Research in the Willow Creek watershed: Estimates of sediment and phosphorus loads from sub-catchments; gauging public response to a constructed wetland; and a quantitative assessment of a conceptual constructed wetland

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Authorization to Submit Thesis

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Abstract

Cultural eutrophication, the accumulation of excess nutrients such as phosphorus (P) and nitrogen (N) in water bodies, is often manifested in blooms of cyanobacteria, also known as blue-green algae. These blooms threaten water quality worldwide because they can produce a suite of the most potent compounds toxic to wildlife and humans. Willow Creek Reservoir (WCR) in Heppner, OR experiences annual long-duration blooms of toxic cyanobacteria related to high loads of catchment-derived nutrients, primarily P. In my thesis, I identify and quantify the source of total P (TP) and total residue (TR, suspended and dissolved solids) from sub-catchments of the Willow Creek watershed. These loads were then combined with a modified export coefficient modeling approach to examine relations between land use and annual load. Contrary to my hypothesis, the majority of constituents were contributed by forested headwater sub-catchments, not agricultural areas in the lower reaches of the watershed. I also used an intercept survey to quantify residents and non-residents awareness of the annual toxic algae bloom and the interference such blooms have on their use of WCR, to examine how the construction of a wetland at the inlet of WCR would impact resident and non-resident use of WCR and to understand public's opinion of how the constructed wetland would be utilized. Overall, the majority of residents and non-residents were aware of the toxic algae bloom and supported a constructed wetland as a potential remediation strategy. Constructed wetlands have been used to target the reduction of P and reduce cyanobacteria. The effectiveness of TP and TR retention in a Free Water Surface (FWS) wetland system design at the inlet of the WCR was evaluated for water years 2010 and 2013. Because of limited space, the calculated removal of TP and TR mass in the wetland system was low and was therefore deemed not feasible. This study highlights the importance of basing management decisions on empirical data.

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Chapter 1: General introduction

Life as we know it depends on access to clean water. To protect our water quality, the Clean Water Act was established in the U.S. in 1972 to regulate pollutant discharge from point-sources (USEPA 1972). Nonpoint source pollutants were not addressed until the Act was amended in 1987 with the addition of a nonpoint source management program section (USEPA 1987). Recently, nonpoint source pollution has been identified as the main source of nutrients, which are considered the major factor contributing to the degradation of water quality worldwide (Carpenter et al. 1998). Compared to point-sources, nonpoint sources of pollution are harder to identify and reduce (Ice 2004). Land use changes have been identified as one of the primary determinants of nonpoint source pollution within a watershed (Schlosser and Karr 1981). Land use changes include, but are not limited to: urbanization, increase of impervious surfaces (Arnold and Gibbons 1996, Brabec 2002) and increased population density resulting in input of raw sewage, forestry, mining, and agriculture (Pitois et al. 2001). These changes have been shown to rapidly degrade water quality due to the input of polluting substances, including nutrients, sediment and toxins (Jeppesen et al. 2009, Shrestha et al. 2012), or altered thermal regimes (Benson et al. 2012).

The influx and accumulation of excess nutrients, particularly phosphorus (P), due to anthropogenic activities is termed cultural eutrophication (Pitois et al. 2001, Carpenter 2005) and is a major factor contributing to the accelerated degradation of aquatic ecosystems worldwide (Carpenter 2005, Camargo and Alonso 2006). Generally nitrogen (N) and P are limiting nutrients in freshwaters (Tilman 1982, Smith 1983, Pick and Lean 1987, Carpenter et al. 1998, Woltemade 2000, Pitois et al. 2001, Anderson et al. 2002, Carpenter 2008, Schindler 2008, Paerl et al. 2011) and the ratio at which the N and P are supplied is a strong determinant of the composition of the algal community (Tilman 1982, Smith 1983, Pick and Lean 1987, Carpenter 2008, Schindler 2008, Paerl et al. 2011).

Research has shown that cyanobacteria, also known as blue-green algae, dominate at low N:P ratios (Tilman et al. 1982, Pick and Lean 1987, Carpenter 2008, Orihel et al. 2011, Harris et al. 2014), indicating that preventing the influx of P to or removing it from aquatic ecosystems is crucial to prevent or mitigate harmful algal blooms. These blooms are generally taken as an indicator of cultural eutrophication (Paerl et al. 2011) and threaten water quality worldwide because they create a multitude of water quality problems (Pick and Lean 1987, Carpenter et al. 1998, Bartram and Chorus 1999, Sharpley et al. 2000, Pitois et al. 2001, Wu et al. 2006). Most importantly, cyanobacteria can produce a suite of toxins that have been linked to the death of pets, wildlife, livestock (Sharpley et al. 2000, Briand 2003, Graham et al. 2009a, Graham et al. 2009b Jacoby and Amand 2009), and humans (Chorus and Bartram 1999). In general, blooms of cyanobacteria are increasing worldwide and are a threat to our drinking water supplies, and the ecological and economic sustainability of our fresh water systems (Chorus and Bartram 1999, Sharpley et al. 2000, Graham et al. 2009a, Paerl et al. 2011).

Willow Creek Dam and Reservoir (WCR) was constructed in 1983 by the U.S. Army Corps of Engineers (USACE) for flood prevention, recreation and more recently irrigation for agriculture (USACE 2005). Since completion and filling of the dam, WCR has had a variety of issues, including low dissolved oxygen, increased production of hydrogen sulfide, ammonia, methane and the occurrence of harmful algae blooms (USACE 2007). The presence of toxic cyanobacteria is a major concern because it results in advisory warnings from the Oregon Department of Health which restricts human contact with the water in the reservoir. Since 2006, the duration of advisory warnings has ranged from 38 to 153 days. In 2012, the bloom's duration was 104 days (September to December), while in 2013 two blooms occurred. The duration of the first bloom was 56 days (June to August) and the duration of the second bloom was 88 days (October 2013-January 2014), totaling 144 days. WCR is located in a semiarid region, defined by the lack of precipitation between July and October (USACE 2007), and is the only significant ‘lake’ in a 100 km (60 mile) radius. Therefore, recreational users are affected by the summer closures of WCR when water-related recreation demand is highest.

Based on experimental large enclosure research, Harris (2012) and Harris et al. (2014) suggested that the overabundance of P in WCR is the main cause of the annual blooms of cyanobacteria. Willow and Balm Fork creeks are the two main inflows into Willow Creek Reservoir, the latter of which has been identified as a minimal nutrient source because it is intermittent for a large part of the year (Adams 2012). Therefore, the reduction of P in water entering WCR via Willow Creek is crucial to recover the water quality in the reservoir. Management strategies targeting and treating the source of nutrients within the watershed are necessary to remediate surface waters. Given the large size of the WCR watershed, it is prudent to identify areas in which the application of remediation actions would make the largest contribution to reducing loads. This is the focus of the second chapter of my thesis. I identified and quantified the source of total P (TP) and total residue (TR, suspended and dissolved solids) from sub-catchments of the Willow Creek watershed. Because land use is one of the primary determinants of nonpoint source pollution in watersheds (Schlosser and Karr 1981), a modified export coefficient modeling approach was used to examine the effects of land uses on measured annual loads. The effectiveness and costs of best management practices (BMPs) targeting the origin of nutrient loads within high-nutrient producing sub-catchments were evaluated. Tools and BMPs evaluated include the Geomorphic Road Analysis and Inventory Package (GRAIP), road restoration and decommissioning, and vegetative filter strips.

Due to increased economic and environmental demands, population growth and differing value systems, conflicts commonly occur when dealing with natural resource management (Ayling 1997). Values stem from ecological, economic, social, and aesthetic ideals and are primarily related to past experiences and education and are therefore deeply rooted among individuals (Lynam et al. 2007). The increase of conflict has stimulated the framework of integrative natural resource management (Rammel et al. 2007). This is an evolutionary process, in which knowledge is used to better understand the gap between disciplines (Rammel et al. 2007, Repko 2008). When considering remediation strategies, such as a constructed wetland, it is important that management decisions consider public perceptions, and values and beliefs to ensure that the proposed strategy encompasses the desires and needs of the public. The importance of including user's objectives and values in natural resource management has stimulated the development of a range of methodologies (Lynam et al. 2007) including social surveys, which are a powerful tool frequently used to collect information about public preferences (Salant and Dillman 1994). In the third chapter of my thesis, I present the results of a social survey designed to quantify residents and non-resident's awareness of the annual toxic algae bloom and the interference such blooms have on their use of WCR, examine how the construction of a wetland at the inlet of WCR would impact resident and non-resident use of WCR and examine the public's opinion of how the constructed wetland would be utilized. The USACE should consider the results of this survey in future management/remediation plans to increase wetland use and functionality.

The selection and application of BMPs to improve water quality is an evolving science. As our understanding of wetlands has increased, we have become aware of their important role as 'kidneys of the landscape' in enhancing water quality. To emulate this function, constructed wetlands have been used by aquatic resource managers to reduce nutrient delivery, in some cases specifically targeting the frequency and severity of blooms of cyanobacteria (Wu et al. 2010, Zhong et al. 2011). Specifically, wetlands reduce P concentrations in receiving waters from a variety of removal mechanisms including sorption, plant uptake, soil accretion, filtration, oxidation, reduction, chemical precipitation, and microbial interactions (Woltemade 2000, Kadlec and Wallace 2009). In the fourth chapter of my thesis, I evaluated the cost and effectiveness of TP and TR retention using a conceptual design for a free water surface wetland at the inlet of WCR.

I provide a summary to the entire thesis in chapter 5 by collating all findings and proposed management strategies highlighted in the previous chapters. In addition, research questions and potential remediation strategies emerging specifically from this thesis are highlighted.

Chapters 2-4 have been written as individual manuscript for publication, therefore they contain a detailed introduction and discussion. Additionally, all chapters have been formatted using style guidelines of the peer-reviewed journal *Lake and Reservoir Management*.

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Chapter 2: Use of high resolution sampling to identify candidate sub-catchments for potential remediation to improve water quality in receiving water bodies

Abstract

The burgeoning human population, combined with anthropogenic changes to land use, have greatly altered the quantity and ratios of limiting nutrients (phosphorus (P), and nitrogen (N)) delivered to water bodies worldwide. This results in cultural eutrophication, which is often manifested in blooms of cyanobacteria. To maintain and remediate surface waters requires an understanding of nutrient sources to effectively target corrective actions on the landscape. Willow Creek Reservoir (WCR) in Heppner, OR experiences annual long-duration blooms of toxic cyanobacteria related to high loads of catchment-derived P. The main objective of this research was to identify and quantify the source of total P (TP) and total residue (TR, suspended and dissolved solids) from sub-catchments of the Willow Creek watershed. To understand the origin of these loads, I instrumented sub-catchments with automated samplers and depth loggers to obtain daily samples for one year to calculate annual loads. A modified export coefficient modeling approach was then used to examine the effects of land uses on annual loads. Surprisingly, the majority of constituents were contributed by the forested headwater sub-catchments, not the agricultural areas in the lower reaches of the watershed. Increased loading from the headwaters of Willow Creek is likely due to logging activities and associated road construction. These results suggest future remediation efforts should be concentrated in headwaters of Willow Creek to optimize monetary investment and the reduction of sediment and nutrient loads to the reservoir. An examination of applicable BMPs and their effectiveness showed that the Geomorphic Road Analysis and Inventory Package should be used to identify roads that contribute high annual sediment loads. Remediation efforts, including road decommissioning and restoration, should be implemented in identified

sites. Vegetated filter strips should be planted to further minimize loading to Willow Creek. This study highlights the importance of basing management decisions on empirical data.

Introduction

Water is arguably the most essential and adaptable resource on the planet. Since industrialization and the explosion of the human population, there has been a large increase in the amount of nutrients, including nitrogen (N) and phosphorous (P) entering fresh water systems (Paerl et al. 2011). The influx of nutrients resulting from anthropogenic activities is termed 'cultural eutrophication' (Pitois et al. 2001, Carpenter 2005) and is a major factor contributing to the accelerated degradation of aquatic ecosystems worldwide (Carpenter 2005, Camargo and Alonso 2006). This accelerated degradation limits access to clean water, which is essential for life. Nitrogen and P are typically the limiting nutrients in freshwaters (Tilman 1982, Smith 1983, Pick and Lean 1987, Carpenter et al. 1998, Woltemade 2000, Pitois et al. 2001, Anderson et al. 2002, Carpenter 2008, Schindler 2008, Paerl et al. 2011) and concern over them is well-justified as small increases in their mass can result in large increases in algal biomass (Tilman 1982, Arbuckle and Downing 2001).

The ratio at which the N and P are supplied strongly determines the composition of the algal community (Tilman 1982, Smith 1983, Pick and Lean 1987, Carpenter 2008, Schindler 2008, Paerl et al. 2011). For example, a ratio of total nitrogen (TN) to total P (TP) of 7:1 is considered balanced (Redfield 1958, Schindler 2008), while a ratio of <7 is considered N-limited, and a ratio >7 is considered P-limited. P-limitation generally limits plant growth and is a desirable state for aquatic ecosystems (Smith 1983, Pick and Lean 1987, Carpenter 2008, Schindler 2008, Paerl et al. 2011). In contrast, nitrogen-limitation typically promotes the growth of cyanobacteria (formerly known as blue-green algae) (Schindler 1977, Smith 1983, Pick and Lean 1987, Carpenter 2008, Schindler 2008, Paerl et al. 2011) because many of these algae can fix atmospheric N and thus overcome the N-limitation (Schindler 1977, Smith 1983, Pick and Lean 1987, Carpenter 2008, Schindler 2008, Paerl et al. 2011). Cyanobacteria create taste and odor problems (Pick and Lean 1987, Carpenter et al. 1998, Bartram and Chorus 1999, Sharpley et al. 2000, Pitois et al. 2001, Wu et al. 2006), decrease the aesthetics (Bartram and Chorus 1999), deplete dissolved oxygen when they decompose (Pick and Lean 1987, Bartram and Chorus 1999, Carpenter 2008, Schindler 2008), and most importantly can produce a suite of the most potent toxins known to humans (Pick and Lean 1987, Chorus and Bartram 1999, Sharpley et al. 2000, Pitois et al. 2001). These cyanotoxins include hepatotoxins (the most prominent being microcystin), neurotoxins, and dermatotoxins (Graham et al. 2009a), which have killed pets, wildlife, livestock (Sharpley et al. 2000, Briand 2003, Graham et al. 2009a, Graham et al. 2009b) and humans (Chorus and Bartram 1999). Recently, there has been a general increase of algae blooms including the dominance of blooms by cyanobacteria (Winter et al. 2011). These blooms have been and are a threat to our drinking water supplies, and the ecological and economic sustainability of our fresh water systems (Chorus and Bartram 1999, Sharpley et al. 2000, Graham et al. 2009a, Paerl et al. 2011).

Schindler (2012) convincingly argued that the control of cyanobacteria requires the control of P rather than N and P together as other have suggested (e.g., Dodds et al. 1989, Elser et al. 2007, Lewis and Wurtsbaugh 2008, Paerl et al. 2011). Because P is a highly reactive element, it rarely occurs in ionic from and generally partitions (adsorbs) to a solid phase (Heathwaite et al. 2005). Because of this, P is susceptible to transport via surface flow which moves particles (Walter et al. 1979, Jin 2006). It is estimated that in agricultural areas, 60-90% of P is transported in the particulate phase (Sharpley et al. 2000). Once P is transported into a stream via surface runoff, it can be assimilated by microorganisms and plants, adsorb to vegetation and suspended solids, or be deposited in the stream with associated sediments (Abu-Zreig et al. 2003). Previous research has shown a positive relationship between sediment and P transported in runoff, thus a reduction in erosion reduces P concentrations in receiving waters (Walling 2005, Martin 2007, Adams 2012). Phosphorus does not have a gas phase (Lijklema 1986, Moshiri 1993, Pettersson 1998, Lehman 2011), so unless it is removed via biomass, outflow, or dredging, the mass of P continuously accumulates in receiving water bodies. Thus eliminating or greatly reducing the nonpoint sources of P within a watershed is crucial to protecting water quality.

One of the primary determinants of nonpoint source pollution and thus water quality is the land use in the watershed (Schlosser and Karr 1981). Worldwide, the water quality in streams has declined as a result of changes in land use in their watersheds (Carpenter et al. 1998, Pitois et al. 2001, Jordan et al. 2003, Allan 2004). These changes include, but are not limited to urbanization, increased impervious surfaces (Arnold and Gibbons 1996, Brabec 2002), increased population density resulting in input of raw sewage, and runoff and pollution from industries such as forestry, mining, and agriculture (Pitois et al. 2001). All of these can contribute high sediment loads and associated contaminants to water bodies. Carpenter et al. (1998) reported that nonpoint pollution including N and P from agriculture were a major source of degradation of aquatic ecosystems in the United States.

Erosion is one of the most important challenges facing natural resource managers and the main source of sediments in streams and reservoirs (Ward and Trimble 2003). Activities such as logging disrupt the land surface and reduce plant cover (Adams et al. 1991, Macdonald et al. 2003) consequently increasing suspended sediment concentrations and bank erosion within a stream channel (Beschta 1978, Stott et al. 2001, Macdonald et al. 2003). Logging and other activities with heavy machinery also increase soil compaction which decreases infiltration and thus increases surface runoff into streams (Hutchinson and Moore 2000, Macdonald et al. 2003). Erosion of sediment and resulting loads in streams have been linked to the infilling of reservoirs located downstream of logging activities (Stott et al. 2001). Sediment loading in forested watersheds can be elevated for several years after logging. For example, after a watershed in Oregon was clear cut, the total sediment load increased 67 fold over pre-logging loads and remained elevated for the following 10 years (Grant and Wolff 1991). Road construction associated with logging can cause unstable slopes and thus increase surface erosion and sedimentation rates (Brown and Krygier 1971, Beschta 1978). Roads associated with logging activities have been linked to higher erosion rates than the logging activities themselves (Brown and Krygier 1971). Because of the high sediment loads associated with runoff from logging activities, particulate P loading is usually greater than dissolved P loading following logging events (Piirainen et al. 2007) and should thus be the main focus for remediation efforts in sub-catchments with logging activities.

Best management practices (BMPs) have been used to reduce nonpoint source pollution, including erosion, originating from a variety of land uses (Allan 2004). Because P is of main concern when dealing with cyanobacteria blooms, BMPs aimed to reduce P concentrations are of utmost importance. There are many different kinds of BMPs that can be implemented in watersheds receiving nonpoint source pollution. These include but are not limited to, riparian buffer zones, road decommissioning, vegetative filter strips, and constructed wetlands (Castelle et al. 1994, Keppeler et al. 2007, Kadlec and Wallace 2009).

The main objective of this research was to identify and quantify the source of total P (TP) and total residue (TR, suspended and dissolved solids) from sub-catchments of the Willow Creek watershed. Specifically, I examined the effects of land uses on annual sub-catchment TP and TR loading. I also undertook an evaluation of applicable BMPs and their effectiveness for sub-catchments that contributed the majority of annual nutrient loads.

Materials and Methods

Study Site

Willow Creek Dam and Reservoir (WCR) was constructed in 1983 by the U.S. Army Corps of Engineers (USACE) immediately south of the town of Heppner (Figure 2.1). A secondary use of the reservoir is recreation, and more recently irrigation for agriculture (USACE 2005). Since completion and filling of the dam, suspended sediment and associated nutrients have accumulated in the reservoir and contributed to- and influenced its annual cycles. Willow Creek Reservoir has had a variety of issues, including low dissolved oxygen, increased production of hydrogen sulfide, ammonia, methane, and the occurrence of harmful algae blooms (USACE 2007). Of these, the latter is a major concern because it results in advisory warnings from the Oregon Department of Health, which restrict human contact with the water in the reservoir and thus decrease its potential for recreational activities. This is an important facet of WCR because it is the only significant 'lake' in a 100 km (60 mile) radius and because providing safe and high quality water is a primary objective of the USACE.

Between 2010 and 2012, experiments in large mesocosms in WCR showed that rebalancing the N:P ratio by adding N reduced or eliminated the dominance of cyanobacteria and toxin production (Harris 2012, Harris et al. 2014). These results suggest that the overabundance of P in WCR is a main contributor to the annual blooms of cyanobacteria. Thus its reduction in water entering WCR is deemed crucial to recover water quality and emphasizes the need for restoration activities or the application of BMPs in the watershed.

Willow and Balm Fork creeks are the main inflows into Willow Creek Reservoir. Balm Fork Creek is an intermittent stream that contributes 10% of the annual inflow while Willow Creek is a perennial stream that contributes 90% of the annual inflow (DeBano and Wooster

2004). During 1964-1968, annual sediment loads in Willow Creek varied from 110 to 65,026 tons (Koelliker 1979) and were directly related to annual discharge increases. Adams (2012) reported that between April 2009 and April 2010 6,872 metric tons (98%) of sediment and 3,304 kg (95.5%) of TP entered WCR via Willow Creek, which was approximately double the sediment load of 3,623 tons for a similar discharge measured in 1967 by Koelliker (1979) (Table 2.1). In contrast Balm Fork Creek only contributed 130 kg (4.5%) of TP and 145 metric tons (2%) of sediment to WCR (Adams 2012). Given this distribution of contributions of discharge and loads, contributions from the Willow Creek sub-catchment should be of main focus for restoration or application of BMPs.

Detailed description of the Willow Creek watershed

The Willow Creek basin is predominantly characterized as semiarid because of the lack of precipitation between July and October (USACE 2007). Typically, daily air temperature in the watershed ranges from -29.4 to 43.3 °C with an annual mean of 10 °C (USACE 2007), while annual precipitation ranges from 203.2 mm to 863.6 mm (USACE 2007). Summer days are warm, while nights are cool. In winter, diurnal temperature ranges are moderate and predominantly cold. Most of the annual precipitation occurs as rain or snow at high (approximately > 900 m above sea level - a.s.l.) elevations, and as rain at low (approximately < 600 m a.s.l.) elevations between October and June (DeBano and Wooster 2004).

Sub-catchments within the Willow Creek watershed

The Willow Creek watershed has four sub-catchments, which were identified using digital elevation model (DEM) data obtained from the Oregon Geospatial Enterprise Office (http://www.oregon.gov/DAS/CIO/GEO/pages/data/dems.aspx) and the watershed delineation process in ArcGIS 10 (Trent University 2012). Sub-catchments include: Valley Bottom (VB) located closest to the reservoir, Skinner Creek (SK), North Fork (NF) and Willow

Creek Headwaters (WCH) (Figure 2.1). Each sub-catchment contributes 14 to 29% of the total 17,605 hectares in the entire Willow Creek watershed (Table 2.2).

Geologic composition of the sub-catchments in the Willow Creek watershed

Basalt is the dominant rock type within the VB (100%) and SK (100%) but only accounts for half (55%) and a fifth (22%) of the NF and WCH sub-catchments, respectively (Figure 2.2, obtained from the USGS mineral resource on-line spatial dataset, http://mrdata.usgs.gov/geology/state/state.php?state=OR). The remainder of the NF is composed of andesite (37%) and meta-argillite (8%). The dominant rock type in the WCH is andesite (46%), while the remainder is quartz diorite (18%) and meta-argillite (15%).

USDA Forest Service lands within sub-catchments of Willow Creek watershed

The Umatilla National Forest, totaling 2,679 ha, accounts for 18% and 45% of the land area in NF and WCH sub-catchments, respectively (Figure 2.3). Based on land cover type, the Umatilla National Forest accounts for a third (28%) and over half (56%) of the forested lands in NF and WCH, respectively. Roads within the Umatilla National Forest account for half (49%) and the majority (92%) of total roadways in the NF and WCH, respectively. The national forest area is managed by the USDA Forest Service, Heppner Ranger District.

History of timber harvesting within sub-catchments of the Willow Creek watershed

Timber harvest operations within the NF and WCH date to 1959 when trees were partially removed from 68 and 214 ha, respectively. Three additional logging operations occurred in the NF sub-catchment during 1960, 1962 and 1983. A total of 197 ha or approximately 7.9% of the total sub-catchment area has been logged (Figure 2.3). Fourteen logging operations occurred in WCH between 1960 and 2011 over an area of 829 ha which is

16.8% of the total sub-catchment area (Figure 2.3). The majority of these logging operations occurred in close proximity to streams (Figure 2.3).

Grazing allotments in the Willow Creek watershed

Grazing allotments account for 18% (458 hectares) and 40% (1,997 hectares) of the land area in NF and WCH sub-catchments, respectively. Of this area, 99.6 and 89.6% are located within the NF and WCH Forest Service lands, respectively, portions of which are grazed year round (Kate Day, Hydrologist Umatilla National Forest, personal communication, April 2014).

Current status and land use activities in the Willow Creek watershed

The creation of WCR as well as long-term land use changes, such as the conversion of native grasslands to dryland agriculture, the reduction of shade-producing riparian vegetation, channel widening, the introduction of irrigated agriculture in valley bottom, livestock grazing, transportation and timber harvest were identified in the listing of Willow Creek under Section 303(d) of the U.S. Clean Water Act for water temperature from the mouth of Willow Creek to its forested headwaters, and pH in the outflow downstream of the reservoir (ODEQ 2007). During periods of high runoff, tributaries contribute significant loads of sediment and nutrients, including P, to the reservoir from the watershed (USACE 2007, Adams 2012). The contribution of this load from the sub-catchments and associated land uses were not known, but are crucial to effectively implement BMPs.

Activities in the lower reaches of the Willow Creek watershed (above WCR), including hay production, which dominates during summer and fall (June-November) and overwintering of cattle in the winter and spring (December-May), have been hypothesized to contribute high sediment and nutrient loads to Willow Creek. In spring, flood irrigation is used to water these areas to promote growth of grass for the production of hay. Lush riparian vegetation, primarily reed canary grass, grows long the stream banks in the lower reaches of the watershed starting in early spring. This growth continues into the late fall.

Methods

Calculation of annual sub-catchment loads of TP and TR

To identify and quantify the source of total P (TP) and total residue (TR, suspended and dissolved solids) from sub-catchments of the Willow Creek watershed, I installed four automated stream samplers (Teledyne ISCO # 6712) at the mouth of each sub-catchment. Specifically, samplers were located on Willow Creek at the USGS Gauging Station (#14034470) near the inlet of WCR; on Skinner Creek at the confluence with Willow Creek (SK); on the North Fork of Willow Creek at the confluence with Willow Creek (NF); and on Willow Creek just above the confluence of the North Fork of Willow Creek (WCH) (Figure 2.1). Samplers were programmed to collect daily water samples of 500 ml at 15:00 from 22-Sep-12 to 20-Sep-13 to determine annual variation in flow, and sediment and nutrient loads. Because of travel time from the University of Idaho (over 4.5 h), it was unrealistic to undertake event-based sampling.

Because of mechanical and electrical malfunctions, and sub-zero temperatures, not all samplers took all 363 samples. The inlet sampler did not collect samples on Jan 2, 5, 17, 20-23, and Feb 7, 2013. The SK sampler failed to collect samples on Jan 2, 5, 20, 22, 23, and Jun 28 to Jul 1, 2013. The NF sampler did not collect samples on Dec 25, 26, 30, 31 in 2012, and Jan 1-3, 11-13, Mar 23, Apr 1-5, and Jul 16-29, 2013. The WCH sampler did not collect samples during Jan 1-3, 13-16, Mar 20-22, Apr 21-24 and May 3-6, 2013. Missed samples were estimated using linear regression between adjacent dates. On two occasions (Apr 20, 25, 2013) the sampler at WCH had collected pebbles. Because we were interested in the relationship between TP and TR and it is known that TP readily adsorbs to clays and silts (Jin et al. 2006) and not rocks, values on these dates were interpolated as for missing samples.

To estimate the relationship between total P (TP) and dissolved P (DP), I collected grab samples from each site when I visited each between 16 Nov, 2012 and 20 Sep 2013. Samples for the analysis of DP were filtered through 0.45 μm membrane filters immediately after collection and transported on ice to the University of Idaho Limnology Laboratory where they were analyzed within 48h of collection. All collected samples were analyzed using method 4500-P (Eaton et al. 2005, Appendix A), TR using method 2540-B (Eaton et al. 2005, Appendix B). Stream discharge at the site located near the inlet of WCR was obtained from the USGS online Real-time Stream-flow for Willow Creek (USGS Gauging Station #14034470). Daily discharge values at all other sites were calculated using site-specific stage–discharge relationships developed over the course of this study (USGS 1983, Gordon et al. 1999, Appendix C-F). Total annual discharge (m^3/yr) was determined for each sub-catchment by adding all continuous discharge data for the year.

Annual sub-catchment TP and TR loads were calculated using the nonparametric smearing approach (Duan 1983, Colin 1995, Helsel and Hirsch 2002, Appendix G). Sub-catchment TP and TR yields (tons/ha/yr) were calculated by dividing annual loads by the corresponding catchment area. To determine if a relationship existed between the amount of TP and TR, daily values of TR were regressed as a function of TP using least-squares regression.

Calculation of annual land-use load of TP for sub-catchments

To identify and quantify the source of TP from land uses within sub-catchments, I determined land cover and land-uses within the sub-catchment from a digital landcover dataset on the Oregon explorer website (http://tools.oregonexplorer.info/oe_map_viewer_2_0/viewer.html?Viewer=OE) derived from a combination of multi-season satellite imagery and digital elevation model derived datasets. Additionally, a road layer was obtained from the Umatilla National Forest Geospatial Database (http://www.fs.fed.us/r6/data-library/gis/umatilla/). Land uses were categorized into six broad land use types including: CRP lands, agriculture, forested area, shrub-lands or grasslands, riparian or wetland areas and roads (Figure 2.4), and areas determined with ArcGIS 10.

To determine the nutrient loads from each land use type, a modified export coefficient modeling approach was used (Reckhow et al. 1980). This approach easily can be applied to a wide variety of watersheds, is relatively inexpensive, and requires data that are typically readily available (Winter and Duthie 2000). The model uses nutrient export coefficients to estimate loading from land uses (Reckhow et al. 1980, McFarland and Hauck 1999, Winter and Duthie 2000). Because I did not measure export coefficients in the Willow Creek waters and the model is sensitive to them (Beaulac and Reckhow 1982), I used export coefficients most often cited in the literature for the land uses most closely resembling those in the Willow Creek watershed. For the lower reaches of the watershed I used two different export coefficients depending on time of year because it has two distinct land uses (hay/alfalfa production from June-Nov, and cattle pasture from Dec-May). The Morrow County Soil and Water Conservation District (Janet Greenup, District Manager, Morrow County Soil and Water Conservation District, personal communication, October 2014) identified native grasslands as the main land use of CRP lands and riparian/wetland areas; therefore a single coefficient was used for CRP lands, wetland/riparian areas, and shrublands/grasslands. Due to the lack of TR export coefficients in the literature the model was only used to estimate land use specific loading of TP.

Evaluation of potential BMP effectiveness and implementation

Potential tools and BMPs to identify and reduce sediment and TP were evaluated for the sub-catchment contributing the largest TP load. BMPs selected for evaluation were based on literature research and personal communication with experts currently implementing BMPs in Oregon. Tools and BMPs included: Geomorphic Road Analysis and Inventory Package (GRAIP) analysis, road restoration and decommissioning, and vegetative filter strip (VFS) planting. The Geomorphic Road Analysis and Inventory Package (GRAIP) is a tool used by the USDA Forest Service to assess the impact of erosion from roads. In 2010, a GRAIP analysis was completed in the Wall Creek watershed, an adjacent watershed to Willow Creek, in the Umatilla National Forest (Nelson et al. 2012). Results, including estimates of sediment production and delivery from crushed rock, native, paved, herbaceous and brush/trees/debris roads. Presented costs were evaluated to estimate the cost per mile of running a GRAIP analysis in the Willow Creek watershed. Because of limited data on road restoration and decommissioning effects on sediment reduction efficiencies in the U.S., I undertook a literature review of annual mean erosion (m^3) for treated (restored roadways) and untreated (roads not modified after original construction) roads in the western U.S. Google Scholar with the search term "the effects of road decommissioning on sediment loads" was used to locate estimates of erosion volumes. Additional estimates were located from citation searches. I calculated an average annual erosion rate for untreated and treated roads. Average costs of road restoration efforts in the Umatilla National Forest were obtained from the Umatilla National Forest Service (USDA 2014).

To evaluate the size and removal efficiencies of vegetated filter strips, I performed a literature review of vegetative filter strips focused on removal of P and sediment. I used the search terms ""phosphorus/sediment retention in vegetative filter strips" in Google Scholar to find rates of P and sediment removal. Additional sizes, rates and efficiencies were located using citation searches. All reported riparian vegetation restoration efforts that have occurred in Oregon were obtained from the Oregon Watershed Restoration Inventory (OWRI) (Bobbi Riggers, OWRI Data Coordinator, personal communication, February 2014). I obtained cost of projects focused on plantings of shrubs/grasses.

Results

Calculation of annual sub-catchment TP and TR loading

Daily TP concentrations for samples from the four catchments ranged from a low of 0.028 mg TP/L to a high of 0.202 mg TP/L (Table 2.3, Appendix H). The mean daily concentrations of TP differed two fold from a low 0.049 mg TP/L for the WCH sub-catchment to a high of 0.099 mg TP/L for the SK sub-catchment (Table 2.3, Appendix H).

Daily TR concentrations for samples from the four catchments ranged from a low of 41 mg TR/L to a high of 9,663 mg TR/L (Table 2.3, Appendix I). The mean daily concentrations of TR differed 2.5 fold from a low 140 mg TR/L for the NF sub-catchment to a high of 323 mg TR/L for the WCH sub-catchment (Table 2.3, Appendix I).

These measured TP and TR concentrations of Willow Creek at the inlet of the reservoir were similar to historic values. Before construction of the reservoir, TP concentrations in Willow Creek ranged from 0.09 to 0.20 mg P/L (USACE 1973), while in 2009-2010 Adams (2012) measured concentrations ranging from 0.03 to 0.82 mg TP/L and 94 to 2,170 mg TR/L.

Analysis of biweekly grab samples showed that the fraction of DP varied seasonally. In general, DP constituted the largest fraction of TP, ranging from 72 to 81% for the VB and NF sub-catchments, respectively (Table 2.4, Appendix J). Large seasonal variations were noted, for example, during spring runoff (April to May), the fraction of DP decreased markedly and the majority of P was in particulate phase, ranging from 28 % for the SK sub-catchment to 71% for the inlet of the reservoir (Table 2.4, Appendix J). Over half (53%) of the P load entered the reservoir during March 2013-April 2013 in particulate phase.

The September 21, 2012 to September 21, 2013 hydrographs for the Willow Creek watershed sub-catchments showed typically arid climate patterns. The hydrographs (Figure

2.5) generally remained low between 0.004 and 0.5 m^3/s during the dry season (June-January) indicating base flow conditions. Minimum values, ranging from 0.004 to 0.01 m^3/s for the SK and NF sub-catchments, occurred during September and August. During the wet season of February to May the hydrographs showed several spikes indicating snowmelt and/or rain events. During this time, Willow Creek delivered 72% of its annual discharge to the reservoir. Maximum values, ranging from 0.31 to 3.75 m^3/s for the NF and WCH sub-catchments occurred during April for the inlet of the reservoir, NF and WCH sub-catchments. Maximum values occurred earlier in the SK sub-catchment, reaching values 0.46 m^3/s in February. The early onset of the wet season in SK can be explained by the lack of snow in the lower elevations. Annual discharge within the sub-catchments ranged from 1,923,262 to 9,661,746 m^3/yr for SK sub-catchment and the inlet of the reservoir, respectively (Figure 2.6).

Annual TP loading to Willow Creek Reservoir was calculated to be 0.81 metric tons. Of this, the VB sub-catchment was a net sink, removing -0.06 tons, while the WCH sub-catchment contributed a high of 0.50 metric tons (Table 2.5). The SK and NF sub-catchments contributed approximately equal loads of 0.19 and 0.18 tons, respectively (Table 2.5). The majority of the annual TP load (74%) entered the reservoir during the annual wet period of February-May. Of this load, sub-catchment contributions were 4, 17, 19, and 60% from VB, SK, NF and WCH, respectively. During the month of April, the reservoir received 0.27 tons of P, which was 34% of the annual load.

The annual load of TR was 1,762, -8,965, 263, 323 and 10,140 tons for the inlet, VB, SK, NF and WCH, respectively (Table 2.6). The majority of the annual TR load (1,264 tons, 72%) entered the reservoir during the wet period of February-May. During these four months 9,638 tons came from the WCH, while 140 and 206 tons came from SK and NF, respectively. Data indicate that during the wet period, the VB was a sink for 8,721 tons of sediment. About a third

(32%) of the annual sediment load entered the reservoir in April, during which time SK, NF and WCH contributed 39, 78 and 8,559 tons, respectively, while the VB was a sink for 8,116 tons of sediment. Thus during the month of April 91% of the total annual sediment load was deposited in the VB. It is also important to note that half (50%) of the sediment exported from the WCH occurred in the 3 day period of April 20-22, 2013. This 3-day period accounted for almost a tenth (9.5%) of the annual discharge.

Annual yields of TP and TR were largest in WCH followed by NF, SK and VB. Annual TP yields for VB, SK, NF and WCH were -0.01, 0.04, 0.07 and 0.10 kg/ha/yr respectively (Table 2.7). Annual TR yields for VB, SK, NF, and WCH were -1,800, 51, 129 and 2,050 kg/ha/yr respectively (Table 2.7). Annual yields of TP and TR from the WCH were approximately 1.5 and 16 times greater than those from the NF sub-catchment.

Daily load measurements showed a strong linear regression relationship between TP as a function of TR at the inlet of the reservoir (R^2=0.99, Figure 2.7a), Skinner Creek (R^2=0.99, Figure 2.7b), North Fork (R^2=0.99, Figure 2.7c) and Willow Creek Headwaters (R^2=0.73, Figure 2.7d).

Calculation of annual land-use load of TP for sub-catchments

The land use in the VB sub-catchment was primarily shrubland/grassland (84.70%), while the remainder of the land use was comprised of agriculture (5.85%), CRP lands (5.55%), riparian/wetland (3.34%), forested area (0.31%), and roads (0.25%) (Figure 2.8a). In the SK sub-catchment, land use was primarily shrubland/grasslands (79.11%) with the remainder of the land use comprised of forested area (13.40%), agriculture (2.70%), CRP lands (2.65%), and riparian/wetland (2.15%) (Figure 2.8b). The dominant land use switched from shrubland/grasslands to forest along the gradient from valley bottom to the headwaters. Land use in the NF was primarily forest (66.11%), the remainder of the land was comprised of shrubland/grasslands (29.55%), riparian/wetland (3.55%), agriculture (0.50%), and roads (0.29%) (Figure 2.8c). Land use in the WCH sub-catchment was primarily forested area (80.28%), while the remainder of the land was comprised of shurbland/grasslands (15.37%), riparian/wetland (3.42%), agriculture (0.62%), and roads (0.32%) (Figure 2.8d).

Phosphorus export coefficients for CRPS lands, agriculture (June-November), agriculture (December-May), forested area, shrubland/grasslands, riparian/wetland and roads used in the modified export coefficient modeling approach ranged from 0.13 to 2.35 (Table 2.8). Because the VB only contributed to annual P-loading during the months of March and April, the model was run only for this time period for this sub-catchment. In the lower reaches of the watershed, the majority of the load came from shrubland/grasslands, accounting for 46.6 and 55.2% of the annual load in the VB and SK, and agriculture, accounting for 45.8 and 24.5% of the annual load in the VB and SK (Figure 2.8a,b). Forest lands accounted for 72.9 and 81.7% of the annual load from the NF and WCH sub-catchments (Figure 2.8c,d).

Evaluation of potential BMP effectiveness and implementation

The GRAIP analysis completed in the Wall Creek Watershed showed that native surface roads produced and delivered the majority of sediment in the basin (Table 2.9) (Nelson et al. 2010). Native surface roads delivered 4 and 235 times more sediment than gravel and paved roads, respectively (Nelson et al. 2012). Sediment production from native surface roads accounted for 77% of the road-delivered sediment in the watershed (Nelson et al. 2012). Similar to other GRAIP analyses, 90% of the sediment load originating from roads was produced from a small percentage (12%) of the total inventoried roads (Nelson et al. 2012). Unlike other GRAIP analyses (e.g., Bear Creek in Northern Idaho, Stromberg IDEQ personal communication), the Wall Creek GRAIP analysis indicated that road-related sediment transport only represented <5% of the total annual sediment load within the Wall Creek watershed

(Nelson et al. 2012). Average costs of the GRAIP analysis were estimated at $240/mile, including field inventory, data processing, modeling and analysis (Nelson et al. 2012). There are 20.4 miles of road within the WCH, over half of which were identified as native surface roads (56%). The majority of native roads (99.6%) are found within the Umatilla National Forest. The estimated cost of GRAIP analysis for all roads in the WCH was $4,896, while analysis of native surface roads would require $2,448.

Mean annual erosion (m^3) for untreated roads was higher than treated roads (Table 2.10). On average, untreated and treated roads have a mean annual erosion of 51 and 688 m^3/yr, respectively, indicating that on average, treating roads could reduce erosion by 93% in the Willow Creek watershed. Average costs of decommissioning (simple), decommissioning (complex), and reconstruction and storm damage risk reduction are $3,600, $5,600, and $16,000 per mile (USDA 2014). Average costs of culvert removal ranged from $800 (simple) to $5,000 (complex) (USDA 2014).

A total of 17 buffer strips reported in the literature were evaluated. An average buffer width of 8.8 m was found with average P and sediment removal efficiencies of 65.8 to 79.2%, respectively (Table 2.11). Based on information from the Oregon Watershed Enhancement Board (OWEB), the average cost per mile of 17 riparian restoration projects completed in Oregon was $7,460 and the average cost per acre was $2,245 (Table 2.12). Known project participants included but were not limited to OWEB, Oregon State University (OSU) Extension Service, Oregon Department of Fish and Wildlife, United States Fish and Wildlife Service, various Soil and Water Conservation Districts and private landowners.

Discussion

Average concentrations of particulate and dissolved P in the Willow Creek watershed were similar to values measured in other areas of Oregon. For example, in the control

Watershed #9 at the H.J. Andrews Experimental Forest in Oregon, dissolved and particulate P accounted for 80 and 20% of streamwater TP, respectively (NCASI 2001). Due to the elevated P-content in basalt-derived soils (Brady 1977), high P concentrations have been documented in Oregon groundwater, reaching concentrations of up to 2.6 mg/l (Abrams and Jarrell 1995). Examples include the Tualatin River Basin, in northwestern Oregon, in which P-rich soil and groundwater have been identified as a main contributor to elevated P concentrations in the Tualatin River (Kelly et al. 1999, Wilson et al. 1999). Similarly, P-rich soils in the Dairy-McKay Creek watershed in northwestern Oregon were identified as a nonpoint P-source for both surface and groundwater. P-rich soils and P-rich groundwater are likely nonpoint sources of P that contribute to dissolved-P concentrations in the Willow Creek watershed. The abundance of basalt in NF and SK sub-catchments could explain the higher TP concentrations relative to the other sub-catchments. Given the dominance of soils of basalt origin in the WC watershed, it may be difficult to reduce loads to WCR, and highlights the conclusions of the original 1974 EIS for the dam, which predicted poor water quality in the reservoir after dam closure (USACE 1973).

The hydrologic regime within the Willow Creek watershed is typical for watersheds in the semi-arid western United States. Peaks in discharge occur during rain-on-snow events in the high elevation portions of the watershed, and during rain events in the lower portions of the watershed. During my study, the VB was a hydrologic sink in which water in the stream and water diverted from the stream for flood irrigation recharged groundwater, a known consequence of flood irrigation (Kendy and Bredehoeft 2006). This can explain the decrease in stream flow in Willow Creek between the WCH sampler and the inlet sampler. During the summer, fall and winter, flow is dominated by groundwater within the watershed, which is common in the western U.S. (Ward and Trimble 2003, Kendy and Bredehoeft 2006). Thus it is not unreasonable that during months when groundwater dominates flow, groundwater-derived P is a significant source of P to WCR. Although this background load may be high, as explained above, it is a fraction of the load contributed to WCR relative to snowmelt runoff, when 74% of the annual P load arrives.

The annual discharge measured at the inlet of the reservoir during 2013-2012 was approximately 4.0 $\times 10^6$ m^3 (29%) lower than that measured in 2009-2010 by Adams (2012). Consequently, the calculated nutrient and sediment load to WCR during this study were 4 fold lower than that estimated by Adams (2012) who measured an annual TP and TR load of 3,304 kg and 6,872 metric tons, respectively. This inter-annual variation is not surprising given the tight relationship between discharge and load (Likens 2013). What was interesting was the switch in dominant fraction of TP from the dissolved to the particulate phase during runoff, when the reservoir received the majority of its annual TP and TR load. A similar pattern was observed in the Johnson Creek Basin, OR during 2007-2010 when more than 70% of the annual sediment load was transported during months with high-flow runoff (Stonewall and Bragg 2012). The delivery of the majority of the P load in particulate phase during a concentrated period of the year would appear to bode well for focusing removal efforts. However, because the loads move with runoff water (March-April), which represent the bulk (51%) of the annual hydrograph, typical means such as wetlands or settling basins used to remove sediment and associated P (Woltemade 2000, Jordan et al. 2003, Díaz et al. 2012) likely will be of limited use. Their effectiveness will be overwhelmed by the inability to adequately deal with the high volume of water (see chapter 4 for detailed analysis of this issue). Thus, continued loading of P and sediment to WCR will likely continue into the foreseeable future.

