Comparison of Two Methods to Estimate Within-Lake Regenerated Nutrients and Determine Their Role in Harmful Algal Blooms

A Thesis
Presented in Partial Fulfillment for the Requirements for the
Degree of Master of Science
with a
Major in Natural Resources
in the
College of Graduate Studies
University of Idaho
by
Sarah Halley Burnet

Major Professor: Frank M. Wilhelm, Ph.D.
Committee Members: Daniel G. Strawn, Ph.D., Matthew J. Morra, Ph.D.
Department Administrator: Lisette P. Waits, Ph.D.

May 2016

Authorization to Submit Thesis

This thesis of Sarah Halley Burnet, submitted for the degree of Master of Science with a Major in Natural Resources and titled "Comparison of Two Methods to Estimate Within-Lake Regenerated Nutrients and Determine Their Role in Harmful Algal Blooms," has been reviewed in final form. Permission, as indicated by the signatures and dates below, is now granted to submit final copies to the College of Graduate Studies for approval.

Major Professor: ____________________ Date: ____________
Frank M. Wilhelm, Ph.D.

Committee Members: ____________________ Date: ____________
Daniel G. Strawn, Ph.D.

____________________ Date: ____________
Matthew J. Morra, Ph.D.

Department
Administrator: ____________________ Date: ____________
Lisette P. Waits, Ph.D.

Abstract

Harmful algal blooms (HABs) in surface waters world-wide decreases the aesthetic, recreational value, and use of potable source waters. This is important in the face of the expanding human population that relies on access to clean water. To remediate HABs requires whole-lake nutrient budgets including internal loading which can contribute significantly to HABs. I used a dual approach to quantify the internal phosphorus (P) load at Willow Creek Reservoir (WCR), OR. I calculated the volume-weighted concentration of P from field-collected samples during summer anoxia and from laboratory incubations of sediment cores collected from various sites in WCR; both commonly used approaches, but rarely applied together. The load calculated from field collected samples was 1.7 fold higher than that calculated from sediment core incubations over a 90-day period indicating that the latter would severely underestimate internal loading rates in WCR. I also found a large interannual difference between 2014 and 2015 that was likely related to annual precipitation and reservoir drawdown. The comparison of internal loading along with external P sources is needed to select appropriate in-lake and watershed remediation efforts to reduce HABs.

Acknowledgements

Multiple individuals are responsible for aiding and encouraging me throughout this project. First, I would like to thank Dr. Frank Wilhelm for his mentoring, guidance, and support which made this thesis possible. I am especially grateful for not only his guidance during this research, but also when providing life-long advice on becoming a contributing member to the scientific community. I also would like to thank my committee members, Drs. Daniel Strawn and Matthew Morra, for their knowledge, input, and comments regarding sediment and nutrient dynamics. Kathryn Tackley, Tina Lundell, Daniel Turner, and Dan Dunnett of the US Army Corps of Engineers provided funding and support while field sampling. Dr. Timothy Johnson provided direction and support on data analysis for Chapters 2 and 3. I also would like to thank Cindy Adams and Hallie Rajkovich for providing detailed methodology and data regarding discharge:TP relationships at Willow Creek Reservoir. Trea LaCroix showed me standard operating procedures for analysis of samples as well as advice and encouragement. Finally, I would like to thank the never ending support of my family and friends who were always willing to offer words of encouragement while I pursued this endeavor. The Oregon Lakes Association, North American Lakes Management Society, and the Graduate Professional Student Association provided funding for travel to numerous meetings. The US Army Corps of Engineers provided funding for this research.

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Chapter 1: General introduction

The millions of lakes on Earth resulting from glacial scouring, tectonic activity, volcanic eruptions, the activities of humans, and other animals, etc., are major sources of freshwater. From the time a lake is formed, sediments begin to accumulate and fill the basin, typically giving rise to a natural shift from an oligotrophic to a eutrophic state (Schindler and Vallentyne 2008). While the natural process to eutrophy may take millennia, this process is rapidly accelerated by land use alterations from anthropogenic activities that result in nutrient over-enrichment, also termed 'cultural' eutrophication (Paerl and Otten 2013). Cultural eutrophication negatively affects water resources used for consumption, recreation, and agricultural purposes. It can also result in economic losses stemming from loss of fish and wildlife production, increased water treatment costs, loss of recreational amenities, and agricultural losses. Reducing cultural eutrophication is one of the greatest threat to the quality of freshwater worldwide (Schindler 1977, Downing 2013) and is the impetus of the Clean Water Act in the USA, and similar legislation in other countries. With a finite supply of freshwater world-wide, we must protect and recover degraded surface waters to support the ever expanding human population and life as we know it that relies on access to clean water.

The addition of excess nutrients, particularly nitrogen (N) and phosphorus (P), to freshwaters typically stimulates algal productivity in freshwater and estuarine systems (Schindler 1977) but also can greatly alter the ratio at which N and P are available in the water column (Campbell and Torgersen 1980, Carignan and Flett 1981). Of the two nutrients, P is typically considered the limiting nutrient for plant growth in freshwaters (Schindler 1977). Redfield (1958) determined that across a wide array of ecosystems the balanced ratio of primary producers was 7:1 (N:P) by mass, indicating that a slight increase in P would greatly increase the overall biomass. The N:P ratio also indicates that if the delivery of N and P becomes disproportionate, one element will become limiting and present a selective pressure on algae. For example, in ideal conditions when a water body is phosphorus limited, the N:P ratio is >7. If excess P enters a water body, the ratio will decrease to <7 resulting in N-limitation, often favoring cyanobacteria that can survive at low N, or fix N_2 from the atmosphere (Ferber et al. 2004, Paerl and Huisman 2008, Paerl and Otten 2013). Blooms of cyanobacteria typically form unsightly surface scums which decrease a lake's aesthetics, decrease water clarity, and alter zooplankton and rotifer feeding habits. However, more importantly, cyanobacteria can produce some of the most potent toxins known to humans (Chorus and Bartram 1999, Paerl et al. 2014). This often results in the closure of water bodies due to harmful algal blooms (HABs) that cannot be removed via usual means of water treatment (Westerick et al. 2010). Such loss of access to water bodies must be rectified in the face of the expanding human population and its need for access to clean water.

Because phosphate is highly reactive, P is adsorbed to sediment particles (Bostrom et al. 1988) and transported via runoff mobilized sediment from the landscape to aquatic ecosystems (Carpenter et al. 2001, Carpenter 2008). However, the P transported in this manner typically settles to the lake bottom bound to redox-sensitive compounds including elements such as iron, aluminum, manganese, and calcium (Søndergaard et al. 2001, 2003), and is generally unavailable for uptake by biota. It is the flux of P in this pool that can contribute significantly to the annual nutrient load in lakes. For example, in shallow lakes, sediments resuspended by wind are a well-known source of nutrient loading (Hamilton and Mitchell 1996, Selig 2003). Fish communities also can contribute significant amounts of water column P via excretion and egestion (Vanni 2002, Eilers et al. 2011). However, it is the change in redox conditions at the sediment-water interface that greatly influence internal P dynamics. During low-oxygen or anoxic conditions when the dissolved oxygen (DO) concentration in the hypolimnion is <1 mg/L, changes in redox conditions to a reduced state allows P to solubilize and re-enter the water column in what is termed 'internal loading' (Nürnberg 1985, 1988). Additionally, early spring algae blooms which senesce and sink can create or exacerbate anoxic conditions and also contribute to the release of P into the water column (Paerl et al. 2011). Internal loading of P from anoxic sediments can represent the main summer P load to lakes and reservoirs (Welch and Jacoby 2001), but can be difficult to distinguish from other sources such as inflow, senescing algae, atmospheric deposition, or precipitation (Nürnberg 1985, 2009). Internally loaded P can be especially problematic in lakes that are strongly stratified, have anoxic hypolimnia, and are located in geographic regions where summer inflows are greatly reduced resulting in very long water renewal rates. Internally loaded P can greatly skew the N:P ratio to <7, setting the stage for blooms of cyanobacteria.

Willow Creek Reservoir (WCR), located in the high desert of northeast Oregon, suffers from annual blooms of toxic algae due to imbalances of the N:P ratio (Harris 2014 a, b). The dam was constructed in 1983 for flood control and serves as an irrigation supply for agriculture as well as recreational purposes. As WCR is the only water body within 60 miles, it is the only source nearby for recreational purposes such as boating, kayaking, fishing, and swimming. The regular occurrence of toxic algal blooms make WCR an ideal site to study. Algal blooms and toxicity have been monitored closely since 2006 during which time no contact water advisories have ranged from 14 to 153 days (OHA 2016) as a result of microsystin concentrations ranging up to 1500 µg/L. In Oregon, the microcystin limit is 10 µg/L for primary contact (OHA 2005). To formulate a remediation strategy for this reservoir requires assembly of a whole-lake nutrient budget. While most components are known (USACE 2007, Adams 2012, Harris 2014 a,b, Rajkovich 2014), what remains unquantified is the contribution of internal loading during the summer anoxic period.

My primary objective was to quantify the internal loading of phosphorus (P) and its contribution to the annual nutrient budget of WCR. To quantify the internal load, I used two methods including field-based measurements (Chapter 2) and laboratory studies (Chapter 3). For the field component, I collected high resolution (temporal and spatial) profiles of temperature, dissolved oxygen, pH, conductivity, and water samples for analysis of total and dissolved phosphorus at bi-weekly intervals. These data were combined with existing GIS and bathymetric data to calculate the annual internal P load which was combined with data from Adams (2012) and Rajkovich (2014) to determine a whole-lake P budget. To examine specific release rates of P under oxidized and reduced conditions, I incubated sediment cores from different areas of WCR in the laboratory. The purpose of these experiments was to i) corroborate the field-collected data, and ii) to test the hypothesis that all parts of WCR contribute P at similar rates. The goal of the latter part was to identify potential areas of high P release to optimize remediation actions. In Chapter 4, I compare the internal P loads derived from the field and laboratory experiments for 2014 and 2015 and determine variation in the overall contribution of internal loading to the P mass balance. In the general discussion (Chapter 5), I synthesize all data chapters, provide context for the internal loading in WCR, and present possible strategies for best sampling practices to determine internal loads using the experience derived from WCR as a base example for other water bodies.

Chapters 2-4 are written as individual manuscripts for publication and contain detailed introductions and discussions. All chapter are formatted for submission to the journal *Lake and Reservoir Management*.

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Chapter 2: Quantifying the contribution of internal loading to the annual phosphorus budget of Willow Creek Reservoir, OR using water column measurements

Abstract

The increasing occurrence of harmful algal blooms (HABs) in waters world-wide not only decreases the aesthetic and recreational value of surface waters, but also their use as potable source waters. This is especially important in the face of the expanding human population that relies on access to clean water. In many stratified lakes and reservoirs, internal loading of phosphorus (P) from an anoxic hypolimnion can be a significant contribution to the annual mass balance and can fuel summer HABs. To determine the contribution of internal loading to the annual P mass balance in Willow Creek Reservoir (WCR) located in Heppner, OR, I collected phosphorus samples from different depths and sites at bi-weekly intervals in 2014 and 2015 during the summer anoxic period to calculate a volume-weighted mass of P and estimate its contribution in the whole-lake P mass balance. The proportional contribution of P from internal loading was two times greater in 2015 than 2014, representing 8 and 29% of the total annual P budget. However, during the summer anoxic period when inflows were very low, internal loading contributed 73 and 93% of the P budget. Thus, there is a need to focus on both external and internal reduction of P to remediate this water body to prevent the occurrence of HABs.

Introduction

Anthropogenic activities worldwide negatively affect the quality and quantity of clean water. The continuing expanding human population and associated altered patterns of land use negatively affect public water resources used for consumption, recreation, and agricultural purposes. The USGS estimated that in 2010, the public supply of water for domestic, industrial, and commercial use in the US accounted for 12% of the total 355,000 Mgal/day water withdrawn (Maupin et al. 2014). Of water withdrawn for public supply, 63% came from surface waters such as lakes, reservoirs, and streams, demonstrating the importance of this source and the need to protect it. Factors negatively affecting the quantity of clean water include nutrient over-enrichment (eutrophication), logging of forests within watersheds, industrial pollution, water diversions, and salinization (Paerl and Otten 2013). While the reduction of nutrient sources to freshwaters via point sources has been successful, the elimination of non-point sources is proving problematic and now contribute a majority of the nutrient pollution load in many systems. It is also the reason why they have become the main focus of recovery and restoration efforts (Ongley et al. 2010).

Contribution of nutrients to harmful algae blooms (HABs)

The addition of excess nutrients, particularly N and P, to freshwaters can greatly alter the ratio at which they are available in the water column (Campbell and Torgersen 1980, Carignan and Flett 1981) and typically stimulate algal productivity in freshwater and estuarine systems (Schindler 1977, Smith 1983). The addition of nutrients above background or natural rates is termed ‘cultural’ eutrophication, and poses the greatest threat to the water quality of freshwaters worldwide (Schindler 1977, Downing 2013). Of the two nutrients, P is typically considered the limiting nutrient for plant growth in freshwaters (Schindler 1977) because of the 7:1 (N:P) ratio by mass at which they occur across a wide range of aquatic ecosystems (Redfield 1958). If the delivery of N and P is disproportionate, it skews the above ratio and one element will become limiting which presents a selective pressure on algae. As a result, those that can overcome such limits will have a competitive advantage. Nitrogen-limitation (excess P) tends to result in algal communities dominated by cyanobacteria that can fix atmospheric nitrogen (N_2) (Levine and Schindler 1999, Ferber et al. 2004, Paerl and Huisman 2008, Paerl and Otten 2013) affording them a competitive advantage over other algal species. Cyanobacteria are also not palatable to- or interfere with the filtering mechanisms and feeding patterns of zooplankton (Gliwicz 1990, Gliwicz and Lampert 1990, Bollens 2013), which can prevent the transfer of energy to higher trophic levels (Stockner and Brandt 2006). Surface blooms of cyanobacteria also form unsightly surface scums that decrease a lake's aesthetics and water clarity. Furthermore, the decay of dense surface blooms can have foul odors associated with it that are disliked by lakeshore residents and recreationists. Increases in water temperatures observed in response to global climatic change (O'Reilly et al. 2015) is predicted to increase the frequency of HABs blooms because cyanobacteria generally thrive at higher temperatures compared to other algae (Reynolds 2006, Jöhnk et al. 2008, Paerl and Huisman 2008, O'Reilly et al 2015). Increases in temperature also have the potential to strengthen the vertical stratification of lakes and reservoirs (Schindler et al. 1996) as well as lengthening the period of stratification, thus increasing optimal conditions for HABs to occur (Paerl and Huisman 2008).

Blooms of cyanobacteria are especially worrisome because some species are capable of producing some of the most potent toxins known to humans (Chorus and Bartram 1999, Paerl et al. 2014). As a result, toxin producing blooms, termed harmful algal blooms (HABs), often result in the closure of water bodies (OHA 2016), and the shutdown of municipal water supply systems (e.g., City of Toledo – 500,000 residents in 2014, Wines 2014) because toxins cannot be removed via usual water treatment methods (Westerick et al. 2010). To avoid HABs requires control of P inputs to the water column (Schindler 2012, Schindler et al. 2008), which has been a focus of the Clean Water Act (CWA) (1972) in the USA and similar legislation in other countries. However, the return of legacy phosphorus stored in lake-bottom sediments often delays the recovery of waterbodies even if external sources are controlled (Søndergaard et al. 2001, 2003, 2007, Welch and Jacoby 2001). This requires that we fully understand internal P dynamics as we attempt remediation.

Internal loading of phosphorus

Nutrients associated with sediment entering a lake from external sources (during January to May high runoff periods) typically settle to the lake bottom bound to redox-sensitive compounds including elements such as iron, aluminum, manganese, and calcium (Søndergaard et al. 2001, 2003) and are generally unavailable for uptake by biota. Because P is typically bound to sediment particles (Bostrom et al. 1988), sediment runoff from the landscape tends to increase the transport of P to aquatic ecosystems (Carpenter et al. 2001, Carpenter 2008). Resuspended sediments due to wind are a well-known source of nutrients in shallow water bodies (Hamilton and Mitchell 1996, Selig 2003), but may not be a major source in deep lakes and reservoirs where wind turbulence does not reach the bottom with sufficient force to resuspend sediment (Blais and Kalff 1995).

During low-oxygen or anoxic conditions when the dissolved oxygen (DO) concentration in the hypolimnion is <1 mg/L, changes in redox conditions to a reduced state allows P to solubilize and re-enter the water column in what is termed 'internal loading' (Nürnberg 1985, 1988). Additionally, early spring algae blooms that sink and senesce can create or exacerbate anoxic conditions and also contribute to the release of P into the water column (Paerl et al. 2011). Internal loading of P from anoxic sediments can represent the main load of P in lakes and reservoirs during summer (Welch and Jacoby 2001) but can be difficult to distinguish from other sources such as inflow, atmospheric deposition, or precipitation (Nürnberg 1985, 2009). Internally loaded P also contributes to high concentrations of dissolved P (directly available for uptake by biota), altering the N:P ratio and setting the stage for a high abundance of cyanobacteria.

Project objectives and past research

My primary objective was to quantify the internal loading of phosphorus (P) and its contribution to the annual nutrient budget of Willow Creek Reservoir (WCR), OR. Since dam closure, WCR has suffered annual blooms of cyanobacteria that are often toxic (USACE 2007). Past research has identified excess phosphorus as a major factor contributing to these blooms (Harris et al. 2014a, b). Adams (2012) and Rajkovich (2014) quantified the P loads from inflow tributaries to WCR, however, blooms generally develop during summer and early autumn when watershed inputs are at their minimum because of reduced stream inflows during the summer dry period. It is also known that the hypolimnion of WCR becomes anoxic during thermal stratification (USACE 2007), meaning that conditions for internal loading exist (Nürnberg 1984, 1985, 1988, 1994). Data from the US Army Corps of Engineers' (USACE) annual monitoring program at WCR show that total phosphorus concentrations in the water column, and the hypolimnion especially, increase during stratification. What has not been quantified is the mass of P released from the sediments of WCR under anoxic conditions and its contribution to the annual P budget.

To quantify the internal load, I used a dual approach including field and laboratory studies. As part of the field component discussed in this chapter, I visited WCR at bi-weekly intervals to collect profiles of temperature, dissolved oxygen, pH, conductivity, and water samples for analysis of total and dissolved phosphorus from different sites. These data were combined with existing GIS and bathymetric data to calculate the annual internal P load. The internal load data were combined with values from Adams (2012) and Rajkovich (2014) to determine a whole-lake P budget.

Methods and Materials

Study site

Willow Creek Dam and Reservoir (WCR) is located in northeastern Oregon, USA just south of the town of Heppner (Figure 2.1). Willow Creek Dam was constructed in 1983 as the first roller-compacted concrete dam built by the US Army Corps of Engineers (Larson 2008) with its primary purpose being flood protection following Oregon's worst flood disaster in June 1903 during which 247 lives were lost (Byrd 2009). Today, WCR is also used for recreation, and recently as an irrigation supply for agriculture (USACE 2007).

At maximum pool (elevation 628.8 m (2063.3 ft) above sea level - a.s.l.), WCR has a volume of 5.3×10^3 m^3 (4325 acre-feet) and a surface area of 0.510 km^2 (126 acres) (USACE 2007). At minimum pool (elevation 623.9 m (2047.0 ft) a.s.l), it contains 3.1×10^3 m^3 (2539 acre-feet) and has a surface area of 0.385 km^2 (95.1 acres) (USACE 2007). Willow Creek is the main inflow (contributing about 90% of annual flow) to the reservoir from the south and drains approximately 228,000 hectares (880 square miles) and ending in the Columbia River. Monthly average flows into WCR recorded at the US Geological Survey gauging station (USGS; Willow Creek station ID 14034470) over the past 33 years ranged from lows of 0.040 m^3/sec (1.4 ft^3/sec) in September to highs of 1.39 m^3/sec (49 ft^3/sec) in April. The intermittent Balm Fork Creek enters from the southwest (USGS; Balm Fork station ID 14034480 - data available for the period 1982-2003) with an annual discharge averaging 0.071 m^3/sec (2.52 ft^3/sec). Flow at Balm Fork creek typically ceases from July to February.

The Willow Creek watershed extends from the Blue Mountains to the Columbia River and ranges in elevation from 80 to 1740 meters (260 to 5700 feet) a.s.l. (DeBano and Wooster 2004). At the high elevations, land use consists primarily of forests (10%) while the remaining watershed area is predominantly agriculture (livestock grazing or hay/alfalfa production), grassland, or shrub-steppe (ODEQ 2007). Approximately 89% of land within the Willow Creek sub-basin is privately owned and used for agriculture (ODEQ 2007, Rajkovich 2014).

Water budget of Willow Creek Reservoir

To construct a water budget, I estimated the amount of water that entered and left WCR from inputs including precipitation and inflow from creeks and subtracted outflows including evaporation and outflow via the dam. Remainders to balance in- or outputs were attributed to groundwater. I used a daily time-step and data to estimate the budget.

The average daily inflow volume was calculated from 15 minute interval discharge data obtained from the USGS gauging station located on Willow Creek immediately upstream of the dam (USGS; Willow Creek station ID 14034470). Discharge data for Balm Fork Creek (BF) were not available during this study because data collection at the USGS gauging station on it was discontinued in 2013. However, historic data show that it contributes approximately 10% of the annual creek inflow to WCR (Adams 2012), which was applied to the inflow portion of the water budget for 2014 and 2015. Any missing 15 min interval data were linearly interpolated from adjacent data (missing inflow data: 17-Jan to 29-Jan-2014, 09-Mar-2014, 12-Nov to 19-Nov-2014, 01-Dec to 06-Dec-2014, 29-Dec-2014 to 03-Jan-2015, 08-Mar-2015, 27-May-2015, 16-Aug-2015, 30-Nov-2015; missing outflow data: 06-Dec-2015) after inspecting the data set to ensure flows before and after the missing period were similar.

To calculate the volume of water added directly to the reservoir on days with precipitation, precipitation depth (obtained from NOAA climate weather website: http://w2.weather.gov/climate/xmacis.php?wfo=pdt) was multiplied by the surface area (determined from forebay elevation and GIS) of the reservoir on each day with precipitation.

Average daily discharge from WCR was calculated from 15 minute interval data obtained from the USGS gauging station (USGS; Willow Creek Outflow station ID 14034500) immediately downstream of the dam (~800 m). Missing data were treated as above for the Willow Creek inflow. To calculate evaporation, I multiplied the nearby regional monthly average evaporation rates by the daily lake surface area (Appendix A). All in- and output values were calculated using a daily time step.

Inputs from or losses to groundwater on a monthly basis were calculated using the following equation:

$$Groundwater = Inflow - Outflow - \Delta Storage \quad (1)$$

where the change in storage was calculated as a monthly change in reservoir volume. A positive groundwater value represented a loss of water from WCR to groundwater, while a negative value represented water entering WCR from groundwater.

Collection of water column samples for the analysis of phosphorus

To quantify the contribution of internal loading of phosphorus to the annual P budget of WCR, water samples were collected for the analysis of total (TP) and dissolved (DP) phosphorus from discrete depths at three sampling sites (Figure 2.2) at approximately biweekly intervals from May 2014 to November 2015 (sampling did not occur between December 2014 to February 2015 due to inclement weather and the inability to access the reservoir with a boat). Three additional sites, including a site near the Willow Creek inflow (UWC) and two sites in the Balm Fork (BF, UBF) arm of the reservoir (Figure 2.2) were sampled at monthly intervals in 2015. The sites were selected *a-priori* to represent depths in WCR that would remain wet and accessible during the summer drawdown associated with water delivery for irrigation from WCR. On each sampling occasion at each site, profiles of temperature (°C), dissolved oxygen (mg/L and %), conductivity, and pH were taken at 1 m intervals from the surface to 1 m above the bottom with a Manta (Eureka Water Probes, Austin, TX) multi-probe interfaced to an amphibian data logger, or a YSI model 556 multi-probe (YSI Incorporated, Yellow Springs, OH).

A 2 L Van Dorn sampler was used to collect water samples for the analysis of total and dissolved phosphorus from the surface, the middle of the epilimnion, at the thermocline, the hypolimnion (occasionally two samples were collected depending on the hypolimnion depth), and 1 m above the bottom. Triplicate samples of water were transferred into individually labeled 125 mL HCl-washed bottles using the overflow method. Water for the analysis of DP was filtered through a 0.45-μm mixed-cellulose membrane filter in the field to fill the 125 mL bottles. After collection and filtering, samples were placed on blue ice in a cooler for transport to the UI Limnology Laboratory where they were analyzed using an AquaMate VIS spectrophotometer (ThermoFisher Scientific, Watham, MA) within 48 h using a modified ascorbic acid method in Standard Method 4500-P (Eaton et al. 2005). If concentrations of TP or DP exceeded the standard curve, they were diluted with deionized (DI) water and re-analyzed.

Analysis of site-specific profiles of water column total and dissolved phosphorus

To analyze these profiles, a segmented regression approach provided the best model for analysis of the data because the strong thermal stratification of WCR with a well-mixed epilimnion and isolated hypolimnion resulted in distinct profiles of phosphorus with constant concentrations in the epilimnion and increasing concentration in the hypolimnion (Appendix B). I grouped all three or six sites sampled on each date and used the segmented data function in R (2013, Vienna, Austria) to determine the best-fit parameters of the epilimnion slope (β0), hypolimnion slope (β1), and the depth at which the change of slope occurred (delta, δ). The slope coefficients were used to calculate TP and DP concentrations (μg/L) for depths not directly sampled in the epi- and hypolimnion, respectively. At the start of my sampling program on July 1st and 15th, 2014, samples were only collected from 0.5, 12 and 23 m depths. Because internal loading and anoxia were just starting, I used linear interpolation to calculate TP and DP concentrations not sampled directly on these two dates.

Calculation of phosphorus loading from water column samples

The total mass of TP and DP in the water column of WCR on each sampling date was calculated as a volume-weighted total by multiplying the volume of each 1 m stratum by its respective phosphorus concentration and summing the values. USGS hydrographic survey data from WCR collected in 2007 (K. Tackley, USACE personal communication) were combined with forebay elevations obtained from the USACE automated database (15 minute data average to obtain daily elevations) to calculate reservoir volumes using the model builder function in ESRI© ArcMap 10.3. To calculate the mass of TP and DP in just the hypolimnion, the depth of the thermocline was determined from temperature profiles (Figure 2.3, Appendix C) and the mass of TP and DP were summed for the volumes below that depth. Similar to methodology used by Nürnberg (1987), the TP and DP mass accrued during anoxic conditions was calculated as the difference between the maximum hypolimnetic P mass and the mass of P before anoxia (Figure 2.4, Appendix C).

Phosphorus budget of Willow Creek Reservoir

Inflow load was calculated from daily TP samples collected by Adams (2012) and Rajkovich (2014) from Willow Creek using automated Teledyne ISCO 7612 samplers (Teledyne, Lincoln, NE) that were analyzed using a modified ascorbic acid method in Standard Method 4500-P (Eaton et al. 2005). Adams (2012) collected data from April 2009 to April 2010, while Rajkovich (2014) collected data from May 2012 to May 2013. Phosphorus load from the BF inflow was estimated at 3.8% using the proportion of TP loaded during 2009-2010 (Adams 2012) when the UGS gauge was still operational. Phosphorus concentrations in the Willow Creek outflow were determined from multiple data sets including bi-weekly samples collected by Adams (2012) during 2009 and 2010, and analyzed at the University of Idaho Analytical Science Laboratory (ASL), Moscow, ID; bi-weekly samples collected in 2010 by Harris (2012) and analyzed at the Cooperative Chemical Analytical Laboratory (CCAL) at Oregon State University, Corvallis, OR; bi-weekly samples collected in 2012-2013 by Rjakovich (2014); and in 2014-2015 by myself that were analyzed at CCAL. Daily TP values for the in- and outflow were predicted from TP concentration - daily discharge relationships using the smearing method (Duan 1983; Appendix D).

Wet and dry deposition P loads for WCR were calculated from the average P deposition rate from Lake Tahoe (Jassby et al. 1994) and Flathead Lake, MT (Ellis et al. 2015) because they are in a similar climatic zone and the only rates available in the literature. A dry deposition rate of 0.73 g TP ha/day was applied to the daily surface area for 2014 and 2015 to calculate kg of TP gained for the year on days where there was no precipitation. A precipitation-weighted concentration of 0.27 g/m^2/day was multiplied by the daily total precipitation added to WCR on that day.

Mass balance of total phosphorus

Mass balance calculations for TP based on water column data follow methods outlined in Nürnberg (1987) for stratified reservoirs with thermocline and anoxic depths that are similar throughout the anoxic period. In short, inputs (inflow, dry, and wet deposition) of TP were summed and outflow TP masses were subtracted each month during which anoxic conditions did not occur (Figure 2.4). For the anoxic period, TP contributed by internal loading was calculated for the entire reservoir and included in the summation of inputs, while outflows were subtracted. The percentage of TP contributed by internal loading was calculated for each year, and for only the anoxic period.

Results

Water budget of Willow Creek Reservoir

In 2014 and 2015, inflow from Willow Creek accounted for 91% of the water that entered WCR. The inflow from Balm Fork Creek was estimated to account for 8%, and precipitation for 1% (Figure 2.5, Appendix E). The hydrograph showed that the majority (90%) of discharge into WCR occurred during the January to May period in 2014 and 2015, respectively (Figure 2.6). Annually, water lost via outflow accounted for 95 and 93% in 2014 and 2015, respectively, while evaporation accounted for 5 and 8% of the loss, respectively (Appendix E). The remaining 8% and 6% loss in 2014 and 2015 were transferred from the reservoir to groundwater. It was interesting to note that during the summer, groundwater was a source of input to WCR, but on an annual basis groundwater represented a net loss from the reservoir (Figure 2.7).

