EFFECTS OF LAND-USE CHANGE ON LAKE SEDIMENTATION RATES FOR THIRTEEN WATERSHEDS IN WEST-CENTRAL ALBERTA, CANADA

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Abstract

EFFECTS OF LAND-USE CHANGE ON LAKE SEDIMENTATION RATES

FOR THIRTEEN WATERSHEDS IN WEST-CENTRAL ALBERTA, CANADA

RICHARD IMMELL

Land-use is an important factor affecting the quantity of accumulating lacustrine sediment. Elevated sedimentation can be harmful to aquatic ecosystems, and impede water purification. A lake sediment based approach to watershed dynamics was used to evaluate land-use impacts on thirteen lakes in west central Alberta Canada. By using historical air photos and recent satellite raster data, land-use change was identified on a roughly decadal scale, and was used to generate indices of land-use intensity. Digital Elevation Models (DEMs) were analyzed in a geographic information system (GIS) to generate indices describing the natural landscape. Lake sediment cores were taken and ^{210}Pb dating was completed to establish sedimentation rates, and a sediment deposition timeline. Regressions were completed to evaluate the correlations between land-use, landscape, and sedimentation. Since the data does not conform to a natural distribution, correlations were also explored with a Spearman rank correlation analysis. Spatial investigations were completed by use of 10m, 50m, 250m, and 500m buffer analysis. The regression and spearman rank correlation analysis did not support a strong relation between watershed variables and sedimentation rates, which indicates that land-use might be a more important factor effecting sedimentation rates. The Spearman rank analyses indicated a significant correlation exists between road and trail density and sedimentation rate increases. Regression analyses found significant

relations between road and trail density at small buffer distances (10m), and well density at moderate distances (50m). Temporal analysis yielded only one significant relation, which was between cumulative road and trail density and sedimentation increase at a 10m buffer distance. Due to heteroscedasticity noted in the plot of the regression, a t-test and F-test were completed to evaluate the difference of means and of variance. The dataset was subset into high and low road and trail density for use in these tests. Results indicate it is more likely that sedimentation will increase with higher cumulative road and trail densities, and that the variability in sedimentation will be high at higher road and trail densities.

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Dedication

This thesis is dedicated to my wife Marcie Immell, and to my kids Arwyn and Corrin Immell. Without their love and support I would not have had the courage, or determination to complete this project. It is also dedicated to my father Robert Immell, who taught me that family is important, and that you only fail when you fail to try.

1. Introduction

1.1. Overview

Sediment yield is a measure of the amount of detrital material particles washed out of a watershed over a defined period of time (Schiefer *et al.,* 2001). Sediment yield measurements are often used as an index of landscape denudation and as a means to assess the environmental processes affecting the land surface. Landscape disturbances, both natural and anthropogenic, can result in increased sediment yields from forested watershed systems. Timber harvesting, for example can have significant effects on both water quality and water quantity (Campbel and Doeg, 1989). Increased sediment yields can have an adverse effect on the water quality of downstream water courses and receiving water bodies. In particular, high levels of fine-grained sediment in streams and lakes can be directly harmful to fish, degrade aquatic habitats, disrupt community drinking water and impede water purification (Kerr, 1995). The impact on aquatic life can be severe for fishes such as salmonids which use substrate as incubation habitats (Bjornn and Reiser, 1991; Curry and MacNeill, 2004). Increased course grained sediment can cause channel aggradation, resulting in reduced flow capacity leading to flooding and channel instability (Nelson and Booth, 2002). The potential severity of such impacts in the future is unknown because of alterations to flood and fire disturbance regimes caused by climate change combined with ongoing land use development. Assessing the degree to which land use change impacts sediment yield in the context of natural occurring variability is vital to understanding and managing this problem.

The lake sediment-based approach for studying watershed dynamics is based on the premise that linkages exist between inherent landscape characteristics and terrestrial disturbances of lake catchments and the quantity of accumulating lacustrine sediments (Schiefer *et al.,* 2000). Lake sediments represent a historical record of sediment yield and drainage basin processes. It has been shown that if properly collected and analyzed lake sediments can be used to develop profiles of quantitative sediment yields (Foster *et al.,* 1990). Sedimentation changes due to land-use change or other catchment disturbances can then be identified and described.

Thirteen lakes (Table 1) were selected in west-central Alberta for the study of natural and anthropogenic disturbances on the sedimentary system. The lakes were selected to span a range of catchment sizes, relief, and land use disturbance intensities. Sediment cores have already been collected from the study lakes and the deposits have been analyzed for ^{210}Pb content.

^{210}Pb dating is frequently used to establish chronologies of lake sediment-cores (Foster *et al.,* 1990). When looking at a time period 200 years or less from the present, ^{210}Pb radiocuclide is well suited for chronological control, because of its half life of 22.26 ± 0.22 years. Cores for the lakes in this study have already been collected, sub-sampled, and analyzed for sedimentation rate reconstruction following the methods of Schiefer (1999). ^{210}Pb is produced via the natural decay of ^{238}U. ^{210}Pb has a predictable rate of decay which can then be used to establish a chronology of lake sediment accumulation. The concentrations of ^{210}Pb were interpreted via the constant rate of supply (CRS) dating model. Because this model allows for fluctuation in ^{210}Pb rates over time, it is a preferred method for assessing the sedimentation rate changes over time. Details of the dating methods are presented by Evans and Rigler (1980) with modifications described by Cornett *et al.* (1984) and Rowan *et al.* (1994).

Table 1. Study lakes

Lake	Latitude	Longitude	Lake area (km^2)	Watershed area (km^2)
1) Bear	53.74 N	-116.15 W	1.54	7.54
2) Dunn	53.65 N	-117.69 W	0.12	0.86
3) Fairfax	52.97 N	-116.58 W	0.31	1.62
4) Fickle	53.45 N	-116.77 W	3.77	102.21
5) Goldeye	52.45 N	-116.19 W	0.10	5.00
6) Iosegun	54.46 N	-116.84 W	13.54	273.21
7) Jarvis	53.45 N	-117.80 W	0.70	31.86
8) Mayan	53.90 N	-117.39 W	0.06	0.73
9) McLeod	54.30 N	-115.65 W	3.42	47.88
10) Musreau	54.54 N	-118.62 W	5.58	104.57
11) Pierre Gray	53.91 N	-118.59 W	0.38	0.50
12) Rainbow	53.91 N	-117.18 W	0.07	4.44
13) Smoke	54.36 N	-116.94 W	9.15	133.93

1.2. Literature review

1.2.1. Watershed sediment transfer

Drainage basins or watersheds are the fundamental landscape unit involved with the collection and distribution of water and sediment. Watersheds are linked with hill slope processes that contribute water and sediment into the channel networks contained within the basin. Regional climate, geology, vegetation, and human land-use, are contributing factors to these hill slope processes (Ritter *et al.,* 2006 pp 136). Input from drainage basins then feeds into the main channels and influences downstream channel morphometry and hydrologic processes (Figure 1).

Ultimately, the source of all river flow is precipitation. Except in arid regions, precipitation rarely makes direct contact with the earth surface. Most precipitation is blocked by the leaves or trunks of the vegetation cover, a process called interception. Interception reduces the erosive potential of a raindrop strike, and the volume of water which reaches the surface. The losses attributed to interception are variable because there are many hydrometeorological factors involved, such as vegetation type, land-use, and seasonality. Additionally storm duration also plays an important role. Interception losses are high in the early portion of the storm and decreases as the storm continues. Typically interception removes 10 to 20 percent of the precipitation where grasses and crops are the dominant vegetation, and up to 50 percent under a forest canopy. Vegetation further reduces the amount of precipitation contributing to stream flow because it is consumed and lost via evapotranspiration.

Water flowing directly into a channel as a result of a precipitation event is called runoff. The process of water entering the soil is referred to as infiltration. The rate at which water is absorbed into the ground is the infiltration capacity. Runoff and surface hydrologic parameters such as sediment discharge are significantly impacted by variations in basin lithology and in the nature of the overlying surficial materials. For water to flow over the land surface, the rainfall intensity must exceed the infiltration capacity. When this happens surficial materials become subject to erosional forces.

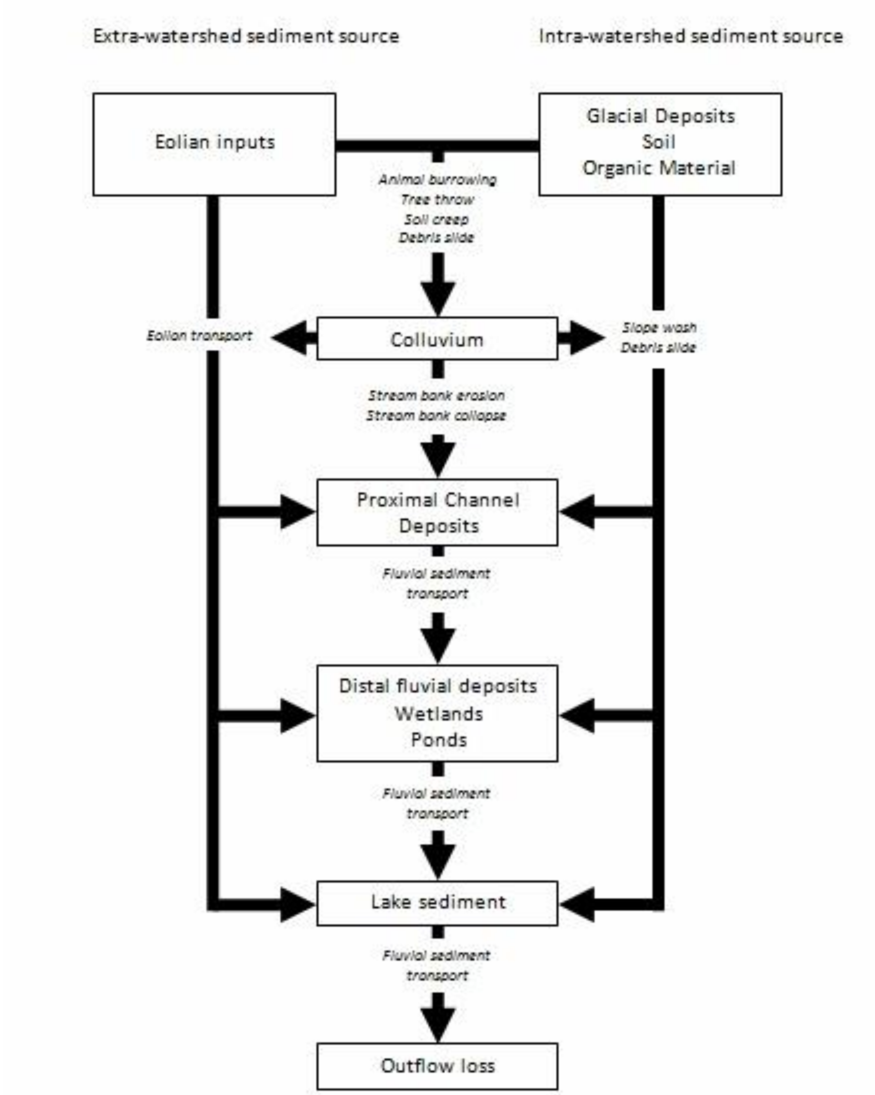


Figure 1. This figure is modified from Robert and Church (1986) and is a conceptual model of sediment transfer for a headland watershed in the Rocky Mountain Foothills and adjacent Alberta Plateau. Boxes indicate principal reservoirs; the principal processes are in italics.

Erosion is the principal force behind channel formation. For erosion to occur, the erosive force of the overland flow must surpass the resistance of the surface material. Force is defined as a shear stress force parallel to the surface by the flowing water. This stress is intensified downslope and downstream because the water depth rises as more water is added to the overland flow. Eventually threshold is reached where force exceeds resistance and ground particles are dislodged or entrained.

Resistance is affected by the type and density of vegetation cover. Vegetation intercepts precipitation before it reaches the ground, which preserves cohesion in the soil structure. Vegetation root systems also act as a binding agent for soil particles. Leaf litter acts as a protective barrier above the ground surface. Vegetation also retards the free flow of water and slows its velocity. In areas without vegetation cover, the soil usually forms a hard crust upon desiccation, which in the initial part of the precipitation event provides high resistance. Resistance may be surpassed as storms progresses and is therefore often related to the precipitation duration.

Erosion due to overland flow is a threshold process that occurs only when resistance forces are exceeded. Erosion typically begins as a series of subparallel rills developments aligned to the slope gradient. Slight variations in surface topography produce areas of greater depth of flow in low spots, which increases the erosive force. Once confined to a channel, erosion will continue to cut into the earth at these locations.

The watershed as the fundamental unit of the fluvial landscape is typically the focus of research, aimed at understanding drainage network processes of water and sediment transfer. Basin morphometry is often used to predict or describe certain hydrogeomorphic processes, such as peak flood, erosion rates, and sediment yield.

Basin morphometry comprises a quantifiable set of geometric properties that define the linear, areal, and relief characteristics of the watershed. There are two general kinds of indices which are used to describe basin morphometry, linear scale measurements and dimensionless number measurements. Scale measurements allow size comparisons of topographic units. Such parameters include watershed area, the length of streams, and basin relief, length, and perimeter. Dimensionless numbers are used to compare basins and are usually derived as ratios of length or areas parameters. Such parameters include stream and basin slopes, stream density, and basin shape indices.

Since dimensional area is the product of linear factors, areal components should also pose a consistent morphometry. The fundamental unit of the areal elements is the area contained within the basin of any given order. It encompasses the area which provides runoff to streams of the given order, all the area of lower order tributary basins, as well as interfluves regions. Area is an important independent variable, but it is also used to derive an array of other parameters, each of which has significance in basin geomorphology. Parameters governing the collection of precipitation and concentration of runoff are of particular importance. Studies have demonstrated that a relationship exists between basin area and discharge. One of the more important areal factors is drainage density.

Drainage density is the average length of streams per unit area and reflects the spacing between drainage channels. Resistant surface materials or those with high infiltration capacities exhibit widely spaced streams and thus have a low drainage density. As surface resistance or permeability decreases runoff is accentuated by closer channels, increasing drainage density. Because vegetation cover tends to increase resistance and infiltration, areas with high vegetation cover (such as densely forested areas) tend to have lower drainage densities than would be expected.

A third group of parameters are related to the vertical aspects of the drainage basin. Relief morphometric relationships include factors of gradient and elevation. Slope between two points is the most important factor affecting the flow velocity of runoff. The most useful relief parameters are the maximum basin relief and the divide-averaged relief. Maximum basin relief is the highest elevation of the basin divide minus the elevation of the mouth of the trunk river. Divide-averaged relief is the average divide elevation minus the elevation of the mouth of the trunk river. Another common measure indicates the overall steepness of the basin in the relief ratio calculated as the maximum basin relief divided by the horizontal distance of the basin measured parallel to the trunk stream.

Erosion and sediment yield are intimately related to the weathering process. Weathering rates are influenced by regolith thickness, because cover thickness regulates water flux into the parent material and determines the efficiency of physical action on bedrock, including frost shattering in cool climate areas. Regolith thickness is in turn regulated by denudation processes which remove the weathered product. Rain is an obvious contributor to erosion, but the severity of its impact is under some debate.

The amount of soil moved by rain droplet splash depends on several interrelated factors. The first factor is the kinetic energy of the raindrop. The energy of the raindrop is directly related to splash movement. The second factor is the soil type being struck. Soil type is involved in the determination of splash movement. A sandy surface will lose more soil than a silt loam surface, due to the higher cohesion of the silt loam. The manner of soil particle aggregation and its dispersive properties are more significant controls than is simple textural composition. The third factor is slope angle. The rate and amount of splash transport appears to be a direct function of slope angle.

Splash also plays a secondary role in erosion. Splash acts to dislodge soil particles, destroying the structure of the soil. This action makes the soil more susceptible to surface flow. As splash disperses the clay, they tend to settle and form a fine-grained crust, which acts as a semi-permeable barrier that reduced infiltration and promoted runoff, increasing soil loss to overland flow.

Most natural slopes are too irregular to have a uniform flow of water or wash, over the entirety of the surface. Instead flow is deeper over depressions and shallower over flat reaches or high spots. The variable depth of flow produces differences in the eroding and transporting capability of water. Areas where sheet flow is possible, only fine-grained particles can be moved with efficiency, and then only when weathering or rain splash has reduced the cohesion of the surface material. Within areas of concentrated flow, the ability of the water to erode depends on the hydraulic force of the water and less on the condition of the surface, so flows are capable of moving larger sediment particles.

There are many inter-related geologic hydrologic, and topographic factors affecting sediment yield. The most important include: climate and its regulation of precipitation and vegetation, basin size, elevation and relief, rock type, and land-use.

Climate and vegetation: It seems obvious that precipitation would be a dominating factor in sediment yield; however its impact is complex. The amount of runoff from a given precipitation event varies with temperature. Vegetation which acts as a barrier to precipitation is dependent on temperature and precipitation. Precipitation cannot be considered a completely independent variable with regard to erosion. The Langbein-Schumm curve suggests that sediment yield increases rapidly as precipitation rises from zero (Langbein and Schumm, 1958). This occurs until the precipitation reaches about 30cm of effective precipitation above which a decline in sediment yield is promoted because the vegetation type and density begins to be a protective factor.

Basin size: Small basins often have a higher relative sediment yield than larger (higher order) basins. There are several reasons for this: first, the smaller basins tend to have steeper valley slopes and high gradient stream channels that can efficiently transport sediment. Second, small basins with significant relief often transport sediment via mass movement and debris flow processes. Third, basins filled to capacity with streams, tend to have high drainage density near the basin divide and will decrease in the central portion of the basin. Fourth, floodplain area increases as the basin expands which leads to lower basin-average slopes and offers greater opportunity for sediment storage along the valley floor. In Canada, however, observations suggest that many small basins have lower relative sediment yield than the larger basins (Church *et al.,* 1999). The Canadian terrain is dominated by glacial landforms, and basins with glaciers at the headwater have a differing sediment yield regime than other terrestrial-based catchments. Glaciers deposited loose sediment preferentially along trunk valley systems and secondary remobilization of this sediment can exceed primary erosion from upland areas.

Elevation and Relief: Mountainous terrain with high elevation and relief produce high amounts of sediment, especially where the rocks are non resistant or have been affected by recent tectonic activity. The highest rates of denudation occur in mountain areas with extreme elevation and relief, and have highly erodible soils. When we look at erosion over time, the denudation rates are not equal. As relief and elevation of a basin gradually diminish over time, the amount of surface material eroded declines at a proportional rate. Thus each successive interval of stripping requires a longer period of time.

Rock Type: Basins underlain by more soluble and poorly lithified sedimentary rocks, low-rank metamorphic rocks, and highly fractured igneous extrusive rocks usually produce abundant sediment loads and have higher rates of denudation than coarse and sparsely fractured crystalline rocks. Although the mechanism behind this process is not understood, it seems likely that properties such as infiltration capacity are systematically related to sediment yield.

Land-use: Most estimates of erosion are considerably higher where humans alter the natural landscape. Anthropogenic factors have the potential to magnify erosion rates by over an order of magnitude. The level of impact is dependent on the type of land-use activity and the sensitivity of the disturbed environment.

1.2.2. Land-use impacts on sediment transfer

Since the 1980s, non-point source pollution has been recognized as an important source of surface water quality tribulations (Novotny and Olem, 1994; Nelson and Booth 2002). Construction, mining, timber harvest, and agriculture accelerate erosion rates which increase the sediment supply to surface water. For example, human activity, particularly urban development, caused an increase in sediment yield of nearly 50% in the Issaquah watershed in western Washington (Nelson and Booth, 2002).

In forested watersheds, land-use changes often lead to increased suspended sediment yields, which play an important role in biochemical cycling within the catchment (Karwan *et al.*, 2007). Streams draining natural forests in New Zealand, showed lower sediment and nutrient rates than streams draining pine plantations and pastures (Quinn and Stroud, 2002). Excess sediment can degrade aquatic and fish habitat, disrupt hyporheic connections, enhance the transport of sorbed pollutants and increases treatment requirements for municipal withdrawal. Garcia-Rodriguez *et al.* (2002) found a relation between land-use change, sediment yield and pollutants in Lake Blanca South East Uruguay, where increased sedimentation followed forestry activity and intensive sheep and cattle grazing. Land-use activities can impact sediment and water quality over comparatively long distances, requiring a heterogeneous regional landscape with large areas of natural forest and wetlands to counter land-use effects (Houlahan and Findlay, 2004). There has been little research on land-use impacts on sedimentation in Alberta Canada; however considerable research has been done in British Columbia and the western US.

Forest roads can have a wide range of geomorphic effects. These effects range from chronic, long-term contributions of sediment into streams, to large scale mass failure of road fill materials during large storms (Gucinski *et al.,* 2001). Major concerns regarding road-related erosion include potential degradation of aquatic habitat and water quality and risks to public safety and structures downstream.

Geomorphic processes are affected by roads via four primary mechanisms: 1) accelerated erosion from the road surface and prism by mass wasting and surface erosion; 2) directly altering channel structure and geometry; 3) changing surface flow paths and extending or diverting channels into previously un-channelized portions of the landscape; and 4) causing interactions among water, sediment, and debris at engineered road-stream crossings (Gucinski *et al.,* 2001). These processes are not uniformly distributed within or among landscapes.

Steep forest areas prone to landslides, for example, will see the greatest effect of road erosion from mass soil movement after road construction (Gucinski *et al.,* 2001). Studies completed in the western United States have shown that the magnitude of mass erosion differs with climate, geology, road age, construction practices, and storm history. Studies in the eastern United States suggest that landslides are driven more by storm magnitude and geology than by land use.

In many areas the dominant source of road-related sediment input into channels, comes from surface erosion from road surfaces (Forman and Alexander, 1998). Increased sediment delivery into streams after road construction is well documented in the Pacific Northwest and in the Eastern United States (Gucinski *et al.,* 2001). Sediment delivery is highest in the first years following the construction of unpaved roads, and is highly correlated with the amount of traffic on the road (Karwan *et al.*, 2007). Erosion is highest where the landscape is highly erodible, particularly landscapes underlain by highly fractured rocks, or poorly consolidated surficial material.

There are several ways that roads interact with stream channels directly, and depend on the roads orientation (parallel, orthogonal) to streams and landscape position (valley bottom, midslope, ridge) (Gucinski *et al.,* 2001). The geomorphic consequences of these effects on erosion rates are potentially significant, especially during large storm events. However these interactions are complex and frequently misunderstood. Jordan (2006) documented a case where forest roads facilitated a debris flow which completely destabilized a channel of Laird Creek in British Columbia. This single event led to an increase in the bed load and suspended sediment yield, and interfered with turbidity measurements and automatic sample collection.

Road construction for timber harvest contributes a large amount of sediment in some areas such as the interior of British Columbia (Jordan, 2006). In this region, some documentation suggests that the harvesting of trees has a negligible impact on sedimentation while the roads created to service these areas promote sediment increases. This is not always the case, some areas such as coastal California, have reported large increases in sedimentation due to logging cuts (Keppeler et al., 2003; Jordan, 2006). In general, the combination of logging and roads increases peak discharges and downstream flooding (Forman and Alexander, 1998). The removal of forest results in lower evapo-transpiration and water-storage capabilities. Roads alone may increase peak discharge rates. Also, flood frequency apparently correlates with the percentage of road cover in a basin.

In forested watersheds, eroded materials from areas of tree harvest, un-harvested areas and roads can be transported in concentrated overland flow into stream channels (Karwan *et al.*, 2007). One important factor in harvested area sediment yield is the harvesting practice. Karwan *et al.,* (2007) found that sediment yield increased significantly only in the clear-cut harvested areas. The other area they studied used a partial cut practice and did not yield statistically significant increases in sediment.

The amount and type of precipitation directly affects the amount of material eroded from forest harvesting cut blocks. In the British Columbia interior for example, the amount of rainfall is usually low and most of the erosion occurs during snow melt (Jordan, 2006). The lower impact logging practices employed in this area are a major contributing factor to the low sediment yield due to logging activities. These harvesting practices include keeping soil disturbances below a specified level; re-contouring skid trails after logging, and leaving unlogged buffer zones adjacent to streams.

The Canadian government is particularly interested in the impacts of forest harvest on sediment yield. Many areas rely entirely on surface streams for their water and obtain it with little or no treatment (Jordan, 2006). Other areas also depend on mountain streams, but use reservoirs and water treatment, but are in areas where forest harvest is in contention.

Oil and gas exploration is a rapidly growing industry in Alberta (Sustainable Resource Development 2008). Natural gas exploration and production is a type of land-use change and involves the construction of roads, well sites, and pipelines. These types of construction can lead to accelerated soil loss due to land cover disturbance, increased slopes, and flow concentration (Wachal *et al*., 2009). Once established, energy extraction development can be a chronic sediment source with annual sediment yield varying with soil type, slope and management practices. In Texas areas with low soil erodibility (sandy loam) and low slope (1.8%) predicted erosion was 12.1 t/ha/yr, while areas with highly erodible soil (silty clay loam) and high slope (4.5%) predicted sediment yield as high as 134.5 t/ha/yr (Wachal *et al.*, 2009).

No matter the source of sediment increase, it is important to understand that land use impacts can increase sediment yield in watersheds. Erosion from any construction site can increase sedimentation up to 40,000 times the natural or background amount (Wachal *et al.*, 2009). Table 2 demonstrates the impact land-use change can have on sediment mobilization. Soil creep for example yields 1 cubic meter of sediment per kilometer per year on forested slopes, and is doubled on cleared slopes. By understanding the impacts of sediment increases and their sources, it is possible to implement management procedures to limit construction impacts on sediment yield, improving the water quality for aquatic habitats and for human consumption.

Table 2. Sediment mobilization and yield from hillside slopes in the Pacific Northwest of North America Reproduced from: Sediment Cascades: An Integrated Approach, Tim Burt (Editor), Robert Allison (Editor), 2010. Results have been generalized to order of magnitude; more specific results are available in Roberts and Church (1986).

Process	Mobilization rate		Yield rate to stream channels	
	Forested slopes	Cleared Slopes	Forested slopes	Cleared slopes
Normal regime				
Soil Creep (including animal effects)	1 $m^3km^{-1}yr^{-1}$	2x	1 $m^3km^{-1}yr^{-1}$	2x
deep-seated creep	10 $m^3km^{-1}yr^{-1}$	1x	10 $m^3km^{-1}yr^{-1}$	1x
Tree Throw	1 $m^3km^{-2}yr^{-1}$	--	--	--
Surface erosion forest floor	<10 $m^3km^{-2}yr^{-1}$		<1 $m^3km^{-2}yr^{-1}$	
surface erosion landslide scars,	>10^3 $m^3km^{-2}yr^{-1}$	1x	>10^3 $m^3km^{-2}yr^{-1}$	1x
Gully Walls	(slide area only)			
Surface erosion: active road surface	--	10^4 $m^3km^{-2}yr^{-1}$	--	10^4 $m^3km^{-2}yr^{-1}$
		(road area only)		(road area only)
Episodic events				
Debris slides	10^2 $m^3km^{-2}yr^{-1}$	2-10x	to 10^4 $m^3km^{-2}yr^{-1}$	to 10x
Rock Failures (fall, slide)	No consistent data: not specifically associated with land use			

1.2.3. Lake sediment records of sediment yield

Watersheds are linked by fluxes of sediment and water directly into downstream lakes or reservoirs (Foster *et al.*, 1988). Any disturbance, both by natural and anthropogenic forces that increase the fluvial transport capacity or that increases sediment production in the watershed, may elevate rates of sediment transfer and accumulation in downstream lakes. The downstream change in lake sedimentation will occur if the change in watershed sediment yield is not absorbed by responses in the ratio of sediment yield in the drainage basin to the total amount of sediment moved by sheet erosion and channel erosion (sediment delivery ratio). It is also important to note that the forcing variables can have a direct impact on the lake directly via other changes water quality.

Because lake sediment deposits represent a continuous record of sediment deposition, they can be useful in reconstructing sediment yields from contributing watersheds (Schiefer, 1999). Several issues surround the collection and analysis of lake and reservoir sediments for reconstruction watershed sediment transfer. Present methods of sediment core correlation and dating allow for the estimation of past sediment rates at 5 to 10 intervals back through the twentieth century (Foster *et al,* 1988).

Trends in accumulation over time can be used to isolate periods of higher or lower average sedimentation rates caused by catchment disturbance (Foster *et al*., 1988). However, these results should be used with care, because minerogenic influx from a watershed is only partly responsible for sedimentation rates in receiving lakes.

Other factors such as the morphology of the lake basin and the dynamics of other sediment sources are also important. A multi-core assessment of absolute sediment yield has advantages over sediment accumulation studies based on a single sediment core. The sediment yield approach requires sediment dating and, some means of core correlation to link a master core chronology to other sediment cores to assess spatial variations in sedimentation rates and to ultimately calculate total sediment influx.

Lake sediment-based studies of sediment transfer have been developed for watersheds over a wide range of temporal scales. Some studies have reconstructed sediment accumulation in lakes for up to 10,000 years. Most of these long-term studies relate increases in sediment to volcanic events or glacial retreat (Foster *et al.,* 1988). Effects of changing lake morphometry, has not been considered in these studies and caution should be used in their interpretation. For more recent time scales, studies have indicated that similarities exist between estimated sediment yields derived from lake sediment accumulation rates and those from contemporary monitoring (Foster *et al.,* 1988; Menounos et al., 2006). Some of these studies also show that the background variation in sediment yield between contemporary and historical land use is broadly synchronous.

When utilizing the bottom sediments of lakes and reservoirs to reconstruct sediment yield history, several issues must be addressed (Foster *et al.*, 1990). These include the identification of sediment sources, how effective the lake is at catching sediment (trap efficiency), resuspension processes, sediment density changes, autochthonous (formed in the location the material is found, i.e. within the lake) and allochthonous (material moved away from location of origin, i.e. the watershed) contributions to the sediment, and the significance of sediment mixing processes.

Trap efficiency: The general pattern of sedimentation is a function of the changing hydraulic conditions (Foster *et al*, 1990). When highly turbulent inflow reaches the slow flowing water within the lake, coarser materials (including the bedload) are usually deposited in the delta while fine silts and clays are deposited further into the lake. Large amounts of variability exist in trap efficiency, and can vary even within one water body depending on inflow conditions (Verstraeten and Poesen, 2000).

Resuspension: The processes of sediment returning to suspension in the water column (resuspension) and then being deposited once again (redeposition), can have a significant bearing on the methods used to estimate sediment yield (Foster *et al*, 1990). Resuspension and redeposition can result in greater sediment accumulation in the deep parts of a lake (sediment focusing), and can be beneficial due to the higher resolution that can be gained from analyzing the deposit (Hilton, 1985). Sometimes sedimentation rates are too slow to be useful, and therefore sediment focusing can provide enough sediment to work with. It is suggested that four processes control the resuspension and possible focusing of lake sediments. These are peripheral wave attack, random redistribution, intermittent complete mixing, and slumping and sliding on slopes. Unfortunately a good understanding of these processes does not exist, particularly for small lakes. This is an important limitation, because the inability to predict sediment focusing has implications on sediment survey techniques.

Sediment density: Sediment density is calculated one of two ways. Reservoir engineers usually view sediment density as the removal of pore water through time (Foster *et al*. 1990). This approach assumes that the increase in compaction is time and/or particle size dependant and will tend towards a finite maximum. This approach is limited by observations made in Lake Biwa Japan, where density increased with depth over 200m of sediment. An alternative approach presented by Hakanson and Jansson (1983), where they assume water content is the key component. Water content will decline with depth in the form of a negative exponential. Changes in sediment density are important when estimating sediment yield. Such changes can occur during deposition, or in post-deposition diagenesis (Foster *et al.*, 1990). The mixture of sediments of various types affect the final density, because different materials will have variation in particle size and pore pressure, and because of different organic and inorganic loadings.

Sediment estimates from a lake basins are frequently inaccurate, because of errors in estimating vertical variation in sediment density, and because spatial variation exist over the lake bed. Variation in density over the lake bed is due to inflow and outflow configuration, secondary sorting processes within the water body, and variations in erosion and deposition across the lake bed.

Autochthonous and allochthonous sources: Lake sediment is composed of material derived from erosional processes within the upstream drainage basin, atmospheric sources, and biotic processes within the circulating water body (Foster *et* *al.*, 1990). It is important to distinguish between these sources where they are likely to contribute significantly to the accumulating sediment.

Traditionally atmospheric contributions to sediment yield are considered negligible; however some studies have shown a considerable input from localized dust fallout (Foster *et al.*, 1990). Some studies suggest that atmospheric contributions could be as high as 9% of the gross sediment. Estimation of the contributions made by internal processes can be made by an analysis of the organic content of the accumulating sediment. The results of this analysis can then be compared to the organic content of the inflowing sediments. Remaining sediment accumulation is assumed to represent allochthonous sources and, therefore, is directly related to watershed sediment yield.

Post-depositional mixing processes: Mixing processes are not significant factors in sediment accumulation, but are relevant to the preservation of the chemical and radiometric stratigraphies (Foster *et al.*, 1990). Separation of the sedimentary record into intervals approaching a decade in resolution is dependent on the mechanisms responsible for the delivery, adsorption and diagenesis of the isotopes which are the basis of radiometric chronologies. There are two major isotopes used for dating recent sediment cores, ^{137}Cs and ^{210}Pb. Laboratory experiments have shown that the use of sediment layers by organisms can affect the movement and diffusion of ^{137}Cs. ^{137}Cs dating is also usually limited to the identification of a single chronohorizon associated with maximum thermonuclear bomb fallout from atmospheric testing during the early 1960s.

An accurate chronology is without doubt the most important aspect of sediment yield reconstruction (Foster *et al.* 1990). For studies spanning the last 200 years, the ^{210}Pb analysis seems to be the most appropriate approach, providing a resolution on a decadal scale. Given the half life of ^{210}Pb of 22.26 ± 0.22 years, this radionuclide is particularly suited to this task, and gives accurate age determinations for up to 150 years.

An important aspect of sediment yield reconstruction using multiple sediment cores is the identification of time synchronous layers within the sediment (Foster *et al*, 1990). To do this, demands some means of core correlation and dating. Several methods of core correlation have been used, and include: visible stratigraphy, paleoecological stratigraphy, chemical stratigraphies, radioisotope records, and magnetic correlations.

