2014

Influence of watershed and soil parameters on water quality in fifty western Washington lakes

Susan F. (Susan Farmer) Horton
Western Washington University

Recommended Citation

Horton, Susan F. (Susan Farmer), "Influence of watershed and soil parameters on water quality in fifty western Washington lakes" (2014). *WWU Graduate School Collection*. 335.
https://cedar.wwu.edu/wwuet/335

INFLUENCE OF WATERSHED AND SOIL PARAMETERS ON WATER QUALITY IN FIFTY WESTERN WASHINGTON LAKES

By

Susan Horton

Accepted in Partial Completion

Of the Requirements for the Degree

Master of Science

Kathleen L. Kitto, Dean of the Graduate School

ADVISORY COMMITTEE

Chair, Dr. Robin Matthews

Dr. Peter Homann

Dr. Leo Bodensteiner

Susan Horton

May 16, 2014

INFLUENCE OF WATERSHED AND SOIL PARAMETERS ON WATER QUALITY IN FIFTY WESTERN WASHINGTON LAKES

A Thesis
Presented to
The Faculty of
Western Washington University

In Partial Fulfillment
Of the Requirements for the Degree
Master of Science

By
Susan Horton
April 2014

Abstract

The purpose of my study was to find reliable patterns in the data that linked watershed characteristics to water quality. The project area was regional in scope, spanning two very different ecoregions, involving 50 lakes many of which have been sampled for 7 years. I found highly significant correlations (Kendall's tau >0.500, p-value <0.001) between total phosphorus, chlorophyll α, total nitrogen, and turbidity. Total phosphorus, chlorophyll α, total nitrogen, and turbidity also strongly correlated with mean and maximum lake depths. I also found highly significant correlations between watershed area, fetch, road length, and population. Road length and population were the parameters that best described residential development in my study. By evaluating lake water quality with regard to total phosphorus, chlorophyll α, and using road length and population as indicators of development, I identified lakes that were at-risk due to development within the watersheds and the likelihood of nutrient resuspension. The most at-risk lake was Reed Lake. Currently Reed Lake is at the high end of the mesotrophic range, but it is at risk of becoming more permanently eutrophic due to the pressures of development on the water quality exacerbated by the likelihood of nutrient resuspension. Using clustering analysis based on principal components, the watersheds in my study formed three stable groups that were related to water quality and lake and watershed morphology. The extent to which soils affect water quality in these lakes was not fully revealed by the results of my work and is worthy of further investigation.

Table of Contents

List of Figures

List of Tables

Introduction

The purpose of my study was to delineate lake and watershed characteristics for 50 lakes in northwest Washington. I wanted to determine the relationship between water quality and watershed parameters across these diverse watersheds. My goal was to find reliable patterns in the watershed data that could be used to predict water quality.

Development is impacting water quality in the Puget Sound basin in the Pacific Northwest region of the United States where forested lands are increasingly being cleared for agricultural, commercial, and residential development altering surface water chemistry and movement of water through the watershed (Cuo et al. 2009, Praskievicz and Chang 2009). The fastest changing ecoregion in the United States is the Puget Lowland ecoregion. This ecoregion is flanked by the Olympic and Cascade Mountain ranges, it is centered in Puget Sound, and includes the Interstate 5 corridor through the state of Washington (Omernik 1987). The primary cause of land use and land cover change in this ecoregion is timber harvesting. The second leading cause of land use changes in this ecoregion is residential development (Sorenson 2012). Higher levels of nitrogen and phosphorus are often found on developed parcels as opposed to undeveloped parcels where the application of nitrogen based fertilizers, abundant animal waste, and inadequate or malfunctioning waste disposal systems are among the likely causes of these higher nutrient levels. Surface and ground water chemistry is altered as it passes through these developed parcels and often leads to excessive nutrients entering waterbodies down slope from the development (Bullard 1966, Soranno et al. 1996, Strayer et al. 2003).

The potential for excessive nutrients to negatively impact receiving waterbodies is variable and depends on the size of the watershed in relation to the scale of the development (Praskievicz and Chang 2009). Water quality degradation is more likely to occur in lakes that have small watersheds with high levels of development than in lakes with larger watersheds and less development. Movement of nutrients through a watershed is influenced by the amount of impervious surfaces and alterations to soil in the watershed. Impervious surfaces increase as commercial and residential densities increase thereby increasing the flow rate of nutrient-enriched water through the watershed. Development also reduces the efficacy of natural filtration systems, such as unaltered soils, native vegetation, wetlands, and flood plains (Coats et al. 2008, Garn et al. 2010). These impacts on water quality are most easily discernible when there is an increased flow rate of nutrient-enriched water through a watershed such as occurs during a storm event (Soranno et al. 1996).

Faster flow rates reduce the contact time between water and the substrate, reducing the removal of waterborne contaminants. These faster flow rates also impede infiltration of nutrient-enriched waters into the ground where the soil serves to remove contaminants from the water (Coats et al. 2008; Praskievicz and Chang 2009). Increased flow rates containing higher nutrient levels traveling over a more hardened, less porous, landscape results in increased nutrients in the receiving waterbodies (Soranno et al. 1996Strayer et al. 2003). Alterations to the landscape, such as development, heighten the challenge of preserving and protecting the aquatic natural resources humans rely upon (Chu et al. 2003).

Algal production of organic matter is one way to characterize the state of a lake (Wetzel 2001). Phytoplankton in lakes produce organic matter. Phosphorus and nitrogen are among the essential nutrients required by phytoplankton for production of organic matter, and algal growth is often limited by the lack of one or both of these essential nutrients. When nutrients increase with watershed development and nutrient-enriched water flows through the watershed and enters a lake, the productivity of that lake can increase. This increased rate of nutrient introduction into a waterbody is known as nutrient loading. Loading can also bring with it metals, pesticides, and other types of contaminants present in the watershed (Mankin et al. 2003). Lakes that become rich in nutrients can shift from low productivity, or oligotrophy, to mid-level (mesotrophy) or highly productive eutrophic lakes (Wetzel 2001). If phytoplankton productivity becomes excessive, it can lead to nuisance algal blooms, increased turbidity, escalated siltation, and reduction in transparency (Mankin et al. 2003).

Bortleson et al. (1973) describes the glacial history of two common lake shapes in Washington: long narrow lakes and rounded lakes. Long narrow lakes were carved by glacial movement while the more rounded lakes were formed by large depositions of ice. Lake and watershed morphology influence water quality. If the lake is large enough, it can absorb some of the negative effects of land use within the watershed without showing a measurable change in water quality (Soranno et al. 1996). The surface area of a lake, its maximum lake depth, ambient air temperature, and water temperature all have some influence on lake productivity (Dickman 1969, Turner et al. 1983, Soballe and Threlkeld, 1985, Davis and Reeder, 2001). The shape of the lake is important when defining fetch. Fetch, the longest distance wind can move across a lake unobstructed by land, is key to internal loading in shallow eutrophic lakes because it influences nutrient resuspension (Wetzel

2001, Niemistö et al. 2008, Thomas and Schallenberg 2008). If the fetch direction aligns with prevailing winds and the wind is unimpeded by watershed terrain, the lake will receive more of the wind's energy. The wind's energy can result in wave action that increases circulation, facilitating resuspension of nutrients in shallow lakes, especially those shallow lakes with a high mean to maximum lake depth ratio or development of volume (D_v) (Bortleson et al. 1973). Wolfram et al. (2009) in their study of alpine lakes characterize shallow lakes as those with a mean depth of <3 meters.

The primary cause of land use/land cover changes in the Puget Lowlands and North Cascades (north central Washington) ecoregions is timber harvesting and the length of time it takes for the replanting of these harvests to mature (Omernik 1987, Sorenson 2012, Wilson 2012). Vegetation is important to water quality. It along with road length, and human population are good indicators of development and are useful in predicting increased nitrogen- and phosphorus-loading, as well as increased lake turbidity. (Coats et al. 2008). Watershed vegetation acts as a natural nutrient filtration system. The density and type of vegetation influences the amount of precipitation that infiltrates the soil, moves as runoff, or is retained by the vegetation itself. Native forests in particular possess superior ability to retard the flow of runoff and nutrients through the system by absorbing water and nutrients at a greater rate than non-native plants such as lawn and pasture grasses (Duggan 2012). As native forests and plant communities are replaced by non-native plants, runoff increases and causes a decrease in the efficacy of the natural nutrient filtration systems. Native forests help protect water quality in other ways as well. Forests provide shade helping to reduce evaporation and to moderate slope temperatures and near shore water temperatures. Leaf litter from native vegetation along the shoreline provides more appropriate organic matter for native fauna than the leaf litter from non-native vegetation. Native vegetation also helps to keep the pH at levels that support native aquatic communities (Sullivan 1999, Duggan 2012).

Slope aspect, the direction the slope faces relative to the sun, is an important factor in watershed dynamics. It can affect surface temperature, the density and type of watershed vegetation, evapotranspiration, and snow accumulation (Soil Survey Division Staff 1993). Generally speaking, in the northern hemisphere, southwest facing slopes are warmer in the summer than northeast facing slopes because southwest facing slopes receive more direct solar radiation. For the same reason, flat surfaces are typically warmer than sloped surfaces, depending on the aspect. Higher elevations receive more solar radiation than lower elevations but this effect is modified due to the fact that air temperature is typically cooler at higher elevations. Snow accumulation and solar radiation influences the amount and timing of surface runoff, which affects runoff temperature, and ultimately, the water temperature of the receiving water bodies.

Steepness, measured as the slope, of a watershed is important in the loading of nutrients and contaminants into lakes. Steep watersheds have less contact time between water and soil, reducing the time available for the bonding that strips the runoff of nutrients or pollutants. But lakes in watersheds with lower percentages of steep slopes are more likely to have high levels of development and can accumulate higher concentrations of nutrients and pollutants, so the influence of slope is complicated.

Some watersheds contain two or more lakes that are hydrologically linked by surface streams or groundwater. Lakes that are hydrologically linked often share water quality characteristics and may show an upstream /downstream influence as water flows from one lake to the next. Upstream lakes can hold nutrients acting as nutrient sinks, but can also export nutrients, pollutants, and invasive species. Knowing whether lakes are linked hydrologically may help improve our approach to lake management (Epstein et al. 2013).

Studying water quality responses to development is an increasing priority for entities charged with management of natural resources, as well as for private citizens invested in the aesthetic and recreational properties of local lakes. The Institute for Watershed Studies (IWS) at Western Washington University (WWU) has collected water quality data from more than fifty lakes in four Northwest Washington counties (Figure 1) for more than seven years. The project is known as the Northwest Lakes Monitoring Program and includes lakes located in Island County (Figure 2), Skagit County (Figure 3), Snohomish County (Figure 4), and Whatcom County (Figure 5). All of these counties border the Salish Sea (North Puget Sound) and are found in the Puget Lowland and North Cascades ecoregions (Omernik 1987; Figure 6). The Puget Lowland ecoregion is located in a continental glacial trough. The terrain is gradually sloping with numerous islands and peninsulas. The climate is maritime and has a dense human population (Sorenson 2012). The North Cascades ecoregion is sparsely populated with steep mountainous terrain. The North Cascades ecoregion was shaped largely by glaciation and subsequent drainage (Wilson 2012). The east-west range of lake locations sampled by IWS extends from 121°37’54”W, in Mt. Baker-Snoqualmie National Forest, Whatcom County, to 122°39’22”W, Fidalgo Island, Skagit County. The north-south range is from 48°58’46”N, near the US-Canada border, in Whatcom County, to

47°58’29”N, on the south end of Whidbey Island, in Island County (Table 1). The lakes vary in altitude from 2.7 meters to 1,581 meters and range in location from remote mountainous areas to highly urbanized areas. This broad watershed spectrum is valuable when examining relationships between water quality and watershed features because the relationships are more apparent when watershed characteristics are diverse (Groffman et al. 2004). Recently, graduate student Chandra Llewellyn analyzed water quality data from a subset of lakes in the Northwest Lakes Monitoring Program. She found correlations between phosphorous, chlorophyll α, and algal densities. She also found that water chemistry in the high elevation lakes was distinctly different from the water chemistry in lower elevation lakes (Llewellyn 2010).

I examined lake and watershed parameters from the same subset of lakes examined by Llewellyn, extending the water quality by several years, and incorporating additional morphological data for the lakes and their watersheds. I used graphical analysis, bivariate correlations, and multivariate analyses to determine if the water quality and watershed parameters correspond in predictable ways that could be used as indicators of water quality.

Methods

Water Quality Parameters

All water quality data for my project were collected and analyzed by IWS. The samples were collected from near-surface depths (<1 meter) along the shoreline. The water quality measurements included dissolved oxygen, water temperature, pH, specific conductivity, chlorophyll α, alkalinity, turbidity, ammonium, total nitrogen, nitrate/nitrite, total phosphorus and soluble reactive phosphate. The analytical methods, abbreviations, units and detection limits for the water quality analyses are described in Table 2.

I used data from a 50-lake subset of lakes studied by the IWS in its Northwest Lakes Monitoring Program. I create a single representative water quality value for each parameter at each lake by calculating the median values of data collected from June through September, 2006-2012 (Table 3). I used medians for each water quality parameter from each lake to avoid pseudoreplication in the correlation analyses and to match the watershed parameters, which were represented by a single value for each parameter for each lake.

Some of the lakes had nutrient concentrations that fell below the IWS analytical detection limits listed in Table 2. Several methods are widely used to deal with data that fall below the analytical detection limit (BDL data). These include substituting the detection limit value for the BDL value, substituting half the detection limit value for the BDL value, or using the absolute value of the BDL result, which converts negative BDL values to their positive equivalent, (Dr. Robin Matthews, personal communication). These simple data substitution methods are known as censoring and all have the potential to skew statistical analyses. The influence of censoring is relatively low when it affects a small percentage of the data (Jones and Clarke 2005, Helsel 2006) and can be reduced by using rank-based statistical analyses. But when more than 50% of the measured values are BDL, even rank-based statistics are affected because the median is also BDL. Some of the low-nutrient lakes from the IWS water quality data had more than half BDL values for ammonium, nitrate/nitrite, soluble phosphate, and total phosphorus. For these, lakes, the summary statistics are less representative than lakes with higher nutrient levels. Summary statistics for each lake are listed in Table 3. Medians influenced by BDL data are indicated using an asterisk.

Watershed Parameters

I manipulated, extracted, created and stored geospatial data using Geographic Information Systems (GIS). I used shapefiles to define parameters derived from discrete data sets and I used raster files to define parameters derived from continuous data sets (Bolstad 2005). Using the ArcGIS 10 computer program (Environmental Systems Research Institute 2010), I generated the following watershed parameters: lake shoreline length, lake surface area, lake volume, fetch, watershed perimeter, watershed area, vegetative cover, road length, slope gradient, aspect, human population, mean air temperature, maximum air temperature and minimum air temperature. The abbreviations and units for the watershed parameters and GIS data layer properties are described in Table 4.

Lake shoreline length and surface area

The US Department of Agriculture’s (USDA) National Resource Conservation Service (NRCS) soil data layers were used to create the lake polygons. The soil data layers contain information on soils as well as water bodies. I extracted polygons corresponding to each lake where length and area of the polygon were automatically calculated and placed in a related attribute table. These lengths and areas were used to represent lake shorelinelength and surface area, respectively, of the 50 lakes in my study. The lake polygons were also used as the "pourpoint" or lowest area when I created the watershed polygons used to represent watershed perimeter and watershed area (see below).

Lake depth and volume

All but one of the maximum and mean lake depths used in my analysis came from "Reconnaissance Data on Lakes in Washington," Volumes 1 and 2 (Bortleson et al. 1973). The Bortleson et al.(1973) study did not sample Lower Bagley, Upper Bagley, Bug, Cedar, Honeymoon, Mirror, Picture, Summer, Sunset, or Vogler Lakes so depths for these lakes were not available. Similarly, Squires Lake was not included in the Bortleson et al. (1973) study, but lake depths were measured by students in Dr. Leo Bodensteiner's Limnology class (personal communication, 2007). To calculate volume, I multiplied mean lake depth by lake surface area.

Fetch and fetch direction

I measured fetch using the ArcGIS ruler tool then classified fetch orientation for each lake into four categories; north to south, northeast to southwest, east to west, and northwest to southeast.

Watershed perimeter and area

I built and employed a model in GIS to delineate watersheds (Figure 6). To build the model, I modified Digital Elevation Model raster sets (DEMs) to raise lower elevations and to reduce higher elevation in cells that were inconsistent with neighboring cells (Jenson and Domingue, 1988). This rectified imperfections in each DEM and allowed for the creation of more accurate flow accumulation rasters and flow direction rasters needed for the model. Lake polygons were used in the model and served as pourpoints, or the lowest elevation in a particular area. The model of flow accumulation and direction into each pourpoint was what defined each lake's watershed. The end product was a polygon and related attribute table that contained the estimated length of the watershed perimeter and the estimated watershed area for each lake.

Vegetative cover

I estimated percent vegetative cover within a watershed using orthophotographs and the polygon construction tool in Arc Editor. Orthophotographs are aerial photos, georeferenced, with distortions removed which makes it easier to generate accurate measurements within the defined resolution of the photo (USDA 2009). I clipped orthophotos to the extent of each watershed and created a new polygon feature class devoid of any information. Using the clipped orthophoto as the base layer and editing the empty feature class, I drew polygons around all of the vegetative cover within each watershed. My definition of vegetative cover was all vegetation other than lawns and crops. The reason for excluding lawns and crops was that they have an inferior ability to retain and filter runoff (Ball et al. 2010, Chaichana et al. 2011, Duggan 2012). These polygons were added to the feature class where length and area were calculated and placed in a related attribute table. The area of the polygon represented the area within a watershed that had vegetative cover. I then calculated the percent of vegetative cover in relation to the watershed area.

Road length

Road length data are stored in the attribute table of the US Census Bureau's "Streets" shapefiles and are specific to county boundaries. I clipped the appropriate Streets shapefile to the extent of each watershed and then tallied the road length segments to determine total road length for each watershed.

Gradient

The USDA places the upper limit for the strongly sloping slope class at 16% (Soil Survey Staff 1993). I used this value to distinguish between gradual and steep slopes in my study. I created slope rasters from each county's DEM then reclassified this information into two categories (0-15% and 16-100% slope). I then clipped the reclassified slope rasters to the extent of each watershed to create slope polygons specific to each of the watersheds. The watershed slope polygons were used to calculate the percent steep slopes (>15%) in a watershed.

Aspect

I created slope aspect rasters from each county's DEM using the aspect tool. The aspect of the center cell of a 3x3 grid was determined by using nearest neighbor and the directional degrees of the other 8 cells in the grid. The evaluation of the directional degrees begins in the outer cells and moves inward toward the center cell. This was done for all of the cells in the DEM and results in a slope raster that is defined in terms of directional degrees. I reclassified the directional degrees into four categories: north (315° to 45°), east (45° to 135°), south (135° to 225°) and west (225° to 315°). I extracted the aspect data for each watershed and calculated the percentage of each aspect class in each watershed.

Estimated human population

The US Census Bureau maintains shapefiles containing human population information. The files are known as Block shapefiles and are organized by state and county. Within each Block shapefile there are numerous polygons that together represent a county. Each polygon contains census information in its attribute table that is specific to the polygon's location within the county. The people reported to live in each polygon are linked to the polygon not a specific location within the polygon. Watershed boundaries often straddle these polygons, so a fraction of a polygon may lie within the watershed and a fraction of the polygon may lie outside of the watershed. When Block shapefiles are clipped to fit the extent of a watershed and a fraction of a Block polygon is located within the watershed, all of the population data goes with the fractured Block polygon into the newly formed attribute table. This leads to an over estimation of that watershed's population. To estimate the population of a watershed more accurately it is necessary to estimate the population within a fractured Block polygon. To achieve this, I calculated the percent of the fractured Block polygon area in relation to the original Block polygon area and used this percent to estimate the fractured Block polygon population in relation to the original Block polygon population.

Ambient air temperature

The Oregon Climate Service housed at Oregon State University created georeferenced national air temperature maps for average annual, average minimum, and average maximum air temperatures. They used data from a wide range of sources from 1971 through 2000 (USDA 2006). I clipped the air temperature maps to the extent of each watershed then averaged the temperature found within the watershed to estimate average annual, average minimum, and average maximum temperatures for each watershed.

Soil properties

When evaluating soil types I looked at soil parameters that might influence surface water runoff and infiltration of water into the soil. I chose to evaluate drainability, erosion potential, and the potential to hold water. I developed a classification system using these three categories by modifying a classification system used by the USDA. The first category is drainability where I used the first seven USDA drainability classes, but altered the eighth (Soil Survey Staff 1993). The USDA characterizes the eighth class as subaqueous soils. I modified this class to included subaqueous soils in with all other soils that did not fit into the first seven classes. I termed it the not-rated for drainage class. The drainage classes for my soils included:

EWD=excessively well draining,
SED=somewhat excessively draining,
WD=well draining,
MWD=moderately well draining,
SPD=somewhat poorly draining,
PD=poorly draining,
VPD=very poorly draining, and
NRD=not rated for drainage

I classified erosion potential in a similar way by using the first four USDA erosion potential classes (Soil Survey Staff 1993) and, again, modified the fifth class to include soils that did not fall into the first four classes: The erosion potential classes for my soils included:

VSE=very severe erosion potential,
SE=severe erosion potential,
ME=moderate erosion potential,
LE=low erosion potential, and
NRE=not rated for soil erosion potential

To categorize soils on the basis of select water features, I searched the soil descriptions for the terms “ponding, perched or high water table”. If a water feature was mentioned I classified the soil as a type that ponds (P). If no water features were mentioned, I classified it as a soil that does not pond (NP).

Statistics

I analyzed the data using the R statistical program, (version 3.0.0, R Development Core Team, 2009). I used quantile-quantile, or Q-Q plots and boxplots to examine the distributions for each parameter, which revealed that the data were not normally distributed and were not homoscedastic (Zar 1984, Crawley 2007). Because this violates two of the major assumptions for using parametric statistics, I used rank-based nonparametric analyses when possible (Zar 1984).

I used Kendall’s tau ranked correlation analysis to determine monotonic relations between pairs of variables (Zar 1984). Due to the presence of ties in the data, the probability of obtaining some of the Kendall’s tau values will not be exact. To help correct for this uncertainty, I used a conservative filter and focused on correlations with Kendall’s tau ≥0.500.

To simplify this dataset, I used hierarchical clustering based on principal component scores rather than the original variables. The principal components analysis creates a multidimensional correlation matrix that partitions the greatest variance, into the higher order components. Clustering of the first few components can reveal valid data groupings and, in my case, expose important watershed patterns. In general, I followed the procedures described by Ben-Hur and Guyon (2003), with specific directions, and computer code written by Dr. R. Matthews. This approach was particularly helpful for providing additional insight into the Kendall’s tau bivariate correlation results.

Results and Discussion

The majority of the water quality, watershed, and soils parameters had skewed, non-normal distributions with numerous outliers. Only pH had a continuous, normal distribution which was expected because pH values are measured using a log scale. Gradient, southern aspect and well draining soils followed approximately normal distributions except these parameters were represented by percents. Percents that range from 0 to 100% do not actually follow a parametric normal distribution. Most of the parameters had heterogeneous variance, with higher variances occurring in lakes with high mean parameter values, and lower variances in lakes with lower mean parameter values. Because of the non-normal distribution and the heterogeneous variances, when possible, data were examined using median values and nonparametric statistics rather than parametric, variance based statistics.

The purpose of correlation analyses was to look for patterns between pairs of water quality and watershed parameters that helped explain the differences between lakes. I used the rank-based Kendall's tau correlation because the data set had a non-normal distribution with heteroscedastic variance. The analyses resulted in a very large number of statistically significant correlations. To focus on the major bivariate relationships, I restricted my discussion to highly significant correlations ("strong" correlations), which I defined as correlations with Kendall's tau values higher than ±0.500. In addition, I focused primarily on correlations related to water quality parameters and watershed parameters, omitting any discussion of correlations with the soil parameters. This helped reduce some of the issues related to multicolinearity, where groups of related variables, like ponding, and non-ponding soils, are not independent.

Descriptive Summary of Water Quality Parameters

The high elevation lakes (Lower Bagley, Upper Bagley, Lower Twin, and Upper Twin Lakes) had many of the lowest median values for the water quality parameters in my study (Table 3). Lower Bagley Lake had the lowest conductivity. Upper Bagley Lake had the lowest water temperature and ammonium concentration. Lower Twin Lake had the lowest chlorophyll α concentration. Upper Twin Lake had the lowest turbidity, total nitrogen, and soluble reactive phosphate values. Tennant Lake had the lowest median dissolved oxygen concentration. Tennant Lake had relatively cool water temperatures and a mid-range value for chlorophyll α which is the usual pattern for lakes with moderate dissolved oxygen levels.

Wiser Lake had the highest values for conductivity, chlorophyll α, alkalinity, turbidity, total nitrogen, and total phosphorus (Table 3). Ketchum Lake had an extremely high median ammonium concentration (102.7 μg-N/L) compared with the other lakes in the study. The next highest concentration of ammonium was 40.2 μg-N/L found in Lone Lake. Cain Lake had an extremely high median nitrate/nitrite concentration (478.0 μg-N/L) compared with the other lakes in the study. The next highest concentration was 185.0 µg-N/L found in Crabapple Lake. Lower Bagley, Upper Bagley, Bug and Lone Lakes had high levels of dissolved oxygen (Table 3). Lower Bagley and Upper Bagley Lakes were high elevation lakes with colder water temperatures. Colder water has a greater capacity to hold gas than warmer water so high levels of dissolved oxygen in these lakes were expected. Lone Lake also had high dissolved oxygen but was one of the warmest lakes. The high levels of dissolved oxygen in Lone Lake were probably due to the high rates of photosynthesis, which was indicated by the high levels of chlorophyll α found in Lone Lake (40 µg/L).

There were 47 statistically significant Kendall's tau correlations between the water quality parameters out of 66 comparisons. Ten of the correlations had a Kendall's tau value greater than ±0.500 (Table 5). Total phosphorus was highly correlated with chlorophyll α, turbidity, total nitrogen and soluble reactive phosphate (Figure 7). Chlorophyll α was also highly correlated with turbidity and total nitrogen (Figure 8). These correlations were expected because total phosphorus and total nitrogen are essential nutrients for primary producers and chlorophyll α is used as a measure of primary productivity. Turbidity measures suspended solids in the water column and is related to nutrient concentrations because suspended soilds usually contain phosphorus. Turbidity increases during periods of high wind or during runoff events as particulates are resuspended from lake sediments or transported in runoff into the lake. Watershed development often results in high concentrations of pollutants building up on inpervious surfaces and more soil disturbance in the watershed. This results in higher levels of nutrients in waterbodies down slope from the development which in turn results in higher turbidities and higher concentrations of chlorophyll α due to increased algal growth in the lake.

Other strong water quality correlations were between conductivity, alkalinity and pH (Table 5). This was expected because each of these parameters measures a type of dissolved ionic compound. There was also a strong correlation between total phosphorus and soluble reactive phosphate. This also was expected, in that soluble reactive phosphate is a fraction of the total phosphorus concentration. What was somewhat unexpected was that there was no strong inverse correlation between dissolved oxygen and water temperature. Some of the lakes with the warmest water temperatures had high levels of dissolved oxygen. Cooler water holds more dissolved gas and dissolved oxygen would be expected to rise as water temperature falls. But dissolved oxygen concentrations are also influenced by primary productivity, and in warm lakes, nutrient-rich lakes, algal photosynthesis may have caused elevated dissolved oxygen concentrations. All of the samples were collected in the summer, during day light hours, when algal photosynthetic oxygen production would be relatively high.

Descriptive Summary of Watershed Parameters

Eleven watersheds were located in the sparsely populated, largely undeveloped North Cascades ecoregion (Wilson 2012; Figure 9). They were Upper Bagley Lake, Lower Bagley Lake, Canyon Lake, Cavanaugh Lake, Grandy Lake, Mirror Lake, Picture Lake, Silver Lake, Upper Twin Lake, Lower Twin Lake, and Vogler Lake watersheds. All of these North Cascades ecoregion lakes are found at elevations >200 meters except Mirror Lake which has an elevation of 107 meters (Llewellyn 2010). The lakes varied in size, shape, and depth with no distinct pattern except that all but one had a high percentage of steep gradients within the watershed. The Vogler Lake watershed was the only North Cascades ecoregion watershed with <55% of its watershed with steep slopes. It had 2.9% steep slopes (Table 6). Thirty-nine of the watersheds were located in the rapidly developing Puget Lowland ecoregion (Sorenson 2012; Figure 9). All but two of these Puget Lowland ecoregion lakes were at elevations <200 meters. Cedar and Toad Lakes are located at elevations of 470 meters and 246 meters, respectively (Llewellyn 2010). The Puget Lowland lakes varied in size, shape, and depth. There was no distinct watershed pattern within the Puget Lowland watersheds except that watersheds were generally more gradually sloped than those found in the North Cascades ecoregion. All but 6 of the watersheds in the Puget Lowlands ecoregion had percent steep slopes <55%. The watersheds in the Puget Lowlands ecoregion with percent steep slopes >55% were Squires Lake, Cedar Lake, Louise Lake, Sixteen Lake, McMurray Lake, and Reed Lake watersheds. Their percent steep slopes were 68.1%, 64.0%, 62.2%, 60.7%, 57.9%, 56.2%, respectively (Table 6).

Cedar Lake and Picture Lake were the smallest lakes. They had the lowest values for lake shoreline length, surface area and fetch (Table 6). Big Lake and Cavanaugh Lake were the largest lakes. They had the highest values for lake shoreline length, surface area and fetch. Of the lakes with maximum lake depth values, Tennant Lake was the shallowest lake, and Lower Twin Lake was the deepest. Squire Lake was the lake with the least volume, and Cavanaugh Lakes had the greatest volume (Table 6).

Cedar Lake and Picture Lake watersheds were the smallest watersheds. They had the smallest values for watershed perimeter and watershed area in my study. Lower Bagley Lake, Upper Bagley Lake, and Canyon Lake had the steepest watersheds. Eighty-five percent of the slopes in the Lower Bagley Lake, Upper Bagley Lake, and Canyon Lake watersheds were steep. Big Lake, Bug Lake, and Cavanaugh Lake had the largest watersheds. They had the largest values for watershed perimeter, and watershed area. Ketchum Lake, Loma Lake, Squalicum Lake, Tennant Lake, Terrell Lake, and Wiser Lake watersheds had the most gradual slopes; all six of these watersheds had 0% steep slopes (Table 6).

There were several statistically significant Kendall's tau correlations between watershed parameters that suggested important relationships. Two of the correlations suggested relationships between lakes and watersheds and two suggested relationships between watersheds and parameters related to development. Specifically, as lake size (lake surface area and fetch) increased so did the area of the watershed and as the watershed area increased so did road length and population (Figure 10).

Descriptive Summary of Soil Parameters

I used 15 soil parameters arranged in three different categories to describe watershed soils in my study. The categories were soil drainability, ponding and soil erosion potential. Part of my descriptions will center on watersheds that contained at least 20% of a particular soil parameter to help focus on soil parameter dominance in the watersheds. This will minimize discussion on soils found in very small amounts. Soil data were unavailable for five of the high elevation watersheds (Lower Bagley Lake, Upper Bagley Lake, Picture Lake, Lower Twin Lake, and Upper Twin Lake watersheds).

Soil drainage

Well draining soils (soil.WD) and moderately well draining soils (soil.MWD) were the two soil types that dominated the drainage category Thirty-three watersheds had well draining soils and 24 of these watersheds contained >20% well draining soils. Over 75% of the soils in Cedar Lake, Silver Lake, Sixteen Lake, Squires Lake, and Toad Lake watersheds were well draining soils. All of the watersheds but Cedar Lake, Sixteen Lake, and Squires Lake watersheds contained moderately well draining soils. Thirty watersheds contained >20%

moderately well draining soils; Crabapple Lake, Howard Lake, and Martha Lake watersheds containing >90% moderately well draining soils (Table 7).

The remaining soil drainage classes were less important over all, but were key features in individual watersheds. Six watersheds contained >20% of somewhat excessively well draining soils (soil.SED) and two contained >70% including Armstrong Lake (71% soil.SED) and the Ketchum Lake watershed (78% soil.SED). Cranberry Lake watershed was the only watershed that contained >20% somewhat poorly draining soils (33% soil.SPD). Lone Lake, Tennant Lake and Goss Lake watersheds contained >20% poorly draining soils (24%, 27%, and 51% soil.PD, respectively). Wiser Lake watershed was the only watershed that contained >20% very poorly draining soils (27% soil.VPD). Canyon Lake watershed was the only watershed with >20% soils that were not rated for drainage (28% soil.NRD; Table 7).

Soil with water features

Soil with water features, or ponding soils, are soils that hold water either temporarily, seasonally, or throughout the year. Forty-four of the 45 watersheds contained ponding soils (soil.P). The Cedar Lake watershed was the only watershed that had 5% soil.P. Thirty three watersheds contained >20% ponding soils and the Summer Lake, Howard Lake, Crabapple Lake, Martha Lake, and Sunset Lake watersheds contained >90% ponding soils.

Soils with no water features, or non-ponding soils, are soils that do not hold water. Thirty-seven watersheds contained non-ponding soils (soil.NP). Twenty nine of these watersheds contained >20% non-ponding soils and the Toad Lake, Cedar Lake, and Sixteen Lake watersheds containing >90% non-ponding soils (Table 7).

Soil erosion potential

Low erosion potential soils (soil.LE) dominated the soil erosion potential category. Forty-four of the 45 watersheds contained low erosion potential soils. Only the Cedar Lake watershed did not contain any low erosion potential soils. Thirty-five watersheds had >20% low erosion potential soils; the Summer Lake, Wiser Lake, and Lone Lake watersheds contained >90% low erosion potential soils.The remaining soil erosion potential classes were less important over all, but were key features in individual watersheds. Seven watersheds contained >20% very severe erosion potential soils (soil.VSE). The Canyon Lake watershed contained the highest percentage (81% soil.VSE). Thirty-two watersheds had soils with severe erosion potential (soil.SE), of which 13 watersheds contained >20% soil.SE. Mirror Lake watershed contained the highest percentage (62% soil.SE). Twelve watersheds contained >20% moderate erosion potential (soil.ME); the Grandy Lake watershed contained the highest percentage (34% soil.ME; Table 7).

There were 26 significant correlations between water quality and soil parameters, none of which met my definition for strong correlations (Table 5). The watersheds in my study were dominated by well-draining or moderately well draining, and low erosion potential soils (Table 7). There were several broad characterizations of soils that could be made for specific watersheds. For example, the Cedar Lake and Sixteen Lake watersheds largely contained well draining soils that do not pond. Lone Lake watershed soils were predominately low erosion potential soils with a high percentage of poorly draining soils. The Wiser Lake watershed contained predominately low erosion potential soils with a high percentage of very poorly draining soils. The Summer Lake watersheds had predominately low erosion potential soils with a high percentage of soils that pond. The Cedar Lake watershed had no ponding soils and no low erosion potential soils (Table 7).

Descriptive Summary of Nested Watersheds

Nested, or hierarchical, watersheds are watersheds with one lake‘s watershed located within the boundaries of another lake’s watershed. The primary watershed contains the nested watershed. Twenty-two watersheds in my study were hierarchical in nature. Most had one nested watershed within the boundary of the primary watershed, but two primary watersheds had multiple watersheds nested within them (Table 8; Figures 11-19). Primary and nested lakes are linked, hydrologically, creating a biological and chemical hierarchy where the nested watershed properties are a subset of the primary watershed. Lakes in hierarchical watersheds flow in series where the nested lake is upstream from the primary lake. Upstream lakes may have either higher or lower concentrations of nutrients than the downstream lakes and can be a source or a sink for those nutrients. The upstream lake may retain nutrients through sedimentation and biological uptake, thus reducing the nutrient concentrations in the outflow or may export nutrients if there are high rates of sediment resuspension or low rates of biological uptake. And, depending on the sources of nutrients in the watershed, the upstream lake may have higher or lower concentrations of nutrients in the water column. Because the nested watersheds form a hydrological gradient, there can be some similarities in water quality between the nested and primary lakes, especially for parameters like alkalinity and pH, which are influenced by the soils and bedrock compositions in the watershed. But nutrients and chlorophyll α concentrations are not as clearly related to the hydrologic gradient. If the upstream portion of the watershed is relatively undeveloped, it is reasonable to expect lower concentrations of nutrients and chlorophyll α in the upsteream (nested) lake compared to the downstream (primary) lake, especially if residential development increases in the downstream portions of the watershed. But some of the nested watersheds in my study had high levels of residential development throughout the primary watershed, so the upstream nested lake could contain the same or higher concentrations of nutrients and chlorophyll α compared to downstream lake.

To look for water quality patterns within the hierarchical watersheds, I compared water quality parameters between nested lakes and their primary lakes. Three of the hierarchical watersheds had higher water quality parameter concentrations in the downstream primary lake. This pattern was present in the Clear Lake watershed which is nested in the Beaver Lake watershed; the Erie Lake watershed which is nested in the Campbell Lake watershed; and the Toad Lake watershed which is nested in Bug Lake watershed (Table 9). The greatest concentration increase was for total nitrogen, which doubled between each of the nested watersheds and its primary watershed. This seemed like an exceptionally large increase, but the reason for this large increase is unclear. Conversely, Howard Lake which is nested in the Martha Lake had higher conductivity, alkalinity, ammonium, nitrate/nitrite, and soluble reactive phosphate concentrations compared to Martha Lake (Table 9).

The remaining hierarchical watersheds showed variable water quality patterns. Vogler Lake nested in the Grandy Lake watershed had higher concentrations of total nitrogen and total phosphorus, but lower concentrations of most other parameters. Upper Bagley Lake (nested lake) and Lower Bagley Lake had very similar water quality parameters. Squalicum Lake, nested in the Bug Lake watershed, had higher concentrations of chlorophyll α and total nitrogen, but a lower concentration of total phosphorus compared to Bug Lake. Similarly, Sunset Lake nested in the Bug Lake watershed had higher levels of chlorophyll α, conductivity and alkalinity than did Bug Lake, but a lower total phosphorus concentration. Upper Twin Lake, nested in the Lower Twin Lake watershed, had higher conductivity and alkalinity concentrations than Lower Twin Lake, but the other parameters were mostly the same (Table 9).

Two of the hierarchical watersheds in my study contained multiple watersheds nested in one primary watershed. The Bug Lake watershed served as the primary watershed for three other lakes, Squalicum Lake, Sunset Lake, and Toad Lake, but the nested lakes (Squalicum, Sunset, and Toad Lakes) were separate from one another and did not appear to be linked hydrologically. The Shoecraft Lake watershed served as the primary watershed for three other lakes: Loma Lake, Crabapple Lake, and Goodwin Lake. These watersheds were linked hydrologically and had a complicated hierarchy. The Loma Lake watershed was nested in the Crabapple Lake watershed; the Crabapple Lake watershed was nested in the Goodwin Lake watershed; the Goodwin Lake watershed was nested in the Shoecraft Lake watershed. Chlorophyll α, turbidity, total nitrogen and total phosphorus concentrations were higher in the upper (nested) lakes, with Loma Lake having the highest values for these parameters. Conductivity and alkalinity followed a simple downstream gradient, with lower concentrations in the nested lakes and higher concentrations in the primary lakes (Table 9).

Relationship between Water Quality and Watershed Parameters

There were 87 statistically significant Kendall's tau correlations, of which 10 had Kendall's tau values greater than ±0.500 and $p > 0.001$(Table 5). All but one of these strong correlations were related to lake depth. Chlorophyll α, turbidity, total nitrogen, total phosphorus, and soluble reactive phosphate strongly correlated with maximum lake depth (Figure 20). Chlorophyll α, turbidity, total nitrogen, and total phosphorus strongly correlated with mean lake depth. The correlations between nutrients, turbidity, chlorophyll α, and lake depth suggests a possible relationship between dilution of nutrients and lake size. But in my study, there were only 3 significant correlations between lake volume and water quality parameters and none of them met my criteria for strong correlations (Table 5). So lake depth, but not lake volume, is the correlating factor. This may point to the importance of nutrients diffusing or falling to the deeper parts of the lake where they combine with sediments or are utilized by benthos reducing their presence at or near the surface where sampling occurred. Conversely, shallow lakes, those less than 3 meters mean depth (Wolfram et al. 2009) and lakes that have high values for development of volume (D_v= mean depth/maximum depth (Bortleson et al. 1973)) are more susceptible to mixing and resuspension of nutrients into the water column, increasing the likelihood of nutrient availability and subsequent increased productivity.

I wanted to determine if there were patterns between the water quality and the watershed development parameters I measured, specifically, roads and population density. I also wanted to determine which lakes were most likely to be affected by resuspension of nutrients, perhaps related to development, as a result of shallow depth and a high development of volume ratio (D_v). To do this, I looked at lakes surrounded by unprotected land located in the rapidly developing Puget Lowland ecoregion. I used total phosphorus and chlorophyll α as indicators of water quality. Total phosphorus concentrations >20 µg-P/L trigger possible remediation actions in the state of Washington (Washington State Legislature 2006) so I used this concentration as a water quality threshold in my discussion of total phosphorus. I discussed total phosphorus as a trophic state indicator (TSI) where TSI (TP) = 14.42 ln(tp) + 4.15 (Wetzel 2001). Chlorophyll α was strongly correlated with total phosphorus and is a good indicator of algal biomass in a lake. Chlorophyll α can also be used as a trophic state indicator where TSI (CHL) = 9.81 ln(chl) + 30.6 (Wetzel 2001). I calculated TSI using chlorophyll α, as well, and used it in my discussion of water quality and development. TSI <30 indicates oligotrophic conditions, 30 <TSI <50 indicates mesotrophic conditions, 50 <TSI <70 indicates eutrophic conditions, and TSI >70 indicates hypereutrophic conditions. To calculate road and population densities, I calculated the usable watershed area by subtracting lake surface area from the watershed area and converted the units from m^2 to km^2. I then divided either road length or population by the usable watershed area to determine their densities within each watershed.

There were 32 watersheds in the Puget Lowlands ecoregion that were unprotected (Table 10). Fifteen of them had total phosphorus concentrations >20 µg/L. Of those 15, four had both road and population densities above the median values: Wiser, Ketchum, Sunday, and Loma Lakes. Wiser and Ketchum Lakes were hypereutrophic based on the TSI(TP). Wiser Lake was also hypereutrophic using the TSI(CHL), but Ketchum was mesotrophic based on the TSI(CHL). Wiser Lake is shallow, with an average D_v, so resuspension of nutrients and high levels of development were likely contributors to the eutrophy. Ketchum Lake has a D_v of 0.6, but is moderately deep (3-15 m). High levels of development likely contributed to the mesotrophic-eutrophic conditions in Ketchum Lake, but its depth may help reduce algal biomass by decreasing nutrient availability. Sunday and Loma Lakes also had high values for the development parameters. Both lakes were mesotrophic based on the TSI(TP). Loma Lake was on the low end of the eutrophic range based on the

TSI(CHL) and Sunday Lake was mesotrophic based on the TSI(CHL). Both of these lakes had a D_v of 0.4 and both were moderately deep (Table 10). The depth and lower likelihood of resuspension of nutrients may help moderate the total phosphorus concentrations and algal biomass, but both lakes are at risk of a more permanent eutrophic state if development levels increase.

Lone, Fazon, and Sunset Lakes had above median road densities, but below median population densities. Lone Lake was hypereutrophic based on the TSI(TP) and on the high end of eutrophic TSI(CHL). Lone Lake had a D_v of 0.5 and is shallow (Table 10). The trophic state of Lone Lake was likely influenced by resuspension of nutrients as well as development. Fazon and Sunset Lakes were eutrophic with using either total phosphorus or chlorophyll α as the TSI. Fazon Lake had a D_v of 0.6 and a mean depth of 3 meters (Table 10), so resuspension was likely a factor in its trophic state. There was no depth data for Sunset Lake (Table 10).

Bug Lake was the only lake with total phosphorus >20 µg/L that had a below median road density and above median population density. Bug Lake was eutrophic based on the TSI(TP) and on the high end of the mesotrophic scale based on the TSI(CHL). There are no depth data for Bug Lake (Table 10), but it is at risk of a more permanent eutrophic state especially if it is a shallow, due to the potential for additional development in its watershed.

The remaining 7 lakes with total phosphorus >20 µg/L had road and population densities below the median values (Beaver, Campbell, Honeymoon, Squalicum, Armstrong, Big, and Erie Lakes). Campbell Lake was eutrophic based on both TSI(TP) and TSI(CHL). Beaver, Honeymoon, Squalicum, and Armstrong Lakes were eutrophic based on the TSI(TP), and Big and Erie Lakes were eutrophic based on the TSI(CHL). Beaver, Campbell, Squalicum, and Erie Lakes had D_v values of 0.5 and were shallow lakes (Table 10). Resuspension of nutrients was likely a contributing factor to the trophic state of these lakes. Armstrong and Big Lakes had D_v values of 0.6, but were moderately deep lakes (4.6 m and 4.3 m, respectively). These two lakes had concentrations of total phosphorus >20 µg/L, were marginally eutrophic yet had lower levels of development in their watersheds (Table 10). The higher total phosphorus concentrations may be due to the higher D_v and resuspension of nutrients even though the lakes were moderately deep. Squalicum, Armstrong, Big, and Erie Lakes are all at risk of a more permanent eutrophic state as a result of resuspension of nutrients. There were no depth data for Honeymoon Lake. Depth data might help identify the risk of Honeymoon Lake becoming more permanently eutrophic through the contribution of nutrient resuspension.

There were 17 unprotected lakes in the Puget Lowlands that had total phosphorus ≤ 20 µg/L. Seven of these lakes had above median densities for both roads and population and 4 had below median densities for both roads and population. All of the lakes were moderately deep, ranging from 3.4 meters in Reed Lake to 10.1 meters in Martha and Ki Lakes with no depth data for Summer or Cedar Lakes. None of them were eutrophic when using either TSI(TP) or TSI(CHL) but many of them were on the high end of the mesotrophic range (Table 10). The most at-risk lake in this group was Reed Lake. It is at risk of becoming more permanently eutrophic, with a TSI (TP) of 45.3 and TSI (CHL) of 43.4. Reed Lake had above median road density, almost twice the median density for population, a D_v of 0.6 and mean depth of 3.4 meters. The TSI values were close to the eutrophic range, the lake was on the shallow end of the moderately deep range and it had a D_v above median. It is likely that the D_v and depth will lead to resuspension of nutrients and that nutrients will be abundant as a result of development pressures.

Multivariate Analyses

To look deeper into these relationships between the water quality, watershed, and soils parameters, I wanted to see if the lakes formed natural groups and if so, what parameters helped to differentiate the groups. I did this using principal components analysis (PCA) and hierarchical clustering. I needed to identify both strong and noisy signals using PCA as a pretreatment of my complex data set prior to hierarchical clustering in order to ensure the formation of naturally, stable groups. Though PCA is designed to cut through noise, it, too, can benefit from pretreatment of the data set (Ben-Hur and Guyon, 2003). The pretreatment prior to PCA entailed removal of redundant and dependent parameters. All of the water quality parameters were retained. I omitted, mean lake depth because it was used in lake volume calculations and it was somewhat redundant with maximum lake depth. I omitted fetch direction because it was directional, not quantitative. Because of the multicolinearity of the aspect categories, I chose to use one of them, westerly aspect, in multivariate analyses. My assumption was that slopes exposed to the sun from the west in the summer in North America would have the warmest surface temperature therefore having the greatest impact on watershed dynamics. I retained average air temperature and omitted minimum and maximum air temperatures. I assumed that average annual air temperature would be the best representative of ambient air temperature. I retained one soil parameter from each soil parameter category. I retained well draining soils, soils that pond, and soils with very severe erosion potential. Variables with missing values are omitted from PCA computation and there were several lakes in my study without maximum lake depth values. Rather than omit maximum lake depth from PCA, I omitted the lakes with no maximum lake depth values (Lower Bagley Lake, Upper Bagley Lake, Bug Lake, Cedar Lake, Honeymoon Lake, Mirror Lake, Picture Lake, Summer Lake, Sunset Lake, and Vogler Lake).

Additional pretreatment of the data included centering and scaling. Parameter variance was centered at zero-mean and proportionally scaled prior to PCA. Centering was used to reduce the noise on wide ranging means so the focus is on fluctuations in variance not the wide ranging means (van den Berg et al. 2006). A scaling factor was used to adjust the variance scales of the parameters to bring them into proportion with one another (van den Berg et al. 2006). The result was a correlation-based PCA (personal communication, R. Matthews, January 29, 2014).

Principal components analysis finds a set of orthogonal standardized linear combinations of parameters. These linear combinations explain all of the variation in a data set (Crawley 2007). Each linear combination is known as a component and there are as many components as there are parameters. My final data set contained 28 parameters, so PCA would find 28 components, or 28 linear dimensions. This high dimensional space is impossible to interpret effectively. The usefulness of PCA is its ability to identify the fewest components that account for the most variance in a data set. This lowers the dimensional space, making interpretation of data set dynamics possible.

Using the first few principal components, as outlined in the clustering procedure by Ben-Hur and Guyon (2003), I clustered the data hierarchically. The goal was the formation of “stable” clusters using the fewest principal components. To determine stability, clustering is repeated using decreasing numbers of components, and the results are examined to find the point when cluster separation begins to blur (Ben-Hur and Guyon, 2003, personal communication, R. Matthews, January 29, 2014). The first four components accounted for 66% of data set variance and were chosen for hierarchical clustering. This reduced the linear dimensions from 28 to 4. The clustering was based on Euclidean distance and Wards minimum variance (Crawley 2007, personal communication, R. Matthews, January 29, 2014) where shorter distances showed more similarity between watersheds or groups of watersheds, and longer distances showed more dissimilarity. Clustering revealed three distinct groups, which are labeled by watershed (Figure 21; Table 11).

