Sediment and Phosphorus Inputs from Perennial Streams to Lake Whatcom, Washington State

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ABSTRACT

Relationships among suspended sediment, phosphorus, and discharge vary temporally and spatially in the Lake Whatcom watershed, a 125-km², high-relief, moderately developed, forested basin in northwestern Washington State. The lake is subject to a Total Maximum Daily Load to limit phosphorus inputs. Phosphorus, which largely enters the lake adsorbed to suspended sediment in streams, has led to increased algae growth and depletion of dissolved oxygen. We used the results of high-resolution storm event sediment and phosphorous sampling in five streams to examine the effects of varying watershed features on loading and to develop sediment-discharge and phosphorus-discharge models to estimate phosphorus loading to the lake during the 2013 water year. During most storm events, the sediment peak preceded the discharge peak. The magnitude of hydrograph rise was the best predictor of the maximum sediment concentration during the event. Of the five basins studied, a large, forested watershed that contains steep slopes susceptible to mass wasting yielded the most sediment per area. The highest phosphorus yield was from a smaller, lower-relief watershed containing 29 percent residential development. Our sediment and phosphorous yields were comparable to estimates from similar streams in the Puget Sound region in northwest Washington State. 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.

INTRODUCTION

Understanding phosphorus transport in watersheds is important because elevated phosphorus is one of the most common causes of lake impairment in the United States (EPA, 2014). Algae growth resulting from elevated phosphorus inputs can cause dissolved oxygen concentrations to decrease as bacteria metabolize algal carbon. Both algae and dissolved oxygen depletion are degrading the water quality in Lake Whatcom, located in northwestern Washington State (WA; Figure 1). Quantifying phosphorus loading and designing mitigation strategies are challenging because much of the phosphorus enters the lake adsorbed to suspended sediment in perennial streams that discharge to the lake (Matthews et al., 2014). The amount of suspended sediment in streams is controlled by sediment availability and sediment transport capacity, which, in turn, depend on a wide range of hydrologic and watershed factors (Asselman, 1999; Gellis, 2012). Sediment can be eroded from the banks and bed of the channel or from hillslopes and roads in the surrounding watershed (Lu and Richards, 2008). A study of the Issaquah Creek watershed (Nelson and Booth, 2002)—which is located 30 km southeast of Seattle, WA, 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. Sediment transport 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 percent of the annual suspended sediment load was produced during the 15 days of the year with the highest streamflow (Gonzalez-Hidalgo et al., 2010).

As of 1998, Lake Whatcom has been subject to a Total Maximum Daily Load (TMDL) to limit...
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Figure 1. Location of the Lake Whatcom watershed in northwest Washington State and the five basins used in this study.

phosphorus inputs. The Washington State Department of Ecology 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 (Pickett and Hood, 2008). 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. 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 (Hood, 2013). 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.

We aimed to determine how streamflow variability during rainstorm events and basin characteristics affect sediment and phosphorus loading to Lake Whatcom. Storm data are particularly useful because the amount of sediment and phosphorus transport is normally higher during periods of elevated streamflow. We 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. We examined how these relationships varied among storm events and among different streams in the watershed and developed a set of linear stream discharge models to estimate fluxes of phosphorus and suspended sediment to the lake during WY 2013. Understanding sediment and nutrient inputs will ultimately assist water managers in modeling and mitigating water quality issues in Lake Whatcom.