Duration of water column anoxia and extent of hypolimnetic volume

Based on water column DO profiles, anoxia began on July 1st, 2014, and lasted for 159 days until December 6th, 2014. The peak mass of TP in the hypolimnion occurred on October 7th resulting in 98 days of TP loading using the approach of Nürnberg (1987) (Figure 2.8). Based on the depth where anoxia started, the hypolimnetic volume, at the start of the 2014 anoxic period (July 1st) was 3.40×10^6 m^3 or 49% of the total water volume, while the volume on October 7th was 1.43×10^6 m^3 or 33% of the total water volume. In 2015, anoxia began on June 2nd and lasted for 161 days until November 9th. The peak mass of TP in the hypolimnion occurred on September 8th, resulting in 98 days of internal TP loading (Figure 2.8). The hypolimnetic volume at the start of the 2015 anoxic period (June 2nd) was 4.56×10^6 m^3 or 68% of the total water volume, while the volume on September 8th was 1.22×10^6 m^3 or 35% of the total water volume.

Coefficients of β_0, β_1, and δ from the segmented regressions for TP and DP varied among sites and between years (Table 2.1).

Phosphorus budget and mass balance of Willow Creek Reservoir

In 2014, the hypolimnetic mass of TP at the start of anoxia was 379 kg (78% of all TP in WCR; Table 2.2, Figure 2.8, Appendix F). A TP maximum mass of 503 kg was recorded on October 7th (79% of all TP in WCR), resulting in a difference in TP mass of 125 kg. A large fraction (84%, 105 kg) of the TP in the hypolimnion was in the dissolved phase (Table 2.2). In 2015, the hypolimnetic mass of TP at the start of anoxia was 214 kg (84% of all TP in WCR) and a maximum mass of 532 kg TP occurred on September 8th (81% of all TP in WCR), resulting in a difference in TP mass of 318 kg. Again, a large fraction (84%, 267 kg) of the TP in the hypolimnion was in the dissolved phase (Table 2.2). Internal loading during anoxic conditions only accounted for 73% in 2014 and 93% in 2015 of loaded P.

Input of TP, not including internal loading, from inflows, dry, and wet deposition for the entire year was 1525 kg and 794 kg in 2014 and 2015, respectively (Figure 2.9, Appendix F). The output of TP from WCR was 779 kg and 457 kg in 2014 and 2015, respectively. Including internal loading, the annual mass of TP retained in WCR was 871 kg and 794 kg in 2014 and 2015, respectively, accounting for 8 and 29% of the annual mass balance (Appendix F).

Input of TP during anoxic conditions only, not including internal loading, from inflows, dry, and wet deposition was 45 kg and 25 kg in 2014 and 2015, respectively (Figure 2.10, Appendix F). The output of TP from WCR was 206 kg and 207 kg in 2014 and 2015, respectively. Including internal loading during anoxic conditions, 36 kg of TP was removed from WCR in 2014 compared to a retention of 136 kg in 2015 (Figure 2.10).

Discussion

Internal loading of phosphorus from water column

The similarity in length of the anoxic period in 2014 and 2015 was surprising given the differences in start and end dates and the peak TP mass. Because anoxic conditions began earlier in 2015, the hypolimnetic water volume was greater and extended over a larger surface area than in 2014, contributing to a larger volume and area that was exposed to high TP concentrations. This likely explains the 2.5 times greater internal TP contribution in 2015 compared to 2014 and highlights the potential for large interannual variation in the contribution of internal loading.

The WCR internal load of TP in 2014 fell within the range (68±21% of total summer load contributed by internal loading) reported by Welch and Jacoby (2001) for western Washington lakes. The values of external and internal loads in WCR in 2014 were similar to the western Washington lakes of similar depth including Lake Roesiger, American Lake, and Stevens Lake. However, the internal load in 2015 was much higher than those reported by Welch and Jacoby (2001) for western Washington lakes and reflects interannual variation not captured in single-year studies. This observed large interannual variation underscores the importance of multi-year datasets to obtain realistic mass balance estimates at the whole-lake scale. While the mass balance estimates provided by Welch and Jacoby (2001) provide an overview of the 17 lakes they examined, one must wonder about the potential range of internal loading rates and their conclusions should interannual variability in those lakes be as great as in WCR. Future sampling at WCR should continue the internal loading measures to increase our understanding of the interannual variability of the contribution of internal loading.

The relatively small percentage (10-30%) that internal loading contributed to the annual P budget could cause it to be dismissed as an unimportant source compared to the inflow which contributed 66-86%. However, considering that the percentage contributed by internal loading increased to 73-93% during the stratified period clearly indicates it needs to be considered and has important implications if considering lake management efforts to decrease TP. It clearly indicates the need to not only control external sources, but also internal sources. It is important to remember that the majority of the internal P load occurs as DP which is readily available for uptake by plants, and can fuel cyanobacteria blooms. In the case of stratified lakes and reservoirs it is unclear how much of the internally loaded P actually becomes available because much of it is trapped in the hypolimnion by density gradients related to water temperature. Mixing of lakes and reservoirs by wind events causing the erosion of the metalimnion can release the DP from the hypolimnion into the upper epilimnion leading to blooms. Future research should examine potential relationships between wind events (such as direction, duration, and speed), metalimnetic entrainment, lag times, and the occurrence of blooms. Such relationships could serve to predict the future occurrence of algal blooms which would be highly useful for lake managers.

Comparison of 2014 and 2015 water budget and total phosphorus load

Comparison of water volumes including TP input and output, and the duration of anoxia between 2014 and 2015 provide insights to interannual variation. For example, the inflow and outflow volume in 2014 was nearly double that of 2015 (Figure 2.9) which had implications for the amount of material delivered to and retained in the reservoir. Extending this comparison to other years of the recent record for WCR, flow volumes in 2011 were three times greater than that in 2014 and 6.5 times greater than in 2015. Although large quantities of water travel through the reservoir during runoff related to snowmelt, much of the material transported by this runoff is retained in the reservoir and has potential to contribute to internal loading. It is unclear how much of the spring load or that delivered in previous years contributes to the internal load. This would be an interesting area of research as it could lead to predictive relationships concerning HABs in relation to the quantity of material delivered and indicate burial/removal rates in the sediment. LaCroix (2015) in her research at Fernan Lake, ID suggested that the TP increase in the water column during summer was related to the amount of material transported and retained in the lake during spring runoff, with higher water column TP concentrations in years with high spring runoff. If this pattern also holds in WCR, then it should be possible to develop a runoff-sediment-internal loading relationship which would be predictive and could be easily measured. This remains to be explored.

Even though the TP contributed by inflows was greater in 2014 compared to 2015, the contribution from internal loading was greater in 2015 compared to 2014 (Figures 2.9, 2.10). This may be caused by the change in the depth at which anoxic conditions occur and the surface area of the reservoir bottom affected by anoxia (Appendix G). When anoxic depth and surface area become large with increasing anoxic conditions, the amount of TP and DP that are released also increase. It is important to note when comparing 2014 and 2015 values that the total reservoir volume was greater in 2014 than 2015. However, less of the WCR volume in 2014 was anoxic than in 2015 resulting in less of the surface area releasing P via internal loading. As discussed above, the variation in anoxic conditions monitored by DO and temperature profiles are crucial if sediment core analysis is completed.

Variation in volume and TP load entering and leaving WCR as well as the contribution of internal loading between years may alter the frequency and severity of algal blooms. As mentioned above, the average depth and volume of the reservoir was greater in 2014 compared to 2015 and the anoxic depth and thus volume of water that was influenced by anoxic conditions was lower than in 2015. This greater volume of overlaying water in 2014 may make it difficult for wind mixing resulting in P trapped below the metalimnion that is not brought to the surface where it could stimulate algal blooms. Epilimnetic water overlaying cold hypolimnetic water in stratified lakes and reservoirs creates a water density gradient which prevents mixing by wind. Further analysis of wind speed and direction data during the 2014 and 2015 field season may provide insight into this question. A lower anoxic plane height in 2015 compared to 2014 may have aided in decreased bloom occurrences, since the duration of water advisories lasted 14 days in 2015 compared to 39 days in 2014 (OHA 2016). Increased drawdown at WCR also may expose cyanobacteria akinetes to freezing temperatures, decreasing the potential of bloom returns during the next year (Pichrtová 2014). In addition, the decrease in average volume as a result of the deep drawdown at WCR in 2014 and 2015 may have contributed to the relatively short HABs and advisories. This deserves further exploration in the future, as deep drawdowns are forecast to continue into the immediate future.

Further analysis of data

Although the segmented regression approach adequately provided relationships over time to estimate the TP concentration in the hypolimnion, data were insufficient to compare variation among sites. Additional data (finer depth resolution of P samples) would allow analysis of covariance (ANCOVA) comparisons among sites to test the hypothesis that the water column concentration of P is independent of collection site. Failure to support this hypothesis would indicate that the reservoir water column should be spatially compartmentalized to accurately estimate the whole-lake P mass. This would be valuable to future studies and sampling and would be an interesting undertaking to further understand the magnitude of errors associated with whole-lake P mass estimates.

Conclusions

In-situ sampling is an important tool to characterize the contribution and connectivity between internal loading and poor reservoir water quality manifested by blooms of toxic algae.

The in situ measurements can provide a valuable comparison for methodology used by lake managers and further understanding of the overall phosphorus mass balance of WCR. For remediation strategies to be effectively implemented at WCR, water and phosphorus budget data, and water column profiles collected improve insight into processes within the reservoir. Multiple years of data collected increase our understanding of interannual variation and will aid the selection of appropriate implementation strategies to reduce nutrients to achieve desired algal bloom controls. As more detailed information on WCR becomes available, best methods for watershed P reductions from inflows should be considered as well as summer internal loading which contributed as much as 93% of the summer TP load. Future research on summer mixing connecting storm and wind events and the release of P via metalimnetic entrainment would also provide further understanding of drivers of algal blooms in WCR.

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Table 2.1. Coefficients of β_0, β_1 and δ for segmented regressions for total (TP) and dissolved phosphorus (DP) as a function of depth in Willow Creek Reservoir, OR over 2014 and 2015. Coefficient β_0 represents the concentration (μg/L) in each 1 m section of the epilimnion; β_1 represents the slope in the hypolimnion; while delta (δ) is the estimated depth of transition between β_0 and β_1. Delta values not detected are listed as NA.

Date	TP β_0	TP β_1	TP δ	DP β_0	DP β_1	DP δ
29-Jul-14	27.98	20.77	6.94	19.16	20.30	7.05
12-Aug-14	27.80	20.71	5.59	16.03	17.71	4.80
26-Aug-14	39.57	24.01	5.57	13.98	22.42	4.79
9-Sep-14	44.72	30.67	4.89	16.81	30.12	4.61
23-Sep-14	40.86	39.65	4.69	18.27	40.19	4.69
7-Oct-14	54.24	47.03	4.75	32.36	48.64	5.07
21-Oct-14	79.86	50.30	6.35	49.19	50.55	6.34
4-Nov-14	109.62	127.40	10.63	71.07	129.85	10.83
6-Dec-14	115.62	1.45	2.60	98.60	0.75	NA
12-Apr-15	36.95	4.12	5.64	22.57	1.56	0.21
25-Apr-15	24.43	5.24	9.85	14.60	0.76	6.51
9-May-15	28.63	2.44	9.00	13.65	1.39	1.60
19-May-15	30.19	3.87	9.64	11.49	3.02	4.77
2-Jun-15	25.52	5.81	8.67	19.46	5.04	8.10
16-Jun-15	23.37	6.11	5.72	14.33	5.81	5.16
30-Jun-15	18.63	10.30	5.94	13.03	10.94	6.92
14-Jul-15	25.77	15.29	6.39	16.62	14.88	6.67
27-Jul-15	28.10	15.17	4.51	16.99	14.34	4.53
11-Aug-15	24.67	23.16	4.88	15.87	24.68	5.78
25-Aug-15	32.47	29.94	4.33	14.89	30.33	4.54
8-Sep-15	53.33	54.44	4.81	22.30	50.37	4.64
5-Oct-15	58.17	42.28	4.46	28.22	42.73	4.28
18-Oct-15	62.08	41.49	3.15	29.48	45.68	3.64
9-Nov-15	140.50	15.54	7.55	110.75	6.07	5.12

Table 2.2. Estimated total (TP) and dissolved (DP) phosphorus loads from internal loading for Willow Creek Reservoir, OR from water column data. The first date listed for both 2014 and 2015 was the start of anoxic conditions while the second date was peak phosphorus mass (kg) in the water column.

Date	TP (kg)		DP (kg)			
	Whole lake	Hypolimnion only	Whole lake	Hypolimnion only	% TP in hypolimnion	% DP in hypolimnion
2014						
1-Jul-14	487	379	409	318	78	78
7-Oct-14	634	503	533	423	79	79
Δ in reservoir	147	124	123	105		
2015						
2-Jun-15	256	214	215	180	84	84
8-Sep-15	659	532	553	447	81	81
Δ in reservoir	402	318	338	267		

Figure 2.1. Location of Willow Creek Reservoir (marked with star) near Heppner, OR in Morrow County, Oregon, USA. Source: Google Earth; accessed 16 April 2015.

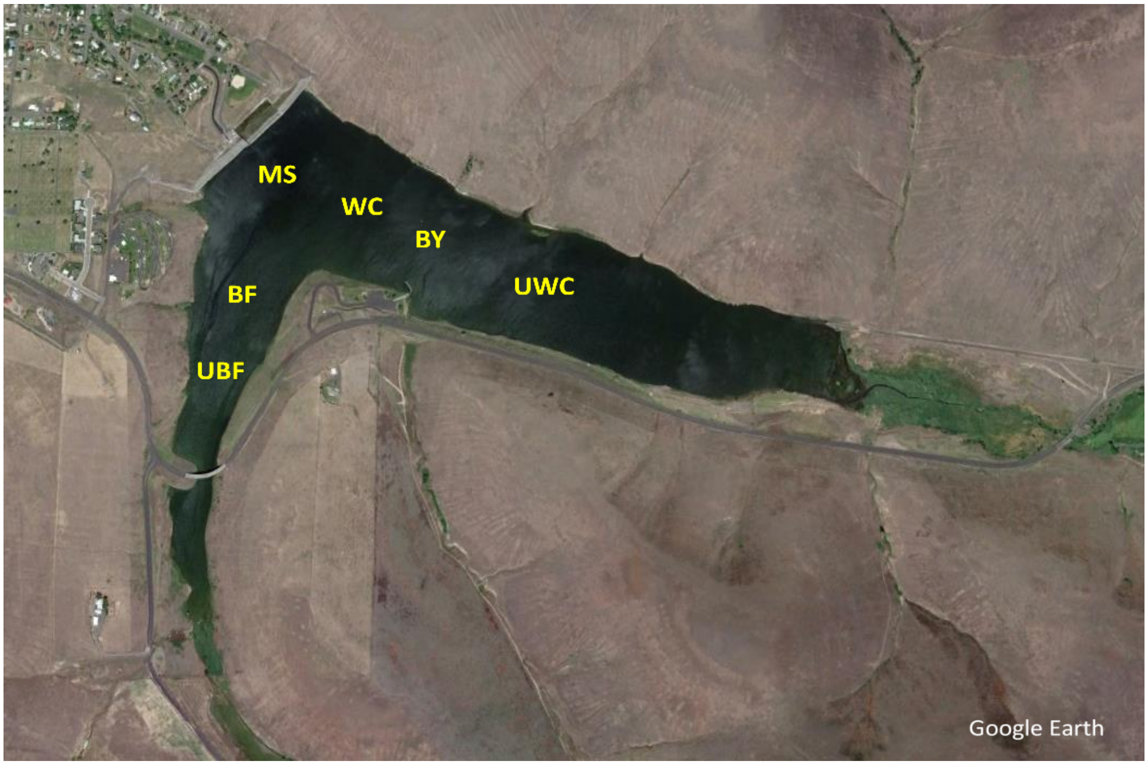

Figure 2.2. Water column sampling sites in Willow Creek Reservoir, Heppner, OR. Site names are Main Site (MS), Willow Creek (WC), Weather Buoy (BY), Upper Willow Creek (UWC), Balm Fork (BF), and Upper Balm Fork (UBF). Source: Google Earth; accessed 16 April 2015.

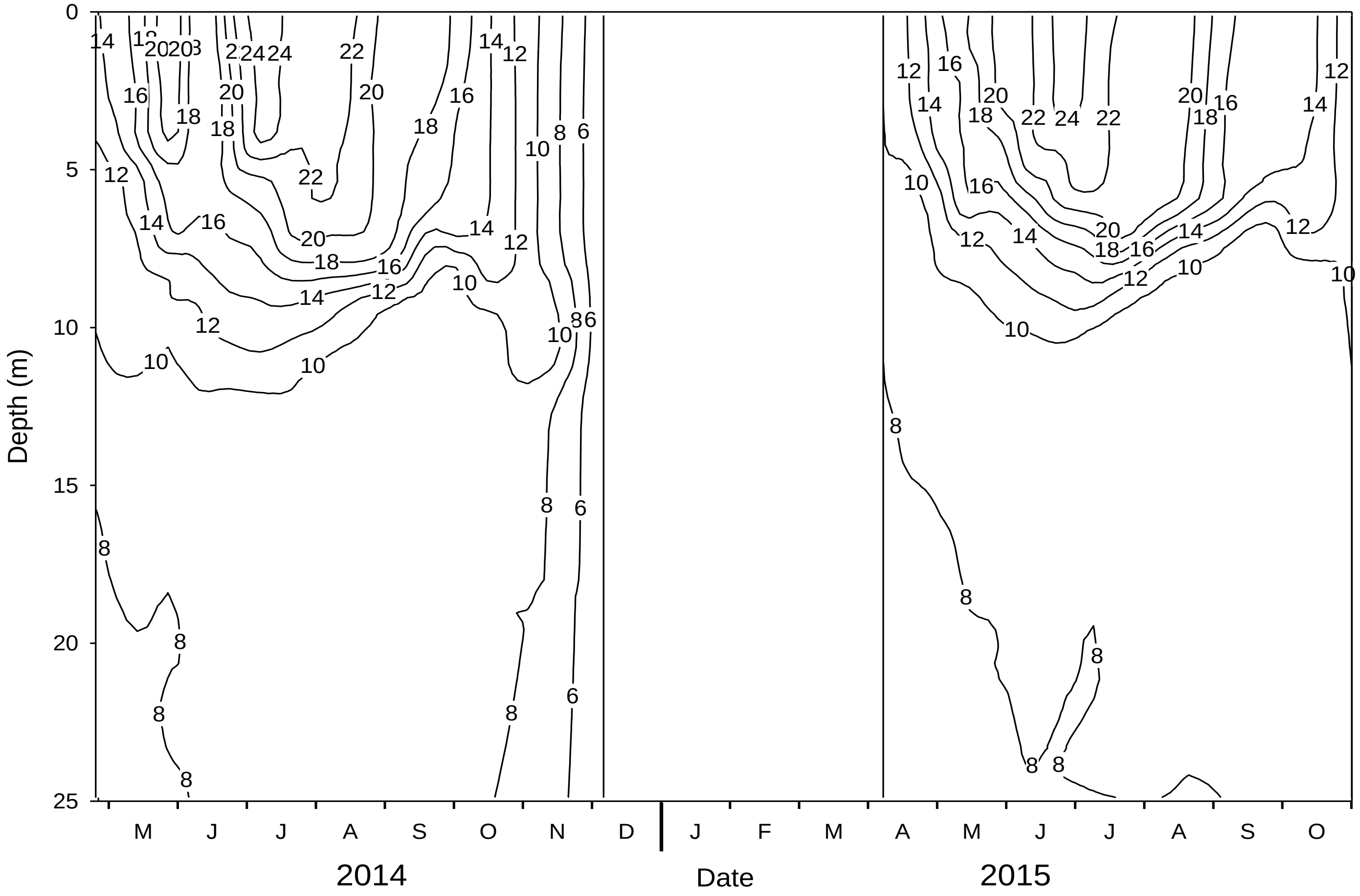

Figure 2.3. Temperature (°C) isopleths for the period 2014 to 2015 at biweekly intervals from Willow Creek Reservoir, OR in 2014 and 2015. Sampling did not occur during winter months.

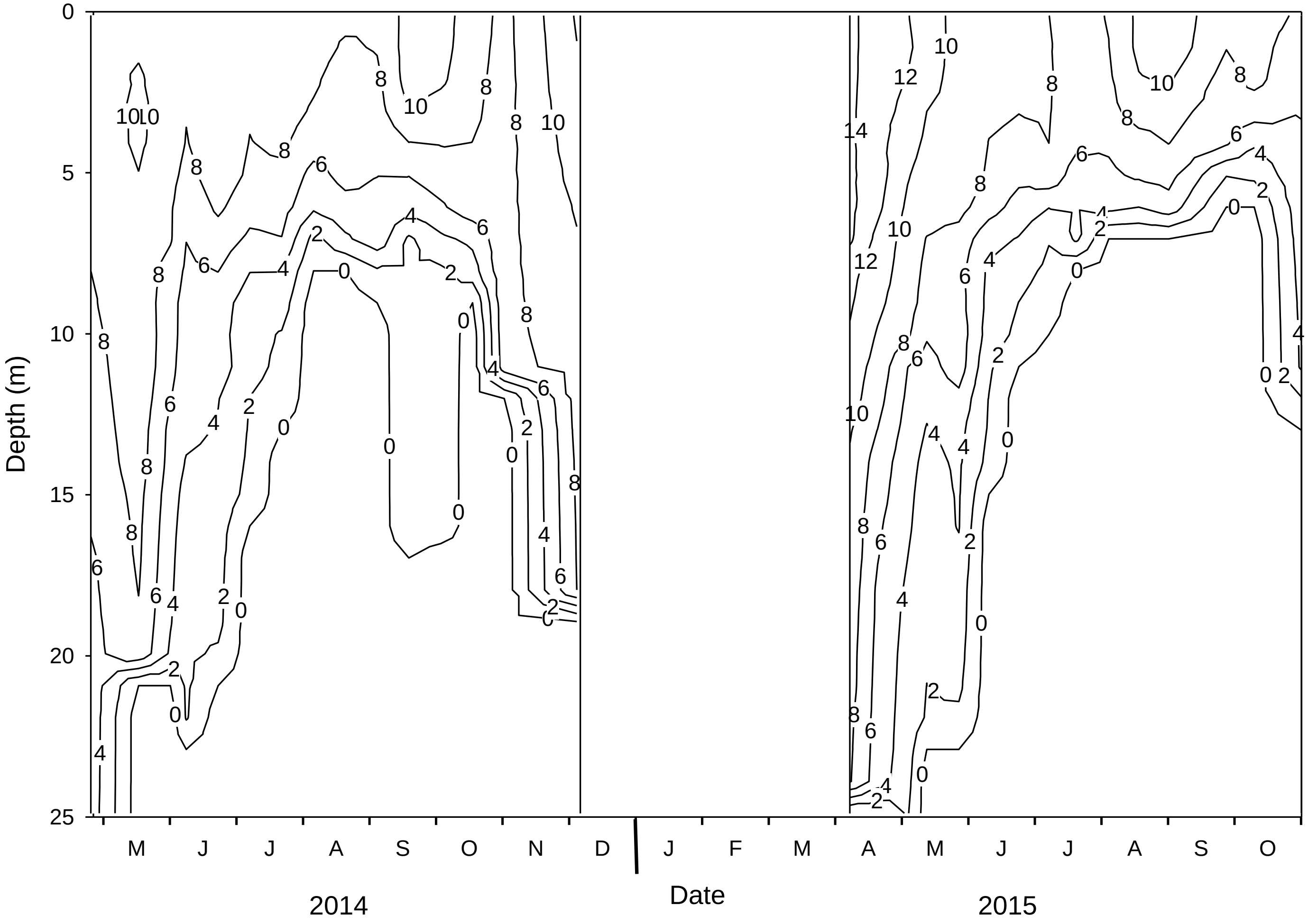

Figure 2.4. Dissolved oxygen (DO, mg/L) isopleths at biweekly sampling intervals from Willow Creek Reservoir, OR in 2014 and 2015. Sampling did not occur during winter months.

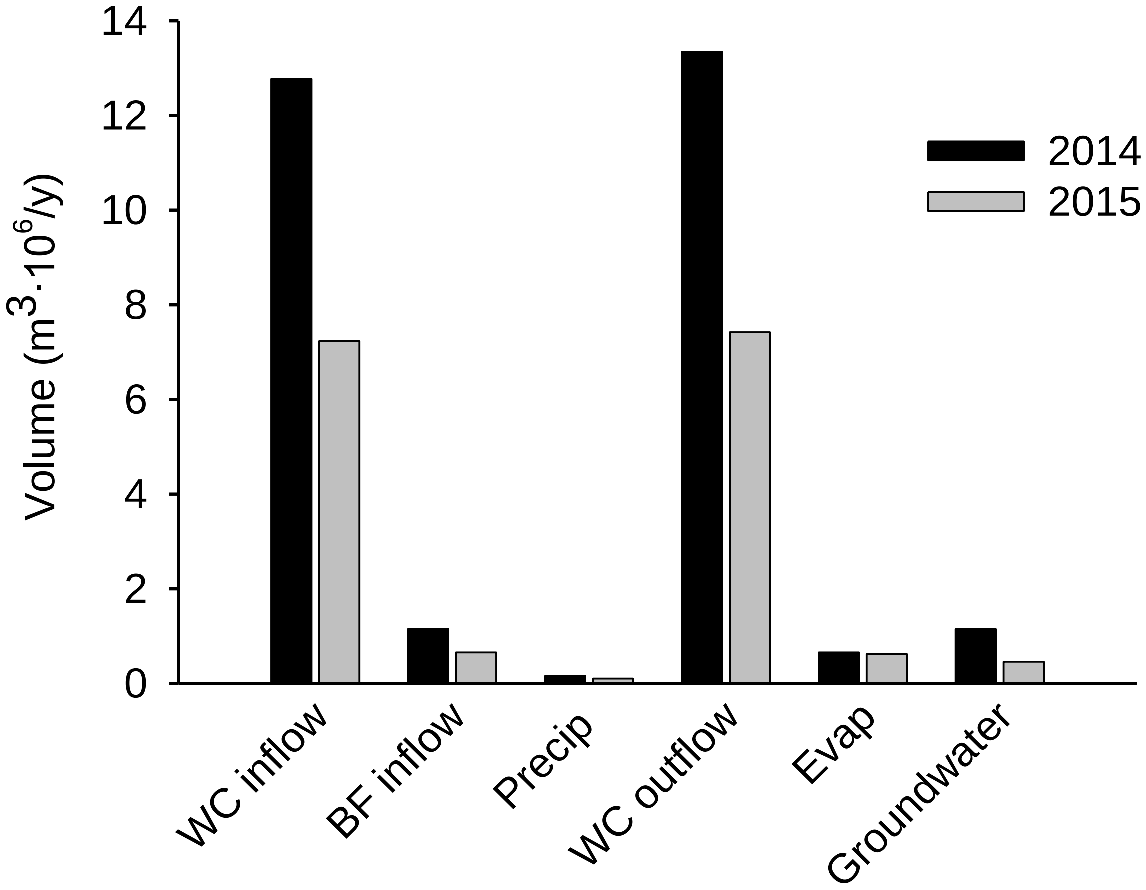

Figure 2.5. Annual water budget for Willow Creek Reservoir for 2014 and 2015. Willow Creek inflow and outflow indicated by WC while Balm Fork indicated by BF.

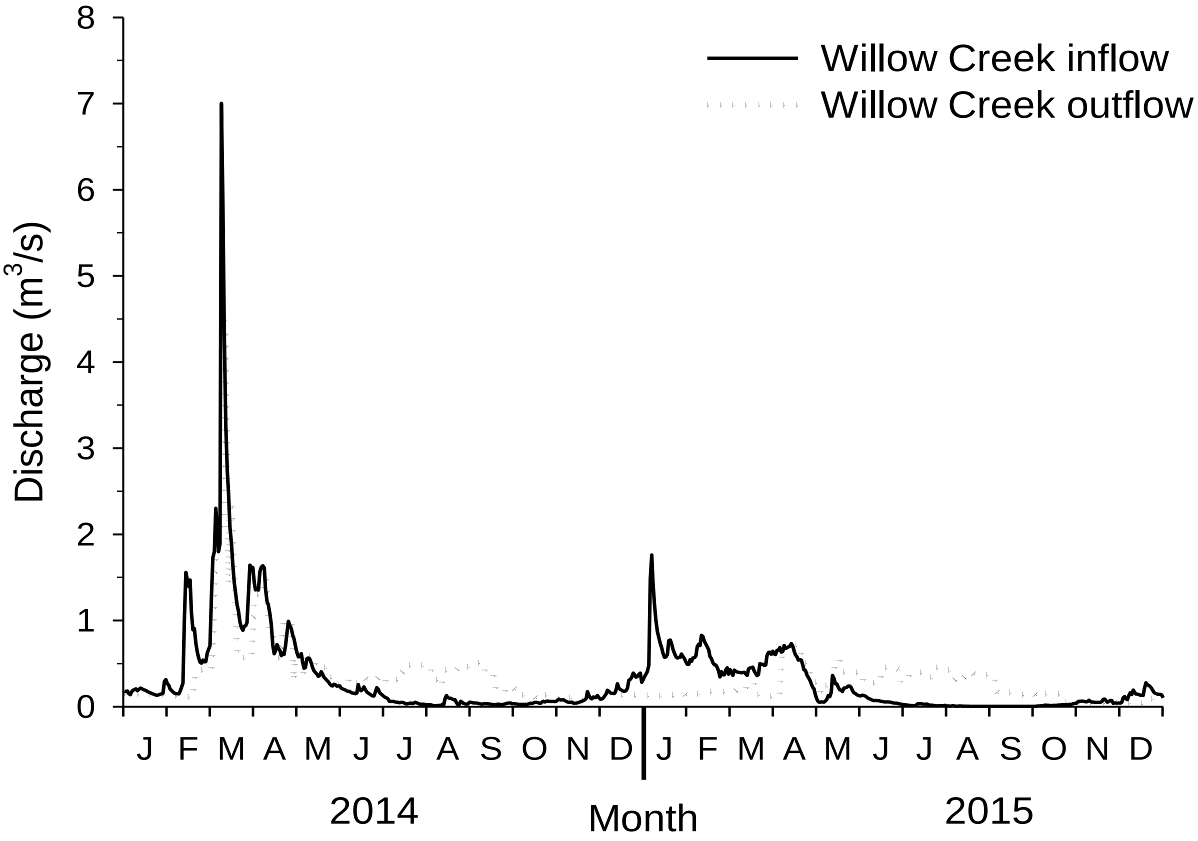

Figure 2.6. Hydrograph of discharge (m^3/s) as a function of time for Willow Creek inflow (solid line) and Willow Creek dam (outflow; dotted line) sampling during 2014 and 2015.