Twenty-four percent of the variance was accounted for in the first principal component (PC1). There were 13 parameters that strongly influenced the ordination along PC1 (personal communication, R. Matthews, January 29, 2014; Table 12). I separated the lakes based on their cluster groups and calculated the group median values of the 13 parameters that formed the primary basis for separation on PC1. To find dissimilarities between the groups that helped to separate the groups, I compared the group median values using Wilcoxon rank sum pairwise comparisons. Group 1 had the poorest water quality and was the most dissimilar group. It had the highest median values for the water quality parameters with significantly high medians for conductivity, turbidity, and alkalinity. The lakes in Group 1 were large and shallow with moderate percentages of steep slopes within the watershed (Table 13). Group 2 had the best water quality. The lakes in this group were small and deep and the watersheds had the lowest percentages of steep slopes among the 3 groups (Table 13). Group 3 had moderate water quality though this group had the lowest median value for total nitrogen. The lakes in this group were mid-sized, moderate in depth with the watersheds having the highest percentages of steep slopes (Table 13). Group 3 illustrates the strong negative correlation between total nitrogen and a high percent of steep slopes within a watershed.

Conclusion

The lakes and watersheds in my study differed in size, shape, location, and water chemistry. This diversity was valuable when trying to find links between water quality and watershed parameters (Groffman et al. 2004). Large scale studies involving numerous watersheds over broad regions help to identify watersheds at-risk of water quality degradation on a regional basis (Chu et al. 2003). The lakes in my study were found in two ecoregions, the Puget Lowlands and the North Cascades ecoregions, where the Puget Lowlands ecoregions has been identified as the most rapidly developing ecoregion in the United States (Sorensen 2012). As such, the lakes in the Puget Lowlands ecoregion are likely to be experiencing pressure on water quality as a result of this intense development (Coats et al. 2008, Garn et al. 2010, Soranno et al. 1996, Strayer et al. 2003). Correlation analyses revealed strong correlations between total phosphorus, chlorophyll α, total nitrogen and turbidity. Total phosphorus, chlorophyll α, total nitrogen, and turbidity all strongly and negatively correlated with mean and maximum lake depth and watershed area correlated strongly with fetch, road length, and population.

I wanted to investigate these correlations further. I evaluated the lakes on unprotected land within the rapidly developing Puget Lowlands ecoregion on the basis of total phosphorus, chlorophyll α, trophic conditions, lake depth, and development of lake volume. I discovered some lakes were at a greater risk of change to their trophic state likely due to development and nutrient resuspension (Bortleson et al. 1973, Niemistö et al. 2008, Thomas and Schallenberg 2008, Wetzel 2001). Reed Lake was arguably the most at-risk lake in the Puget Lowlands ecoregion. Its trophic state values were on the high end of the mesotrophic range. Reed Lake watershed had higher than median densities for both roads and population. Its Dv is 0.6 and its mean depth is 3.4 meters. Without reducing the pressures on the water quality of this lake, it could become more permanently eutrophic. Sunday and Loma Lakes were meso- to eutrophic lakes and were at risk of becoming more permanently eutrophic as development pressures persist. Squalicum, Armstrong, Big, and Erie Lakes were each at risk of a more permanent eutrophic state as a result of resuspension of nutrients. The depths of Bug, Honeymoon, and Summer Lakes should be determined. Their trophic state indicator values are on the border between mesotrophy and eutrophy. Mean lake depth and development of volume would help to identify the likelihood of these three lakes becoming more permanently eutrophic.

Three distinct groups emerged from cluster analysis. Broadly speaking, the groups differed by water quality, lake size, and steepness of the watershed. Group 1 was the most dissimilar of the three groups. It had the poorest water quality with the largest, most shallow lakes. Significantly higher levels of conductivity, turbidity and alkalinity helped to differentiate Group 1 from the others. Group 2 had the best water quality with small, deep lakes. This reinforces the idea of a link between water quality and lake depth. Group 3 had the mid-range for water quality and size and depth of lakes. Significantly lower total nitrogen and a significantly higher percent of steep slopes in the watersheds in this group were important in setting Group 3 apart from Groups 1 and 2.

My study has identified strong correlations between water quality and watershed parameters that help to identify at risk watersheds within the project area. This same combination of parameters, likely, can be used to indentify other watersheds in rapidly developing regions that might be at-risk of heightened productivity. I also determined that the lakes in my study clustered into groups according to water quality and lake and watershed morphology. The data set was quite large so the avenues of exploration were not exhausted. Very severe erosion potential soils was an important parameter in clustering the watersheds into groups, yet soils had no strong correlation to water quality. Soils somehow play a role in the affects of watersheds on the water quality of lakes that was not revealed in my study. This is worthy of further investigation.

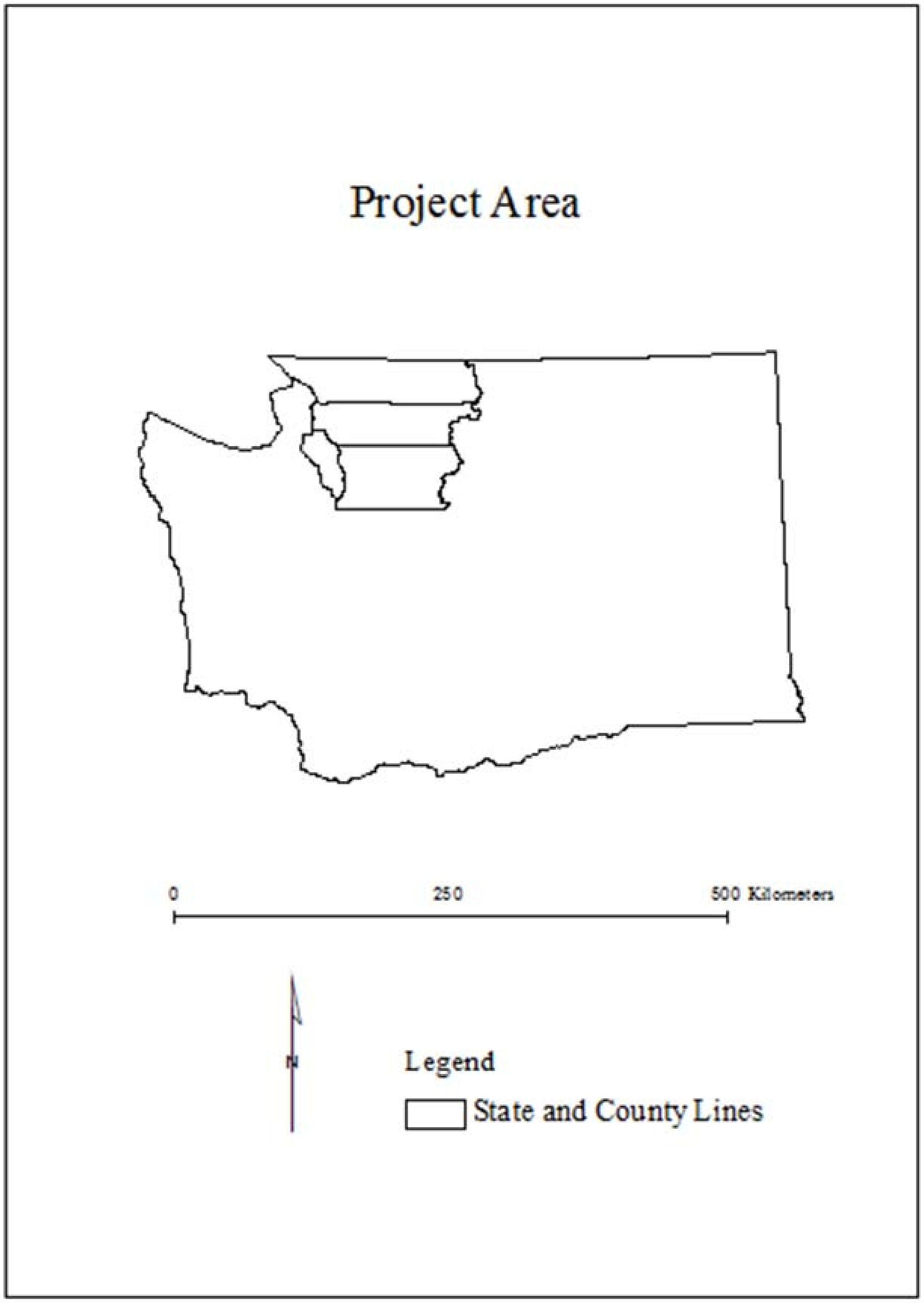


Figure 1. Project area for the IWS Northwest Lakes Monitoring Program in Island, Skagit, Snohomish and Whatcom Counties.

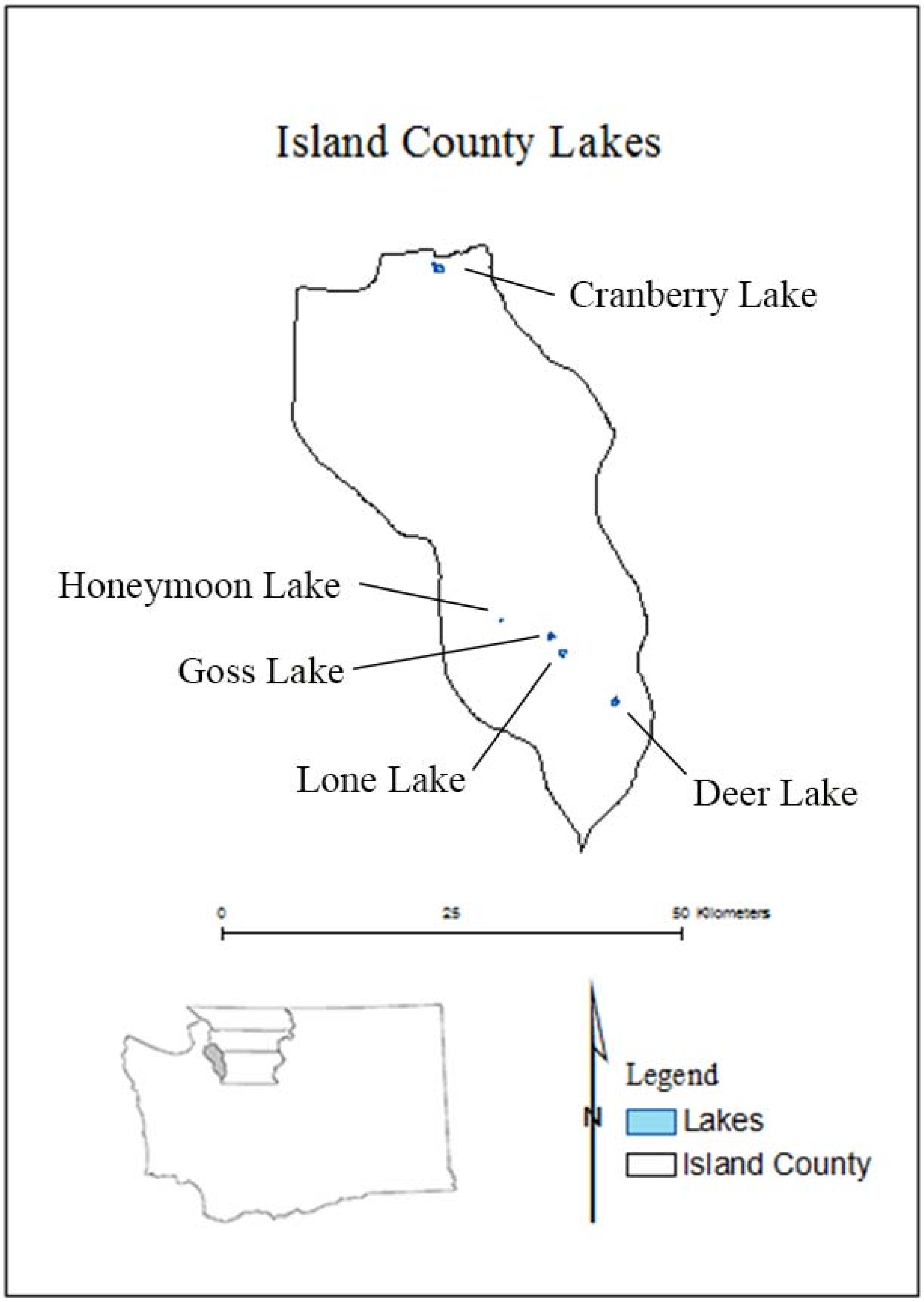


Figure 2. Island County lakes monitored for the IWS Northwest Lakes Monitoring Program.

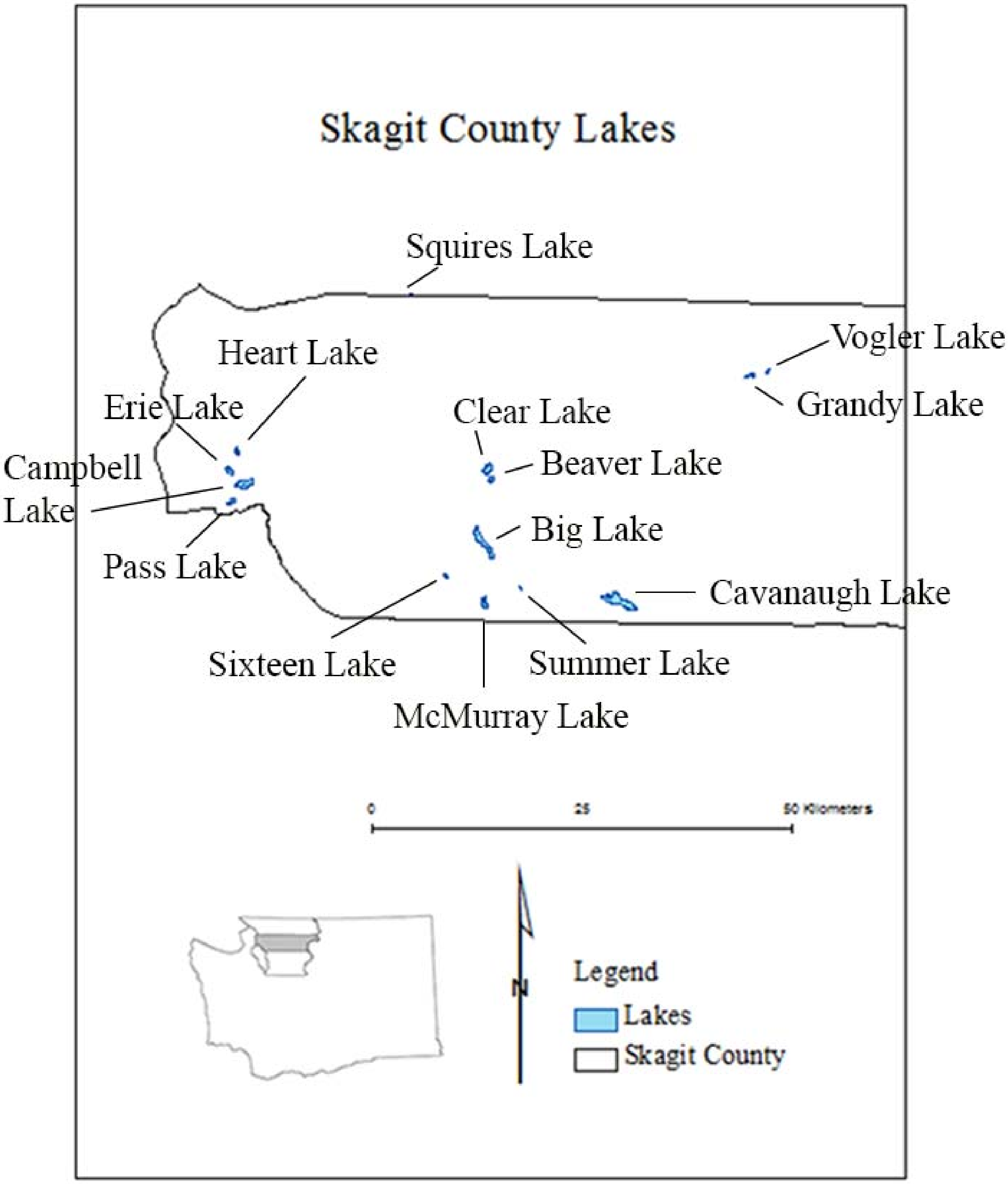


Figure 3. Skagit County lakes monitored for the IWS Northwest Lakes Monitoring Program.

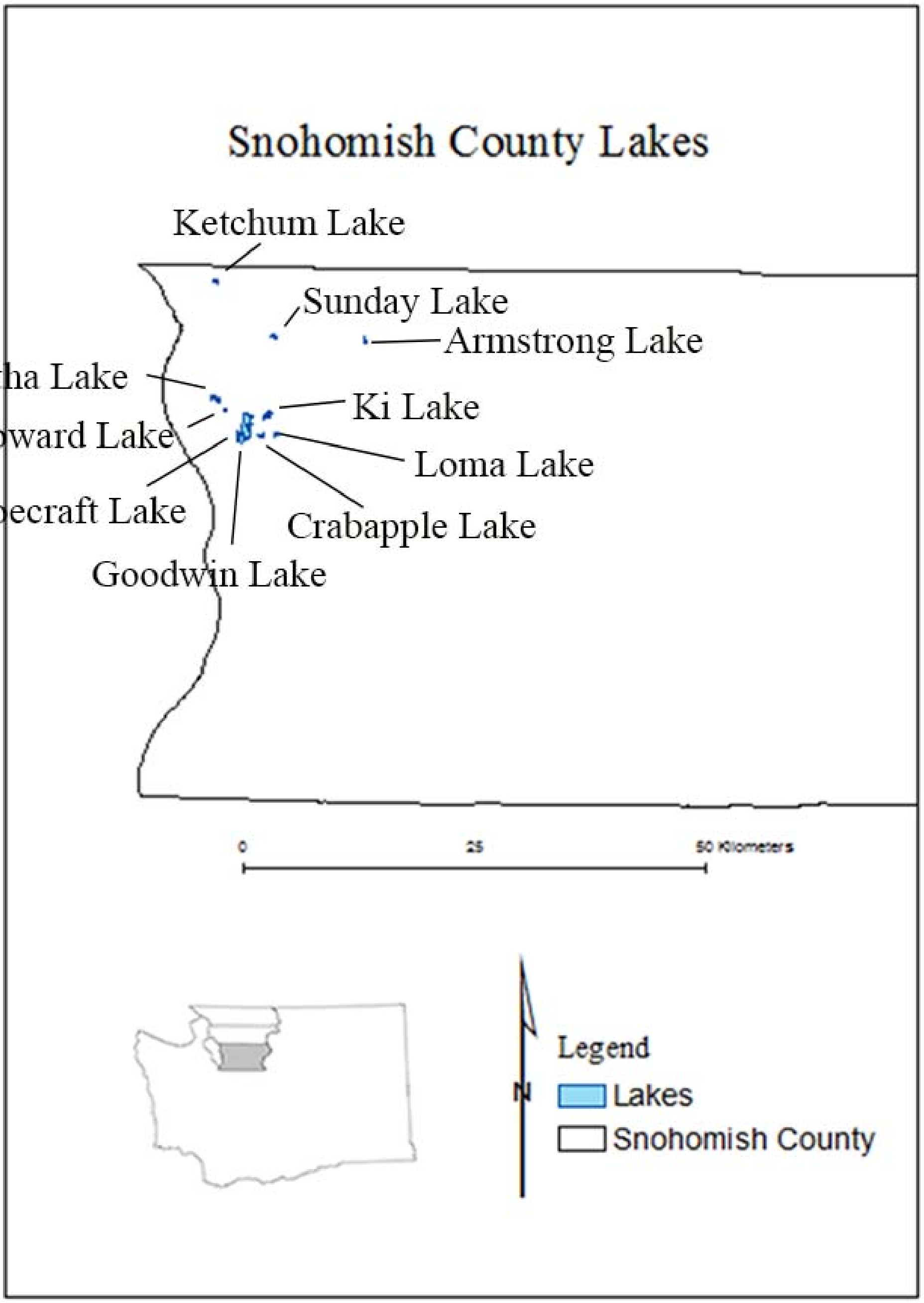


Figure 4. Snohomish County lakes monitored for the IWS Northwest Lakes Monitoring Program.

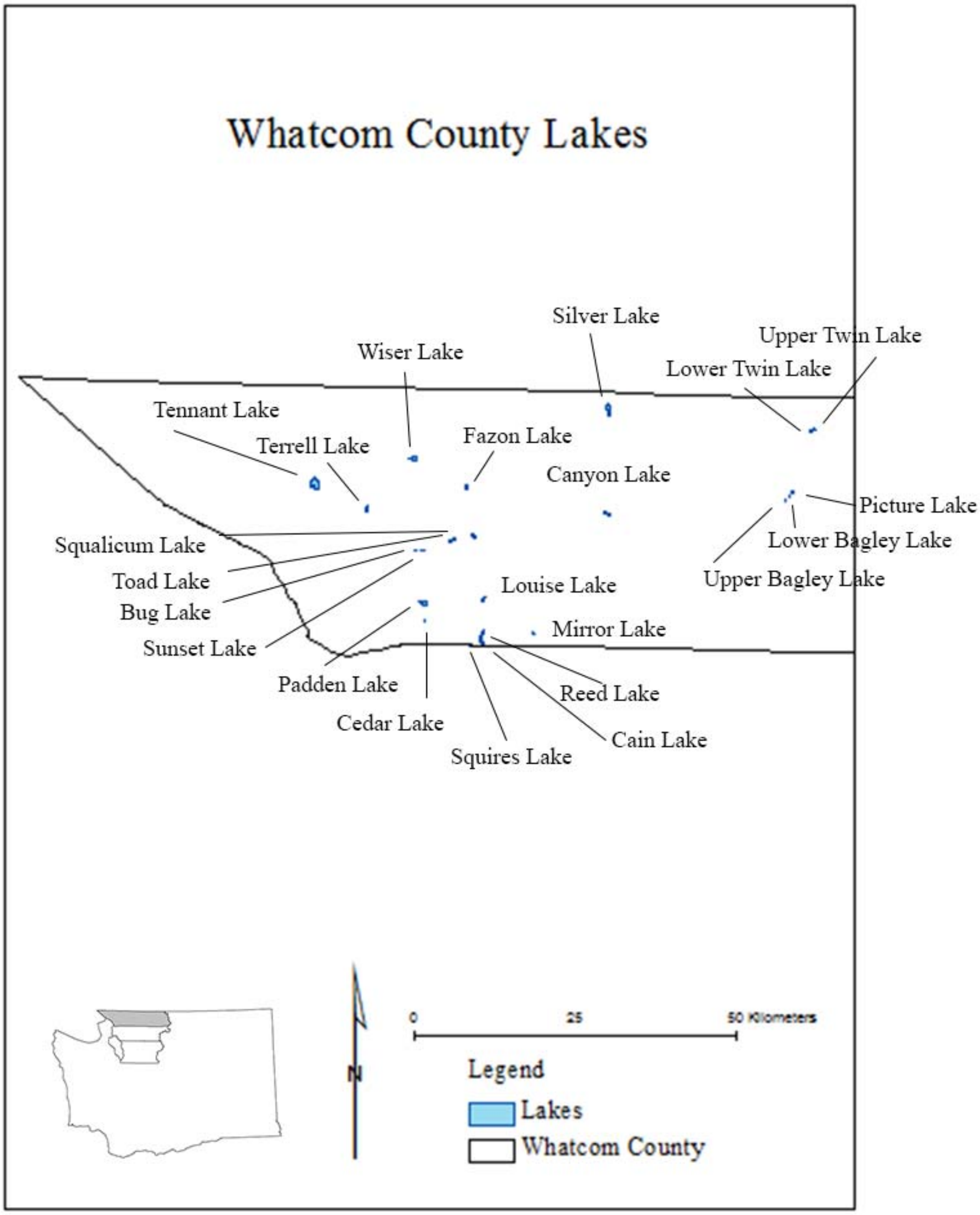


Figure 5. Whatcom County lakes monitored for the IWS Northwest Lakes Monitoring Program.

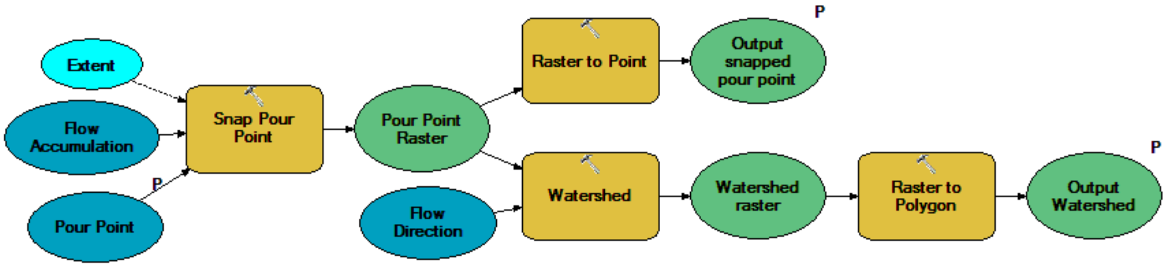


Figure 6. ArcGIS 10 watershed model diagram.

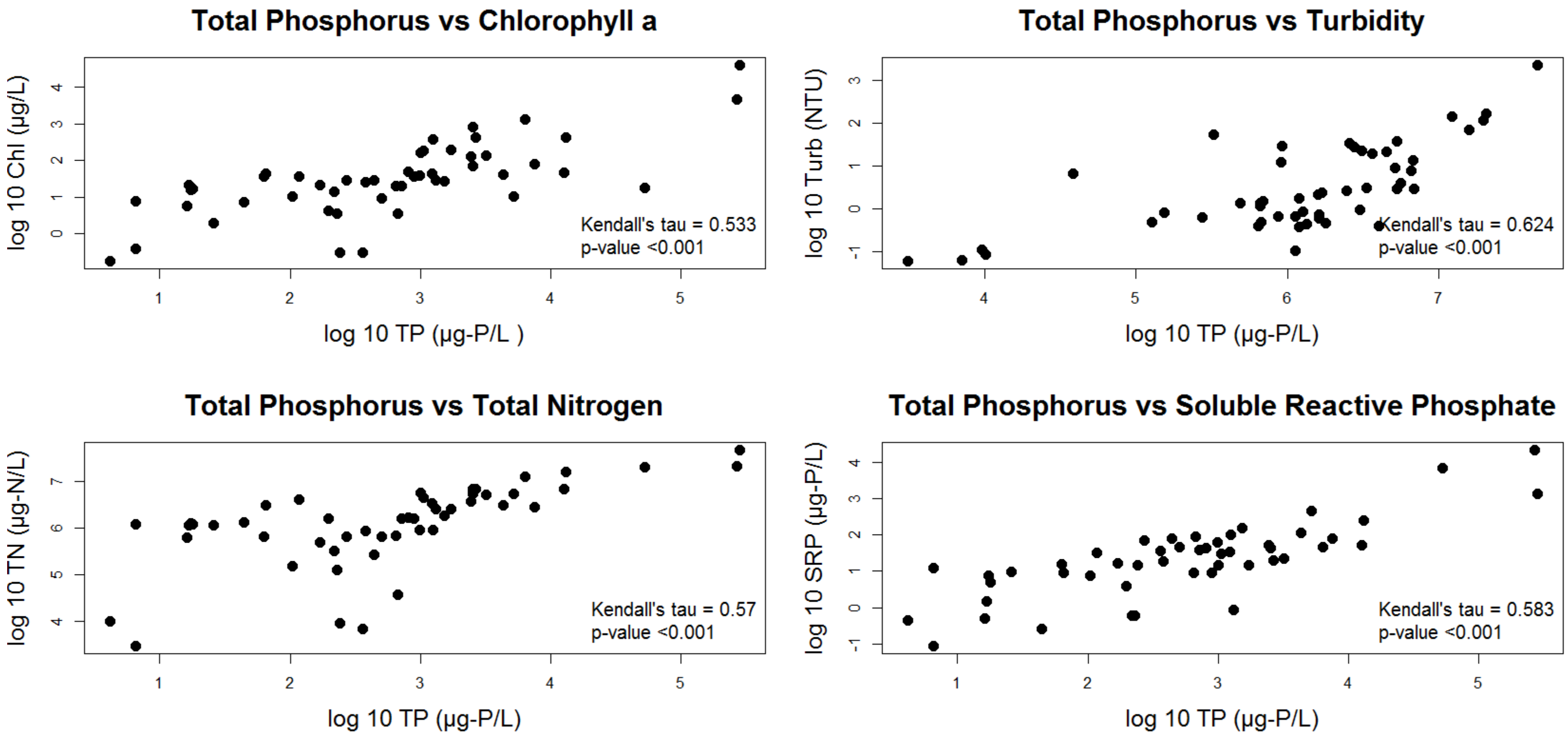


Figure 7. Scatterplots of water quality parameters that were highly correlated with total phosphorus.

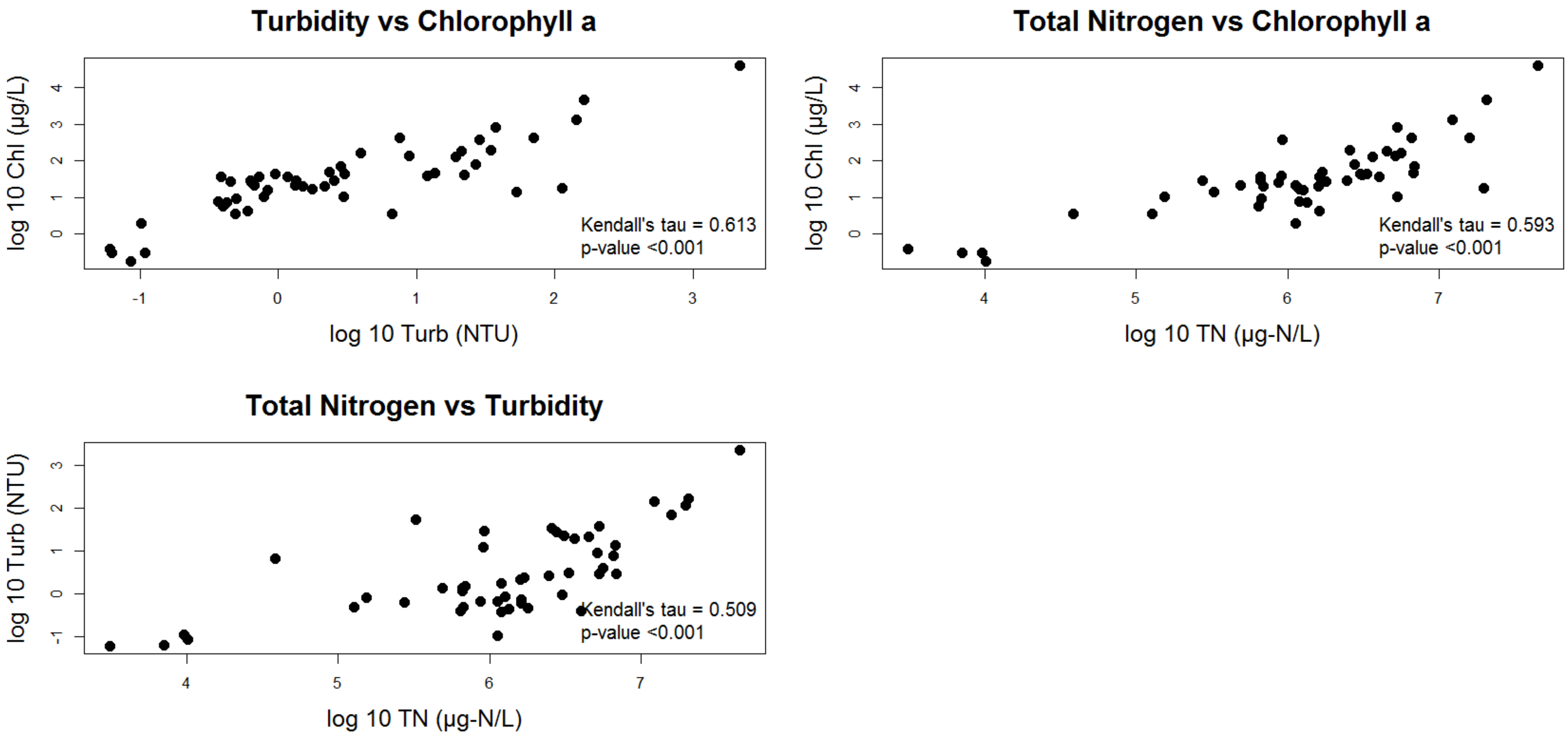


Figure 8. Scatterplots showing correlations between chlorophyll α, turbidity, and total nitrogen.

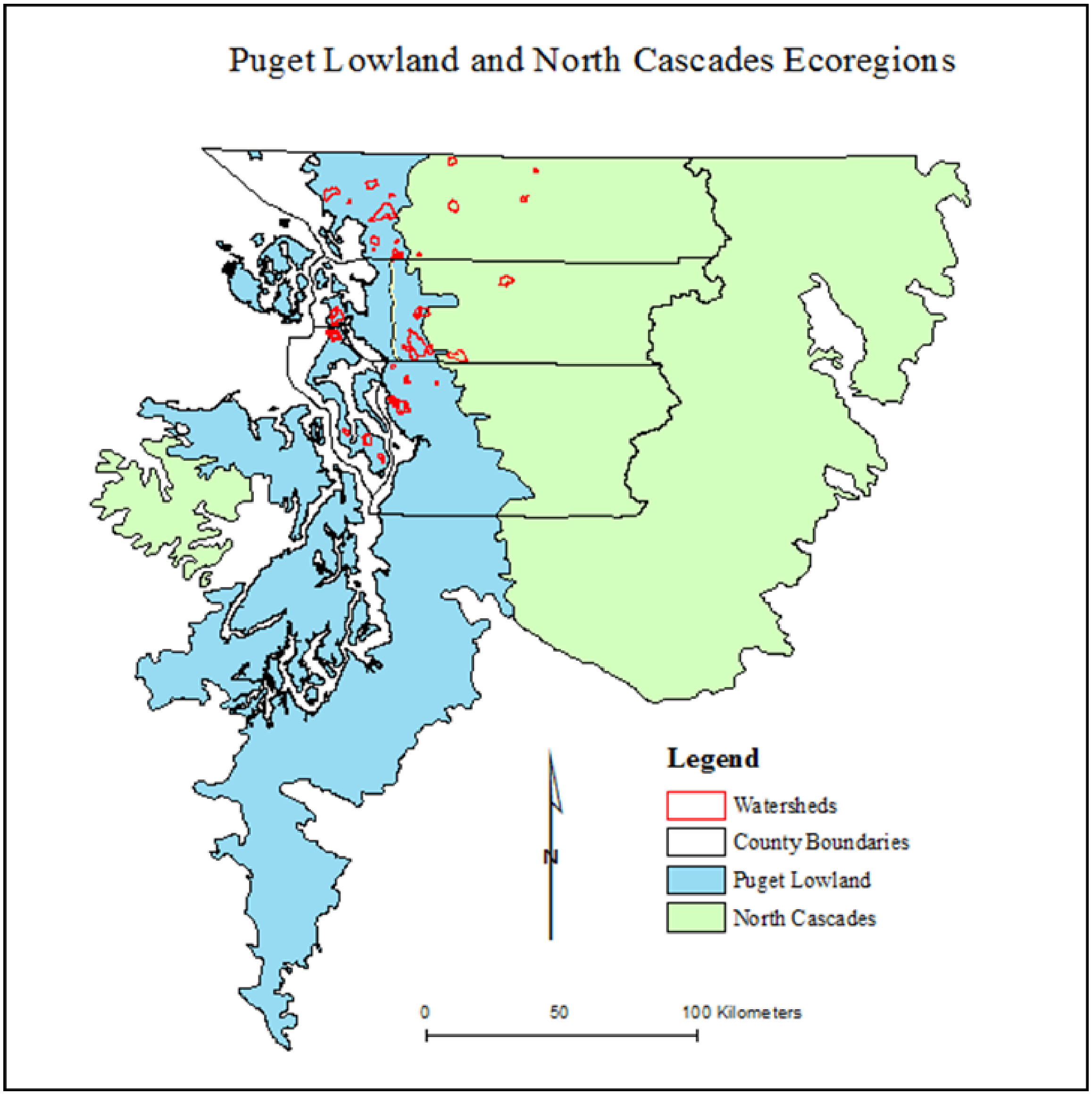
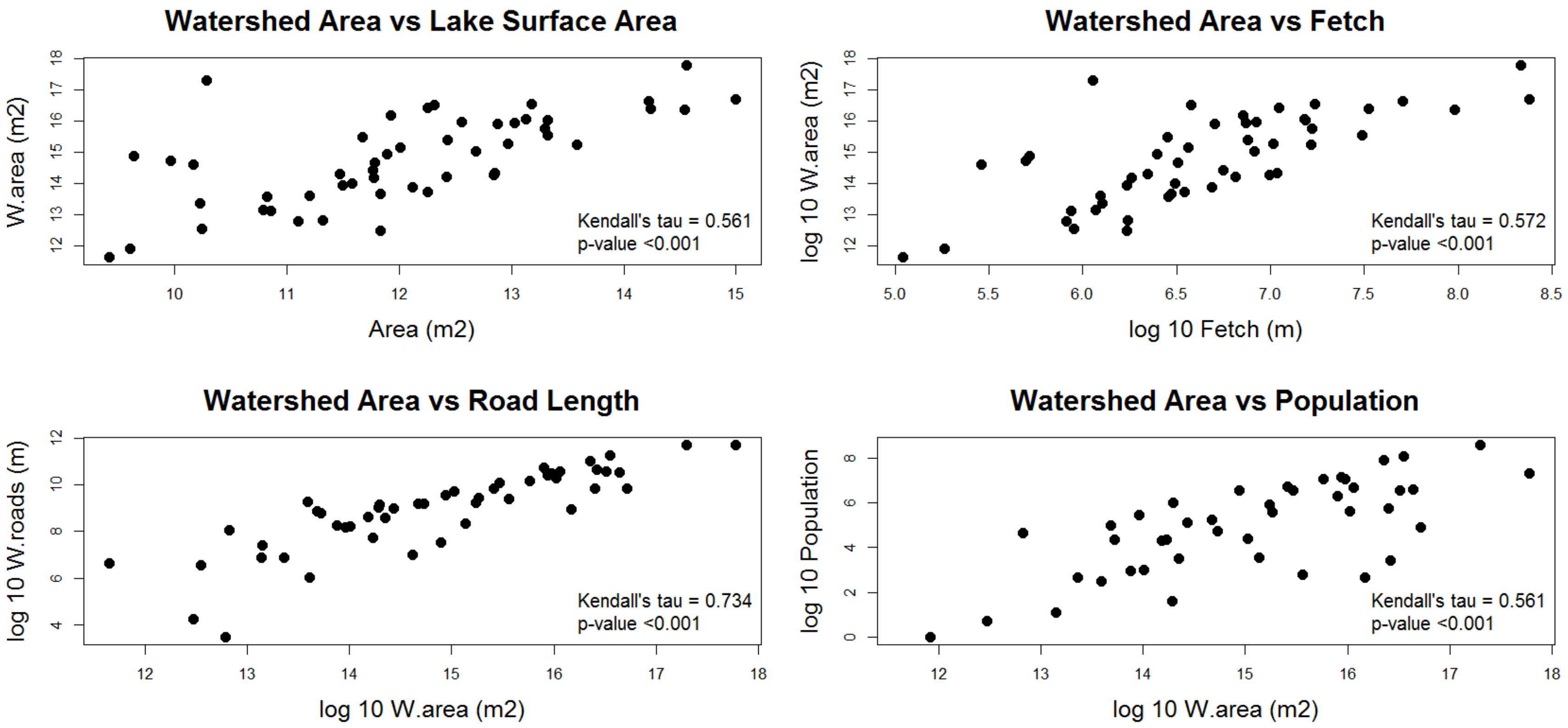


Figure 9. Project area for the IWS Northwest Washington Lakes Monitoring Program showing locations within the Puget Lowland and North Cascades ecoregions.


Watershed Area vs Lake Surface Area

Watershed Area vs Fetch

Watershed Area vs Road Length

Watershed Area vs Population

Figure 10. Scatterplots of highly correlated watershed parameters. Road length and population represent development in this study.

.

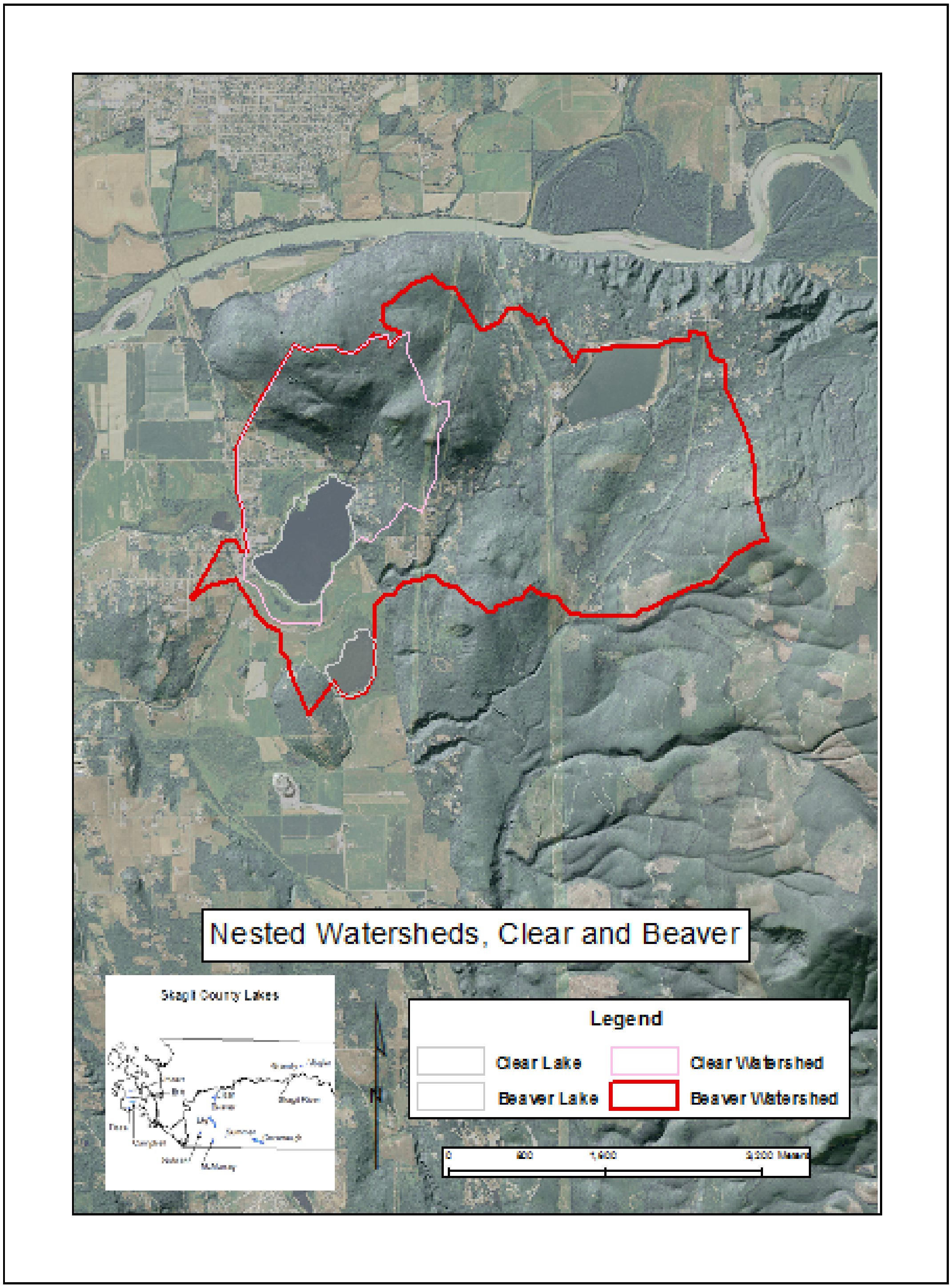


Figure 11. Clear Lake watershed nested in Beaver Lake watershed.

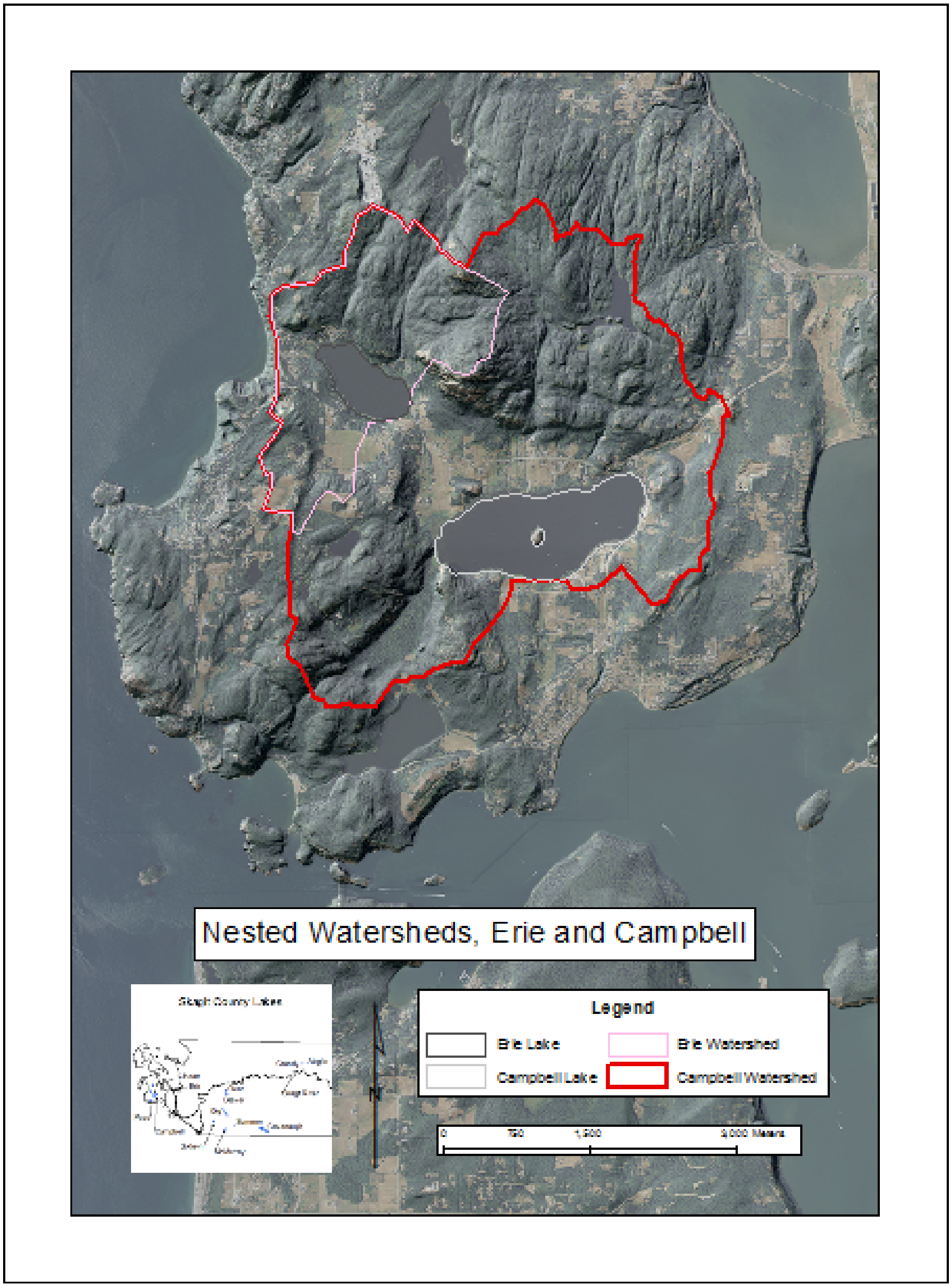


Figure 12. Erie Lake watershed nested in Campbell Lake watershed.

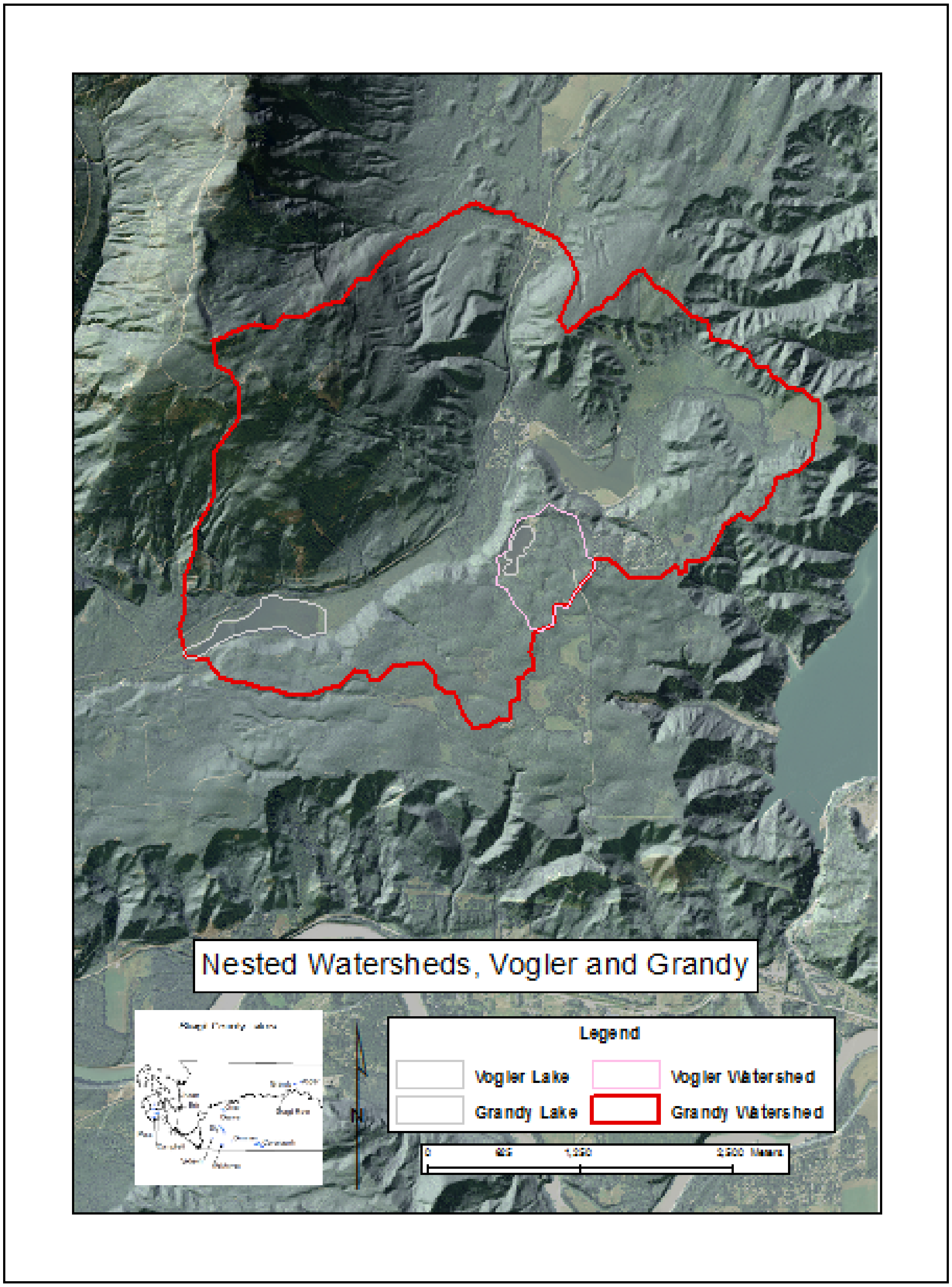


Figure 13. Vogler Lake watershed nested in Grandy Lake watershed.