**STUDY SITE**

Lake Whatcom is of glacial origin and has a surface area of 20.3 km². The southern portion of the lake (basins 3N and 3S; Figure 1) contains about 96 percent of the 0.95-km³ lake volume (Mitchell et al., 2010). The area of the Lake Whatcom watershed is about 126 km², not including the lake itself (Pickett and Hood, 2008). The watershed has high relief, with elevations ranging from 95 to 1,027 m above mean sea level (Mitchell et al., 2010). The underlying geology consists of two bedrock units: the Chuckanut Formation and the Darrington Phyllite, as well as unconsolidated glacial and alluvial sediments (Lapen, 2000). Soils in the watershed are mainly classified as loam (Miller and White, 1998). Most of the watershed (81 percent) is vegetated with a combination of deciduous, evergreen, and mixed forest. The watershed was extensively logged near the beginning of the 1900s and up through the 1940s (WADNR, 1997). Currently, about 80 percent of the forest cover is mature; the remaining 20 percent is immature as a result of periodic harvesting over the past 40 years (WADNR, 1997; Kennedy et al., 2010). Residential development covers an additional 7 percent of the watershed, with the remainder mostly consisting of shrubland, grassland, and wetland. Less than 1 percent of the watershed area is used for agriculture (NOAA, 2011). Developed areas are mostly concentrated at the northwest end and along the central west side of Lake Whatcom. These areas also contain the highest density of paved roads; unpaved logging roads dominate the upper regions of the watershed (Figure 1; WADNR, 2016). The Lake Whatcom watershed is divided into basins, five of which (Anderson, Austin, Brannian, Silver Beach, and Smith Creeks) are analyzed in this study (Figure 1).

Water enters Lake Whatcom primarily through surface runoff, groundwater, and direct precipitation onto the lake and, to a small degree, through intermittent diversion via a pipeline from the Middle Fork of the Nooksack River. Diverted water enters a settling pond and then flows to Lake Whatcom via Anderson Creek (Figure 1; Tracy, 2001). Surface water inputs comprise perennial and intermittent streams, surface runoff directly into the lake, and engineered drainage systems (Delahunt, 1990; Pickett and Hood, 2008). The lake level is partially controlled by a dam at the head waters of Whatcom Creek, the only natural surface outlet of the lake at the northwest end of Basin 1 (Figure 1). Outputs from Lake Whatcom include evaporation, the outlet at Whatcom Creek, and water removed for municipal and industrial use. The lake serves as the drinking water source for approximately 100,000 people in the city of Bellingham, WA, and the surrounding areas (Hood, 2013).

Precipitation in the Lake Whatcom watershed is distributed across frequent, low-intensity rainfall events and occasional high-intensity storms, especially between the months of October and April, which typifies the region’s maritime climate. Average annual rainfall is higher in the southern part of the watershed than in the northern part as a result of storm patterns and an orographic effect caused by the high relief in the watershed. Between WY 2002 and WY 2013, the average recorded yearly rainfall ranged from 101 cm at the north end of the lake to 151 cm at the south end of the lake. 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 (approximately 77 percent of the 30-year regional precipitation mean). In contrast, our sampling period (WY 2013) occurred during one of the wettest of recent years (approximately 130 percent of the 30-year regional precipitation mean).

**Effect of Phosphorus Inputs on Lake Water Quality**

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 algae growth (Matthews et al., 2002). As bacteria metabolize algal carbon, they consume large amounts of oxygen from the water (Coveney and Wetzel, 1989). Resulting problems include loss of aquatic habitat and release of other contaminants due to anoxic lake conditions. From a drinking water standpoint, algal blooms may be problematic because they can clog water intake filters, and some algae can produce unpleasant tastes and odors in drinking water (Matthews et al., 2014). In watershed settings, phosphorus mainly occurs adsorbed to sediment particles (Lee et al., 2012). In the Lake Whatcom watershed, more than half of the adsorbed phosphorus is thought to be available for biota to use and thus has the potential to contribute to algae growth (Liang, 1994; Groce, 2011). Therefore, for management
purposes, it is important to characterize stream sediment discharging to the lake.

