Sediment and phosphorus inputs from perennial streams to Lake Whatcom, northwestern Washington State

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SEDIMENT AND PHOSPHORUS INPUTS FROM PERENNIAL STREAMS TO LAKE WHATCOM, NORTHWESTERN WASHINGTON STATE

By
Katherine Beeler

Accepted in Partial Completion
Of the Requirements for the Degree
Master of Science

Kathleen Kitto, Dean of the Graduate School

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MASTER’S THESIS

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Katherine Beeler

November 14, 2014
SEDIMENT AND PHOSPHORUS INPUTS FROM PERENNIAL STREAMS TO LAKE WHATCOM, NORTHWESTERN WASHINGTON STATE

A Thesis
Presented to
The Faculty of
Western Washington University

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

By
Katherine Beeler
November 2014
Abstract

Nutrient enrichment presents a common problem in lakes and streams by promoting algae growth and the depletion of dissolved oxygen. Lake Whatcom in northwestern Washington State is subject to a Total Maximum Daily Load (TMDL) to limit phosphorus input. The 20-km² lake is supported by runoff from numerous perennial streams in a steep, 125-km², moderately developed, forested watershed. Much of the phosphorus entering the lake is adsorbed to suspended sediment in streams and is transported to the lake during storm events. Understanding sediment and phosphorus transport to the lake is important for managing the TMDL and for maintaining water quality in general because the lake serves as the drinking water source for about 100,000 people.

My objectives were to calculate sediment and phosphorus fluxes into Lake Whatcom and examine relationships among precipitation, discharge, sediment concentrations, and phosphorus concentrations. I collected a series of water samples near the mouth of Smith Creek in the Lake Whatcom watershed during 22 storm events between February 2013 and January 2014. The samples were analyzed for total suspended solids and total phosphorus. I used data from Smith Creek and four other streams to examine the effects of varying basin features on loading and to develop sediment-discharge and phosphorus-discharge models to estimate loading to the lake during the 2013 water year.

Relationships among sediment, phosphorus, and discharge varied temporally and spatially in the watershed. During most storm events, the sediment peak preceded the discharge peak, indicating that transport was limited by sediment availability. In Smith Creek, the magnitude of hydrograph rise was the best predictor of the maximum sediment concentration during the event. Among the five streams studied, sediment yields ranged from 11.5 to 143
tonnes/km²/year. The steep, forested Smith Creek basin yielded the most sediment per area. Phosphorus yields ranged from 25.7 to 68.5 kg/km²/year, with the highest phosphorus yield coming from a small, low-relief basin containing 29% residential development. My sediment and phosphorous yields were comparable to estimates from similar streams in the Puget Sound region. Total suspended solids and total phosphorus were significantly correlated to discharge in most streams in the watershed, but variability within and among storm events resulted in uncertainty when calculating fluxes based on discharge. Continuous turbidity monitoring could allow for improved models and flux estimates.
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1.0 Introduction

Nutrient pollution is a widespread problem in lakes and streams. High levels of nutrients are one of the most common causes of lake impairment in the United States, affecting about 18% of the total lake area classified as impaired or threatened (EPA, 2014). Elevated concentrations of nutrients can lead to excessive algae and plant growth, which can be damaging to water quality and ecosystem health. Phosphorus, along with nitrogen, is one of the major nutrients of concern. Phosphorus has both natural and anthropogenic sources and moves through the environment in complex biogeochemical cycles (Lee, et al., 2012). Understanding phosphorus transport in watersheds is important for analyzing and addressing the water quality problems that can result from high phosphorus concentrations in surface water. In this study, I examined stream phosphorus and sediment concentrations in a watershed in the Pacific Northwest to better understand relationships among phosphorus, sediment, and streamflow.

Lake Whatcom is located in northwestern Washington State, just east of the city of Bellingham (Figure 1). Inputs of phosphorus have caused lake water quality to decline because phosphorus promotes algae growth and decomposition of organic matter, leading to depletion of dissolved oxygen (Pickett & Hood, 2008). As such, Lake Whatcom is listed as impaired by the United States Environmental Protection Agency, which is problematic because the lake serves as the drinking water source for about 100,000 people in Bellingham and surrounding areas (Hood, 2013). Phosphorus largely enters the lake adsorbed to suspended sediment (Matthews, et al., 2013).

The Clean Water Act requires that states maintain their own sets of standards to protect, restore, and preserve water quality. Every two years, each state must prepare a list (303(d) list) of water bodies that do not meet water quality criteria and develop a Total Maximum Daily Load
The Total Maximum Daily Load (TMDL) for each water body on the list. The TMDL specifies the amount of a given pollutant that can be discharged to the water body and allocates the acceptable load among different sources. In Washington State, 195 of the 324 lakes currently listed because of water quality concerns are listed for phosphorus (Ecology, 2014a).

Lake Whatcom is included on the Washington State 303(d) list and is subject to a TMDL to limit the amount of phosphorus entering the lake. The Washington State Department of Ecology (Ecology) added Lake Whatcom to the state’s 303(d) list in 1998 after finding evidence that dissolved oxygen concentrations were declining. Ecology has published two technical reports summarizing the assessment of the Lake Whatcom TMDL. The Ecology authors of the first report (Volume 1; Pickett & Hood, 2008) used a landcover-based phosphorus loading model coupled with a lake water quality and hydrodynamic model to determine the total amount of phosphorus that can be discharged to Lake Whatcom without causing dissolved oxygen concentrations to drop below acceptable levels. The phosphorus loading model was based on weather and land use conditions from the 2003 water year (WY) and calibrated to measured streamflow and phosphorus concentrations. The study was limited in that 2002-2003 was an unusually dry year, the calibration included a relatively small amount of phosphorus data, and sediment loading was not calculated (Figure 2; Cadmus & CDM, 2007).

The second report (Volume 2; Hood, 2013) set phosphorus reduction goals, established phosphorus loading allocations for each subbasin, and outlined an implementation strategy to achieve water quality standards. Loading goals were set to represent the amount of phosphorus the lake could assimilate during a year based on the precipitation, temperature, and wind conditions that occurred during WY 2003. Achieving the TMDL goals will require reducing total phosphorus loading from streams from 3,958 kg/2003 year to 2,534 kg/2003 year. Phosphorus
inputs from groundwater, direct precipitation onto the lake, and water diverted from the Middle Fork of the Nooksack River were considered in the models, but allowable loads were not specified for these sources. The next period of model recalibration is scheduled to begin in 2018 (Hood, 2013).

The goal of my study was to provide information that could be incorporated into future sediment and phosphorus loading models for the Lake Whatcom watershed, potentially improving model calibrations and mitigation strategies. Data collected during storms are particularly useful because the amount of sediment and phosphorus transport is normally higher during periods of elevated streamflow. I used the results of high-resolution storm event sampling along with hydrologic and other watershed data to determine relationships among total phosphorus (TP), total suspended solids (TSS), and stream discharge within the Lake Whatcom watershed. I examined how these relationships varied within and among storm events and among different streams in the watershed and developed a set of linear models to estimate fluxes of phosphorus and suspended sediment to the lake during the 2013 water year.

2.0 Background

2.1 Lake Whatcom Watershed

2.1.1 Lake and Watershed Characteristics

Lake Whatcom is of glacial origin and has a surface area of 20.3 square kilometers (km²). The lake consists of distinct basins separated by sills. Basin 3 is located south of Basins 1 and 2 and contains about 96% of the lake’s total volume. The Sunnyside Sill further divides Basin 3 into a relatively deep southern basin (Basin 3S) and a relatively shallow northern basin (Basin 3N).
Compared to Basins 1 and 2, Basins 3S and 3N are deeper and have greater surface area (Mitchell, et al., 2010; Figure 3).

Lake Whatcom has a watershed area of about 126 km², not including the lake itself (Pickett & Hood, 2008; Figure 1). The watershed is high-relief, with elevations ranging from 95 to 1027 meters (m) above mean sea level (Mitchell, et al., 2010). Steep slopes occur throughout the watershed (Figure 4). The underlying geology consists of two bedrock units: the Eocene Chuckanut Formation and the Jurassic Darrington Phyllite, as well as unconsolidated glacial and alluvial sediments (Lapen, 2000; Figure 5). Soils in the watershed include the Chuckanut, Sehome, Squalicum, Squires, and Wickersham series and are mainly classified as loam, with some areas of loamy sand and silty loam (NRCS, 1992; Miller & White, 1998; Kelleher, 2006; Groce, 2011; Figure 6). Most of the watershed (81%) is vegetated with a combination of deciduous, evergreen, and mixed forest. Residential development covers an additional 7% of the watershed, with the remainder mostly consisting of shrubland, grassland, and wetland (NOAA, 2011). Less than 1% of the watershed area is used for agriculture. Developed areas are mostly concentrated at the northwest end of Lake Whatcom where the watershed intersects the City of Bellingham and in Sudden Valley along the central west side of the lake (Figure 7). These areas also contain the highest density of roads in the watershed (Figure 8).

Water enters Lake Whatcom through surface runoff, groundwater, direct precipitation onto the lake, and diversion from the Middle Fork of the Nooksack River (Matthews, et al., 2013). Diverted water enters Mirror Lake, which acts as a settling pond, and then flows to Lake Whatcom via Anderson Creek (Tracey, 2001). Outputs from Lake Whatcom include evaporation, the outlet at Whatcom Creek, and water removed for municipal and industrial use (Matthews, et al., 2013). Surface water inputs comprise perennial and intermittent streams, surface runoff
directly into the lake, and engineered drainage systems (Delahunt, 1990; Pickett & Hood, 2008). The Lake Whatcom watershed receives occasional snowfall. Although snowmelt within the watershed does not play a role in its hydrology during most of the year, the combination of rainfall and snowmelt can create episodic high volumes of storm runoff (Buchanan & Savigny, 1990).

Precipitation in the watershed is distributed across frequent, low-intensity rainfall events, especially between the months of October and April, which typifies the region’s maritime climate (Kelleher, 2006; WRCC, 2014). On average, rainfall is highest in December and January and lowest in July and August (WRCC, 2014). Average annual rainfall is higher in the southern part of the watershed than in the northern part due to storm patterns from the Skagit Valley and an orographic effect; the amount of precipitation increases with elevation (Kelleher, 2006).

Between WY 2002 and WY 2013, the average recorded yearly rainfall was 101 centimeters (cm) at the Bloedel-Donovan gauge, 111 cm at the Geneva gauge, 112 cm at the North Shore weather station, and 151 cm at the Brannian Creek gauge (Figure 9).

Precipitation varies from year to year in the Lake Whatcom watershed. The Lake Whatcom TMDL is based on conditions from WY 2003, which was the driest year in the period from 2002 to 2013. During WY 2003, the total gauged precipitation ranged from 73 cm at the North Shore weather station to 111 cm at the Brannian Creek gauge (the Bloedel-Donovan gauge was not operating in WY 2003). In contrast, my sampling period (WY 2013) occurred during one of the wettest of recent years, with total precipitation that ranged from 122 cm at the Bloedel-Donovan gauge to 169 cm at the Brannian Creek gauge (Table 1).
2.1.2 Effect of Phosphorus Inputs on Lake Water Quality

Lake Whatcom was added to the Washington State 303(d) list of impaired water bodies in 1998 due to declining concentrations of dissolved oxygen. The lake is subject to a TMDL to restrict the amount of phosphorus that can be discharged into the lake, with the goal of improving dissolved oxygen by reducing the amount of algal growth in the lake (Pickett & Hood, 2008). Phosphorus is the limiting nutrient for biological productivity in Lake Whatcom, controlling the growth of algae and other vegetation such that increased inputs of phosphorus lead to more algal growth (Bittner, 1993; Liang, 1994; McDonald, 1994; Matthews, et al., 2002). As bacteria metabolize algal carbon, they consume large amounts of oxygen from the water (Coveney & Wetzel, 1989). Resulting problems include loss of aquatic habitat, release of other contaminants due to anoxic lake conditions, and algal blooms. From a drinking water standpoint, algal blooms may be problematic because they can clog filters, necessitate increased use of water treatment chemicals that produce harmful byproducts, and increase treatment costs. Some algae can produce unpleasant tastes and odors in drinking water (Pickett & Hood, 2008). In watershed settings, phosphorus mainly occurs adsorbed to sediment particles (Schlesinger, 1997; Lee, et al., 2012). In the Lake Whatcom watershed, about half of the adsorbed phosphorus is thought to be available for biota to use and thus has the potential to contribute to algae growth (R. Matthews, personal communication, September 26, 2014). Therefore, it is important to know how much sediment streams are discharging to the lake.

2.2 Sediment and Phosphorus Transport in Streams

2.2.1 Sediment

The amount of suspended sediment in streams is controlled by sediment availability and energy conditions, which, in turn, depend on a wide range of hydrologic and watershed factors
Sediment can be eroded from the banks and bed of the channel or from hillslopes and roads in the surrounding watershed (Lu & Richards, 2008). Sediment transport in streams largely occurs during periods of high discharge, such that the amount of sediment moved during occasional high-flow events often exceeds the total transport during longer periods of low flow (Swanson, et al., 1982). A review of long-term suspended sediment records found that, among 77 Pacific Northwest catchments, an average of 52.8% of the annual suspended sediment load was produced during the 15 days of the year with the highest streamflow (Gonzalez-Hidalgo, et al., 2010).

A study of the Issaquah Creek watershed, which is located 30 km southeast of Seattle and is similar to the Lake Whatcom watershed in size, relief, landcover, and climate, found that its main sources of sediment were landslides, channel bank erosion, and road-surface erosion. Landslides were the dominant sediment source in forested areas and contributed the greatest mass of sediment to the creek (Nelson & Booth, 2002). Given the similarities between the two watersheds, a comparable set of processes may control sediment production in the subbasins surrounding Lake Whatcom.

New slope failures and erosion of existing mass movement deposits could both contribute sediment to streams in the Lake Whatcom watershed. Mass wasting is common during the wet season in the Puget Sound region of Washington (Chleborad, et al., 2006). Prominent debris torrents occurred in the Smith Creek subbasin of the Lake Whatcom watershed in 1917, 1949, 1971, and 1983. Thirty-three scarps were identified on aerial photos of the Smith Creek subbasin taken in 1983 (Syverson, 1984; Buchanan & Savigny, 1990). During the 1983 event, debris flows and debris floods occurred on at least 10 creeks in the vicinity of Lake Whatcom (KWL, 2004). Major debris events have also occurred in the Austin, Blue Canyon, Olsen, and South Bay
subbasins in the last century (CH2M Hill, 2008). High concentrations of suspended sediment observed in Austin, Blue Canyon, and Smith Creeks during a November 1990 storm event were attributed to hillslope failures upstream (Walker, et al., 1992). In January 2009, a major storm triggered mass movements throughout western Washington, mostly originating in steep, forested terrain (Grizzel, et al., 2009).

Channel erosion likely plays a role in determining the amount of sediment suspended in Lake Whatcom watershed streams, particularly during high flow events. Channels with erodible beds and banks can grow larger in response to elevated flows. Paved surfaces associated with urbanization can increase the magnitude of storm flows, thereby increasing channel-bank erosion (Nelson & Booth, 2002). Stream channels within the Lake Whatcom watershed have been altered due to storm runoff, construction activities, and debris flows and floods (Syverson, 1984; Matthews, et al., 2010). A large amount of streambed scouring was noted in Austin and Smith Creeks following the January 2009 storm (Matthews, et al., 2010).