In the Willow Creek watershed, the majority of the annual sediment load originated from the WCH, but this load was deposited in the VB before water reached the inlet of the reservoir. Such depositional events in watersheds are not uncommon. For example, approximately 4 billion tons of soils are eroded annually in the US, but only 0.5 billion tons of these sediments are delivered to the sea by rivers (Ward and Trimble 2003). The remaining 3.5 billion tons are deposited in reservoirs, stream channels and floodplains (Ward and Trimble 2003). Deposition of sediments in the stream bank or flood plains occurs when flows are either diverted from the stream or exceed bankfull discharge (Ward and Trimble 2003). After sediments are deposited outside the immediate stream channel, they can be remobilized by fluvial processes at any time, thus adding to future sediment yields (Ward and Trimble 2003). This can help explain the decreasing sediment loads along the length of the Willow Creek watershed during non-runoff periods.

The lush riparian vegetation in the lower reaches of the watershed (primarily VB and SK) likely plays a significant role in controlling the annual export of TP and TR loads from the watershed to WCR. Riparian vegetation, such as reed canary grass, requires P for growth and seed production during the growing season (Kao et al. 2003), which reduces the P in the water column. Riparian vegetation along the stream increases infiltration and decreasing velocity of water, thereby allowing deposition of TR and concomitantly TP when surface runoff occurs due to precipitation or flood irrigation (Lee et al. 2000, 2003, Abu-Zreig et al. 2003, Blanco-Canqui et al. 2004, Ma et al. 2013). This increased deposition likely reduces sediment and P delivery to the stream, further explaining the reduction of loads in VB.

The variable TR and TP yields calculated among sub-catchments indicates uneven nutrient loading within the Willow Creek watershed. Because the annual TP and TR yields were largest in WCH, this suggests that remediation efforts should be focused in it to optimize money spent on BMPs and the amount of TP and sediment removed from Willow Creek.

Recent logging activities and perhaps fires in the forested area in the headwaters of Willow Creek may be contributing to annual P loads. It is unlikely that P export from fires is significant given that areas burned from 1970 to 2009 ranged from ~0.4 ha to 4.7 ha (Kate Day, Hydrologist Umatilla National Forest, personal communication, February 2014). The most recent logging activities in the WCH took place in 2010 and 2011 during which 110 and 12 hectares of land were commercially thinned, respectively. A logging activity of this magnitude has not taken place in the NF sub-catchment since 1962 during which 104 hectares of land were partially harvested. The effects of increased frequency and magnitude of logging activities in the WCH may be reflected in the increased annual nutrient loads. It is well-known that logging activities increase dissolved-P concentrations in streams for several years after logging activities have ceased (Adamson and Hornung 1990, Piirainen et al. 2007). General patterns include a peak in dissolved P two years after logging (Adamson and Hornung 1990). As discussed previously, erosional and compaction effects caused by logging and built roads (Hutchinson and Moore 2000, Stott et al. 2001, Macdonald et al. 2003) contribute to annual particulate P loads. Based on positive relationships between road density in a watershed and sediment transport to streams (Brown and Krygier 1971, Beschta 1978), it is highly probable that the high road density within the WCH significantly contributes to the annual sediment load and deserves further examination.

Roads were identified as a major contributor of sediment to Wall Creek (a watershed adjacent to Willow Creek) (Nelson et al. 2012) resulting in its listing on the 2004/2006 Oregon 303(d) list of impaired waters under the CWA (Buchholz 2012). The Umatilla National Forest and the Pacific Northwest Region of the Forest Service used a watershed GRAIP analysis to identify and prioritize high-risk sites for restoration (Buchholz 2012, Nelson et al. 2012). Results from the GRAIP analysis indicated the majority of sediment originated from a small percentage of roads with native surfaces (Nelson et al. 2012). Although road-related sediment transport was a relatively small contribution of the annual sediment load, the Forest Service is aggressively reducing road-related erosion (Kate Day, Hydrologist Umatilla National Forest, personal communication, February 2014). Due to the recent logging activities and increased road density in close proximity to streams within the Willow Creek watershed, they should be carefully examined as a potential nutrient source. To reduce costs while maximizing benefits for potential remediation, a GRAIP analysis could be completed on roads with native surfaces, because this road-type was identified as the highest sediment contributor in Wall Creek. Based on costs in the Wall Creek analysis, this would cost approximately $2,500 in the WCH sub-catchment. Given the proximity and similarity of the Wall Creek watershed to the Willow Creek watershed, it is highly probable that proposed restoration activities there including installing drainage features, stabilizing road surfaces, installing cattle guards, removing culverts, and decommissioning unused roads (Day 2012) would be equally effective in the Willow Creek watershed.

Standard practices have been put into place to protect the health of freshwater systems. Of these, regulations have been established that require logging operations on USDA Forest Service lands to leave a fixed-width buffer strip (defined by distance only not by composition of vegetation) between all activities and a stream bank, known as the riparian habitat conservation area (USDA 1995). The Umatilla National Forest follows PACFISH guidelines for buffer widths (USDA 1995), which require a buffer width of 45.7 m (150 ft) for non-fish bearing perennial streams (USDA 1995). For intermittent streams, a buffer width of 30.5 m (100 ft) is required for key watersheds and 15.2 m (50 ft) for non-key watersheds (USDA 1995). Key watersheds are areas that provide high quality water important for maintenance of downstream populations or are crucial to threatened or endangered fish and aquatic species of concern or interest (USDA 1995). Studies indicate that fixed-width buffer strips are insufficient to minimize sediment and nutrient loading (Naiman 1993, Castelle et al. 1994). Because of this, managers should focus on alternative strategies such as vegetative filter strips (VFS – defined width of densely planted vegetation) (Richardson et al. 2012).

Vegetative filter strips (VFS) have been adopted as a BMP in a variety of landscapes with the overall goal of increasing wildlife habitat and water quality by reducing the transport of sediments and nutrients to lotic waters. Vegetated filter strips are long strips of permanent vegetation parallel and adjacent to waterbodies, including streams (Castelle et al. 1994, Fischer and Fischenich 2000, Abu-Zreig et al. 2003). These strips are generally small, comprising about 1% of the total watershed area (Fischer and Fischenich 2000), but offer many ecological benefits (USDA 1995, Fischer and Fischenich 2000, Blanco-Canqui et al. 2004). In small to mid-order streams, VFS can maintain low water temperature, stabilize stream banks from erosion, reduce nonpoint source nutrient loading, and provide habitat for wildlife and plant species (Osborne and Kovacic 1993, USDA 1995, Fischer and Fischenich 2000). Similar to the reed canary grass in the VB and SK, these strips reduce nutrient and sediment loading by increasing infiltration and by decreasing surface flow which allows deposition of water-borne particles (Lee et al. 2000, 2003, Abu-Zreig et al. 2003, Blanco-Canqui et al. 2004, Ma et al. 2013).

The challenge of installing and increasing the use of VFS in watersheds is related to watershed characteristics, land uses, ownership, and management goals. Because watersheds are highly variable with respect to physical properties, there is no one designated buffers strip width (Osborne and Kovacic 1993, Fischer and Fischenich 2000). Rather, width depends on the purpose of the strip. Generally, the trapping efficiency of sediments of VFS increases with width (Abu-Zreig et al. 2003, Blanco-Canqui et al. 2004, Ma et al. 2013) and a width of 5-30 m is usually suggested for VFS with a primary function of water quality protection (Fischer and Fischenich 2000). Widths are usually widest in watersheds where the main function is to address ecological concerns, including riparian habitat and creation of movement corridors for wildlife (Fischer and Fischenich 2000). Generally narrower buffer strips are accepted when stream banks are in good condition and the adjacent land use has low impact potential (e.g., native, non-logged forest) (Castelle et al. 1994), whereas wide buffer strips are recommended when stream banks are in poor condition and the adjacent land use has high impact potential (e.g., row crop agriculture) (Castelle et al. 1994). Given the presence of bare soil immediately adjacent to Willow Creek in the WCH, it is not surprising that a high sediment load occurs in this sub-catchment. Although the tree canopy present adjacent to the creek protects the soil from the erosive power of falling rain, it offers little resistance to overland flow that typically results in rill and sheet erosion (Walling 2005). Thus some management consideration should be given to how best to implement VFS in this sub-catchment. Indeed, placement of VFS in a watershed is an important management decision. For example, riparian buffer strips in headwater streams generally have a greater influence on overall water-quality than those located in lower reaches (Fischer and Fischenich 2000). Buffer strips also are most efficient when placed at or near the source of nonpoint source pollution. Based on values given in the literature (Young et al. 1980, Dillaha et al. 1989, Daniels and Gilliam 1996, Lee et al. 1998, Schmitt et al. 1999, Abu-Zreig et al. 2003, Lee et al. 2003, Blanco-Canqui et al. 2004, Borin et al. 2005), I recommend an average buffer width of 8.8 m along stream segments of the Willow Creek watershed that currently do not have high density vegetation.

Costs associated with installation of VFS include the cost of planting, establishing, and maintaining buffers (Helmers et al. 2008). Additional costs can occur if the intended location of the VFS is currently used for other purposes, which would require compensation for the loss associated with that use, or if it must be purchased. (Helmers et al. 2008). To maximize sediment and TP removal in the Willow Creek watershed, VFS should only be planted in the WCH sub-catchment that are identified as high-risk areas. In terms of the high-risk areas identified within the Umatilla National Forest, the designated 45.7 m fixed width buffer strip would provide the necessary space for planting. Therefore, additional costs associated with land-use compensation would be minimized thus reducing the overall cost of implementation. Costs of planting VFS obtained from the Oregon Watershed Enhancement Board (OWEB) were less than estimated costs for a constructed wetland (see Chapter 4). Due to their high removal efficiencies and relatively low costs, VFS are recommended as a remediation strategy to reduce the influx of nutrients into WCR.

Restoration monitoring should be included in any management decisions that are made within the watershed. Historically, monitoring has been used as a tool to document long-term ecosystem changes and trends, and to differentiate between natural and human caused changes within a system (Wolfe et al. 1987). For this project, monitoring will be important to evaluate treatment effectiveness and water quality changes within the Willow Creek watershed. The lag time associated with BMPs, defined as the time between the implementation of BMPs and the measureable effects on water quality (Meals et al. 2010), should be considered when developing a monitoring plan. The lag time of a BMP is highly dependent on the time it takes for a BMP to be fully installed and operational (Meals et al. 2010). In the case of VFS, this includes the time it takes for the vegetation to establish along the streambanks. Specifically, monitoring efforts should include annual nutrient measurements over the next several years, in which annual trends and effects of implemented BMPs can be evaluated in terms of reductions in annual nutrient loads.

Additionally, a further understanding of the nutrient cycle within the WCR is necessary to understand how implemented BMPs would affect reservoir water quality. A whole reservoir budget and total maximum daily load (TMDL) assessment are needed to understand what the daily maximum load into the reservoir needs to be to achieve a water P concentration that will increase water quality and therefore decrease the dominant cyanobacteria algal blooms. If base flow background P concentrations originating from the potentially nutrient-loaded spring water in the watershed were measured, it would be possible to determine if the daily maximum load could be met.

Conclusion

Annual cyanobacteria blooms in the WCR results in water contact advisory warnings from the Oregon Department of Health which restricts use of the reservoir. Identifying the source of P loads within the Willow Creek watershed was important to focus and optimize future restoration efforts. Basalt-derived P-rich soils and groundwater likely contribute high background concentrations. The majority of P and sediment are contributed by the forested lands in the Willow Creek Headwaters sub-catchment, and not by the agricultural areas in the Valley Bottom. High loading in the Willow Creek Headwaters sub-catchment may be related to logging activities and the density of roads. Dense riparian vegetation including reed canary grass in the lower reaches of the Willow Creek watershed likely play a significant role in minimizing annual nutrient loads. These finding highlight the importance of basing management decisions on empirical data. Focusing remediation efforts in the Willow Creek Headwaters should provide the greatest improvement in the water quality of WCR. A GRAIP analysis would identify high risk sites where remediation efforts should be focused. Based on previous studies, sediment and subsequent P loading from remediated areas should be reduced significantly following treatment. If funding is limited, the GRAIP analysis should focus on native surface roads, as these have been identified as the dominant sediment producing road type. Vegetated filter strips adjacent to water bodies are efficient at reducing both P and sediment loading and should be used to minimize additional loading, including that originating from logging activities. Implementation costs can be minimized by planting VFS in areas that have been identified as high risk. These efforts will decrease nutrient loading within the Willow Creek watershed and increase water quality in the WCR, which would assist the U.S. Army Corps of Engineers in reaching one of its main goals of providing safe and high quality water.

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Table 2.1: Current and historic suspended sediment and total residue (denoted by *) loads in the Willow Creek Watershed. Discharge values are presented as the sum of daily averages.

Water Year	Suspended sediment (tons)	Discharge (1×10^4 m^3)	Reference
2013	1,762	966 *	This study
2010	6,872	1,357 *	Adams 2012
1968	110	231	Koelliker 1979
1967	3,623	1,498	Koelliker 1979
1966	558	482	Koelliker 1979
1965	65,026	2,924	Koelliker 1979
1964	1,407	979	Koelliker 1979

Table 2.2: Sub-catchment area (hectares) and percent of total watershed area in the Willow Creek watershed, Heppner, OR (see Figure 1 for location of sub-catchments).

Sub-Catchment	Area (hectares)	%
Valley Bottom (VB)	4,979	28
Skinner Fork (SK)	5,188	29
North Fork (NF)	2,496	14
WC Headwaters (WCH)	4,941	28

Table 2.3: Mean and range of concentrations of total phosphorus (TP) and total residue (TR) at the inlet of Willow Creek Reservoir, Skinner Creek, North Fork, and Willow Creek Headwaters for the 2012-2013 study period.

Constituent	Sub-catchment	Mean (mg/L)	Range (mg/L)
TP	Inlet (VB)	0.079	0.033-0.181
	Skinner Creek (SK)	0.099	0.054-0.183
	North Fork (NF)	0.086	0.036-0.190
	WC Headwaters (WCH)	0.049	0.028-0.202
TR	Inlet (VB)	185	77-687
	Skinner Creek (SK)	163	41-289
	North Fork (NF)	140	41-450
	WC Headwaters (WCH)	323	54-9663

Table 2.4: Mean and range of dissolved and particulate fraction of total phosphorus concentrations at the inlet of Willow Creek Reservoir, Skinner Creek, North Fork, and Willow Creek Headwaters for the 2012-2013 study period.

Constituent	Sub-catchment	Mean (%)	Range (%)
Dissolved P	Inlet (VB)	72.20	28.66-90.04
	Skinner Creek (SK)	77.61	71.93-88.52
	North Fork (NF)	81.56	63.99-90.28
	WC Headwaters (WCH)	76.97	45.96-94.39
Particulate P	Inlet (VB)	27.80	9.96-71.34
	Skinner Creek (SK)	22.39	11.48-28.07
	North Fork (NF)	18.44	9.72-36.01
	WC Headwaters (WCH)	23.03	5.61-54.04

Table 2.5: Annual and monthly inlet and sub-catchment loads of total phosphorus (TP) for the Willow Creek watershed, OR calculated using the smearing method. Note: The total annual load is given in kg and metric tons.

	Monthly TP load (kg)				
Month	Inlet	Valley Bottom	Skinner Creek	North Fork	WC Headwaters
January	43	- 28	31	14	25
February	81	- 1	31	21	31
March	160	41	34	31	54
April	274	12	29	40	193
May	83	- 28	10	20	81
June	61	- 7	7	12	49
July	14	- 2	2	5	9
August	5	- 6	2	4	6
September	5	- 7	2	5	5
October	16	- 10	9	8	9
November	29	- 12	14	10	16
December	41	- 11	14	13	25
Annual total					
kg	**812**	- 61	187	183	503
Tons	**0.81**	- 0.06	0.19	0.18	0.50

Table 2.6: Annual and monthly inlet and sub-catchment loads of total residue (TR) for the Willow Creek watershed, OR calculated using the smearing method. Note: The total annual load is given metric tons.

	Monthly TR loading (tons)				
Month	Inlet	Valley Bottom	Skinner Creek	North Fork	WC Headwaters
January	98	- 38	41	24	71
February	179	19	40	37	84
March	340	- 35	45	57	273
April	561	-8,116	39	78	8,559
May	184	- 589	16	35	722
June	138	- 81	12	20	186
July	34	- 8	4	7	31
August	14	- 19	4	6	22
September	12	- 20	4	8	19
October	39	- 20	14	12	33
November	68	- 20	22	17	50
December	95	- 38	22	22	89
Annaul total (tons)	**1,762**	-8,965	263	323	10,140

Table 2.7: Annual aerial yields (kg/ha) of total phosphorus (TP) and total residue (TR) for sub-catchments of the Willow Creek watershed, OR.

Constituent	Sub-catchment	Annual yield (kg/ha)
TP	Valley Bottom (VB)	- 0.01
	Skinner Creek (SK)	0.04
	North Fork (NF)	0.07
	WC Headwaters (WCH)	0.10
TR	Valley Bottom (VB)	-1,800
	Skinner Creek (SK)	51
	North Fork (NF)	129
	WC Headwaters (WCH)	2,052

Table 2.8: Land use, definition of coefficient, total phosphorus (TP) export coefficient used to estimate loading from land uses (kg/ha/yr), high and low export coefficients found in the literature (kg/ha/yr) and associated references.

Land use	Definition of coefficient	Export coefficient (kg TP/ha/yr)	Low, High coefficient (kg TP/ha/yr)	Reference
CRP Lands	Average native grasslands	0.13	0.01,0.25	Timmons and Holt 1977
Agriculture (Jun-Nov)	Weighted mean of mixed agricultural watershed	1.13	0.08,3.25	Reckhow et al. 1980
Agriculture (Dec-May)	Average land receiving manure	1.85	0.80,2.90	Loehr et al. 1989
Forested Area	Weighted mean of forested watershed	0.24	0.019,0.830	Reckhow et al. 1980
Shrubland/Grassland	Average native grasslands	0.13	0.01,0.25	Timmons and Holt 1977
Riparian/Wetland	Average native grasslands	0.13	0.01.0.25	Timmons and Holt 1977
Roads	Average U.S. roads	2.35	1.31,36.99	USEPA 1983, Dudley et al. 1997

Table 2.9: Annual sediment production and delivery for various road types in the Wall Creek watershed including: crushed rock, native, paved, herbaceous veg, brush/trees/debris (Nelson et al. 2010).

Road type	Sediment production (kg/yr)	Sediment delivery (kg/yr)
Crushed rock	11,365	3,643
Native	66,256	16,228
Paved	202	69
Herbaceous veg	3,473	974
Brush/trees/debris	148	62

Table 2.10: Road type (treated and untreated) and mean annual sediment erosion (m^3); averages are presented in bold text.

Road type	Mean erosion (m^3)	Reference
Treated	25	Keppeler et al. (2007)
Treated	27	Keppeler et al. (2007)
Treated	50	Madej (2000)
Treated	12	Klein (2003)
Treated	27	Klein (1987)
Treated	20	Flanagan (2012)
Treated	21	Flanagan (2012)
Treated	11	Flanagan (2012)
Treated	71	Bloom (1998)
Treated	247	Bloom (1998)
Average	**51**	-
Untreated	1,411	Hagans et al. (1986)
Untreated	641	Hagans et al. (1986)
Untreated	32	Hagans et al. (1986)
Untreated	378	Hagans et al. (1986)
Untreated	700	Hagans et al. (1986)
Untreated	2,839	Bloom (1998)
Untreated	772	Bloom (1998)
Untreated	395	McCashion and Rice (1983)
Untreated	186	Best et al. (1995)
Untreated	144	Best et al. (1995)
Untreated	74	Best et al. (1995)
Average	**688**	-

Table 2.11: Literature-derived values of phosphorus (P) and sediment removal efficiencies (%) for vegetative filter strips of different widths (m)

Width (m)	P removal efficiency (%)	Sediment removal efficiency (%)	Reference
2.0	32	65	Abu-Zreig et al. 2003
3.0	37	66	Lee et al. 1998
4.0		93	Blanco-Canqui et al. 2004
4.6	61	70	Dillaha et al. 1989
5.0	54	81	Abu-Zreig et al. 2003
6.0	60	80	Daniels and Gilliam 1996
6.0	80	93	Borin et al. 2005
6.0	52	77	Lee et al. 1998
7.1	78	95	Lee et al. 2003
7.5	55	76	Schmitt et al. 1999
8.0		97	Blanco-Canqui et al. 2004
9.1	79	84	Dillaha et al. 1989
10.0	67	92	Abu-Zreig et al. 2003
15.0	79	93	Schmitt et al. 1999
15.0	79	9	Abu-Zreig et al. 2003
16.3	91	97	Lee et al. 2003
24.4	83	79	Young et al. 1980

Table 2.12: Riparian vegetation plantings that have occurred within Oregon during 1999-2012, obtained from the Oregon Watershed Restoration Inventory. Data includes the project number, sub-basin, year completed, total costs, cost/mile and cost/acre.

Project number	Sub-basin	Year completed	Total costs ($)	Cost/mile ($)	Cost/acre ($)
19990139	Sixes	1999	994	7,646	3,976
19990613	Umpqua	1999	181		181
19990614	Umpqua	1999	320		320
19990615	Umpqua	1999	293		195
20001078	Umpqua	2000	361		181
20050449	Nehalem	2005	12,306	12,430	6,153
20050721	Applegate	2003	300	3,000	300
20060718	Lower Deschutes	2006	4,342	7,237	
20070030	Upper Deschutes	2007	218,575		3,262
20070602	Middle Columbia-Hood	2007	40	667	
20080344	Upper Willamette	2008	6,025	10,042	6,025
20100007	Upper Malheur	2010	300		3,000
20100526	Lower John Day	2010	2,766	11,064	1,844
20110265	Upper Klamath Lake	2011	2,500	10,000	2,500
20120345	Lower Columbia-Sandy	2012	500	2,381	625
20120409	Umpqua	2012	1,000	2,000	2,000
20120734	Umpqua	2012	3,118	15,590	3,118

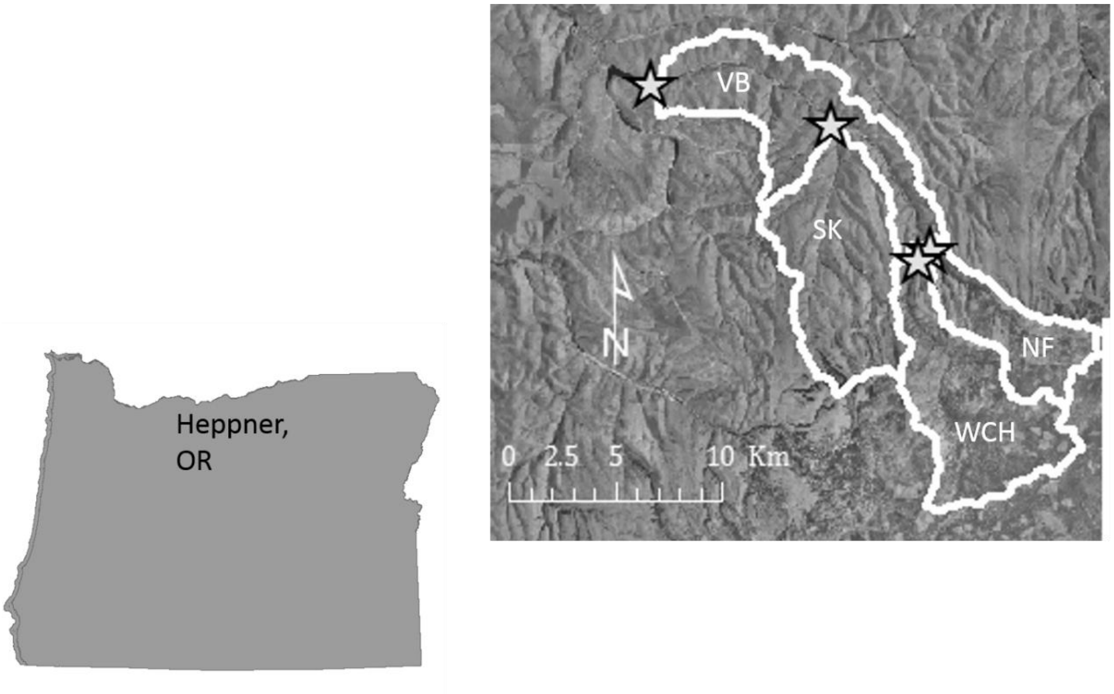

Figure 2.1: Location of the Willow Creek watershed in Morrow County, Oregon, USA close to the town of Heppner. Sub-catchments identified by letter abbreviations are: WCH - Willow Creek Headwaters, NF – North Fork, SK – Skinner Creek and VB – Valley Bottom. The location of four (4) ISCO automated water samplers within the watershed are indicated by the white stars.

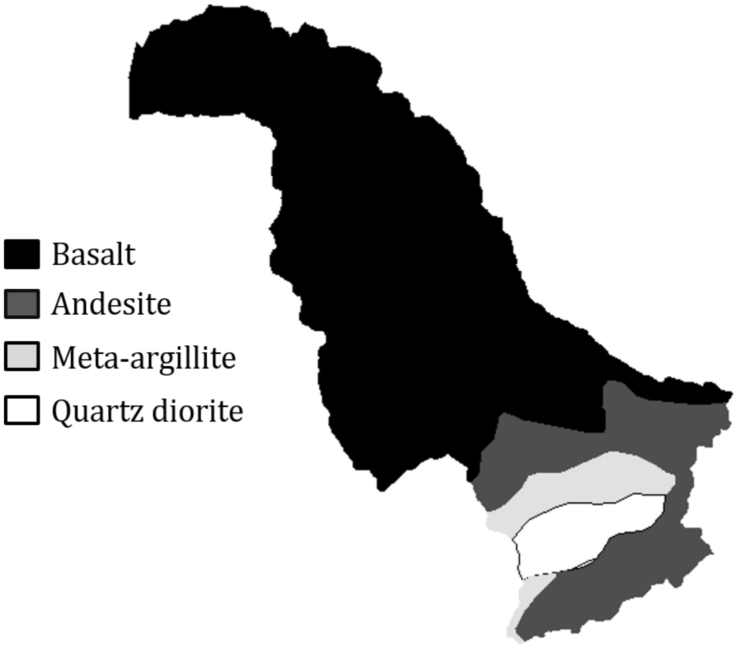

Figure 2.2: A map of the geologic makeup of the Willow Creek watershed including: basalt, andesite, meta-argillite and quartz diorite (obtained from the USGS mineral resource on-line spatial dataset, http://mrdata.usgs.gov/geology/state/state.php?state=OR).

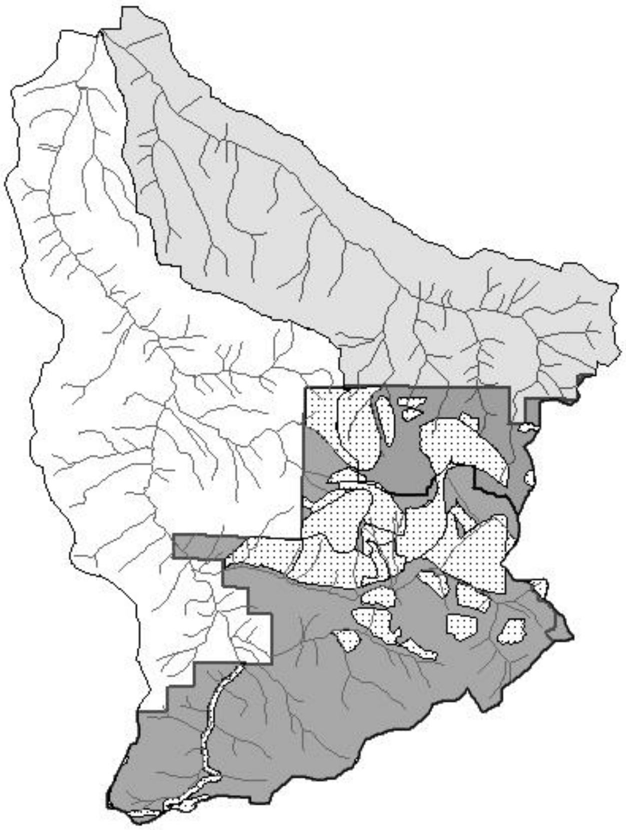

Figure 2.3: Visual representation of areas of past logging activities (stippled) in the North Fork (light grey) and Willow Creek Headwaters (white) sub-catchments comprised of Umatilla National Forest (dark grey); streams shown as light grey lines.

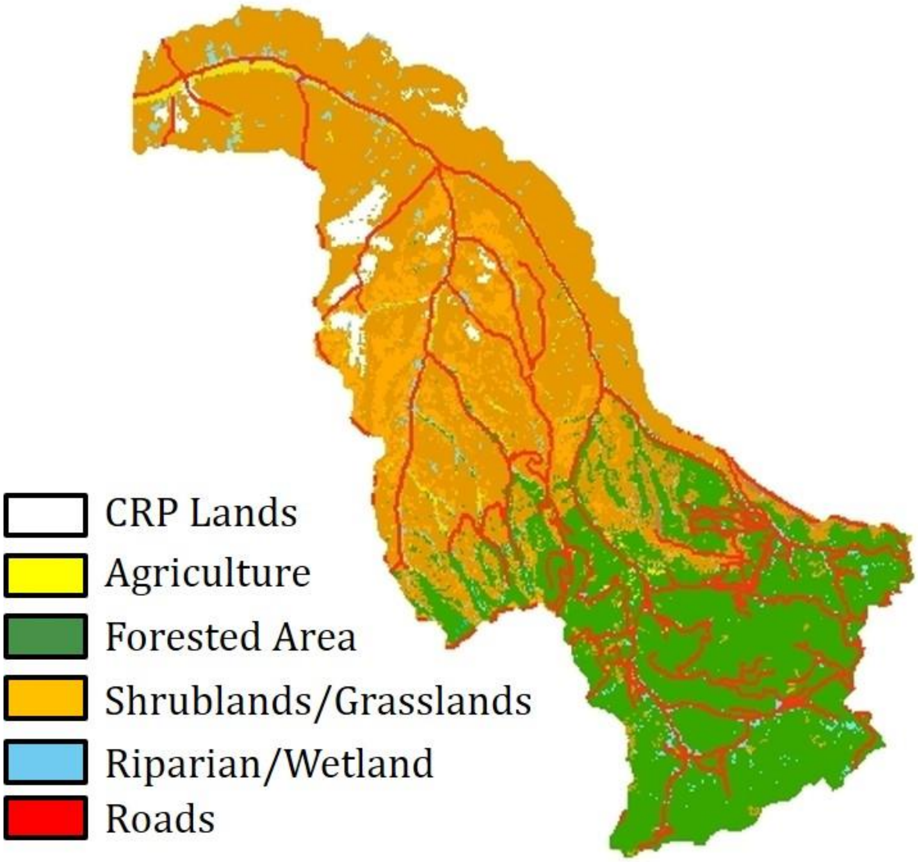

Figure 2.4: A map of the distribution of the 6 broad land use types identified for the Willow Creek Watershed including CRP lands, Agriculture, Forested Area, Shrublands/Grasslands, Riparian/Wetland and Roads.

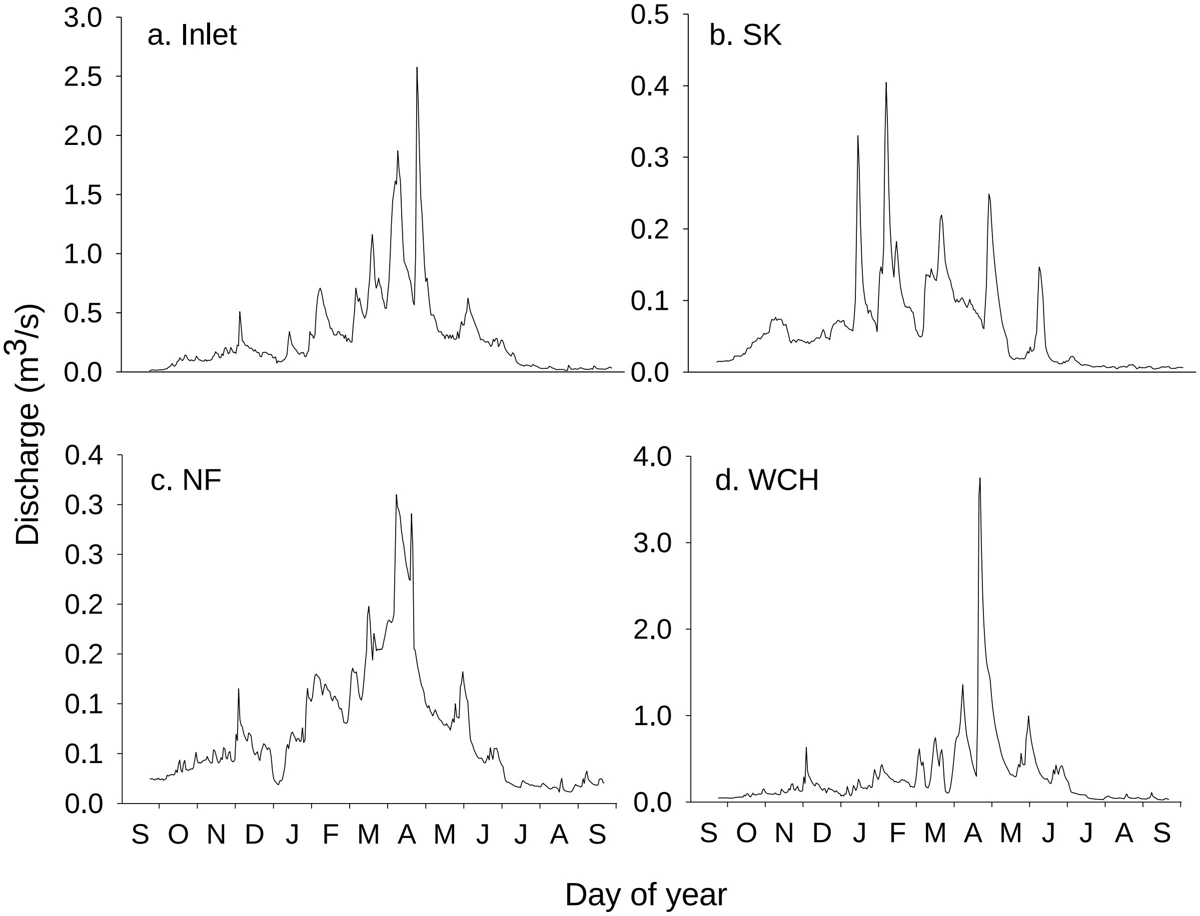

Figure 2.5: Hydrograph of discharge (m^3/s) for the Inlet (a), SK-Skinner Creek (b), NF-North Fork (c) and WCH-Willow Creek Headwaters (d) for the period September 20, 2012 to September 21, 2013.

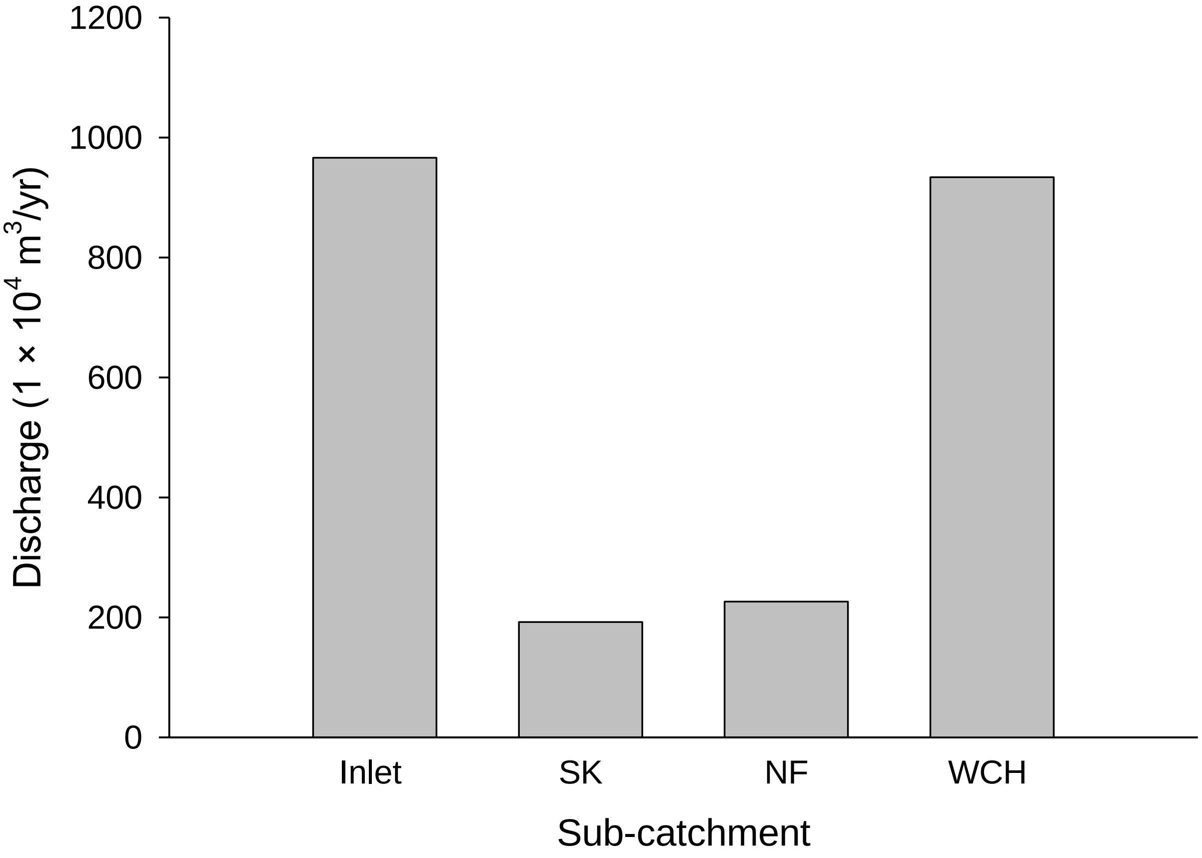

Figure 2.6: Annual discharge (m³/yr) for the inlet of Willow Creek reservoir, SK-Skinner Creek, the NF-North Fork and WCH-Willow Creek Headwaters sub-catchments for the period September 20, 2012 to September 21, 2013.

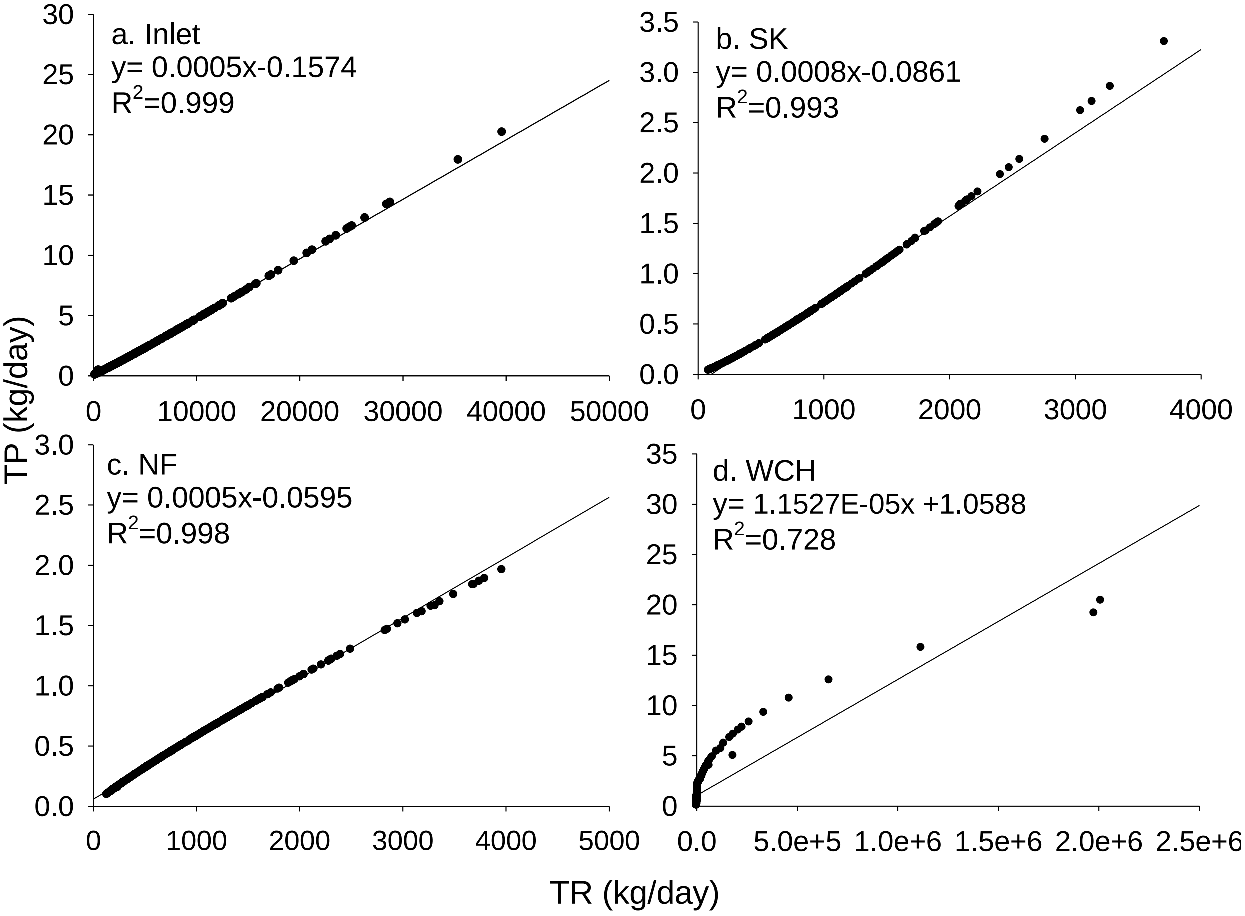

Figure 2.7: Total phosphorus (TP) as a function of total residue (TR) for the (a) inlet, and sub-catchments (b) SK-Skinner Creek, (c) NF-North Fork, and (d) WCH-Willow Creek Headwaters in the Willow Creek Watershed, OR. Linear least-squares regressions in the form y=mx+b and coefficients of determination (R^2) are given on each panel.

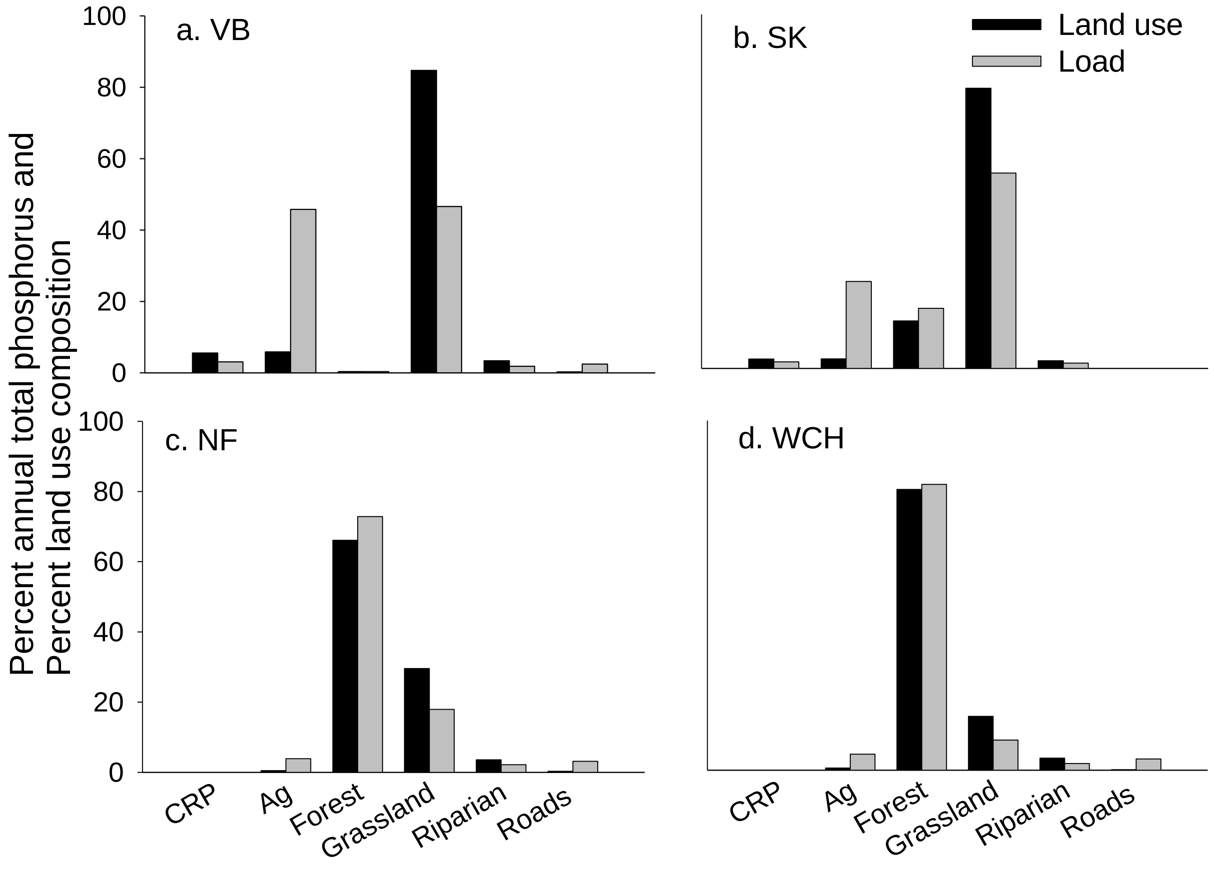

Figure 2.8: Percent of annual total phosphorus (TP) load and percent land use composition in size broad land use types for sub-catchments (a) VB-valley bottom, (b) SK-Skinner Creek, (c) NF-North Fork and (d) WCH-Willow Creek Headwaters in the Willow Creek Watershed, OR.