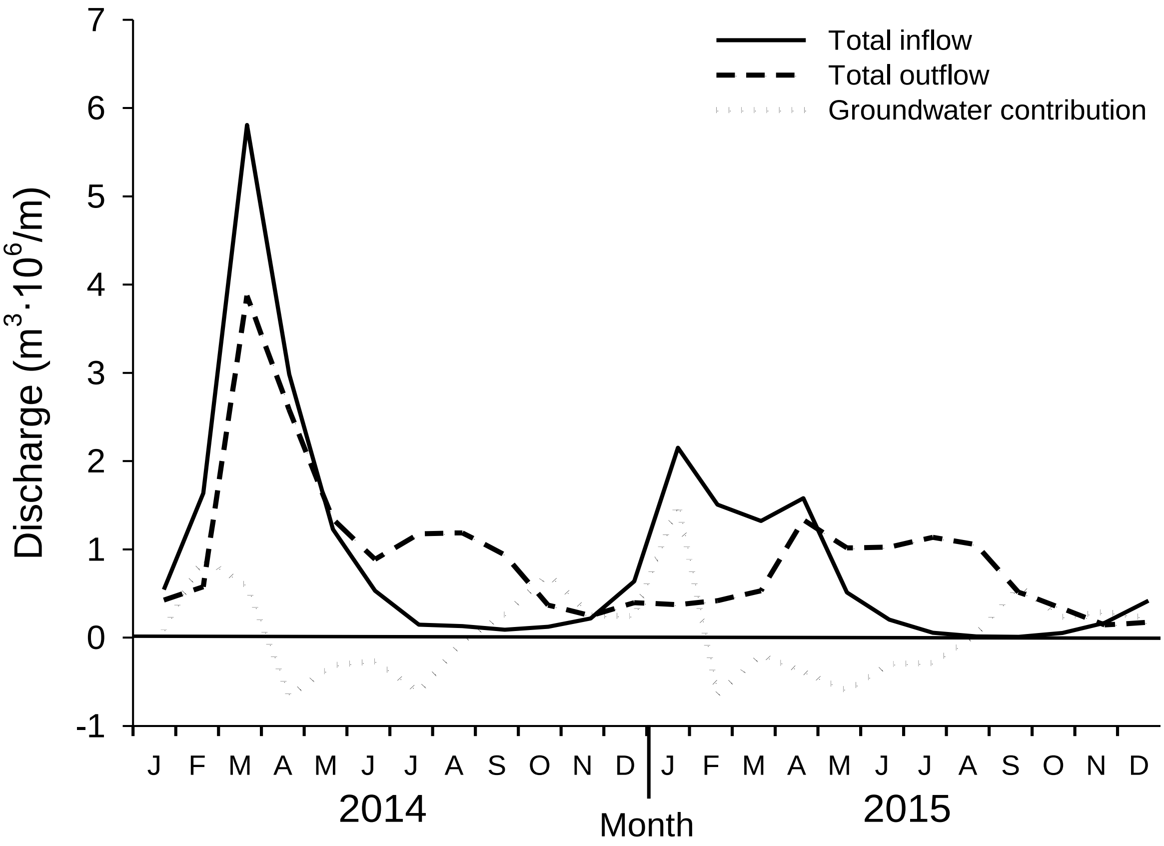

Figure 2.7. Volumes of water from total inflow, total outflow, and groundwater contributions from Willow Creek Reservoir (WCR), OR from 2014 and 2015. Positive groundwater volumes indicate a water transfer from WCR to groundwater and negative volumes indicate a transfer from groundwater to WCR.

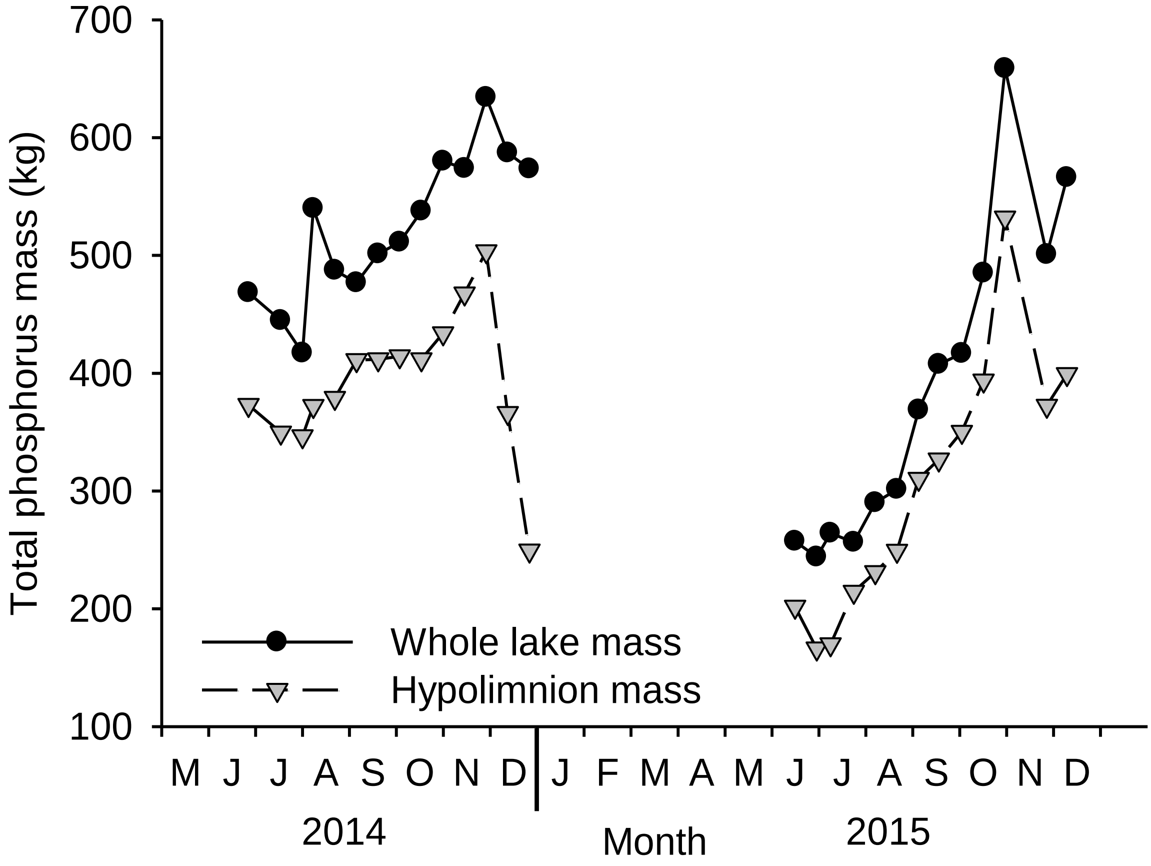

Figure 2.8. Biweekly mass of total phosphorus (TP) in the whole lake (black dots) and hypolimnion only (inverted gray triangles) at Willow Creek Reservoir during 2014 and 2015.

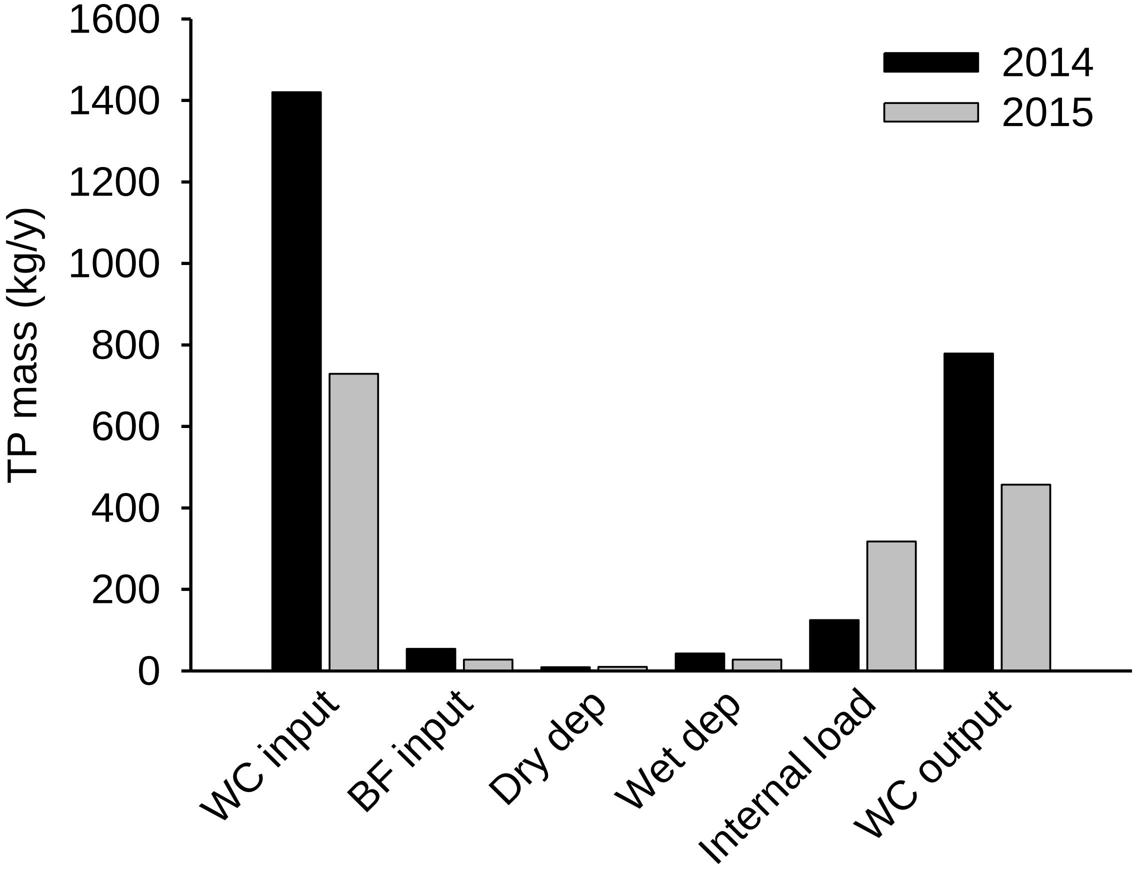

Figure 2.9. Annual total phosphorus budget for Willow Creek Reservoir, OR for 2014 and 2015. Internal loading values were estimated from water column sampling (see methods). Willow Creek input and output are indicated by WC, while Balm Fork is indicated by BF.

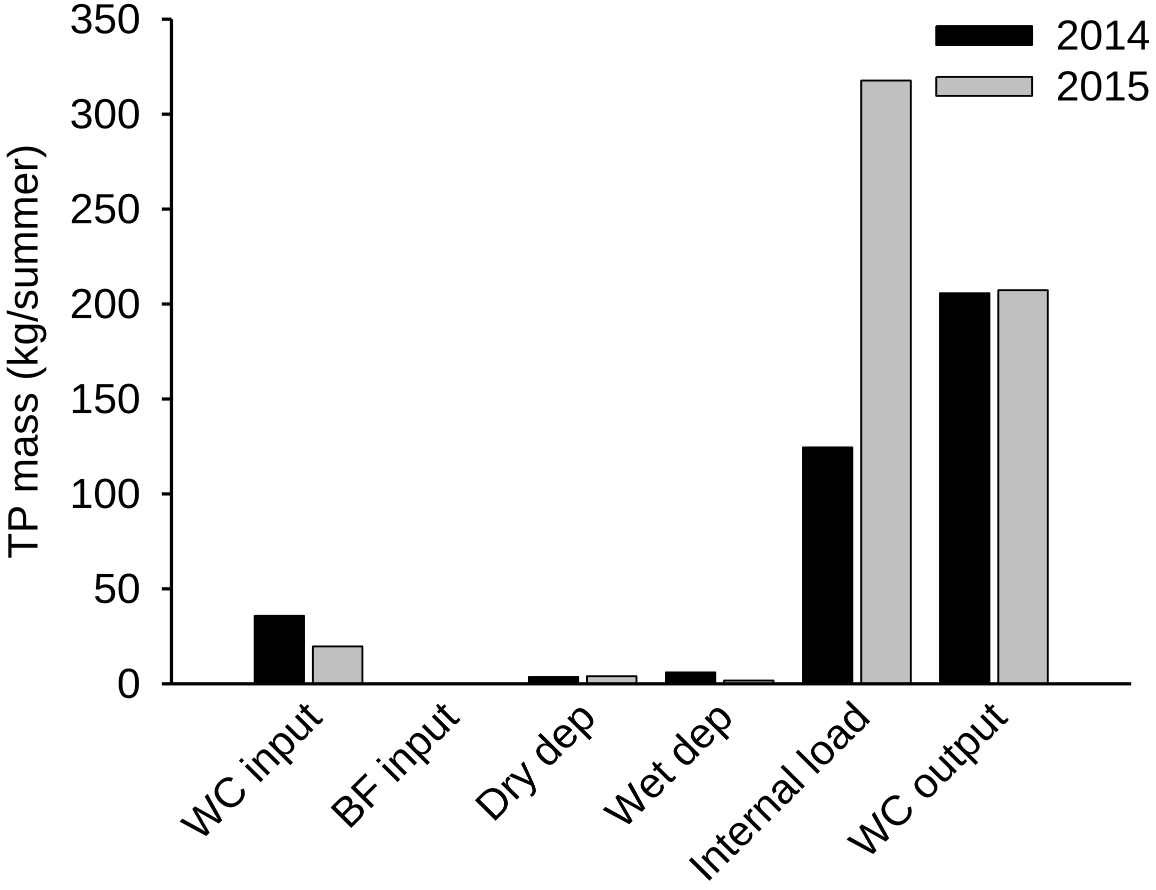

Figure 2.10. Total phosphorus budget for Willow Creek Reservoir, OR for the anoxic period only in 2014 and 2015. Internal loading values were estimated from water column sampling (see methods). Willow Creek input and output are indicated by WC, while Balm Fork is indicated by BF.

Chapter 3: Contributions of sediment-released phosphorus to the nutrient mass balance of Willow Creek Reservoir, OR determined from laboratory incubated cores across a spatial extent

Abstract

The increasing occurrence of harmful algal blooms (HABs) in surface waters world-wide not only decreases their aesthetic and recreational value, but also their utility as potable source waters. This is especially important in the face of the expanding human population that relies on access to clean water. In many stratified lakes and reservoirs, internal loading of nutrients, particularly soluble phosphorus, from an anoxic hypolimnion can be significant in the annual nutrient mass balance, and can fuel summer HABs. Many remediation feasibility studies require understanding the nutrient mass balance including that from internal loading, which is often determined using laboratory-incubated sediment cores. A question that has not been thoroughly addressed in the literature is where to collect cores to obtain representative whole-lake rates. Triplicate sediment cores collected from six spatially separated sites in Willow Creek Reservoir, OR had anoxic release rates that ranged widely from 4.47 to 14.63 mg P/m^2/d even among similarly deep sites. These data show that cores from multiple sites are needed to provide meaningful measures of internal P loading in Willow Creek Reservoir and likely other lakes and reservoirs. Thus, managers should ensure that an adequate number of sites are used to obtain accurate mass balance estimates.

Introduction

Worldwide, the expanding human population and increased anthropogenic activities on the landscape generally negatively affect the quality and quantity of clean water. This is threatening water resources used for consumption, recreation, and agriculture. The USGS estimated that in 2010, the public supply of water for domestic, industrial, and commercial use in the US accounted for 12% of the total 355,000 Mgal/day water withdrawn (Maupin et al. 2014). Of water withdrawn for public supply, 63% came from surface waters such as lakes, reservoirs, and streams, demonstrating the importance of this source and the need to protect it. Some examples of factors negatively affecting water quality include nutrient enrichment (eutrophication), logging of forested watersheds, industrial pollution, water abstraction, and salinization (Paerl and Otten 2013). Unlike the elimination/reduction of point sources under legislation such as the Clean Water Act in the USA, reducing nonpoint sources is much more difficult and currently has become a main focus of many recovery and restoration efforts.

Nutrient type and their contribution to harmful algae blooms (HABs)

The addition of excess nutrients, particularly N and P, to freshwaters generally results in eutrophication (Schindler 1977, Schindler and Vallentyne 2008, Smith 1983) and is typically manifested in 'green' water with abundant algae, some of which form surface scums and can be highly toxic (Codd et al. 1989, Keijola et al. 1988, Lahti and Hiisvirta 1989, Lawton and Robertson 1999, Chorus and Bartram 1999). Eutrophication can also alter the ratio at which N and P are available in the water column (Campbell and Torgersen 1980, Carignan and Flett 1981), which has cascading consequences. Phosphorus typically limits plant growth in freshwaters (Schindler 1977) because of the 7:1 (N:P) ratio by mass at which it occurs across a wide range of aquatic ecosystems (Redfield 1958). An altered N to P ratio presents a selective pressure on algae, favoring dominance by species able to overcome such limits. Nitrogen-limitation (excess P) tends to result in algal communities dominated by cyanobacteria which can fix atmospheric nitrogen (N_2) (Levine and Schindler 1999, Ferber et al. 2004, Paerl and Huisman 2008, Paerl and Otten 2013) affording them a competitive advantage over other algal species in N-limited environments. Cyanobacteria are also not palatable to- or interfere with the filtering mechanism and feeding patterns of zooplankton (Gliwicz 1990, Gliwicz and Lampert 1990, Bollens 2013), which can prevent the transfer of energy to higher trophic levels (Stockner and Brandt 2006). Blooms of cyanobacteria are especially worrisome because some species are capable of producing some of the most potent toxins known to humans (Chorus and Bartram 1999, Paerl et al. 2014). As a result, toxin producing blooms, termed harmful algal blooms (HABs), often result in the closure of water bodies (OHA 2016) and the shutdown of municipal water supply systems (Wines 2014) because toxins cannot be removed via usual water treatment methods (Westerick et al. 2010). The requirement to access atmospheric N_2 also means that cyanobacteria tend to form unsightly surface scums, decreasing the aesthetic value of aquatic ecosystems. To avoid HABs requires control of P inputs to the water column (Schindler et al. 2008, Schindler 2012) which has been a focus of the Clean Water Act (CWA) of 1972 in the USA, and similar legislation in other countries. However, the return of legacy phosphorus stored in lake-bottom sediments often delays the recovery of waterbodies even if external sources are controlled (Søndergaard et al. 2001, 2003, 2007, Welch and Jacoby 2001). This requires that we fully understand internal P dynamics as we attempt remediation.

Internal loading of phosphorus

Runoff from the landscape that moves sediment tends to transport P to aquatic ecosystems (Carpenter et al. 2001, Carpenter 2008) because P is highly reactive and is typically adsorbed to sediment particles (Bostrom et al. 1988) or bound to redox-sensitive compounds such as iron (Søndergaard et al. 2003). Once in a waterbody, it typically settles to the lake bottom and is generally unavailable for uptake by biota. However, if sediments are resuspended due to high winds, especially in shallow lakes, P may re-enter the water column (Hamilton and Mitchell 1996, Selig 2003). Alternatively, if the lake bottom becomes anoxic, P can be released because of changes in redox reactions (Nürnberg 1985, 1988). It is the latter process that tends to dominate what is called ‘internal loading’ which occurs when the dissolved oxygen (DO) concentration decreases below 1 mg/L (hypoxia) at the sediment-water interface or decreases to zero (anoxia). This changes redox conditions to a reduced state which allows P to solubilize and re-enter the water column as dissolved phosphate. Internal loading can contribute up to 71% of P to lakes in summer (e.g., Welch and Jacoby 2001) but can be difficult to distinguish from other sources such as inflow, atmospheric deposition, or precipitation (Nürnberg 1985, 2009). Overall, these additional sources of nutrients, many due to anthropogenic actions, have decreased the water quality of many lakes and reservoirs.

Project objectives and past research

Since dam closure, Willow Creek Reservoir (WCR), located in the high desert of northeastern Oregon, has suffered annual toxic blooms of cyanobacteria (USACE 2007). Past research has identified excess phosphorus in the water column as a major factor contributing to these blooms (Harris et al. 2014a, b). Adams (2012) and Rajkovich (2014) quantified the P load from inflow tributaries to WCR, however, blooms usually occur during summer when watershed loads are at the annual minimum because of reduced stream inflows during the summer dry period. It is also known that the hypolimnion of WCR becomes anoxic during thermal stratification (USACE 2007), meaning that conditions for internal loading exist in the hypolimnion (e.g., Nürnberg 1984, 1985, 1988, 1994). Data from the US Army Corps of Engineers' (USACE) annual monitoring program at WCR show that total phosphorus concentrations in the water column, especially in the hypolimnion, increase during stratification. What has not been quantified is the mass of P released from the sediments of WCR under anoxic conditions and its contribution to the annual P budget. One method commonly used to estimate the contribution of internal loading to the annual mass balance is to measure the P released from laboratory-incubated sediment cores (Nürnberg 1987, 1988, 2009, Steinman and Ogdalh 2015). However, it is unclear how many sites or where they should be spatially located to accurately estimate whole-lake P loads. Here I test the hypothesis that internal loading of P in WCR from laboratory-incubated sediments does not differ spatially. I measured P release rates under oxic and anoxic conditions from cores collected from spatially separated areas of the reservoir to calculate whole-reservoir loads. Site means were compared to examine any spatial differences and the average load was compared to the pre-existing whole-lake nutrient budget to determine the importance of internal loading.

Methods and Materials

Study site

Willow Creek Dam and Reservoir (WCR) is located in northeastern Oregon, USA just south of the town of Heppner (Figure 3.1). Willow Creek Dam was constructed in 1983 as the first roller-compacted concrete dam built by the US Army Corps of Engineers (USACE) (Larson 2008), with the primary purpose of flood protection following Oregon's worst flood disaster in June 1903 during which 247 lives were lost (Byrd 2009). Today, WCR is also used for recreation, and recently as an irrigation supply for agriculture (USACE 2007).

At maximum pool (elevation 628.8 m (2063.3 ft) above sea level - a.s.l.), WCR has a volume of 5.3×10^3 m^3 (4325 acre-feet) and a surface area of 0.510 km^2 (126 acres) (USACE 2007). At minimum pool (elevation 623.9 m (2047.0 ft) a.s.l), it contains 3.1×10^3 m^3 (2539 acre-feet) and has a surface area of 0.385 km^2 (95.1 acres) (USACE 2007). Willow Creek is the main inflow (contributing about 90% of flow) to the reservoir from the south and drains approximately 228,000 hectares (880 square miles). Monthly average flows into WCR recorded at the US Geological Survey gauging station (USGS; Willow Creek station ID 14034470) over the past 33 years range from lows of 0.040 m^3/sec (1.4 ft^3/sec) in September to highs of 1.39 m^3/sec (49 ft^3/sec) in April. The intermittent Balm Fork Creek enters from the southwest with an annual discharge averaging 0.071 m^3/sec (2.52 ft^3/sec) (USGS; Balm Fork station ID 14034480 - data available for the period 1982-2003). Flow typically ceases from July to February.

The WCR headwaters are located in the Blue Mountains and the Umatilla National Forest ranging in elevation from 80 to 1740 meters (260 to 5700 feet) a.s.l. (DeBano and Wooster 2004) and ends in the Columbia River. The upper ten percent of the watershed area is forested, while the landcover of the remaining watershed area is predominantly agricultural (livestock grazing or hay/alfalfa production), grassland, or shrub-steppe (ODEQ 2007). Approximately 89% of land within the Willow Creek sub-basin is privately owned and used for agriculture (ODEQ 2007), such as hay production or grazing.

Water budget of Willow Creek Reservoir

To construct a water budget, I estimated the amount of water that entered and left WCR from daily inputs including precipitation, and inflow from creeks and subtracted outflows including evaporation and outflow via the dam. Groundwater gain or loss was also calculated on a monthly basis as the difference between inputs and outputs. The average daily inflow volume was calculated from 15 minute interval discharge data obtained from the USGS gauging station located on Willow Creek immediately upstream of the dam (USGS; Willow Creek station ID 14034470). Discharge data from Balm Fork Creek (BF) were not available during this study because the USGS gauging station was discontinued in 2013. However, historic data show that it contributes approximately 10% of the annual creek inflow to WCR (Adams 2012) which was applied to the inflow portion of the water budget for 2014 and 2015. Any missing 15 min interval data were linearly interpolated from adjacent data (Missing inflow data: 17-Jan to 29-Jan-2014, 09-Mar-2014, 12-Nov to 19-Nov-2014, 01-Dec to 06-Dec-2014, 29-Dec-2014 to 03-Jan-2015, 08-Mar-2015, 27-May-2015, 16-Aug-2015, 30-Nov-2015; missing outflow data:

06-Dec-2015) after inspecting the data set to ensure flows before and after the missing period were similar.

To calculate the volume of water added directly to the lake on days with precipitation, precipitation depth (obtained from NOAA climate weather website: http://w2.weather.gov/climate/xmacis.php?wfo=pdt) was multiplied by the reservoir surface area (determined from forebay elevation and GIS) of the lake on each day with precipitation.

Average daily discharge from WCR was calculated from 15 minute interval data obtained from the USGS gauging station (USGS; Willow Creek Outflow station ID 14034500) immediately downstream of the dam (~800 m). Missing data were treated as above for the Willow Creek inflow. To calculate evaporation, I multiplied the nearby regional monthly average evaporation rates by the daily lake surface area (Appendix A). All in- and output values were calculated using a daily time step.

Inputs from or losses to groundwater on a monthly basis were calculated using the following equation:

$$Groundwater = Inflow - Outflow - \Delta Storage \qquad (1)$$

where a positive groundwater value represented a loss of water from WCR to the aquifer and a negative value represented water entering WCR from the aquifer.

Sediment core collection and analysis

To test the hypothesis that sediment release rates in WCR did not differ spatially, I measured the flux of P from the bottom sediment into overlying water from six sites using laboratory-incubated sediment cores. Triplicate sediment cores, unless otherwise noted below, were retrieved with a Kajak-Brinkhurst (K-B) gravity corer with 7.62 cm diam. × 61 cm long clear polyvinyl chloride (PVC) core barrels from each site (Figure 3.2) on March 6th and May 9th, 2015. These dates were chosen to collect cores before the hypolimnion became anoxic and TP was released from the sediment. On March 6th cores were collected from the Main (MS), Willow Creek (WC), Weather Buoy (BY), and Balm Fork (BF) sites (Figure 3.2). One MS core was disturbed during transport, and not used, while 4 replicates were analyzed from the BY site. On May 19th, 2015, cores were collected from Upper Willow Creek (UWC – four cores), Upper Balm Form (UBF), and the main site (MS). All cores were transported to the University of Idaho upright in 20 L plastic buckets with holes in the lids to support the core tubes and prevent tipping. In addition, 20 L of lake water was collected from the hypolimnion each time cores were collected. This water was filtered through a 0.45-µm membrane filter in the laboratory and served as replacement water for the quantity removed from each core during sampling for P analysis.

In the laboratory, cores were incubated in total darkness in a walk-in environmental chamber set to 9 °C to mimic the lake bottom temperature at time of collection. The volume of water in each core above the sediment was adjusted to 1L by siphoning off excess water. To deliver either nitrogen gas (-O_2) or compressed air (+O_2), a plastic disc with the inside diameter of the core tube was placed on top of each core tube. Each disc had a 6 mm hole to pass a vinyl gas delivery tube which was connected to a 4-way splitter to regulate the delivery of gas. Each delivery tube was terminated by a standard aquarium air stone suspended 4 cm above the sediment to prevent sediment resuspension. All 12 cores were connected to a single gas line operated at approximately 138 kPa (20 PSI).

Before the start of incubations, cores were left undisturbed for 24 h to allow any suspended particulates to settle; this type of disturbance was negligible for all cores collected for the present study but was included to make these data comparable to other studies. Temperature, dissolved oxygen (DO) concentrations, and pH in each core were measured on each sampling occasion with a Hach (Loveland, CO, USA) LDO 101 and pHC281 sensor connected to a Hach HQd 40 portable meter (model HQ40D53000000) prior to bubbling with nitrogen (N_2) gas. After the DO in a core decreased to <1.0 mg/L, two 10 mL water samples for the analysis of total (TP) and dissolved phosphorus (DP), respectively, were removed daily until day 8, after which the sampling interval was increased to once every two days. This protocol was similar to the sampling and core set-up of Steinman and Ogdahl (2015) and was used to facilitate inter-study comparisons. Sampling continued until water P concentrations ceased to increase or strong trends were observed. At this time, cores were bubbled with oxygen gas to determine the rate at which P was removed from the water column. Samples for the analysis of P were collected as above daily until day 8 and then every other day until P concentrations remained constant. Water removed during sampling was replaced with 0.45 µm-filtered lake water with a known P concentration to maintain the 1 L volume in each core throughout the experiment. All TP and DP samples were analyzed using a modified ascorbic acid method in Standard Method 4500-P (Eaton et al. 2005).