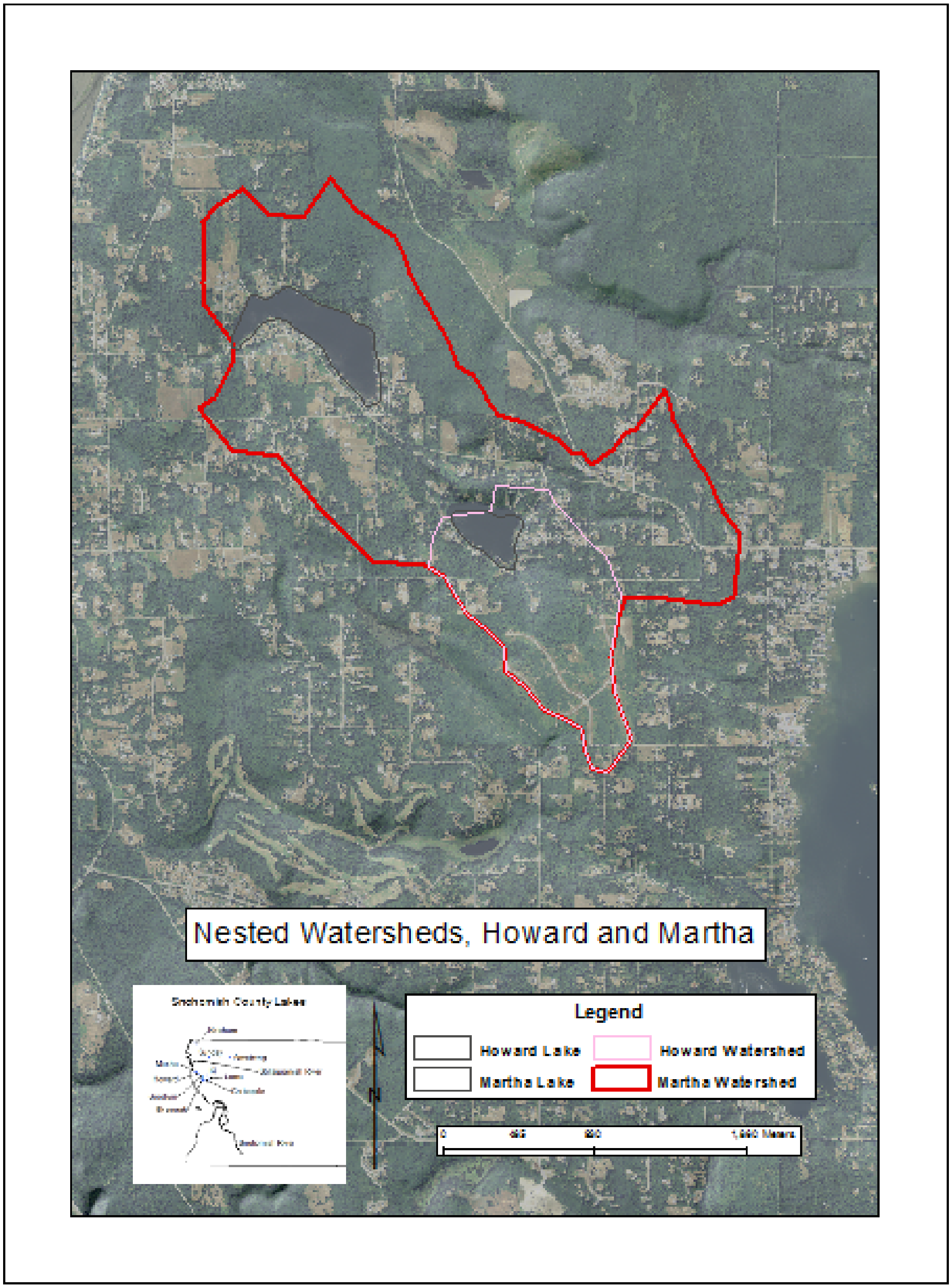


Figure 14. Howard Lake watershed nested in Martha Lake watershed.

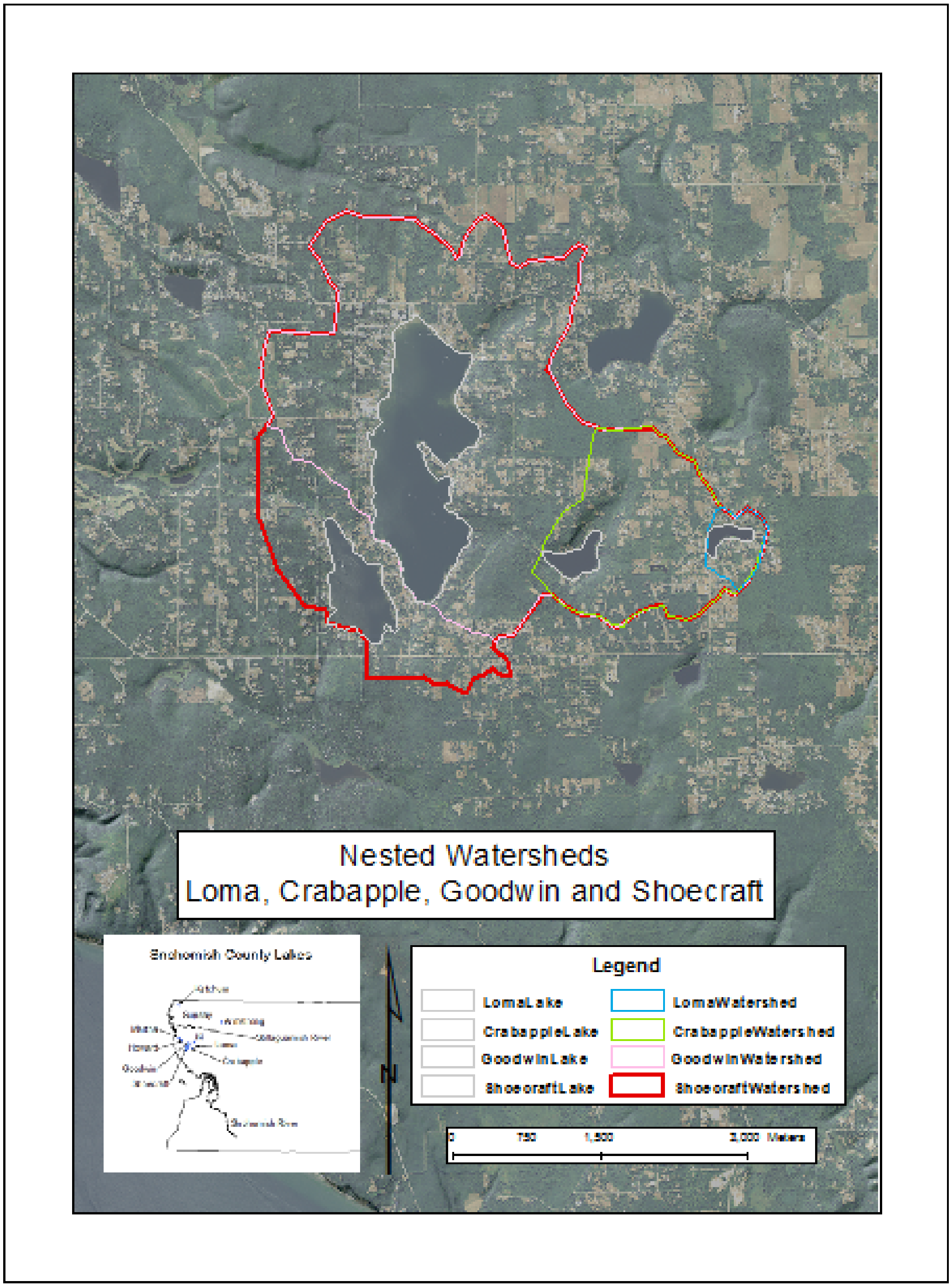


Figure 15. Loma Lake watershed nested in Crabapple Lake watershed nested in Goodwin Lake watershed nested in Shoecraft Lake watershed.

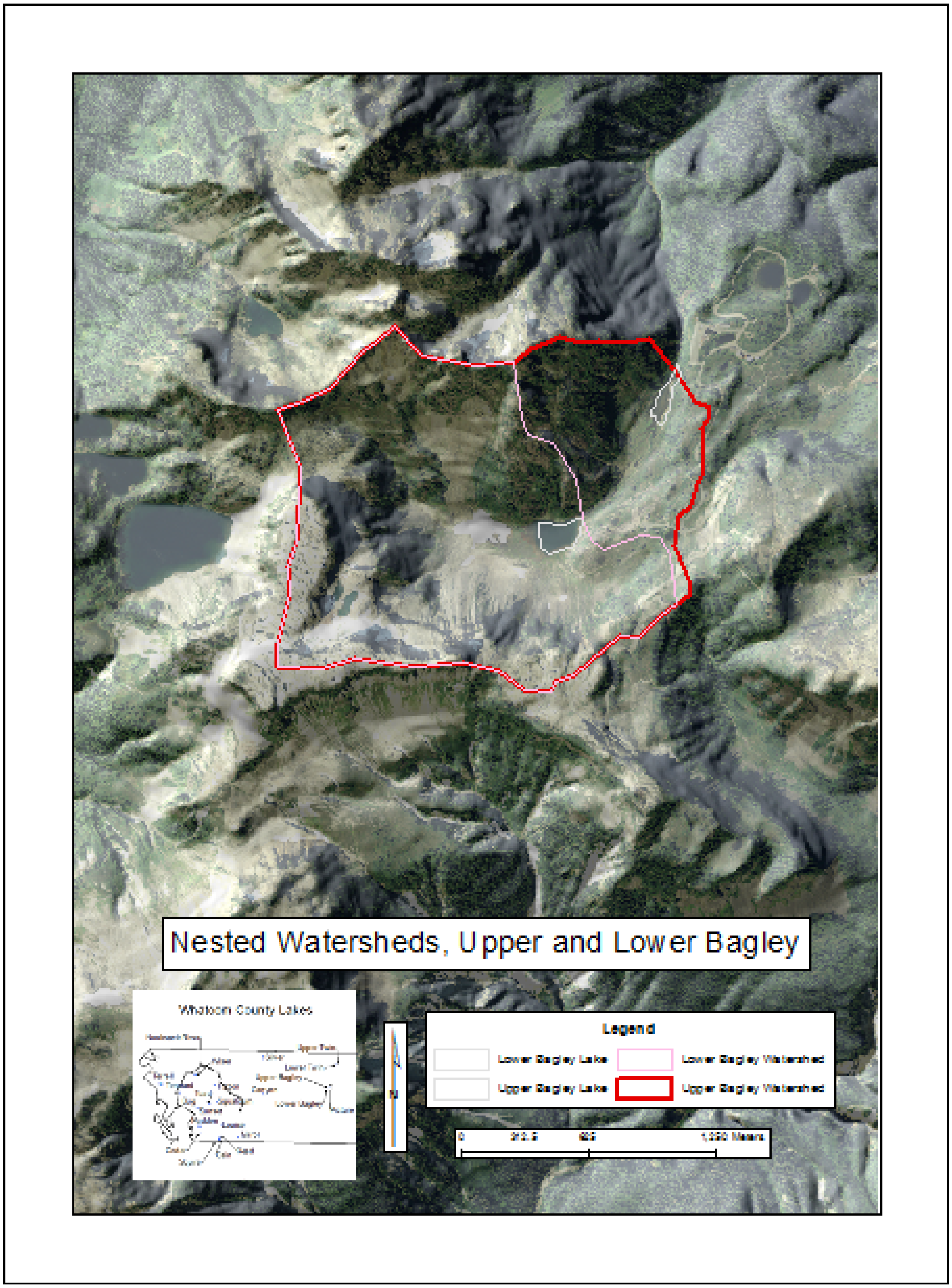


Figure 16. Upper Bagley Lake watershed nested in Lower Bagley Lake watershed.

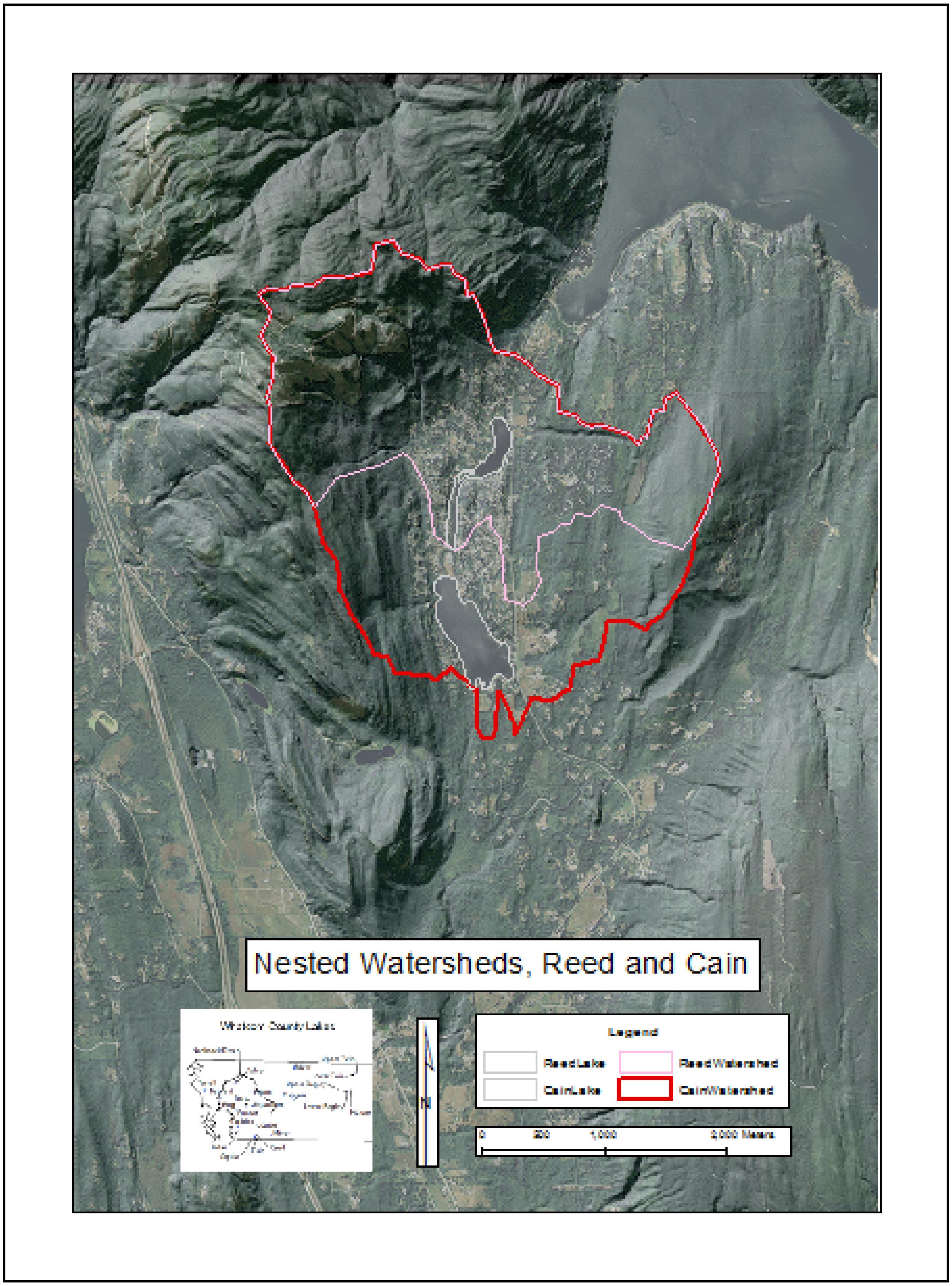


Figure 17. Reed Lake watershed nested in Cain Lake watershed.

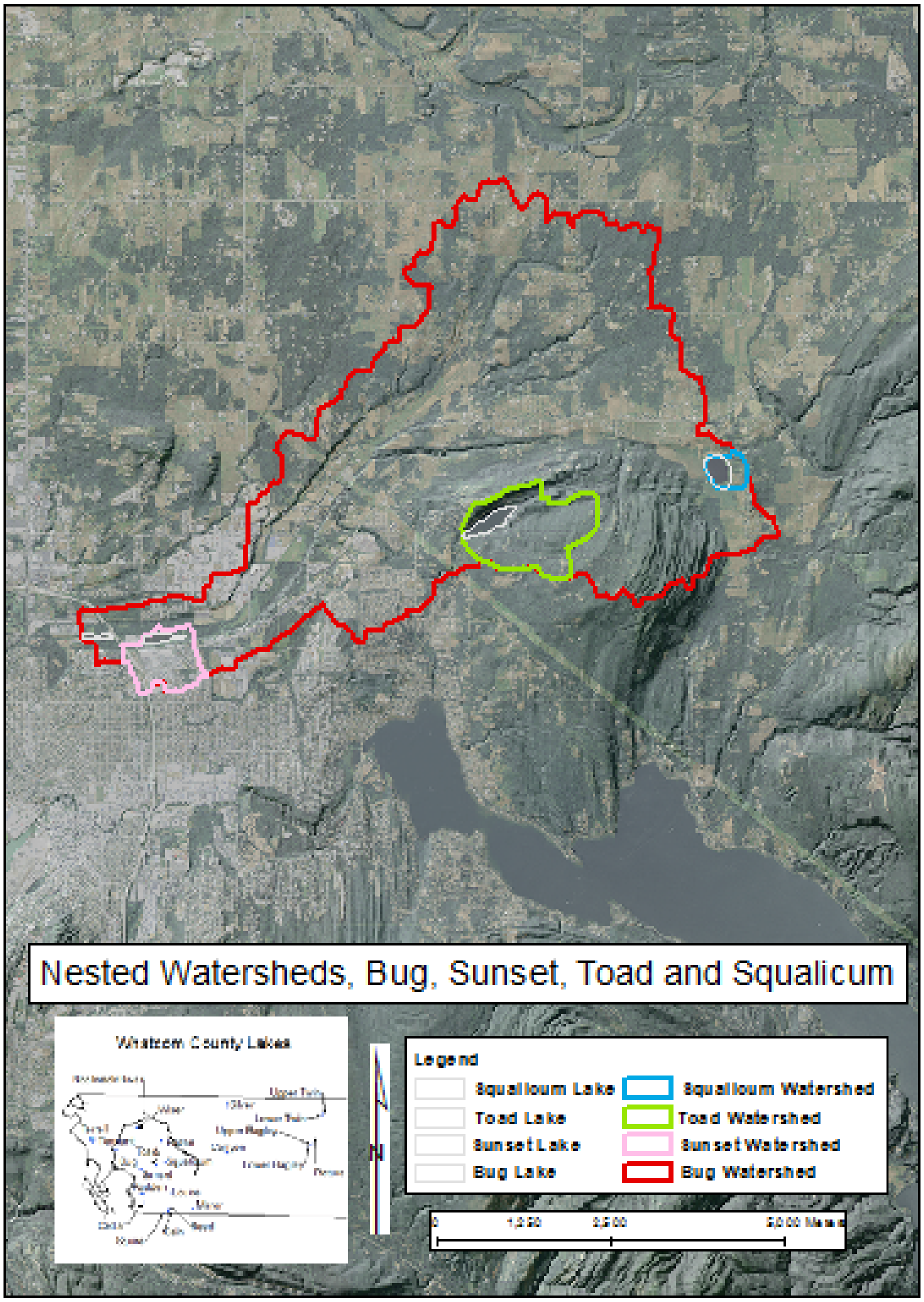


Figure 18. Sunset, Toad and Squalicum Lake watersheds nested in Bug Lake watershed.

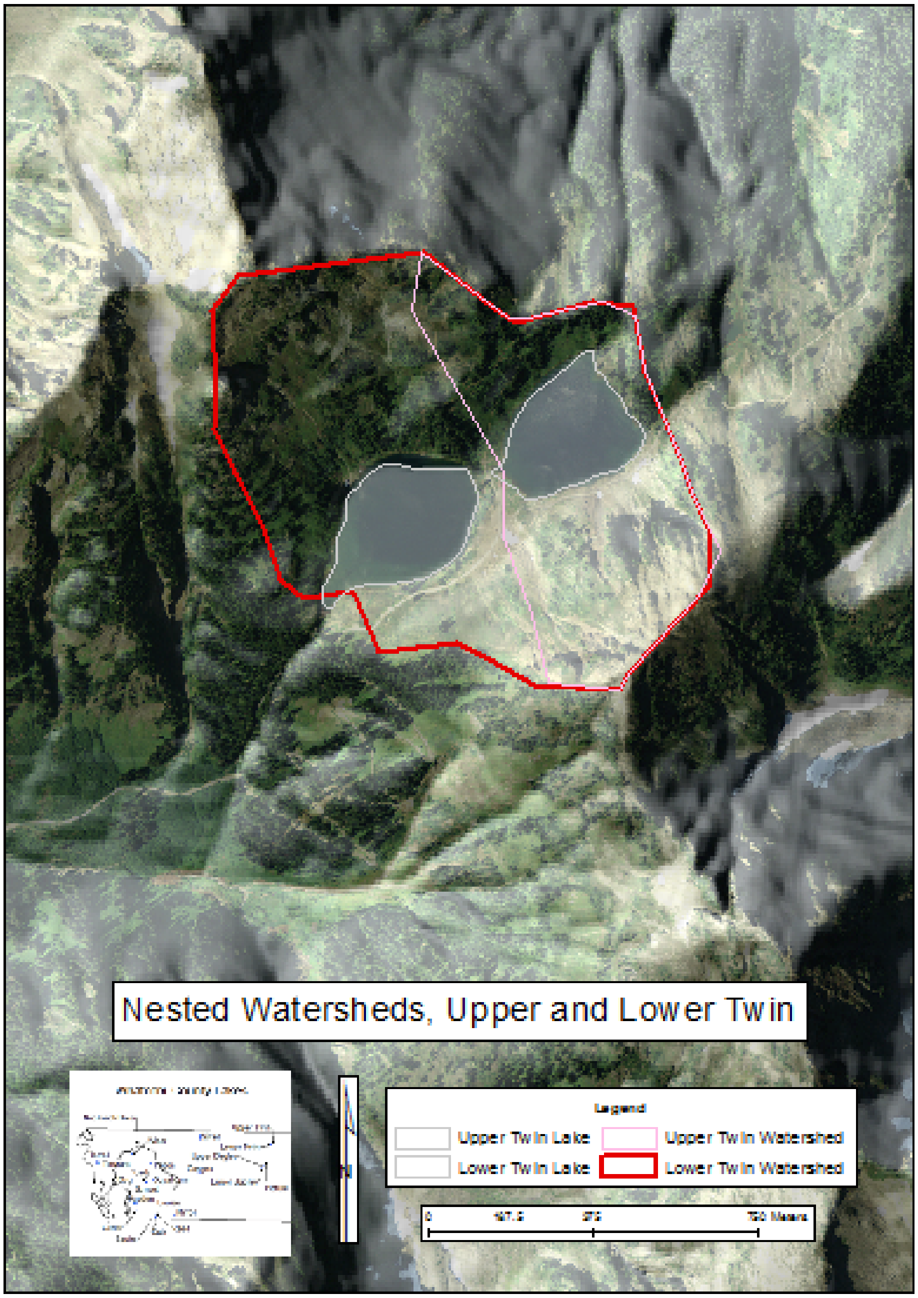
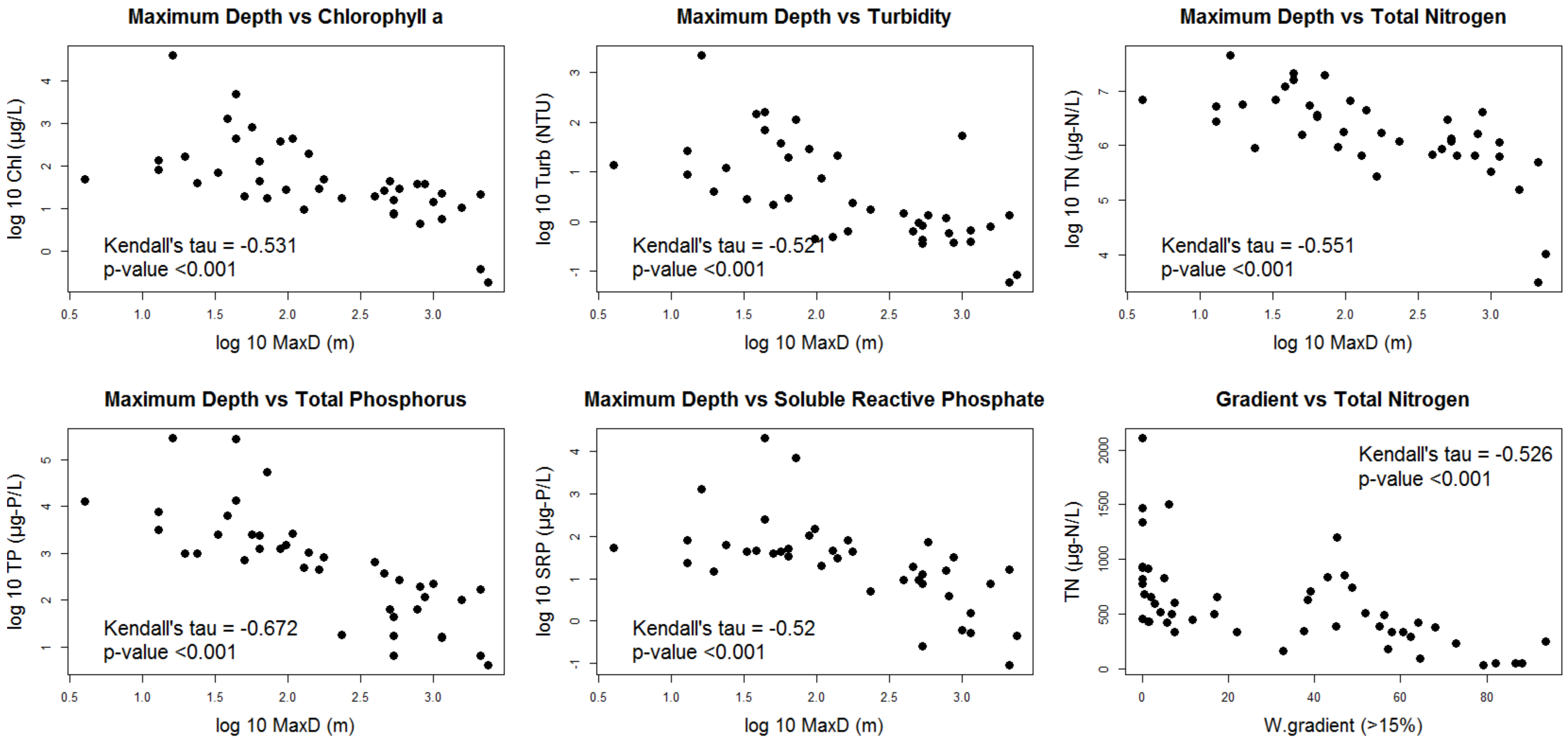


Figure 19. Upper Twin Lake watershed nested in Lower Twin Lake watershed.


Maximum Depth vs Chlorophyll a

Maximum Depth vs Turbidity

Maximum Depth vs Total Nitrogen

Maximum Depth vs Total Phosphorus

Maximum Depth vs Soluble Reactive Phosphate

Gradient vs Total Nitrogen

Figure 20. Scatterplots of strong correlations between selected water quality and watershed parameters.

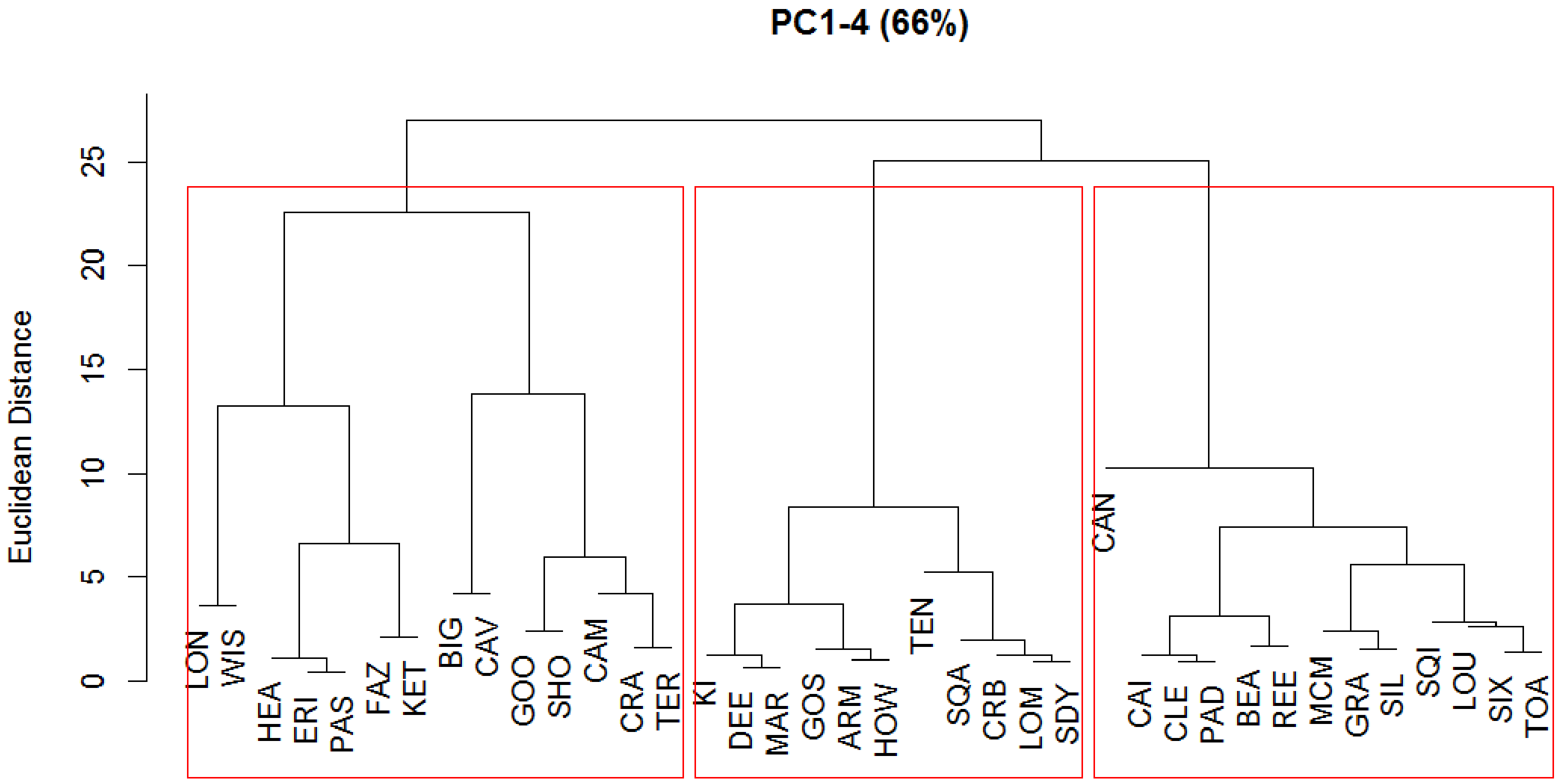


Figure 21. Lake clusters based on Euclidean distance, Wards minimum variance, and according to the first four principal components.

Table 1. Lake codes, names, counties, and geographic coordinates of the 50 lakes in this study.

Lake Code	Full Lake Name	County	Geographic Latitude and Longitude	
ARM	Armstrong	Snohomish	48.2258	-122.12291
BGL	Lower Bagley	Whatcom	48.8542	-122.69177
BGU	Upper Bagley	Whatcom	48.8596	-121.68474
BEA	Beaver	Skagit	48.4467	-122.22084
BIG	Big	Skagit	48.3849	-122.23322
BUG	Bug	Whatcom	48.7765	-122.47315
CAI	Cain	Whatcom	48.6470	-122.32909
CAM	Campbell	Skagit	48.4404	-122.62045
CAN	Canyon	Whatcom	48.8326	-122.06995
CAV	Cavanaugh	Skagit	48.3182	-122.00169
CED	Cedar	Whatcom	48.6778	-122.44936
CLE	Clear	Skagit	48.4614	-122.22576
CRB	Crabapple	Snohomish	48.1315	-122.27302
CRA	Cranberry	Island	48.3953	-122.65655
DEE	Deer	Island	47.9748	-122.38214
ERI	Erie	Skagit	48.4524	-122.63944
FAZ	Fazon	Whatcom	48.8655	-122.36901
GOO	Goodwin	Snohomish	48.1390	-122.29508
GOS	Goss	Island	48.0386	-122.47909
GRA	Grandy	Skagit	48.5659	-121.80090
HEA	Heart	Skagit	48.4750	-122.63100
HON	Honeymoon	Island	48.0520	-122.55100
HOW	Howard	Snohomish	48.1577	-122.32711
KET	Ketchum	Snohomish	48.2819	-122.34369
KI	Ki	Snohomish	48.1515	-122.26500
LOM	Loma	Snohomish	48.1342	-122.25284
LON	Lone	Island	48.0235	-122.45906
LOU	Louise	Whatcom	48.7092	-122.32766
MAR	Martha	Snohomish	48.1681	-122.33975
MCM	McMurray	Skagit	48.3155	-122.22689
MIR	Mirror	Whatcom	48.6630	-122.21937
PAD	Padden	Whatcom	48.7002	-122.44789
PAS	Pass	Skagit	48.4191	-122.63761
PIC	Picture	Whatcom	48.8654	-121.67709
REE	Reed	Whatcom	48.6568	-122.33132
SHO	Shoecraft	Snohomish	48.1306	-122.30319
SIL	Silver	Whatcom	48.9778	-122.06970
SIX	Sixteen	Skagit	48.3438	-122.28907
SQA	Squalicum	Whatcom	48.7984	-122.34969
SQI	Squire	Skagit/Whatcom	48.6459	-122.35393
SUM	Summer	Skagit	48.3329	-122.16783
SDY	Sunday	Snohomish	48.2289	-122.25691
SUN	Sunset	Whatcom	48.7763	-122.46124
TEN	Tennant	Whatcom	48.8311	-122.57962
TER	Terrell	Whatcom	48.8606	-122.68476
TOA	Toad	Whatcom	48.7906	-122.39653
TWL	Lower Twin	Whatcom	48.9507	-121.63925
TWU	Upper Twin	Whatcom	48.9522	-122.63408
VOG	Vogler	Skagit	48.5712	-121.77370
WIS	Wiser	Whatcom	48.9032	-122.48040

Table 2. Analytical methods and detection limits used for the Institute for Watershed Studies Northwest Lakes Monitoring Program.

Abbreviation	Parameter	Method Reference	Detection Limit (DL) or Sensitivity (±)
YSI field meter:			
do	Dissolved Oxygen	APHA (2005) #4500-O G, Membrane electrode	±0.1 mg/L
temp	Temperature, C	APHA (2005) #2550 Thermistor	±0.1 C
IWS laboratory analyses:			
do	Dissolved oxygen, mg/L	APHA (2005) #4500-O.C.; SOP-IWS-12	-
pH	pH	APHA (2005) #4500-H+; SOP-IWS-8	-
cond	Conductivity, µS	APHA (2005) #2510; SOP-IWS-19	-
chl	Chlorophyll α, µg/L	APHA (2005) #10200 H; SOP-IWS-16	-
alk	Alkalinity, mg/L	APHA (2005) #2320; SOP-IWS-15	-
turb	Turbidity, NTU	APHA (2005) #2130; SOP-IWS-11	-
nh3	Ammonium, µg-N/L	APHA (2005) #4500-NH3 H;SOP-IWS-19	10 µg-N/L
tn	T. nitrogen, µg-N/L	APHA (2005) #4500-N C; SOP-IWS-19	10 µg-N/L
no3	Nitrate/nitrite, µg-N/L	APHA (2005) #4500-NO3 I; SOP-IWS-19	10 µg-N/L
tp	T. phosphate, µg-P/L	APHA (2005) #4500-P H; SOP-IWS-19	5 µg-P/L
srp	Sol. phosphate, µg-P/L	APHA (2005) #4500-P G; SOP-IWS-19	3 µg-P/L

Table 3. Descriptive water quality statistics sampled by IWS, June-September, 2006-2012, for each of the 50 lakes analyzed in this project. Medians identified with an asterisk (*) had >50% of the measured values below analytical detection limits.

Lake		do (mg/L)	temp (C)	pH	cond (µgS)	chl (µg/L)	alk (µg/L)	turb (NTU)	nh3 (µg-N/L)	tn (µg-N/L)	no3 (µg-N/L)	tp (µg-P/L)	srp (µg-P/L)
All Lakes	Min	0.8	7.3	6.5	12.6	0.5	3.3	0.3	1.3	32.8	1.1	-2.1	0.4
	Med	8.7	20.6	7.8	91.4	4.3	31.7	1.3	8.7	495.5	4.2	17.2	4.1
	Max	11.7	22.9	9.1	381.0	99.5	83.3	28.2	102.7	2108.0	478.0	234.0	75.4
ARM	Min	8.6	20.2	7.5	53.2	3.0	21.1	0.6	<10	480.0	<10	16.9	7.7
	Med	8.9	20.9	7.7	57.4	4.2	22.6	0.7	13.6	520.0	6.0*	24.2	8.9
	Max	9.8	21.4	7.7	67.8	9.2	28.3	0.9	25.6	524.0	117.0	25.3	12.1
BGL	Min	8.7	5.7	6.4	9.5	0.2	3.7	0.2	<10	<10	<10	<5	3.0
	Med	10.7	8.2	7.1	12.6	0.6	5.4	0.4	3.4*	53.5	6.6*	10.9	3.2
	Max	12.2	13.2	7.2	15.3	5.7	6.5	2.5	8.0	112.0	12.2	16.1	6.5
BGU	Min	10.4	2.7	6.5	11.8	0.1	4.7	0.1	<10	20.5	<10	<5	3.8
	Med	11.7	7.3	7.0	12.6	0.6	5.1	0.3	1.3*	46.9	18.6*	12.9	4.7
	Max	12.4	8.6	7.2	15.0	1.3	6.0	1.4	12.7	144.0	24.1	30.8	9
BEA	Min	3.0	19.8	7.1	98.6	4.8	43.7	3.4	<10	544.0	<10	33.1	5.9
	Med	5.6	21.6	7.2	102.4	6.8	46.2	4.2	5.0*	627.5	4.2*	48.5	6.8
	Max	7.3	22.3	7.4	127.0	66.0	55.5	30.6	5.4	1669.0	7.1	139.0	8.1
BIG	Min	7.3	19.9	7.5	79.0	4.7	29.6	1.5	<10	258.0	<10	15	<3
	Med	8.5	21.9	7.7	99.4	13.1	38.3	4.3	5.5*	390.0	4.5*	22.1	7.5
	Max	9.6	23.4	8.5	102.4	27.8	40.3	6.9	13.5	567.0	7	37.6	12.6
BUG	Min	5.1	17.5	7.5	123.2	2.8	49.6	2.0	<10	500.0	<10	21.8	<3
	Med	10.8	22.2	9.1	149.9	5.0	60.1	3.9	11.4	658.6	2.9*	37.9	7.9
	Max	21.5	25.3	10.5	177.0	25.75	88.7	9.4	61.2	942.0	121.0	55.8	17.2
CAI	Min	8.3	16.7	7.7	50.9	2.7	16.1	0.6	<10	652.9	411.0	<5	<3
	Med	9.2	20.4	8.2	58.9	4.8	17.9	0.7	9.2*	739.0	478.0	7.9	4.5
	Max	10.0	22.4	8.6	64.7	12.5	21.0	1.11	25.1	830.4	561.6	12.8	7.4
CAM	Min	6.8	19.5	7.8	254.0	7.5	72.0	2.2	<10	650.0	<10	20.4	<3
	Med	8.5	20.7	8.3	268.0	22.6	83.3	8.6	12.1	1198.0	3.6*	45.1	5.3
	Max	10.7	21.8	9.2	281.0	87.9	92.3	25.4	35.5	1498.4	7.9	82.2	5.6
CAN	Min	-	-	-	-	-	-	-	-	-	-	-	-
	Med	8.8	12.4	6.6	19.1	3.2	6.9	5.6	12.8	248.3	76.1	10.4	<3
	Max	-	-	-	-	-	-	-	-	-	-	-	-

Table 3. Continued.

Lake		do (mg/L)	temp (C)	pH	cond (µgS)	chl (µg/L)	alk (µg/L)	turb (NTU)	nh3 (µg-N/L)	tn (µg-N/L)	no3 (µg-N/L)	tp (µg-P/L)	srp (µg-P/L)
CAV	Min	7.7	19.3	7.0	29.1	1.9	9	0.7	<10	161.0	<10	<5	<3
	Med	8.5	21.0	7.4	30.5	2.8	9.5	0.9	9.1*	179.0	18.9	7.5	2.4*
	Max	9.5	24.5	7.5	44.2	5.6	17.1	2.1	21.5	236.0	64.7	18.8	4.3
CED	Min	-	-	-	-	-	-	-	-	-	-	-	-
	Med	6.8	19.6	7.17	55.3	1.35	14.6	0.4	10.6	425.2	115.9	<5	<3
	Max	-	-	-	-	-	-	-	-	-	-	-	-
CLE	Min	6.2	20.5	7.0	83.0	2.5	30.1	1.0	<10	287.0	<10	6.4	<3
	Med	6.7	21.5	7.2	86.2	3.7	32.3	1.2	4.6*	343.0	2.0*	16.7	2.6*
	Max	9.3	22.3	7.8	90.7	7.0	34.6	2.9	8.7	486.0	7.0	22.6	8.8
CRB	Min	7.9	17.7	7.2	49.1	2.9	9.3	0.8	<10	529.0	42.3	<5	<3
	Med	8.4	20.5	7.4	51.7	5.2	10.5	1.0	8.6*	653.0	185.0	6.2	2.6*
	Max	8.9	24.5	7.7	57.6	9.5	11.1	1.5	26.0	715.0	231.0	8.8	3.2
CRA	Min	7.5	19.2	7.6	25.3	7.1	35.4	1.1	<10	766.5	<10	25.2	<3
	Med	8.6	20.3	8.2	278.0	14.1	63.6	2.4	10.2	916.1	1.1*	30.8	3.7
	Max	11.6	21.0	9.0	288.0	43.8	67.1	7.4	18.3	1073.0	6.4	76.1	7.8
DEE	Min	7.7	17.9	7.5	75.7	1.9	20.3	0.5	<10	413.9	<10	<5	<3
	Med	8.9	21.4	7.6	83.6	2.4	21.4	0.7	9.2*	457.5	3.0*	5.2	0.6*
	Max	9.5	23.7	7.8	85.5	2.8	22.1	13.4	24.7	581.0	6.9	8.7	3.9
ERI	Min	6.5	19.3	7.6	238.0	1.6	64.9	1.0	<10	675.0	<10	17.8	<3
	Med	8.8	20.9	8.3	256.0	9.2	70.1	1.8	12.3	855.0	1.1*	20.1	3.2
	Max	9.7	21.8	9.6	285.0	28.4	82.3	6.6	29.5	1420.0	6.3	60.3	6.6
FAZ	Min	4.8	17.7	7.0	262.0	9.4	48.1	1.2	<10	1035.0	<10	56.7	4.9
	Med	8.0	21.0	7.6	366.0	14.0	52.4	6.3	10.9	1337.5	5.0*	61.4	11.0
	Max	9.2	22.8	8.9	446.0	44.1	55.4	21.2	776.7	2666.0	15.5	335.0	51.4
GOO	Min	8.1	17.6	7.7	89.3	2.1	28.3	0.6	<10	383.0	<10	<5	<3
	Med	8.8	20.7	7.9	91.8	2.5	31.3	0.6	8.8*	435.0	3.8*	-0.5*	3.0
	Max	9.8	23.6	8.1	101.0	4.8	39.7	1.07	13.4	461.0	7.4	4.7	6.9
GOS	Min	8.37	20.5	7.5	117.9	1.4	29.9	0.3	<10	337.7	<10	5.1	<3
	Med	8.7	22.1	7.9	124.2	1.9	31.5	0.8	11.4	498.0	1.3*	9.9	1.8*
	Max	9.4	23.8	8.1	133.0	2.5	34.4	1.14	31.2	543.0	91.4	12.5	2.3

Table 3. Continued.

Lake		do (mg/L)	temp (C)	pH	cond (µgS)	chl (µg/L)	alk (µg/L)	turb (NTU)	nh3 (µg-N/L)	tn (µg-N/L)	no3 (µg-N/L)	tp (µg-P/L)	srp (µg-P/L)
GRA	Min	7.0	16.8	7.7	116.5	2.5	53.6	2.3	<10	196.0	<10	13.9	4.5
	Med	8.7	19.4	7.8	136.5	5.0	66.9	2.9	19.3	387.5	3.9*	20.0	6.1
	Max	8.9	20.9	7.9	137.2	8.5	70.1	4.1	19.9	431.0	6.9	27.6	43.3
HEA	Min	7.7	19.7	7.7	217.0	13.2	53.3	1.5	<10	629.5	<10	19.8	<3
	Med	9.7	20.6	8.7	235.0	18.4	73.8	4.8	7.4*	834.0	3.0*	30.1	5.2
	Max	11.4	22.5	9.3	249.0	28.6	76.7	7.9	17.8	1017.0	6.2	43.7	18.9
HON	Min	8.2	18.0	7.8	116.6	1.3	43.3	0.7	<10	423.0	<10	<5	<3
	Med	9.7	20.3	7.8	167.8	2.8	65.6	1.6	7.0*	830.0	8.1*	41.1	14.3
	Max	11.1	21.7	8.1	229.0	5.1	79.5	2.0	48.8	896.0	170.0	53.2	16.1
HOW	Min	8.2	18.0	7.8	116.6	1.3	43.3	0.7	<10	423.0	<10	<5	<3
	Med	8.5	20.0	7.9	117.2	3.3	43.8	0.9	18.0	447.0	7.7*	3.5*	2.4
	Max	8.9	23.9	7.9	125.0	4.3	46.6	1.7	27.5	551.0	89.3	5.9	3.7
KET	Min	3.4	20.9	7.3	126.5	1.2	35.7	4.3	<10	1017.0	<10	46.1	3.5
	Med	9.4	21.2	8.1	140.5	3.5	41.1	7.8	102.7	1469.5	52.3	112.5	46.9
	Max	15.3	23.0	9.9	168.0	323.0	47.1	13.3	481.0	1753.0	128.0	218.0	119.0
KI	Min	8.2	17.6	7.3	43.9	1.1	9.3	0.6	<10	305.0	<10	<5	<3
	Med	8.8	20.7	7.4	44.3	2.2	9.6	0.7	7.7*	332.0	4.1*	-2.1*	0.8*
	Max	9.1	24.1	8.0	46.6	4.7	10.0	0.7	30.2	350.0	13.9	<5	4.6
LOM	Min	7.2	17.1	6.8	44.4	3.1	8.1	0.8	<10	626.0	<10	18.1	<3
	Med	7.9	20.6	7.0	47.4	9.8	9.0	3.8	15.0	776.0	3.0*	20.6	4.4
	Max	8.6	24.9	7.0	57.4	30.5	9.4	6.4	38.6	1016.0	18.4	25.6	11.6
LON	Min	5.1	19.8	8.0	159.8	10.5	56.9	3.2	<10	1275.0	<10	89.0	27.3
	Med	10.5	21.6	9.0	183.9	40.0	66.8	9.1	40.2	1505.1	5.2*	228.0	75.4
	Max	11.1	23.4	9.1	196.0	596.0	68.8	32.8	389.0	2671.0	36.3	363.6	223.0
LOU	Min	7.1	17.2	7.5	62	2.8	19.4	0.8	<10	282.0	<10	<5	<3
	Med	8.5	21.7	7.7	68.1	3.8	23.1	1.1	7.0*	295.0	6.0*	9.3	3.4
	Max	9.4	23.6	7.8	73.9	10.9	24.3	3.8	12.3	350.0	68.6	11.5	7.4
MAR	Min	8.3	18.3	7.7	100.9	2.0	28.8	0.6	<10	378.0	<10	<5	<3
	Med	8.7	20.3	7.9	102.5	3.9	30.4	0.8	6.5*	426.0	2.5*	2.7*	1.2*
	Max	9.1	24.2	8.0	110.0	6.6	32.6	1.3	22.6	480.0	6.8	5.5	1.9

Table 3. Continued.