Chapter 3: Exploring the public's opinion of a constructed wetland at the inlet of Willow Creek Reservoir, Heppner, OR.

Abstract

Land use changes from anthropogenic activities have rapidly degraded water quality due to the input of polluting substances including excess nutrients that fuel harmful algae blooms. Constructed wetlands have been used successfully to improve the water quality of receiving waters and may be an option for Willow Creek Reservoir (WCR) in Oregon, U.S.A. where the influx of high nutrients, especially phosphorous results in annual toxic blooms of cyanobacteria. However, the negative stigma long associated with wetlands (e.g., swamped with work; bogged down; insect infested good for nothing lands) could mean that that residents and visitors of WCR would not be in favor of such an approach. I used an intercept survey to: i) quantify resident's and non-resident's awareness of the annual toxic algae bloom and the interference such blooms have on their use of WCR, ii) examine how the construction of a wetland at the inlet of WCR would impact resident and non-resident use of WCR, and iii) understand the public's opinion of how the constructed wetland would be used. Respondents were aware of the toxic algae bloom and the bloom's interference of use of WCR was dependent on residential status (p-values =0.001 and 0.003 respectively). However, residential status was independent of whether or not a constructed wetland would impact respondent's use of WCR, (p-value= 0.241). The majority of residents and non-residents indicated they would use a constructed wetland similarly either for wildlife viewing or walking/exercise. Boardwalk use and the effect on enjoyment by adding educational or informational signs were independent of residential status (p-value=0.080 and 0.158 respectively). It is important for the information gathered in this survey to be incorporated into management decisions to harmonize management and potential user desires if a wetland is constructed.

Introduction

Life as we know it depends on access to clean water. Water is primarily used for irrigation, domestic supply, transportation, industrial supply, and recreation such as swimming and fishing (Carpenter et al. 1998). Land use changes from anthropogenic activities have rapidly degraded water quality due to the input of polluting substances, including nutrients, sediment and toxins (Jeppesen et al. 2009, Shrestha et al. 2012), or altered thermal regimes (Benson et al. 2012). This degradation increases the costs of monitoring and management (Hoagland et al. 2002), and negatively affects property values (Leggett and Bockstael 2000), commercial and recreational fisheries, recreation and tourism, and most importantly, public health. Thus, it is in a community's best interest to maintain or increase water quality to sustain itself.

Blooms of cyanobacteria, formerly known as blue-green algae, are a threat to water quality worldwide because they create a multitude of water quality problems including taste and odor in drinking water (Pick and Lean 1987, Carpenter et al. 1998, Bartram and Chorus 1999, Sharpley et al. 2000, Pitois et al. 2001, Wu et al. 2006), decreased aesthetics due to the presence of surface scums and odors (Bartram and Chorus 1999), decreased water column dissolved oxygen when they decompose (Pick and Lean 1987, Bartram and Chorus 1999, Carpenter 2008, Schindler 2008), and most importantly, the production of a suite of the most potent toxins known to humans (Chorus and Bartram 1999). The toxins produced include hepatotoxins (the most prominent being microcystin), neurotoxins and dermatotoxins (Graham et al. 2009). Presence of these toxins have killed pets, wildlife, livestock (Sharpley et al. 2000, Briand 2003, Graham et al. 2009a, Graham et al. 2009b), and humans (Chorus and Bartram 1999, Sharpley et al. 2000, Briand 2003, Graham et al. 2009a, Graham et al. 2009b). The frequency of such harmful algal blooms (HABs) is increasing worldwide and they are a threat to our drinking water supplies and the ecological and economic sustainability of our fresh water systems in general (Chorus and Bartram 1999, Graham et al. 2009a, Sharpley et al. 2000, Paerl et al. 2011) .

Currently there are no U.S. federal guidelines, standards or regulations for the management of cyanobacteria blooms. The World Health Organization (WHO) suggests a microcystin-LR limit of 1 μg/L in drinking water, but there is no uniform enforcement of this limit across the U.S. As a result, individual states have set toxin standards and test for toxins in cyanobacteria blooms. For example, the Oregon Department of Health Services (ODHS) has a microcystin toxin limit of 8 μg/L for recreational contact (ODHS 2008). When water bodies exceed this limit, advisories and warnings are posted to warn visitors to avoid direct contact with the water (USACE 2007, ODHS 2008).

Several hypotheses exist to explain the occurrence of blooms of cyanobacteria among which the quantity of nutrients (nitrogen – N and phosphorus - P) available and their ratio dominate (Schindler 1977, Smith 1983, Harris et al. 2014). For example, cultural eutrophication (the acceleration of natural lake evolution to higher trophic states resulting from anthropogenic activities) continues to be a major factor affecting the water quality of the world's surface waters (Downing 2013). This means that reducing inputs of nutrients, primarily N and P, because they typically limit primary production in freshwaters (Schindler 1977, Smith 2012), should receive our attention to limit algal blooms. In addition, research has shown that cyanobacteria dominate at low N:P ratios (Tilman et al. 1982, Pick and Lean 1987, Carpenter 2008, Orihel et al. 2011, Harris et al. 2014), indicating that preventing the influx of P to- or reducing it from aquatic ecosystems is crucial to prevent or mitigate harmful algal blooms. Thus, maintaining or recovering high water quality with respect to HABs depends on reducing the overall abundance of nutrients, especially P. A variety of strategies are available to aquatic resource managers to reduce the influx of nutrients or reduce their availability once in the system (Cooke et al. 2005). Among these, constructed wetlands have been used to specifically target the reduction of the occurrence of cyanobacteria (Wu et al. 2010, Zhong et al. 2011).

Wetlands play an important role in aquatic ecosystems because they can improve the water quality of receiving waters (Carpenter et al. 1998, Woltemade 2000, Díaz et al. 2012, Jordan et al. 2003). For example, wetlands control the cycling of elements, particularly nutrients such as N and P (Mitsch and Gosselink 2007), and reduce concentrations of contaminants such as suspended solids, trace metals, trace organics, pathogens and pesticides (Carpenter et al. 1998, Woltemade 2000, Jordan et al. 2003, Díaz et al. 2012). In addition to improving water quality, wetlands also offer other benefits including wildlife habitat which supports biodiversity, landscape diversity, decreased flooding and erosion, and educational opportunities (Jordan et al. 2003, Zedler 2003, Richardson et al. 2011, Díaz et al. 2012). Given the large loss of wetlands across the United States, which has been estimated at 53% (Dahl 1990), and our recent discovery of their benefits, hydraulic engineers and land-use planners are incorporating constructed wetlands to manage aquatic resources and restore ecosystem function (EPA 1993). Significant and successful constructed wetlands include the Lakeland and Orlando wetlands that were constructed in Florida, both wetlands are 500 ha and are used for the treatment of municipal wastewater (Kadlec and Wallace 2009). Other examples include six treatment wetlands created in southern Florida, totaling over 16,000 ha, which were constructed for the treatment of municipal wastewater (Kadlec and Wallace 2009). However, the long negative stigma associated with wetlands (Urban 2005) requires much education of the public for constructed wetland to gain widespread acceptance. Thus it is not surprising that wetland education has increased in popularity as the value of wetlands to society has been recognized.

Educational programs focused on wetlands generate knowledge through experimentation and exploration and allow for hands-on learning including the creation, restoration, enhancement and monitoring of local wetlands (Kent 2000). This puts people directly in contact with wetlands, and is a highly effective education method. Nationally in the U.S., there are many wetland education programs that can be easily incorporated into existing K-12 curricula. Three of the most well-known programs include POW! The Planning of Wetlands (Ripple and Garbisch 2000), *WOW! The Wonders of Wetlands* (Slattery 1991) and *Project WILD Aquatic Education Activity Guide* (Mycio-Mommers and Canadian Wildlife Federation 1990). Thus when considering the construction of a wetland, planners often consider the potential educational aspects and many constructed wetlands include some educational component such as a nature boardwalk or wildlife observation area (Trapp et al. 1994, Brochu and Merriman 2003). This brings the public into the wetland and helps overcome the negative stigma associated with wetlands.

When considering remediation strategies, such as a constructed wetland, it is important that management decisions consider public perceptions, values and beliefs to ensure that the proposed strategy encompasses the desires and needs of the public. When dealing with natural resources, discrepancies between management and user objectives often lead to conflict and inefficient use (West 1989). User objectives are derived from their values which stem from ecological, economic, social, and aesthetic ideals, and are primarily related to an individual's past experience and education (Lynam et al. 2007). The importance of including user's objectives and values in natural resource management has stimulated the development of a range of methodologies (Lynam et al. 2007) including social surveys, which are a powerful tool frequently used to collect information about public preferences (Salant and Dillman 1994). I incorporated a social survey into my thesis to explore the public perception of cyanobacteria blooms and the potential of using a constructed wetland to help remediate the annual cyanobacteria bloom at Willow Creek Reservoir (WCR) in Heppner, OR. This gave me exposure to this methodology, and it would contribute important information to the U. S. Army Corps of Engineers (USACE) as it seeks to implement strategies to reduce frequency and severity of cyanobacteria blooms at WCR.

The Willow Creek Dam and was constructed by the U.S. Army Corps of Engineers immediately south of the town of Heppner, OR to protect the town from devastating floods, one of which in 1903, caused the loss of 247 lives and resulted in significant property damage (Byrd 2009). A secondary use of the resulting reservoir is recreation, and more recently irrigation for agriculture (USACE 2005). Since completion and filling of the dam, WCR has had a variety of issues, including low dissolved oxygen, increased production of hydrogen sulfide, ammonia, methane and the occurrence of harmful algae blooms (USACE 2007). Of these, the latter is a major concern because it results in advisory warnings from the Oregon Department of Health, which restricts human contact with the water in the reservoir and thus decreases its potential for recreational activities. Recreation is an important facet of WCR because it is the only significant 'lake' in a 100 km (60 mile) radius. In addition, providing safe and high quality water is a primary objective of the U.S. Army Corps of Engineers.

Because WCR plays such an important role in the community, I surveyed residents and non-residents of Heppner, OR and WCR to determine their opinion towards the potential use of a constructed wetland to remediate the harmful cyanobacteria blooms in the reservoir. Specifically, I was interested to quantify i) the awareness of residents and non-residents of the annual toxic algae bloom and the any interference such blooms have on their use of WCR ii) examine how the construction of a wetland at the inlet of WCR could impact the use of WCR by residents and non-residents, and iii) understand how the constructed wetland would be utilized by residents and non-residents. I hypothesized that respondent's awareness of the annual bloom and any interference of the bloom on their use of WCR was independent of residential status. I also hypothesized that the impact of a constructed wetland and its potential use was independent of residential status.

Methods

Study site

Willow Creek Reservoir is located in Morrow County, OR immediately south of the town of Heppner. The drainage basin is predominantly characterized as semiarid because of the lack of precipitation between July and October (USACE 2007). Typically, daily air temperature in the watershed ranges from -29.4 to 43.3°C with an annual mean of 10 °C (USACE 2007), while annual precipitation ranges from 203.2 mm to 863.6 mm (USACE 2007). Summer days are warm, while nights are cool. In winter, diurnal temperature ranges are moderate and predominantly cold. Most of the annual precipitation occurs as rain or snow at high (approximately > 900 m above sea level - a.s.l.) elevations, and rain at low (approximately < 600 m a.s.l.) elevations between October and June (DeBano and Wooster 2004). The reservoir has a surface area of 109 ha (0.5 km wide and 1.6 km long), and is approximately 26 m deep at its deepest point. A maximum microcystin concentration of 1,150 μg/L was recorded in 2005 (USACE 2007), which far surpassed the WHO (6 μg/L) and ODHS (8 μg/L) toxin limits for recreational contact. Due to these recurring cyanobacteria blooms, advisory warnings occurred on WCR since 2006, restricting human access for periods ranging from 38 to 153 days during the summer. In 2012 the bloom's duration was 104 days (September to December), while in 2013 two blooms occurred. The duration of the first bloom was 56 days (June to August) and the duration of the second bloom was 88 days (October 2013-January 2014).

Selection of survey participants, and duration of survey

A paper intercept in-person survey (Oishi 2003) was given to individuals over the age of 18 (see Appendix K, for survey used) encountered randomly while they were in Heppner or at WCR between November 2012 and August 2013. Additional survey locations included the Morrow County Fair and Oregon Trail Pro Rodeo, the local school district and the local offices of the Forest Service, Soil and Water Conservation District Office, and the Oregon State University Extension Office. All adults present, individually or in groups, were asked to participate in the survey. The survey typically required 5 minutes or less to complete. For simplicity sake, rather than referring to visitors to WCR and Heppner, I classified survey respondents as residents and non-residents of WCR and Heppner, even though there are no residences at WCR. Residents and non-residents were distinguished based on information provided in the first question of the survey, which asked respondents if they were residents of Heppner, OR and were provided with the answers yes and no. Those that answered yes were considered Heppner residents. Those that answered no were considered non-residents and were asked to provide their zip-code to determine distance travelled from their hometown to Heppner.

Statistical analysis of survey responses

To test the hypothesis that awareness of the toxic algae bloom was independent of residential status, I used a Pearson's chi-square test of independence (Cohen et al. 2011) to examine responses to question # 7 (aware/unaware of bloom, coded as 1 and 2 respectively) classified by question #1 (residential status of WCR or Heppner, residents and non-residents, coded as 1 and 2 respectively). To determine if bloom awareness was independent of the number of years of residency or visitation, or annual visitation to WCR, the percent of aware and unaware residents and non-residents was determined from responses to question #2 and #6 which were Likert scale responses to years of residency or visitation (< 1; 2-5; 6-10; and >10 years) and frequency of annual WCR visits (0-1; 2-5; 6-10; and >10 times per year). The Likert scale is one of the most commonly used scales in the social sciences because it is easily understood by respondents and is useful in self-administered surveys (Salant and Dillman 1994).

To address the hypothesis that residential status does not affect the toxic algae bloom's interference with WCR use, question # 8 (Likert scale with response of: doesn't interfere; seldom interferes; occasionally interferes; frequently interferes; and always interferes) was analyzed with a Mann-Whitney U test. Non-parametric statistics such as the Mann-Whitney U test are commonly used as a substitution for t-tests (Cohen et al. 2011) when sample sizes are small or data represent non-normal distributions. To determine if annual WCR visitation is affected by bloom interference, resident and non-resident responses were separated by annual WCR visitation (question #6) and the percent of aware and unaware residents and non-residents were determined for each WCR visitation bracket.

To test the hypothesis that the impact of potential wetland construction is independent of residential status, I used a Pearson's chi-square test of independence to analyze question # 9 (potential impact on your use and enjoyment of WCR or Heppner, OR with responses of: positive; no impact; or negative) and residence status (as explained above).

To test the hypothesis that potential use of the wetland is independent of residential status, respondents were asked a series of questions. Respondents were asked to identify how they would use the constructed wetland given choices including: wildlife viewing, walking or exercise, aesthetic or scenery viewing, photography, I would bring my students here or I wouldn't use it. I was particularly interested to determine the main use for residents and non-resident and the percentage of respondents in each residential category that would not use the wetland. Respondents were then asked if they would use the wetland if a boardwalk was installed. In addition, they were asked if the installation of educational or informational signs would add to their enjoyment of WCR or Heppner, OR. Pearson's chi-square tests of independence were performed to determine if boardwalk use or the effect of educational or information signs on WCR enjoyment were independent of residential status.

Because incorporating wetland education into curricula has become popular across the U.S. as the value of wetlands to society has been recognized, I was interested to determine if respondents who identified themselves as teachers would bring students to a constructed wetland and incorporate it into their curriculum. To do this, I separated the respondents who marked 'teacher' in question #4. Of these respondents, I calculated the percentage of those who marked 'I would bring my students here', and 'I would not use it' in response to question 10. Because only a small sample size (n=20) of respondents identified themselves as teachers, no statistical tests were undertaken, as it is known that such small sample size may not accurately represent the entire population.

Because a potential constructed wetland could interfere with the livelihood of farmers and ranchers who own land above the reservoir, I also was interested to analyze responses of those who identified themselves as landowners in question 3. I was particularly interested in landowner's awareness of the annual bloom, if such blooms interfere with their use of WCR, and how the construction of a wetland would impact their use of it or WCR. A small sample size (n=8) precluded rigorous statistical analysis, and trends should be interpreted with caution.

Results

General description of respondents

A total of 102 surveys were administered during the survey period. Of the respondents 59% (n=60) identified themselves as residents, while the remaining 41% (n=42) were non-residents. The majority of non-residents (59%, n=23) travelled under 80.5 km (50 miles) to Heppner (Table 3.1, Figure 3.1). Almost half of the non-residents (48%, n=11) visited from Lexington, OR, a town 14.5 km (9 miles) away. Of these respondents, the majority (64%, n=7) visited WCR 0-1 times per year. The furthest distance a non-resident travelled was 565 km (351 miles) from Ocean Shores, WA. Overall, there was a negative relationship between number of visitors and distance traveled to WCR.

When asked their main association with WCR or Heppner, OR, (question #4) the majority of residents (72 %, n=43) and non-residents (69%, n=29) identified themselves as residents and visitors, respectively. Residents were composed of government employees (28%, n=17), teachers (27%, n=16), ranchers (13%, n=8), farmers (10%, n=6) and other (6%, n=10), while non-residents were composed of government employees (14%, n=6), teachers (10%, n=4) and other (12%, n=5). Because respondents were allowed to check all applicable associations, the total number of responses is greater than the number of surveyed respondents.

Responses of residents and nonresidents to blooms on WCR

Among respondents identified as residents, none had lived in Heppner for less than 1 year, while the majority 68% (n=41) had been residents for >10 years; 17% (n=10) had been residents for 6-10 years, and the remaining 15% (n=9) had been residents for 2-5 years. Of respondents identified as non-residents, 10% had visited Heppner or WCR for less than 1 year, 14% (n=6) for 6-10 years, 12% (n=5) for 2-5 years, while 64% (n=27) visited Heppner, OR or WCR for >10 years.

For residents, about a third (35%, n=21) indicated they visit WCR 2-5 times per year while, 28% (n=17), 23% (n=14) and 13% (n=8) of residents indicated they visited 0-1, >10 and 6-10 times per year, respectively. Half of non-residents (52%, n=22) indicated they visit WCR 0-1 times per year, while 40 % (n=17), 5% (n=2) and 2% (n=1) indicated they visited 2-5, >10 and 6-10 times per year respectively.

The majority of residents (97%, n=58) and non-residents (71%, n=30) indicated they were aware of the annual toxic algae bloom. The relation between residential status and bloom awareness was significant (X^2=11.24, df=1, p-value < 0.001), indicating that a respondent's awareness of the toxic algae bloom was dependent on residential status; with residents being more aware of the blooms than non-residents (Figure 3.2). Surprisingly, all (n=2) residents unaware of the blooms at WCR had been residents for >10 years (Figure 3.2), and their visitation rate was 2-5 times a year (Figure 3.3). Greater than half of the unaware non-residents (58%, n=7) had visited for >10 years (Figure 3.2) at a rate of 0-1 times per year (Figure 3.3).

When respondents were asked to what degree the toxic algae bloom interfered with their use of the WCR, about a third of the residents (27%, n=16) indicated the bloom did not or frequently interfered with their use (Figure 3.4). In contrast, over half of the non-residents (55%, n=23) indicated the bloom did not interfere with their use (Figure 3.4). Analysis indicated that residential status was related to the bloom's interference of use of WCR (Mann-Whitney U=1680.5, p-value=0.003) with residents being more affected than non-residents. When separated by annual WCR visitation, 50% (n=13) of the residents who indicated the bloom did not interfere with their use of WCR visited the reservoir 0-1 times per year, 31 % (n=8) visited 2-5 times per year and the remaining 19% (n=5) visited more than 10 times a year (Table 3.2). Of those residents who indicated the bloom frequently interfered with their use, 38% (n=10) visited 2-5 times per year, 25% (n= 7) visited 0-1 times per year, and 19% (n=5) visited 6-10 and >10 times per year. Of the 55% of non-residents who indicated the bloom did not interfere with their use, 57 % (n=31) visited WCR 0-1 times per year, 35 % (n=19) visited 2-5 times a year, and 4% (n=2) visited 6-10 and >10 times a year (Table 3.3).

Response of residents and nonresidents to potential remediation strategies

Over half of residents (57%, n=34) indicated a potential constructed wetland would have a positive impact, while the remainder (43%, n=26) indicated it would have no impact on their use of WCR. For non-residents, over half (57%, n=24) indicated a constructed wetland would have no impact, while the remainder (43%, n=18) indicated it would have a positive impact on their use of WCR. Analyses indicated that residential status was independent of whether or not a constructed wetland would impact use of WCR (X^2=1.37, df=1, p-value=0.241). None of the respondents indicated the potential construction of a wetland would have a negative impact on their use of WCR.

The majority of residents indicated they would use a constructed wetland for wildlife viewing (57%, n=34), and walking/exercise (52%, n=31), while 18 % (n=11) indicated they would not use it (Figure 3.5). The majority of non-residents indicated they would use the wetland for wildlife viewing (60%, n=25) while about a third of the respondents indicated they would either use it for walking/exercise (31%, n=13) or not use it at all (33%, n=14) (Figure 3.5). These percentages surpass 100% because respondents were able to check all uses they would pursue in the wetland.

The majority of residents (85%, n=51) and non-residents (67%, n=28) indicated they would use a boardwalk in the wetland. Analysis indicated that boardwalk use was independent of residential status (X^2=3.07, df=1, p-value=0.080).

The majority of residents (82%, n=49) and non-residents (69%, n=29) indicated that the installation of educational or informational signs would increase their enjoyment of the wetland. Analysis indicated that the effect on enjoyment by adding educational or informational signs was independent of residential status (X^2=2.00, df=1, p-value=0.158). Interestingly, of the residents who indicated they would not use the wetland, 45% (n=5) indicated they would use both a boardwalk and educational signs, while 21% (n=3) and 36% (n=5) of non-residents indicated they would use a boardwalk and educational signs, respectively.

Of the teachers surveyed, the majority (75%, n=15) indicated they would not bring their students to the constructed wetland. Of the respondents who identified themselves as landowners, all were aware of the annual cyanobacteria bloom. Of these, 38% (n=3) indicated the annual bloom occasionally interfered with their use of WCR, while for 25% (n=2) the blooms did not interfere with their use (Figure 3.6). The majority of the landowners (63%, n=5) indicated the construction of a wetland would positively impact their use of WCR. The majority of the landowners indicated they would use the wetland for wildlife viewing (75%, n=6), while half of the respondents (50%, n=4) indicated they would use it for walking or exercise, aesthetics or scenery viewing and photography (Figure 3.7). Only one respondent (13%, n=1) indicated they would not use the constructed wetland. All of the landowners indicated they would use the boardwalk (100%, n=8), while the majority (88%, n=7) indicated educational signs would add to their enjoyment of WCR.

Discussion

The water quality issue in WCR caused by annual blooms of cyanobacteria needs to be addressed because it is the only significant 'lake' in a 100 km radius, which makes it a destination hotspot for local residents of Heppner and other surrounding towns. For example, almost half of the non-residents surveyed were from Lexington, OR, a neighboring town only 14.4 km (9 miles) away. These users and their pets are at risk when exposed to the cyanobacteria bloom and potential toxins in WCR, as there are many documented cases of these toxins killing pets, wildlife, livestock (Sharpley et al. 2000, Briand 2003, Graham et al. 2009a, Graham et al. 2009b), and humans (Chorus and Bartram 1999, Sharpley et al. 2000, Briand 2003, Graham et al. 2009 a; Graham et al. 2009b) that have been exposed to cyanobacteria toxins. These short-distance or 'local' visitors have easy access to WCR, but the majority of them only visit WCR 0-1 times per year. The relatively infrequent visitation may be due to the annual toxic algae bloom, as it is known that recreation and tourism decrease with the onset of a cyanobacteria bloom (Zingone and Enevoldsen 2000, Hoagland et al. 2002). Cyanobacteria blooms can cause fish kills, water discoloration, odors, and produce toxins, all of which generally deter users from recreating or visiting a water body (Zingone and Enevoldsen 2000, Hoagland et al. 2002) . A remediation strategy is necessary that increases water quality while incorporating management needs and perceived user features.

Previous research (Harris 2012) suggests that the overabundance of P is the main cause of the annual blooms of cyanobacteria in WCR. Thus its reduction in water entering WCR is crucial to recover water quality. Many documented cases exist of managers using wetlands to reduce P concentrations and increase water quality (Niswander and Mitsch 1995, Reinelt and Horner 1995, Raisin 1997, Fink and Mitsch 2004, Fink and Mitsch 2007). Based on the known effectiveness of wetlands and the available land at the inflow of Willow

Creek to the reservoir, a constructed wetland may be a feasible strategy to increase water quality in WCR (see chapter 4). Improved water quality could reduce human exposure to cyanotoxins and thus protect public health, which would assist the U.S. Army Corps of Engineers in reaching one of its main goals of providing safe and high quality water. Due to the strong connection between water resources and recreation, if the water quality in the reservoir were to increase, the annual visitation to WCR would also be expected to increase (Bockstael et al. 1987, Vesterinen et al. 2010). This could contribute positively to Heppner's economy. It is well documented that as local recreational opportunities increase so does gross income and employment opportunities (Bergstrom et al. 1990).

Overall, the water quality in WCR affects both residents and non-residents and needs to be addressed. Until the water quality issue in WCR is addressed and the frequency of occurrence and severity of toxic algal blooms is reduced, public awareness of these water quality issues needs to increase. This survey aimed to quantify resident's and non-resident's awareness of the annual toxic algae bloom and the interference the bloom has on their use of WCR. Another objective was to quantify how the construction of a wetland at the inlet of WCR will impact residents and non-residents use of WCR and the public's opinion of how the constructed wetland would be utilized by residents and non-residents.

Responses of residents and nonresidents to blooms on WCR

Results indicate that residents were more aware of the annual toxic algae bloom than non-residents, which was consistent with the findings of previous research at WCR (Adams 2012). Adams (2012) expressed the importance of making visitors aware and the need for additional signage at the reservoir indicating toxin levels, which could help deter users from entering the reservoir. This is in line with related research, which indicates recreational activity is a major route of exposure. Given limited management options, the discouragement of use is frequently used as a management tool (Chorus and Bartram 1999). The majority of residents and visitors who were unaware of the bloom visit WCR between 0-5 times per year and had visited the area for over ten years. One would expect that for the number of years respondents have visited the area, they would be aware of the bloom, as it is has been a reoccurring issue (USACE 2007). Adams (2012) concluded that the majority of people who visit WCR do so in early summer, specifically around Memorial Day weekend, before the bloom begins. During this time the water in the reservoir is still cool and the lake has not thermally stratified. With the onset of warmer water temperatures and lake stratification, conditions become ideal for cyanobacteria (Jones and Poplawski 1998, Chorus and Bartram 1999) . This year the bloom began on June 18th, 2013, while in 2012 the bloom did not begin until September 14, 2013. In both years, the onset of the bloom was well after major holiday weekends such as Memorial Day, which typically kicks off water-related recreation in the region. If the majority of WCR visitors visit before the onset of the bloom, this could explain why they are unaware of it. For the users that visit WCR after Memorial Day, it is important they are made aware of the annual bloom. As previously recommended by Adams (2012), additional signage may be needed to achieve this awareness.

According to the survey results, the annual bloom interferes with resident's use more than non-residents. This is not surprising because residents have increased access to the reservoir given their proximity to it and their higher frequency of visits. This increased frequency means that residents may be more likely to visit the reservoir after the lake has stratified and the bloom has formed. Once the bloom has formed, an advisory warning is posted by the Oregon Department of Health to encourage the public to limit direct contact with the reservoir, which would limit recreational opportunities. This would explain the increased interference for residents. Non-residents are likely less affected because their annual visitation occurs early in the summer, when blooms are absent allowing full access to the reservoir and recreational activities.

Response of residents and nonresidents to potential remediation strategies

Overall, respondents were in favor of a constructed wetland as a potential remediation strategy, indicating the construction of a wetland would either positively impact their use and enjoyment of WCR or have no impact at all. No respondents indicated it would negatively impact their use. The majority of residents and non-residents indicated they would use the wetland for wildlife viewing and for walking or exercise. A known way to enhance wildlife viewing and exercise opportunities in wetland designs is the use of boardwalks and signage (Trapp et al. 1994, Brochu and Merriman 2003). Almost half of the residents and a third of the non-residents who indicated they would not use the wetland, indicated they would use a boardwalk, and that educational or informational signs would add to their enjoyment of WCR. This suggests the percentage of respondents who would not use the wetland would likely decrease if a boardwalk and educational or informational signs were installed. Thus if a wetland is seriously considered, the managing agency would be well advised to incorporate a boardwalk during the very initial design phase.

Boardwalks are a design tool that allows access to wetlands for a wide variety of citizens, including those with disabilities, provide a stage for science education, and help facilitate wildlife viewing. Boardwalks can provide sitting or observation platforms where nature can be viewed comfortably while keeping visitors out of the water and mud (Trapp et al. 1994). These boardwalks can provide visitors the opportunity to study the wetland and its dynamic functions (Brochu and Merriman 2003). Wetlands with boardwalks have been known to attract a wider audience then wetlands without a boardwalk and enhance the visitor's experience which encourages return visits (Brochu and Merriman 2003). A boardwalk could be used in conjunction with educational and informational signs to highlight main wetland functions and increase wildlife viewing.

Educational and informational signs could serve many purposes throughout the constructed wetland. For instance, they could be used to promote education and stewardship. With the access provided by a boardwalk, signage could be used to guide a visitor through the interconnected ecosystem. Wetlands highlight many important ecological processes such as water filtration, and plant growth and decay (Kadlec and Wallace 2009), important information which can be transmitted by signs. The signs could also be used to heighten awareness of the dangers of cyanobacteria and the ways the wetland contributes to minimize the annual toxic algae bloom in WCR.

Based on the public's opinion of the installation of a boardwalk and educational/informational signs and the known benefits of both in wetlands to the general public, it is important that they be included in any design of a constructed wetland for WCR. The ultimate goal of a constructed boardwalk and educational or informational signs would be to optimize a visitor's experience by allowing access to the wetland and transmit information about the wetland function that would otherwise remain unavailable. Due to the nature of boardwalks and signage, they also provide a solid foundation for environmental education, linking visitors with vegetation, hydrology, wildlife and the habitat.

It was surprising that the majority of teachers indicated they would not bring their students to the constructed wetland, because as indicated above, incorporating wetland education into the curriculum has become popular across the U.S. It is also well-known that field trips in curricula provide experiential educational opportunities outside of the classroom which effectively engage different learning styles (Hofstein and Rosenfeld 1996, Scarce 1997). Thus it was surprising that local teachers would not avail themselves of such an opportunity. Perhaps the teachers may feel they do not have the appropriate training to teach in an outdoor setting, an issue which has been documented for science field trips (Orion 1994, Tal 2001). If this is the case, perhaps teachers could avail themselves of readily available units/programs dealing with educational opportunities in wetlands e.g., POW! The Planning of Wetlands (Ripple and Garbisch 2000), *WOW! The Wonders of Wetlands* (Slattery 1991) and *Project WILD Aquatic Education Activity Guide* (Mycio-Mommers and Canadian Wildlife Federation 1990). These programs generate knowledge through experimentation and exploration by allowing hands-on learning (Kent 2000) and can easily be incorporated into existing lesson plans. Teachers may be concerned that their students will be over-stimulated in the outdoor setting and it will be hard to keep them focused. However, such concerns have been addressed with specific lesson plans. For example, 'Looking Tubes' (Preston et al. 2005) uses PVC pipes to restrict the stimuli of students during observations which gives teachers the opportunity to guide learning towards a specific goal and keep students focused. Teachers may be reluctant to take students to the wetland because of budgetary concerns, which has been the cause of fewer field trips and extracurricular activities nation-wide. If teachers are able to find funding to bring their students to the wetland, both the boardwalk and educational/ information signs would promote a safe and informative location for lesson plans, exploration, and learning.

All respondents who identified themselves as landowners were aware of the water quality issue in WCR and the construction of a wetland would not interfere with their livelihood. This awareness was not surprising because WCR is located between their properties and the town of Heppner, meaning they are continuously exposed to the changing nature of the WCR during commutes. The majority of the landowners indicated the construction of a wetland would positively affect their use of WCR. Only one landowner indicated they would not use the wetland, while the majority of them said they would use it for wildlife viewing. All of the landowners indicated they would use a boardwalk if it was installed and the majority of them indicated educational or informational signs would add to their enjoyment of WCR. This implies, if a boardwalk were installed, the landowner who indicated they would not use the wetland would actually use it. Thus the incorporation of specific design features could be used to influence the audience reached and increase interactions in ways that would not be possible in the absence of such features. This again highlights the importance of understanding public opinions before launching into design and management decisions.

Overall, the majority of residents and non-residents were aware of the toxic algae bloom and were in favor of a constructed wetland as a potential remediation strategy. From those that indicated they would not use the constructed wetland, their use could be expect to increase if a boardwalk and education/information signs were installed. The boardwalk would allow users the opportunity to view wildlife up closely and provide a space for walking/exercise, both of which the majority of respondents indicated would be their primary use of the wetland. The educational/informational signs could help increase awareness of the annual bloom, highlight the important wetland functions that are working to reduce unwanted contaminates such as P and emphasize public health benefits.

Public participation and the opinions of the individuals such as the information gathered in this social survey are often used to inform decision making in natural resource management. Including the public in management decisions broadens knowledge which can assist in decision making (Parkins and Mitchell 2005). In addition, this inclusionary participation cultivates a trusting relationship between the public and managers (Smith and McDono 2001). It is understood that when the public's opinion are included in outcomes they tend to be more satisfied with the management decisions (Smith and McDono 2001, Parkins and Mitchell 2005) which leads to continued support (Smith and McDono 2001). This survey response demonstrates how evaluating user's opinions and values can inform lake and reservoir managers how to increase wetland use and functionality.

From this survey it is now known that the public is in favor of a constructed wetland and their enjoyment and use of it would increase with the installation of a boardwalk and educational/informational signs. Therefore, it is in the management agency's best interest to include both a boardwalk and signage in the wetland design. Because the majority of respondents had mutually positive opinions towards a boardwalk and the educational/informational signs, including both of these features should not create any conflicts among users. If these wants and needs were not included in the wetland design, conflict may occur between users and management because the users may feel misrepresented or uninvolved (West 1989). The process of using social surveys to obtain users wants and needs can be easily conducted in similar watersheds where cyanobacteria blooms are interfering with the public's use and enjoyment of a water body and the implementation of remediation strategies are necessary to ensure the public's health and safety.

Conclusion

The water quality in WCR is of concern for residents and non-residents and the public feels that it needs to be addressed. Like many other lakes around the world, WCR's annual toxic algae bloom puts recreational users at potential risk, which likely negatively affects annual visitation. A remediation strategy that incorporates management needs and features desired by users is necessary to address the negative impacts of the cyanobacteria blooms. If the water quality in WCR improves, it is not unrealistic to expect an increase in overall public satisfaction, protection of health, and increased use of the reservoir. Based on the survey responses, both residents and non-residents are supportive of a constructed wetland if implemented as a potential remediation strategy for WCR.

A constructed wetland would have an overall positive impact on residents and non-residents, giving them the opportunity to watch wildlife and to walk or exercise via a boardwalk. Respondents indicated that educational or informational signs would add to their enjoyment of WCR. The boardwalk and signage would provide the opportunity to highlight how wetland functions work to increase water quality and the effect that has on the annual bloom of cyanobacteria. The boardwalk and signage could also provide a solid foundation for environmental education, linking visitors with vegetation, hydrology, wildlife and their habitats. If the U.S. Army Corps of Engineers decides that a constructed wetland is an effective remediation strategy to pursue, it would be important to include a boardwalk and educational signs. By incorporating the information gathered in this survey into management decisions, discrepancies between management and user objectives can be minimized and resource health and use can be maximized.

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Table 3.1: The number of non-residents, zip code, zip code hometown and distance to Heppner, OR, or Willow Creek Reservoir. Three respondents did not provide a home zip code.

Number of non-residents	Zip code	Hometown	Distance (km) from Heppner,OR to zip code hometown (miles in bracket)
11	97836	Lexington, OR	14 (9)
4	97843	Ione, OR	29 (18)
3	97880	Ukiah, OR	76 (47)
4	97838	Hermiston, OR	76 (47)
1	97875	Stanfield, OR	80 (50)
2	97844	Irrigon, OR	98 (61)
2	97818	Boardman, OR	98 (61)
1	97801	Tutuilla, OR	126 (78)
2	97058	The Dalles, OR	175 (109)
2	97213/927210	Portland, OR	309 (192)
2	98683	Vancouver, WA	315 (196)
1	97842	Imnaha, OR	354 (220)
1	97381	Silverton, OR	365 (227)
2	98611	Castle Rock, WA	388 (241)
1	98569	Ocean Shores, WA	565 (351)

Table 3.2: The degree to which the annual toxic algae bloom interferes with resident's use of Willow Creek Reservoir (WCR), separated by annual WCR visitation. Each row adds up to 100%, being the total number of respondents for each level of interference.

Interference	Resident's annual WCR visitation (%)			
	0-1	2-5	6-10	>10
Didn't Answer (n=0)	0	0	0	0
Doesn't Interfere (n=27)	50	31	0	19
Seldom Interferes (n=13)	25	38	13	25
Occasionally Interferes (n=22)	23	38	8	31
Frequently Interferes (n=27)	25	38	19	19
Always Interferes (n=12)	0	29	43	29

Table 3.3: Degree to which the annual toxic algae bloom interferes with non-resident's use of Willow Creek Reservoir (WCR), separated by annual WCR visitation. Each row adds up to 100%, being the total number of respondents for each level of interference.

Interference	Non-resident's annual WCR visitation (%)			
	0-1	2-5	6-10	>10
Didn't Answer (n=2)	100	0	0	0
Doesn't Interfere (n=55)	57	35	4	4
Seldom Interferes (n=12)	40	60	0	0
Occasionally Interferes (n=14)	33	67	0	0
Frequently Interferes (n=5)	0	100	0	0
Always Interferes (n=12)	80	0	0	20

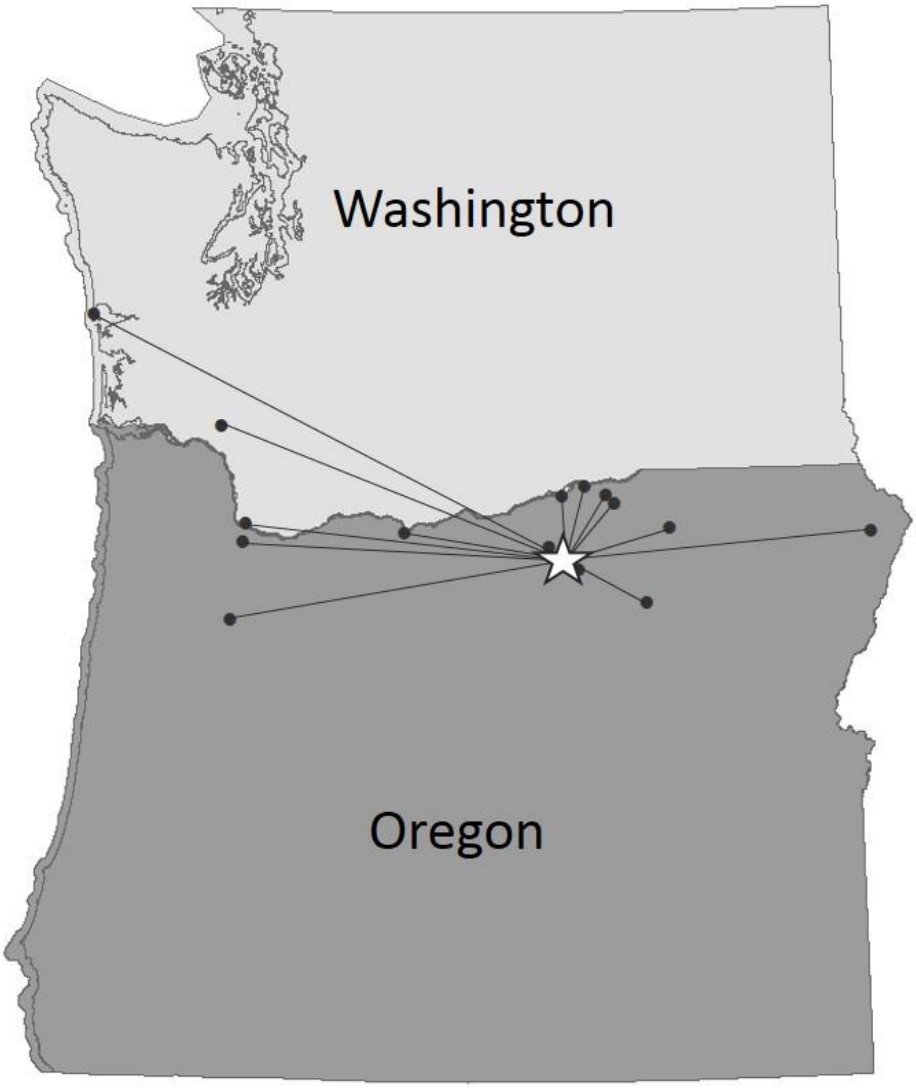

Figure 3.1: Visual representation of the distance travelled by non-residents to arrive at Heppner, OR or Willow Creek Reservoir. The shortest and longest distances traveled being 14.5 km (9 miles) and 565 km (351 miles) respectively.

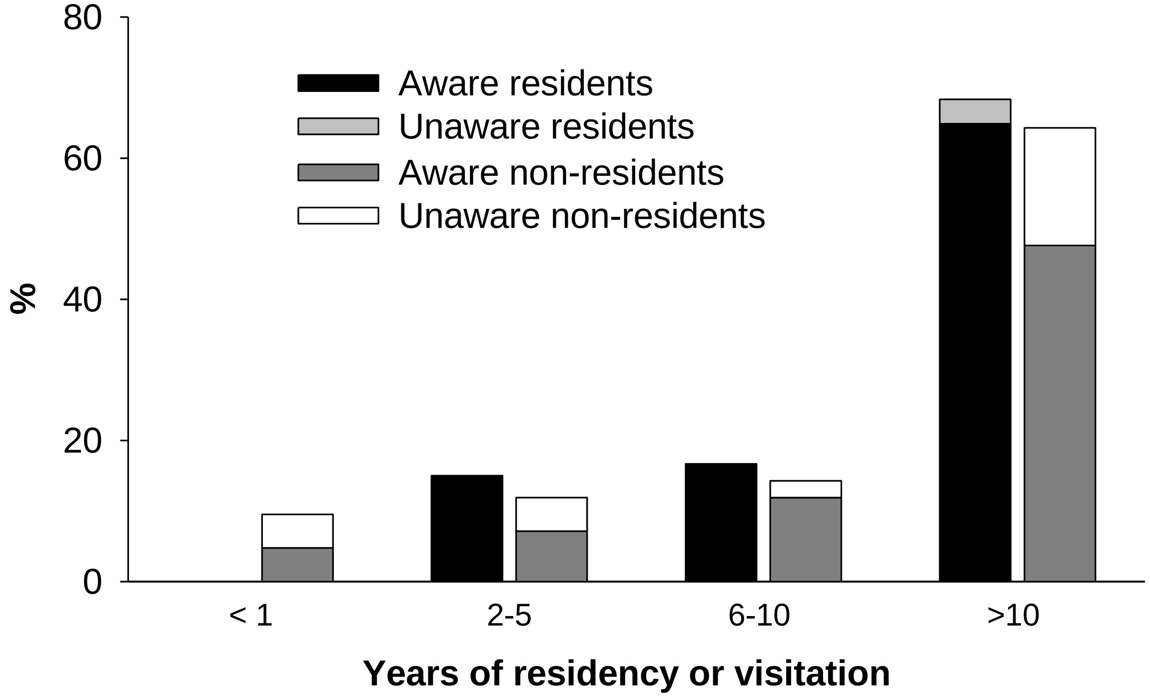

Figure 3.2: Percent of aware and unaware residents (n=60) and non-residents (n=42) of the annual toxic algae bloom categorized by their years of residency or visitation to Heppner, OR or WCR.