The total influx of sediment is usually obtained by multiplying the associated mean wet sediment volume of each core for a particular time period (determined by sediment dating) by the percentage weight loss measured by oven drying to convert from a wet sediment volume to a dry sediment density (Foster et al 1990). Accuracy is improved if the dry density is determined for various locations in the lake, ideally stratified for water depth and proximity to inflows. A map can then be produced which shows the dry density of sediment for each time period. The total mass of dry sediment can then be calculated with the measurement of the area of lake bed receiving different amounts of dry sediment. This procedure accounts for spatial variability in sedimentation rates across the lake bed.

1.2.4. Use of GIS to characterize watershed sediment yields

Geographic information systems (GIS) can be a useful tool to characterize sediment yield potential from a watershed. The power of the GIS lies in its ability to store, manipulate, and tabulate spatial data associated with watershed sediment transfer. Hydrologists and geomorphologists have come to rely upon the GIS to tackle many water resource and sedimentation issues, such as flood mitigation, water resources management, erosion assessment, and sediment budgeting (Maidment, 2002). Spicer (1999) and Schiefer (1999) for example, utilized a GIS to assess land-use impacts on lake catchment systems in western Canada.

To relate catchment characteristics to sediment yield, accurate data is needed for a GIS-based analysis. Typical data sources for extracting topographic structure include digital base maps, including topographic, geologic, vegetation, and water body maps, and often Digital Elevation Models (DEM) (Jenson and Dominque, 1988). Other sources of data are also important when considering how land-use change impacts water resources, and include air photos, satellite imagery, or land-use maps when available.

Watershed description: One function of the GIS is to store and extract information describing the watershed. DEMs are a useful data source which can be used to derive a wealth of information about the morphology of land surfaces (Jenson and Dominque, 1988). Traditional methods of raster processing used a neighborhood operation to calculate slope, aspect, and points of inflection. Additional algorithms have been developed which allow other features to be generated from the DEM, specifically topographic depressions, and flow directions.

A watershed is an area that drains surface water to a common outlet and is the basic unit often used for the management and planning of natural resources. A watershed analysis often refers to the process of using a DEM to derive raster datasets and topographic information, such as stream networks (Chang, 2006). There are two basic ways to delineate a watershed via GIS. First there is an area-based method which divides a study area into a series of watersheds one for each stream section. The second method is point based and uses a point or many points to define outlets, gauge stations, or other flow points of interest.

Regardless of the method used, a watershed analysis follows a series of steps, and begins with a filled DEM (Chang, 2006). A filled DEM does not have any unwanted surface depressions. A depression is a cell in the elevation raster which is surrounded by higher-elevation values, and therefore represents an area of internal drainage. Some of these depressions are true features perhaps quarries or glaciated potholes, but the majority are imperfections in the DEM and are therefore removed. One way to achieve this is to raise the cell value to the lowest overflow point out of the sink. This results in a flat surface which presents its own challenge. Flow must be established and a slight gradient is applied to force flow away from higher elevations surrounding the flattened area and towards the edge with lower elevation.

Once obtained, a filled DEM can be used to derive a flow direction raster, which shows the direction water will flow out of each cell of the filled DEM (Chang, 2006). In

ArcGIS, the D8 method is commonly used to generate the flow direction raster. This method uses the 8 surrounding cell values to identify the steepest distance-weighted gradient. The D8 method is very useful when applied to zones of convergent flows and along well-defined valleys, but can produce flows in parallel lines along principal directions, and is not good at representing divergent flows over convex slopes and ridges. Other algorithms have been proposed which might address these issues. One called D∞ (D infinity), partitions flow from a cell into two adjacent cells. Eight triangles are formed between the center cell and the center of the surrounding cells. The triangle with the maximum downhill slope is selected and the flow is distributed to the two cells which construct the triangle. The proportion of flow to each cell is determined by their closeness to the aspect of the triangle. This method is available as an extension in ArcGIS.

A flow accumulation raster can be derived from the flow direction raster. This raster tabulates the number of cells which will flow into it (Chang, 2006). In essence this raster records the number of upstream cells which will contribute drainage to each cell in the raster. Cells with high accumulation values correspond to stream channels, while accumulation values of 0 usually represent ridge lines. By multiplying the area of the cell by the accumulation value, you calculate the drainage area.

Since the flow accumulation is related to stream channel delineation, it stands to reason that to derive stream networks, we use the flow accumulation raster (Chang, 2006). This analysis requires a threshold value to be applied. The threshold value determines the minimum number of contributing cells required to delineate the stream network. The higher the threshold the less dense the network will be. The threshold value is necessary, but is often arbitrary. Each section of the stream network can be assigned a unique value and then associated with flow direction to produce a stream link raster.

Once all the previous rasters are derived the watershed can be delineated. Area wide watershed analysis uses the flow direction raster and the stream link raster to determine the watershed for each section of the network (Chang, 2006). To delineate the watershed for points of interest such as a dam or lake, a pour point is used. The pour point is a raster which identifies the area or areas where the water will pour into. Therefore this analysis requires the flow direction raster and a pour point raster.

There are various applications for watershed analysis. Watershed management applies to the organization and planning of human activities by recognizing the interrelationships among land-use, soil, and water as applied to upstream and downstream areas (Chang, 2006). Watershed analysis can also provide necessary inputs for hydrologic and geomorphic modeling.

Land-use change description: Aerial photography and satellite imagery can be used to map land cover change over time (Awasthi *et al*. 2002; Franklin *et al.,* 2005), which may influence sediment transfer processes within a watershed. Historical rates and patterns of land cover change can be documented and there is the potential to predict future rates and patterns of change based on an understanding of land-use processes. Several studies have indicated that maps of land cover change can be generated by comparing land cover information interpreted from various sources.

Typically a GIS database is used to house and provide a suite of tools for comparing the results of existing maps, aerial photos, and satellite image analysis.

Narumalani *et al.* (2004) used air photos and IKONOS pan sharpened data to identify areas where natural land cover areas were affected by human influence, particularly through residential growth. Franklin *et al*. (2005) used aerial photographs and satellite imagery to look at land cover change in the Foothills Model Forest of Alberta Canada. Land cover changes in the last century are assumed to be related to natural disturbances and human development. Imagery was obtained from various time periods and sources, and used to construct land cover maps. These maps were then used to identify land cover changes, by comparing them, with the goal of identifying and understanding significant changes which occurred from 1950-1999. In this study land use changes were noted as harvesting activities and silverculture activities affecting large areas of trees. Awasthi *et al*. (2002) used aerial photos to derive land use maps for two watersheds in Nepal, by interpreting 1978 and 1996 photos. The resulting data was then analyzed in a GIS. Land use was found to be highly dynamic and significant areas of agriculture had been abandoned by 1996.

Extracting landscape and land-use data to relate to sediment yield records: GIS is a vital tool when looking at spatial data, and offers a suite of tools suited to extracting landscape and land-use data. Once the data is extracted, it is possible to relate the derived data to sediment yield records. Spicer (1999) and Schiefer (1999) both used GIS derived data and sediment yield records derived from lake sediment deposits to investigate spatial and temporal patterns of sediment yield.

Spicer (1999) used GIS technology and ^{210}Pb dating to generate regional datasets which contain annual harvest activities and corresponding sediment yields for 11 central interior and 10 coastal catchments in British Columbia, Canada. A GIS was used to delineate the catchment boundaries from contour layers. Forest cover maps were also used as input into the GIS. With these inputs other basin features were extracted, including area, slope, forest cover history in the form of stand age classes, dates and area of harvest, and total area of disturbance over each basin. Catchment stream length and road extent were extracted from digital maps, facilitating the calculation of road densities and percentage of stream lengths harvested in each basin.

Using the sediment yield data for each basin, derived via lake sediment cores and GIS-derived catchment data, including watershed morphometry and disturbance extents, Spicer (1999) was able to relate land-use and sediment yield. Estimates of logging related sediment yield increases were made by comparing the yield at the start of logging activities to the following maximum peak in sediment yield. Results indicate that increases in sediment yield are potentially due to the onset of forestry activities, as well as other disturbances such as earthquakes, storms, and fire activity. Streamside harvesting, stream crossings, road construction and forest cut blocks on steep slopes all seem to contribute to increased sediment yields.

Schiefer (1999) completed a similar study relating catchment characteristics to patterns of sediment yield. A GIS was used to derive two types of indices for the analysis. Landscape indices were developed which constitute the static elements of the landscape. The indices were: drainage basin area, study lake area, total area of lakes upstream, wetland area, valley flat area, stream length, elevation statistics, and slope statistics. The second set of indices was used to describe land-use and is dynamic, changing over time. These indices were: percentage of basin logged, road density, percentage of streams logged, number of stream crossings, and shape index of cut areas.

These indices were related to data obtained from lake sediment core collection and associated laboratory analysis. Sediment yield was derived from the sediment core processing for each study lake. Schiefer (1999) found that sediment yield was increasing in all lakes regardless of land-use change. This could be due to changing precipitation regime. There was difficulty in separating out land-use change and sediment yield increases; however it was apparent for some heavily disturbed lake catchments.

GIS is also used to study and predict sediment transfer and rates of sediment yield over time scales significantly longer and shorter than in either the Spicer (1999) or Schiefer (1999) studies previously discussed. At shorter event-based timescales, physically-based sediment transport models have been developed over the last couple of decades, such as the Water Erosion Prediction Project (Cochrane and Flanagan, 1999). These models are still limited because not all processes associated with sediment transfer in forested terrain are included and they have very large GIS data requirements which cannot be met for most remote and rural watersheds. At significantly longer timescales, numerical modeling approaches have been developed to assess spatial patterns of landscape evolution which span several thousands of years (Martin and Church, 2004). These approaches still appear to be limited for use in assessing land-use disturbances to sedimentary systems at the intermediate time scales most relevant to landscape management.

1.3. Study area

1.3.1. Climate

The boreal and foothills natural regions of west-central Alberta Canada are characterized by short wet summers with peak precipitation occurring July (Beverly *et al*., 2009). Mean annual precipitation ranges from 461mm to 588mm. Mean daily temperatures between May and September are 11–13°C.

A comparison of two weather stations (Edson and Jasper, Figure 2) near the study lakes indicates that there is little variation between temperature and precipitation between the two sites. Edson located at 53°35'N, 116°28'W, has its peak rain in June, averaging about 106.7 mm, with the lowest rain arriving in February with an average of 0.5 mm (Environment Canada, National Climate Data and Information Archive, 2010). Snow fall peaks in January with 35.8 cm, and is lowest in July where no snow fall occurs. July has the highest average temperature at 14.6°C, and January has the lowest average temperature of -11.8°C.

Jasper's peak rain fall occurs in July averaging 60.1 mm of rain, with the lowest average rainfall in Febuary with 2.8mm (Environment Canada, National Climate Data and Information Archive, 2010). Snow fall peaks in January with 30.5 cm, and is lowest in July where no snow fall occurs. July has the highest average temperature at 15°C, and January has the lowest average temperature of -9.8°C. The largest variation in climate, between the two weather stations occurs in June July and August where convectional activity increases rain activity away from the mountains and foothills.

1.3.2. Vegetation

Dominant tree species include aspen (*P. tremuloides Michx*.), lodgepole pine (*P. contorta Dougl*. *ex Loud. var*. *latifolia Engelm*.), white spruce (*P. glauca Moench Voss*), and balsam poplar (*Populus balsamifera L*.) (Natural Regions Committee 2006). Variation in the vegetation is considerable between the lower and upper foothill sub regions. The lower foothills sub region is dominated by mixedwood and deciduous stands, while the upper foothills sub region is dominated by conifer stands. The dry mixedwood sub region is dominated by aspen forests. According to the Atlas of Canada (http://atlas.nrcan.gc.ca/site/english/index.html), the study lakes all fall within the Boreal Plain region of Canada. Forest is mostly continuous over the region except where lakes exist or where timber has been harvested.

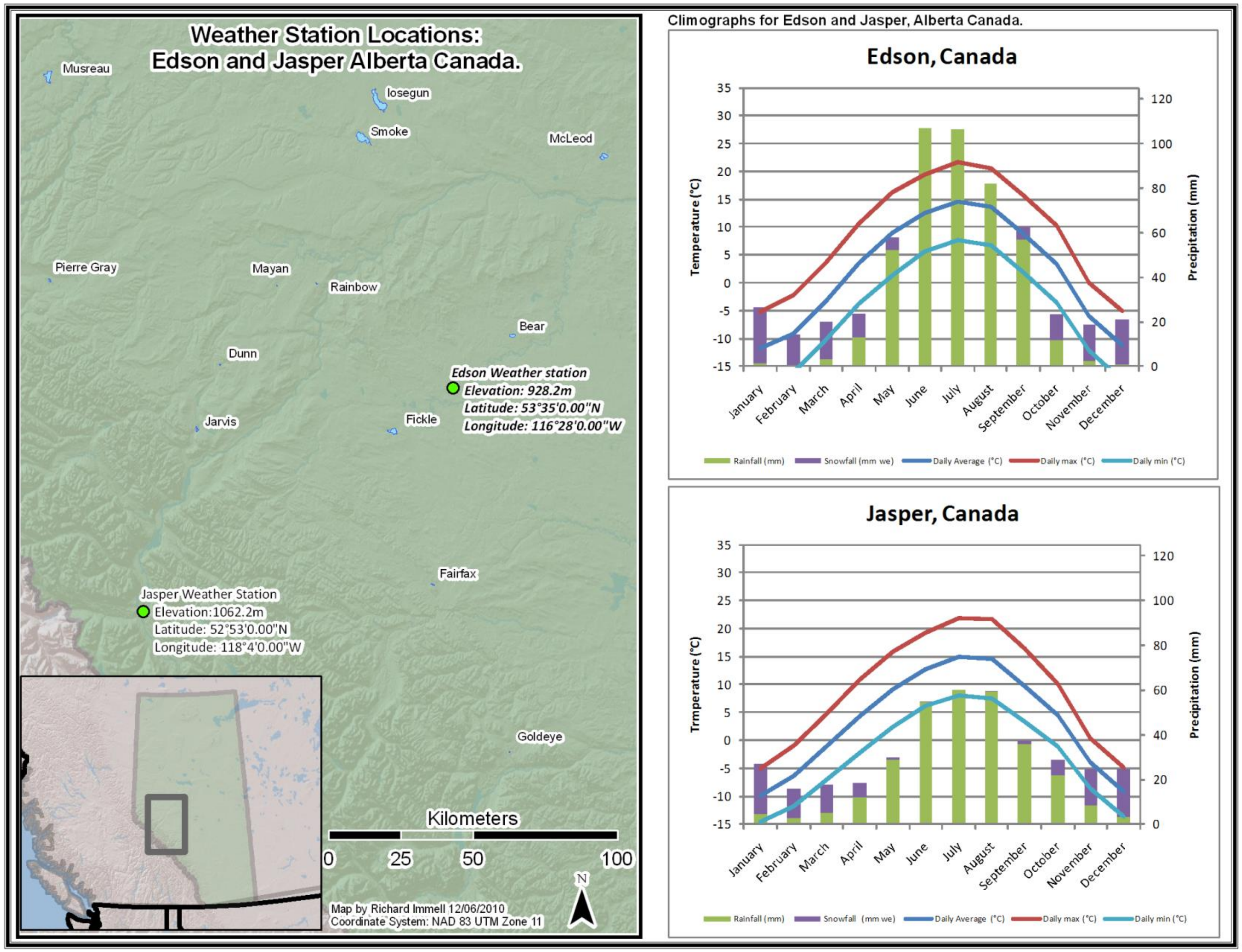


Figure 2. Map showing the study lakes and Edson and Jasper weather stations, and Climographs for each location

1.3.3. Geology and surficial materials

Most of the study area lies within the Cenozoic Paskapoo Formation (Figure 3), which is broken into two formations, the Paskapoo and the upper Paskapoo (Alberta Geological Survey 2009). The Paskapoo formation is generally comprised of mudstone, siltstone and sandstone with subordinate limestone, coal, pebble conglomerate and bentonite. Other geologic formations include the Brazeau formation, coalspar formation, and the Scollard formation. Similar to the Paskapoo formation, the Scollard formation is generally comprised of sandstone, siltstone, mudstone, thin discontinuous bentonites and thick coal seams. The Brazeau formation is comprised mostly of nonmarine sandstones, shales, conglomerates and coals. Nonmarine sandstones, siltstones, shales and coals are the primary components of the coalspar formation.

The surficial geology of West-central Alberta is dominated by glacial till possibly from one glacial event. The retreat of the glacier in central Alberta was largely by stagnation (Alberta Geological Survey 2009). The majority of drainage from central Alberta is northeasterly in direction, which follows the glacial retreat. Thus the melt waters were largely impounded behind the glacier, producing large relatively short lived lakes many hundreds of square miles in area. The rapid recession of the glacier allowed these proglacial lakes to find new outlets. As a result of this most proglaical lakes in the region lack beaches.

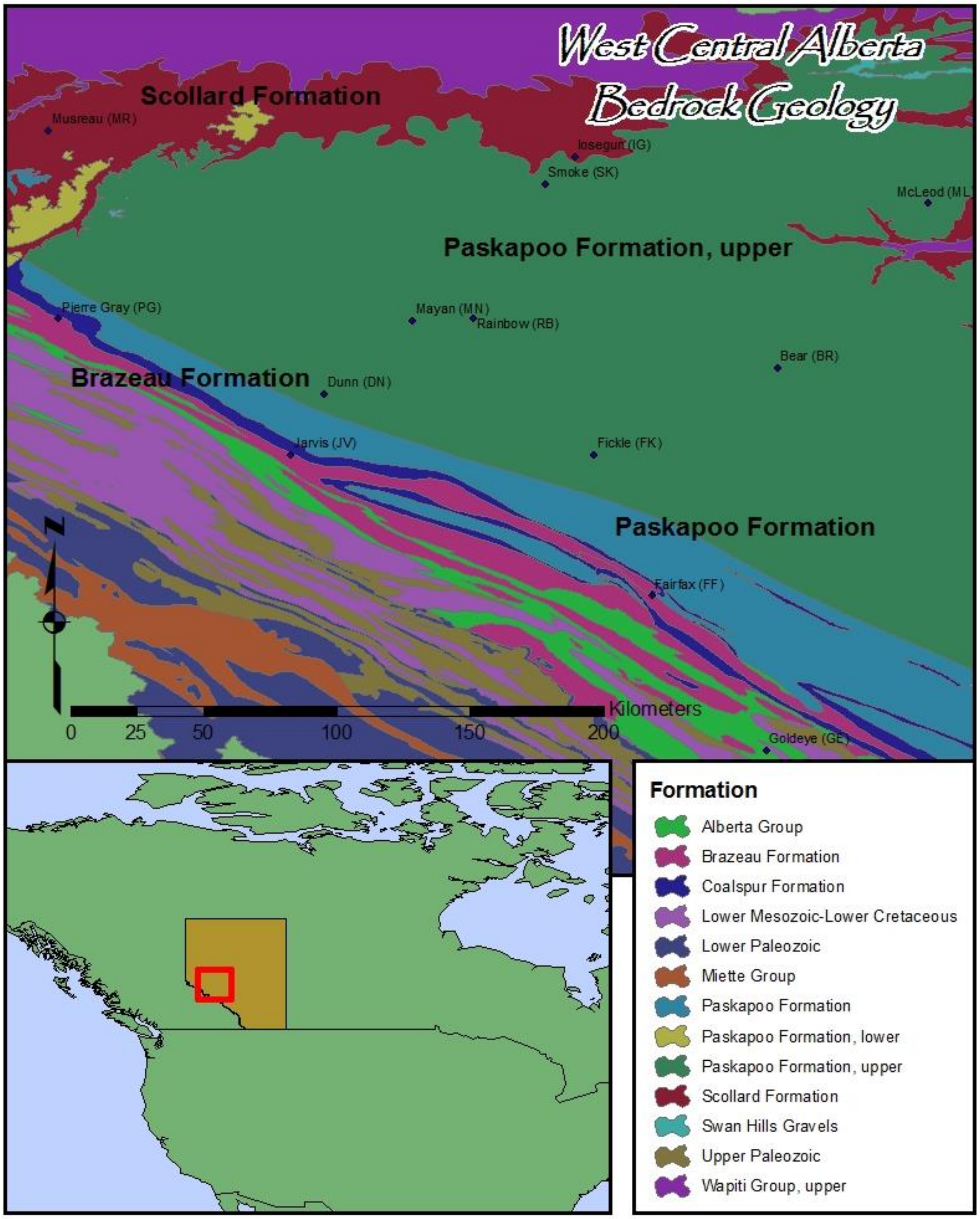


Figure 3. Study lake locations and bedrock geology of the study area.

1.3.4. Land-use

Natural and anthropogenic factors play a crucial role in terrestrial ecosystem functioning, and influence resource availability and productivity across a spectrum of spatial and temporal dimensions (Hilker et al. 2009). Disturbances such as fires, insects, and human activities related to cultivation, settlement, or resource extraction, exhibit a strong influence on the natural functions of the environment.

Over the last decade, Alberta Canada has experienced an unprecedented economic growth due to the rapid expansion of the oil sands industry (Sustainable Resource Development 2008). Developing Alberta's oil resources has been an important facet of Alberta since 1914 when the first major oil field was discovered (Energy 2008). Alberta has an extensive infrastructure in place to facilitate the continued drive to locate, drill and transport oil and natural gas. .

Forest harvesting provides another means of revenue for Canada. The forest products industry is one of Canada's leading manufacturing sectors and its largest exporter (Industry Canada, 2009). It is the corner stone of the economy and a major component of industrial structure and employment base for many regions, including the Rocky Mountain foothills of Alberta.

Both of these activities require the construction of roads and infrastructure in order to maintain a functioning industry. Research has shown that logging activities, like those associated with road construction or clear cutting, lead to an increase in sediment loading to streams (Gucinski *et al*., 2001). The influence of land use on sediment delivery has not been previously investigated in this study area.

1.4. Thesis (Purpose/Objectives)

Thesis Statement: What are the effects of land use change on the accumulation rates of lacustrine sedimentation in lake-catchments in West Central Alberta Canada? Does the core analysis combined with GIS offer a good measure of land use impacts on sediment yield? How does the magnitude and recovery time of highly disturbed watersheds compare to moderately disturbed water sheds?

Objectives: There are two main objectives of this project, which deal with the spatial and temporal aspects of watershed sedimentation:

1) At a decade scale, assess regional patterns of sediment transport in forested catchments of west-central Alberta Canada, and generate general landscape models to predict spatial trends in sediment yield.
2) Identify catchments which have experienced significant sediment delivery over the last century and examine the contributing source areas, the magnitude and duration of the response and underlying causes of the temporal disturbances.

2. Methods

2.1. Data Acquisition

Sedimentation data: The sediment core samples for each lake were collected by Erik Schiefer Ph.D. in July of 2008. Lakes were selected that had experienced a range of historic land use intensities for their contributing watershed areas. Lakes had to be deep enough to minimize the effects of wind mixing and lake/river currents. Sediment cores were sampled via a 2" diameter Kajak-Brinkhurst (K-B) corer (Glew et al., 2001) from the deepest part of the lake. ^{210}Pb dating was completed by Jack Cornett of Mycore Scientific. Detailed descriptions of the sediment core sampling and associated laboratory procedure are available in Schiefer (1999).

Construction of watershed inventory: Use of GIS was an essential part of the development, maintenance and analysis of the watershed inventory database. I used Environmental Systems Research Institute (ESRI) ArcGIS 9.3.1 software, to process the data and derive landscape (Table 3) and historical land use (Table 4) indices used in this analysis. Most of the work was done on a DELL PC, with back up provided by a 280GB external hard drive. There were two main sources of data, topographic data (digital elevation models (DEMs) and shapefiles), and historical imagery (aerial photos and satellite raster data). Topographic vector features are from the National Topographic System (NTS) of Canada, available from Natural Resources Canada (http://ftp2.cits.rncan.gc.ca/pub/bndt/50k_shp_en). The DEMs are from the Canadian Digital Elevation Data (CDED) product, downloaded from the GeoBase website (http://www.geobase.ca/geobase/en/index.html). A brief description of the datasets are as follows:

National Topographic System: This dataset provides general-purpose topographic map features for Canada. The dataset contains detailed ground relief (landforms and terrain), drainage (lakes and rivers), forest cover, administrative areas, populated areas, transportation routes and facilities (includes roads, trails, and railways), as well as other man made features (Natural Resources Canada, 2007). Data is downloaded by 1:50,000 NTS map sheets, and come in a Geographic Coordinate System (GCS) North American Datum 1983 (NAD83).

Canadian Digital Elevation Data: CDED is composed of an ordered array of elevations of regularly spaced intervals (GeoBase, 2010). CDED was extracted from hypsographic and hydrographic elements of the National Topographic Database (NTDB) or various scaled positional data acquired from the provinces and territories of Canada. Grid spacing depends on the latitude of the CDED section, which varies in resolution from a minimum of 0.75 arc seconds to a maximum of 3 arc seconds for the 1:50,000 NTS tiles. Ground Elevations are recorded in meters relative to mean sea level (MSL), and are based on the North American Datum 1983 (NAD83) horizontal reference datum. CDED files are made up of a western and eastern section corresponding to half an NTS map sheet. Downloaded data arrives as ASCII data files.

Table 3. Landscape Indices.

Landscape Indices	Description	Units
1)Watershed Area	Total land area of the lake catchment	km^2
2)Proportion Study Lake Area	Area of the inventoried lake per area watershed	km^2/km^2
3)Proportion Water Features	Total surface area of wetlands (swamps and marsh land) and other lakes except the study lake, within the lake catchment, per area	km^2/km^2
4)Drainage Density	Length of river and streams per area of the catchment	km/km^2
5)Elevation Statistics	Maximum, and minimum elevation, and mean slope	km

Table 4. Land-use Indices.

Land Use Indices	Description	Units
1)Percent Area Cut	Percentage of total land area of the lake catchment that has been logged (includes proportions within a given distance via buffers)	km^2/km^2
2)Road Density	Density of roads within the lake catchment (includes road densities for each road type and/or within a given distance via buffers)	km/km^2
3)Well Density	Density of wells within the lake catchment (includes well densities within a given distance via buffers)	$\#wells/km^2$
4)Cutline Density	Density of cut lines within the lake catchment (includes cut line densities within a given distance via buffers)	km/km^2

Aerial Photos & Satellite Imagery: Air photos were accessed from the National provincial Air Photo reference library, 9920 – 108 Street, Main Floor, Edmonton, Alberta Canada T5K 2M4. Erik Schiefer Ph.D. obtained digital images of the air photos covering the thirteen watersheds, with repeat photography at an approximately decadal interval. These digital images were made available to me for use in this project. Air photos were mostly panchromatic, although a few infrared and color photos were included. Nominal photo scales varied from course, small scale-photography (1:60,000) to fine, large-scale photography (1:15,000). To capture more recent land-use features (2000-2009) in the absence of recent aerial photography, Google Earth imagery was used.

2.2. Data processing and Analysis

2.2.1. Database generation and base map construction

The initial acquisition of the NTS vector data files produced some spatial data unnecessary for this project (e.g. golf courses, communication towers, and vegetation types). Therefore unnecessary shapefiles were removed from the dataset, and the remaining shapefiles were renamed. This file organization was completed using ESRI ArcCatalog. The retained files are listed below in Table 5:

Table 5. NTS data retained for analyses.

Topographic feature	Shapefile name	Shapefile type
Roads	road	polyline
Cut Lines	cut_ln	polyline
Trails	trail	polyline
Streams	water_c	polyline
Lakes	water_b	polygon
Wetlands	wetland	polygon
Wells	well	point

A directory was generated for each lake to house the data, and keep it organized. All derived features for the analysis are also housed in these folders. Some lakes required more than one NTS 1:50,000 topographic map sheet, and in these cases the shapefiles for one map sheet were renamed with data from the remaining map sheets appended, via the ArcMap append tool (ArcToolbox => Data management Tools => General => Append). An ArcGIS map document (.MXD) was generated for each lake and the .MXD housed in the appropriate lake data folder. Shapefiles were added to the .MXD for each lake, in preparation for data extraction and analysis. The study lake for each dataset was extracted out of the water_b shapefile, via the ArcGIS selection tool, and exporting the selected feature to a new shapefile named Study_Lake. Jarvis Lake was extracted and a portion of the lake removed (Figure 4), because a portion of the lake sits in a different watershed, and does not actively contribute to the sedimentation in the portion of the lake where the sediment core was collected.

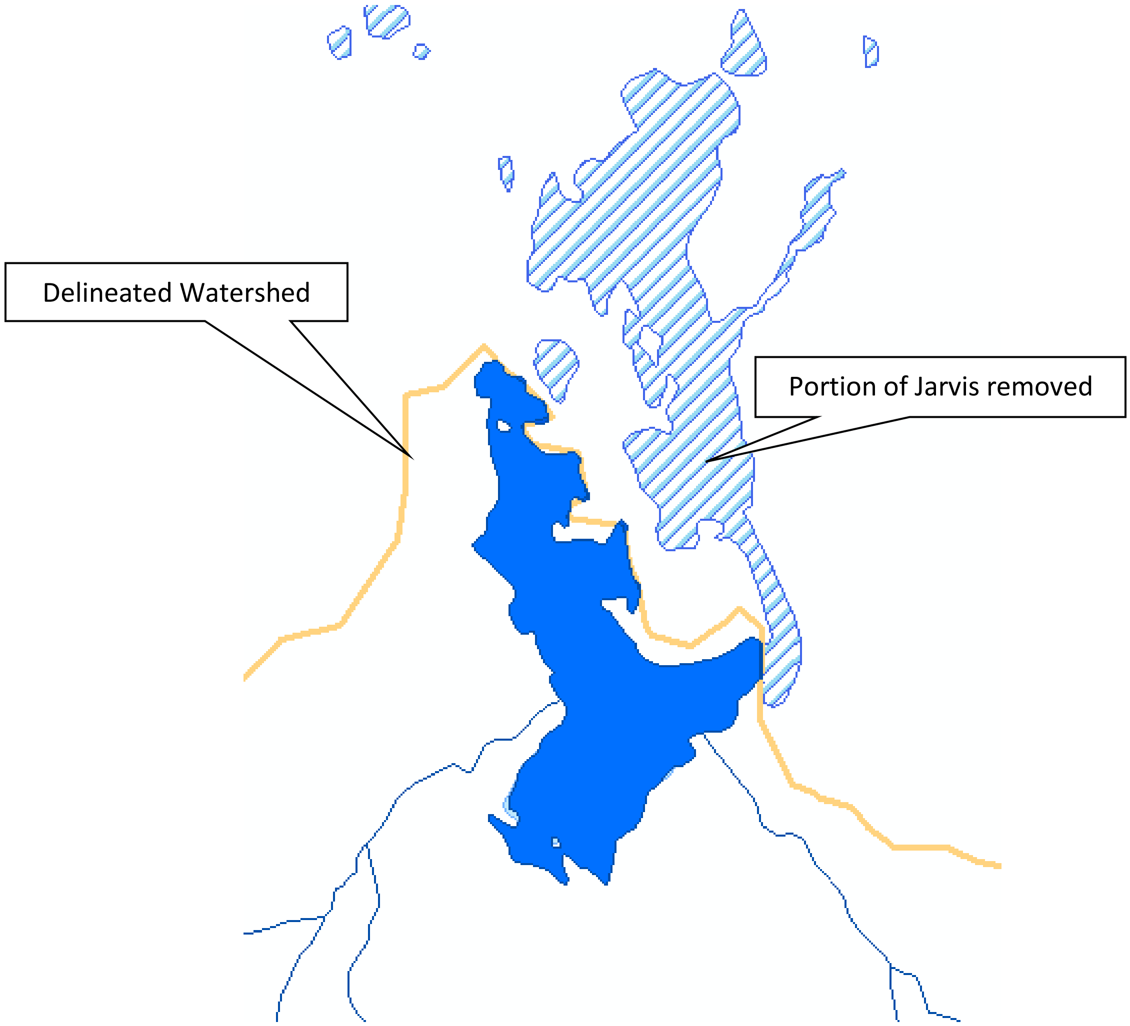


Figure 4. Jarvis Lake indicating the portion removed as part of the analysis.

DEMs were downloaded, decompressed and stored in a raster folder, for each study lake. In order to cover the entire watershed, multiple DEMs were downloaded as required for each lake. The decompressed DEM is in ASCII format which was converted to an ESRI raster (Grid format) for use in GIS analysis. This was accomplished by use of the ArcGIS DEM to Raster tool (ArcToolbox => Conversion Tools => To Raster => DEM to Raster), and the output data type was set to integer. Once all DEM's were converted to a raster format, they needed to be merged into one continuous feature covering the entire watershed. The ArcGIS mosaic tool (ArcToolbox => Data management Tools =>

Raster => Mosaic) would accomplish this task, but first one DEM for each lake was placed into the main GIS data folder and renamed "dem". This was done to accommodate the function of the mosaic tool, as it adds a set of DEM's to a target raster. In this case the target raster would be the renamed DEM.

The final piece of data required to begin extraction of the land-use and landscape indices is a watershed boundary. The DEM for each lake was used to delineate this feature; however the DEM and NTS vector files did not arrive in the same coordinate system. Thus it was necessary to re-project the raster so that the two datasets had the same projection (NAD83 UTM Zone 11N). This was accomplished with the Project Raster tool (ArcToolbox=>Data Management Tools=>Projections and Transformations=>Project Raster).

To delineate a watered using a DEM, several steps are required (Figure 5). To eliminate sinks, which would interfere with the overall flow modeling, the Fill tool is used (ArcToolbox => Spatial Analyst Tools => Fill) (DeMers, 2002). Flow direction is calculated next via use of the Flow Direction tool (ArcToolbox => Spatial Analyst Tools => Flow Direction), with the filled DEM as input to the tool. The study lake shapefile is converted to a Raster to be used as the pour point in the watershed analysis. This was completed by use of the Feature to Raster tool (ArcToolbox => Conversion Tools => To Raster => Feature to Raster). It is now possible to delineate the watershed by use of the ArcToolbox tool Watershed, which will analyze the flow direction and determine the area from which water will flow into our pour point, which is the lowest point in the basin (in this case the study lake). The watershed is generated, but the output is raster, thus the final step is to convert the raster to a polygon to make future analyses more convenient. This is accomplished with the ArcToolbox tool Raster to Polygon tool (ArcToolbox => Conversion Tools => From Raster => Raster to Polygon).