Lake		do (mg/L)	temp (C)	pH	cond (µgS)	chl (µg/L)	alk (µg/L)	turb (NTU)	nh3 (µg-N/L)	tn (µg-N/L)	no3 (µg-N/L)	tp (µg-P/L)	srp (µg-P/L)
MCM	Min	7.8	20.2	7.9	94.4	2.5	29.6	0.7	<10	243.0	<10	6.4	<3
	Med	9.0	21.2	8.5	101.4	4.3	33.2	1.1	14.0	336.0	19.2*	11.4	6.4
	Max	10.7	24.2	8.8	104.0	12.4	33.8	1.8	15.6	591.0	257.0	19.2	10.8
MIR	Min	7.7	9.0	7.0	39.2	0.9	12.8	0.8	<10	66.0	<10	<5	<3
	Med	9.1	15.8	7.3	49.1	1.8	14.3	2.3	1.8	97.7	16	16.9	7.1
	Max	11.8	20.4	7.7	57.9	7.8	21.8	24	11.8	347.0	71.8	42.4	9.0
PAD	Min	8.2	16.5	7.5	97.3	4.4	27.1	0.7	<10	291.7	<10	<5	<3
	Med	9.0	20.6	8.0	99.8	4.8	28.2	1.1	8.1*	337.8	1.6*	6.1	3.3*
	Max	10.2	22.8	8.2	104.4	10.6	30.9	2.0	15.6	422.0	145.0	18.0	4.1
PAS	Min	7.6	19.2	8.1	278.0	5.9	72.4	2.0	<10	527.0	<10	8.6	<3
	Med	8.8	19.9	8.4	288.0	8.2	76.3	3.6	5.9*	705.0	1.2*	29.6	5.5
	Max	9.7	20.3	8.8	296.0	41.2	81.2	6.7	20.7	862.5	6.0	31.7	6.9
PIC	Min	8.2	13.9	6.2	9.9	0.9	2.5	0.5	<10	85.0	<10	<5	<3
	Med	8.5	16.4	6.7	13.1	1.8	3.4	0.7	3.9*	164.3	3.3*	10.6	0.8*
	Max	9.8	22.1	7.1	51.2	3.9	4.2	1.9	10.6	237.0	9.4	13.3	3.0
REE	Min	5.6	15.8	6.8	46.5	2.5	15.5	0.9	<10	318.1	<10	14.0	<3
	Med	8.3	19.7	7.2	53.1	3.7	16.3	1.4	17.2	493.0	7.7*	17.4	4.9
	Max	9.6	22.0	7.9	81.9	24.0	35.9	3.1	73.3	693.0	374.0	52.6	7.8
SHO	Min	8.3	17.2	7.6	97.1	2.2	33.8	0.9	<10	405.0	<10	<5	<3
	Med	8.4	18.7	7.9	99.8	3.5	36.3	1.3	4.7*	435.0	4.0*	1.3*	2.0*
	Max	8.6	22.8	7.9	114.0	4.9	41.0	6.3	18.4	489.0	7.0	13.8	4.9
SIL	Min	7.5	17.5	7.6	136.7	1.3	50.6	0.6	<10	208.8	<10	5.9	3.8
	Med	8.5	20.1	7.9	141.4	4.3	55.3	0.8	12.8	229.0	3.7*	14.1	6.7
	Max	9.5	23.2	8.1	149.8	11.6	58.5	5.8	28.7	584.0	12.8	18.4	20.9
SIX	Min	7.5	19.3	7.3	83.0	1.9	29.9	0.7	<10	323.0	<10	11.4	3.0
	Med	8.1	21.0	7.6	88.5	2.7	31.9	0.7	8.3*	338.0	3.9*	14.9	5.3
	Max	9.5	24.9	8.0	90.7	4.0	34.3	1.2	11.3	469.0	14.2	24.6	7.2
SQA	Min	4.5	17.3	6.8	67.9	1.8	25.8	0.9	<10	704.1	<10	23.3	<3
	Med	7.2	20.6	7.1	68.9	6.4	27.5	1.6	10.6	929.6	4.3*	30.0	5.2
	Max	10.1	23.4	7.8	77.1	117.9	39.9	7.1	12.0	1743.0	59.1	87.3	7.8

Table 3. Continued.

Lake		do (mg/L)	temp (C)	pH	cond (µgS)	chl (µg/L)	alk (µg/L)	turb (NTU)	nh3 (µg-N/L)	tn (µg-N/L)	no3 (µg-N/L)	tp (µg-P/L)	srp (µg-P/L)
SQI	Min	2.7	16.4	6.1	41.1	2.3	15.5	0.6	<10	285.0	<10	7.3	<3
	Med	6.4	19.8	6.9	43.6	4.2	16.2	0.8	6.6*	378.6	3.7*	13.2	3.6
	Max	9.6	23.1	7.3	46.3	54.6	17.7	4.4	16.1	751.2	8.1	42.6	13.8
SUM	Min	1.6	18.9	6.2	29.2	3.1	9.0	0.6	<10	369.0	<10	16.0	<3
	Med	4.6	19.8	6.5	33.2	4.9	11.0	0.9	7.5*	498.0	4.5*	19.2	2.6
	Max	6.5	20.8	6.7	35.2	8.2	30.0	1.0	10.0	559.0	9.6	37.0	3.8
SDY	Min	6.4	20.5	7.0	83.4	3.4	24.2	0.9	<10	553.0	<10	17.6	<3
	Med	7.2	21.2	7.3	88.5	5.2	24.5	1.6	8.0	678.5	5.8*	22.0	4.6
	Max	7.9	22.4	7.7	96.1	5.7	27.2	1.7	21.2	945.0	7.6	24.5	8.5
SUN	Min	8.5	16.6	7.5	139.3	3.1	60.7	2.3	<10	468.0	<10	18.3	<3
	Med	10.1	22.9	8.8	152.7	9.9	65.8	4.7	8.6*	607.5	3.5*	25.4	3.2
	Max	15.5	23.8	9.6	175.8	44.6	80.0	9.9	37.7	751.1	144.7	61.5	11.8
TEN	Min	0.5	14.9	6.3	122.8	2.1	50.4	1.7	<10	628.0	<10	45.3	<3
	Med	0.8	16.1	6.8	145.1	5.4	54.9	3.1	26.0	928.0	4.5*	60.5	5.6
	Max	4.5	17.1	6.9	182.7	21.4	64.3	5.5	53.2	1186.3	10.4	107.7	11.5
TER	Min	6.5	16.9	7.3	89.9	1.7	27.6	1.4	<10	770.0	<10	19.2	<3
	Med	8.8	19.7	8.8	91.1	8.6	33.1	2.6	8.6*	821.0	4.5*	33.4	3.9
	Max	11.2	22.9	8.9	105.8	35.5	49.8	9.6	72.2	1054.0	11.2	49.4	30.4
TOA	Min	6.6	16.6	7.8	109.9	2.5	40.9	0.9	<10	396.0	<10	<5	<3
	Med	9.7	20.3	8.2	110.8	5.5	45.0	1.5	21.0	505.0	55.9	18.3	5.2
	Max	11.2	22.8	9.1	120.0	15.9	47.3	2.3	47.9	984.0	701.0	28.3	9.4
TWL	Min	8.7	10.3	7.8	54.2	0.5	24.4	0.2	<10	31.1	<10	<5	<3
	Med	8.8	12.6	7.9	54.5	0.5	25.7	0.3	5.9*	54.9	3.0*	1.9*	0.7*
	Max	9.0	14.9	8.0	54.7	0.5	27.0	0.5	6.9	78.6	3.0	3.1	0.8
TWU	Min	9.0	9.5	7.9	72.2	0.7	33.7	0.2	<10	30.9	<10	<5	<3
	Med	9.0	11.8	8.0	73.0	0.7	34.2	0.3	4.6*	32.8	3.2*	2.3*	0.4*
	Max	9.0	14.0	8.01	73.7	0.7	34.6	0.4	9.0	34.6	3.4	4.2	0.7
VOG	Min	7.7	17.2	6.4	12.1	1.6	2.7	1.2	<10	517.0	<10	15.8	<3
	Med	7.9	19.6	6.6	13.8	4.4	3.3	1.5	6.3*	598.0	3.3*	22.6	1.0*
	Max	8.3	22.9	6.7	15.2	8.1	9.8	3.0	9.1	701.0	7.6	31.2	2.0
WIS	Min	7.6	18.2	8.1	347.0	6.4	64.0	6.2	<10	1119.9	<10	101.7	7.1
	Med	9.4	22.0	9.0	381.0	99.5	78.7	28.2	18.0	2108.0	1.6*	234.0	22.6
	Max	21.0	23.3	10.3	405.0	210.4	82.4	314.0	156.2	9760.0	58.0	949.0	31.5

Table 4. Watershed parameters with pertinent GIS layer metadata.

Abbreviations	Parameter	GIS Layer Metadata
shore	Lake shoreline length, m	Water body polygons were extracted from soil data layers maintained by US Department of Agriculture's National Resource Conservation Service (NRCS). Soil layers are defined by county. Island County soil layer was accurate to map scale 1:31,680 with currentness reference 20120628. Skagit, Snohomish and Whatcom Counties were accurate to map scale 1:24,000 with currentness references 20120629 (http://websoilsurvey.sc.egov.usda.gov/App/WebSoilSurvey.aspx)
area	Lake surface area, m^2	
maxD	Maximum lake depth, m	
meanD	Mean lake depth, m	
volume	Lake volume, m^3	
fetch	Fetch, m	
fetchdir	Fetch direction, 1=North (N) to South (S), 2= NE to SW, 3= East (E) to West (W), and 4= NW to SE	
perimeter	Watershed perimeter, m	Digital Elevation Model raster sets (DEM) used were produced by the United States Geological Survey (USGS) and maintained in the National Elevation Dataset (NED). They had 30 meter resolution and currentness reference 20090201. (http://ned.usgs.gov).
W.area	Watershed area, m^2	
W.veg	Vegetative cover, % excluding lawn, pasture and cropland	Orthophotos used were generated in 2009, defined by county, 1 meter resolution and currentness reference 20091008. (http://gis.ess.washington.edu/data/raster/naip2009ccm_wa/index.html).
W.roads	Road length, m	US Census Bureau Street shapefiles used were created in 2010, maintained by the NRCS, defined by county and accurate to map scale 1:100,000 (http://datagateway.nrcs.usda.gov/).
W.gradient (>15%)	Steep gradient, %	DEMs used were produced by USGS, maintained in NED with 30 meter resolution and currentness reference 20090201 (http://ned.usgs.gov).
W.aspectN (315° to 45°)	North slopes, %	DEMs used were produced by USGS, maintained in NED with 30 meter resolution and currentness reference 20090201 (http://ned.usgs.gov).
W.aspectE (45° to 135°)	East slopes, %	DEMs used were produced by USGS, maintained in NED with 30 meter resolution and currentness reference 20090201 (http://ned.usgs.gov).
W.aspectS (135° to 225°)	South slopes, %	DEMs used were produced by USGS, maintained in NED with 30 meter resolution and currentness reference 20090201 (http://ned.usgs.gov).

Table 4. Continued.

Abbreviations	Parameter	GIS Layer Metadata
W.aspectW (225° to 315°)	West slopes, %	DEMs used were produced by USGS, maintained in NED with 30 meter resolution and currentness reference 20090201 (http://ned.usgs.gov).
population	Estimated human population	US Census Bureau Block shapefiles were created in 2000, maintained by the NRCS, defined by county, accurate to map scale 1:100,000 (http://www.census.gov/census2000/states/wa.html).
air.temp	Annual mean air temperature, C	Temperature data was collected between 1971-2000, maps were created by Oregon Climate Service, Oregon State University, published in 2006, maintained and distributed by NRCS, organized by state and accurate to map scale 1:250,000 (http://datagateway.nrcs.usda.gov/).
air.tempMax	Mean annual maximum air temperature, C	
air.tempMin	Mean annual minimum air temperature, C	
soil.xxx EWD=Excessively well draining SED=Somewhat excessively draining WD=Well draining MWD=Moderately well draining SPD=Somewhat poorly draining PD=Poorly draining VPD=Very poorly draining NRD=Not rated for drainage	Soil drainability , %	Soil data layers were maintained by the NRCS and defined by county. Island County soil layer was accurate to map scale 1:31,680 with currentness reference 20120628. Skagit, Snohomish and Whatcom County soil layers were accurate to map scale 1:24,000 with currentness reference 20120629 (http://websoilsurvey.sc.egov.usda.gov/App/WebSoilSurvey.aspx).
soil.xxx P=Ponding NP=No ponding	Soil water features (i.e. ponding, perched, high water table), %	Soil data layers were maintained by the NRCS and defined by county. Island County soil layer was accurate to map scale 1:31,680 with currentness reference 20120628. Skagit, Snohomish and Whatcom County soil layers were accurate to map scale 1:24,000 with currentness reference 20120629 (http://websoilsurvey.sc.egov.usda.gov/App/WebSoilSurvey.aspx).
soil.xxx VSE=Very severe erosion SE=Severe erosion ME=Moderate erosion LE=Low erosion NRE=Not rated for soil erosion	Soil erosion potential, %	Soil data layers were maintained by the NRCS and defined by county. Island County soil layer was accurate to map scale 1:31,680 with currentness reference 20120628. Skagit, Snohomish and Whatcom County soil layers were accurate to map scale 1:24,000 with currentness reference 20120629 (http://websoilsurvey.sc.egov.usda.gov/App/WebSoilSurvey.aspx).

Table 5. Kendall’s tau correlation coefficients between water quality, watershed and soil parameters.

Parameter	do (mg/L)	temp (C)	pH	cond (µgS)	chl (µg/L)	alk (µg/L)	turb (NTU)	nh3 (µgN/L)	tn (µgN/L)	no3 (µg N/L)	tp (µgP/L)	srp (µgP/L)
do (mg/L)	-											
temp (C)	ns	-										
pH	0.489***	0.274**	-									
cond (µgS)	ns	0.303**	**0.549*** **	-								
chl (µg/L)	ns	0.303**	0.291**	0.442***	-							
alk (µg/L)	ns	0.26**	**0.549*** **	**0.826*** **	0.425***	-						
turb (NTU)	ns	0.253**	0.212*	0.427***	**0.613*** **	0.414***	-					
nh3 (µgN/L)	ns	0.206*	0.221*	0.285**	0.267**	0.23*	0.264**	-				
tn (µgN/L)	ns	0.298**	0.244*	0.457***	**0.593*** **	0.388***	**0.509*** **	0.366***	-			
no3 (µgN/L)	ns	ns	ns	-0.249*	ns	-0.256**	ns	ns	ns	-		
tp (µg-P/L)	ns	0.225*	ns	0.36***	**0.533*** **	0.343***	**0.624*** **	0.23*	**0.57*** **	ns	-	
srp (µg-P/L)	ns	0.236*	0.209*	0.356***	0.36***	0.36***	0.429***	0.262**	0.351***	ns	**0.583*** **	-
shore (m)	ns	0.232*	0.274**	0.256**	0.226*	0.254**	ns	ns	ns	ns	ns	ns
area (m^2)	ns	0.26**	0.287**	0.272**	0.255**	0.275**	ns	ns	ns	ns	ns	ns
maxD (m)	ns	ns	ns	-0.385**	**-0.531*** **	-0.436***	**-0.521*** **	-0.251*	**-0.551*** **	ns	**-0.672*** **	**-0.52*** **
meanD (m)	ns	ns	ns	-0.319**	**-0.544*** **	-0.376***	**-0.521*** **	-0.252*	**-0.561*** **	ns	**-0.647*** **	-0.484***
volume (m^3)	ns	ns	0.240*	ns	ns	ns	ns	ns	-0.273*	ns	-0.276*	ns
fetch (m)	ns	0.224*	0.276**	0.267**	0.257**	0.275**	ns	ns	ns	ns	ns	ns

Significance values : *p-value<0.05, **p-value<0.01, ***p-value<0.001. **Kendall’s tau >0.500**, ns=not significant.

Table 5. Continued.

Parameter	do (mg/L)	temp (C)	pH	cond (µgS)	chl (µg/L)	alk (µg/L)	turb (NTU)	nh3 (µgN/L)	tn (µgN/L)	no3 (µg N/L)	tp (µgP/L)	srp (µgP/L)
perimeter (m)	ns	0.219*	0.304**	0.239*	ns	0.251*	0.207*	ns	ns	ns	ns	ns
W.area (m^2)	ns	ns	0.279**	0.225*	ns	0.252**	0.195*	ns	ns	ns	ns	ns
W.veg (%)	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
W.roads (m)	ns	0.339***	0.342***	0.297**	0.286**	0.293**	0.259**	0.192*	ns	ns	ns	0.201*
W.gradient (%)	ns	-0.25*	ns	-0.242*	-0.312**	ns	-0.263**	-0.215*	**-0.526*** **	ns	-0.293**	ns
population	ns	0.382***	0.36***	0.326***	0.322**	0.278**	0.264**	0.193*	0.298**	ns	ns	ns
air.temp (C)	ns	0.47***	0.264*	0.375***	0.256*	0.281**	0.226*	ns	0.393**	ns	ns	ns
air.temp Max (C)	ns	0.365***	ns	0.253*	0.286**	ns	0.315**	ns	0.372***	ns	0.315**	0.246*
air.temp Min (C)	ns	0.341***	0.253*	0.409***	0.28**	0.309**	0.224*	ns	0.461***	ns	ns	ns
soil.EWD (%)	ns	ns	ns	ns	ns	0.311*	ns	ns	ns	ns	ns	ns
soil.SED (%)	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	0.313**
soil.WD (%)	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
soil.MWD (%)	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	-0.289**
soil.SPD (%)	ns	0.233*	0.269*	0.4***	0.376**	0.39***	0.358**	ns	0.403***	ns	0.423***	0.285*
soil.PD (%)	ns	0.369***	0.245*	0.355**	ns	0.317**	ns	ns	ns	ns	0.239*	ns

Significance values : *p-value<0.05, **p-value<0.01, ***p-value<0.001. **Kendall's tau >0.500**, ns=not significant.

Table 5. Continued.

Parameter	do (mg/L)	temp (C)	pH	cond (µgS)	chl (µg/L)	alk (µg/L)	turb (NTU)	nh3 (µgN/L)	tn (µgN/L)	no3 (µg N/L)	tp (µgP/L)	srp (µgP/L)
soil.VPD (%)	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	0.247*	0.221*
soil.NRD (%)	ns	ns	ns	ns	ns	ns	0.265*	ns	ns	ns	ns	ns
soil.NP (%)	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	0.219*
soil.P (%)	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
soil.VSE (%)	ns	ns	ns	ns	ns	ns	ns	ns	-0.371***	ns	ns	ns
soil.SE (%)	ns	ns	ns	ns	ns	ns	ns	ns	-0.302**	ns	ns	ns
soil.ME (%)	ns	ns	ns	ns	ns	ns	ns	ns	-0.231*	ns	ns	ns
soil.LE (%)	ns	ns	ns	ns	ns	ns	ns	ns	0.404***	ns	ns	ns
soil.NRE (%)	ns	ns	ns	ns	ns	ns	0.316**	ns	ns	ns	ns	ns

Significance values : *p-value<0.05, **p-value<0.01, ***p-value<0.001. **Kendall's tau >0.500**, ns=not significant.

Table 6. Descriptive watershed statistics for each of the 50 lakes analyzed in this project.

Lake	shore (m)	area (m^2)	maxD (m)	meanD (m)	volume (m^3)	fetch (m)	fetchdir	perimeter (m)	W.area (m^2)	W.veg (%)
All Lakes (medians)	1927	157356	8.8	5.2	681711	714	3	7816	2714905	59.3
ARM	1687	107251	7.3	4.6	490353.4	660	4	4832	1217761	74.4
BGL	662	25890	NA	NA	NA	235	2	6549	2236946	37.7
BGU	687	15360	NA	NA	NA	303	2	7072	2932937	50.3
BEA	1944	223219	3.0	1.5	340185	719	2	20051	14762577	68.7
BIG	10101	2106257	7.0	4.3	8987818	4162	4	49553	52506222	79.7
BUG	945	29313	NA	NA	NA	426	3	34993	32423748	52.1
CAI	2815	284290	18.9	9.1	2599546	1018	4	14556	8648973	67.7
CAM	5976	1503978	4.9	2.4	3667299	2214	3	19761	16904777	65.7
CAN	2136	150739	20.1	7.6	1148628	945	4	12674	10557027	76.9
CAV	12585	3262827	24.4	13.4	43758427	4355	4	23987	18084678	64.8
CED	504	14814	NA	NA	NA	193	4	1590	150538.6	89.1
CLE	3989	791286	13.4	7.0	5547231	1362	2	9049	4152571	59.2
CRB	1872	146576	14.9	5.5	804174	599	2	7362	3092950	51.7
CRA	4133	501664	7.6	4.0	1987793	1317	4	16145	9395798	55.2
DEE	2956	323281	15.2	6.1	1970718	1007	2	9634	3333338	56.6
ERI	2789	430117	3.7	1.8	786598	1111	4	10468	4246558	68.1
FAZ	1382	130251	5.2	3.0	397005	522	2	6691	1446459	40.1
GOO	8454	2064434	15.24	7.0	14472508	2928	1	18343	12702680	48.7
GOS	2421	209698	18.3	9.8	2045307	693	2	4916	912005	59.5
GRA	2857	208820	4.0	2.1	445537	1146	2	17663	13537829	75.9
HEA	2645	248491	5.8	2.7	681660	910	1	5886	1514597	78.0
HON	788	21263	NA	NA	NA	297	2	8270	2496873	77.9
HOW	1320	98287	15.2	8.8	868778	510	4	4843	1153934	61.3
KET	1903	95682	6.4	3.7	349966	571	4	4996	1610719	35.6

NA=Data not available

Table 6. Continued.

Lake	shore (m)	area (m^2)	maxD (m)	meanD (m)	volume (m^3)	fetch (m)	fetchdir	perimeter (m)	W.area (m^2)	W.veg (%)
KI	3020	378250	21.3	10.1	3804585	1093	2	6684	1593335	42.5
LOM	1456	82668	8.5	3.4	277170	514	3	2462	372759	27.9
LON	2657	390312	5.2	2.7	1070703	814	3	14846	8049629	68.9
LOU	1907	137392	27.7	10.4	1423819	646	2	4518	873948.7	53.9
MAR	2865	249892	21.3	10.1	2513516	971	4	12324	4917614	46.8
MCM	4282	608485	15.8	8.8	5378517	1322	4	15036	9108098	69.9
MIR	948	51870	NA	NA	NA	379	4	3954	507652	60.7
PAD	3446	594312	18.0	8.2	4890949	1365	4	11079	7021655	60.2
PAS	3081	382185	6.1	4.6	1747348	1137	2	5716	1700729	60.4
PIC	411	12260	NA	NA	NA	154	2	1618	114783.8	61.3
REE	3094	116855	5.5	3.4	391790	632	1	13719	5236282	63.2
SHO	3770	527813	10.7	5.5	2895794	1386	4	20112	15381396	48.4
SIL	5456	612294	9.1	5.2	3172663	1782	1	10107	5695443	53.9
SIX	1721	163973	8.2	5.5	899619	7099	4	10128	3756731	81.9
SQA	1381	138170	4.6	2.1	294799	511	4	1950	262253	13.7
SQI	975	27479	14.4	5.3	145148	448	4	3783	635602	80.3
SUM	926	28091	NA	NA	NA	386	1	2272	281240	43.8
SDY	1578	130345	6.1	2.4	317832	669	4	8383	2347883	45.9
SUN	1404	49934	NA	NA	NA	637	3	3981	800916.3	21.5
TEN	1910	182480	1.8	0.9	166859	801	1	4379	1061902	23.2
TER	5703	1531103	3.0	2.1	3266762	1848	4	21563	13230349	32.9
TOA	1857	128795	9.4	6.1	785136	852	2	6085	1848457	83.2
TWL	1109	73316	29.3	12.8	938560	444	2	3589	815235	19.5
TWU	1037	66404	27.7	13.4	890561	369	2	2727	358681	18.2
VOG	1189	48584	NA	NA	NA	432	2	2989	516001	65.2
WIS	3662	455775	3.4	1.8	833521	962	4	15683	8361436	9.0

NA=Data not available.

Table 6. Continued.

Lake	W.roads (m)	W.gradient (%)	W.aspectN (%)	W.aspectE (%)	W.aspectS (%)	W.aspectW (%)	population	air.temp (C)	air.tempMax (C)	air.tempMin (C)
All Lakes (medians)	9694	27.3	30.0	15.9	27.7	21.4	108	9.4	22.2	-0.6
ARM	3749	4.2	12.3	9.3	27.7	50.7	20	10. 6	22. 8	0. 6
BGL	1099	88.0	37.4	24.1	35.7	2.9	0	3.3	17. 8	-6.4
BGU	1884	86.6	34.5	26.7	33.9	4.9	0	3. 9	18.3	-6.4
BEA	38778	38.4	29.4	17.4	26.8	26.3	702	9. 5	22. 8	-0. 6
BIG	120977	45.0	32.2	20.7	28.2	18.9	1465	9. 5	21. 7	0.4
BUG	120315	17.3	46.8	12.1	22.6	18.5	5250	10. 2	22.5	-1.1
CAI	35512	48.7	9.2	37.2	27.7	25.9	1178	8. 9	22.5	-1.4
CAM	37980	45.3	25.2	21.3	34.1	19.4	718	10	22. 8	1.1
CAN	7597	93.7	34.9	4.2	30.6	30.3	14	6. 3	19.4	-4. 8
CAV	19277	57.1	62.9	6.4	25.3	9.5	133	8.7	21. 7	-1.4
CED	0	64.0	44.7	28.9	9.6	16.7	1	8. 9	21. 7	-0. 6
CLE	10091	37.6	12.9	17.4	50.8	18.8	377	10	23.3	-0. 6
CRB	14447	2.1	21.8	5.4	23.0	49.8	691	10	21. 7	0. 6
CRA	38463	1.5	27.3	5.7	27.0	40.0	786	10	20. 6	1.1
DEE	16518	0.1	29.9	31.0	15.6	23.5	81	10. 6	22. 8	0. 6
ERI	12789	46.9	29.9	18.7	29.7	21.8	260	10. 2	22.2	1. 3
FAZ	5587	0.2	42.4	10.5	29.3	17.9	73	10	23. 9	-0. 6
GOO	62459	1.5	30.1	13.7	25.4	30.8	2728	10	22.2	0. 6
GOS	6495	6.8	35.2	1.7	46.0	17.0	76	10. 6	22. 8	1.1
GRA	43306	55.1	21.6	25.2	41.3	11.9	30	8.1	22.0	-2.9
HEA	2293	43.1	30.0	21.7	14.0	34.3	78	10	23.3	0. 6
HON	9849	5.1	17.8	49.9	26.9	5.5	112	10. 6	22.2	1.1
HOW	3639	11.7	60.7	10.9	7.4	21.0	232	10. 6	22.2	0. 6

Table 6. Continued.

Lake	W.roads (m)	W.gradient (%)	W.aspectN (%)	W.aspectE (%)	W.aspectS (%)	W.aspectW (%)	population	air.temp (C)	air.tempMax (C)	air.tempMin (C)
KET	9636	0	18.6	17.0	13.1	51.3	401	10	22. 8	0. 6
KI	8316	7.4	54.9	11.5	14.4	19.1	5	10	21. 7	0. 6
LOM	3218	0	48.6	7.5	18.3	25.6	103	10	21. 7	0. 6
LON	46544	6.2	15.5	23.0	36.4	25.1	530	10. 6	22. 8	0.8
LOU	7262	62.2	52.0	19.2	15.2	13.6	143	9.4	23.3	-1.1
MAR	18865	5.8	36.7	10.6	23.8	28.9	817	10. 6	22.2	0. 6
MCM	29763	57.9	34.0	22.3	35.2	8.5	271	8. 9	21.2	0.3
MIR	963	64.5	22.2	19.6	37.2	20.9	0	9.4	23. 9	-1.1
PAD	25766	21.9	17.1	12.7	37.6	32.5	1145	10	22. 8	-1.1
PAS	5303	39.2	29.7	16.2	40.3	13.8	33	9.4	21.1	0.9
PIC	767	32.8	33.9	28.2	35.6	2.3	0	5	19.4	-4.4
REE	23835	56.1	10.7	33.5	32.2	23.6	703	8. 9	22.5	-1.4
SHO	77497	1.5	31.5	15.9	24.6	27.9	3258	10	22.2	0. 6
SIL	12210	72.7	9.2	11.4	27.2	52.2	16	7. 8	22.2	-2. 8
SIX	4184	60.7	16.9	6.6	59.2	17.3	34	9.4	20.9	0. 2
SQA	70	0	15.8	9.4	20.9	53.9	2	9.4	22. 8	-0. 6
SQI	978	68.1	29.0	15.9	33.2	21.9	14	9.4	22. 8	-1. 1
SUM	697	16.8	25.8	22.5	12.8	39.0	0	9.4	22. 3	-0. 6
SDY	9752	0.6	25.2	25.4	28.8	20.6	189	10	22. 8	0. 6
SUN	10543	7.5	59.2	4.2	11.1	25.4	12	10. 6	23.3	-0. 6
TEN	3929	0	11.2	21.6	35.7	31.5	19	9.4	22. 8	-0. 6
TER	18566	0	36.7	13.2	26.4	23.7	314	9.4	22.0	-0. 6
TOA	7933	51.9	62.5	2.6	20.4	14.4	169	9.4	22.2	-1.1
TWL	410	82.0	36.2	15.3	40.7	7.8	0	3.3	17. 8	-6. 7
TWU	32	79.2	49.4	10.1	29.1	11.4	0	3.3	17. 8	-6. 7
VOG	1658	2.9	31.1	13.9	22.2	32.8	3	8.3	23. 9	-2. 8
WIS	33550	0	45.3	10.9	30.1	13.7	1253	9.4	23. 9	-0. 6

Table 7. Descriptive soil statistics based on percent of each soil type contained within each of the watersheds. All lake median values are included.

Lake	soil. EWD (%)	soil. SED (%)	soil. WD (%)	soil. MWD (%)	soil. SPD (%)	soil. PD (%)	soil. VPD (%)	soil. NRD (%)	soil. NP (%)	soil. P (%)	soil. VSE (%)	soil. SE (%)	soil. ME (%)	soil. LE (%)	soil. NRE (%)
All Lakes (medians)	0	0.2	32.3	34.5	0	0.2	0.4	0	49.4	45.8	0	8.5	9.5	66.0	0
ARM	0	70.9	12.3	5.6	0	0	2.5	0	83.2	8.1	0	10.6	0.2	80.5	0
BGL	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
BGU	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
BEA	0	3.0	56.6	21.5	1.0	6.3	1.4	0	59.1	30.6	5.1	19.2	19.5	45.9	0
BIG	0	2.7	53.3	31.6	0.7	4.5	1.7	0	55.6	39.0	18.2	25.6	21.4	29.4	0
BUG	0	1.0	15.8	70.0	0.2	10.6	1.1	0.2	16.8	81.9	0	9.3	9.5	79.8	0
CAI	0	0.2	42.8	52.4	0	0	0	0	43.0	52.4	10.0	23.8	16.1	45.3	0
CAM	0.2	0	51.0	26.1	7.7	2.1	0	0	51.2	35.9	11.8	39.2	5.6	30.6	0
CAN	0	0	34.8	35.7	0	0	0	28.0	63.0	35.7	81.2	10.7	5.6	1.0	0.2
CAV	0	5.0	57.0	17.3	0	0	2.0	0	62.0	19.3	29.4	19.0	29.5	3.3	0
CED	0	0	90.2	0	0	0	0	0	90.2	0	14.6	45.3	30.3	0	0
CLE	0	0	34.4	37.5	0	8.6	0.4	0	32.8	48.1	5.2	19.4	14.4	41.9	0
CRB	0	0.2	0	91.4	0	0	0.9	0	0.2	92.4	0	0.4	8.6	83.6	0
CRA	0	27.5	6.8	18.3	32.5	3.3	6.2	0	29.8	64.8	0	0	26.4	68.3	0
DEE	0	0	7.0	76.7	5.6	0.2	0	0	0.2	89.3	0	0	0	89.5	0
ERI	0.4	0	49.0	39.0	0.3	0.8	0	0	49.4	40.2	4.7	44.3	7.3	33.3	0
FAZ	0	6.0	32.3	25.5	2.5	17.1	7.7	0	38.3	52.8	0	0	2.7	88.5	0
GOO	0	0.5	0	80.4	0	0.2	0.8	0	0.5	81.4	0	0.1	4.2	77.7	0
GOS	0	9.1	0	17.4	0	50.8	0	0	59.9	17.4	0	0	0	77.3	0
GRA	10.2	31.9	35.8	16.0	0	0	2.2	0	72.6	23.5	20.5	21.9	34.0	19.6	0
HEA	0	0	52.7	31.0	0	0	0	0	52.7	31.0	1.9	50.7	27.7	3.3	0
HON	0	12.7	16.7	50.1	19.4	0	0.2	0	12.7	86.5	0	0	16.7	82.5	0
HOW	0	0	0	91.6	0	0	0.1	0	0	91.7	0	9.1	14.8	67.9	0

NA=Data not available.

Table 7. Continued.

Lake	soil. EWD (%)	soil. SED (%)	soil. WD (%)	soil. MWD (%)	soil. SPD (%)	soil. PD (%)	soil. VPD (%)	soil. NRD (%)	soil. NP (%)	soil. P (%)	soil. VSE (%)	soil. SE (%)	soil. ME (%)	soil. LE (%)	soil. NRE (%)
KET	0	77.5	0	9.8	0	1.0	5.6	0	77.5	16.4	0	0	10.7	83.2	0
KI	0	0	0	76.4	0	0	0	0	0	76.4	0	9.1	0	67.3	0
LOM	0	0	0	78.1	0	0	0	0	0	78.1	0	0	0	78.1	0
LON	0	26.8	8.2	31.6	4.7	23.8	0	0	49.4	45.8	0	0	0	95.2	0
LOU	0	0	44.9	39.4	0	0	0	0	44.9	39.4	11.6	34.6	17.4	20.7	0
MAR	0	0	0	91.1	0	0.9	0.9	0	0	92.9	0	3.3	7.6	82.1	0
MCM	0	0.4	74.8	14.2	0	2.7	1.3	0	74.8	18.5	51.7	4.0	20.6	17.1	0
MIR	0	3.6	67.6	16.8	0	0	2.1	0	71.1	18.9	0.0	61.7	12.7	15.7	0
PAD	0	4.5	56.2	29.4	0	1.1	0	0	60.7	30.5	2.2	8.5	32.0	48.5	0
PAS	0	0	31.3	46.3	0	0	0	0	31.3	46.3	0.8	30.5	21.5	24.8	0
PIC	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
REE	0	0	50.7	47.0	0	0	0	0	50.7	47.0	16.6	23.6	20.2	37.2	0
SHO	0	0.5	0	79.7	0	0.5	0.9	0	0.5	81.2	0	0.1	3.5	78.1	0
SIL	0	11.5	75.2	2.3	0	0.3	0	0	86.7	2.6	53.3	3.2	18.8	13.9	0
SIX	0	0	93.2	0	0	2.4	0	0	93.2	2.4	25.1	52.1	16.0	2.4	0
SQA	0	0	0	34.5	0	0	13.8	0	0	48.3	0	2.9	0	45.4	0
SQI	0	0	87.9	0	0	0	7.9	0	87.9	7.9	35.8	38.1	5.1	16.7	0
SUM	0	0	0	76.1	0	0	14.0	0	0	90.2	0	0	0	90.2	0
SDY	0	7.4	0.8	77.9	0	4.7	3.3	0	8.2	85.9	0	0	8.0	86.1	0
SUN	0	0	0	85.0	0	8.8	0	0	0	93.8	0	6.5	0	87.3	0
TEN	0	0	0	54.1	0	26.5	2.4	0	0	83.0	0	0	0	83.0	0
TER	0	0	5.3	52.7	1.9	19.2	9.1	0.2	5.4	83.0	0.3	0.3	0	87.7	0.1
TOA	0	0	90.1	2.9	0	0	0	0	90.1	2.9	0	10.7	24.5	57.8	0
TWL	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA

NA=Data not available.

Table 7. Continued.

Lake	soil. EWD (%)	soil. SED (%)	soil. WD (%)	soil. MWD (%)	soil. SPD (%)	soil. PD (%)	soil. VPD (%)	soil. NRD (%)	soil. NP (%)	soil. P (%)	soil. VSE (%)	soil. SE (%)	soil. ME (%)	soil. LE (%)	soil. NRE (%)
TWU	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
VOG	0	21.6	50.3	18.7	0	0	0	0	71.9	18.7	0	0	24.6	66.0	0
WIS	0	1.1	59.9	2.5	3.7	0	27.3	0	61.0	33.6	0	0	0	94.6	0

NA=Data not available.

Table 8. Primary and nested watersheds.

County	Primary watershed (km^2)	Nested watershed (km^2)	Reference
Skagit	Beaver Lake (14.76)	Clear Lake (4.15)	Figure 11
Skagit	Campbell Lake (16.90)	Erie Lake (4.24)	Figure 12
Skagit	Grandy Lake (13.53)	Vogler (0.51)	Figure 13
Snohomish	Martha Lake (4.91)	Howard Lake (1.15)	Figure 14
Snohomish	Crabapple Lake (3.09)	Loma Lake (0.37)	Figure 15
Snohomish	Goodwin Lake (12.70)	Crabapple Lake (3.09)	Figure 15
Snohomish	Shoecraft Lake (15.38)	Goodwin Lake (12.70)	Figure 15
Whatcom	Lower Bagley Lake (2.23)	Upper Bagley Lake (2.93)	Figure 16
Whatcom	Cain Lake (8.64)	Reed Lake (5.23)	Figure 17
Whatcom	Bug Lake (32.42)	Sunset Lake (0.80), Toad Lake (1.84), Squalicum Lake (0.26)	Figure 18
Whatcom	Lower Twin Lake (0.81)	Upper Twin Lake (0.35)	Figure 19

Table 9. Nutrient gradients for lakes in nested and primary watersheds.

Lakes	do (mg/L)	temp (C)	pH	cond (µgS)	chl (µg/L)	alk (µg/L)	turb (NTU)	nh3 (µg-N/L)	tn (µg-N/L)	no3 (µg-N/L)	tp (µg-P/L)	srp (µg-P/L)
CLE→	6.7 ↑	21.5	7.2	86.2 ↓	3.7 ↓	32.3 ↓	1.2 ↓	<10	343.0 ↓	<10	16.7 ↓	<3 ↓
BEA	5.6	21.6	7.2	102.4	6.8	46.2	4.2	<10	627.5	<10	48.5	6.8
ERI→	8.8	20.9	8.3	256.0 ↓	9.2 ↓	70.1 ↓	1.8 ↓	12.3	855.0 ↓	<10	20.1 ↓	3.2 ↓
CAM	8.5	20.7	8.3	268.0	22.6	83.3	8.6	12.1	1198.0	<10	45.1	5.3
VOG→	7.9	19.6	6.6 ↓	13.8 ↓	4.4	3.3 ↓	1.5 ↓	<10 ↓	598.0 ↑	<10	22.6 ↑	<3 ↓
GRA	8.7	19.4	7.8	136.5	5.0	66.9	2.9	19.3	387.5	<10	20.0	6.1
HOW→	8.5	20.0	7.9	117.2 ↑	3.3	43.8 ↑	0.9	18.0 ↑	447.0 ↑	<10	<5	<3
MAR	8.7	20.3	7.9	102.5	3.9	30.4	0.8	<10	426.0	<10	<5	<3
LOM→	7.9	20.6	7.0	47.4 ↓	9.8 ↑	9.0 ↓	3.8 ↑	15.0 ↑	776.0 ↑	<10 ↓	20.6 ↑	4.4 ↑
CRB→	8.4	20.5	7.4	51.7 ↓	5.2 ↑	10.5 ↓	1.0	<10	653.0 ↑	185.0 ↑	6.2 ↑	<3
GOO→	8.8	20.7 ↓	7.9	91.8 ↓	2.5 ↓	31.3 ↓	0.6	<10	435.0	<10	<5 ↓	3.0
SHO	8.4	18.7	7.9	99.8	3.5	36.3 ↓	1.3	<10	435.0	<10	<5	<3
BGU→	11.7	7.3	7.0	12.6	0.6	5.1	0.3	<10	46.9 ↓	18.6 ↑	12.9 ↑	4.7 ↑
BGL	10.7	8.2	7.1	12.6	0.6	5.4	0.4	<10	53.5	<10	10.9	3.2
REE→	8.3	19.7	7.2 ↓	53.1 ↓	3.7 ↓	16.3 ↓	1.4	17.2 ↑	493.0 ↓	<10 ↓	17.4 ↑	4.9
CAI	9.2	20.4	8.2	58.9	4.8	17.9	0.7	<10	739.0	478.0	7.9	4.5
SQA→	7.2 ↓	20.6 ↓	7.1 ↓	68.9 ↓	6.4 ↑	27.5 ↓	1.6 ↓	10.6	929.6 ↑	<10	30.0 ↓	5.2 ↓
BUG	10.8	22.2	9.1	149.9	5.0	60.1	3.9	11.4	658.6	<10	37.9	7.9
SUN→	10.1	22.9	8.8	152.7 ↑	9.9 ↑	65.8 ↑	4.7	<10 ↓	607.5 ↓	<10	25.4 ↓	3.2 ↓
BUG	10.8	22.2	9.1	149.9	5.0	60.1	3.9	11.4	658.6	<10	37.9	7.9
TOA→	9.7 ↓	20.3 ↓	8.2	110.8 ↓	5.5	45.0 ↓	1.5 ↓	21.0 ↑	505.0 ↓	55.9 ↑	18.3 ↓	5.2 ↓
BUG	10.8	22.2	9.1	149.9	5.0	60.1	3.9	11.4	658.6	<10	37.9	7.9
TWU→	9.0	11.8	8.0	73.0 ↑	0.7	34.2 ↑	0.3	<10	32.8 ↓	<10	<5	<3
TWL	8.8	12.6	7.9	54.5	0.5	25.7	0.3	<10	54.9	<10	<5	<3

→ gradient from nested lake to primary lake,
↑ upper lake(s) value was higher than primary lake (>1.0),
↓ upper lake(s) value was lower than primary lake (<1.0).

Table 10. Water quality and watershed development in unprotected watersheds located in the Puget Lowlands ecoregion.

Lake	tp (µg-P/L)	TSI (TP)	chl (µg/L)	TSI (CHL)	Usable Watershed Area (km^2)	Road Density (m^2/km^2)	Population Density ($/km^2$)	Development of Volume (D_v =meanD/maxD)	meanD
Medians	18.75		4.8		3.19	4137	77	-	-
WIS	234	82.8	99.5	75.7	7.91	4242	158	0.5	1.8
LON	228	82.4	40	66.8	7.66	6076	69	0.5	2.7
KET	112.5	72.3	3.5	42.9	1.52	6339	264	0.6	3.7
FAZ	61.4	63.5	14	56.5	1.32	4233	55	0.6	3.0
BEA	48.5	60.1	6.8	49.4	14.54	2667	48	0.5	1.5
CAM	45.1	59.1	22.6	61.2	15.40	2466	47	0.5	2.4
HON	41.1	57.7	2.8	40.7	2.48	3971	45	na	na
BUG	37.9	56.6	5	46.4	32.39	3715	162	na	na
SQA	30	53.2	6.4	48.8	0.12	582	17	0.5	2.1
SUN	25.4	50.8	9.9	53.1	0.75	14057	16	na	na
ARM	24.2	50.1	4.2	44.7	1.11	3377	18	0.6	4.6
BIG	22.1	48.8	13.1	55.8	50.40	2400	30	0.6	4.3
SDY	22	48.7	5.2	46.8	2.22	4393	85	0.4	2.4
LOM	20.6	47.8	9.8	53.0	0.29	11097	355	0.4	3.4
ERI	20.1	47.4	9.2	52.4	3.82	3348	68	0.5	1.8
SUM	19.2	46.8	4.9	46.2	0.25	2786	0	na	na
TOA	18.3	46.1	5.5	47.3	1.72	4612	98	0.6	6.1
REE	17.4	45.3	3.7	43.4	5.12	4655	137	0.6	3.4
CLE	16.7	44.7	3.7	43.4	3.36	3003	112	0.5	7.0
SIX	14.9	43.1	2.7	40.3	3.59	1166	9	0.7	5.5
MCM	11.4	39.2	4.3	44.9	8.50	3502	32	0.6	8.8
GOS	9.9	37.2	1.9	36.9	0.70	9281	109	0.5	9.8
CAI	7.9	34.0	4.8	46.0	8.36	4248	141	0.5	9.1
CRB	6.2	30.5	5.2	46.8	2.95	4897	234	0.4	5.5
PAD	6.1	30.2	4.8	46.0	6.43	4007	178	0.5	8.2
DEE	5.2	27.9	2.4	39.2	3.01	5506	27	0.4	6.1
CED	<5	<27.4	1.4	33.9	0.14	0	7	na	na
HOW	<5	<27.4	3.3	42.3	1.06	3433	219	0.6	8.8

TSI(TP)=14.42ln(tp)+4.15 (Wetzel 2001), TSI(CHL)=9.81ln(chl)+30.6 (Wetzel 2001), na=data not available

TSI<30=oligotrophy, TSI 30-50=mesotrophy, TSI 50-70=eutrophy, TSI>70=hypereutrophy

Table 10. Continued.

Lake	tp (µg-P/L)	TSI (TP)	chl (µg/L)	TSI (CHL)	Usable Watershed Area (km^2)	Road Density (m^2/km^2)	Population Density (/km^2)	Development of Volume (D_v =meanD/maxD)	meanD
Medians	18.75		4.8		3.19	4137	77	-	-
MAR	<5	<27.4	3.9	44.0	4.67	4040	175	0.5	10.1
SHO	<5	<27.4	3.5	42.9	14.85	5219	219	0.5	5.5
GOO	<5	<27.4	2.5	39.6	10.64	5870	256	0.5	7.0
KI	<5	<27.4	2.2	38.3	1.22	6817	4	0.5	10.1

TSI(TP)=14.42ln(tp)+4.15 (Wetzel 2001), TSI(CHL)=9.81ln(chl)+30.6 (Wetzel 2001), na=data not available

TSI<30=oligotrophy, TSI 30-50=mesotrophy, TSI 50-70=eutrophy, TSI>70=hypereutrophy

Table 11. Lake groups according to hierarchical clustering based on first four principal component scores.

Lake Groups		
Group 1	Group 2	Group 3
LON	KI	CAN
WIS	DEE	CAI
HEA	MAR	CLE
ERI	GOS	PAD
PAS	ARM	BEA
FAZ	HOW	REE
KET	TEN	MCM
BIG	SQA	GRA
CAV	CRB	SIL
GOO	LOM	SQI
SHO	SDY	LOU
CAM		SIX
CRA		TOA
TER		

Table 12. Component scores for parameters with the greatest influence on ordination in the first four principal components.

Parameter	PC1	Parameter	PC2	Parameter	PC3	Parameter	PC4
tn	0.335	population	-0.202	soil.WD	0.399	soil.VSE	0.237
tp	0.287	turb	-0.212	W.gradient	0.393	W.aspectW	0.222
cond	0.244	chl	-0.226	soil.VSE	0.326	W.veg	-0.263
turb	0.239	ph	-0.229	W.veg	0.243	ph	-0.311
chl	0.236	area	-0.291	population	-0.236	do	-0.344
srp	0.224	fetch	-0.301	air.temp	-0.302	air.temp	-0.378
alk	0.205	shore	-0.307	soil.P	-0.406	temp	-0.486
shore	-0.203	W.roads	-0.309				
maxD	-0.212	W.area	-0.313				
volume	-0.216	perimeter	-0.332				
soil.VSE	-0.219						
fetch	-0.221						
W.gradient	-0.229						

Table 13. Parameters influencing ordination of PC1 and differences between group medians using Wilcoxon rank sum pairwise comparisons.

Parameter	Group1	Group2	Group3
tp (µg-P/L)	30.5	9.9	14.1
tn (µg-N/L)	844.5	520.0	343.0
cond (µgS)	209.4	83.6	88.5
turb (NTU)	4.0	0.9	1.1
chl (µg/L)*	11.1	4.2	4.3
srp (µg-P/L)	5.3	2.6	4.9
alk (µg/L)	58.0	24.5	31.9
shore (m)*	3716	1872	2815
maxD (m)	5.9	14.9	13.4
volume (m^3)	1867570	804174	1148628
soil.VSE (%)**	0.1	0.0	16.6
fetch (m)*	1227.0	668.7	945.1
W.gradient (%)	3.9	2.1	56.2

Medians in shaded cells were significantly different from medians in non-shaded cells for the same parameter.

*Group 1 median was not different from Group 2 median, Group 2 median was not different from Group 3 median, but Group 1 median was significantly different from Group 3 median.

**Each group median was significantly different from the other group medians for this parameter.

Literature Cited

Ball BA, Kominoski JS, Adams HE, Jones SE, Kane ES, Loecke TD, Mahaney WM, Martina JP, Prather CM, Robinson TMP, Solomon CT (2010) Direct and terrestrial vegetation-mediate effects of environmental change on aquatic ecosystem processes. *BioScience* 60(8):590-601.

Ben-Hur A, Guyon I (2003) Detecting stable clusters using principal component analysis. In Functional Genomics:Methods and Protocols. Brownstein MJ, Kohodursky A (eds) Humana press pp 159-182.

Bolstad P (2005) GIS Fundamentals: A first text of geographic information systems, 2nd ed. White Bear Lake (MN): Eider Press.

Bortleson GC, Dion NP, McConnell JB, Nelson LM (1973). Reconnaissance data on lakes in Washington. *Water Supply Bulletin* 43(1,2).

Bullard WE (1966) Effects of land use on water resources. *Water Pollution Control Federation* 38(4): 645-659.