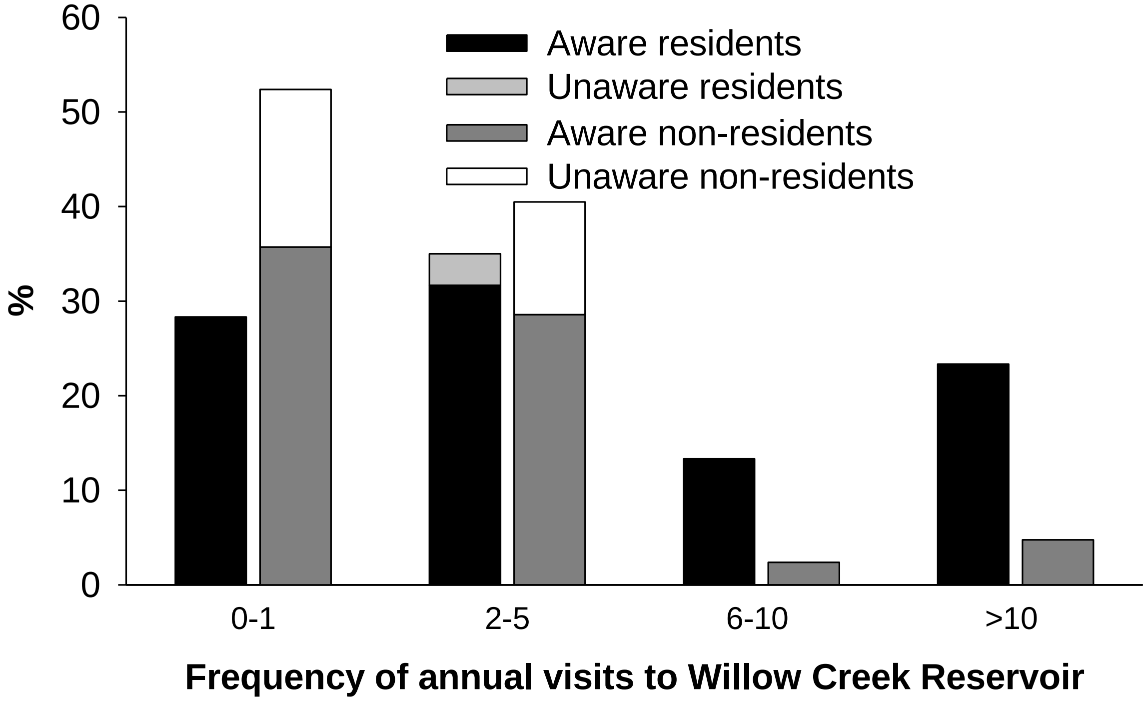

Figure 3.3: Percent of aware and unaware residents (n=60) and non-residents (n=42) of the annual toxic algae bloom categorized by the frequency of annual visits to Willow Creek Reservoir.

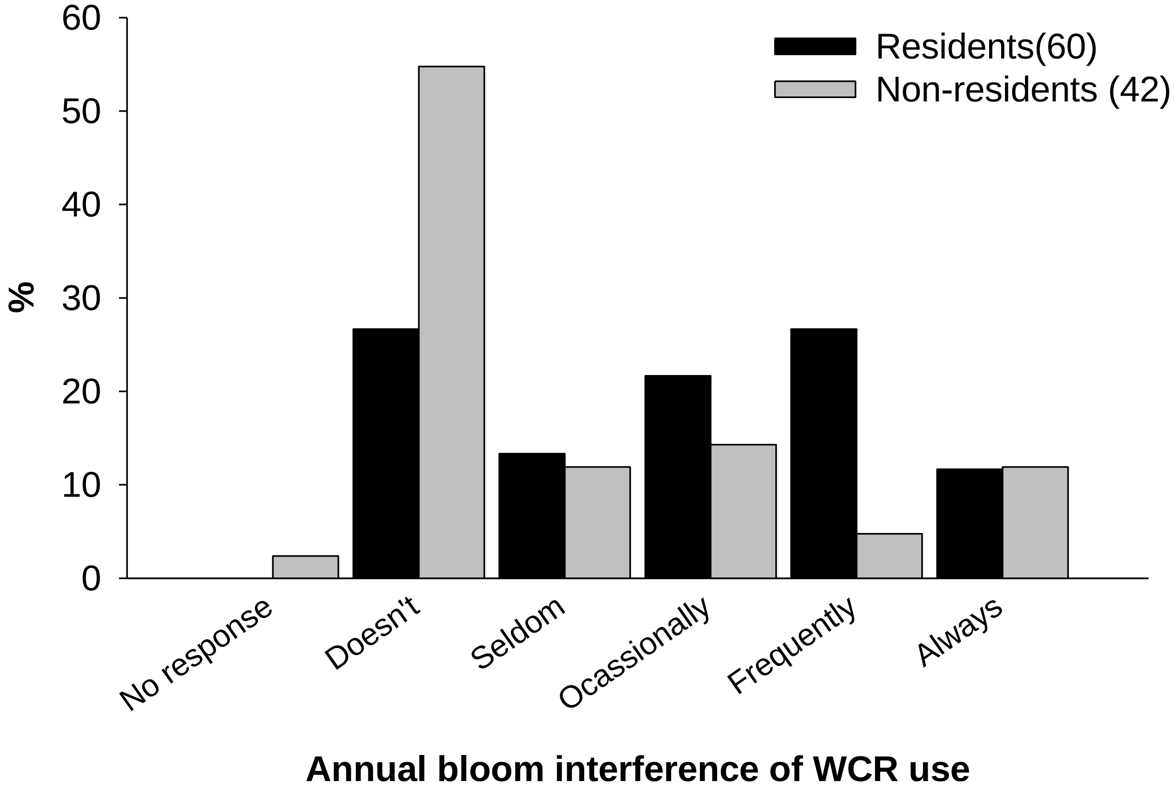

Figure 3.4: Degree to which to annual toxic algae bloom interferes with resident's and non-resident's use of Willow Creek Reservoir (WCR).

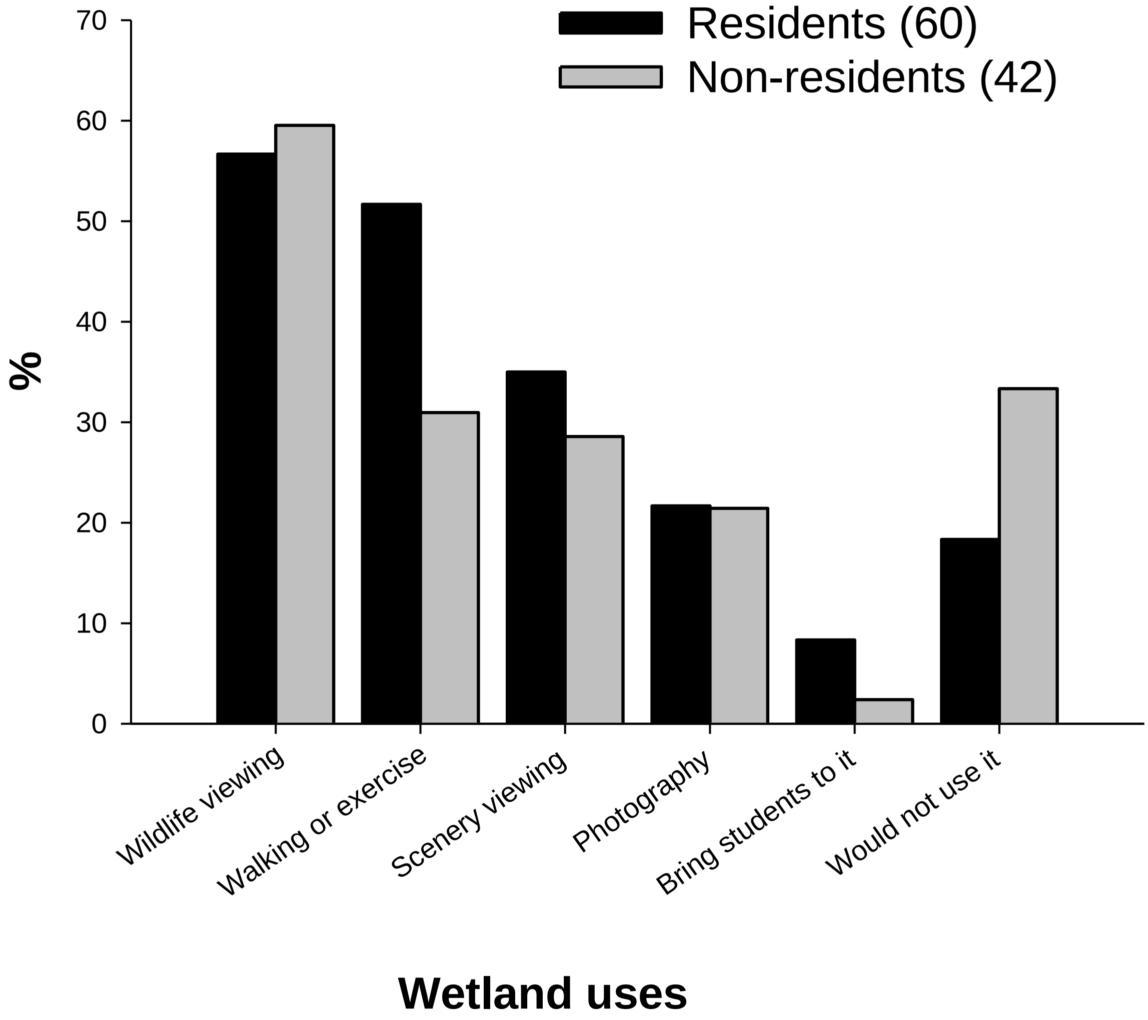

Figure 3.5: Survey response to “If a wetland was constructed at the inlet of the reservoir how would you use it?” grouped by residential status and plotted as percent of total group responses. Total percentages surpass 100 % because respondents were able to check all uses that applied.

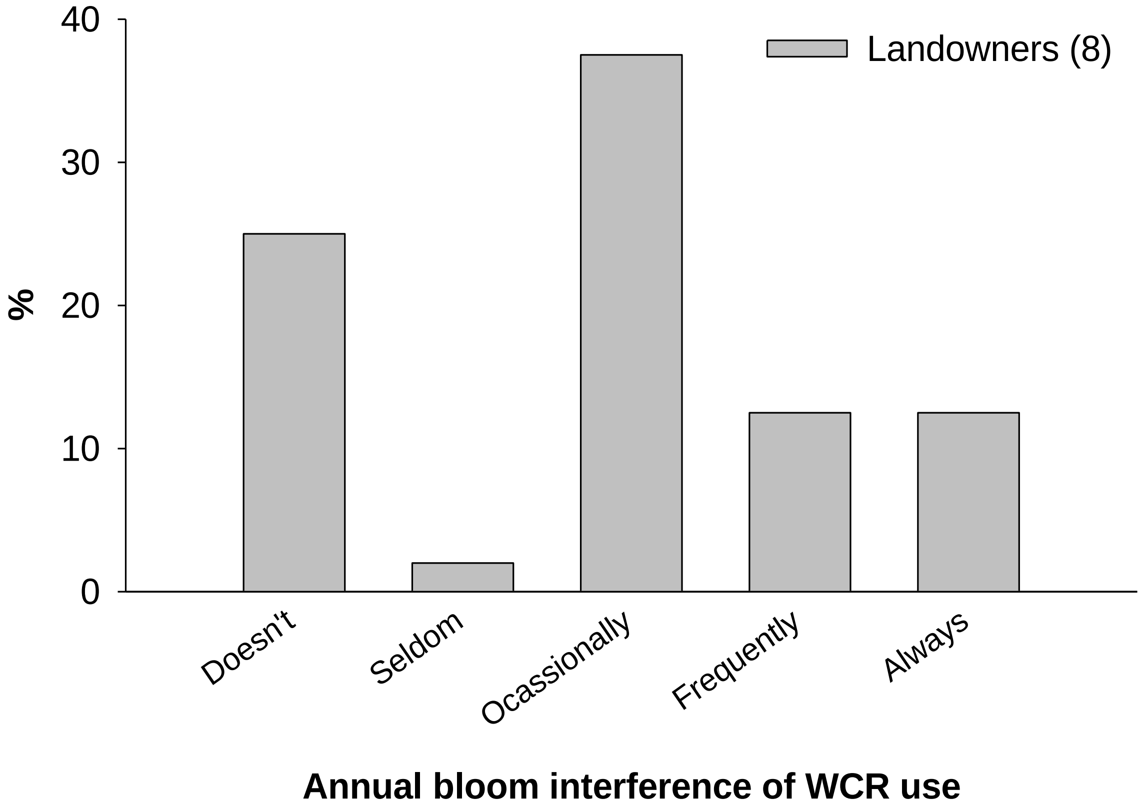

Figure 3.6: Degree to which to annual toxic algae bloom interferes with landowner's use of Willow Creek Reservoir (WCR).

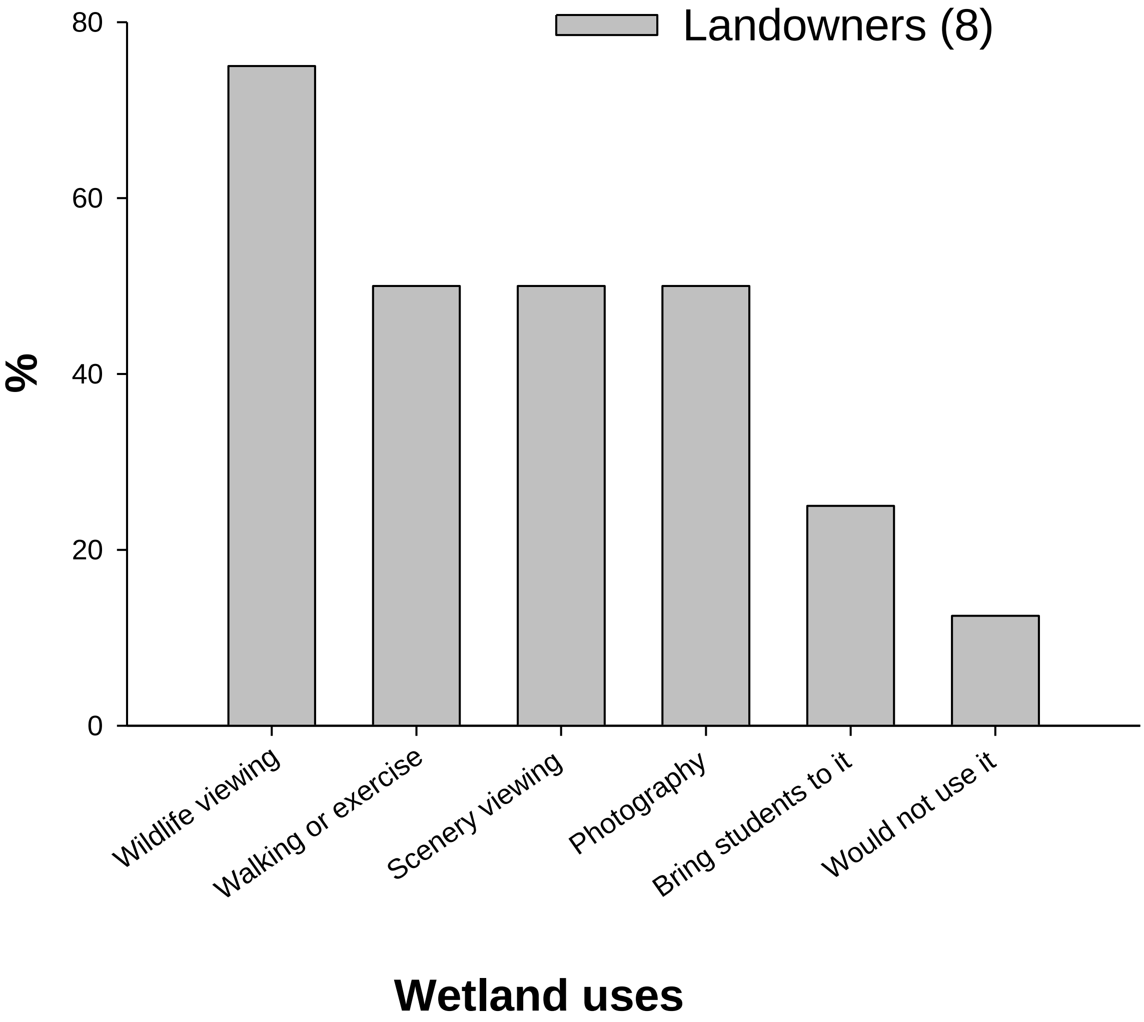

Figure 3.7: Landowners response to the survey question, "If a wetland was constructed at the inlet of the reservoir, how would you use it?" Total percentages surpass 100 % because respondents were able to check all that applied.

Chapter 4: A conceptual constructed wetland design for the inlet of Willow Creek Reservoir to evaluate efficiency for removal of sediment and phosphorus

Abstract

Land use changes from anthropogenic activities have rapidly degraded water quality due to the input of polluting substances including excess nutrients that fuel harmful algae blooms. Willow Creek Reservoir in Oregon, U.S.A. experiences annual toxic blooms of cyanobacteria, due to the influx of high nutrients, especially phosphorus (P). Free water surface (FWS) constructed wetlands have been used successfully to improve the water quality of receiving waters. Using a conceptual design, I evaluated the effectiveness of total P (TP) and total residue (TR) retention in a system including two FWS wetlands, each with a sedimentation basin and five wetland cells, constrained by available land area. A tank-in-series model was used to estimate area-based first-order P-removal in the sedimentation basin and wetland cells for which monthly P-removal constants were obtained from the literature, while 60% removal of annual TR load was assumed in the sedimentation basin. Effluent sediment concentrations from the settling basins were calculated with an input-output regression from the literature. To maximize removal efficiencies, discharge into the FWS system was adjusted to maintain a minimum hydraulic residence time of 5 days. Wetland efficiency was evaluated for TP and TR loads measured in the 2010 and 2013 water years. Concentration removal efficiencies for P averaged 32 % in the entire system. Concentration removal efficiencies for TR was held constant at 60% in the sedimentation but averaged 70.1 % in the wetland cells. Areal mass removal for P averaged 0.1 g-TP/m^2/yr, while for TR it averaged 3,354 and 434 g-TR/m^2/yr, in the sedimentation basins and wetland cells, respectively, totaling 3,788 g-TR/m^2/yr. Total P and TR removal followed a seasonal pattern, generally increasing in the summer months (June-September), and was greater in 2013 when annual discharge was lower compared to 2010. The overall mass of

TP and TR removed from Willow Creek averaged 5.8 and 23.1%, respectively. Values were lower than annual efficiencies because during months with high flows the majority of the discharge containing high loads of TP and TR would be shunted past the wetland system. Average cost of the conceptual wetland using a linear relationship between size and estimates of costs/ha from the literature was approximately $1,145,000. Because the space constraints dictated by existing infrastructure limit the size of the conceptual wetland that is not sufficiently large to treat the high volume of spring runoff, a FWS wetland is not recommended as a remediation strategy for the influx of nutrients into WCR.

Introduction

Access to clean water is vital for life as we know it. Worldwide, the water quality in streams has declined as a result of changes in land use in their watersheds (Carpenter et al. 1998; Pitois et al. 2001; Jordan et al. 2003; Allan 2004). These land use changes increase the input of polluting substances, including nutrients, sediment, and toxins (Jeppesen et al. 2009; Shrestha et al. 2012), or alter thermal regimes (Benson et al. 2012). This influx of nutrients to water bodies is termed cultural eutrophication (Pitois et al. 2001; Carpenter 2005) and is a major factor contributing to the accelerated degradation of aquatic ecosystems worldwide (Carpenter 2005; Camargo and Alonso 2006).

Nitrogen (N) and phosphorus (P) are typically the limiting nutrients in freshwaters (Tilman 1982; Smith 1983; Pick and Lean 1987; Carpenter et al. 1998; Woltemade 2000; Pitois et al. 2001; Anderson et al. 2002; Carpenter 2008; Schindler 2008; Paerl et al. 2011), and their ratio is a strong determinant of the composition of the algal community (Tilman 1982; Smith 1983; Pick and Lean 1987; Carpenter 2008; Schindler 2008; Paerl et al. 2011). For example, a ratio of total nitrogen (TN) to total P (TP) of 7:1 is considered balanced (Redfield 1958; Schindler 2008), while a ratio of <7 is considered N-limited, and a ratio of

>7 is considered P-limited. P-limitation generally limits plant growth and is a desirable state for aquatic ecosystems (Smith 1983; Pick and Lean 1987; Carpenter 2008; Schindler 2008; Paerl et al. 2011). Research has shown that generally cyanobacteria (formerly known as blue-green algae) dominate the phytoplankton community at low N:P ratios (Carpenter 2008, Tilman et al. 1982, Orihel et al. 2011, Harris et al. 2014, Pick and Lean 1987). This is of particular concern because cyanobacteria can present a host of problems in waterbodies.

The frequency of occurrence of cyanobacteria blooms in water bodies world-wide is increasing (Chorus and Bartram 1999; Sharpley et al. 2000; Graham et al. 2009; Paerl et al. 2011). Such blooms are of concern because they cause taste and odor issues in drinking water (Pick and Lean 1987; Carpenter et al. 1998; Bartram and Chorus 1999; Sharpley et al. 2000; Pitois et al. 2001; Wu et al. 2006), decrease aesthetics due to the presence of surface scums and odors (Bartram and Chorus 1999), decrease water column dissolved oxygen when they decompose (Pick and Lean 1987; Bartram and Chorus 1999; Carpenter 2008; Schindler 2008), and most importantly, they produce a suite of the most potent toxins known to humans (Pick and Lean 1987; Bartram and Chorus 1999; Sharpley et al. 2000; Pitois et al. 2001). These toxins have killed pets, wildlife, livestock (Sharpley et al. 2000; Briand 2003; Graham, Jacoby, and Amand 2009; Graham, Loftin and Kamman 2009), and humans (Chorus and Bartram 1999). Because P is of main concern when dealing with cyanobacteria blooms, reducing or eliminating P from aquatic ecosystems is crucial to prevent or mitigate harmful algal blooms.

For a long time, nonpoint source pollution has been identified as an important source of nutrients contributing to water degradation worldwide (Carpenter et al. 1998). Best management practices (BMPs) to reduce nonpoint source pollution and increase water quality are commonly implemented in watersheds (Allan 2004).

Wetlands play an important role in the cycling and control of elements, particularly nutrients in aquatic ecosystems (Mitsch and Gosselink 2007) and have been used to reduce the occurrence of cyanobacteria blooms (Wu et al. 2010; Zhong et al. 2011). For example, wetlands reduce water contaminant concentrations including N, P, suspended solids, trace metals, trace organics, pathogens and pesticides (Carpenter et al. 1998; Woltemade 2000; Jordan et al. 2003; Díaz et al. 2012). Constructed wetlands aim to exploit the role of natural wetlands to improve water quality, but do so in a controlled engineered environment (Spenser 1993). Significant and successful constructed wetlands include the 500 ha Lakeland and Orlando wetlands in Florida that were constructed to treat municipal wastewater (Kadlec and Wallace 2009). Other examples include six treatment wetlands built in southern Florida, totaling over 16,000 ha, which also treat municipal wastewater (Kadlec and Wallace 2009). These constructed wetlands have been successful at reducing effluent concentrations by replacing some of the functions of a natural wetland.

Hydraulic functions in wetlands affect the chemical and physical processes that govern the dynamics of suspended solids and nutrients (Mitsch and Gosselink 2007). For example, hydraulic loading and residence time interact to determine removal effectiveness. The hydraulic loading rate (HLR), defined as the average depth of water passed through the wetland. The hydraulic residence time (HRT) is defined as the length of time is takes for water to travel through a wetland, and affects a wetland's ability to reduce contaminant concentrations. In constructed wetlands, this is generally used as a primary design criterion because it is directly related to the effectiveness (Kadlec and Wallace 2009). The HRT is proportional to the size of the wetland, generally the larger the wetland, the longer the retention time (Kadlec and Wallace 2009). Wetland HRT can be temporarily overwhelmed during high flow events such as cloud burst storms or spring runoff from snowmelt (Jordan et al. 2003). A HRT of 5 to 14 days is generally suggested to optimize treatment efficiency in constructed wetlands (Mitsch and Gosselink 2007). In generally, P removal is maximized when flow (loading rate) is minimized and wetland area and HRT are maximized (Jordan et al. 2003; Fink and Mitsch 2004; Mitsch and Gosselink 2007).

The amount of P retained in a wetland is site-specific and varies with the design and function of the constructed wetland. Sorption and plant uptake are common short-term removal mechanisms that can be saturated (Kadlec and Wallace 2009). The long-term sustainable removal mechanism is soil accretion due to plant uptake and subsequent burial of plant biomass (Kadlec and Wallace 2009). Other removal mechanisms include filtration, oxidation, reduction, chemical precipitation, and microbial interactions. However, these are not as effective or dominant as burial (Woltemade 2000; Kadlec and Wallace 2009).

Retention rate, the capacity of a wetland to remove P (g-P/m^2/yr), is a commonly used measure to determine its efficiency (Mitsch and Gosselink 2007; Kadlec and Wallace 2009). Wetlands in cold or seasonal environments that receive nonpoint source pollution can have a retention rate of 0.1 to 6 g-P/m^2/yr (Table 4.1) (Mitsch and Gosselink 2007). For example, a 1.2 ha constructed wetland in the Ohio River Basin, OH, USA reduced the nutrient (P) load by 41% from a 17 ha agricultural watershed, retaining 6.2 g-P/m^2/yr over a two year study period (Fink and Mitsch 2004). The amount of P that is retained in a wetland throughout the year varies depending on the hydraulic function, water and surface soil temperatures, and season (Mitsch and Gosselink 2007) and have been reported as both sources and sinks of P (Raisin et al. 1997).

Wetlands in cold climates generally experience two peaks of P uptake, one in the spring and one in the fall. Retention is typically higher during annual growth periods in spring, when P is required for plant and algal growth (Kadlec and Wallace 2009). The peak in the fall occurs when plants begin to store P in their roots, which is used for growth in the spring. During the summer months, under maximum temperatures, microbial and plant uptake are at their highest, but decomposition processes, which release P, negatively affect total retention. The biotic cycle, including growth, death and decomposition of biomass, will release most of the assimilated P back into the surface water but 10-20% of that P is buried in the sediment and soils (Kadlec 2005). Microbial processes add to a seasonal variation in retention, with maximum retention occurring during periods of plant growth, while release occurs during periods of plant decomposition (Spenser 1993). This seasonal retention rate is an important factor for the design of a wetland and for selection of the type and amount of vegetation to plant in the wetland.

Constructed wetlands tend to have high initial P retention which decreases as the soil becomes saturated with P (Moshiri 1993). Once soils are saturated with P, wetlands can still retain P, but at a much lower rate (Kadlec and Wallace 2009; Ardón et al. 2010). This retention is driven by chemical precipitation, accretion and particulate settling, and uptake by new plant growth (Kadlec and Wallace 2009). In some cases, constructed wetlands established over lands previously used for agriculture may be a net source of P as soils desorp and come into equilibrium with P in incoming water (Pant et al. 2002; Ardón et al. 2010; Steinman and Ogdahl 2011). This means that careful attention must be given to the parent soils on which wetlands are constructed and the quantity of material retained will determine the life-span of constructed wetlands. These are important considerations for long-range planning purposes.

In addition to the improving water quality, wetlands provide wildlife habitat which supports high biodiversity, landscape diversity, decreased flooding and erosion, and educational opportunities (Spenser 1993; Jordan et al. 2003; Zedler 2003; Richardson et al. 2011; Díaz et al. 2012). Of these, the latter has increased in significance as the value of wetlands to society has been recognized. Given the estimated loss of 53% of original wetlands across the United States (Dahl 1990) coupled with our increasing understanding of their benefit, hydraulic engineers and land-use planners are incorporating constructed wetlands to manage aquatic resources and restore ecosystem function (EPA 1993).

A common design used to maximize P removal in an area receiving nonpoint source loading is a Free Water Surface (FWS) wetland with a series of cells (Higgins et al. 1993; Moshiri 1993; Brackney 1994; Kadlec and Wallace 2009). A large wetland area is needed for P removal because it is one of the least efficient removal processes, especially for areas receiving high loads (Kadlec and Wallace 2009). When space is limited, a common practice is to reduce the P concentrations before they enter the wetland. Sedimentation basins or ponds are used to remove sediments and P (Brown et al. 1981; Higgins et al. 1993; Kadlec and Wallace 2009). With the high loads of both sediment and P in Willow Creek, a FWS and sedimentation basin would be an ideal design to maximize nutrient removal. The objective of this chapter was to evaluate the capacity of a conceptualized FWS wetland to improve water quality in Willow Creek before it enters the reservoir. The costs of the conceptualized wetland model were also evaluated.

Materials and Methods

Study Site

Willow Creek Dam and Reservoir (WCR) (Figure 4.1) was constructed by the U.S. Army Corps of Engineers (USACE) immediately south of the town of Heppner, OR in 1983 for flood protection, recreation, and more recently irrigation for agriculture (USACE 2005). Typical of dams worldwide (Petts 1984; Naiman 1993; Maingi and Marsh 2002; Pearce 2007), WCR has altered the flow pattern and greatly decreased the energy regime of Willow and Balm Fork creeks, its two tributaries. Since the completion and the filing of the dam, WCR has had a variety of issues, including low dissolved oxygen, increased production of hydrogen sulfide, ammonia, methane and the occurrence of harmful algae blooms (USACE 2007). Of these, the latter is a major concern because it results in advisory warnings from the Oregon Department of Health which restricts human contact with the water in the reservoir and thus decreases its potential for recreational activities. This is an important facet of WCR because it is the only significant 'lake' in a 100 km (60 mile) radius and because providing safe and high quality water is a primary objective of the USACE.

Balm Fork Creek is intermittent and contributes 10% of the annual inflow, while Willow Creek is perennial and contributes 90% of the annual inflow (DeBano and Wooster 2004). Adams (2012) reported that 6,872 metric tons (98%) of sediment and 3,304 kg (95.5%) of TP entered WCR via Willow Creek during 2009-2010 (denoted as the 2010 water year). In contrast, Balm Fork Creek only contributed 130 kg (4.5%) of TP and 145 metric tons (2%) of sediment to WCR (Adams 2012). Given this disparity in contributions from the Willow Creek sub-catchments, it should be the main focus of remediation efforts.

Willow Creek at 127 km (79 miles) long originates in the Blue Mountains of OR and is a tributary of the Columbia River. Discharge in Willow Creek ranges widely from 0.09 m^3/sec (3.2 CFS) in late September to over 2.6 m^3/s (93 CFS) in spring (records from the U.S. Geological Survey (USGS) gauging station at the inflow to WCR -USGS gauge station # 14034470). During periods of high runoff, tributaries from sub-catchments in the Willow Creek watershed contribute significant loads of sediment and nutrients, including P, to the reservoir from the upper watershed (Chapter 2). Willow Creek is listed under Section 303(d) of the US Clean Water Act for water temperature from the mouth of Willow Creek to its forested headwaters, and pH in the outflow downstream of the reservoir (ODEQ 2007).

The Willow Creek basin is characterized as semiarid because of the lack of precipitation between July and October (USACE 2007). Typically, air temperature in the watershed ranges from -29.4 to 43.3 C°, with an annual mean of 10 C° (USACE 2007), while precipitation ranges from 203.2to 863.6 mm (USACE 2007). Summer days are warm, while nights are cool. In winter, diurnal temperature ranges are moderate and predominantly cold. Most of the annual precipitation occurs as rain or snow at high (approximately > 900 m above sea level - a.s.l.) elevations, and rain at low (approximately < 900 m a.s.l.) elevations between October and June (DeBano and Wooster 2004). The dominant soils in the watershed are silt, sandy silt and angular rock fragments above basalt (USACE 2007). The dominant land cover in the upper Willow Creek sub-catchments is forest and includes a portion of the Umatilla National Forest. Grasslands dominate the lower portion of the Willow Creek watershed above the reservoir. Some overwintering of cattle occurs in the valley bottom floodplains immediately adjacent to Willow Creek.

A public survey was used to determine the opinions of residents and non-residents of Heppner, OR and WCR towards the potential use of a constructed wetland to remediate the harmful cyanobacteria blooms in the reservoir (Chapter 3). Based on the positive results of the survey, this evaluation of a conceptual FWS wetland was deemed a worthwhile effort.

Estimates of wetland area, TP and TR concentrations and loads, and discharge

The area for the constructed wetland was estimated with land survey data from the USACE. The total space available for the wetland is approximately 140,000 m^2, located in a basin confined by roads, the reservoir, and the valley sides. The available area is further constrained by local topography in the proposed basin. Wetland efficiencies were evaluated for the 2010 and 2013 water years. Daily TP and TR concentrations and load values for the

2010 water year were obtained from Adams (2012) and averaged to obtain monthly values. Data for the 2013 water year (Sep 2012-Sep 2013) were taken from Chapter 2. Daily discharge data were obtained from the USGS online Real-time Stream-flow for Willow Creek (USGS gauge station # 14034470) and averaged to obtain monthly estimates.

Estimates of long-term P removal in the conceptual wetland cells based on the P-k-C * model

A tank-in-series model (P-k-C*) (Kadlec and Wallace 2009, Appendix M), where *P* is the number of tanks in series modeled as continuously stirred tank reactors; k is the P-removal coefficient (m/day); and C* is the background P-concentration (mg/L), was used to estimate area-based first-order P-removal in the wetland cells. In a tank-in-series model, a wetland is partitioned into a series of pieces, each of which is assumed to be completely mixed (Kadlec and Wallace 2009). A *P*-value of 1 represents a reactor that is completely mixed. An infinite *P*-value represents a plug-flow reactor, in which chemical reactions within a wetland are continuous and dynamic. Commonly, a *P*-value of 6 is used when estimating nutrient retention in FWS wetlands with >3 cells (Beutel2013, Beutel et al. 2014) and was therefore used in the conceptual model based on the layout described below.

Treatment wetlands typically contain multiple cells to cut down on water short circuiting through the wetland and to promote sediment removal in initial cells to protect downstream wetland cells from filling with sediment. If the composition of P within Willow Creek was primarily particulate, high P-retention could be expected in the sedimentation basin in association with sediment deposition. On average, the majority (72%) of P in Willow Creek is in the dissolved phase (Chapter 2). Because the majority of P will enter the wetland system in the dissolved phase, high P-removal in the sedimentation basin was not expected and P-removal in the sedimentation basin was modeled as a wetland cell. So the wetland systems in the proposed design contained 5 wetland cells in series and a sedimentation basin (Figure 4.2).

This tank-in-series model incorporates background concentrations of P in wetlands which are present due to P resistance to storage, hydraulic bypass, its association with particulate P, and additional P input near the outlet of the wetland (Kadlec and Wallace 2009). Commonly, a background P-concentration (C*) of 0.002 mg/L is the default value used to model FWS wetlands (Kadlec and Wallace 2009). Because the background concentration of the proposed wetland is unknown, 0.022 mg/L was used. To account for seasonal fluctuations in P uptake in a wetland, monthly P-removal rate constants (*k)* for the system were used (Table 4.2) (Kadlec and Wallace 2009). The P-efficiency values presented represent retention in the entire wetland system.

To ensure that constituent removal is maximized in the conceptual wetland, the amount of water entering the wetland system should be held constant. Because hydraulic residence time (HRT) is generally used as a primary design criterion for constructed wetlands (Kadlec and Wallace 2009), it was used to determine monthly discharge values into the wetland system. Discharge values into the wetland system, for the 2010 water year, were adjusted to model a HRT of 5, 6, 7, 8, 9, and 10 days in the tanks-in-series model (Appendix N). The annual mass removal was maximized when the HRT was held constant at 5 days, therefore a HRT of 5 days was used in the conceptual model and discharge into the system was adjusted to maintain this design criterion. The HLR (*q)* was estimated by dividing the inflow discharge by surface area.

Removal efficiencies were quantified based on three common approaches presented by Kadlec and Wallace (2009): concentration removal (%), areal removal rate (g-P/m^2/yr), and mass removal rate (%) (Appendix O). The annual mass removal was calculated as the total mass of P removed by the wetland divided by the total annual mass of P in Willow Creek. Uncertainty in the model, represented as high and low monthly and annual mass removal, was determined by propagating 95% confidence interval values of monthly TP concentrations and discharge (Appendix P). To estimate the amount of area needed to remove 50% of TP and maximum TP removal, the total wetland area was increased while adjusting discharge values to maintain the design criteria of a 5 days HRT.

Estimates of sediment retention in the sedimentation basin and wetland cells

Sedimentation basins can remove 60-95% of suspended sediments (Brown et al. 1981; Hammer 1989; Higgins et al. 1993; Moshiri 1993). Due to Willow Creek's hydrologic regime, including high seasonal fluctuations, 95% removal of sediment is not realistic, therefore a conservative value (60% TR removal) was used for the sedimentation basin. Removal efficiencies within the sedimentation basin were quantified as concentration removal (%), areal removal rate (g-TR/m^2/yr), and mass removal rate (%).

Sediments within a wetland settle at various rates, depending on particle size, and many are easily forced into suspension by disturbances (Kadlec and Wallace 2009). Due to this internal cycling, it is hard to determine a background concentration for sediments within a wetland. However, an input-output regression equation can be used to determine effluent sediment concentrations (Kadlec and Wallace 2009). Kadlec and Wallace (2009) reviewed inlet (C_i) and outlet (C_o) sediment concentrations of 136 wetlands to derive the regression equation: $C_o = 1.5 + 0.22\ C_i$ ($R^2 = 0.65$). This equation was applied to sediment concentrations following 60% removal in the sedimentation basin to estimate sediment removal in the wetland cells in lieu of a site-specific equation. Uncertainty in the model, represented as high and low monthly and annual mass removal estimates, was determined by propagating 95% confidence interval values of monthly TR concentrations and discharge

(Appendix P). Removal efficiencies within the sedimentation basin were quantified as concentration removal (%), areal removal rate (g-TR/m^2/yr), and mass removal rate (%). The overall mass removal rate (%) was calculated for the sedimentation basin and the wetland cells.

The annual depth of sediment accumulation in the sedimentation basin was calculated for 1, 5, and 10-year time intervals based on estimated retention during the 2010 and 2013 water years. Because the dominant soils in the watershed are silt and sandy silt (USACE 2007), a sediment density of 2650 kg/m3 (2.65 kg/l) was used (Or et al. 2009). The values calculated represent the dry weight and depth, meaning before sediments are removed from the basin all water should be routed around the system to allow the accumulated sediments to dry out. These calculations will be used to address the management of the sedimentation basin.

Costs of constructed wetlands

Kadlec and Wallace (2009) argue that because wetland construction, operation and maintenance is completed using local labor and materials, it is difficult to estimate universal costs of wetland construction. The main determinant of constructed wetland costs is the proposed area of the system, therefore Kadlec and Wallace (2009) present a relationship of cost as a function of area to estimate the cost of constructed wetlands. They evaluated the area (A, ha) and cost (C, thousands of dollars) of 84 FWS wetlands and developed a linear relationship in the form of $C=194 \times A^{0.690}$ ($R^2= 0.79$) (Kadlec and Wallace 2009). The U.S. EPA (2000) presented high and low cost estimates for FWS wetland systems at $145,050/ ha and $255,012/ha, respectively. The details of what is or is not included in the total cost of wetland construction is often unclear (U.S. EPA 2000; Kadlec and Wallace 2009), therefore the presented relationship may include costs of a sedimentation basin in the wetland system. Using the defined linear regression equation and the high and low estimates presented by the U.S. EPA, the proposed size of the treatment area with and without the sedimentation basin was used to estimate costs.

Results

Estimates of wetland area, TP and TR concentrations and loads, and discharge

To use the natural stream channel in the proposed area, the installation of two banks of wetland cells, one on either side of the channel, is proposed (Figure 4.2). The total area available for installing a treatment wetland is 67,965 m^2 consisting of two sedimentation basins (13,798 m^2) and two banks of wetlands, each containing five tanks-in-series cells (54,167 m^2). The TP concentrations and loads used followed a seasonal pattern with maximum values occurring during high flow months, reaching maximum concentrations of 0.25 and 0.12 (mg/l) and maximum loads of 1,528 and 274 (kg/month) for the 2010 and 2013 water year, respectively, for which TP loads were available (Table 4.3). The lowest concentrations and loads occurred during summer months, reaching minimum concentrations of 0.05 (mg/l) for both water years and minimum loads of 7 and 5 (kg/month) for the 2010 and 2013 water year, respectively (Table 4.3). Similar seasonal patterns were present for TR as well, reaching maximum concentrations of 566 and 238 (mg/l), and maximum loads of 3,480 and 184 (tons/month) for the 2010 and 2013 water year, respectively (Table 4.4). Minimum concentrations were 156 and 145 (mg/l) and minimum loads were 16 and 12 (tons/month) for the 2010 and 2013 water year, respectively (Table 4.4). Concentrations and loads were generally higher in the 2010 water year. Annual discharge was higher in 2010, totaling 14,644,149 m^3 compared to 9,661,746 m^3 in 2013 (Table 4.5). Discharge peaked in May and April, reaching values of 4,210,557 and 3,110,719 m^3/month, for 2010 and 2013, respectively.

Estimates of long-term P removal in the conceptual wetland cells based on the P-k-C * model

To maintain a HRT of 5 days or greater, daily discharge values into the systems were held constant at a total of 13,500 m^3/day from December to June in 2010 and from January to June in 2013 (Table 4.5). Discharge above this value (21 to 90 %) would need to be shunted around the system. During the remainder of each year, daily discharge values did not exceed 13,500 m^3/day, meaning the entire discharge of Willow Creek could be routed into the system. The HRT for these remaining months increased over the designed 5 days, reaching 68 and 30 days for 2010 and 2013, respectively (Table 4.6). The monthly HLR followed similar seasonal patterns, with the lowest depths, 1 and 3 cm/day for 2010 and 2013, respectively, occurring during the low flow months (Table 4.7).

Concentration removal was greatest in the summer, reaching 92 and 74 % in 2010 and 2013, respectively (Table 4.8, 4.9). Concentration removal was inefficient during months with high discharge, achieving only 10 and 9 % in 2010 and 2013, respectively. Annual areal mass removal was 0.13 and 0.10 g-P/m^2/yr in 2010 and 2013, respectively (Table 4.8, 4.9). Annual mass removal, representing the total percent of TP removed from Willow Creek, was 3 and 8 % in 2010 and 2013, respectively (Table 4.10, 4.11). Mass removal was greatest during low flow months and became inefficient during high flow months, decreasing to 2 %. To increase mass removal to 50 or 70 % an area of 3.03 km^2 (1.17 mi^2) and 76.5 km^2 (29.5 mi^2), respectively would be needed.

Estimates of sediment retention in the sedimentation basin and wetland cells

Reduction in sediment concentration via the sedimentation basin was held constant at 60% resulting in an annual areal mass removal of 3,772 and 2,935 g-TR/m^2/year in 2010 and 2013, respectively (Table 4.12, 4.13). Annual mass removal, representing the total percent of TR removed from Willow Creek in the sedimentation basin, was 8 and 23 %, respectively (Table 4.12, 4.13). Similar to TP removal in the wetland, TR removal in the sedimentation basin followed a seasonal pattern with higher efficiencies during low flow months.

Sediment concentration removal in the wetland cells ranged from 75-77% in 2010 and 2013 (Table 4.14, 4.15), while the annual areal mass removal was 490 and 378 g-TR/m^2/year in 2010 and 2013, respectively (Table 4.14, 4.15). Annual mass removal, representing the total percent of TR removed from Willow Creek in the wetland cells, was 4 and 12 %, respectively. Total annual mass removal, representing the total percent of TR removed from Willow Creek in the sedimentation basin and wetland cells combined, was 11.5 and 34.7% in 2010 and 2013, respectively (Table 4.16, 4.17). Mass removal was greatest during low flow months and became inefficient during high flow months, decreasing to a minimum of 6 and 15.5 % in 2010 and 2013, respectively.

The weight of accumulated sediments for the 2010 water year was 523, 2,617 and 5,234 metric tons after 1, 5, and 10 years, respectively (Table 4.18). The depth of the accumulated sediment would be 1.4, 7.2 and 14.3 cm. The weight of accumulated sediments for the 2013 water year were 406, 2,030 and 4,060 metric tons after 1, 5, and 10 years, respectively (Table 4.18), while the depth of the accumulated sediment would be 1.1, 5.6 and 11.1 cm. The average weight and depth for the two water years was 465, 2,323 and 4,647 metric tons and 1.3, 6.4 and 12.7 cm after 1, 5 and 10 years, respectively (Table 4.18).

Cost of constructed wetlands

The cost of the wetland cells ranged from \$666,413 to \$1,381,324, averaging \$929,810 (Table 4.19). The total cost of the system, including the sedimentation basin, ranged from \$727,912 to \$1,733,189, averaging \$1,148,978.

Discussion

The space constraints in the proposed wetland design dictated by existing infrastructure limit the size of the conceptual wetland to a size that cannot effectively treat the high volume of spring runoff. During spring runoff, an additional 20% of flow has to be shunted past the wetland compared to the average annual amount to maintain the 5 day HRT design criteria. This greatly decreases monthly TP (3%) and TR (11%) mass removal efficiencies. This is important for the overall efficiency of the wetland because it is during this time that the majority of constituents enter the reservoir. Therefore, to increase annual efficiency, the constructed wetland would have to be able to manage and treat high flows.