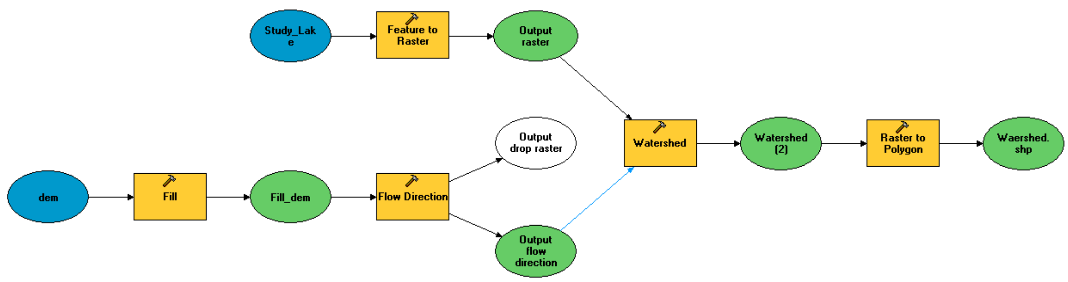


Figure 5. Work flow for delineation of a watershed from DEM.

2.2.2.   Landscape and land-use indices

Landscape indices (Table 3): To derive the watershed area, an area attribute was added to the watershed attribute table and the Calculate Geometry function, available under options in the attribute table, was used to calculate the area. Proportion study lake area, proportion water features and drainage density were calculated in Microsoft (MS) Excel. Elevation statistics were calculated by use of the Zonal Statistics as Table tool (ArcToolbox => Spatial Analyst Tools => Zonal => Zonal Statistic as Table). This tool uses a raster or vector feature to identify a zone and summarize the raster values within the zone. The input for the zone feature was the watershed shapefile, thus the elevation and slope raster values outside the watershed would not be included. The elevation raster used was the DEM (elevation in meters), and the slope raster was generated from the DEM raster via use of the Slope tool (ArcToolbox => 3D Analyst tools => Raster Surface => Slope). Slope was calculated in degrees.

Land-use indices (Table 4): To derive the land use indices, it is necessary to calculate the area (clear cuts), length (cut lines, roads, and trails), or number (wells) of land use features within the watershed for each lake, and assign a time frame for construction of said feature. This was accomplished by confirming the NTS land use features in the air photos and assigning an appropriate time for construction based on the date of the earliest the air photo that contained the feature.

Air photos were separated into folders based on the lake, then into sub-folders based on the year the photo was taken. By adding the aerial photos to their respective lake's map document and geo-referencing them, it was possible to confirm the existence of land-use features, and establish a time period over which the feature was constructed. Two attributes (photo_null and photo_exist) were added to all shapefiles to house this data. Starting with the earliest set of air photos and moving forward towards 2009 imagery, vector features were confirmed and dates for each added to the attribute table. The date of the previous photo (which did not show the feature) was added to the photo_null attribute, and the date of the current photo was added to the photo_exist attribute. If a feature appeared in the photo but did not exist in the NTS data, the feature was digitized, and the photo date attributes added. Prior to beginning this process, the NTS vector data was re-projected into NAD83 Universal Transverse Mercator (UTM) Zone 11N projection, to change map units from degrees to meters.

Once all features were confirmed and dated via air photos and Google Earth imagery, they were clipped to the watershed boundary. A new attribute was added to the attribute table for each feature except wells, to store the area or length of the respective feature. The Calculate Geometry function was used to calculate the area for the cuts, and to calculate the length for road, trail and cut_ln, features.

The total area and length for each time period was calculated by use of the Summarize function under options in the attribute table. This function generates a database table (dBASE) based on user selected attributes. In this case Summarize was used on the photo_exist attribute, and would calculate the minimum, maximum, average, sum, standard deviation and variance, for the length or area of the feature. These dBASE files were opened in MS Excel and combined into one workbook containing the data for each lake in a separate worksheet with cumulative totals calculated, and a worksheet containing the data for all lakes. Data was standardized by dividing lengths, counts, and areas by the watershed area, to derive land use densities.

Land-use indices were also produced at various buffer distances from water features (study lake and streams). Streams in the watershed were included only if they flowed directly into the lake. Other water bodies act like sediment sinks, thus streams flowing into these sinks would not contribute to the sediment in the study lake.

Buffers were generated at 10, 50, 250, and 500 meters from the study lake and associated streams, with land-use features clipped to these buffer zones. To facilitate a timely completion of this process, several models were built (Appendix. 7.1). These models automated the generation of buffers, extraction of land-use features, and the calculation of areas or lengths. One model was built for each process, with the extraction and calculation models completing the process for all 4 buffer distances simultaneously. The lengths and areas were summarized and the data added to the MS Excel workbook. The area of watershed within each buffer distance was calculated and used to calculate the density of land use within the buffers.

2.2.3. Sedimentation data

Sediment base data was received from Mycore Labs, which included a sediment accumulation rate (SAR) ($g/m^2/yr$) and Age at the top of sediment core sub-sections per lake. This data was used to calculate background sedimentation rates, percent above background, specific background sedimentation rates, and specific sediment yield. The following equations were used to calculate these variables:

1) Background sedimentation rates: $\frac{sum\ (sedimentation\ rate)}{n}$, where sedimentation rates are defined as those having dates prior to major land-use identification and which occurred after 1900. n is the number of rates with dates after1900 and before major land-use. Values older than 1900 were excluded because they had high amounts of uncertainty.
2) Background sedimentation yield: $background\ sedimentation\ rate \times lake\ area$
3) Background specific sediment yield: $\frac{background\ sedimentation\ rate \times lake\ area}{watershed\ area}$
4) Percent above background (calculated for time intervals following the onset of land use): $\left(\frac{sedimentation\ rate - background\ sedimentation}{background\ sedimentation}\right) 100$

Note that for Bear, Jarvis, and Pierre Gray, there was a slight deviation in the calculation of background sedimentation rate, due to outlier data points. It was felt that background sedimentation rates for these lakes were more accurately represented when omitting these outliers. Because the photo intervals do not match the dates for the ages at the top of each section of sediment, it was necessary to calculate average sedimentation rates and average percent above background values for the photo intervals. This was done by assigning the sedimentation rate of the top of each section to all dates less than or equal to the date associated with the top section. Once completed an average could be calculated for the interval between photos.

2.2.4. Statistical analysis

Statistical analyses consisted of correlation tests (Spearman's Rank) and bivariate and multivariate regressions. Comparisons were made among various landscape and land-use indices between those indices and the sedimentation data. Statistics were calculated in MS Excel, and in R. Some of the statistics were computed using the XLStat add in for MS Excel by Addinsoft.

Watershed analysis: Regressions were run on all the static landscape variables, to evaluate their relations with sedimentation rates, and to evaluate relations between landscape variables. Since the data does not conform to a normal distribution, a spearman's rank correlation (non-parametric test) was also run on these datasets. All analyses in this step used MS Excel with some analyses using the XLStat add in. Logarithmic and power transformations were applied to the data to also explore potential non-linear relations between variables.

Spatial analysis: Bivariate regressions were run between the averaged percent above background sedimentation data for the total time interval following the onset of land-use and each of the land-use density variables (buffers and watershed totals). Since the data does not conform to a normal distribution, a Spearman's rank correlation (non-parametric test) was also run on these datasets. All analyses in this step used MS Excel with some analyses using the XLStat add in. Multivariate regressions were also explored using R.

Temporal analysis: To accommodate the temporal analysis, each lake was broken into intervals corresponding to the air photo dates. Thus land-use is identified for each air photo interval, representing the temporal aspect of land-use. The date of the top layer of sediment was used and averaged over the photo intervals, to get sedimentation rates for said intervals. Bivariate and multivariate regressions were completed for all land-use categories, comparing land-use datasets with the percent average above background sedimentation dataset. These regressions were completed in the R statistics software package. Due to some heteroscedasticity with the regression results, the data was subset into high and low land-use densities and a Welch Two Sample t-test (difference of means) and an F test (difference in variation) were performed in R.

Note: For all statistic analyses trails and roads are combined. I had to verify the existence of trails in air photos, and only large trails which are used by vehicles were visible. Thus trails and roads have little variation in function, and are assumed to have similar impacts on sedimentation rates.

3. Results

3.1. Watershed analysis

3.1.1. Bear

Sedimentation: The background sedimentation rate was calculated as 57.11 $g/m^2/yr$, but was modified to 52.20 $g/m^2/yr$ when outlier points were removed from the calculation. Specific sediment yield was found to be 10.69 $g/m^2/yr$ (4th highest of the lakes). Average sediment accumulation rate above background following the onset of regular land-use activities was 70.7$g/m^2/yr$ (2nd lowest of the lakes). Average Sediment accumulation rates and average percent above background values were calculated for each photo interval and are as follows:

Date interval	Average SAR	Average Percent above Background
1949-1951	52.23	-8.56
1952-1958	52.23	-7.69
1959-1969	52.85	-2.46
1970-1980	57.12	0.03
1981-1989	63.29	10.82
1990-2000	70.67	23.74
2001-2009	86.18	50.90

Land-use: The Bear lake watershed (7.54km^2) has 7.84km of cut lines, 5.82km of roads, 2.46km of trails, 1.77km^2 of clear cut, and 0 wells within its boundary. Land-use density was calculated, with 1.04km/km^2 of cut lines, 0.77km/km^2 of roads, 0.33km/km^2 of trails, and 0 wells/km^2. Percent area cut is 0.24%. 4.6km of roads and 0.94km^2 of clear cuts existed prior to the first photo dated 1949, but no other land-use was noted until 1969. Between 1958 and 1969 2.37km of cut lines, 5.67km of roads, 1.5 km of trails, and 1.3461km^{2}of clear cut land-use was evident. Cut lines increased again between 1969 and 1980 rising to 3.21km and maxing out in 1989 with 7.84km. Roads and trails increased between 1980 and 1989, maxing out at 5.82km and 2.46km respectively. Clear cuts increased between 1969 and 1980, 1989 and 2000, 2000 and 2009, increasing to 1.72km^2, 1.73km^2, and 1.78km^2 respectively. No wells were identified in the catchment.

Cleared land is concentrated along the eastern edge of the catchment. Trails are located directly north of the lake. Cut lines are noted throughout the watershed, with most occurring north of the lake. Roads run along the eastern and southern portion of the catchment. About 15 homes constructed between 1951 and 1958, occupy the southern shore of the lake. There is also a campground and boat launch ramp on the southern shore. Minor agricultural activity takes place at the eastern edge of the watershed.

Visual inspection of plots for cutline, road, and trail densities, percent area cut, and percent above background (Appendix 7.2.1) indicates a possible correlation between sedimentation and land use variables. As seen in the graphs the increase in land-use (particularly cutlines) corresponds with an increase of sedimentation above background rates beginning around 1980.

3.1.2. Dunn

Sedimentation: The background sedimentation rate was calculated as 36.19 g/m^2/yr. Specific sediment yield was found to be 5.0369 g/m^2/yr (5th lowest). Sediment accumulation rate above background was 72.6 g/m^2/yr (3rd lowest). Average sediment accumulation rates and average percent above background values were calculated for each photo interval and are as follows:

Date interval	Average SAR	Average Percent above Background
1952-1963	44.16	-14.48
1964-1981	53.36	16.98
1982-1988	60.70	39.11
1989-2001	72.85	67.11
2001-2008	97.91	112.29

Land-use: The Dunn watershed (0.86km^2) has 1.44km of cut lines, 0.62km of roads, and 0.72km of trails. Clear cut land totals 0.12km^2 and there are no wells identified in the area. The first air photo used for this area was dated 1952, although no land-use was identified. Land use near Dunn appeared first in the 1963 photo and showed 0.72km of trails. Cut lines appeared fist between the 1963 and 1981 photo interval, with 0.34km of cut lines, which increased to 1.44km in 1988. Roads did not appear until 2001, when 0.62km of roads were visible within the catchment. Clear cuts also appeared in 2001, with 0.12km^{2}of land cleared.

Cleared land is found only in the north east portion of the catchment. Cut lines are noted to the east and north of the lake. Roads and trails run in the east west direction in the northern portion of the catchment. A minor trail runs down to the north shore of the lake where a boat can be launched.

Visual inspection of plots of cut line, road, and trail densities, percent area cut, and percent above background (Appendix 7.2.2) indicates a potential correlation between sedimentation increases over background and land-use change. Starting close to 1980, the percent above background begins to increase rapidly, with corresponding changes in percent area cut, cut line density and road density.

3.1.3. Fairfax

Sedimentation: The background sedimentation rate was calculated as 112.6 $g/m^2/yr$. Specific sediment yield was found to be 21.89 $g/m^2/yr$ (2nd highest). Sediment accumulation rate above background was 160.6 $g/m^2/yr$ (5th highest). Average sediment accumulation rates and average percent above background values were calculated for each photo interval and are as follows:

Date interval	Average SAR	Average Percent above Background
1952-1957	121.28	7.73
1958-1970	133.38	18.47
1971-1973	143.90	27.82
1974-1978	152.27	35.25
1978-1980	151.54	34.60
1981-2002	166.64	48.02
2003-2009	148.68	32.06

Land-use: The Fairfax watershed ($1.62km^2$) has 1.0km of cut lines, 0.44km of roads, and 0km of trails. Clear cut land totals $0.45km^2$ and there are no wells identified in the area. The first air photo used for this area was dated 1952, although no land-use was identified. Land use For Fairfax first appeared first in the 1970 photo and showed 0.20km of cut lines and .44km of roads. Cut lines increased between the 1973 and 1978 photo interval, totaling .65km of cut lines, which increased to 1.0km in 2002. Clear cuts also appeared in 2002, with $0.04km^2$of land cleared, and increased to $0.45km^2$ in 2009.

Cleared land appears on all sides of Fairfax Lake, with the largest area cleared to the north. Cut lines are concentrated on the east end of the lake. There is one road visible within the catchment and it is located in the western most portion of the catchment. There is a campground and a boat launching ramp on the south side of the lake.

Visual inspection of plots of cut line, road, and trail densities, percent area cut, and percent above background (Appendix 7.2.3) indicates a potential correlation between sedimentation increases over background and land-use change. Percent above background increases steadily from 1950 to past 1990. Road, cut line and trail density also increases over this point. Percent above background drops about 2000 and again begins to increase; this trend is not noted in the land use graphs.

3.1.4. Fickle

Sedimentation: The background sedimentation rate was calculated as 75.0 $g/m^2/yr$. Specific sediment yield was found to be 2.76 $g/m^2/yr$ (4th lowest). Sediment accumulation rate above background was 100.6 $g/m^2/yr$ (5th lowest). Average sediment accumulation rates and average percent above background values were calculated for each photo interval and are as follows:

Date interval	Average SAR	Average Percent above Background
1951-1965	79.44	5.92
1966-1970	74.16	-1.12
1971-1973	74.08	-1.23
1974-1981	74.93	-0.10
1982-1989	81.59	8.78
1990-2000	99.20	32.26
2001-2009	129.81	95.30

Land-use: The Fickle watershed (102.20km^2) has 351.30km of cut lines, 33.30km of roads, and 8.39km of trails. There are 17 wells, and no clear cut land is evident. Land-use was first evident in 1965 when 71.21km of cut lines were identified in the air photos. Cut lines increased in all photo intervals, increasing in 1970, 1973, 1981, 1989, 2000, and 2009, with totals of 136.77km, 141.83km, 144.67km, 223.84km, 351.1km, and 351.3km respectively. Roads are first noted in 1970 with 11.27km of roads. Roads increase in each successive photo interval, 1973, 1981, 1989, 2000, 2009, totaling 11.79km, 12.66km, 22.50km, 29.74km, and 33.3km respectively. Trails first appear in 1973 totaling 5.42km, increasing in 1989 to a maximum of 8.39km. Wells first appear in 1981 and increase in each subsequent photo interval 1989, 2000, and 2009 totaling 3, 7, 11, and 17 wells respectively. There is no cleared land evident.

Cut lines are noted over the entire catchment. Roads run mostly north and south, and are located in the middle of the catchment and along the western edge. Wells are scattered over the catchment but are concentrated near the roads. There is a campground and boat launching ramp on the east side of the lake.

Visual inspection of plots of cut line, road, trail, and well densities, and percent above background (Appendix 7.2.4) indicates a potential correlation between sedimentation increases over background and land-use change. The percent above background increases steadily beginning after 1980. A similar trend is evident with well density and cutline density.

3.1.5. Goldeye

Sedimentation: The background sedimentation rate was calculated as 48.2 g/m^2/yr. Specific sediment yield was found to be 0.98 g/m^2/yr (lowest of the lakes). Sediment accumulation rate above background was 80.8 g/m^2/yr (4th lowest). Average sediment accumulation rates and average percent above background values were calculated for each photo interval and are as follows:

Date interval	Average SAR	Average Percent above Background
1950-1958	60.64	25.75
1959-1974	66.83	38.58
1975-1980	66.74	38.41
1981-1983	67.61	40.20
1984-1991	69.87	44.90
1992-2002	73.70	52.83
2003-2008	101.39	110.26

Land-use: The Goldeye watershed (5km^2) has 1.82km of cut lines, 4.11km of roads, and 0km of trails. There is 0.07km^2 of clear cut land, and 0 wells evident. Land-use was evident in the earliest photo with 0.83km of roads appearing in the 1950 photos. Road length increased in 1974 to the max of 4.11km. Cut lines first appeared in the 1974 photos totaling 1.82km. Cut lines did not appear in later photo intervals. Cleared land first appeared in the 1974 photos, totaling 0.07km^2. Additional cleared land was not evident in subsequent intervals. There were 0 trails and 0 wells noted in the catchment.

Cut lines and cleared land were identified immediately to the north east of the lake. Roads run north south dividing the catchment roughly in half. There is a lodge, campground, and boat launch ramp on the east side of the lake.

Visual inspection of plots of cut line, road, and trail densities, percent area cut, and percent above background (Appendix 7.2.5) does not indicate a potential correlation between sedimentation increases over background and land-use change. Percent above background increases steadily beginning in 1950, and increasing rapidly after about 2000. Land use begins to increase in just prior to 1960 but stabilizes prior to 1980.

3.1.6. Iosegun

Sedimentation: The background sedimentation rate was calculated as 154.8 $g/m^2/yr$. Specific sediment yield was found to be 7.67 $g/m^2/yr$ (6^{th} highest). Sediment accumulation rate above background was 449.4 $g/m^2/yr$ (highest of all lakes). Average sediment accumulation rates and average percent above background values were calculated for each photo interval and are as follows:

Date interval	Average SAR	Average Percent above Background
1949-1957	298.62	92.87
1958-1970	362.97	134.42
1971-1981	386.77	149.80
1982-1991	447.11	188.77
1992-1998	453.58	192.95
1999-2008	507.13	227.54

Land-use: The Iosegun watershed (273.21km^2) has 504.59km of cut lines, 227.83km of roads, and 27.91km of trails. There is 19.99km^2 of clear cut land, and 131 wells evident. Land-use was appeared in the 1957 photos with 210.01km of cut lines, 21.13km of roads 6.25km of trails. Road length increased in all subsequent air photo intervals, 1970, 1981, 1991, 1998, and 2008, with totals of, 130.77, 181.99, 211.02, 227.21, 227.82 km respectively. Cut lines increased in all subsequent photo intervals; 1970, 1981, 1991, 1998, and 2008, with totals of, 408.2, 443.56, 485.74, 504.25, and 504.59 km respectively. Cleared land first appeared in the 1970 photos, totaling 4.54km^2. Additional cleared land was evident the following three photos: 1981, 1991, and 1998 totaling 6.8, 14.89, and 19.99 km^2 respectively. Wells also appeared in the 1970 photos with 40 wells, and increased in all subsequent photos 1981, 1991, 1998, and 2008, with totals of 73, 90, 121, and 131 respectively.

Cut lines are disbursed throughout the catchment, and are noted running to the shore of the lake and crossing streams and wetlands. Wells are found over the entire catchment, but are clustered near the lake and the south western portion of the watershed (which borders the smoke watershed). Roads are found over the entire catchment but are more concentrated south of the lake. Trails are dispersed east-west along the middle of the catchment. Cleared land is only found in the southern portion of the watershed. There is a campground and boat launching ramp on the east side of the lake. The small town of Fox Creek is located within the watershed about 5km south of the lake.

Visual inspection of plots of cut line, road, and trail densities, percent area cut, and percent above background (Appendix 7.2.6) indicates a potential correlation between sedimentation increases over background and land-use change. Percent above background increases steadily beginning in 1950, and increasing rapidly after about 2000with a sharp decline in about 2005, rebounding sharply. Land use begins to increase in roughly around 1950 and increases at a steady pace. However, there is no noticeable decline in land-use corresponding to the sharp decline in percent above background which occurs between 2000 and 2005.

3.1.7. Jarvis

Sedimentation: The background sedimentation rate was calculated as 103.98 g/m2/yr, but was modified to 75.7 g/m2/yr when outlier points were removed from the calculation. Specific sediment yield was found to be 1.67 g/m2/yr (3rd lowest). Sediment accumulation rate above background was 159.6 g/m2/yr (6th highest). Average Sediment accumulation rates and average percent above background values were calculated for each photo interval and are as follows:

Date interval	Average SAR	Average Percent above Background
1951-1965	157.09	51.07
1966-1974	134.64	29.49
1975-1981	134.64	29.49
1982-1985	209.28	101.26
1986-1989	209.28	101.26
1990-2008	149.44	43.71

Land-use: The Jarvis watershed (31.86km^2) has 14.62km of cut lines, 19.44km of roads, and 28.99km of trails. There is 1.43km^2 of clear cut land, and 5 wells evident. 12.31km of roads were visible in the earliest photos dated 1951. Roads increased in all but two of the subsequent photo intervals, increasing in the 1965, 1974, 1985, and 1989 photos. Totals were 12.76, 18.31, 19.31, and 19.44km respectively. Cut lines first appeared in the 1965 photos with increases noted in the 1974, and 1985 photos. Totals were 12.39, 13.75, 14.62 km respectively. 24.11 km of trails were identified in the 1989 which increased to 28.99km in the 2008 imagery. Cleared land was not evident except in the 2008 imagery. Wells first appeared in the 1974 photos, with 4 wells. One well was added during the 1981-1985 interval.

Cut lines are disbursed throughout the catchment. Wells are located near the lake and along the border of the watershed to the southeast of the lake. Roads are found only in the eastern half of the watershed. Trails are concentrated in the south east and western portions of the catchment. Cleared land is only found in the north-central portion of the watershed. Jarvis Lake is located entirely within the William A Switzer Provincial Park and there are several lodges, campgrounds, and boat launching ramps surrounding the lake. A Nordic center is located south of the lake within the park. Most of the watershed is outside the park boundary.

Visual inspection of plots of cut line, road, and trail densities, percent area cut, and percent above background (Appendix 7.2.7) does not indicate a potential correlation between sedimentation increases over background and land-use change. Percent above background rises and falls repeatedly, beginning just after 1960. There are no similar trends with any of the land-use plots, with the exception of trails which increases and peaks in synch with the percent above background plots between 1980 and 1990.

3.1.8. Mayan

Sedimentation: The background sedimentation rate was calculated as 75.2 $g/m^2/yr$. Specific sediment yield was found to be 6.55 $g/m^2/yr$ (middle of all lakes). Sediment accumulation rate above background was 112.0 $g/m^2/yr$ (6^{th} lowest). Average sediment accumulation rates and average percent above background values were calculated for each photo interval and are as follows:

Date interval	Average SAR	Average Percent above Background
1957-1970	81.37	8.22
1971-1981	80.03	6.43
1982-1993	90.87	20.84
1994-2008	127.06	75.63

Land-use: The Mayan watershed (0.73km^2) has 2.0km of cut lines, 1.75km of roads, and 0km of trails. There is 0.25km^2 of clear cut land, and 2 wells evident. Land use first appeared in the 1970 photos, with 1.97km of cut lines. This increased to 2.0km in the 1981-1993 photo interval. Roads, cleared land, and wells all appeared in the last photo interval (1993-2008). A minor trails runs down to the west margin of the lake where it is possible to launch a small boat.

Cut lines are found in the southern half of the catchment. The two wells are found in the north-west portion of the watershed. Roads were identified throughout the catchment, with the exception of the northernmost portion of the watershed. Trails are concentrated in the south east and western portions of the catchment. Cleared land is only found in the north-central portion of the watershed.

Visual inspection of plots of cut line, road, and trail densities, percent area cut, and percent above background (Appendix 7.2.8) indicates a potential correlation between sedimentation increases over background and land-use change. Percent above background increases steadily from about 1960 to about 1995 when it begins to increase more rapidly. Well and road density and percent area cut all increase dramatically at about the same time interval.

3.1.9. McLeod

Sedimentation: The background sedimentation rate was calculated as 86.9 $g/m^2/yr$. Specific sediment yield was found to be 6.21 $g/m^2/yr$ (6th lowest). Sediment accumulation rate above background was 305.6 $g/m^2/yr$ (3rd highest). Average sediment accumulation rates and average percent above background values were calculated for each photo interval and are as follows:

Date interval	Average SAR	Average Percent above Background
1971-1982	162.47	87.03
1983-1991	235.17	170.72
1994-2008	322.99	285.16

Land-use: The McLeod watershed (47.88km^2) has 55.95km of cut lines, 45.48km of roads, 11.14km of trails, 8.40km^2 of cleared land, and 25 wells. Cut lines, roads, trails, and wells were evident in the earliest photos (1971), which totaled 54.125km cut lines, 45.39km roads, 10.34km trails, and 19 wells. Cut lines and trails increased during the 1982-1991 photo interval, to 55.95km roads and 11.14km of trails. Roads increased in the 1971-1982 photo interval to a maximum of 45.48km. New wells were identified in the 1982 and 1991 photos increasing the total of wells to 23 and 25 respectively.

Wells, cut lines and roads are dispersed throughout the catchment. Trails are found along the border of the lake. Clear cut land is concentrated in the northern half of the catchment, with the exception of a small clear cut at the southern most point of the watershed. McLeod Lake is situated entirely within the Carson-Pegasus Provincial Park. There is a visitor center, boat launch, park pavilions, and campgrounds located on the prominent peninsula that dissects the lake body, As with Jarvis Lake, most of the watershed is outside the park boundary.

Visual inspection of plots of cut line, road, and trail densities, percent area cut, and percent above background (Appendix 7.2.9) indicates a potential correlation between sedimentation increases over background and land-use change, particularly with area cut. Percent above background increases sharply from starting roughly in 1960, with higher rates noted after 1980. Percent area cut begins to increase rapidly just after 1980. Other land-use is mostly stable during this time.

3.1.10. Musreau

Sedimentation: The background sedimentation rate was calculated as 284.4 $g/m^2/yr$. Specific sediment yield was found to be 15.18 $g/m^2/yr$ (3rd highest). Sediment accumulation rate above background was 441.3 $g/m^2/yr$ (2nd highest). Average sediment accumulation rates and average percent above background values were calculated for each photo interval and are as follows:

Date interval	Average SAR	Average Percent above Background
1950-1957	334.02	17.43
1958-1975	411.86	44.79
1976-1986	504.00	77.19
1987-1995	419.57	91.95
1996-2008	404.20	42.10

Land-use: The Musreau watershed (104.57km^2) has 141.54km of cut lines, 56.34km of roads, 0.77km of trails, 42.77km^2 of cleared land, and 24 wells. Cut lines, roads and trails all appeared in the 1957 photos, and totaled 58.32km of cut lines, 8.48km of roads, and 0.60km of trails. Cut lines increased in all subsequent photo intervals except the exception of 1995-2008 image interval. Cutline totals were 131.63km in the 1975 photos, 140.96km in the 1986 photos, 141.54km in the 1995 photos. Roads increased over all photo intervals, with road total lengths of 19.57km, 54.14km, 54.70km, and 56.34km, as noted in the photos dated 1975, 1986, 1995, and 2008. Cleared land increased in areas in the following photo intervals, 1975-1986, 1986-1995, and 1995-2008, with totals of 27.18km^2, 40.91 km^2, and 42.77km^2 respectively.

Cut lines are disbursed throughout the catchment, and are noted running to the shore of the lake and crossing streams and wetlands. Roads and Wells are dispersed over the western and northern portions of the catchment. Trails are found bordering the lake. Cleared land dispersed over the entire watershed with a lower density noted near the lake. There is a large campground and boat launch on the north shore of the lake.

Visual inspection of plots of cut line, road, and trail densities, percent area cut, and percent above background (Appendix 7.2.10) does not indicate a correlation between sedimentation increases over background and land-use change. Percent above background increases steadily from 1940 to roughly 1990, when there is a drop in percent above background, until about 2000 when it begins to increase again. These trends are not seen in any of the land-use plots. Cutline density grows quickly early then stabilizes. Roads grow slightly in the mid 1990's and stabilize, while trail and well densities remaining low throughout. Area cleared experiences a rapid increased during the period percent above background is in decline.

3.1.11. Pierre Gray

Sedimentation: The background sedimentation rate was calculated as 75.56 g/m2/yr, but was modified to 70.3 g/m2/yr when outlier points were removed from the calculation. Specific sediment yield was found to be 53.73 g/m2/yr (highest of all lakes). Sediment accumulation rate above background was 53.74 g/m2/yr (lowest of the lakes). Average Sediment accumulation rates and average percent above background values were calculated for each photo interval and are as follows:

Date interval	Average SAR	Average Percent above Background
1951-1958	81.33	7.64
1959-1975	64.16	-15.08
1976-1981	53.40	-29.32
1982-1990	53.56	-29.11
1991-1999	59.08	-21.81
2000-2008	76.73	1.55

Land-use: The Pierre Gray watershed ($0.50km^2$) has 0km of cut lines, 0.27km of roads, 0km of trails, $0km^2$ of cleared land, and 0 wells. Roads appear in the 1975 photos with 0.27km of roads. No increases are noted in subsequent photo intervals. Roads are found to the west of the lake. There is a large campground and boat launching ramp on the west shore of the lake. The entire watershed is now protected land within Pierre Gray's Lakes Provincial Park.

Visual inspection of plots of cut l.ne, road, and trail densities, percent area cut, and percent above background (Appendix 7.2.11) does not indicate a correlation between sedimentation increases over background and land-use change. Percent above background is erratic positive between about 1935 and 1960, then again between 2005 and 2010. These trends are not seen in any of the land-use plots.

3.1.12. Rainbow

Sedimentation: The background sedimentation rate was calculated as 79.1 $g/m^2/yr$. Specific sediment yield was found to be 1.19 $g/m^2/yr$ (2nd lowest). Sediment accumulation rate above background was 113.3 $g/m^2/yr$ (middle of all lakes). Average Sediment accumulation rates and average percent above background values were calculated for each photo interval and are as follows:

Date interval	**Average SAR**	**Average Percent above Background**
1951-1957	84.50	6.75
1958-1970	88.54	11.86
1971-1981	95.99	21.28
1982-1993	100.47	26.94
1994-2009	129.74	63.92

Land-use: The Rainbow watershed (4.44km^2) has 11.15km of cut lines, 5.06km of roads, 0km of trails, 0km^2 of cleared land, and 0 wells. Roads appear in the 1957 photos with 1.09km of roads. Road length increases in all subsequent photo intervals except the final interval, with totals of 4.13km, 6.22km, and 11.15km appearing in the 1970, 1981, and 1993 photos. Roads are not evident until the 1993 photos, with 1.63km of roads visible in the imagery. Roads increase between 1993 and 2009 totaling 5.06km.

Cut lines are dispersed over the catchment, with a higher density in the southern portion of the watershed. Roads run along the western and northern border of the catchment. The cut line that runs down to the north shore of the lake makes for a very rough trail for accessing the lake and launching a portable boat.

Visual inspection of plots of cut line, road, and trail densities, percent area cut, and percent above background (Appendix 7.2.12) indicates a potential correlation between sedimentation increases over background and land-use change. Percent above background increases steadily beginning after 1970, and increases steadily, until a sharp increase between 2000 and 2005. Cutline density begins in the 1950's and grows steadily until the 1990's when it levels off. Road density increases steadily beginning after 1980. The plot for road density seems to be a good fit with percent above background sedimentation rates.

3.1.13. Smoke

Sedimentation: The background sedimentation rate was calculated as 112.6 $g/m^2/yr$. Specific sediment yield was found to be 7.69 $g/m^2/yr$ (5^{th} highest). Sediment accumulation rate above background was 167.3 $g/m^2/yr$ (4^{th} highest). Average Sediment accumulation rates and average percent above background values were calculated for each photo interval and are as follows:

Date interval	Average SAR	Average Percent above Background
1949-1958	106.75	-5.18
1959-1970	123.34	9.56
1971-1981	129.29	14.85
1982-1991	147.61	31.12
1992-1998	169.23	50.31

1999-2008	206.69	83.60

Land-use: The Smoke watershed (133.93km^2) has 208.70km of cut lines, 119.13km of roads, and 4.70km of trails. There is 35.12km^2 of clear cut land, and 104 wells evident. Land-use was appeared in the 1958 photos with 88.6km of cut lines, 2.0km of roads 1.96km of trails. Road length increased in all subsequent air photo intervals, 1958-1970, 1971-1981, 1982-1991, 1992-1998, and 1999-2008, with totals of, 91.22km, 100.04km, 108.83km, 118.42km, and 119.13km respectively. Cut lines increased in all subsequent photo intervals except the final interval, with totals of, 173.92km, 183.10km, 202.19km, and 208.70km respectively. Cleared land first appeared in the 1970 photos, totaling 6.85km^2. Additional cleared land was evident the following four photos: 1981, 1991, 1998, and 2008 totaling 10.10km^2, 33.23 km^2, 34.65 km^2, and 35.12 km^2, respectively. Wells also appeared in the 1970 photos with 68 wells, and increased in all subsequent photos intervals, with totals of 81, 92, 99, and 104 wells respectively.