Analysis of sediment core phosphorus release rates

To test the hypothesis that the release rates from the six sites in WCR did not differ spatially, I calculated the release rate in each core using least squares linear regression with phosphorus concentration as the response variable and time as the independent variable. The slope of each of these regressions was the release rate in units of mg P/m^2/d. Release rates (slopes) among sites were compared with an analysis of variance (ANOVA) and the multiple cores from each site served as replicates. A post-hoc Tukey test was used to identify site means that differed. All statistical tests were completed using R (2013, Vienna, Austria).

Calculation of whole-lake phosphorus loads using sediment core release rates

To calculate the whole-lake load of P released from the sediment, P release rates from the cores were multiplied by the anoxic area of the reservoir on a daily time step (Nürnberg

1987; Appendix G). Because sediment cores were only collected and analyzed in 2015, those release rates were applied to 2014 data to obtain a TP and DP load. However, because lake bottom temperatures, rate of influx of sediment, settling of algal material and anoxic conditions were similar between years, I considered the 2015 release rates to be representative for WCR and used them to approximate 2014 sediment release rates to afford an interannual comparison. Steinman and Ogdahl (2015) estimated release rates of cores in Bear Lake, MI in summer 2011 and 2012 and determined that the release rates were within a standard error of one another (6.69 ± 1.93 mg P/m^2/d in August 2011 and 3.92 ± 1.31 mg P/m^2/d in July 2012). Similarly, data reported by Nürnberg (1987) for Chub Lake, MN showed that over 9 years (1976-1984) the summer loading rate was of 21.4 ± 4.4 mg P/m^2/summer. These data suggest that internal loading rates from sediment incubated cores differ little between years and lend support for the approach of applying 2015 release rates for WCR in 2014.

The duration of anoxia was obtained from 1 m interval bi-weekly site-specific profile monitoring in 2014 and 2015 using a Manta (Eureka Water Probes, Austin, TX) multi-sensor data sonde (Figure 3.3, Appendix C). The start and end date of anoxia was determined as the date on which the DO concentrations decreased or increased below or above 1 mg/L, respectively. To determine the depth of the anoxic boundary layer from bi-weekly profiles of temperature and DO data (Figure 3.3, 3.4, Appendix C), I used a relative thermal resistance to mixing (RTRM) spreadsheet (Kortmann, Ecosystem Consulting Service, Inc.). Daily forebay elevations (in meters above sea level – a.sl.) were obtained from the USGS gauging station (USGS; Willow Creek Lake ID 14034490) and the depth of the anoxic boundary was subtracted to determine the depth of the anoxic layer.

To calculate the anoxic area, I used 2007 USGS hydrographic survey data from WCR (Kathryn Tackley, USACE personal communication) and ESRI© ArcMap 10.3 GIS software. The software's Model Builder function was used with the daily depth of the anoxic boundary layer to calculate the 3D area (m^2) below the anoxic boundary.

Calculation of the phosphorus budget of Willow Creek Reservoir

Inflow load was calculated from Adams (2012) and Rajkovich (2014) who collected daily samples from the Willow Creek using automated Teledyne ISCO 7612 samplers (Teledyne, Lincoln, NE) that were analyzed using a modified ascorbic acid method in Standard Method 4500-P (Eaton et al. 2005). Adams (2012) collected data from April 2009 to April 2010, while Rajkovich (2014) collected data from May 2012 to May 2013. The phosphorus load from the BF inflow in 2014 and 2015 was estimated using the proportion of TP loaded from the BF inflow (3.8%) measured by Adams (2012). Phosphorus concentration in Willow Creek outflow was determined from bi-weekly samples collected by Adams (2012) during 2009 and 2010, and analyzed at the University of Idaho Analytical Science Laboratory (ASL), Moscow, ID. Additional outflow concentrations were taken from bi-weekly samples collected in 2010 by Harris (2012) and analyzed at the Cooperative Chemical Analytical Laboratory (CCAL) at Oregon State University, Corvallis, OR. Bi-weekly samples collected in 2012-2013 by Rajkovich (2014) and in 2014-2015 by myself were analyzed at CCAL. Daily TP values for the in- and outflow were predicted from TP concentration - daily discharge relationships using the smearing method (Duan 1983) (Appendix D).

Wet and dry deposition P loads for WCR were calculated from the average P deposition rate from Lake Tahoe (Jassby et al. 1994) and Flathead Lake, MT (Ellis et al. 2015) because they are in a similar climatic zone and the only rates available in the literature. A dry deposition rate of 0.73 g TP ha/d was applied to the daily surface area for 2014 and 2015 to calculate mass of TP gained for the year on days on which there was no precipitation. A precipitation-weighted concentration of 0.27 g/m^2/d was multiplied by the daily total precipitation added to WCR on that day.

Mass balance calculations for TP generally followed methods outlined in Nürnberg (1987). Briefly, input loads (inflow, dry, and wet deposition) of TP were summed, while outflow TP loads were subtracted for each month when the lake as not anoxic. During the anoxic period, I used the mean sediment release rate calculated from all six sites (MS, WC, BY, BF, UWC, and UBF) to determine the internal load.

Results

Water budget of Willow Creek Reservoir

In 2014 and 2015, inflow from Willow Creek accounted for 91% of the water that entered WCR. Balm Fork inflow was estimated to account for 8% and precipitation accounted for 1% (Figure 3.5, Appendix E). The hydrograph showed that the majority of discharge into WCR occurred during the January to May period, accounting for 90% of the inflow in 2014 and 2015 (Figure 3.6). Outflow via the dam accounted for 88 and 87%, while evaporation accounted for 4 and 7% of output in 2014 and 2015, respectively (Figure 3.6, Appendix E). The remaining 8% in 2014 and 5% in 2015 were assumed to be transferred to groundwater. At a finer time scale, water was transferred to groundwater during the winter and early spring months, while during summer, groundwater represented an input to the reservoir (Figure 3.7).

Phosphorus release rates from sediment cores

Anoxia began on July 1, 2014 and lasted for 159 days ending on December 6th. In 2015, anoxia lasted for 161 days starting on June 2nd and lasted until November 9th. The peak bottom area that was anoxic in 2014 was 335250 m^2 on August 12th, while in 2015 it was 300565 m^2 on

July 23rd. Total phosphorus release rates from the sediment cores ranged from a low of 3.70 ± 0.67 (mean ± SE) mg P/m^2/d for UBF to a high of 14.63 ± 1.88 mg P/m^2/d for BY. The mean rate for all six sites was 8.41 ± 0.89 mg P/m^2/d (Appendix H).

Total phosphorus release rates differed among sites (ANOVA, $F_{5,16} = 12.8$, $P < 0.001$). The Tukey *post hoc* comparison showed that although the BY site had the highest release rate, it was similar to the WC site (Figure 3.8). Release rates at the UWC and UBF sites were the lowest and differed from all others (Figure 3.8), while the MS, BF, and WC release rates were intermediate and close to the overall average of 8.41 ± 0.89 mg P/m^2/d.

The release rate of dissolved P (DP) ranged from 3.00 ± 0.45 mg P/m^2/d for UBF to 11.18 ± 1.73 mg P/m^2/d for BY. The whole lake mean for DP was 6.64 ± 0.69 mg P/m^2/d (Table 3.1, Appendix H). The Tukey *post hoc* comparison for release rates of dissolved phosphorus showed that the BY, MS and WC sites were similar, but were significantly higher than those from the BF, UWC, and UBF sites (Figure 3.9).

Phosphorus budget and mass balance of Willow Creek Reservoir

The mean annual contribution of internal loading in 2015 in WCR was 305 kg (range 133 to 531 kg). Of this, 241 kg or 79% was DP (range 109 kg to 406 kg; Table 3.2, Figure 3.10, Appendix I). Assuming the sediment release rates are invariant between years, according to the justification above, the internal load contribution in 2014 was 246 kg (range 108 to 428 kg; Table 3.5). Of this, 195 kg or 79% was DP (range 88 kg to 327 kg). Overall, the mass balance shows that WCR retained and average of 642 kg TP (range 472 to 868 kg·yr^{-1}) in 2015, while in 2014 an average of 993 kg TP (range 854 to 1176 kg TP) was retained. A mass balance during the wet season only (January to May) determined that in 2014, 63% (809 kg) and in 2015, 74% (468 kg) of TP remained in the reservoir following spring runoff (Appendix 3.10).

The mean contribution during the anoxic period only showed an annual retention (or loss with negative values) in 2014 of 132 kg (range -7 to 314 kg) and in 2015 of 117 kg (range -55 to 343 kg; Figure 3.11, Appendix I). During the 2015 anoxic period, 87% of the total P loaded to the reservoir was from internal loading, while the remaining 13% came from Willow Creek and dry and wet deposition.

Discussion

Comparison of 2014 and 2015 water budget

Analogous to many lakes in the western United States, the majority of inflow to WCR occurs between January to May as a result of snow melt from a snowpack accumulated at high elevations, and spring precipitation in the form of rain (Hidalgo et al. 2009, Hamlet et. al 2005, Hamlet and Lettenmaier 1999). During this study, 86-88% of the annual water budget entered WCR during this wet season and included transport of sediment and nutrients as evidenced by highly turbid inflows (personal observations). While a majority of the inflow of sediment and nutrients enter during the wet season, this input steadily decreases as summer progresses. At WCR in particular, Balm Fork has run dry the last 10 years beginning in July and Willow Creek contributed only 12-14% of the annual flow from June to December. Only the occurrence of severe storms, such as the Heppner flood in June 1904, provide occasional significant water input outside of the January to May wet period (Byrd 2009). This means that nutrient dynamics in the reservoir during summer are primarily controlled via internal processes. If internal loading is not monitored in lakes and reservoirs throughout the summer, a major source of P would be missed in the mass balance.

Interannual comparisons of the water and P budgets as well as the anoxic period and its timing provide valuable information about WCR. For example, inflow and outflow in 2014 was nearly double that of 2015 (Appendix E). However, in 2011, inflow was over 3-fold greater than in 2014, and 6.5-fold greater than in 2015, indicating large interannual variability. Precipitation was also higher in 2014 than 2015, further contributing to a greater volume of water in WCR in 2014 compared to 2015, resulting in a dilution effect for any internally loaded P. It may be possible that the duration of HABs which have ranged from 10 to 141 days is related to these factors and deserves further examination for possible predictive relationships. Such relationships would greatly aid managers in gauging potential toxic HABs and thus regulation of access by the public.

Variation in sediment phosphorus release rates

The significant variation in P release rates among sites in WCR does not support the original hypothesis that P release rates are similar across the reservoir. The three distinct clusterings of the six sites (BY and WC highest, UBF and UWC lowest, and MS and BF intermediate – see results) shows a distinct pattern across the reservoir bottom which is consistent with typical reservoir dynamics (Wetzel 2001). Reservoirs are low energy environments causing inflows to deposit material in a graded sequence from the inflow to the dam wall. Coarse particles requiring the most energy to transport are deposited near the inflow, while fine particulate matter and associated adsorbed elements such as phosphorus are transported further into the reservoir (Wetzel 2001). Thus particles deposited at the most upstream sites (UBF and UWC) are coarse grained and likely include inorganics such as sand and small cobble, which tend to have relatively low adsorbed P (Selig 2003). This could explain the low observed release rates at these sites in WCR.

Smaller particles such as fine particulate matter, and clays and silts are transported further into the reservoir than sands and cobble. Because silt and clay particles have a high surface:volume ratio, they typically carry high loads of phosphorus and it may be expected that the locations where these particles settle could have high concentrations of phosphorus. Under anoxic conditions, one would expect these areas to exhibit the highest P release rates (Selig 2003). This would partially explain the highest release rate observed at the BY site, located in the middle of the Willow Creek arm of WCR (Figure 3.2). Sites closer to the dam such as WC and MS also exhibited high release rates, but only the rate at the WC site was similar to the release rate at the BY site. It is unclear if the sites with the highest release rates also had the smallest particles, and this deserves further investigation. If particle size is related to release rate, it may serve as a simple analogue to undertaking extensive sediment release rate experiments.

The variation of release rates has important implications for lake managers and researchers that require an accurate mass balance that includes an internal loading component. The large range of release rates I measured demonstrates that site selection could greatly influence the contribution attributed to internal loading. This is important especially if management decisions are based on such a mass balance. For example, treatment effectiveness (the amount/dose applied) depends on knowing the magnitude of the problem to be corrected. Underestimating the problem would result in an ineffective treatment, meaning it would need to be repeated in short order, while overestimation would result in the excess application of treatment material. Both result in the unnecessary expenditure of funds that are typically in short supply. Thus it is vital that managers select appropriate sites to adequately capture release rates and internal loads. I feel confident that the six sites sampled adequately represent the range of release rates likely to occur across WCR. If funds for sampling only one or two sites were available, sampling at the deepest site (a favorite site of limnologists) MS in WCR, would yield results representative of the whole-lake average and thus should allow adequate estimation of treatments to be applied. Steinman and Ogdahl (2015) examined the release rate of P from 4 sites in polymictic Bear Lake, MI where site 1 and 2 release rates were close to the whole lake mean (all sites averaged) over the whole year sampled. Other researchers have also found that release rates from the deepest site tend to be reflective of the whole-lake mean release rate (Table 3.3). Thus, this may indicate a pattern whereby the deepest site can be used to approximate the whole-lake mean release rate. However, such a generalization should be approached cautiously, especially if significant funds are to be expended as a result of the various mass balance components.

Comparison of 2014 and 2015 total phosphorus load

Dynamics of TP in WCR in 2014 and 2015 followed similar trends to the water budget in that 2× the inflow TP loaded into WCR occurred in 2014 compared to 2015. The main sources of TP in WCR were contributions by inflows from Willow and Balm Fork creeks and internal loading. Because WCR is located in a dry arid climate, wet and dry deposition did not contribute significantly to the mass balance, accounting for only 52 kg in 2014 and 38 kg in 2015 and <4% overall (Figure 3.10, Appendix I). The contribution via groundwater remains to be empirically quantified and was beyond the scope of this study.

Even though the TP contributed by inflows was greater in 2014 compared to 2015, the contribution from internal loading was greater in 2015 compared to 2014 (keeping in mind that 2014 internal loads were estimated from cores collected in 2015). This may be caused by the change in the depth at which anoxic conditions occur and the surface area of the reservoir bottom affected by anoxic conditions. When anoxic depth and surface area become more prevalent with increasing anoxic conditions, a higher load of TP and DP is released. It is important to note when comparing 2014 and 2015 values that the total reservoir volume was greater in 2014 than 2015 (Table 3.4). However, less of the WCR volume in 2014 was anoxic than in 2015 resulting in less of the surface area releasing P via internal loading. As discussed above, the variation in anoxic conditions monitored by DO and temperature profiles are crucial if sediment core analysis is completed.

Variation in water volume and TP load entering and leaving WCR as well as the contribution of internal loading between years may alter the frequency and severity of algae blooms. As mentioned above, the average water depth and volume of the reservoir was greater in 2014 compared to 2015 and the anoxic depth and thus volume of water that was influenced by anoxic conditions was lower than in 2015. This greater volume of overlaying water in 2014 may make it difficult for wind mixing leading to P trapped below the metalimnion to mix to the surface where it would lead to algal blooms. Epilimnetic water overlying cold hypolimnetic water in stratified lakes and reservoirs creates a water density gradient and therefore an added deterrent to mixing. Further analysis of wind speed and direction data during the 2014 and 2015 may provide insight into this question. A lower anoxic depth in 2014 may have aided in decreased bloom occurrence because the duration of water advisories lasted 14 days in 2015 compared to 39 days in 2014 (OHA 2016). Increased drawdown at WCR also may expose cyanobacteria akinetes to freezing temperatures, decreasing the potential of bloom returns during the next year (Pichrtová 2014). The decrease in average volume as a result of the deep drawdown at WCR in 2014 and 2015 may have contributed to the relatively short HABs and advisories.

Sources of error and future sampling

It is possible that using the whole-lake mean sediment core release rate and estimating loads induced errors. To account for this, additional core sampling (~30 cores) within WCR and analysis of iron and phosphorus extraction to determine the potential release of phosphorus can provide a more thorough spatial representation of potential release rates. Analysis of particle size may indicate where fine particles with the highest surface area and highest P binding occur in the reservoir. By sectioning the reservoir into spatial areas by P release rates, a more accurate estimate of internal loading should be possible.

Other errors applied to the mass balance include lack of information on the influence of senescent algae on internal load calculations. Also, in stratified lakes and reservoirs the metalimnion can provide a barrier for algae and prevent or slow their sinking into the hypolimnion thereby creating a deep chlorophyll layer (DCL; Watkins el al. 2015). Because chlorophyll sampling at WCR currently only occurs at the surface, collection of chlorophyll samples or a fluorescence profile over the depth of the water body may provide further detail about algal densities and a DCL. Both may need to be considered when calculating the hypolimnetic TP load. I also did not directly account for the potential redistribution of P due to wind mixing and metalimnetic entrainment. The HAB advisories in 2014 and 2015 occurred a month prior to destratification, which could indicate that wind events may have aided in the redistribution of internally loaded P to surface water as winds tend to increase in autumn. Excretion of P from fish has also been cited as a contributor of P to the water column (Vanni 2002, Eilers et al. 2011), which cannot be accounted for with sediment cores. These potential errors should be quantified in future attempts to refine the mass balance.

Conclusions

The hypothesis that sediment P release rates under anoxic conditions were uniform across the bottom of Willow Creek Reservoir was not supported While this has implications for whole-lake mass balances based on one or a few sites, I did find that the deepest site approximated the average release rate in WCR and this release rate was similar to those reported in other studies. Thus it may be possible to simply estimate whole-lake release rates, but this should be used cautiously given the relatively low number of studies which report release rates from multiple sites in the same water body. The paucity of such data is likely related to the significant effort needed to obtain release rates using laboratory incubated cores. An alternative may be to examine release rates in relation to sediment particle size, which will be the focus of a future study. The two years of data presented here also demonstrate the large interannual variability that managers and those requiring accurate mass balance data face. In light of this, managers should strive to assemble long-term datasets to provide insights to internal processes and inform management decisions.

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Table 3.1. Total (TP) and dissolved phosphorus (DP) release rates (mg P/m^2/d) ± SE and overall means for six sites sampled in Willow Creek Reservoir, OR in 2015. Sites are Main Site (MS), Willow Creek (WC), Weather Buoy (BY), Balm Fork (BF), Upper Balm Fork (UBF), and Upper Willow Creek (UWC).

Constituent	Site	Release Rate (mg/m^2/d)	± SE
TP	MS	9.27	0.54
	WC	9.54	1.18
	BY	14.63	1.88
	BF	7.49	1.09
	UBF	3.70	0.67
	UWC	4.47	0.78
	Mean	**8.41**	**0.89**
DP	MS	7.38	0.56
	WC	7.62	1.02
	BY	11.18	1.73
	BF	5.93	0.67
	UBF	3.00	0.45
	UWC	3.70	0.64
	Mean	**6.64**	**0.69**

Table 3.2. Annual loads of total (TP) and dissolved phosphorus (DP) ± SE contributed via internal loading in Willow Creek Reservoir, Heppner, OR from each of six sites in 2014 and 2015. Site names are Main Site (MS), Willow Creek (WC), Weather Buoy (BY), Balm Fork (BF), Upper Balm Fork (UBF), and Upper Willow Creek (UWC). Values for the 2014 TP and DP load ± SE are shaded as they are estimated from sediment cores collected and analyzed in 2015.

Constituent	Site	2014 Load (kg)	± SE	2015 Load (kg)	± SE
TP	MS	271.51	15.71	336.35	19.46
	WC	279.60	34.55	346.37	42.80
	BY	428.72	55.11	531.10	68.26
	BF	219.62	31.93	272.06	39.56
	UBF	107.54	19.33	133.22	23.95
	UWC	131.01	22.81	162.30	28.26
	Mean	246.33	26.12	305.15	32.35
DP	MS	216.25	16.31	267.89	20.21
	WC	223.22	29.80	276.53	36.92
	BY	327.60	50.72	405.83	62.83
	BF	173.76	19.72	215.26	24.43
	UBF	88.05	13.22	109.08	16.38
	UWC	108.56	18.69	134.49	23.15
	Mean	194.59	20.26	241.06	25.10

Table 3.3. Comparison of total phosphorus (TP) release rates (RR) ± SE and depths of means of all sediment cores and the deepest site at various lakes/reservoirs.

Lake/Reservoir (year sampled)	Mean RR ± SE (mg P/m^2/d)	Mean depth (m)	Deep site RR ± SE (mg P/m^2/d)	Deep site depth (m)	Source
Willow Creek Reservoir, OR (2015)	**8.41 ± 0.89**	**15.0**	**9.27 ± 0.54**	**20**	**This study**
Bear Lake, MI (2011)	6.69 ± 1.93	2.1	3.49 ± 0.53	3.05	Steinman et al. 2015
Bear Lake, MI (2012)	3.92 ± 1.13	2.1	1.79 ± 0.52	3.05	Steinman et al. 2015
Mona Lake, MI (2006, 2007)	11.38 ± 3.29	13.0	7.06 ± 2.88	8.3	Steinman et al. 2009a
Spring Lake, MI (2003)	17.97 ± 5.19	5.5	16.02 ± 9.27	10.1	Steinman et al. 2004
White Lake, MI (2007)	3.75 ± 1.08	7.0	3.21 ± 0.93	16.1	Steinman et al. 2009b
St. George, ON (1984)	2.22 ± 0.673	5.5	2.22 ± 0.673	NA	Nürnberg 1987, 1988
Red Chalk Lake, ON (1984)	0.05 ± 0.04	5.7	0.097 ± 0.028	NA	Nürnberg 1987, 1988
PT-10, ON (1984)	0.04 ± 0.07	3.2	0.108 ±0.026	NA	Nürnberg 1987, 1988
Chub Lake, ON (1984)	1.43 ± 0.16	8.9	1.53 ± 0.086	NA	Nürnberg 1987, 1988
Gravenhurst Lake, ON (1984)	5.27 ± 0.731	9.8	5.27 ± 0.73	NA	Nürnberg 1987, 1988
Lake Waramaug, CT (1984)	9.22 ± 1.00	7.0	8.08 ± 0.75	NA	Nürnberg 1987, 1988

Table 3.4. Whole reservoir and anoxic period only comparison during 2014 and 2015 field seasons at Willow Creek Reservoir, Heppner, OR. Whole and anoxic only reservoir conditions of average reservoir height (m a.s.l.), average 3D area (m^2), and average volume (m^3).

Characteristic	Parameter	2014	2015
Whole reservoir	Average reservoir height (m a.s.l.)	627.36	626.96
	Average 3D area (m^2)	$4.69 \cdot 10^5$	$4.58 \cdot 10^5$
	Average Volume (m^3)	$4.47 \cdot 10^6$	$4.30 \cdot 10^6$
Anoxic only	Average reservoir height (m a.s.l.)	615.81	617.71
	Average 3D area (m^2)	$1.84 \cdot 10^5$	$2.25 \cdot 10^5$
	Average Volume (m^3)	$9.53 \cdot 10^5$	$1.22 \cdot 10^6$

Figure 3.1. Location of Willow Creek Reservoir (marked with star) near Heppner, OR in Morrow County, Oregon, USA. Source: Google Earth; accessed 16 April 2015.

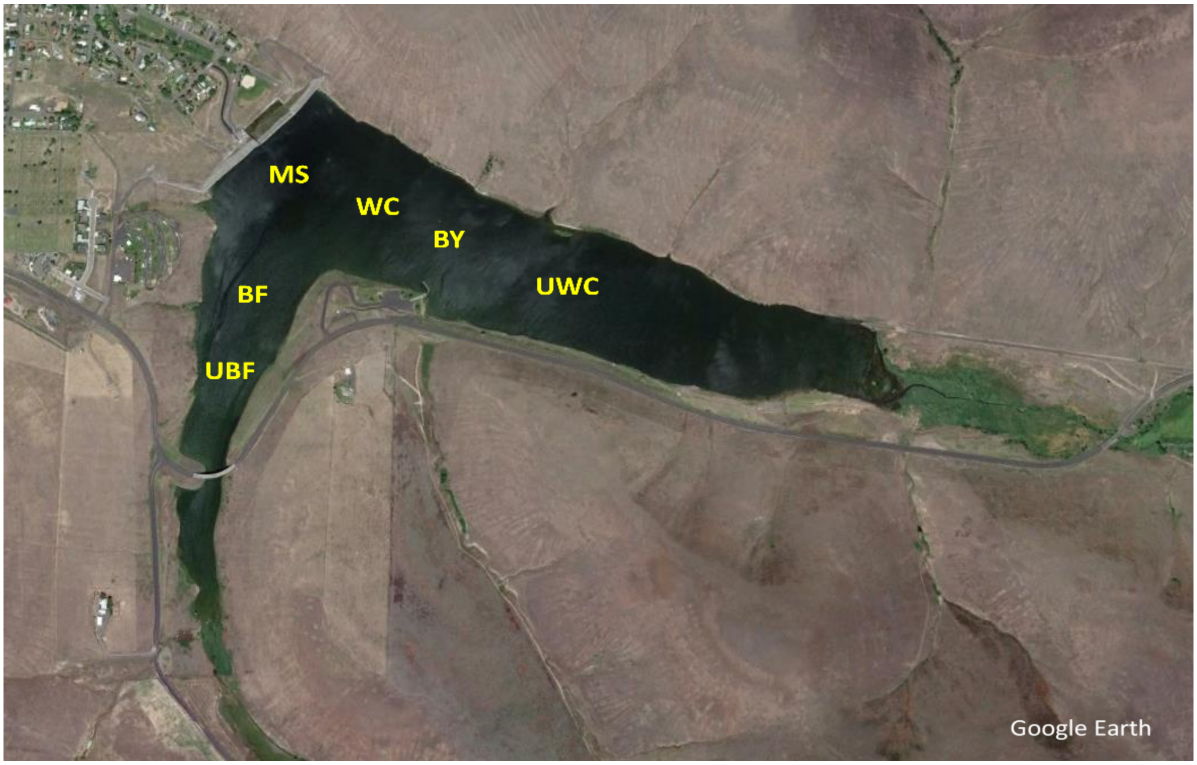

Figure 3.2. Sediment core sampling sites at Willow Creek Reservoir, Heppner, OR. Site names are Main Site (MS), Willow Creek (WC), Weather Buoy (BY), Upper Willow Creek (UWC), Balm Fork (BF), and Upper Balm Fork (UBF). Source: Google Earth; accessed 16 April 2015.

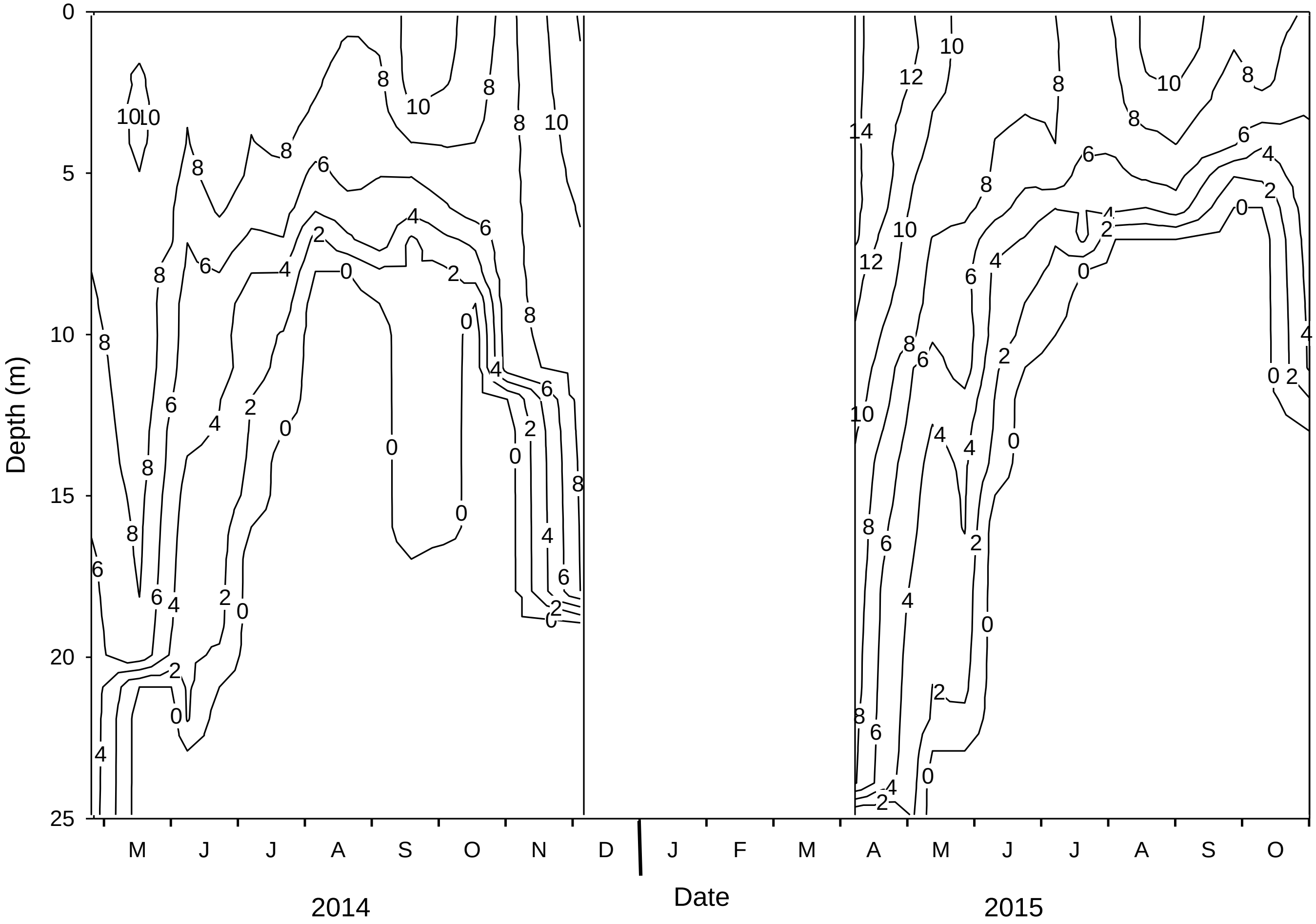

Figure 3.3 Dissolved oxygen (DO, mg/L) isopleths at two-week intervals from Willow Creek Reservoir, OR in 2014 and 2015. Sampling did not occur during winter months.