Erosion from bare surfaces could add sediment to the streams that drain into Lake Whatcom, particularly in the more urban areas of the watershed. Sheetwash makes up a relatively small part of total erosion in forested Pacific Northwest watersheds due to high soil permeability and a thick humus layer at the soil surface (Swanson, et al., 1982), but heavy rainfall can erode dirt roads, construction sites, and other areas cleared of vegetation (Pickett & Hood, 2008). Nelson and Booth (2002) found that, of the various land uses in the Issaquah Creek watershed, construction and other land-clearing activities yielded the most sediment per unit area. These areas made up a very small percentage of the Issaquah Creek watershed, so they were not a major sediment source. Similarly, construction sites do not cover a large portion of the Lake Whatcom watershed (Figure 7). Clearing activities that expose more than 500 square
feet of soil are not permitted on land parcels in the watershed between October and May (WCC, 2014).

During individual storms, sediment availability can change as soil is eroded from areas in and around the stream channel (Asselman, 1999). Sediment source depletion can result in a clockwise hysteresis effect, producing higher suspended sediment concentrations on the rising leg of a storm hydrograph relative to those measured at equivalent flows on the falling leg. Dilution by groundwater flow can also reduce sediment concentrations on the falling leg of the hydrograph (Bača, 2008). This pattern is characteristic of forested basins with limited sediment availability (Gellis, 2012). Sediment eroded and deposited during a storm event is stored within the channel and becomes a sediment source during the rising leg of the next event. The sediment is remobilized and rapidly delivered to the stream, causing the sediment peak to lead the discharge peak (Smith & Dragovich, 2009; Gellis, 2012). Clockwise hysteresis has been observed within the Lake Whatcom watershed for several years. TSS increased during storm events at Silver Beach Creek (Figure 1), with the sediment peak typically occurring earlier than the discharge peak (Matthews, et al., 2011; 2012; 2013). Remobilization of stored material may help control the timing and amount of suspended sediment in other streams in the watershed.

2.2.2 Phosphorus

Phosphorus in soil is naturally derived from the weathering of calcium phosphate minerals, such as apatite (Schlesinger, 1997) and can be re-released to the soil environment by the decomposition of leaf litter and other organic matter (Groce, 2011). Precipitation, dry atmospheric deposition, and anthropogenic sources such as fertilizers, detergents, and wastewater can also contribute phosphorus to the landscape (Brett, et al., 2005; Anderson & Downing, 2006).
In soil and in freshwater systems, phosphorus may be accumulated by biota or adsorbed to soil particles, forming bonds with aluminum and iron oxide minerals (Schlesinger, 1997; Hart, et al., 2004). Phosphorus adsorbed to soil particles enters streams by the erosion of surface soil and stream channel material. Phosphorus is removed from sediment by a combination of physical, chemical, and biotic processes. Dissolved phosphorus originates from the release of phosphorus from soil, vegetation, or suspended sediment, or from anthropogenic sources (Hart, et al., 2004; Sharpley, et al., 2008). Stream concentrations of dissolved phosphorus tend to be low because phosphorus is limiting to biota, adsorbs easily to soil, and is not very soluble. Streams mostly transport phosphorus in the suspended load, either as adsorbed inorganic phosphorus or as organic phosphate (Schlesinger, 1997). Berner & Berner (1987) estimated that the global ratio of particulate to dissolved phosphorus in rivers is 18:1.

Not all of the phosphorus delivered to lakes contributes to algae growth. Bioavailable phosphorus consists of phosphorus that is immediately available to lake biota for the production of organic matter (orthophosphate and some organic phosphates) as well as phosphorus that can be transformed into an available form by natural processes such as dissolution, desorption, decomposition, and enzymatic release, primarily through action of alkaline phosphatase (Boström, et al., 1988; Rengefors, et al., 2001; Shi, et al., 2011). Groce (2011) estimated that, in the Lake Whatcom watershed, 54% of the phosphorus in soil is bioavailable. Ongoing research suggests that this value may underestimate the amount of phosphorus made available through enzymatic release (R.A. Matthews, personal communication, September 26, 2014).

Like sediment fluxes, phosphorus fluxes to streams are dominated by storm flow. High flows and high phosphorus concentrations tend to coincide (Brett, et al., 2005). The proportion of particulate phosphorus increases during storm events due to increased erosion and resuspension
of stream sediment (Sharpley, et al., 2008). Groce (2011) found this to be the case in the Lake Whatcom watershed. In a model predicting phosphorus concentrations based on TSS, the predicted and measured phosphorus values were most similar during peak flows, implying that most of the phosphorus transported to the lake during storms is carried by suspended sediment. Storm flows can also dilute phosphorus concentrations in streams. One year of daily sampling in four Seattle area streams (22.0-87.1% urban) showed that TP was most strongly correlated with seasonal base flow, followed by antecedent flow conditions, short-term flow fluctuations, and rainfall. Researchers attributed the strong correlation between phosphorus and base flow to a seasonal trend in soluble phosphate. Soluble phosphate concentrations tend to be higher in the summer than in the winter because summer flows are dominated by groundwater (Brett, et al., 2005).

Land cover can influence the amount of phosphorus exported from a watershed in streams. A study of 12 watersheds in southwest Washington found that TP was inversely related to the amount of forest cover in the watershed and directly related to the amount of urban development (Deemer, et al., 2012). This is consistent with the idea that stream phosphorus is largely a function of sediment content. Trees have the ability to reduce erosion by intercepting rainfall, holding soil together in their roots, and transpiring water that would otherwise run off, leading to lower stream concentrations of sediment and particulate phosphorus.

### 2.3 Previous Estimates of Sediment and Phosphorus Fluxes to Lake Whatcom

#### 2.3.1 Storm Water Runoff Monitoring Project

In 1992, researchers from Western Washington University’s Institute for Watershed Studies (IWS) estimated sediment inputs from several streams in the Lake Whatcom watershed as part of the Lake Whatcom Storm Water Runoff Monitoring Project (Walker, et al., 1992). The estimates
were based on discharge simulated using the Hydrological Simulation Program–Fortran (HSPF) watershed model and water quality samples collected during six storm events between May 1990 and April 1991, with six samples collected at each stream during each event. The hydrologic model was calibrated to mean daily discharge measured at Austin, Olsen, and Smith Creeks during the 1968 and 1969 water years because there were no stream gauging sites in the watershed during 1990-1991. Predicted sediment loads were 4,900,170 kg/year from Anderson Creek, 45,022,268 kg/year from Austin Creek, 79,457 kg/year from Silver Beach Creek, and 35,945,036 kg/year from Smith Creek (Figure 1). The model predicted total phosphorus loads of 15,463 kg/year from Anderson Creek, 11,640 kg/year from Austin Creek, 164 kg/year from Silver Beach Creek, and 15,207 kg/year from Smith Creek. The results suggested that the smaller streams at the north end of the lake contribute disproportionately high levels of soluble phosphorus relative to their flow volume, but this trend was not observed for TP. A major storm event in November 1990 led to unusually high concentrations of sediment and other constituents in several creeks within the Lake Whatcom watershed. The IWS researchers attributed the particularly high concentrations observed in Austin Creek, Smith Creek, and one of the creeks in the Blue Canyon subbasin to mass wasting within these subbasins. During the November 1990 event, TSS values up to 5,956 mg/L and 7,495 mg/L were recorded at Austin Creek and Smith Creek, respectively.

2.3.2 TMDL Study

The current phosphorus TMDL is based on the HSPF watershed model developed in 2007 for the Washington State Department of Ecology. The HSPF model incorporated information on land use, soils, rainfall, and evapotranspiration and was calibrated to measured flow and phosphorus at six streams in the watershed. It was coupled with the CE-QUAL-W2 lake response model,
which simulated hydrodynamics and eutrophication processes within the lake and predicted dissolved oxygen concentrations. The CE-QUAL-W2 model was calibrated using streamflow and phosphorus results from the HSPF model. The model did not incorporate stream sediment data or predict fluxes of sediment to the lake (Pickett & Hood, 2008).

For the period from 2000 to 2005, the HSPF model predicted average annual phosphorus loads to Lake Whatcom between 3,206 and 3,597 kilograms (kg), depending on whether the total was calculated by land cover type, by lake inflows, or by subwatershed (Cadmus & CDM, 2007). The phosphorus loading rate in the TMDL Base Scenario, which represented conditions in WY 2003, was 6,282 kg/year. The annual total included 3,623 kg from streams, 2,203 kg from groundwater, 293 kg from the Middle Fork Nooksack River diversion, and 163 kg from direct precipitation (Pickett & Hood, 2008). The Existing Conditions Scenario, developed to account for land use changes that occurred between 2002 and 2009, estimated that streams input 3,958 kg of phosphorus per 2003 year. The TMDL states that, to meet water quality standards, this value would need to be reduced to 2,534 kg/2003 year (Hood, 2013). Phosphorus loading estimates and target values were calculated for each subbasin in the Lake Whatcom watershed, as well as for groundwater, direct precipitation onto the lake, and the Middle Fork Nooksack River diversion (Table 2).

2.4 Lake Whatcom Watershed Monitoring

Water quality monitoring is conducted by IWS at five sites on Lake Whatcom and in several streams that drain into the lake. Monthly grab samples are collected every other year from twelve stream sites throughout the watershed (Figure 10) and analyzed for TSS, TP, soluble phosphate, total nitrogen, ammonium, nitrate/nitrite, and fecal coliforms. Alkalinity, conductivity, dissolved
oxygen, pH, temperature, and turbidity are also measured at each stream. Total organic carbon is monitored twice per year in alternate years (Matthews, et al., 2013).

In addition to regular water quality monitoring, IWS conducted high-resolution storm event sampling at Silver Beach Creek between 2009 and 2012 (Figure 1). Samples were analyzed to measure turbidity, TSS, TP, soluble phosphate, total nitrogen, and nitrate/nitrite. Each of these parameters was significantly correlated with stream stage and discharge. When all data were considered, turbidity, TSS, and TP were highly correlated with one another. Within individual storm events, correlations ranged from insignificant to very highly significant (Matthews, et al., 2011; 2012; 2013). Between January 2013 and December 2015, IWS will continue to collect storm event data from multiple streams in the Lake Whatcom watershed (at least five storms per year per stream). Austin, Anderson, and Brannian Creeks were sampled in 2013.

Brown and Caldwell consultants conducted storm event monitoring between August 2010 and June 2013, sampling a total of 28 streams in the Lake Whatcom watershed for turbidity, TSS, and TP. Analyses for total dissolved phosphorus, soluble phosphate, and fecal coliforms were added for selected sites and events (Patrick Weber, personal communication, January 17, 2014).

Stream stage and discharge are monitored by IWS in Austin and Smith Creeks. The United States Geological Survey (USGS) monitors stream discharge in an additional seven streams in the Lake Whatcom watershed, including Anderson, Brannian, Carpenter, Euclid, Millwheel, Olsen, and Silver Beach Creeks (Figure 10). Real-time hydrologic data are available from the Anderson and Olsen stream gauges (USGS, 2014). For each creek, a continuous record
of discharge is produced by applying a stage-discharge rating curve to high-resolution stage data. Precipitation data are collected at four stations within the Lake Whatcom watershed (Figure 9).

3.0 Methods

3.1 Scope of Work

The goal of my research was to use high-resolution storm event sampling and spatial watershed data to explore relationships among TP, TSS, and stream discharge in the Lake Whatcom watershed and calculate sediment and phosphorus fluxes from streams to the lake. To achieve this goal, I established the following scope of work.

1. Collect a series of water samples from Smith Creek before, during, and after storm events for one year (February 2013 – January 2014). Analyze the samples for TSS and TP.

2. Obtain and process available TSS, TP, discharge, precipitation, and watershed data for the nine gauged streams in the Lake Whatcom watershed, as well as several ungauged areas where modeled discharge is available.

3. Develop linear models to calculate sediment and phosphorus loading to Lake Whatcom during the 2013 water year.

4. Perform statistical analyses to determine factors that influence the relationships among precipitation, stream discharge, and sediment and phosphorus concentrations at Smith Creek.

5. Compare sediment and phosphorus concentrations in different subbasins of the Lake Whatcom watershed to examine correlations to spatial data.
3.2 Stream Sampling

I sampled for TP and TSS near the mouth of Smith Creek during 22 storm events between February 2013 and January 2014. Samples were collected in accordance with USGS protocols for measuring fluvial sediment (Edwards & Glysson, 1999). For each event, I used a Teledyne Isco automated sampler to collect a series of discrete, 500-mL water samples near the IWS gauging station on Smith Creek, located about one kilometer upstream from Lake Whatcom (Figure 1). Smith Creek was selected for sediment and phosphorus monitoring because it is one of the largest streams in the Lake Whatcom watershed, has an established stream gauge, and is monitored regularly for water quality. The Smith Creek basin is also undeveloped and forested, so it serves as a baseline catchment for understanding natural sedimentation processes.

Stage height at Smith Creek was measured with a Sutron SDI-12 shaft encoder and sent to a Sutron 8210 data recorder. The gauge was set up in a deep pool in the stream and recorded the water level at 15-minute intervals. Discharge was measured weekly using the USGS midpoint method. Aquarius software was used to 1) plot stage data against measured discharge values to create rating curves and 2) apply the rating curves to the stage series to generate hydrographs (Matthews, et al., 2014). I also monitored the stream stage height using a water-level and velocity sensor connected to the Isco sampler. The sensor allowed for trigger-paced sampling, in which the collection frequency is set to vary according to stream flow, producing higher resolution leading up to the peak of the storm.

At the Smith Creek sampling site, a 12-m length of 3/8-inch vinyl tubing connected the sampler to a plastic strainer. The strainer and flow sensor were taped to a cinder block and placed below the water surface in the stream (Figure 11). The strainer was placed with the goal of obtaining representative suspended sediment concentrations for the selected location along the
In most streams, coarser particles are concentrated near the streambed, whereas fine sediment tends to be uniformly distributed throughout the water column (Edwards & Glysson, 1999). Strainer placement on the cinder block allowed the sampler to collect suspended sediment while avoiding the sand and gravel at the bottom of the channel. The main sampling location was at moderate depth, toward the center of the channel, and in an area of relatively laminar flow compared to the areas immediately upstream and downstream. I moved the cinder block laterally in the channel as needed to maintain consistent sampling.

For each event, my goals were to collect samples during both the rising leg and the falling leg of the hydrograph and to sample near the time of peak discharge. This sampling strategy provided water quality data at a wide range of discharge values. At the IWS-monitored sites in Anderson, Austin, and Brannian Creeks, sample collection, discharge measurements, and stage monitoring all occur at the same location. For some of the storms, samples taken by IWS were collected at intervals of equal flow volume, typically yielding 10-30 discrete samples per event. I did not use this type of flow sampling method at Smith Creek because the sampling location (downstream from the gauging station) lacked a well-defined cross-section and rating curve. Instead, the sampling interval was adjusted manually based on weather forecasts, readings from the water-level and velocity sensor at Smith Creek, and real-time stage data from Anderson and Olsen Creeks. During some events, sample collection was set to vary according to an event-specific trigger. For example, during some events, the sampler was programmed to collect every four hours until the water level rose to a given value, and then begin collecting every hour.