MATERIALS AND METHODS

Sampling and Laboratory Analysis

We collected discharge data and water samples for TSS and TP analyses near the mouth of each creek in five basins (Figure 1) in accordance with U.S. Geological Survey (USGS) protocols for measuring fluvial sediment (Rantz, 1982; Edwards and Glysson, 1999). A stream gauge at each stream recorded the water level (stage) at 15-minute intervals. Discharge is measured regularly (weekly to several times per year) at each of the gauging stations. Updated stage-discharge rating curves, unique to each stream, were used to produce discharge hydrographs at 15-minute resolution. We used Teledyne Isco automated water samplers to collect a series of samples over the duration of each storm event. In most streams, coarser particles are concentrated near the streambed, whereas fine sediment tends to be uniformly distributed throughout the water column (Edwards and Glysson, 1999). The sample intake was placed approximately 20 cm above the bottom of the stream, with the goal of obtaining representative suspended sediment concentrations for the selected location along the stream. For each event, our objectives 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. At Anderson, Austin, and Brannian Creeks, sample collection, discharge measurements, and stage monitoring all occurred at the same location. Samples were typically collected at intervals of equal flow volume, yielding 10–30 discrete samples per event. At Smith Creek, the sampling location was located about 30 m downstream from the gauging station. Here, the sampling interval was adjusted manually (1 to 4 hours) 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. This sampling strategy provided water quality data at a wide range of discharge values. The City of Bellingham, WA, provided precipitation data recorded at 15-minute intervals at four stations in the Lake Whatcom watershed.

Stream water samples, including lab blanks and replicates, were analyzed for TSS and TP at the Institute for Watershed Studies (IWS) state-certified water quality lab at Western Washington University (WADOE, 2014; No. 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. Detection limits were 2 mg/L for TSS and 5 μg/L for TP.

Storm Parameters

We examined hydrograph, precipitation, TSS, and TP data in more detail in the Smith Creek basin (Figure 1) because it is one of the largest undeveloped and forested basins in the watershed and thus serves as a baseline for understanding natural sedimentation processes. Storm event size was quantified by calculating peak discharge, magnitude and duration of rise, event-flow volume, and precipitation magnitude. In calculating event-flow volume, we estimated and removed baseflow by drawing a straight line from the start of the rising leg to a point on the falling leg where flow began to level off and integrated under the resulting storm hydrograph. 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. We used the maximum recorded TSS and TP to quantify the sediment and phosphorus response to each storm event. These parameters are typically underestimates because the exact moment of maximum concentration is likely to occur between automated sampling intervals (typically 1 to 2 hours). Precipitation data were collected at the North Shore weather station located northwest of the Smith Creek basin (Figure 1).

Calculation of Sediment and Phosphorus Fluxes

We analyzed the data and calculated the sediment and phosphorus fluxes from five streams in the Lake Whatcom watershed over WY 2013 using R, an open-source statistical analysis package (R Core Team, 2012). We plotted TSS and TP against discharge, applied a logarithmic transformation to TSS and TP to linearize the relationship, and fit a linear model to the transformed data (Helsel and Hirsch, 2002; USFS, 2007). The TSS data were uncensored and contain negative values (for samples that contain very little sediment, the mass before filtering may exceed the mass after filtering as a result of the limitations of the balance). When developing the TSS-discharge models, we added a constant (3.3) before transformation to avoid taking the logarithm of a negative number. We 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 percent confidence interval, one at the mean, and one at the upper 95 percent confidence interval. Duan’s smearing estimator was applied to correct for re-transformation 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). We estimated the sediment and phosphorus loading from each stream by multiplying flow volumes by TSS and TP concentrations (Glysson, 1987; Gray and Simões, 2008). We also converted results from kilograms to tons and divided by the watershed area to determine yields in tons per square kilometer per year.

Basin Characteristics

We compiled and analyzed digital watershed data for the five gauged sub-basins to determine whether sediment and phosphorus loading relate to spatial watershed features including basin area, relief, slope, drainage density, bedrock type, paved and unpaved roads, and degree of urban development. Sub-basins and spatial watershed features were delineated in ArcGIS 10.1 using a LiDAR bare earth terrain map with 2-m resolution (PSLC, 2006), landcover (NOAA, 2011), geology (WADNR, 2010), and roads (WADNR, 2016).

