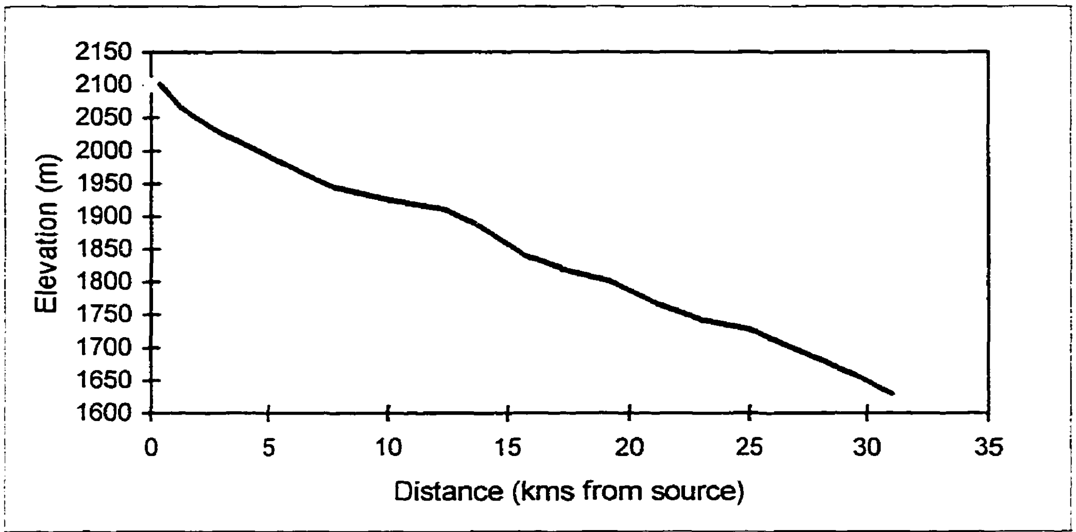


Figure 5.4: Long Profile of the Main Channel Within Site 4.

Main channel profiles were used. alongside preceding stream density composition descriptions, and average basin slope (Table 4.4) in Chapter Four, to provide visual description of channel slope for each site and to reinforce the argument for similarity in drainage efficiency between all sites. In general, long profiles have a concave shape, where channel headwaters at the source are generally steep, then become progressively lower gradient toward the outlet (Clowes and Comfort, 1982). Because the drainage basins within the research had large portions of low-lying, depressional areas within the upper and central parts of their catchments profiles were expected to tend toward straight and convex. Sites 1, 2 and 3 do indicate straight to convex profile slopes with no steepening in the upper portion of the basin. The long profile for Site 4 is observed to have a steeper headwater section with a uniform drop in gradient through the middle of the profile, to basin outlet. This follows with average basin slope values for the sites, where Sites 1, 2 and 3 have slope values of 0.02%, and Site 4 has a basin slope of 0.03% (Table 4.4). Differences between sites in stream profiles and average basin slope percentages are not regarded as significantly different. All profiles are similar in shape, with gradual, uniform drop, and there are no observable extremes in gradient at any of the four sites.

Stream profiles were also used to locate ideal station controls for the stage-discharge relationship and slope control for discharge and suspended sediment measurement. "In order to have a permanent and stable stage-discharge relation the stream channel at the gauging station must be capable of stabilizing and regulating flow past the station so that for a given stage the discharge through the measuring section will always be the same" (Herschy, 1995). Stream profiles enabled the location of uniform channel profiles which offered steady flow velocities. Irregular profiles with sharp changes in slope are likely to create turbulence and extraneous velocity measurements, or negative flow values where sharp concave profiles create reverse flows at hydraulic jumps (Leopold and Maddock, 1959, and Dingman, 1984). Consistent slope profiles were also necessary to ensure adequate mixing of suspended sediments, and to avoid unnecessary fluctuations in sediment concentration due to turbulence or backwash (Asquin and Jablonski, 1988). Stream long profiles for all sites near basin outlets indicated no observable adjustments in slope that would give undesirable stage, discharge or suspended sediment concentration results.

5.3: Field Methodology

5.3.1: Stage and Discharge Measurements

Because stage and discharge were expected to vary from high spring runoff to low flow periods during late summer it necessitated the collection of discharge measurements over a range of stage variations. In order to obtain a continuous record of discharge and to establish a stage-discharge relation stage was recorded continuously by data logger and discharge was recorded manually, then later computed from a correlation of stage and discharge.

Selection of stilling well sites for stage measurement and stream gauging for discharge was completed with the requisites outlined by Harrelson et al (1994), and Herschy (1995). Stilling wells were constructed during the months of March and April, 1996. All wells were located on the downstream sides of road-stream intersections, at the basin outlet for each site. The purpose of this was to avoid stage irregularities due to backing up of stream flow on upstream sides of road culverts during peak discharge events. Equipment included sewage piping for the housing, pulley with float and weight attached with notched cable, and data logger. The well housing was set 0.5 to 1.25 meters into the stream bed and stabilized by three 12 foot T-bars. This amount of buried depth was important as the beds of many of the streams consisted of fine, unconsolidated silts and sand. Stage measurements were recorded by voltage readings, and recorded in data loggers every 15 minutes. Voltage range was from 0-2.5 volts. Initial voltage set-up was at 1.2 volts. Stage was also visually recorded by a non-recording staff gauge placed in the stream close to the stilling well. Stage was recorded from this gauge at the times when velocity measurements were taken, and used as a visual reference to voltage recordings, also as a backup in case voltage recordings were interrupted (Herschy, 1995).

Stream velocity measurements commenced in the later part of April, 1996. Ice build-up on the bottom of stream beds and flowing ice blocks in streams proved problematic for both the safety of the measurer and the equipment. This problem, combined with growing velocities from spring runoff necessitated the collection of velocity measurements from culverts until the mid to later part of May, depending on the site. Velocity measurements were recorded at the downstream side of road-stream intersections at all four study sites. Flow was measured indirectly by sampling the velocity profile of the stream. Measurements of velocity were made along verticals located at a cross-section of the stream. Each of the verticals were located so that less than 10% of the total flow was estimated by one vertical section. By measuring a velocity profile at each section, the average velocity through each section could be estimated. The sum of the product of the average velocity and the area of each component of the section was then equal to the total flow. Stage-discharge rating curves for each gauging station are given in Appendix D.

Three types of velocity recorders were used over the course of the measuring period: these were the Swoffer 2100 current meter, Marsh McBurny, and Price current meters. To overcome the potential for inconsistency in the data all three instruments were calibrated together at the end of the season and velocity measurements were adjusted accordingly.

Figure 5.5: Velocity Measurements at Site 1.

5.3.2: Suspended Sediment Measurements

Suspended sediment measurements were collected at the same location and time of stream velocity measurements. Samples were collected upstream of road-stream intersections to avoid the erosional influence of road banks. Procedure for determination of sampling point was taken from Guy and Norman (1970), and Asquin and Jablonski (1988). The following considerations were taken into account when collecting suspended sediment samples:

- The sampling site was located in approximately the center of the stream; determined by the point in the cross section where mean suspended sediment concentration occurred.

- Sampling was done in a straight reach, and in a uniform slope profile (comments on stream profiles are found in section 5.3.2).
- Sampling was avoided in backwaters, pools, or behind obstructions (boulders, logs).
- Sampling was done far enough upstream to eliminate the influence of the roadway as a point source.
- Sampling was done far enough downstream from a potential point source to allow for adequate mixing between a source and sampling point.
- Two samples were taken at each measurement, then later averaged.

A DH48 depth-integrated sediment sampler was employed for sediment collection. This sampler is designed for use in slow wadable streams. A uniform fill rate was maintained to ensure that samples represented equal distribution of sediment concentration through the vertical water column. These samples were exclusive of the bottom 10cm for two reasons outlined by Burkham (1985):

- Significant error in the amount of sediment trapped in the sampler may result if the sampler is allowed to rest momentarily on the channel bed, or by gouging or dipping the nozzle into the face of a dune.
- The suspended sediment samples usually represent sediment concentration of the flow exclusive of the bottom 0.3 to 0.5 foot of depth at each vertical; inclusion of coarse material found near the streambed is important in studies of channel behaviour but usually not significant in studies involving fine material.

Exclusion of suspended sediments near the streambed was most important in this study because in faster flowing streams the streambed substrate was mostly sand, and in low flowing streams organic fines and fine silt which lay on the bottom of the bed could be easily disturbed into the flow. When stream depths were too low for use of the DH48 sediment sampler, grab samples were taken manually (Guy and Norman, 1970). This required lowering of the sediment sample bottle through the stream profile by hand. Site 3 had low stage levels in the later part of summer and this procedure was necessary at this time.

Samples were collected in standard pint bottles, covered and refrigerated until filtered to prevent evaporation and algae growth. Each sediment sample was filtered onto a pre-weighed 0.45micron filter paper, air dried for 24 hours, oven dried at 13^{0}C, and weighed again. The remaining liquid sample was also measured and recorded. Sediment weights were combined with their fluid data component to give mg/L suspended sediment concentration (SSC). Because sediment measurements gave only occasional samples of the sediment discharge suspended sediment data was collected over as full a range of stream discharges as possible within the time and the budget available for the study. Sediment samples were measured on average every 2.8 days from beginning of measuring period through peak flow period to the end of May, and 3.9 days from June to the end August.

5.3.3: Precipitation Measurements

Three sites had rainfall gauges located at stream outlets near gauging stations. Gauge locations have been included in each of the site figures in Chapter 4 (Site 1 - Figure 4.6, Site 2 - Figure 4.7, Site 3 - Figure 4.9, and Site 4 - Figure 4.10). Rainfall and stage measurements at each of these sites were recorded onto one 2-channel data logger. Two types of rain gauges were used in the research: Belford gauges recorded rainfall based on calibrated weight and recorded that weight every 15 minutes onto a data logger, and tipping buckets which recorded tips of 0.25mm each of rainfall every 15 minutes.

Optimal rain gauge location is always a concern when studying precipitation within a drainage basin. The spatial variability of precipitation and the intended use of the data should initially determine network density. Herschy (1995) determined that a relatively sparse network of stations would suffice for studies of large general storms or for determining annual averages over large areas of level terrain. Whereas a dense network would be required to determine the rainfall pattern of thunderstorms. The probability that a storm center will be recorded by a gauge varies with network density; Eagleson (1967) therefore states that a network should be planned to yield a representative picture of the areal distribution of precipitation. Alternatively, the cost of installing and maintaining a network and accessibility of the gauge site to an observer are always important considerations. While keeping in mind the recommendations by Eagleson (1967), and Herschy (1995) gauge location for this research was chiefly determined by physical and timely accessibility. Roads and trails that may have been frozen and passable during early spring to allow for gauge setup were quite different once the ground thawed in early summer. Because of the subdued gradient and wet nature of the local topography, and the shortage of usable roads gauges in the larger basins were strategically located to optimize prevailing weather patterns and to share precipitation values where two basins were proximally located. Examples of this are found at Site 1 (Figure 4.6) where gauges were located evenly around the drainage basin to ensure ample coverage of storm events and prevailing northeast weather tracks, and at Sites 3 and 4 (Figures 4.9 and 4.10) the close proximity of basins and gauges allowed the sharing of data for precipitation events. Every effort was made to select sites that provided exposure to natural rainfall while providing adequate protection from unfavorable wind activity, animal and human disturbance. Figure 5.6 provides an example of tipping bucket location near tall vegetation.

Figure 5.6: Tipping Bucket Used for Precipitation Collection.

5.3.4: Satellite Imagery

Remotely sensed data was collected for the complete study area on July 12, 1996 during the BOREAS field season. This satellite imagery was corrected geometrically and radiometrically, and classified into land use classes by Golder Associates Inc., of Calgary. Ground truthing for the verification of land use types was done in late spring while the ground was frozen and sites still accessible. This was done with the use of GPS units and GIS maps supplied by Weyerhaeuser, Saskatchewan. Satellite Imagery figures for all sites are found in Appendix C and land use results from classification in Table 4.3.

5.4: Individual Site Methodology

5.4.1: Site 1

Velocity and stage measurements were recorded from April 20 to October 22 1996. A stilling well was located downstream of the road-stream intersection at the basin outlet. Velocity measurements were taken in a straight, but short section of stream two meters from the stilling well. Two meters downstream from the meter section was a rocky ledge that ran the width of the channel creating a section control that enabled a strong stage-discharge relationship throughout the period of measure.

Four rain gauges were located around the drainage basin; two tipping buckets and two Belfort gauges. Gauge locations are outlined in Figure 4.6. Two of these gauges were located within the boundary of the drainage basin, while the other two skirted the outside.

Suspended sediment measurements were taken above the road-stream intersection concurrently with velocity measurements.

5.4.2: Site 2

Velocity and Stage measurements were collected from April 1st to October 22 1996. These measurements were taken downstream of the culvert at Highway 120. This site experienced a number of influences on changing stage-discharge relationship throughout the measuring period. Changes in stage level resulted from ice in the stream during the months of April and early May, and changing aquatic vegetation coverage near the exit point of the culvert downstream of the road-stream intersection. One of the most important influences on the stage measurement however, was the location of the staff. This stream did not offer an ideal location for stage measurement because a relatively long reach was not available. The staff was located approximately 6 meters downstream from the culvert exit, and 10 meters upstream from a sharp left turn in the channel.

One tipping bucket was used to collect rainfall data within the basin and another was located outside, to the east of the basin. Gauges locations can be seen in Figure 4.7. Suspended sediment measurements were take concurrently with velocity measurements.

5.4.3: Site 3

Velocity and stage measurements were recorded downstream of the road-stream intersection from April 22 to October 28 1996. In the early part of spring a large section of stream bank slide into the stream at the stilling well site, causing a lean of 45° for the well. The stilling well was then removed and resurveyed at a site 100m downstream.

No rain gauges were placed inside this basin due to access problems, but three outside gauges were used to obtain rainfall measurements. One gauge was located at the outlet, and two gauges located for the Site 4 were also used because of their close proximity to this site. These gauge locations are outlined in Figure 4.9.

Suspended sediment measurements were collected above the road-stream intersection at Wapawekka Road.

5.4.4: Site 4

Velocity and stage measurements were recorded from April 20 to October 12 1996. Velocity measurements were recorded from both culverts on the downstream side of the road-stream intersection during the peak flow period April to end of May. After which velocity measurements were taken in a straight reach 20 meters downstream of the stilling well, and approximately 40 meters downstream of the culvert exit.

No rain gauges were placed inside this basin due to access problems, but four outside gauges were used to obtain rainfall measurements. One rain gauge was located at the basin outlet, a second was located in the south-east on the eastern side of Little Bear Lake, the third was located on the south-western side of the basin, and the fourth was the gauge used at Site 3 outlet. These gauge locations are found in Figure 4.10.

Suspended sediment measurements were collected on the upstream side of the road-stream intersection at Wapawekka Road.

5.5: Data Treatment

5.5.1: Precipitation

At some rain gauge stations short breaks (caused by battery failure or data logger problems) in station measurements required the estimation of missing precipitation data. Procedure for estimation of this data was followed from Linsley et al., (1982), and Singh (1989). Normally, precipitation amounts are estimated from observations at three stations, as close to and as evenly spaced as possible around the station with the missing record. For those gauges where rainfall values could not be interpolated from a number of proximal stations, comparisons were made between existing rainfall data at each of the closest stations and the gauge with missing data, a correlation coefficient was determined, then linear regression was performed between the outlying station with the highest correlation and the station with missing data.

The Thiessen method was used to determine average depth of precipitation over each basin. "The average depth of precipitation over a specific area, on a storm, seasonal, or annual basis, is required in many types of hydrologic problems" (Singh, 1989). The Thiessen method attempts to allow for a nonuniform distribution of gages by providing a weighting factor for each gage. It is used to convert point data to areal data. Procedure for the estimation of average areal rainfall at each of the sites was adopted from Chow (1964) and Dunne and Leopold (1978) and was conducted as follows: Gauge stations for each site were plotted on a 1:50,000 topographic map, and connecting lines were drawn between them. Perpendicular bisectors of these connecting lines were constructed to form polygons around each station. These polygons represented their respective areas of influence. The area of each polygon was determined by GIS and was expressed as a percentage of the total area. Weighted average rainfall for the total area was then computed by multiplying the precipitation at each station by its assigned percentage of the area and totaling.

The results of the Thiessen Method are usually more accurate than those obtained by simple arithmetic averaging. One advantage of this method, as found by Linsley et al., (1982), is that the influence of stations outside the area can be included. Also, this method worked well in this location where gradients were low and orographic influence was reduced. The greatest limitation of the Thiessen method in this project was its inflexibility; Thiessen diagrams had to be adjusted whenever there was a change in the gauge network.

5.5.2: Stage and Discharge

Initial data treatment of stage and discharge required the establishment of a stage-discharge relationship with the use of stage rating curves (Appendix D). These were constructed from voltage values recorded at the time of stream gauging, and discharge values calculated from velocity and area (section 5.3.1). Stage rating curves were constructed for each site and regression analysis used to find discharge values from hourly intervals of stage measurement.

5.5.3: Suspended Sediment

Two steps were taken to prepare suspended sediment data before final analysis. The first was for check for measurement consistency by calculating the sampling error, and the second was to convert suspended sediment concentration (SSC) to suspended sediment load (SSL).

To check for variation of difference between the computed and true value of the SSC of the two sampled concentrations taken at a point the following equation was used:

$$(SE)^2 = \frac{\sum[(C_{\bar{x}}+R_{\bar{x},1})-(C_{\bar{x}}+R_{\bar{x},2})]^2}{N} \qquad (5.4)$$

where: SE is the standard sampling error

$C_{\bar{x}}$ is the mean of the two samples taken at a point

$R_{\bar{x},1}$ is the difference between sample 1 and the mean ($C_{\bar{x}}$)

$R_{\bar{x},2}$ is the difference between sample 2 and the mean ($C_{\bar{x}}$)

N is the number of pairs of samples (Haan, 1977).

Table 5.2 gives the results for the analysis of sampling error. The results indicate similar error percent for Sites 1, 2 and 4 between 20% and 27%. Sampling error (SE) was highest at Site 3, with a value of 52%. This error value is expected because of the method of sampling in the summer season when this stream stage was its lowest. At this time stream depth was approximately 15cm, making measurement by standard equipment impossible. Samples were collected by the grab sampling method outlined by Guy and Norman (1970) in which the sediment collection bottle was lowered manually through the stream profile. This type of collection allows for a crude estimation of SSC but increases the likelihood of inconsistency between two samples taken at one time period of measurement. Error percent for Sites 1, 2 and 4 are consistent and accepted as moderate. No adjustments were made to the original data.

Table 5.2: Standard Sampling Error for Paired Suspended Sediment Samples.

Site #	Standard Sampling Error (SE)	Percent Error ($SE/C_{\bar{x}}$)*100
Site 1	0.00116	20%
Site 2	0.00125	27%
Site 3	0.00561	52%
Site 4	0.00427	21%

Final data preparation for suspended sediment required change of standard units and conversion from concentration to load. It was expected that sediment loads coming from the streams at the sites would not be high in relation to large rivers in other parts of the continent, and therefore units of gm/day were used in place of the more commonly used ton/day (Sheppard, 1976). Paired samples were then combined and averaged and SSC was converted to SSL.

5.6: Statistical Analysis

Statistical analysis was used in the research as a tool for determining relationships, and strength of associations between variables, as well as optimization when more extensive range of data were required. Analysis included derivation of descriptive statistics, simple linear regression, time series analysis, and multiple regression. The statistical package SSPS™ was used for all statistical analyses.

5.6.1: Descriptive Statistics

Descriptive statistics were utilized to summarize and communicate what was found in the data, and to satisfy the requirement of tests for normality. Measures of central tendency; mean (the average of the measurements), and median (the middle number of the measurements), were used to describe the "average" characteristic of the data. Data that was normally distributed was expected to hold similar values for mean, and median. (Jarrett and Kraft, 1989; Mendenhall and Sincich, 1995). Standard deviation (a measure of variation - is equal to the square root of the variance, and is measured in the same units as the variable being measured), was used to measure dispersion (Mendenhall and Sincich, 1995).

5.6.2: Time Series Analysis

Time series analysis, cross correlation is often utilized to forecast values for one time series using values from a second time series. Discharge and suspended sediment for this cross-correlation are used as series one and two respectively. When the two series are moved past each other the degree of correspondence between the overlapped sequences is calculated (Davis, 1973). The equation used in cross-correlation is the same as the linear correlation coefficient (Davis, 1973). If the two series are designated as SSL and Q and n* is defined as the number of overlapped positions between the two series the cross-correlation for matched position m is:

$$r_m = \frac{n^*\Sigma SSL\, Q - \Sigma SSL\, \Sigma Q}{\{[n^*\Sigma SSL^2 - (\Sigma SSL)^2][n^*\Sigma Q^2 - (\Sigma Q)^2]\}^{1/2}} \qquad (5.5)$$

where r_m is the cross correlation for the matched position,
SSL is suspended sediment load (gm/day),
Q is discharge (m^3/sec)
n* is the number of overlapped positions in the two series.

5.6.3: Simple Linear Regression

The objective of simple regression within this study was to provide a mathematical relationship that would be used as a means of predicting or estimating one variable, the dependent variable, from knowledge of a second variable, the independent variable. Correlation was further used as a measure of the strength of that relationship.

Linear regression analysis had a two part purpose for this research: in deriving missing values for rainfall at stations where data gaps occurred throughout the season, and for optimization where known values of SSL and Q were used to construct a rating curve that would enable the derivation of SSL over the remainder of the season.

The general model used for simple linear regression is:

$$y = b_0 + b_1 x \pm e_i \qquad (5.6)$$

where:

y is the dependent variable (suspended sediment load)

x is the independent variable (discharge)

b_0 is the y-intercept of the line

b_1 is the slope of the line

e_i is the random error component (Jarrett and Kraft, 1989).