Cut lines are disbursed throughout the catchment, and are noted running to the shore of the lake and crossing streams and wetlands. Wells are found over the entire catchment, but are clustered near the lake and through the central portion of the watershed. Roads are found over the entire catchment. Trails are dispersed east-west along the middle of the catchment. Cleared land is concentrated in the southern portion of the watershed. There is a refinery constructed between 1958 and 1970, located within the watershed about 2.5km to the southeast of the lake.

Visual inspection of plots of cut line, road, and trail densities, percent area cut, and percent above background (Appendix 7.2.13) indicates a potential correlation between sedimentation increases over background and land-use change. Percent above background increases steadily beginning after 1970, and increases steadily. Land use begins to increase in roughly around 1960 and increases at a steady pace, with the exception of percent area cut, which dramatically after 1980 and levels off after 1990.

3.1.14. Combined watersheds

Land-use (Table 6) and landscape variables (Table 7) for all lakes were compared and analyzed. This analysis used cumulative land-use totals for each catchment. Spearman's rank correlation and regression analyses were utilized to compare the 13 lakes, and determine where correlations exist. The data does not conform to a normal distribution; and therefore non-parametric tests are more suited to these analyses. Despite this weakness regressions were used to evaluate the relations between variables. Spearman's rank correlation is a non-parametric test, and is used to confirm the significance of any identified relations in the regression analysis.

Table 6. Land-use indices.

Lake	Cutline Density km/km^2	Road and Trail Densities km/km^2 *(RT)*	Percent Area Cut	Well Density *(W)*
Bear	1.040	1.098	0.236	0.000
Dunn	1.669	1.549	0.141	0.000
Fairfax	0.619	0.275	0.278	0.000
Fickle	3.437	0.408	0.000	0.166
Goldeye	0.364	0.823	0.013	0.000
Iosegun	1.847	0.936	0.073	0.479
Jarvis	0.459	1.520	0.045	0.157
Mayan	2.744	2.391	0.346	2.740
McLeod	1.169	1.182	0.175	0.522
Musreau	1.353	0.546	0.409	0.230
Pierre Gray	0.000	0.530	0.000	0.000
Rainbow	2.510	1.139	0.000	0.000
Smoke	1.558	0.925	0.262	0.777

Table 7. Landscape indices.

Lake	Watershed area km^2 (W_{Area})	Lake area km^2 (L_{Area})	Lake area Watershed area	Drainage density km/km^2	% Area of water features $(WF_{Percent})$	Mean slope (S_{Mean})
Bear	7.542	1.544	0.205	0.000	0.121	2.100
Dunn	0.865	0.120	0.139	0.000	0.138	3.820
Fairfax	1.617	0.314	0.194	0.002	0.000	5.219
Fickle	102.207	3.766	0.037	0.345	0.103	1.701
Goldeye	4.995	0.101	0.020	0.000	0.085	3.455
Iosegun	273.211	13.545	0.050	0.485	0.085	1.283
Jarvis	31.857	0.701	0.022	0.857	0.009	9.408
Mayan	0.730	0.064	0.087	0.000	0.000	2.546
McLeod	47.876	3.422	0.071	0.525	0.029	2.408
Musreau	104.573	5.580	0.053	0.685	0.008	2.722
Pierre Gray	0.502	0.384	0.764	0.000	0.045	0.249
Rainbow	4.443	0.067	0.015	0.195	0.022	3.941
Smoke	133.932	9.151	0.068	0.712	0.006	2.104

Table 7 Continued.

Lake	Elev max km *(E_{Max})*	Elev. min km	Background Sedimentation Rate *(BS_{Rate})*	Specific Sediment Yield *(SSY)*	Sediment Accumulation Rate Average Above Background	Average Percent Above Background *(APAB)*
Bear	0.932	0.871	52.222	10.691	70.700	35.441
Dunn	1.206	1.280	36.186	5.037	72.600	100.628
Fairfax	1.431	1.323	112.582	21.887	160.600	42.629
Fickle	1.131	0.981	75.003	2.763	100.600	34.133
Goldeye	1.475	1.375	48.222	0.979	80.800	67.635
Iosegun	0.983	0.773	154.834	7.676	449.400	190.310
Jarvis	1.753	1.153	75.702	1.666	159.600	110.832
Mayan	1.075	1.009	75.196	6.549	112.000	48.936
McLeod	1.109	0.858	86.865	6.209	305.600	251.669
Musreau	1.070	0.873	284.447	15.179	441.300	55.169
Pierre Gray	1.270	1.267	70.284	53.724	68.800	-2.134
Rainbow	1.160	1.035	79.150	1.189	113.300	43.236
Smoke	1.077	0.836	112.582	7.692	167.300	48.579

Regression analyses: Simple bivariate regressions were run between all of the landscape variables for the 13 lakes. Most of these analyses yielded no significant relations. However there were a few instances where the results were significant. Regression results that were statistically significant (α=0.05) are described below.

The regression of lake area vs. watershed area (Figure 6) yielded a highly significant result. The relations noted is linear in nature and the regression equation is $L_{Area} = 0.193 + 0.051W_{Area}$, with an R^2value of 0.95.

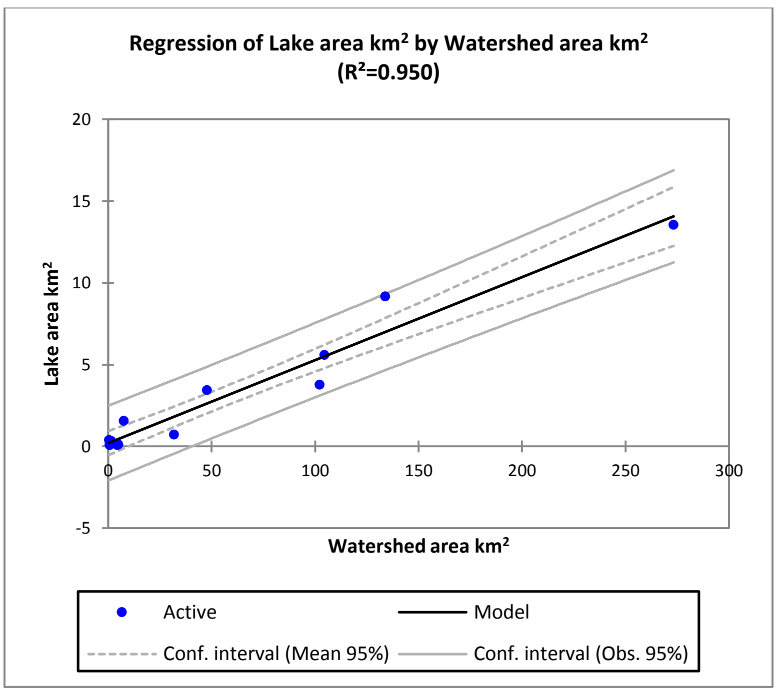


Figure 6. Linear regression for Lake area and watershed area

A regression analysis was completed for max elevation vs. slope (Figure 7). The linear regression resulted in a R^2value of 0.63 and the equation is $E_{Max} = 7.924S_{Mean} + 0.956$.

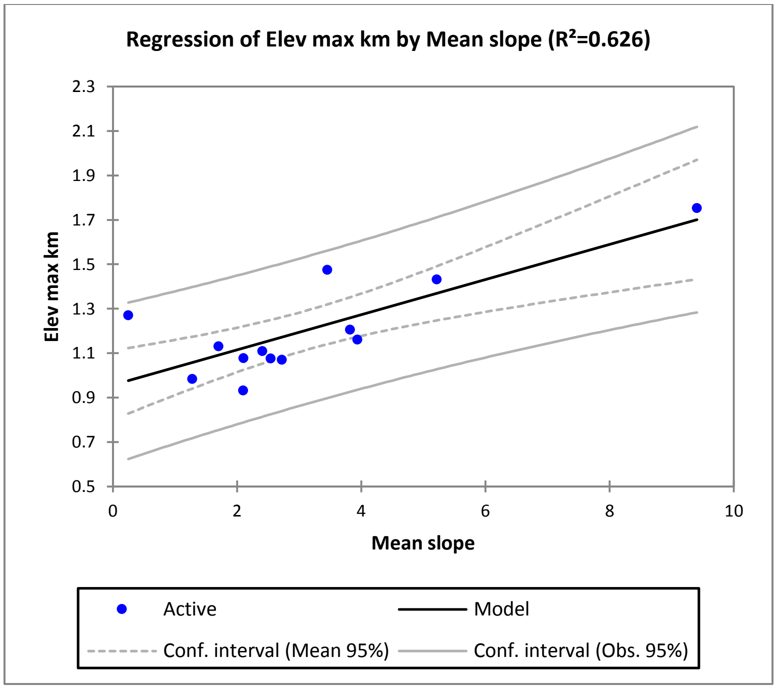


Figure 7. Regression of mean slope and maximum elevation.

The background sedimentation rate vs. watershed area regression (Figure 8) resulted in a significant power correlation. The regression equation is $BS_{Rate} = 0.0002W_{Area}^{0.2.458}$, with a R^2 value of 0.35.

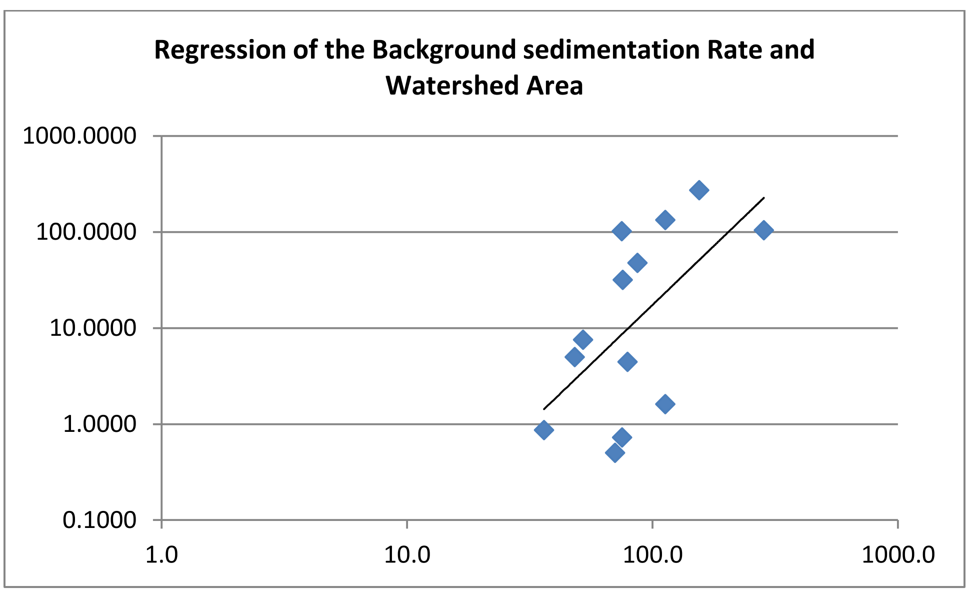


Figure 8. Regression of background sedimentation rate and watershed area.

The best fit for the specific sediment yield regression (Figure 9) is a power function, and the equation is $SSY = 21.915W_{Area}^{-0.369}$, with a R^2 value of 0.037. Although this is not a significant result, it is presented here because this type of scaling analysis is commonly conducted for sediment yield data.

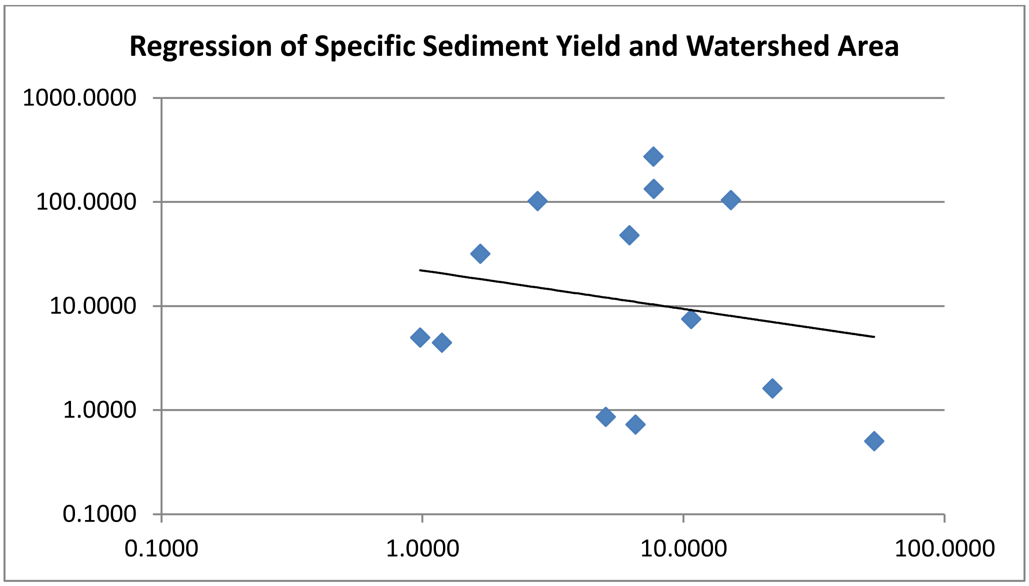


Figure 9. Regression of specific sediment yield and watershed area.

The background sediment accumulation rate vs. percent water features regression (Figure 10) yielded a logarithmic equation of interest. The linear equation was not significant and is not reported here. The logarithmic function, $BS_{Rate} = -0.053\ln(PWF) + 0.287$, has a R^2 value of 0.3224.

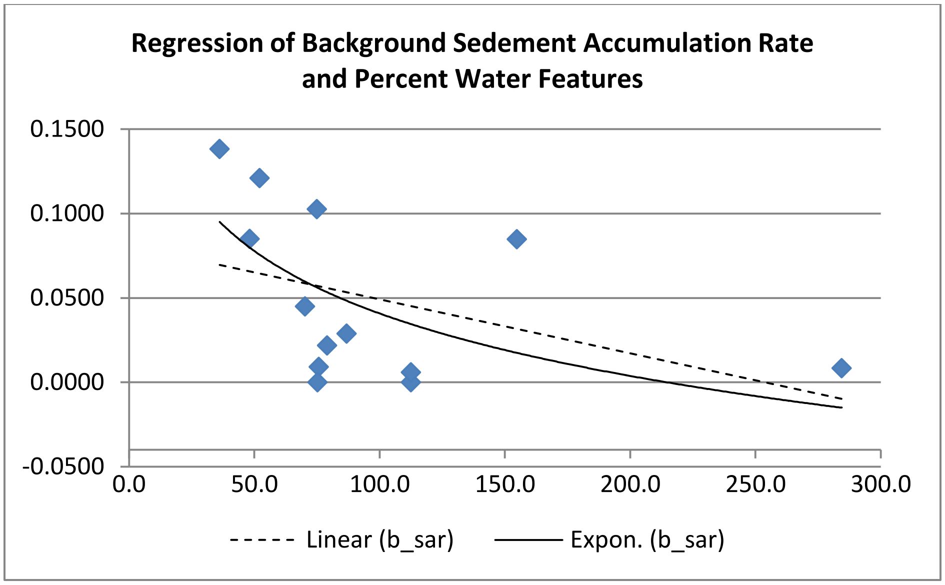
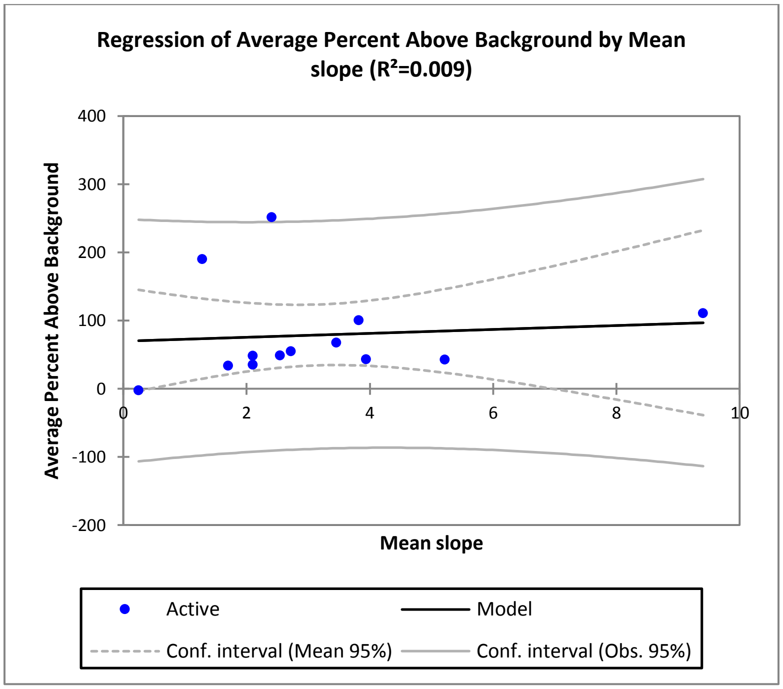


Figure 10. Regression of background sedimentation rate and the percent of water features in the watershed.

The average percent above background vs. slope regression (Figure 11) yielded an equation of APAB= $8.006S_{Mean} + 40.667$, with an R^2 value of 0.009. If outliers Iosegun and McLeod are removed, the equation is APAB= $10.142S_{Mean} + 18.821$ with a highly significant R^2 value of 0.60

Regression all lakes.



Regression with outliers removed.

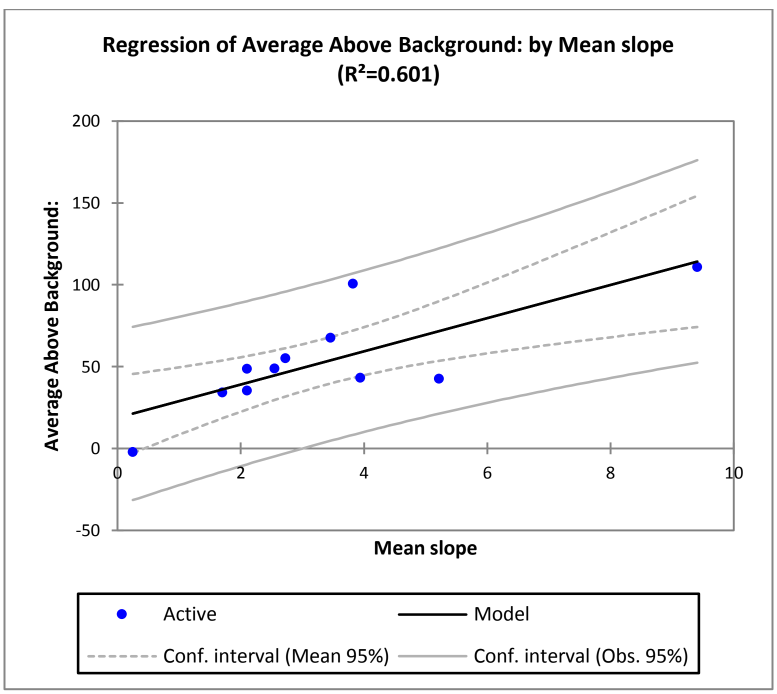


Figure 11. Regression of the average percent above background sedimentation and mean slope, with and without outliers Iosegun and McLeod removed.

Spearman's rank correlation: Since not all of the data conform to a normal distribution, spearman rank analyses (Appendix 7.3.1) were used to confirm the significance of the previous regressions. A one tail test with 95% confidence was used. Lake area vs. watershed area exhibited a highly statistically significant correlation with a p-value of >0.0001. Maximum elevation and mean slope were statistically correlated with p-value of 0.049. Background sedimentation rate vs. watershed area also yielded a significant correlation with a p-value of 0.041. Background sedimentation rates and the percent water features also showed a significant correlation with a p-value of 0.018.

3.2. Spatial analysis

Regression analysis: Regressions were run on land use features clipped to 10m, 50m, 250m, and 500m buffers. This was completed to determine if there is a spatial correlation between land-use and sedimentation rates. Multivariate regressions were run on all land-use categories, and in various combinations. All regressions were completed with use of R statistical software and verified with the XLStat add in for MS Excel. The following are the significant results:

Average percent above background vs. road and trail densities over a 10m buffer (figure 12): This linear regression resulted in a equation of $\mathrm{APAB}_{\mathrm{RT10m}} = 146.825RT_{10m} + 37.452$, with a R^2 value of 0.40.

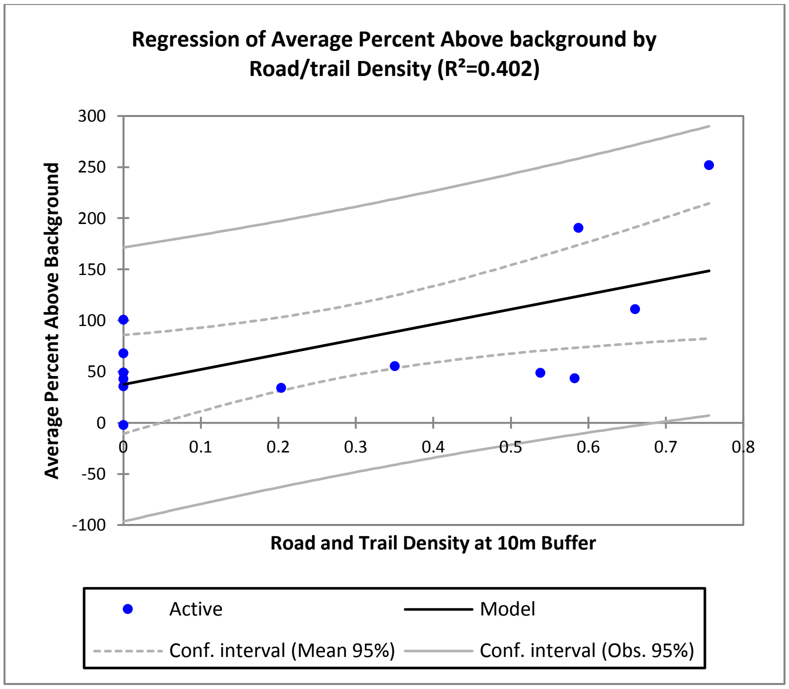
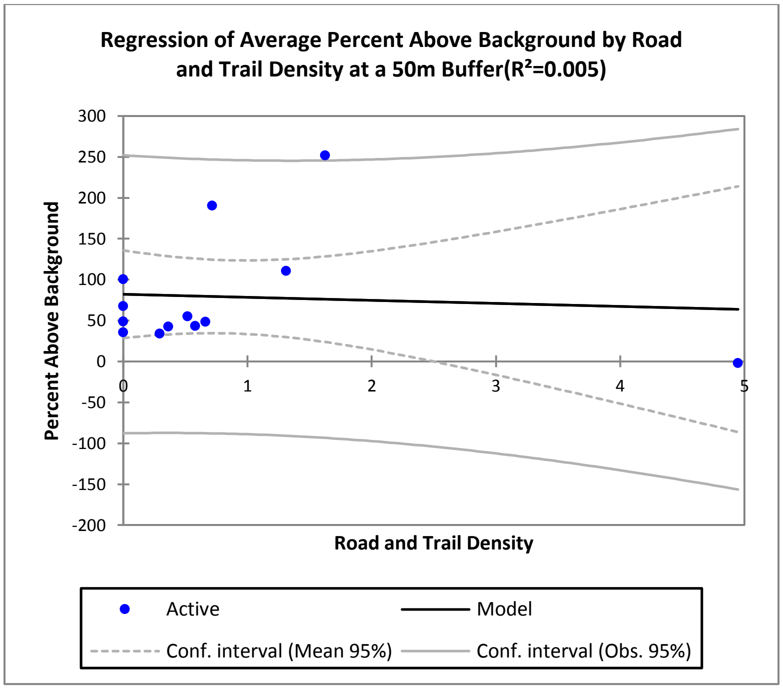


Figure 12. Regression of the percent average above background and road and trail density over a 10 meter buffer.

Average percent above background vs. road and trail densities over a 50m buffer: This linear regression yielded an equation of $\mathrm{APAB_{RT50m}} = -3.703RT_{50m} + 82.138$, with a R^2 value of 0.0049. This regression is not significant, however if the outlier Pierre Gray is removed (Figure 13), we get an equation of $\mathrm{APAB_{RT50m}} = 91.827RT_{50m} + 39.324$, with an R^2 value of 0.50.

With Pierre Gray outlier included.



With Pierre Gray outlier removed.

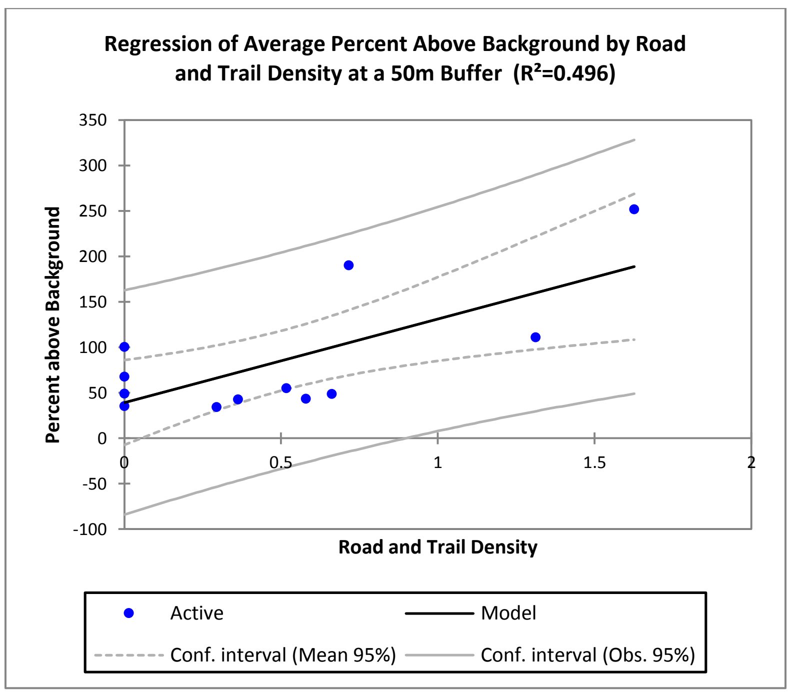


Figure 13. Regression of the percent average above background and road and trail density over a 50 meter buffer, with and without outlier Pierre Gray removed.

Average percent above background vs. well density over a 10m buffer (Figure 14): This linear regression resulted in an equation of $\mathrm{APAB}_{\mathrm{W10m}} = 32.719W_{10m} +$

76.0, with a R^2 value of 0.013. Although this R^2 value is low, the remaining buffer distances yield more significant R^2 values.

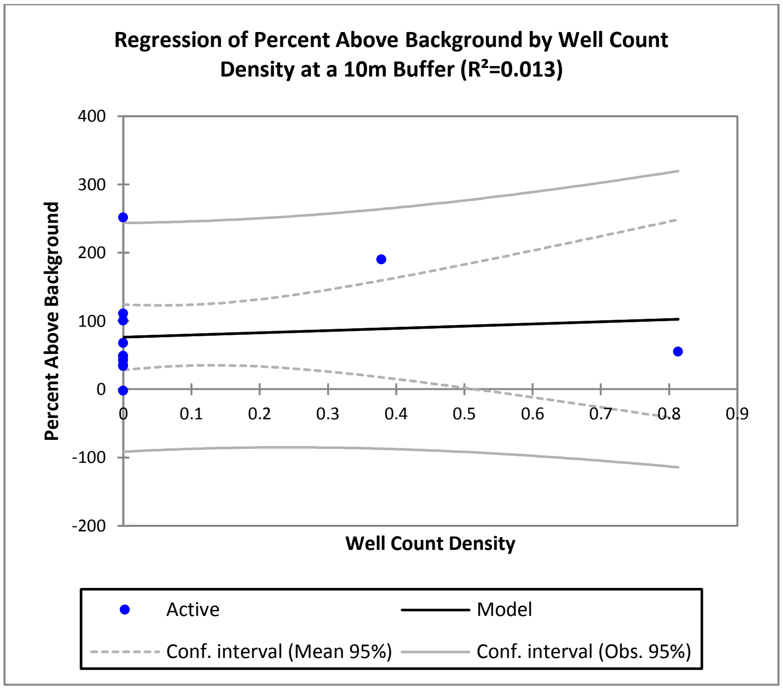


Figure 14. Regression of the percent average above background and well density over a 10 meter buffer.

Average percent above background vs. well density over a 50m buffer (Figure 15): This regression yielded an equation of $\mathrm{APAB}_{\mathrm{W50m}} = 215.796W_{50m} + 50.265$, with an R^2 value of 0.516.

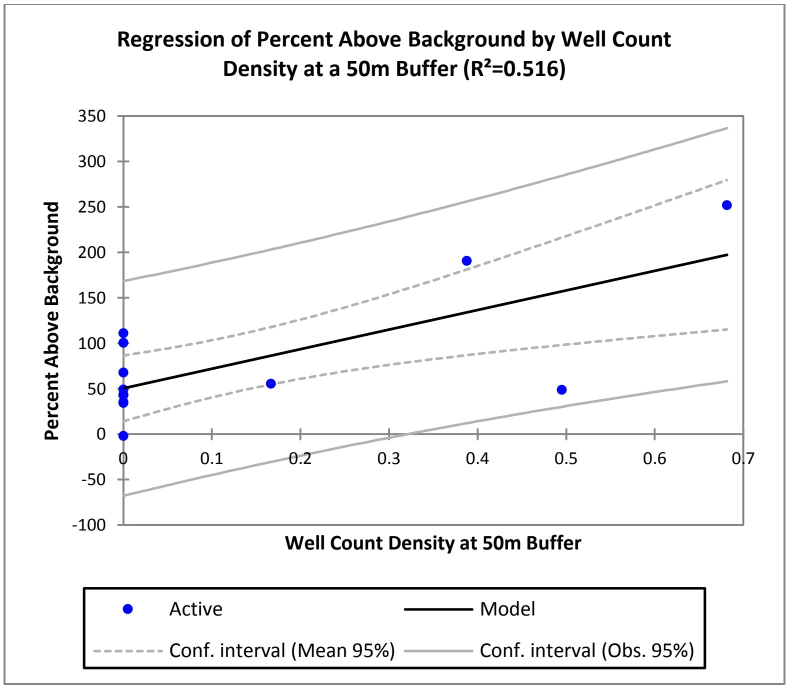


Figure 15. Regression of the percent average above background and well density over a 50 meter buffer.

Average percent above background vs. well density over a 250m buffer (Figure 16): This regression equation is $\mathrm{APAB}_{\mathrm{W250m}} = 139.186W_{500m} + 50.502$, with a R^2 value of 0.3051.

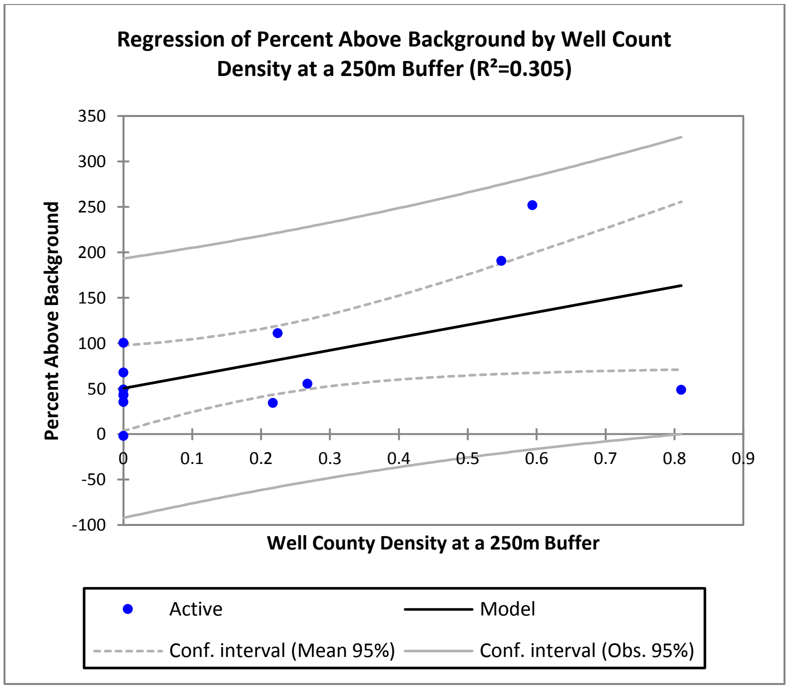


Figure 16. Regression of the percent average above background and well density over a 250 meter buffer.

Average percent above background vs. well density over a 500m buffer (Figure17): This linear regression yielded an equation of $\mathrm{APAB}_{\mathrm{W500m}} = 140.932W_{500m} + 51.739$ and has a R^2 value of 0.283.

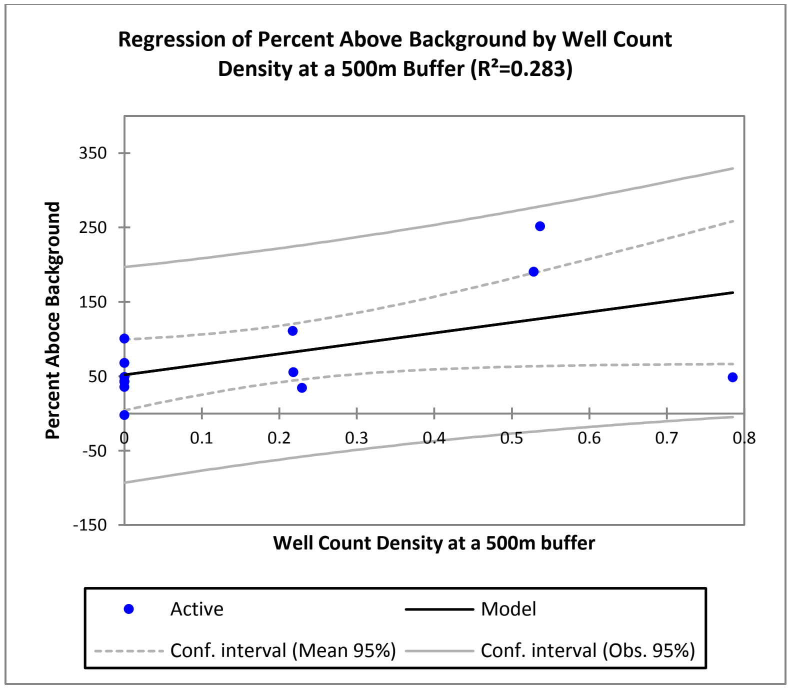


Figure 17. Regression of the percent average above background and well density over a 500 meter buffer.