Correlation Analysis

Correlation analysis is a method used to examine the monotonic relationship between two variables. We used Kendall’s tau (\(\tau\)) rank-based correlations, calculated in R, to test for significant correlations between discharge, TSS, and TP over each stream’s full data set and within individual storm events. Kendall’s tau is resistant to the effects of outliers and well suited to data sets that exhibit a skewed distribution (Helsel and Hirsch, 2002). We compared the Smith Creek storm events to one another and tested for correlations among precipitation, discharge, and water quality parameters. The \(\tau\) test statistic ranges from \(-1\) to \(+1\); the closer to \(\pm 1\), the stronger the correlation. The \(p\)-value indicates statistical significance; significant correlations have \(p\)-values of less than 0.05. Kendall’s tau values around 0.7 or above are considered strong correlations.

RESULTS

Sediment and phosphorus were correlated to one another in all of the sampled streams, but the relationship between them varied throughout the watershed (Figure 2). Sediment and phosphorus were significantly correlated to discharge in all of the sampled streams (Figure 3). The correlation between sediment and discharge tended to be stronger (higher Kendall’s tau) than the correlation between phosphorus and discharge. Although correlations between sediment, phosphorus, and discharge were statistically significant for most sites, there was a high degree of variability within each site. Ratios of phosphorus to sediment tended to be relatively high in Silver Beach Creek (Figure 2). Silver Beach Creek had higher levels of sediment and phosphorus relative to discharge when compared to Anderson, Austin, Brannian, and Smith Creeks (Figure 3).

Among the five basins, mean calculated sediment fluxes for WY2013 were highest at Smith Creek, and phosphorus fluxes were highest at Austin Creek (Table 1). The Smith Creek watershed produced the most sediment per square kilometer, and the Silver Beach Creek watershed produced the most phosphorus per square kilometer (Table 2). We also calculated fluxes from the five basins by month, revealing that the highest sediment loads came from Smith Creek during large winter storm events, and most phosphorus loading from the five streams occurred between November and May, the rainier months of the year.

We examined hydrograph, TSS, and TP data in more detail in the Smith Creek basin because it serves as a forested baseline basin, with the lowest percentage of development of the five basins studied (Table 3). In the Smith Creek basin, about 87 percent of the forest cover is mature and about 13 percent immature as a result.
Table 1. Calculated suspended sediment and phosphorus fluxes from five basins of the Lake Whatcom watershed, WY 2013.

<table>
<thead>
<tr>
<th></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>294</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>225</td>
<td>273,000</td>
<td>405,000</td>
<td>609,000</td>
<td>450</td>
<td>549</td>
<td>677</td>
</tr>
<tr>
<td>Brannian</td>
<td>211</td>
<td>94,500</td>
<td>136,000</td>
<td>194,000</td>
<td>182</td>
<td>244</td>
<td>331</td>
</tr>
<tr>
<td>Silver Beach</td>
<td>566</td>
<td>157,000</td>
<td>240,000</td>
<td>378,000</td>
<td>179</td>
<td>212</td>
<td>256</td>
</tr>
<tr>
<td>Smith</td>
<td>497</td>
<td>1,190,000</td>
<td>1,940,000</td>
<td>3,200,000</td>
<td>322</td>
<td>431</td>
<td>599</td>
</tr>
</tbody>
</table>

CI = confidence interval.

of logging activities over the last 40 years (WADNR, 1997; Kennedy et al., 2010). Peaks in stream discharge typically followed peaks in precipitation. During most events, sediment and phosphorus peaks were higher on the rising leg of the discharge hydrograph and lower on the falling leg, forming a clockwise hysteresis loop when plotted against discharge (Figure 4). Although the spatial characteristics are different for each of the five basins (Table 3), the TSS, TP, and discharge patterns (e.g., hysteresis) are similar. Sediment and phosphorus generally increased with discharge and were significantly correlated with each other in all of the Smith Creek events, but the TSS- and TP-discharge relationships were unique for each storm event (Figure 5). Sediment was significantly correlated with discharge in 18 of 22 Smith Creek events, and phosphorus was significantly correlated with discharge in 16 of 22 events. Sediment and phosphorus were usually correlated more strongly to one another than to discharge (Figures 2 and 3).