5.6.4: Multiple Regression

Multiple regression provides a mathematical equation of the relation between a single dependent variable and the independent variables. It also provides a measure of the accuracy of the defined relation and measures of the usefulness of each independent variable in the equation (Thomas and Benson, 1975; McCuen and Snyder, 1986; Mendenhall and Sincich, 1995). These are visually represented in a correlation matrix.

Regression analysis was used in this study to build a correlation matrix that would determine which variables are closely correlated with burn treatment, which variables make the best prediction of suspended sediment loads in streams after fire disturbance, and to develop a mathematical equation that would be used as an indicator of sediment load response to changes in vegetation coverage. Because the number of cases (four sites) used in the regression were too small for a reliable analysis the results would be used as an indicator and not a prediction of suspended sediment load after disturbance. The dependent variable for this regression is stated as the average suspended sediment load density per drainage area (SLD). The goal of the regression was to arrive at a set of regression coefficients for the independent variables that would bring the dependent variable developed from the equation as close as possible to the dependent variables obtained by measurement (Sandrock et al., 1992; Tabachnick and Fidell, 1996).

Physical and hydrologic characteristics of the basins which conceptually might have influenced streamflow needed to be expressed by simplified representative indices. These characteristics had to be intuitively and physically connected to the response of the dependent variable. Four independent, predictor variables (2 hydrologic, and 2 physical basin characteristics) were selected which were expected to influence the dependent variable. These variables were selected on the basis of previous research (Anderson, 1954; Thomas and Benson, 1979; and Peters, 1984) and on their ability to give quantitative expression to characteristics that influenced and contributed to sediment discharge.

- total discharge per drainage basin area (TQ),
- average infiltration rate (IR),
- ratio of burn to total basin area (B_R),
- average basin slope (S).

The regression model used for this study is outlined below:

$$y = b_0 + b_1x_1 + b_2x_2 + \dots + b_qx_q \pm e_i \qquad (5.8)$$

where: y is the sum of the effects of q separate, independent variables.

b_0 is the y-intercept of the line

$b_1 \dots b_q$ are the coefficients of the explanatory variables

$x_1 \dots x_q$ are the explanatory variables

e_i is the error term

Suspended sediment load has been shown to be a useful measure of the degree of response to physical change within a drainage basin (Knighton, 1984). The purpose of multiple regression analysis in this research is to develop a mathematical model that can be used as an indicator of sediment response from a watershed given hydrologic and physical variables that are expected to influence that response. The equation for the dependent variable average suspended sediment load density in the regression analysis is as follows:

$$SLD = SSL_{Av}/A \qquad (5.9)$$

where: SLD is the average suspended sediment load density (gm/day/km^2)
SSL_{Av} is the daily average suspended sediment load (gm/day)
A is drainage basin area (km^2)

As stated, regression analysis was expected to produce optimum results if the independent was closely related to the dependent variable (Anderson, 1954; Thomas and Benson, 1979; and Sandrock et. al., 1992). Explanation and equations for the independent variables are:

5.6.4.1: Stream Discharge

Stream discharge is the main form of transportation of eroded materials from a drainage basin, and is closely associated with suspended sediment load in that, as discharge increases so does suspended load (Meade et al., 1990). Drainage basin area is an important consideration with respect to total sediment yield (Walling, 1983), therefore total discharge measured from each drainage basins is expected to be closely related to total sediment yield per basin area. Total discharge volume for each site was calculated from beginning to end of field work measurement, then divided by drainage basin area. The equation used to determine total discharge per basin area is:

$$TQ = Q_T/A \qquad (5.10)$$

where: TQ is total seasonal discharge per drainage area (m^3/km^2)
Q_T is the total seasonal discharge volume (m^3)
A is drainage basin area (km^2)

5.6.4.2: Infiltration Rate

The infiltration rate is determined by the physical ability of the soil to allow moisture to percolate into the solum (Cooke and Doornkamp, 1990). If the infiltration rate is exceeded runoff occurs. Runoff in turn contributes strongly to the movement of materials into the stream, thereafter termed as sediment load. Infiltration rates are expected to be inversely related to suspended sediment loads; as infiltration rates decrease, sediment loads increase. The equation used for determining infiltration rate follows. Further explanation of infiltration rate analysis is found in Section 6.1.1 of Chapter Six.

$$IR = \frac{P - R}{D} \qquad (5.11)$$

where: IR is the average infiltration rate (Ø Index)(mm/hr)

P is precipitation (mm)

R is runoff (mm)

D is the duration of time (hrs) when rainfall equals the volume of runoff.

5.6.4.3: Forest Fire Coverage

Vegetation within a watershed affects streamflow through the processes of transpiration and precipitation interception. When fire removes vegetation modification of this hydrologic relationship is expected to occur. Although fire does not directly affect suspended sediment loads in streams it does directly influence the nature of the soils (Baker, 1990), their susceptibility to erosion, and the availability of material to be carried to the stream (Giovannini et al., 1988). For this reason ratio of burn coverage in a drainage basin is expect to be related to the amount of suspended sediment load carried in the basin streams. The spatial coverage of burn area was classified from satellite imagery then defined as a ratio of burn to drainage basin area. The equation used to determine burn ratio is:

$$B_R = B/A \qquad (5.12)$$

where: B_R is the ratio of basin burned

B is the area of burn within the drainage basin (km^2)

A is drainage basin area (km^2)

5.6.4.4: Slope

Slope of a drainage basin is a factor which can intuitively be assumed to influence suspended sediment load. Higher slope values incur higher flow velocities on land surfaces and in channels (Ward and Elliot, 1995), and higher discharge peaks (Saxton and Shiau, 1990). This would mean that larger amounts of material are carried from the land into the stream system. The equation used for determination of average basin slope is:

$$S = \frac{(1/2C_o + C_1 + C_2 + \ldots + C_{n-1} + 1/2C_n)d_m}{nA_o} \qquad (5.13)$$

where: S is the average basin slope

C_o,C_1, etc., are the lengths of the contours

d_m is maximum basin height

n is the number of contours

A_o is the drainage basin area (Chow, 1964)

CHAPTER SIX: ANALYSIS AND RESULTS

6.1: Infiltration and Runoff

6.1.1: Infiltration Rate

Three rainfall events from each of spring, summer, and fall were selected from site hydro-hyetographs (Figures 6.1 to 6.4) to provide a seasonal comparison of infiltration rates between burn and undisturbed drainage basins. Dates for infiltration analysis are found in Table 6.1.

Table 6.1: Dates for Collection of Infiltration Rate.

Site #	Spring	Summer	Fall
Site 1	May 17	July 12	September 5
Site 2	May 17	June 18	September 5
Site 3	May 17	June 26	September 22
Site 4	May 17	June 26	September 22

The Phi (Ø) Index, the mean infiltration rate occurring for the duration of a storm, was used for this comparison (Singh, 1992). Hourly rainfall amounts were collected for each station and the Thiessen Method was used to determine average rainfall depth (mm) for each event. Runoff volume (mm) was also calculated along with rainfall duration. The following equation was used to derive an assumed Ø Index.

$$IR = \frac{P - R_d}{D} \qquad (6.1)$$

where: IR is the average infiltration rate (Ø Index)(mm/hr)

P is precipitation (mm)

R_d is direct runoff (mm) as determined by equation 6.2

D is the duration of time (hrs) when rainfall equals the volume of runoff.

$$\textbf{Direct Runoff (mm)} = \frac{\textbf{Total direct flow (m^3/s) * 3600sec/hr * 1000}}{\textbf{Area of basin}(m^2)} \qquad (6.2)$$

This value of Ø was then subtracted from hourly rainfall intensity values. Negative values indicated rainfall intensity less than the infiltration rate and were set to zero (Hjelmefelt and Cassidy, 1975). The volume of rainfall excess was expected to equal the volume of direct runoff as measured if the correct value of Ø was assumed. If not, a new value of Ø was assumed and the process repeated.

Results calculated for infiltration rate as defined by the Ø Index, for Sites 1-4 are presented in Table 6.2.

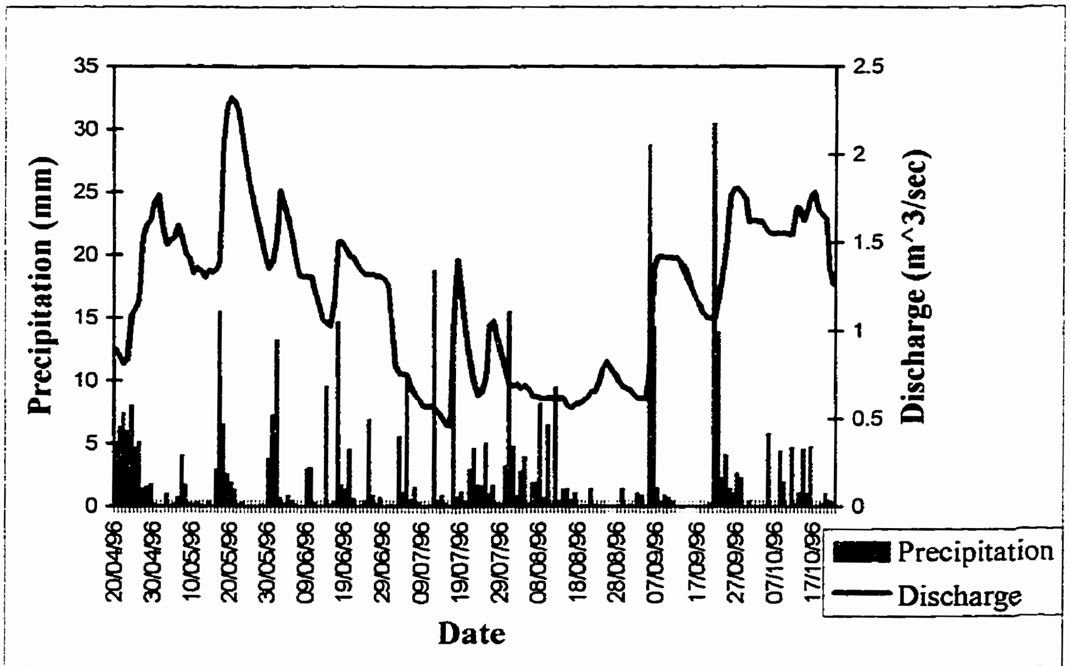


Figure 6.1: Stream Discharge and Rainfall for the Period of Measurement, Site 1.

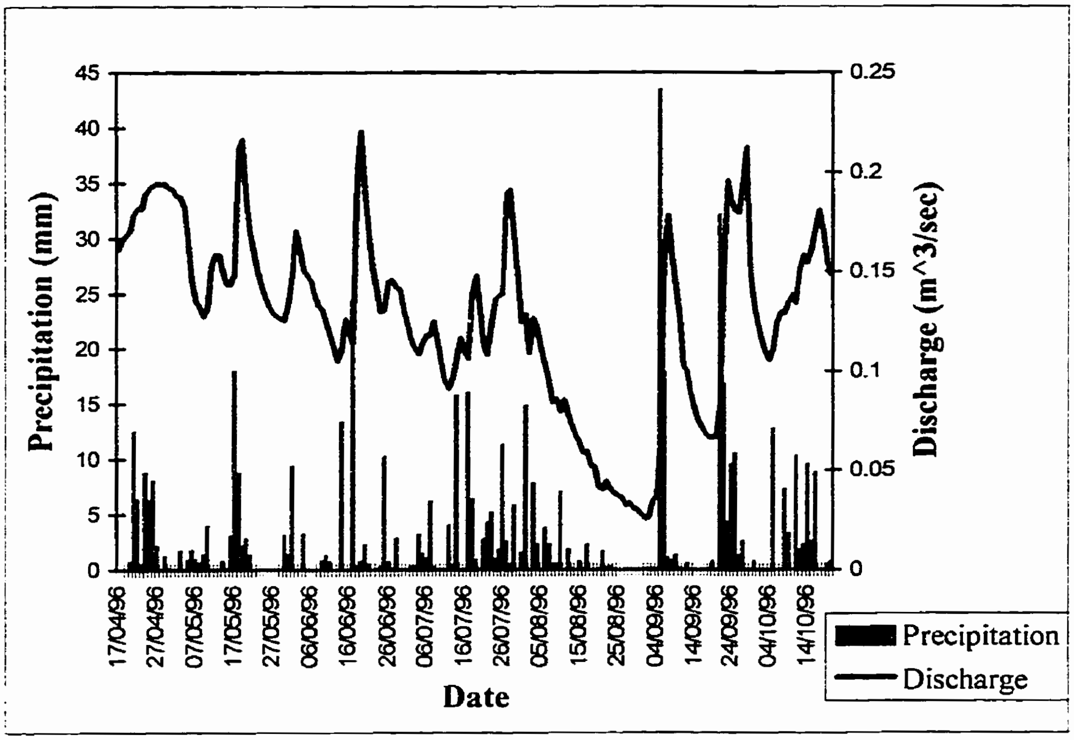


Figure 6.2: Stream Discharge and Rainfall for the Period of Measurement. Site 2.

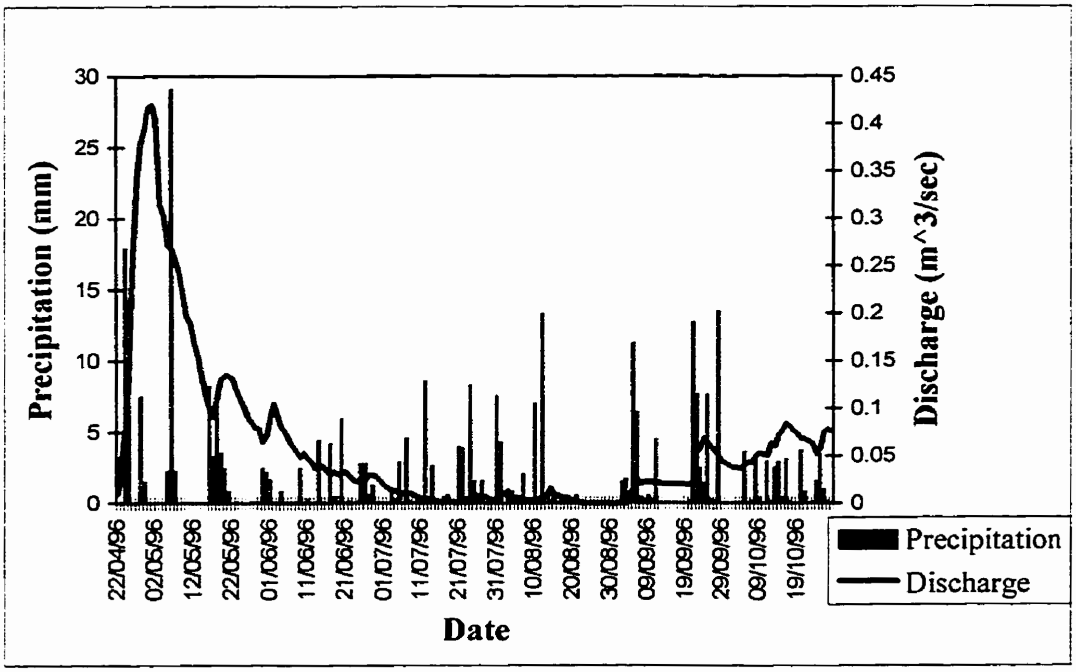


Figure 6.3: Stream Discharge and Rainfall for the Period of Measurement, Site 3.

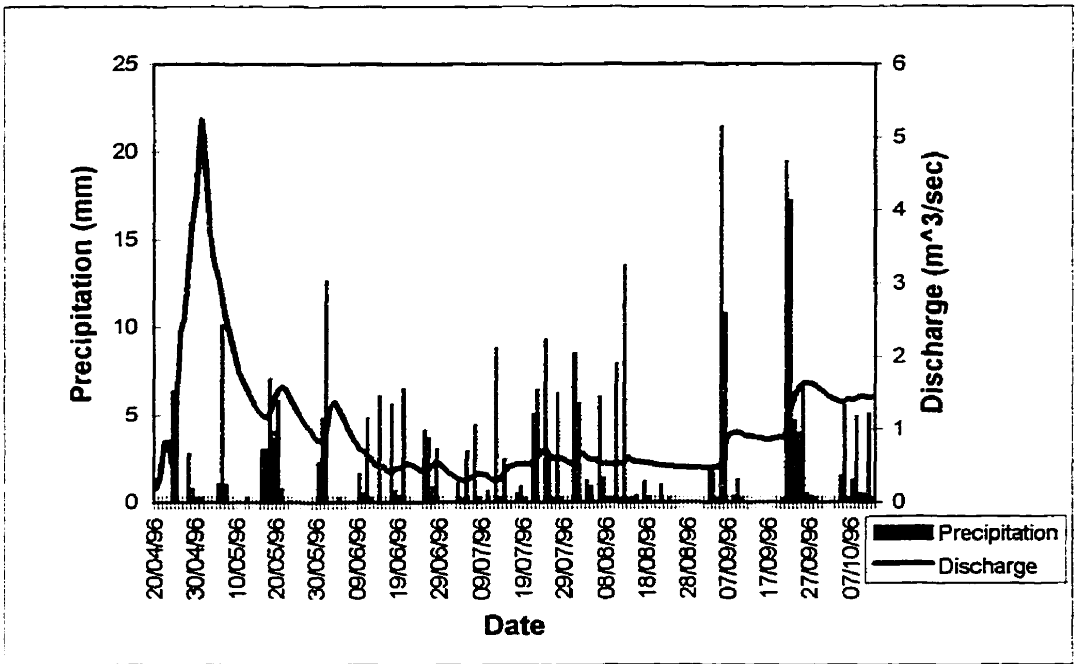


Figure 6.4: Stream Discharge and Rainfall for the Period of Measurement. Site 4.

Table 6.2: Ø Index Results for Spring, Summer and Fall at all Sites.

Site #	Mean Infiltration Rate (mm/hr)		
	Spring	Summer	Fall
Site 1	1.50	5.0	3.66
Site 2	2.10	8.24	6.28
Site 3	0.51	1.35	0.44
Site 4	0.49	1.13	0.65
Averaged IR for Undisturbed Sites	1.80	6.62	4.97
Averaged IR for Burned Sites	0.50	1.24	0.55
Percent Difference between Undisturbed and Burned Sites	110%	137%	160%

In Table 6.2 there is a marked reduction in infiltration rates at burn sites. Two factors which would account for this are vegetation cover and soil properties. From Table 4.3 the undisturbed sites have between 60% and 77% vegetation cover, including deciduous, coniferous and young growth. In contrast the burn sites have only 4.5% and 9.6% of this vegetation remaining, and between 62% and 78% of the land covered by fire disturbance.

The results of infiltration rate analysis show a clear relationship between the amount of vegetation covering the ground surface and the rate at which rainfall infiltrates into the soil when that vegetation is removed.

The second factor is the change to soil structure after fire. Structural alteration of the soil leading to surface sealing of small fines, and chemical change leading to the formation of a hydrophobic layer may also have contributed to reduced infiltration rates at the burn sites. More detailed soil analysis would best quantify this relationship between infiltration and soil structure, and soil chemistry. Reference has been made to studies on soil alterations after fire in Section 3.2 of Chapter Three, on Land Use Change.

As well as distinct differences in infiltration rates between those sites with disturbance and those without there is also a contrast in seasonal values for infiltration rate that is common to all sites. From Table 6.2, infiltration rates at all sites are low in the spring, high in the summer and moderate in the fall. This trend is in keeping with the pattern observed in the hydro-hyetographs in Figures 6.1 through 6.4, where water storage is at a maximum in the spring during the time of snow melt, at deficit in the summer and partially recovered by the fall. Soil water infiltration rates are at their lowest for all sites in the spring; the result of frozen soils that impede water percolation.

Infiltration rates are highest in the summer for all sites, coinciding with lowered baseflows and higher evapotranspiration rates. Although vegetation coverage in the burn sites is still considerably reduced.

Infiltration rates fall in the autumn at all sites. This coincides with rising baseflows at all sites (Figures 6.1 through 6.4) and following with Newson's (1996) results on seasonal infiltration after burning (Section 2.2.2: Infiltration). Differences between infiltration rates at burn and undisturbed sites are still wide, following with the same conditions present in the summer.

The results also indicate a distinct separation of infiltration rates between sites with land use change and those without. This divergence is evident from spring through fall where percentage difference between infiltration rates calculated between burned and non-burned sites over the period of measure ranges from 110% to 160% (from Table 6.2). Averaged infiltration rates for the undisturbed sites, for spring, were calculated at 1.80mm/hr, but in comparison infiltration rates were 0.50mm/hr in the burn sites for the same season. This is a 110% difference between the two types of treatment. The percentage difference increases to 137% in the summer, and to 160% in the fall. One possible cause for this divergence is soil characteristics effected by fire in the burn basins that would reduce infiltration. Giovannini et al., (1987) investigated soils before, immediately after, and up to three years following fire occurrence. They noted two important results. That "three years after the passage of the fire the surficial A1 horizon regained the original organic matter content ... and aggregate stability", and that the "subsurficial B1 and B horizons ... in which the fire had accumulated hydrophobic organic matter, maintained this translocated hydrophobic organic matter quantitatively unaltered during the three years, but they appeared more strongly cemented" (Giovannini et al., 1987). This subsurface layer may have been responsible for continued obstruction of infiltration in the burn basins ever though visual observation did confirm that some vegetation regrowth had occurred.

6.1.2: Runoff

Runoff from storms is that part of the precipitation, as well as any other flow contributions, which appears in streams. It is the flow collected from the drainage basin as surface and subsurface flow, and which appears at the basin outlet. The paths taken by runoff are often determined by the characteristics of soil and landscape within a drainage basin (Chow, 1964; Dunne and Leopold, 1978).