Spearman's rank correlation: Since the data does not conform to a normal distribution, Spearman rank analysis (Appendix 7.3.2) was used to evaluate the relation between the percent average above background sedimentation, and land-use at a watershed scale. A one tail test with 95% confidence was used. The only significant correlation was with road and trail density, with a p-value of 0.046.

3.3. Temporal analysis

A similar regression analysis was run on the temporal dataset. It should be noted that to evaluate the temporal aspect, it was necessary to use the land-use values for each interval for each lake. There was only one regression which yielded significant results and that is the regression of road and trail densities within a 10m buffer distance (Figure 18). The regression resulted in a linear equation of $APAB_{temporal10m} = 1.528RT_{temporal\ 10m} + 0.212$, with a R^2 value of 0.379. To further evaluate this relationship, a Welch two sample t-test and an F test to compare two variances were used.

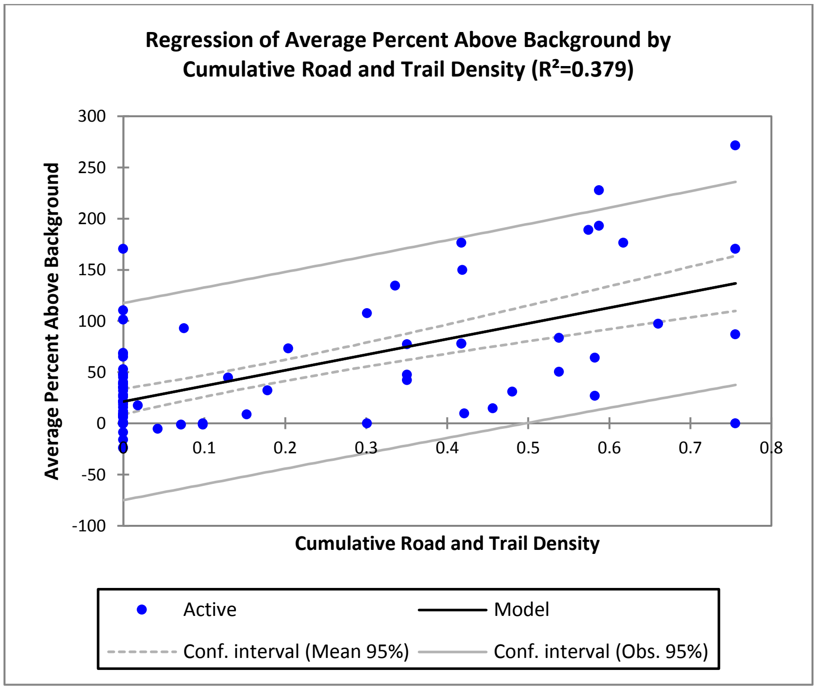


Figure 18. Temporal regression of average percent above background sedimentation data, and road/trail density over a 10m buffer.

Welch two sample t-test: Because of obvious heteroscedasticity, visible in the plot for the temporal analysis (Figure 18), the dataset was subset into high and low road/trail densities, for use in a t-test analysis. The result of the t-test was: t= -4.392, df = 21.617, and the p-value is 0.00024.

F test to compare two variances: To further evaluate the dataset, a F-test was also run. The result of the F=test was: F = 0.226, numerator df = 19, denominator df = 19, p-value = $6.138e^{-6}$.

4. Discussion

4.1. Watershed analysis

The regression for lake area and watershed area yielded a R^2 value of 0.95, which indicates a highly statistically significant relation at a confidence interval of 95%. This relation indicates that the larger catchments in this study tend to have larger lakes. Although this seems intuitive, it is not always the norm.

With a R^2 value of 0.35, the power regression for the background sediment yield and watershed area indicates a moderately strong relation between these variables. The relationship indicates that for the 13 lakes in this study, as the catchments get larger, they have higher sedimentation rates. This is an expected correlation, because the more area being drained the more source material there is for sedimentation. This is why catchment sediment yields are commonly reported as specific sediment yield (i.e. yield data is standardized by the watershed area and therefore represents yield per unit catchment area).

Although there was not a significant relation between specific sediment yield and watershed area (R^2 of 0.037), this result is worth noting. A weak relationship here indicates that there is no scaling relation, or that the model conforms (very weakly) to the conventional model of specific sediment yield. In the conventional model, larger catchments exhibit lower specific yields because of the corresponding increase in sediment storage zones along more developed floodplains and within intervening standing water features (e.g. wetlands, ponds, lakes) (Chorley *et al.,* 1984). In western Canada, many catchments do not follow the conventional model, due to the effects of recent glaciation, which scoured sediment supplies in upland areas and deposited thick sequences of Quaternary sediment downstream (Church and Slaymaker, 1989). The lack of a strong scaling relation suggests that it is reasonable to compare sediment yield fluctuation among the study catchment of differing sizes without any scaling adjustments.

A statistically significant relation is noted with the regression of maximum catchment elevation and mean catchment slope (R^2 of 0.626), which indicates that the higher elevation watersheds have steeper slopes. Most of the 13 lakes in this study are in the plains, although a few are close to the foothills, and thus have higher elevation. The closer the lake is to the foothills, the steeper the terrain.

The background sediment accumulation rate vs. percent water features regression indicates a relation between the variables (R^2 of 0.322). As the percent water features increases, there is a decrease in the background sedimentation rate. This could be the result of sediment trapping in these other water features, as upstream wetlands and other lakes act as sinks for incoming sedimentation. This result supports the exclusion of streams that flow into large wetlands and lakes upstream to the study lake in the spatial analyses discussed below.

A possible relation exists between the average percent above background sedimentation following land-use onset and mean catchment slope, although the relation is only strong after outliers are removed. This relation indicates that steeper catchments may be more susceptible to increased sedimentation following land-use activities.

There were no other significant watershed relations, which might indicate that there is not a complex relationship between the watershed variables and sedimentation rates. Therefore, land-use might be a more important factor influencing contemporary sedimentation in these lakes. All of the relations presented above also exhibit significant Spearman rank correlations, suggesting the robustness of the results to the underlying assumptions of normality.

4.2. Spatial analysis

Land-use in forested watersheds often leads to increases in sedimentation (Karwan *et al.*, 2007). In this study there were only two significant results indicating a relation between land-use and sedimentation. The Spearman rank correlations, which was run on the cumulative land-use totals for each lake, indicated a strong relation between road and trail density and the average percent increase in sedimentation above background following the onset of land-use activities (p-value of 0.046). This result was corroborated by the various regressions of land-use with and without buffer distances, with sediment response above background. Land-use effects can have effects on sedimentation at long distances (Houlahan and Findlay, 2004), however regressions in this study indicated that a significant relation exists between road and trail density at small buffer distances (10 and 50 meters) and average percent above background sedimentation. Well densities at moderate buffer distances (50 and 250 meter buffer) and average percent above background sedimentation also indicate that a significant relation exists between these variables.

Road-related sediment is the dominant source of sediment input in many areas (Forman and Alexander, 1998). One of the strongest relations was noted with the road and trail density vs. average percent above background regression, at 10 and 50 meter buffer distances. Roads within such short distances are more likely to interact with the streams and lakes directly. Road orientation and position relative to water sources is an important factor determining the impact roads have on sedimentation (Gucinski *et al.,* 2001). The relation between road and trail density and average percent above background at the 10m and 50m buffer distance, was even stronger when the outlier Pierre Gray was removed. Impervious surfaces (such as paved roads) contribute little to sediment output (Reid and Dunne, 1984). Pierre Gray's roads and trails are very minor (used to access well maintained campsites in the park) and mostly paved, which means that they would not contribute significantly to sedimentation.

Vegetation acts as a buffer or sink, slowing overland flow causing sediment to be deposited in the buffer (Muñoz-Carpena *et al.*, 1999**).** Larger buffer distances showed no significant relation between sedimentation and road and trail densities. This could be because at greater distances, there is more opportunity for sediment to be lost to hill slope sinks on its way to stream channels. Also roads can act as channels (Gucinski *et al.,* 2001), which at greater buffer distances might lead runoff away from lakes (roads close to water features are more likely to intersect with water features).

Oil and gas exploration often leads to sedimentation increases (Wachal *et al.* 2009). The spatial regressions indicated that a strong significant relation exists between well density and sedimentation at moderate buffer distances. The 10 meter buffer results may be spurious because of low well counts within the 10 meter buffers (well counts were only 2 at this distance). The 50 meter buffer analysis indicated the strongest relationship between well density and average percent above background. The progressively larger buffer distances also yielded significant relations between well density and sedimentation, but the significance is reduced at the distances above 50m.

Well density is related to road and trail density, in that roads and trials are built to access wells (Wachal *et al.* 2009). Thus it is not surprising that if one of these two variables has a strong correlation to sedimentation that the other variable does also. However, when a multivariate regression is run with both land-use variables (road and trail densities, and well density) and average percent increase of sedimentation above background, the resultant regression indicates a weaker relation between either of the lands-use variables alone.

4.3. Temporal analysis

Regressions were also run (both bivariate and multivariate) on the temporal dataset. There was only one significant result, which was a bivariate regression between cumulative road and rail densities and the average percent above background sedimentation. Roads continue to contribute to sediment increases in the years following construction, and are correlated with traffic volume (Karwan *et al.* 2007). The results of the regression could indicate that roads and trails continue to have an impact on sedimentation after they are constructed. Considering the nature of roads and trails, and the fact that they are used frequently by vehicles, which loosen and kick up sediment, this is not an unexpected result.

Under a normal regime, the sediment yield rate to stream channels (generalized to an order of magnitude from Table 2) is between 1 and 10m^3km^{-2} yr^{-1} (Burt and Allison, 2010). Road surfaces generate a sediment yield rate of $10^4m^3km^{-2}yr^{-1}$. Considering a road density of 1km km^{-2} (roughly the midrange road density for the lakes in my study area), and assuming an average road width of 0.005km, we get a sediment yield of 0.005km^2 km^{-2}. This times the road surface sediment yield rate, gives us a sediment yield rate of 50$m^3km^{-2}yr^{-1}$, which is 5 to 50 times greater than the normal regime. Sediment yield rates for my study area ~~are only approximately~~only increased up to 3.5 times the normal regime, less than the literature suggests. Therefore roads do increase sediment yield rates for the lakes in my study area but at a lower rate than expected. Generally the literature focuses on sediment yield rates for steep catchments, which have higher sedimentation rates than the relatively flat lands which characterize the catchments in this study. My work averaged sediment yield over a long period of time, and most sediment studies are comparatively short term studies which could also contribute to the differences in sediment yield rates.

Closer inspection of the regression plot shows that there is a significant amount of heteroscedasticity. To further investigate the relationship between these variables, the road and trail density data was subset into high and low densities using a midpoint threshold of 0.4km/km^2, and subjected to a t-test to evaluate the difference of mean sedimentation increase, and an F-test to evaluate differences in the variances of sediment increases.

The Welch two sample t-test indicated that there is a true difference between the means of the subset data (p-value of 0.00024). For cumulative lengths of roads greater than 0.4km/km^2, higher average sedimentation rates will likely exist. The F-test indicated that the true ratio of variance is not equal to one (p-value of 6.138e^{-6}). Therefore there is higher variability in sedimentation rates for cumulative lengths of road and trail densities above 0.4km/km^2. A direct relationship does not exist between sedimentation and the road and trail density at 10 meter buffer over time. However this analysis does indicate that it is more likely that sedimentation will increase with higher cumulative road and trail densities, and that the variability in sedimentation will be high at higher road and trail densities.

5. Conclusion

5.1. Summary of Findings

Land-use can have impacts on downstream sedimentation rates in receiving lakes. Sediment sampling coupled with GIS analysis was utilized to investigate historical lacustrine sedimentation and land-use, in thirteen lake catchments in west central Alberta Canada. Lakes were selected which had a variety of historical land-use intensities and which vary in contributing catchment size. Air photos and satellite imagery were used to document time intervals for land-use change, and ^{210}Pb analysis was used to develop a chronology of sediment deposition. A GIS was used to analyze and extract land-use and landscape indices for use in statistical analyses. The primary objectives of this project were; 1) to determine background (natural) sedimentation rates, and 2) determine the impact of land-use (oil and gas extraction, logging activity, and road construction), on more recent sedimentation rates using spatially- and temporally-based analyses.

Background sedimentation rates were calculated for all thirteen lakes, by taking the average of sedimentation rated provided by the ^{210}Pb dating, which occurred after 1900 and before major land-use. This data was then used to calculate the average percent above background sedimentation data for each lake, which would facilitate analysis between lakes of various sizes and land-use histories.

Regressions and Spearman rank analyses were used to determine the relations between landscape variables and sedimentation. Landscape features were not strongly correlated with sedimentation data, but did indicate a conventional sedimentation model might exist for the lakes in this study. Because of a lack of strong correlations between landscape variables and sedimentation, it is reasonable to assume that land-use might be a more important factor in sedimentation rates.

Of the land-use variables assessed in this study, only road and trail densities yielded a significant relation with the percent above background sedimentation data at the watershed level (non temporal). When 10m, 50m, 250m, 500m, buffer analysis was used to look at spatial correlations and the data, both road and trail densities and well densities yielded significant correlations with average percent above background sedimentation data. Road and trail densities in close proximity (10m) to water features (lake and streams), were positively correlated with sedimentation increases. A stronger relation was noted at 50m buffer distance when the outlier Pierre Gray (which the roads are paved and would not contribute much to sedimentation), was removed. Weaker correlations were observed at the larger buffer distances.

Well density was also positively correlated with sedimentation increases for moderate buffer distances (50 and 250 meter buffer distances). The strongest correlation existed within the 50m buffer, with weaker positive correlations at the larger buffer distances.

When the dataset was expanded to include a temporal aspect, only one statistically significant correlation was identified. Cumulative road and trail densities at a 10m buffer were found to be positively correlated with percent above background sedimentation data. This suggests that roads continue to influence sedimentation after construction, but only at close distances to water courses. The plot of this regression indicated a high degree of heteroscedasticity, and thus the data was subset into high and low road and trail densities, for use in a t-test and F-test. The results of these statistical tests indicated that on average, sedimentation increases with higher cumulative road and trail densities, and that the variability in sedimentation will be greater at higher road and trail densities.

It should be noted that outflow losses of sediment were not considered in this project. I do not believe this is a significant potential limitation to my study because the size range for selected lakes in this study typically have greater than %90 trapping efficiency (Brune, 1953).

5.2. Future Work

Although this research does seem to indicate that land-use influences sedimentation when it is within close proximity to the water source, further research is needed to determine if other factors could influence sedimentation rates. There is a high degree of uncertainty from the ^{210}Pb dating, which combined with the coarse temporal resolution of the land-use data throws some doubt on the accuracy of these findings. Future work could include higher resolution land-use data, and explore other sediment dating techniques.

Land-use practices change over time, and this study did not take this into consideration. Timber harvesting and oil and gas extraction practices have changed over the decades, and would therefore have different effects upon sedimentation. There was no attempt to document road size or use intensity, which would also influence sedimentation rates.

Changes in weather patterns might have a strong impact on sedimentation; a dry period could reduce sedimentation rates while a wet period would have the opposite effect. Such climatic factors were not included in this analysis.

Land-use outside the watershed could potentially impact sedimentation rates within the catchment as well. Vehicle activity outside the watershed could kick up dust which might settle in lakes or streams within the watershed impacting sedimentation rates. A similar analysis to the one completed in this project, but including land-use at various distances away from the watershed boundary would be required to address this issue.

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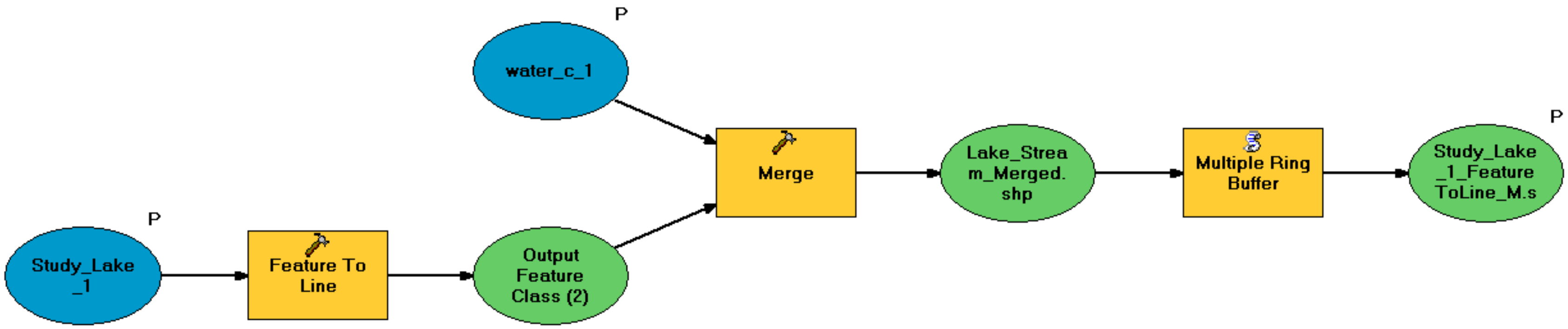
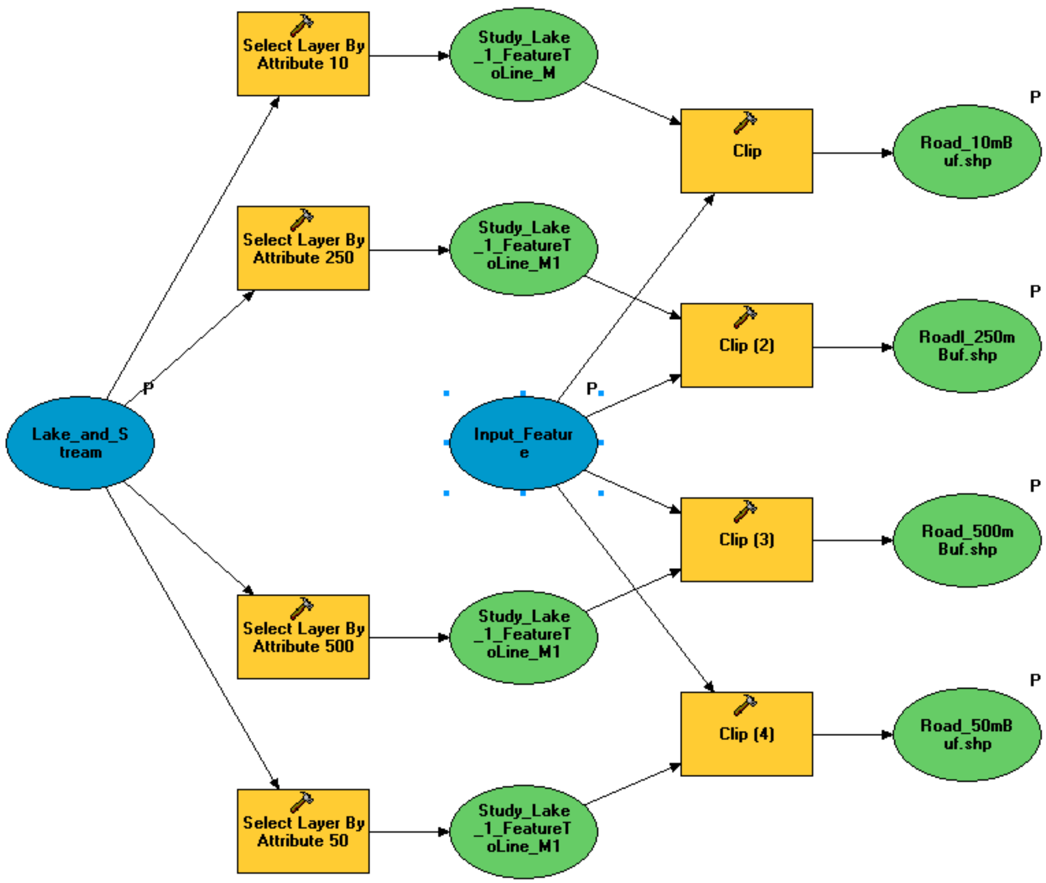
7. Appendix

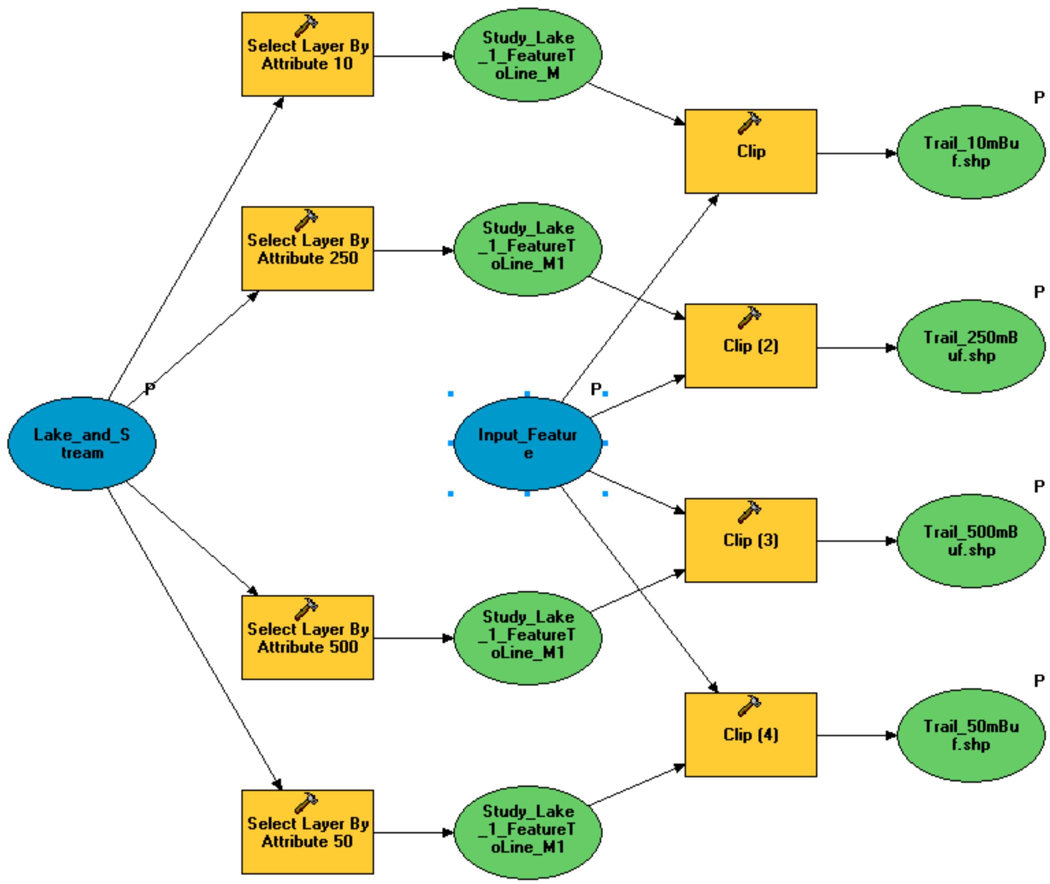
7.1. Models



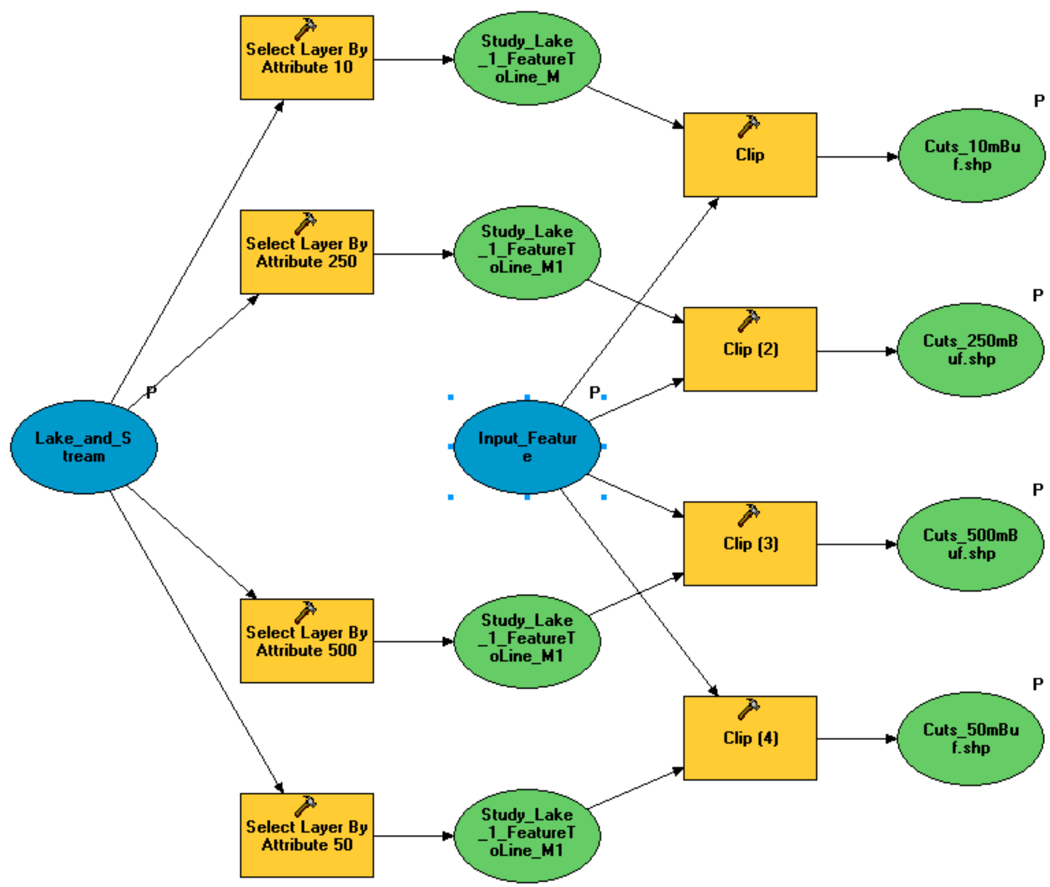
Appendix 7.1.1. Multi Ring Buffer model.



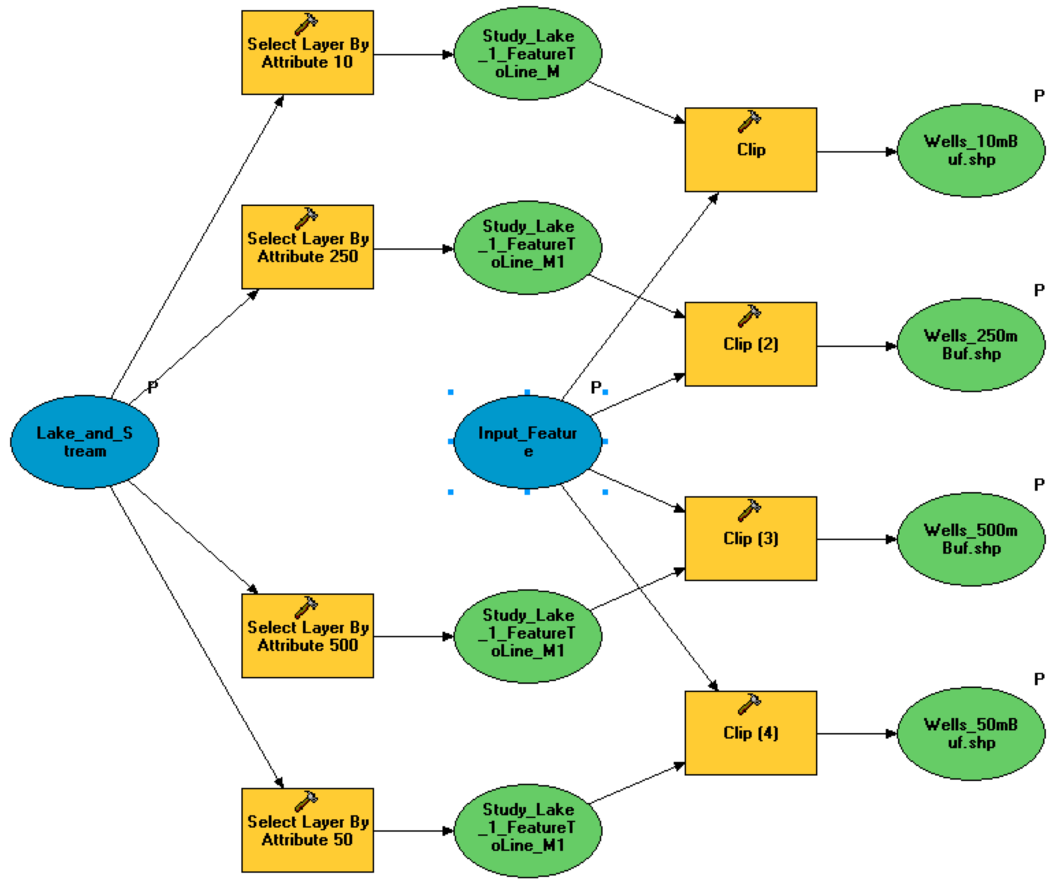
Appendix 7.1.2. Road extraction for the 4 buffer distances.



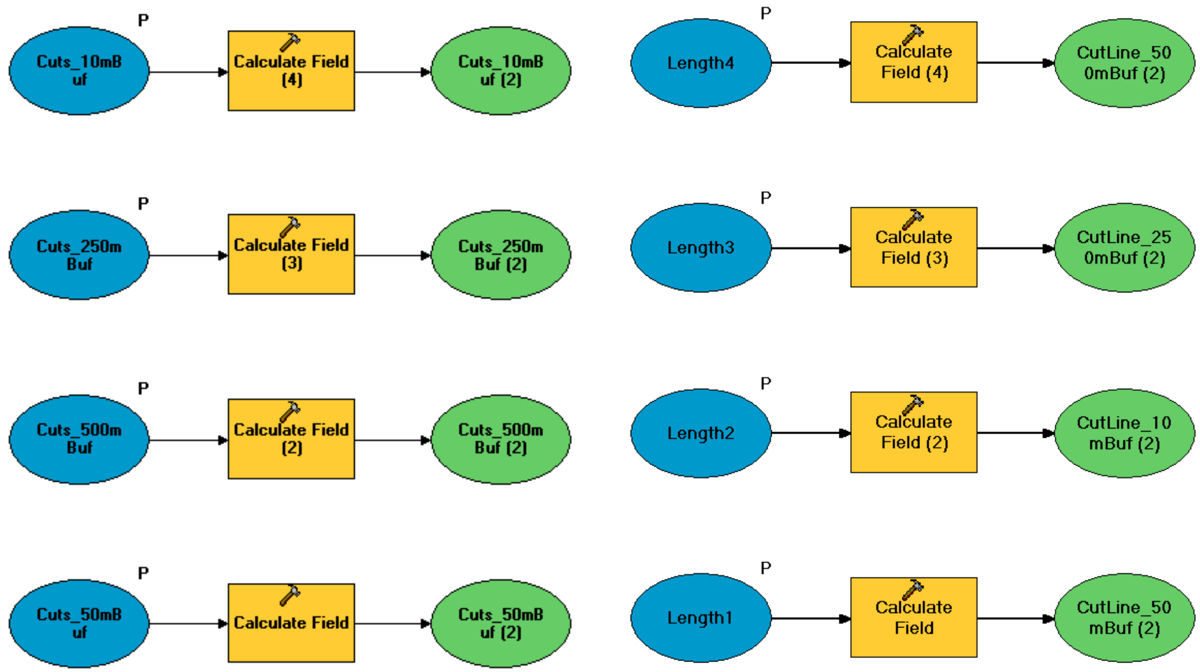
Appendix 7.1.3. Trail extraction for the 4 buffer distances.



Appendix 7.1.4. Cuts extraction for all 4 buffer distances.

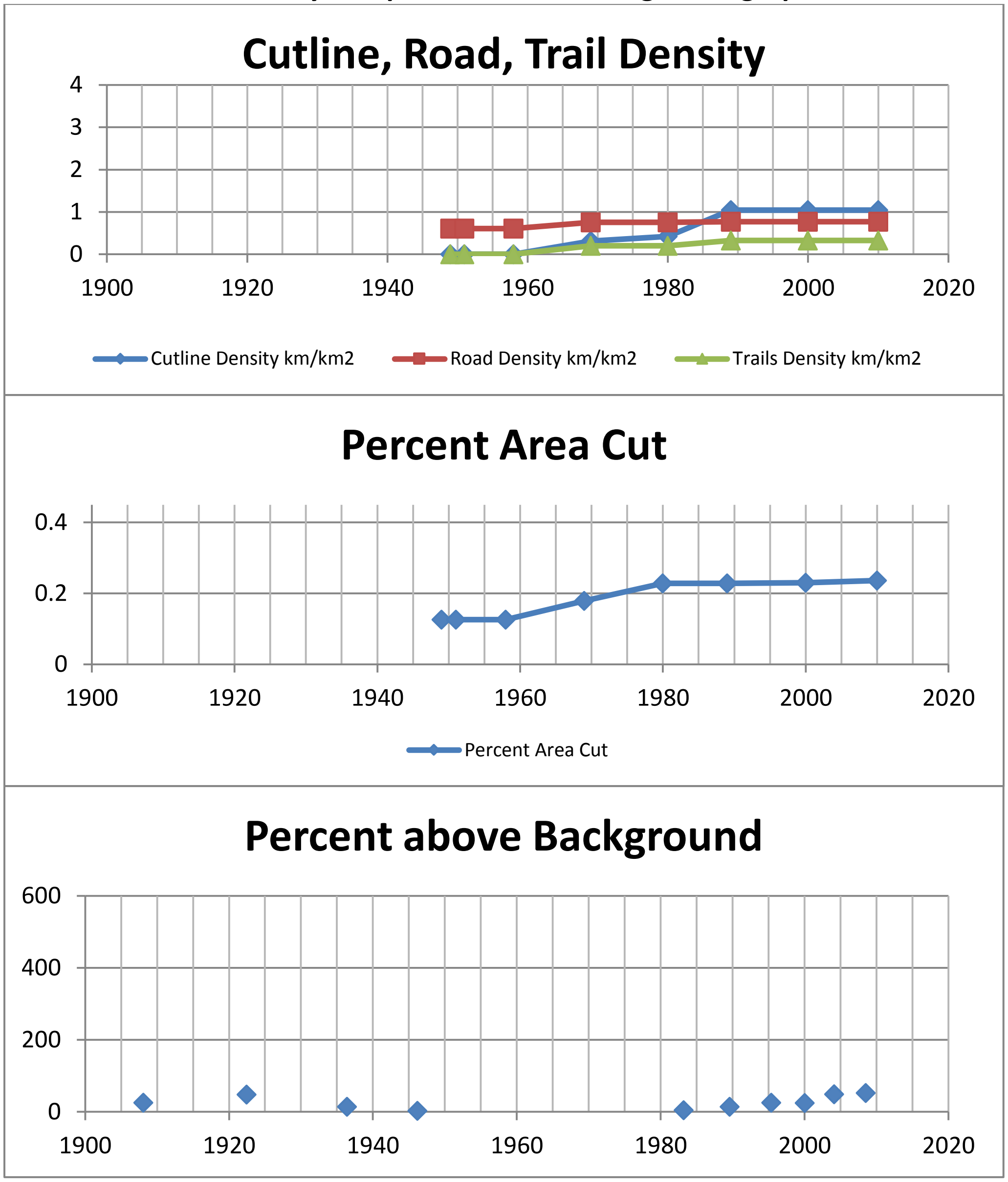


Appendix 7.1.5. Well feature extraction for all 4 buffet distances.