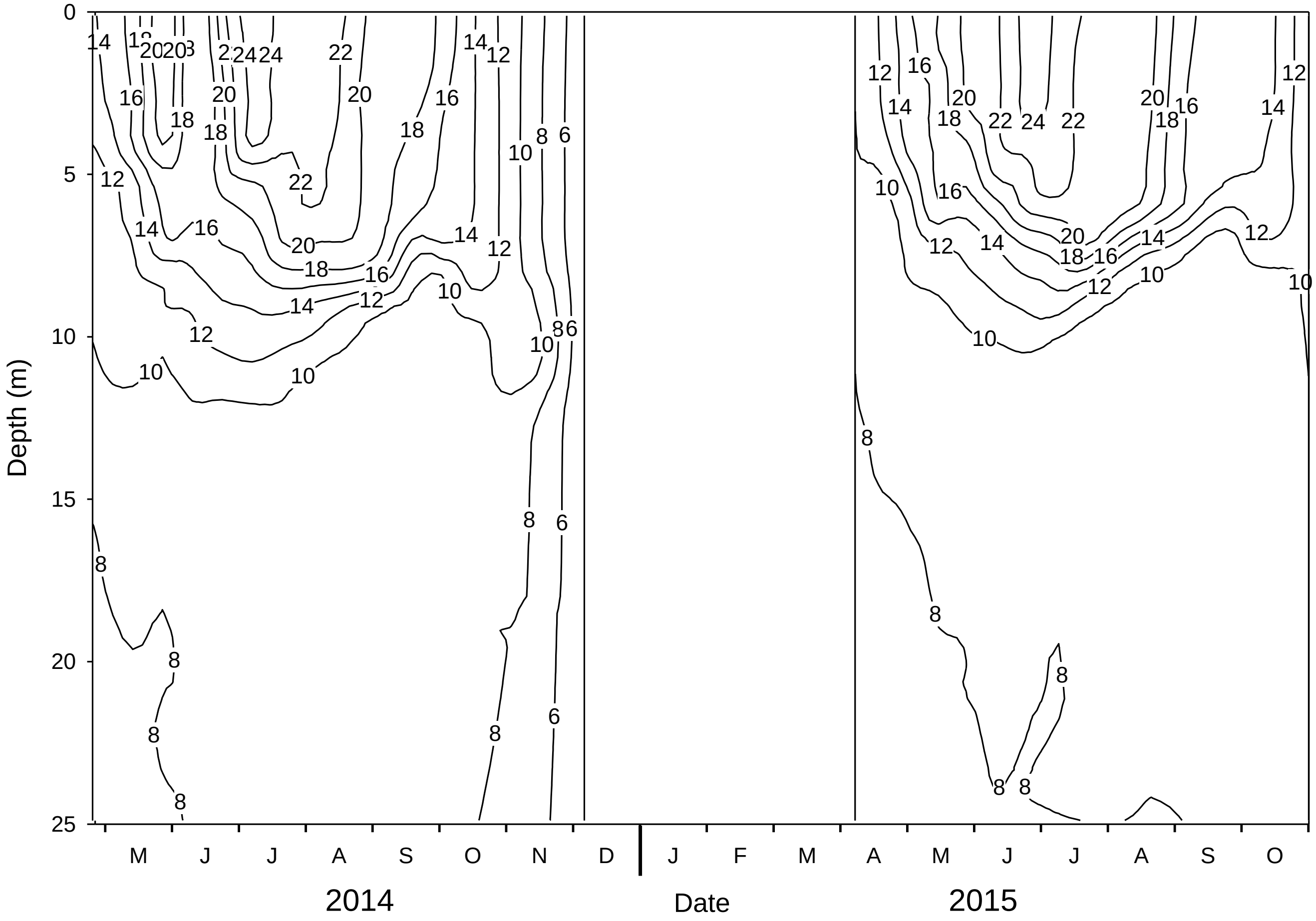

Figure 3.4. Temperature (°C) isopleths for the period 2014 to 2015 at biweekly intervals from Willow Creek Reservoir, OR. Sampling did not occur during winter months.

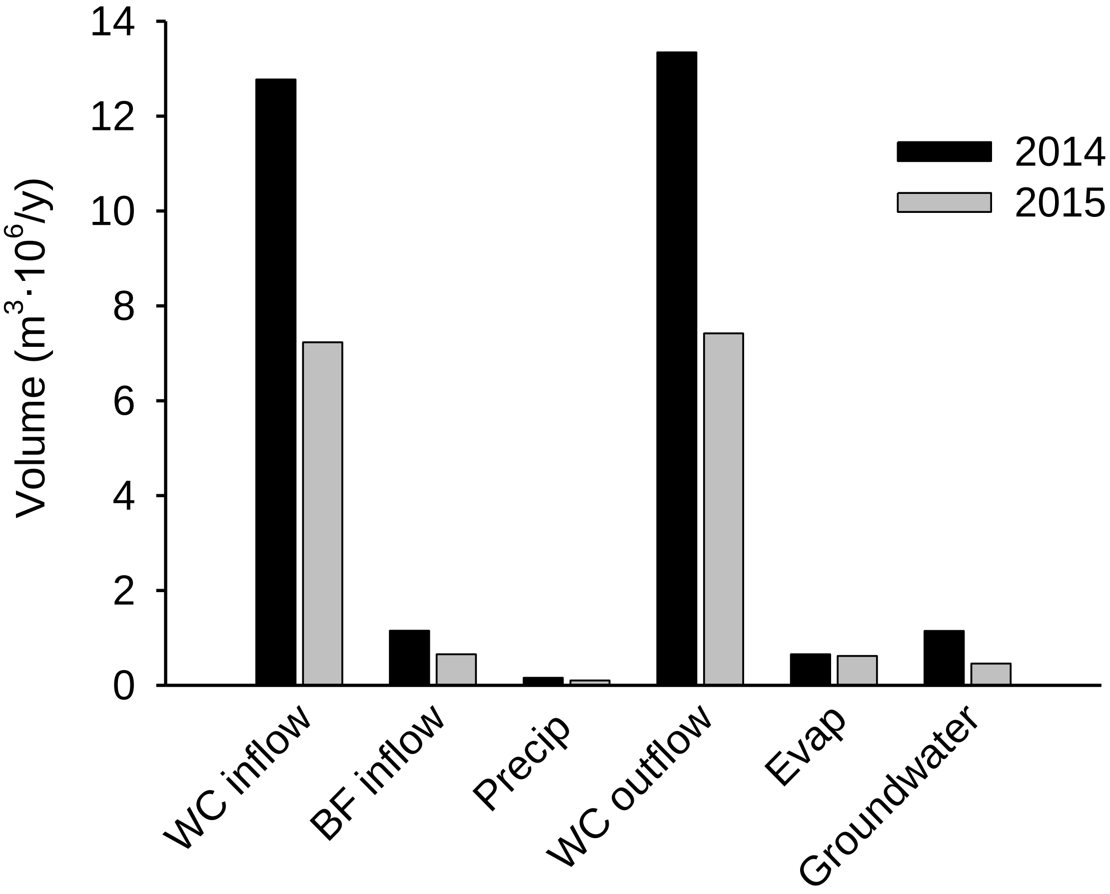

Figure 3.5. Annual water budget for Willow Creek Reservoir for 2014 and 2015. Willow Creek inflow and outflow are indicated by WC, while Balm Fork is indicated by BF.

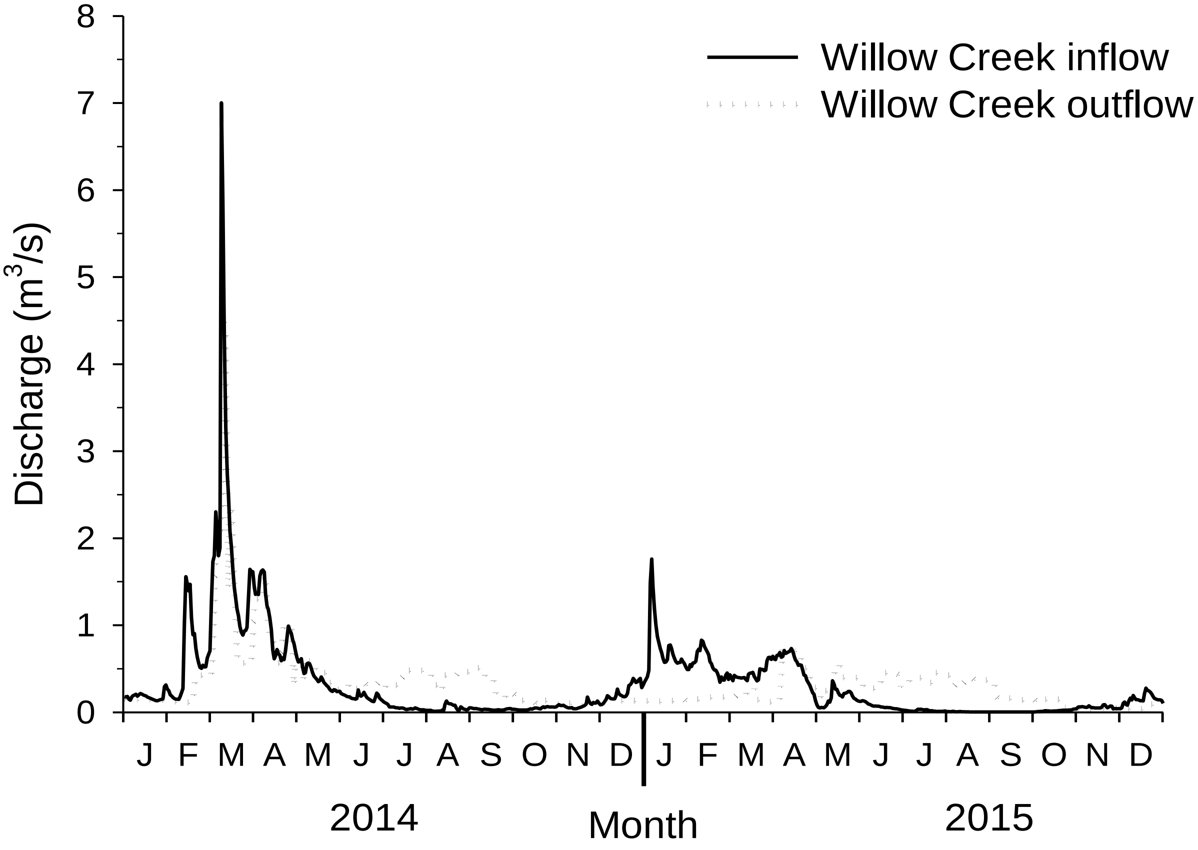

Figure 3.6. Hydrograph of discharge (m³/s) as a function of time for Willow Creek inflow (solid line) and Willow Creek dam (outflow; dotted line) sampling during 2014 and 2015.

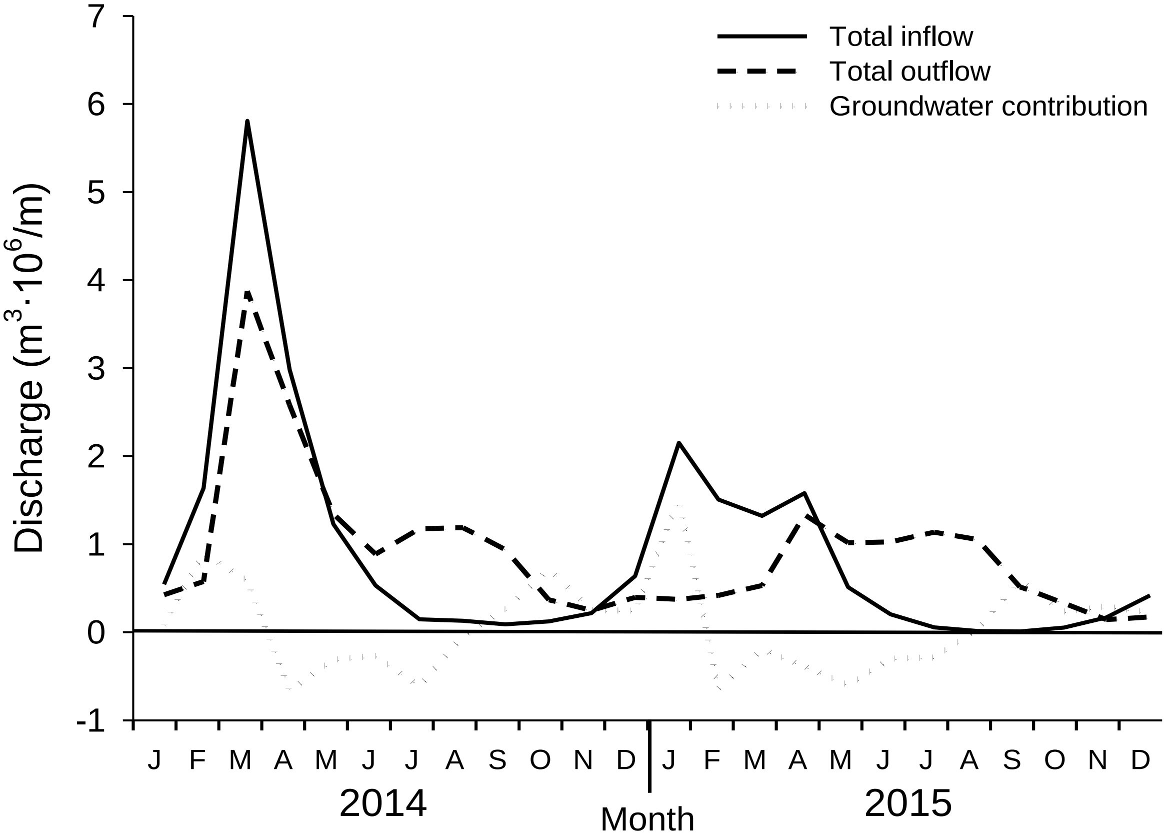

Figure 3.7. Volumes of water from total inflow, total outflow, and groundwater contributions from Willow Creek Reservoir (WCR), OR from 2014 and 2015. Positive groundwater volumes indicate a water transfer from WCR to groundwater and negative volumes indicate a transfer from groundwater to WCR.

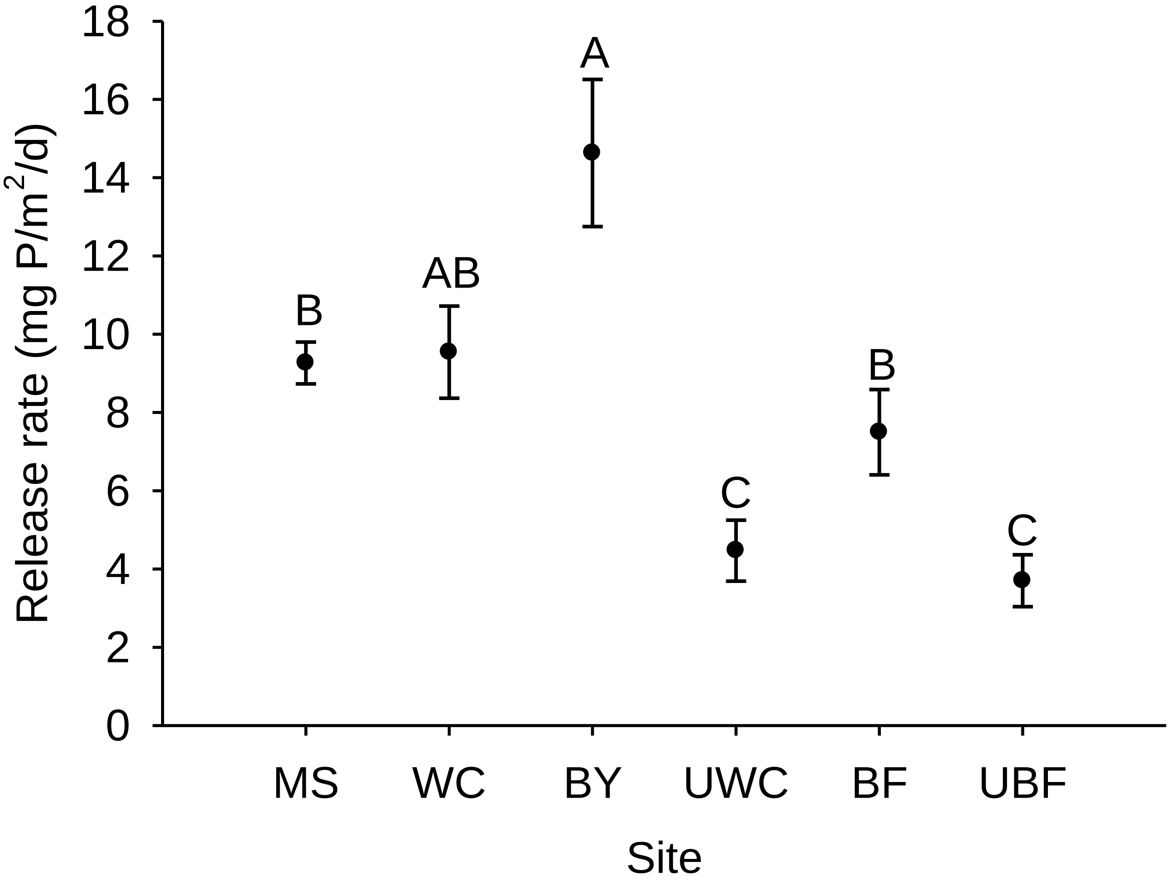

Figure 3.8. Mean release rates ± SE of total phosphorus (TP) in Willow Creek Reservoir, Heppner, OR at six sites. Sites with different letters differed (*P*<0.05) from each other.

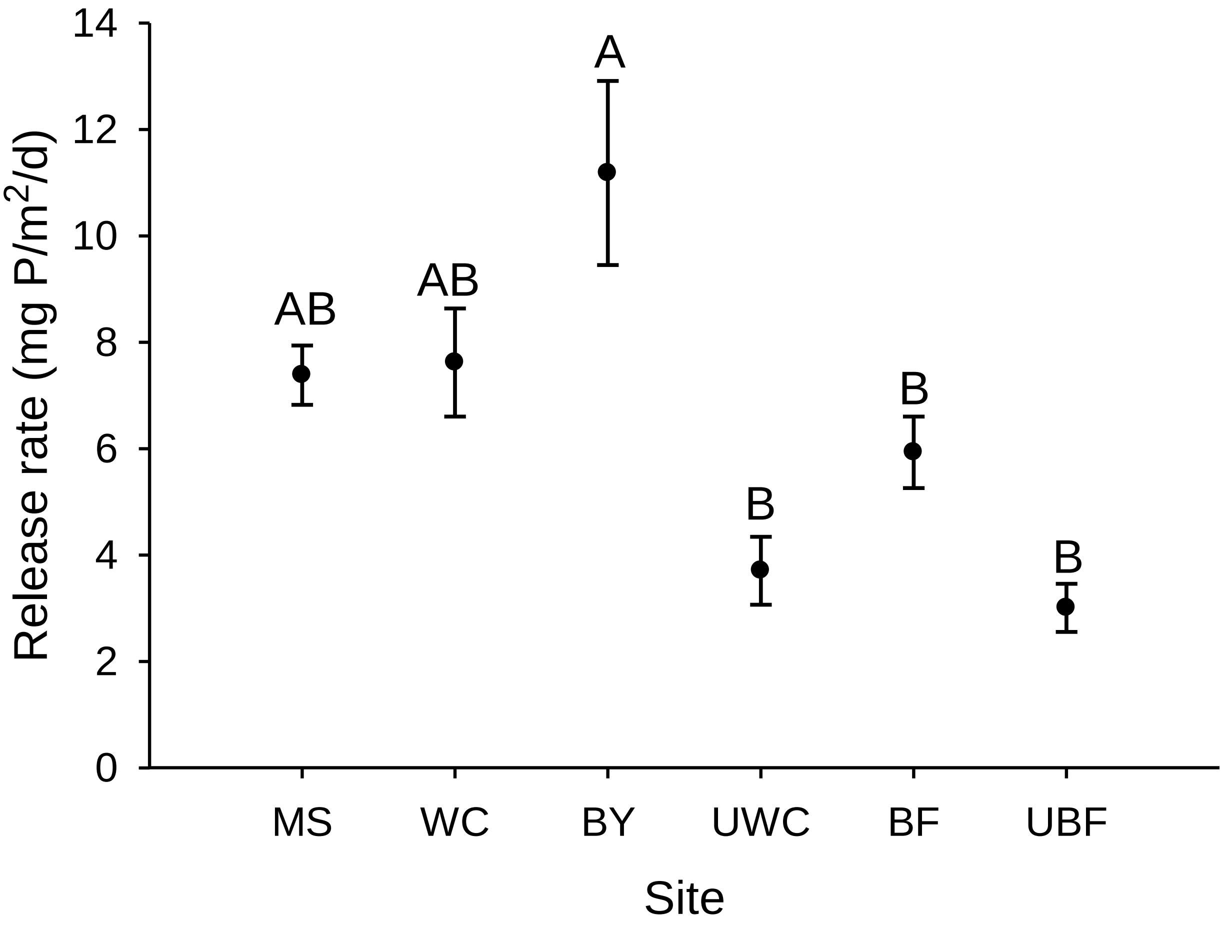

Figure 3.9. Mean release rates ± SE of dissolved phosphorus (DP) in Willow Creek Reservoir, Heppner, OR at six sites. Sites with different letters differed (*P*<0.05) from each other.

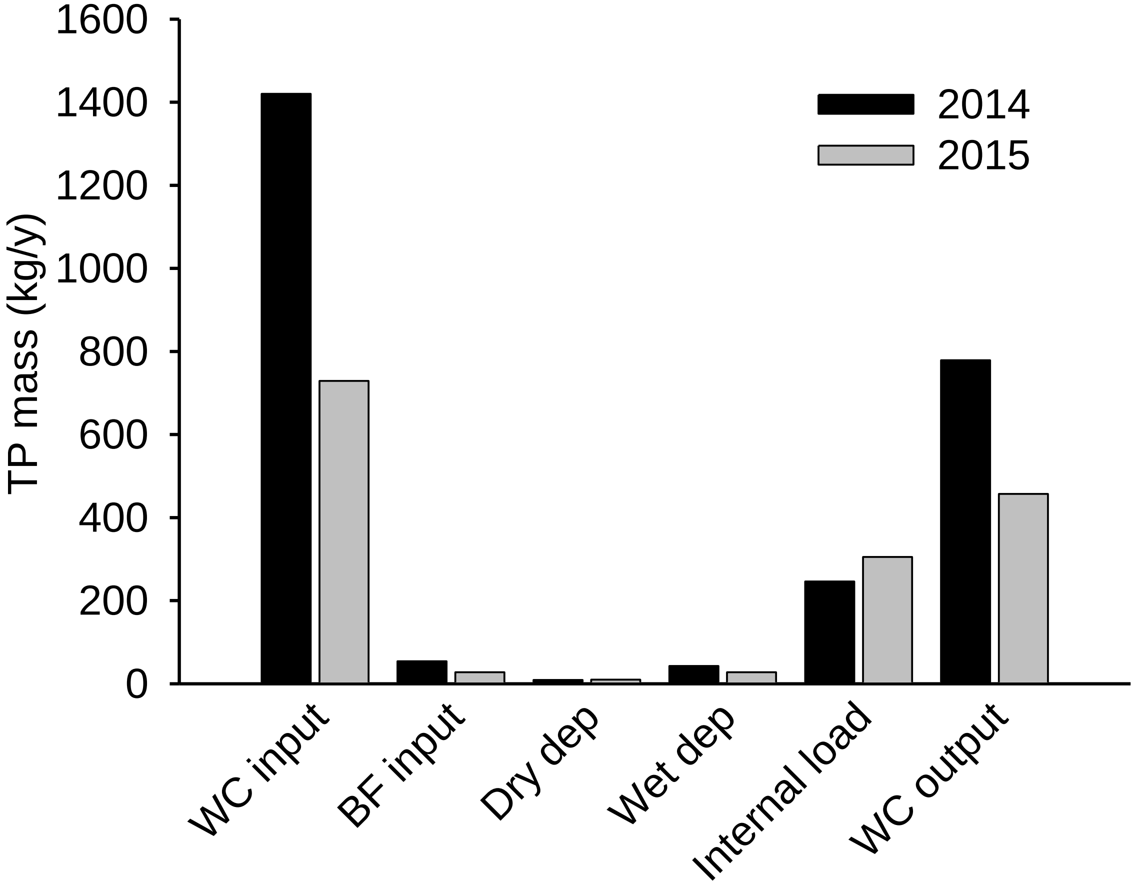

Figure 3.10. Annual total phosphorus (TP) budget for Willow Creek Reservoir, OR for 2014 and 2015. Internal loading values were estimated from sediment core sampling using mean TP load of all six sites (see methods). Willow Creek input and output indicated by WC while Balm Fork indicated by BF.

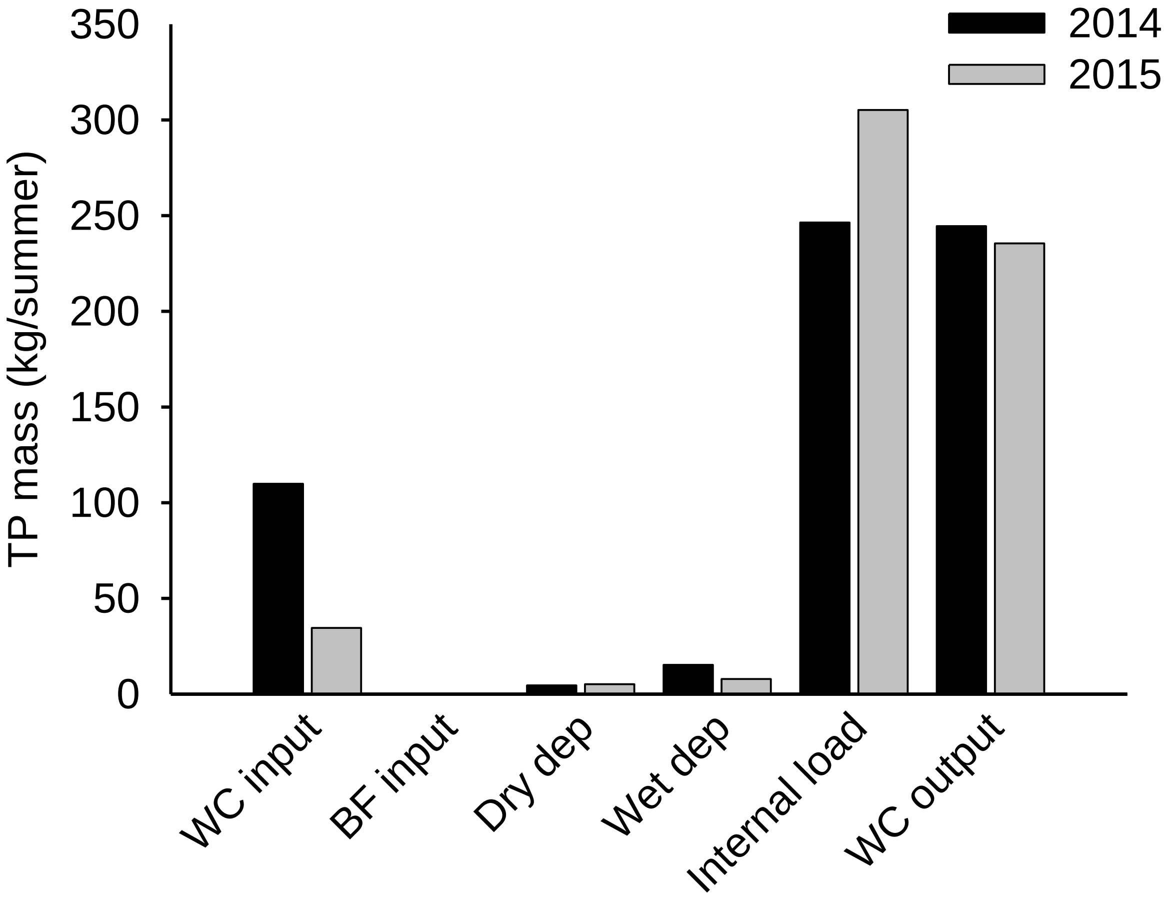

Figure 3.11. Anoxic total phosphorus budget for Willow Creek Reservoir, OR for 2014 and 2015. Internal loading values were estimated from sediment core sampling using mean TP load of all six sites (see methods). Willow Creek input and output indicated by WC while Balm Fork indicated by BF.

Chapter 4: A comparison of two methods to predict internal loading of phosphorus in a stratified reservoir

Abstract

In many stratified lakes and reservoirs, internal loading of nutrients from sediments under anoxic conditions can be a significant contribution to a water body's annual nutrient mass balance and may be responsible for summer algal blooms, some of which can be toxic and are typically referred to as harmful algal blooms (HABs). Programs to remediate HABs require an understanding of the whole-lake mass balance including internal loading. Several methods exist to quantify internal loading, including directly measuring increases in water column P during the anoxic period and measuring the release rate in the laboratory from sediment cores. Both methods are widely used, but rarely are they compared side-by-side given the effort expended for each. Here I test the hypothesis that both methods yield similar internal loading rates in Willow Creek Reservoir (WCR), OR. Sediment cores for laboratory incubation under anoxic conditions were collected in early 2015, while in situ water column measurements were made throughout the 2014 and 2015 stratified period. When adjusted to a 90 day anoxic period, the load calculated using release rates from sediment cores was 171 kg (range 74 to 299 kg), while the load estimated from water column measurements was 114 kg in 2014 and 292 kg in 2015 leading me to accept the null hypothesis that both methods yield similar results. Even though both methods yielded similar results, because water column measurements directly measure concentrations present in the water, I recommend that this method be used preferentially to estimate internal loading.