Runoff coefficients were employed as a means of identifying how the basins' landscapes physically responded to rainfall input. Coefficients, previously established for land use types were used as comparisons between forested and burned sites for this study. It was expected that with diminished infiltration rates within the burned basins higher volumes of runoff would be generated, and that these sites would differentiate from the non-burned sites when runoff coefficients were compared.

Runoff coefficients were determined for each of the study sites based on total amount of rainfall received, and total discharge which passed through the basin outlet. Stream discharge (m^3/sec) for each site, was first summed for each site from beginning to end of measurement period, then converted to total amount of discharge in mm (Q_T). Equation 6.3 outlines the derivation of total discharge.

$$Q_T = \frac{\sum Q_C * 3(hrs) * 3600(sec/hr) * 1000(mm/m)}{A\ (m^2)} \qquad (6.3)$$

where: Q_T is the total amount of discharge in mm

$\sum Q_C$ is the sum of discharge taken at 3 hour intervals in m^3/sec

A is the drainage basin area in m^2

Total rainfall (P_T) for the period of measure (mid April to mid October) was also calculated then used in the following equation to provide a runoff coefficient for each site. The equation used in determination of the runoff coefficient follows below. Individual site rainfall and discharge total volumes together with runoff coefficients are outlined in Table 6.3.

$$R_C = Q_T/P_T \qquad (6.4)$$

where: R_C is the runoff coefficient

Q_T is total discharge over the period of measure

P_T is total precipitation over the period of measure

Table 6.3: Runoff Coefficient Values for All Sites.

Site #	Total Rainfall (mm)(P_T)	Total Discharge (mm) (Q_T)	Runoff Coefficient (R_C)
Site 1	383.13	88.87	0.23
Site 2	519.76	106.71	0.21
Site 3	275.75	62.97	0.23
Site 4	319.69	122.96	0.38
Averaged Runoff Coefficient for Non-Burn Sites = 0.22			
Averaged Runoff Coefficient for Burn Sites = 0.31			

Individual and averaged (burn versus undisturbed averages) site runoff values were used to compare land use types. Dunne and Leopold (1978) listed the runoff coefficients expected for a sandy soil in a forested area at 0.10 to 0.15. Higher values for runoff coefficients were found by Dunne and Leopold (1978) to be indicative of soils that have a shallow impeding horizon, or soil textures that have lowered infiltration capacities, i.e. higher loam or clay content. Those coefficient values that were found in the lower range for vegetated areas were expected to have sandy soils or soils with structure that promoted water movement. All sites in the research have been identified as having large proportions of sandy soils. From Table 6.3 runoff coefficients for all sites range from 0.21 to 0.38. These values are higher than other researcher's findings, but of no surprise, because it is expected that high water tables associated with fen and bogs would contribute to increased runoff coefficients in these locations.

Runoff coefficients for Sites 1 and 2 are 0.23 and 0.21 respectively. Sites 3 and 4 have coefficients of 0.23 and 0.38 respectively. The low runoff coefficient at Site 3 may be explained by the lower drainage density at Site 3 relative to Site 4. When the averages are calculated for the two types of basin treatment the burn sites separate more distinctively from the undisturbed sites; non-burned sites have a runoff coefficient of 0.22 whereas the burned sites have a coefficient of 0.31, giving a 17% difference between treatments. Higher runoff coefficients are expected for basins with burn disturbance because here infiltration is lowered by physical and chemical changes that have occurred in the soil, and the reduced effect of vegetation which would otherwise promote infiltration and transpiration. Linsley et al., (1992) found that runoff coefficients for grassed areas ranged from 0.05 - 0.30, and asphalt and concrete pavement coefficients ranging from 0.85 - 1.0. Beasley and Granillo, (1988) found runoff coefficients of 0.21 in clear-cut areas of Arkansas, and Sahin and Hall (1996) found 0.54 for burned scrub in France. Runoff coefficient results for this research clearly indicate that those drainage basins with fire disturbance produce higher volumes of rainfall runoff than those basin with no fire disturbance.

6.2: Stream Discharge and Suspended Sediment Load Relationship

Because previous studies have shown that SSL is closely related to stream discharge (Q) (Knighton, 1984; Meade et al., 1990), it was anticipated in this study that changes in discharge resulting from land use would also be reflected in levels of SSL. Suspended sediment load analysis required the determination of timing of peak sediment concentrations in relation to discharge, the construction of sediment-discharge rating curves to help determine SSL over the period of measure, and the measurement of the strength of association between Q and SSL, at both the undisturbed and burned sites.

The following figures were developed from concurrent measurements taken for SSL and Q. They demonstrate the association between the between SSL and Q, and provide an initial overview of seasonal trends for both parameters.

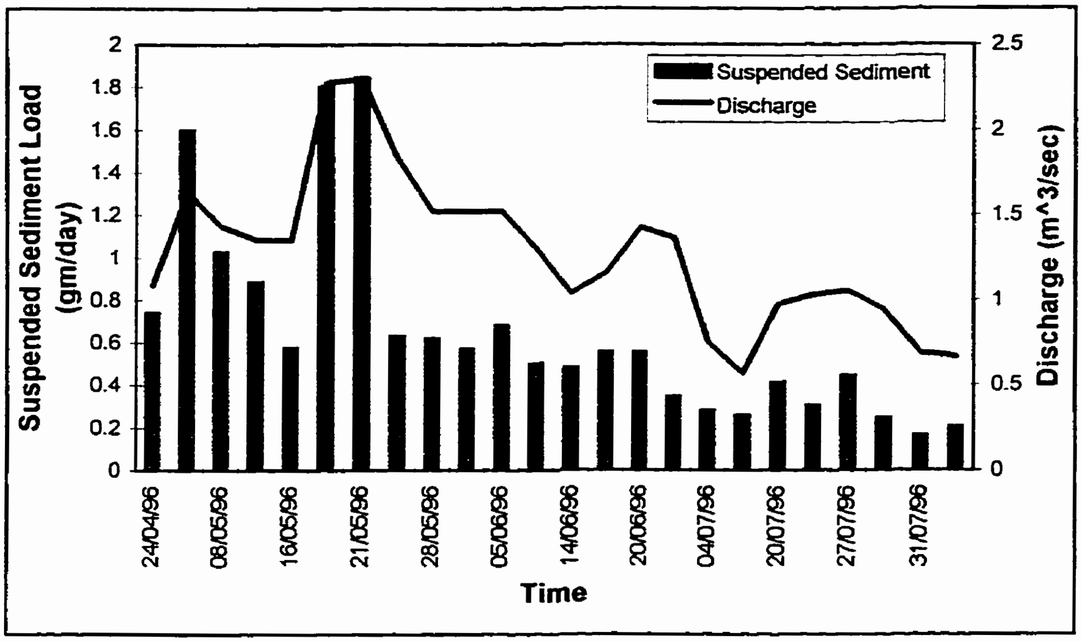


Figure 6.5: Suspended Sediment Load and Discharge Relationship for Site 1.

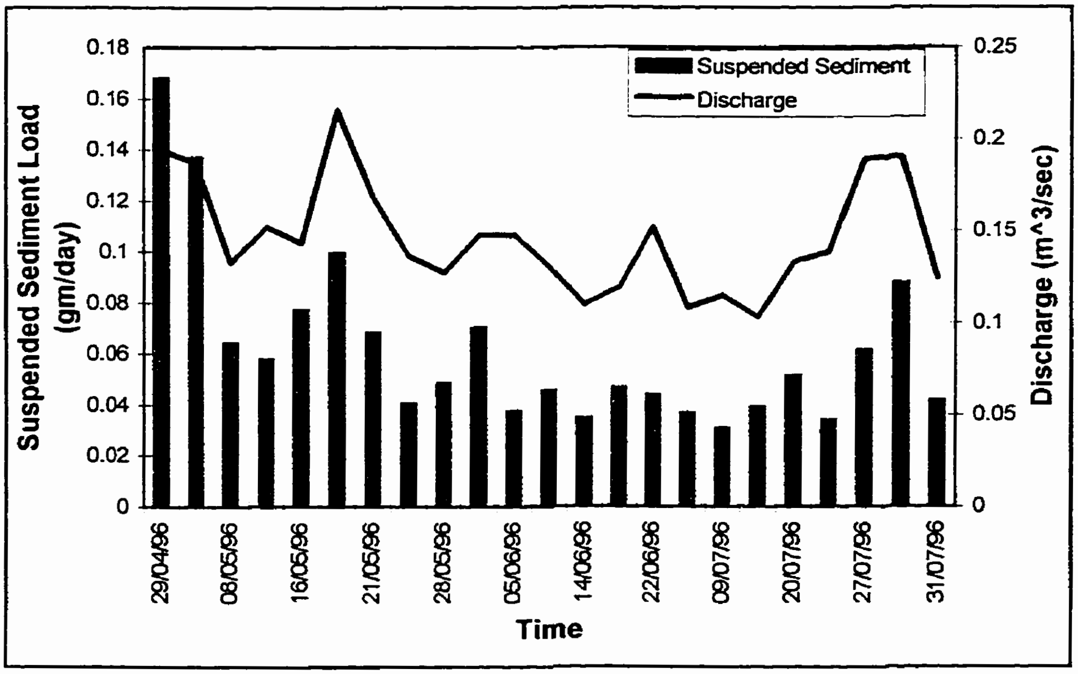


Figure 6.6: Suspended Sediment Load and Discharge Relationship for Site 2.

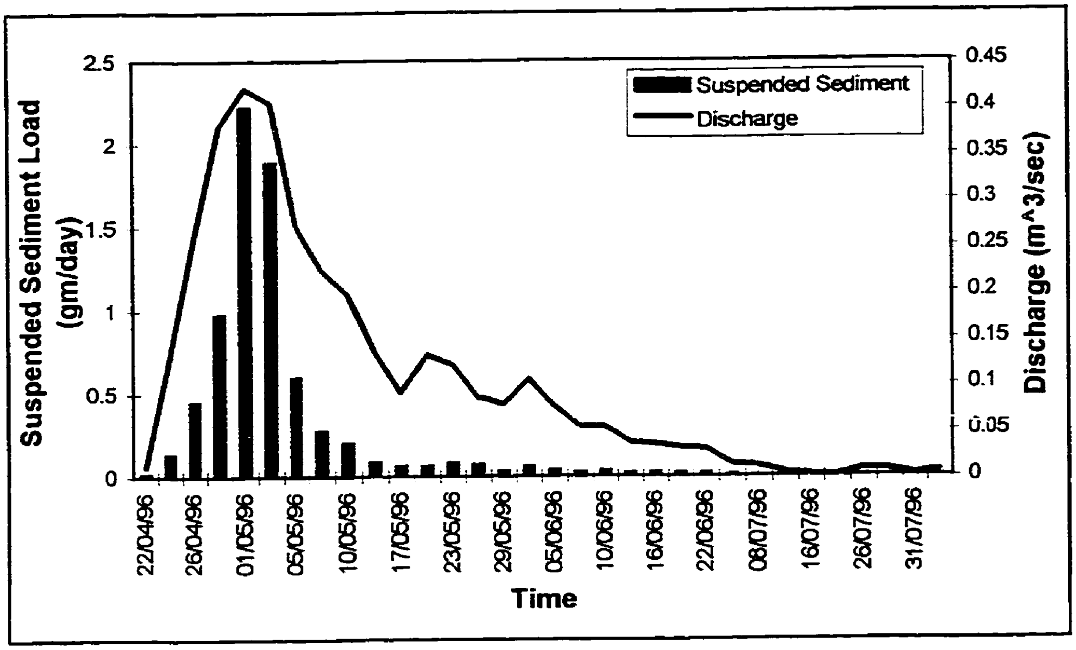


Figure 6.7: Suspended Sediment Load and Discharge Relationship for Site 3.

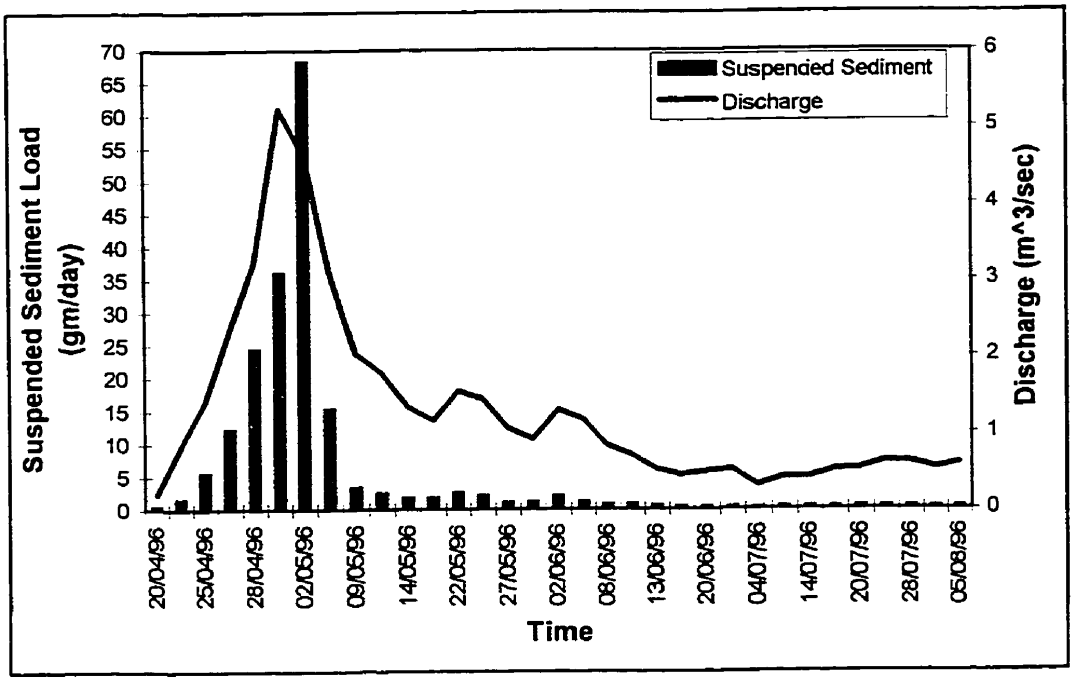


Figure 6.8: Suspended Sediment Load and Discharge Relationship for Site 4.

When Figures 6.5 through 6.8 are examined a close relationship is observed between SSL and Q at all sites.

Two separate, but distinctive peaks of SSL and Q occur at Site 1 (Figure 6.5) and Site 2 (Figure 6.6) for two different discharge events in the beginning of the season. The initial peaks are associated with an earlier, but temporary spring thaw, whereas the second peaks coincide with a longer warming period and a more significant melting of the snow pack, and consequent peak spring discharge event. Lesser, but still noticeable peaks in SSL are associated with smaller discharge events throughout the remainder of the season at this site.

The most significant peak in SSL at Site 2 (Figure 6.6) is found with the first measurement of SSL in the spring. Also, following with Site 1 this site shows similar, lesser SSL peaks during the remainder of the season which are still visibly synchronous with rises in Q for rainfall events.

The burn sites, 3 and 4 (Figures 6.7 and 6.8), both show a significant relationship between SSL and Q. Both sites experience the highest volumes of SSL at the time of peak spring discharge associated with spring snow melt. For the remainder of the summer and into fall very small concentrations of SSL are found in the stream at the basin outlet, and only small rises in SSL are visibly associated with peaks in discharge over the remaining period of measure. Further, more detailed analysis of seasonal patterns of SSL and Q is found in Section 5.3.1 Seasonal Comparison of Discharge and Suspended Sediment Loads.

6.2.1: Time Series Analysis

As was previously established suspended sediment concentrations usually increase within the stream coinciding with increasing water discharge, and most stream sediment is transported at or close to the highest water discharges. Because measurements of SSL were taken on average every 2.8 days during the early field work portion of this study it is very likely that actual peak of SSL occurred outside of a measurement time. It is recognized from the literature that peak SSL could have occurred prior to the peak of Q and to physically record this occurrence SSL would need to be measured at closer time frames (Sheppard, 1976). However, it is not the aim of this study to determine the exact timing of SSL in relation to Q but to determine if indeed there is any relationship between the SSL and Q, and to statistically measure and compare the strength of that relationship within the burn and undisturbed sites.

The results from time series analysis were expected to establish on which days of measurement SSL and Q had the closest relationship; the closest coincidence of peaks. These results would then serve as a pre-analysis of timing of when the strongest correlations of regressed data were most likely to occur. Once this was known a sediment-discharge curve could be constructed and a total sediment load could be established for each site, for the complete period of measurement.

Time series analysis, cross correlation was performed for each site. A preliminary step for the cross correlation involved differencing; the replacement of each value of the original series with the difference between adjacent values in the original series. This was done to make sure the two series (SSL and Q) were stationary - that is the mean and variance of each of the series stayed about the same during the series. Figures 6.9 through 6.12 present the correlograms for each of the sites.

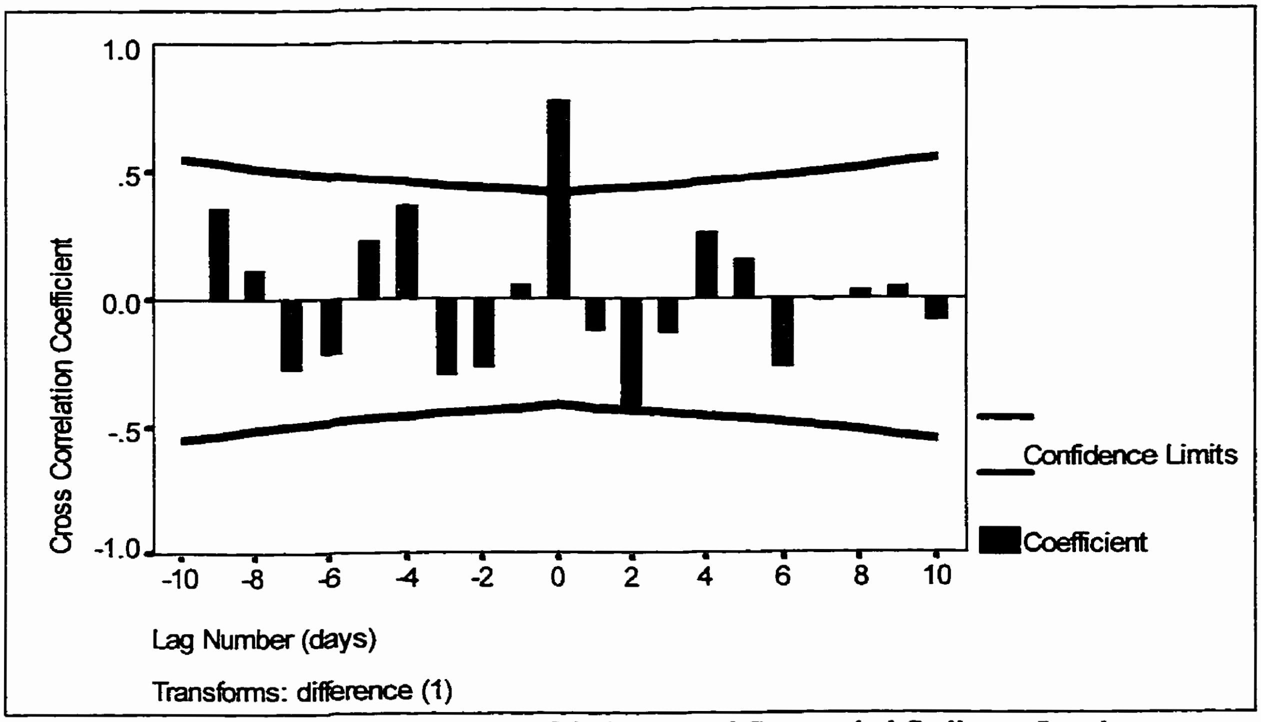


Figure 6.9: Cross Correlation Between Discharge and Suspended Sediment Load for Site 1.

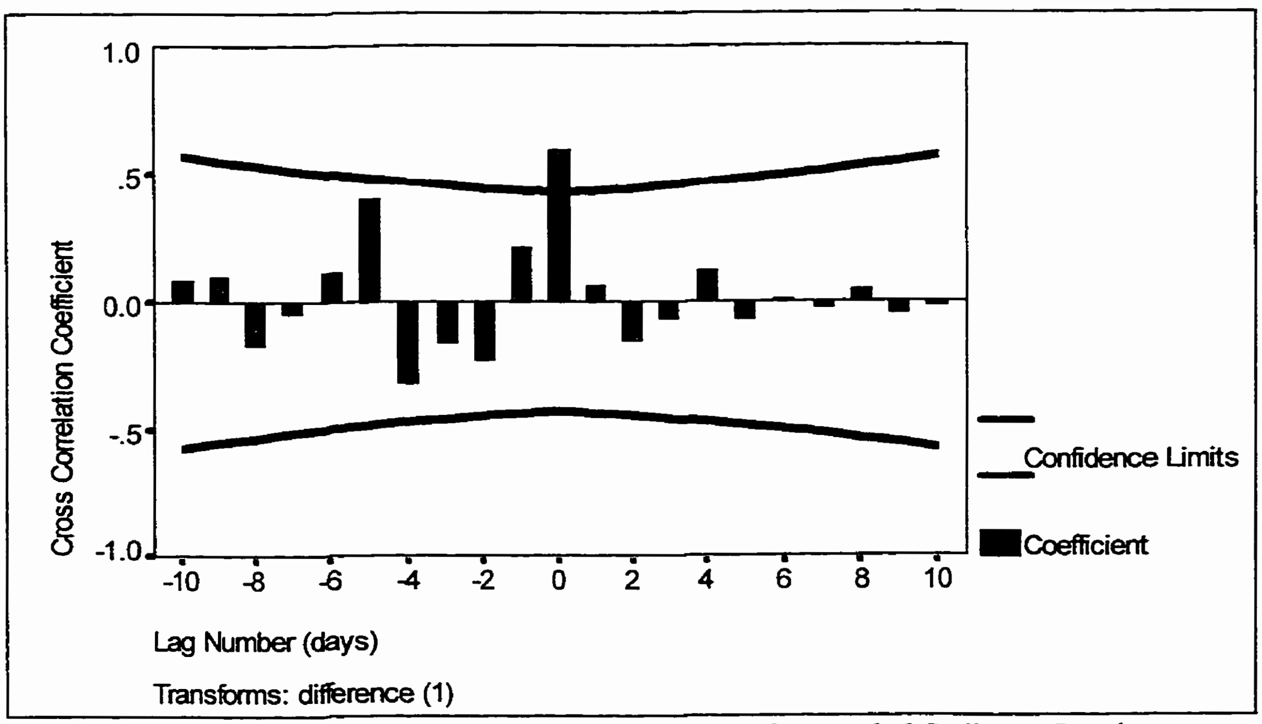


Figure 6.10: Cross Correlation Between Discharge and Suspended Sediment Load for Site 2.