Chaichana R, Leah R, Moss B (2011) Conservation of pond systems: A case study of intractability, Brown Moss, UK. *Hydrobiologia* 664:17-33.

Chu C, Minns C, Mandrak N (2003) Comparative regional assessment of factors impacting freshwater fish biodiversity in Canada. *Canadian Journal of Fisheries and Aquatic Sciences* 60:624-634.

Coats R, Larsen M, Heyvaert A, Thomas J, Luck M, Reuter J (2008) Nutrient and sediment production, watershed characteristics, and land use in the Tahoe Basin, California-Nevada. *Journal of the American Water Resources Association* 44(3): 754-770.

Crawley MJ (2007) The R book. West Sussex (GB): John Wiley and Sons, Ltd.

Cuo L, Lettenmaier DP, Alberti M, Richey JE (2009) Effects of a century of land cover and climate change on the hydrology of the Puget Sound basin. *Hydrological Processes* 23(6): 907-933.

Davis SE, Reeder BC (2001) Spatial characterization of water quality in seven eastern Kentucky reservoirs using multivariate analyses. *Aquatic Ecosystem Health and Management* 4:463-477.

Dickman M (1969) Some effects of lake renewal on phytoplankton productivity and species composition. *Limnology and Oceanography* 14:660-666.

Duggan IC (2012) Urban planning provides potential for lake restoration through catchment revegetation. *Urban Forestry and Urban Greening* 11:95-99.

Epstein D, Neilson B, Goodman K, Stevens D, Wurtsbaugh W (2013) A modeling approach for assessing the effect of multiple alpine lakes in sequence on nutrient transport. *Aquatic Sciences* 75(2):199-212.

Garn HS, Robertson DM, Rose WJ, Saad DA (2010) Hydrology, water quality, and response to changes in phosphorus loading of Minocqua and Kawaguesaga Lakes, Oneida County, Wisconsin, with special emphasis on effects of urbanization. *U.S. Geological Survey Scientific Investigations Report* 2010-5196:

Groffman PM, Law NL, Belt KT, Band LE, Fisher GT (2004) Nitrogen Fluxes and Retention in Urban Watershed Ecosystems. *Ecosystems* 7(4): 393-403.

Helsel DR (2006) Fabricating data: How substituting values for nondetects can ruin results, and what can be done about it. *Chemosphere* 65, 2434-2439.

James, RT, Havens K, Zhu G, and Qin B (2009) Comparative analysis of nutrients, chlorophyll and transparency in two large shallow lakes. *Hydrobilolgia* 627:211-231.

Jenson SK, Domingue JO (1988) Extracting Topographic Structure and Digital Elevation Data for Geographic Information System Analysis. *Photogrammetric Engineering and Remote Sensing* 54(11):1593-1600.

Jones RP, Clarke JU (2005) Analytical chemistry detection limits and the evaluation of dredged sediment. U.S. Army Engineer Research and Development Center, Vicksburg, MS. ERDC/TN EEDP-04-36

Llewellyn, C (2010) Predicting cyanobacteria blooms in 50 Lakes in Northwest Washington. *Master's Thesis:Western Washington University*. p.22, Appendix 2.

Mankin KR, Wang SH, Koelliker JK, Huggins DG, deNoyelles F (2003) Watershed-lake water quality modeling: verification and application. *Journal of Soil and Water Conservation* 58(4):188-197.

Niemistö J, Holmroos H, Pekcan-Hekim Z, Horppila J (2008) Interactions between sediment resuspension and sediment quality decrease the TN:TP ratio in a shallow lake. *Limnology and Oceanography* 53(6):2407-2415.

Omernik, J (1987) Ecoregions of the conterminous United States. Map (scale 1:7,500,000). *Annals of the Association of American Geographers* 77(1):118-125.

Praskievicz S, Chang H (2009) A review of hydrological modeling of basin-scale climate change and urban development impacts. *Progress in Physical Geography* 33(5): 650-671.

R Development Core Team (2009) R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. ISBN 3-900051-07-0. http://www.R-project.org.

Soballe DM, Threlkeld ST (1985) Advection, phytoplankton biomass, and nutrient transformations in a rapidly flushed impoundment. Arch. Hydrobiol. 105(2):187-203.

Soil Survey Division Staff (1993) Soil survey manual. Soil Conservation Service. U.S. Department of Agriculture Handbook 18. Available online at: http://www.nrcs.usda.gov/wps/portal/nrcs/detail/soils/survey/?cid=nrcs142p2_054242 accessed October 2011.

Soranno PA, Hubler SL, Carpenter SR, Lathrop RC (1996) Phosphorus loads to surface waters: a simple model to account for spatial pattern of land use. *Ecological Applications* 6(3):865-878.

Sorenson D (2012) Summary of land-cover trends-Puget Lowland ecoregion, United State Geological Survey Land Cover Trends Project.Available online at: http://landcovertrends.usgs.gov/west/eco2Report.html accessed April 2014.

Strayer DL, Beighley E, Thompson LC, Brooks S, Nilsson C, Pinay G, Naiman RJ (2003) Effects of land cover on stream ecosystems: roles of empirical models and scaling issues. *Ecosystems* 6:407-423.

Sullivan TJ, Charles DF, Bernert JA, McMartin B, Vache KB, Zehr J (1999) Relationship between landscape characteristics, history, and lakewater acidification in the Adirondack Mountains, New York. *Water, Air, and Soil Pollution* 112:407-427.

Thomas DB, Schallenberg M (2008) Benthic shear stress gradient defines three mutually exclusive modes of non-biological internal nutrient loading in shallow lakes. *Hydrobiologia* 610:1–11

Turner R, Laws EA, Harriss RC (1983) Nutrient retention and transformation in relation to hydraulic flushing rate in a small impoundment. Freshwater Biology 13, 113-127.

United States Census Bureau (2000) TIGER/Line Shapefiles, Block and Street files.Available online at: http://www.census.gov/geo/maps-data/data/tiger.html, accessed October 2010.

United States Geological Survey (2009) National Elevation Dataset (NED). Available online at: http://ned.usgs.gov, accessed October 2010.

United States Department of Agriculture (2006). 1971-2000 annual average, average minimum, and average maximum temperature maps by State. Available online at Natural Resources Conservation Service Data Gateway http://datagateway.nrcs.usda.gov/GDGOrder.aspx, accessed October 2010.

United States Department of Agriculture (2009) High resolution orthophotos. Available online at Natural Resources Conservation Service Data Gateway http://datagateway.nrcs.usda.gov/GDGOrder.aspx, accessed October 2010

van den Berg RA, Hoefsloot HCJ, Westerhuis JA, Smilde AK, van der Werf MJ (2006) Centering, scaling, and transformations: improving the biological information content of metabolomics data. *BCM Genomics* 7:142.

Washington State Legislature (2006) Washington Administrative Code 173201A. Available online at: http://apps.leg.wa.gov/WAC/default.aspx?cite=173201A-230. accessed February 2014.

Wetzel R G (2001) Limnology, lake and river ecosystems, 3rd ed. San Diego (CA): Elsevier Academic Press.

Wilson T (2012) North Cascades ecoregion summary, United State Geological Survey Land Cover Trends Project. Available online at: http://landcovertrends.usgs.gov/west/eco77Report.html. accessed April 2014.

Wolfram G, Argillier C, de Bortoli J, Buzzi F, Dalmiglio A, Dokulil M, Hoehn E, Marchetto A, Martinez P, Morabito G, Reichmann M, Rekar S, Riedmuller U, Rioury C, Chaumburg J, Schultz L, Urbanic G (2009) Reference conditions and WFD compliant class boundaries for phytoplankton biomass and chlorophyll-α in alpine lakes. *Hydorbiologia* 633:45-58.

Zar JH (1984) Biostatistical analysis, 2nd ed. Englewood Cliffs (NJ): Prentice-Hall, Inc.

Appendix 1.

Watershed Maps

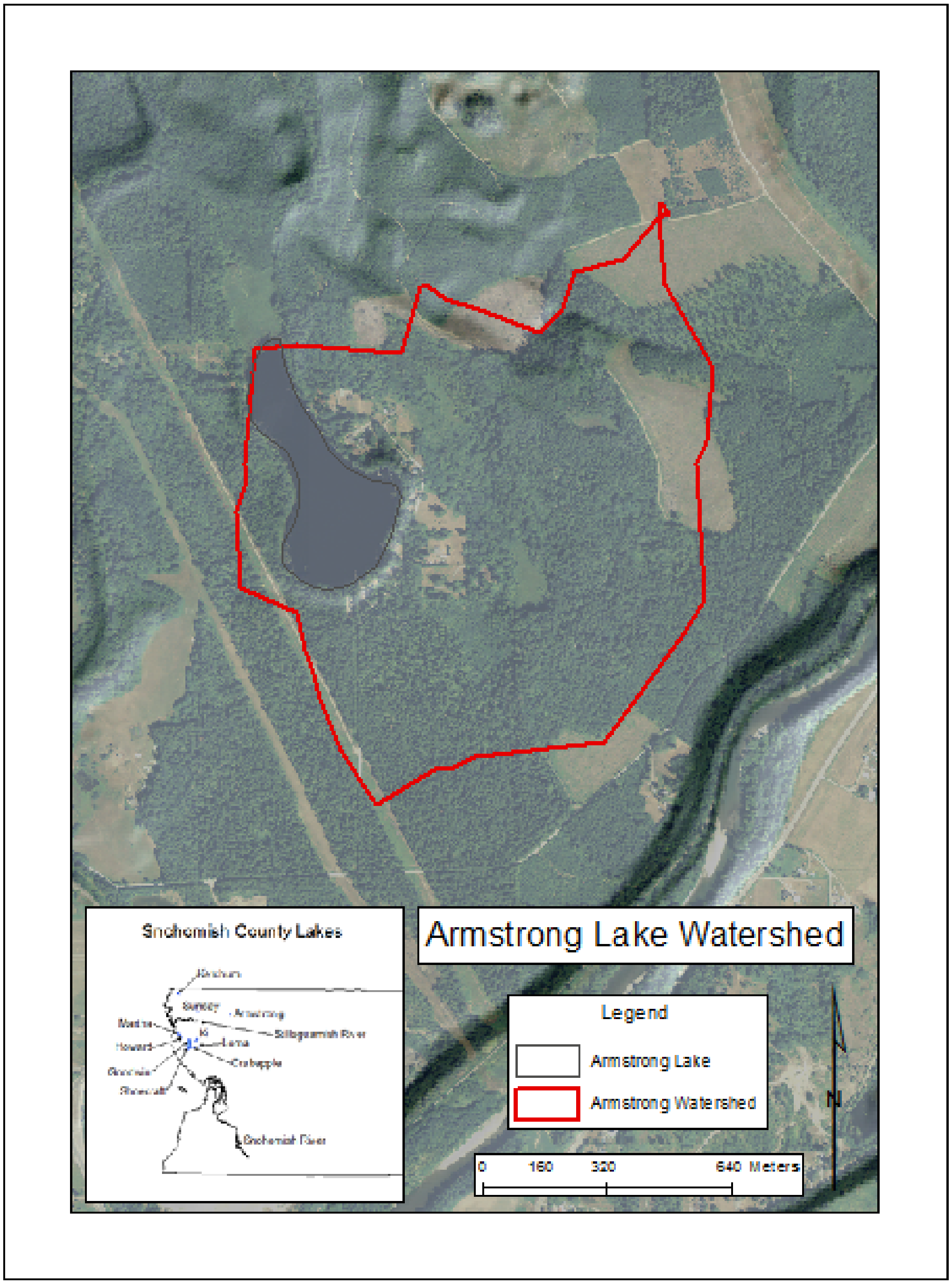


Figure 22. Armstrong Lake watershed, Snohomish County, WA.

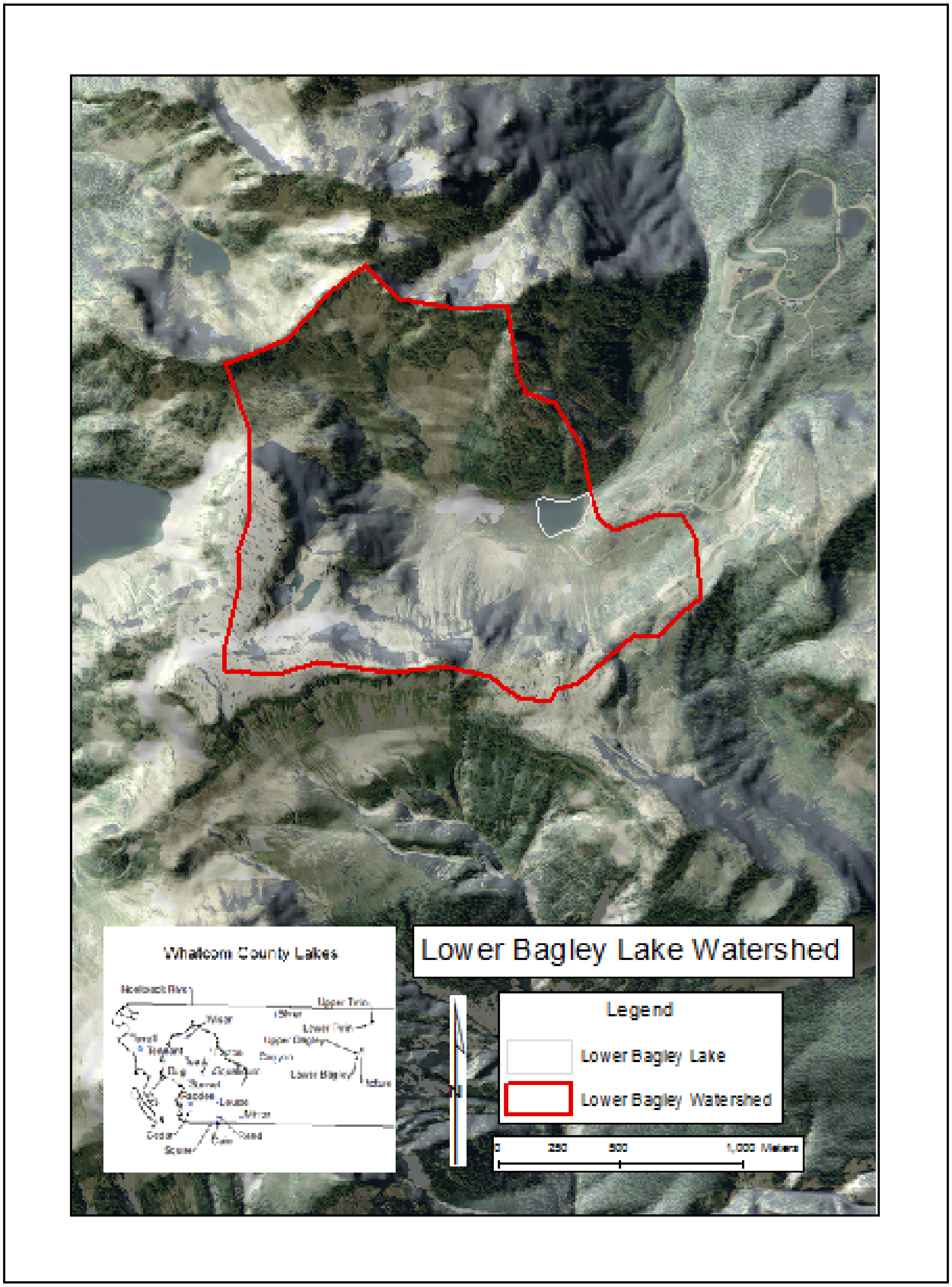


Figure 23. Lower Bagley watershed, Whatcom County, WA.

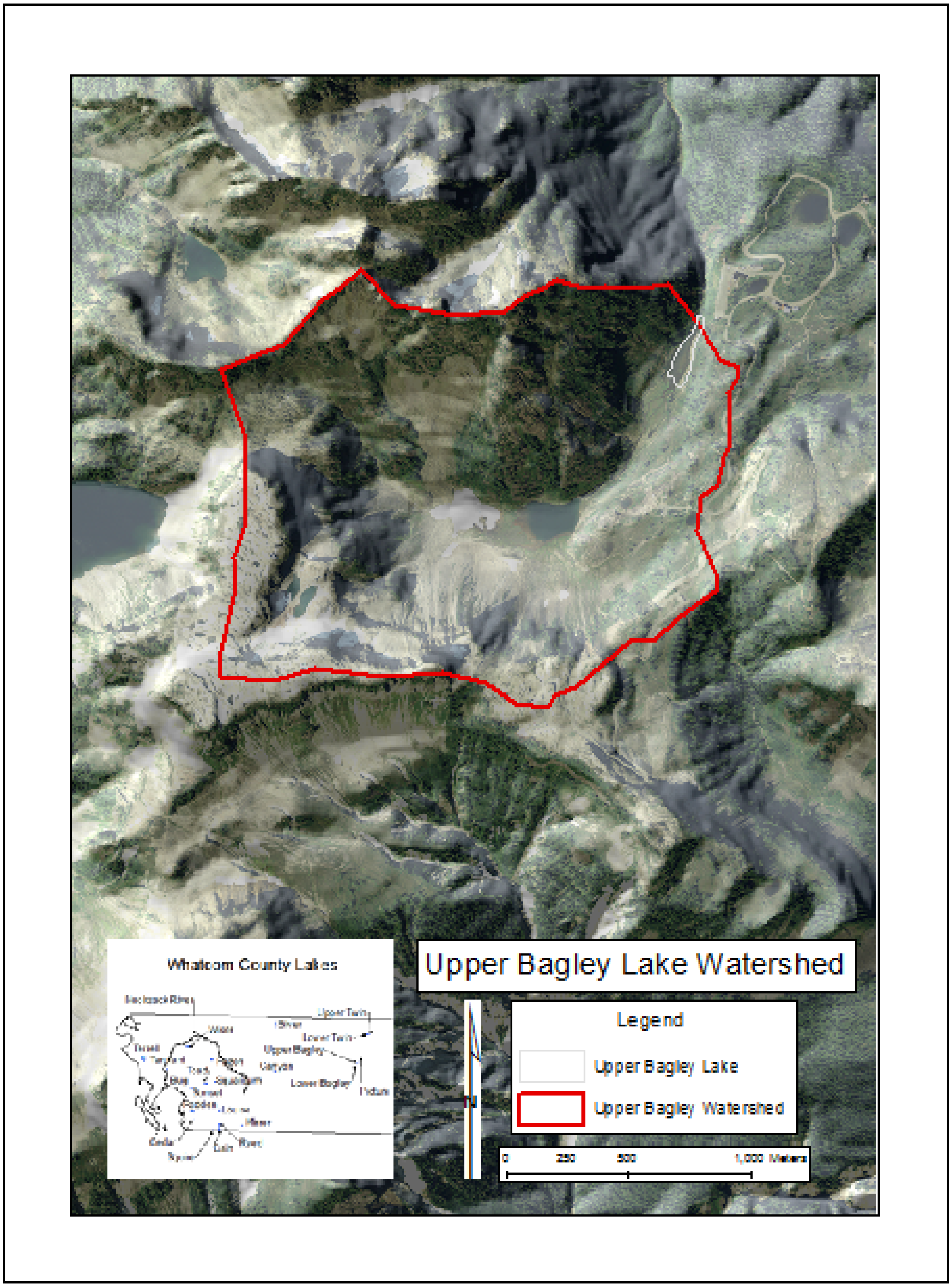


Figure 24. Upper Bagley Lake watershed, Whatcom County, WA.

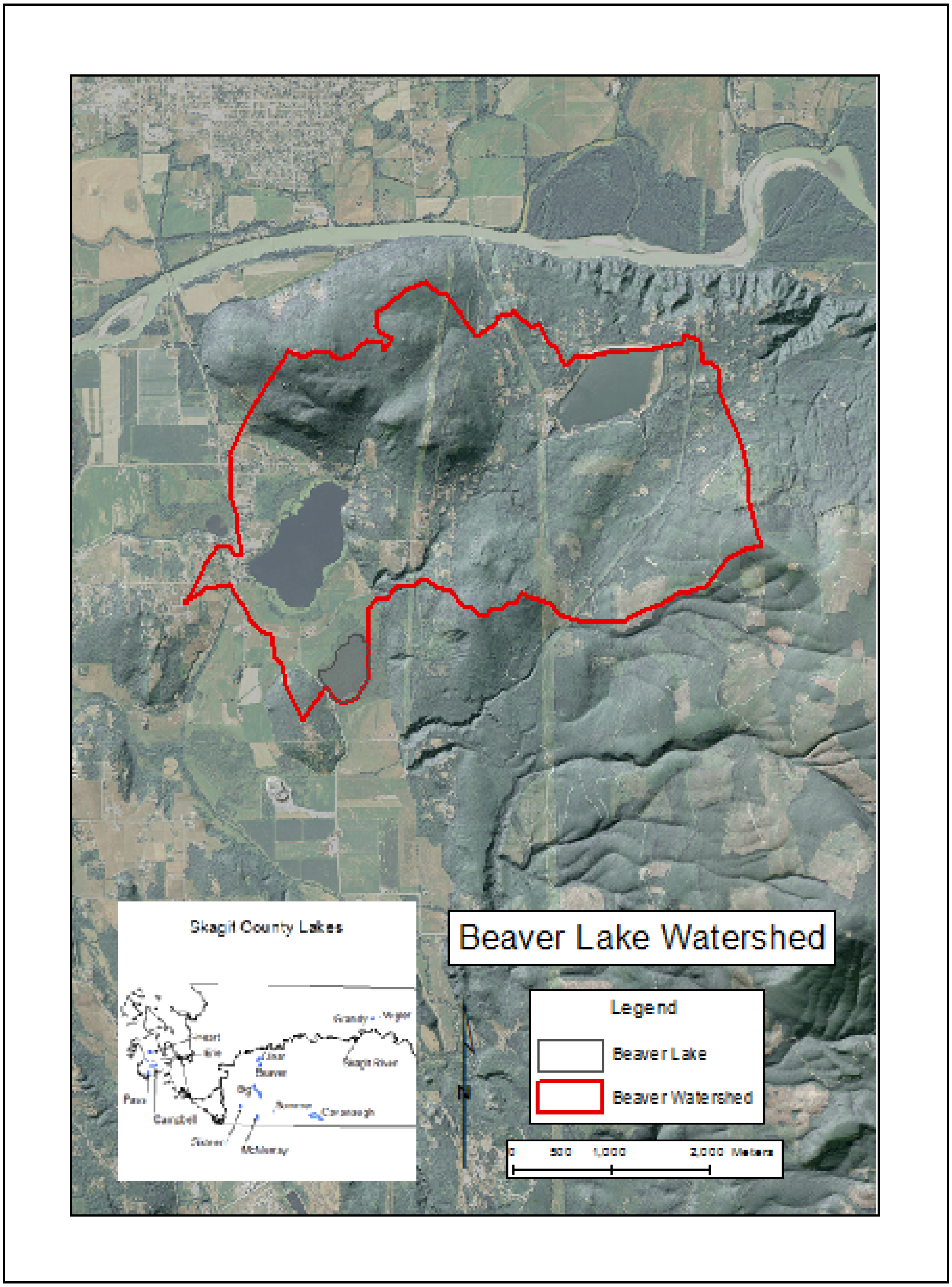


Figure 25. Beaver Lake watershed, Skagit County, WA

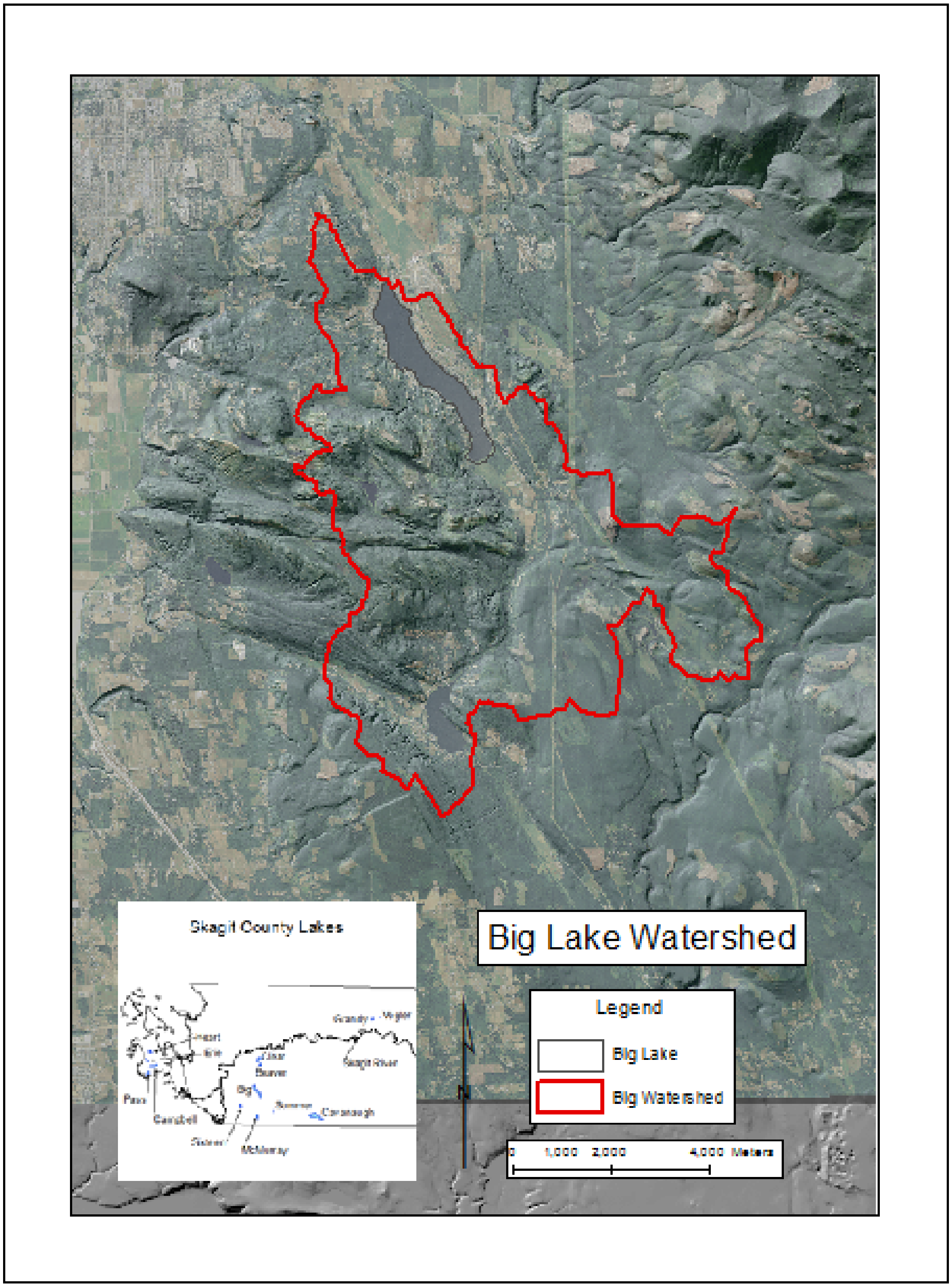


Figure 26. Big Lake watershed, Skagit County, WA.

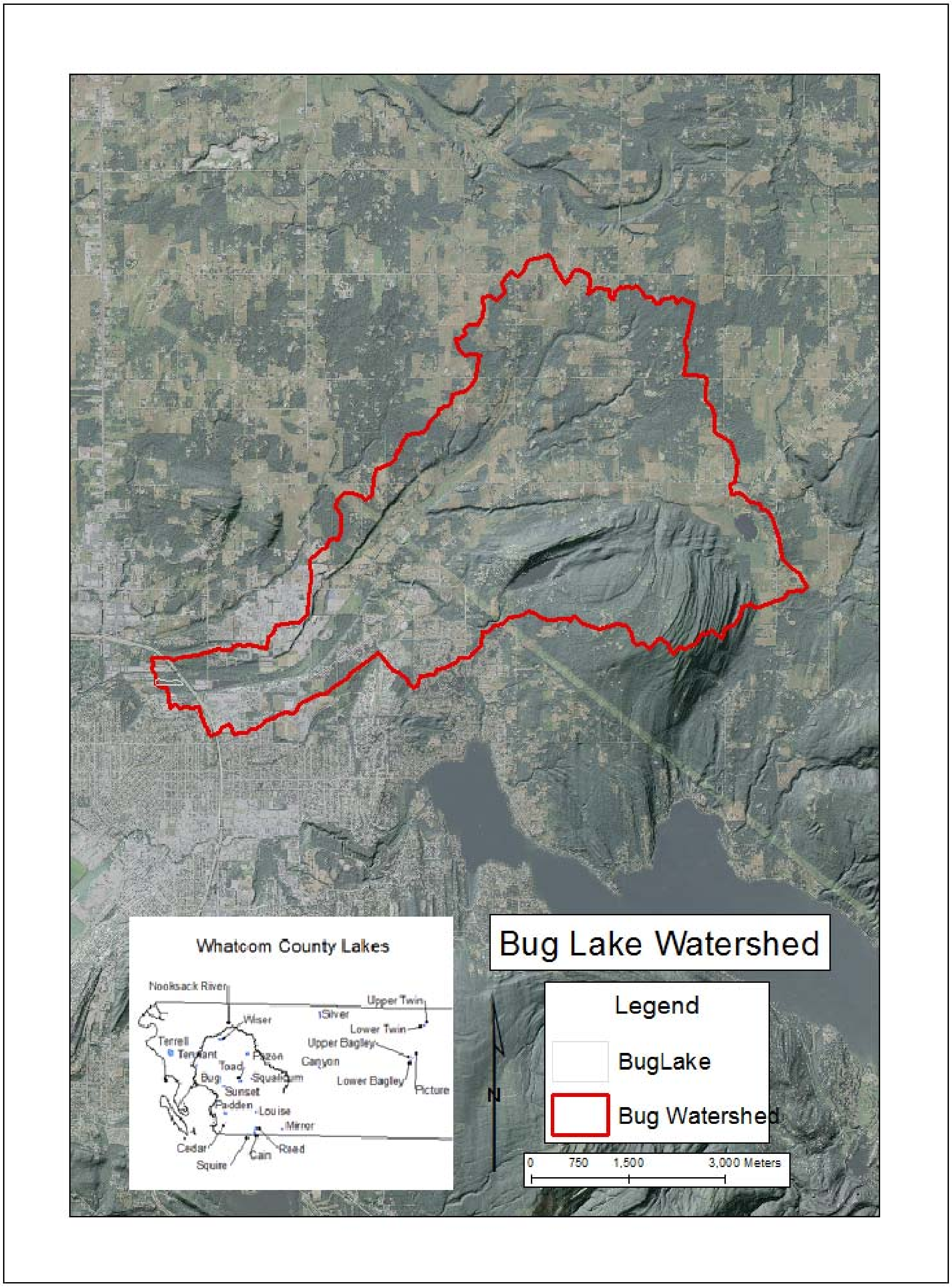


Figure 27. Bug Lake watershed, Whatcom County, WA.

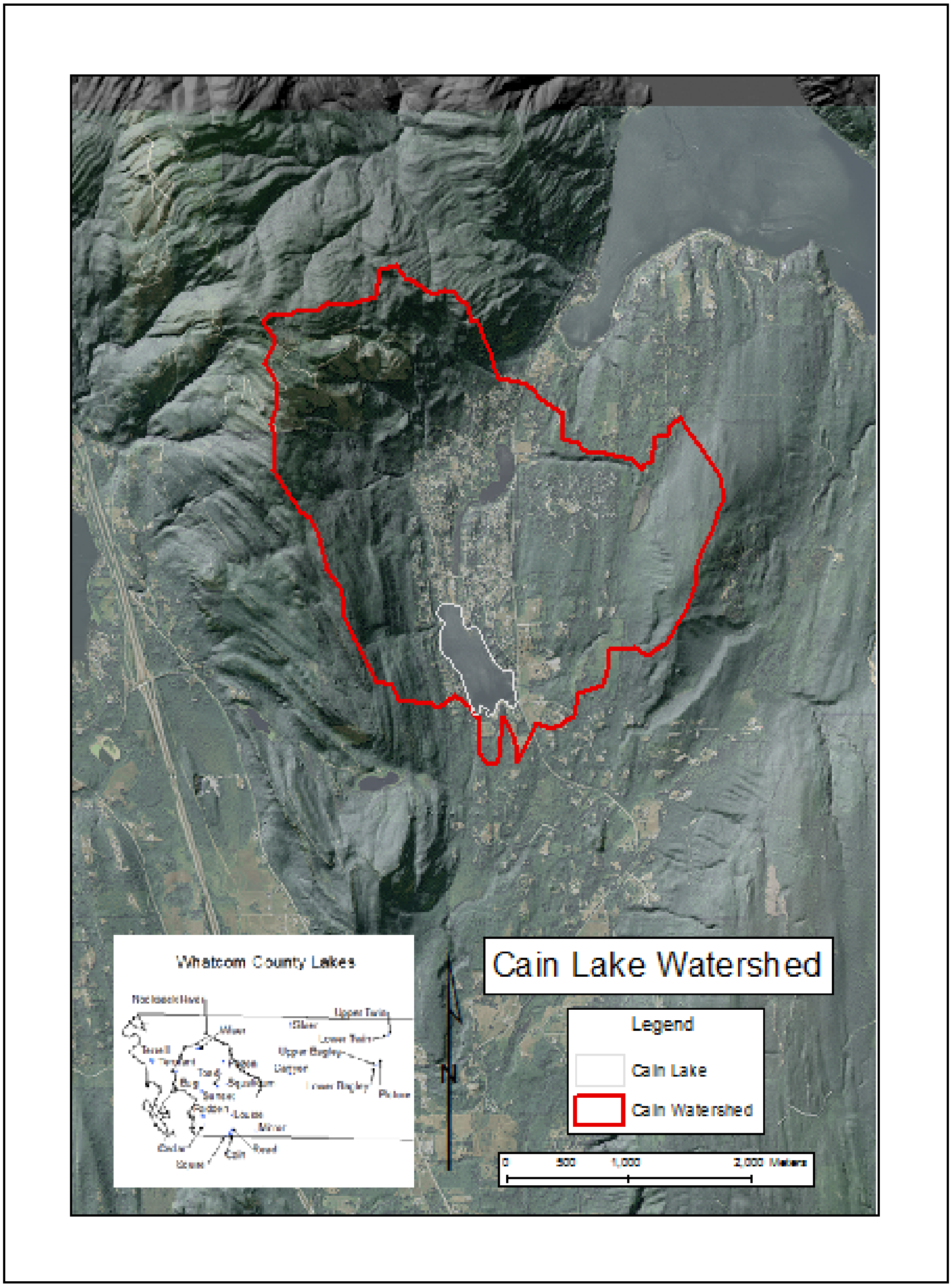


Figure 28. Cain Lake watershed, Whatcom County, WA.

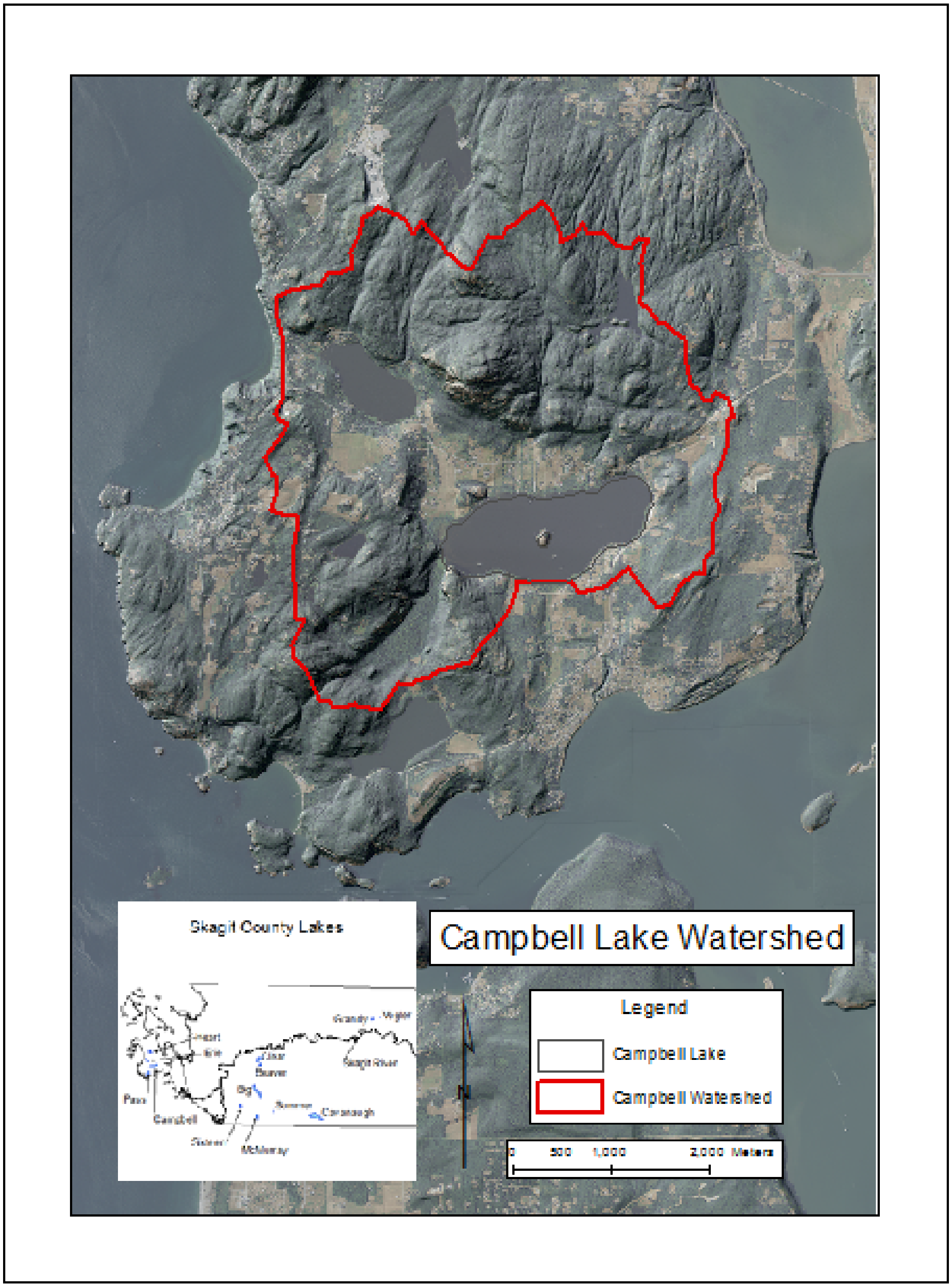


Figure 29. Campbell Lake watershed, Skagit County, WA.

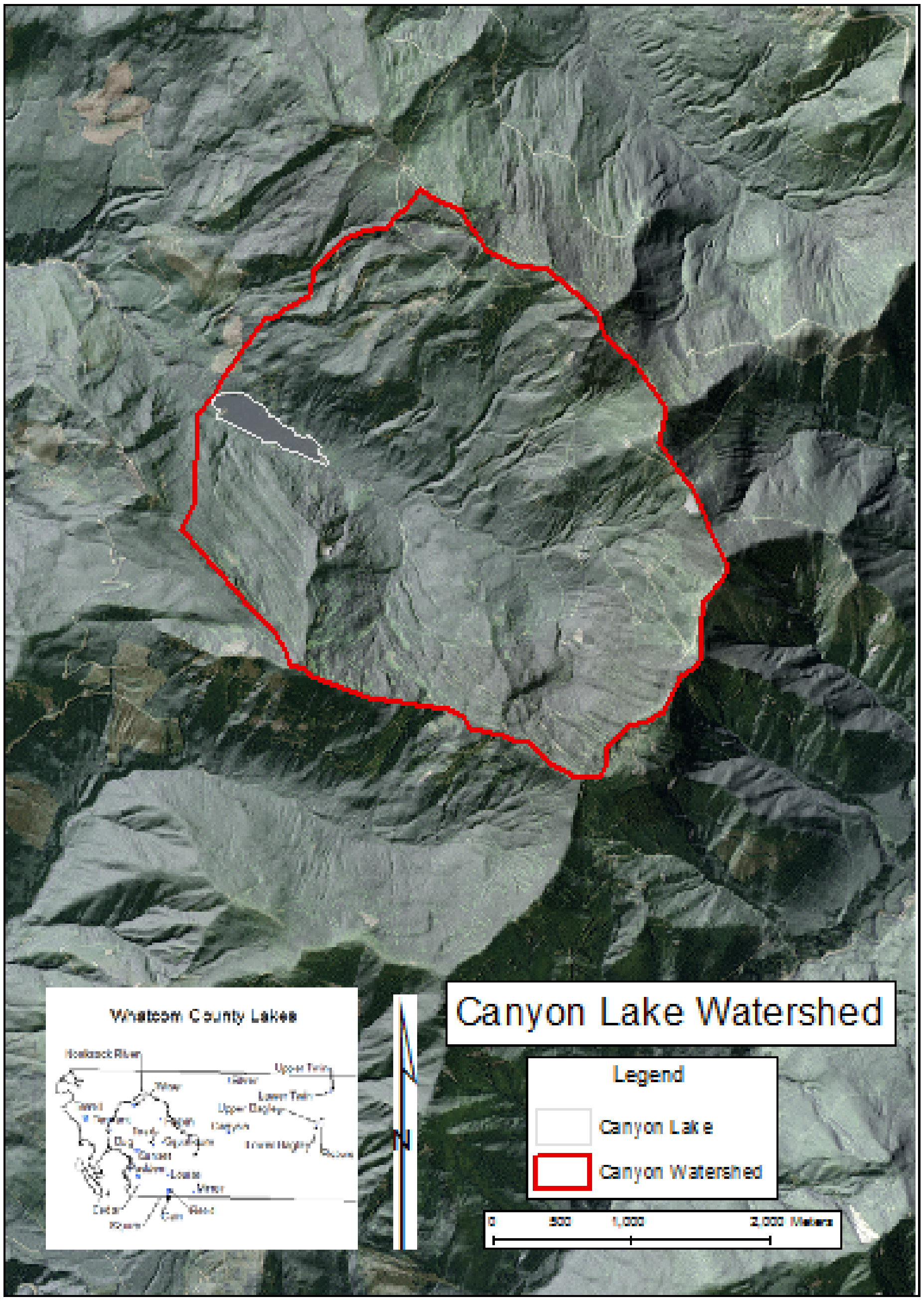


Figure 30. Canyon Lake watershed, Whatcom County, WA.

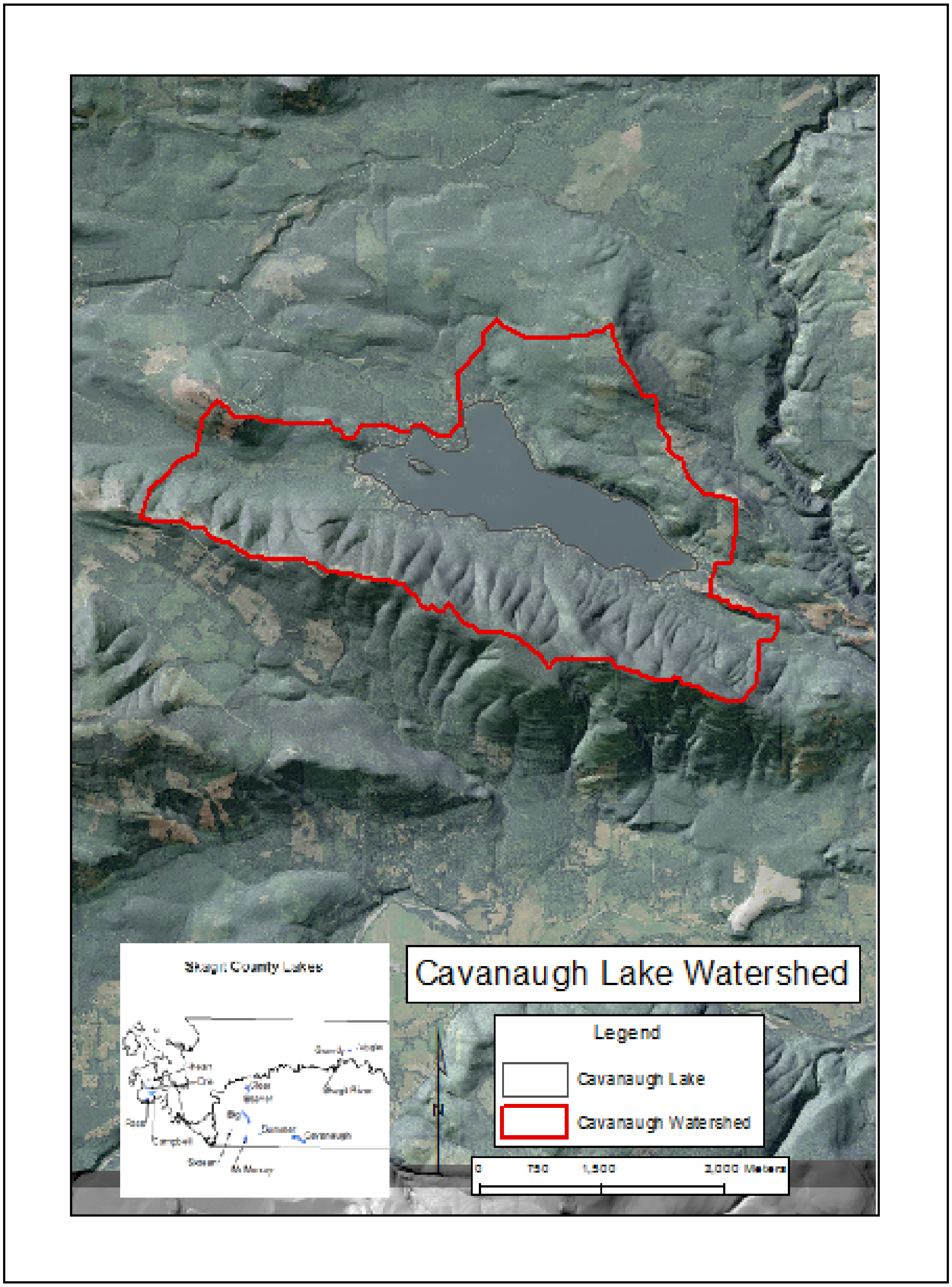


Figure 31. Cavanaugh Lake watershed, Skagit County, WA.

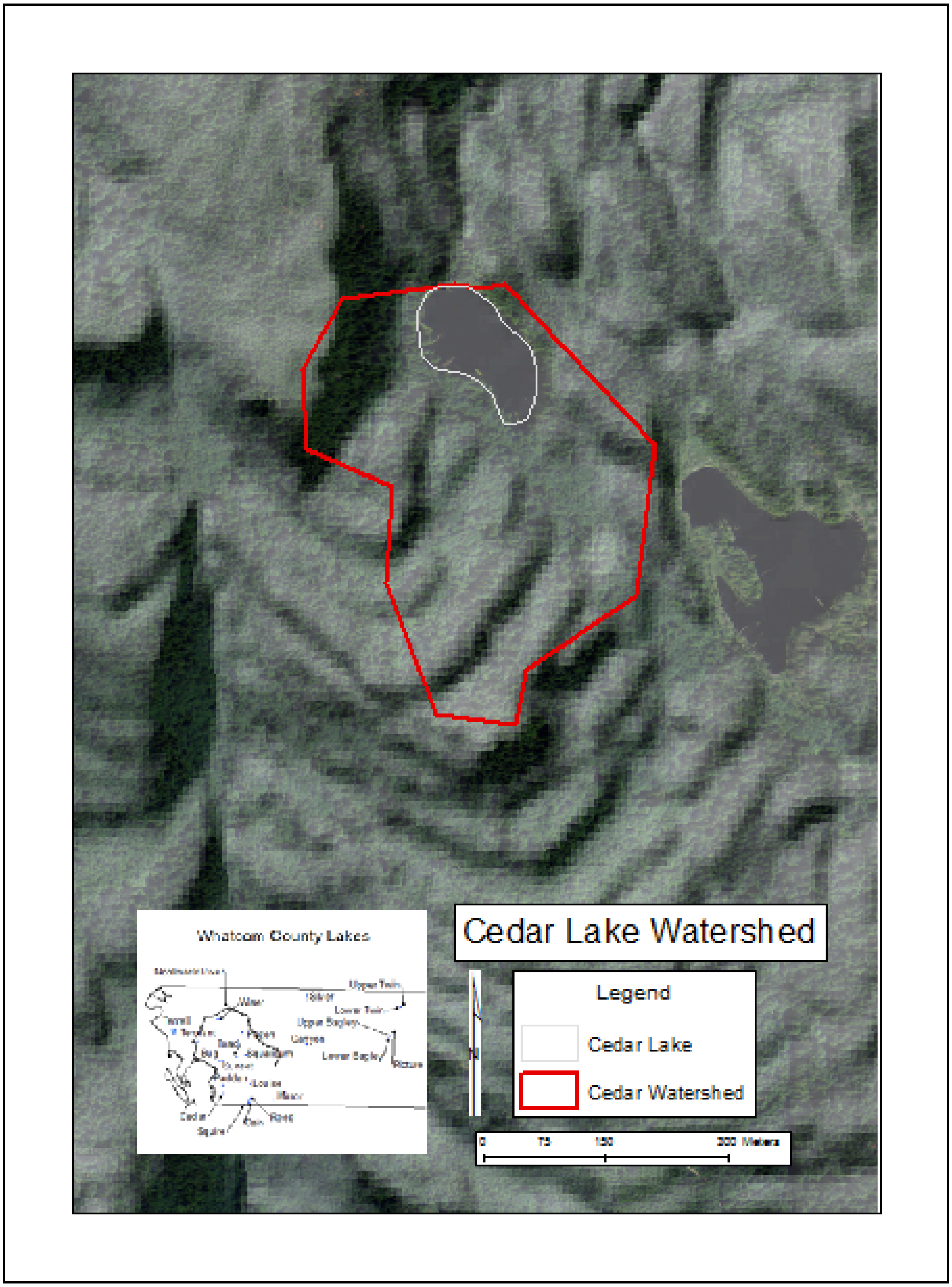


Figure 32. Cedar Lake watershed, Whatcom County, WA.