A variation in the seasonal efficiency was seen when comparing water years. For example, mass removal efficiency was higher during 2013 when discharge was lower than in 2010, because less discharge containing high loads of TP and TR had to be shunted past the system to maintain the designed HRT. This dependency has implications for trends expected as a result of global climatic change. For the Pacific northwest, future climate predictions are that annual snow pack will decrease, rain on snow events will increase and timing of runoff will be protracted and occur earlier in the year relative to long-term historic trends (Mote et al. 2003, Mote and Salathe 2010). The combined effect of this would be that the majority of the annual load of TP and TR to WCR would occur in a very short period of time meaning that even more flow would need to be diverted past a treatment wetland. Thus efficiency would decrease further because a lower volume containing the highest load would be treated. Planners must consider these forecasts of long-term climatic trends as they contemplate the use of constructed wetlands to remediate receiving water bodies.

This study highlights the importance of identifying P composition of waterbodies within a watershed before management strategies are implemented. For example, the P composition within Willow Creek can explain why annual removal of TR mass was higher than TP removal. On average, dissolved P dominates annual composition in Willow Creek (Chapter 2), therefore additional TR retention can occur with minimal reduction in TP. Because sampling was conducted to determine P composition in the Willow Creek watershed, appropriate adjustments were made to accurately model retention. If P composition within Willow Creek was primarily particulate, increased removal could be except to occur within the wetland system. Lake and reservoir managers should carefully consider P composition and the implications it can have on BMP removal efficiencies.

Phosphorus and sediment removal through the conceptual wetland system was dependent on season, similar to other constructed wetlands (Kadlec and Wallace 2009). The TP and TR removal efficiency was also highly depended on hydrologic variables including the HLR and the HRT. The average HLR in the wetland cells was higher than typical values. In an evaluation of 282 wetlands, the average HLR was 12.3 cm/d (Kadlec and Wallace 2009). Due to the limited space in the defined wetland area and the high water volume in Willow Creek, a fine balance between the amount of water entering the system and efficiency exists. If the HLR was reduced to 12.3 cm/d additional water would have to be shunted around the system and therefore efficiency would decrease. Constituent removal increased during the low flow months when the HRT exceeded the suggested value of 5 to 14 days (Mitsch and Gossenlink 2007) and the HLR decreased. During this time, the P and sediment rich waters had more time to interact with the wetland system, therefore retention increased (Toet et al. 2005; Kadlec and Wallace 2009).

The average TP concentration removal (%) in the wetland system falls in the range of values reported in the literature but was lower than the reported average. The average concentration removal of 10 cold-climate wetlands was 52.3% (Kadlec and Wallace 2009), compared to 32.5% and 30.4% for the conceptual model considered here. The decreased concentration removal is likely due to the limited wetland area and high inflow volumes. Because the sustainable removal mechanism of P is soil accretion, a large wetland area is needed to treat large volumes of water (Kadlec and Wallace 2009). If the wetland inflow was decreased or the wetland area was increased, concentration removal would increase.

Total residue (TR) concentration removal in the wetland cells (averaging 76.2 and 75.9% for the 2010 and 2013 year) was within the range (61.1 to 86.9%) reported in the literature (Kadlec and Wallace 2009). Of the evaluated wetlands, five included designs with a sedimentation basin in which on average 86.9% (61.1 to 86.9%) of sediments were removed (Kadlec and Wallace). Thus my estimate of 60% removal in the sedimentation basin was highly conservative and if increased would increase the amount TR removed. Even with an increase of 20%, this would not be sufficient to make significant reductions in the amount of TP and TR entering WCR, and it would not make the conceptual design feasible.

The annual P areal mass removal rate in this study, ~ 0.1 g/m^2/yr (Tables 4.8 and 4.9) were on the low end of other values presented in the literature, ranging from 0.4 to 6.2 g-P/m^2/yr (Niswander and Mitsch 1995; Reinelt and Horner 1995; Raisin 1997; Fink and Mitsch 2004, 2007). One explanation could be because inlet P concentrations, ~0.1 mg/L (Table 4.3) were low. Reduced mass removal is commonly seen when inlet concentrations are low, if the inlet concentrations were increased one would expect to see an increase in mass removal (Kadlec and Wallace 2009). Annual TR areal mass removal rates in the sedimentation basin were also lower than values presented in the literature, ranging from 10,055 to 22,871 g-TR/m^2/yr (Kadlec and Wallace 2009). Annual TR areal mass removal rates in the wetland were also lower than values presented in the literature; the mass removal rate for the five evaluated wetlands including the sedimentation basins were between 742 to 1,181 g/m^2/yr (Kadlec and Wallace 2009). Not surprisingly, the total load removed from the sedimentation basin and the wetland cells was less than values presented (11,473 to 23,804 g/m^2/yr) (Kadlec and Wallace 2009). Similar to concentration removal, these low values are likely due to the limited wetland area and high inflow volumes.

The accumulation of sediment in the sedimentation basin will limit sediment accumulation in the wetland cells, which is convenient because access to sediment removal would be easier in the sedimentation basin than the wetland cells. Based on accumulation values calculated, the sedimentation basin should not be expect to fill with sediments quickly, totaling 12.7 cm in 10 years, but the management of these sediments should be of concern. A small increase in the height of accumulated sediments results in a large increase in the associated weight. For example, in only one year an average of 1.3 cm of sediment accumulation is expected, weighing 465 metric tons. To remove the accumulated sediments, all water would have to be diverted around the sedimentation basin to allow the sediments to dry. Such cleaning would be easily facilitated by the dual design of this wetland. One sedimentation basin could be drained and rejuvenated while all flow is diverted to the second bank of cells which should be able to treat all of the water volume in Willow Creek while maintaining the designed HRT.

Limitations of the models used to calculated TR retention were encountered during the low flow months because TR mass removal exceeded 100%. High sediment removal during summer months has been reported by Higgins et al. (1993) who found 100% sediment removal during the summer months in a constructed wetland system including a sedimentation basin. However, in their system evapotranspiration limited outflows from the system. In the Willow Creek system, outflows are not expected to be limited, therefore a removal of 100% is unrealistic. This overestimation likely occurred because the linear model used does not accurately represent TR retention in low flow months. If the USACE decides to adopt a constructed wetland at the inlet of WCR, the uncertainty surrounding efficiency estimates is justification for future monitoring to evaluate treatment effectiveness and expected changes to water quality within the Willow Creek watershed.

Removal rates in the conceptual model would be expected to increase if more space was available for the design. Based on modeled calculations, the area of the wetland system would have to increase by 45% to increase TP removal efficiencies to 50%. The defined space, bound by the reservoir and roadways, is not sufficiently large to hold a wetland of this size. Average predicted wetland costs, using the U.S. EPA (2002) high and low estimates ($/ha) and a linear relationship presented by Kadlec and Wallace (2009), were higher than other remediation strategies presented in Chapter 2 also suggesting that other options besides a wetland should be pursued.

It is important to note that constructed wetlands, like all systems, have some negative effects. In the case of free water surface (FWS) wetlands, the potential of human exposure to contaminants is high (Kadlec and Wallace 2009). For this reason they are rarely used for secondary treatment. Mosquito control is also of concern due to the large amounts of exposed water (Kadlec and Wallace 2009). If a constructed wetland is considered, these negative effects must be included in management decisions.

Although constructed wetlands have been used to reduce of the occurrence of cyanobacteria blooms (Wu et al. 2010; Zhong et al. 2011), a FWS wetland is not recommended as a remediation strategy for the influx of nutrients into WCR. The exploration of other innovative systems such as the installation of small constructed wetlands in the WCH and the use of floating treatment wetlands in the reservoir could be beneficial and is recommended for future study.

Conclusion

The frequency of cyanobacteria blooms are increasing world-wide and present a threat to water bodies (Chorus and Bartram 1999; Sharpley et al. 2000; Graham et al. 2009; Paerl et al. 2011). Because cyanobacteria tend to dominate at low N:P ratios (Carpenter 2008, Tilman et al. 1982, Orihel et al. 2011, Harris et al. 2014 , Pick and Lean 1987), preventing the influx of P to- or reducing it from aquatic ecosystems is crucial to prevent or mitigate harmful algal blooms. Constructed wetlands have long been used by aquatic resource managers to reduce the influx of nutrients into a system (Carpenter et al. 1998; Woltemade 2000; Jordan et al. 2003; Díaz et al. 2012), and have been used to specifically target the reduction of the occurrence of cyanobacteria (Wu et al. 2010; Zhong et al. 2011). The objective of this study was to evaluate the ability of a conceptual wetland model to improve water quality in Willow Creek before it enters WCR. Overall, due to the limited space and the high volume of discharge that has to bypass the wetland system during spring runoff when the majority of TP and TR is delivered to the reservoir, annual TP and TR removal is low. This low efficiency coupled with high costs make a constructed wetland at the inlet of the reservoir unrealistic and thus it is not recommended as a remediation strategy for annual load reductions to Willow Creek Reservoir. Although a traditional constructed wetland system is not recommended, the exploration of other innovative systems such as the installation of small constructed wetlands in the WCH and the use of floating treatment wetlands in the reservoir could be beneficial and is recommended for future study.

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Table 4.1: Phosphorus retention in various wetlands in nonpoint source catchments.

Modified from Table 13.7 pg 451, Mitsch and Gosselink (2007).

Wetland type and location	Catchment size (ha)	Wetland size (ha)	Retention (g P m^{-2} yr^{-1})	Concentration removal (%)	Reference
Paulstrine freshwater Bellvue, WA, USA					Reinhelt and Horner 1995
urban area	187	2	0.4	14	
rural area	87	2	3.0	56	
Constructed wetland Victoria, Australia	90	450	2.8	17	Raisin et al. 1997
Agricultural wetland Rush Creek Township, OH, USA	17	1	6.2	59	Fink and Mitsch2004
Created instream wetland Franklin County, OH, USA	260	6	2.9	16	Niswander and Mitsch 2004
Created riparian wetland Columbus, OH, USA		3	4.5	26	Fink and Mitsch 2007

Table 4.2: Average monthly phosphorus-removal rate constants (k) in meters per year (m/yr) obtained from Kadlec and Wallace (2009).

Month	k (m/yr)
January	7.5
February	7.5
March	7.5
April	30.0
May	20.0
June	20.0
July	15.0
August	15.0
September	20.0
October	25.0
November	20.0
December	10.0

Table 4.3: Average monthly phosphorus (P) concentrations (mg/l) and loads (kg/month) for the 2010 and 2013 water years in Willow Creek, OR.

Month	2010 TP (mg/L)	2010 TP (kg/month)	2013 TP (mg/L)	2013 TP (kg/month)
January	0.10	216	0.07	43
February	0.09	329	0.08	81
March	0.07	80	0.07	160
April	0.16	963	0.09	274
May	0.25	1,528	0.12	83
June	0.10	55	0.08	61
July	0.08	10	0.09	14
August	0.08	7	0.08	5
September	0.08	9	0.08	5
October	0.05	14	0.06	16
November	0.06	29	0.07	29
December	0.05	64	0.05	41
Average	0.10 ± 0.005	275 ± 138	0.08 ± 0.005	68 ± 22

Table 4.4: Average monthly total residue (TR) concentrations (mg/l) and loads (kg/month) for the 2010 and 2013 water years in Willow Creek, OR

Month	2010 TR (mg/L)	2010 TR (kg/month)	2013 TR (mg/L)	2013 TR (kg/month)
January	204	426,880	164	98,476
February	183	591,187	145	179,142
March	156	185,558	166	339,867
April	320	1,721,218	238	560,600
May	566	3,479,897	187	183,988
June	176	101,027	178	137,885
July	195	22,739	191	34,162
August	187	16,085	209	13,540
September	198	23,705	203	12,081
October	175	42,828	185	39,310
November	203	85,465	198	68,183
December	187	175,703	160	94,682
Average	229 ± 12	572,690 ± 298,408	185 ± 7	146,826 ± 46,253

Table 4.5: Actual monthly discharge values (m^3/month), design discharge values (m^3/month), discharge shunted past the system to maintain the designed HRT (%) and TP and TR that was not retained within the wetland system (%) for the 2010 and 2013 water years in Willow Creek, OR.

	2010					2013				
Month	Actual discharge (m^3/month)	Design discharge (m^3/month)	Missed discharge (%)	Missed TP-mass (%)	Missed TR-mass (%)	Actual discharge (m^3/month)	Design discharge (m^3/day)	Missed discharge (%)	Missed TP-mass (%)	Missed TR-mass (%)
January	1,681,287	405,000	76	98	82	533,455	405,000	24	94	39
February	2,468,595	405,000	84	99	89	979,053	405,000	59	96	70
March	1,097,778	405,000	63	97	69	1,870,764	405,000	78	98	82
April	3,349,362	405,000	88	98	93	3,110,719	405,000	87	96	84
May	4,210,557	405,000	90	98	94	1,004,085	405,000	60	87	63
June	671,340	405,000	40	84	36	749,942	405,000	46	87	53
July	158,807	158,807	-	47	-23	182,466	182,466	0	61	8
August	77,508	77,508	-	44	19	71,329	71,329	0	27	0
September	29,995	29,995	-	75	77	69,845	69,845	0	16	-6
October	202,381	202,381	-	65	25	210,349	210,349	0	64	10
November	331,266	331,266	-	81	29	367,315	367,315	0	77	4
December	365,274	365,274	-	94	65	512,423	405,000	21	93	38
Total	**14,644,149**	**3,595,231**	**75**	**97**	**89**	**9,661,746**	**3,736,305**	**61**	**92**	**65**

Table 4.6: The calculated hydraulic residence times (HRT) for the 2010 and 2013 water years for a conceptual wetland design for Willow Creek Reservoir, OR. (Note: the increased HRT represent low flow months).

Month	2010 HRT (days)	2013 HRT (days)
January	5.0	5.0
February	5.0	5.0
March	5.0	5.0
April	5.0	5.0
May	5.0	5.0
June	5.0	5.0
July	13.3	11.2
August	27.2	29.5
September	68.0	29.2
October	10.4	10.0
November	6.2	5.6
December	5.8	5.0

Table 4.7: The calculated hydraulic loading rates (HLR, q) for the 2010 and 2013 water years for a conceptual wetland design for Willow Creek Reservoir, OR. (Note: The decreased HLR represent low flow months).

Month	2010 q (cm/day)	2013 q (cm/day)
January	20	20
February	20	20
March	20	20
April	20	20
May	20	20
June	20	20
July	8	9
August	4	3
September	1	3
October	10	10
November	16	18
December	17	20

Table 4.8: Average total phosphorus (TP), outlet concentration (C_o, mg TP/L), concentration removal (%) and areal mass removal (g-P/m^2/month) for the 2010 water year for a conceptual wetland design for Willow Creek, OR.

Month (2010 year)	TP C_o (mg/L)	TP concentration removal (%)	Areal mass removal (g-P/m^2/month)
January	0.09	9.54	0.005
February	0.09	9.54	0.005
March	0.06	9.45	0.004
April	0.11	32.57	0.032
May	0.19	23.45	0.036
June	0.07	23.15	0.013
July	0.05	39.69	0.008
August	0.03	62.50	0.006
September	0.01	92.02	0.003
October	0.03	47.14	0.007
November	0.04	27.05	0.008
December	0.04	13.83	0.003
Annual			0.13

Table 4.9: Average total phosphorus (TP), outlet concentration (C_o, mg TP/L), concentration removal (%) and areal mass removal (g-P/m^2/month) for the 2013 water year for a conceptual wetland design for Willow Creek, OR.

Month (2013 year)	TP C_o (mg/L)	TP concentration removal (%)	Areal Mass Removal (g-P/m^2/month)
January	0.06	9.45	0.004
February	0.07	9.50	0.005
March	0.07	9.49	0.004
April	0.06	32.27	0.018
May	0.09	23.23	0.016
June	0.07	23.08	0.012
July	0.06	34.93	0.008
August	0.03	65.24	0.005
September	0.02	73.93	0.006
October	0.03	46.18	0.008
November	0.05	24.97	0.010
December	0.05	12.28	0.004
Annual			0.10

Table 4.10: Monthly total phosphorus (TP) mass removal in the sedimentation basin and wetland cells (%) for the 2010 water year, for a conceptual wetland design for Willow Creek, OR. Annual values represent the total percent of TP removed from Willow Creek from the system. High and low estimates represent 95% confidence interval error propagation.

Month (2010 year)	Total TP mass removal in basin and wetland (%)	High-Low estimates
January	1.7	8.1 -4.7
February	1.4	3.6 1.4
March	3.1	6.0 3.1
April	2.4	4.0 2.4
May	1.6	3.3 1.6
June	16.4	20.3 16.4
July	52.8	68.6 46.4
August	56.4	73.8 45.9
September	24.7	25.2 24.3
October	34.8	43.0 31.3
November	19.2	25.8 17.5
December	5.7	9.0 5.1
Annual	2.8	5.1 2.3

Table 4.11: Monthly total phosphorus (TP) mass removal in the sedimentation basin and wetland cells (%) for the 2013 water year, for a conceptual wetland design for Willow Creek, OR. Annual values represent the total percent of TP removed from Willow Creek from the system. High and low estimates represent 95% confidence interval error propagation.

Month (2013 year)	Total TP mass removal in basin and wetland (%)	High-low estimates (%)
January	5.9	17.8 -6.0
February	3.8	10.3 -2.7
March	1.8	4.0 -0.4
April	4.5	5.5 3.5
May	13.2	16.5 9.9
June	13.0	18.5 7.4
July	39.5	55.5 26.7
August	72.6	81.5 63.3
September	83.6	92.4 74.8
October	36.1	43.8 29.2
November	23.1	29.9 16.5
December	6.5	15 -1.9
Annual	8.4	12.4 4.5

Table 4.12: Average total residue (TR) C_o (mg/L), concentration removal (%), areal mass removal (g-TR/m^2/month) and mass removal (%) in the sedimentation basin for the 2010 water year for a conceptual wetland design for Willow Creek, OR. Mass removal refers to the overall mass removal from Willow Creek, OR that occurred in the sedimentation basin.

Month (2010 year)	TR Co (mg/l)	Sed basin concentration removal (%)	Sed basin areal mass removal (g-TR/m^2/month)	Sed basin mass removal (%)
January	82	60	360	12
February	73	60	322	8
March	63	60	275	20
April	128	60	563	5
May	226	60	996	4
June	70	60	310	42
July	78	60	130	60
August	75	60	61	54
September	79	60	26	15
October	70	60	149	50
November	81	60	292	47
December	75	60	288	23
Annual			3,772	8

Table 4.13: Average total residue (TR) C_o (mg/L), concentration removal (%), areal mass removal (g-TR/m^2/month) and mass removal (%) in the sedimentation basin for the 2013 water year for a conceptual wetland design for Willow Creek, OR. Mass removal refers to the overall mass removal from Willow Creek, OR that occurred in the sedimentation basin.

Month (2013 year)	TR Co (mg/l)	Sed basin concentration removal (%)	Sed basin areal mass removal (g-TR/m^2/month)	Sed basin mass removal (%)
January	65	60	288	40
February	58	60	256	20
March	66	60	292	12
April	95	60	418	10
May	75	60	330	25
June	71	60	314	31
July	76	60	152	61
August	84	60	63	66
September	81	60	62	59
October	74	60	164	59
November	79	60	316	64
December	64	60	282	41
Annual			2,935	23

Table 4.14: Average total residue (TR) C_o (mg/L), concentration removal (%), areal mass removal (g-TR/m^2/month) and mass removal (%) in the wetland cells for the 2010 water year for a conceptual wetland design for Willow Creek, OR. Mass removal refers to the overall mass removal from Willow Creek, OR that occurred in the wetland cell.

Month (2010 year)	TR Co (mg/l)	Wetland concentration removal (%)	Wetland areal mass removal (g-TR/m^2/month)	Wetland mass removal (%)
January	19	76	47	6
February	18	76	41	4
March	15	76	35	10
April	30	77	73	2
May	51	77	131	2
June	17	76	40	21
July	19	76	17	41
August	18	76	8	27
September	19	76	3	8
October	17	76	19	25
November	19	76	38	24
December	18	76	37	12
Annual			490	4

Table 4.15: Average total residue (TR) C_o (mg/L), concentration removal (%), areal mass removal (g-TR/m^2/month) and mass removal (%) in the wetland cells for the 2013 water year for a conceptual wetland design for Willow Creek, OR. Mass removal refers to the overall mass removal from Willow Creek, OR that occurred in the wetland cell.

Month (2013 year)	TR Co (mg/l)	Wetland concentration removal (%)	Wetland areal mass removal (g-TR/m^2/month)	Wetland mass removal (%)
January	16	76	37	20
February	14	75	33	10
March	16	76	38	6
April	22	76	54	5
May	18	76	43	13
June	17	76	40	16
July	18	76	20	31
August	20	76	8	34
September	19	76	8	36
October	18	76	21	30
November	19	76	41	32
December	16	76	36	21
Annual			378	12

Table 4.16: Monthly total residue (TR) mass removal in the sedimentation basin and wetland cells (%) for the 2010 water year for a conceptual wetland design for Willow Creek, OR. Annual values represent the total percent of TR removed refers to the overall mass removal from Willow Creek, OR that occurred in the system. High and low estimates represent 95% confidence interval error propagation.

Month (2010 year)	Total TR mass removal in basin and wetland (%)	High and low estimates (%)
January	17.5	19.1 9.2
February	11.3	12.2 5.6
March	30.8	33.4 19.3
April	6.8	7.4 3.3
May	6.0	6.5 3.0
June	63.8	69.2 40.7
July	123.1	133.7 72.5
August	81.4	88.3 51.0
September	22.6	24.5 14.5
October	74.8	81.2 48.0
November	71.1	77.5 36.5
December	35.2	38.2 21.65
Annual	11.5	12.5 6.2

Table 4.17: Monthly total residue (TR) mass removal in the sedimentation basin and wetland cells (%) for the 2013 water year for a conceptual wetland design for Willow Creek, OR. Annual values represent the total percent of TR removed refers to the overall mass removal from Willow Creek, OR that occurred in the system. High and low estimates represent 95% confidence interval error propagation.

Month (2013 year)	Total TR mass removal in basin and wetland (%)	High and low estimates (%)
January	60.8	66.0 38.0
February	29.6	32.2 18.4
March	17.8	19.4 10.9
April	15.5	16.9 9.2
May	37.3	40.5 23.6
June	47.3	51.3 29.5
July	92.3	100.2 57.3
August	99.6	108.0 63.3
September	106.4	115.5 66.3
October	89.6	97.2 56.6
November	96.3	104.5 60.5
December	61.7	67.1 38.6
Annual	34.7	37.7 21.5

Table 4.18: Weight (metric tons) and associated depth of accumulated (cm) of sediments in the proposed sedimentation basin over time for a conceptual wetland design for Willow Creek, OR. Values presented include retention values based on the 2010 and 2013 water years and their averages.

Years	2010 water year weight (tons)	2010 water year accumulation (cm)	2013 water year weight (tons)	2013 water year accumulation (cm)	**Average weight (tons)**	**Average accumulation (cm)**
1	523	1	406	1.1	465	1.27
5	2,617	7	2,030	5.6	2,323	6.35
10	5,234	14	4,060	11.1	4,647	12.71

Table 4.19: Cost of wetland cells, sedimentation basin and total costs based on the linear relationship, C=194 * $A^{0.690}$ (R^2= 0.79) (Kadlec and Wallace 2009) and the U.S. EPA (2000) high and low capital cost estimates for FWS wetland systems.

Component	Linear relationship cost ($)	U.S. EPA low estimate cost ($)	U.S. EPA high estimate cost ($)	**Average cost ($)**
Wetland cells	622,413	785,692	1,381,324	929,810
Sedimentation basin	242,256	200,140	351,866	264,754
Total system	727,912	985,832	1,733,189	1,148,978

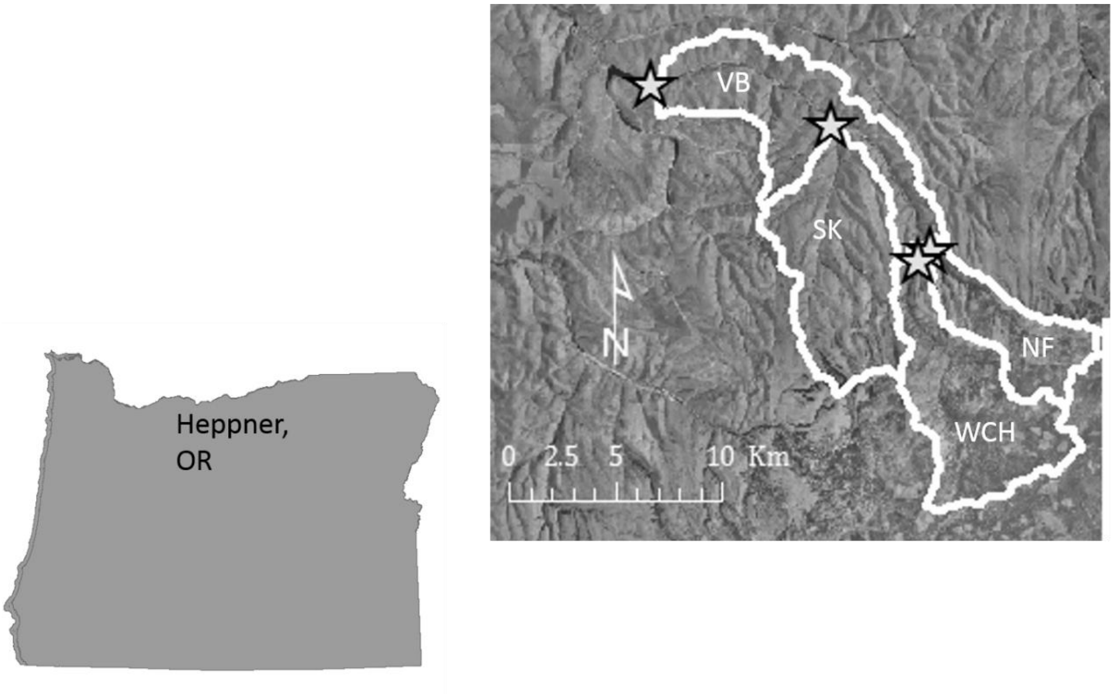

Figure 4.1: Location of the Willow Creek watershed in Morrow County, Oregon, USA close to the town of Heppner. Sub-catchments identified by letter abbreviations are: WCH - Willow Creek Headwaters, NF – North Fork, SK – Skinner Creek and VB – Valley Bottom. The location of four (4) ISCO automated samplers instrumented within the watershed are indicated by the white stars.

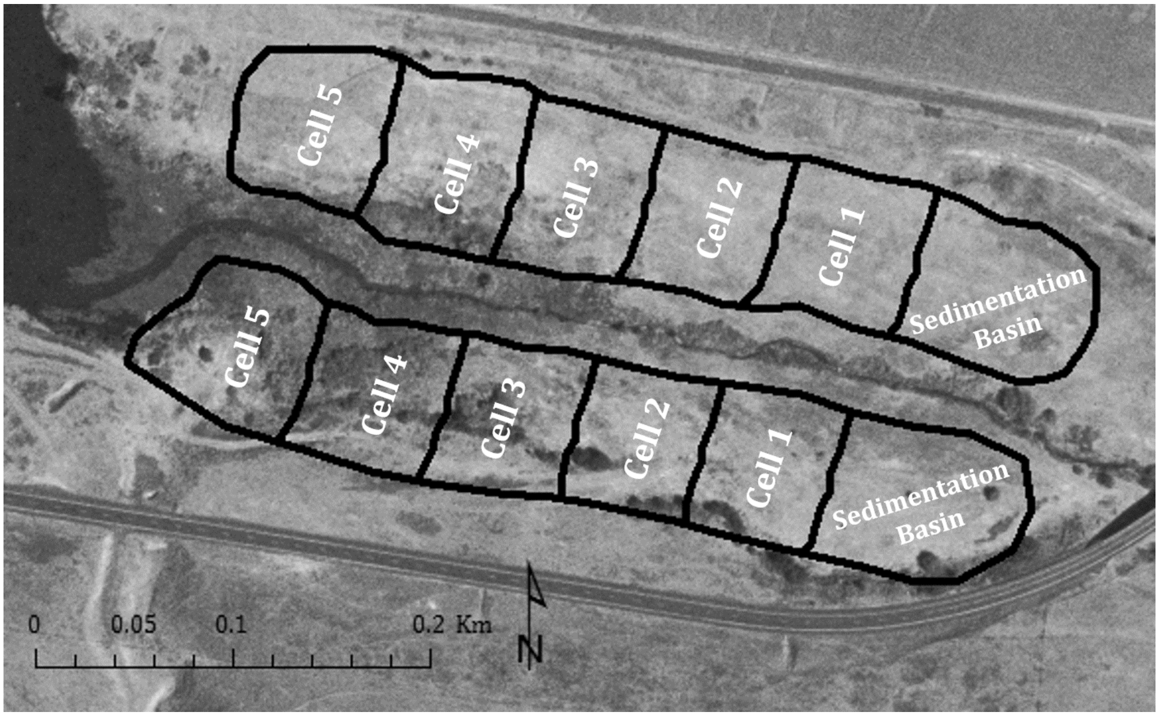

Figure 4.2: Proposed design of a conceptual wetland for the inlet of Willow Creek Reservoir, Morrow County, OR, USA. Design includes a natural stream channel in the center with two sedimentation basins followed by 5 wetland cells on either side (map obtained from USGS landcover data).

Chapter 5: Summary and Management Options

Blooms of cyanobacteria, also known as blue-green algae, are a threat to water quality worldwide. Willow Creek Dam and Reservoir (WCR), constructed in 1983, has experienced an annual blooms of toxic algae since 2006. Results of these blooms include advisory warnings from the Oregon Department of Health, which restrict human contact with the water in the reservoir and thus decrease its potential for recreational activities. This is important because it is the only water body within 100 miles that provides recreational opportunities.

Experiments, conducted in large mesocosms in WCR, showed that the elimination of nitrogen (N)-limitation, reduced or eliminated the dominance of cyanobacteria in the algal community (Harris 2012, Harris et al. 2014). These results suggest that the overabundance of phosphorus (P) in WCR is the main cause of the annual blooms of cyanobacteria. Thus its reduction in water entering WCR is crucial to recover and maintain water quality and emphasizes the need for restoration activities in the watershed. During periods of high runoff, tributaries from sub-catchments of Willow Creek contribute significant loads of P and sediment to the reservoir from the watershed (USACE 2007, Adams 2012). The sub-catchments in which these nutrients originated was unknown, therefore my research was designed to identify the source of nutrient loads within the Willow Creek watershed and propose potential remediation strategies to reduce annual loading.

Constructed wetlands have been used successfully to improve the water quality of receiving waters (Carpenter et al. 1998; Woltemade 2000; Jordan et al. 2003; Díaz et al. 2012) and may therefore be an option for Willow Creek Reservoir. It is understood that when the public's opinion are considered and included in management activities they tend to be more satisfied with decisions (Smith and McDono 2001; Parkins and Mitchell 2005), which leads to continued support for the project (Smith and McDono 2001). A survey was administered to evaluate user's opinions of the installation of a constructed wetland to improve water quality in Willow Creek before it enters the reservoir. A conceptual design was developed to determine the effectiveness of total P (TP) and total residue (TR) retention in a constructed wetland at the inlet of the reservoir. Throughout this experience, additional questions and management options developed, therefore, a summary including continued research opportunities for each chapter is provided below.

Chapter 2: Use of high resolution sampling to identify candidate sub-catchments for potential remediation to improve water quality in receiving water bodies

In chapter 2, I identified and quantified the source of total P (TP) and total residue (TR) from sub-catchments of the Willow Creek watershed. Activities such as overwintering cattle and hay production in the lower reaches (Valley Bottom - VB) of the Willow Creek watershed (Figure 5.1) were thought to contribute high nutrient and sediment and loads to Willow Creek. For example, in 1979, a watershed analysis identified cropland and rangeland as the main land uses from which sediment originated in the basin (Koelliker 1979). During the spring, flood irrigation is used to provide water to the agricultural areas (Figure 5.2). High resolution sampling conducted during this study indicated that the VB is a net sink for TP and TR, not a source.

Lush riparian vegetation, primarily reed canary grass, grows along the stream banks in the lower reaches of the watershed from early spring into the late fall (Figure 5.3). In contrast, dense forest floor riparian vegetation is limited in the upper reaches of the watershed (Figure 5.4). The lush riparian vegetation in the VB likely plays a significant role in minimizing the annual TP and TR loads as it is known that riparian vegetation, like reed canary grass, takes up P for growth and reproduction during the growing season (Kao et al.

2003). When surface runoff occurs, the riparian vegetation along the stream promotes infiltration thereby decreasing surface flow which deposits TR and subsequent TP before it reaches the stream (Lee et al. 2000, 2003; Abu-Zreig et al. 2003; Blanco-Canqui et al. 2004; Ma et al. 2013). To better understand the nutrient cycling in the VB, the role of nutrient uptake by riparian plants should be quantified.

Biweekly grab samples showed, on average, that the majority of P in the Willow Creek watershed was in the dissolved phase. In general, the composition of P changed during spring runoff, during which the majority of P was in the particulate phase. P-rich soils and P-rich groundwater are likely nonpoint sources of P that contribute to the dissolved-P concentrations that dominate throughout much of the year in the Willow Creek watershed. Instrumentation should be set in place to identify background nutrient concentrations associated with spring water. Because the majority of the annual P-load enters the reservoir during spring runoff when it predominantly in the particulate phase, identifying the origin of sediment-bound P is also important. Predictive models can be used to estimate soil erosion in watersheds, typically used models include the Universal Soil Loss Equation (USLE) and the Water Erosion Predication Project (WEPP) (Ward and Trimble 2003).

A modified export coefficient modeling approach was taken to quantify land-use specific loading. For this, export coefficients that were commonly cited in the literature and that best represented the Willow Creek watershed were used. Because nutrient exports of land uses vary depending on the climate and physiographic characteristics (Beaulac and Reckhow 1982), creating site-specific nutrient export coefficients would be an important step to accurately model nutrient loads associated with different land uses in the Willow Creek watershed. Using the chosen coefficients, forest lands in the Willow Creek headwaters

(WCH) were identified as the main contributor of annual loads in the Willow Creek watershed. Further instrumentation should be used to identify the originating source of TP and TR loads within the WCH sub-catchment.

Based on known relationships between logging roads and associated sediment transport (Brown and Krygier 1971; Beschta 1978), the increased road density within the WCH sub-catchment may contribute significantly to the annual sediment load and should be evaluated in detail. A Geomorphic Road Analysis and Inventory Package (GRAIP) analysis should be completed to identify and prioritize high-risk roads. Results from a recent GRAIP analysis in the Wall Creek watershed, indicated high sediment production and delivery was associated with native surface roads (Nelson et al. 2012). To reduce costs while maximizing benefits, a GRAIP analysis could be completed on native roads only. Based on the lengths of native surface roads in the WCH and costs per mile, I estimated that a GRAIP analysis would cost approximately $2,500. This would identify which, if any, road segments contribute to loading. Once these high-risk roads are identified, road restoration and decommissioning could be used to reduce impacts on Willow Creek. This has been found to be highly effective in other watersheds where roads were a significant source of sediment and nutrients (McCashion and Rice 1983; Hagans et al. 1986; Klein 1987; Best et al. 1995; Bloom 1998; Madej 2001; Keppeler et al. 2007; Flanagan et al. 2012). Costs associated with remediation will vary depending on the extent of effort (USDA 2014).

Vegetative filter strips (VFS), which have been adopted as a BMP in a wide variety of landscapes, should be implemented to reduce additional loading of nutrients and sediments from the WCH. Similar to the reed canary grass in the lower reaches of the Willow Creek watershed, VFS reduce nutrient and sediment loading by increasing infiltration thereby decreasing surface flow which allows deposition of sediments to occur (Lee et al. 2000, 2003; Abu-Zreig et al. 2003; Blanco-Canqui et al. 2004; Ma et al. 2013). Based on the evaluation of 17 buffer strips, a buffer width of 8.8 m is recommended which could be expected to have P and sediment removal efficiencies around 65.8 to 79.2%, respectively (See Table 2.11 for full list of references). Associated costs of VFS, obtained from the Oregon Watershed Enhancement Board (OWEB), indicated that the average cost per mile was $7,460 and the average cost per acre was $2,245.

If the origin of loads is identified and reduced within WCH, annual nutrient cycles could be expected to change throughout the watershed. The recommended management practices would be aimed to primarily reduce particulate P, which is the dominant form of P during spring runoff and contributes the largest proportion of P. Reduction of this fraction would shift spring runoff to be dominated by dissolved P. This would mean that P in runoff water would continue to be high, but the total load entering Willow Creek Reservoir would decrease. This has been observed in the Tualatin basin, OR, where the groundwater is P rich. Although many steps have been taken to reduce P loads within the Tualatin watershed, P concentrations continually exceed TMDL limits due to contribution of P via groundwater (Kelly et al. 1999). Additionally, if loads from the headwaters in Willow Creek were reduced, the effects of annual loading from the VB may increase. Restoration monitoring should be included in any management decisions that are made to evaluate treatment effectiveness and water quality/nutrient loading changes in the Willow Creek watershed.

Additionally, a further understanding of the nutrient cycle within the WCR is necessary to understand how implemented BMPs would affect reservoir water quality. A whole-reservoir budget and TMDL are needed to understand what the daily maximum load into the reservoir needs to be to achieve a water P concentration that will increase water quality and therefore decrease the dominant cyanobacteria algal blooms. If background base flow P concentrations originating from spring water were measured in the watershed, one could determine if the daily maximum load could be met.

Chapter 3: Exploring the public's opinion of a constructed wetland at the inlet of Willow Creek Reservoir, Heppner, OR.

In chapter 3, I used a social survey to quantify the awareness of residents and non-residents of the annual toxic algae bloom in WCR. Results indicate residents were more aware of the annual toxic algae bloom than non-residents. All of the residents and over half of the non-residents who were unaware of the bloom had lived in Heppner or visited the WCR for more than 10 years. Residents who were unaware indicated they visit the reservoir 2-5 times per year, while non-residents visited only 0-1 times per year. This is alarming due to the annual reoccurrence of the bloom and mandatory signs that are posted when the blooms is present. Adams (2012) suggested that the majority of people who visit WCR do so in early summer, specifically around Memorial Day weekend, before blooms begin and signs are posted. Thus, these visitors would not be aware of bloom-related closures later in the summer.

Further investigation into why respondents were unaware of the annual bloom should occur. It is important for all visitors of WCR to be aware of potential issues related to the often toxic algae blooms. Given limited options, the discouragement of use is frequently used as a management tool when dealing with cyanobacteria (Chorus and Bartram 1999). Therefore, extra signage should be posted at the reservoir indicating toxin levels which may help deter users from entering the reservoir. Additional efforts to inform community members and visitors that are unaware should be made, this could include extending efforts that are taking place at the reservoir into Heppner. Posting signs were they are more accessible, like in town, may increase awareness. Given the limited economy in the rural town of Heppner, careful consideration should be given to such efforts so as not to negatively affect tourism not related to the reservoir.

Because incorporating wetland education into curricula has become popular across the U.S. as the value of wetlands to society has been recognized, I was interested to determine if respondents who identified themselves as teachers would bring students to a constructed wetland and incorporate it into their curriculum. Surprisingly, the majority of teachers indicated they would not bring their students to the constructed wetland. Perhaps, teachers feel they do not have the appropriate training to teach in an outdoor setting, an issue which has been documented for science field trips (Orion 1994; Tal 2001). Teachers may also be reluctant to take students to the wetland because of budgetary concerns, which has been the cause of fewer field trips and extracurricular activities nation-wide. Further investigation of why teachers indicated they would not bring their students to the wetland need not be investigated because the wetland is not a proposed mitigation strategy for the Willow Creek watershed. Although, the general concept behind the divide between children and nature should be considered. In recently published literature, this divide, coined "nature-deficit disorder", has been blamed for trends of concern including childhood obesity, depression and attention disorders (Richard Louv 2005). If a constructed wetland was built at the inlet of the reservoir, teachers should be encouraged to incorporate it into the curriculum which will help foster the relationship between children and nature.

Chapter 4: A conceptual design for a constructed wetland for the inlet of Willow Creek reservoir to evaluate sediment and phosphorus removal efficiencies

In chapter 4, I used a conceptual design for a constructed wetland, to quantify its potential effectiveness to remove TP and TR loads at the inflow to Willow Creek Reservoir. The overall TP and TR mass removal from Willow Creek averaged 5.6 and 23.1%, respectively. Annual efficiencies were low because the majority of the discharge, containing high loads of TP and TR, would have to be rerouted around the wetland system during high flow months. Average predicted wetland costs were $1,148,978 based on estimates from the USEPA (2000) and Kadlec and Walace (2009). Due to the low efficiency and high costs, a constructed wetland at the inlet of the reservoir is not recommended as a remediation strategy to reduce annual loads of TP and TR. Although a traditional constructed wetland system is not recommended, the exploration of other innovative systems could be beneficial.

Many studies have examined the efficiency of nutrient removal in small constructed wetlands that receive runoff with nonpoint source pollution stemming from agriculture (Knight et al. 2000; Braskerud 2002; Reinhardt et al. 2005). Knight et al. (2000) examined 135 small constructed wetlands with an average and median size of 0.6 and 0.03 ha, respectively, that were used to treat livestock waste. The majority of these systems had a design flow of less than 10 m^3/day with average removal efficiencies of 42 % for TP and 53% for total suspended solids (TSS) (Knight et al. 2000). The use of constructed wetlands in forested watersheds has not been reported extensively in the literature, but one could assume the outcomes would be similar to- or better than those in agricultural areas. Ideally, these small wetlands would treat the high nutrient water at the source and therefore contribute to reducing annual loads into the reservoir. These small wetlands would require less space and may be able to function efficiently during spring runoff unlike a large wetland at the inlet to the lake. Further investigation of the efficiency and feasibility of installing distributed small constructed wetlands in the WCH should be completed.

Floating treatment wetlands (FTW) are a treatment option that have been used as an alternative to constructed wetlands. Rather than rooted in sediments, emergent plants grow on buoyant mats floating on the water surface. The roots of these plants provide a large surface-area for the development of biofilm which reduces P and sediment concentrations in the water column (Tanner and Headley 2011). Typical mats used are 0.36 m^2 BioHaven™ Floating Islands (Floating Island International, Sheperd, Montana, USA) (Tanner et al. 2005; Headley and Tanner 2009; Tanner and Headley 2011). The areal mass removal of P in floating mats has been recorded between 0.5–8.5 mg-P/m^2/d (Tanner and Headley 2011). Areal mass removal of dissolved reactive P (DRP) has been recorded at even higher rates of 8.9 mg-P/m^2/d (Tanner et al. 2005). Due to the small space requirements and high efficiencies, the use of FTW for eutrophic systems is becoming more popular throughout the world. The inlet of WCR experience seasonal fluctuations in water level, therefore, investigation of the feasibility of installing FWS wetlands in WCR should be completed.

If the mitigation strategies proposed in this research were implemented and nutrient loading in the reservoir decreases, the water quality in WCR could be expected to improve. If this occurs, one can expect an increase in overall public satisfaction, protection of health, and increased use of the reservoir.

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Figure 5.1: Example wintering area for cattle in the Valley Bottom of the Willow Creek watershed (Dec-May), during which time cattle have direct access to the stream.

Figure 5.2: Flood irrigation practices used in the agricultural areas of the Valley Bottom of the Willow Creek watershed.

Figure 5.3: Lush riparian vegetation, primarily reed canary grass, along the stream banks in the lower reaches of the Willow Creek watershed.

Figure 5.4: Riparian vegetation on the banks of the Willow Creek headwaters in the Willow Creek watershed.

Appendix A

Methods for the analysis of total phosphorous

A modified ascorbic acid method for the analysis of P was used to to analyze total (TP) and dissolved P (DP) (Eaton et al. 2005). Before analysis, premixed reagent was made by dissolving 3 g ammonium molybdate into 330 mL of double distilled water (DDW). Then 0.07 g antimony potassium tartrate followed by 28 mL of concentrated sulphuric acid were added. The solution was kept in the refrigerator in a dark bottle, to minimize degradation from exposure to light. From this premixed reagent a mixed reagent was made by dissolving 1.2925 g L-ascorbic acid in 25 ml of DDW, followed by the addition of 100 ml of pre-mixed reagent. For the analysis of TP and DP, three (3) 20 ml aliquots of unfiltered and 0.045 µm-filtered samples were added to individual glass vials. Each sample received 0.2 g of potassium persulphate and was autoclaved (Steris, Amsco Lab 250) at 103.421 KPa (15 p.s.i) for 30 min to convert all fractions of P into dissolved form. Two (2) ml of the mixed reagent was added to each sample (1:10 ratio), causing P to bind and turn a shade of blue. After a reaction time of at least 12 minutes, the samples were transferred to a 5 cm pathlength cuvette and the absorbance read at 885 nm in a ThermoScientific, Aquamate VIS spectrophotometer. Measured absorbance was then converted to P concentration using the equation for the standard curve run with each set of samples at the time of analysis. The three daily concentrations of P (µg/L) were averaged and used to represent the daily TP concentration.