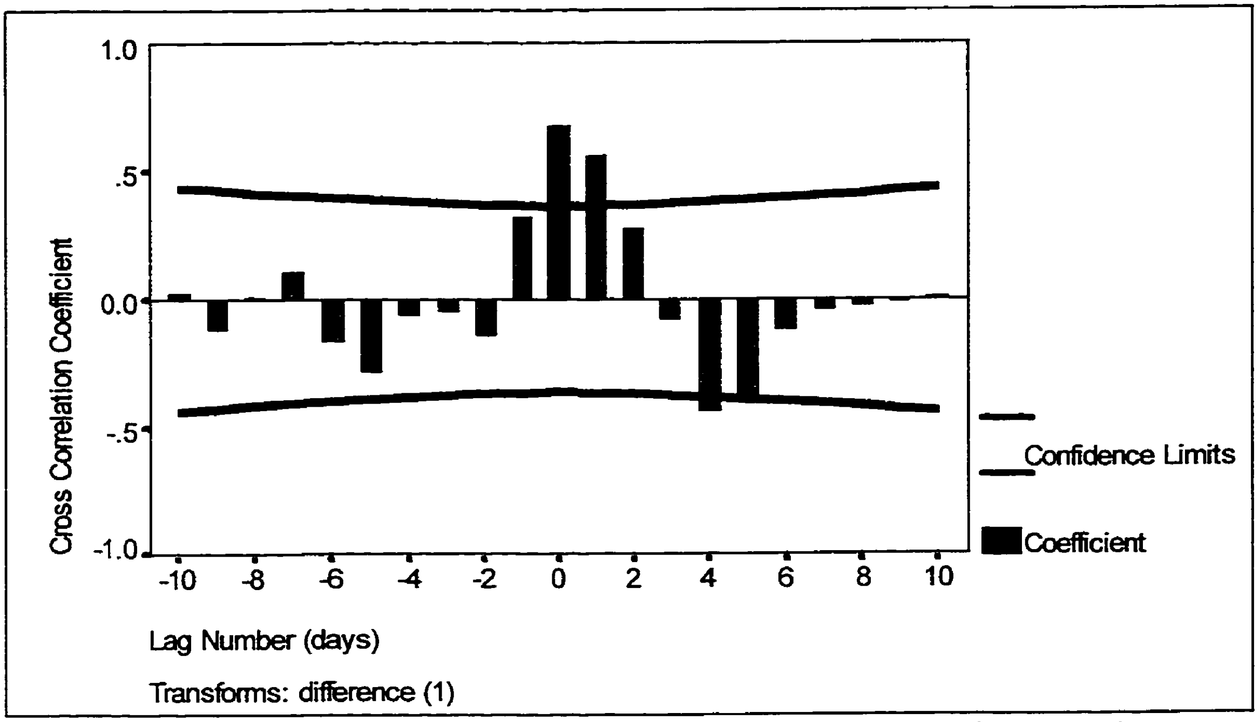


Figure 6.11: Cross Correlation Between Discharge and Suspended Sediment Load for Site 3.

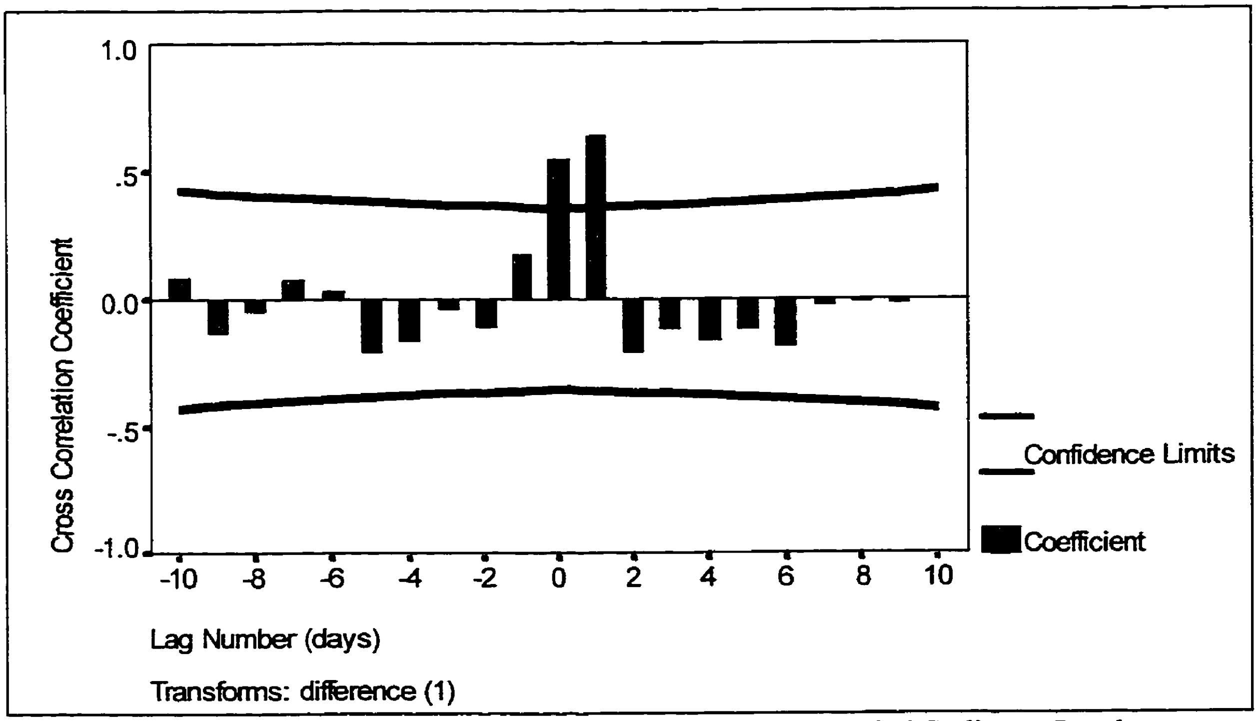


Figure 6.12: Cross Correlation Between Discharge and Suspended Sediment Load for Site 4.

The results of the cross correlation are located in Table 6.4. Ten successive comparisons, or lags (both positive and negative) were made. Negative lags indicate that the second series (suspended sediment load) is the leading indicator, or the predictor of discharge. Positive lags indicate that the first series (discharge) is the predictor, or leading indicator. Zero lag indicates that the correlation is for the two series when neither one is lagged (Norusis, 1993).

Table 6.4: Results of Cross Correlations for Sites 1 to 4. Lag time is one day. Highest Cross Correlation Coefficients for each Site are marked in bold.

Site #	Lag Time (days)									
	-5	-4	-3	-2	-1	0	1	2	3	4	5
Site 1	0.23	0.36	-0.29	-0.27	0.06	**0.78**	-0.12	-0.42	-0.13	0.26	0.15
Site 2	0.40	-0.32	-0.16	-0.23	0.22	**0.59**	0.06	-0.15	-0.07	0.12	-0.06
Site 3	-0.28	-0.06	-0.05	-0.14	0.32	**0.67**	**0.57**	0.27	-0.08	-0.43	-0.38
Site 4	-0.21	-0.16	-0.04	-0.11	0.17	**0.55**	**0.64**	-0.21	-0.11	-0.16	-0.11

From Figures 6.9 and 6.12, and from Table 6.4 a strong relationship exists between SSL and Q at the undisturbed sites with R^2 values of 0.78 and 0.59 respectively, at zero days of lag. No relationship exists at -1 day and +1 days of lag. The above results from time series analysis for sites without burn disturbance allowed for regression analysis at zero lag.

At Site 3 SSL and Q also have a strong relationship at zero days of lag where the R^2 value is 0.67, but also show a strong relationship at +1 day lag ($R^2 = 0.57$). For Site 4 a slightly stronger correlation of 0.64 exists at +1 day of lag, compared with 0.55 at zero lag. Based on the small difference between the two R^2 values at the two burn sites, and from previous research that shows SSL is more likely to peak prior to discharge peak than after, it was decided to proceed with the regression analysis for these two sites at the zero days of lag, when the SSL was actually measured in conjunction with discharge.

Cross correlation results in Table 6.4 reveal an important shift in timing of SSL with Q. The undisturbed sites have a defined period, at zero day lag, when peak SSL occurs with Q. In comparison the burn sites have a strong correlation between SSL and Q over a longer period of time. Suspended sediment loads carried from the burned basins tend to be carried from the basin not just at peak Q, but also prior to and following the peak storm event. In particular, the smaller of the two burn basins has the strongest correlations over the other burn site, at -1 and +2 days of lag, indicating that removal of SSL from this basin began earlier and finished later in the storm event. One explanation would be that because this basin is small in relation to Site 4 storm distribution patterns would be more uniform, spatially and temporally, leading to more complete rainfall coverage and more efficient removal of sediment into stream channels. This situation would be of greater importance during summer months when high intensity convective rainfall patterns predominated. The combined results for the two burned basins indicate that basins with large areas of burn disturbance are more likely to exhibit instability in SSL concentrations when storm events occur. This condition would be expected to stabilize with increased vegetation and infiltration rates.

6.2.2: Data Transformation

Sediment-rating curves relating SSL and Q were constructed for all four sites and inspected for linearity. The coefficient of correlation was then used to measure the strength of the linear relationship between these two variables. Initial curves for all sites showed poor association. Further to this the residual plots with e_i (residual) versus x_i (predicted) appeared heteroscedastic in all four plots. The decision was made to transform SSL and Q logarithmically, to improve the linear relationship between these variables. Following this the data was checked for outliers. Deviations from true values that represented random errors resulting perhaps from turbulent fluctuations in streamflow and sediment transport were removed. The sediment data was then analyzed for relative frequency distribution to fill the requirement of regression analysis that the deviations of the dependent variable about the regression line are normally distributed. "When you transform the dependent variable, its distribution is changed. This new distribution must satisfy the assumption of the analysis" (Norusis 1993). Histograms of log suspended sediment were constructed, and distribution means and standard deviations were calculated as a check for normal distribution.

6.2.3: Suspended Sediment Load Rating Curves

Scatter plots for variables SSL and Q at each site were developed and regression analysis was performed between the dependent variable SSL and the independent variable Q. The reliability of the regression was measured by the standard error, and the strength of the association between the two variables was measured by the correlation coefficient. The confidence interval was set at 95%. The F-Ratio was used to estimate the variability within the individual groups, and variability between groups by using the mean square (the estimate of the average variability within discharge and suspended sediment load). The F-Ratio was used as test for linear relationship. The null hypothesis was that there was no linear relationship between the two variables Q and SSL. F is the ratio of the mean square for regression to the mean square of the residual. If there was a linear relationship the variability estimate based on the regression will be much larger than the estimate of variability based on the residuals: i.e., large F values suggest that there is a linear relationship between the two variables. In all cases the F-Ratios were larger than the observed significance levels, so the null hypotheses were rejected (Tabachnick and Fidell, 1996).

Scatter plots for the variables along with lines of best fit are found in Figures 6.13 through 6.16. Equations developed from regression, along with correlation coefficient and standard error are found in Table 6.5.

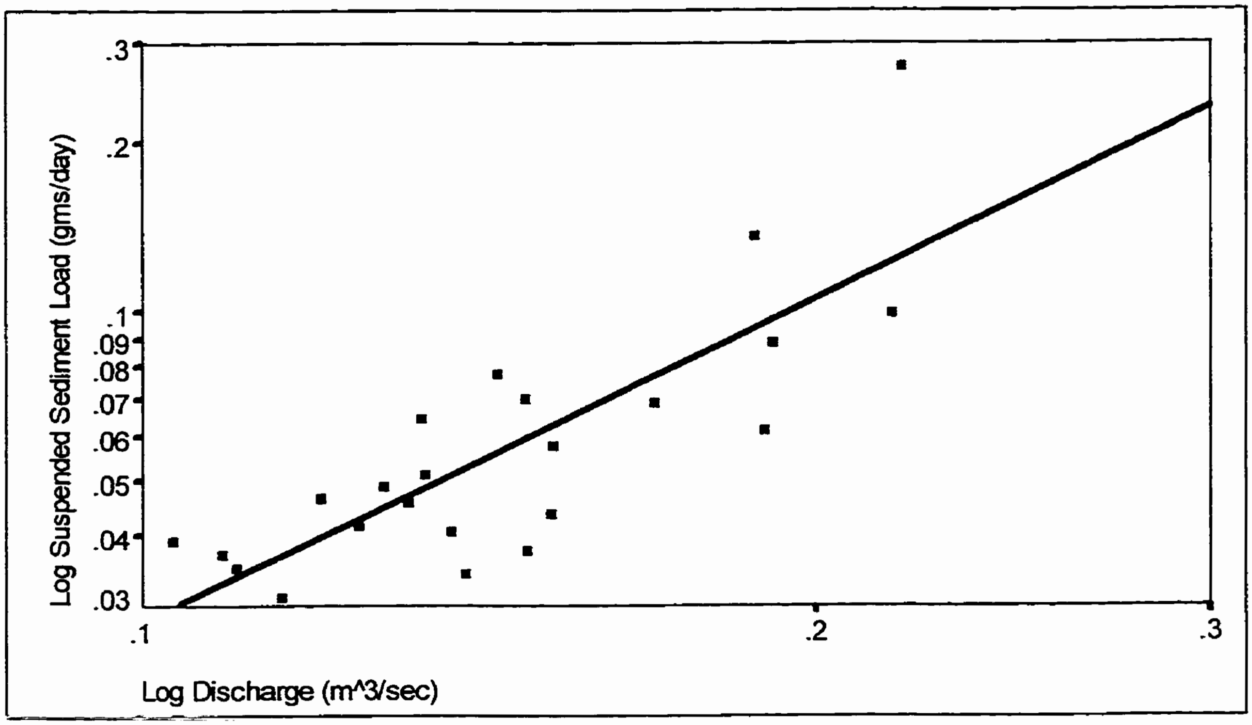


Figure 6.13: Suspended Sediment Concentration and Discharge Relationship for Site 1.

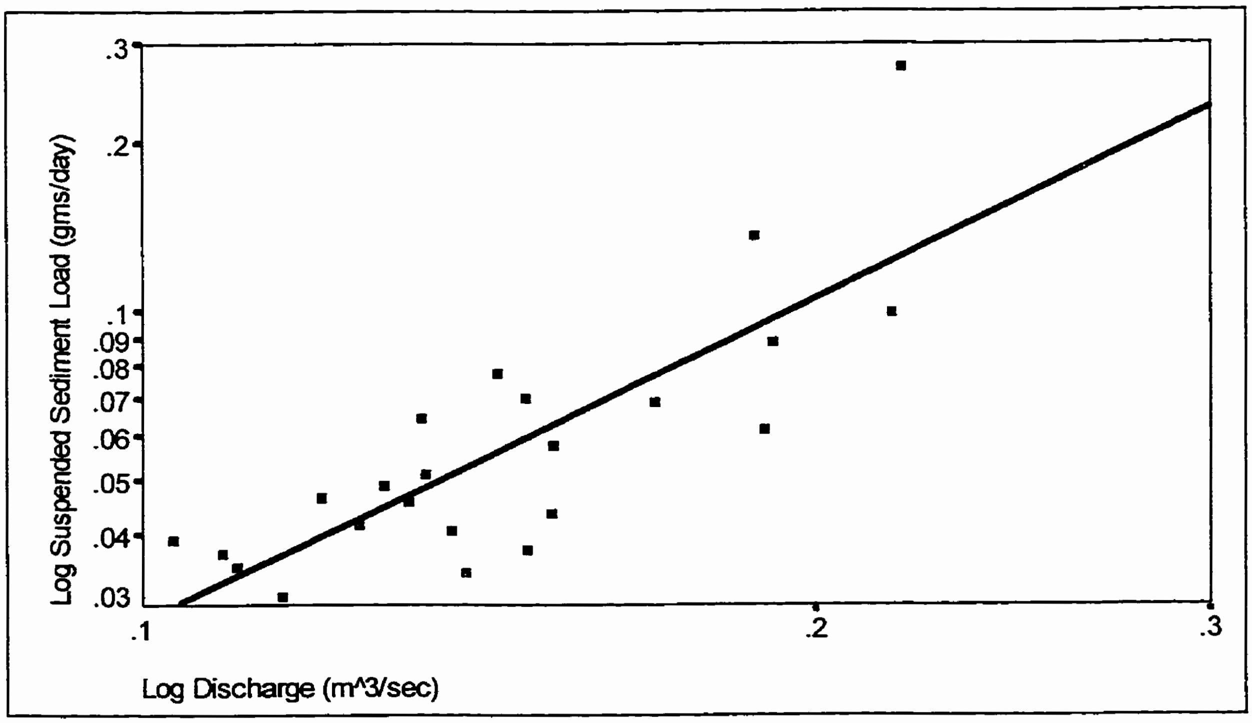


Figure 6.14: Suspended Sediment Concentration and Discharge Relationship for Site 2.

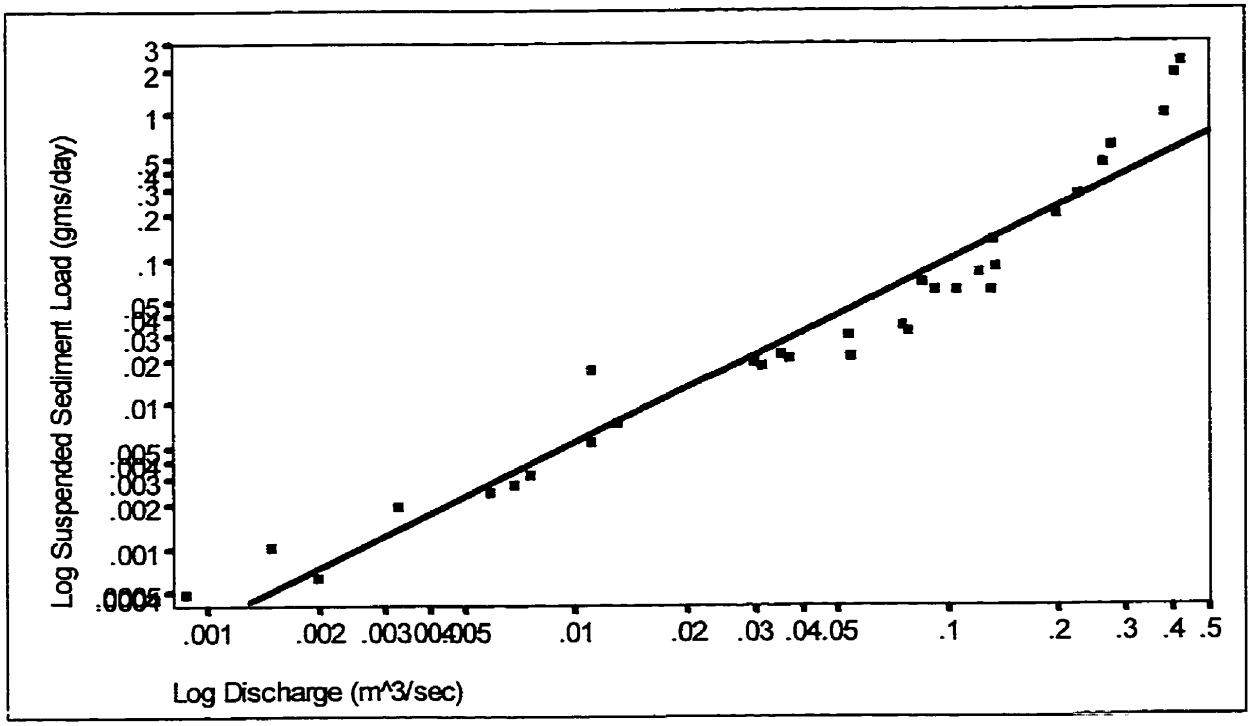


Figure 6.15: Suspended Sediment Concentration and Discharge Relationship for Site 3.