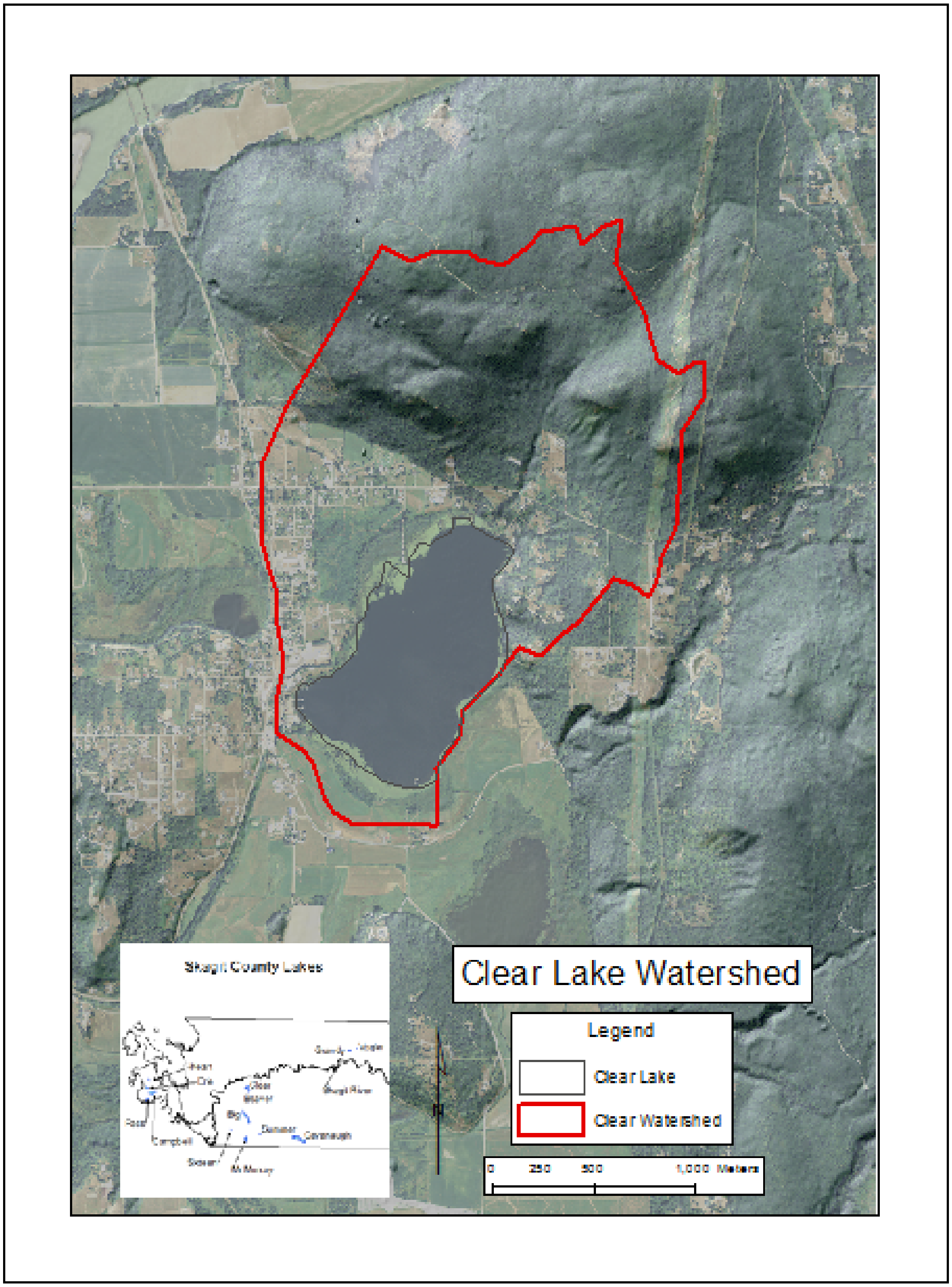


Figure 33. Clear Lake watershed, Skagit County, WA.

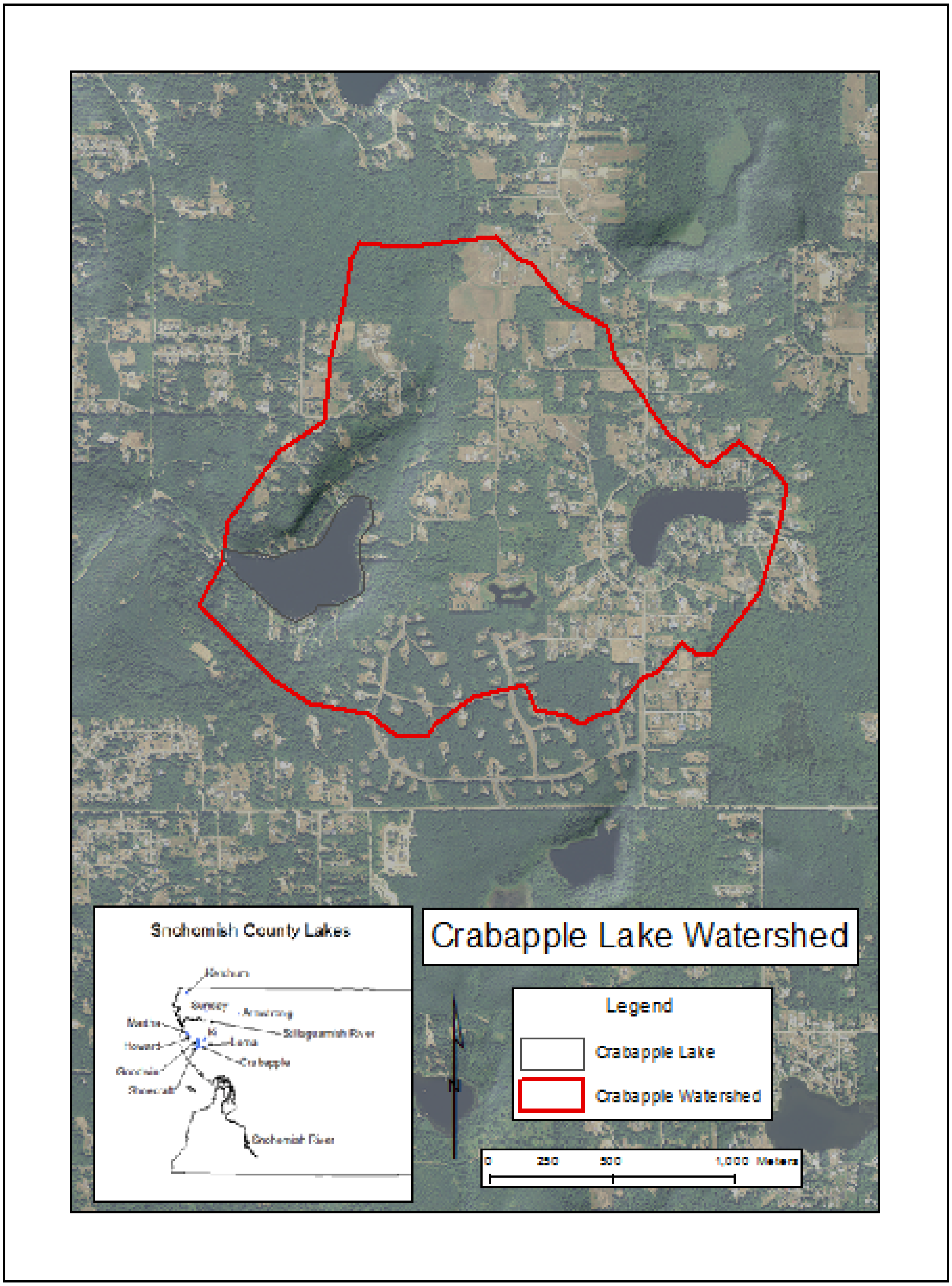


Figure 34. Crabapple Lake watershed, Snohomish County, WA.

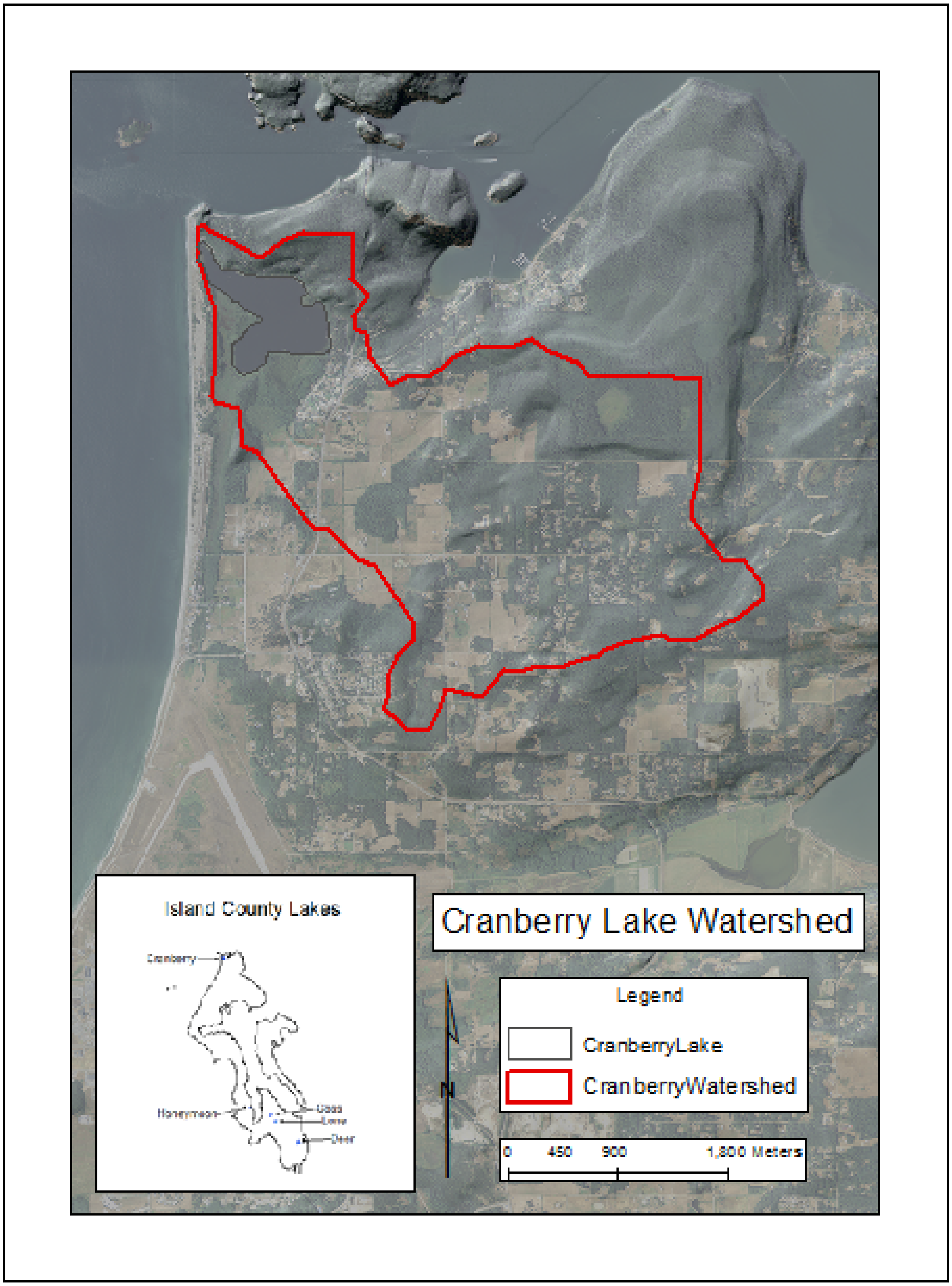


Figure 35. Cranberry Lake watershed, Island County, WA.

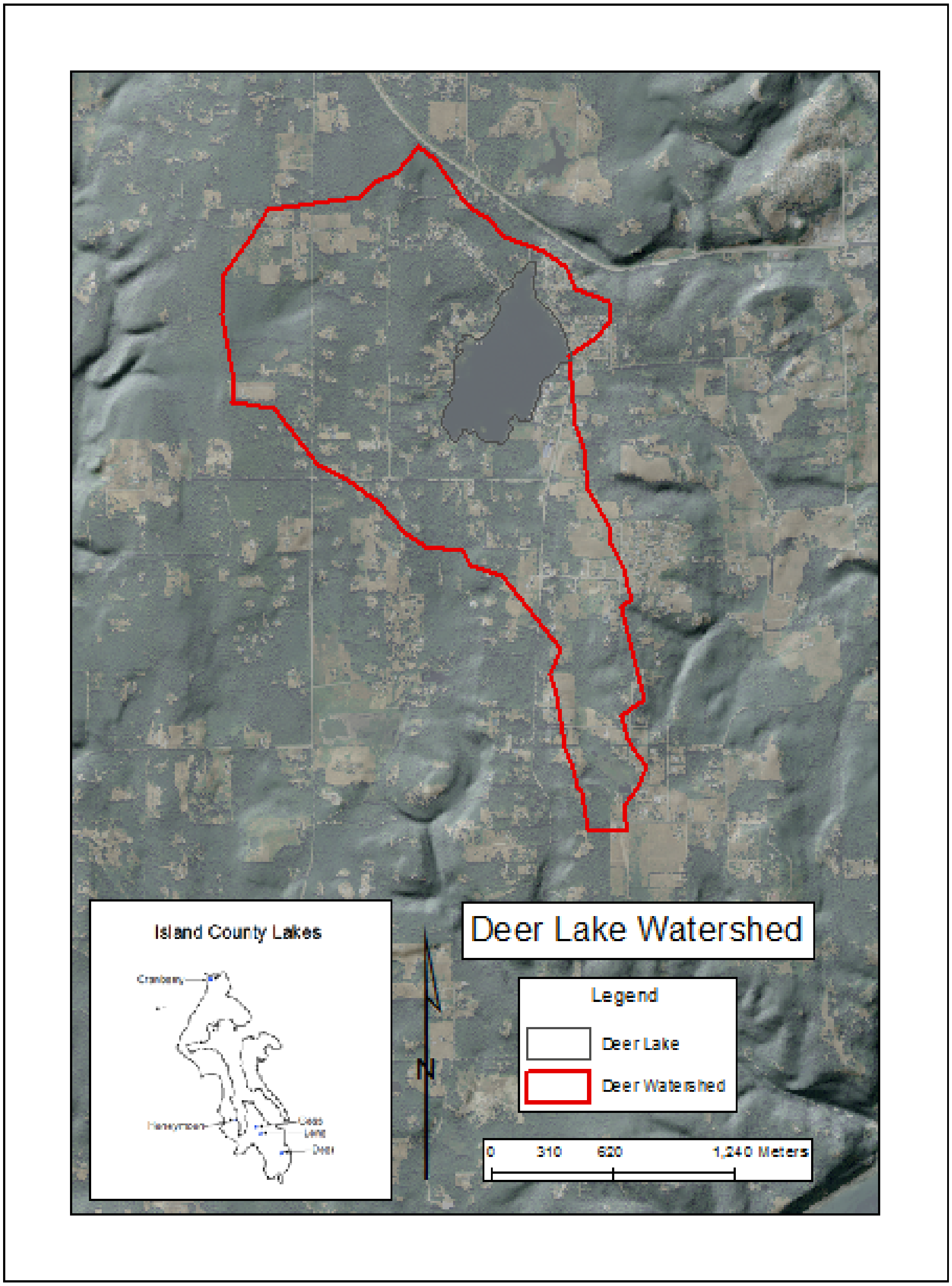


Figure 36. Deer Lake watershed, Island County, WA.

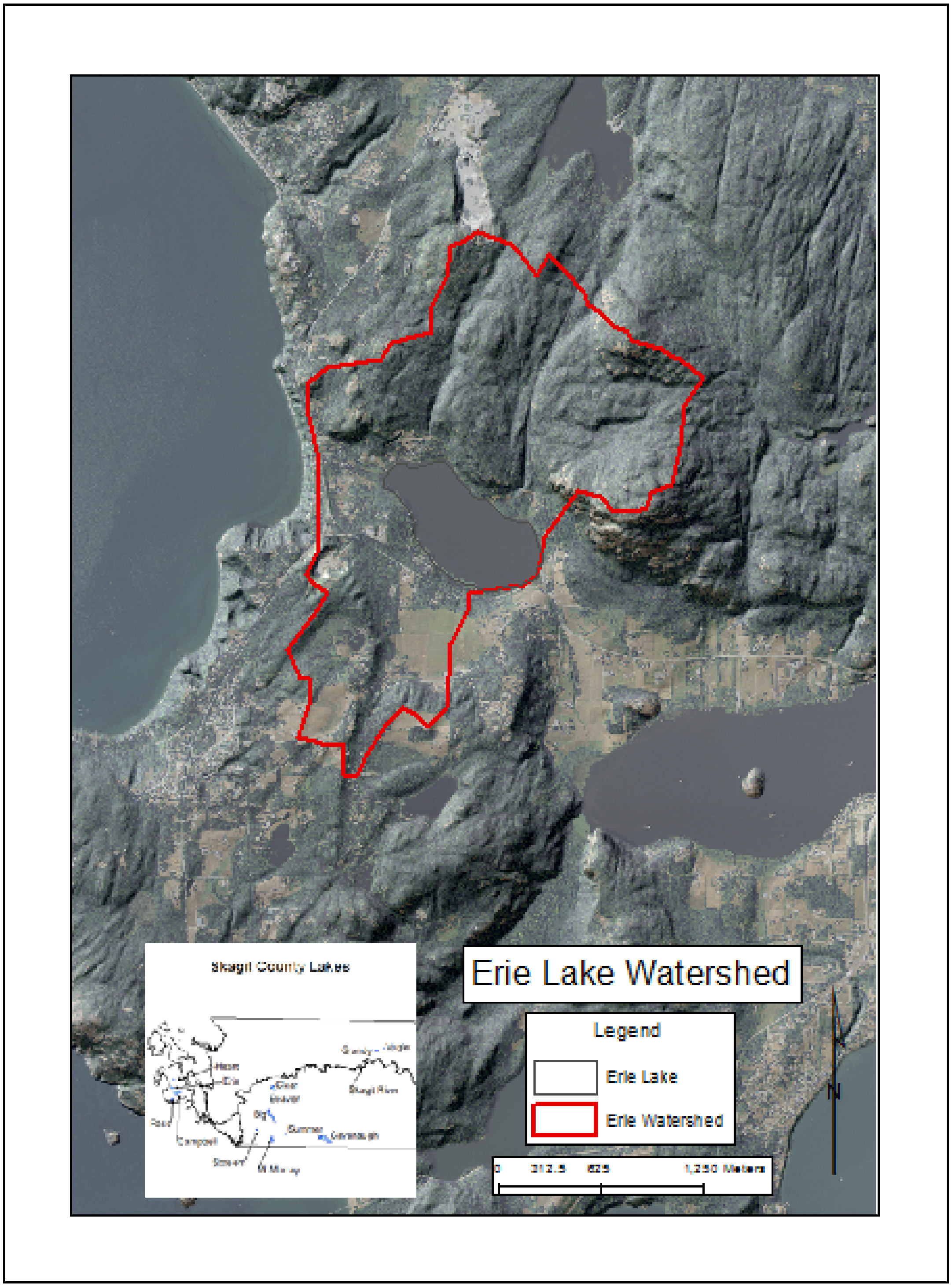


Figure 37. Erie Lake watershed, Skagit County, WA.

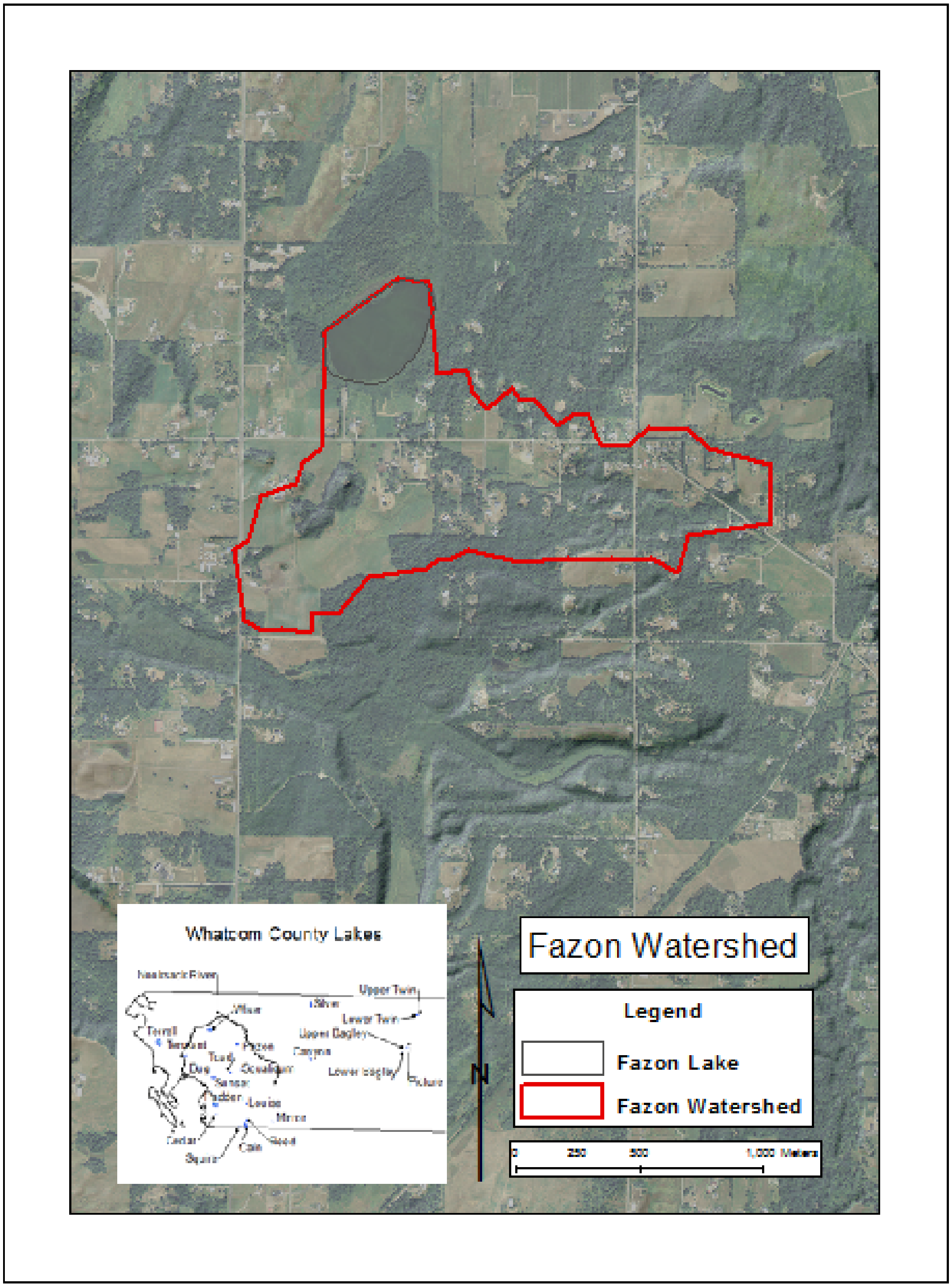


Figure 38. Fazon Lake watershed, Whatcom County, WA.

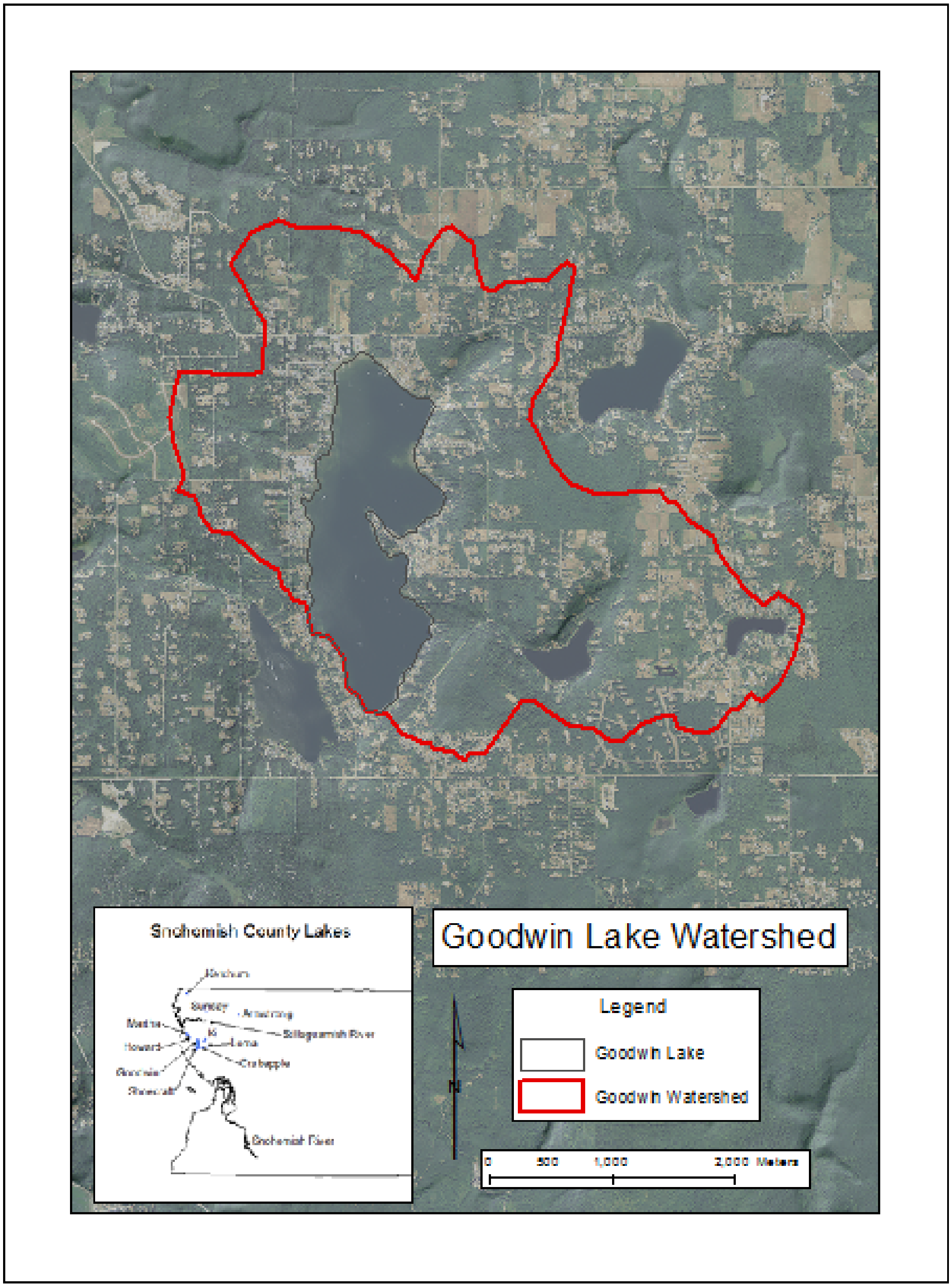


Figure 39. Goodwin Lake watershed, Snohomish County, WA.

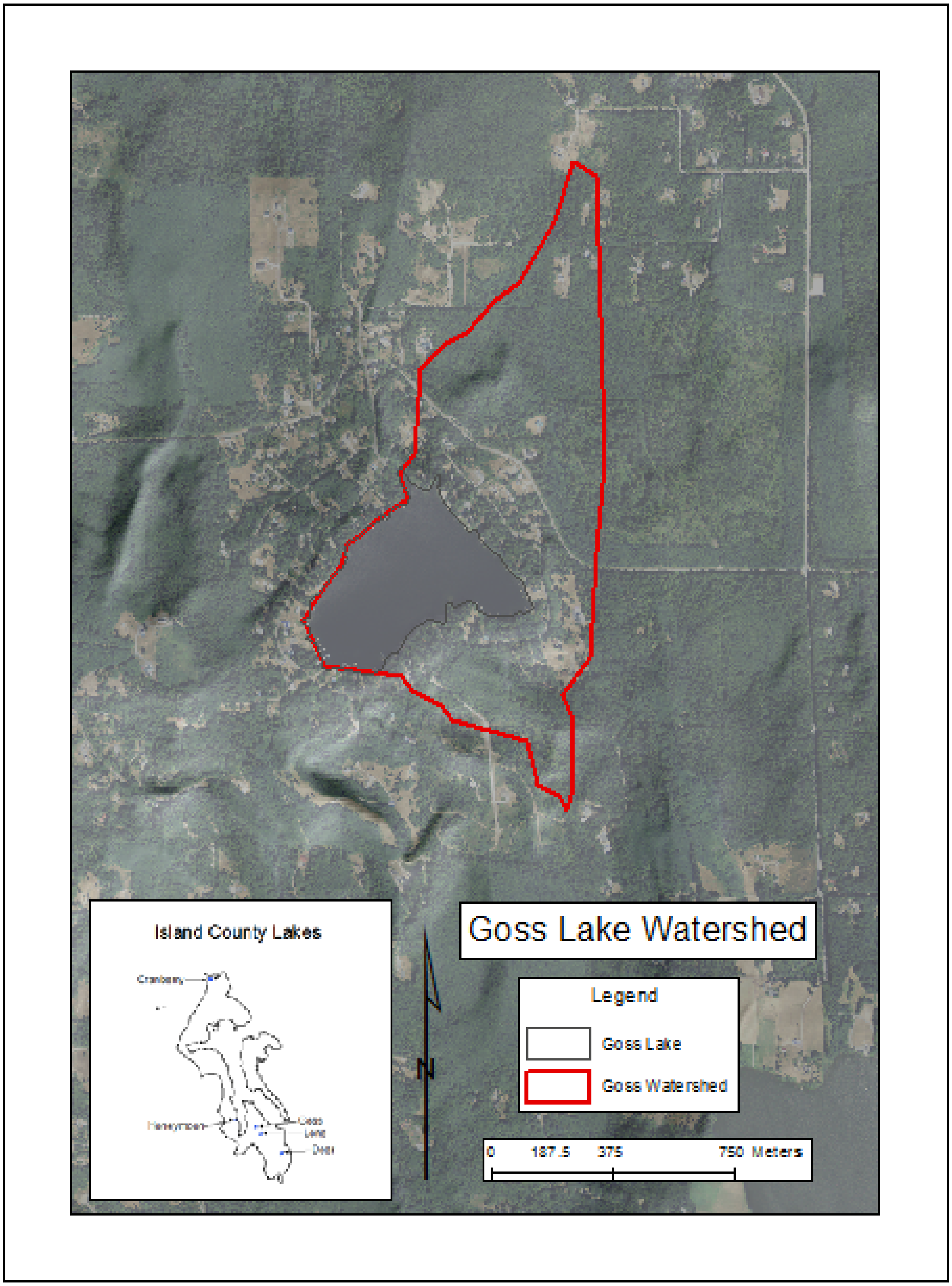


Figure 40. Goss Lake watershed, Island County, WA.

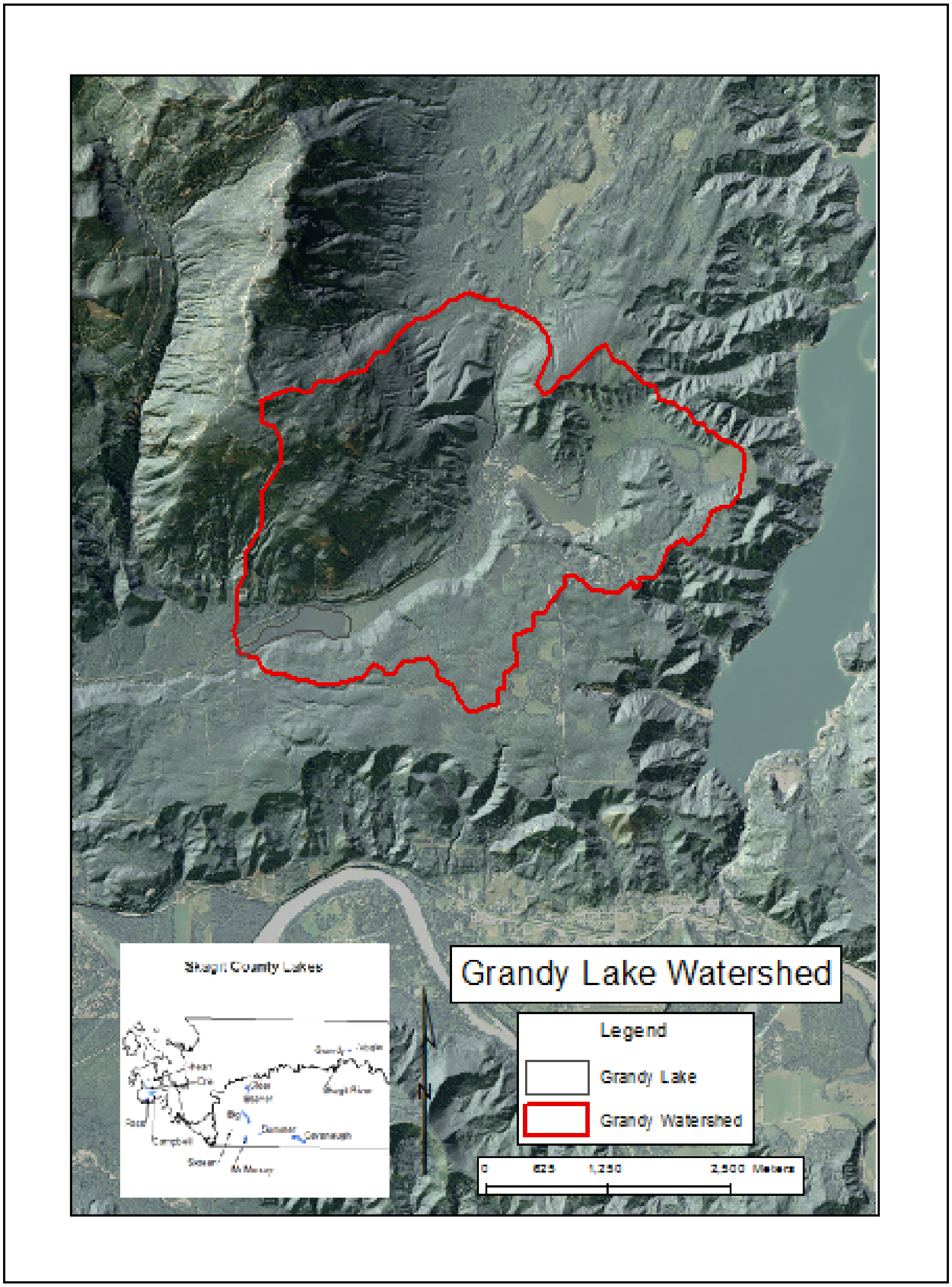


Figure 41. Grandy Lake watershed, Skagit County, WA.

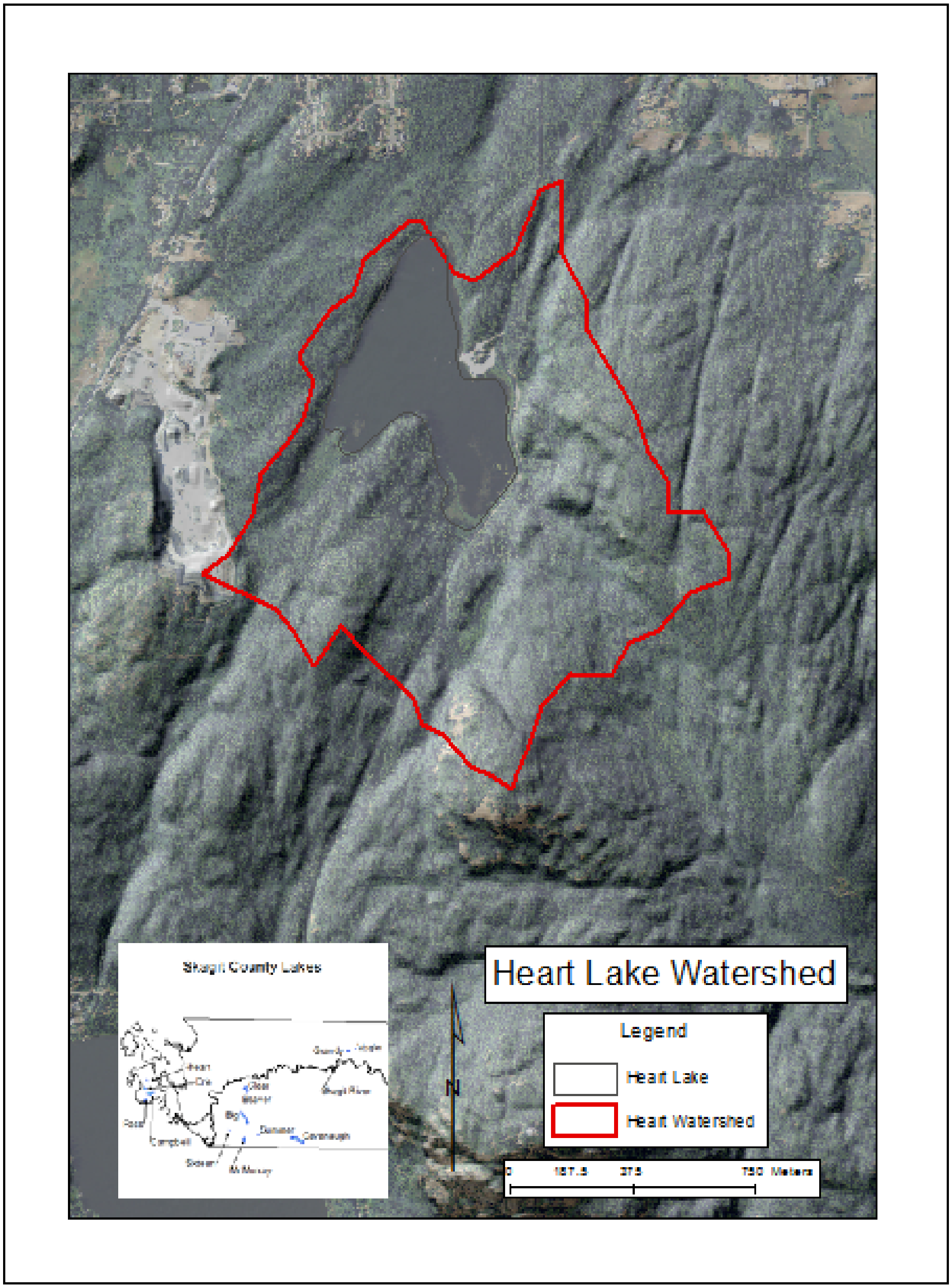


Figure 42. Heart Lake watershed, Skagit County, WA.

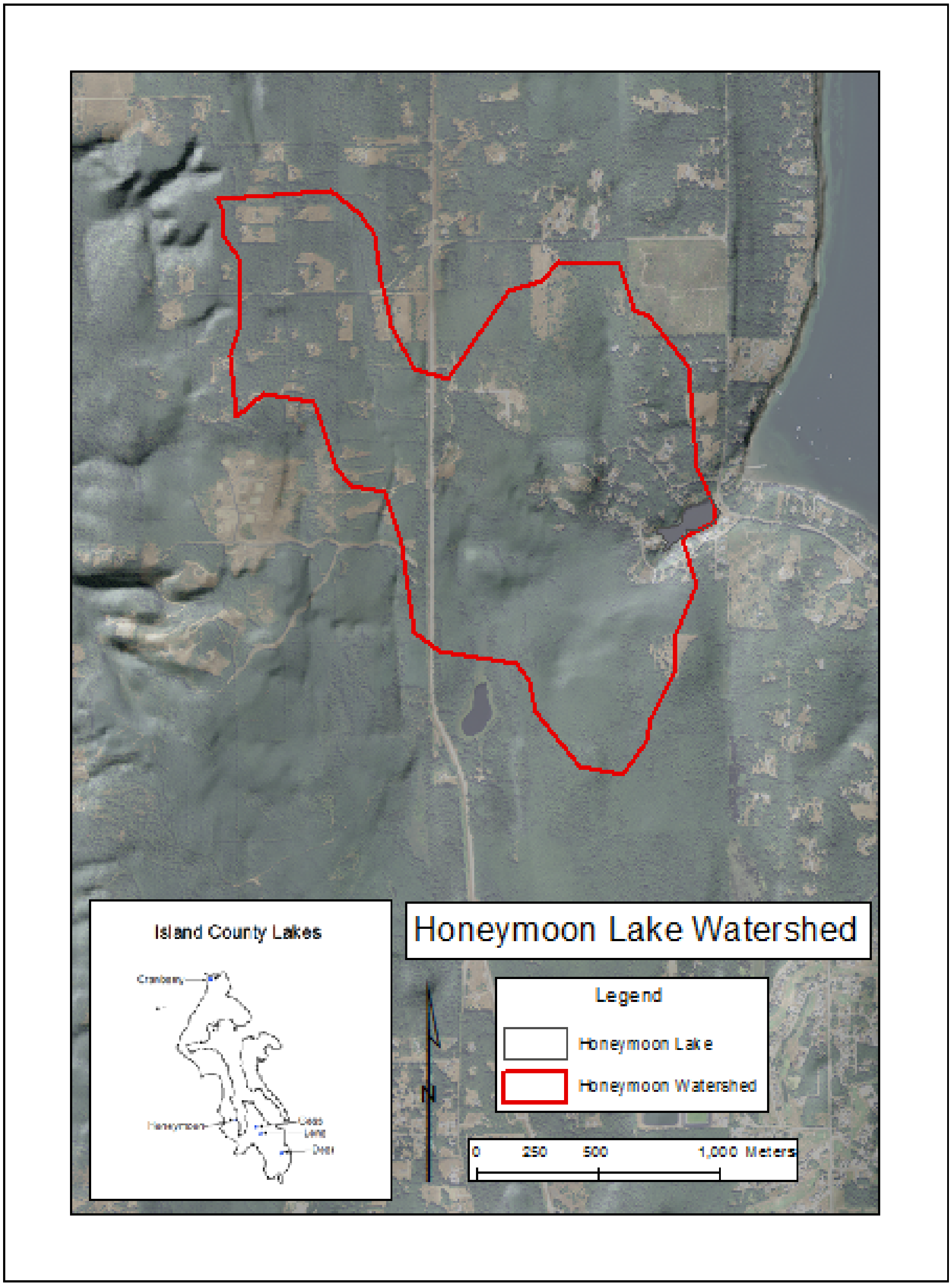


Figure 43. Honeymoon Lake watershed, Island County, WA.

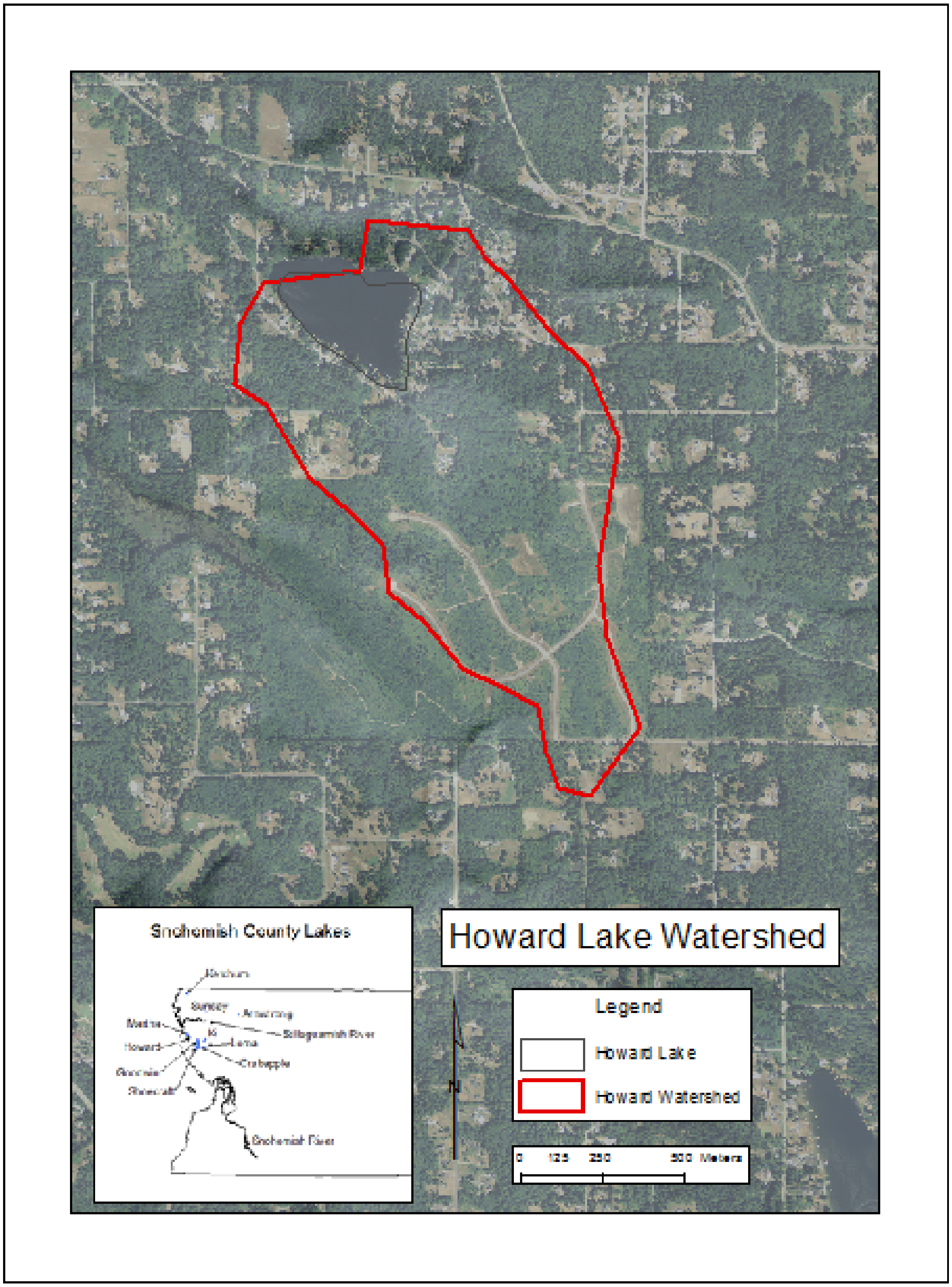


Figure 44. Howard Lake watershed, Snohomish County, WA.

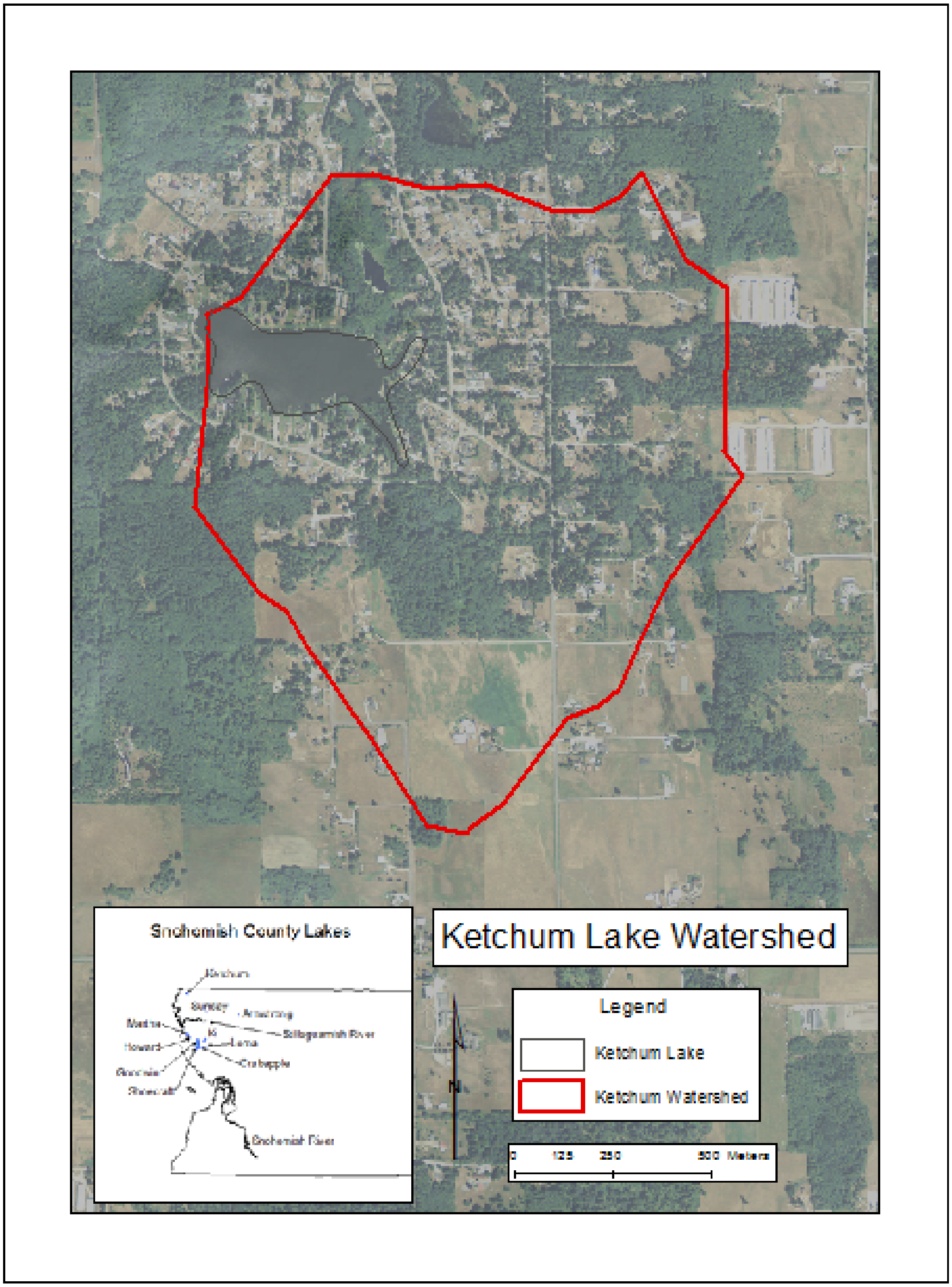


Figure 45. Ketchum Lake watershed, Snohomish County, WA.