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 4 and Figure 1). Large precipitation events tended to produce large hydrograph peaks (Table 4). Event rainfall was correlated significantly, but weakly, to peak discharge ($\tau = 0.424$), magnitude of hydrograph rise ($\tau = 0.493$), duration of rise ($\tau = 0.35$), event-flow volume ($\tau = 0.483$), and shorter

Figure 3. TSS vs. discharge and TP vs. discharge correlations for five streams in the Lake Whatcom watershed. Dashed lines represent 95 percent confidence intervals.
Calculated suspended sediment and phosphorus yields from five basins of the Lake Whatcom watershed, WY 2013.

<table>
<thead>
<tr>
<th>District</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>294</td>
<td>9.31</td>
<td>11.5</td>
<td>14.1</td>
<td>38.1</td>
<td>44.5</td>
<td>52.0</td>
</tr>
<tr>
<td>Austin</td>
<td>225</td>
<td>12.8</td>
<td>18.9</td>
<td>28.5</td>
<td>21.0</td>
<td>25.7</td>
<td>31.6</td>
</tr>
<tr>
<td>Brannian</td>
<td>211</td>
<td>10.8</td>
<td>15.5</td>
<td>22.2</td>
<td>20.8</td>
<td>27.9</td>
<td>37.8</td>
</tr>
<tr>
<td>Silver Beach</td>
<td>566</td>
<td>50.5</td>
<td>77.6</td>
<td>122</td>
<td>57.6</td>
<td>68.5</td>
<td>82.6</td>
</tr>
<tr>
<td>Smith</td>
<td>497</td>
<td>87.8</td>
<td>143</td>
<td>236</td>
<td>23.7</td>
<td>31.7</td>
<td>44.1</td>
</tr>
</tbody>
</table>

CI = confidence interval.

term (3 days; $\tau = 0.436$) and longer term (15 days; $\tau = 0.439$) antecedent precipitation. Although rainfall and hydrograph rise were correlated, rainfall alone did not necessarily predict flow. For example, a 2.9-cm precipitation event in late September only resulted in a 0.28-m$^3$/s hydrograph rise due to precipitation loss to soil storage, whereas a similar-sized rain event in late December (2.9 cm of precipitation) increased discharge by 1.9 m$^3$/s because antecedent soil conditions were closer to field capacity (Table 4). When normalized to precipitation magnitude, the flow response was highest in the late winter, decreased and remained low through the summer, and increased again in the fall. Maximum sediment was significantly correlated to the magnitude of rise ($\tau = 0.717$), peak discharge ($\tau = 0.657$), event-flow volume ($\tau = 0.506$), and event rainfall ($\tau = 0.5$), but not to the duration of rise. Maximum phosphorus was correlated to event rainfall ($\tau = 0.404$), but not to any of the hydrograph magnitude parameters.

### DISCUSSION

Given that the high-relief Smith Creek basin is almost entirely forested with the highest unpaved road density (Table 3), the stream’s main sources of sediment are likely to be the erosion of mass wasting deposits (sediments deposited during major slope movements, such as landslides) and channel erosion. Historically, mass wasting has occurred in the Smith Creek watershed during rainstorms, but we found no evidence of failures during our sampled storm events. However, it is possible that mass wasting occurred between sampling periods. Event maximum sediment concentrations consistently occurred near hydrograph peaks and are strongly correlated with the magnitude of rise, with no unusual spikes that would signal a large mass wasting event. The observed sediment peaks almost always follow precipitation peaks.