3.3 Laboratory Analysis

Water samples were analyzed for TSS and TP at the IWS state-certified water quality lab at Western Washington University (Ecology, 2014b; #A543-12). The analysis for TSS involved
running samples through a filter, determining the mass of the residue, and dividing by the sample volume. The analysis for TP was conducted on an OI Analytical FS3100 automated nutrient analyzer. The analyzer determined phosphorus levels by adding reagents and comparing the resulting color intensity to a standard curve. Detection limits were 2 mg/L for TSS and 5 μg/L for TP (Matthews, et al., 2014). The following IWS Standard Operating Procedures (SOPs) describe relevant laboratory methods (IWS, 2012):

- Washing Nalgene Bottles (SOP #3)
- Total Suspended Solids Analysis (SOP #13)
- Methods for Nutrients on the OIFS3100 (SOP #22)

### 3.4 Data Processing and Hydrologic Modeling

#### 3.4.1 Precipitation

The City of Bellingham provided precipitation data recorded at 15-minute intervals at four stations in the Lake Whatcom watershed (Figure 9). I filled gaps in the North Shore precipitation series using data from the Bloedel-Donovan gauge. I filled gaps in the Brannian series using hourly data from the Plantation rain gauge, located just outside the watershed boundary on the southwest side (Appendix A).

#### 3.4.2 Hydrographs

Hydrographs for gauged streams were obtained from IWS and USGS (Figure 12; Matthews, et al., 2014; USGS, 2014). The hydrograph for Anderson Creek included both watershed inputs and inputs from the Middle Fork Nooksack River diversion. Joanne Greenberg provided hourly HSPF-modeled discharge to fill occasional gaps in these hydrographs (Appendix A) and simulate discharge from the Lake Whatcom subbasins lacking gauged streams (Figure 13). Combined, the
nine gauged subbasins and ten HSPF-modeled areas represent the entire Lake Whatcom watershed.

In addition, discharge was simulated for 14 of the streams sampled by Brown and Caldwell (Figure 14). These smaller streams are contained within the HSPF-modeled regions of the watershed but were not simulated individually within the HSPF model. In order to establish sediment-discharge and phosphorus-discharge relationships in these small streams, simulations were performed using the Distributed Hydrology, Soils, and Vegetation Model (DHSVM). The DHSVM is a spatially-distributed model that simulates physical hydrologic processes including evapotranspiration, canopy interception, soil water infiltration, soil water storage, snow water equivalent, surface runoff, and saturated subsurface flow. The DHSVM calculates the flux of water and energy at each pixel of a digital elevation model over a user-defined time step. Model inputs include GIS layers for the watershed boundary, topography, soil type, soil thickness, vegetation, and stream network, as well as meteorological inputs that include temperature, precipitation, wind speed, relative humidity, and incoming shortwave and longwave radiation (Wigmosta, et al., 1994).

Dr. Robert Mitchell provided model inputs for the Lake Whatcom watershed, including watershed parameters and meteorological data from the North Shore, Bloedel-Donovan, Brannian, Plantation, and Geneva stations, calibrated the model to the Smith Creek subbasin, and ran the model to obtain a discharge series for each stream (see Appendix A in Dickerson, 2010 for modeling procedures). In addition to the 14 target streams, I saved DHSVM model outputs for Smith and Austin Creeks and compared them to the discharge calculated using rating curves and continuous stage data.
I matched water quality data with stage and discharge values at the time of sampling. For samples that were collected between 15-minute time intervals, I calculated discharge using a linear weighted average of the surrounding discharge measurements. If stage data and a consistent stage-discharge rating curve were available for a particular stream, I took a weighted average of surrounding stage measurements and applied the rating curve to determine discharge. Rating curves for the gauged streams are available from IWS and USGS (Matthews, et al., 2014; USGS, 2014).

3.4.3 Storm Parameters
I calculated a variety of storm event parameters for Smith Creek based on precipitation, discharge, and water quality data (Table 3). Events sampled between January 2013 and March 2014 were numbered from 1 to 25. I assigned numbers to the Smith Creek events and renumbered the Anderson, Austin, and Brannian Creek events so that event numbers for all four streams were consistent (Table 4). The events were divided into season groups based on the solstices and equinoxes (March 20, June 22, September 22, and December 21 in 2013) with the exception of Event 15, which was considered a fall event even though it occurred several days before the fall equinox. I grouped Event 15 with the fall events because it resulted in the first substantial (albeit relatively small) hydrograph peak following dry summer conditions (Figure 15).

I quantified event size by calculating peak discharge, magnitude and duration of rise, event flow volume, hydrograph centroid, and precipitation magnitude. These parameters are related, but they measure different aspects of the event. For example, a small storm that begins when the stream is already elevated might reach a high peak discharge, but the magnitude of rise would be low. Precipitation magnitude does not necessarily correspond to the size of the storm
hydrograph because rainwater may be stored in soil or intercepted by vegetation rather than running off into the stream.

Calculating some of the parameters required separating the baseflow from the response hydrograph. The response hydrograph represents the additional streamflow contributed by event runoff and is determined by subtracting baseflow from the total hydrograph (Dingman, 2002). I estimated baseflow by drawing a line from the start of the rising leg to a point on the falling leg where flow began to level off. If another event began before the falling leg reached an inflection point, the endpoint of the baseflow line was set at the start of rise of that next event.

Discharge, sediment, and phosphorus centroids were all calculated by plotting the parameter against time, defining the area under the curve, and finding the centroid of that area. The centroid \((\bar{x}, \bar{y})\) of a planar shape bounded by continuous functions \(f(x)\) and \(g(x)\) on the interval \([a,b]\) is given by

\[
\bar{x} = \frac{1}{A} \int_a^b x[f(x) - g(x)]dx
\]

\[
\bar{y} = \frac{1}{A} \int_a^b \left[\frac{f(x) + g(x)}{2}\right][f(x) - g(x)]dx
\]

where \(A\) is the area of the shape (Larson, et al., 1998). The discharge centroid is the centroid of the area under the response hydrograph. The sediment and phosphorus centroids are the centroids of the areas under sediment (i.e., TSS) and phosphorus (TP) curves determined by interpolating concentrations by linear weighted average at 15-minute intervals throughout each storm event. When calculating discharge, sediment, and phosphorus centroids, the lower boundary of the shape is the x-axis, so \(g(x) = 0\). Eliminating the \(g(x)\) term allowed me to simplify the equations above and obtain the centroid equations in Table 3.
I used the maximum recorded TSS and the TSS centroid to quantify the sediment response to each storm event. Similarly, I used the maximum TP and TP centroid to quantify the phosphorus response. The maximum value has the advantage of being a more direct measurement. The benefit of using the centroid is that it takes the full sediment or phosphorus curve into account, which is helpful because samples were not necessarily collected right at the sediment or phosphorus peak. Both parameters are underestimates, especially when there is a large discrepancy between the measured maximum and the actual maximum.

I also calculated the lag times between the precipitation peak and the times when maximum recorded sediment and phosphorus occurred. Longer lag times tend to correspond to high-duration, low-intensity precipitation events that cause a gradual hydrograph rise and sudden sediment peak. Lag time outliers might signal a change in erosional processes such as mass wasting, bank erosion, or resuspension of settled material (Clement, 2014).

3.4.4 Basin Characteristics

I compiled watershed data for the nine gauged subbasins to determine whether sediment and phosphorus loading relate to basin size, shape, relief, slope, drainage density, bedrock type, roads, or degree of urban development. I used ArcGIS to calculate these parameters for each subbasin based on topography, landcover (NOAA, 2011), geology (Mitchell, et al., 2010), and roads (U.S. Census, 2013). Subbasins were delineated using a LiDAR bare earth terrain map with 2-meter resolution. I used this LiDAR dataset to delineate streams for calculating drainage density and length of overland flow. I used the area and perimeter of each subbasin to calculate shape parameters, which included basin length, elongation ratio, compactness coefficient, circulatory ratio, basin shape factor, and form factor (Kanth & Hassan, 2012). These parameters were not calculated for the ungauged basins, but the basin areas were determined based on
TMDL basin designations for the purpose of calculating sediment and phosphorus yields (Pickett & Hood, 2008).

3.5 Calculation of Sediment and Phosphorus Fluxes

I calculated the sediment and phosphorus fluxes from 25 streams in the Lake Whatcom watershed over the 2013 water year. I generated plots and calculated linear models using R, an open-source statistical analysis package (R Core Team, 2012). For the streams with available TSS and TP data, I plotted each parameter against discharge, applied a logarithmic transformation to linearize the relationship, and fit a linear model to the transformed data (Helsel & Hirsch, 2002; USFS, 2007). The TSS data were uncensored and contained negative values (for samples that contain very little sediment, the mass before filtering may exceed the mass after filtering due to the limitations of the balance). When developing the TSS-discharge models, I added a constant (3.3) before transformation to avoid taking the logarithm of a negative number. I used the linear relationships to calculate three TSS values and three TP values for each 15-minute interval throughout the water year: one at the lower 95% confidence interval, one at the mean, and one at the upper 95% confidence interval. Duan’s smearing estimator was applied to correct for retransformation bias when calculating TSS and TP from the log-transformed model (Duan, 1983). The bias occurs because regression predicts the mean of a normal distribution, and the transformed mean of the distribution is not equivalent to the mean of the transformed distribution (USFS, 2007). I estimated the sediment and phosphorus loading from each area by multiplying flow volumes by the calculated TSS and TP concentrations (Glysson, 1987; Gray and Simões, 2008). I also converted results from kilograms to tonnes and divided by the watershed area to determine yields in tonnes per square kilometer per year.
I used modeled or proxy data to calculate fluxes from ungauged areas of the watershed. I developed the linear models for Donovan and Fir Creeks based on TSS and TP sampling data and HSPF-modeled discharge. I calculated fluxes from the Academy, Blue Canyon, Silver Beach Area (distinct from the gauged Silver Beach Creek subbasin), South Bay, Strawberry, and Sudden Valley HSPF-modeled areas by pairing DHSVM-modeled discharge with measured TSS and TP for the individual streams in that area, creating a single linear model based on those pairs, and multiplying by HSPF flow volumes to calculate fluxes. No water quality data were collected from the Bloedel area, so I applied the linear model from nearby Euclid Creek to the Bloedel discharge series to calculate fluxes from this area. Similarly, the North Shore area did not have any water quality data that could be matched with DHSVM discharge, so I applied the Smith Creek linear model to the North Shore discharge series.

3.6 Correlation Analysis

Correlation analysis is used to examine the monotonic relationship between two variables. I used Kendall’s tau rank-based correlations, calculated in R, to test for significant correlations between stage, discharge, TSS, and TP over each stream’s full dataset and within individual storm events. I compared the Smith Creek storm events to one another and tested for correlations among precipitation, discharge, and water quality parameters (Table 3). The test statistic (τ) ranges from −1 to +1; the closer to ±1, the stronger the correlation. The p-value indicates statistical significance; significant correlations have p-values less than 0.05 (Matthews, et al., 2014). Tau values around 0.7 or above are considered strong correlations. Kendall’s tau is resistant to the effects of outliers and well-suited to datasets that exhibit a skewed distribution (Helsel & Hirsch, 2002).
4.0 Results

4.1 Parameter Correlations and Loading Estimates

4.1.1 Correlations among Sediment, Phosphorus, and Discharge

Sediment and phosphorus were correlated to one another in all the sampled streams, but the relationship between them varied throughout the watershed (Figure 16). Sediment and phosphorus were significantly correlated to discharge in most of the streams, including all of the most heavily sampled streams (Figures 17-18). Compared to Smith and Silver Beach Creeks, sediment-discharge correlations were relatively strong at Austin and Brannian Creeks and relatively weak at Anderson Creek. Phosphorus-discharge correlations were relatively strong at Brannian Creek and weak at Austin and Anderson Creeks. The correlation between sediment and discharge was stronger (higher Kendall’s $\tau$) than the correlation between phosphorus and discharge at 20 of the 22 streams in which discharge was correlated to sediment, phosphorus, or both. At Anderson Creek, the ratio of sediment to discharge tended to be somewhat lower during events when water was being diverted from the Middle Fork Nooksack River (Figure 17).

Although correlations between sediment, phosphorus, and discharge were statistically significant for most sites, there was a lot of variability within each site ($|\tau| = 0.385-0.708$ among significant sediment-discharge correlations; $|\tau| = 0.129-0.669$ among significant phosphorus-discharge correlations). The uncertainty in these relationships results from variability both within and among storm events. For example, individual Smith Creek storm events had water quality trends that were distinct from one another (Figure 19). Separating the Smith Creek events into groups based on season or storm magnitude did not improve the quality of sediment-discharge correlations. Phosphorus-discharge correlations were somewhat stronger when grouped by
seasons, with the exception of the spring events, but did not improve when events were grouped by magnitude (Figures 20-21).

4.1.2 Fluxes and Yields

Among the five subbasins in which more than 200 samples per subbasin were collected (Anderson, Austin, Brannian, Silver Beach, and Smith Creeks), mean calculated sediment fluxes for the 2013 water year ranged from 119,000 kg/year (Anderson Creek) to 1,940,000 kg/year (Smith Creek), and phosphorus fluxes ranged from 212 kg/year (Silver Beach Creek) to 549 kg/year (Austin Creek) (Table 6). Of these subbasins, the Smith Creek basin produced the most sediment per square kilometer, and the Silver Beach Creek basin produced the most phosphorus per square kilometer (Table 7). Among the areas of the watershed with fewer than 100 samples per subbasin, flux results often had very large confidence intervals and are not included here.

Fluxes from the five most thoroughly sampled subbasins were separated by month, revealing that the highest sediment loads came from Austin Creek, Silver Beach Creek, and particularly Smith Creek during November and January (Figure 22). The fluxes were dominated by storms that peaked on November 19, 2012 and January 9, 2013 (Figure 12). Phosphorus fluxes were spread out more evenly between November and May (Figure 21).

4.2 Individual Storm Events

For each of the Smith Creek storm events, a peak in stream discharge followed a peak in precipitation (Figure 23). Sediment and phosphorus generally increased with discharge (Figures 24-25) and were significantly correlated with each other in all events (Figure 26). During most events, the sediment and phosphorus peaks occurred on the rising leg of the discharge hydrograph, forming a clockwise hysteresis loop when plotted against stage or discharge (Figures 27-28). The sediment peak also led the discharge peak in all the Anderson, Austin, and
Brannian Creek events (Matthews, et al., 2014) and most of the Silver Beach Creek events (Matthews, et al., 2011; 2012; 2013).

Sediment was significantly correlated with stage in 18 of 22 Smith Creek events, and phosphorus was significantly correlated with stage in 16 of 22 events (Table 5). Very similar correlations existed when comparing sediment and phosphorus to discharge rather than stage. I used stage for comparisons within the same stream because it is a more direct measurement and is not affected by the quality of the stage-discharge rating curve. Sediment-stage correlations tended to be stronger than phosphorus-stage correlations during the fall; the opposite was true during the spring and summer (Figures 27-28). Sediment and phosphorus were usually correlated more strongly to one another than to stage (Figure 26). Event correlation coefficients are not directly comparable to one another because sampling frequency and distribution were not consistent. For example, Event 15 had perfect rank-based sediment-stage and phosphorus-stage correlations, but this may not have been the case if both legs of the hydrograph had been sampled.