Introduction

Worldwide, the eutrophication (addition of excess nutrients) of natural waters is recognized as a major threat to water quality (Pitois et al. 2001, Schindler and Vallentyne 2008, Schindler et al. 2008, Downing 2013, Schindler 2012). Eutrophication stimulates excessive primary production which can result in toxic blooms of cyanobacteria (also termed harmful algal blooms - HABs) (Schindler 1977, Chorus and Bartram 1999, Schindler and Vallentyne 2008), contribute to low dissolved oxygen when the biomass decomposes (Nürnberg et al. 1986, Paerl et al. 2011), produce unpleasant taste and odors in drinking water (Westerick et al. 2010, Paerl et al. 2011), and decrease overall aesthetic values (Lansford and Jones 1995, Olden and Tamayo 2014, Liao et al. 2016). While limnologists recognize that lakes fill naturally and generally progress along a trajectory of increasing eutrophy over their lifetime (Wetzel 2001), this is a long process on the order of millennial timescales, compared to 'cultural' eutrophication, which is the acceleration of this process due to anthropogenic activities that greatly intensify the delivery of nutrients to aquatic ecosystems (Schindler 1977 , Smith 1983, Carpenter et al. 2001, Pitois et al. 2001, Carpenter 2008, Paerl and Huisman 2008, Schindler and Vallentyne 2008, Paerl and Otten 2013) and thus significantly shorten the time to eutrophy. Cultural eutrophication not only has direct impacts such as negatively affecting water resources used for potable supplies, recreation, and agricultural purposes, but it also indirectly affects economics, typically manifested in losses stemming from reduced production of fish and wildlife, increased water treatment costs, loss of recreational amenities, and agricultural losses. It is the intent of laws such as the Clean Water Act (1972) in the USA to prevent eutrophication and recover those aquatic ecosystems already negatively affected.

The first step in a remediation program is to take stock of inputs and outputs (mass balance) to understand major sources and help focus recovery actions (Olem and Flock 1990, Cooke et al. 2005). While typical inputs and outputs such as wet/dry deposition, inflows/outflows, point and non-point sources (USEPA 1991) can be identified, in lakes and reservoirs that directly stratify and in which the hypolimnion becomes anoxic, a process called internal loading can contribute significant amounts of nutrients, particularly P, to the annual mass balance (Nürnberg 1985, 1988, Welch and Jacoby 2001). Internal loading can be difficult to distinguish from other sources such as inflow, senescing algae, atmospheric deposition, or precipitation (Nürnberg 1985, 2009) and thus requires special attention and effort to quantify. It is commonly quantified by directly measuring the increase in the water column P over the anoxic stratified period (Welch and Jacoby 2001, Nürnberg 1985, 1987, 1988, 2009) or by incubating sediment cores retrieved from the lake bottom under anoxic conditions in the laboratory (Holdren and Armstong 1980, Moore et al. 1991, 1998, Steinman and Ogdahl 2015). Both of these processes have advantages and disadvantages – including temperature and DO controls, sampling procedures and analysis, uncertainty in anoxic area and duration; but each requires significant effort, to the point that either one or the other is generally used but rarely are both used at the same time (but see Nürnberg 1987, Nürnberg et al. 2013). Given I used both approaches to quantify internal loading in Willow Creek Reservoir, OR, (see Chapters 2 and 3), I was interested to test the hypothesis that both methods yield similar results. Here I standardize the results from Chapters 2 and 3 to 90 days, the typical time frame considered for internal loading contributions under anoxic conditions (Welch and Jacoby 2001) to directly compare the two methods.

Methods and Materials

Study site

Willow Creek Reservoir (WCR) is located in the high desert of northeast Oregon and suffers from annual blooms of toxic algae due to imbalances of the N:P ratio (Harris 2014 a, b). The dam was constructed in 1983 primarily for flood control, but the reservoir now also is used for recreation, and as an irrigation supply for agriculture (USACE 2007). Toxic algae blooms, with microcystin concentration up to 1500 µg/L in some cases (the primary contact limit in

Oregon is 10 μg/L; OHA 2005) that last from 14 to 153 days have been noted regularly since intensive monitoring started in 2006 (OHA 2016). Because extensive background monitoring data are available since dam closure, WCR is an ideal study site.

Additional information about the study site and methodology for determining the internal load of TP and DP using in situ measurement and the incubation of sediment cores in the laboratory are described in Chapters 2 and 3, respectively. Water column concentrations were available for 2014 and 2015, to directly calculate internal loads. In contrast, sediment release rates were only measured in 2015. However, because lake bottom temperatures, rate of influx of sediment, settling of algal material, and anoxic conditions were similar between years, I considered the 2015 release rates to be representative for WCR and used them to approximate 2014 sediment release rates to afford an interannual comparison. This justification is supported by data from other lakes. For example, Steinman and Ogdahl (2015) estimated release rates of cores in Bear Lake, MI in summer 2011 and 2012 and determined that the release rates were within one standard error (6.69 ± 1.93 mg P/m^2/d in August 2011 and 3.92 ± 1.31 mg P/m^2/d in July 2012). Similarly, data reported by Nürnberg (1987) for Chub Lake MN showed that over 9 years (1976-1984) the summer loading rate was of 21.4 ± 4.4 mg P/m^{-2}/summer. I assumed that internal loading rates from sediment incubated cores did not differ between years for WCR.

To compare whole-lake loads determined with each method, the time of anoxia considered was standardized to the first 90 days, the typical time period used in the literature for similar comparisons (e.g., Welch and Jacoby 2001). Given that in both years of water column sampling, the duration was 98 days from start of anoxia to peak P mass in the hypolimnion, standardizing to 90 days only eliminated 8 days of data, and did not significantly skew the results given the linear nature of the release rates. The sediment core anoxic period from start of anoxic conditions to destratification lasted 159 and 161 days in 2014 and 2015, respectively. To calculate loading of TP for 90 days of sediment core data, each TP load was divided by the number of days of anoxia and multiplied by 90. In addition, a whole-lake average release rate for TP and DP was calculated using all sites and cores examined in Chapter 3. All other in- and output data were also converted to the same 90 day window for comparison.

Results

In 2014, the 90 day adjusted internal load of TP and DP from the water column measurements was 114 kg and 103 kg, respectively, while in 2015 it was 292 kg and 262 for TP and DP, respectively (Table 4.1, Figure 4.1). In 2014, the 90 day adjusted internal load for TP and DP from sediment cores was 139 kg and 110 kg, respectively, while in 2015 it was 171 kg and 135 kg for TP and DP, respectively (Table 4.1, Figure 4.1).

When the phosphorus budget (including inputs and outputs) during anoxic conditions was adjusted to 90 days, a retention of TP was exhibited from both methods except from water column data in 2014. In the case of sediment core data, 75 kg of TP in 2014 and 66 kg in 2015 was retained in WCR. Using sediment cores, internal loading contributed 66% in 2014 and 87% in 2015 of the TP during the anoxic period. Compared to the water column data, 33 kg of TP in 2014 was lost from WCR and 125 kg was retained in 2015 during the 90 day period. Using the water column data, internal loading contributed 73% in 2014 and 93% in 2015 (Table 4.1).

Discussion

I hypothesized that internal loads in WCR estimated from the water column (Chapter 2) and sediment core incubations (Chapter 3) methods would be similar. Over two years of study, internal loading using both methods contributed 66% to 93% of P to WCR during anoxic conditions. Comparing the two methods in 2014, internal loading estimated over 90 days was greater for the incubated sediment cores than that measured in the water column, but the difference was only 31 kg. Because the sediment cores were collected in 2015, the estimate from

2014 may not provide a proper comparison if sediment deposition following spring runoff varied between the two years, potentially influencing the release rates. Higher discharge rates and inflow volumes seen in 2014 compared to 2015 will carry more silt and clay particles further into the WCR, causing varying distribution of sediment and potentially the release rates throughout WCR. To account for sediment distribution throughout WCR, additional core sampling (~30 cores) and analysis of iron and phosphorus extraction to determine the potential release of phosphorus can provide a more thorough spatial representation of release rates. Analysis of particle size may indicate where fine particles with the highest surface area and highest P binding sites settle in the reservoir. By apportioning the reservoir into spatial areas by P release rates, a better understanding of variation in release rates in WCR and the overall P load may be determined. Length of anoxic condition (159 day in 2014 and 161 days in 2015) and similarities in bottom temperature and DO concentrations can also alter release rates of P (Holdren and Armstrong 1980). With these facts in mind, I believe the two years of data can still provide an understanding of the internal loading contribution to WCR and the overall mass balance.

In 2015, the internal load estimated from water column measurements was 1.7× greater than that estimated from the sediment cores indicating a large discrepancy. This is not surprising given the water column estimates tend to be larger than those reported from sediment release rates (Nürnberg et al. 2013). For example, in Lake Simcoe, Nürnberg et al. (2013) reported that over a 21 year period, the internal P load estimate from water column measurements was always greater than that estimated from sediment cores and the amount of data collected over time accounts for natural variability in Lake Simcoe. With only two years of data comparing in situ and core measurements, the range of natural variability similar to that observed in Lake Simcoe is unlikely to have been captured for Willow Creek Reservoir.

Given that water column measurements reflect the amount of P present, I would suggest it is the most accurate estimate of internal P loading at the whole-lake scale. However, the accuracy of such estimates depends on the availability of high resolution bathymetry, as the volume of the hypolimnion must be estimated accurately. As well, high resolution temperature and oxygen profiles are needed to accurately estimate the depth at which the hypolimnion and anoxic layers start. The WCR bathymetry is based on recent (2007) high resolution sampling undertaken by the USGS, while temperature and DO profiles were collected at bi-weekly intervals. Phosphorus concentrations in water samples were determined using standard methods. Based on these facts, I am confident that the water column estimates are more accurate than those from the sediment cores. Other sources of P within WCR are accounted for with water column sampling such as planktonic snow, sources from inflow and deposition, and groundwater. Unknown contributions of TP to the water column that was not accounted for in this study includes the advection of P due to groundwater. With P present in pore water during anoxic conditions, the flux of groundwater into WCR during summer could elevate the P load to the water column. This would only need to be considered if groundwater was entering directly into WCR where anoxic conditions were occurring. Currently, it is not known where groundwater enters WCR, so I am unable to asses this potential contribution. It could be possible that spatial variation in water sample concentrations could add error to my estimates, which should be examined in the future. Perhaps it will be necessary to use a spatially-weighted approach to calculate the P concentration in a water stratum. However, given the wind events that occur on a daily basis at WCR, it is unlikely that water column P concentrations will vary greatly. It would be interesting to know the amount of P moved from the hypolimnion to the epilimnion via wind mixing and metalimnetic entrainment. To my knowledge this has not been quantified, but could be important because it would reveal the true magnitude of internally loaded P that becomes available to primary production in the epilimnion. It would also provide insight to the potential contribution to the formation of HABs.

In lakes and reservoirs in which a majority of external loading occurs during winter and spring months, the majority of the P is loaded from external sources. When external loads become negligible during low summer inflows, yet water column P concentrations continue to increase, the source of P must be an internal one. In the case of WCR, internal loading is a dominating force behind WCR summer TP concentrations as over two thirds of summer TP can be attributed to internal loading. Dissolved phosphorus (DP), which is readily bioavailable accounts for approximately 80% of the TP loaded from internal sources. This high amount of DP has the potential to contribute to severe algae blooms if the metalimnion is disturbed by mixing from strong wind events or destratification. Also, it can be difficult to differentiate between internal and external sources of P within the water column during the year. Differentiating between P loading from sediments (upward flux) or what may be settling (downward flux) such as senescing algae or dry and wet deposition can also make it difficult to distinguish between sources.

Overall, the quantity of TP contributed by internal loading was greater in 2015 compared to 2014. This difference is likely due to the variation in the depth of anoxia (m a.s.l.). Even with a greater whole reservoir volume in 2014 compared to 2015, the anoxic conditions in 2014 were not as aerially extensive as in 2015. This resulted in a greater load of TP released due to internal loading in 2015. Also, the WCR forebay elevation was lower in 2015 compared to 2014 due to reservoir drawdown, which may decrease chances of WCR mixing due to protection from wind events such as the steep topography of WCR and dam wall. Further analysis of wind speed and direction data during the 2014 and 2015 may provide insight into this question.

Internal loading estimates determined from laboratory core samples also are subject to several sources of error. Sediment cores incubated in the laboratory are not exposed to a natural system which features senescing algae, advection of P due to groundwater, wind disturbances, or fish excretion and disturbance by benthic feeders. Excretion of P from fish has been cited as a contributor to P sources as well (Vanni 2002, Eilers et al. 2011), but water column sampling will include P from excretion while sediment core sampling will not. Even if excretions are considered, removal of fish can be used as a technique to decrease bloom frequency. While in the lab, potential errors also may have occurred including resuspension of sediment during bubbling with N_2 or O_2, re-oxygenation or lack of continuous anoxic conditions in the cores, or possible contamination from probes or pipettes. Additionally, as much as we attempt to mimic lake bottom conditions by placing cores in dark, cold environments, it is not an exact replication. The cores during our experiments were overlaid with one liter of lake water while entire lakes and reservoirs overlay the sediment in natural environments allowing the release P to move freely within those system which is something that cannot be replicated in cores.

Conclusions

Here I compared two commonly used methods to estimate internal loading in lentic ecosystem. I found that internal loading estimates from water column measurements were 1.7x greater compared to those estimated from sediment core incubations. Given the water column values integrate processes in the water column e.g., fish excretion, losses and gains from exchange with the epilimnion, I suggest that internal loading for a whole-lake mass balance be estimated from water column measurements.

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Table 4.1. Mass balance of total phosphorus for Willow Creek Reservoir, OR adjusted for a 90-day period for the 2014 and 2015 study period. Positive Δ P storage values indicate a retention of total phosphorus while negative indicates a loss.

	2014		**2015**		
	Water Column	**Sediment Cores**	**Water Column**	**Sediment Cores**	
Inputs	Mass (kg/y)	Mass (kg/y)	Mass (kg/y)	Mass (kg/y)	Source
Willow Creek	33	61	18	19	This study
Balm Fork Creek	Negligible	Negligible	Negligible	Negligible	Estimated from Adams (2012)
Dry deposition	3	3	4	3	Jassby et al. 1994
Wet deposition	6	9	2	4	Jassby et al. 1994; Ellis et al. 2015
Internal loading	114	139	292	171	This study
Outputs					
Willow Creek Dam	189	137	190	132	This study
Δ P Storage	-33	75	125	66	This study

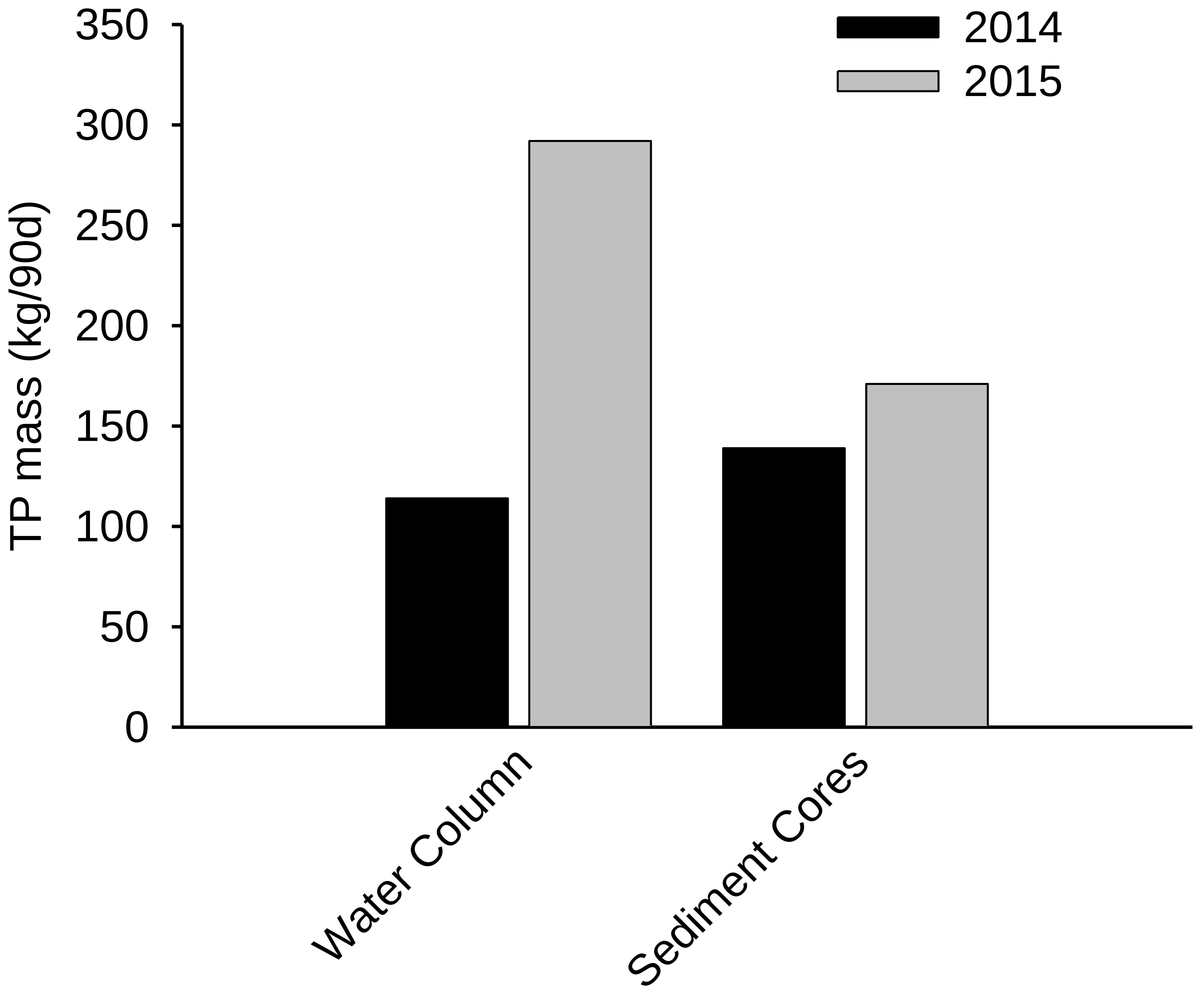

Figure 4.1. Adjusted 90-day anoxic period estimates of internal loading of total phosphorus from water column measurements and sediment core release rates in Willow Creek Reservoir, OR in 2014 and 2015.

Chapter 5: Summary and Conclusions

Our future well-being depends on access to clean water which is threatened by the burgeoning human populations and the significant changes it imposes on the environment that sustains it. One of these changes is the rapid transport of large quantities of sediment and nutrients to aquatic ecosystems resulting in 'cultural' eutrophication. This comes from activities such as logging of forests within watersheds, industrial effluent, agriculture and release of treatment plant effluent (Pitois et al. 2001, Wetzel 2001, Paerl and Otten 2013). While the reduction of nutrients to freshwaters via point sources has been successful, the elimination of non-point sources is proving problematic and now contributes a majority of the nutrient pollution load in many systems (Ongley et al. 2010). It is also why non-point sources have become the main focus of recovery and restoration efforts (Ongley et al. 2010).

The addition of excess nutrients, particularly N and P, to freshwaters generally results in eutrophication (Schindler 1977, Schindler and Vallentyne 2008, Smith 1983) and is typically manifested in 'green' water with abundant algae, some of which form surface scums and can be highly toxic (Codd et al. 1989, Keijola et al. 1988, Lahti and Hiisvirta 1989, Lawton and Robertson 1999, Chorus and Bartram 1999). To avoid such toxic blooms and recover already degraded systems requires that we select and implement appropriate management strategies. The first step in this process is to understand all sources and sinks – in short this requires a mass balance. This will allow managers to target the largest sources and invest limited resources wisely. A general problem when targeting reduction in P is the contribution of legacy sources embedded in the system. Because P does not have a gas phase, unless it is removed via the outflow or biomass, it remains in the system. This then raises the possibility of it returning in bioavailable form under the right redox conditions. Thus, even with significant reductions of watershed P sources, the return of legacy phosphorus stored in lake-bottom sediments often delays the recovery of waterbodies (Søndergaard et al. 2001, 2003, 2007, Welch and Jacoby 2001). Therefore, it is important to understand the contribution of internal loads to the whole-system mass balance.

In Chapter 2, I quantified the internal load in Willow Creek Reservoir, a 51 ha, 26 m (maximum depth) deep reservoir in northeast Oregon via in-situ sampling of the water column at bi-weekly intervals in 2014 and 2015 to collect high resolution profiles of temperature, dissolved oxygen, and water samples for analysis of total and dissolved phosphorus from different sites. These data were combined with existing GIS and bathymetric data to calculate the annual internal P load as well as the load during anoxic conditions only. In 2014, the hypolimnetic mass of TP resulted in an internal load contribution of 125 kg while in 2015, internal loading contributed 318 kg. During the summer anoxic period when inflows dropped to very low volumes, internal loading contributed 73 and 93% of the P budget, highlighting the importance of this source and the need to address it in future remediation efforts. However, the proportional contribution of TP from internal loading was two times greater in 2015 than 2014, it only represented 8 and 29% of the total annual P budget indicating the need to focus on reducing external sources as well.

In-situ sampling is an important tool to characterize the contribution and connectivity of internal loading to poor lake and reservoir quality manifested in toxic algal blooms. The multiple years of data collected at WCR provide insight to the interannual variability indicating the potential range of the remediation strategy to be applied to achieve desired nutrient reductions to meet future water quality goals. Because the annual budget showed the importance of the inflow as a source during spring runoff, watershed remediation should focus on reducing this load. However, during summer when inflow sources were low, internal loading accounted for up to 93% of the mass balance, indicating that its inactivation should also be a priority. Because it is unclear how much of the P loaded into the hypolimnion is transformed into algal biomass, future studies should examine this to definitively demonstrate the relationship between internal loading and production of primary productivity.

In Chapter 3, I determined that the P release rates from laboratory-incubated sediment cores collected at different sites in WCR differed by site, leading me to reject the null hypothesis of similar release rates among sites. The anoxic release rates of the cores ranged widely from 4.47 to 14.63 mg P/m^2/d, even among similarly deep sites. These data reinforce the importance of obtaining data from multiple sites within a lake to estimate the mean contribution of internal loading. Similar to Chapter 2, the mean annual contribution of internal loading in 2015 in WCR was 305 kg (range 133 to 531 kg) with 241 kg of TP represented by DP. Assuming the sediment release rates are invariant between years, the internal load contribution in 2014 was 246 kg (range 108 to 428 kg) with 195 kg represented by DP. During anoxic conditions in summer, internal loading represented 66% and 87% of the TP input in 2014 and 2015, respectively. Overall, the annual mass balance showed that WCR retained an average of 993 kg TP (range 854 to 1176 kg TP) in 2014, while 642 kg TP (range 472 to 868 kg/yr) were retained in 2015. From the annual load, the contribution of mean internal loading to the TP load decreased to 14% in 2014 and 28% in 2015 again indicating the importance of an annual mass balance with specific interest during summer anoxic conditions when algal blooms are likely to occur. Indicated by the variation in external and internal loading contributions when analyzing an annual versus anoxic P budget, it is important to not only collect P data all year, but also from varying sources to best estimate the P load.

In Chapter 4, I tested the hypothesis that in-situ sampling (Chapter 2) and sediment core (Chapter 3) methods yielded similar internal loading rates and contributions to the phosphorus mass balance. When adjusted to a 90-day anoxic period, the mean internal P load calculated using release rates from sediment cores was 171 kg (range 74 to 299 kg), while the load estimated from water column measurements was 114 kg in 2014 and 292 kg in 2015 leading me to accept the null hypothesis and state that results of both methods are similar. Previous studies have shown mixed results when both methods were used simultaneously (Nürnberg et al. 2013), which was not the case when compared to WCR.

Because water column measurements directly measure concentrations present in the water, I recommend that this method be used to estimate internal loading. As the water column estimate provides values determined by direct measurement within the reservoir itself, the natural mixing that occurs within the reservoir provides a more accurate representation of actual conditions occurring within WCR. The average sediment core release rates and the estimated loads calculated from them can induce error if over or underestimating the variation in release rates. To account for this, additional core sampling (~30 cores) within WCR and analysis of iron and phosphorus extraction to determine the potential release of phosphorus can provide a more thorough spatial representation of release rates. Analysis of particle size may indicate where fine particles with the highest surface area and highest P binding occur in the reservoir. By sectioning the reservoir into spatial areas by P release rates, a more accurate estimate of internal loading should be possible.

Particular attention should be drawn to the fact that a majority of the internal load is in the DP fraction that is readily bioavailable. This means that if it reaches surface waters it has a high potential to quickly stimulate the formation of algae blooms in WCR. To accurately estimate the potential of this P to form blooms requires understanding the hypolimnion to epilimnion transfer rate which to my knowledge has not been investigated thoroughly, and should be focus of future studies. Such research should also focus on wind events (direction, duration, and speed), metalimnetic entrainment, and lag times. Formulation of a strong predictive relationship would allow managers to proactively manage lakes and the public, rather than reacting to a bloom event.

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Appendix A

Calculation of monthly evaporation values

Evaporation data used in the water balance of Willow Creek Reservoir, OR was estimated from standard daily pan evaporation measured using a four-foot diameter Class A evaporation pan (WRCC 2016). As precipitation events occur, the pan level reading is adjusted to only measure evaporation. To account for radiation from the side walls of pans and heat exchange with pan materials, most Class A pans are above ground. To adjust evaporation rates which are closer to natural water bodies, the rates were multiplied by 0.7 (WRCC 2016). Monthly evaporation values (Table A.1) from Hermiston, Moro, and Pendleton, OR were multiplied by 0.7 to estimate evaporations rates for Willow Creek Reservoir, OR. Daily averages were multiplied by the surface area of Willow Creek Reservoir, OR at daily intervals. Because values for January, February, November, and December were not recorded, they were estimated from the average evaporation rates in March and October.

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Table A.1. Average monthly, daily and adjusted daily evaporation rates at the three sites (Hermiston, Moro, and Pendleton) in Oregon close to Willow Creek Reservoir.

Month	Monthly Average (mm/month)	Daily Average (mm/day)	Adjusted *0.7 (mm/day)
January	62.64	2.02	1.41
February	62.64	2.24	1.57
March	83.06	2.68	1.88
April	132.33	4.41	3.09
May	191.18	6.17	4.32
June	237.74	7.92	5.55
July	300.06	9.68	6.78
August	268.31	8.66	6.06
September	173.48	5.78	4.05
October	95.93	3.09	2.17
November	62.64	2.09	1.46
December	62.64	2.02	1.41

Appendix B

Total (TP) and dissolved (DP) phosphorus measured within water column of Willow Creek Reservoir, Heppner, OR

Water column total (TP) and dissolved (DP) phosphorus concentrations (μg/L) ± SE measured at various depths and sites in WCR in 2014 and 2015. Site names are Main Site (MS), Willow Creek (WC), Balm Fork (BF), Upper Balm Fork (UBF), Weather Buoy (BY), and Upper Willow Creek (UWC). Concentrations in samples were analyzed using an AquaMate VIS spectrophotometer (ThermoFisher Scientific, Watham, MA) within 48 h using a modified ascorbic acid method in Standard Method 4500-P (Eaton et al. 2005).

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Table B.1. Total (TP) and dissolved (DP) phosphorus concentrations (µg/L) ± SE from various depths and sites in Willow Creek Reservoir, Heppner, OR in 2014 and 2015. Site names are Main Site (MS), Willow Creek (WC), Balm Fork (BF), Upper Balm Fork (UBF), Weather Buoy (BY), and Upper Willow Creek (UWC). Samples identified as "-" were not collected.