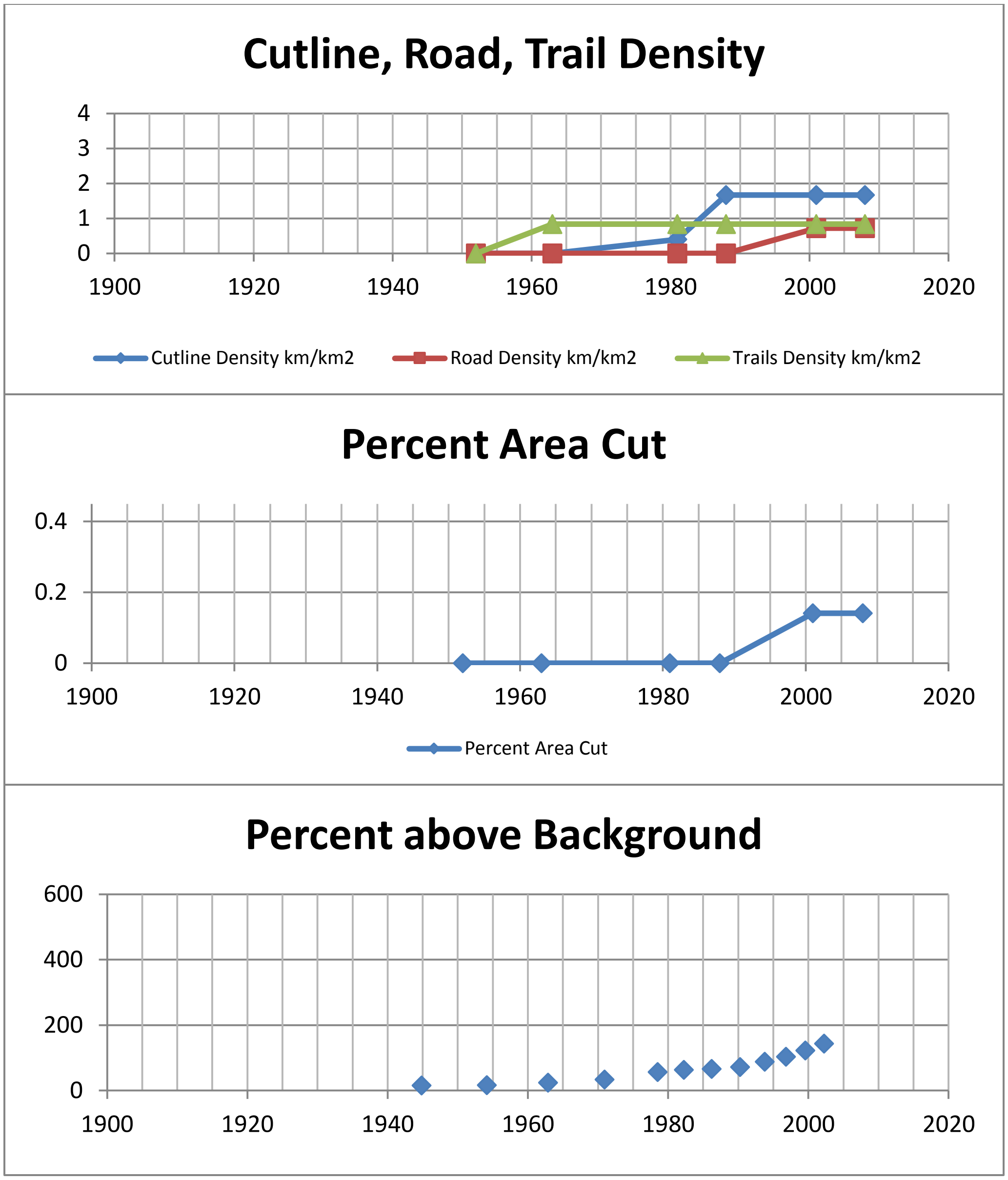


Appendix 7.1.6. Area and length field calculation.

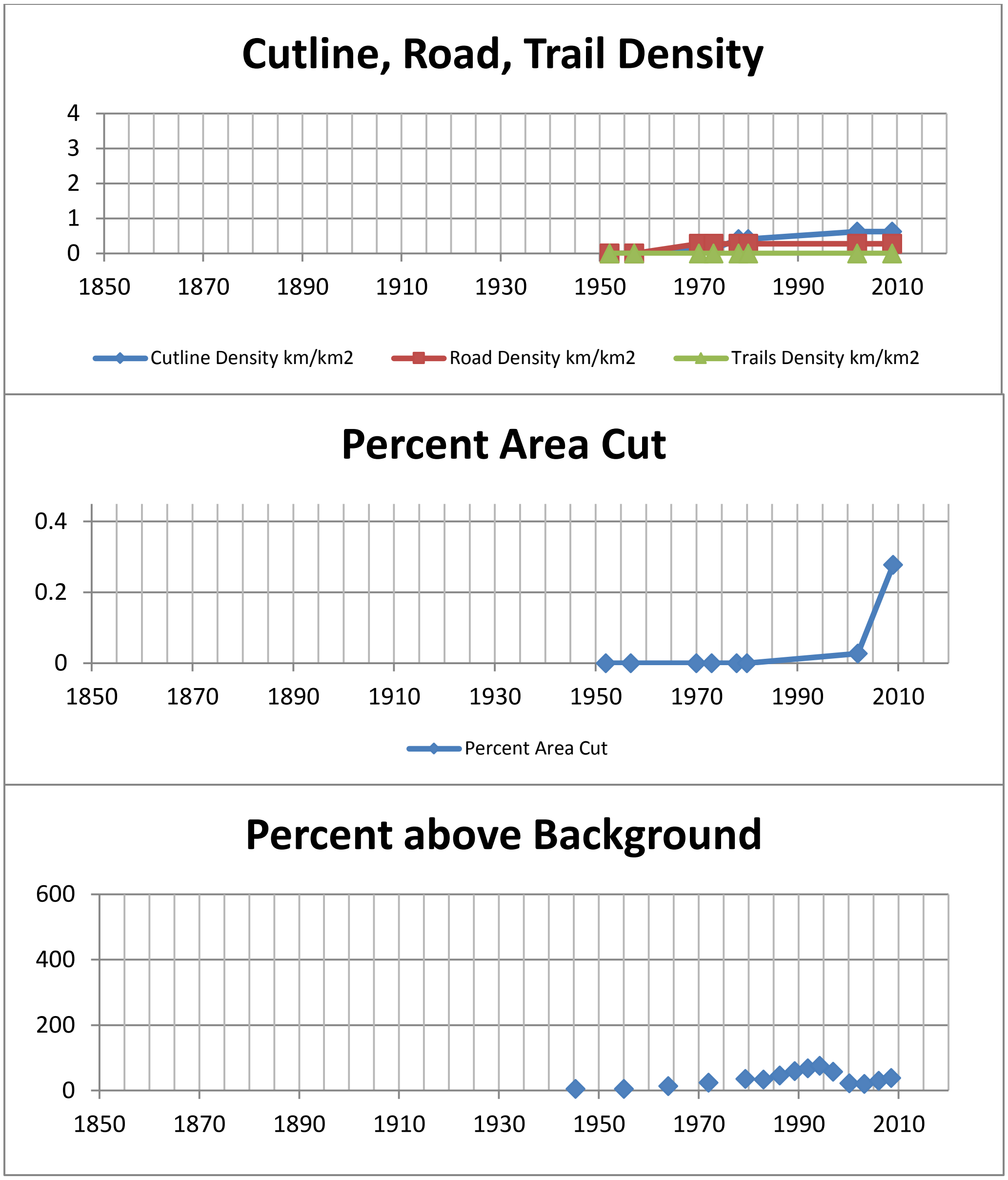
7.2. Land-use density and percent above background graphs.



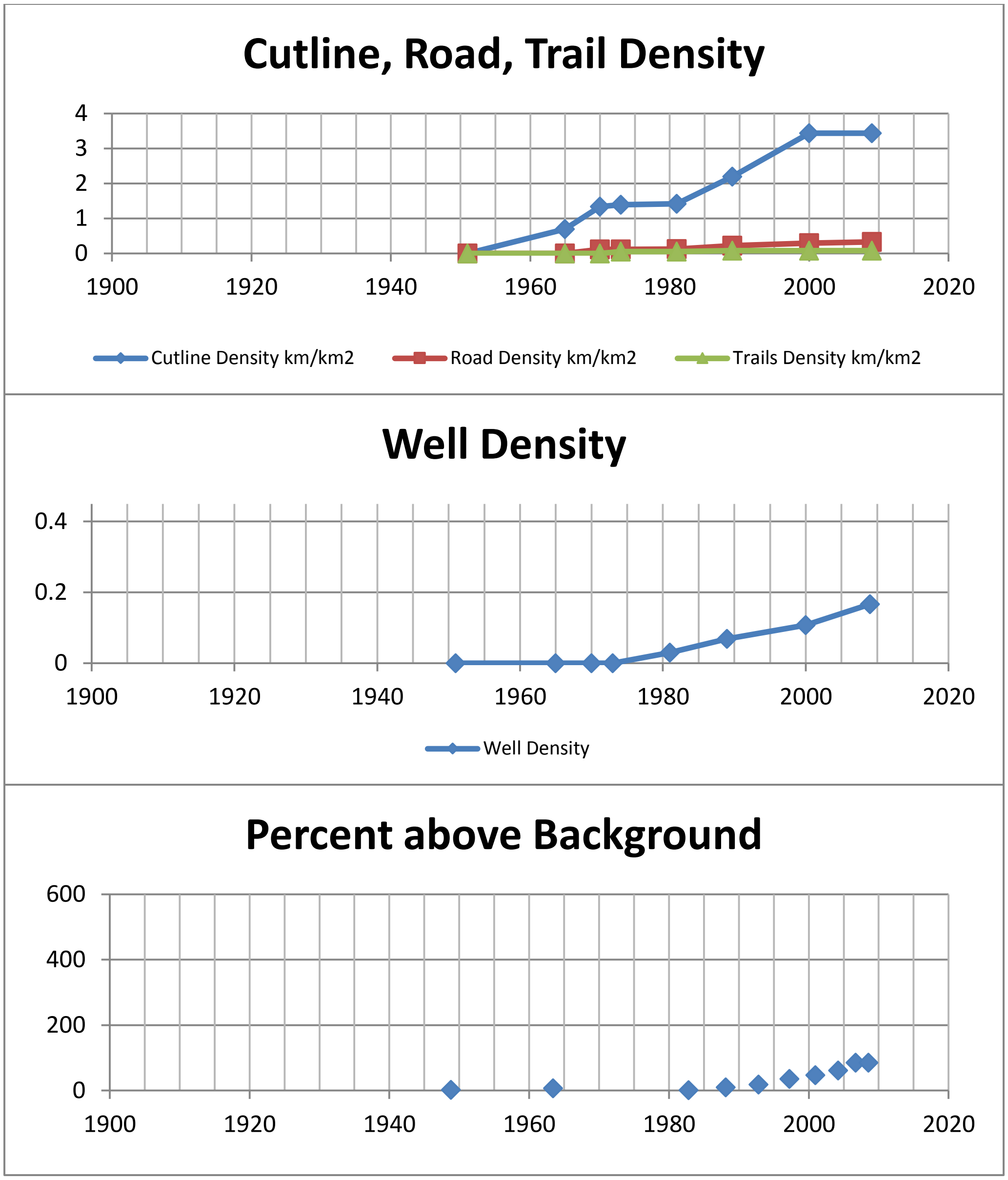
Appendix 7.2.1. Graphs of Cut line, road and trail densities, percent area cut, and percent above background for the Bear Lake watershed.



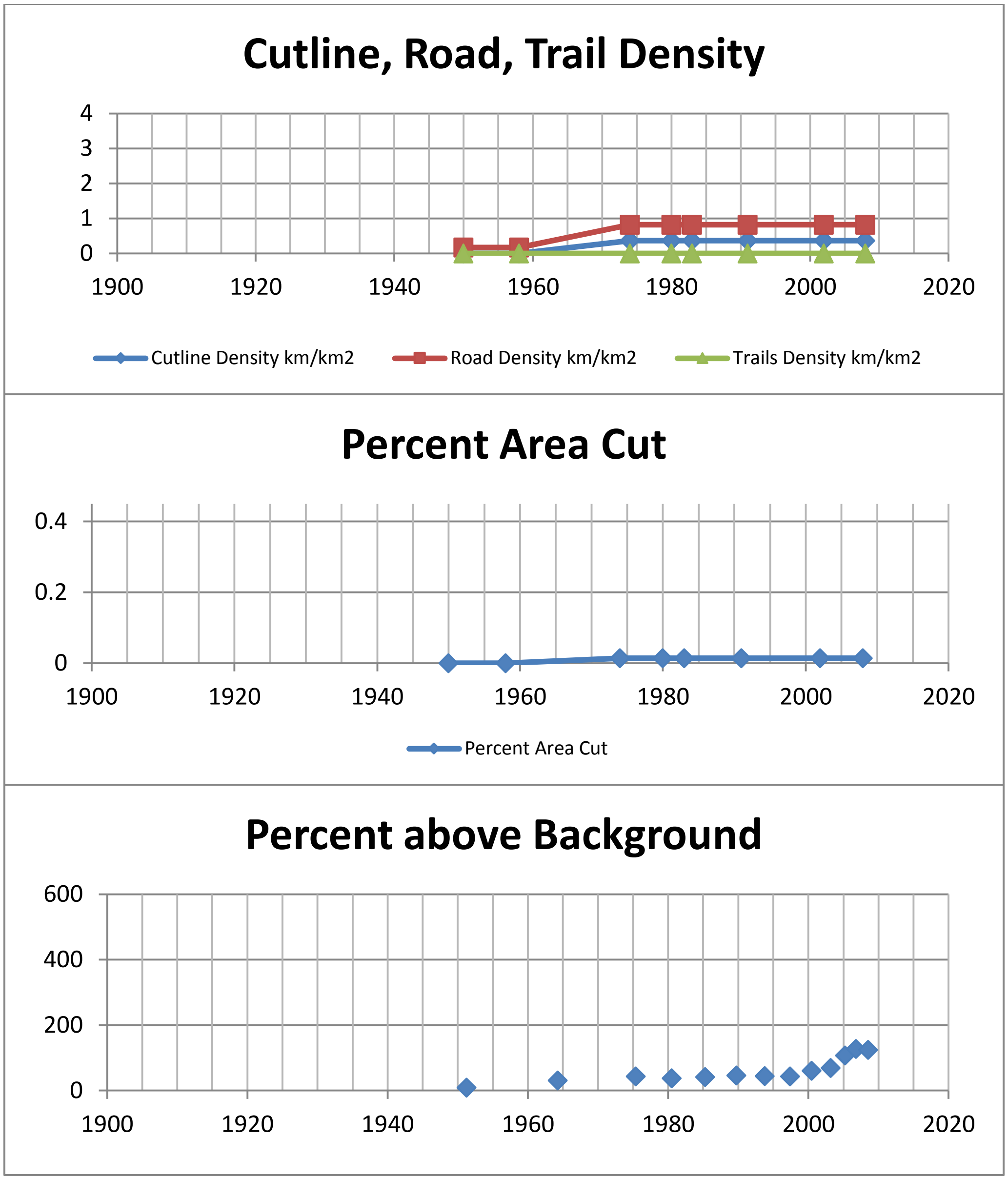
Appendix 7.2.2. Graphs of Cut line, road and trail densities, percent area cut, and percent above background for the Dunn Lake watershed.



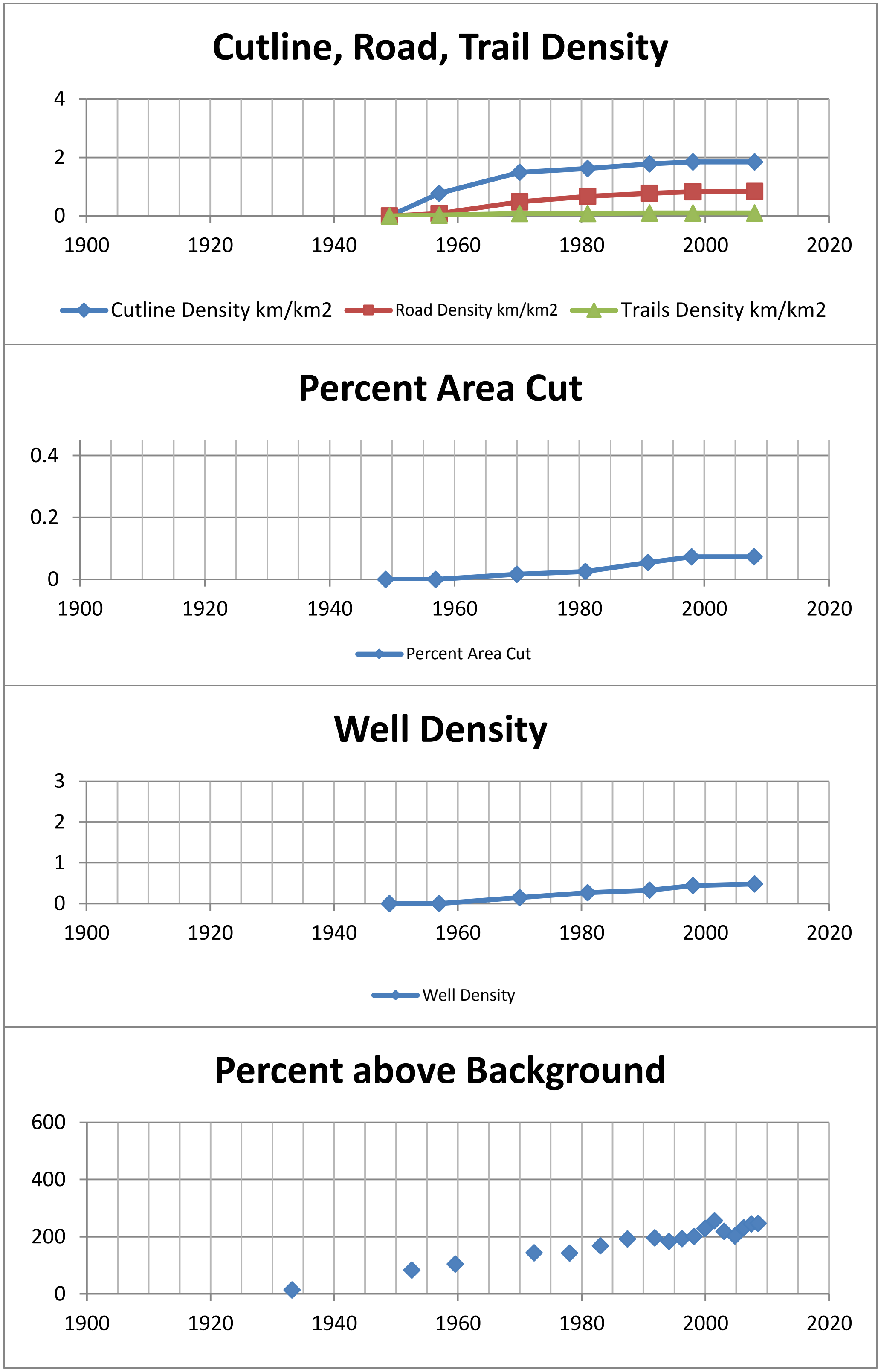
Appendix 7.2.3. Graphs of Cut line, road and trail densities, percent area cut, and percent above background for the Fairfax Lake watershed.



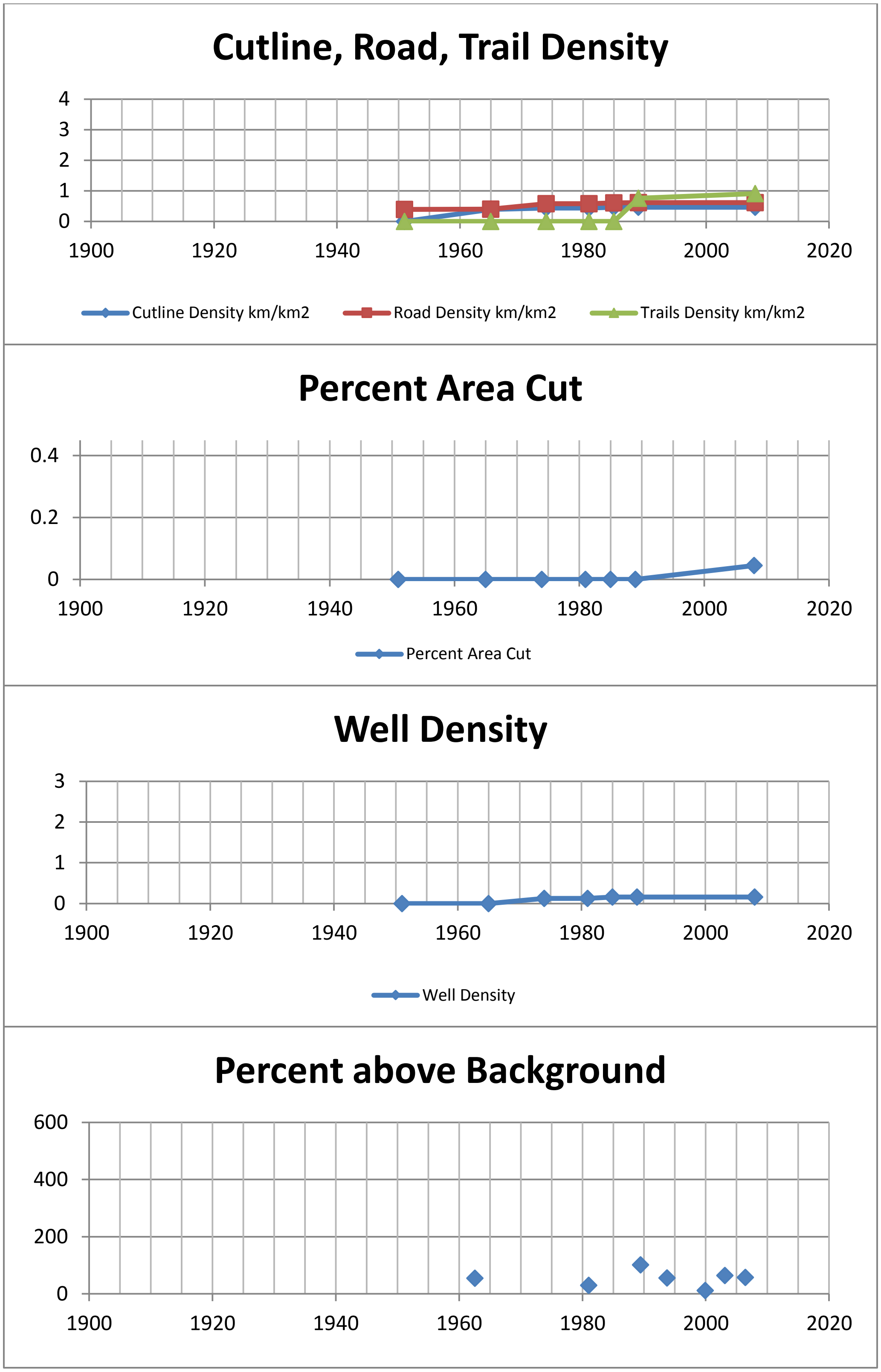
Appendix 7.2.4. Graphs of Cut line, road and trail densities, percent area cut, and percent above background for the Fickle Lake watershed.



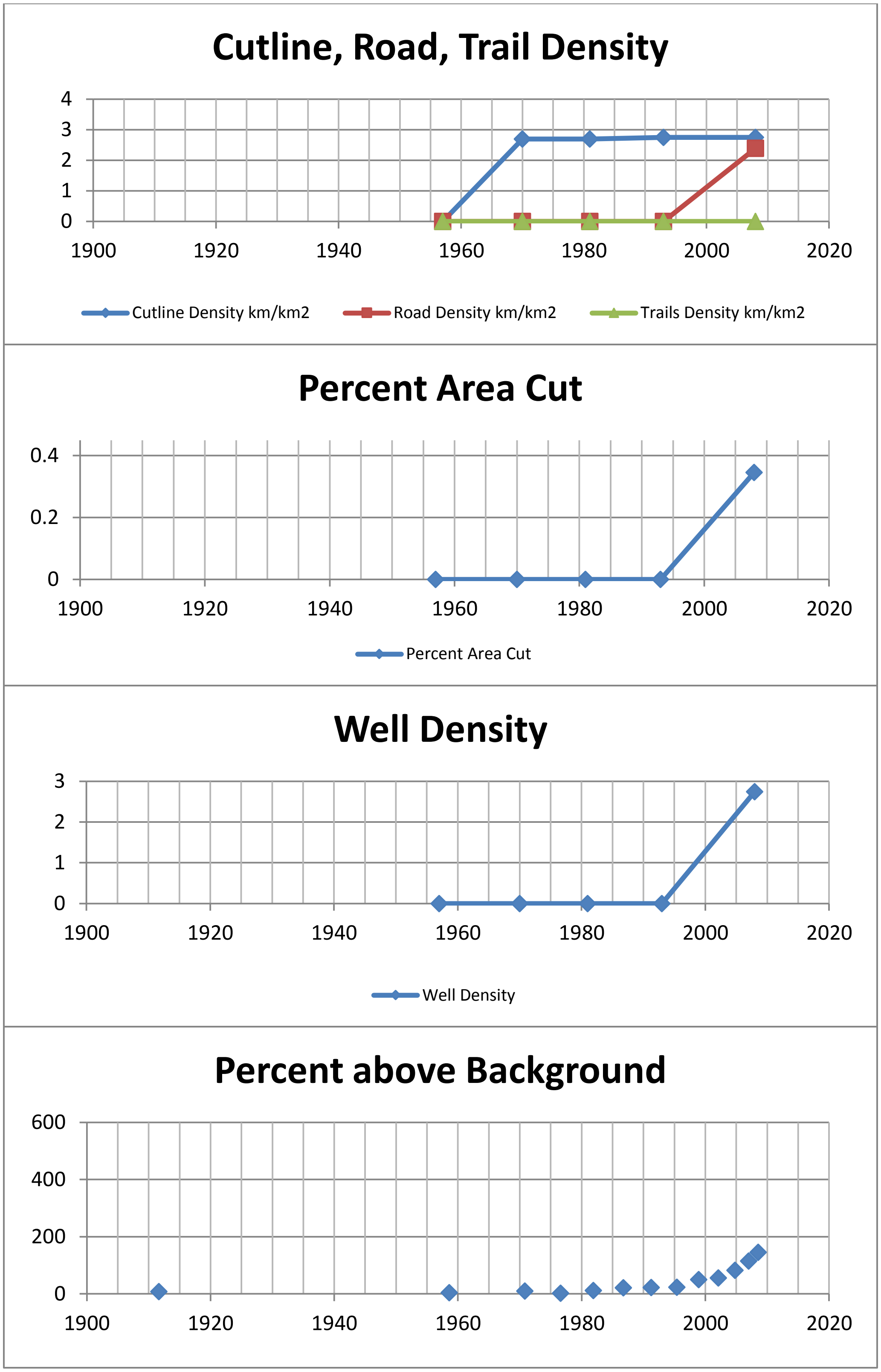
Appendix 7.2.5. Graphs of Cut line, road and trail densities, percent area cut, and percent above background for the Goldeye Lake watershed.



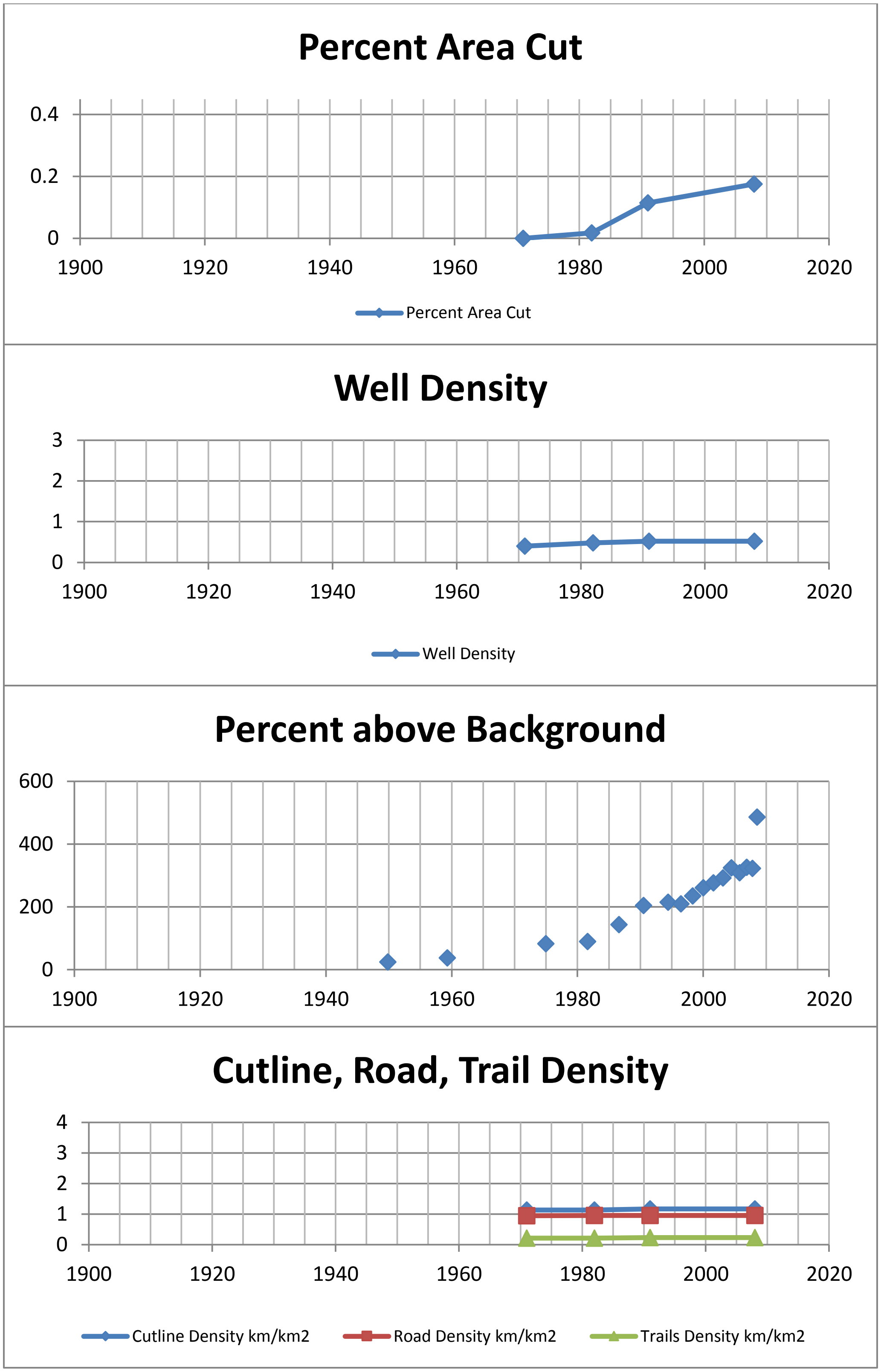
Appendix 7.2.6. Graphs of Cut line, road and trail densities, percent area cut, and percent above background for the Iosegun Lake watershed.



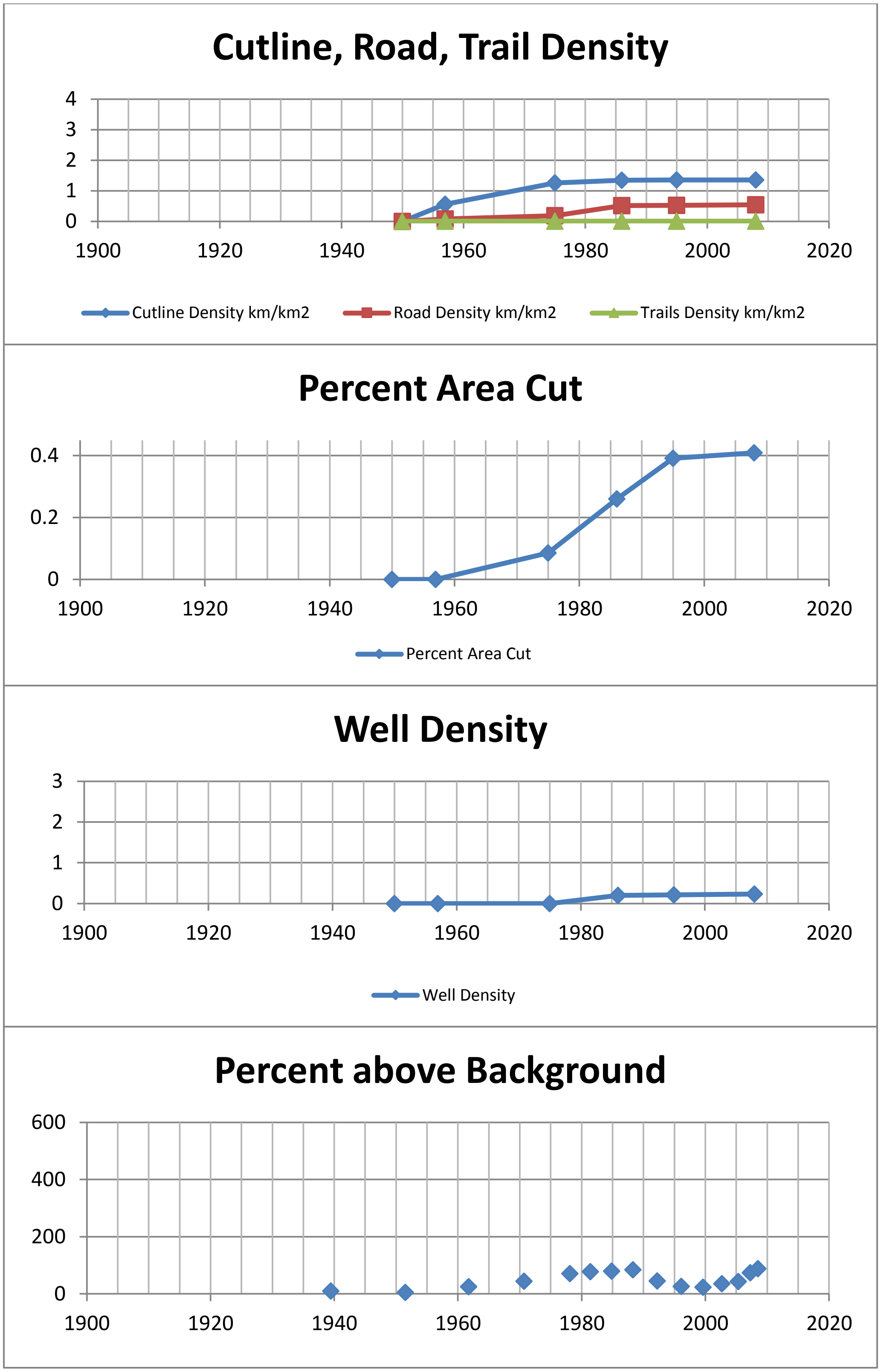
Appendix 7.2.7. Graphs of Cut line, road and trail densities, percent area cut, and percent above background for the Jarvis Lake watershed.