4.3 Storm Event Comparisons

Total storm event rainfall for the Smith Creek events ranged from 0.660 to 4.55 cm, as measured at the North Shore weather station (Table 8). The largest sampled storm events by precipitation magnitude occurred in June (Event 11) and January (Event 24), and the smallest events (12-14) occurred in August and early September. Large precipitation events tended to produce large hydrograph peaks. Event rainfall was correlated significantly, but weakly, to peak discharge ($\tau = 0.424$), magnitude of rise ($\tau = 0.493$), duration of rise ($\tau = 0.35$), and event flow volume ($\tau = 0.483$) (Table 9). The correlation between rainfall and the discharge centroid was not quite significant at the 95% confidence level ($\tau = 0.291$, p-value = 0.059). Magnitude of rise was
significantly correlated to shorter term (3 days; $\tau = 0.436$) and longer term (15 days; $\tau = 0.439$) antecedent precipitation and duration of precipitation ($\tau = 0.32$). Magnitude of rise was not significantly correlated to precipitation intensity.

Although rainfall and hydrograph rise were correlated, rainfall alone did not necessarily predict flow. For example, a 2.87-cm precipitation event in late September (Event 16) only resulted in a 10.0 cfs (0.283 m$^3$/s) hydrograph rise, whereas a similar-sized event in late December (Event 22; precipitation = 2.92 cm) increased discharge by 41.6 cfs (1.18 m$^3$/s). When normalized to precipitation magnitude, the flow response was highest in the late winter, decreased and remains low through the summer, and increased again in the fall (Figure 29).

Maximum sediment and the sediment centroid both represent the sediment response to the storm event and were strongly correlated to one another ($\tau = 0.81$), but maximum sediment produced slightly higher correlation coefficients when compared to hydrograph magnitude parameters (Table 9). Maximum sediment was significantly correlated to the magnitude of rise ($\tau = 0.717$), peak discharge ($\tau = 0.657$), event flow volume ($\tau = 0.506$), event rainfall ($\tau = 0.5$), and discharge centroid ($\tau = 0.446$), but not to the duration of rise. Maximum phosphorus correlated well with the phosphorus centroid ($\tau = 0.714$). Maximum phosphorus was correlated to event rainfall ($\tau = 0.404$), but not to any of the hydrograph magnitude parameters. The phosphorus centroid was correlated to the magnitude of rise ($\tau = 0.578$), peak discharge ($\tau = 0.439$), event rainfall ($\tau = 0.396$), and event flow volume ($\tau = 0.359$).

Ratios of event maximum sediment and phosphorus concentrations to discharge were much higher in the summer than in the rest of the year. When normalized to the discharge centroid, maximum sediment and phosphorus concentrations were higher in the fall than in the
spring, but this pattern was not apparent when the maximum concentrations were normalized to the other hydrograph magnitude parameters (Figure 30).

Among the 22 Smith Creek storm events, the lag time between maximum precipitation and maximum recorded sediment concentration ranged from -9.5 hours (i.e., the sediment peak occurred 9.5 hours before the precipitation peak) to 26.5 hours. Phosphorus lag times ranged from -9.5 to 16.75 hours (Table 8). Outliers corresponded to events with multiple peaks (Events 16 & 24), a gap in sample collection (Event 5), and a high TSS value that occurred on the falling leg of the hydrograph (Event 4) (Figures 23-25). My analysis did not account for the potential effects of frozen ground and precipitation storage in snowpack. An inspection of minimum temperatures and precipitation at the North Shore Weather Station (Figure 9) during the study period indicated that freezing conditions and snowpack were brief and infrequent, having little effect on lag times or other results.

4.4 Subbasin Comparisons

4.4.1 Watershed Characteristics

The nine gauged subbasins fall into two groups based on size, shape, and relief. The watersheds of Anderson, Austin, Brannian, Olsen, and Smith Creeks are relatively large and rounded, with more relief and steeper slopes. The watersheds of Carpenter, Euclid, Millwheel, and Silver Beach Creeks are relatively small and elongated, with less relief and shallower slopes. The smaller basins also tend to have more residential development and higher road density compared to the larger basins. The exceptions include Carpenter Creek, which is small but forested, and Austin Creek, which has a high road density despite having a low percentage of development (Table 10). Darrington Phyllite is the dominant bedrock type in the Anderson and Brannian
Creek subbasins, and the Chuckanut Formation makes up the bedrock in the other basins (Figure 5). Among the gauged streams, flow volume was strongly correlated to basin area (Figure 31).

As observed at the gauging sites, located near the mouths of the streams, channel beds and banks in the Lake Whatcom watershed are typically composed of a combination of soil, sand, gravel, and cobbles, with boulders in some of the larger streams (e.g. Austin Creek, Smith Creek). The bed and bank material varies among the nine gauged streams. Streambanks in the smaller, urbanizing subbasins generally contain more soil, whereas those in the larger, forested subbasins are mostly made up of coarse sediment. Even so, coarse bed and bank material was observed at all nine sites (Figure 32). Channel bed material was only observed at the gauging stations and may vary higher in the watershed.

4.4.2 Sediment and Phosphorus Variation among Subbasins

The relationships between sediment, phosphorus, and discharge varied among the different streams in the Lake Whatcom watershed. The ratio of phosphorus to sediment tended to be higher in Silver Beach Creek than in Smith Creek. Samples from Anderson Creek also tended to have relatively high concentrations of phosphorus relative to sediment (Figure 35). When compared to Anderson, Austin, Brannian, and Smith Creeks, Silver Beach Creek had higher levels of sediment and phosphorus relative to discharge (Figures 36-37). In general, wider ranges of sediment-discharge and phosphorus-discharge ratios were observed in the smaller basins. For example, TSS values above 100 mg/L were measured at Carpenter, Euclid, and Silver Beach Creeks when discharge was less than 15 cfs (0.425 m³/s), whereas these relatively high TSS concentrations were only measured in the larger basins at higher flows. When discharge was below 15 cfs (0.425 m³/s), measured TSS did not rise above 32.5 mg/L in Anderson Creek, 13.3 mg/L in Austin Creek, 18.0 mg/L in Brannian Creek, and 34.9 mg/L in Smith Creek (Figure 17).
A positive correlation between phosphorus flux and total stream length was the only significant correlation between loading estimates and the subbasin parameters listed in Table 10. Other parameters may or may not correlate to sediment and phosphorus loading; significant correlation coefficients were rare because the analysis only included five streams (Figures 38-39). Additional correlations could emerge with a larger sample size.

5.0 Discussion

The objectives of my project were to calculate sediment and phosphorus loading to Lake Whatcom from several streams and to determine how basin characteristics, precipitation, discharge, sediment, and phosphorus influence one another within the watershed. In the following sections, I discuss factors that could affect sediment and phosphorus loading at Smith Creek and throughout the Lake Whatcom watershed. I evaluate the quality of my flux results and compare them to previous estimates of loading to Lake Whatcom, TMDL criteria, and results from other watersheds in the region. I also suggest additional data that could be collected to improve loading estimates.

5.1 Sediment and Phosphorus Transport in the Smith Creek Subbasin

5.1.1 Sediment Sources

Because the Smith Creek watershed is almost entirely forested, with few roads (Table 10), the stream’s main sources of sediment are likely to be the erosion of mass movement deposits and channel erosion. Clockwise sediment-discharge hysteresis within individual storm events indicates that sediment loading is limited, not only by stream energy, but by sediment availability (Gellis, 2012). The hysteresis pattern is consistent with the idea that channel sediment is resuspended as discharge increases, resulting in early sediment peaks. During back-to-back storm events, sediment-discharge ratios were not necessarily lower in the second event,
indicating that these events do not scour out the channel entirely, but deposit sediment in the streambed as flows subside.

Large mass wasting events occur in the Smith Creek watershed, but I found no evidence of mass wasting in the TSS results for any of my sampled storm events; however, it is possible that mass wasting occurred between sampled storm events. Event maximum sediment concentrations consistently occurred near hydrograph peaks and were strongly correlated with the magnitude of rise, with no unusual spikes that would signal a large mass movement event. The observed sediment peaks almost always followed precipitation peaks (Figures 23-24). Lag times between the precipitation peak and the sediment peak were fairly invariable (Table 8), suggesting that erosional processes were consistent among events. An unexpectedly high TSS value occurred at the end of Event 4 (February 25-26, 2013) but appeared to be an isolated anomaly. The relatively high sediment concentration was only observed in one sample and does not appear to have influenced results from the beginning of Event 5 two days later (Figure 24).

Precipitation intensity-duration probability thresholds calculated for the Jones Creek watershed, which borders the east side of the Lake Whatcom watershed, suggest that shallow slope failures would be possible, but not particularly likely, during most of the storm events sampled at Smith Creek (Brayfield, 2013). Based on Brayfield’s results from the South landslide in the Jones Creek watershed, rainfall Event 11 in the Smith Creek basin produced a maximum failure probability between 0.4 and 0.6, with probabilities of 0.3-0.4 for Events 15, 18, and 24 and probabilities of 0.2-0.3 for Events 3, 8, and 17. Maximum failure probabilities were less than 0.2 for all other events. Failures were less likely on the Straight landslide, with no maximum failure probabilities above 0.3 and probabilities above 0.2 only occurring for Events 11 and 24 (Figure 40).
Failure thresholds from the Jones Creek watershed are not directly applicable to the Smith Creek watershed because they were calculated for specific landslides, the bedrock type is Darrington Phyllite rather than the Chuckanut Formation, slopes are shallower, and the toes of the landslides are unvegetated. Forest cover makes landslides in the Smith Creek basin less likely because trees intercept rainfall and stabilize soil, whereas steeper slopes could increase the likelihood of landslides. Still, Brayfield’s thresholds were similar to the thresholds produced by Godt (2004) for the Seattle region and thus give a sense of the precipitation durations and intensities that might trigger major mass movements in the Smith Creek basin and the Lake Whatcom watershed in general. Based on this comparison to Brayfield’s results, sediment transported in the stream during the events sampled in the Smith Creek basin was likely sourced from the erosion of existing deposits near the stream channel rather than from large mass wasting events.

Another model suggests that mass wasting could have occurred during a few of the events sampled in 2013. Chleborad’s cumulative precipitation threshold, which is based on analysis of landslides in the Seattle area, compares 3-day and 15-day antecedent precipitation and predicts whether mass wasting is likely to occur (Chleborad, 2000). Chleborad’s model predicted mass wasting during the November 1990 event and during Events 8, 17, and 24 in 2013. Sediment concentrations in Smith Creek increased during each of these three 2013 events, but it is difficult to discern whether mass wasting occurred. The sediment peaks occurred near the discharge peaks, which would be expected if the sediment were sourced from existing deposits in the stream channel (Figure 24). Still, the antecedent precipitation model indicates that mass wasting could occur during these types of storm events.
5.1.2 Seasonal and Storm Event Variation

Seasonal variations in the relationship between streamflow magnitude and precipitation (Figure 29), and hence sediment and phosphorus fluxes to the lake, are highly influenced by antecedent soil conditions. During the summer and early fall, discharge tends to stay low even when there is substantial rainfall. The low initial water content in soil leads to greater soil suction, causing more of the water input to infiltrate and adhere to soil particles, thus increasing soil storage, rather than contributing to direct runoff. Because the water table is relatively low during the dry season, input water may go into recharging groundwater rather than contributing to streamflow. Vegetation may intercept a greater amount of rainfall during summer events because there is greater leaf area in the summer and because leaves are less likely to already be holding water from previous precipitation events, thus increasing storage potential. Some of the intercepted water evaporates rather than reaching the ground surface (Dingman, 2002). The highest ratios of TSS to discharge at Smith Creek occurred in the summer (Figure 30) because some erosion was occurring even when flows were very low. Increased algae concentrations in the stream due to warmer summer soil temperatures can contribute to the suspended material measured at low flow (Lee, et al., 2012). Summer storms may flush off particulate matter accumulated in the canopy during the long periods between rain events, contributing sediment to the stream (Dingman, 2002). High TP-discharge ratios during the summer may reflect inputs of soluble phosphate from groundwater (Brett, et al., 2005). Although summer TSS-discharge and TP-discharge ratios were unusually high, discharge was so low relative to the rest of the year that summer storms did not have much influence on yearly fluxes (Figure 22).

As precipitation increases in the fall and winter, soils become increasingly saturated, so a greater percentage of rainfall contributes to the storm hydrograph as runoff. By spring, interflow
and saturated overland flow are the dominant processes transporting water to the stream. Water moves as interflow through the permeable humus layer at the top of the soil column, with saturated overland flow occurring in areas where water rises above the humus layer (Dingman, 2002). More of the water reaches the stream following precipitation events, leading to greater increases in discharge and greater flow volumes. Because sediment and phosphorus concentrations tend to be correlated to discharge, a precipitation event occurring in the winter or spring is likely to produce higher loads than an equivalent event occurring in the fall.

Based on the hydrograph magnitude parameters that I calculated, there was not a discernible seasonal pattern that predicted the relationships of sediment and phosphorus concentrations to discharge during the fall, winter, and spring. Plots of event maximum sediment and phosphorus relative to the discharge centroid suggest higher sediment-discharge and phosphorus-discharge ratios in the fall than in the spring, but this discrepancy was only present with respect to the discharge centroid and not any of the other hydrograph parameters (Figure 30). With the exception of high ratios during the summer, it appears that sediment-discharge and phosphorus-discharge ratios do not vary seasonally. The seasons affect sediment and phosphorus loading because they affect stream discharge, not because the relationship between concentrations and discharge varies by season. Note that mass wasting events, which are more probable in the winter, would change this relationship.

Among the events that I sampled at Smith Creek, discharge was the main factor influencing sediment and phosphorus loading. Of the hydrograph magnitude parameters, magnitude of rise was the best predictor of sediment and phosphorus response to a storm event (Table 9). The relationship between hydrograph rise and maximum TSS was fairly consistent among storm events from different seasons and of different magnitudes. The correlation suggests
that the increase in discharge, rather than peak flow, total flow volume, time of year, or antecedent rainfall, is the most important factor to consider when predicting stream sediment concentrations. The strong relationship between hydrograph rise and sediment loading makes sense in the context of Smith Creek sediment sources. Streams have a lot of energy to erode and suspend sediment in and around the channel when discharge is higher, and many of the storms with high increases in discharge also had high peak flows. The magnitude of rise also takes antecedent flow into account. A small storm that begins when discharge is already high might reach a high peak flow but produce relatively little sediment because the previous flow has already eroded the most readily available material. Magnitude of rise is better than event flow volume for predicting sediment peaks because sediment peaks occur on the rising leg of the hydrograph and are thus largely indifferent to the slope of the recession curve, which greatly impacts flow volume, and because of the uncertainty in separating baseflow to calculate flow volume.