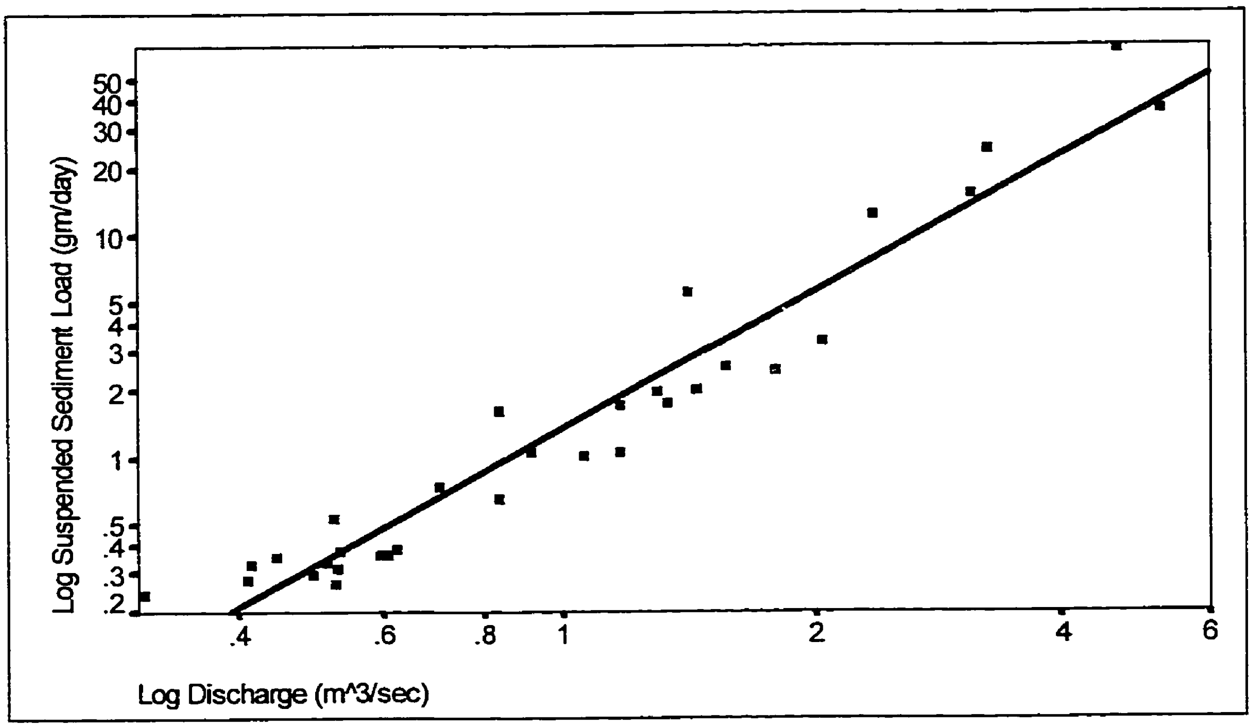


Figure 6.16: Suspended Sediment Concentration and Discharge Relationship for Site 4.

Table 6.5: Correlation and Regression Analysis Results for All Sites.

Site #	Equations for Determining log SSL	Coefficient of Determination (R^2)(%)	Standard Error (gm/day)
Site 1	log SSL = 1.5401 log Q - 0.3997	74	0.14
Site 2	log SSL = 1.9282 log Q + 0.3741	65	0.13
Site 3	log SSL = 1.2419 log Q + 0.2219	94	0.25
Site 4	log SSL = 1.8662 log Q + 0.1562	89	0.23

Results from regression analysis in Table 6.5 indicate a significant relationship is found between SSL and Q at the burn sites. This is based on results from the F-Ratio at a confidence interval of 95%. Site 3 has an R^2 value of 94% and Site 4 has an R^2 value of 89%. In comparison the undisturbed sites do not have as strong a relationship between the Q and SSL. Again, from Table 6.5 coefficients of determination for Sites 1 and 2 are 74% and 69% respectively, where a 1.0m^3/sec log unit rise in discharge at Site 1 is equaled with a 1.54 gm/day (ten-fold) increase in SSL, and a 1.0m^3/sec rise in discharge at Site 2 is equaled with a 5.54gm/day (ten-fold) increase in SSL.

The final analysis of SSL and Q required the use of the sediment-discharge rating curves developed in Figures 6.13 through 6.16 and their respective regression equations (Table 6.5) to find those values for SSL when measurements were not taken. Predicted SSL values were then retransformed by antilog.

To compare how much sediment was carried from the burn sites versus the undisturbed sites ratios of SSL to Q were calculated for each site. Total SSL (gms/day) was determined from the predicted values of daily average SSL, along with known daily average discharge (m^3/sec) for all sites, from beginning to end of measurement period. The results of these calculations are found in Table 6.6 and are given as ratios of SSL to Q.

Table 6.6: Ratio of Suspended Sediment Load to Discharge.

Site #	Total Q (m^3/sec)	Total SSL (gms/day)	Ratio SSL to Q
Site 1	1763.40	818.38	0.46
Site 2	246.97	155.74	0.63
Site 3	92.35	95.39	1.03
Site 4	1403.83	3407.99	2.43
Averaged Ratios for Undisturbed Basins			0.55
Averaged Ratios for Burned Basins			1.73

When all sites are compared in Table 6.6 there is a distinct separation between sites that have no disturbance treatment and those which have. Site 4 has the highest concentration of SSL to Q at 2.43, with Site 3 closely behind at 1.03. The undisturbed sites have a much lower suspended sediment load to discharge volume; with 0.46 for Site 1 and 0.63 for Site 2. When averaged ratios for each type of land treatment are compared the burn sites have three times the amount of SSL to Q over the non-burned sites. The results indicate that the amount of suspended sediment load to discharge volume is highest in those sites where disturbance from burning occurred.

The results clearly indicate that suspended sediment load sensitivity increases with disturbance. This has been shown graphically by the relationship between SSL and Q (Figures 6.5 - 6.8) where sediment loads are more closely linked to rises in the discharge hydrograph at the sites with disturbance; also, through scatterplots and regression analysis (Figures 6.13 - 6.16) where points about the lines of best fit are less scattered at the burn sites than at the undisturbed; by statistical analysis (Table 6.5), where coefficients of determination are more significant at the disturbed sites; and by ratios between SSL and Q (Table 6.6) which indicate that higher volumes of SSL are associated with Q in those streams that exit burned basins.

6.3: Multiple Regression Analysis

As previously indicated the results of land use change within drainage basins are often manifested in the SSL response in streams exciting drainage basins. Multiple regression was used to statistically measure SSL response in this study.

In this analysis average suspended sediment load density per drainage basin area (SLD) was used as the dependent variable. The four independent, predictor variables selected were:

- total discharge per drainage basin area (TQ),
- ratio of burn to total basin area (B),
- average basin slope (S),
- average infiltration capacity (IR).

Calculations for determining the values of the independent and dependent variables are found in Chapter 5; Equations 5.9 through 5.13. The regression equation used for this model is located in Chapter 5, Equation 5.8.

Two objectives were sought through the use of multiple regression in this project. The first was to build a correlation matrix that would outline relationships between all variables and the independent variable for burn. Analysis of the correlation matrix would determine if the percentage of burn at the burn sites closely related to the physical properties of infiltration and slope, and the hydrologic factors of total discharge and sediment load (dependent variable). Results are located in the correlation matrix (Appendix E). These results indicate that burn ratio is indeed significantly related to suspended sediment load density, bifurcation ratio, and infiltration capacity; and is strongly related to slope. A very weak relationship exists between burn ratio and total discharge volume (see Table 6.4).

The second objective required the analysis of relationship between the dependent variable (SLD) and independent variables. Stepwise multiple regression was performed. The independent variable burn ratio (B) was the only independent variable accepted in the regression with an R^2 value of 97%. When each of infiltration rate (IF), and slope (S) were added to the equation using Enter Method their contributions to were less than 2%. The F-Ratio for the analysis was calculated at 71.36. This value was smaller than the critical F value, so the null hypothesis was accepted: there was no linear relationship between SLD and B. These results determined that a significant relationship could not be statistically established between the amount of suspended sediment load carried from drainage basins and the amount of burn coverage in those basins. The reason for the small F-Ratio was the number of values entered for each of the variables. Because only 4 drainage basins were analyzed, four values were compiled for each of the variables SLD and B. The small number of cases violated the analysis and was insufficient to use as a model as a reliable predictor of SLD. The results do suggest that the proportion of burn area within a basin does have a marked effect on suspended sediment loads and that this variable alone can be used to indicate SLD for basins with similar physical features and hydrologic characteristics.

6.4: Drainage Basin Hydrograph Analysis

6.4.1: Seasonal Comparison of Discharge and Suspended Sediment Loads

Discharge hydrographs from spring snowmelt runoff to freeze-up in the fall were graphed (Figures 6.1 through 6.4) and used to identify similarities in response to seasonal fluctuations in rainfall input, basin evapotranspiration, and runoff outputs. Similar trends in hydrograph shape were observed for all sites, where discharge is high in the spring, low during the summer months and rises again in the fall. Further discussion on these trends is found in Chapter Seven.

Ratios of average discharge and average suspended sediment load were used to compare drainage basin response to storm events. Daily average discharges were averaged for early season and mid-late season at each site. A ratio was then taken between the two seasonal discharge averages for each site. From Figures 6.5 through 6.8, and from results in Table 6.7 a marked difference occurs between those sites with fire treatment, and those without.

Table 6.7: Seasonal Discharge and Suspended Sediment Load Ratios

Site #	Ratio of Early Season Discharge to Mid-Late Season Discharge	Ratio of Early Season SSL to Mid-Late Season SSL
Site 1	1.49	1.73
Site 2	1.87	1.48
Site 3	8.39	14.19
Site 4	7.58	7.56
Averaged Values for Undisturbed Sites	1.68	1.61
Averaged Values for Burn Sites	7.99	10.88

Table 6.8: Percent Differences in Seasonal Discharge and Suspended Sediment Load (SSL) Between Burned and Non-Burned Sites.

Percent Difference in Seasonal Discharge	Percent Difference in SSL
130%	148%

In Table 6.7 Sites 1 and 2 show an average ratio value 1.68 between average discharge in the spring and average discharge in the summer. In comparison Sites 3 and 4 have a relatively higher average ratio value of 7.99 and a more distinct separation between discharges volumes in the spring and summer. The percent difference of seasonal discharge between the two types of treatment is 130% (from Table 6.8). Suspended sediment loads for the four basins were treated in the same manner as discharge values. Results for sediment load indicate similar trends in difference as those for seasonal discharge. Sites 1 and 2 show little separation between daily average SSL for spring and mid-late summer (averaged ratio of 1.61). In contrast, Sites 3 and 4 show a marked difference in daily average SSL output between spring and summer (averaged ratio of 10.88). The percent difference of seasonal suspended sediment load between the two treatments is 148% (from Table 6.8).

Seasonal discharge ratios indicate that non-burned basins produce a steadier water yield over the total period, as outlined by the small separation between averaged discharges. In contrast, burned basins produce a greater divergence, and more tendency for "flashiness" between spring runoff and summer storm. Suggested reasons for the higher discharge peaks at burn sites would be larger snow accumulations as found by Pomeroy (1996) (see Appendix B, Table 1), and higher snow depths and water equivalents as found from snow course measurements taken during this research (see Appendix B, Table 2). In addition reduced vegetation coverage would effect infiltration rates in the early season following fire disturbance.

Suspended sediment load ratios are also more pronounced at the burn sites than the sites with no disturbance. Suggestions for this are: the larger volume of sediment material available on the land immediately after the fire, along stream banks and within the stream that can be eroded and carried from the basin. and the association of higher discharges from the burn basins that increases bank and stream bed scouring and more efficient transportation of suspended materials.

6.4.2: Timing and Volume of Spring Runoff

In the above analysis magnitude of spring runoff is greater in the burn basins than in the non-burned basins. In addition, when discharge graphs are examined in Figures 6.1 through to 6.8 timing of spring runoff is also significantly different between the two types of treated sites. Peak spring runoff occurred during May 17th and May 21st at the sites with no burn disturbance, and between the 30th of April and 3rd of the May at the sites with burn. Overall, an increase in discharge volume and an approximate 2 week advance in spring runoff is identified when burn treatment occurred.

6.4.3: Unit Hydrograph Analysis

Synthetic and composite unit hydrographs were developed for burn and undisturbed sites and used as a baseline to assess hydrologic effects of land use change. It was proposed that discharge volumes determined by the synthetic unit hydrograph, in relation to basin size, could be used to show that each of the four sites would deal with precipitation in a similar manner if left undisturbed. In addition, the two types of hydrograph, synthetic and measured, were expected to be a useful means of comparing discharge parameters within basins and between basins when land use change occurs.

6.4.3.1: Synthetic Unit Hydrograph

Indices for the synthetic hydrograph were determined from basin area, main channel length, and channel length from basin outlet to a point in the channel 90° to the basin centroid for each site. Procedure for hydrograph development was taken from Snyder's Unit Hydrograph, in Linsley et al., (1982). Values for C_t and C_p were taken from Snyder's Unit Hydrograph analysis because formulas for the boreal forest have not yet been established. The following equations were used to derive the indices:

$$t_p = C_t (L\, L_{ca})^{0.3} \tag{6.5}$$

$$Q_{Pk} = \frac{C_p (A)}{tpk} \tag{6.6}$$

$$T = 3 + 3tpk \tag{6.7}$$

where

tp = time lag in hours from center mass of rainstorm to the hydrograph peak

Q_{Pk} = peak rate of discharge in m^3/sec

T = base time in hours

C_t = empirical coefficient accounting for the slope of the drainage basin (1.4 - 1.7 km^2), where lower values correspond with steeper slopes. C_t values of 1.6 were used for all four drainage basins in the study.

L = length of main channel (kms)

L_{ca} = length of channel from outlet to a point in the channel 90^O to the basin centroid (kms)

C_p = empirical coefficient 0.15 - 0.19 and 1mm excess rainfall (runoff), lower values are used when C_t is high. C_p values of 0.16 were used for all drainage basins in the study.

A = basin area (km^2)

tpk = corrected time to peak (hrs)

$$tpk = tp + \frac{(t_R - t_r)}{4} \quad (6.8)$$

where:

t_R = new time of excess rainfall (1 hour)

t_r = old excess rainfall duration in hours (0.18*tp)

(Linsley et al.,1982).

Empirical formulas used to estimate width of hydrograph at 50% (W50) and 75% (W75) of the peak are as follows:

$$W50 = \frac{770\ (A)}{Q_p^{1.08}} \quad (6.9)$$

$$W75 = \frac{440\ (A)}{Q_p^{1.08}} \quad (6.10)$$

Calculations for Q_{Pk}, T, tpk, W50 and W75 were used to graph the hydrograph. from which total discharge volume per unit area was determined for each. One hour synthetic unit hydrographs were developed for all four sites. The basic form of the synthetic unit hydrograph, with applicable indices is found in Figure 6.17. Actual values for drainage basin areas, for total discharge volume (Q_V), discharge at peak of hydrograph (Q_{Pk}), and time of occurrence of hydrograph peak (tpk), for the four sites, are found in Table 6.9. Equation 6.10 gives depth of direct runoff, and accounts for basin size.

$$\text{Depth of Direct Runoff} = \frac{Q_v * 1000\text{mm}}{A(\text{km}^2) * 1{,}000{,}000\text{m}^2} \tag{6.10}$$

where: Q_v is discharge volume in m^3

A is basin area in km^2

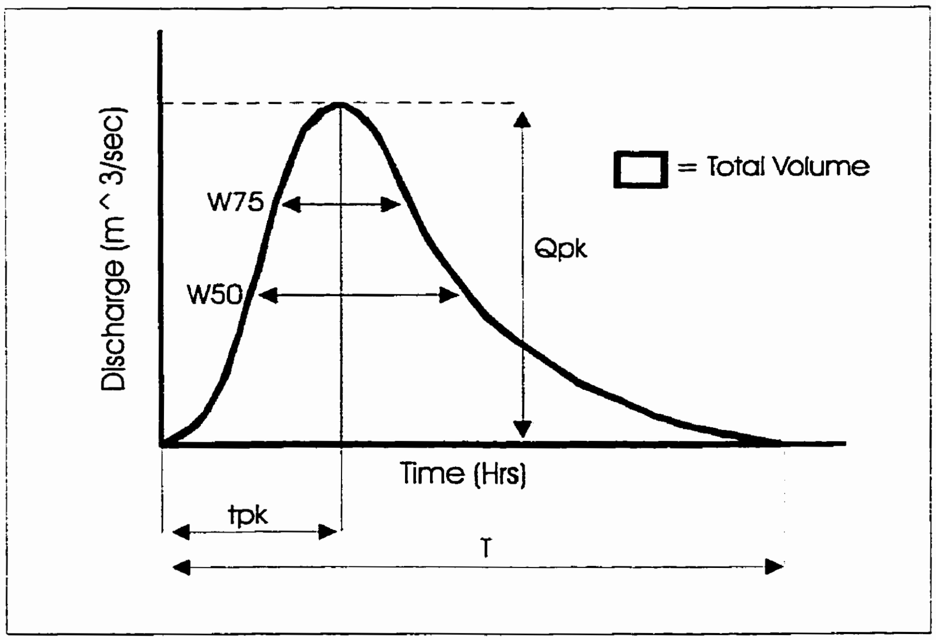


Figure 6.17: Synthetic Unit Hydrograph Form.

Table 6.9: Synthetic Unit Hydrograph Indices for all Sites.

Site #	Area (km^2)	Total Discharge Volume (Q_V) (m^3)	Discharge at Hydrograph Peak (Q_{Pk}) (m^3/sec)	Time to Peak Discharge (tpk) (Hrs)	Depth of Direct Runoff (mm)
Site 1	214.30	173520.00	3.38	10	0.81
Site 2	24.81	24588.00	1.31	3	0.99
Site 3	15.72	15784.83	0.75	3	1.00
Site 4	123.30	101374.26	1.87	11	0.82

From analysis of the synthetic unit hydrographs it is expected that if land use was not accounted for at all sites each drainage basin's response to rainfall input would be dependent on basin size and distance from outlet to centroid. The results indicate that the larger basins produce greater discharge volumes based on larger catchment areas for precipitation. They also produce higher discharge peaks, which pass through basin outlets later than the smaller basins, due to the greater distance from basin perimeter to outlet.

6.4.3.2: Composite Unit Hydrograph

Composite unit hydrographs were developed from discharge measurements for the period and used to explain how each basin responded to precipitation inputs. Composite unit hydrographs accounted for the physical properties within the drainage basins that controlled runoff output, namely soil, vegetation and slope, that were in effect during the time of measurement. These physical properties are accounted for in C_t and C_p in the synthetic unit hydrograph.

Hydro-hyetographs for each of the four sites (Figures 6.1 through 6.4) were used to determine rainfall events that were associated with rises in the discharge hydrograph for the hydrograph analysis. Individual storm events were selected and isolated according to period of rainfall excess.

Hourly discharge rates were compiled, the data was averaged to smooth the hydrographs, then baseflows were separated from direct runoff. Determination of baseflow separation and individual unit hydrograph ordinates was followed from the outline given by Linsely et al., (1982). To separate baseflow a vertical line was drawn from the peak discharge of the hydrograph to time on the x axis. While maintaining the slope of the recession arm of the previous event a line was drawn from the base of the rising limb to the intersect of the peak discharge line then upwards at a reverse slope angle to the intersect of the recession arm. For those events (particularly in the fall) which had only a partial recession arm a continuation line was drawn between existing arm and baseflow line.

Consistency was maintained for separation of all baseflows for all hydrographs. This was in following with Wisler and Brater, (1959) who emphasize that "the actual method of selecting a base line separating surface runoff from ground-water flow is not as important as being consistent in its use." After baseflow was separated the values for direct flow were summed to give total direct flow. The following equation was used to establish direct runoff (Linsley et al., 1982):

$$\textbf{Direct Runoff (mm)} = \frac{\textbf{Total direct flow (m^3/s) * 3600sec/hr * 1000}}{\textbf{Area of basin(m}^2\textbf{)}} \qquad \textbf{(6.11)}$$

The direct runoff value was then divided into individual discharge values to give individual unit hydrograph ordinates (m^3/sec/mm of runoff), and a complete event hydrograph.

Hourly rainfall amounts for each event were compiled and effective rainfall, the duration of rainfall that contributed to the direct runoff from a storm event, was determined using the Ø Index method. This duration of rainfall was then assigned to the individual unit hydrographs for each event.

Because effective rainfall periods for each hydrograph, as determined by the Ø Index, gave varying durations for each event all hydrographs for the basins were brought to a common duration of one hour, using the S Curve method (Summation Curve) (Linsley et al., 1982). The S Curve method allowed the conversion of individual unit hydrographs to shorter durations. An S Curve is constructed by adding together a series of unit hydrographs, each lagged with respect to the preceding one (Linsley et al., 1982 and Singh, 1992). This procedure provided for consistent unit duration of unit hydrographs and enabled a more precise comparison with the previously developed synthetic unit hydrographs for each basin.

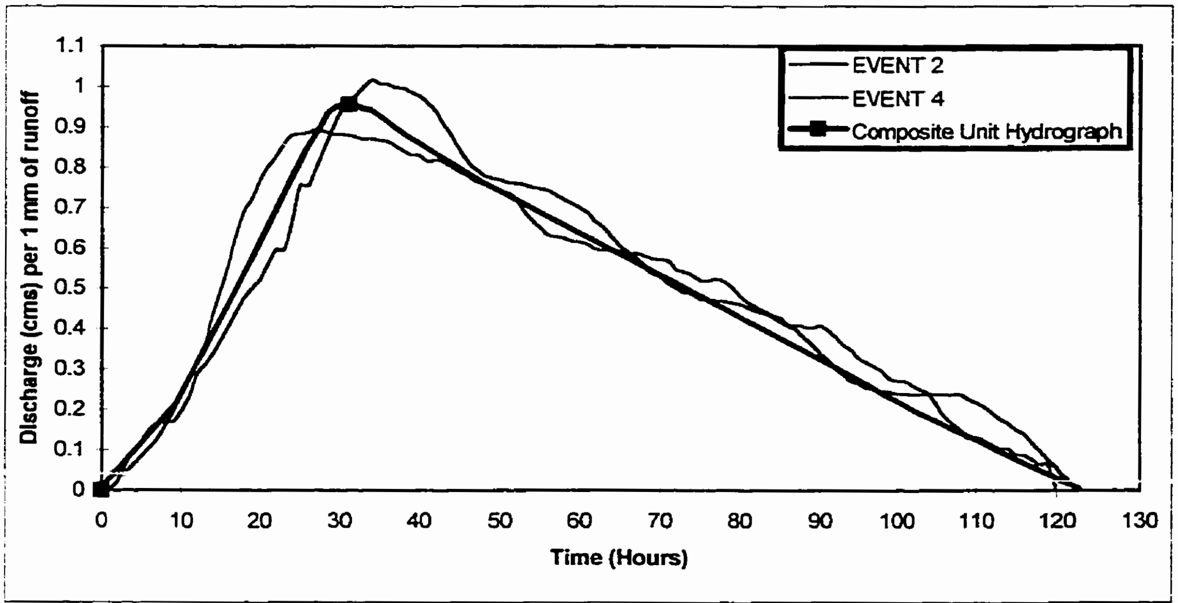


Figure 6.18: Individual Event Hydrographs and Composite Unit Hydrograph for Site 1.