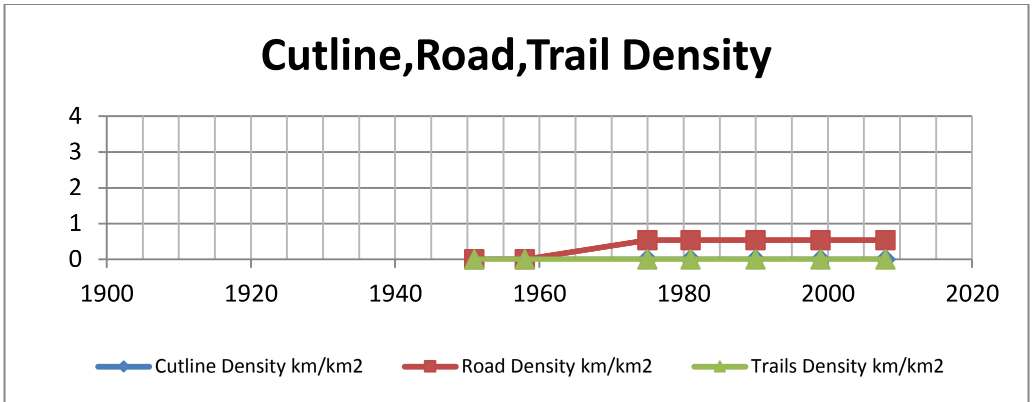
Appendix 7.2.8. Graphs of Cut line, road and trail densities, percent area cut, and percent above background for the Mayan Lake watershed.

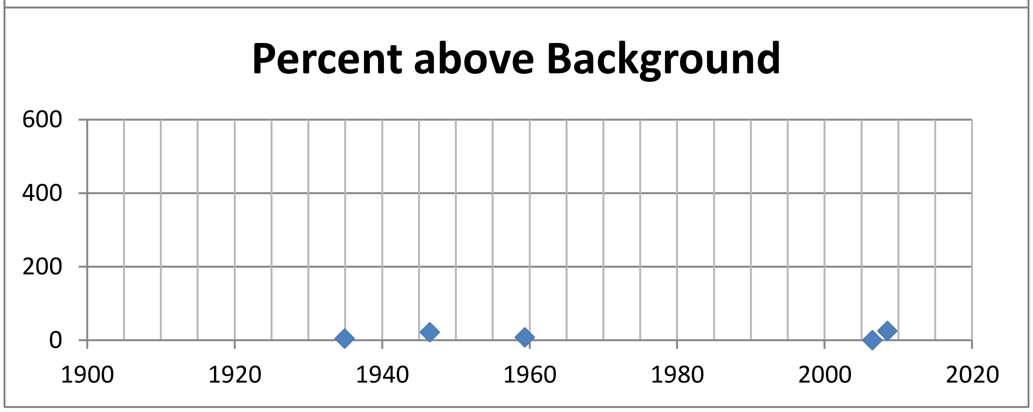


Appendix 7.2.9. Graphs of Cut line, road and trail densities, percent area cut, and percent above background for the McLeod Lake watershed.

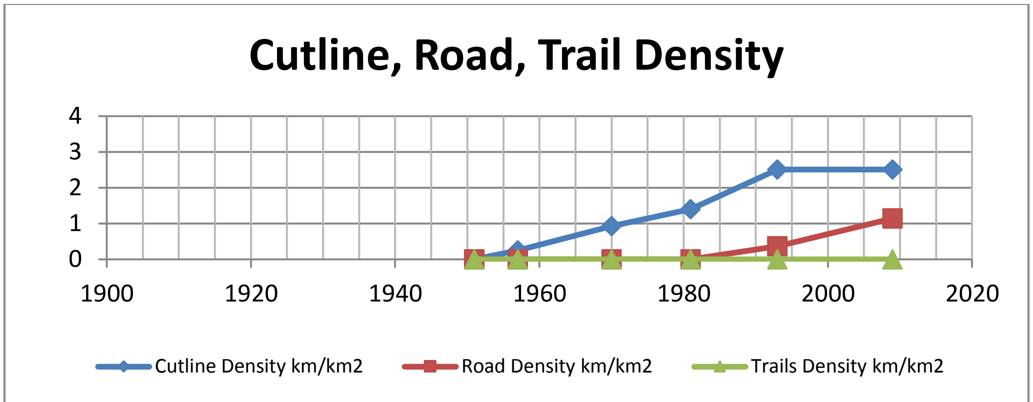


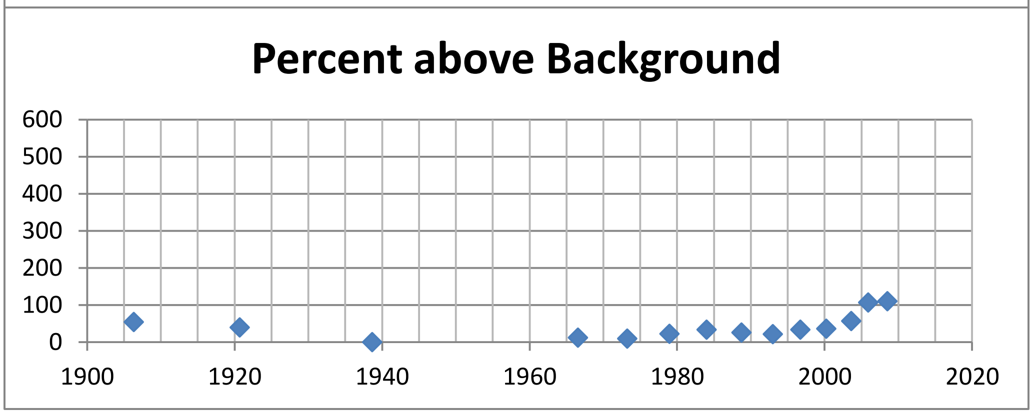
Appendix 7.2.10. Graphs of Cut line, road and trail densities, percent area cut, and percent above background for the Musreau Lake watershed.



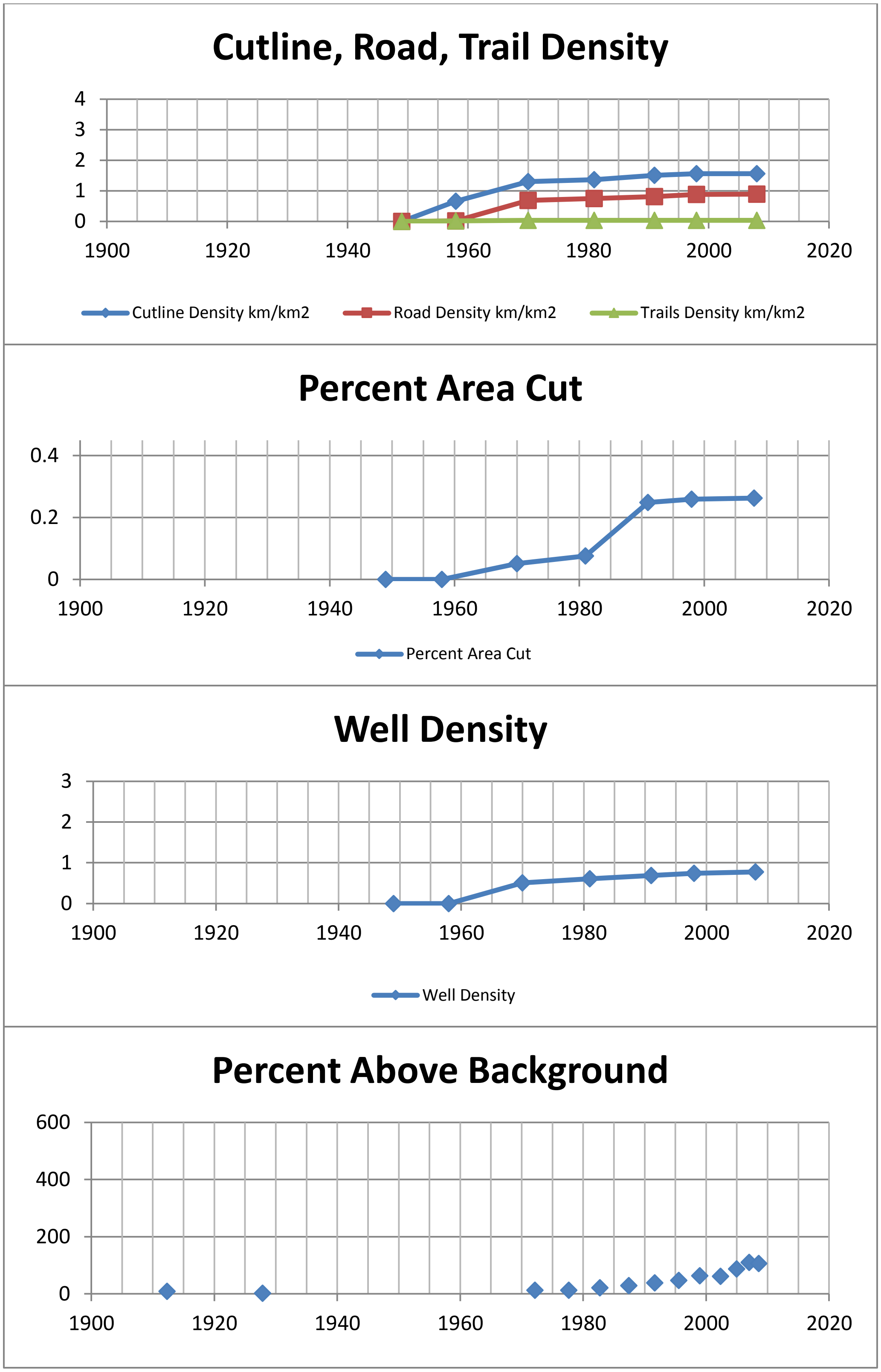


Appendix 7.2.11. Graphs of Cut line, road and trail densities, percent area cut, and percent above background for the Pierre Gray Lake watershed.





Appendix 7.2.12. Graphs of Cut line, road and trail densities, percent area cut, and percent above background for the Rainbow Lake watershed.



Appendix 7.2.13. Graphs of Cut line, road and trail densities, percent area cut, and percent above background for the Smoke Lake watershed.

7.3. Spearman Rank Correlation Matrix.

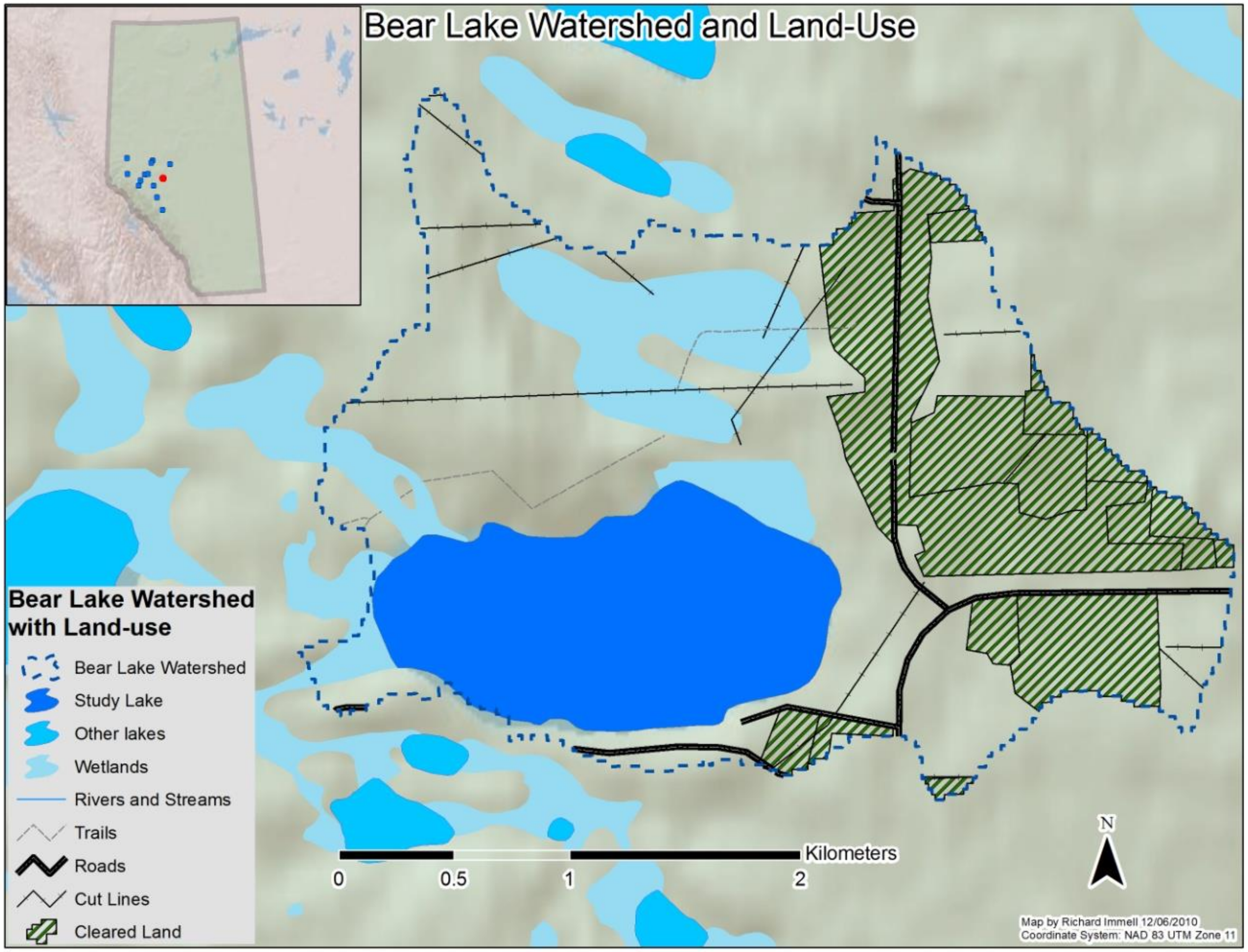
Variables	Watershed area km2	Lake area km2	Lake area Watershed area	Drainage length km	Drainage density km/km2	Area of water features w/o study lake km2	% Area of water features	Mean slope	Elev max km	Elev. min km	Background Sedimentation Rate	Specific Background Sedimentation rate	Specific Sediment Yield
Watershed area km2	**0**	**< 0.0001**	0.135	**< 0.0001**	**0.003**	**0.000**	0.957	0.415	0.125	**0.005**	**0.041**	**0.001**	0.863
Lake area km2	**< 0.0001**	**0**	0.964	**0.002**	**0.017**	**0.002**	0.785	**0.074**	**0.097**	**0.004**	**0.063**	**< 0.0001**	0.243
Lake area Watershed area	0.135	0.964	**0**	0.123	0.123	0.353	0.971	0.271	0.493	0.942	0.579	0.863	**0.002**
Drainage length km	**< 0.0001**	**0.002**	0.123	**0**	**< 0.0001**	**0.034**	0.406	0.633	0.320	**0.017**	**0.003**	**0.011**	0.926
Drainage density km/km2	**0.003**	**0.017**	0.123	**< 0.0001**	**0**	0.144	0.192	0.654	0.845	**0.075**	**0.009**	**0.056**	0.845
Area of water features w/o study lake km2	**0.000**	**0.002**	0.353	**0.034**	0.144	**0**	0.100	**0.086**	**0.079**	**0.010**	0.517	**0.001**	0.689
% Area of water features	0.957	0.785	0.971	0.406	0.192	0.100	**0**	0.258	0.885	0.892	**0.018**	0.470	0.329
Mean slope	0.415	**0.074**	0.271	0.633	0.654	**0.086**	0.258	**0**	**0.049**	**0.049**	0.899	**0.029**	0.170
Elev max km	0.125	**0.097**	0.493	0.320	0.845	**0.079**	0.885	**0.049**	**0**	**0.001**	0.280	**0.091**	0.217
Elev. min km	**0.005**	**0.004**	0.942	**0.017**	**0.075**	**0.010**	0.892	**0.049**	**0.001**	**0**	**0.078**	**0.003**	0.470
Background Sedimentation Rate	**0.041**	**0.063**	0.579	**0.003**	**0.009**	0.517	**0.018**	0.899	0.280	**0.078**	**0**	0.247	0.220
Specific Background Sedimentation rate	**0.001**	**< 0.0001**	0.863	**0.011**	**0.056**	**0.001**	0.470	**0.029**	**0.091**	**0.003**	0.247	**0**	0.383
Specific Sediment Yield	0.863	0.243	**0.002**	0.926	0.845	0.689	0.329	0.170	0.217	0.470	0.220	0.383	**0**

Appendix 7.3.1. Spearman rank correlation matrix (p-values) for landscape features.

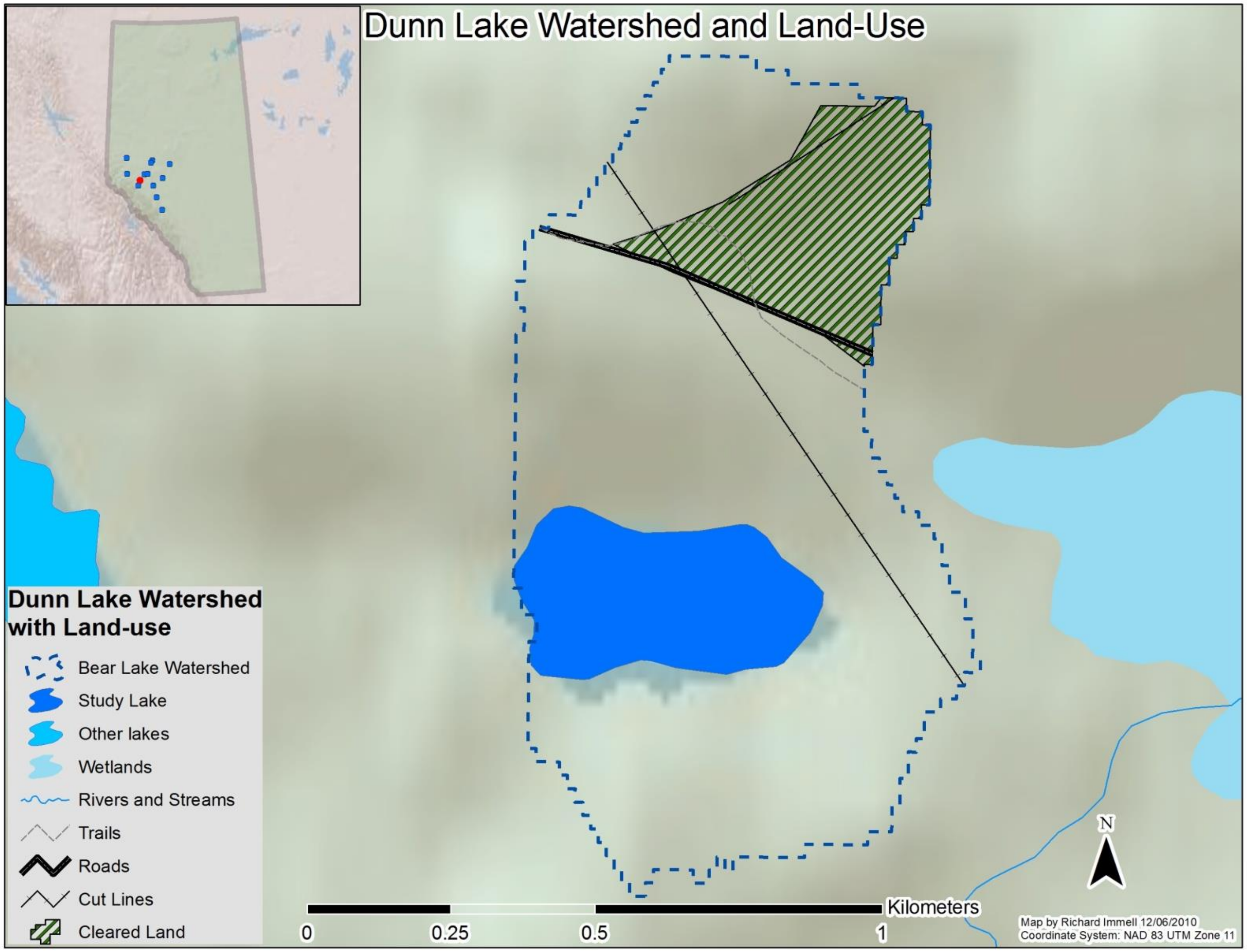
Variables	Average Above Background:	Cutline Density km/km2	Road Density km/km2	Percent Area Cut	Well Density
Average Above Background:	**0**	0.683	**0.046**	0.356	0.533
Cutline Density km/km2	0.683	**0**	0.378	0.841	0.107
Road Density km/km2	**0.046**	0.378	**0**	0.674	0.374
Percent Area Cut	0.356	0.841	0.674	**0**	0.122
Well Density	0.533	0.107	0.374	0.122	**0**

Appendix 7.3.2. Spearman rank correlation matrix (p-values) for land-use features.

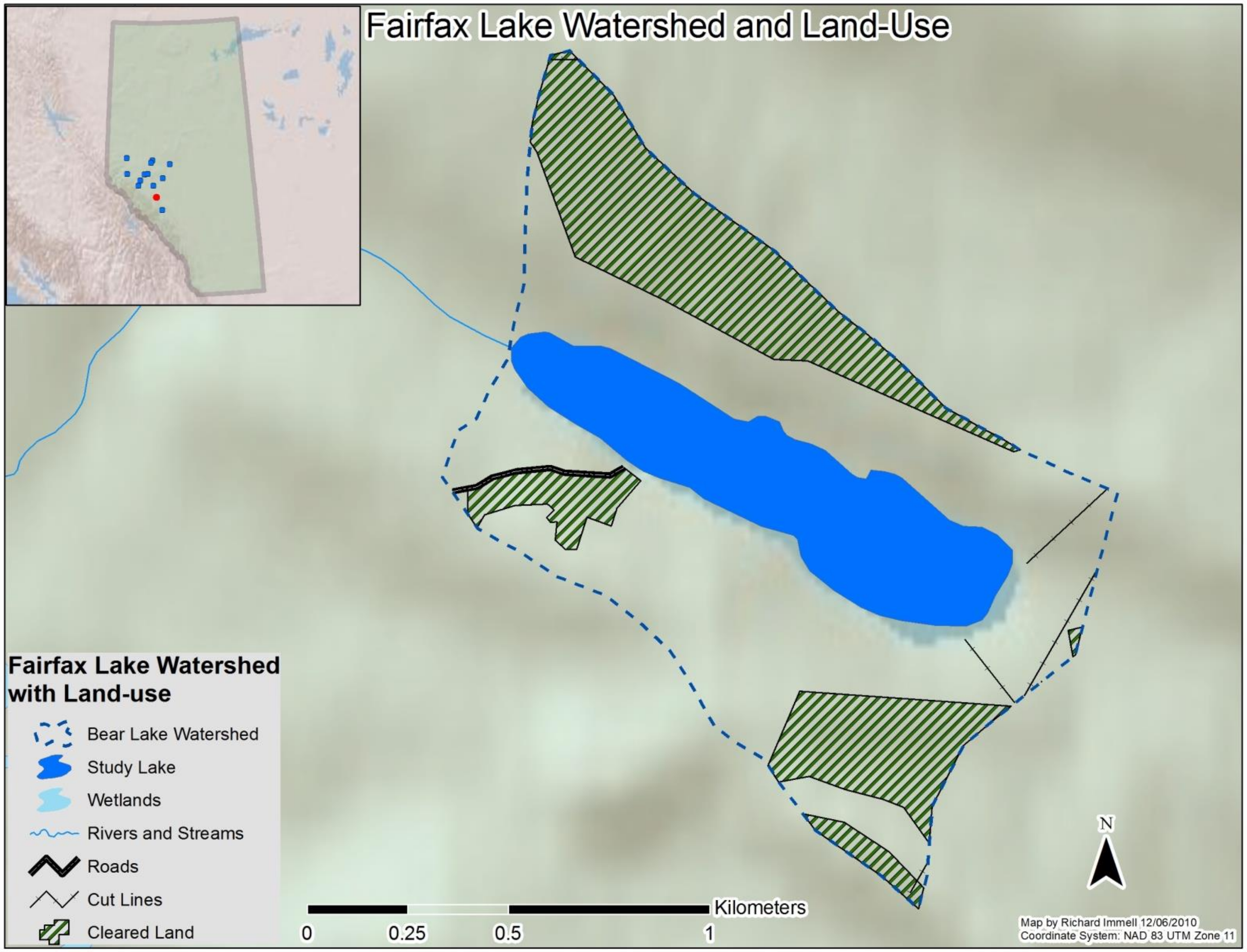
7.4. Land-use Maps.



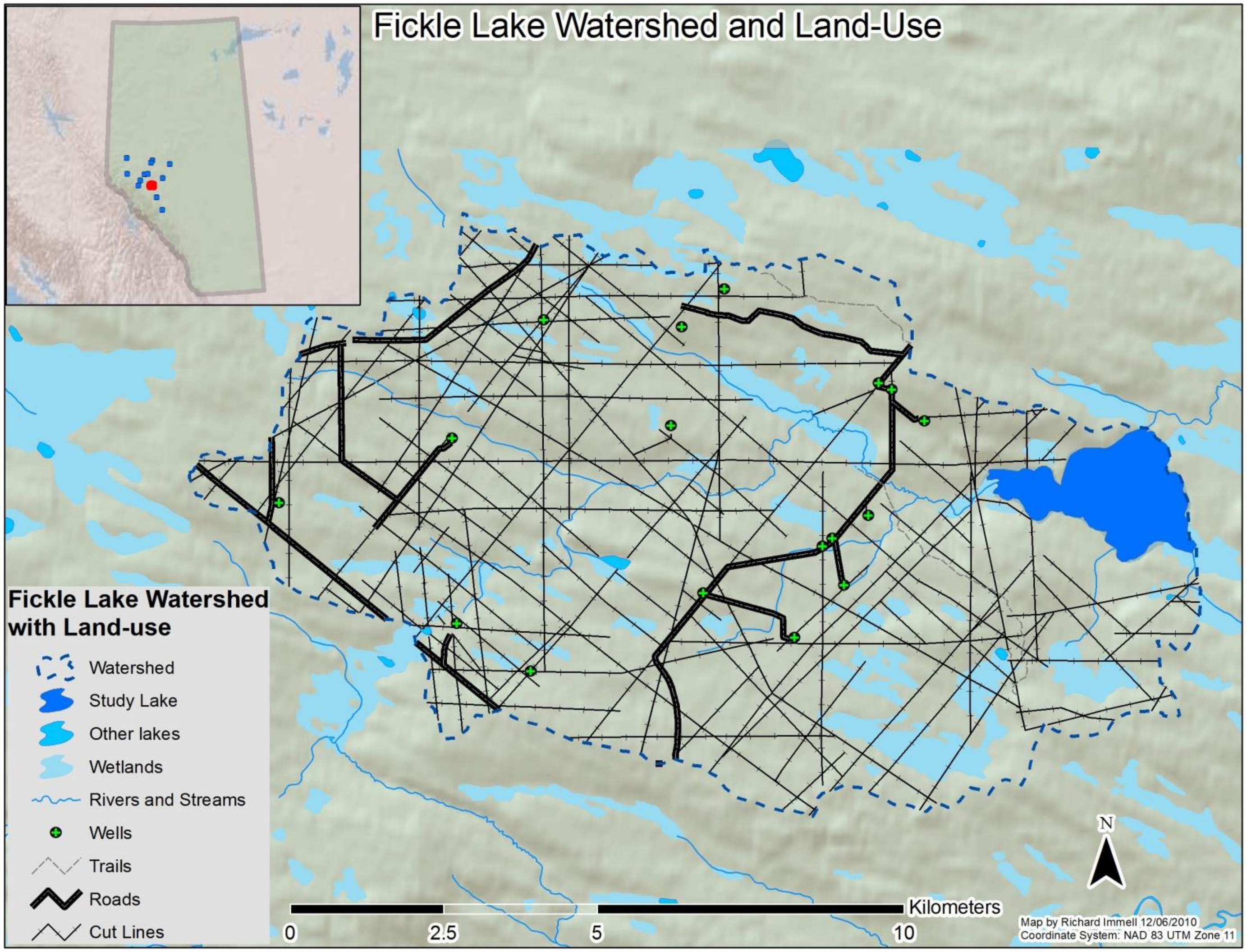
Appendix 7.4.1. Map of Bear lake watershed, indicating land-use.



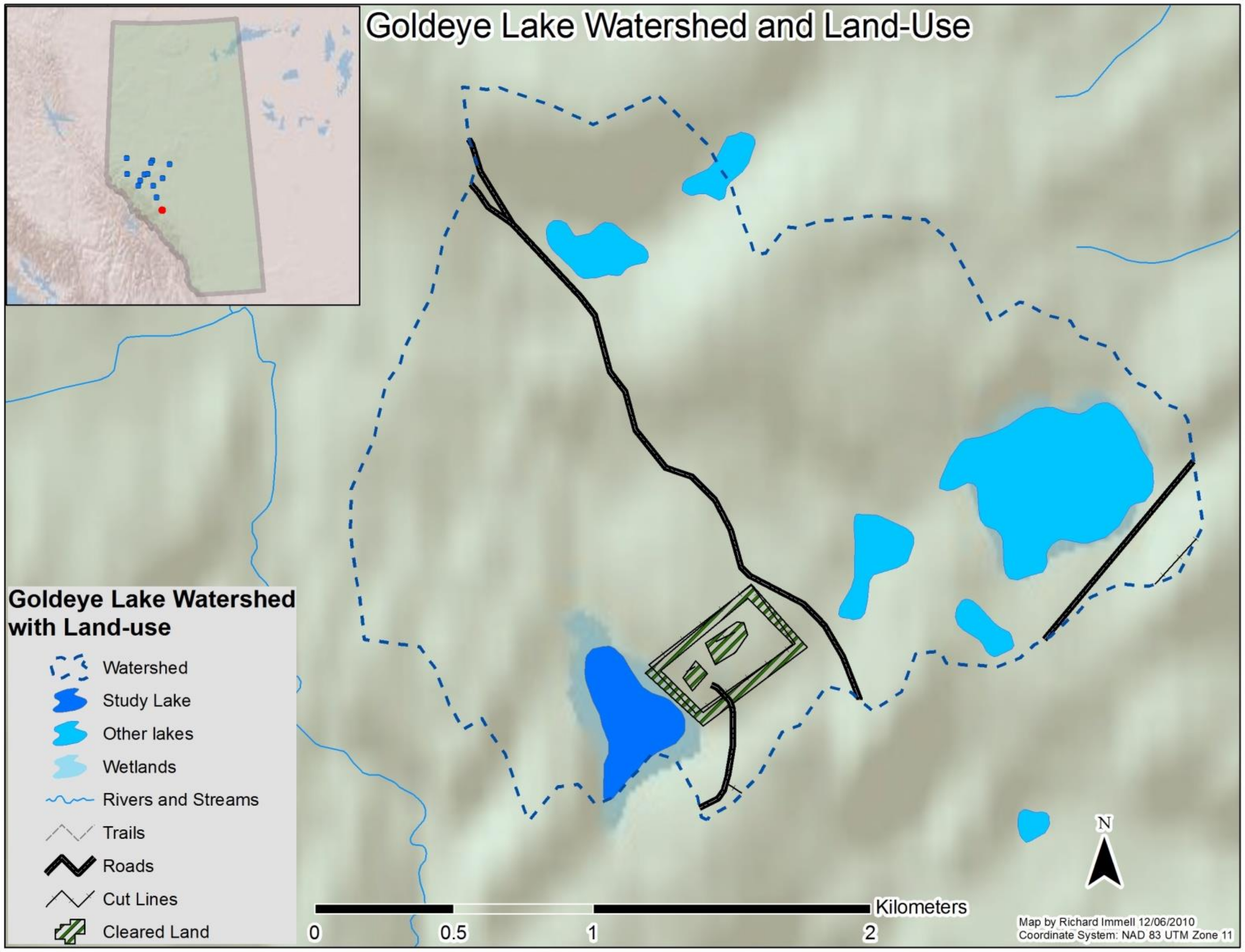
Appendix 7.4.2. Map of Dunn lake watershed, indicating land-use.