5.2 Spatial Variation in the Lake Whatcom Watershed

5.2.1 Sediment and Phosphorus Yields

Relief, slope, bedrock lithology, soil type, and urban development may explain the differences in sediment and phosphorus yields among the Lake Whatcom subbasins. The Smith Creek subbasin has high relief and steep, forested slopes (Figure 4). Its steep channels are susceptible to mass wasting at large and small scales, which contributes sediment to the stream (Syverson, 1984; Buchanan & Savigny, 1990). Although mass wasting does not appear to have occurred during the events I sampled, erosion of existing mass wasting deposits could explain the relatively high sediment yields from the Smith Creek basin (Table 7). The watersheds of Anderson, Austin, and Brannian Creeks also contain steep slopes (Table 10), but they produced less sediment per area.
Differences in bedrock type may partly account for the differences in yields. The Anderson and Brannian Creek subbasins are underlain by Darrington Phyllite rather than the Chuckanut Formation (Figure 5), which may have led to lower sediment yields from these basins. The Chuckanut Formation is highly erodible, with soils that tend to slip along the surface of the bedrock when saturated. Water permeates the soil and collects at the soil-bedrock interface, increasing pore pressure and causing soil to slide. Although landslides occur in basins underlain by Darrington Phyllite, soil slippage on hillslopes is less common than in the Chuckanut Formation because the phyllite is more permeable and has greater surface roughness (DNR, 1996).

In addition, Anderson Creek is unique in that it includes flows from the Middle Fork Nooksack River diversion, which could influence sediment yields. Samples collected while the diversion was operating had relatively low ratios of TSS to discharge (Figure 17), suggesting that dilution is the dominant process by which the diverted water influences sediment concentrations in Anderson Creek. Fine sediment in the diverted water settles in Mirror Lake (Tracey, 2001). During storms or periods of high diversion flow, outflows from Mirror Lake contribute low-TSS water to Anderson Creek, decreasing suspended sediment concentrations at the sampling point downstream. The effects of the diversion may partly account for the relatively weak correlation between TSS and discharge in Anderson Creek.

The Silver Beach Creek subbasin has lower relief than the Anderson, Austin, Brannian, and Smith Creek basins, but it also has a somewhat higher drainage density and percentage of urban development (Table 10). Channel erosion may play a greater role in generating sediment in the smaller, urbanizing basins than in the larger, forested basins because of differences in relief, landcover, and bed material. Shallower slopes decrease the likelihood of mass wasting but
tend to have thicker soils. The presence of impervious surfaces in developed areas may result in
greater runoff and higher erosion rates as the water level rises during storm events. Impervious
surfaces have little impact on yearly flow volumes (Figure 31), but water may be delivered to the
streams more rapidly, leading to higher storm flows and more erosion. As observed at the
gauging stations, soil beds are more common in the smaller streams than in the larger streams
(Figure 32). High flows may have scoured out the channels of the larger creeks over time,
leaving behind coarse sediment that is more difficult to erode. Clockwise sediment-discharge
hysteresis occurred in all five basins, but it occurred less consistently among the Silver Beach
Creek storm events. During a few of the events sampled at Silver Beach Creek, the relationship
between TSS and discharge was relatively linear, suggesting a constant supply of sediment
(Figures 33-34). In contrast, the events at Smith Creek consistently produced clockwise
hysteresis loops (Figure 27). Linear TSS-discharge relationships during some of the Silver Beach
Creek events are consistent with the idea that thick soils along the channel are eroding and
contributing sediment to the stream during high flows.

The Austin Creek and Smith Creek subbasins have similar relief, bedrock, and landcover,
but sediment yields were substantially higher at Smith Creek. The linear model may have
overestimated fluxes and yields from Smith Creek or underestimated those from Austin Creek,
but there also may be a real discrepancy in loading between the two creeks. The Austin Creek
model was highly influenced by its two largest events (24 and 25), which had unusually low
ratios of TSS to discharge (Figure 17). The low ratios may indicate limited sediment availability
at high discharge. Sediment depletion could affect Austin Creek more than Smith Creek because
paved roads in the Austin Creek subbasin limit sediment production in the lower part of the
watershed (Figures 7-8). Paved surfaces can also increase storm sediment concentrations by
producing higher hydrograph peaks. However, elevated storm flows may have relatively little impact on Austin Creek compared to the smaller subbasins in the Lake Whatcom watershed because of its thin soils and coarse channel material.

The difference between Austin and Smith Creeks could also have resulted from differences in sampling. Event 25 was not sampled at Smith Creek, and sampling during Event 24 began after the initial hydrograph rise due to a sampler error (Figures 27-28). Relatively low sediment concentrations at high discharge might occur at Smith Creek, but the linear model did not capture this effect. Calculated phosphorus yields at Austin Creek may have been higher if sampling had occurred downstream of the Sudden Valley Golf Course adjacent to Lake Whatcom. The quality of flux estimates is discussed further in Section 5.3.

5.2.2 Phosphorus-Sediment Ratios

Variation in the phosphorus-sediment ratio in different streams in the Lake Whatcom watershed could be the result of differences in water or soil chemistry. The relatively high TP-TSS ratios observed in the Anderson Creek water samples (Figure 35) could reflect relatively high concentrations of phosphorus in soil. Groce (2011) found that the Squires soil series, which is predominant in the Anderson Creek subbasin, had slightly higher values of TP than the other soil series in the Lake Whatcom watershed. Phosphorus concentrations may also be elevated due to organic inputs from pastureland in the Anderson Creek subbasin (Figure 7). Flows from the Middle Fork Nooksack River diversion could affect TP-TSS ratios in Anderson Creek. The higher concentrations of phosphorus relative to sediment, which occurred even when the diversion was on (Figure 16), are surprising because the Middle Fork Nooksack River carries fine glacial sediment containing little organic material and, thus, little particulate phosphorus (Tracey, 2001). It is likely that most of the phosphorus in Anderson Creek originates within the
Anderson Creek subbasin. Although concentrations of dissolved phosphorus in streams tend to be low (Schlesinger, 1997), some phosphorus may be transported from the Middle Fork Nooksack River in the dissolved load.

Soil type does not explain the higher phosphorus-sediment ratios in Silver Beach Creek. Most of the soil in the Silver Beach Creek subbasin is from the Squalicum series, which does not have particularly high phosphorus concentrations (Groce, 2011). Instead, higher phosphorus yields from the Silver Beach Creek subbasin could be attributed to local variations in soil phosphorus or, more likely, anthropogenic sources associated with urban development.

5.3 Quality of Flux Estimates

5.3.1 Hydrograph Quality

The accuracy of discharge data influences the accuracy of sediment and phosphorus fluxes. Discharge series at the gauged streams depend on stage-discharge rating curves, which are often uncertain at high flows because the maximum stream stage exceeds the maximum stage at which discharge has been measured. The quality of the rating curve is limited by the quality of actual peak flow measurements, which are infrequent. Overall, the rating curve-derived discharge series for Austin and Smith Creeks were similar to those generated using the DHSVM. When comparing rating curve-derived discharge to DHSVM-derived discharge in the 2013 water year, Nash-Sutcliffe (1970) efficiencies (E) were 0.72 for Austin Creek and 0.67 for Smith Creek (E ranges from 1 to -∞, with 1 indicating a perfect fit) and coefficients of determination (r²; Krause, et al., 2005) were 0.75 for Austin Creek and 0.70 for Smith Creek (r² ranges from 0 to 1, with values closer to 1 indicating a better fit). The DHSVM predicted somewhat lower discharge values for both creeks, particularly at the discharge peaks. When the DHSVM discharge series were used in place of the rating curve discharge series, mean sediment fluxes dropped from
405,000 to 298,000 kg/year at Austin Creek and from 1,940,000 to 428,000 kg/year at Smith Creek. Mean phosphorus fluxes decreased from 549 to 528 kg/year at Austin Creek and from 431 to 297 kg/year at Smith Creek. It is not clear that one method of estimating discharge peaks is more accurate than the other, but the comparison illustrates the variability introduced when discharge is uncertain.

5.3.2 Suspended Load vs. Bed Load

Suspended sediment measurements exclude portions of the total sediment flux. The TSS measurement method is biased low when sand makes up more than about 25% of the sample’s total sediment mass because the coarser particles settle quickly when subsamples are poured from the original sample container (Gray, et al., 2000). In general, the Smith Creek samples did not contain much sand, although this issue may have affected a few of the high-flow data points. More significantly, the sediment data did not include bed load, which typically makes up 5-20% of the total sediment load (Czuba, et al., 2011). Direct observations of sand and gravel moving along the creek beds, the watershed’s history of debris flows, and the coarse-grained deltas at the ends of some of the streams indicate that measurements of suspended material do not fully account for the mass of sediment being transported downstream. Although bedload is a component of the total sediment flux to the lake, I focused on measuring the suspended load because phosphorus tends to be adsorbed to fine sediment carried in suspension (Stone & Mudroch, 1989; Groce, 2011). Coarser sediment is more likely to settle out before or shortly after entering the lake, so bedload may not have much effect on lake water quality. In addition, finer sediment has a higher ratio of surface area to volume and may contain more organic matter, making it a better carrier of adsorbed phosphorus.
5.3.3 Limitations of Sediment-Discharge and Phosphorus-Discharge Models

Prediction of sediment concentrations based on discharge is limited because there is not a one-to-one relationship between sediment and flow. Combining data over long periods of time produced significant correlations between TSS and discharge, but the sediment-discharge relationship was unique for each storm event (Figure 19). Even within individual events, the relationship was often circular rather than linear or exponential (Figure 27). The linear model assumed equal sediment concentrations at equal discharges on the rising and falling limbs of the storm hydrograph. In reality, sediment concentrations were usually higher on the rising limb and lower on the falling limb (Figure 24). The sediment-discharge model overestimates sediment concentrations during periods of decreasing flow and baseflow and may underestimate concentrations during periods of rapidly increasing flow.

The model did not account for mass wasting or other sudden deliveries of sediment to the stream, such as the release of built-up sediment when debris is dislodged. Mass movements are more common during the winter months following periods of precipitation, but they can occur at any level of discharge and may result in unusually high sediment-discharge ratios (Chleborad, et al., 2006). Short-term variations can have a substantial impact on load estimates (e.g., Walker, et al., 1992) but are not taken into account by models that relate sediment concentration to discharge.

The same challenges are faced when predicting phosphorus concentrations based on discharge. The complexity of phosphorus cycling within streams and their watersheds makes phosphorus concentrations more difficult to predict than sediment concentrations, as seen in the relatively weak phosphorus-discharge correlations compared to sediment-discharge correlations (Figures 17-18).
5.3.4 Sample Collection Times

Sample collection times also affected the quality of flux estimates. I timed my sampling periods to coincide with storm events, with the goal of sampling most frequently around the rising leg and peak of the hydrograph. The linear models are sensitive to individual storms and data points, particularly at high flows, so results can vary depending on which storms and samples are included. For example, Events 24 and 25 produced high flows at Austin Creek (up to 254 cfs [7.19 m³/s]), but TSS and TP were not as high as expected based on results from previous events (Figures 17-18). Excluding these events from the linear model increased the mean sediment flux from 288,000 to 4,770,000 kg/year and increased the mean phosphorus flux from 440 to 709 kg/year. Comparisons among subbasins are limited in that different events were sampled at different streams (Table 4). At any of the streams, sampling at higher discharges or sampling any event with unusual trends could impact flux values but would not necessarily improve their accuracy because the relationships between water quality and flow vary among events.

5.4 Comparison to Other Calculated Fluxes and Yields

5.4.1 Comparison to Regional Estimates

The calculated sediment yields for Anderson, Austin, Brannian, Silver Beach, and Smith Creeks were at the low end of the range of yields estimated for streams in the Pacific Northwest. Sediment yields on the order of 10 tonnes/km²/year (Anderson, Austin, and Brannian Creeks) are common in the Puget Lowland. Yields around 100 tonnes/km²/year (Silver Beach and Smith Creeks) are more typical of the mountainous catchments in the region (Czuba, et al., 2012). Yields from the Lake Whatcom watershed were comparable to those from the Issaquah Creek watershed, a similar catchment located southeast of Seattle. Nelson and Booth (2002) calculated a sediment yield of 44 tonnes/km²/year and a pre-development yield of 24 tonnes/km²/year for
the Issaquah Creek basin. Some basins in the region yield more sediment. For example, yields from streams draining the volcanic, glaciated slopes of Mt. Rainier tend to be around 1,000 tonnes/km²/year, with yields of up to 14,000 tonnes/km²/year in the smaller catchments near the volcano (Czuba, et al., 2012). Sediment yield estimates for the landslide-dominated Swift Creek watershed, located about 15 km northeast of Lake Whatcom, range from 1,960 to 13,100 tonnes/km²/year (Clement, 2014; PSE, 2012).

My range of calculated phosphorus yields (25.7-68.5 kg/km²/year) was consistent with the findings of Embrey and Inkpen (1998), who estimated yields in the range of 24.5-105 kg/km²/year for four streams in the northern Puget Sound region. The yields were reasonable when compared to the results of the USGS SPARROW model, which calculated an average phosphorus yield of 54 kg/km²/year in the Puget Sound region, with yields from 21 to >70 kg/km²/year in the vicinity of Lake Whatcom (Wise & Johnson, 2011; 2013).

5.4.2 Comparison to Storm Water Runoff Monitoring Project

Compared to the 1992 estimates by Walker and others, the sediment and phosphorus loads that I calculated were higher for Silver Beach Creek and much lower for Anderson, Austin, and Smith Creeks. Part of the discrepancy may be attributed to improved discharge estimates and differences in rainfall between the two sampling periods. The authors of the 1992 study calculated fluxes using modeled daily discharge, whereas the WY 2013 hydrographs were based on high-resolution stage data and frequent discharge measurements (discharge was measured weekly at Austin and Smith Creeks and several times per year at Anderson and Silver Beach Creeks). It is not clear whether limited hydrologic data would have biased the 1992 results high or low, but increased data collection lends credibility to the more recent results.
Another factor to consider is that the 1992 report was based on a wet year relative to WY 2013. Bellingham International Airport, located 9 km from the north end of Lake Whatcom, received 136 cm of precipitation between May 1, 1990 and April 30, 1991 (the period of the study), compared to 80 cm in WY 2013 (Weather Underground, 2014). Even without considering the effect of mass wasting, greater total precipitation may have led to greater discharge and therefore greater sediment and phosphorus fluxes in 1990 and 1991.

The 1992 fluxes for Silver Beach Creek did not fall within the 95% confidence intervals of my estimates, but they were similar enough that yearly variability and differences in the calculation methods can account for the difference in results. For Anderson, Austin, and Smith Creeks, the results differ by orders of magnitude. For Austin and Smith Creeks, a good explanation for the discrepancy between my results and those presented in the Storm Water Runoff Monitoring Project report is the influence of the November 1990 storm event on the earlier model. This storm led to exceptionally high stream flows. High antecedent precipitation and intense rain during November 8-10 resulted in major floods throughout the region (USACE, 1991). The event had higher 3-day (9.25 cm) and 15-day (12.6 cm) antecedent precipitation totals than any of the events I sampled in 2013 (Table 8; Weather Underground, 2014). Walker and coworkers separated out the largest storms from their study period and calculated those fluxes separately, multiplying discharge by the average concentration from the November 10-12, 1990 storm event. Applying the unusually high sediment and phosphorus concentrations from this event to other events led to high calculated loads at Austin and Smith Creeks.