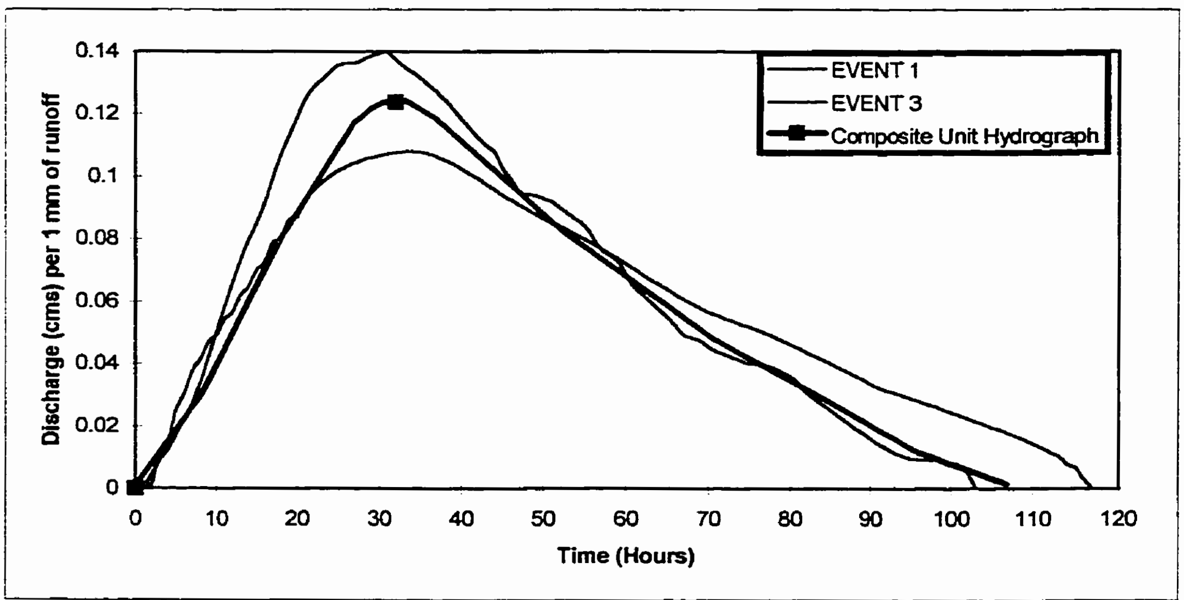


Figure 6.19: Individual Event Hydrographs and Composite Unit Hydrograph for Site 2.

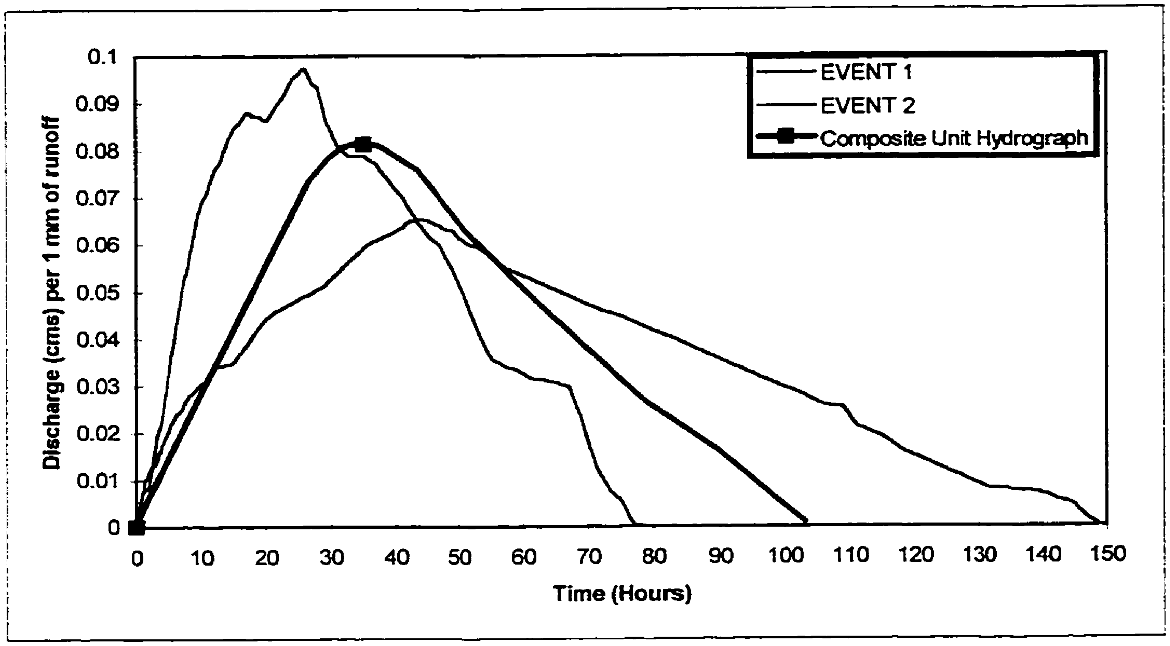


Figure 6.20: Individual Event Hydrographs and Composite Unit Hydrograph for Site 3.

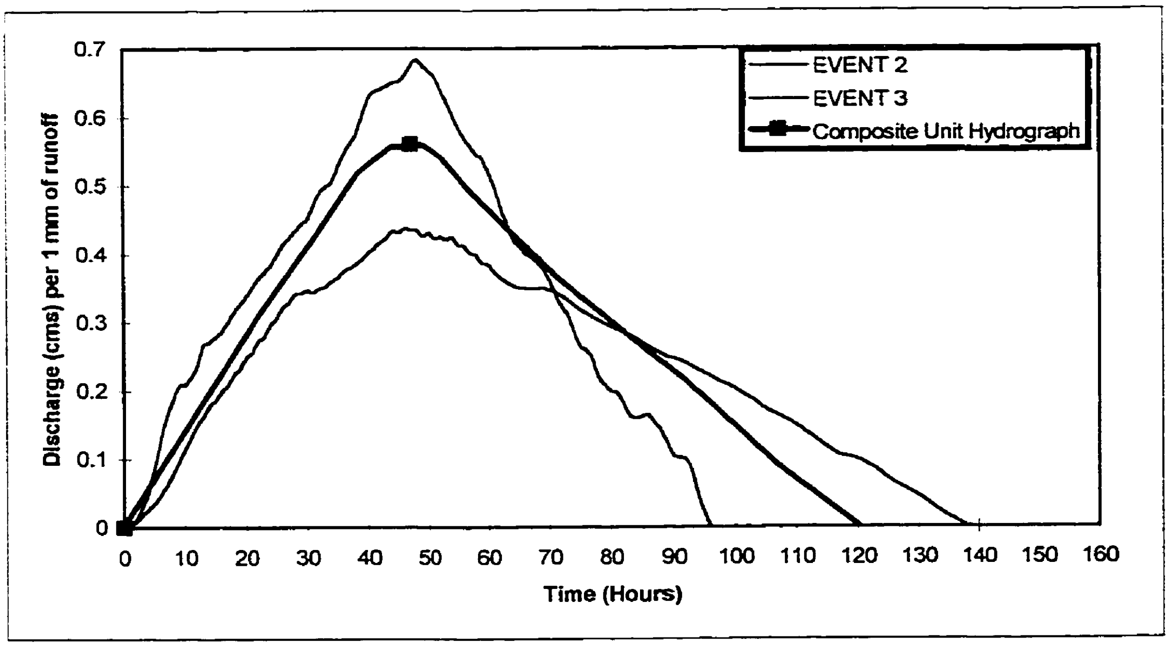


Figure 6.21: Individual Event Hydrographs and Composite Unit Hydrograph for Site 4.

All event hydrographs for a site were then combined using the procedure outlined by Hjelmfelt and Cassidy (1975), Dunne and Leopold (1978), and Linsley et al., (1982). Those hydrographs with double peaks, or that exhibited extreme events were removed. Averages for discharge at peak, and time to peak were taken from individual one hour unit hydrographs for each site, and were superimposed along with hydrograph outlines on Figures 6.18 to 6.21. A composite unit hydrograph was then sketched by freehand, connecting the two averaged points while maintaining an appropriate hydrograph sketch closely matching in form to the individual events. Total volume of discharge (m^3) was then determined for composite unit hydrographs for each site. The three indices: total discharge volume (Q_V), discharge at hydrograph peak (Q_{Pk}), and time to peak discharge (tpk) are found in Table 6.10.

Table 6.10: Composite Unit Hydrograph Indices for All Sites.

Site #	Area (km^2)	Total Discharge Volume (Q_V) (m^3)	Discharge at Hydrograph Peak (Q_{Pk}) (m^3/sec)	Time to Peak Discharge (tpk) (Hrs)	Depth of Direct Runoff (mm)
Site 1	214.30	214451.90	0.95	30	1.00
Site 2	24.81	24754.72	0.12	33	0.99
Site 3	15.72	14720.37	0.08	35	0.94
Site 4	123.30	124687.67	0.56	47	1.00

Results from composite unit hydrograph analysis (Table 6.10) indicate that total discharge values and discharge at hydrograph peak are closely linked to each site's related drainage basin area.

The most surprising result of the composite unit hydrograph analysis appears in the time to peak discharge (tpk) values at the burn sites. Where a shorter duration between initial rise in discharge to the peak of the hydrograph was expected, as a result of reduced infiltration and earlier storm runoff, the opposite scenario occurs. Values for tpk at the burn sites show a distinct departure from results in the literature that have shown that with disturbance time to peak discharge would be foreshortened. There is also a noticeable difference in tpk when the burn and undisturbed sites are compared, and when the two undisturbed sites are compared. Sites 3 and 4 show tpk times of 35 hours and 47 hours respectively, whereas Sites 1 and 2 give tpk times of 30 and 33 hours. When Sites 1 and 2 are compared, Site 2 has a tpk time that is very close to that of Site 1; an unexpected result, given that the drainage area of Site 2 is approximately one eight that of Site 1. The same result occurs when comparing between the two burn sites. Site 3 has a slightly shorter time to peak than that of Site 4 even though Site 3 has one eight the basin area of Site 4. These results may indicate the role played by the significantly large proportion of the drainage basins occupied by areas of wetland (see Site Area and Land Use Ratios, Table 4.2). They may also indicate that excess rainfall may have been used to replenish depressional areas or to reduce water deficit encouraged by higher evaporation rates in burn areas.

6.4.3.3: Results of Synthetic and Composite Unit Hydrograph Analysis

Ratios for synthesized and composite unit hydrographs, for total discharge, time to peak and peak discharge were recorded for all sites and are located in Table 6.11. These ratios represent a mathematical comparison between the two methods of hydrograph analysis. The synthetic unit hydrograph method gives values for the three parameters based on empirical equations established by Snyder, then adopted for the boreal forest basins. The composite unit hydrograph values for the three parameters were based on actual discharge and rainfall values taken from mid April to mid October in 1996 at boreal basin sites.

Table 6.11: Ratios (Synthetic Unit Hydrograph / Unit Hydrograph) for Total Discharge (Q_T), Discharge at Peak of Hydrograph (Q_{Pk}), and Time to Peak Discharge (tpk), for all Sites.

Site #	Basin Area (km^2)	Ratio of Total Discharge (Q_T) (m^3) (UH/SUH)	Ratio of Discharge at Hydrograph Peak (Q_{Pk}) (m^3/sec)	Time to Peak Discharge (tpk) (Hrs) (SUH/UH)	Depth of Direct Runoff (mm) (UH/SUH)
Site 1	214.30	1.24	0.28	0.33	1.23
Site 2	24.81	1.01	0.09	0.09	1.00
Site 3	15.72	0.93	0.11	0.09	0.94
Site 4	123.30	1.23	0.30	0.23	1.22

The following results emerge when the ratios of the three measured indices from observed and synthesized hydrographs are compiled. From Table 6.11 ratios for total discharge from synthetic and composite unit hydrographs show close similarity for all sites. Closer inspection of the results show that the ratios increase with drainage basin size. The smaller basins, Sites 2 and 3 are more closely matched between the two hydrograph analyses, whereas the larger sites, Sites 1 and 4 have larger discharge volumes exiting the drainage basins when the composite unit hydrograph method is used (i.e., when land use, soils, slope etc., are taken into account).

Comparisons of ratios for timing of discharge to peak of the hydrograph indicate that peak discharge timing did not decrease with burn treatment. Explanations for this are influence of wetlands areas and increased evaporation, covered in the previous section 6.4.3.2 Composite Unit Hydrograph.

When the ratios of discharge at hydrograph peak are compared between the two types of treatment there is a 10% difference in hydrograph peak at the burn sites. The increase in peak discharge at burn sites indicates that burn basins are 10% more responsive to storm events when burn treatment occurs. These results follow closely with those in Section 6.4.1: Season Comparison of Discharge and Suspended Sediment Loads where burn sites produced more unsteady flows after burn treatment.

CHAPTER SEVEN: DISCUSSION, CONCLUSION, AND RECOMMENDATIONS

7.1: Introduction and Discussion

Four drainage basins have been selected and used in this study to quantify the effects of fire disturbance. The main focus of research has been the alteration to the hydrologic regime and sediment load delivery influenced by infiltration at the stand scale, and runoff and erosion at the drainage basin scale. Two of the four basins were used as controls where there was no appreciable disturbance by harvesting, fire or anthropogenic alteration. This was established by a study of basin soils, topography and vegetation. The remaining two basins had sizable portions of drainage area affected by fire; 62% in one basin and 76% in the other. This fire occurred in the fall of 1995.

Prior to the fall of 1995 all four drainage basins were characterized by the same properties of soil and vegetation type, and geomorphic processes. Soils in this region have been shown to be mostly of glaciofluvial and fluvial-lacustrine origin (Edmund, 1947). These soils are predominantly coarse textured, with high sand composition. In general the gradient change is small from watershed perimeters to basin outlets and the local topography is flat and rolling. This study has also described how the mostly coniferous-type vegetation is located on dry hills and uplands with wetland communities predominating in low depressions. Furthermore, before the fall of 1995, there was no significant amount of harvesting and no road construction in any of the four basins, and similar climatic conditions prevailed over the general area.

The above characterizations lead to the speculation that the hydrologic processes influenced by and resulting from these properties and conditions would have been similar for all four watersheds before disturbance occurred, ie., all basins were expected to be similarly predisposed before the fire.

7.2: Infiltration

After fire removed substantial areas of vegetation from two of the basins chemical and physical changes are believed to have occurred in the soil, and to the hydrologic processes associated with those soils.

Steedman and Morash (1995) have shown that intense fires break down soil aggregates into small fines which are more susceptible to rainsplash erosion, but which also fill pore spaces, blocking the entrance of water into the lower layers of the soil. Studies by Giovannini and Lucchieci (1983) have also shown that a hydrophobic layer is also formed when there is a chemical change in the soil which results from the break down of organic matter during the fire. The residues of this chemical change form a hydrophobic layer just below the soil surface, further reducing the filtering of water through the soil profile. Research has shown that as a consequence of fire soils that were once characterized by high infiltration rates, where precipitation was absorbed readily into the soil, were altered such that infiltration rates were noticeably reduced.

This study has demonstrated through the use of the phi index, (results are found in Table 6.2) that infiltration rates for those basins with fire disturbance are significantly lower than the control basins for each of the seasons - spring, summer and fall, in the year following the fire.

The results also indicate seasonal differences in infiltration (Table 6.2). This may lead to the suggestion that in this study infiltration rates were controlled not only by soil characteristics, but also by timing of the fire and the presence of existing vegetation, and in seasonal variation in soil water storage.

In spring, a combination of factors may have served to influence infiltration rates at all sites. Parts of the ground may still have been partially frozen, or some sections of the soil highly saturated from spring snow melt. Temperatures at this time of the year are normally low due to the low angle of the sun. Also, vegetation is not yet well established. Soil impediments would have lowered the potential of infiltration and the combination of low vegetational activity and low temperature values would have meant reduced evapotranspiration rates at all sites.

In the burn locations reduced infiltration would have been further compounded by the timing of the fire. Because it occurred in the later part of the previous growing season no vegetation was able to re-establish prior to the onset of winter. So that in spring no overhead foliage was available to slow the impact of raindrops. Less vegetation would have also meant that less water was being removed from the soil through transpiration, further preserving the soil water content and reducing the rate at which more moisture could percolate in.

Visual observations made at the burn sites over the period of field research showed a slow development of new vegetation over the spring and summer. In the spring no vegetation, coniferous or deciduous was present, but by the middle of summer spotted distributions of deciduous shrubs and ground level plants had begun to appear. The lack of vegetation at the burn sites in conjunction with the possible presence of a hydrophobic layer in the soil would have contributed to reduced infiltration rates recorded for summer. By comparison vegetation was firmly established at undisturbed locations by mid summer; infiltration rates at this time are shown to be correspondingly higher.

7.3: Runoff

The results from Chapter Six clearly indicate that a definite interaction exists between infiltration rate and runoff for burned and non-burned sites. As Singh (1992) found, and as the results from this study concur, there is an inverse relationship between infiltration and runoff; the more the infiltration is reduced the greater the runoff volume. Runoff has been shown to be a function of vegetation coverage, infiltration rate, slope and drainage network. Generally, it is agreed that forests are characterized by a low water yield and runoff coefficient, in comparison to other land covers. Reasons include: increased interception, increased transpiration, and higher storage capacity in the leaf litter (Hetherington, 1987). Land classification results in Table 4.2 indicated that the non-burned

Sites 1 and 2 had 60% and 71% of the land covered by forest and the burned Sites 3 and 4 had 8% and 4% covered by forest. Averaged runoff coefficients for burned and non-burned sites (Table 5.2) indicate that those basins with higher percentages of forest and vegetation cover do exhibit lower runoff values. These results are in agreement with Beasley and Granillo (1988), who calculated runoff coefficients in disturbed (0.21) and undisturbed (0.12) basins in Arkansas, and with Sahin and Hall (1996) who looked at runoff coefficients for burned (0.47) and vegetated cover (0.17) in South Africa.

When individual runoff coefficients for each site are analyzed a noticeable result is observed. Site 4 has by far the largest coefficient of all sites (0.38), higher still than the other burn basin, Site 3 (0.23). Singh (1992) has noted that drainage basins with high drainage densities have a large proportion of precipitation that runs off the land; whereas in low drainage densities most rainfall infiltrates the ground and few channels are required to carry the runoff. The drainage density for Site 4 (Table 3.3) is double that of the other sites, including the other burn basin, Site 3. This link between runoff coefficient and drainage density would infer that after fire disturbance higher surface runoff volumes would be entering the stream channels and larger discharge volumes measured at the basin outlet because of increased drainage efficiency.

Another important consideration when comparing runoff coefficients for sites is the slope values of each site. From Table 3.3 slope values for all sites are all relatively small, reflecting little variation in regional topography. Site 4 has an average slope value of 0.03% whereas the remaining sites have a value of 0.02%. This difference would not be expected to be large enough to cause differing runoff values. Naslas et. al., (1994) confirms this in their findings on the effects of soil type, slope and vegetation coverage on runoff. They found that runoff is minimal with soil types of low erodibility, vegetation and low vegetation coverage, and low average slope.

7.4: Suspended Sediment Load

The magnitude of sediment delivery is influenced by the extent and location of sediment sources, relief and slope characteristics, the drainage pattern, vegetation cover, land use and soil texture (Walling, 1983). When comparing the volume of suspended sediment carried from the four drainage basins a defined separation exists between those basins with burn and those undisturbed. Singh, (1992) noted that there is an inverse relation between sediment yield and infiltration capacity. This relation is confirmed in the results where infiltration is lower in the burn basins, and suspended sediment load in streams exiting those basins is higher than the undisturbed basins. When the ratio of SSL to Q was calculated (Table 6.6) those basins with burn treatment produced three times the ratio of SSL to Q. Regression analyses results also clearly indicate that there is a strong relationship between Q and SSL in drainage basins disturbed by fire, as evidenced by the coefficients of determination for Sites 3 and 4 (94% and 89% respectively). Numerous studies have concluded and concur with these results in that SSL noticeably increases after disturbance. An example is a most recent and well known forest fire which occurred in Yellowstone National Park, 1988. Ewing, (1996) studied pre-fire, and fire-related changes in SSL up to four years following the fire. His conclusions and those of this research are in agreement that suspended sediment loads increase in streams after fire has physically changed the vegetation and soil properties of a basin, and that there is a strong relationship between suspended sediment load and stream discharge after fire.

Another important note is that the literature has demonstrated that average annual production of sediment per unit square kilometer of drainage area decreases with increasing drainage area. For example Saxton and Shiau, (1990) found that sediment production per unit area is greater for smaller than for larger drainage areas. These findings may apply to basins where disturbance is not a factor, however, when a significant portion of a basin is burned basin size may not be a precondition to sediment load versus amount of discharge. In this research, Site 4, with a basin area of 123km^2 gave the highest ratio of SSL to Q, higher than its neighboring burn site which had a much smaller basin size of $16km^2$. Walling (1983) found that only a small fraction of sediment eroded within a drainage basin will find its way to the basin outlet. Deposition and temporary or permanent storage may occur particularly where gradients decline. The relative magnitude of this loss tends to increase however, with increasing basin size, when sediment availability is high, and land use change has had a major impact (Ashmore and Day, 1988; Church et. al., 1989). When the two burn sites in this research are compared the ratio of SSL to Q at Site 4 is double that of Site 3. One explanation for this is that these results may also suggest that perhaps drainage density and slope contribute to the amount of SSL exiting this basin. As previously mentioned Site 4 has the highest drainage density and the higher average slope of all four sites.