Among the events that we sampled at Smith Creek, discharge, rather than sediment and phosphorus concentration, was the main factor influencing loading. Of the hydrograph magnitude parameters, magnitude of rise was the best predictor of sediment and phosphorus response to a storm event. 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 sedi-

<table>
<thead>
<tr>
<th>Area (km$^2$)</th>
<th>Drainage density (km$^{-1}$)</th>
<th>Main Bedrock Type</th>
<th>Relief (m)</th>
<th>Mean Slope (°)</th>
<th>Percent Developed</th>
<th>Paved Road Density (km$^{-1}$)</th>
<th>Unpaved Road Density (km$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Anderson</td>
<td>10.4</td>
<td>3.18</td>
<td>DP$^a$</td>
<td>800</td>
<td>19.9</td>
<td>0.26</td>
<td>0.48</td>
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<tr>
<td>Austin</td>
<td>21.4</td>
<td>2.95</td>
<td>DP$^a$</td>
<td>722</td>
<td>19.1</td>
<td>5.63</td>
<td>2.19</td>
</tr>
<tr>
<td>Brannian</td>
<td>8.7</td>
<td>3.17</td>
<td>CF$^b$</td>
<td>772</td>
<td>16.0</td>
<td>0.26</td>
<td>0.60</td>
</tr>
<tr>
<td>Silver Beach</td>
<td>3.1$^c$</td>
<td>4.23</td>
<td>CF</td>
<td>362</td>
<td>8.2</td>
<td>28.6</td>
<td>2.98</td>
</tr>
<tr>
<td>Smith</td>
<td>13.6</td>
<td>2.22</td>
<td>CF</td>
<td>835</td>
<td>26.5</td>
<td>0.06</td>
<td>0.14</td>
</tr>
</tbody>
</table>

$^a$DP = Darrington Phyllite.

$^b$CF = Chuckanut Formation.

$^c$The watershed area for Silver Beach Creek is based on the catchment area reported by the USGS (2014). This value was selected because of discrepancies in how the watershed was delineated in the LiDAR basins shapefiles and TMDL basins map.
Figure 4. Precipitation, discharge, TSS, and TP data collected during a representative storm event (15-17 November 2013) at Smith Creek.

iment 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 affects flow volume estimates. The event-flow volume also has a level of uncertainty due to baseflow separation inaccuracies.

Relief, slope, bedrock lithology, soil type, density of unpaved roads, and urban development likely explain the differences in sediment and phosphorus yields among the Lake Whatcom basins. The Smith Creek basin has high unpaved road density, high relief, and forested slopes (Table 3). Its steep channels are susceptible to mass wasting at large and small scales, which contributes sediment to the stream (Syverson, 1984; Buchanan and Savigny, 1990; and WADNR, 1997). Al-

Figure 5. Relationships between sediment and phosphorus concentrations and discharge at Smith Creek, with events separated by season. The overall linear model is a compilation of many distinct trends.
Sediment and Phosphorus Inputs to Lake Whatcom

Table 4. Parameters calculated for Smith Creek storm events.