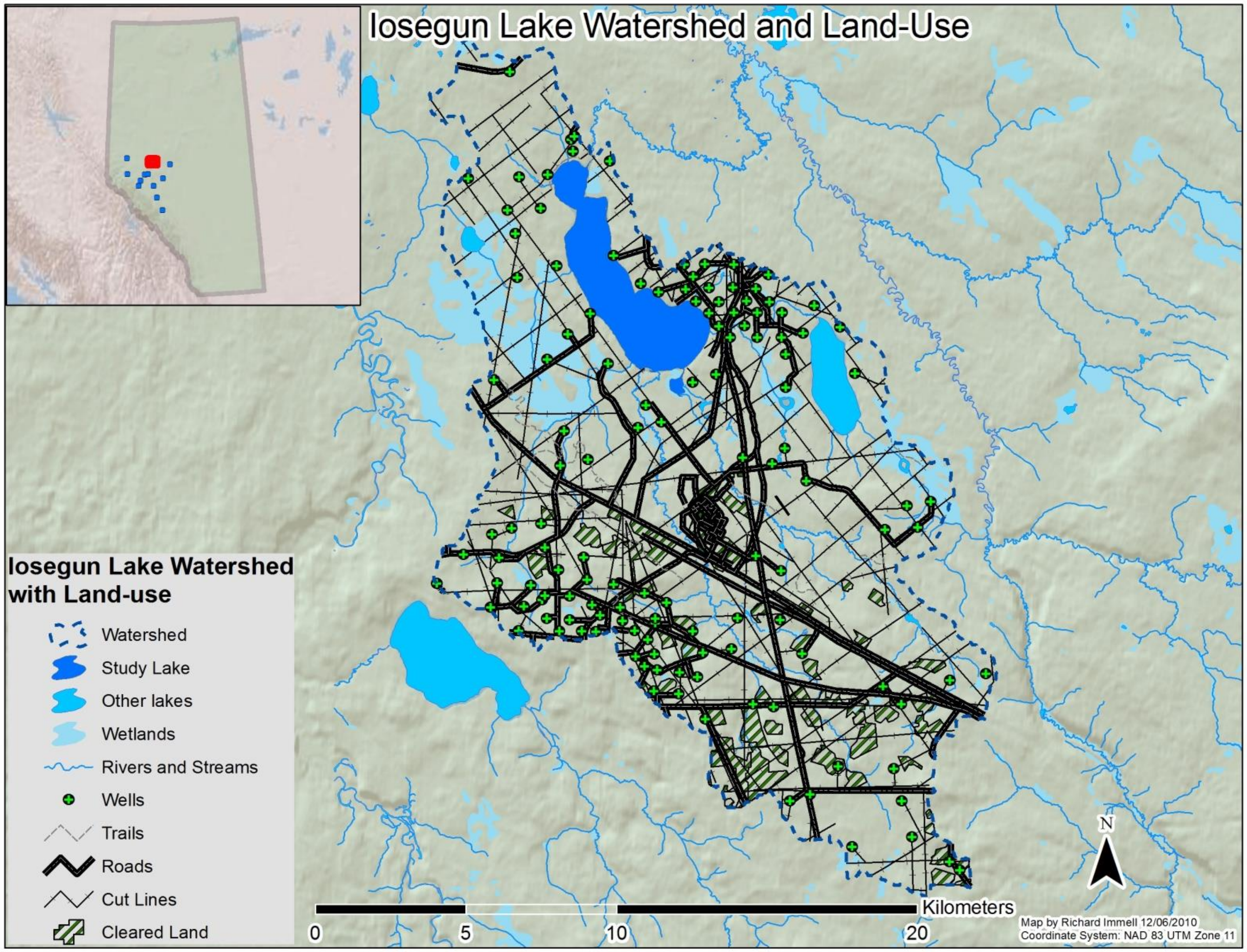
Appendix 7.4.3. Map of Fairfax Lake, indicating land-use.



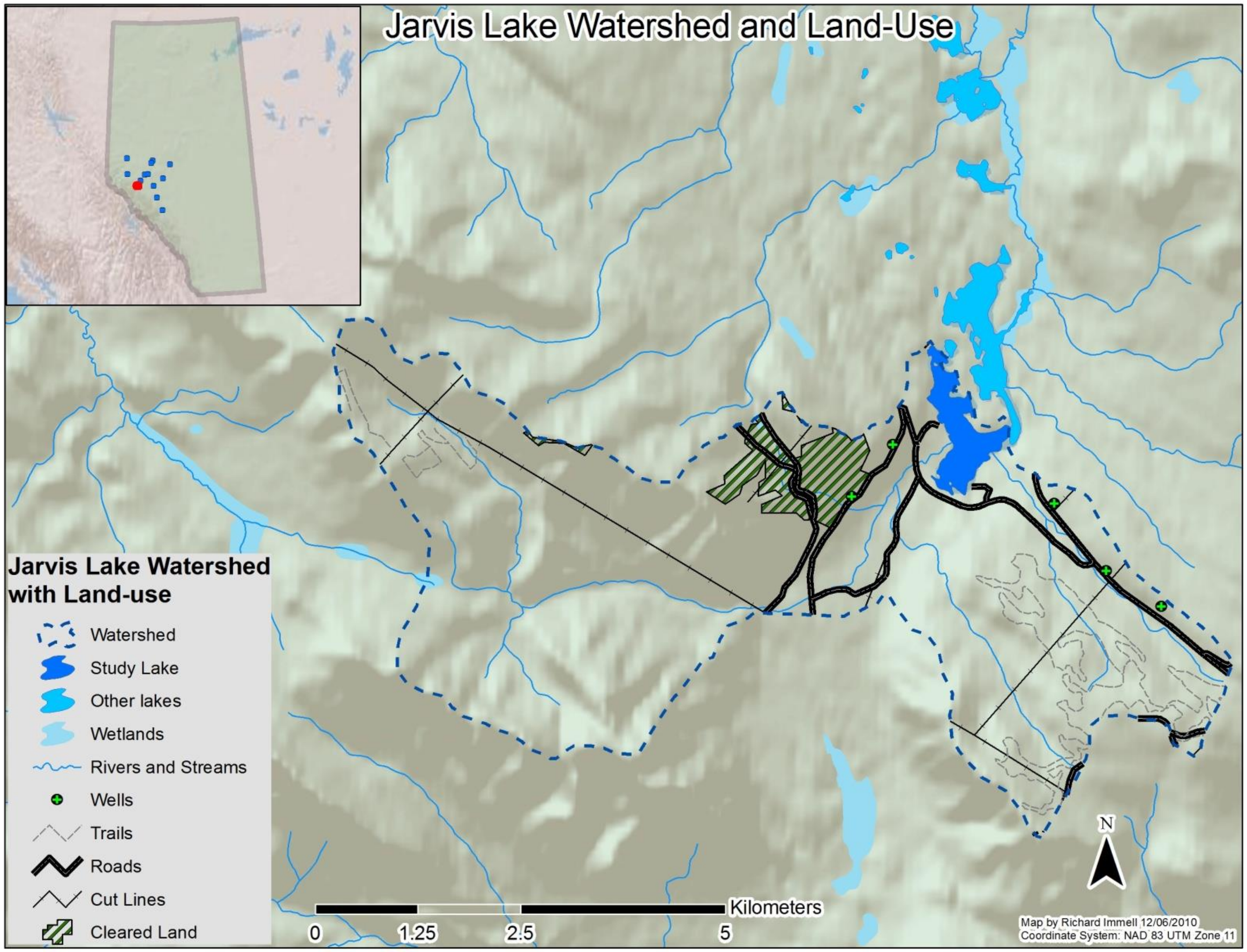
Appendix 7.4.4. Map of Fickle Lake, indicating land-use.



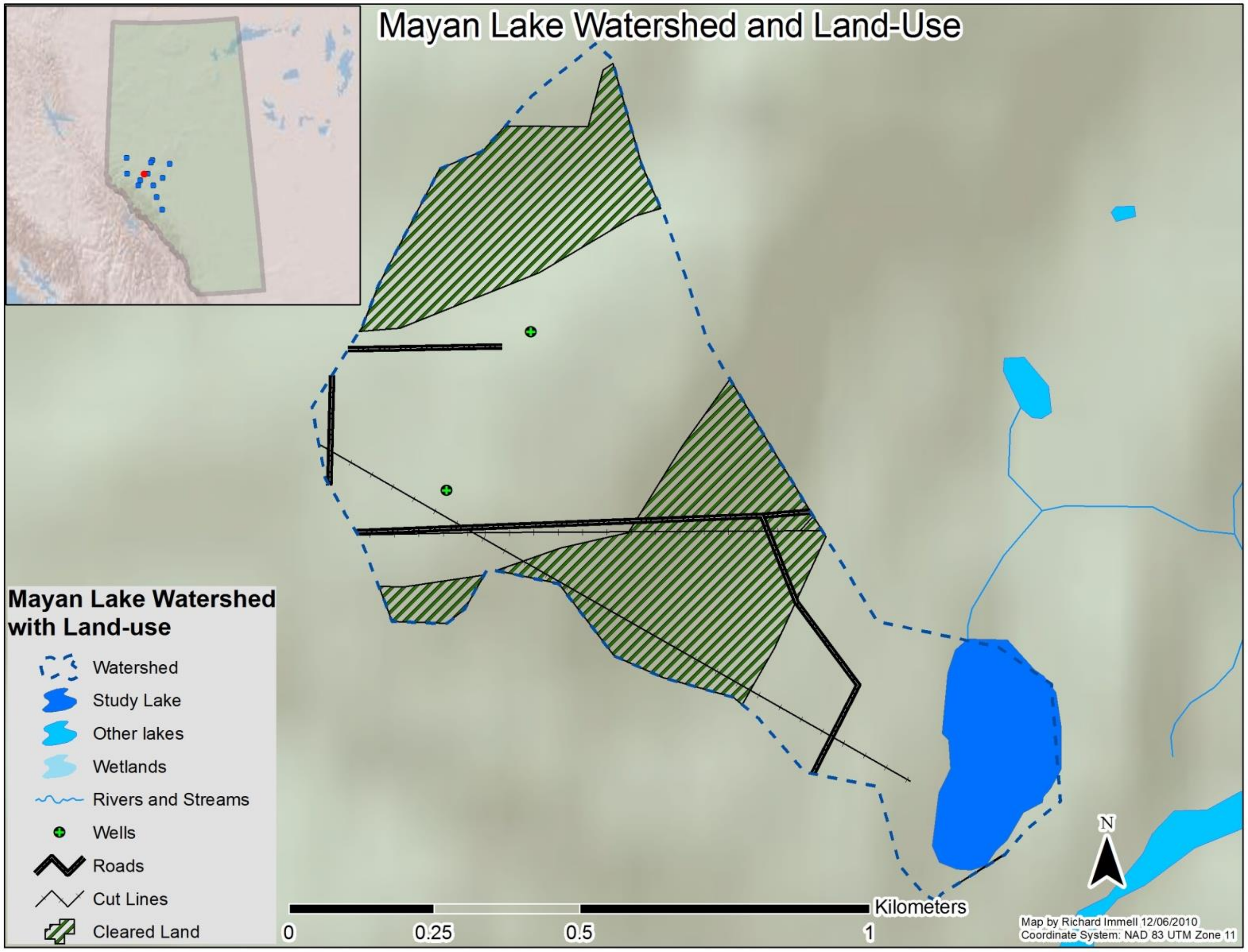
Appendix 7.4.5. Map of Goldeye Lake, indicating land-use.



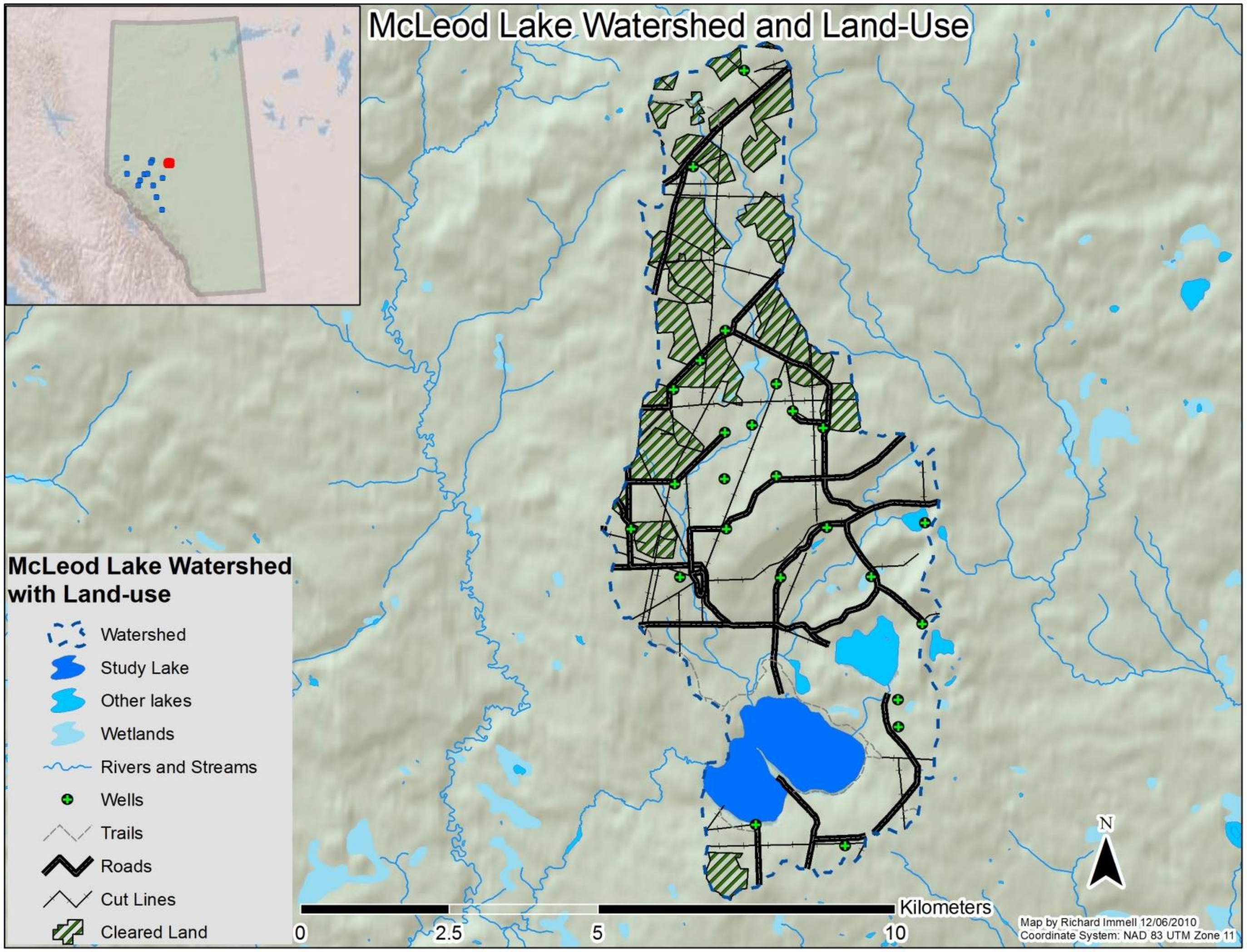
Appendix 7.4.6. Map of Iosegun Lake, indicating land-use.



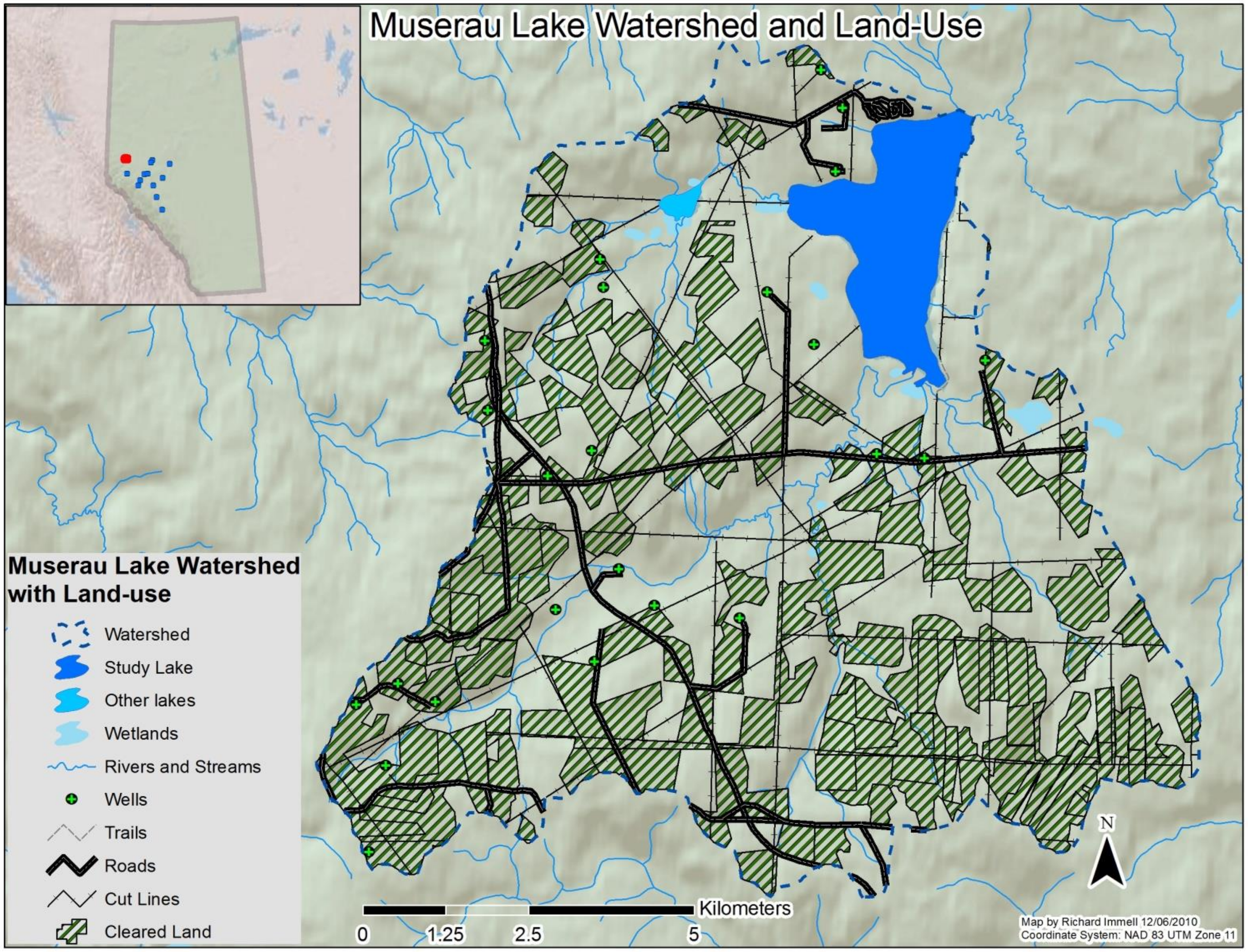
Appendix 7.4.7. Map of Jarvis Lake, indicating land-use.



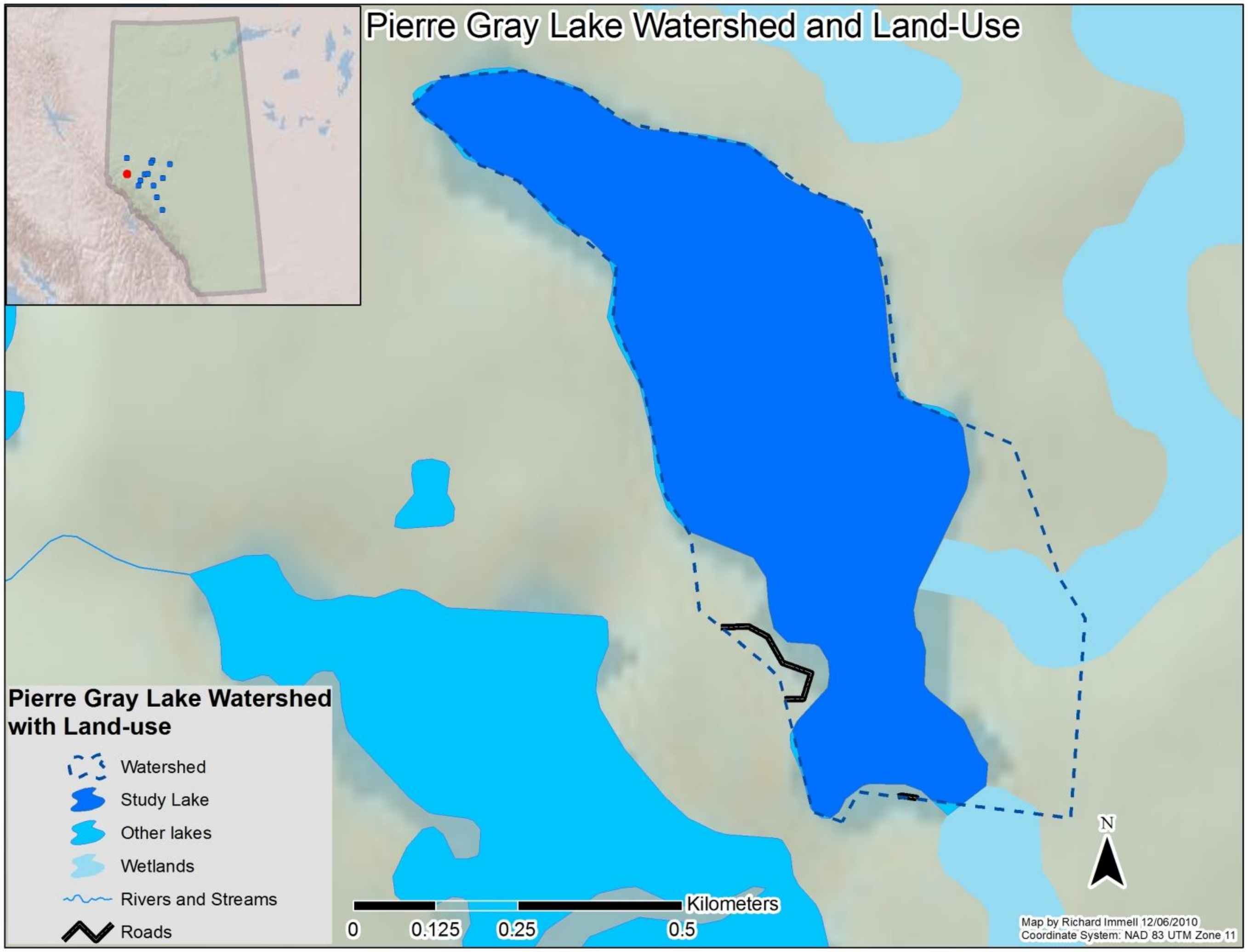
Appendix 7.4.8. Map of Mayan Lake, indicating land-use.



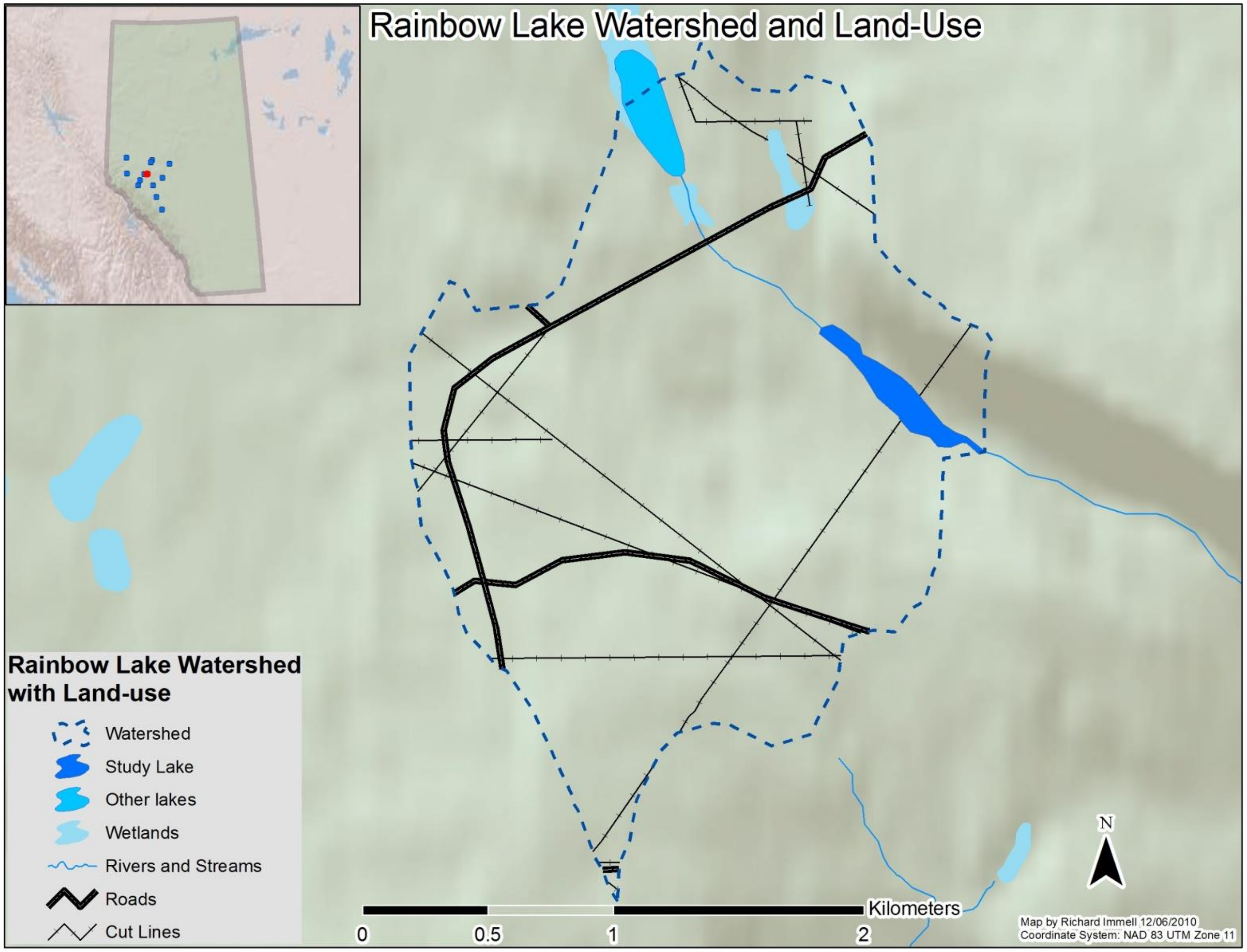
Appendix 7.4.9. Map of McLeod Lake, indicating land-use.



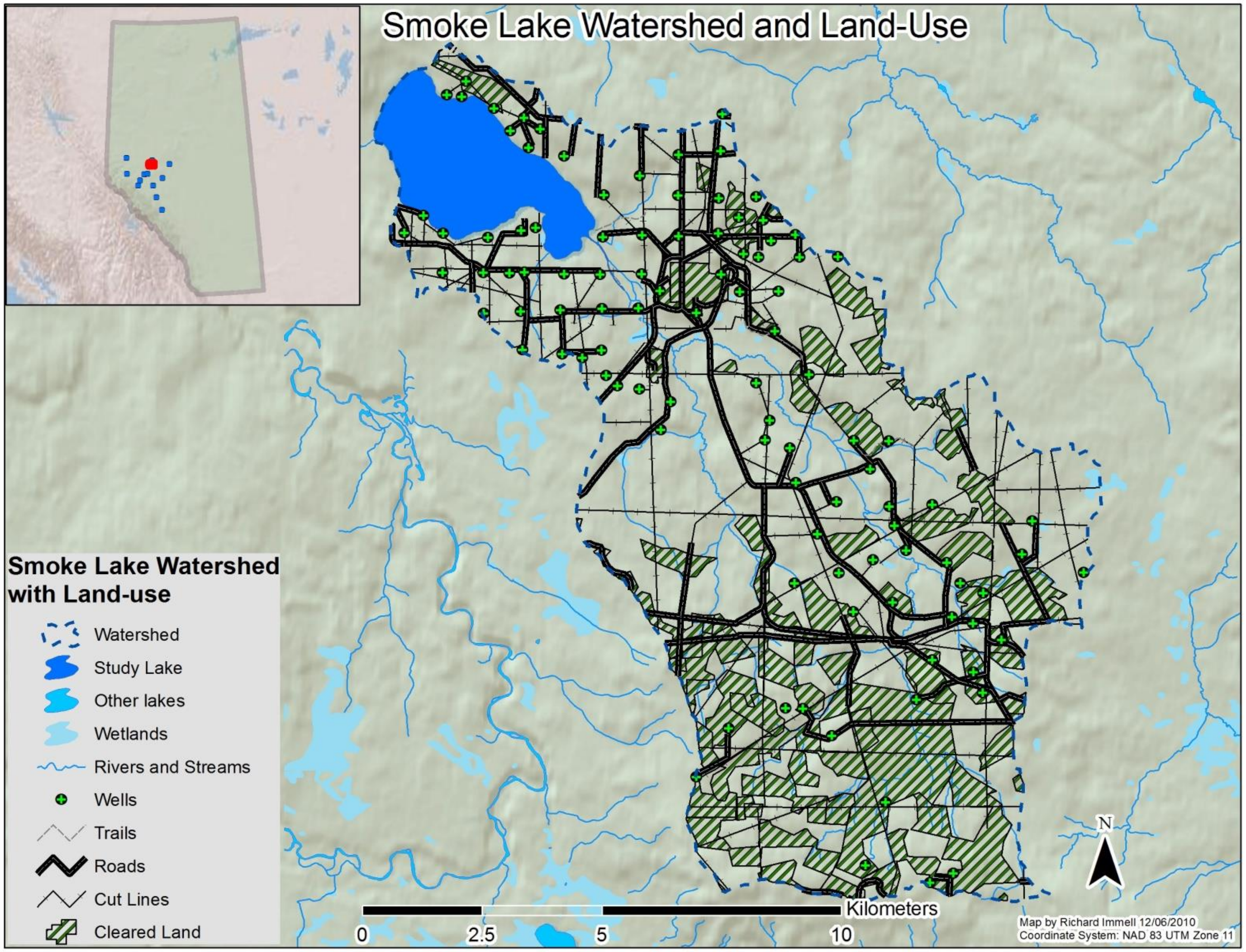
Appendix 7.4.10. Map of Muserau Lake, indicating land-use.



Appendix 7.4.11. Map of Pierre Gray Lake, indicating land-use.

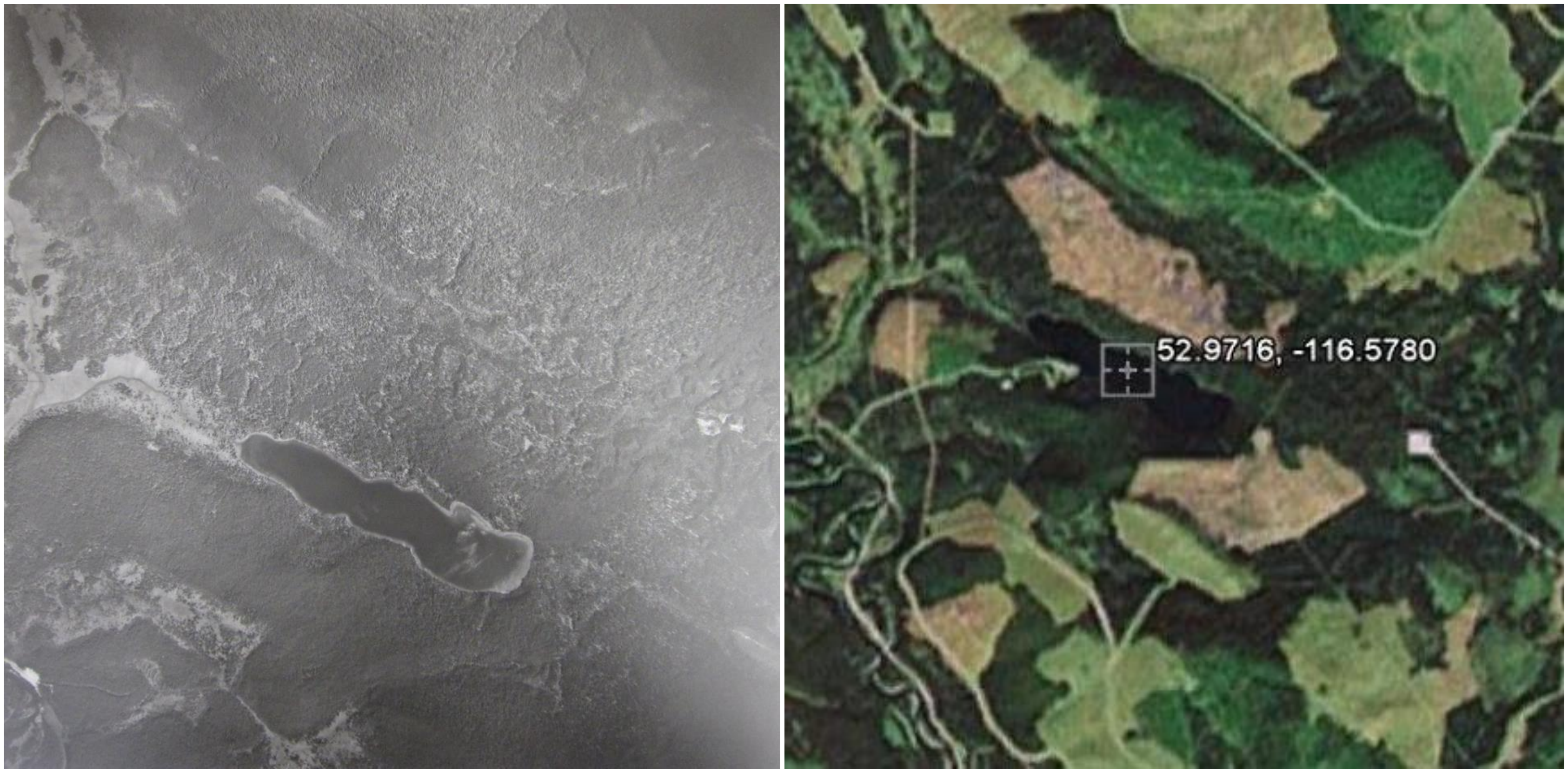


Appendix 7.4.12. Map of Rainbow Lake, indicating land-use.



Appendix 7.4.13. Map of Smoke Lake, indicating land-use.

7.5 Samples of air photos: indicating low and heavy land-use.



Appendix 7.5.1. Fairfax Lake in 1952 and in 2009. Land use was minimal in 1952, and widespread in 2009.