Date	**Site**	**Depth (m)**	**[TP] (µg/L)**	**± SE**	**[DP] (µg/L)**	**± SE**
29-Jul-14	MS	0	25.07	0.67	14.67	0.58
29-Jul-14	MS	3	32.27	0.35	21.87	1.14
29-Jul-14	MS	8	50.80	1.74	-	-
29-Jul-14	MS	10	68.67	3.83	-	-
29-Jul-14	MS	12	147.20	11.79	136.00	1.60
29-Jul-14	MS	14	157.87	7.47	-	-
29-Jul-14	MS	16	192.00	5.77	-	-
29-Jul-14	MS	18	222.40	13.98	235.20	10.41
29-Jul-14	MS	20	289.60	7.33	-	-
29-Jul-14	MS	22	372.27	17.44	365.33	3.50
29-Jul-14	WC	0	22.80	1.97	13.87	0.13
29-Jul-14	WC	6	35.33	0.58	24.13	1.04
29-Jul-14	WC	8	43.20	0.23	-	-
29-Jul-14	WC	10	78.13	8.84	-	-
29-Jul-14	WC	12	160.00	0.92	152.00	3.20
29-Jul-14	WC	14	189.60	0.80	-	-
29-Jul-14	WC	16	224.80	4.00	-	-
29-Jul-14	WC	17	224.00	4.80	218.40	4.00
29-Jul-14	BY	0	20.67	0.58	20.40	0.83
29-Jul-14	BY	6	31.73	0.87	20.00	0.61
29-Jul-14	BY	8	38.93	0.67	-	-
29-Jul-14	BY	10	110.13	1.57	-	-
29-Jul-14	BY	12	169.07	5.57	126.00	9.96
29-Jul-14	BY	14	177.07	5.09	-	-
29-Jul-14	BY	15	193.07	2.32	182.40	5.14
12-Aug-14	MS	0	27.32	0.89	16.31	0.97
12-Aug-14	MS	5	27.74	2.44	-	-
12-Aug-14	MS	9	103.33	3.12	92.38	1.26
12-Aug-14	MS	12	160.00	12.86	160.48	2.65
12-Aug-14	MS	17	229.05	2.08	-	-
12-Aug-14	MS	21	396.88	4.77	339.58	3.76
12-Aug-14	WC	0	27.98	0.12	17.86	0.21
12-Aug-14	WC	4	31.31	0.48	-	-
12-Aug-14	WC	9	125.71	2.86	112.86	2.18
12-Aug-14	WC	12	172.86	9.37	-	-
12-Aug-14	WC	16	240.95	1.90	220.48	1.72
12-Aug-14	WC	18	240.63	0.00	207.29	9.94

Table B.1 continued

Date	**Site**	**Depth (m)**	**[TP] (µg/L)**	**± SE**	**[DP] (µg/L)**	**± SE**
12-Aug-14	BY	0	24.64	0.36	12.74	0.43
12-Aug-14	BY	9	70.95	5.97	-	-
12-Aug-14	BY	13	197.14	5.02	-	-
26-Aug-14	MS	0	47.07	2.25	11.11	0.44
26-Aug-14	MS	5	32.22	0.71	-	-
26-Aug-14	MS	8	104.09	0.86	-	-
26-Aug-14	MS	12	194.84	1.29	187.56	1.18
26-Aug-14	MS	15	247.31	0.86	-	-
26-Aug-14	MS	18	335.56	9.09	338.89	2.22
26-Aug-14	MS	18.5	367.74	6.72	-	-
26-Aug-14	WC	0	42.32	0.71	11.72	0.79
26-Aug-14	WC	5	29.70	1.15	-	-
26-Aug-14	WC	8	72.73	1.21	-	-
26-Aug-14	WC	12	196.36	1.21	182.22	1.62
26-Aug-14	WC	15	242.83	2.14	-	-
26-Aug-14	WC	17	309.09	1.75	254.55	3.50
26-Aug-14	BY	0	45.44	0.91	19.11	0.78
26-Aug-14	BY	5	40.67	2.03	-	-
26-Aug-14	BY	9	140.22	3.10	-	-
26-Aug-14	BY	13	246.88	1.14	221.94	3.94
9-Sep-14	MS	0	42.92	1.27	15.94	0.48
9-Sep-14	MS	5	46.36	1.06	-	-
9-Sep-14	MS	8	165.83	0.83	-	-
9-Sep-14	MS	12	221.67	1.10	201.67	1.50
9-Sep-14	MS	14	272.73	1.85	-	-
9-Sep-14	MS	16	350.00	1.80	-	-
9-Sep-14	MS	18	506.06	11.47	485.86	8.98
9-Sep-14	WC	0	44.90	0.73	20.21	0.28
9-Sep-14	WC	6	44.17	1.35	-	-
9-Sep-14	WC	9	205.66	2.46	-	-
9-Sep-14	WC	12	235.42	2.92	214.17	2.73
9-Sep-14	WC	15	362.50	1.80	346.88	1.80
9-Sep-14	BY	0	46.35	0.91	14.27	0.91
9-Sep-14	BY	5	47.71	0.55	-	-
9-Sep-14	BY	8	167.92	2.20	-	-
9-Sep-14	BY	11	267.08	1.50	252.08	1.82

Table B.1 continued

Date	**Site**	**Depth (m)**	**[TP] (µg/L)**	**± SE**	**[DP] (µg/L)**	**± SE**
23-Sep-14	MS	0	42.22	2.76	17.67	0.69
23-Sep-14	MS	5	51.78	1.87	-	-
23-Sep-14	MS	7	146.00	4.67	-	-
23-Sep-14	MS	9	212.00	1.33	-	-
23-Sep-14	MS	12	301.33	0.77	301.78	6.98
23-Sep-14	MS	15	492.71	13.78	464.58	2.08
23-Sep-14	WC	0	42.22	1.66	23.33	3.17
23-Sep-14	WC	5	54.22	2.80	-	-
23-Sep-14	WC	7	141.33	0.00	125.33	0.77
23-Sep-14	WC	9	230.00	2.89	-	-
23-Sep-14	WC	12.5	330.21	2.76	314.58	2.08
23-Sep-14	BY	0	38.14	0.87	13.82	0.59
23-Sep-14	BY	5	50.98	0.71	-	-
23-Sep-14	BY	7	119.58	3.97	96.67	0.83
7-Oct-14	MS	0	53.13	1.24	31.21	0.52
7-Oct-14	MS	3	55.25	0.27	-	-
7-Oct-14	MS	6	84.04	1.76	-	-
7-Oct-14	MS	9	280.00	1.85	-	-
7-Oct-14	MS	12	362.83	4.92	346.67	2.42
7-Oct-14	MS	14.5	544.44	8.63	489.90	4.40
7-Oct-14	WC	0	48.69	0.40	31.41	0.61
7-Oct-14	WC	3	57.58	0.87	-	-
7-Oct-14	WC	6	87.27	0.70	-	-
7-Oct-14	WC	9	284.44	2.02	-	-
7-Oct-14	WC	12	349.09	0.70	335.35	2.25
7-Oct-14	WC	14	469.70	6.31	456.57	8.27
7-Oct-14	BY	0	56.57	0.36	27.98	0.66
7-Oct-14	BY	5	75.45	1.32	-	-
7-Oct-14	BY	8	218.59	1.46	-	-
7-Oct-14	BY	10	346.26	1.76	332.12	3.05
21-Oct-14	MS	0	80.51	1.75	53.94	0.30
21-Oct-14	MS	6	89.29	0.10	-	-
21-Oct-14	MS	9	286.87	7.08	-	-
21-Oct-14	MS	12	418.99	5.06	406.06	4.26
21-Oct-14	MS	15	534.34	10.25	-	-
21-Oct-14	MS	17	595.96	8.98	590.91	6.31

Table B.1 continued

Date	**Site**	**Depth (m)**	**[TP] (µg/L)**	**± SE**	**[DP] (µg/L)**	**± SE**
21-Oct-14	WC	0	80.10	0.88	56.06	0.80
21-Oct-14	WC	4	81.72	0.86	-	-
21-Oct-14	WC	7	88.48	4.85	-	-
21-Oct-14	WC	9	132.16	1.41	120.78	3.14
21-Oct-14	WC	13	382.35	5.09	344.12	8.99
21-Oct-14	BY	0	75.00	0.68	51.18	1.22
21-Oct-14	BY	6	72.55	2.99	-	-
21-Oct-14	BY	9	243.92	3.06	-	-
21-Oct-14	BY	10.5	292.16	1.41	264.71	3.40
4-Nov-14	MS	0	107.04	1.82	85.65	2.98
4-Nov-14	MS	5	108.15	1.67	-	-
4-Nov-14	MS	8	107.05	1.01	-	-
4-Nov-14	MS	12	291.67	10.52	263.89	9.62
4-Nov-14	MS	14	611.11	1.60	-	-
4-Nov-14	MS	16	765.71	3.30	702.86	7.56
4-Nov-14	WC	0	106.11	1.21	80.65	0.67
4-Nov-14	WC	5	107.50	1.58	-	-
4-Nov-14	WC	8	112.59	2.43	88.89	3.39
4-Nov-14	WC	11	190.74	9.80	-	-
4-Nov-14	WC	13.5	538.10	10.61	511.11	3.21
4-Nov-14	BY	0	113.33	3.29	83.33	2.31
4-Nov-14	BY	5	111.85	4.01	-	-
4-Nov-14	BY	8	112.96	1.34	-	-
4-Nov-14	BY	12	196.30	7.58	123.81	0.95
6-Dec-14	MS	0	108.24	4.24	97.65	1.80
6-Dec-14	MS	5	116.47	0.00	-	-
6-Dec-14	MS	8	113.73	0.39	-	-
6-Dec-14	MS	12	130.39	1.96	112.75	1.96
6-Dec-14	MS	15	130.39	0.98	-	-
6-Dec-14	MS	17.5	120.59	1.70	105.88	11.14
6-Dec-14	WC	0	115.29	0.68	100.78	1.04
6-Dec-14	WC	3.5	115.29	0.00	-	-
6-Dec-14	WC	7	114.90	1.41	102.35	0.00
6-Dec-14	WC	10.5	142.19	7.51	-	-
6-Dec-14	WC	14	150.00	9.38	108.82	4.49
6-Dec-14	BY	0	123.33	1.50	106.25	0.72
6-Dec-14	BY	3.5	120.42	1.10	-	-
6-Dec-14	BY	7.5	122.92	1.50	-	-
6-Dec-14	BY	10	132.29	1.04	125.00	6.51

Table B.1 continued

Date	**Site**	**Depth (m)**	**[TP] (µg/L)**	**± SE**	**[DP] (µg/L)**	**± SE**
12-Apr-15	MS	0	39.38	3.90	16.04	1.16
12-Apr-15	MS	12	52.08	1.10	27.92	1.99
12-Apr-15	MS	24	100.63	1.25	55.00	1.30
12-Apr-15	WC	0	36.25	0.72	14.79	1.46
12-Apr-15	WC	12	62.08	1.10	27.50	1.25
12-Apr-15	WC	20.5	101.88	0.72	58.13	1.65
12-Apr-15	BY	0	35.21	1.67	36.88	1.10
12-Apr-15	BY	9	51.46	0.42	51.88	0.55
12-Apr-15	BY	17.5	109.79	1.37	62.71	2.35
25-Apr-15	MS	0	22.48	1.25	15.43	1.51
25-Apr-15	MS	12	28.76	0.50	17.71	0.57
25-Apr-15	MS	23	96.57	2.93	31.81	0.19
25-Apr-15	WC	0	24.00	0.57	15.05	0.19
25-Apr-15	WC	10	28.19	0.69	19.81	0.50
25-Apr-15	WC	21	71.62	2.43	21.52	0.83
25-Apr-15	BY	0	24.95	1.82	13.33	1.01
25-Apr-15	BY	9	26.29	2.01	16.19	0.38
25-Apr-15	BY	18	79.24	1.33	21.33	1.69
9-May-15	MS	0	29.38	1.25	12.08	0.55
9-May-15	MS	12	31.46	2.18	25.42	1.67
9-May-15	MS	22	59.38	1.65	45.00	0.72
9-May-15	WC	0	23.75	0.72	16.25	1.88
9-May-15	WC	10	26.46	0.55	22.08	0.55
9-May-15	WC	21	55.63	0.72	44.38	0.95
9-May-15	BY	0	24.17	0.55	12.29	0.21
9-May-15	BY	9	25.00	0.72	18.13	0.00
9-May-15	BY	18	49.17	0.21	35.63	0.36
9-May-15	UWC	0	26.67	0.75	13.13	0.36
9-May-15	UWC	6	26.88	0.95	20.42	0.83
9-May-15	UWC	13	48.13	0.95	30.21	1.16
9-May-15	BF	0	31.25	0.62	16.25	0.63
9-May-15	BF	7	27.71	1.16	24.69	0.36
9-May-15	BF	15	55.42	0.83	31.25	0.00
9-May-15	UBF	0	33.54	0.55	11.88	0.36
9-May-15	UBF	5	34.38	0.00	24.79	0.21
9-May-15	UBF	15	36.25	0.36	26.04	0.21
19-May-15	MS	0	33.33	0.50	11.81	0.38
19-May-15	MS	12	31.43	0.87	26.48	0.50
19-May-15	MS	21	71.24	0.19	58.48	0.38

Table B.1 continued

Date	Site	Depth (m)	[TP] (µg/L)	± SE	[DP] (µg/L)	± SE
19-May-15	WC	0	29.90	1.63	10.29	1.84
19-May-15	WC	11	36.76	0.69	31.43	0.57
19-May-15	WC	21	75.05	0.38	61.33	0.38
19-May-15	BY	0	29.52	0.50	12.38	0.69
19-May-15	BY	9	28.00	0.66	24.76	0.50
19-May-15	BY	17	67.24	1.25	55.05	1.01
2-Jun-15	MS	0	25.05	0.40	20.00	0.35
2-Jun-15	MS	12	37.37	0.40	35.35	0.53
2-Jun-15	MS	16	59.19	0.73	-	-
2-Jun-15	MS	21	87.88	0.35	79.19	0.53
2-Jun-15	WC	0	25.86	0.20	19.60	0.20
2-Jun-15	WC	10	29.09	0.35	24.24	0.61
2-Jun-15	WC	15	67.88	0.61	-	-
2-Jun-15	WC	19	93.74	0.73	78.18	2.13
2-Jun-15	BY	0	25.66	0.20	18.79	0.35
2-Jun-15	BY	9	27.07	0.20	22.83	0.73
2-Jun-15	BY	14	72.12	0.35	-	-
2-Jun-15	BY	18	80.20	0.40	67.88	0.93
16-Jun-15	MS	0	22.16	1.68	13.33	0.20
16-Jun-15	MS	6	32.55	2.41	-	-
16-Jun-15	MS	12	50.20	0.39	45.49	0.78
16-Jun-15	MS	18	92.16	3.40	-	-
16-Jun-15	MS	21.5	119.02	0.52	104.51	0.78
16-Jun-15	WC	0	20.20	0.78	13.14	0.52
16-Jun-15	WC	6	26.08	1.41	-	-
16-Jun-15	WC	10	28.24	0.90	20.98	1.04
16-Jun-15	WC	14	82.75	0.85	-	-
16-Jun-15	WC	19	104.31	1.37	95.88	1.48
16-Jun-15	BY	0	20.59	0.00	14.31	0.52
16-Jun-15	BY	5	32.16	1.74	-	-
16-Jun-15	BY	9	22.75	0.71	15.10	0.20
16-Jun-15	BY	12	62.94	0.34	-	-
16-Jun-15	BY	16	101.96	1.74	91.18	1.18
16-Jun-15	UWC	0	23.92	3.16	14.71	0.00
16-Jun-15	UWC	3	23.14	0.52	-	-
16-Jun-15	UWC	6	27.84	1.37	19.22	2.08
16-Jun-15	UWC	8	28.04	3.35	-	-
16-Jun-15	UWC	11	65.10	0.39	56.86	0.39

Table B.1 continued

Date	Site	Depth (m)	[TP] (µg/L)	± SE	[DP] (µg/L)	± SE
16-Jun-15	BF	0	20.98	0.78	13.73	0.20
16-Jun-15	BF	3	20.39	0.20	-	-
16-Jun-15	BF	6	26.27	0.52	16.67	1.41
16-Jun-15	BF	9	30.59	0.59	-	-
16-Jun-15	BF	12	77.06	2.96	66.67	0.52
16-Jun-15	UBF	0	21.96	0.85	14.90	0.85
16-Jun-15	UBF	3	28.24	0.68	-	-
16-Jun-15	UBF	6	43.14	1.53	23.73	3.16
16-Jun-15	UBF	8	32.75	1.19	-	-
16-Jun-15	UBF	11	64.71	2.23	73.14	1.53
30-Jun-15	MS	0	16.57	0.20	12.32	0.40
30-Jun-15	MS	6	25.05	1.23	-	-
30-Jun-15	MS	12	78.59	1.23	69.29	0.73
30-Jun-15	MS	15	101.41	0.20	-	-
30-Jun-15	MS	19	129.49	1.76	119.60	1.32
30-Jun-15	WC	0	12.93	0.20	13.13	0.40
30-Jun-15	WC	5	24.65	0.40	-	-
30-Jun-15	WC	10	50.30	0.61	34.34	0.88
30-Jun-15	WC	15	115.15	0.35	-	-
30-Jun-15	WC	19	169.09	2.13	164.04	0.88
30-Jun-15	BY	0	17.78	0.40	12.32	0.53
30-Jun-15	BY	4	21.21	0.00	-	-
30-Jun-15	BY	8	27.47	0.53	20.81	0.81
30-Jun-15	BY	12	105.05	0.53	-	-
30-Jun-15	BY	16	132.53	0.20	123.03	1.05
14-Jul-15	MS	0	20.20	0.40	13.33	0.35
14-Jul-15	MS	6	25.66	1.12	-	-
14-Jul-15	MS	12	104.65	1.58	93.74	0.20
14-Jul-15	MS	18	178.38	3.33	-	-
14-Jul-15	MS	21	294.95	3.45	274.34	3.59
14-Jul-15	WC	0	21.21	0.35	14.55	0.35
14-Jul-15	WC	5	26.87	3.64	-	-
14-Jul-15	WC	9	57.58	1.95	49.09	0.35
14-Jul-15	WC	14	122.02	1.12	-	-
14-Jul-15	WC	18	164.04	2.81	160.40	0.81
14-Jul-15	BY	0	22.02	0.73	17.78	0.88
14-Jul-15	BY	4	28.69	0.40	-	-
14-Jul-15	BY	8	33.33	1.05	22.42	0.35
14-Jul-15	BY	12	123.64	1.40	-	-
14-Jul-15	BY	16	174.55	3.21	141.41	1.46

Table B.1 continued

Date	Site	Depth (m)	[TP] (µg/L)	± SE	[DP] (µg/L)	± SE
14-Jul-15	UWC	0	25.10	1.09	17.65	1.22
14-Jul-15	UWC	4	26.47	2.72	-	-
14-Jul-15	UWC	8	42.94	1.22	21.18	2.04
14-Jul-15	UWC	10.5	144.31	0.71	123.73	4.05
14-Jul-15	BF	0	24.90	1.41	19.41	1.36
14-Jul-15	BF	3	27.65	3.40	-	-
14-Jul-15	BF	6	29.22	1.19	22.75	0.39
14-Jul-15	BF	9	65.10	1.96	-	-
14-Jul-15	BF	11	98.43	1.99	82.75	0.98
14-Jul-15	UBF	0	26.86	1.04	16.27	0.71
14-Jul-15	UBF	4	30.20	1.87	-	-
14-Jul-15	UBF	7	48.82	1.56	31.76	2.65
27-Jul-15	MS	0	25.15	0.35	17.58	0.46
27-Jul-15	MS	5	28.59	0.20	-	-
27-Jul-15	MS	12	131.31	0.73	122.02	0.53
27-Jul-15	MS	15	185.45	3.70	-	-
27-Jul-15	MS	19.5	239.19	1.76	199.19	1.46
27-Jul-15	WC	0	25.35	0.10	15.25	0.20
27-Jul-15	WC	4	28.59	0.36	-	-
27-Jul-15	WC	9	86.26	1.32	69.29	0.53
27-Jul-15	WC	13	170.51	0.81	-	-
27-Jul-15	WC	18	225.86	0.81	219.39	2.80
27-Jul-15	BY	0	25.86	0.86	15.56	0.27
27-Jul-15	BY	4	35.56	0.61	-	-
27-Jul-15	BY	8	62.63	0.73	43.64	2.13
27-Jul-15	BY	11	153.74	1.32	-	-
27-Jul-15	BY	13	187.07	2.14	172.93	2.14
11-Aug-15	MS	0	23.05	0.10	17.90	0.10
11-Aug-15	MS	4	26.95	1.24	-	-
11-Aug-15	MS	8	112.76	2.02	-	-
11-Aug-15	MS	12	168.38	0.38	152.00	0.66
11-Aug-15	MS	16	209.52	3.81	-	-
11-Aug-15	MS	18	398.99	3.64	385.86	4.40
11-Aug-15	WC	0	23.62	0.25	15.52	0.10
11-Aug-15	WC	4	26.76	0.83	-	-
11-Aug-15	WC	8	100.38	2.32	86.67	13.81
11-Aug-15	WC	12	155.43	1.14	-	-
11-Aug-15	WC	16	278.79	0.00	271.72	2.67

Table B.1 continued

Date	Site	Depth (m)	[TP] (µg/L)	± SE	[DP] (µg/L)	± SE
11-Aug-15	BY	0	23.05	0.19	14.38	0.42
11-Aug-15	BY	4	25.33	0.34	-	-
11-Aug-15	BY	8	71.05	1.25	69.33	1.16
11-Aug-15	BY	12	169.14	1.98	-	-
11-Aug-15	BY	15	285.86	5.34	278.79	6.06
11-Aug-15	UWC	0	23.43	0.29	14.95	0.25
11-Aug-15	UWC	4	26.00	0.59	19.43	0.87
11-Aug-15	UWC	7.5	142.42	0.00	78.79	0.00
11-Aug-15	BF	0	22.95	0.38	17.24	0.67
11-Aug-15	BF	3	26.86	0.16	-	-
11-Aug-15	BF	6	42.10	4.67	22.38	0.19
11-Aug-15	BF	8.5	140.76	1.37	89.90	0.83
11-Aug-15	UBF	0	23.33	0.34	12.76	0.19
11-Aug-15	UBF	2	24.67	0.53	-	-
11-Aug-15	UBF	5	32.29	0.16	19.71	0.44
25-Aug-15	MS	0	34.75	0.86	12.73	0.46
25-Aug-15	MS	4	29.19	0.56	-	-
25-Aug-15	MS	8	151.52	2.10	-	-
25-Aug-15	MS	12	210.51	1.46	196.36	0.00
25-Aug-15	MS	15	335.35	4.40	-	-
25-Aug-15	MS	18	479.80	2.02	466.67	3.03
25-Aug-15	WC	0	33.23	0.10	11.31	0.20
25-Aug-15	WC	4	32.22	0.10	-	-
25-Aug-15	WC	8	160.81	3.16	131.72	1.46
25-Aug-15	WC	12	236.77	2.46	-	-
25-Aug-15	WC	16	363.64	4.63	352.53	2.67
25-Aug-15	BY	0	33.23	1.01	11.92	0.20
25-Aug-15	BY	3	32.22	0.61	-	-
25-Aug-15	BY	6	61.31	1.01	36.97	0.30
25-Aug-15	BY	8	160.40	2.83	-	-
25-Aug-15	BY	11	282.83	2.67	266.67	3.50
8-Sep-15	MS	0	62.72	1.10	16.05	2.35
8-Sep-15	MS	4	46.67	2.04	-	-
8-Sep-15	MS	7	168.89	5.61	-	-
8-Sep-15	MS	12	456.79	7.51	354.32	9.64
8-Sep-15	MS	16	713.58	9.64	653.09	8.64

Table B.1 continued

Date	Site	Depth (m)	[TP] (µg/L)	± SE	[DP] (µg/L)	± SE
8-Sep-15	WC	0	60.12	1.39	17.90	0.65
8-Sep-15	WC	4	42.72	0.33	-	-
8-Sep-15	WC	7	175.31	4.39	147.65	2.15
8-Sep-15	WC	11	359.26	3.70	-	-
8-Sep-15	WC	14	509.88	8.10	460.49	7.51
8-Sep-15	BY	0	58.93	1.80	16.19	0.83
8-Sep-15	BY	4	58.81	1.37	-	-
8-Sep-15	BY	7	183.81	6.87	169.52	5.85
8-Sep-15	BY	10.5	355.95	6.30	330.95	1.19
8-Sep-15	UWC	0	53.45	1.75	18.33	0.12
8-Sep-15	UWC	5	58.69	2.11	24.88	0.86
8-Sep-15	BF	0	50.60	2.28	17.14	0.55
8-Sep-15	BF	4	47.50	2.14	23.57	0.90
8-Sep-15	BF	8	269.05	5.49	218.57	5.02
8-Sep-15	UBF	0	54.76	1.26	22.62	0.86
8-Sep-15	UBF	2.5	50.36	1.35	29.05	0.12
5-Oct-15	MS	0	57.45	1.63	22.65	0.45
5-Oct-15	MS	4	57.25	1.13	-	-
5-Oct-15	MS	8	214.12	1.36	-	-
5-Oct-15	MS	12	376.47	2.94	354.90	0.98
5-Oct-15	MS	15	459.80	8.02	438.24	2.94
5-Oct-15	WC	0	56.57	0.60	23.73	0.20
5-Oct-15	WC	3	53.33	0.26	-	-
5-Oct-15	WC	6	79.22	1.41	59.61	3.14
5-Oct-15	WC	9	254.90	4.90	-	-
5-Oct-15	WC	13	444.12	1.70	440.20	0.98
5-Oct-15	BY	0	58.33	1.09	22.25	0.77
5-Oct-15	BY	3	66.08	0.80	-	-
5-Oct-15	BY	6	109.80	6.60	-	-
5-Oct-15	BY	9	316.67	1.96	293.14	4.27
18-Oct-15	MS	0	52.12	0.17	21.31	0.90
18-Oct-15	MS	4	78.38	3.16	-	-
18-Oct-15	MS	8	304.04	8.81	-	-
18-Oct-15	MS	12	376.77	2.67	363.64	7.00
18-Oct-15	MS	14	468.69	3.64	455.56	5.62
18-Oct-15	WC	0	56.06	0.30	20.61	0.52
18-Oct-15	WC	3	59.80	3.45	-	-
18-Oct-15	WC	6	121.21	1.75	83.84	5.05
18-Oct-15	WC	9	350.51	6.62	-	-
18-Oct-15	WC	12	477.78	3.64	461.62	2.02

Table B.1 continued

Date	Site	Depth (m)	[TP] (µg/L)	± SE	[DP] (µg/L)	± SE
18-Oct-15	BY	0	58.28	0.73	22.12	0.63
18-Oct-15	BY	3	77.58	1.85	-	-
18-Oct-15	BY	6	198.99	6.14	-	-
18-Oct-15	BY	8.5	352.53	4.40	340.40	3.64
18-Oct-15	BF	0	58.79	1.67	23.03	0.17
18-Oct-15	BF	3	71.92	2.25	-	-
18-Oct-15	BF	7	194.95	2.67	168.69	1.01
9-Nov-15	MS	0	132.50	0.48	104.06	0.83
9-Nov-15	MS	4	140.00	0.72	-	-
9-Nov-15	MS	8	147.92	3.76	-	-
9-Nov-15	MS	12	217.71	2.76	156.25	4.77
9-Nov-15	MS	13.5	262.50	3.13	188.54	4.54
9-Nov-15	WC	0	132.92	0.63	105.21	0.68
9-Nov-15	WC	4	140.00	1.44	-	-
9-Nov-15	WC	8	153.13	1.80	127.08	5.51
9-Nov-15	WC	11.5	159.38	1.80	120.83	3.76
9-Nov-15	BY	0	136.35	0.81	104.69	1.26
9-Nov-15	BY	4	145.42	1.10	-	-
9-Nov-15	BY	8.5	169.79	4.54	128.13	1.80
9-Nov-15	BF	0	135.63	0.79	103.96	0.55
9-Nov-15	BF	3	145.42	1.82	-	-
9-Nov-15	BF	6	156.25	1.80	131.25	1.80

Appendix C

Temperature and oxygen profiles

Bi-weekly profile data of temperature and dissolved oxygen (DO) collected at 1 m intervals from the surface to the 1 m above the lake bottom from the deepest site (MS) in Willow Creek Reservoir, Heppner, OR in 2014 and 2015. Temperature and DO were measured using a Manta (Eureka Water Probes, Austin, TX) multi-probe interfaced to an amphibian data logger, or a YSI model 556 multi-probe (YSI Incorporated, Yellow Springs, OH). Data indicated with "-" represents missing data. Negative values for DO should be considered a 0 as this was a functional error of the Manta profile that was confirmed multiple times throughout the year with the YSI and possibly caused by a probe interference due to hydrogen sulfide in the hypolimnion (Ric Bertrand, Eureka Water Probes, personal communication).

Table C.1. Profiles of depth (m), depth (m a.s.l.), temperature (°C), and dissolved oxygen (mg/L) for the 2014 and 2015 study period for Willow Creek Reservoir, Heppner, OR, measured at the deepest (main) site.