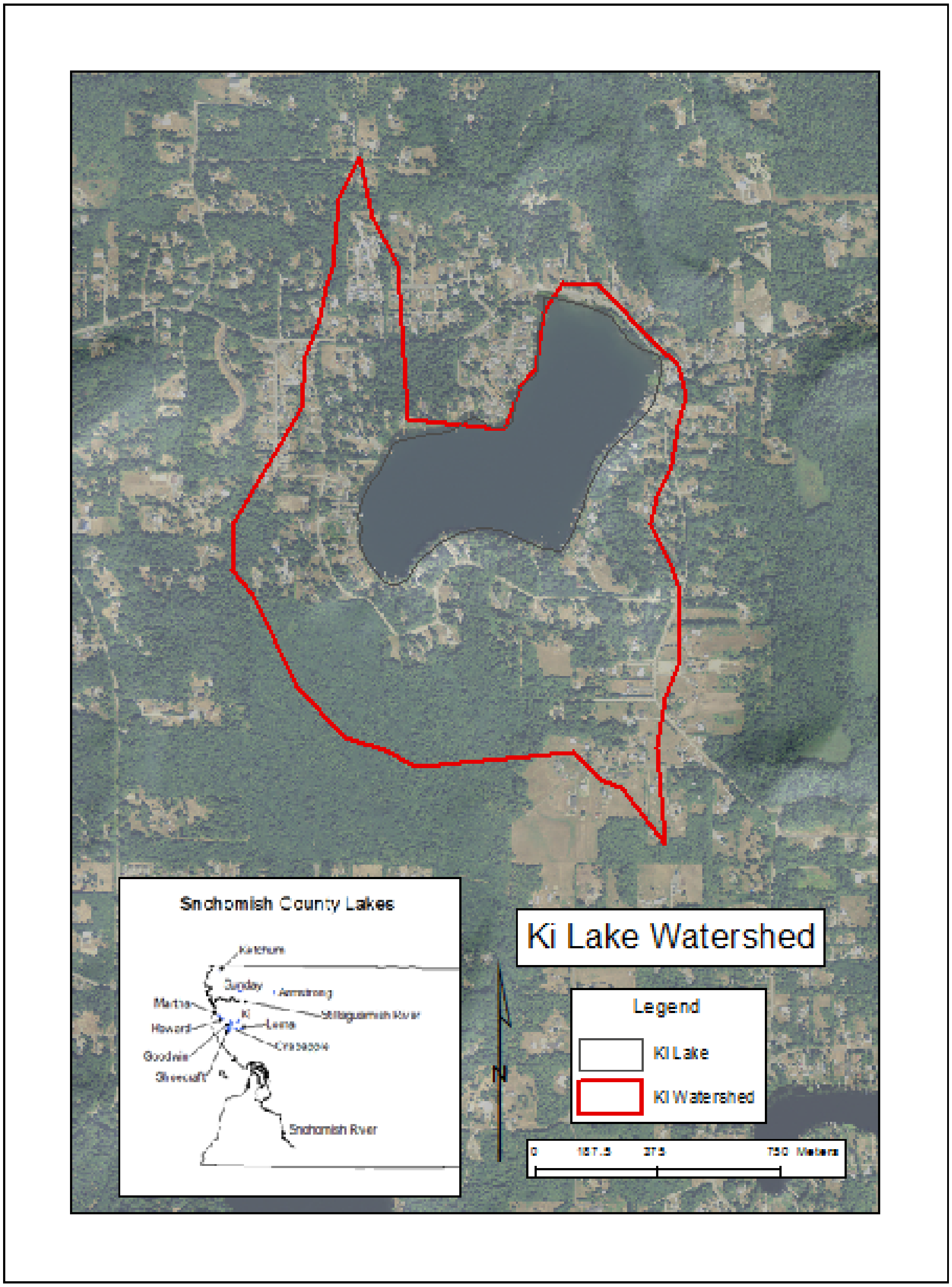


Figure 46. Ki Lake watershed, Snohomish County, WA.

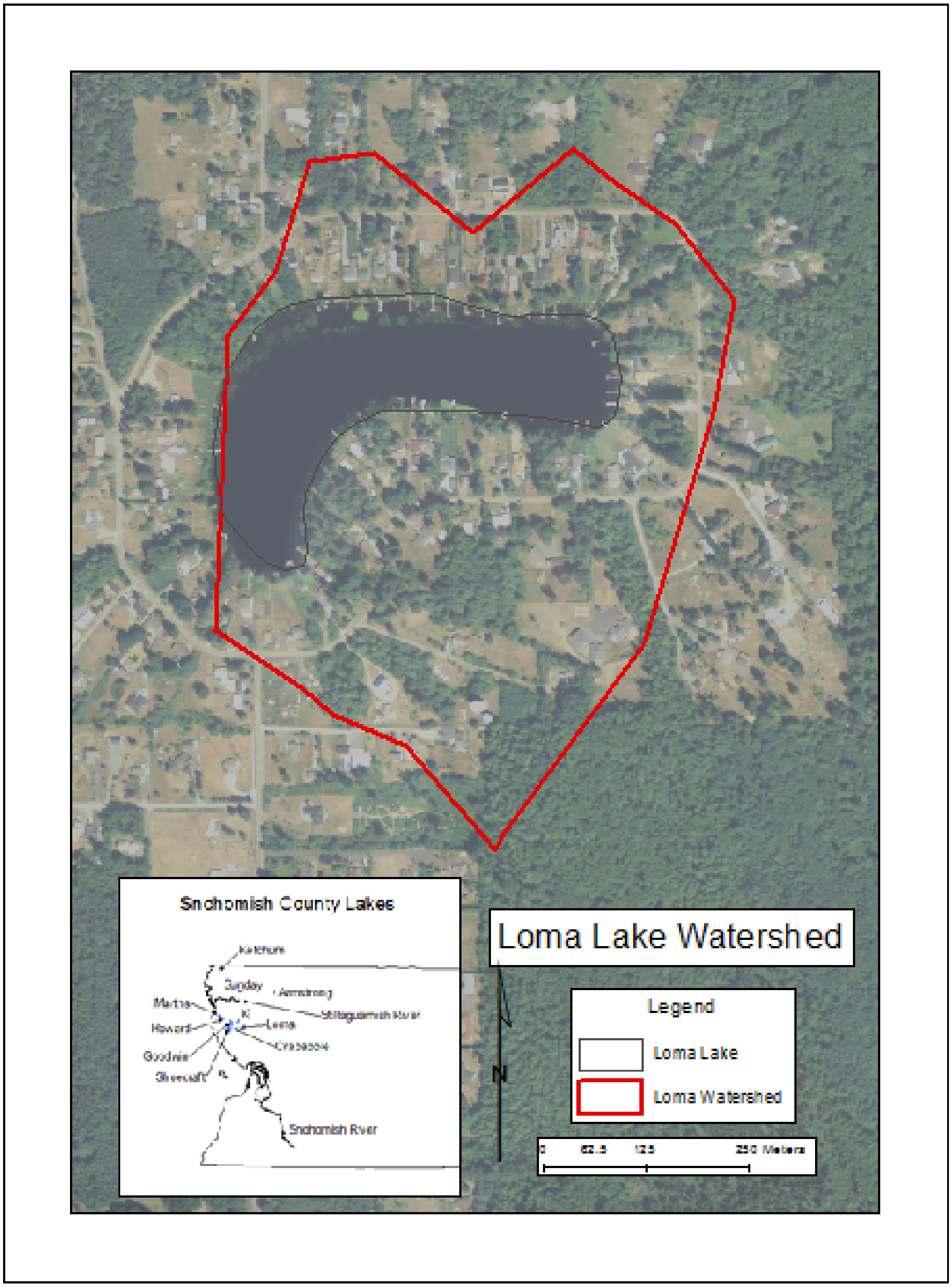


Figure 47. Loma Lake watershed, Snohomish County, WA.

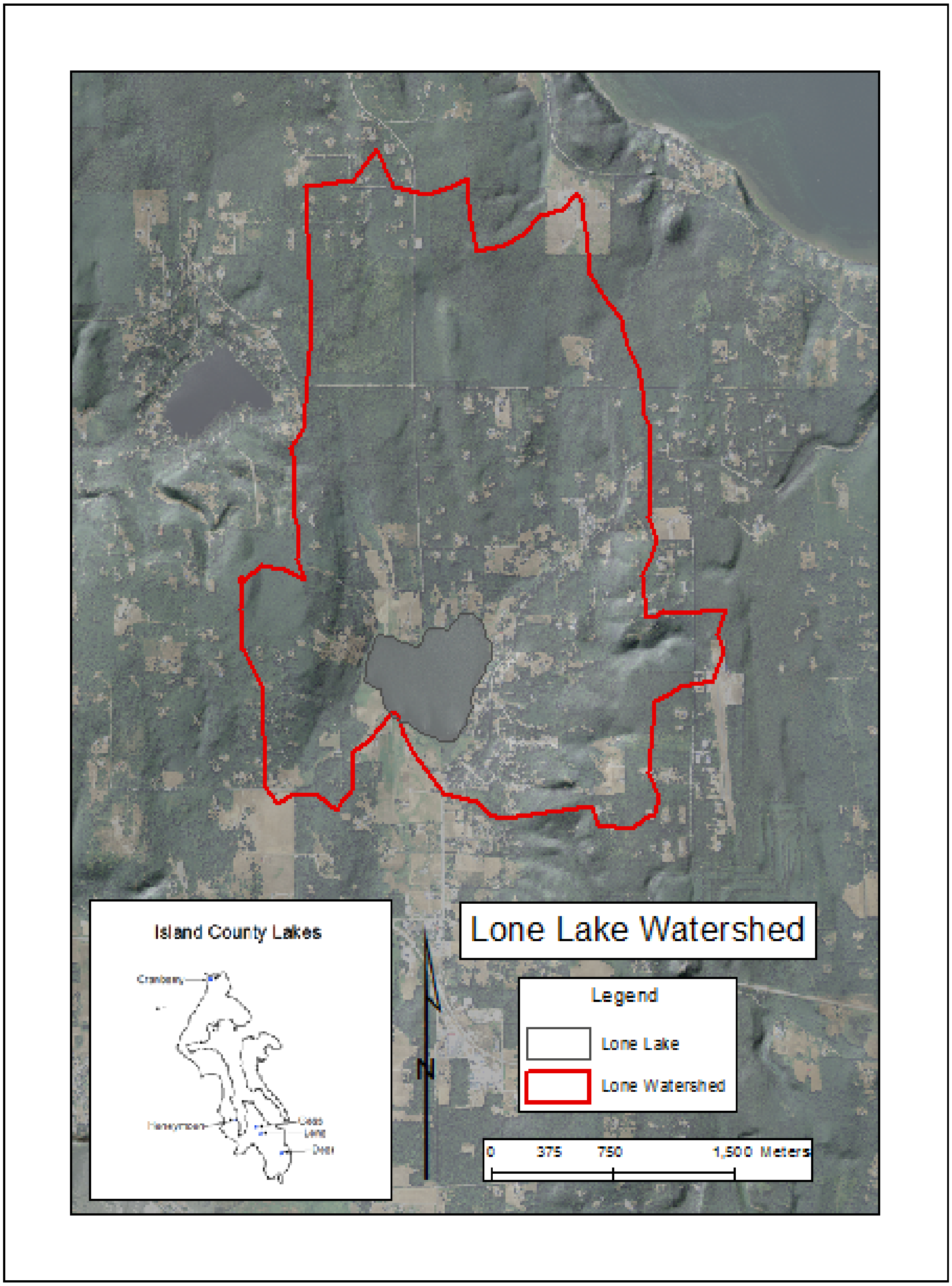


Figure 48. Lone Lake watershed, Island County, WA.

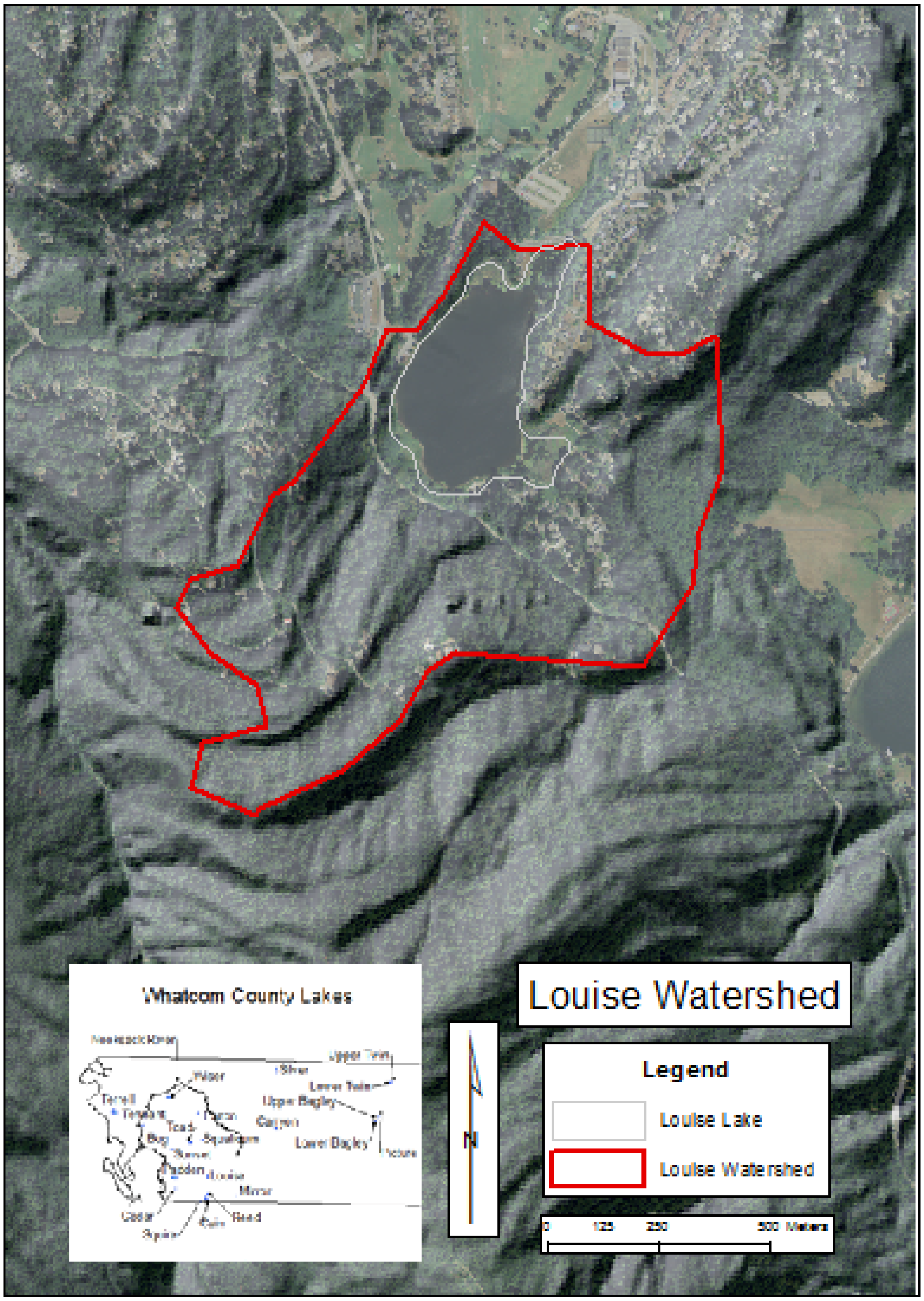


Figure 49. Louise Lake watershed, Whatcom County, WA.

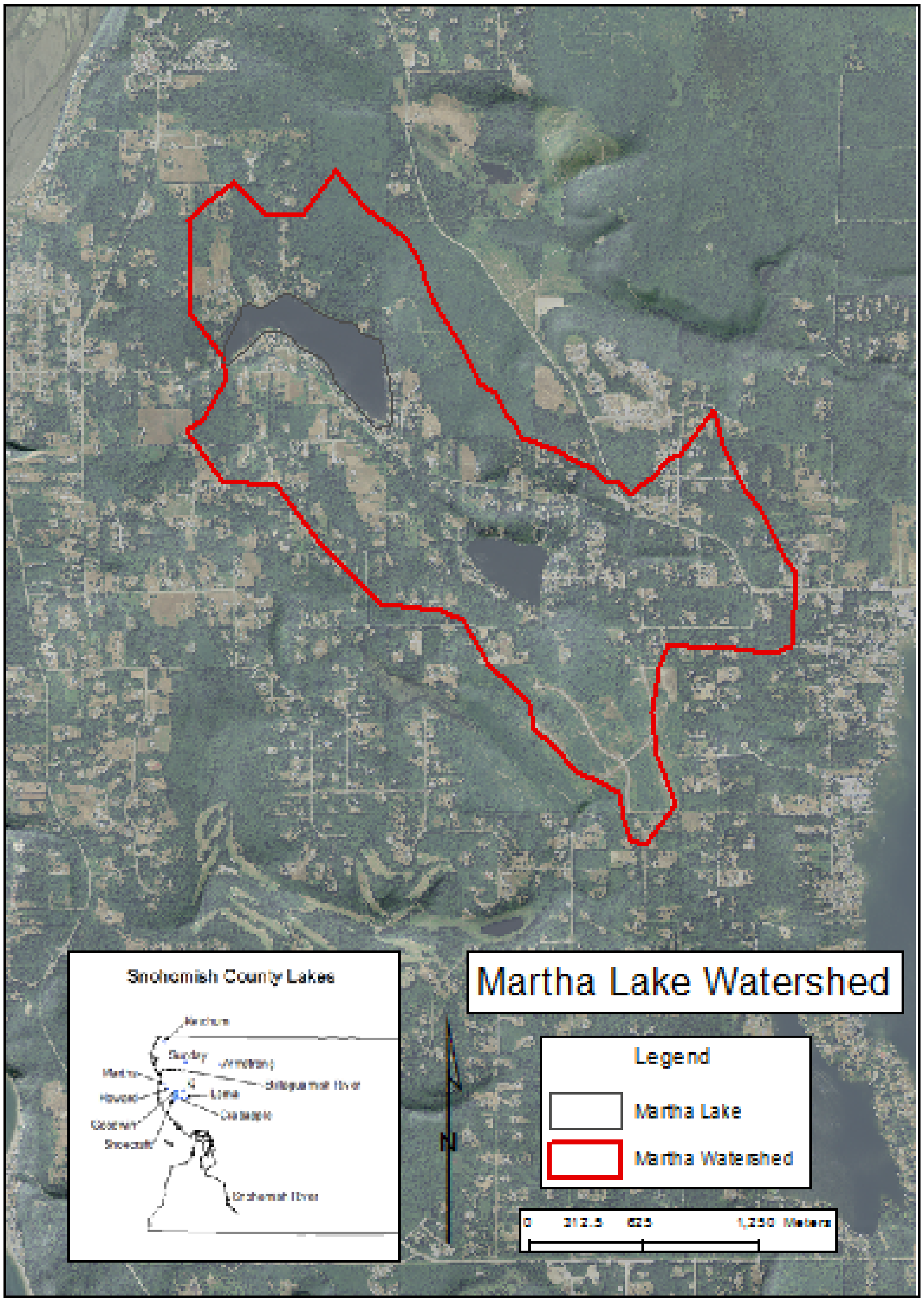


Figure 50. Martha Lake watershed, Snohomish County, WA.

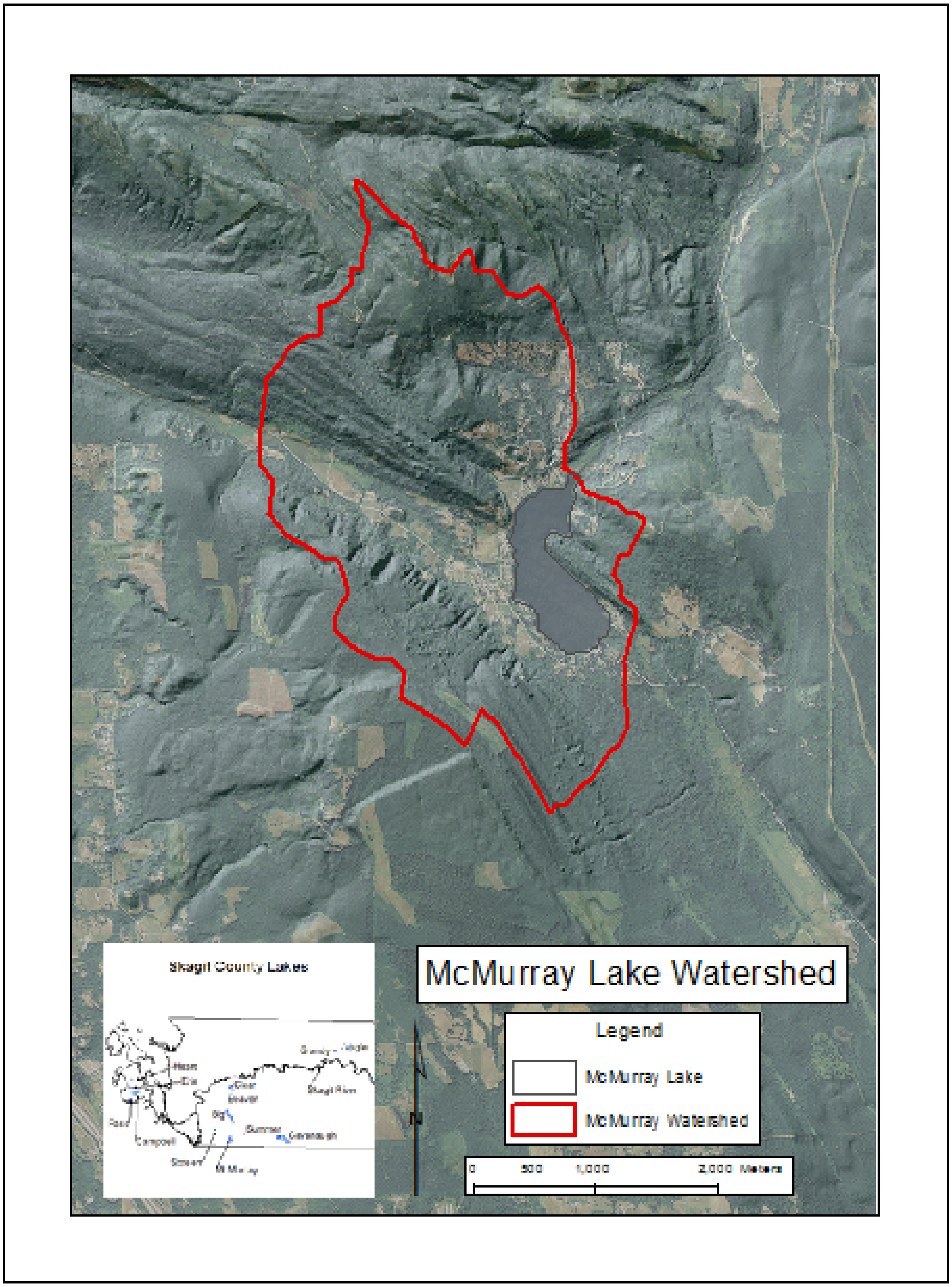


Figure 51. McMurray Lake watershed, Skagit County, WA.

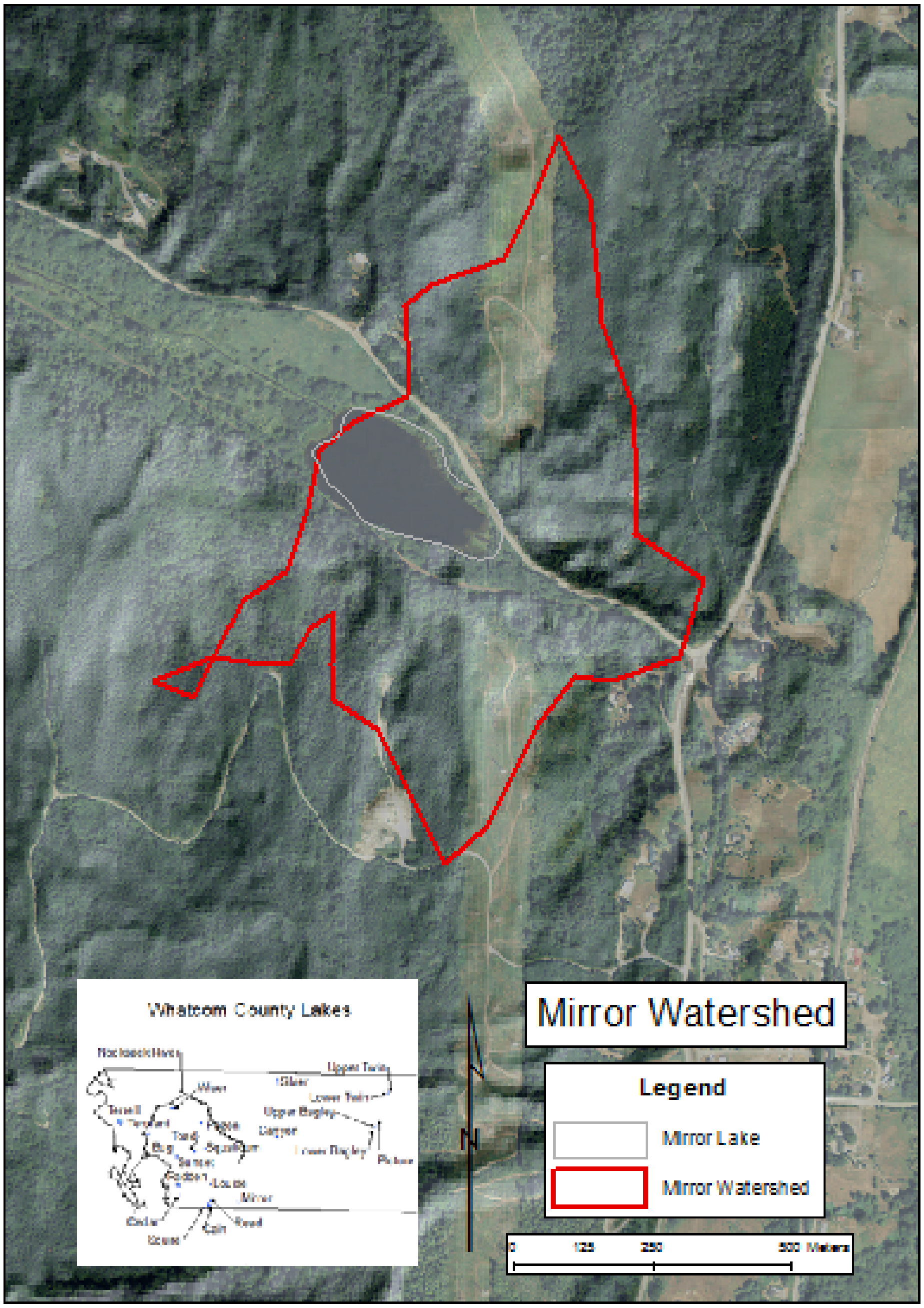


Figure 52. Mirror Lake watershed, Whatcom County, WA.

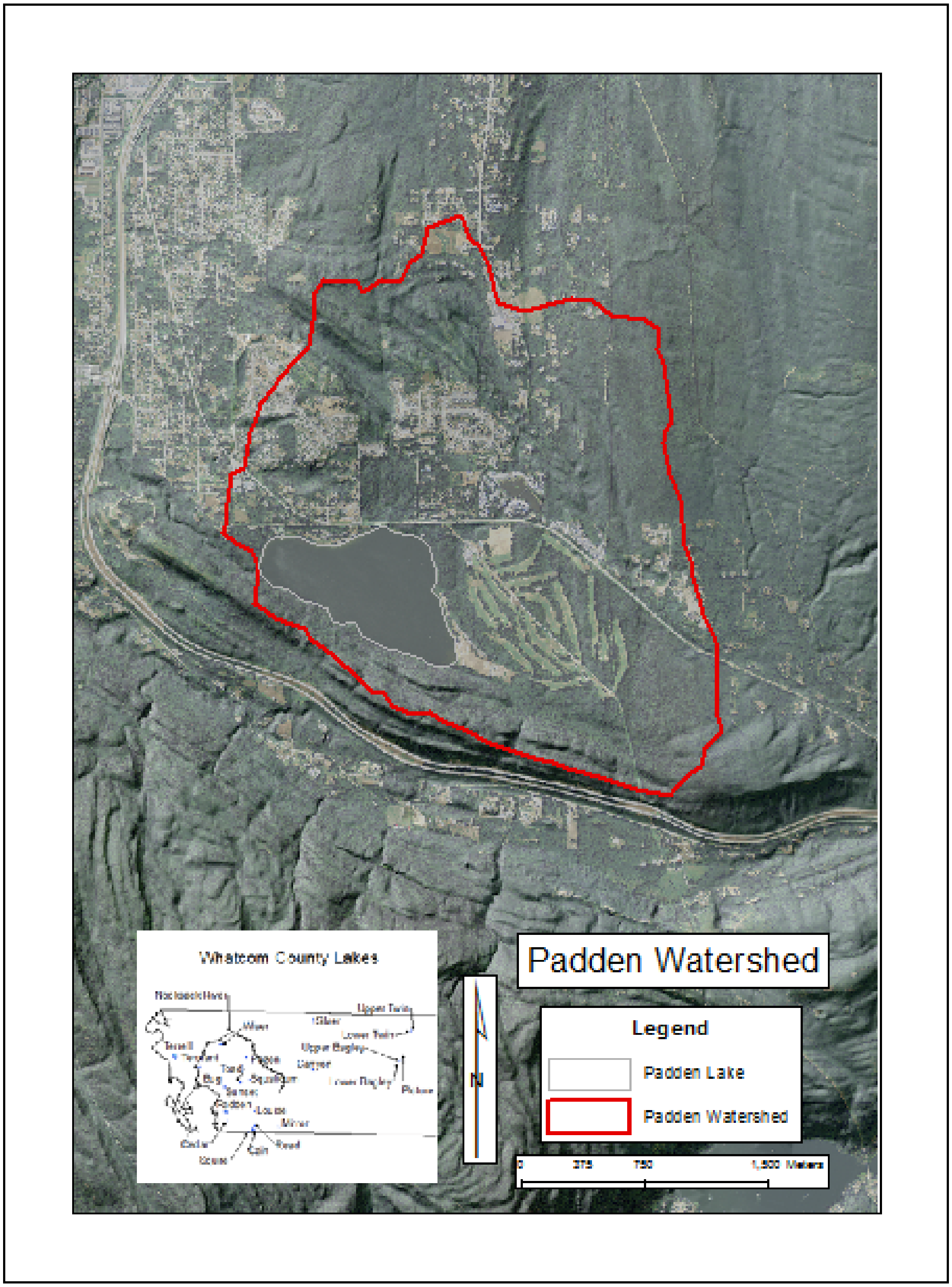


Figure 53. Padden Lake watershed, Whatcom County, WA.

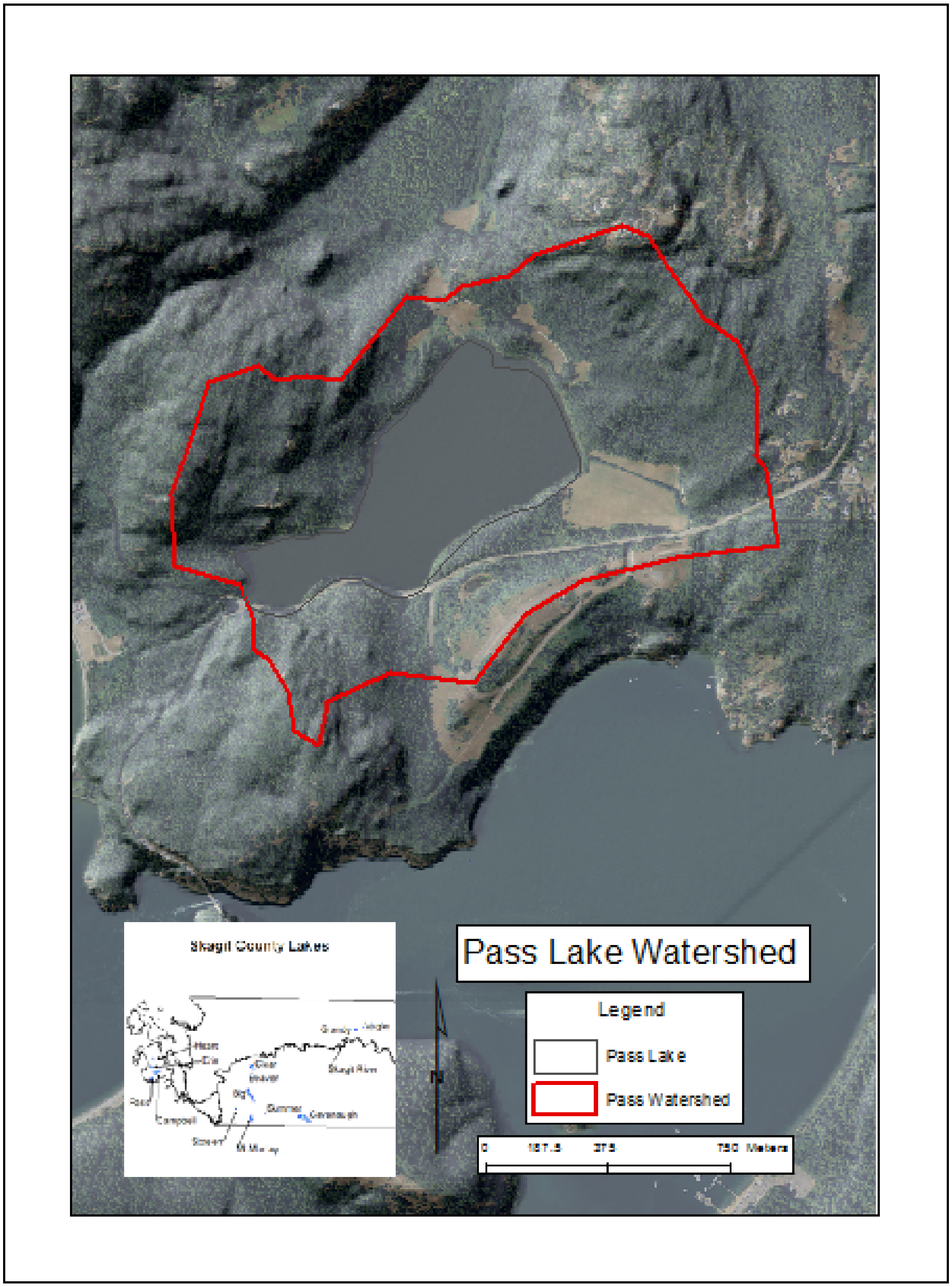


Figure 54. Pass Lake watershed, Skagit County, WA.

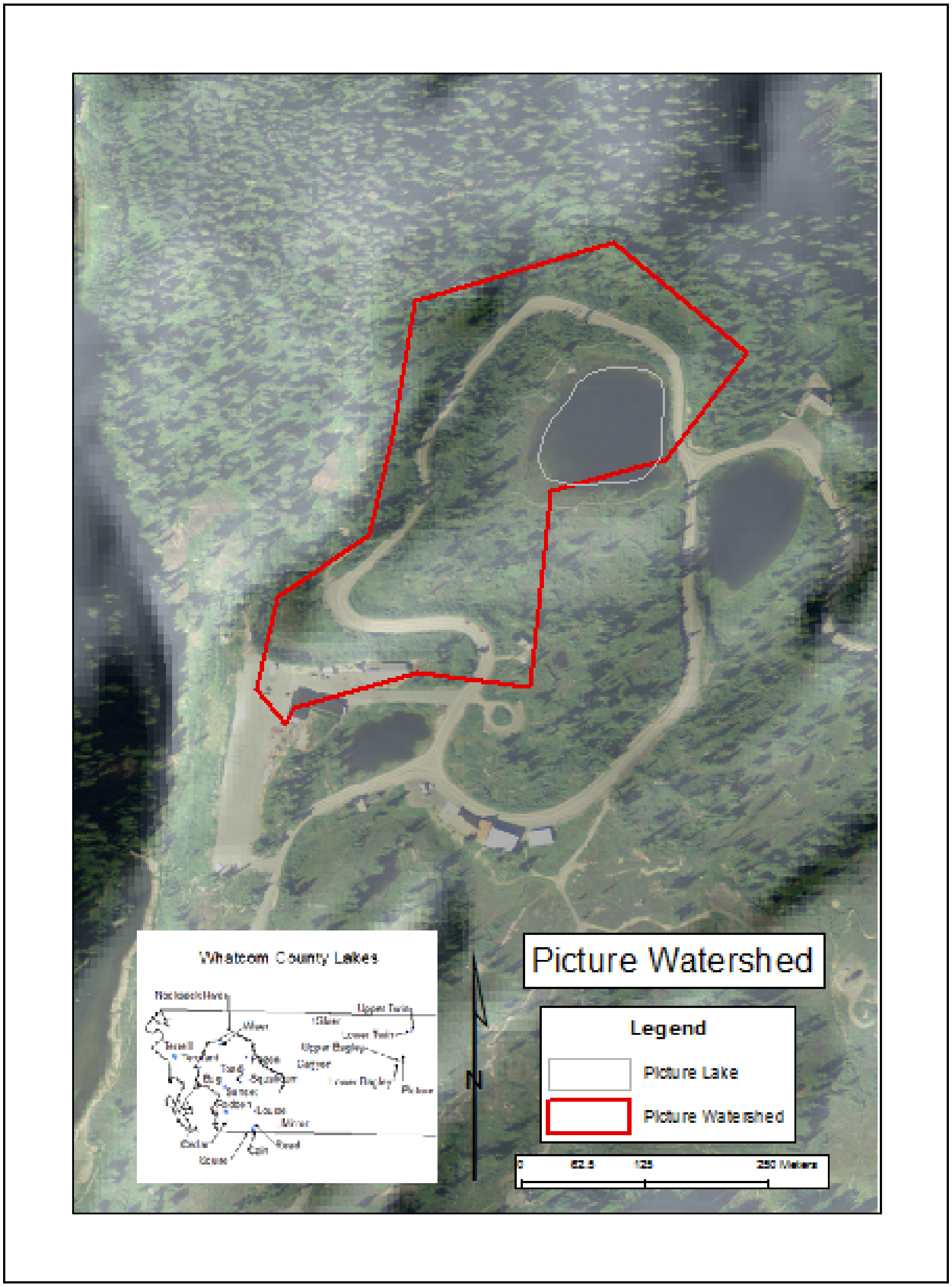


Figure 55. Picture Lake watershed, Whatcom County, WA.

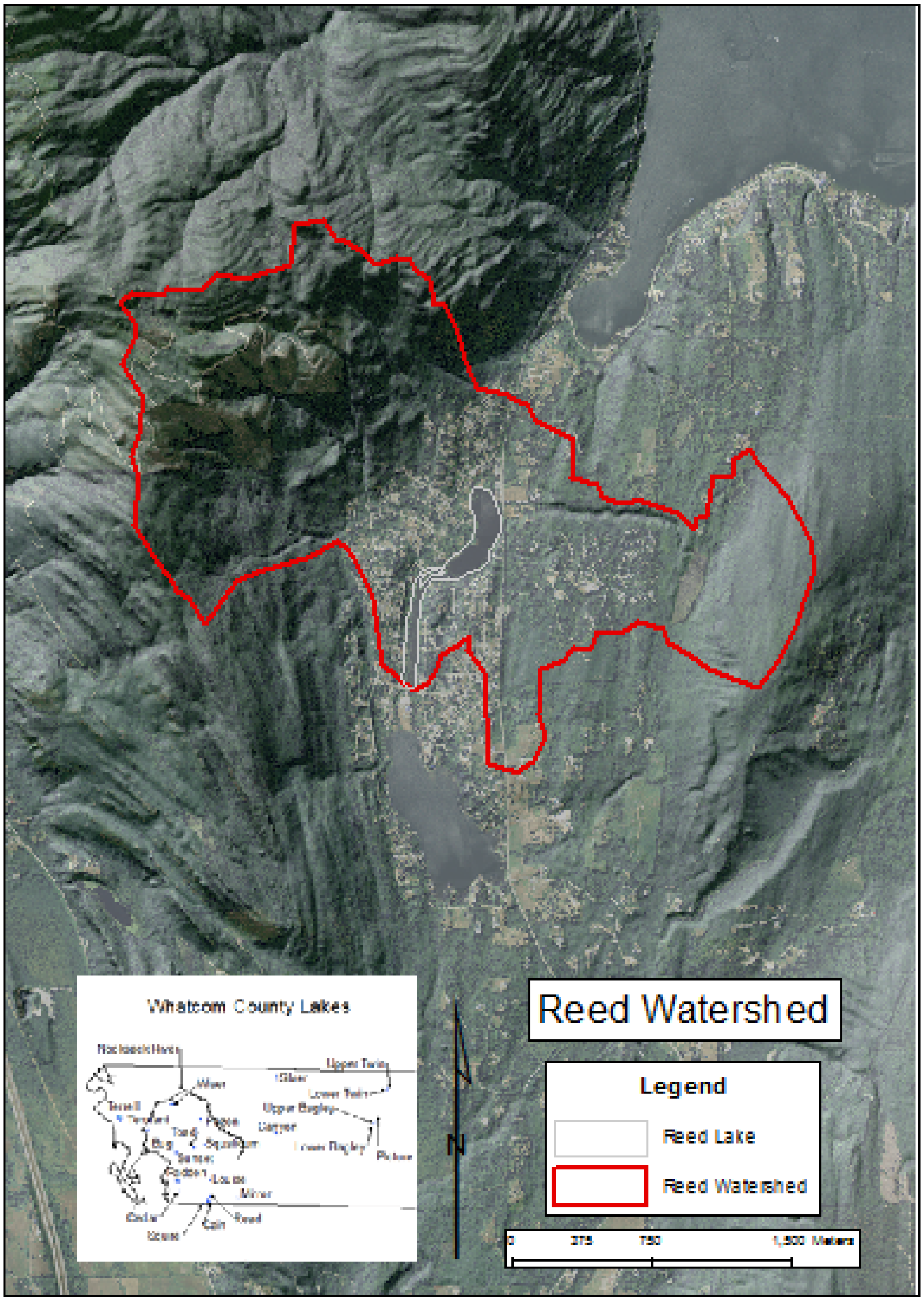


Figure 56. Reed Lake watershed, Whatcom County, WA.

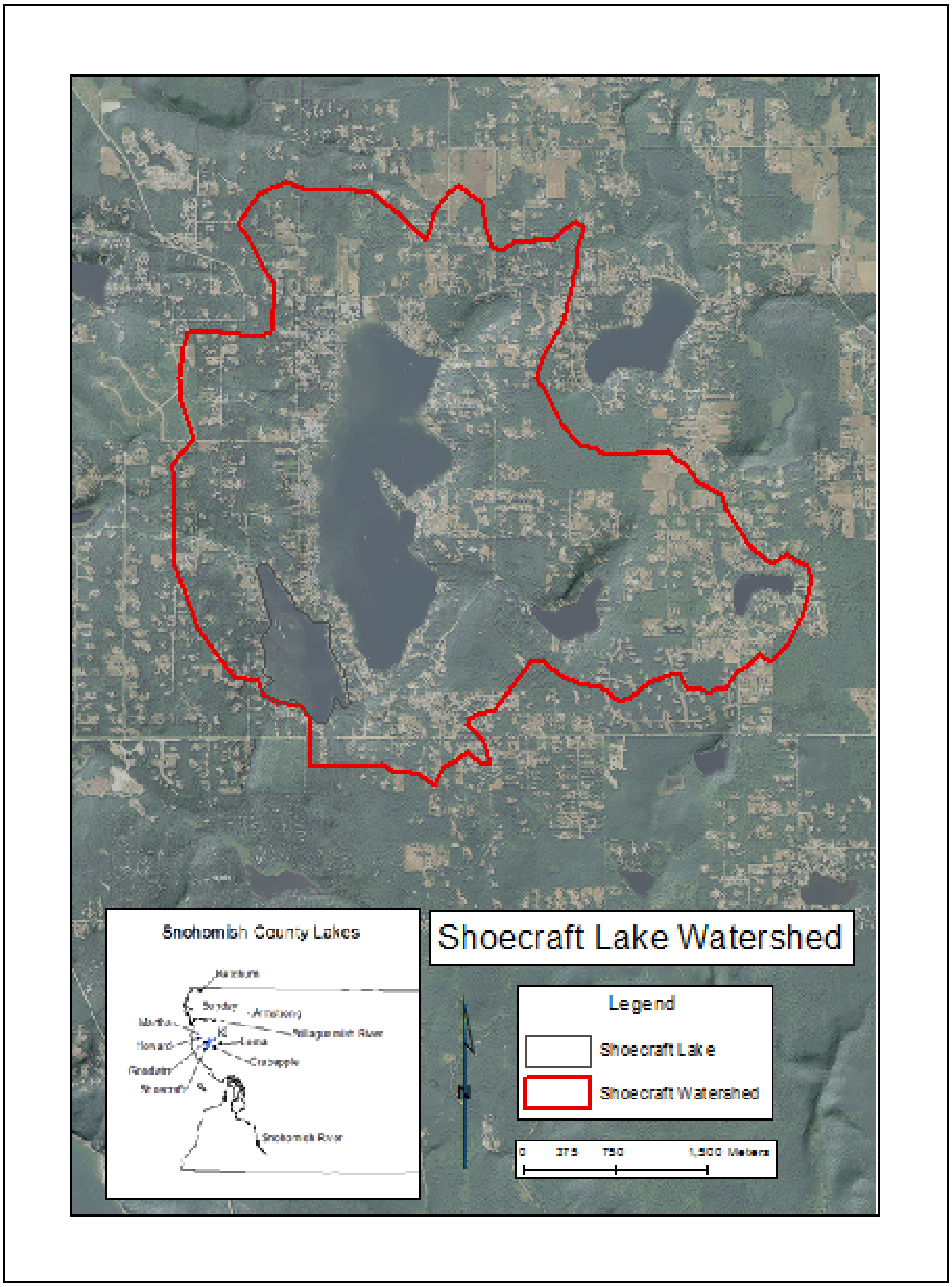


Figure 57. Shoecraft Lake watershed, Snohomish County, WA.

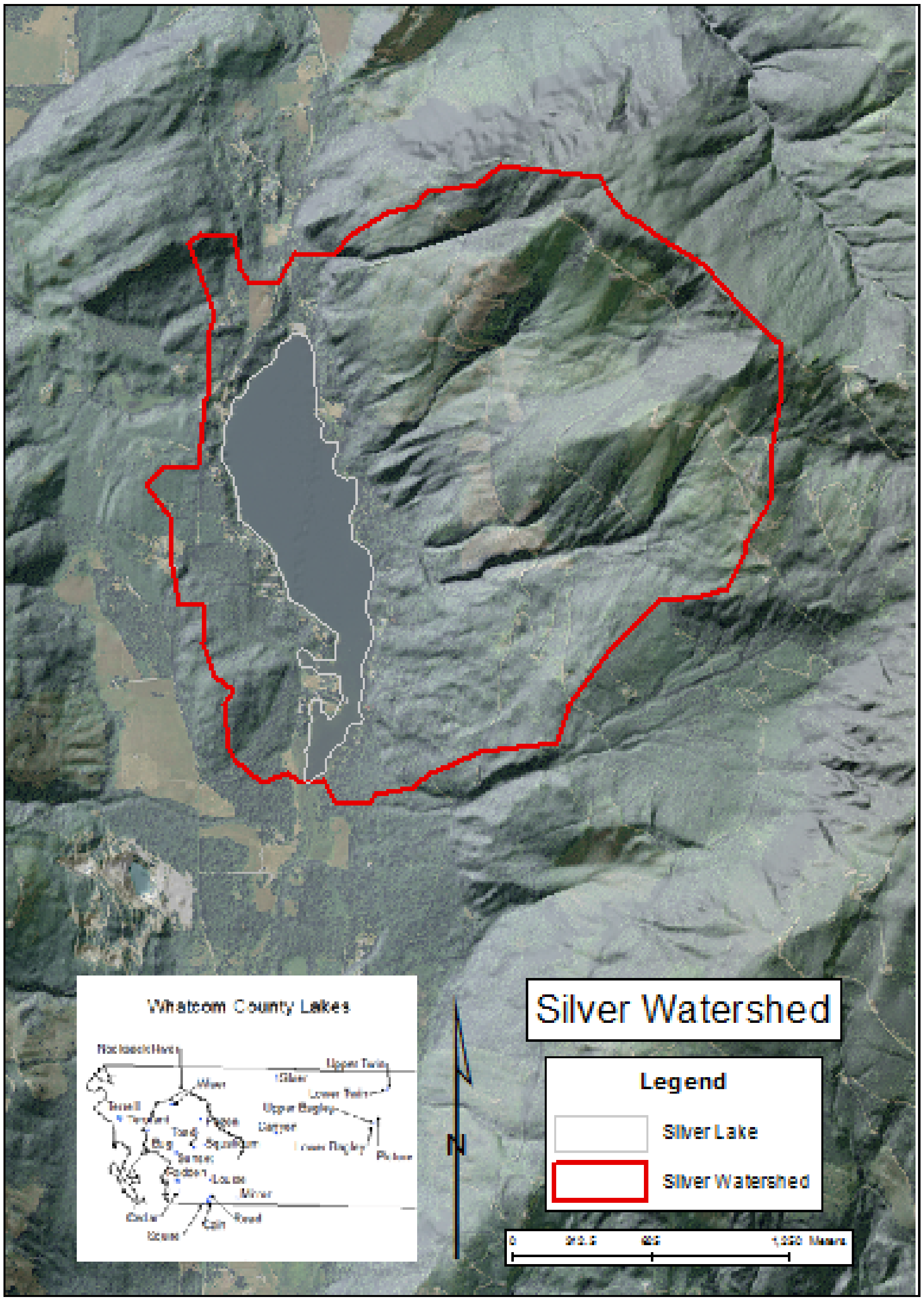


Figure 58. Silver Lake watershed, Whatcom County, WA.