<table>
<thead>
<tr>
<th>Event Dates</th>
<th>W</th>
<th>W₃</th>
<th>W₁₅</th>
<th>Qₚk</th>
<th>Q₉</th>
<th>T₉</th>
<th>EFV</th>
<th>TSSmax</th>
<th>TPmax</th>
</tr>
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<tbody>
<tr>
<td>22–24 Feb 2013</td>
<td>2.0</td>
<td>2.34</td>
<td>3.28</td>
<td>0.73</td>
<td>0.51</td>
<td>15.0</td>
<td>25,000</td>
<td>32.4</td>
<td>34.5</td>
</tr>
<tr>
<td>25–26 Feb 2013</td>
<td>1.9</td>
<td>2.82</td>
<td>5.03</td>
<td>0.76</td>
<td>0.40</td>
<td>4.5</td>
<td>16,000</td>
<td>13.3</td>
<td>17.4</td>
</tr>
<tr>
<td>28 Feb–3 Mar 2013</td>
<td>2.5</td>
<td>2.49</td>
<td>7.52</td>
<td>2.2</td>
<td>1.8</td>
<td>32.5</td>
<td>390,000</td>
<td>77.3</td>
<td>43.7</td>
</tr>
<tr>
<td>12–14 Mar 2013</td>
<td>2.4</td>
<td>2.67</td>
<td>7.30</td>
<td>1.2</td>
<td>0.91</td>
<td>32.5</td>
<td>110,000</td>
<td>29.2</td>
<td>31.1</td>
</tr>
<tr>
<td>6–7 Apr 2013</td>
<td>1.4</td>
<td>4.12</td>
<td>4.12</td>
<td>0.85</td>
<td>0.49</td>
<td>2.5</td>
<td>7,000</td>
<td>44.8</td>
<td>43.1</td>
</tr>
<tr>
<td>7–9 Apr 2013</td>
<td>1.7</td>
<td>5.72</td>
<td>5.87</td>
<td>1.1</td>
<td>0.48</td>
<td>9.8</td>
<td>57,000</td>
<td>32.9</td>
<td>32.2</td>
</tr>
<tr>
<td>10–12 Apr 2013</td>
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W = event rainfall (cm); W₃ = rainfall in the 3 days preceding the event (cm); W₁₅ = rainfall in the 15 days preceding the event (cm); Qₚk = discharge peak (m³/s); Q₉ = hydrograph rise (m³/s); T₉ = duration of hydrograph rise (hours); EFV = event-flow volume (m³); TSSmax = maximum recorded TSS (mg/L); TPmax = maximum recorded TP (μg/L).

though mass wasting does not appear to have occurred during the events that we sampled, erosion of existing mass wasting deposits is the likely source for the relatively high sediment yields from the Smith Creek watershed. The basins of Anderson, Austin, and Brannian Creeks also contain unpaved roads and steep slopes (Table 3), but they produce less sediment per area (Table 2). Differences in bedrock type partly account for the differences in yields. The shallow soil deposits on the Chuckanut Formation are more susceptible to shallow (infinite slope) failures because they 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, decreasing shear strength, and causing shallow-soil failures. The Anderson and Brannian Creek basins are underlain by Darrington Phyllite rather than the Chuckanut Formation. Although landslides occur in watersheds underlain by Darrington Phyllite, soil slippage on hillslopes is less common than in the Chuckanut Formation because the phyllite is more permeable, allowing soils to drain more quickly. The phyllite, in general, is more susceptible to deep-seated landslides rather than shallow infinite slope failures (WADNR, 1997).

In addition, Anderson Creek is unique in that it includes flows from the Middle Fork Nooksack River diversion, which could influence sediment yields. Fine sediment in the diverted water settles in a small lake before entering Anderson Creek, decreasing suspended sediment concentrations at the sampling point downstream. Samples collected while the diversion was operating had relatively low ratios of TSS to discharge, suggesting that dilution is the dominant process by which the diverted water influences sediment concentrations in Anderson Creek. The effects of the diversion may partly account for the relatively weak correlation between TSS and discharge at Anderson Creek.

The Austin Creek and Smith Creek basins have similar bedrock and landcover, but sediment yields were substantially higher at Smith Creek. The Austin Creek basin has more urban development, lower relief, and a lower mean slope angle than the Smith Creek basin (Figure 1 and Table 3). The Austin Creek TSS-discharge model was also highly influenced by its two largest events, which had unusually low ratios of TSS to discharge (Figure 3).

The Silver Beach Creek basin 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 3). Channel erosion may play a greater role in generating sediment in the smaller, urbanizing watersheds than in the larger, forested watersheds because of differences in relief, landcover, and bed material. Shallower slopes decrease the likelihood of mass wasting, and lower-relief basins 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. Water may be delivered to the streams more rapidly, leading to higher storm flows and more erosion. In addition, high flows may have scoured out the channels of the larger creeks over time, leaving behind coarse sediment that is more difficult to suspend. The Silver Beach Creek basin has a relatively low density of unpaved roads, which may contribute to its relatively low sediment yields.