The high concentrations during the November 1990 event are thought to have resulted from mass wasting in the Austin and Smith subbasins (Walker, et al., 1992). In contrast, mass wasting does not appear to have occurred during any of my sampled events. Measured sediment
and phosphorus concentrations were lower, leading to lower load estimates. One possibility is that my calculations underestimated loads, failing to account for mass wasting that occurred between sampled storm events. Another possibility is that Walker and others overestimated loads at Austin and Smith Creeks by extrapolating high concentrations to storms in which there was no mass wasting. Alternatively, mass wasting may have occurred in 1990-1991 and not occurred in WY 2013, leading to a real discrepancy in fluxes.

The mass wasting hypothesis does not explain the differences in flux results at Anderson Creek. Relatively high concentrations of sediment and phosphorus were observed during the November 1990 storm event, but the increases were not as dramatic as at Austin and Smith Creeks. High fluxes at Anderson Creek during the 1990-1991 study period may be attributed to high diversion flows. During this period, modeled discharge reached values over 350 cfs (9.91 m$^3$/s) and frequently exceeded 100 cfs (2.83 m$^3$/s) (Walker, et al., 1992). In comparison, the maximum discharge at Anderson Creek during WY 2013 was 89.0 cfs (2.52 m$^3$/s) (USGS, 2014). Multiplying measured concentrations, including those from the November 1990 event, by higher discharge values resulted in the higher sediment and phosphorus fluxes at Anderson Creek.

5.4.3 Comparison to TMDL

My phosphorus flux estimates were below the TMDL loading goals. Precipitation in the Lake Whatcom watershed was low in the 2003 water year compared to the 2013 water year (66% lower at the Brannian rain gauge and 55% lower at both the Geneva rain gauge and the North Shore weather station). I applied the phosphorus-discharge linear models to DHSVM-modeled hydrographs for the 2003 water year to allow for comparison to the TMDL estimates, which are expressed in kilograms per 2003 year (Figure 41). Based on this calculation, phosphorus fluxes
from Anderson, Austin, Brannian, and Smith Creeks were well below the TMDL Base Scenario, Existing Conditions Scenario, and Allowable Inputs (Table 11). Fluxes from Silver Beach Creek are not directly comparable to TMDL estimates because of discrepancies in basin delineation (compare Figure 1 to Figure 10). Assuming a watershed area that includes the Hillsdale subbasin and 30% of the Silver Beach subbasin, as defined in the TMDL, the calculated phosphorus flux from Silver Beach Creek was lower than the Base Scenario, Existing Conditions Scenario, and Allowable Inputs (Table 11).

Based on my linear models, loading estimates for the 2003 water year were much lower than those for the 2013 water year. As discussed above, discharge estimated using the DHSVM tends to be somewhat lower (especially peaks) than that estimated using a stage-discharge rating curve, but the main reason for the lower fluxes in the 2003 water year is the lower precipitation. In the 2013 water year, a large proportion of sediment loading occurred during a few major storm events (Figure 22). The 2003 water year lacked the large hydrograph rises that produce high fluxes (Figure 41). Soil storage and interception amplify the effect of reduced precipitation; during a dry year, more of the precipitation contributes to soil storage and groundwater recharge rather than direct runoff, reducing the height of hydrograph peaks (Dingman, 2002). The differences between the 2003 water year, the 2013 water year, and years with large storm events such as in November of 1990 illustrate that sediment and phosphorus loading can vary considerably from year to year. Hence, a model developed to predict fluxes during a particular year may or may not accurately predict fluxes during a different year.
5.5 Future Work

5.5.1 Continuous Turbidity Monitoring

When paired with storm event sampling, continuous turbidity monitoring could improve the quality of sediment and phosphorus flux estimates. If the data are of high quality, turbidity is a better surrogate than stage or discharge for predicting sediment concentrations (USFS, 2007; Lewis & Eads, 2009). The turbidity method provides a higher-resolution dataset from which to calculate concentrations and fluxes, avoids the uncertainty associated with choosing sampling times, and does not assume a consistent relationship between sediment concentration and stream flow. Among Silver Beach Creek storm event data collected during the 2012 water year, TSS was correlated more strongly to turbidity ($\tau = 0.866$) than to either stage ($\tau = 0.536$) or discharge ($\tau = 0.48$). Correlations were also stronger between TP and turbidity ($\tau = 0.868$) than between TP and stage ($\tau = 0.551$) or discharge ($\tau = 0.48$) (Matthews, et al., 2013).

The USGS began collecting turbidity data at Anderson Creek on November 20, 2013, with measurements taken every 15 minutes (USGS, 2014). Between November 20, 2013 and March 10, 2014, IWS sampled three storm events at Anderson Creek (Events 23-25). Event 24 occurred during a gap in the turbidity data (Figure 42), but samples from Events 23 and 25 indicated a strong correlation between TSS and turbidity. Sediment and phosphorus were correlated more strongly with turbidity than with stage (Figures 43-44). This finding suggests that using a turbidity-based model could improve estimates of sediment and phosphorus concentrations.

Further investigation would be needed to assess the reliability of turbidity measurements at each individual stream. Stray light, bubbles from dissolved gases, debris such as twigs and leaves, freezing temperatures, and variation in particle size and shape can affect turbidity
readings (Anderson, 2005; Lewis & Eads, 2009). The turbidity meter at Anderson Creek recorded several unusually high values on February 17, 2014 (Figure 42), which could suggest either high sediment concentrations (e.g., from a sudden mass wasting event) or a problem with the sensor. Proper maintenance, sensor placement, and calibration to measured sediment concentrations can improve the quality of turbidity results (Lewis & Eads, 2009).

5.5.2 Sampling Additional Subbasins

Extending storm event sampling to more subbasins could also improve estimates of sediment and phosphorus loading to Lake Whatcom. The Anderson, Austin, Brannian, Silver Beach, and Smith Creek subbasins make up about 50% of the Lake Whatcom watershed. Further sampling would allow for better estimates of inputs from the rest of the watershed, particularly from the smaller, more urban subbasins at the north end of the lake. Although these areas have relatively low flows, results from Silver Beach Creek suggest that small catchments can still deliver significant fluxes of sediment and phosphorus to the lake. Furthermore, phosphorus contributed at the north end of the lake could have a disproportionate effect on lake water quality because the streams drain into the smaller, shallower lake basins (Figure 3; Walker, et al., 1992).

6.0 Conclusions

Relationships among sediment, phosphorus, and discharge varied temporally and spatially in the Lake Whatcom watershed. Transport was limited by sediment availability and varied among subbasins according to watershed characteristics such as topography, bedrock lithology, and landcover. Sediment and phosphorus concentrations were significantly correlated to discharge in most of the streams, but sediment-discharge and phosphorus-discharge relationships were not consistent within or among storm events, which resulted in uncertainty when calculating fluxes
based on discharge. At Smith Creek, the magnitude of hydrograph rise was the best predictor of the maximum sediment and phosphorus concentrations resulting from a storm event. My phosphorus loading estimates were below the TMDL criteria and were comparable to loading estimates for other streams in the region.

Improving water quality in Lake Whatcom is necessary by law because the lake is currently impaired and on the Washington State 303(d) list. My study provides a better understanding of sediment and phosphorus dynamics in the Lake Whatcom watershed, including what factors influence the amount of sediment and phosphorus that streams deliver to the lake. It also highlights the challenges of predicting fluxes in the Lake Whatcom watershed, a system with a high degree of variability. Sediment and phosphorus concentrations measured at Smith Creek are freely available and could be incorporated into future phosphorus loading models, which have the potential to influence revisions to the TMDL, development restrictions, and other watershed management decisions.
7.0 References


Donnell, C. B., 2007. Quantifying the glacial meltwater component of streamflow in the Middle Fork Nooksack River, Whatcom County, WA, using a distributed hydrology model. M.S. Thesis, Geology Department, Western Washington University, Bellingham, WA.


### 8.0 Tables

Table 1. Total yearly precipitation (cm) recorded at four stations in the Lake Whatcom watershed.

<table>
<thead>
<tr>
<th>Water Year</th>
<th>North Shore</th>
<th>Bloedel-Donovan</th>
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^a The record of the Bloedel-Donovan precipitation gauge begins in October 2006.
Table 2. TMDL modeled phosphorus loading to Lake Whatcom (modified from Pickett & Hood, 2008; Hood, 2013).

<table>
<thead>
<tr>
<th>Subbasin</th>
<th>Base Scenario (kg/yr)</th>
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<th>Allowable Inputs (kg/2003 yr)</th>
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<td>Blue Canyon</td>
<td>407.8</td>
<td>402.4</td>
<td>377.3</td>
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<td>Brannian</td>
<td>232.9</td>
<td>285.1</td>
<td>229.2</td>
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<td>Cable</td>
<td>16.5</td>
<td>26.3</td>
<td>5.3</td>
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<tr>
<td>Carpenter</td>
<td>142.7</td>
<td>196.4</td>
<td>80.8</td>
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<tr>
<td>Donovan</td>
<td>7.7</td>
<td>14.7</td>
<td>3.0</td>
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<tr>
<td>Fir</td>
<td>64.0</td>
<td>28.3</td>
<td>6.6</td>
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<td>Eagle Ridge</td>
<td>13.5</td>
<td>19.8</td>
<td>7.8</td>
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<tr>
<td>Geneva (Euclid Creek)</td>
<td>18.1</td>
<td>60.2</td>
<td>58.0</td>
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<td>Hillsdale (Silver Beach Creek)</td>
<td>133.7</td>
<td>174.4</td>
<td>34.1</td>
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<td>North Shore</td>
<td>163.3</td>
<td>40.6</td>
<td>14.3</td>
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<td>Olsen</td>
<td>325.8</td>
<td>181.6</td>
<td>87.9</td>
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<td>Oriental (Mill Creek)</td>
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<td>30.1</td>
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<td>Smith</td>
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<td>235.8</td>
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<td>Strawberry</td>
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<td>Sudden Valley</td>
<td>133.3</td>
<td>182.6</td>
<td>60.6</td>
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<tr>
<td><strong>Total</strong></td>
<td><strong>3623.0</strong></td>
<td><strong>3958.4</strong></td>
<td><strong>2534.4</strong></td>
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**Other Sources**

<table>
<thead>
<tr>
<th>Source</th>
<th>Base Scenario (kg/yr)</th>
<th>Existing Conditions Scenario (kg/2003 yr)</th>
<th>Allowable Inputs (kg/2003 yr)</th>
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<tbody>
<tr>
<td>Middle Fork Nooksack River Diversion</td>
<td>293.1</td>
<td>293.1</td>
<td>293.1</td>
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<tr>
<td>Groundwater</td>
<td>2203.4</td>
<td>2203.4</td>
<td>2203.4</td>
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<td>Direct Precipitation</td>
<td>162.6</td>
<td>162.6</td>
<td>162.6</td>
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<td><strong>Total</strong></td>
<td><strong>6281.8</strong></td>
<td><strong>6617.5</strong></td>
<td><strong>5193.5</strong></td>
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</table>
Table 3. Descriptions of parameters calculated for Smith Creek storm events. Table continues on the following page.

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<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Units</th>
<th>Description</th>
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</thead>
<tbody>
<tr>
<td><strong>Precipitation parameters</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Precipitation duration</td>
<td>$T_w$</td>
<td>hours</td>
<td>Duration of event precipitation based on the hyetograph at the nearest rain gauge.</td>
</tr>
<tr>
<td>Precipitation magnitude</td>
<td>$W$</td>
<td>cm</td>
<td>Sum of event precipitation based on the hyetograph at the nearest rain gauge.</td>
</tr>
<tr>
<td>Precipitation intensity</td>
<td>$I$</td>
<td>cm/hr</td>
<td>Precipitation magnitude divided by precipitation duration.</td>
</tr>
<tr>
<td>Antecedent precipitation, shorter-term</td>
<td>$P_3$</td>
<td>cm</td>
<td>Total precipitation occurring during the three days before the hydrograph peak, measured at the nearest rain gauge.</td>
</tr>
<tr>
<td>Antecedent precipitation, longer-term</td>
<td>$P_{15}$</td>
<td>cm</td>
<td>Total precipitation occurring during the 15 days before the hydrograph peak, measured at the nearest rain gauge.</td>
</tr>
<tr>
<td><strong>Hydrograph magnitude parameters</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Peak discharge</td>
<td>$Q_{pk}$</td>
<td>cfs</td>
<td>Discharge at the peak of the total hydrograph.</td>
</tr>
<tr>
<td>Magnitude of rise</td>
<td>$Q_r$</td>
<td>cfs</td>
<td>Discharge difference between the base and peak of the hydrograph.</td>
</tr>
<tr>
<td>Duration of rise</td>
<td>$T_r$</td>
<td>hours</td>
<td>Time between the base and peak of the hydrograph.</td>
</tr>
<tr>
<td>Event flow volume</td>
<td>$EFV$</td>
<td>ft$^3$</td>
<td>Volume of water passing through the channel during the event, calculated by approximating the area under the response hydrograph using Simpson’s rule: $EFV = \int_{t_1}^{t_n} Q(t) , dt \approx \frac{\Delta t}{3} \left[ Q(t_1) + 4 \cdot Q(t_2) + 2 \cdot Q(t_3) + \ldots + 4 \cdot Q(t_{n-1}) + Q(t_n) \right]$ where $\Delta t$ is the time difference between discharge measurements (15 minutes) and $Q(t_i)$ is the response hydrograph discharge at time $t_i$ (Larson, et al., 1998).</td>
</tr>
<tr>
<td>Hydrograph centroid</td>
<td>$Q_c$</td>
<td>cfs</td>
<td>Centroid of the response hydrograph, approximated using the equation $Q_c = \frac{1}{A} \int_{t_0}^{t_n} \frac{[Q(t)]^2}{2} , dt \approx \frac{\sum_{i=1}^{n} Q(t_i)^2}{2} \frac{1}{\sum_{i=1}^{n} Q(t_i)}$ where $t_0$ and $t_n$ are the start and end times of the event, $Q(t)$ is the response hydrograph discharge at time $t$, and $A$ is the area under the response hydrograph, defined by $\int Q(t) , dt$.</td>
</tr>
</tbody>
</table>
### Sediment and phosphorus parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Unit</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum sediment</td>
<td>TSS$_{\text{max}}$</td>
<td>mg/L</td>
<td>Highest recorded sediment concentration during the event.</td>
</tr>
<tr>
<td>Maximum phosphorus</td>
<td>TP$_{\text{max}}$</td>
<td>μg/L</td>
<td>Highest recorded phosphorus concentration during the event.</td>
</tr>
<tr>
<td>Sediment centroid</td>
<td>TSS$_c$</td>
<td>mg/L</td>
<td>Centroid of the interpolated sediment curve, approximated using the equation</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>$TSS_c = \frac{1}{A} \int_{t_0}^{t_n} [TSS(t)]^2 , dt \approx \frac{\sum_{i=1}^{n} TSS(t_i)^2}{2 \sum_{i=1}^{n} TSS(t_i)}$</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>where $t_0$ and $t_n$ are the start and end times of the event, TSS(t) is the total suspended solids concentration at time t, and A is the area under the sediment curve, defined by $\int TSS(t) , dt$.</td>
</tr>
<tr>
<td>Phosphorus centroid</td>
<td>TP$_c$</td>
<td>μg/L</td>
<td>Centroid of the interpolated phosphorus curve, approximated using the equation</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>$TP_c = \frac{1}{A} \int_{t_0}^{t_n} [TP(t)]^2 , dt \approx \frac{\sum_{i=1}^{n} TP(t_i)^2}{2 \sum_{i=1}^{n} TP(t_i)}$</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>where $t_0$ and $t_n$ are the start and end times of the event, TP(t) is the total phosphorus concentration at time t, and A is the area under the phosphorus curve, defined by $\int TP(t) , dt$.</td>
</tr>
<tr>
<td>Sediment lag time</td>
<td>TSS$_{\text{lag}}$</td>
<td>hours</td>
<td>Time between the time of maximum precipitation and the time of maximum sediment.</td>
</tr>
<tr>
<td>Phosphorus lag time</td>
<td>TP$_{\text{lag}}$</td>
<td>hours</td>
<td>Time between the time of maximum precipitation and the time of maximum phosphorus.</td>
</tr>
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</table>
Table 4. Storm events sampled between January 2013 and January 2014.