7.4.1: Prediction of Suspended Sediment Load Response

From the multiple regression correlation matrix an important relationship has been demonstrated to exist between the amount of burn disturbance, suspended sediment loads carried from a drainage basin, and the infiltration rate of the soils within a basin (Appendix E). From stepwise regression the proportion of burn area is also a strong indicator of sediment load. Average suspended sediment load has also shown to increase with fire disturbance from linear regression analysis (Table 6.5), and ratios of SSL to Q figure prominently at burn basins (Figure 6.5). Overall a clear relationship exists between fire treatment and suspended sediment load in this research. These results reinforce the conclusion that physical change within a drainage basin is closely related to suspended sediment output, and they closely concur with similar studies elsewhere (Helvey, 1980; Ewing, 1996).

7.5: Basin Discharge

Some general remarks can be made on discharge hydrographs for the sites. Hydrographs are strongly seasonal at all sites; there is a marked peak for each site during snowmelt and a general pattern of high base flows occurring in the spring, which then lowers through the summer and rises again in the fall. This is illustrated by Figures 6.1 through 6.4.

These results concur with similar findings in the literature that trends in the discharge hydrographs from spring to fall are evidence that changes in baseflows and storage capacities change through the seasons. The seasonal variation of flow regimes at all sites (Figures 6.1 through 6.4) is largely due to variability of the climatic factors of precipitation and temperature, and soil moisture storage. This is confirmed by Bosch and Hewlett (1982) who found that soil water content is generally greatest during the spring following snowmelt. Storm rainfall causes high points of quickflow through the summer and fall months, but in general water content decreases during the summer due to high rates of evapotranspiration associated with warm temperatures and rapid plant growth. Riggs and Harvey (1990), and Gehrels and Mulamoottil (1990) observed that evapotranspiration has a major effect on streamflow, whereby losses to evapotranspiration can significantly reduce streamflow during the summer months. Also in summer the extended ground cover reduces runoff and promotes infiltration. This is the period when infiltration is expected to be at its highest rate and is confirmed in the results for all sites in Table 6.2. In the fall, temperatures are lower, and evapotranspiration is reduced. The soil moisture deficit which occurred during the summer was reduced in the fall when excess precipitation was stored in the soil at the end of the dry season (Dunne and Leopold, 1978). This deficit was partially recovered in the fall at all sites as indicated by rising discharge levels in the hydrographs.

The large differences between averaged discharge and averaged suspended sediment loads at burned and non-burned sites (Table 6.7) indicate pronounced instability in hydrologic regime when burning occurs. Burned sites produced greater volumes of runoff and sediment in the spring, and reduced runoff through the summer months. Figures 6.5 to 6.8 show a higher magnitude in discharge and suspended sediment load delivery during the spring at the burn sites. Physical inspection of the basin outlets at the time of peak spring runoff also reinforced this difference between sites. Stream flows from the burn sites were larger than the culverts carrying stream under Wapawekka Road (Figures 4.9 and 4.10) could manage efficiently. At both sites stream flow backed up on the upstream side of the culvert, causing an approximate 2 meter rise in stage measured from the top of the culverts. These results conclude that when significant fire disturbance occurs in the summer preceding spring runoff, discharge volumes are greatly increased in the following spring. This result can be affected by a number of factors which include: reduced transpiration due to lack of vegetation, increased snow accumulations, reduced infiltration due to physical and chemical changes in the soil, and frozen ground.

Peak flows from snowmelt at the burned sites also occurred well in advance of peak flows at the undisturbed sites. Possible causes for streamflow change are given by Cheng (1989). He suggests that a more efficient and speedier conversion of watershed snowpack to streamflow results from higher snowmelt rates over a shorter period after the removal of shade-providing trees. Also, reduction of evapotranspiration losses in disturbed areas immediately after disturbance also results in reduced soil water deficits and lower soil moisture recharge requirements. Consequently, more water would be available for streamflow. This is evidenced in the larger averaged discharge ratios for spring and summer at the burn sites (Table 6.6).

At burn locations in Prince Albert National Park Pomeroy et. al., (1996) found that snow accumulations were higher in the winter at burn, clear cut, and open sites, and along with Meng et. al, (1995) found that snowmelt occurred up to two weeks earlier in open sites because of larger canopy openings that encouraged greater wind speeds and hence, higher sensible and latent heat transfers. Their findings concur with those of this research - snow accumulations were higher in burn locations than coniferous forest locations (Appendix A, Table 2), and spring runoff from the burn basins did precede that of one of the undisturbed basins.

7.5.1: Unit Hydrograph Comparisons

Synthetic and composite unit hydrographs were developed for burn and undisturbed sites and used as a comparison to assess hydrologic effects of land use change. The synthesized unit hydrograph was used as a baseline for discharge time of peak, discharge at peak and total discharge for each site with no land use change. The composite unit hydrograph was developed from observed measurements, after land use modification, and was expected to indicate an alteration in these discharge values. This alteration was expected to reproduce similar results as observed by Bosch and Hewlet (1982), Hetherington (1987), and Steedman and Morash (1995) where changes in forest cover increased yields and peak flows.

The results of comparisons between basin unit hydrographs were surprising in that no significant changes to total discharge and timing of discharge were observed at sites with burn treatment. There was however, a 10% increase in peak discharge from sites with burn treatment. This increased responsiveness indicates that reduced infiltration rates and increased runoff after burning is reflected at the basin outlet by higher stream stages.

Three possible explanations for no change in timing of peak and total discharge are suggested. The first is that data collection error occurred, the second is that errors in model calculations occurred, and the third is that drainage basin physical properties and hydrologic regimes for this region do not follow those of the above studies. Careful inspection was made of the data and calculations in connection with the first two possibilities, and no obvious errors were found.

An important agreement is evident from the results of the unit hydrograph analysis. That is, there is no noticeable increase in total discharge exiting the burn basins after fire disturbance over the total season of measurement, or in the time to peak of discharge passing through burned basin outlets. Several explanations are proposed. These are: the influence of burn on precipitation accumulations and evaporation, and the influence of large areas of depressional storage, wetland complexes, and subsurface water on the hydrologic regime throughout the burn basins.

Most studies of hydrologic processes as related to disturbance have been performed in regions outside the boreal forest and on other types of disturbance, such as timber harvesting. Both Swanson et. al., (1986), Garman and Moring (1991), and Sahin and Hall (1996) in their investigations of streamflow change after timber harvesting disturbance attributed streamflow increases to decreases in evapotranspirative losses. In contrast, in this study similar streamflow changes did not occur suggesting that hydrologic responses to forest fire may not parallel that of timber harvesting or that of regions outside of the boreal forest.

Two processes may explain this departure. Evaporation rates within burn sites were higher because of increased heat transfers, and storm runoff found its way to depressional areas and wetlands where evaporation was also key in removing moisture from the basin.

Both Armson (1979) and Wright and Bailey (1982) found that after a fire minimum and maximum soil temperatures are usually greater than previously. This results from the removal of both vegetation and part or all of the surface organic layers which act to insulate the soil. The greater insulation received by the soil and its darkened surface will increase the heat absorbed and this will cause temperatures to increase. Also where a water table exists within the rooting zone, it will generally rise, reflecting the reduced transpirational loss. When little or no organic cover remains over the mineral soil, conditions may be quite different. In this research, for all of spring and much of early summer large sections of the burn sites had no vegetation. The ground and remaining dead vegetation was covered by blacken ash and charcoal. Higher temperatures in these locations could have influenced increased evaporation loss from the soils particularly in the warmer summer months.

Other researchers who have also studied hydrologic processes in landscapes similar to the boreal region of Saskatchewan identified stream discharge levels often affected by the presence of large depression areas and evapotranspiration. Gehrels and Mulamoottil (1990) and Price and Maloney (1994) determined that as evapotranspiration increased in late spring and over summer in wetland complexes there was a corresponding decrease in discharge from the surface outflow. Then later in the fall evapotranspiration decreased and surface outflow increased. In general their findings were that large depression storage of wetland systems enhanced evapotranspiration losses. In the burn sites the land use class percentage for fen and bog was 29% and 16% for Sites 3 and 4 respectively. This would indicate that a sizable percentage of the basin was still capable of evapotranspiration processes through the summer months, and along with evaporation loss from burned locations would have contributed to reducing the discharge output from streams leaving these basins.

7.6: Conclusion

Four goals were originally outlined in the Project Objective of Chapter One. Those goals and the conclusions drawn are outlined below:

- The first goal was to study the relationship between the proportion of burn treatment and the physical and hydrologic characteristics of the four drainage basins.

Infiltration rates and runoff coefficients were compared between basins with and without burn treatment. The burn basins, with between 60% and 77% of vegetation removed by fire showed a marked reduction in infiltration rates. Infiltration rates fluctuated from spring to fall, following with similar influences at the undisturbed sites, but remained low in comparison. Runoff coefficients were 17% higher in the burn sites. Factors that influenced infiltration and runoff in the burn sites were loss of overhead vegetation and surface organic matter that reduce rainsplash and increase infiltration, and alterations to soil texture and chemistry that lowered infiltration rates and encouraged storm runoff. In addition the multiple regression correlation matrix outlined a close relationship between burn coverage, infiltration, slope, and suspended sediment loads.

- The second goal was to verify the relationship between suspended sediment load and discharge with previous research and to explore the strength of the relationship between these two variables in burned basins.

Study of the literature has shown that suspended sediment load is transported at the highest water discharges. Further evidence that discharge and suspended sediment increase at equal rates has been found in this research. This rapid increase of suspended load with discharge is interpreted as indicating that conditions of rainfall and runoff on the watershed combine to furnish to the streams a large increment of debris for each increment of water. Through the use of Time Series Analysis basins with large burn areas are demonstrated to be more likely to exhibit instability in SSL concentration during storm events. Sediment rating curves and correlation coefficients testify that in basins that experience burn treatment larger volumes of sediment are supplied to the streams. Ratios of suspended load to discharge are three times greater in streams exiting burn basins. Furthermore, basins with burn treatment show a greater variation between SSL sediment loads averaged from spring and summer, suggesting larger volumes of sediment available for transport immediately after fire and higher discharges available to carry that material.

- The third goal was to demonstrate that drainage basins with the same physical variables and with the same land use treatment will handle hydrologic input similarly over time.

Initial site investigation demonstrated that the two types of basin treatment shared similar drainage basin characteristics (stream order, drainage density, slope and stream profile). Climatic conditions, soil and vegetation types, and anthropogenic disturbance were also consistent for the two treatments. Differences in basin size at the 4 sites was accommodated by averaging results for each treatment type.

Discharge outputs were used as a measure of hydrologic inputs. Seasonal hydrograph analysis verifies similar patterns of baseline adjustment from spring to fall at all sites. In addition, synthetic hydrographs indicate corresponding outputs to basin size when land use treatment was not applied.

- The final goal was to confirm that changes to a drainage basin's land use will be answered with a change in that basin's hydrologic output.

Adjustments to hydrologic output were observed at the stand scale where infiltration decreased and runoff increased. It is speculated that these adjustments were affected by physical alteration to soil properties and by removal of vegetation. Adjustments to hydrologic output at the basin scale were observed in the spring when discharge peak was accelerated by approximately two weeks and a magnified increase in discharge occurred at the burn sites. No adjustments to total discharge output were found from late spring to fall. Explanation for this is that a portion of the runoff through the mid and later part of the season was used to fill depression storage and/or lost to evaporation, and did not find its way from the basin via stream channels.

Composite unit hydrographs developed after land use treatment indicated a 10% increase in discharge peak as a response to alteration of physical characteristics after fire.

7.7: Recommendations

Time and financial constraints necessitated that for this research a six month period of discharge, stage, rainfall and suspended sediment data was available. On a relative scale this would be considered a short period of data collection. This, together with no historical data to include in the research combined to give only a short glimpse of hydrologic response to fire disturbance. A longer period of data would certainly increase accuracy of predictions, and would also benefit toward temporal comparison made before and after fire disturbance.

Hydrologic response to disturbance is a result of many interrelated and dynamic variables in a watershed. This research focused primarily on hydrologic input data collected from rainfall gauges and from hydrologic output data collected as discharge at basin outlets. A large proportion of land area in boreal basins, and in particular the basins used in this research, encompass wetlands. To improve the accuracy of any further research and test the findings of this project it would be applicable to include measures of subsurface water response to fire disturbance, as well as evaporation response over burned forest and wetland sites.

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Appendix A.

Forest Fire History of the General Study Area (1945 - 1983)

			Causes				
Year	No. of Fires	Area Burned (km^2)	Recreation	Settlement	Industry	Lightning	Unknown
1945	22	32.19		2	2	2	16
1946	64	94.15		17	5	1	41
1947	82	71.22		13	6	6	57
1948	61	172.05		15		2	44
1949	147	1776.61		39	4	8	96
1950	42	378.40		14		4	24
1951	11	13.13		2		2	7
1952	54	40.67	1	6	6	4	37
1953	53	271.16		4	7	4	38
1954	14	3.53		2	2	1	9
1955	57	152.18		5	4	13	35
1956	33	19.51		4	1	7	21
1957	39	21.07		6		12	21
1958	70	92.96	1	12	2	8	47
1959	44	8.41	1	3	1	7	32
1960	37	15.24	1	5		8	23
1961	129	951.44	7	14	5	52	51
1962	91	9.30	8	6		50	27
1963	64	92.10	3	7	1	25	28
1964	130	1061.69	9	17	1	68	35
1965	23	3.06	2	1		9	11
1966	38	7.08	5	2	1	11	19
1967	129	108.85	18	25	5	29	52
1968	96	558.58	18	12	2	27	37
1969	110	32.31	18	8	3	33	48
1970	82	904.72	13	3	1	47	18
1971	69	27.01	8	10	7	17	27
1972	149	80.91	24	19	3	51	52
1973	70	4.90	4	17	11	17	21
1974	46	1.03	3	1	4	22	16
1975	64	1.94	12	6	5	19	22
1976	137	35.76	32	20	10	43	32
1977	116	1,045.97	18	13	7	58	20
1978	102	2.23	27	12	2	53	8
1979	56	7.31	9	4	5	32	6
1980	161	2511.96	19	14	12	80	36
1981	190	197.95	45	30	13	76	26
1982	173	10.75	35	12	4	68	54
1983	71	1.04	19	10	7	24	11
Total	3,126	10,820.37	360	412	149	1,000	1,205
Percent	100.00	100.00	11.52	13.18	4.77	31.98	38.55

Source: Saskatchewan Parks and Renewable Resources.

Appendix B

Table 1: Sub-canopy Snowfall for Undisturbed and Disturbed Terrain Types.

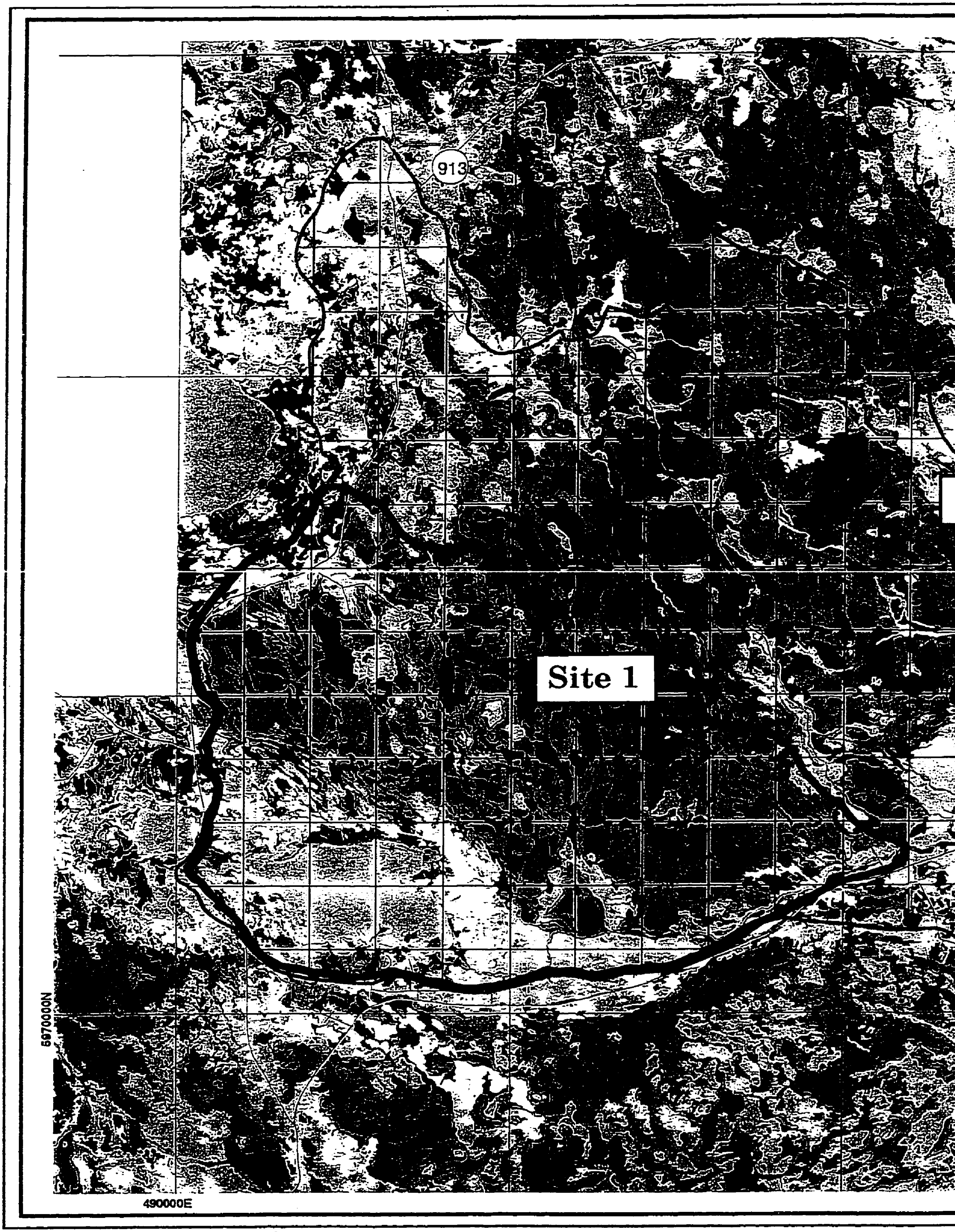
Terrain Type	Percentage of Open Area Snow Accumulation 1994 - 95	Percentage of Open Area Snow Accumulation 1995 - 96
Open	100	100
Clear-cut	100	94
Burn	100	94
Mixed	91	85
Pine	70	80
Spruce	58	56

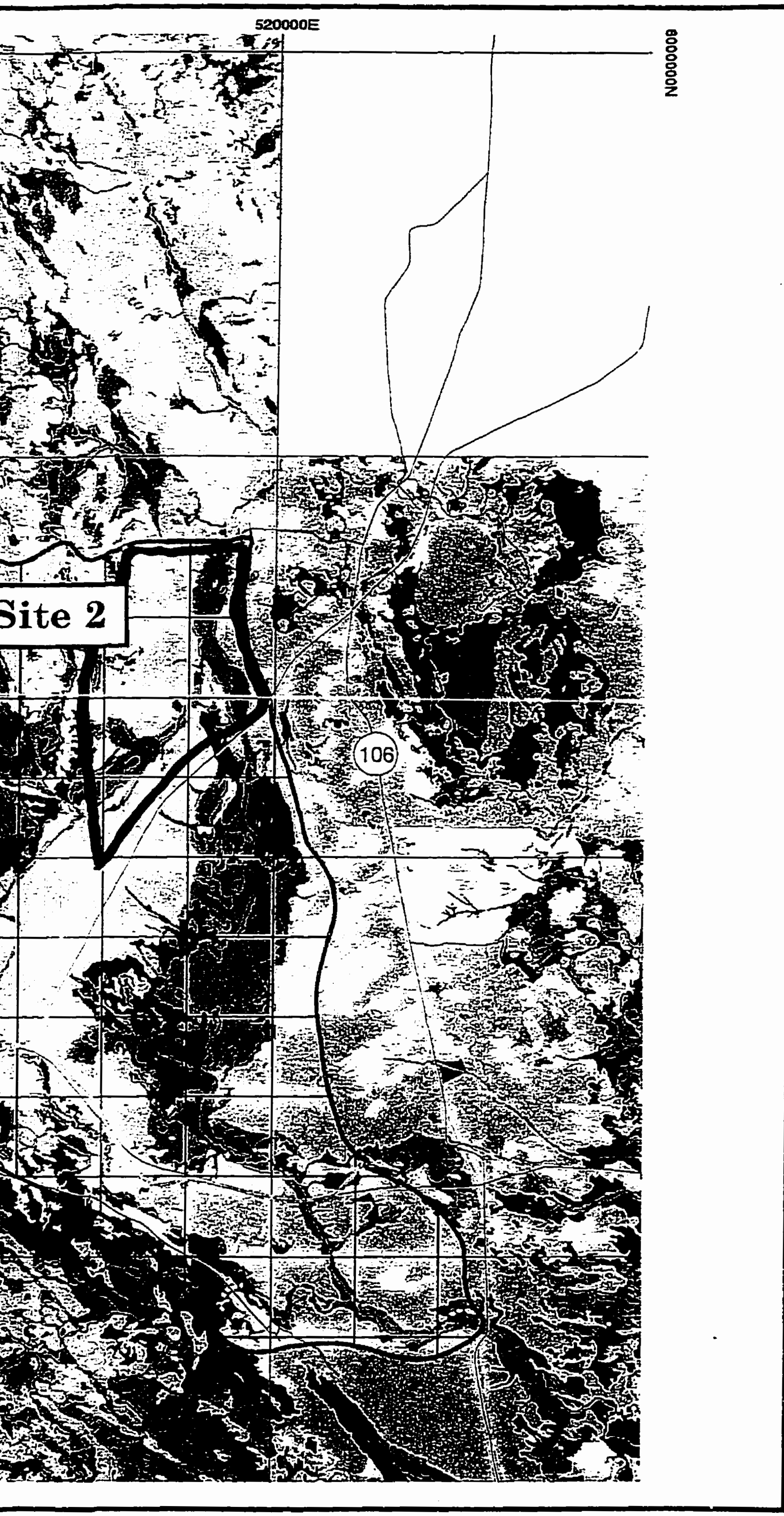
Source: Pomeroy et. al. 1996
Note: Snowfall is expressed as a percentage of total snow accumulation in open areas at the end of the winter.