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Appendix B

Methods for the analysis of total residue

Concentrations of total residue (TR) were calculated using standard method 2540-B (Eaton et al. 2005). Porcelain dishes were washed and placed in an oven (ThermoScientific, Lindberg Blue M) at 103°C to 105°C to dry. Once dried, dishes were placed in a desiccator to cool. Dishes were weighed immediately before use. Sample water remaining after P analysis (determined with a graduated cylinder) was evaporated in the pre-weighed dishes at 105°C until dried. Once samples were dried they were placed in a desiccator to cool before re-weighing. TR concentrations (mg/l) were calculated using:

$$\frac{(\text{weight of dried residue} + \text{dish (mg)} - \text{ weight of dish(mg))x1000}}{\text{sample volume (ml)}}$$

References

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Appendix C

Measurement of stream discharge measurement using salt injection

During low stream flow, discharge was measured using the salt injection method (USGS 1988). In the laboratory, a NaCl tracer was made by dissolving 250 g of NaCl in 9 liters of H_2o. The conductivity (µS-EC) of the tracer solution was then determined with a Manta (Eureka Environmenta) multi-probe. In the field, the background conductivity (µs-EC) was determined with a Eureka Manta multi-probe. The manta was then programmed to measure conductivity at a 1-sec interval. A known volume of NaCl tracer (usually 1000 ml) was then added to the stream upstream of the Eureka Manta. Conductivity was recorded until values returned to background concentrations. Discharge (m^3/s) was determined using the following equation:

$$Q = \frac{V_1 C_1}{\int_0^x (C - C_b)dt}$$

Where:

V is the volume of the tracer solution introduced into the stream in cubic meters (to convert ml to m^3 divide ml by 1 million)

C_1 is the conductivity of the tracer solution injected into the stream in µS

C is the measured tracer conductivity at a given time at the downstream sampling site in µS

C_b is the background conductivity of the stream in µS, and

t is time in seconds

The denominator is the total area under the conductivity-time curve.

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Appendix D

Measurement of stream discharge using cross section/velocity measurements

I used standard U.S. Geological Survey methods (1983) to calculate discharge from cross-section/velocity measurements. Rebar was placed vertically on either side of the stream to ensure that cross section and velocity were measured at the same location on each visit. A meter tape was stretched across the width of the stream and the stream was divided into verticals, the distance of which were recorded (w, in m). Using a wading rod and a Marsh McBirney Flowmate 2000 and OTT MF PRO flow meter, the vertical depth (D, in m) and velocity (v, in m/s) (measured at six-tenths of the depth) was obtained for each location. Discharge (m3/s) was calculated using the following equation:

$$Q= w_1D_1v_1 + w_2D_2v_2 +\ldots+ w_nD_nv_n$$

* From October 2012 to April 2013 a Marsh McBirney 2000 flow meter was used to determine flow. After April 2013 an OTT MF Pro flow meter was used. To assure the meters gave similar flow readings, they were both used on May 07, 2013 to determine velocity at three (3) locations, the inlet of the reservoir, Skinner Creek and North Fork (Table D.1–D.3). A t-test assuming equal variances was performed to test the hypothesis that there was no difference among the meters. Results indicated there was no significant difference between the two flow meters (*t*= 1.99, df= 70, *p*= 0.34).

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Table D.1: Velocity measurements taken using the Marsh McBirney 2000 and OTT MF Pro measured at the inlet of the reservoir.

Distance from bank (m)	Depth (m)	Marsh McBirney velocity (m/sec)	OTT MF Pro velocity (m/sec)
0.91	0.06	0.08	0.04
1.22	0.06	0.42	0.40
1.43	0.07	0.23	0.37
1.52	0.08	0.15	0.09
1.68	0.09	0.16	0.14
1.83	0.14	0.16	0.12
2.13	0.21	0.70	0.61
2.29	0.24	0.51	0.55
2.44	0.30	0.97	0.75
2.59	0.32	1.11	0.77
2.74	0.27	1.37	1.34
2.90	0.29	0.82	0.94
3.05	0.30	0.91	0.90
3.20	0.31	0.94	0.79
3.35	0.27	0.96	0.83
3.51	0.24	0.97	0.96
3.66	0.30	0.63	0.35

Table D.2: Velocity measurements taken using the Marsh McBirney 2000 and OTT MF Pro measured at Skinner Creek.

Distance from bank (m)	Depth (m)	Marsh McBirney velocity (m/sec)	OTT MF Pro velocity (m/sec)
0.15	0.15	0.16	0.13
0.30	0.16	0.20	0.20
0.46	0.17	0.21	0.20
0.61	0.17	0.22	0.21
0.76	0.16	0.21	0.21
0.91	0.17	0.22	0.19
1.07	0.18	0.16	0.17
1.22	0.18	0.19	0.16
1.37	0.15	0.16	0.16

Table D.3: Velocity measurements taken using the Marsh McBirney 2000 and OTT MF Pro measured at the North Fork.

Distance from bank (m)	Depth (m)	Marsh McBirney velocity (m/sec)	OTT MF Pro velocity (m/sec)
0.91	0.06	0.08	0.11
1.07	0.06	0.12	0.17
1.22	0.09	0.51	0.33
1.37	0.15	0.48	0.55
1.52	0.20	0.51	0.52
1.68	0.21	0.54	0.60
1.83	0.18	0.41	0.27
1.98	0.15	0.42	0.59
2.13	0.12	0.53	0.56
2.29	0.12	0.09	0.07

Appendix E

Statistical analysis of discharge values calculated using salt injections and traditional cross section/velocity measurements

To assure discharge measurements calculated using salt injects and traditional cross section/velocity measurements were comparable, both methods were used to calculate discharge at Skinner Creek, North Fork and Willow Creek headwaters (Table E.1) on one occasion. Two tracer volumes were used at WCH, 1000 and 2000 ml. Discharge values were calculated using methods presented in Appendix C and D. A paired t-test assuming equal variances (homogeneity of variances confirmed with *F*-test before analysis) was performed to test the hypothesis that discharge determined with either method did not differ. Results indicated there was no significant difference between the two methods of determining discharge (t= 3.18, df= 3, p= 0.48).

Table E.1: Discharge measurements (Q, m^3/s) calculated using the salt injection method (Salt) and traditional cross section/velocity measurements (Cross-section) for SK, NF and WCH.

Sub-catchment	Salt Q m^3/s	Cross-section Q m^3/s
SK	0.008	0.003
NF	0.007	0.007
WCH	0.028	0.029
WCH	0.024	0.029

Appendix F

Development of stage-discharge rating curves

To relate stream stage (height) to discharge, I developed stage-discharge curves for each sub-catchment. This is the most common rating used to compute stream flow (Sauer 2002). For this project, discharge was measured each time samples were retrieved using a variety of methods including salt injections (USGS 1988, Appendix C) and/or traditional cross-section/velocity measurements (USGS 1983, Appendix D). Statistical analysis indicated discharge values calculated using both methods were similar (p-value= 0.48, Appendix E). Discharge at the North Fork location was not calculated on November 3, 2013 due to equipment malfunction. From September 22-November 3, 2013 discharge at the Skinner Creek location was measured at the inlet of a culvert, these values were not representative of the actual flow of the stream because of eddies, so the location of the cross-section was moved to the end of the culvert for the remainder of the sampling period (November 16, 2012-September 20, 2013). The previous discharge values were excluded from the stage-discharge curve. To construct stage-discharge relationships, stage was measured each time discharge was calculated. Rebar was placed in the stream at each site and used as a datum for the entirety of the study. Measured discharge (m^3/s) and stage values (m) for Skinner Creek, North Fork and Willow Creek Headwaters are presented in Table F.1.

Discharge values were graphed as a function of stage to create sub-catchment-specific rating curves and analyzed with the relationship of:

$$y = a \times x^b$$

Where y is discharge (m^3/s), x is stage height (m), and a and b are fitted parameters. The parameters were estimated by least-squares regression analysis using Microsoft Excel's solver function. This type of analysis is commonly used in rating curve development (Reddy 2005, Ajmera and Goyal 2012) which estimates parameter values that minimizes the sum of squared residuals. The fitted parameters for each sub-catchment station are summarized in Table F.2.

HOBO (Onset Computer Corp) water level data loggers (model number U20-001-01) and HOBOware software were used to obtain stream depth at 15 minute intervals. These 15 minute depth data were then converted to discharge using sub-catchment-specific stage-discharge regressions (Appendix G) and averaged to obtain daily discharge (m^3/s). Daily discharge (m^3/s) was plotted as a function of time to create sub-catchment specific hydrographs.

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Table F.1: Discharge (Q) and stage values measured at the inlet of Willow Creek Reservoir, Skinner Creek, North Fork, and Willow Creek Headwaters, over the 2012-2013 sampling period.

Date	Skinner Creek		North Fork		WC Headwaters	
	Q (m^3/s)	Stage (m)	Q (m^3/s)	Stage (m)	Q (m^3/s)	Stage (m)
22-Sep-12	-	-	0.004	0.121	0.025	0.159
6-Oct-12	-	-	0.007	0.121	0.028	0.165
20-Oct-12	-	-	0.027	0.159	0.055	0.200
3-Nov-12	-	-	-	-	0.036	0.197
16-Nov-12	0.023	0.552	0.019	0.159	0.046	0.203
1-Dec-12	0.026	0.521	0.038	0.178	0.140	0.248
13-Dec-12	0.045	0.533	0.037	0.184	0.103	0.222
29-Dec-12	0.046	0.559	0.048	0.175	0.120	0.210
12-Jan-13	0.170	0.660	0.053	0.171	0.189	0.222
25-Jan-13	0.075	0.559	0.048	0.203	0.165	0.260
8-Feb-13	0.201	0.616	0.143	0.241	0.261	0.279
23-Feb-13	0.095	0.572	0.070	0.216	0.173	0.248
7-Mar-13	0.178	0.610	0.160	0.254	0.311	0.311
23-Mar-13	0.130	0.610	0.191	0.267	0.642	0.315
6-Apr-13	0.056	0.584	0.259	0.305	1.491	0.386
20-Apr-13	0.107	0.610	0.332	0.411	2.487	0.533
7-May-13	0.041	0.508	0.089	0.213	0.411	0.356
20-May-13	0.021	0.457	0.049	0.197	0.209	0.279
4-Jun-13	0.091	0.584	0.088	0.229	0.325	0.330
18-Jun-13	0.018	0.432	0.029	0.156	0.124	0.254
2-Jul-13	0.011	0.432	0.020	0.146	0.095	0.254
16-Jul-13	0.004	0.406	0.015	0.102	0.053	0.191
30-Jul-13	0.001	0.381	0.008	0.108	0.035	0.140
15-Aug-13	0.000	0.381	0.005	0.095	0.023	0.152
27-Aug-13	0.003	0.394	0.008	0.095	0.034	0.165
10-Sep-13	0.003	0.387	0.010	0.114	0.037	0.165
20-Sep-13	0.004	0.406	0.008	0.114	0.032	0.140

Table F.2: Fitted parameters of a and b and corresponding R^2 values of the measured data obtained in sub-catchment specific rating curve used to calculate continuous discharge.

Sub-Catchment	a	b	R^2
Skinner Creek (SK)	3.36	6.69	0.87
North Fork (NF)	2.78	2.26	0.92
WC Headwaters (WCH)	21.44	3.37	0.80

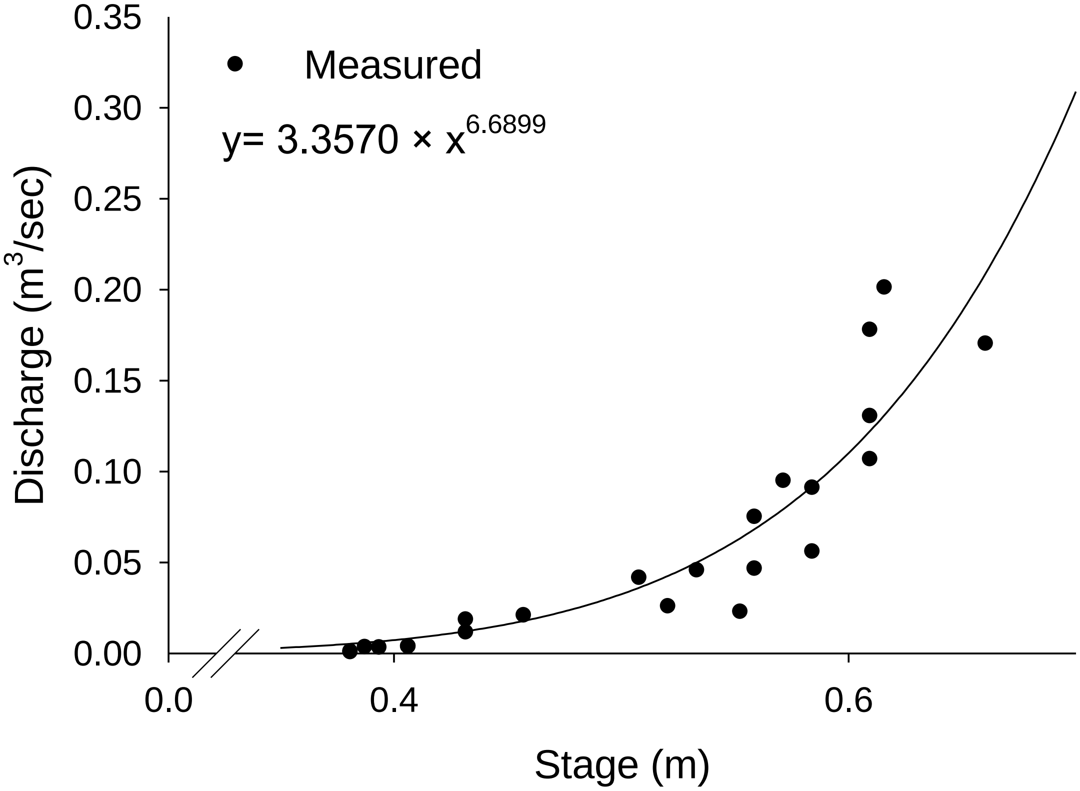

Figure F.1: Discharge as a function of stage for SK-Skinner Creek sub-catchment in the Willow Creek watershed, OR. The least square regression in the form Y = a +X^b is presented as the solid line.

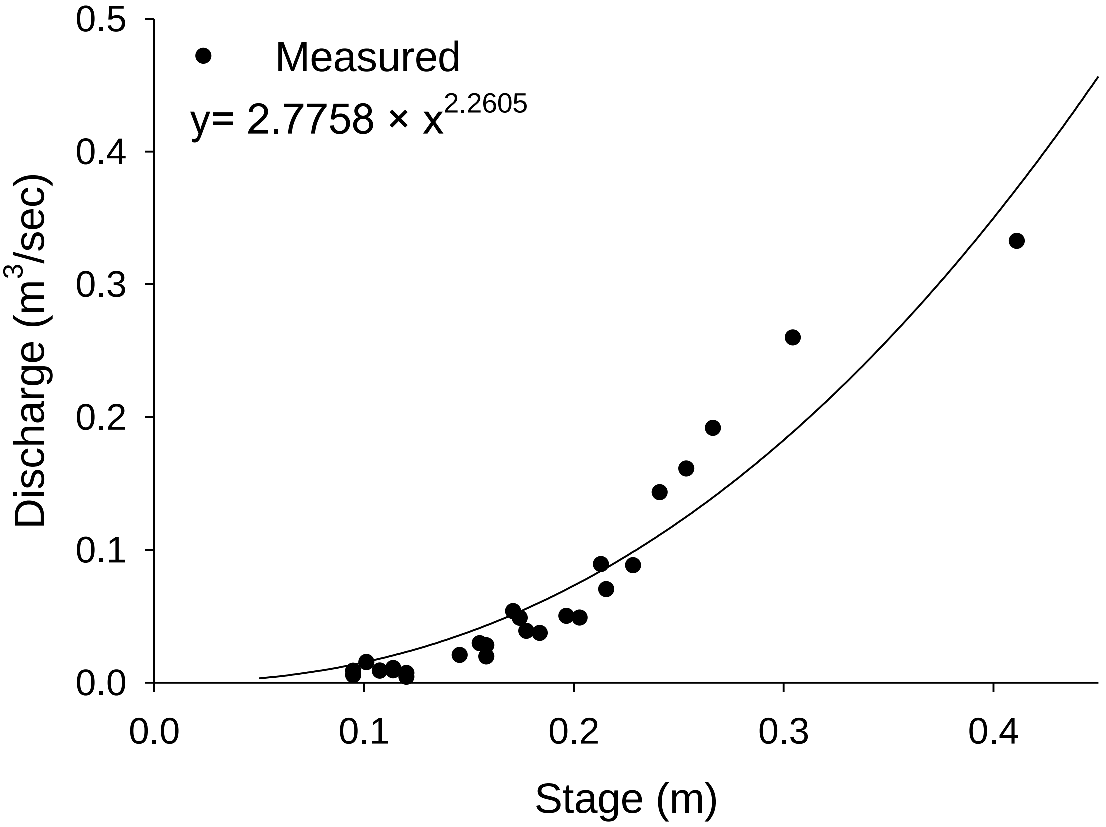

Figure F.2: Discharge as a function of stage for NF-North Fork sub-catchment in the Willow Creek watershed, OR. The least square regression in the form Y = a +X^b is presented as the solid line.

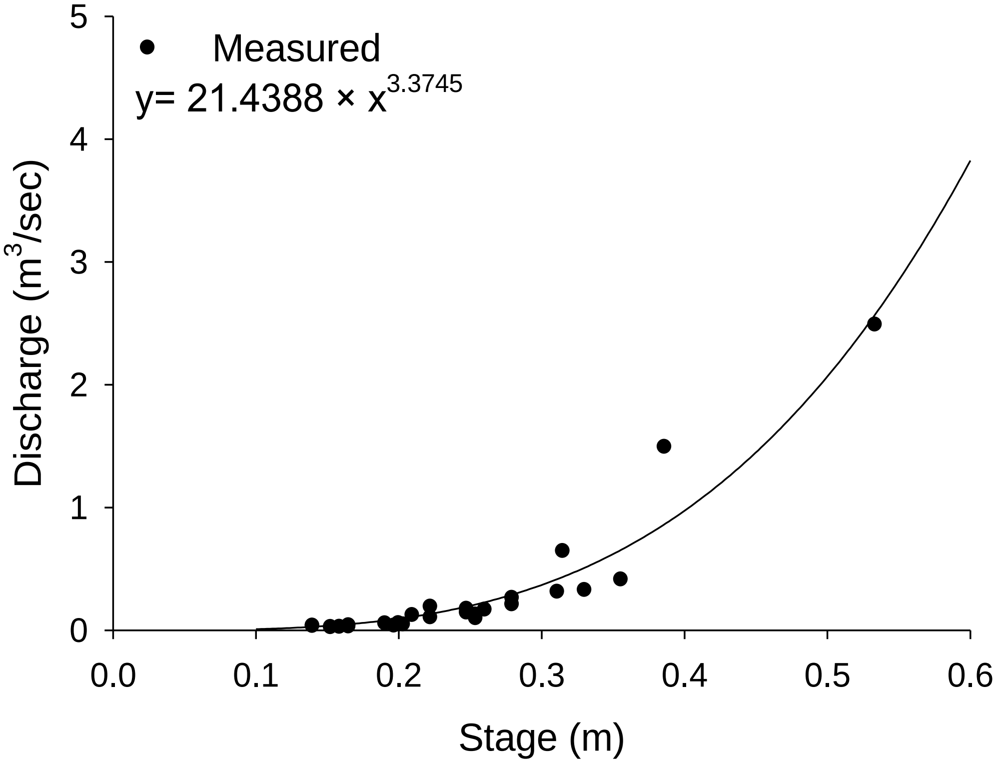

Figure F.3: Discharge as a function of stage for WCH- Willow Creek Headwaters sub-catchment in the Willow Creek watershed, OR. The least square regression in the form Y = a +X^b is presented as the solid line.

Appendix G

Calculation of annual total phosphorus (TP) and total residue (TR) loads using the smearing method (Duan 1983)

Annual sub-catchment total phosphorus (TP) and total residue (TR) loading was calculated using the nonparametric smearing approach (Duan 1983, Colin 1995, Helsel and Hirsch 2002). Using this approach, loads were calculated by multiplying measured nutrient concentrations by the corresponding discharge values (both occurring at 15:00). The natural log of daily nutrient loads was then plotted as a function of the natural log of discharge and a linear relationship was determined. A bias-correction factor was estimated as the mean of the residuals. To estimate daily loading, the linear model and corresponding bias-correction factor was applied to the continuous discharge data for each sub-catchment in the log transformed form:

$$Load = \exp\left[b_o + \ b_1 \ln(Q) \times \frac{\sum_{i=1}^{n} \exp(e_i)}{n}\right]$$

Where Q is discharge (m^3/s), e_i are the residuals, n is the number of residuals, and b_o and b_1 are sub-catchment-specific fitted parameters. The daily loading estimates were summed to estimate annual loads. The Valley Bottom contribution was calculated by difference.

Annual TP (Figure G.1-G.4) and TR (Figure G.5-G.8) loads were graphed versus discharge and a nutrient specific linear relationship was determined for each sub-catchment. The fitted parameters, bias correction factor and corresponding R^2 values for TP and TR loading are presented Table G.1 and G.2, respectively. It is important to note that in high flow events, it is common for hydrologic relationships to have a breakpoint, which is the time in a series when the slope of the trend line changes (Gordon et al. 1999). Using segmented regression, a breakpoint for the natural log of WCH discharge (m^3/s) was estimated at -1.05 (R2 = 0.92). Linear relationships determined were then applied to continuous discharge data to estimate 15 minute interval TP and TR loading for each sub-catchment.

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Table G.1: Fitted parameters, bias-correction factor and corresponding R^2 values used to calculate sub-catchment specific continuous TP loading calculated using the smearing method.

Sub-catchment	b_o	b_1	bias-correction factor	R^2
Inlet	11.31	1.05	1.06	0.94
Skinner Creek	11.41	0.98	1.03	0.96
North Fork	11.07	0.91	1.03	0.90
WC Headwaters	10.91	1.08	1.03	0.96

Table G.2: Fitted parameters, bias-correction factor and corresponding R^2 values used to calculate sub-catchment specific continuous TR loading calculated using the smearing method. A breakpoint of -1.05 was determined for Willow Creek headwaters.

Sub-catchment	b_o	b_1	bias-correction factor	R^2
Inlet	5.17	0.99	1.03	0.97
Skinner Creek	4.48	0.83	1.03	0.94
North Fork	4.98	1.03	1.05	0.88
WC Headwaters (-3.8 to -1.05)	4.67	0.85	1.03	0.89
WC Headwaters (-1.05 to 1.27)	6.35	2.45	1.57	0.67

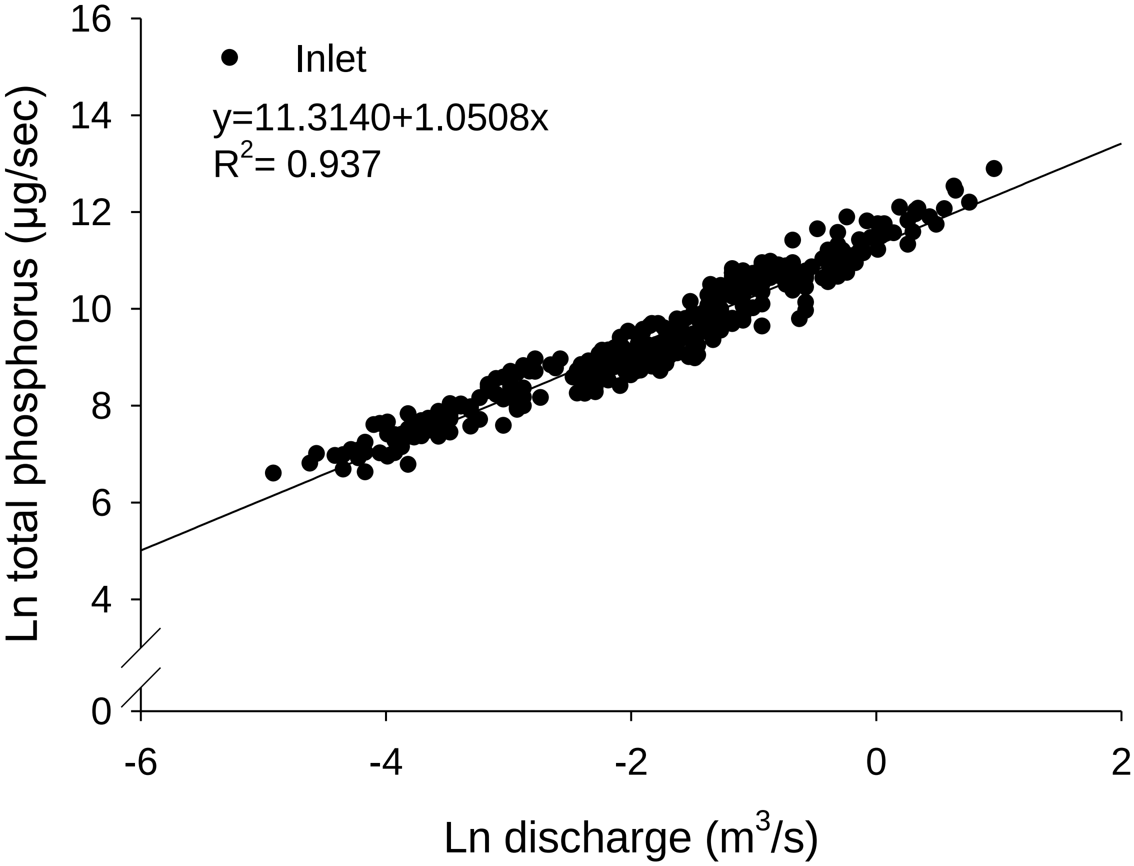


Figure G.1: Ln total phosphorus as a function of discharge for the inlet of Willow Creek Reservoir in the Willow Creek Watershed, OR for the period September 20, 2012 to September 21, 2013.

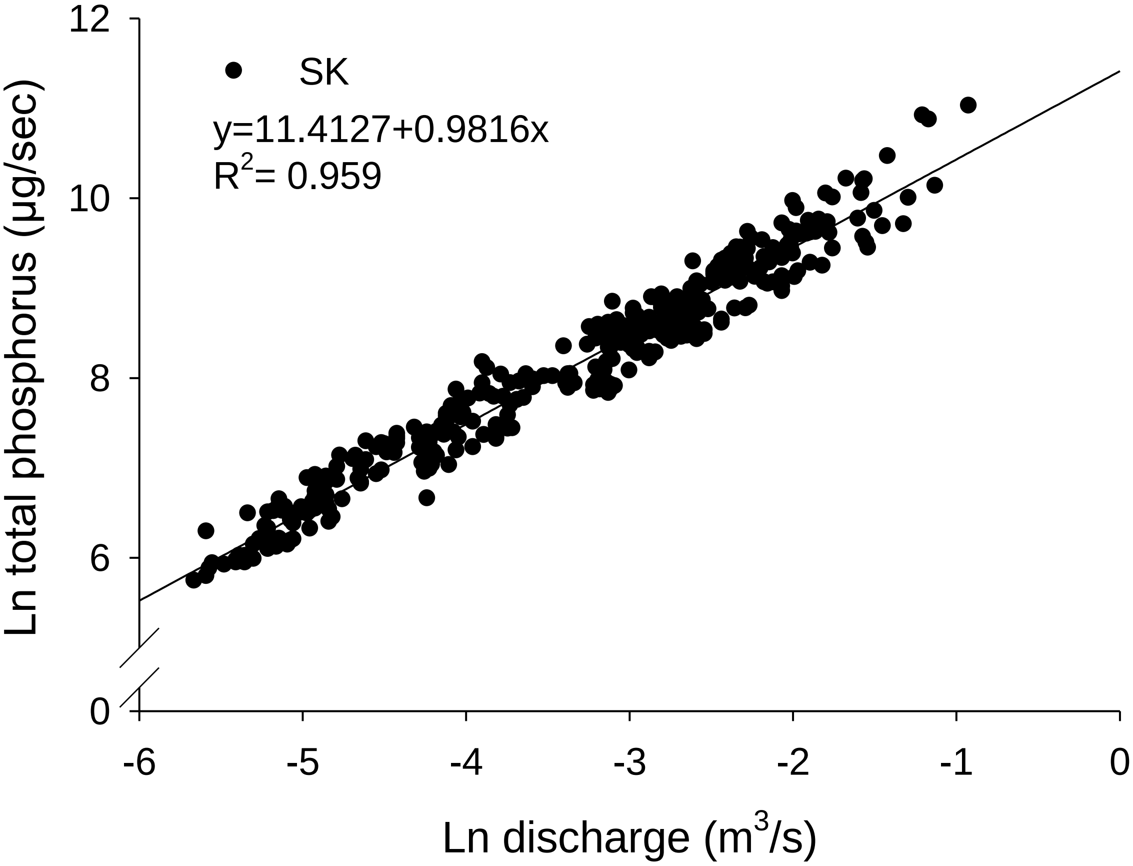


Figure G.2: Ln total phosphorus as a function of discharge for SK- Skinner Creek sub-catchment in the Willow Creek Watershed, OR for the period September 20, 2012 to September 21, 2013.

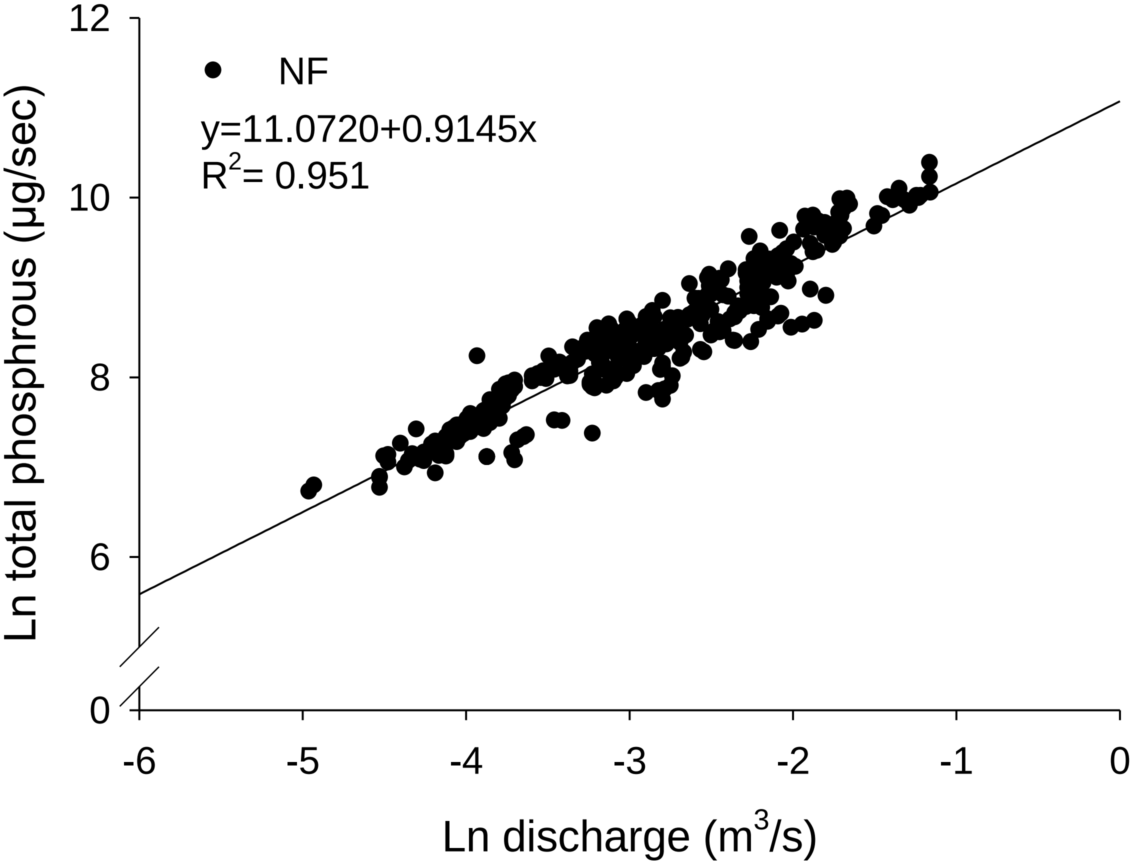


Figure G.3: Ln total phosphorus as a function of discharge for NF- North Fork sub-catchment in the Willow Creek Watershed, OR for the period September 20, 2012 to September 21, 2013.

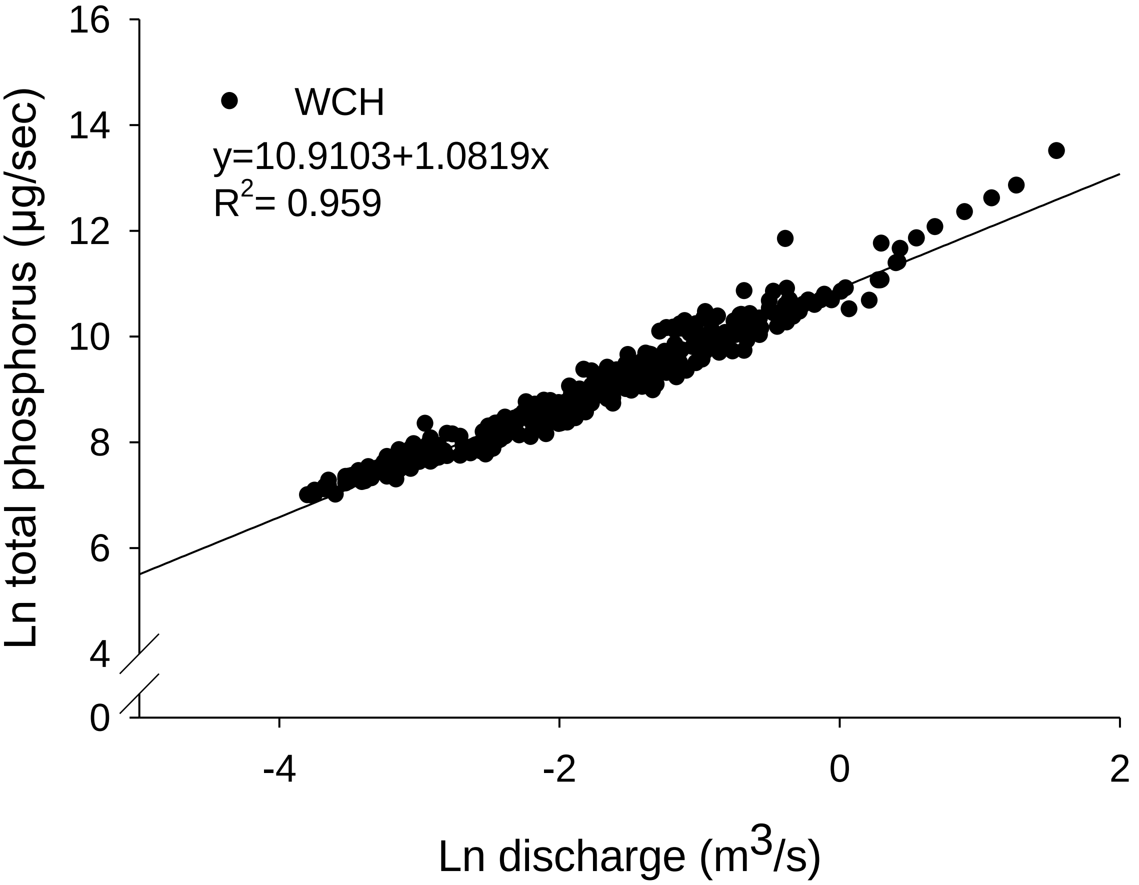


Figure G.4: Ln total phosphorus as a function of discharge for WCH- Willow Creek Headwaters sub-catchment in the Willow Creek Watershed, OR for the period September 20, 2012 to September 21, 2013.

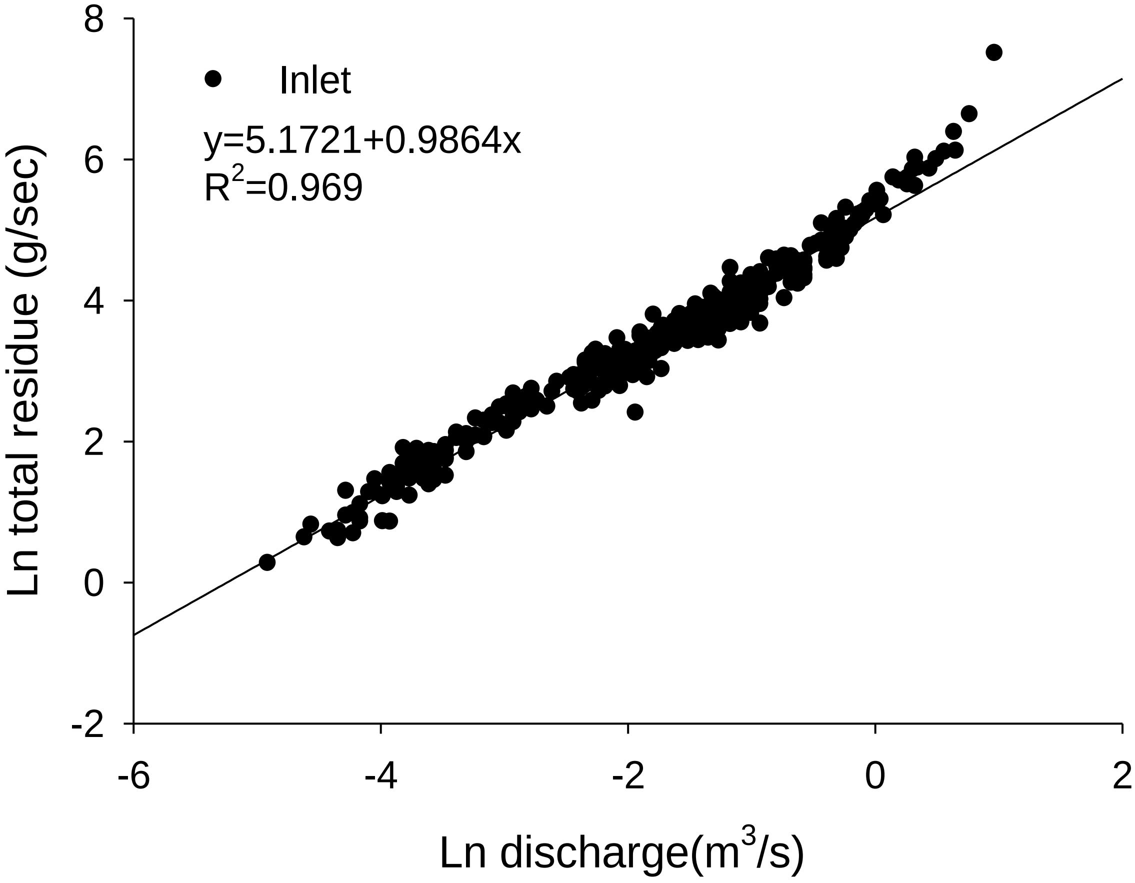


Figure G.5: Ln total residue as a function of discharge for the inlet of Willow Creek Reservoir in the Willow Creek Watershed, OR for the period September 20, 2012 to September 21, 2013.

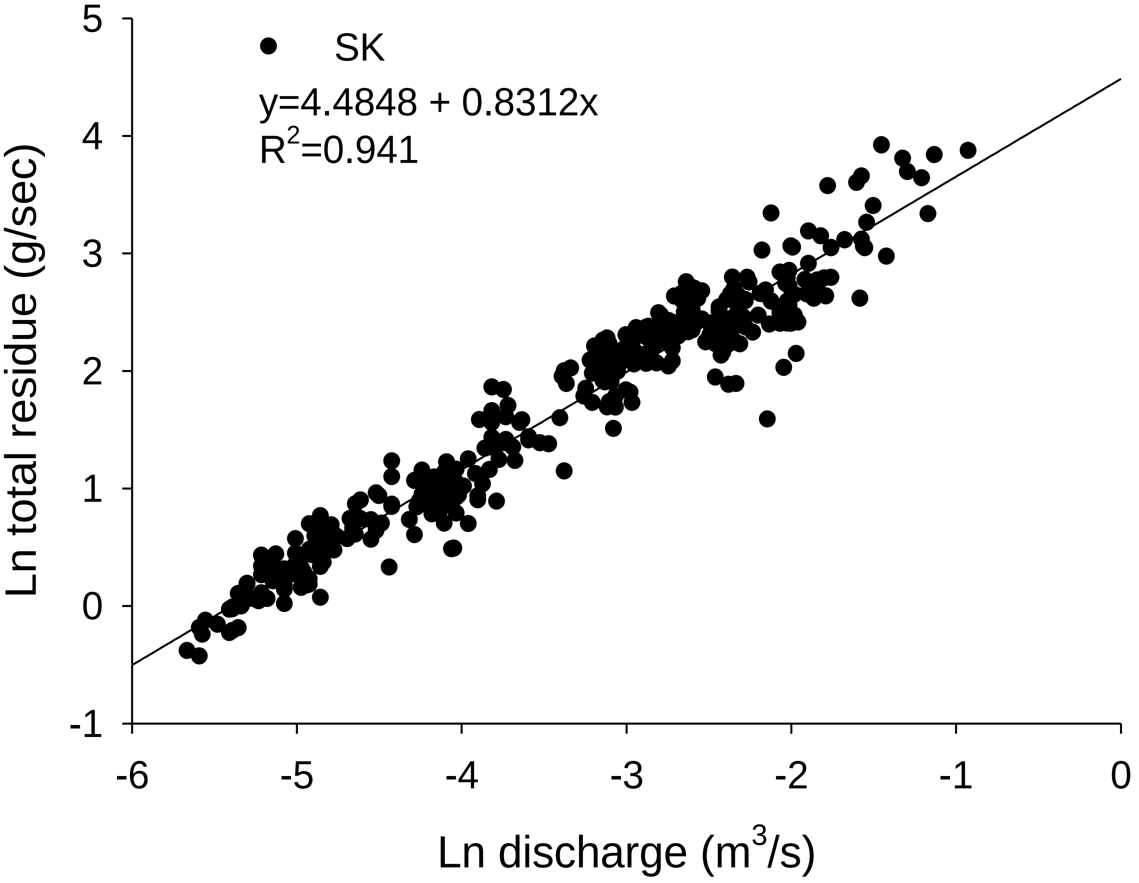


Figure G.6: Ln total residue as a function of discharge for SK- Skinner Creek sub-catchment in the Willow Creek Watershed, OR for the period September 20, 2012 to September 21, 2013.

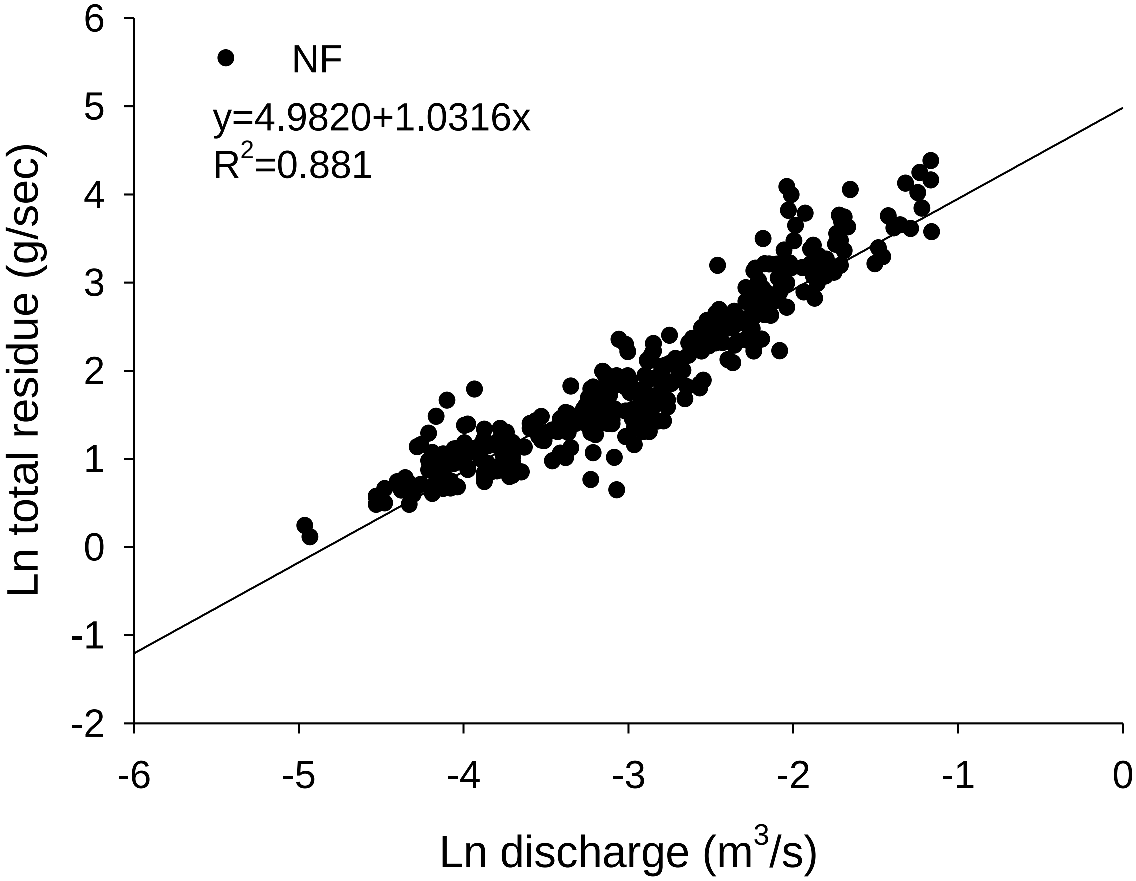


Figure G.7: Ln total residue as a function of discharge for NF- North Fork sub-catchment in the Willow Creek Watershed, OR for the period September 20, 2012 to September 21, 2013.