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. Higher TP-TSS ratios were associated with areas with more urban development and agricultural influences. The relatively high TP-TSS ratios observed in the Anderson Creek water samples could reflect relatively high concentrations of phosphorus in soil or organic inputs from pastureland and wetlands that reside in the lower reaches in the Anderson Creek basin. Although the Middle Fork Nooksack River carries fine glacial sediment containing little organic material and, thus, little particulate phosphorus, higher concentrations of phosphorus, relative to sediment, occurred even when the diversion was on, likely as a result of lateral erosion of stream channels in lower relief pasturelands and wetlands. Higher phosphorus yields from the Silver Beach Creek basin could be due to more developed soils, but they are more likely associated with anthropogenic sources such as fertilizers, detergents, and wastewater, given that the basin contains about 30 percent urban development and a high paved-road density (Table 3).

Several factors influence the accuracy of sediment and phosphorus flux estimates. The quality of loading estimates depends on hydrograph quality. Stage-discharge rating curves are often uncertain at high flows because the maximum stream stage exceeds the maximum stage at which discharge has been measured. The sediment data do not include bed load, which typically makes up 5–20 percent of the total sediment load (Czuba et al., 2011). Although bedload is a component of the total sediment flux to the lake, we focused on measuring the suspended load because phosphorus tends to be adsorbed to fine sediment carried in suspension (Stone and Mudroch, 1989). 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 mass and may contain more organic matter, making it a better carrier of adsorbed phosphorus.

Sample collection times also affect the quality of flux estimates. 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. 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 and many storm events (22 in Smith Creek) produces significant correlations between TSS and discharge, but the sediment-discharge relationship was unique for each storm event (Figure 5). Even within individual events, the relationship was most often circular (hysteretic) rather than linear or exponential. The linear models (Figure 3) assume equal sediment concentrations at equal discharges on the rising and falling legs of the storm hydrograph. In reality, sediment concentrations were usually higher on the rising leg and lower on the falling leg (Figure 4). The models do 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 wasting can occur at any level of discharge and may result in unusually high sediment-discharge ratios, affecting load estimates (Chleborad et al., 2006).

The calculated sediment yields based on our measurements and models were at the low end of the range of yields estimated for streams in the Pacific Northwest. Sediment yields on the order of 10 tons/km²/yr (Anderson, Austin, and Brannian Creeks) are common in the Puget Lowland. Yields of around 100 tons/km²/yr (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, WA (44 tons/km²/yr; Nelson and Booth, 2002). The range of calculated phosphorus yields is reasonable when compared with the findings of Embrey and Inkpen (1998), who estimated yields in the range of 24.5–105 kg/km²/yr for four streams in the northern Puget Sound, and the USGS SPARROW model, which calculated an average phosphorus yield of 54 kg/km²/yr in the Puget Sound region (Wise and Johnson, 2011, 2013).

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 basins according to spatial characteristics such as topography, bedrock lithology, and landcover. Sediment and phosphorus concentrations were significantly correlated to discharge in most streams, but sediment-discharge and phosphorus-discharge relationships were not consistent within or among storm events, which resulted in uncertainty when calculating fluxes based solely 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.

Improving water quality in Lake Whatcom is necessary by law because the lake is currently impaired and on the Washington State 303(d) list. Our study provides a better understanding of sediment and phosphorus dynamics in the Lake Whatcom watershed, including which factors influence the amount of sediment and phosphorus that streams deliver to the lake, which will improve modeling estimates for lake management purposes. It also highlights the challenges of predicting fluxes for management and modeling purposes in natural systems with a high degree of variability.

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REFERENCES


Beeler and Mitchell