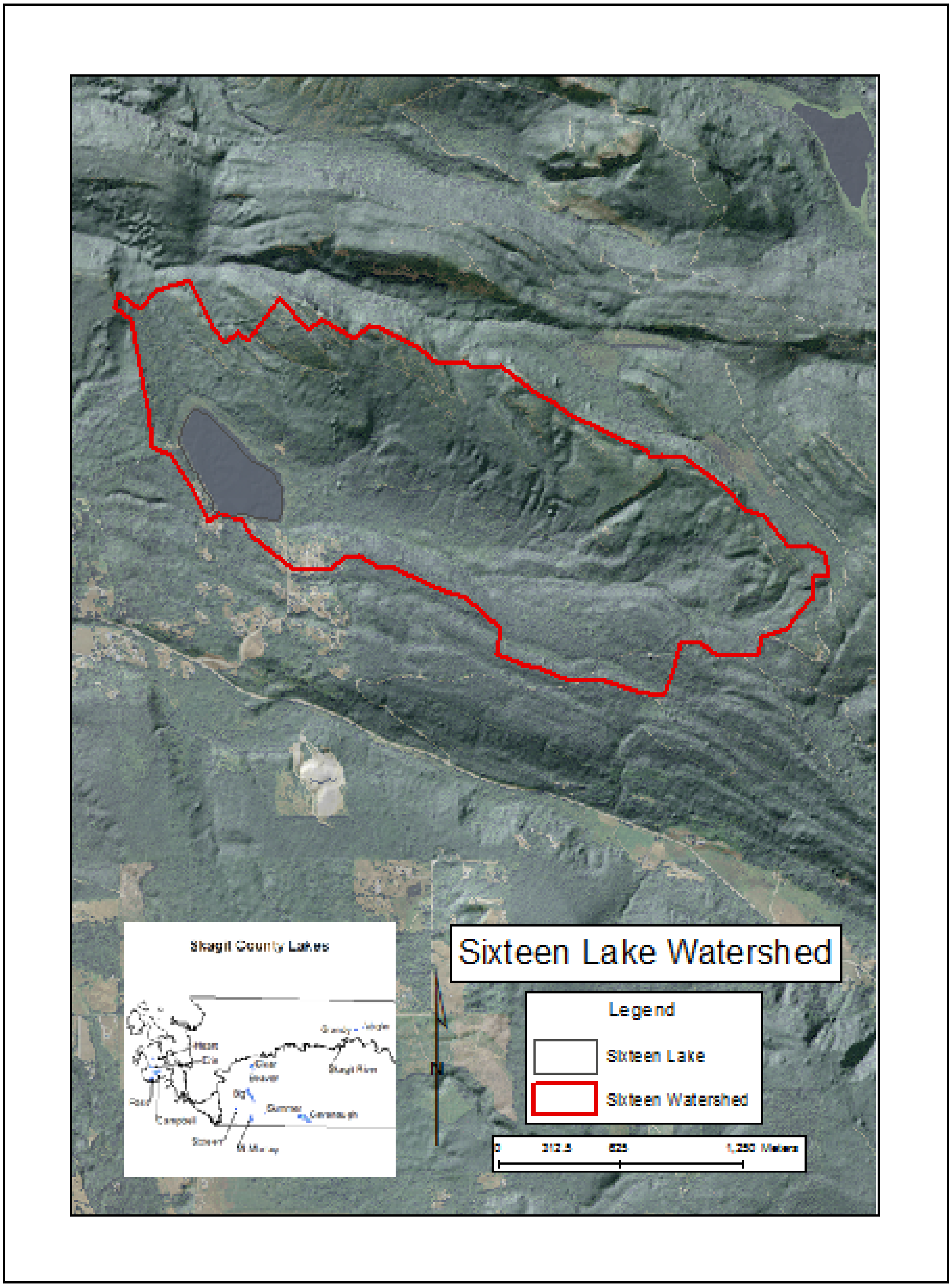


Figure 59. Sixteen Lake watershed, Skagit County, WA.

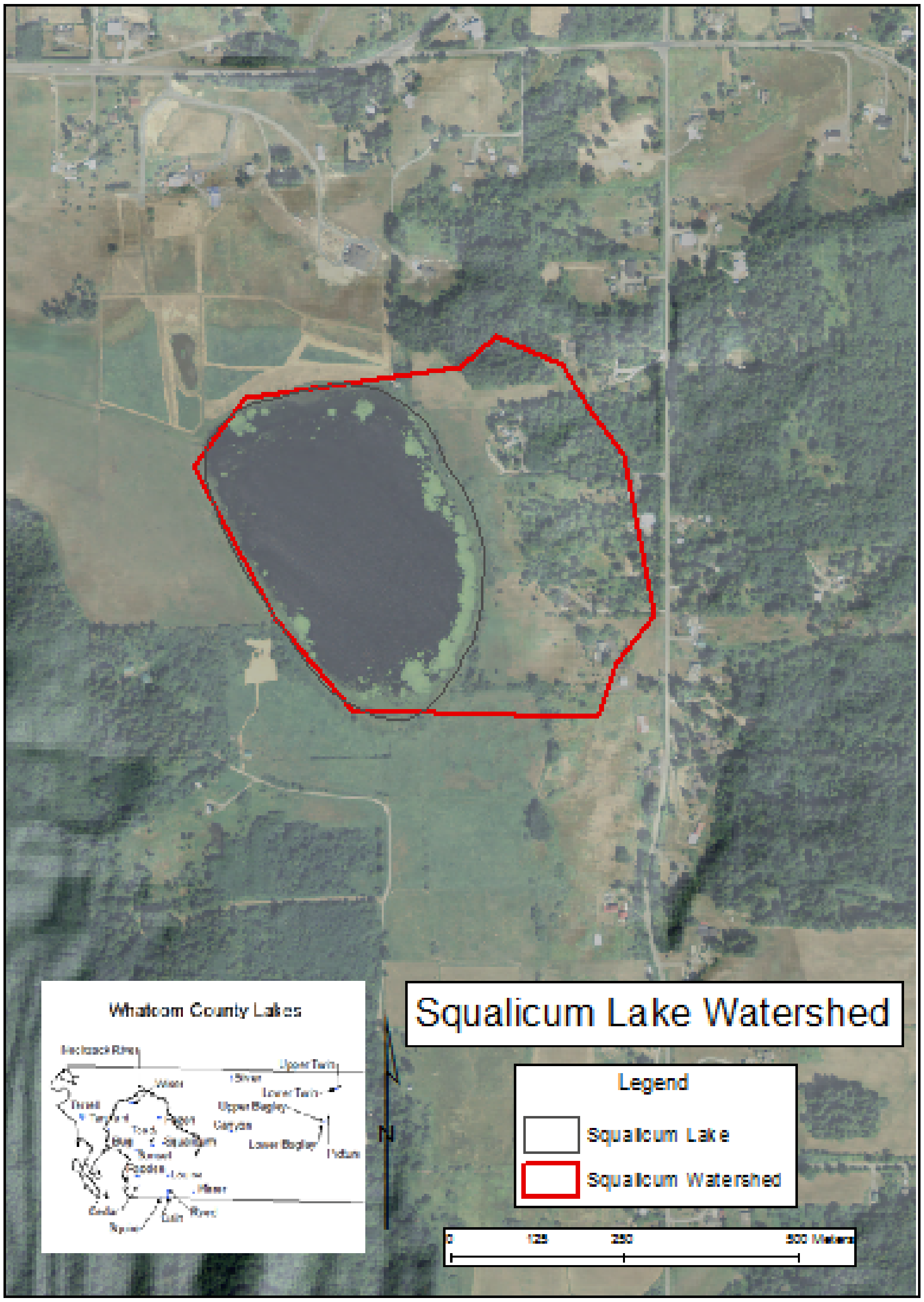


Figure 60. Squalicum Lake watershed, Whatcom County, WA.

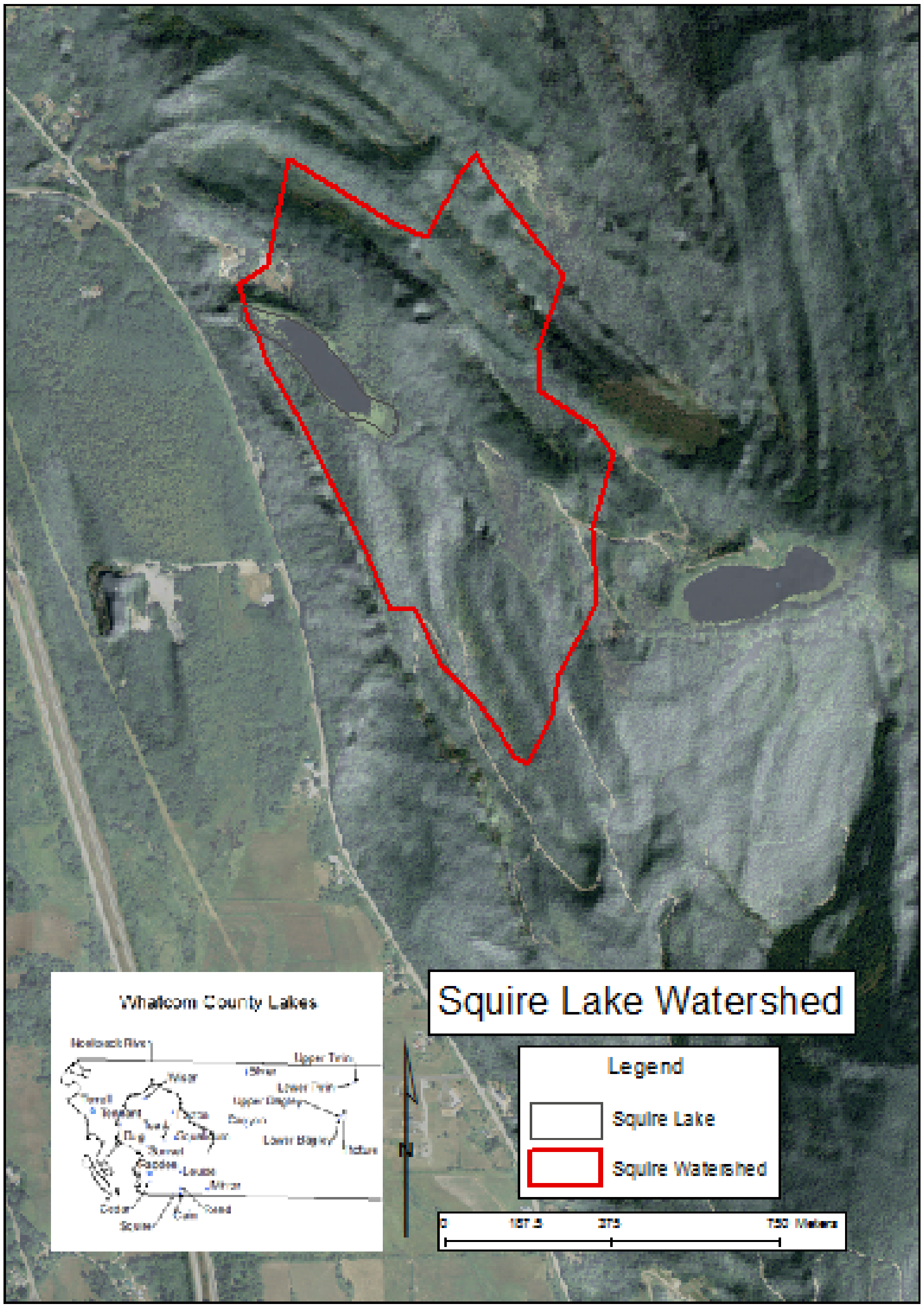


Figure 61. Squire Lake watershed, Whatcom County, WA.

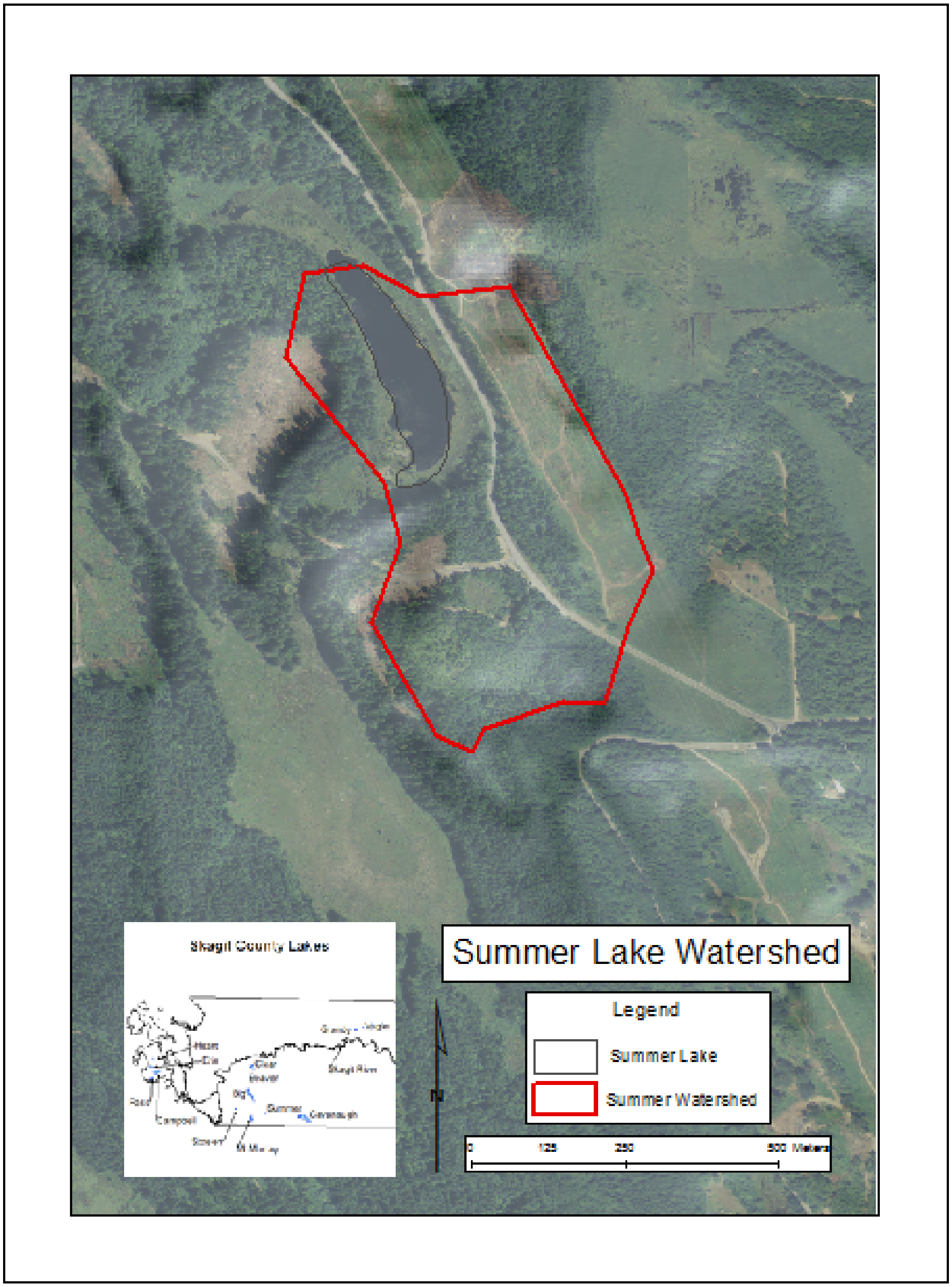


Figure 62. Summer Lake watershed, Skagit County, WA.

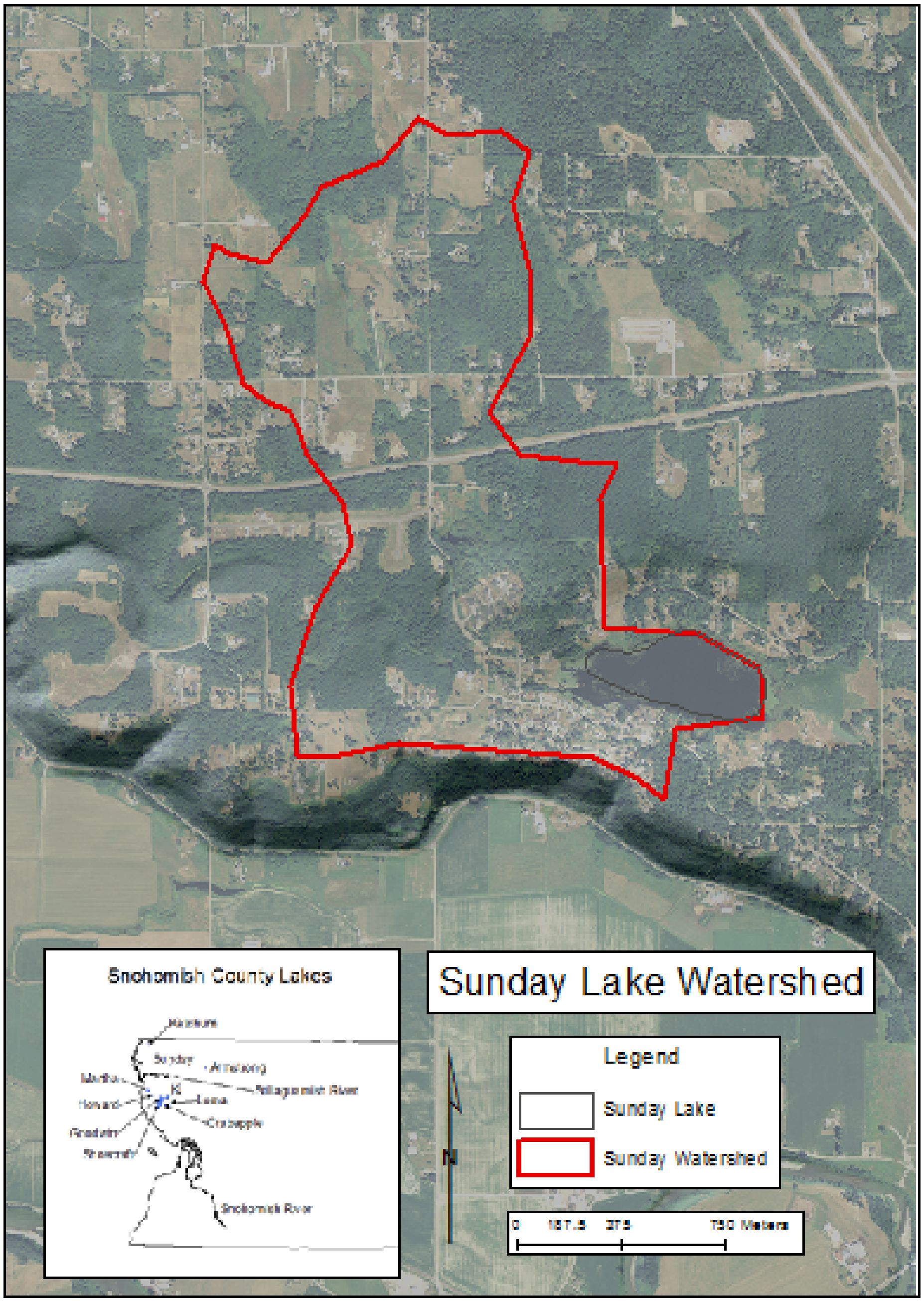


Figure 63. Sunday Lake watershed, Snohomish County, WA.

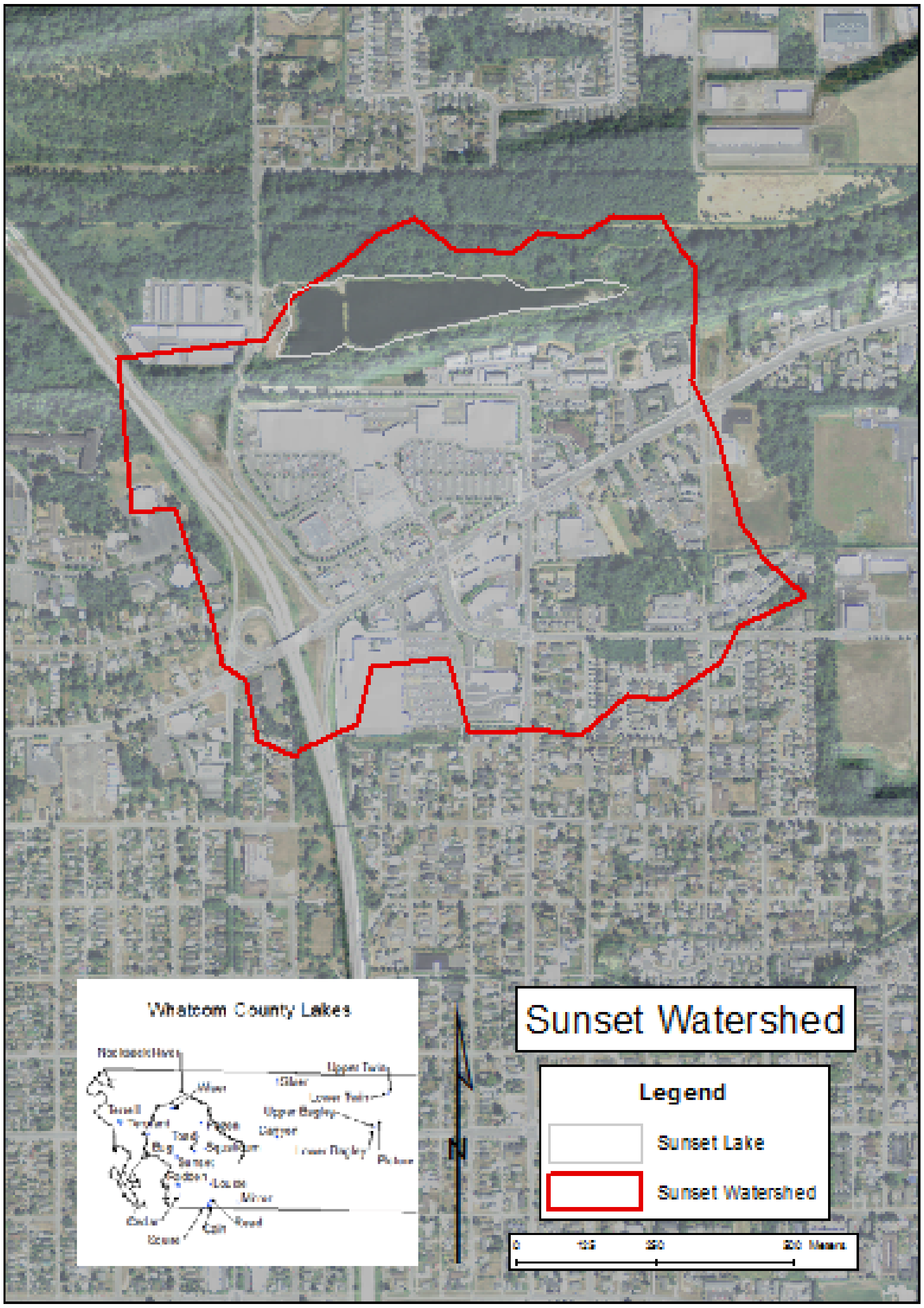


Figure 64. Sunset Lake watershed, Whatcom County, WA.

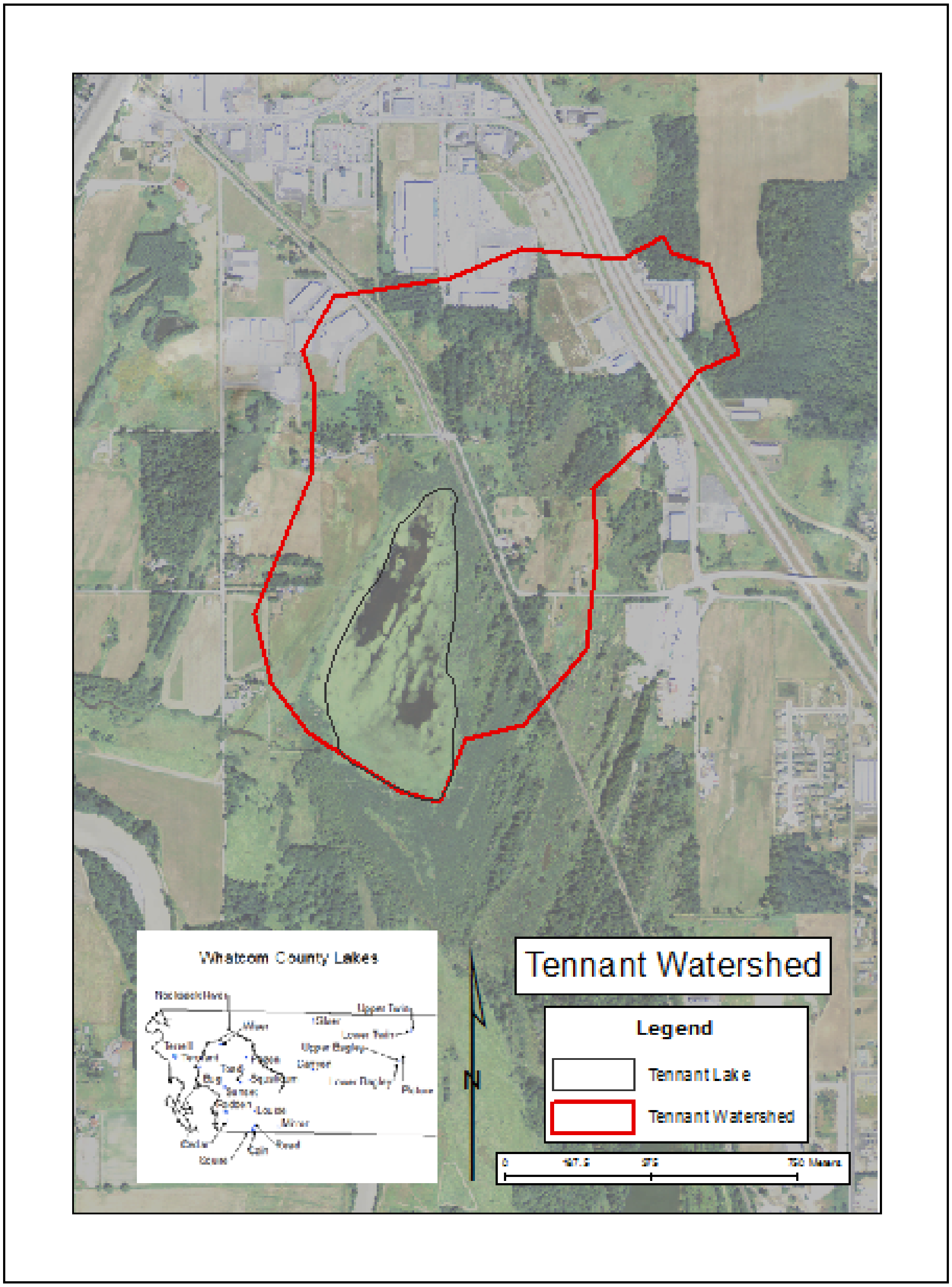


Figure 65. Tennant Lake watershed, Whatcom County, WA.

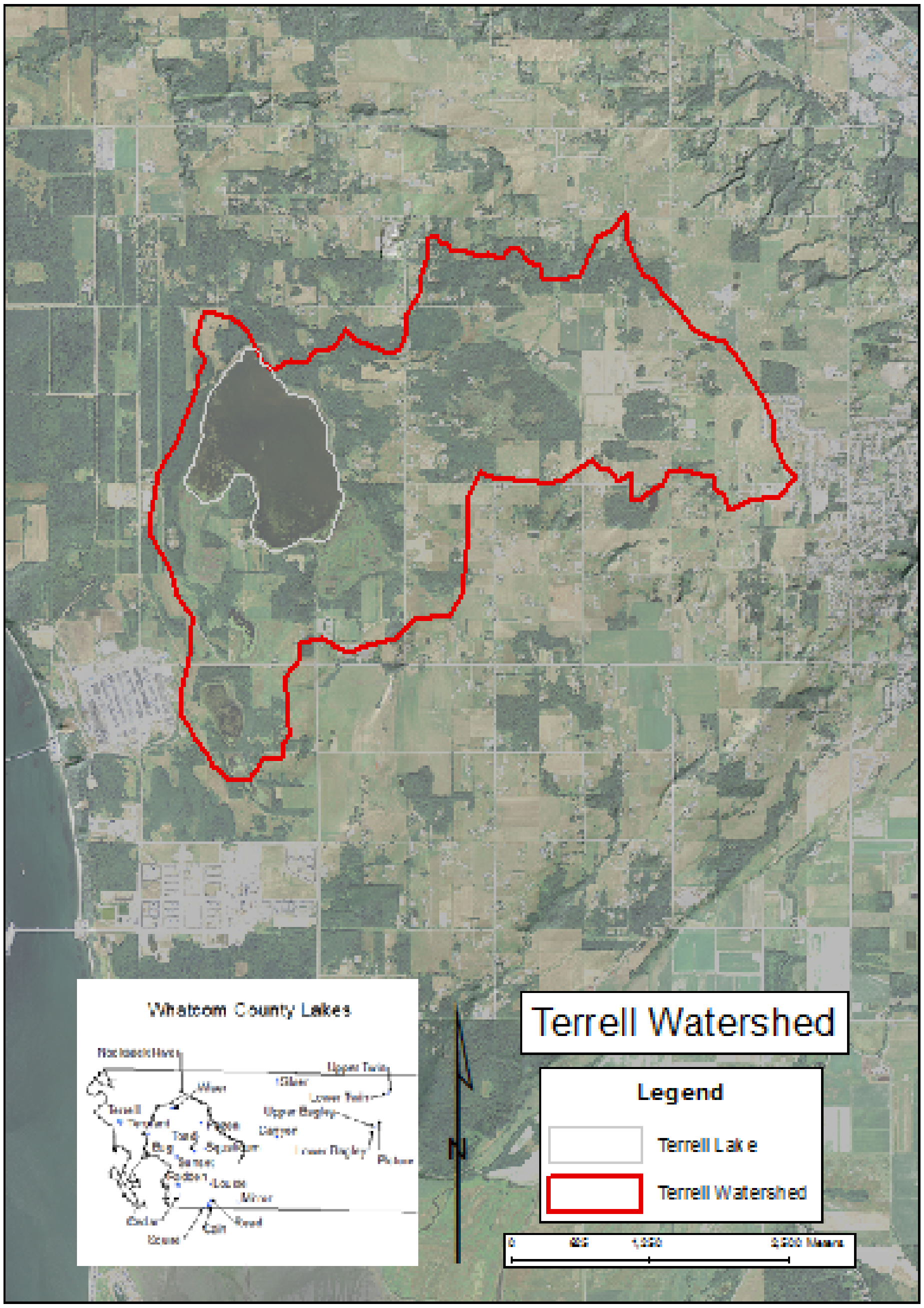


Figure 66. Terrell Lake watershed, Whatcom County, WA.

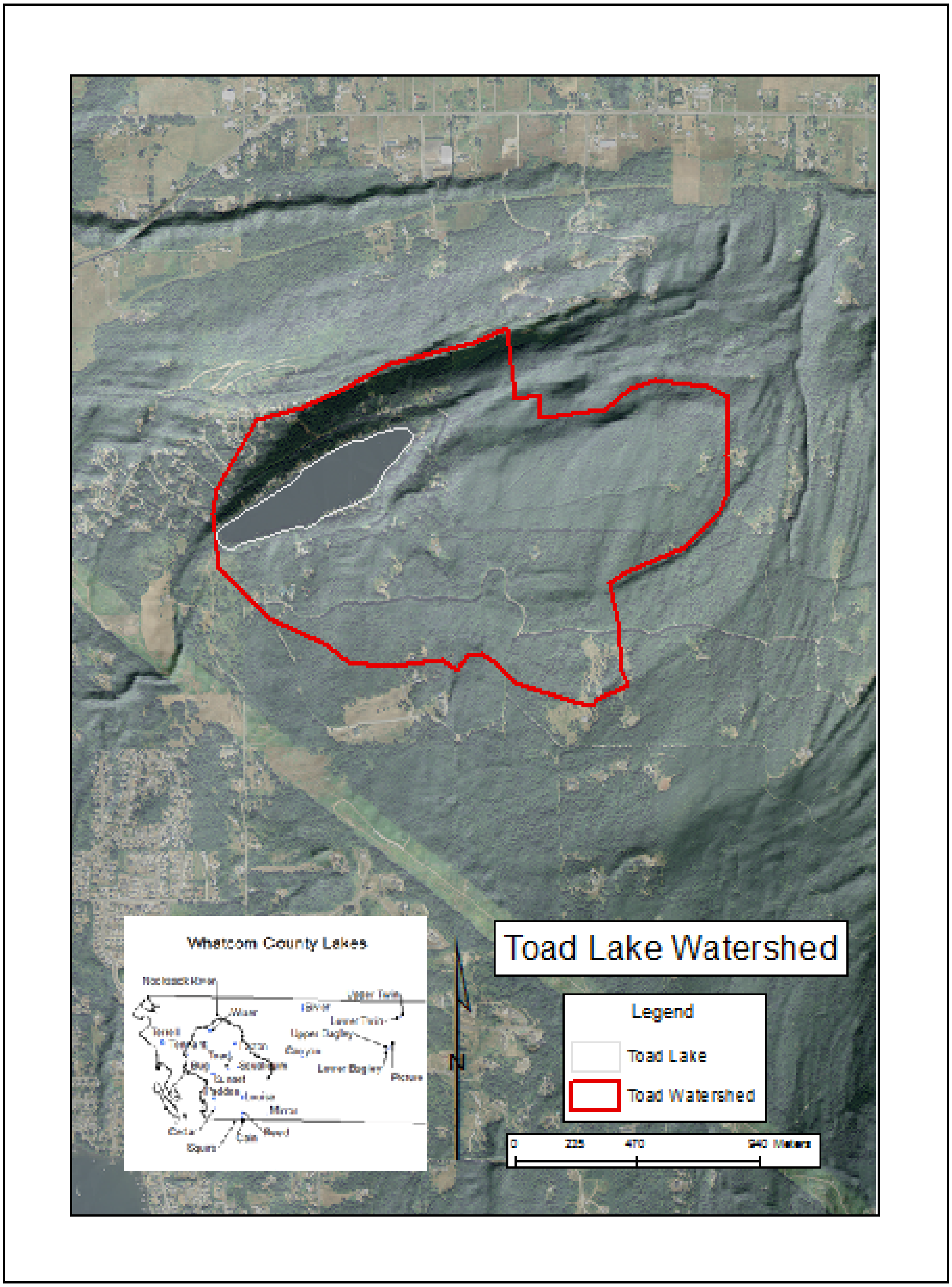


Figure 67. Toad Lake watershed, Whatcom County, WA.

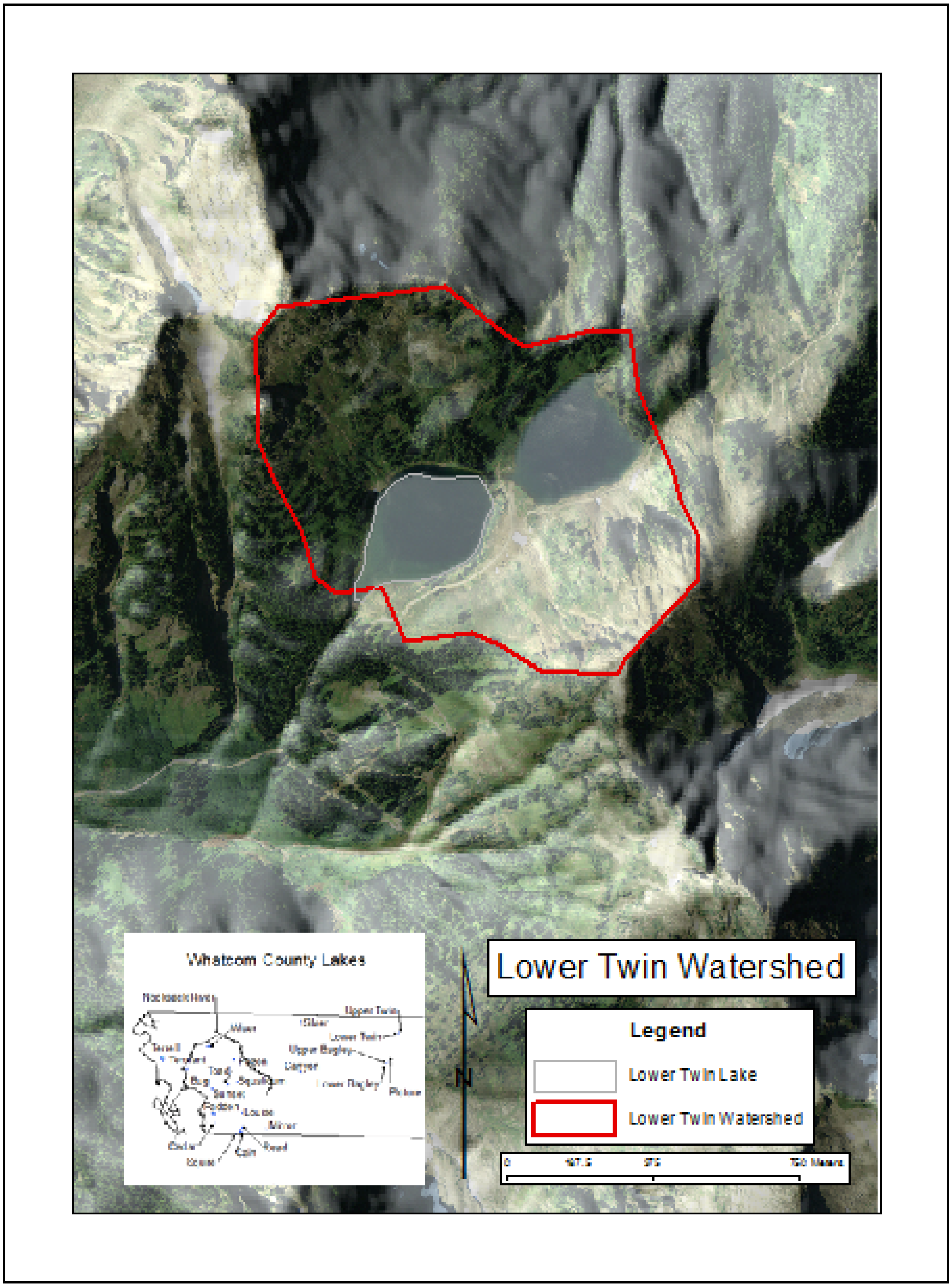


Figure 68. Lower Twin Lake watershed, Whatcom County, WA.

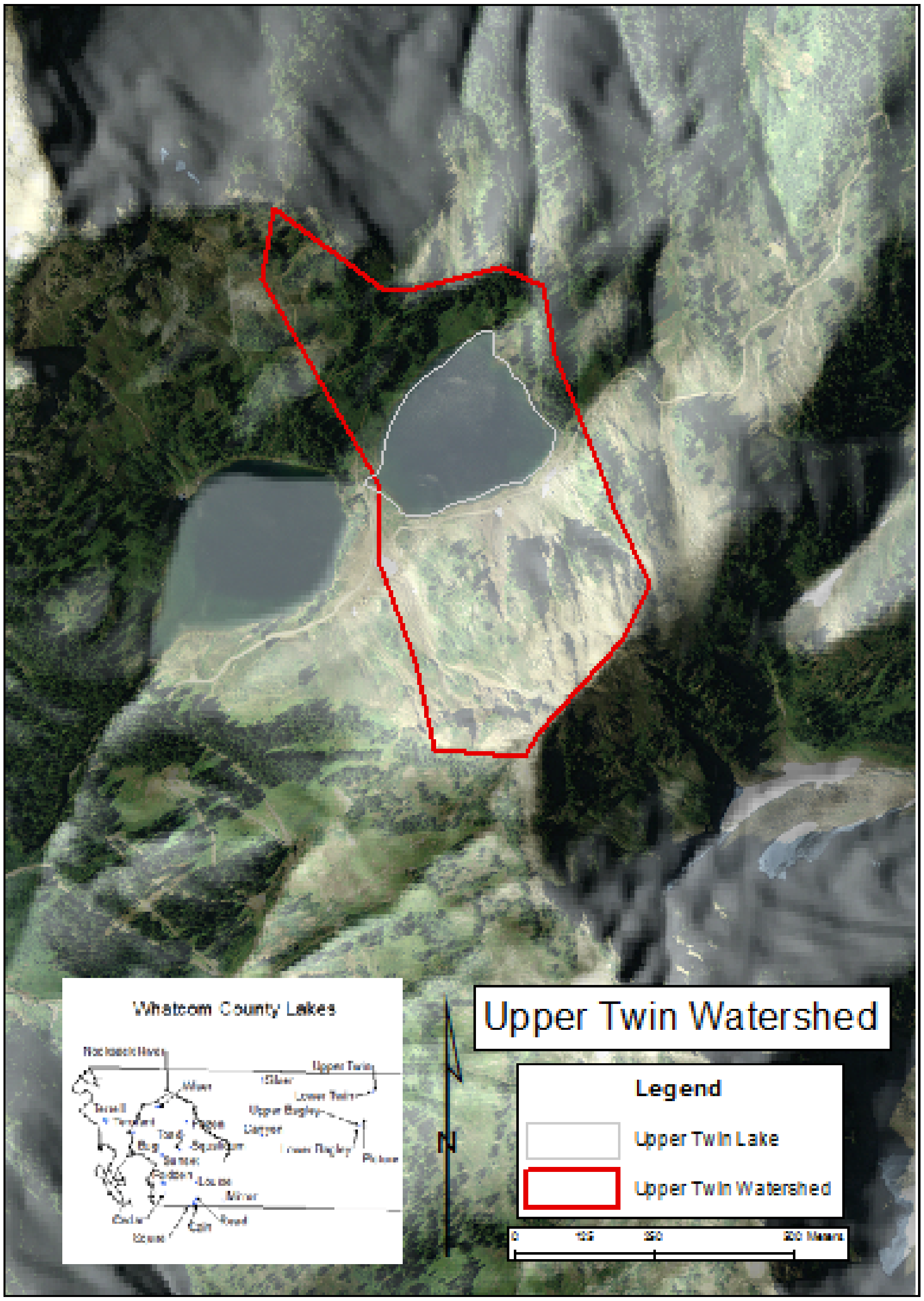


Figure 69. Upper Twin Lake watershed, Whatcom County, WA.

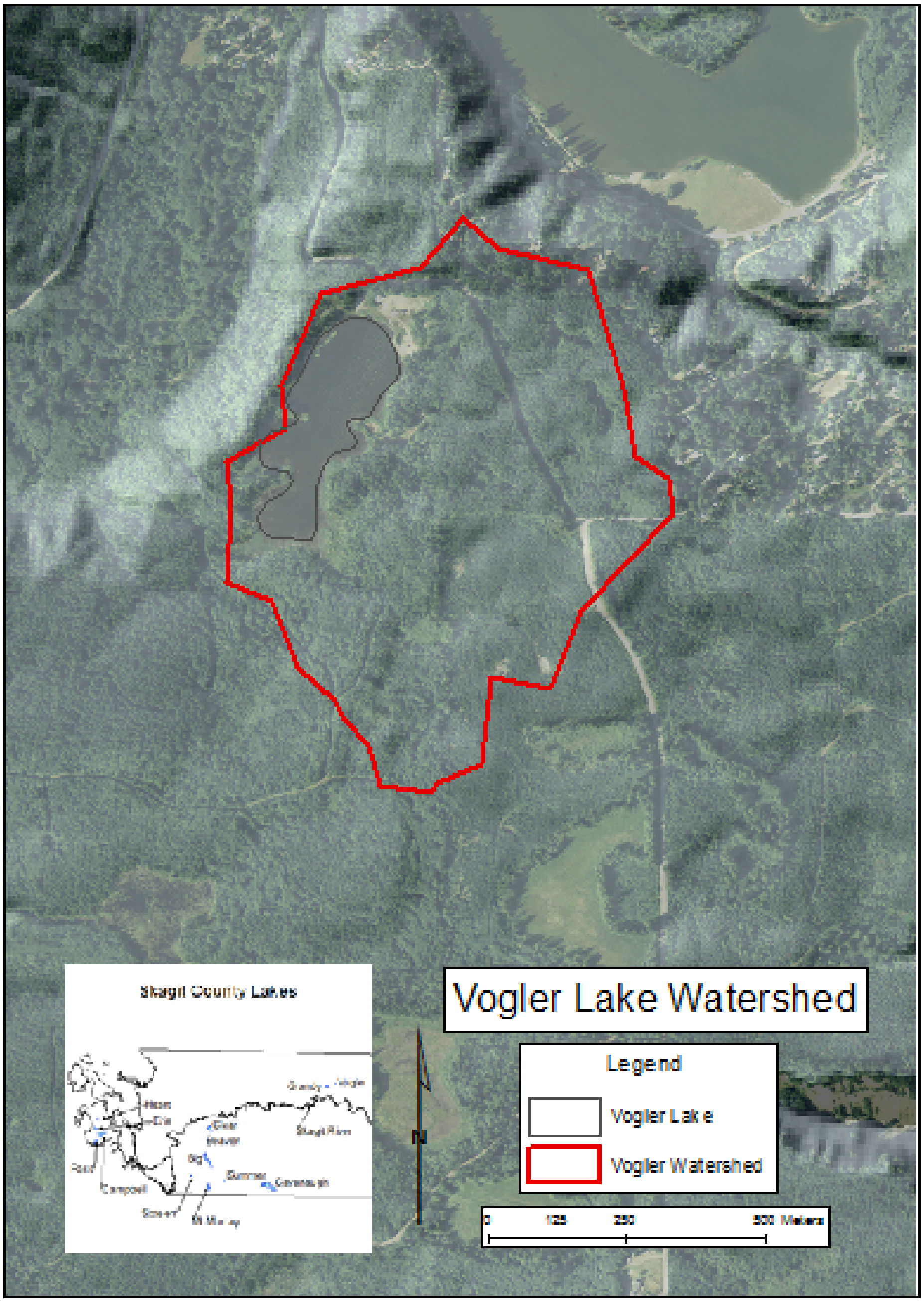


Figure 70. Vogler Lake watershed, Skagit County, WA.

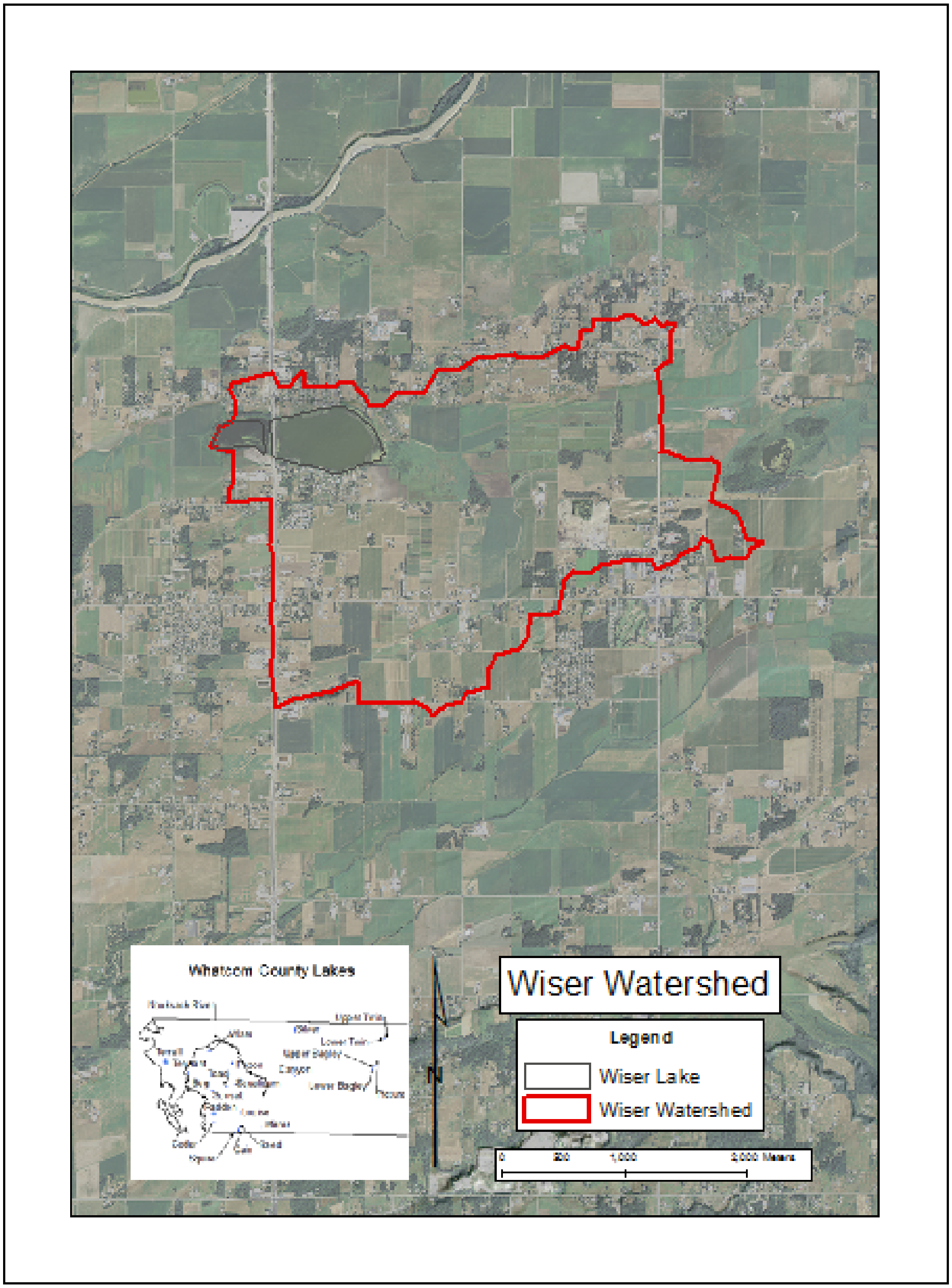


Figure 71. Wiser Lake watershed, Whatcom County, WA.