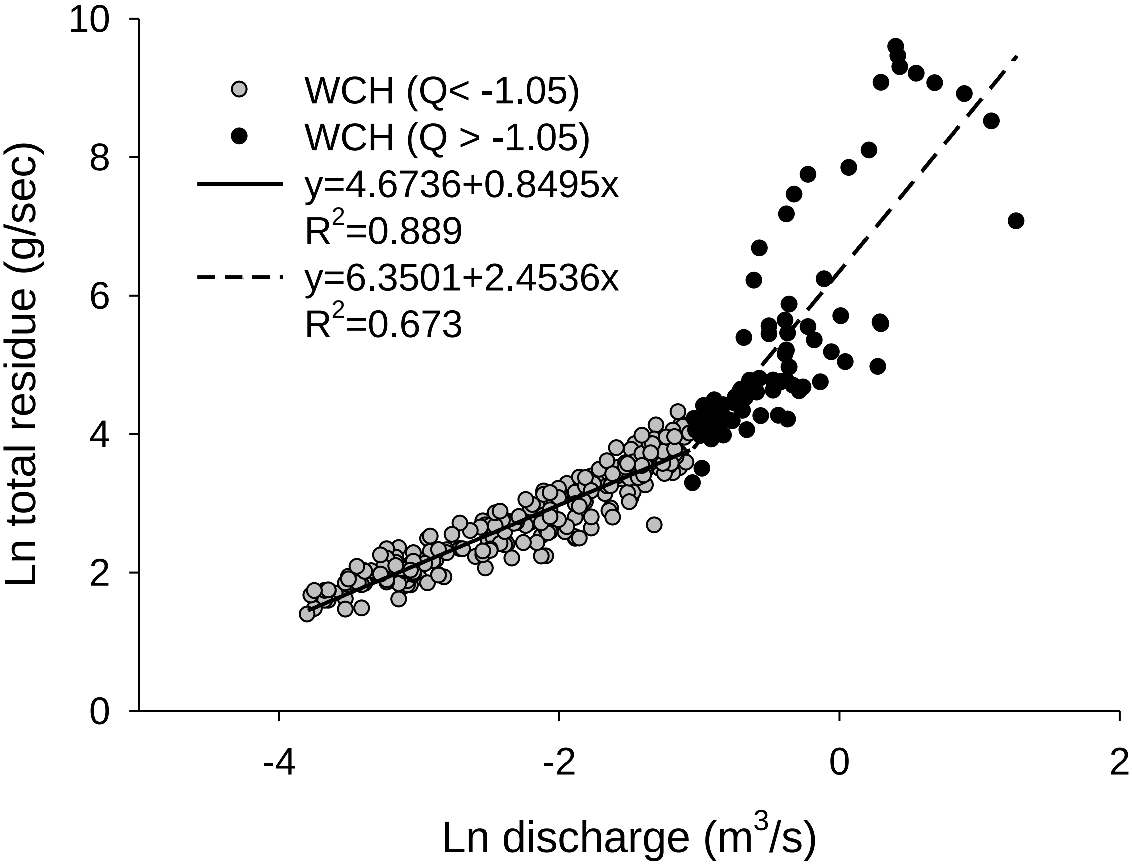


Figure G.8: Ln total residue as a function of discharge for WCH- Willow Creek Headwaters sub-catchment in the Willow Creek Watershed, OR for the period September 20, 2012 to September 21, 2013. Using segmented regression a breakpoint of -1.05 was found, discharge data < -1.05 is presented in grey, data > -1.05 is presented in black.

Appendix H

Daily total phosphorus concentrations for sub-catchments of the Willow Creek watershed

Table H.1: Total phosphorus concentrations [TP] (μg/L) as measured for daily samples for all four sample locations in the Willow Creek watershed. Blank stand errors (SE) signify interpolated [TP].

Date	Inlet [TP]	+/- SE	SK [TP]	+/- SE	NF [TP]	+/- SE	WCH [TP]	+/- SE
22-Sep-12	89.86	1.76	73.48	0.75	109.86	7.26	40.58	3.99
23-Sep-12	88.26	2.64	85.36	1.05	115.22	4.53	41.16	0.77
24-Sep-12	86.96	0.43	77.39	10.78	107.54	0.77	42.03	1.82
25-Sep-12	81.59	1.67	77.97	4.28	114.49	1.95	41.88	2.32
26-Sep-12	84.35	2.55	82.03	2.64	116.96	6.22	41.74	1.51
27-Sep-12	85.80	1.67	73.33	8.67	104.20	7.54	43.77	0.63
28-Sep-12	79.13	0.66	53.77	1.63	111.30	0.50	44.78	0.43
29-Sep-12	60.58	1.43	75.80	2.13	116.09	2.89	46.38	0.58
30-Sep-12	71.59	5.33	110.29	4.03	114.20	6.85	44.78	1.33
1-Oct-12	54.93	1.51	98.55	2.09	110.72	1.59	44.78	0.50
2-Oct-12	67.54	2.90	85.80	3.39	106.96	0.91	45.07	0.81
3-Oct-12	77.10	3.48	67.97	5.60	105.36	0.63	40.00	1.99
4-Oct-12	73.77	3.94	129.28	7.10	111.16	5.76	43.48	1.76
5-Oct-12	65.65	4.35	111.59	1.85	107.25	2.03	43.48	0.91
6-Oct-12	54.39	5.53	79.39	2.00	102.73	2.50	39.55	0.00
7-Oct-12	51.97	1.09	75.45	7.73	101.21	2.26	37.58	0.99
8-Oct-12	55.45	1.64	72.58	4.49	96.82	1.14	41.52	2.00
9-Oct-12	40.45	1.72	73.33	3.43	104.24	0.40	38.79	5.78
10-Oct-12	46.67	2.12	70.15	4.31	104.70	2.76	42.12	1.29
11-Oct-12	51.06	4.27	68.18	3.55	107.58	2.44	38.48	0.55
12-Oct-12	50.30	1.21	69.55	0.69	122.42	3.43	38.18	1.20
13-Oct-12	60.00	0.69	71.06	8.79	106.97	3.13	38.48	2.35
14-Oct-12	52.88	4.37	91.06	4.09	107.27	5.36	34.09	3.09
15-Oct-12	65.91	3.87	90.76	5.30	108.94	0.66	41.82	1.46
16-Oct-12	76.21	3.15	89.24	2.88	100.15	1.45	40.76	1.32
17-Oct-12	75.15	1.84	82.42	0.15	97.88	0.61	40.30	0.80
18-Oct-12	63.79	1.90	77.42	1.45	102.12	1.97	37.12	0.66
19-Oct-12	53.18	2.84	78.33	5.41	103.18	1.64	37.12	2.12
20-Oct-12	63.62	1.61	93.48	1.90	83.19	2.61	48.26	0.50
21-Oct-12	67.10	1.51	82.03	3.07	87.54	4.16	42.17	1.15
22-Oct-12	58.55	1.26	81.59	1.01	98.26	0.66	48.55	0.38
23-Oct-12	62.32	3.86	94.64	1.78	89.42	2.39	41.88	1.05
24-Oct-12	57.39	0.25	104.64	3.42	98.70	1.90	46.09	1.53
25-Oct-12	56.09	2.01	110.14	3.99	86.52	1.96	42.32	1.67
26-Oct-12	53.48	1.00	105.22	1.53	91.01	2.16	45.22	1.81

Table H.1: Continued.

Date	Inlet [TP]	+/- SE	SK [TP]	+/- SE	NF [TP]	+/- SE	WCH [TP]	+/- SE
27-Oct-12	54.93	0.81	103.04	2.89	98.84	1.24	40.29	1.47
28-Oct-12	54.78	1.15	118.84	3.03	81.88	1.82	49.13	1.81
29-Oct-12	67.25	0.38	125.22	1.81	75.51	2.01	57.83	1.33
30-Oct-12	63.19	2.51	102.46	1.90	81.59	3.18	52.61	1.57
31-Oct-12	68.70	1.33	89.13	1.33	68.84	3.07	46.67	1.88
1-Nov-12	76.52	1.90	79.13	1.00	71.16	2.91	45.80	3.66
2-Nov-12	81.01	2.61	74.64	2.11	76.81	2.03	35.65	0.43
3-Nov-12	67.36	0.73	80.69	0.73	104.86	1.08	40.69	1.84
4-Nov-12	61.94	0.69	81.81	1.32	123.75	0.96	34.58	1.25
5-Nov-12	61.67	2.10	83.47	1.45	110.56	1.08	41.53	2.07
6-Nov-12	60.83	0.64	92.36	1.23	114.86	0.73	47.92	0.96
7-Nov-12	96.25	0.48	105.00	4.61	114.31	0.91	40.00	0.87
8-Nov-12	61.11	0.84	100.42	0.72	121.11	0.69	42.08	1.44
9-Nov-12	63.75	0.72	147.36	3.37	107.64	1.53	34.44	0.97
10-Nov-12	62.78	0.91	103.89	1.00	109.44	2.42	30.83	0.87
11-Nov-12	55.28	1.32	94.44	0.69	94.72	0.14	38.33	1.34
12-Nov-12	63.33	0.87	94.58	3.78	99.44	0.61	49.86	0.56
13-Nov-12	60.42	1.05	94.72	0.14	83.49	1.56	45.97	1.00
14-Nov-12	60.97	1.23	92.50	0.87	76.67	1.50	31.81	0.91
15-Nov-12	61.81	1.69	80.42	3.47	75.00	1.10	32.92	0.96
16-Nov-12	81.06	2.89	70.15	1.69	67.88	1.06	34.24	0.66
17-Nov-12	72.88	0.92	64.70	2.64	69.39	0.40	29.39	1.67
18-Nov-12	94.09	2.05	64.09	0.52	66.67	1.84	29.85	0.80
19-Nov-12	81.52	2.23	61.82	2.05	66.82	1.89	30.61	0.40
20-Nov-12	83.79	2.12	68.03	1.84	68.18	1.14	34.39	0.15
21-Nov-12	86.67	2.00	65.15	3.06	71.67	1.71	33.94	1.75
22-Nov-12	88.48	1.35	75.45	2.24	64.09	2.15	31.21	1.67
23-Nov-12	89.39	1.45	70.30	1.86	62.58	1.35	30.76	1.32
24-Nov-12	66.21	1.58	58.79	1.18	62.42	1.24	50.91	0.95
25-Nov-12	83.33	1.35	60.45	1.72	65.45	1.05	50.15	0.84
26-Nov-12	81.67	0.80	59.39	0.66	68.03	0.99	45.61	2.19
27-Nov-12	77.73	1.60	57.12	1.32	66.52	1.06	51.67	0.84
28-Nov-12	63.03	1.97	63.94	1.54	64.85	2.12	53.18	1.20
29-Nov-12	62.88	1.35	61.82	1.14	62.12	1.18	47.27	1.39
30-Nov-12	74.09	1.05	62.58	0.30	63.64	1.20	48.03	1.18
1-Dec-12	61.11	0.61	133.61	2.22	79.86	1.21	50.14	1.96
2-Dec-12	181.25	3.15	130.00	5.01	102.92	2.68	202.22	6.87

Table H.1: Continued.

Date	Inlet [TP]	+/- SE	SK [TP]	+/- SE	NF [TP]	+/- SE	WCH [TP]	+/- SE
3-Dec-12	59.86	1.14	112.92	2.10	76.11	1.71	77.64	1.45
4-Dec-12	49.72	1.81	111.11	2.24	69.31	2.24	78.75	2.10
5-Dec-12	56.25	2.84	124.72	2.57	75.28	0.91	47.78	1.21
6-Dec-12	48.89	1.37	113.19	0.50	78.89	2.10	44.58	3.00
7-Dec-12	52.22	1.57	111.25	2.93	72.92	2.55	54.72	1.69
8-Dec-12	52.08	1.10	105.42	0.87	70.14	0.91	53.33	2.32
9-Dec-12	50.14	3.64	103.89	2.85	68.19	1.19	45.56	0.84
10-Dec-12	56.81	2.41	101.11	1.23	66.67	0.48	43.61	0.14
11-Dec-12	53.47	2.68	98.89	1.57	81.81	1.45	50.97	2.90
12-Dec-12	59.72	4.50	104.44	1.74	85.28	1.84	44.44	1.81
13-Dec-12	40.90	2.67	77.95	3.30	73.21	2.16	37.95	0.56
14-Dec-12	42.82	1.81	77.44	0.92	79.36	1.67	42.82	0.84
15-Dec-12	45.38	1.18	100.26	3.24	90.26	1.22	35.77	1.55
16-Dec-12	44.62	3.32	92.56	1.79	75.38	0.67	30.38	0.22
17-Dec-12	44.87	0.46	94.87	1.36	75.26	0.78	27.82	1.22
18-Dec-12	51.41	2.78	92.44	3.03	79.49	2.76	42.31	2.14
19-Dec-12	48.97	3.24	96.92	2.44	81.28	1.30	39.87	0.34
20-Dec-12	50.38	2.12	106.41	3.12	79.23	0.89	36.79	0.68
21-Dec-12	48.46	2.99	108.85	1.18	86.67	1.22	35.51	0.34
22-Dec-12	46.03	0.92	115.13	4.16	76.41	0.13	43.97	0.46
23-Dec-12	47.95	3.24	108.46	0.59	79.74	0.71	35.64	0.90
24-Dec-12	62.05	1.00	83.97	1.44	72.95	1.36	34.62	0.38
25-Dec-12	41.28	1.89	89.49	3.11	71.28		38.72	0.90
26-Dec-12	47.82	2.06	60.51	2.53	69.62		38.72	0.92
27-Dec-12	47.69	2.12	97.95	3.98	67.95	0.46	38.46	2.25
28-Dec-12	48.33	1.89	83.08	2.69	81.15	1.73	40.13	0.92
29-Dec-12	45.52	1.24	80.34	1.74	58.16	0.70	29.08	1.78
30-Dec-12	35.52	1.82	75.29	3.43	58.20		31.49	0.50
31-Dec-12	50.80	0.11	95.75	2.40	58.24		33.33	0.61
1-Jan-13	43.79	1.19	80.00	1.74	58.28		34.48	
2-Jan-13	43.16		76.38		58.31		35.63	
3-Jan-13	42.53	0.41	72.76	3.35	58.35		36.78	
4-Jan-13	42.30	2.13	69.31	1.44	58.39	2.49	37.93	0.91
5-Jan-13	40.29		67.30		52.30	0.90	30.80	0.94
6-Jan-13	38.28	0.72	65.29	2.18	47.47	2.67	33.91	3.80
7-Jan-13	54.94	1.44	63.79	3.29	55.06	1.02	38.62	2.30
8-Jan-13	57.13	1.60	75.52	4.71	39.77	2.18	40.34	1.63
9-Jan-13	104.83	2.08	84.94	1.33	37.82	1.99	44.37	1.17
10-Jan-13	126.67	2.04	77.70	0.98	42.53	1.49	43.45	0.91
11-Jan-13	104.83	1.21	79.89	0.80	44.90		47.47	1.60

Table H.1: Continued.

Date	Inlet [TP]	+/- SE	SK [TP]	+/- SE	NF [TP]	+/- SE	WCH [TP]	+/- SE
12-Jan-13	67.44	4.95	62.78	1.87	47.26		41.00	1.90
13-Jan-13	49.00	2.31	63.56	1.85	49.63		40.62	
14-Jan-13	54.56	1.68	64.56	1.75	52.00	1.84	40.24	
15-Jan-13	46.33	2.14	63.56	1.47	56.00	3.24	39.87	
16-Jan-13	44.11	0.87	63.22	5.71	53.56	0.56	39.49	
17-Jan-13	43.94		67.56	2.23	53.22	2.44	39.11	0.95
18-Jan-13	43.78	1.31	61.11	5.44	53.44	2.26	31.56	0.87
19-Jan-13	34.89	1.06	62.44	2.61	76.67	5.32	37.89	0.87
20-Jan-13	36.78		64.67		54.22	0.40	34.89	2.19
21-Jan-13	38.67		66.89	2.04	56.44	2.23	38.78	2.35
22-Jan-13	40.56		68.33		41.89	0.87	45.22	2.12
23-Jan-13	42.44		69.78		41.78	2.04	42.33	2.50
24-Jan-13	44.33	1.00	71.22	4.06	46.11	2.80	41.00	0.51
25-Jan-13	98.97	1.11	121.95	1.22	108.16	1.28	80.23	1.99
26-Jan-13	115.06	1.41	146.32	0.98	92.53	1.13	84.14	1.77
27-Jan-13	101.61	0.94	115.98	1.22	83.45	1.11	56.44	0.57
28-Jan-13	97.24	1.58	113.91	1.49	77.70	2.19	57.24	1.59
29-Jan-13	91.38	1.63	109.08	4.26	82.64	0.83	60.34	1.58
30-Jan-13	97.24	2.59	108.39	3.05	88.51	1.55	61.15	1.20
31-Jan-13	174.71	1.36	183.33	5.91	83.68	1.62	75.63	0.41
1-Feb-13	180.92	1.00	154.25	4.25	92.64	0.50	76.21	0.80
2-Feb-13	141.95	1.28	168.51	0.70	94.14	1.74	87.59	2.81
3-Feb-13	116.44	2.90	144.60	0.50	78.28	2.41	85.17	0.87
4-Feb-13	106.90	12.42	144.71	1.20	91.84	2.39	85.17	1.11
5-Feb-13	83.33	1.51	138.85	1.00	77.36	1.81	87.36	6.68
6-Feb-13	75.75	1.28	141.38	2.02	83.10	1.00	85.98	2.49
7-Feb-13	86.39		130.34	0.72	95.17	2.30	89.54	0.83
8-Feb-13	97.02	1.46	128.45	2.27	71.07	2.03	57.38	0.43
9-Feb-13	110.95	3.43	127.50	1.97	80.60	2.08	60.00	1.44
10-Feb-13	92.86	0.36	99.52	0.66	60.83	1.92	51.67	0.78
11-Feb-13	90.48	0.72	98.81	1.96	47.50	1.09	52.38	0.66
12-Feb-13	95.95	0.93	91.31	1.34	74.52	3.40	48.21	0.94
13-Feb-13	85.95	1.37	84.88	0.63	57.02	1.06	42.14	0.74
14-Feb-13	83.57	0.41	97.86	2.79	74.76	1.34	43.93	0.71
15-Feb-13	91.90	0.97	97.14	0.74	72.26	1.86	45.60	0.63
16-Feb-13	92.98	3.64	126.90	1.95	59.52	2.07	48.93	0.90
17-Feb-13	90.24	3.29	117.74	0.31	60.95	2.72	62.62	1.87
18-Feb-13	55.36	0.82	121.79	0.62	70.60	1.78	55.24	0.66
19-Feb-13	50.12	0.63	124.64	0.82	63.45	1.45	49.64	0.62
20-Feb-13	50.95	0.31	124.76	1.40	64.17	3.71	47.74	0.52

Table H.1: Continued.

Date	Inlet [TP]	+/- SE	SK [TP]	+/- SE	NF [TP]	+/- SE	WCH [TP]	+/- SE
21-Feb-13	52.02	0.93	111.31	0.31	63.45	1.14	43.69	0.72
22-Feb-13	53.69	1.14	115.60	0.78	67.02	1.57	53.93	0.41
23-Feb-13	56.22	1.66	92.11	1.68	55.89	1.13	32.22	0.78
24-Feb-13	38.22	0.78	84.89	1.85	60.67	0.88	57.78	2.88
25-Feb-13	34.22	1.56	88.11	0.99	57.22	1.35	58.67	2.52
26-Feb-13	43.11	0.59	87.33	0.84	56.33	0.51	56.11	1.49
27-Feb-13	35.44	0.62	85.67	2.03	59.00	0.38	40.11	1.16
28-Feb-13	39.11	1.25	79.67	2.55	61.22	1.16	36.56	0.68
1-Mar-13	38.22	1.06	90.11	1.28	64.00	0.88	45.78	0.62
2-Mar-13	62.11	2.32	90.44	1.16	65.11	1.16	81.11	1.16
3-Mar-13	64.33	1.58	98.33	0.77	77.78	5.19	101.11	1.61
4-Mar-13	43.67	1.39	93.44	0.59	73.44	0.91	75.00	0.77
5-Mar-13	32.78	1.06	90.22	0.80	79.11	0.78	65.78	0.87
6-Mar-13	36.89	2.00	93.44	0.73	77.56	3.99	51.33	1.64
7-Mar-13	59.78	1.16	100.11	0.78	72.89	1.85	63.00	1.20
8-Mar-13	76.28	2.24	111.54	0.44	78.46	1.76	59.10	2.31
9-Mar-13	77.56	2.71	61.28	0.78	81.92	0.89	35.64	0.90
10-Mar-13	60.13	1.34	88.59	5.11	77.56	1.79	50.00	1.02
11-Mar-13	74.49	1.56	72.31	2.56	86.28	1.99	53.33	3.46
12-Mar-13	71.54	2.04	69.36	1.48	120.64	2.83	57.18	1.10
13-Mar-13	85.26	3.27	72.31	1.24	97.18	0.78	62.95	2.24
14-Mar-13	78.72	1.22	68.33	0.92	121.15	1.68	78.08	0.44
15-Mar-13	97.44	1.22	58.72	1.26	104.23	2.04	57.56	1.26
16-Mar-13	89.23	1.55	112.44	2.45	105.26	4.44	69.87	0.92
17-Mar-13	78.59	2.57	100.00	0.44	118.59	2.01	61.28	0.46
18-Mar-13	57.69	1.46	96.67	0.34	116.54	1.55	52.44	1.05
19-Mar-13	55.64	1.94	98.97	1.05	105.64	2.10	48.08	1.18
20-Mar-13	57.31	0.80	103.85	0.80	114.10	1.00	54.03	
21-Mar-13	64.49	0.78	87.31	2.00	86.79	1.58	59.99	
22-Mar-13	59.62	2.56	95.77	0.67	76.92	1.18	65.95	
23-Mar-13	94.64	1.49	72.62	2.58	75.78		71.90	3.02
24-Mar-13	82.38	1.75	90.24	0.72	74.64	0.41	58.57	0.74
25-Mar-13	72.86	1.80	87.86	0.90	101.31	1.04	50.95	1.06
26-Mar-13	81.55	1.26	99.17	1.40	86.43	1.44	49.17	1.06
27-Mar-13	82.98	0.66	98.69	0.93	77.62	1.75	43.57	0.62
28-Mar-13	86.90	3.30	102.86	1.69	105.95	3.40	48.93	1.24
29-Mar-13	110.12	3.26	112.98	2.52	100.00	2.58	66.90	0.83
30-Mar-13	122.98	0.86	120.95	3.51	90.12	2.07	65.83	0.97
31-Mar-13	144.76	1.92	109.88	0.72	102.86	0.90	60.48	2.56
1-Apr-13	118.93	0.82	109.40	2.37	97.94		61.90	2.07

Table H.1: Continued.

Date	Inlet [TP]	+/- SE	SK [TP]	+/- SE	NF [TP]	+/- SE	WCH [TP]	+/- SE
2-Apr-13	121.67	1.56	125.12	0.93	93.02		57.62	1.49
3-Apr-13	130.00	3.32	107.14	1.97	88.10		53.33	0.72
4-Apr-13	110.95	1.96	119.17	0.66	83.17		47.02	1.26
5-Apr-13	143.33	3.53	119.17	1.04	78.25		46.90	1.40
6-Apr-13	75.24	1.49	128.69	1.04	73.33	3.39	47.02	1.37
7-Apr-13	92.74	1.60	103.93	0.62	87.86	2.68	51.67	1.21
8-Apr-13	102.62	2.17	100.24	1.98	75.24	3.31	49.17	0.86
9-Apr-13	72.26	2.34	99.64	0.90	77.02	1.87	46.19	3.42
10-Apr-13	77.86	0.62	97.26	1.24	74.29	3.24	45.71	2.58
11-Apr-13	75.83	1.40	115.83	3.46	72.02	0.83	41.90	0.97
12-Apr-13	80.83	0.52	103.21	1.97	79.05	2.74	39.52	1.37
13-Apr-13	65.83	3.75	78.69	1.26	92.86	1.83	39.05	0.52
14-Apr-13	92.50	1.56	89.88	0.93	85.00	2.27	42.98	0.52
15-Apr-13	72.86	2.15	99.29	1.44	90.71	1.35	37.38	1.92
16-Apr-13	64.40	1.56	116.79	1.80	76.19	1.21	33.93	1.89
17-Apr-13	72.98	0.93	123.57	2.50	80.00	1.29	44.40	1.14
18-Apr-13	71.79	3.00	122.02	1.14	71.07	0.62	47.62	0.52
19-Apr-13	142.14	2.47	156.31	0.72	102.98	3.10	153.81	3.40
20-Apr-13	148.69	35.53	127.14	2.58	44.17	0.86	106.55	1.65
21-Apr-13	90.71	0.74	61.43	1.09	52.02	2.03	100.02	
22-Apr-13	97.50	0.82	68.21	1.49	35.83	0.86	93.50	
23-Apr-13	78.10	1.14	86.31	1.72	37.02	1.37	86.98	
24-Apr-13	62.86	1.09	87.74	1.60	38.21	1.15	80.45	
25-Apr-13	92.86	3.52	70.71	1.35	46.90	1.78	73.93	1.44
26-Apr-13	97.62	1.46	66.43	2.43	48.45	2.54	58.21	2.03
27-Apr-13	97.14	4.32	104.52	6.30	47.14	0.94	57.86	0.94
28-Apr-13	102.50	2.58	132.86	1.44	63.45	1.21	93.33	2.78
29-Apr-13	62.86	4.55	131.90	1.45	45.48	1.14	34.52	0.66
30-Apr-13	93.45	3.49	113.69	1.37	41.79	1.09	33.93	1.44
1-May-13	95.95	4.23	109.76	1.24	62.74	1.75	50.12	1.06
2-May-13	109.17	1.87	112.62	0.83	46.55	1.45	53.33	1.55
3-May-13	109.88	1.33	127.38	2.39	61.07	1.61	53.50	
4-May-13	118.33	2.03	112.74	1.68	79.40	1.14	53.67	
5-May-13	113.10	1.14	153.69	0.31	83.10	2.34	53.83	
6-May-13	128.81	1.60	135.48	2.49	63.69	2.08	54.00	
7-May-13	132.86	2.73	158.57	2.68	107.86	2.86	54.17	2.98
8-May-13	140.95	1.72	174.29	3.93	99.40	4.94	32.74	0.97
9-May-13	145.71	0.41	123.69	2.89	102.26	2.42	35.12	1.45
10-May-13	136.31	3.55	115.36	0.82	97.98	5.04	37.62	3.16
11-May-13	146.19	2.78	122.14	5.08	100.12	2.39	49.29	0.90

Table H.1: Continued.

Date	Inlet [TP]	+/- SE	SK [TP]	+/- SE	NF [TP]	+/- SE	WCH [TP]	+/- SE
12-May-13	137.02	2.00	124.64	6.23	91.55	6.87	53.33	0.72
13-May-13	129.52	3.21	137.62	3.29	91.67	2.26	50.60	0.63
14-May-13	159.05	2.12	129.05	7.94	84.76	2.86	47.62	2.20
15-May-13	123.69	2.34	150.48	1.96	95.12	2.27	46.19	1.80
16-May-13	145.60	1.14	111.43	1.25	82.02	0.66	40.95	1.52
17-May-13	135.00	4.44	126.79	1.44	88.93	2.97	38.57	3.32
18-May-13	115.36	4.12	122.50	1.24	75.36	1.56	35.60	0.97
19-May-13	144.17	4.75	117.14	1.15	82.26	2.30	32.02	1.45
20-May-13	113.69	4.86	104.29	2.17	115.95	1.37	41.79	1.83
21-May-13	119.29	2.86	105.71	1.07	113.81	5.59	45.12	0.48
22-May-13	95.48	2.56	92.62	3.86	110.71	2.77	47.98	3.20
23-May-13	89.17	5.36	90.24	0.83	92.86	2.23	44.17	5.23
24-May-13	91.79	5.06	96.79	5.19	135.71	2.68	40.95	2.49
25-May-13	90.83	2.19	96.79	1.49	100.12	1.87	40.95	2.49
26-May-13	96.90	1.17	102.14	4.72	97.98	1.33	42.50	4.32
27-May-13	92.02	1.65	98.21	5.26	90.36	1.29	43.93	5.11
28-May-13	83.93	4.64	102.50	1.24	98.33	1.14	41.19	1.26
29-May-13	105.00	1.99	100.00	6.74	97.74	0.24	45.48	2.27
30-May-13	83.93	0.90	104.29	5.40	94.17	0.83	51.31	1.14
31-May-13	86.31	1.75	101.90	1.92	93.33	0.31	44.88	1.17
1-Jun-13	86.43	3.12	71.43	0.94	85.12	0.72	40.60	0.97
2-Jun-13	108.93	0.71	105.00	1.49	95.48	0.66	42.38	0.97
3-Jun-13	94.76	1.96	81.19	3.04	91.90	1.04	45.48	1.14
4-Jun-13	135.86	1.31	126.32	0.83	81.49	1.00	39.20	1.10
5-Jun-13	132.30	2.39	116.67	2.99	88.97	1.11	43.91	1.10
6-Jun-13	122.18	0.83	82.53	0.75	84.48	1.39	54.48	0.87
7-Jun-13	139.43	0.90	71.72	2.19	87.01	5.71	46.44	0.61
8-Jun-13	112.41	1.11	76.55	3.19	92.18	5.32	44.60	0.70
9-Jun-13	107.59	2.59	98.16	2.04	108.39	1.81	48.16	1.17
10-Jun-13	114.48	0.72	81.26	3.39	93.56	1.36	46.09	0.83
11-Jun-13	112.41	0.91	111.84	1.28	94.83	2.42	43.68	1.72
12-Jun-13	96.90	0.72	127.36	1.00	99.66	0.72	43.91	1.10
13-Jun-13	54.37	1.20	98.62	2.19	72.07	1.59	29.77	0.98
14-Jun-13	56.90	1.70	119.20	1.22	112.87	0.75	34.25	1.22
15-Jun-13	71.26	2.13	114.60	1.13	91.15	0.75	36.78	0.75
16-Jun-13	61.61	0.30	132.30	2.31	98.97	2.79	30.69	0.53
17-Jun-13	56.67	3.61	131.03	1.21	107.70	0.75	37.47	0.30
18-Jun-13	80.00	1.29	118.69	1.04	124.64	1.35	52.02	2.69
19-Jun-13	75.83	3.78	108.69	0.63	100.36	2.47	47.14	1.15
20-Jun-13	66.43	1.09	87.14	0.41	98.57	3.24	46.90	0.24

Table H.1: Continued.

Date	Inlet [TP]	+/- SE	SK [TP]	+/- SE	NF [TP]	+/- SE	WCH [TP]	+/- SE
21-Jun-13	57.02	2.48	106.19	1.49	113.21	11.35	58.45	1.17
22-Jun-13	62.38	3.62	107.50	0.90	102.38	2.69	53.81	0.86
23-Jun-13	64.05	1.98	110.36	0.62	105.12	2.59	53.45	1.24
24-Jun-13	80.95	1.95	111.90	1.26	107.86	0.74	49.40	0.93
25-Jun-13	71.43	1.15	116.31	1.37	97.50	2.17	58.57	1.15
26-Jun-13	57.02	0.52	95.12	2.81	104.52	1.92	36.67	1.49
27-Jun-13	74.76	3.61	94.88	2.72	114.64	2.89	51.67	2.12
28-Jun-13	75.48	1.06	99.77		95.48	2.28	50.12	0.43
29-Jun-13	65.36	3.17	104.65		115.24	1.75	41.90	0.52
30-Jun-13	52.26	4.25	109.54		103.33	0.63	69.29	0.74
1-Jul-13	63.69	2.63	114.42		117.14	0.74	50.48	0.52
2-Jul-13	85.52	3.45	119.31	2.81	92.99	0.41	49.08	0.23
3-Jul-13	102.07	3.72	94.94	1.93	93.91	1.89	49.31	0.80
4-Jul-13	96.32	0.61	96.67	1.99	81.38	1.59	43.10	2.61
5-Jul-13	93.91	1.66	128.39	0.64	88.39	1.80	44.37	1.30
6-Jul-13	72.41	1.31	125.06	1.51	89.08	1.55	47.01	2.26
7-Jul-13	85.29	1.10	127.70	2.24	94.37	2.30	45.75	0.70
8-Jul-13	86.55	0.87	129.08	1.00	89.77	1.22	48.05	0.90
9-Jul-13	95.98	0.30	147.24	1.00	89.89	2.15	45.17	0.60
10-Jul-13	53.22	1.22	126.90	0.87	88.62	1.21	44.02	0.41
11-Jul-13	83.91	1.99	102.53	0.75	75.29	1.61	46.32	1.17
12-Jul-13	61.61	1.26	95.52	0.40	87.13	2.19	38.97	0.34
13-Jul-13	69.43	1.30	93.79	1.05	77.24	1.21	31.95	0.83
14-Jul-13	51.38	0.72	75.40	1.22	79.31	0.34	33.22	0.61
15-Jul-13	74.25	1.74	78.51	0.90	81.95	1.20	37.82	0.23
16-Jul-13	109.46	1.12	133.55	3.94	82.77		46.88	1.32
17-Jul-13	100.75	0.39	132.15	0.94	83.58		48.71	1.12
18-Jul-13	116.67	0.57	147.53	1.03	84.39		48.49	0.84
19-Jul-13	113.01	0.28	89.25	1.41	85.20		51.08	0.94
20-Jul-13	123.33	2.50	137.85	1.63	86.02		53.01	1.67
21-Jul-13	117.85	0.94	119.14	2.08	86.83		50.43	0.75
22-Jul-13	106.77	0.49	121.72	0.39	87.64		46.13	1.04
23-Jul-13	106.56	1.68	123.23	1.16	88.45		51.83	0.92
24-Jul-13	81.94	2.07	113.66	1.37	89.26		40.00	0.81
25-Jul-13	97.96	2.48	116.56	1.51	90.08		54.41	1.97
26-Jul-13	83.55	0.74	114.95	0.94	90.89		49.35	0.49
27-Jul-13	70.97	1.04	119.68	1.04	91.70		47.31	1.09
28-Jul-13	60.32	0.93	140.22	0.92	92.51		49.89	2.33
29-Jul-13	55.16	1.04	143.66	1.21	93.33		52.58	1.80
30-Jul-13	71.26	1.51	136.09	0.61	94.14	0.60	53.10	0.53

Table H.1: Continued.

Date	Inlet [TP]	+/- SE	SK [TP]	+/- SE	NF [TP]	+/- SE	WCH [TP]	+/- SE
31-Jul-13	82.30	2.54	131.26	1.49	98.74	2.31	56.78	1.10
1-Aug-13	77.59	1.82	99.66	1.05	100.69	1.55	48.85	1.61
2-Aug-13	68.28	3.13	98.97	1.19	87.36	1.91	47.82	0.41
3-Aug-13	77.47	1.33	94.48	1.21	82.87	0.50	51.26	1.30
4-Aug-13	89.20	0.83	98.62	0.69	93.45	2.60	59.08	1.17
5-Aug-13	86.67	2.38	100.80	0.70	85.29	0.94	52.41	1.31
6-Aug-13	86.44	2.26	104.83	1.11	85.63	0.64	50.57	1.10
7-Aug-13	39.31	1.31	103.33	1.80	90.11	0.80	56.21	1.19
8-Aug-13	118.51	1.44	95.86	1.21	85.29	1.10	54.94	0.50
9-Aug-13	111.72	1.21	130.69	0.87	86.21	1.21	58.62	1.05
10-Aug-13	111.84	2.19	110.92	1.55	89.89	0.94	55.29	1.02
11-Aug-13	47.70	0.61	96.09	1.51	66.78	1.00	47.36	1.28
12-Aug-13	115.29	1.28	101.84	1.62	90.11	0.50	51.61	0.61
13-Aug-13	111.49	0.90	95.63	1.85	90.11	1.17	48.97	1.82
14-Aug-13	104.02	1.10	89.54	1.20	90.34	0.80	52.30	0.70
15-Aug-13	98.57	1.80	89.76	2.77	118.33	3.16	41.55	0.60
16-Aug-13	85.00	0.62	98.81	2.03	122.74	1.02	48.69	2.07
17-Aug-13	95.24	1.34	106.43	0.55	190.36	2.06	80.24	1.33
18-Aug-13	76.07	0.82	93.10	1.45	122.26	0.66	51.31	0.63
19-Aug-13	76.31	0.86	101.79	2.83	109.29	0.90	45.36	0.55
20-Aug-13	73.45	1.21	95.24	1.87	115.00	1.15	39.64	1.44
21-Aug-13	67.98	0.48	119.05	0.63	110.60	1.90	46.67	0.72
22-Aug-13	67.38	0.72	94.88	1.45	100.71	2.70	40.60	0.86
23-Aug-13	68.21	1.49	102.62	1.55	80.00	2.43	34.40	0.72
24-Aug-13	59.76	2.78	86.67	1.55	89.29	0.74	47.74	0.72
25-Aug-13	75.00	0.74	92.02	0.93	90.24	0.52	41.43	1.64
26-Aug-13	72.26	0.63	87.38	2.08	95.12	1.45	38.69	0.63
27-Aug-13	72.02	0.63	93.33	1.17	94.05	1.21	46.79	1.09
28-Aug-13	68.69	0.72	97.14	0.74	100.48	2.69	42.86	0.94
29-Aug-13	63.45	2.17	88.93	1.15	87.14	1.03	41.90	0.78
30-Aug-13	71.67	1.21	86.79	1.09	93.57	1.29	41.79	1.15
31-Aug-13	64.52	1.24	85.83	1.45	92.38	1.68	46.43	0.74
1-Sep-13	55.83	1.14	92.86	0.55	95.12	1.34	49.17	0.93
2-Sep-13	62.62	0.83	97.14	1.35	86.67	0.97	54.17	0.63
3-Sep-13	69.88	1.40	84.76	1.45	87.38	1.80	42.26	0.63
4-Sep-13	71.90	1.24	108.81	1.26	104.17	0.93	47.26	0.93
5-Sep-13	75.00	0.82	104.52	0.97	107.86	0.94	39.64	0.55
6-Sep-13	100.48	0.83	104.88	1.34	108.81	2.84	54.05	0.78
7-Sep-13	100.71	0.74	113.21	0.55	99.88	1.49	58.45	1.02
8-Sep-13	91.67	1.45	104.17	1.24	98.45	1.86	46.90	0.66

Table H.1: Continued.

Date	Inlet [TP]	+/- SE	SK [TP]	+/- SE	NF [TP]	+/- SE	WCH [TP]	+/- SE
9-Sep-13	81.19	0.97	86.43	1.49	98.21	2.51	49.52	1.24
10-Sep-13	83.68	1.00	84.71	1.13	95.63	0.94	49.66	0.53
11-Sep-13	80.80	0.61	84.25	0.83	97.36	0.61	46.44	0.80
12-Sep-13	85.52	1.77	80.34	1.31	99.31	0.53	46.67	0.94
13-Sep-13	87.13	0.70	79.31	0.72	98.62	0.91	46.21	0.80
14-Sep-13	81.84	1.10	81.03	1.05	99.66	1.39	48.16	0.64
15-Sep-13	81.03	1.31	77.13	1.10	97.93	0.72	45.98	0.61
16-Sep-13	80.00	1.11	77.24	1.00	97.70	1.33	46.90	0.87
17-Sep-13	88.97	1.50	75.29	0.70	100.57	0.75	46.09	0.83
18-Sep-13	93.56	0.80	78.74	0.90	101.15	0.98	52.64	0.80
19-Sep-13	86.90	0.72	77.36	0.80	97.93	0.72	50.80	0.80
20-Sep-13	82.53	0.83	76.78	0.70	99.31	1.55	49.20	0.90
21-Sep-13	84.98		77.65		99.18		48.54	

Appendix I

Daily total residue concentrations for sub-catchments of the Willow Creek watershed

Table I.1: Total residue concentrations [TR] (mg/L) as measured for daily samples for all four sample locations in the Willow Creek watershed.

Date	Inlet [TR]	SK [TR]	NF [TR]	WCH [TR]
22-Sep-12	189.97	176.19	108.64	135.59
23-Sep-12	158.23	172.32	104.48	159.76
24-Sep-12	180.63	169.86	110.57	128.95
25-Sep-12	158.97	182.90	120.00	133.17
26-Sep-12	184.90	164.32	103.45	146.70
27-Sep-12	167.94	170.56	118.69	142.86
28-Sep-12	135.48	217.77	110.45	132.35
29-Sep-12	142.86	167.85	108.37	140.44
30-Sep-12	151.44	180.29	103.70	153.09
1-Oct-12	126.61	179.67	110.84	158.92
2-Oct-12	180.37	186.76	116.05	143.21
3-Oct-12	171.52	186.25	110.77	114.71
4-Oct-12	118.73	200.95	126.58	160.19
5-Oct-12	146.60	178.15	130.65	147.06
6-Oct-12	182.80	188.37	137.50	117.79
7-Oct-12	221.08	169.41	119.51	172.41
8-Oct-12	201.28	288.89	110.12	114.29
9-Oct-12	196.93	213.95	144.96	154.23
10-Oct-12	189.74	232.56	112.50	122.60
11-Oct-12	179.49	236.11	130.98	155.50
12-Oct-12	192.11	223.81	118.52	121.95
13-Oct-12	206.45	263.31	112.12	185.51
14-Oct-12	215.38	206.09	147.13	153.48
15-Oct-12	215.79	180.93	115.76	153.66
16-Oct-12	210.80	189.25	135.00	167.88
17-Oct-12	201.57	206.98	127.50	150.00
18-Oct-12	213.17	213.70	118.18	165.62
19-Oct-12	223.38	210.40	124.05	122.55
20-Oct-12	201.59	157.14	100.50	148.15
21-Oct-12	193.21	137.84	132.83	132.17
22-Oct-12	183.25	158.02	104.33	143.56
23-Oct-12	187.70	177.46	79.75	126.84
24-Oct-12	164.89	176.33	86.29	125.93
25-Oct-12	168.00	163.02	111.39	149.48
26-Oct-12	184.21	167.48	129.44	137.16
27-Oct-12	141.45	159.90	119.59	159.71
28-Oct-12	203.13	172.32	133.74	147.93

Table I.1: Continued.

Date	Inlet [TR]	SK [TR]	NF [TR]	WCH [TR]
29-Oct-12	167.11	163.07	112.78	162.79
30-Oct-12	178.57	199.51	129.03	143.21
31-Oct-12	174.48	187.05	114.71	155.39
1-Nov-12	185.19	184.21	136.99	116.79
2-Nov-12	201.30	161.02	97.86	117.65
3-Nov-12	210.11	160.38	160.12	150.62
4-Nov-12	212.44	168.98	136.09	153.85
5-Nov-12	239.80	190.02	162.24	161.45
6-Nov-12	231.40	160.00	169.10	151.52
7-Nov-12	253.97	190.75	200.00	135.54
8-Nov-12	257.22	160.58	155.88	148.78
9-Nov-12	206.35	203.93	111.44	180.93
10-Nov-12	231.38	165.85	92.26	143.21
11-Nov-12	204.24	177.62	150.00	124.07
12-Nov-12	202.49	140.40	170.45	200.00
13-Nov-12	229.33	172.66	181.82	164.62
14-Nov-12	213.90	174.42	220.59	160.89
15-Nov-12	265.03	167.50	169.14	146.89
16-Nov-12	182.29	188.24	104.59	136.82
17-Nov-12	190.16	200.00	99.04	166.67
18-Nov-12	155.61	200.00	104.71	168.37
19-Nov-12	168.87	217.92	88.16	156.41
20-Nov-12	187.83	200.00	84.83	189.39
21-Nov-12	146.84	219.51	73.11	156.96
22-Nov-12	147.91	181.25	59.38	182.97
23-Nov-12	181.82	219.75	92.31	181.08
24-Nov-12	142.86	188.26	70.18	183.62
25-Nov-12	158.85	205.00	91.58	171.15
26-Nov-12	205.88	170.43	103.12	158.69
27-Nov-12	189.83	195.56	53.30	193.75
28-Nov-12	171.50	214.29	71.24	185.00
29-Nov-12	163.59	207.32	117.35	141.09
30-Nov-12	190.12	213.78	114.21	177.94
1-Dec-12	147.70	161.45	76.19	160.47
2-Dec-12	254.55	178.98	211.48	250.80
3-Dec-12	148.88	176.61	141.79	191.82
4-Dec-12	122.50	153.48	78.09	174.93
5-Dec-12	171.79	154.39	127.88	137.50
6-Dec-12	173.68	155.56	85.43	139.65
7-Dec-12	153.37	151.79	116.35	143.29

Table I.1: Continued.