<table>
<thead>
<tr>
<th>Event</th>
<th>IWS Event Number&lt;sup&gt;a&lt;/sup&gt;</th>
<th>Dates</th>
<th>Season</th>
<th>Sampled Streams</th>
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</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>Jan 23-24, 2013</td>
<td>Winter</td>
<td>x</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>x</td>
</tr>
<tr>
<td>2</td>
<td>2</td>
<td>Jan 29-Feb 1, 2013</td>
<td>Winter</td>
<td>x</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>x</td>
</tr>
<tr>
<td>3</td>
<td>--</td>
<td>Feb 22-24, 2013</td>
<td>Winter</td>
<td>--</td>
</tr>
<tr>
<td>4</td>
<td>--</td>
<td>Feb 25-26, 2013</td>
<td>Winter</td>
<td>--</td>
</tr>
<tr>
<td>5</td>
<td>3</td>
<td>Feb 28-Mar 3, 2013</td>
<td>Winter</td>
<td>x</td>
</tr>
<tr>
<td>6</td>
<td>4</td>
<td>Mar 12-14, 2013</td>
<td>Winter</td>
<td>x</td>
</tr>
<tr>
<td>7</td>
<td>--</td>
<td>Apr 6-7, 2013</td>
<td>Spring</td>
<td>--</td>
</tr>
<tr>
<td>8</td>
<td>--</td>
<td>Apr 7-9, 2013</td>
<td>Spring</td>
<td>--</td>
</tr>
<tr>
<td>9</td>
<td>--</td>
<td>Apr 10-12, 2013</td>
<td>Spring</td>
<td>--</td>
</tr>
<tr>
<td>10</td>
<td>--</td>
<td>May 21-22, 2013</td>
<td>Spring</td>
<td>--</td>
</tr>
<tr>
<td>11</td>
<td>5</td>
<td>Jun 19-21, 2013</td>
<td>Spring</td>
<td>x</td>
</tr>
<tr>
<td>12</td>
<td>--</td>
<td>Aug 2-3, 2013</td>
<td>Summer</td>
<td>--</td>
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<tr>
<td>13</td>
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<td>Aug 29-30, 2013</td>
<td>Summer</td>
<td>--</td>
</tr>
<tr>
<td>14</td>
<td>--</td>
<td>Sept 6-7, 2013</td>
<td>Summer</td>
<td>--</td>
</tr>
<tr>
<td>15</td>
<td>--</td>
<td>Sept 16-17, 2013</td>
<td>Fall</td>
<td>--</td>
</tr>
<tr>
<td>16</td>
<td>--</td>
<td>Sept 22-24, 2013</td>
<td>Fall</td>
<td>--</td>
</tr>
<tr>
<td>17</td>
<td>--</td>
<td>Sept 28-29, 2013</td>
<td>Fall</td>
<td>--</td>
</tr>
<tr>
<td>18</td>
<td>6</td>
<td>Nov 1-4, 2013</td>
<td>Fall</td>
<td>x</td>
</tr>
<tr>
<td>19</td>
<td>7</td>
<td>Nov 6-9, 2013</td>
<td>Fall</td>
<td>x</td>
</tr>
<tr>
<td>20</td>
<td>8</td>
<td>Nov 15-17, 2013</td>
<td>Fall</td>
<td>x&lt;sup&gt;b&lt;/sup&gt;</td>
</tr>
<tr>
<td>21</td>
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<td>Nov 30-Dec 2, 2013</td>
<td>Fall</td>
<td>x</td>
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<tr>
<td>22</td>
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<td>Dec 23-24, 2013</td>
<td>Winter</td>
<td>--</td>
</tr>
<tr>
<td>23</td>
<td>9</td>
<td>Jan 2-4, 2014</td>
<td>Winter</td>
<td>x&lt;sup&gt;b&lt;/sup&gt;</td>
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<tr>
<td>24</td>
<td>10</td>
<td>Jan 10-13, 2014</td>
<td>Winter</td>
<td>x</td>
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<tr>
<td>25</td>
<td>11</td>
<td>Mar 8-10, 2014</td>
<td>Winter</td>
<td>x&lt;sup&gt;b&lt;/sup&gt;</td>
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</tbody>
</table>

<sup>a</sup> Corresponds to event numbers found in the 2013 Lake Whatcom Annual Report (Events 1-8; Matthews, et al., 2014) and 2014 Lake Whatcom Annual Report (Events 9-11; in progress).

<sup>b</sup> The Middle Fork Nooksack River diversion was operating during these events at Anderson Creek.

<sup>c</sup> Samples from Event 25 at Brannian Creek were not included in linear models because no discharge data were available for this event.
Table 5. Kendall’s $\tau$ statistics and p-values for parameter vs. stage correlations within individual storm events. Significant correlations (p<0.05) are shown in bold text.

<table>
<thead>
<tr>
<th></th>
<th>Anderson TSS vs. stage $\tau$</th>
<th>p-value</th>
<th>Austin TP vs. stage $\tau$</th>
<th>p-value</th>
<th>Brannian TSS vs. stage $\tau$</th>
<th>p-value</th>
<th>Smith TP vs. stage $\tau$</th>
<th>p-value</th>
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<tbody>
<tr>
<td>Event 1</td>
<td>0.778</td>
<td>0.002</td>
<td>0.854</td>
<td>&lt;0.001</td>
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<tr>
<td>Event 2</td>
<td>0.565</td>
<td>0.011</td>
<td>0.626</td>
<td>0.005</td>
<td>0.324</td>
<td>0.041</td>
<td>0.213</td>
<td>0.193</td>
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<td>Event 4</td>
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<tr>
<td>Event 5</td>
<td>0.682</td>
<td>&lt;0.001</td>
<td>0.472</td>
<td>0.006</td>
<td>0.618</td>
<td>&lt;0.001</td>
<td>0.444</td>
<td>0.003</td>
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<td>Event 6</td>
<td>0.383</td>
<td>0.047</td>
<td>0.309</td>
<td>0.112</td>
<td>0.557</td>
<td>&lt;0.001</td>
<td>0.25</td>
<td>0.096</td>
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<td>Event 8</td>
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<td>Event 9</td>
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<td>Event 10</td>
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<tr>
<td>Event 11</td>
<td>0.563</td>
<td>&lt;0.001</td>
<td>0.724</td>
<td>&lt;0.001</td>
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<td>Event 12</td>
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<td>Event 13</td>
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<td>Event 14</td>
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<td>Event 15</td>
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<td>Event 16</td>
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<td>Event 17</td>
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<tr>
<td>Event 18</td>
<td>0.304</td>
<td>0.011</td>
<td>0.3</td>
<td>0.011</td>
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<td>--</td>
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<tr>
<td>Event 19</td>
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<td>--</td>
<td>0.341</td>
<td>0.049</td>
<td>0.302</td>
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<td>Event 20</td>
<td>0.382</td>
<td>0.034</td>
<td>0.221</td>
<td>0.236</td>
<td>0.735</td>
<td>&lt;0.001</td>
<td>0.544</td>
<td>0.002</td>
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<tr>
<td>Event 21</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
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<td>--</td>
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</tr>
<tr>
<td>Event 22</td>
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<td>--</td>
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<td>Event 23</td>
<td>0.394</td>
<td>0.086</td>
<td>0.076</td>
<td>0.731</td>
<td>0.818</td>
<td>&lt;0.001</td>
<td>0.565</td>
<td>0.011</td>
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<tr>
<td>Event 24</td>
<td>0.531</td>
<td>&lt;0.001</td>
<td>0.36</td>
<td>0.016</td>
<td>0.657</td>
<td>&lt;0.001</td>
<td>0.554</td>
<td>&lt;0.001</td>
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<tr>
<td>Event 25</td>
<td>0.433</td>
<td>0.032</td>
<td>0.376</td>
<td>0.062</td>
<td>0.11</td>
<td>0.584</td>
<td>0.078</td>
<td>0.701</td>
</tr>
</tbody>
</table>
Table 6. Calculated suspended sediment and phosphorus fluxes from subbasins of the Lake Whatcom watershed, WY 2013 (n>200).

<table>
<thead>
<tr>
<th>Subbasin</th>
<th>n</th>
<th>Lower 95% CI</th>
<th>Mean</th>
<th>Upper 95% CI</th>
<th>Lower 95% CI</th>
<th>Mean</th>
<th>Upper 95% CI</th>
</tr>
</thead>
<tbody>
<tr>
<td>Anderson</td>
<td>294a</td>
<td>96,500</td>
<td>119,000</td>
<td>146,000</td>
<td>395</td>
<td>461</td>
<td>539</td>
</tr>
<tr>
<td>Austin</td>
<td>225b</td>
<td>273,000</td>
<td>405,000</td>
<td>609,000</td>
<td>450</td>
<td>549</td>
<td>677</td>
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<td>1,940,000</td>
<td>3,200,000</td>
<td>322</td>
<td>431</td>
<td>599</td>
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</table>

a 6 Brown & Caldwell storm events (36 samples), 10 IWS storm events (194 samples), and 64 IWS monthly or semiannual samples
b 5 Brown & Caldwell storm events (20 samples), 8 IWS storm events (150 samples), and 55 IWS monthly or semiannual samples
c 6 Brown & Caldwell storm events (31 samples), 8 IWS storm events (141 samples, missing TP for one of these samples), and 39 IWS monthly or semiannual samples
d 5 Brown & Caldwell storm events (25 samples), 21 IWS storm events (509 samples, missing TSS for one of these samples and TP for one other sample), and 32 IWS monthly or semiannual samples
e 22 storm events for this study (408 samples, missing TP for two of these samples), 5 Brown & Caldwell storm events (25 samples), and 64 IWS monthly or semiannual samples
Table 7. Calculated suspended sediment and phosphorus yields from subbasins of the Lake Whatcom watershed, WY 2013 (n>200).

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<th>Upper 95% CI</th>
<th>Lower 95% CI</th>
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<td>21.0</td>
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<td>236</td>
<td>23.7</td>
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<td>44.1</td>
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</table>

a 6 Brown & Caldwell storm events (36 samples), 10 IWS storm events (194 samples), and 64 IWS monthly or semiannual samples
b 5 Brown & Caldwell storm events (20 samples), 8 IWS storm events (150 samples), and 55 IWS monthly or semiannual samples
c 6 Brown & Caldwell storm events (31 samples), 8 IWS storm events (141 samples, missing TP for one of these samples), and 39 IWS monthly or semiannual samples
d 5 Brown & Caldwell storm events (25 samples), 21 IWS storm events (509 samples, missing TSS for one of these samples and TP for one other sample), and 32 IWS monthly or semiannual samples
e 22 storm events for this study (408 samples, missing TP for two of these samples), 5 Brown & Caldwell storm events (25 samples), and 64 IWS monthly or semiannual samples
Table 8. Parameters calculated for Smith Creek storm events. See Table 3 for parameter descriptions and units.

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<tr>
<th>Event</th>
<th>T_w</th>
<th>W</th>
<th>I</th>
<th>P_3</th>
<th>P_15</th>
<th>P_3/P_15</th>
<th>Q_pk</th>
<th>Q_r</th>
<th>T_r</th>
<th>EFV</th>
<th>Q_c</th>
<th>TSS_max</th>
<th>TP_max</th>
<th>TSS_c</th>
<th>TP_c</th>
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<td>18.2</td>
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Table 9. Correlations among Smith Creek storm event parameters. See Table 3 for parameter descriptions and units. Significant correlations (p<0.05) are shown in bold text.

<table>
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<th>Precipitation Parameters</th>
<th>Hydrograph Parameters&lt;sup&gt;a&lt;/sup&gt;</th>
<th>Sediment and Phosphorus Parameters</th>
<th>Sediment and Phosphorus Parameters</th>
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<td>Q&lt;sub&gt;pk&lt;/sub&gt;</td>
<td>T&lt;sub&gt;r&lt;/sub&gt;</td>
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<td>τ p-value</td>
<td>τ p-value</td>
</tr>
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Table 10. Watershed parameters for gauged subbasins within the Lake Whatcom watershed.

<table>
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<tr>
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<th>Area (km²)</th>
<th>Perimeter (km)</th>
<th>WY 2013 total flow volume (ft³)</th>
<th>Total length (km)</th>
<th>Drainage density (km¹)</th>
<th>Length of overland flow (km)</th>
<th>Main bedrock type</th>
<th>Relief (m)</th>
<th>Max slope (deg)</th>
<th>Mean slope (deg)</th>
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<td>54.0</td>
<td>9.7</td>
</tr>
<tr>
<td>Olsen</td>
<td>10.1</td>
<td>27.4</td>
<td>3.10x10⁸</td>
<td>21.4</td>
<td>2.13</td>
<td>0.94</td>
<td>CF</td>
<td>842</td>
<td>78.2</td>
<td>20.5</td>
</tr>
<tr>
<td>Silver Beach</td>
<td>3.1ᵃ</td>
<td>13.3</td>
<td>7.40x10⁷</td>
<td>9.1</td>
<td>4.23</td>
<td>0.47</td>
<td>CF</td>
<td>362</td>
<td>47.9</td>
<td>8.2</td>
</tr>
<tr>
<td>Smith</td>
<td>13.6</td>
<td>28.6</td>
<td>3.99x10⁸</td>
<td>30.2</td>
<td>2.22</td>
<td>0.90</td>
<td>CF</td>
<td>835</td>
<td>75.1</td>
<td>26.5</td>
</tr>
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</table>