Table 2: Average Snow Depth, Snow Density, and Snow Water Equivalent by Vegetation Class

Terrain/Vegetation Type	Snow Depth (m)	Snow Density (g/cm^3)	Snow Water Equivalent (mm)
Jack Pine	0.33	0.19	66
Black Spruce	0.27	0.22	64
Aspen	0.38	0.22	86
Fen	0.37	0.21	79
Regeneration	0.44	0.21	96
Harvest	0.35	0.23	81
Burn	0.37	0.22	84

Note: All sites were visited between March 11 and March 15, 1996.


913
Site 1
597000N
490000E



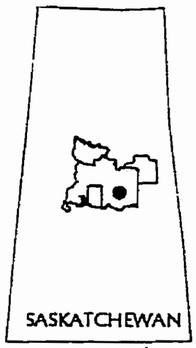
Appendix C

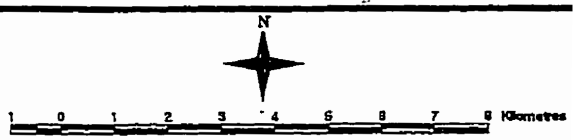
Land Use Classification Sites 1 and 2

LEGEND

- Sites 1and 2
- Basin grid (every 2,000 m)
- UTM grid (every 10,000 m)
- Hydrography
- Roads
- Unclassified
- Wet Conifer
- Dry Conifer, Medium and Old Regeneration
- Mixed Deciduous and Deciduous
- Harvest and Young Regeneration
- Recent Burn
- Fen and Bog
- Deep and Shallow Water

REFERENCE MAP



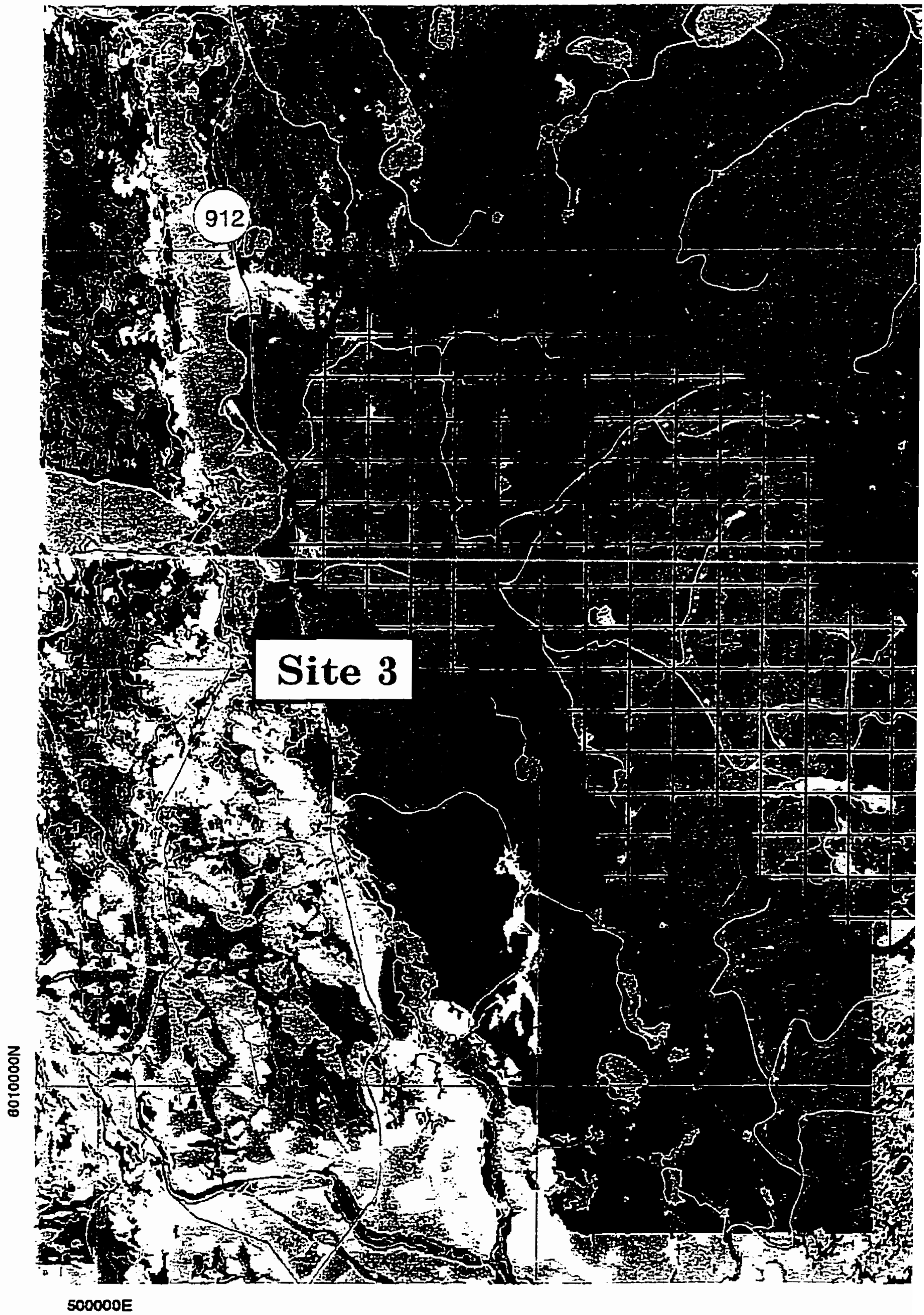


Scale - 1: 150,000

Date: 20 November 1997

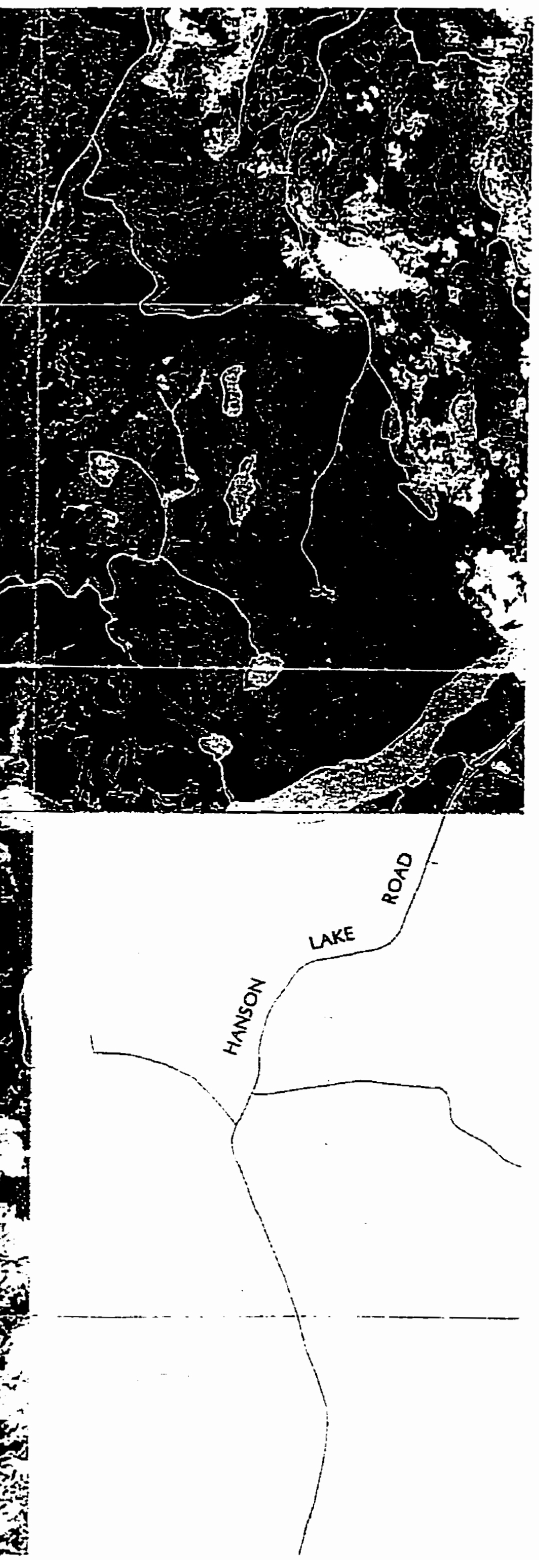
DATA SOURCE:

Base map - Weyerhaeuser base maps
Landcover - Weyerhaeuser Forest Inventory Ma
Watershed - NTS maps


912
Site 3
8010000N
500000E

Appendix C

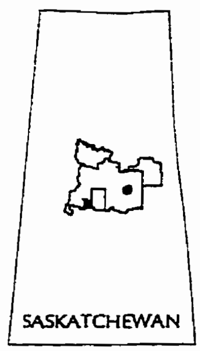
Land Use Classification Sites 3 and 4

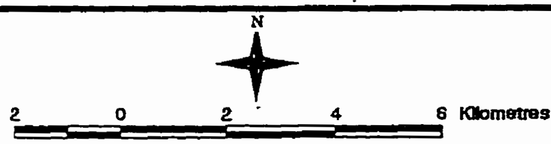


LEGEND

- **Sites 3 and 4**
- Basin grid (every 1,000 m)
- UTM grid (every 10,000 m)
- Hydrography
- Roads
- Unclassified
- Wet Conifer
- Dry Conifer, Medium and Old Regeneration
- Mixed Deciduous and Deciduous
- Harvest and Young Regeneration
- Recent Burn
- Fen and Bog
- Deep and Shallow Water

REFERENCE MAP





Scale = 1: 150,000

Date: 20 November 1997

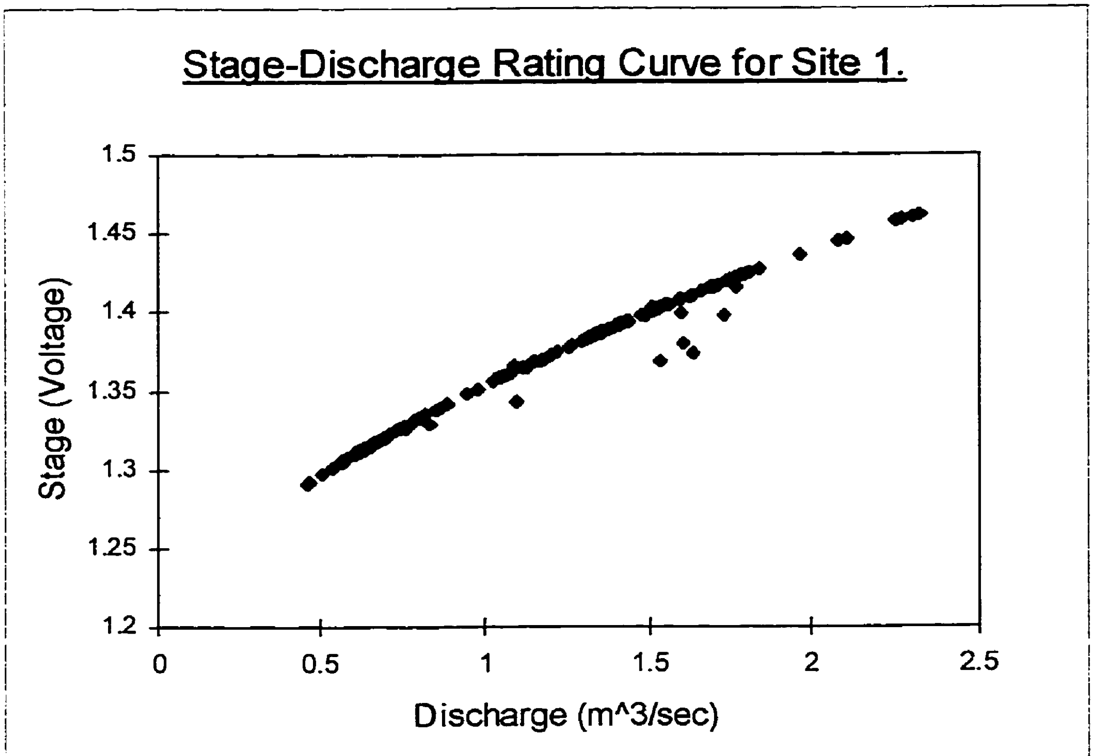
DATA SOURCE:

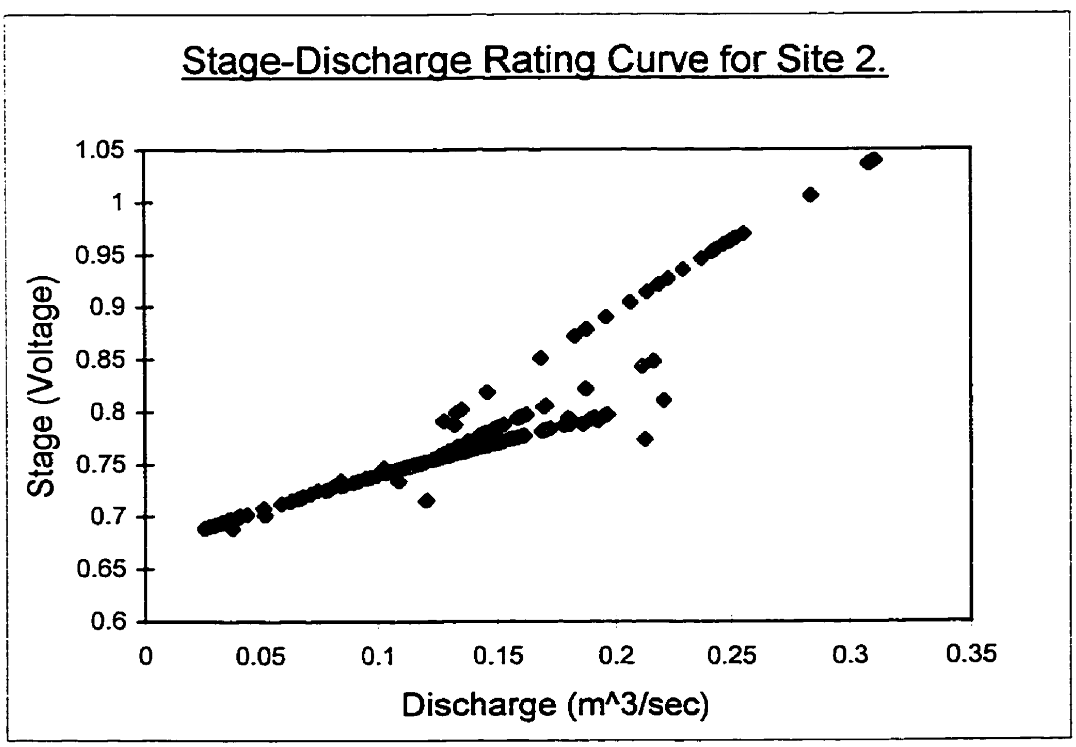
Base map - Weyerhaeuser base maps

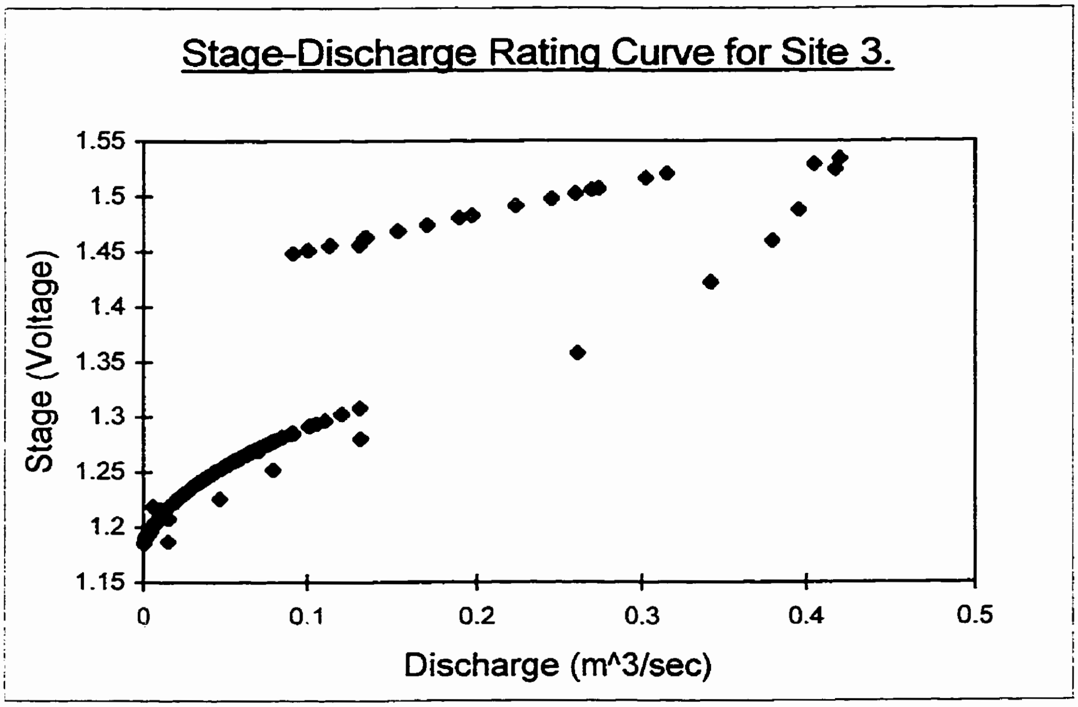
Landcover - Weyerhaeuser Forest Inventory Ma

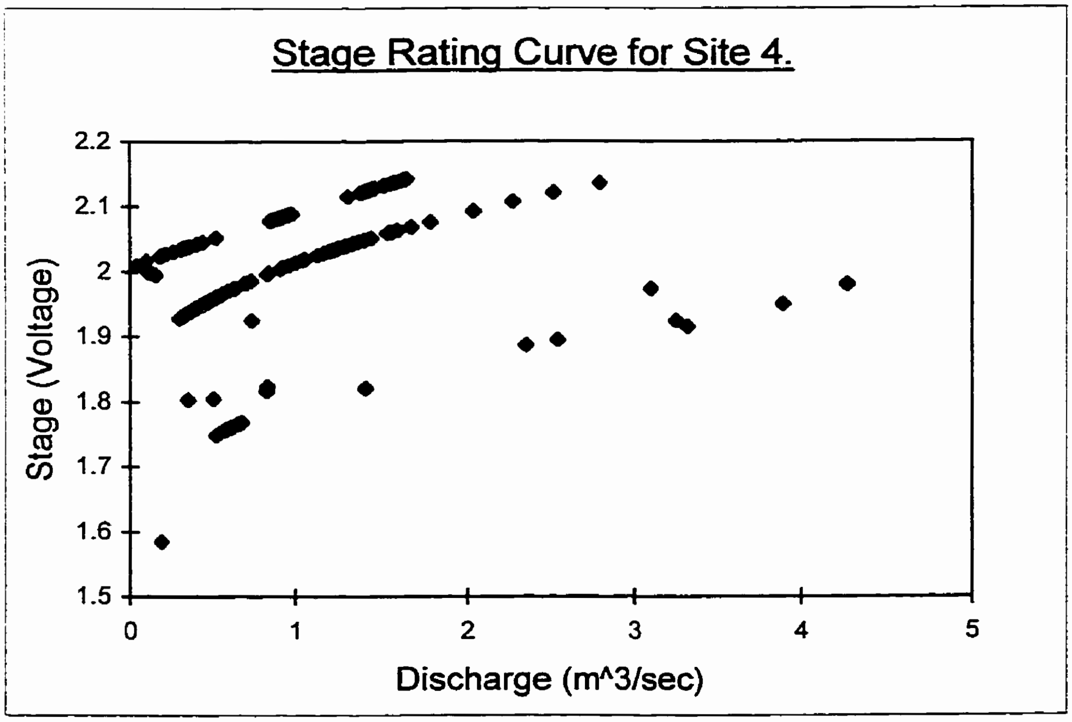
Watershed - NTS maps

Appendix D.


Stage-Discharge Rating Curve for Site 1.
Stage (Voltage)
1.5
1.45
1.4
1.35
1.3
1.25
1.2
0
0.5
1
1.5
2
2.5
Discharge (m^3/sec)


Stage-Discharge Rating Curve for Site 2.
Stage (Voltage)
1.05
1
0.95
0.9
0.85
0.8
0.75
0.7
0.65
0.6
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
Discharge (m^3/sec)


Stage-Discharge Rating Curve for Site 3.
Stage (Voltage)
1.55
1.5
1.45
1.4
1.35
1.3
1.25
1.2
1.15
0
0.1
0.2
0.3
0.4
0.5
Discharge (m^3/sec)


Stage Rating Curve for Site 4.
Stage (Voltage)
2.2
2.1
2
1.9
1.8
1.7
1.6
1.5
0
1
2
3
4
5
Discharge (m^3/sec)

Appendix E: Correlation Matrix

Correlation Matrix: Dependent Variable: Average Sediment Load / Basin Area.

	Average Sediment Load / Basin Area (SLD)	Burn (B_R)	Infiltration Rate (IR)	Slope (S)	Total Discharge / Basin Area (TQ)
Average Sediment Load / Basin Area	1.00	.986	-.907	.795	.188
Burn	.986	1.00	-.909	.703	.069
Infiltration Rate	-.907	-.909	1.00	-.535	.171
Slope	.795	.703	-.535	1.00	.738
Total Discharge / Basin Area	.188	.069	.171	.738	1.00