Date	Inlet [TR]	SK [TR]	NF [TR]	WCH [TR]
8-Dec-12	155.61	121.14	101.56	120.51
9-Dec-12	186.40	158.81	124.03	160.00
10-Dec-12	164.95	126.19	75.32	155.78
11-Dec-12	166.23	148.58	120.51	131.84
12-Dec-12	114.75	179.10	121.12	93.94
13-Dec-12	153.61	191.98	73.31	91.72
14-Dec-12	163.01	181.29	68.25	78.08
15-Dec-12	161.18	166.67	99.72	80.84
16-Dec-12	158.42	178.98	60.79	80.00
17-Dec-12	155.49	177.14	82.86	74.85
18-Dec-12	126.21	154.07	40.50	76.92
19-Dec-12	181.52	146.63	93.75	94.80
20-Dec-12	155.63	197.74	81.33	105.71
21-Dec-12	132.69	206.80	64.33	76.06
22-Dec-12	154.61	196.48	82.60	92.31
23-Dec-12	161.29	176.47	69.07	115.49
24-Dec-12	167.19	170.09	116.34	103.03
25-Dec-12	157.89	177.97	99.85	97.98
26-Dec-12	195.36	185.07	83.36	102.94
27-Dec-12	163.33	202.28	66.87	96.68
28-Dec-12	148.51	217.65	66.67	92.49
29-Dec-12	132.60	185.64	83.33	96.53
30-Dec-12	158.81	150.38	88.63	122.76
31-Dec-12	170.16	118.23	93.93	119.19
1-Jan-13	177.46	166.27	99.23	115.07
2-Jan-13	214.03	161.63	104.53	110.95
3-Jan-13	250.60	157.00	109.83	106.84
4-Jan-13	140.72	144.12	115.13	102.72
5-Jan-13	134.53	158.69	90.43	120.51
6-Jan-13	128.34	173.27	89.97	125.62
7-Jan-13	146.28	183.13	86.51	124.39
8-Jan-13	146.34	179.71	90.91	94.80
9-Jan-13	148.65	133.66	118.99	133.66
10-Jan-13	138.59	142.50	88.31	128.02
11-Jan-13	161.64	145.32	86.55	117.79
12-Jan-13	161.19	98.27	84.78	141.99
13-Jan-13	155.56	142.16	83.02	144.55
14-Jan-13	175.00	133.65	81.25	147.10
15-Jan-13	203.08	156.03	105.13	149.65
16-Jan-13	163.37	113.74	107.69	152.21

Table I.1: Continued.

Date	Inlet [TR]	SK [TR]	NF [TR]	WCH [TR]
17-Jan-13	167.01	171.09	88.61	154.76
18-Jan-13	170.66	144.23	101.27	122.89
19-Jan-13	195.65	139.36	125.94	128.95
20-Jan-13	186.52	143.89	96.77	132.85
21-Jan-13	177.39	148.42	88.08	133.84
22-Jan-13	168.26	143.84	100.00	160.12
23-Jan-13	159.13	139.25	121.83	151.19
24-Jan-13	150.00	134.67	97.19	127.14
25-Jan-13	142.11	97.09	131.81	168.62
26-Jan-13	130.21	103.61	214.72	171.02
27-Jan-13	157.05	82.86	118.52	163.84
28-Jan-13	135.77	94.53	101.54	136.69
29-Jan-13	150.40	84.95	159.51	123.19
30-Jan-13	140.63	95.35	85.17	148.33
31-Jan-13	198.95	126.19	132.35	138.10
1-Feb-13	194.27	120.34	151.62	157.75
2-Feb-13	189.97	89.62	150.89	154.22
3-Feb-13	168.60	80.38	138.42	102.87
4-Feb-13	140.05	119.05	131.96	182.69
5-Feb-13	166.24	97.39	141.62	133.33
6-Feb-13	149.35	101.45	120.44	139.13
7-Feb-13	160.16	94.06	126.47	145.99
8-Feb-13	170.96	100.72	114.58	145.68
9-Feb-13	123.26	120.85	73.17	154.39
10-Feb-13	138.50	99.76	115.18	120.57
11-Feb-13	167.65	117.65	146.79	131.65
12-Feb-13	135.94	41.36	132.81	100.94
13-Feb-13	118.33	94.66	93.02	104.02
14-Feb-13	147.54	130.75	99.50	126.46
15-Feb-13	139.15	99.03	100.49	120.28
16-Feb-13	134.90	70.38	128.83	102.34
17-Feb-13	146.57	110.07	89.11	125.60
18-Feb-13	131.46	94.34	110.82	119.22
19-Feb-13	117.10	95.79	102.04	130.95
20-Feb-13	124.71	113.48	105.00	120.00
21-Feb-13	108.50	119.19	127.66	90.12
22-Feb-13	127.36	107.73	136.36	129.72
23-Feb-13	132.47	120.48	146.63	225.88
24-Feb-13	138.02	153.66	102.72	178.22
25-Feb-13	148.05	138.35	138.64	187.35

Table I.1: Continued.

Date	Inlet [TR]	SK [TR]	NF [TR]	WCH [TR]
26-Feb-13	148.15	167.65	138.18	215.52
27-Feb-13	134.72	125.00	127.22	54.05
28-Feb-13	160.53	119.62	141.18	185.10
1-Mar-13	138.67	108.24	184.21	177.03
2-Mar-13	136.60	154.76	341.11	187.35
3-Mar-13	148.61	91.67	400.00	185.71
4-Mar-13	147.37	128.27	275.07	193.24
5-Mar-13	154.64	122.01	222.87	206.24
6-Mar-13	131.23	100.00	185.84	186.89
7-Mar-13	151.04	107.91	198.81	190.93
8-Mar-13	176.12	95.65	136.90	162.32
9-Mar-13	129.87	86.42	147.50	174.45
10-Mar-13	98.45	88.45	125.31	151.96
11-Mar-13	116.28	96.85	132.65	165.02
12-Mar-13	148.44	60.68	188.12	212.87
13-Mar-13	202.38	93.84	233.04	220.93
14-Mar-13	178.84	107.84	297.77	262.77
15-Mar-13	251.27	120.77	225.00	333.33
16-Mar-13	266.84	66.01	296.76	376.53
17-Mar-13	207.79	82.73	176.62	178.66
18-Mar-13	167.66	87.21	197.01	150.00
19-Mar-13	147.58	94.66	122.85	173.37
20-Mar-13	132.65	78.43	197.04	161.78
21-Mar-13	188.63	81.08	129.35	150.20
22-Mar-13	169.62	58.11	124.69	138.61
23-Mar-13	148.81	125.30	128.02	127.03
24-Mar-13	160.62	105.62	131.34	133.80
25-Mar-13	136.95	123.87	148.68	142.52
26-Mar-13	127.60	101.58	162.16	106.38
27-Mar-13	161.04	116.59	139.36	120.85
28-Mar-13	170.66	111.11	169.64	134.62
29-Mar-13	189.39	141.51	136.17	158.14
30-Mar-13	206.55	129.33	136.36	200.93
31-Mar-13	243.65	112.39	237.04	421.55
1-Apr-13	295.17	92.76	216.23	500.00
2-Apr-13	251.48	67.63	195.42	408.72
3-Apr-13	235.44	103.14	174.60	315.42
4-Apr-13	197.97	81.08	153.79	248.84
5-Apr-13	311.22	108.84	132.98	195.80
6-Apr-13	244.39	141.88	112.17	202.20

Table I.1: Continued.

Date	Inlet [TR]	SK [TR]	NF [TR]	WCH [TR]
7-Apr-13	225.81	149.85	202.94	145.89
8-Apr-13	236.45	112.90	155.88	129.96
9-Apr-13	213.76	146.07	190.02	133.18
10-Apr-13	200.50	128.38	235.71	96.20
11-Apr-13	200.00	126.70	132.08	108.46
12-Apr-13	192.88	119.40	228.07	211.80
13-Apr-13	187.65	116.01	146.57	110.36
14-Apr-13	189.05	144.47	147.27	120.54
15-Apr-13	155.00	139.95	174.53	86.86
16-Apr-13	167.92	130.63	113.48	106.33
17-Apr-13	176.99	159.76	129.03	129.83
18-Apr-13	168.32	125.84	110.31	107.93
19-Apr-13	209.36	156.46	252.38	328.95
20-Apr-13	687.19	184.57	155.34	22232.39
21-Apr-13	352.94	167.58	192.21	19190.00
22-Apr-13	254.34	213.52	107.25	16147.60
23-Apr-13	254.95	180.28	163.27	13105.20
24-Apr-13	215.88	209.04	174.56	10062.81
25-Apr-13	216.42	159.66	168.32	7020.41
26-Apr-13	229.43	153.20	150.62	9662.72
27-Apr-13	205.80	233.45	145.35	6385.96
28-Apr-13	209.36	148.35	167.08	2619.05
29-Apr-13	248.16	154.06	152.71	2350.30
30-Apr-13	194.10	131.58	128.95	292.54
1-May-13	174.02	148.94	135.27	560.83
2-May-13	174.42	156.07	150.29	2843.97
3-May-13	184.54	187.35	128.33	2360.39
4-May-13	194.03	161.97	144.09	1876.82
5-May-13	191.65	172.17	113.37	1393.24
6-May-13	185.19	106.38	280.35	909.66
7-May-13	158.50	134.11	90.38	426.09
8-May-13	148.51	120.57	155.17	138.89
9-May-13	178.66	122.64	168.32	148.51
10-May-13	189.66	121.14	158.81	124.37
11-May-13	194.51	148.94	118.52	168.34
12-May-13	176.81	152.74	142.03	75.58
13-May-13	226.37	124.70	117.79	100.76
14-May-13	275.43	140.48	139.09	113.64
15-May-13	153.09	135.07	138.35	185.75
16-May-13	175.74	141.18	142.86	105.53

Table I.1: Continued.

Date	Inlet [TR]	SK [TR]	NF [TR]	WCH [TR]
17-May-13	177.33	147.83	152.05	186.59
18-May-13	167.08	160.00	116.92	124.07
19-May-13	174.02	179.25	137.59	155.78
20-May-13	193.07	149.40	138.61	158.42
21-May-13	184.54	151.44	150.25	141.44
22-May-13	160.82	152.74	159.71	122.09
23-May-13	201.49	91.13	135.80	186.87
24-May-13	210.40	147.34	159.20	148.61
25-May-13	203.98	126.21	164.59	159.49
26-May-13	154.23	134.29	133.66	150.99
27-May-13	177.33	114.94	121.89	168.60
28-May-13	181.59	150.12	288.18	186.10
29-May-13	212.35	124.09	162.96	136.82
30-May-13	233.42	121.07	449.63	202.00
31-May-13	197.53	112.44	208.33	173.37
1-Jun-13	184.97	110.47	215.69	176.81
2-Jun-13	192.50	110.31	156.72	158.42
3-Jun-13	213.40	125.00	183.17	173.80
4-Jun-13	232.14	147.27	123.46	161.69
5-Jun-13	174.68	182.25	169.95	167.50
6-Jun-13	201.73	167.63	156.52	129.03
7-Jun-13	202.53	104.27	146.04	116.34
8-Jun-13	198.49	93.30	128.64	123.43
9-Jun-13	195.43	137.44	138.01	146.77
10-Jun-13	223.92	144.89	131.89	183.62
11-Jun-13	190.06	177.14	139.13	119.53
12-Jun-13	146.77	154.39	111.38	176.18
13-Jun-13	195.98	131.58	97.32	138.96
14-Jun-13	210.53	195.75	124.39	153.09
15-Jun-13	190.36	177.46	131.39	81.28
16-Jun-13	154.07	191.98	149.12	176.30
17-Jun-13	196.47	171.91	127.10	191.07
18-Jun-13	140.66	161.90	86.21	139.30
19-Jun-13	130.10	116.39	147.78	192.02
20-Jun-13	128.46	92.42	140.74	188.78
21-Jun-13	169.54	141.21	125.00	233.92
22-Jun-13	117.65	159.14	130.22	213.74
23-Jun-13	161.13	145.24	123.76	172.59
24-Jun-13	145.73	134.29	151.36	167.51
25-Jun-13	159.09	169.81	108.64	158.69

Table I.1: Continued.

Date	Inlet [TR]	SK [TR]	NF [TR]	WCH [TR]
26-Jun-13	122.86	181.03	125.00	167.16
27-Jun-13	217.72	154.22	123.15	156.57
28-Jun-13	167.51	172.40	91.13	215.19
29-Jun-13	208.65	190.59	125.31	157.76
30-Jun-13	170.85	208.77	110.29	181.12
1-Jul-13	217.77	226.96	173.91	173.02
2-Jul-13	154.43	245.15	147.13	194.94
3-Jul-13	145.41	221.41	158.16	149.75
4-Jul-13	115.09	236.71	130.43	150.13
5-Jul-13	151.13	247.57	148.61	159.90
6-Jul-13	76.47	283.24	152.49	170.59
7-Jul-13	140.00	227.94	153.27	186.40
8-Jul-13	202.02	164.65	146.77	194.44
9-Jul-13	170.05	208.85	122.81	180.20
10-Jul-13	200.51	192.59	130.00	172.59
11-Jul-13	168.14	136.63	147.06	165.68
12-Jul-13	196.38	167.07	142.50	180.90
13-Jul-13	194.87	177.62	137.84	184.54
14-Jul-13	196.93	181.37	127.88	175.00
15-Jul-13	215.74	186.73	141.39	165.39
16-Jul-13	246.95	223.19	143.75	195.34
17-Jul-13	231.17	237.29	146.11	189.26
18-Jul-13	243.52	188.41	148.47	201.53
19-Jul-13	233.77	208.33	150.83	201.51
20-Jul-13	248.04	170.73	153.20	203.56
21-Jul-13	205.52	273.78	155.56	227.41
22-Jul-13	209.30	202.90	157.92	168.34
23-Jul-13	185.57	209.64	160.28	196.43
24-Jul-13	209.72	259.08	162.64	213.20
25-Jul-13	186.22	206.31	165.00	186.40
26-Jul-13	152.69	273.26	167.37	190.62
27-Jul-13	216.49	238.33	169.73	182.74
28-Jul-13	222.51	198.04	172.09	223.35
29-Jul-13	211.89	220.34	174.45	182.28
30-Jul-13	145.08	205.45	176.81	158.57
31-Jul-13	231.71	235.47	313.59	221.56
1-Aug-13	204.13	219.45	212.21	176.02
2-Aug-13	236.84	189.19	210.53	174.36
3-Aug-13	198.97	195.06	172.91	149.75
4-Aug-13	172.24	206.47	167.63	173.03

Table I.1: Continued.

Date	Inlet [TR]	SK [TR]	NF [TR]	WCH [TR]
5-Aug-13	208.46	231.21	279.31	207.21
6-Aug-13	198.98	210.92	189.27	193.95
7-Aug-13	242.27	208.85	167.63	159.90
8-Aug-13	213.54	194.58	221.90	184.81
9-Aug-13	182.52	191.07	149.43	174.68
10-Aug-13	240.93	244.96	159.38	240.96
11-Aug-13	193.30	189.53	174.79	197.44
12-Aug-13	244.16	202.50	241.28	188.30
13-Aug-13	225.39	181.82	221.90	204.03
14-Aug-13	215.38	195.06	153.41	219.70
15-Aug-13	177.91	214.49	179.41	200.00
16-Aug-13	262.34	261.73	153.06	159.38
17-Aug-13	186.05	193.07	301.00	201.55
18-Aug-13	269.43	254.95	132.50	173.47
19-Aug-13	187.50	279.30	167.92	203.05
20-Aug-13	182.93	204.08	168.14	214.72
21-Aug-13	187.99	186.73	146.84	258.40
22-Aug-13	201.55	163.37	142.86	198.97
23-Aug-13	186.53	194.03	147.96	225.89
24-Aug-13	188.48	248.77	161.21	178.12
25-Aug-13	165.64	201.75	162.24	192.07
26-Aug-13	171.87	172.84	120.91	203.61
27-Aug-13	223.38	204.49	110.28	182.74
28-Aug-13	235.75	225.81	128.14	210.13
29-Aug-13	208.23	202.97	121.83	183.21
30-Aug-13	251.52	175.95	117.99	131.34
31-Aug-13	211.89	211.44	113.35	209.18
1-Sep-13	212.82	240.00	119.40	152.28
2-Sep-13	202.60	216.62	132.17	164.56
3-Sep-13	208.33	236.04	106.60	189.74
4-Sep-13	206.69	219.30	126.10	197.60
5-Sep-13	186.70	161.29	119.59	199.49
6-Sep-13	223.65	210.40	145.36	227.04
7-Sep-13	183.46	219.45	135.00	159.90
8-Sep-13	150.13	165.00	113.07	145.04
9-Sep-13	146.79	173.53	103.24	219.88
10-Sep-13	235.75	214.46	173.80	215.74
11-Sep-13	217.05	175.74	154.04	227.27
12-Sep-13	268.04	232.50	157.36	236.78
13-Sep-13	230.18	210.53	165.39	177.22

Table I.1: Continued.

Date	Inlet [TR]	SK [TR]	NF [TR]	WCH [TR]
14-Sep-13	302.40	236.84	160.24	211.31
15-Sep-13	236.04	182.04	170.43	186.87
16-Sep-13	239.19	205.51	165.00	246.82
17-Sep-13	226.70	212.87	152.12	192.89
18-Sep-13	232.14	237.04	142.13	219.14
19-Sep-13	255.95	215.34	179.94	218.56
20-Sep-13	222.78	236.45	153.65	247.47
21-Sep-13	245.03	218.01	160.50	217.58

Appendix J

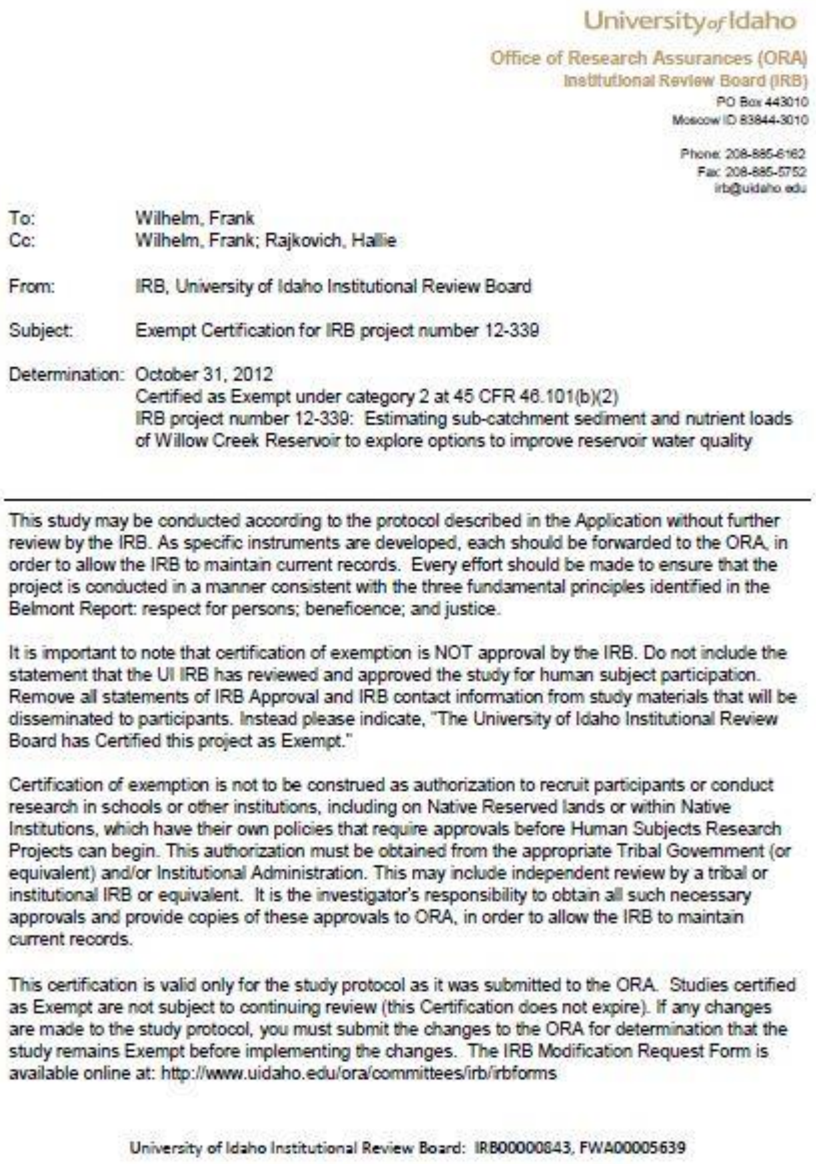
Biweekly total and dissolved phosphorus concentrations for sub-catchments of the Willow Creek watershed

Table J.1: Total phosphorus concentrations [TP] (μg/L) and total dissolved phosphorous [TD] (μg/L) with associated standard errors (SE) as measured for biweekly grab samples for all four sample locations in the Willow Creek watershed.

Date	Inlet [TP]	+/- SE	Inlet [TD]	+/- SE	SK [TP]	+/- SE	SK [TD]	+/- SE	NF [TP]	+/- SE	NF [TD]	+/- SE	WCH [TP]	+/- SE	WCH [TD]	+/- SE
16-Nov-12	82.12	1.06	73.94	0.99	123.75	2.50	105.28	0.91	98.19	1.41	87.92	0.24	31.94	1.21	30.14	0.37
1-Dec-12	56.06	1.18	36.52	3.56	52.58	2.04	42.58	0.66	59.24	1.90	53.48	0.55	29.70	0.40	28.03	0.61
13-Dec-12	43.19	2.82	35.56	0.91	115.56	3.03	86.39	2.34	81.11	1.55	68.47	0.73	53.19	1.21	45.69	1.23
29-Dec-12	66.67	1.56	52.18	1.05	135.64	7.71	97.56	1.36	44.10	0.84	37.18	1.12	78.85	0.97	69.87	2.40
12-Jan-13	86.55	6.94	56.55	1.05	76.09	3.29	67.36	0.75	64.14	0.72	42.18	3.76	47.01	0.80	40.46	1.00
25-Jan-13	39.58	1.47	24.17	1.85	68.23	0.38	58.96	3.61	57.81	1.60	51.77	1.17	39.17	2.35	27.50	0.48
8-Feb-13	70.11	1.13	54.71	1.33	105.52	0.72	90.69	0.53	97.36	0.80	85.98	0.50	58.74	1.02	46.78	2.49
23-Feb-13	49.29	1.86	37.74	1.46	97.26	1.26	71.67	3.48	68.10	0.52	57.62	0.83	37.26	2.32	30.60	0.72
7-Mar-13	60.89	2.33	41.78	1.13	100.67	1.17	82.22	1.85	63.00	1.84	50.78	0.78	48.22	1.42	32.22	0.68
23-Mar-13	88.21	0.34	75.51	1.00	126.15	4.65	109.36	1.68	100.31	0.60	82.05	1.10	70.26	0.78	54.10	0.68
6-Apr-13	109.17	0.24	54.88	1.17	117.50	1.83	103.21	1.83	76.07	2.53	55.24	1.52	69.17	0.78	31.79	0.94
20-Apr-13	191.90	1.87	55.00	0.90	111.07	3.52	86.55	1.14	82.98	3.15	53.10	0.93	83.45	0.86	47.74	2.48
7-May-13	125.95	1.67	54.29	0.74	97.74	1.40	79.76	0.83	73.69	1.34	51.19	0.31	31.43	0.74	22.74	0.78
20-May-13	170.71	0.94	76.55	2.22	114.17	2.00	78.10	3.16	85.12	6.03	56.79	0.82	49.76	1.24	29.40	2.41
4-Jun-13	99.52	1.60	76.55	1.37	113.81	1.40	91.67	0.66	75.00	0.41	55.12	0.86	47.62	0.31	35.83	1.90
18-Jun-13	80.80	0.70	67.93	1.03	111.49	8.05	94.48	1.96	83.33	0.80	70.46	1.20	36.09	0.41	26.78	0.70
2-Jul-13	95.71	1.29	87.50	2.18	90.71	2.15	45.24	2.17	79.64	2.38	71.79	0.36	34.76	0.78	30.48	0.93
16-Jul-13	109.89	0.30	98.39	0.90	170.36	1.03	128.57	0.55	100.57	0.30	92.53	0.98	46.43	0.55	42.50	0.21
30-Jul-13	98.82	1.12	75.70	1.24	195.70	1.45	69.14	1.87	96.56	1.20	86.13	1.41	37.10	1.12	29.68	0.49
15-Aug-13	86.21	2.93	74.48	0.53	102.07	1.82	91.72	3.40	90.23	0.80	76.67	0.64	41.26	0.80	31.72	0.34
27-Aug-13	108.93	1.43	70.83	0.72	154.52	0.72	101.79	0.62	112.02	2.15	96.90	0.63	43.69	0.63	35.12	0.52
10-Sep-13	86.31	0.93	75.83	0.63	125.36	0.94	107.14	0.55	97.38	0.83	80.24	0.93	46.67	1.02	32.86	0.41
20-Sep-13	82.30	1.33	69.89	0.94	82.64	0.83	71.38	0.91	99.54	1.66	80.23	0.64	48.74	0.70	36.21	1.00

Appendix K

Social survey instrument and supporting documentation



University of Idaho
Office of Research Assurances (ORA)
Institutional Review Board (IRB)
PO Box 443010
Moscow ID 83844-3010

Phone: 208-885-6162
Fax: 208-885-5752
irb@uidaho.edu

To: Wilhelm, Frank
Cc: Wilhelm, Frank; Rajkovich, Hallie

From: IRB, University of Idaho Institutional Review Board

Subject: Exempt Certification for IRB project number 12-339

Determination: October 31, 2012
Certified as Exempt under category 2 at 45 CFR 46.101(b)(2)
IRB project number 12-339: Estimating sub-catchment sediment and nutrient loads of Willow Creek Reservoir to explore options to improve reservoir water quality

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This study may be conducted according to the protocol described in the Application without further review by the IRB. As specific instruments are developed, each should be forwarded to the ORA, in order to allow the IRB to maintain current records. Every effort should be made to ensure that the project is conducted in a manner consistent with the three fundamental principles identified in the Belmont Report: respect for persons; beneficence; and justice.

It is important to note that certification of exemption is NOT approval by the IRB. Do not include the statement that the UI IRB has reviewed and approved the study for human subject participation. Remove all statements of IRB Approval and IRB contact information from study materials that will be disseminated to participants. Instead please indicate, "The University of Idaho Institutional Review Board has Certified this project as Exempt."

Certification of exemption is not to be construed as authorization to recruit participants or conduct research in schools or other institutions, including on Native Reserved lands or within Native Institutions, which have their own policies that require approvals before Human Subjects Research Projects can begin. This authorization must be obtained from the appropriate Tribal Government (or equivalent) and/or Institutional Administration. This may include independent review by a tribal or institutional IRB or equivalent. It is the investigator's responsibility to obtain all such necessary approvals and provide copies of these approvals to ORA, in order to allow the IRB to maintain current records.

This certification is valid only for the study protocol as it was submitted to the ORA. Studies certified as Exempt are not subject to continuing review (this Certification does not expire). If any changes are made to the study protocol, you must submit the changes to the ORA for determination that the study remains Exempt before implementing the changes. The IRB Modification Request Form is available online at: http://www.uidaho.edu/ora/committees/irb/irbforms

University of Idaho Institutional Review Board: IRB00000843, FWA00005639

Certificate of Completion

The National Institutes of Health (NIH) Office of Extramural Research certifies that **Hallie Rajkovich** successfully completed the NIH Web-based training course “Protecting Human Research Participants”.

Date of completion: 10/19/2012

Certification Number: 1032803

Public opinion of a constructed wetland at the inlet of Willow Creek Reservoir in Heppner, OR

University of Idaho

The University of Idaho Institutional Review Board has certified this project as exempt.

The purpose of this survey is for partial fulfillment for a degree in Water Resources. I am interested in learning of the public's opinion on natural resources. Your participation in this survey is purely voluntary. Your responses to the survey are confidential and will never be associated with your name. By completing and submitting the survey, you indicate that you consent to participating in the research effort. The survey will take approximately 5 minutes. You may stop at any time.

1. Are you a resident of Heppner, OR? *(Please check one response)*

☐ Yes

☐ No, If No what is your home zip code

(Please specify :_____________________)

2. A. If you are a resident how long have you lived in the Willow Creek Reservoir/Heppner, OR area?
(Please check one response)

☐ Less than one year
☐ 2-5 years
☐ 6-10 years
☐ More than 10 years

2. B. If you are not a resident how long have you been coming to Willow Creek Reservoir/Heppner, OR?
(Please check one response)

☐ Less than one year
☐ 2-5 years
☐ 6-10 years
☐ More than 10 years

3. Do you own land above Willow Creek Reservoir? *(Please check one response)*

☐ Yes
☐ No

4. How are you associated with Willow Creek Reservoir/ Heppner, OR?
(Please check all that apply)

☐ Farmer
☐ Rancher
☐ Teacher
☐ Government Employee
☐ Resident of Heppner, OR
☐ Visitor
☐ Other *(Please specify:___________________________)*

5. What are you doing in the Willow Creek Reservoir/Heppner, OR area today?
(Please check all that apply)

☐ Working
☐ Camping
☐ Boating
☐ Fishing
☐ Swimming
☐ Picnicking
☐ Waterskiing
☐ Nature Viewing
☐ Hunting
☐ Walking dog (s)
☐ Other *(Please specify __________________________)*

6. How many times do you visit Willow Creek Reservoir each year? *(Please check <u>one</u> response)*

☐ 0-1 times per year
☐ 2-5 times per year
☐ 6-10 times per year
☐ 10 or more

7. Are you aware of the annual toxic algae bloom that forms on Willow Creek Reservoir?
(Please check <u>one</u> response)

☐ Yes
☐ No

8. To what degree does the toxic algae bloom interfere with your use of Willow Creek Reservoir? *(Please circle <u>one</u> response)*

Doesn't Interfere	Seldom Interferes	Occasionally Interferes	Frequently Interferes	Always Interferes

Wetlands have been shown to reduce water contaminant concentrations, including sediment and phosphorus which are believed to cause the annual toxic algae bloom in Willow Creek Reservoir.

9. If a wetland was constructed at the inlet of the reservoir how would it impact your use and enjoyment of Willow Creek Reservoir/ Heppner, OR? *(Please check one response)*

☐ Positive
☐ No impact
☐ Negative

Why would it impact you in this way? *(Please use the space below to answer)*

____
____
_

10. If a wetland was constructed at the inlet of the reservoir how would you use it?
(Please check all that apply)

☐ Wildlife viewing
☐ Walking/exercise
☐ Aesthetic/ scenery viewing
☐ Photography
☐ I would bring my students here
☐ I wouldn't use it

11. If a boardwalk was installed in the wetland would you use it? *(Please check one response)*

☐ Yes
☐ No

12. If educational/informational signs were installed would it add to your enjoyment of Willow Creek Reservoir/ Heppner, OR? *(Please check one response)*

☐ Yes
☐ No

13. When were you born? *(Please write in your year of birth)* 19________

Appendix L

Tank-in-series- (P-k-C*) model used to calculate P removal in the wetland cells and sedimentation basin for a conceptual wetland design on Willow Creek, OR (Kadlec and Wallace 2009)

A tank-in-series model (P-k-C*) (Kadlec and Wallace 2009, presented below), in which *P* is the number of tanks in series modeled as continuously stirred tank reactors; k is the P-removal coefficient (m/day); and C* is the background P-concentration (mg/L), was used to estimate area-based first-order P-removal in the wetland cells. In a tank-in-series model, a wetland is partitioned into a series of pieces, each of which is assumed to be completely mixed (Kadlec and Wallace 2009). A *P*-value of 1 represents a reactor that is completely mixed. An infinite *P*-value represents a plug-flow reactor, in which chemical reactions within a wetland are continuous and dynamic. Commonly, a *P*-value of 6 is used when estimating nutrient retention in multi-cell FWS wetlands (Beutel 2013, Beutel et al. 2014) and was therefore used in the conceptual model.

This model incorporates the background concentrations of P in wetlands which are present due to P resistance to storage, hydraulic bypass, its association with particulate P, and additional P input near the outlet of the wetland (Kadlec and Wallace 2009). Commonly, a background P-concentration (C*) of 0.002 mg/L is the default value used for modeling FWS wetlands (Kadlec and Wallace 2009). Because the background concentration of the proposed wetland is unknown, 0.022 mg/L was used.

To account for seasonal fluctuations in P uptake in a wetland, monthly P-removal rate constants (*k)* for the system were used (Kadlec and Wallace 2009).

$$\frac{\mathrm{C_o} - C^*}{\mathrm{C_i} - C^*} = \frac{1}{(1 + \frac{\mathrm{k}}{\mathrm{Pq}})^{\mathrm{P}}}$$

Where:

C_o= outlet concentration (g/m^3)
C_i= starting concentration (g/m^3)
C*= background concentration (g/m^3)
k= areal first order removal rate constant (m/yr)

P= apparent number of tanks in series
q= hydraulic loading rate (m/yr)

References

Beutel MW. 2012. Water quality in a surface-flow constructed treatment wetland polishing tertiary effluent from a municipal wastewater treatment plant. Water Science and Technology. 66: 1977-1983

Beutel MW, Morgan MR, Erlenmeyer JJ, Brouillard ES. 2014. Phosphorus removal in a surface-flow constructed wetland treating agricultural runoff. Journal of Environmental Quality. doi:10.2134/jeq2013.11.0463

Kadlec RH, Wallace SD. 2009. Treatment wetlands. CRC Press.

Appendix M

Calculation of hydraulic residence time (HRT) used in conceptual wetland design

The hydraulic residence time (HRT) of a treatment wetland, known as the amount of time it takes for water to travel through the wetland, affects the wetland's ability to reduce contaminant concentrations and is generally used as a primary design criterion for constructed wetlands (Kadlec and Wallace 2009). Retention times are proportional to the size of the wetland, generally the larger the wetland, the longer the retention time (Kadlec and Wallace 2009). A suggested HRT value of 5 to 14 days should be used to optimize removal efficiency (Mitsch and Gosselink 2007).

Discharge values were adjusted for the 2010 water year to model a HRT of 5 - 10 days. Annual mass removal (%), representing the total percent of TP removed from Willow Creek in the wetland, was evaluated for each HRT (Table M.1 – M.6). The annual mass removal was maximized when the HRT was held constant at 5 days, therefore a HRT of 5 days was used in the conceptual model.

References

Kadlec RH, Wallace SD. 2009. Treatment wetlands. CRC Press.

Mitsch W, Gosselink J. 2007. Wetlands, 4th Edition. John Wiley & Sons.

Table M.1: Monthly design discharge (m³/month), 5 day hydraulic residence time (HRT) and associated mass removal (%), annual mass removal was calculated as the total P-mass removed by the wetland system divided by the total P-mass in Willow Creek, OR annually.

Month	Design discharge (m³/month)	HRT (days)	Mass removal (%)
January	405,000	5.0	1.70
February	405,000	5.0	1.44
March	405,000	5.0	3.13
April	405,000	5.0	2.44
May	405,000	5.0	1.58
June	405,000	5.0	16.39
July	158,807	13.3	52.84
August	77,508	27.2	56.40
September	29,995	68.0	24.71
October	202,381	10.4	34.81
November	331,266	6.2	19.22
December	365,274	5.8	5.74
Annual			2.82

Table M.2: Monthly design discharge (m^3/month), 6 day hydraulic residence time (HRT) and associated mass removal (%), annual mass removal was calculated as the total P-mass removed by the wetland system divided by the total P-mass in Willow Creek annually.

Month	Design discharge (m^3/month)	HRT (days)	Mass removal (%)
January	342,000	6.0	1.68
February	342,000	6.0	1.43
March	342,000	6.0	3.09
April	342,000	6.0	2.34
May	342,000	6.0	1.54
June	342,000	6.0	15.95
July	158,807	13.3	52.84
August	77,508	27.2	56.40
September	29,995	68.0	24.71
October	202,381	10.4	34.81
November	331,266	6.2	19.22
December	342,000	6.0	5.54
Annual			2.76

Table M.3: Monthly design discharge (m^3/month), 7 day hydraulic residence time (HRT) and associated mass removal (%), annual mass removal was calculated as the total P-mass removed by the wetland system divided by the total P-mass in Willow Creek annually.

Month	Design discharge (m^3/month)	HRT (days)	Mass removal (%)
January	291,000	7.0	1.66
February	291,000	7.0	1.41
March	291,000	7.0	3.06
April	291,000	7.0	2.24
May	291,000	7.0	1.49
June	291,000	7.0	15.48
July	158,807	13.3	52.84
August	77,508	27.2	56.40
September	29,995	68.0	24.71
October	202,381	10.4	34.81
November	291,000	7.0	18.76
December	291,000	7.0	5.45
Annual			2.69

Table M.4: Monthly design discharge (m3/month), 8 day hydraulic residence time (HRT) and associated mass removal (%), annual mass removal was calculated as the total P-mass removed by the wetland system divided by the total P-mass in Willow Creek annually.

Month	Design discharge (m^3/month)	HRT (days)	Mass removal (%)
January	255,000	8.0	1.64
February	255,000	8.0	1.40
March	255,000	8.0	3.02
April	255,000	8.0	2.16
May	255,000	8.0	1.45
June	255,000	8.0	15.05
July	158,807	13.3	52.84
August	77,508	27.2	56.40
September	29,995	68.0	24.71
October	202,381	10.4	34.81
November	255,000	8.0	18.24
December	255,000	8.0	5.37
Annual			2.63

Table M.5: Monthly design discharge (m³/month), 9 day hydraulic residence time (HRT) and associated mass removal (%), annual mass removal was calculated as the total P-mass removed by the wetland system divided by the total P-mass in Willow Creek annually.

Month	Design discharge (m³/month)	HRT (days)	Mass removal (%)
January	226,500	9.0	1.63
February	226,500	9.0	1.38
March	226,500	9.0	2.99
April	226,500	9.0	2.07
May	226,500	9.0	1.41
June	226,500	9.0	14.63
July	158,807	13.3	52.84
August	77,508	27.2	56.40
September	29,995	68.0	24.71
October	202,381	10.4	34.81
November	226,500	9.0	17.74
December	226,500	9.0	5.29
Annual			2.57

Table M.6: Monthly design discharge (m^3/month), 10 day hydraulic residence time (HRT) and associated mass removal (%), annual mass removal was calculated as the total P-mass removed by the wetland system divided by the total P-mass in Willow Creek annually.

Month	Design discharge (m^3/month)	HRT (days)	Mass removal (%)
January	204,000	10.0	1.61
February	204,000	10.0	1.36
March	204,000	10.0	2.95
April	204,000	10.0	2.00
May	204,000	10.0	1.37
June	204,000	10.0	14.24
July	158,807	13.3	52.84
August	77,508	27.2	56.40
September	29,995	68.0	24.71
October	202,381	10.4	34.81
November	204,000	10.0	17.26
December	204,000	10.0	5.21
Annual			2.51

Appendix N

Wetland removal efficiency calculations, as presented by Kadlec and Wallace (2009)

Removal efficiencies are commonly quantified based on three common approaches presented by Kadlec and Wallace (2009): concentration removal (%), areal removal rate, and mass removal rate (%), which were calculated as follows:

Concentration removal efficiency (%)= $\frac{\mathrm{C_{in}-C_{out}}}{\mathrm{C_{in}}} \times 100$

Areal removal rate (g-P/m^2/d) = $\mathrm{q} \times (\mathrm{C_{in}} - \mathrm{C_{out}})$

Mass removal in wetland (%) = $\frac{Total\ P\ mass\ removed\ in\ weltnad\ system\ (kg)}{Total\ P\ mass\ in\ Willow\ Creek\ (kg)} \times 100$

Where:

C_{in} is the average inlet P-concentration (mg/L or g/m^3)

C_{out} is the average outlet P-concentration (mg/l or g/m^3)

q= Q/A= hydraulic loading rate (m/d)

Q= discharge (m^3/day or m^3/month)

A= system area (m^2)

References

Kadlec RH, Wallace SD. 2009. Treatment wetlands. CRC Press.

Appendix O

Calculating uncertainty within mass removal estimates

Uncertainty in the P-k-C* model, represented as high and low monthly and annual mass removal estimates, was determined by propagating 95% confidence interval values of monthly TP concentrations and discharge. Average monthly discharge (m^3/day), 95 % confidence intervals (CI) and high and low estimates (m^3/day) are presented in Table O.1 and O.2 for the 2010 and 2013 water years, respectively. Average monthly TP concentrations (mg/l), 95 % confidence intervals (CI) and high and low estimates (mg/l) are presented in Table O.3 and O.4 for the 2010 and 2013 water years, respectively.

The linear model ($C_o = (A + (B * C_1))$) used to calculate TR retention in the wetland (Kadlec and Wallace 2009) has 95% CI fitting parameter estimates, presented as upper and lower bounds (Table O.5). Uncertainty in the model, represented as high and low monthly and annual mass removal estimates, was determined by propagating 95% confidence interval values of monthly TR concentrations and discharge using the upper and lower fitted parameters for the model. Average monthly TR concentrations (m/l), 95 % confidence intervals (CI) and high and low estimates (mg/l) are presented in Table O.6 and O.7 for the 2010 and 2013 water years, respectively.

References

Kadlec RH, Wallace SD. 2009. Treatment wetlands. CRC Press.

Table O.1: Mean daily discharge per month (m³/day, Q), 95% confidence intervals (CI) and the associated high and low daily discharges per month (m³/day) for the 2010 water year.

2010 Water year				
Month	Average Q (m³/day)	95 % CI	High Q (m³/day)	Low Q (m³/day)
January	54,235	11,420	65,655	42,815
February	88,164	9,666	97,830	78,498
March	35,412	4,920	40,332	30,493
April	111,645	26,838	138,484	84,807
May	135,824	32,208	168,033	103,616
June	22,378	3,337	25,715	19,041
July	5,123	973	6,095	4,150
August	2,500	1,063	3,564	1,437
September	1,000	134	1,134	866
October	6,528	1,109	7,638	5,419
November	11,042	1,313	12,355	9,729
December	11,783	1,825	13,608	9,958

Table O.2: Mean daily discharge per month (m^3/day, Q), 95% confidence intervals (CI) and the associated high and low daily discharges per month (m^3/day) for the 2013 water year.

2013 Water year				
Month	Average Q (m^3/day)	95 % CI	High Q (m^3/day)	Low Q (m^3/day)
January	17,208	3,436	20,644	13,772
February	34,966	5,249	40,215	29,717
March	60,347	7,073	67,421	53,274
April	103,691	18,473	122,164	85,217
May	32,390	3,241	35,631	29,149
June	24,998	3,054	28,052	21,944
July	5,886	1,427	7,313	4,459
August	2,301	349	2,650	1,952
September	2,328	513	2,841	1,815
October	6,785	1,344	8,130	5,441
November	12,244	1,424	13,668	10,820
December	16,530	2,906	19,436	13,624

Table O.3: Average monthly TP concentrations (mg/l), 95% confidence intervals (CI) and the associated high and low concentrations (mg/l) for the 2010 water year.

	2010 Water year			
Month	Average TP (mg/l)	95% CI	High TP (mg/l)	Low TP (mg/l)
January	0.095	0.038	0.133	0.058
February	0.122	0.020	0.142	0.103
March	0.065	0.006	0.071	0.059
April	0.178	0.057	0.235	0.121
May	0.254	0.085	0.339	0.169
June	0.097	0.007	0.104	0.090
July	0.083	0.009	0.092	0.075
August	0.082	0.011	0.093	0.072
September	0.077	0.008	0.085	0.069
October	0.052	0.006	0.058	0.046
November	0.062	0.006	0.068	0.056
December	0.071	0.005	0.076	0.066

Table O.4: Average monthly TP concentrations (mg/l), 95% confidence intervals (CI) and the associated high and low concentrations (mg/l) for the 2013 water year.

	2013 Water year			
Month	Average TP (mg/l)	95% CI	High TP (mg/l)	Low TP (mg/l)
January	0.067	0.014	0.080	0.053
February	0.080	0.014	0.094	0.065
March	0.074	0.010	0.084	0.064
April	0.094	0.010	0.104	0.084
May	0.117	0.009	0.126	0.108
June	0.085	0.011	0.096	0.074
July	0.086	0.008	0.094	0.078
August	0.081	0.008	0.089	0.073
September	0.082	0.004	0.086	0.078
October	0.060	0.004	0.064	0.057
November	0.073	0.005	0.078	0.068
December	0.054	0.010	0.064	0.044

Table O.5: Upper bound, central tendency and lower bound fitting parameters used to calculate TR retention in the wetland cells, presented in Kadlec and Wallace (2009).

	A (mg/L)	B (Dimentionless)
Upper bound	5.0	0.95
Central tendency	1.5	0.22
Lower bound	0.7	0.04

Table O.6: Average monthly TR concentrations (mg/l), 95% confidence intervals (CI) and the associated high and low concentrations (mg/l) for the 2010 water year.

2010 Water year				
Month	Average TR (mg/L)	95 % CI	High TR (mg/L)	Low TR (mg/L)
January	204	63	267	141
February	223	30	253	192
March	156	10	166	147
April	344	115	460	229
May	566	225	791	340
June	176	7	183	169
July	201	26	227	176
August	192	8	200	184
September	198	7	204	191
October	175	6	181	170
November	201	72	273	129
December	198	7	206	191

Table O.7: Average monthly TR concentrations (mg/l), 95% confidence intervals (CI) and the associated high and low concentrations (mg/l) for the 2013 water year.

2013 Water year				
Month	Average TR (mg/L)	95 % CI	High TR (mg/L)	Low TR (mg/L)
January	164	11	175	153
February	145	9	154	136
March	166	16	181	150
April	238	39	277	199
May	187	10	198	177
June	178	13	191	165
July	191	16	208	175
August	209	11	220	198
September	203	17	220	187
October	185	11	196	175
November	198	14	211	184
December	160	10	170	150