<table>
<thead>
<tr>
<th>Subbasin</th>
<th>Basin length (km)</th>
<th>Elongation ratio</th>
<th>Compactness coefficient</th>
<th>Circulatory ratio</th>
<th>Basin shape factor</th>
<th>Form factor</th>
<th>Developed area (km²)</th>
<th>% Developed</th>
<th>Total road length (km)</th>
<th>Road density (km⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Anderson</td>
<td>5.0</td>
<td>0.73</td>
<td>2.03</td>
<td>0.24</td>
<td>2.37</td>
<td>0.42</td>
<td>0.03</td>
<td>0.26%</td>
<td>7.3</td>
<td>0.71</td>
</tr>
<tr>
<td>Austin</td>
<td>7.5</td>
<td>0.70</td>
<td>2.49</td>
<td>0.16</td>
<td>2.61</td>
<td>0.38</td>
<td>1.20</td>
<td>5.63%</td>
<td>69.5</td>
<td>3.25</td>
</tr>
<tr>
<td>Brannian</td>
<td>4.5</td>
<td>0.74</td>
<td>2.20</td>
<td>0.21</td>
<td>2.31</td>
<td>0.43</td>
<td>0.02</td>
<td>0.26%</td>
<td>9.8</td>
<td>1.12</td>
</tr>
<tr>
<td>Carpenter</td>
<td>1.8</td>
<td>0.83</td>
<td>2.37</td>
<td>0.18</td>
<td>1.85</td>
<td>0.54</td>
<td>0.07</td>
<td>3.85%</td>
<td>6.9</td>
<td>4.06</td>
</tr>
<tr>
<td>Euclid</td>
<td>1.3</td>
<td>0.86</td>
<td>2.63</td>
<td>0.14</td>
<td>1.70</td>
<td>0.59</td>
<td>0.26</td>
<td>28.19%</td>
<td>4.7</td>
<td>5.06</td>
</tr>
<tr>
<td>Millwheel</td>
<td>2.0</td>
<td>0.82</td>
<td>2.44</td>
<td>0.17</td>
<td>1.90</td>
<td>0.53</td>
<td>0.52</td>
<td>25.02%</td>
<td>8.9</td>
<td>4.30</td>
</tr>
<tr>
<td>Olsen</td>
<td>4.9</td>
<td>0.74</td>
<td>2.43</td>
<td>0.17</td>
<td>2.36</td>
<td>0.42</td>
<td>0.07</td>
<td>0.66%</td>
<td>8.0</td>
<td>0.79</td>
</tr>
<tr>
<td>Silver Beach</td>
<td>2.0</td>
<td>0.82</td>
<td>2.57</td>
<td>0.15</td>
<td>1.91</td>
<td>0.52</td>
<td>0.62</td>
<td>28.64%</td>
<td>8.7</td>
<td>4.04</td>
</tr>
<tr>
<td>Smith</td>
<td>5.8</td>
<td>0.72</td>
<td>2.19</td>
<td>0.21</td>
<td>2.45</td>
<td>0.41</td>
<td>0.01</td>
<td>0.06%</td>
<td>4.6</td>
<td>0.34</td>
</tr>
</tbody>
</table>

ᵃ The basin area for Silver Beach Creek is based on the catchment area reported by USGS (2014). This value was selected because of discrepancies in how the basin was delineated in the LiDAR subbasin shapefiles, HSPF model, and TMDL subbasins map.
ᵇ DP = Darrington Phyllite
ᶜ CF = Chuckanut Formation
Table 11. Phosphorus fluxes calculated by applying the WY 2013 linear models to WY 2003 modeled hydrographs, compared to TMDL phosphorus fluxes (includes streams for which n>200).

<table>
<thead>
<tr>
<th>Location</th>
<th>Phosphorus (kg/2003 year)</th>
<th>Base Scenario (kg/2003 year)(^\text{b})</th>
<th>Existing Conditions Scenario (kg/2003 year)(^\text{c})</th>
<th>Allowable Inputs (kg/2003 year)(^\text{c})</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Lower 95% CI</td>
<td>Mean</td>
<td>Upper 95% CI</td>
<td>Anderson</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Austin</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Brannian</td>
</tr>
<tr>
<td>Silver Beach(^\text{a})</td>
<td>21.5</td>
<td>23.2</td>
<td>25.1</td>
<td>133.7 (Hillsdale)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Smith</td>
</tr>
</tbody>
</table>

\(^\text{a}\) In the TMDL reports, the area upstream of the gauge at Silver Beach Creek comprises the Hillsdale subbasin and a portion (~30%) of the Silver Beach subbasin (Pickett & Hood, 2008; Hood, 2013).

\(^\text{b}\) Pickett & Hood, 2008

\(^\text{c}\) Hood, 2013
Figure 1. Location of the Lake Whatcom watershed and subbasins as defined in the TMDL reports (Pickett & Hood, 2008).
Figure 2. Simulated and observed phosphorus concentrations in six Lake Whatcom watershed streams, 2002-2005 (Cadmus & CDM, 2007). Used with permission.
Figure 3. Lake Whatcom bathymetry, basins, and sills (Mitchell, et al., 2010).
Figure 4. Land surface slope in the Lake Whatcom watershed (Sandborn, 2006).
Figure 5. Geologic units in the Lake Whatcom watershed (Mitchell, et al., 2010).
Figure 6. Soils in the Lake Whatcom watershed (NRCS, 1998).
Figure 7. Landcover in the Lake Whatcom watershed (NOAA, 2011).
Figure 8. Roads in the Lake Whatcom watershed (U.S. Census, 2013).
Figure 9. Precipitation stations in the Lake Whatcom watershed (R. Mitchell, personal communication, October 1, 2014).
Figure 10. IWS water quality monitoring sites in the Lake Whatcom watershed (Matthews, et al., 2013). The Austin and Smith Creek gauges are operated by IWS, and the other gauges are operated by USGS.
Figure 11. Equipment set up at the Smith Creek sampling site.
Figure 12. Hydrographs for the gauged streams in the Lake Whatcom watershed (WY 2013). Note scale on each plot. Figure continues on the following page.
Figure 12 (continued)
Figure 13. Hydrographs for the ungauged areas of the Lake Whatcom watershed (WY 2013), modeled by Joanne Greenberg using HSPF. Note scale on each plot. Figure continues on the following page.
Figure 13 (continued)
Figure 14. DHSVM stream model for the Lake Whatcom watershed. Discharge series were obtained for the nine gauged basins (see Figure 10) and for the streams shown in red.
Figure 15. Hydrographs with sampled events labeled, January 1, 2013 – March 31, 2014. The Anderson Creek hydrograph includes diversion flows. Brannian Creek hydrograph data after January 15, 2014 are not available. Note scale on each plot.
Figure 16. TP vs. TSS correlations and linear models for 25 streams in the Lake Whatcom watershed. Dashed lines represent 95% confidence intervals. Data represented by gray triangles were collected while the Middle Fork Nooksack River diversion was operating at Anderson Creek. Note scale on each plot. Figure continues on the following pages.
Figure 16 (continued)
Figure 16 (continued)
Figure 16 (continued)
Figure 17. TSS vs. discharge correlations and linear models for 25 streams in the Lake Whatcom watershed. Dashed lines represent 95% confidence intervals. Data represented by gray triangles were collected while the Middle Fork Nooksack River diversion was operating at Anderson Creek. Note scale on each plot. Figure continues on the following pages.
Figure 17 (continued)
Figure 17 (continued)
Figure 17 (continued)

\[ \text{tss} = 10^{(0.917 \times \text{discharge} + 1.333)} - 3.3 \]

\[ \text{Adj. R-squared} = 0.191 \]

\[ p\text{-value} = 0.029 \]
Figure 18. TP vs. discharge correlations and linear models for 25 streams in the Lake Whatcom watershed. Dashed lines represent 95% confidence intervals. Data represented by gray triangles were collected while the Middle Fork Nooksack River diversion was operating at Anderson Creek. Note scale on each plot. Figure continues on the following pages.
Figure 18 (continued)
Figure 18 (continued)
Figure 18 (continued)

Sudden Valley

log10 TP (μg/L)

Kendall's τ = -0.123
p-value = 0.413

tp = 10^{0.201 \cdot \text{discharge} + 1.988}
Adj. R-squared = -0.021
p-value = 0.466
Figure 19. Smith Creek TSS and TP vs. stage (February 2013 – January 2014) separated by season. Note scale on each plot.
Figure 20. TSS-discharge and TP-discharge correlations and linear models for Smith Creek storm events, separated by season. Note scale on each plot.
Figure 21. TSS-discharge and TP-discharge correlations and linear models for Smith Creek storm events, separated by magnitude of hydrograph rise (Q_r). Note scale on each plot.
Figure 22. Monthly fluxes of suspended sediment and phosphorus for five Lake Whatcom watershed streams, WY 2013 (n>200). The mean linear model was used to calculate the values shown. Note scale on each plot.
Figure 23. Smith Creek storm event hydrographs with 15-minute precipitation totals. Note scale on each plot. Figure continues on the following page.
Figure 23 (continued)
Figure 24. Smith Creek storm event hydrographs with TSS. Note scale on each plot. Figure continues on the following page.
Figure 24 (continued)
Figure 25. Smith Creek storm hydrographs with TP. Note scale on each plot. Figure continues on the following page.
Figure 25 (continued)
Figure 26. TP vs. TSS for individual storm events at Smith Creek. Note scale on each plot. Figure continues on the following page.
Figure 26 (continued)

- **Event 15**: Kendall's tau = 1, p-value < 0.001
- **Event 16**: Kendall's tau = 0.56, p-value < 0.001
- **Event 17**: Kendall's tau = 0.88, p-value < 0.001
- **Event 18**: Kendall's tau = 0.665, p-value < 0.001
- **Event 19**: Kendall's tau = 0.608, p-value < 0.001
- **Event 20**: Kendall's tau = 0.833, p-value < 0.001
- **Event 21**: Kendall's tau = 0.597, p-value = 0.005
- **Event 22**: Kendall's tau = 0.811, p-value < 0.001
- **Event 23**: Kendall's tau = 0.638, p-value < 0.001
- **Event 24**: Kendall's tau = 0.809, p-value < 0.001
Figure 27. TSS vs. stage for individual storm events at Smith Creek. Arrows show the order in which samples were collected. Note scale on each plot. Figure continues on the following page.
Figure 27 (continued)
Figure 28. TP vs. stage for individual storm events at Smith Creek. Arrows show the order in which samples were collected. Note scale on each plot. Figure continues on the following page.
Figure 28 (continued)
Figure 29. Flow magnitude ($Q_r$, $Q_{pk}$, $Q_c$, and EFV) normalized to precipitation magnitude (W) for Smith Creek storm events. See Table 3 for parameter descriptions.
Figure 30. Maximum TSS and TP normalized to flow magnitude (Qr, Qpk, Qc, and EFV) for Smith Creek storm events. See Table 3 for parameter descriptions.
Figure 31. Flow volume vs. area for the gauged subbasins in the Lake Whatcom watershed. Anderson Creek has high flow relative to its area because of inputs from the Middle Fork Nooksack River diversion.
Figure 32. Stream bed material observed at several of the stream gauges in the Lake Whatcom watershed. Photos of Euclid, Olsen, and Silver Beach Creeks are from the USGS Washington Water Science Center (USGS, 2014).
Figure 33. Silver Beach Creek storm event hydrographs with TSS. Discharge data are not available for the September 28, 2009 event. Note scale on each plot. Figure continues on the following page.
Figure 33 (continued)
Figure 34. TSS vs. discharge for individual storm events at Silver Beach Creek (Matthews, et al., 2011; 2012; 2013). Arrows show the order in which samples were collected. Note scale on each plot. Figure continues on the following page.
Figure 34 (continued)
Figure 35. TP vs. TSS for five streams in the Lake Whatcom watershed (n>200).
Figure 36. TSS vs. discharge for five streams in the Lake Whatcom watershed (n>200).
Figure 37. TP vs. discharge for five streams in the Lake Whatcom watershed (n>200).
Figure 38. WY 2013 sediment flux vs. key basin parameters for five streams in the Lake Whatcom watershed (n>200).
Figure 39. WY 2013 phosphorus flux vs. key basin parameters for five streams in the Lake Whatcom watershed (n>200).
Figure 40. Precipitation intensity-duration probability thresholds for shallow slope failure on the toes of the Straight and South landslides in the Jones Creek watershed (Brayfield, 2013).
Figure 41. DHSVM-modeled hydrographs for five streams in the Lake Whatcom watershed, October 1, 2002 – September 30, 2003. Note scale on each plot.
Figure 42. Anderson Creek discharge and turbidity, November 20, 2013 – April 14, 2014 (USGS, 2014). The full peak on February 17, 2014 is not shown.
Figure 43. TSS as a function of turbidity and stage at Anderson Creek, November 20, 2013 – April 14, 2014. Dashed lines represent 95% confidence intervals.

\[
t_{\text{TSS}} = 10^{(0.714 \times \text{stage} + -0.943)}
\]

\[
\text{Adj. R-squared} = 0.794
\]

\[
p\text{-value} < 0.001
\]

\[
\log_{10}\text{TSS} = 10^{(0.714 \times \text{stage} + -0.943)}
\]

\[
\text{Adj. R-squared} = 0.794
\]

\[
p\text{-value} < 0.001
\]

\[
l_{\text{TSS}} = 10^{(1.329 \times \text{turbidity} + -0.195)}
\]

\[
\text{Adj. R-squared} = 0.889
\]

\[
p\text{-value} < 0.001
\]
Figure 44. TP as a function of turbidity and stage at Anderson Creek, November 20, 2013 – April 14, 2014. Dashed lines represent 95% confidence intervals.
Appendix A. Precipitation and Hydrograph Data Gaps

WY 2013 Precipitation Data Gaps

Brannian Gauge
10/4/2012 11:15 to 12:30
1/23/2013 7:00 to 2/7/2013 6:45

Geneva Gauge
10/1/2012 0:00 to 10/4/2012 12:00

North Shore Weather Station
10/1/2012 0:00 to 11/20/2012 23:45
5/15/2013 9:00 to 11:00

WY 2013 Hydrograph Data Gaps

Anderson Creek
11/30/2012 0:00 to 12/3/2012 23:45
12/11/2012 10:00 to 10:30
1/4/2013 0:00 to 1/5/2013 23:45
5/2/2013 23:00 to 5/29/2013 22:45
6/5/2013 10:30
6/19/2013 12:00 to 6/20/2013 1:45
6/21/2013 19:00 to 6/22/2013 4:45
8/12/2013 10:00 to 8/13/2013 4:45
8/13/2013 14:00 to 21:45
(USGS data provisional after 6/19/2013)

Brannian Creek
6/5/2013 15:30 to 6/15/2013 11:00
6/15/2013 11:30 to 6/19/2013 11:30
7/11/2013 15:30 to 15:45
(USGS data provisional after 6/19/2013)

Carpenter Creek
11/19/2012 14:45
11/19/2012 15:15
11/19/2012 15:45
11/19/2012 16:15
11/19/2012 16:45
11/19/2012 20:15
11/19/2012 20:45
11/21/2012 0:00 to 12/8/2012 23:45
12/20/2012 0:00 to 1/4/2013 23:45
1/7/2013 15:00 to 16:45
4/11/2013 10:30
(USGS data provisional after 4/10/2013)

Euclid Creek
2/6/2013 14:15
3/27/2013 23:00 to 4/3/2013 22:45
4/10/2013 8:45
(USGS data provisional after 4/10/2013)

Millwheel Creek
10/1/2012 0:00 to 10/2/2012 22:45
7/2/2013 13:00
8/12/2013 14:00
(USGS data provisional after 2/6/2013)

Olsen Creek
11/30/2012 10:00 to 11:00
1/4/2013 11:15 to 11:30
1/12/2013 9:15 to 9:30
1/12/2013 11:30
1/12/2013 12:30 to 12:45
1/12/2013 13:15
1/13/2013 12:15
3/2/2013 0:00 to 3/4/2013 23:45
12/31/2013 6:00 to 1/6/2014 11:15
(USGS data provisional after 4/10/2013)

Silver Beach Creek
6/26/2013 10:15 to 6/30/2013 22:45
(USGS data provisional after 4/10/2013)