Date	Depth (m)	Depth (m a.s.l.)	Temp (°C)	DO (mg/L)
6-May-14	0.25	632.72	13.79	9.80
6-May-14	1.00	631.97	13.68	9.68
6-May-14	2.00	630.97	13.63	9.50
6-May-14	2.93	630.04	13.39	9.18
6-May-14	3.84	629.13	11.99	9.15
6-May-14	5.04	627.93	10.90	8.85
6-May-14	5.98	626.99	10.59	8.58
6-May-14	7.04	625.93	10.47	8.22
6-May-14	7.98	624.99	10.28	8.00
6-May-14	9.11	623.86	10.09	7.74
6-May-14	10.01	622.96	10.02	7.47
6-May-14	10.96	622.01	9.79	7.07
6-May-14	11.99	620.98	9.51	6.90
6-May-14	13.02	619.95	9.22	6.84
6-May-14	13.97	619.00	8.89	6.60
6-May-14	15.04	617.93	8.29	6.40
6-May-14	15.87	617.10	7.94	6.14
6-May-14	17.03	615.94	7.76	5.71
6-May-14	18.01	614.96	7.69	5.58
6-May-14	19.04	613.93	7.64	5.46
6-May-14	20.03	612.94	7.57	5.35
6-May-14	21.02	611.95	7.56	5.25
6-May-14	22.02	610.95	7.55	5.20
6-May-14	22.96	610.01	7.56	5.19
6-May-14	24.04	608.93	7.52	5.13
6-May-14	24.96	608.01	7.48	5.06
6-May-14	26.00	606.97	7.40	4.61

Table C.1. continued

Date	Depth (m)	Depth (m a.s.l.)	Temp (°C)	DO (mg/L)
27-May-14	0.00	632.84	18.05	9.71
27-May-14	1.00	631.84	17.97	9.90
27-May-14	2.00	630.84	17.54	10.11
27-May-14	3.00	629.84	17.46	10.24
27-May-14	4.00	628.84	17.26	10.23
27-May-14	5.00	627.84	14.59	9.97
27-May-14	6.00	626.84	13.84	9.75
27-May-14	7.00	625.84	12.88	9.63
27-May-14	8.00	624.84	12.04	9.47
27-May-14	9.00	623.84	11.13	9.62
27-May-14	10.00	622.84	10.82	9.58
27-May-14	11.00	621.84	10.22	9.64
27-May-14	12.00	620.84	9.61	9.41
27-May-14	13.00	619.84	9.24	9.11
27-May-14	14.00	618.84	9.18	8.98
27-May-14	15.00	617.84	8.73	8.59
27-May-14	16.00	616.84	8.63	8.38
27-May-14	17.00	615.84	8.54	8.28
27-May-14	18.00	614.84	8.23	8.06
27-May-14	19.00	613.84	8.07	7.74
27-May-14	20.00	612.84	7.96	7.49

Table C.1. continued

Date	Depth (m)	Depth (m a.s.l.)	Temp (°C)	DO (mg/L)
10-Jun-14	0.00	632.62	20.54	9.42
10-Jun-14	1.00	631.62	20.54	9.49
10-Jun-14	2.00	630.62	20.27	9.55
10-Jun-14	3.00	629.62	20.12	9.45
10-Jun-14	4.00	628.62	19.66	9.22
10-Jun-14	5.00	627.62	17.45	8.70
10-Jun-14	6.00	626.62	16.91	8.26
10-Jun-14	7.00	625.62	16.01	8.21
10-Jun-14	8.00	624.62	12.82	7.15
10-Jun-14	9.00	623.62	12.14	6.61
10-Jun-14	10.00	622.62	10.45	6.75
10-Jun-14	11.00	621.62	10.08	6.56
10-Jun-14	12.00	620.62	9.38	6.08
10-Jun-14	13.00	619.62	8.89	5.48
10-Jun-14	14.00	618.62	8.57	5.34
10-Jun-14	15.00	617.62	8.32	4.98
10-Jun-14	16.00	616.62	8.23	4.74
10-Jun-14	17.00	615.62	8.14	4.54
10-Jun-14	18.00	614.62	8.08	4.36
10-Jun-14	19.00	613.62	8.02	4.14
10-Jun-14	20.00	612.62	7.97	3.71

Table C.1. continued

Date	Depth (m)	Depth (m a.s.l.)	Temp (°C)	DO (mg/L)
17-Jun-14	0.42	632.02	16.67	8.66
17-Jun-14	1.07	631.37	16.67	8.55
17-Jun-14	1.95	630.49	16.67	8.45
17-Jun-14	2.89	629.55	16.67	8.12
17-Jun-14	3.77	628.67	16.67	7.88
17-Jun-14	5.57	626.87	16.63	7.33
17-Jun-14	5.53	626.91	-	-
17-Jun-14	7.00	625.44	15.23	6.04
17-Jun-14	8.02	624.42	13.60	5.67
17-Jun-14	8.96	623.48	12.17	5.32
17-Jun-14	9.97	622.47	11.29	5.11
17-Jun-14	11.01	621.43	10.64	4.94
17-Jun-14	12.01	620.43	9.90	4.75
17-Jun-14	13.00	619.44	9.06	4.56
17-Jun-14	14.00	618.44	8.71	3.84
17-Jun-14	15.00	617.44	8.52	3.24
17-Jun-14	15.98	616.46	8.46	2.89
17-Jun-14	17.00	615.44	8.38	2.61
17-Jun-14	18.00	614.44	8.34	2.51
17-Jun-14	19.00	613.44	8.31	2.46
17-Jun-14	20.03	612.41	8.26	2.40
17-Jun-14	21.00	611.44	8.23	2.30
17-Jun-14	22.03	610.41	8.20	2.18

Table C.1. continued

Date	Depth (m)	Depth (m a.s.l.)	Temp (°C)	DO (mg/L)
1-Jul-14	0.00	632.04	20.85	9.33
1-Jul-14	1.00	631.04	20.23	9.54
1-Jul-14	2.00	630.04	19.34	9.46
1-Jul-14	3.00	629.04	19.13	9.65
1-Jul-14	4.00	628.04	18.86	9.39
1-Jul-14	5.00	627.04	18.65	9.17
1-Jul-14	6.00	626.04	17.32	8.37
1-Jul-14	7.00	625.04	16.04	7.10
1-Jul-14	8.00	624.04	15.07	6.03
1-Jul-14	9.00	623.04	13.72	4.91
1-Jul-14	10.00	622.04	12.56	4.76
1-Jul-14	11.00	621.04	11.22	5.01
1-Jul-14	12.00	620.04	9.89	4.08
1-Jul-14	13.00	619.04	9.11	3.84
1-Jul-14	14.00	618.04	8.72	3.45
1-Jul-14	15.00	617.04	8.56	3.19
1-Jul-14	16.00	616.04	8.43	2.93
1-Jul-14	17.00	615.04	8.35	2.79
1-Jul-14	18.00	614.04	8.31	2.63
1-Jul-14	19.00	613.04	8.27	2.53
1-Jul-14	20.00	612.04	8.21	1.72

Table C.1. continued

Date	Depth (m)	Depth (m a.s.l.)	Temp (°C)	DO (mg/L)
15-Jul-14	0.31	631.11	24.76	8.56
15-Jul-14	1.01	630.41	24.62	8.61
15-Jul-14	2.04	629.38	24.55	8.44
15-Jul-14	3.04	628.38	24.50	8.16
15-Jul-14	4.03	627.39	24.38	7.94
15-Jul-14	5.00	626.42	20.35	7.64
15-Jul-14	6.00	625.42	18.54	6.71
15-Jul-14	7.02	624.40	16.87	5.63
15-Jul-14	7.99	623.43	15.73	4.05
15-Jul-14	8.96	622.46	14.13	3.03
15-Jul-14	10.04	621.38	13.14	2.68
15-Jul-14	11.02	620.40	11.56	2.65
15-Jul-14	11.99	619.43	10.02	1.96
15-Jul-14	13.03	618.39	9.36	1.82
15-Jul-14	14.03	617.39	9.00	1.66
15-Jul-14	15.00	616.42	8.75	1.41
15-Jul-14	16.03	615.39	8.64	0.84
15-Jul-14	17.06	614.36	8.60	0.74
15-Jul-14	18.06	613.36	8.56	0.53
15-Jul-14	18.97	612.45	8.54	0.46
15-Jul-14	19.99	611.43	8.51	0.29
15-Jul-14	21.06	610.36	8.47	0.15
15-Jul-14	22.04	609.38	8.40	0.02
15-Jul-14	23.05	608.37	8.36	0.00

Table C.1. continued

Date	Depth (m)	Depth (m a.s.l.)	Temp (°C)	DO (mg/L)
29-Jul-14	0.28	630.07	23.32	9.01
29-Jul-14	1.00	629.35	23.18	9.25
29-Jul-14	2.01	628.34	23.11	9.14
29-Jul-14	2.97	627.38	23.05	8.83
29-Jul-14	4.00	626.35	22.24	8.32
29-Jul-14	5.03	625.32	21.46	7.64
29-Jul-14	6.03	624.32	21.07	6.84
29-Jul-14	7.03	623.32	20.28	5.93
29-Jul-14	8.00	622.35	17.53	4.03
29-Jul-14	9.04	621.31	14.51	3.00
29-Jul-14	10.08	620.27	12.53	1.84
29-Jul-14	11.00	619.35	10.86	1.53
29-Jul-14	12.04	618.31	9.91	1.11
29-Jul-14	12.99	617.36	9.51	0.91
29-Jul-14	13.98	616.37	9.05	0.81
29-Jul-14	15.04	615.31	8.86	0.75
29-Jul-14	15.97	614.38	8.79	0.55
29-Jul-14	17.03	613.32	8.72	0.28
29-Jul-14	18.02	612.33	8.65	0.06
29-Jul-14	18.95	611.40	8.59	0.00
29-Jul-14	20.02	610.33	8.55	0.00
29-Jul-14	21.06	609.29	8.49	0.00
29-Jul-14	22.00	608.35	8.45	0.00
29-Jul-14	23.02	607.33	8.45	0.00

Table C.1. continued

Date	Depth (m)	Depth (m a.s.l.)	Temp (°C)	DO (mg/L)
12-Aug-14	0.00	629.40	23.45	8.67
12-Aug-14	1.00	628.40	23.43	8.77
12-Aug-14	2.00	627.40	23.30	8.31
12-Aug-14	3.00	626.40	23.18	7.76
12-Aug-14	4.00	625.40	22.43	6.89
12-Aug-14	5.00	624.40	22.15	5.31
12-Aug-14	6.00	623.40	21.95	4.35
12-Aug-14	7.00	622.40	20.08	1.33
12-Aug-14	8.00	621.40	17.60	0.64
12-Aug-14	9.00	620.40	13.52	0.28
12-Aug-14	10.00	619.40	11.73	0.20
12-Aug-14	11.00	618.40	9.75	0.37
12-Aug-14	12.00	617.40	9.07	0.30
12-Aug-14	13.00	616.40	8.73	0.15
12-Aug-14	14.00	615.40	8.57	0.06
12-Aug-14	15.00	614.40	8.51	0.04
12-Aug-14	16.00	613.40	8.46	0.04
12-Aug-14	17.00	612.40	8.41	0.04
12-Aug-14	18.00	611.40	8.39	0.05
12-Aug-14	19.00	610.40	8.35	0.05
12-Aug-14	20.00	609.40	8.31	0.04

Table C.1. continued

Date	Depth (m)	Depth (m a.s.l.)	Temp (°C)	DO (mg/L)
26-Aug-14	0.00	628.35	21.77	8.47
26-Aug-14	1.00	627.35	21.33	7.75
26-Aug-14	2.00	626.35	21.21	7.00
26-Aug-14	3.00	625.35	21.15	6.89
26-Aug-14	4.00	624.35	21.06	6.75
26-Aug-14	5.00	623.35	21.00	6.61
26-Aug-14	6.00	622.35	20.77	5.34
26-Aug-14	7.00	621.35	20.00	3.65
26-Aug-14	8.00	620.35	17.52	0.28
26-Aug-14	9.00	619.35	12.14	0.11
26-Aug-14	10.00	618.35	10.22	0.08
26-Aug-14	11.00	617.35	9.30	0.06
26-Aug-14	12.00	616.35	8.88	0.06
26-Aug-14	13.00	615.35	8.72	0.05
26-Aug-14	14.00	614.35	8.62	0.05
26-Aug-14	15.00	613.35	8.58	0.05
26-Aug-14	16.00	612.35	8.51	0.05
26-Aug-14	17.00	611.35	8.46	0.04
26-Aug-14	18.00	610.35	8.41	0.04
26-Aug-14	19.00	609.35	8.36	0.04
26-Aug-14	20.00	608.35	8.33	0.03
26-Aug-14	21.00	607.35	8.28	0.04

Table C.1. continued

Date	Depth (m)	Depth (m a.s.l.)	Temp (°C)	DO (mg/L)
9-Sep-14	0.00	627.04	18.92	8.11
9-Sep-14	1.00	626.04	18.96	8.13
9-Sep-14	2.00	625.04	18.44	7.61
9-Sep-14	3.00	624.04	18.78	7.22
9-Sep-14	4.00	623.04	18.67	6.34
9-Sep-14	5.00	622.04	18.61	6.03
9-Sep-14	6.00	621.04	18.55	5.56
9-Sep-14	7.00	620.04	18.33	5.24
9-Sep-14	8.00	619.04	15.95	1.73
9-Sep-14	9.00	618.04	10.54	0.35
9-Sep-14	10.00	617.04	9.40	0.20
9-Sep-14	11.00	616.04	9.14	0.14
9-Sep-14	12.00	615.04	8.93	0.13
9-Sep-14	13.00	614.04	8.74	0.10
9-Sep-14	14.00	613.04	8.66	0.08
9-Sep-14	15.00	612.04	8.63	0.08
9-Sep-14	16.00	611.04	8.61	0.07
9-Sep-14	17.00	610.04	8.56	0.07
9-Sep-14	18.00	609.04	8.47	0.07
9-Sep-14	19.00	608.04	8.42	0.06
9-Sep-14	19.78	607.26	8.40	0.06
23-Sep-14	0.21	625.82	19.14	10.89
23-Sep-14	0.97	625.06	19.13	10.92
23-Sep-14	1.99	624.04	19.11	10.88
23-Sep-14	3.03	623.00	18.40	10.03
23-Sep-14	4.01	622.02	17.71	7.94
23-Sep-14	5.02	621.01	17.31	6.05
23-Sep-14	6.04	619.99	16.79	4.72
23-Sep-14	7.01	619.02	13.82	1.67
23-Sep-14	8.00	618.03	-	-
23-Sep-14	8.96	617.07	9.45	1.67
23-Sep-14	10.03	616.00	9.00	1.72
23-Sep-14	11.00	615.03	8.87	1.67
23-Sep-14	12.02	614.01	8.78	1.62
23-Sep-14	13.03	613.00	8.75	1.59
23-Sep-14	14.03	612.00	8.66	1.58
23-Sep-14	15.01	611.02	8.62	1.58
23-Sep-14	15.77	610.26	8.53	1.51

Table C.1. continued

Date	Depth (m)	Depth (m a.s.l.)	Temp (°C)	DO (mg/L)
7-Oct-14	0.00	625.49	17.28	10.77
7-Oct-14	1.00	624.49	17.14	10.76
7-Oct-14	2.00	623.49	16.59	10.38
7-Oct-14	3.00	622.49	15.97	9.09
7-Oct-14	4.00	621.49	15.68	8.10
7-Oct-14	5.00	620.49	15.52	6.95
7-Oct-14	6.00	619.49	15.07	5.72
7-Oct-14	7.00	618.49	14.37	3.59
7-Oct-14	8.00	617.49	10.16	1.65
7-Oct-14	9.00	616.49	9.47	1.48
7-Oct-14	10.00	615.49	9.12	1.48
7-Oct-14	11.00	614.49	9.02	1.37
7-Oct-14	12.00	613.49	8.94	1.32
7-Oct-14	13.00	612.49	8.88	1.27
7-Oct-14	14.00	611.49	8.77	1.27
7-Oct-14	15.00	610.49	8.65	1.28
7-Oct-14	15.23	610.26	8.65	1.25
21-Oct-14	0.00	625.18	13.94	9.05
21-Oct-14	1.00	624.18	13.90	8.76
21-Oct-14	2.00	623.18	13.95	8.54
21-Oct-14	3.00	622.18	13.95	8.27
21-Oct-14	4.00	621.18	13.92	7.98
21-Oct-14	5.00	620.18	13.91	7.67
21-Oct-14	6.00	619.18	13.87	7.19
21-Oct-14	7.00	618.18	13.43	4.47
21-Oct-14	8.00	617.18	13.05	3.12
21-Oct-14	9.00	616.18	10.88	0.50
21-Oct-14	10.00	615.18	9.36	0.38
21-Oct-14	11.00	614.18	9.06	0.23
21-Oct-14	12.00	613.18	8.96	0.19
21-Oct-14	13.00	612.18	8.92	0.11
21-Oct-14	14.00	611.18	8.84	0.04
21-Oct-14	15.00	610.18	8.80	0.00
21-Oct-14	16.00	609.18	8.75	0.00
21-Oct-14	17.00	608.18	8.73	0.00
21-Oct-14	18.00	607.18	8.72	0.00

Table C.1. continued

Date	Depth (m)	Depth (m a.s.l.)	Temp (°C)	DO (mg/L)
4-Nov-14	0.00	625.00	11.17	7.40
4-Nov-14	1.00	624.00	11.16	7.37
4-Nov-14	2.00	623.00	11.15	7.31
4-Nov-14	3.00	622.00	11.16	7.39
4-Nov-14	4.00	621.00	11.15	7.38
4-Nov-14	5.00	620.00	11.15	7.45
4-Nov-14	6.00	619.00	11.16	7.48
4-Nov-14	7.00	618.00	11.15	7.49
4-Nov-14	8.00	617.00	11.15	7.50
4-Nov-14	9.00	616.00	11.14	7.47
4-Nov-14	10.00	615.00	11.11	7.40
4-Nov-14	11.00	614.00	11.06	7.18
4-Nov-14	12.00	613.00	9.61	0.45
4-Nov-14	13.00	612.00	8.83	0.24
4-Nov-14	14.00	611.00	8.73	0.14
4-Nov-14	15.00	610.00	8.67	0.10
4-Nov-14	16.00	609.00	8.65	0.09
4-Nov-14	17.00	608.00	8.61	0.07
4-Nov-14	18.00	607.00	8.60	0.06
6-Dec-14	0.28	624.69	4.69	12.22
6-Dec-14	1.01	623.96	4.64	11.96
6-Dec-14	2.03	622.94	4.61	11.77
6-Dec-14	3.03	621.94	4.56	11.40
6-Dec-14	4.02	620.95	4.56	10.96
6-Dec-14	4.98	619.99	4.56	10.62
6-Dec-14	6.05	618.92	4.56	10.19
6-Dec-14	7.05	617.92	4.55	9.89
6-Dec-14	8.00	616.97	4.55	9.56
6-Dec-14	9.02	615.95	4.54	9.36
6-Dec-14	10.01	614.96	4.54	9.15
6-Dec-14	11.05	613.92	4.54	8.96
6-Dec-14	12.03	612.94	4.54	8.77
6-Dec-14	13.00	611.97	4.53	8.61
6-Dec-14	14.05	610.92	4.53	8.38
6-Dec-14	14.98	609.99	4.53	8.28
6-Dec-14	16.02	608.95	4.52	8.18
6-Dec-14	16.99	607.98	4.52	8.11
6-Dec-14	18.09	606.88	4.53	8.04

Table C.1. continued

Date	Depth (m)	Depth (m a.s.l.)	Temp (°C)	DO (mg/L)
12-Apr-15	0.00	632.98	10.24	14.50
12-Apr-15	1.00	631.98	10.19	14.52
12-Apr-15	2.00	630.98	10.05	14.52
12-Apr-15	3.00	629.98	9.99	14.43
12-Apr-15	4.00	628.98	9.93	14.38
12-Apr-15	5.00	627.98	9.89	14.36
12-Apr-15	6.00	626.98	9.54	14.49
12-Apr-15	7.00	625.98	9.35	14.34
12-Apr-15	8.00	624.98	8.44	12.56
12-Apr-15	9.00	623.98	8.42	12.25
12-Apr-15	10.00	622.98	8.24	11.82
12-Apr-15	11.00	621.98	8.00	11.04
12-Apr-15	12.00	620.98	7.90	10.89
12-Apr-15	13.00	619.98	7.57	10.18
12-Apr-15	14.00	618.98	7.40	9.76
12-Apr-15	15.00	617.98	7.39	9.64
12-Apr-15	16.00	616.98	7.38	9.55
12-Apr-15	17.00	615.98	7.29	9.49
12-Apr-15	18.00	614.98	7.24	9.28
12-Apr-15	19.00	613.98	7.21	9.06
12-Apr-15	20.00	612.98	7.20	8.89
12-Apr-15	21.00	611.98	7.17	8.85
12-Apr-15	22.00	610.98	7.12	8.48
12-Apr-15	23.00	609.98	7.11	8.33
12-Apr-15	24.00	608.98	7.10	8.16

Table C.1. continued

Date	Depth (m)	Depth (m a.s.l.)	Temp (°C)	DO (mg/L)
25-Apr-15	0.20	632.58	12.42	12.93
25-Apr-15	1.00	631.78	12.34	12.86
25-Apr-15	2.00	630.78	12.26	12.67
25-Apr-15	3.02	629.76	12.11	12.54
25-Apr-15	4.03	628.75	11.25	12.59
25-Apr-15	4.99	627.79	9.94	12.91
25-Apr-15	6.01	626.77	9.53	12.45
25-Apr-15	7.04	625.74	9.31	11.46
25-Apr-15	8.07	624.71	9.16	11.02
25-Apr-15	9.04	623.74	9.04	10.43
25-Apr-15	9.93	622.85	8.97	9.83
25-Apr-15	11.03	621.75	8.82	9.33
25-Apr-15	12.04	620.74	8.65	8.73
25-Apr-15	13.00	619.78	8.44	7.97
25-Apr-15	14.03	618.75	8.23	7.19
25-Apr-15	15.03	617.75	7.95	6.84
25-Apr-15	16.01	616.77	7.75	6.36
25-Apr-15	17.01	615.77	7.64	6.09
25-Apr-15	18.10	614.68	7.59	5.67
25-Apr-15	18.93	613.85	7.57	5.62
25-Apr-15	19.96	612.82	7.55	5.46
25-Apr-15	21.00	611.78	7.54	5.33
25-Apr-15	22.06	610.72	7.52	5.23
25-Apr-15	23.09	609.69	7.51	5.18
25-Apr-15	23.73	609.05	7.49	5.04

Table C.1. continued

Date	Depth (m)	Depth (m a.s.l.)	Temp (°C)	DO (mg/L)
9-May-15	0.25	632.18	16.10	12.10
9-May-15	1.02	631.41	15.58	12.34
9-May-15	1.93	630.50	15.35	11.93
9-May-15	3.03	629.40	15.25	11.61
9-May-15	4.01	628.42	15.07	10.87
9-May-15	5.05	627.38	13.31	10.15
9-May-15	6.05	626.38	11.86	9.65
9-May-15	7.08	625.35	10.89	9.16
9-May-15	8.00	624.43	10.22	8.94
9-May-15	8.94	623.49	9.52	8.83
9-May-15	10.00	622.43	9.00	8.30
9-May-15	11.06	621.37	8.64	6.03
9-May-15	12.00	620.43	8.41	5.64
9-May-15	12.32	620.11	8.37	5.24
9-May-15	14.02	618.41	8.13	4.79
9-May-15	15.01	617.42	8.07	4.57
9-May-15	16.05	616.38	8.01	4.35
9-May-15	17.01	615.42	7.93	4.01
9-May-15	17.98	614.45	7.88	3.69
9-May-15	19.07	613.36	7.85	3.45
9-May-15	20.05	612.38	7.84	3.28
9-May-15	21.03	611.40	7.81	3.19
9-May-15	22.04	610.39	7.79	3.08
9-May-15	22.97	609.46	7.78	2.94
9-May-15	24.09	608.34	7.75	2.65
9-May-15	25.01	607.42	7.73	2.20
9-May-15	25.77	606.66	7.72	1.23

Table C.1. continued

Date	Depth (m)	Depth (m a.s.l.)	Temp (°C)	DO (mg/L)
18-May-15	0.21	632.00	17.54	11.02
18-May-15	1.00	631.21	17.46	11.10
18-May-15	1.99	630.22	16.26	10.67
18-May-15	3.02	629.19	16.19	10.00
18-May-15	4.03	628.18	16.05	9.58
18-May-15	5.02	627.19	15.96	9.12
18-May-15	6.02	626.19	15.24	8.77
18-May-15	7.02	625.19	12.12	7.92
18-May-15	8.00	624.21	10.62	7.56
18-May-15	9.02	623.19	9.56	7.19
18-May-15	10.06	622.15	8.96	6.23
18-May-15	11.03	621.18	8.59	5.16
18-May-15	12.04	620.17	8.30	4.50
18-May-15	13.00	619.21	8.20	3.87
18-May-15	14.00	618.21	8.11	3.37
18-May-15	14.99	617.22	8.08	2.99
18-May-15	16.01	616.20	8.06	2.80
18-May-15	17.03	615.18	8.04	2.61
18-May-15	18.01	614.20	8.01	2.48
18-May-15	19.03	613.18	7.98	2.31
18-May-15	20.05	612.16	7.95	2.11
18-May-15	21.00	611.21	7.94	1.99
18-May-15	22.00	610.21	7.91	1.84

Table C.1. continued

Date	Depth (m)	Depth (m a.s.l.)	Temp (°C)	DO (mg/L)
2-Jun-15	0.26	631.41	20.29	9.27
2-Jun-15	1.01	630.66	20.27	9.28
2-Jun-15	2.02	629.65	20.14	9.29
2-Jun-15	3.06	628.61	19.79	9.38
2-Jun-15	3.98	627.69	17.59	9.86
2-Jun-15	4.96	626.71	16.38	9.74
2-Jun-15	6.05	625.62	14.60	8.69
2-Jun-15	7.01	624.66	12.69	7.20
2-Jun-15	7.98	623.69	11.72	6.60
2-Jun-15	8.93	622.74	10.63	6.82
2-Jun-15	10.08	621.59	9.72	7.22
2-Jun-15	10.99	620.68	9.34	7.05
2-Jun-15	12.03	619.64	8.85	5.47
2-Jun-15	13.14	618.53	8.47	4.62
2-Jun-15	14.01	617.66	8.32	4.31
2-Jun-15	15.00	616.67	8.25	4.18
2-Jun-15	15.97	615.70	8.20	4.12
2-Jun-15	16.87	614.80	8.14	3.56
2-Jun-15	18.02	613.65	8.07	3.13
2-Jun-15	18.99	612.68	8.03	3.02
2-Jun-15	20.05	611.62	7.99	2.75
2-Jun-15	21.06	610.61	8.00	2.43
2-Jun-15	22.03	609.64	7.92	1.57

Table C.1. continued

Date	Depth (m)	Depth (m a.s.l.)	Temp (°C)	DO (mg/L)
16-Jun-15	0.37	630.80	21.58	8.95
16-Jun-15	1.08	630.09	21.52	8.75
16-Jun-15	1.99	629.18	21.42	8.57
16-Jun-15	3.04	628.13	21.35	8.29
16-Jun-15	3.97	627.20	21.32	7.95
16-Jun-15	5.00	626.17	20.00	7.65
16-Jun-15	6.01	625.16	16.93	6.81
16-Jun-15	7.01	624.16	14.22	4.72
16-Jun-15	8.03	623.14	12.72	3.63
16-Jun-15	8.99	622.18	11.49	3.44
16-Jun-15	10.03	621.14	10.12	3.11
16-Jun-15	11.02	620.15	9.24	2.35
16-Jun-15	12.00	619.17	8.89	1.93
16-Jun-15	13.03	618.14	8.56	1.78
16-Jun-15	14.05	617.12	8.44	1.41
16-Jun-15	15.05	616.12	8.36	0.76
16-Jun-15	16.01	615.16	8.30	0.46
16-Jun-15	16.94	614.23	8.26	0.24
16-Jun-15	18.00	613.17	8.24	0.00
16-Jun-15	19.05	612.12	8.22	0.00
16-Jun-15	20.01	611.16	8.19	0.00
16-Jun-15	20.99	610.18	8.14	0.00
16-Jun-15	21.98	609.19	8.11	0.00
16-Jun-15	22.98	608.19	8.06	0.00
16-Jun-15	23.90	607.27	8.00	0.00
16-Jun-15	24.62	606.55	7.96	0.00

Table C.1. continued

Date	Depth (m)	Depth (m a.s.l.)	Temp (°C)	DO (mg/L)
30-Jun-15	0.29	629.96	24.54	8.71
30-Jun-15	0.99	629.26	24.41	8.66
30-Jun-15	2.03	628.22	24.31	8.37
30-Jun-15	3.02	627.23	24.25	8.03
30-Jun-15	4.00	626.25	22.64	7.66
30-Jun-15	4.99	625.26	21.12	6.47
30-Jun-15	6.00	624.25	20.17	5.26
30-Jun-15	7.05	623.20	16.37	3.86
30-Jun-15	7.96	622.29	14.11	2.69
30-Jun-15	9.02	621.23	12.28	1.97
30-Jun-15	10.01	620.24	10.71	1.48
30-Jun-15	11.01	619.24	9.38	0.85
30-Jun-15	12.01	618.24	9.00	0.58
30-Jun-15	13.02	617.23	8.71	0.23
30-Jun-15	14.01	616.24	8.51	0.13
30-Jun-15	15.01	615.24	8.40	0.00
30-Jun-15	16.03	614.22	8.34	0.00
30-Jun-15	17.08	613.17	8.31	0.00
30-Jun-15	17.99	612.26	8.28	0.00
30-Jun-15	18.99	611.26	8.25	0.00
30-Jun-15	20.06	610.19	8.22	0.00
30-Jun-15	20.64	609.61	8.19	0.00

Table C.1. continued

Date	Depth (m)	Depth (m a.s.l.)	Temp (°C)	DO (mg/L)
14-Jul-15	0.00	629.39	23.84	8.01
14-Jul-15	1.00	628.39	23.71	8.10
14-Jul-15	2.00	627.39	23.56	8.15
14-Jul-15	3.00	626.39	23.53	8.11
14-Jul-15	4.00	625.39	23.48	8.00
14-Jul-15	5.00	624.39	23.29	7.43
14-Jul-15	6.00	623.39	21.00	4.05
14-Jul-15	7.00	622.39	17.70	2.11
14-Jul-15	8.00	621.39	14.94	1.58
14-Jul-15	9.00	620.39	13.01	0.99
14-Jul-15	10.00	619.39	10.06	0.35
14-Jul-15	11.00	618.39	9.12	0.11
14-Jul-15	12.00	617.39	8.54	0.04
14-Jul-15	13.00	616.39	8.34	0.03
14-Jul-15	14.00	615.39	8.23	0.03
14-Jul-15	15.00	614.39	8.18	0.03
14-Jul-15	16.00	613.39	8.13	0.03
14-Jul-15	17.00	612.39	8.07	0.03
14-Jul-15	18.00	611.39	8.04	0.03
14-Jul-15	19.00	610.39	8.01	0.03
14-Jul-15	20.00	609.39	7.98	0.03
14-Jul-15	21.00	608.39	7.95	0.03

Table C.1. continued

Date	Depth (m)	Depth (m a.s.l.)	Temp (°C)	DO (mg/L)
27-Jul-15	0.35	628.08	21.90	7.37
27-Jul-15	1.03	627.40	21.54	7.33
27-Jul-15	2.01	626.42	21.40	7.13
27-Jul-15	3.06	625.37	21.30	6.76
27-Jul-15	4.01	624.42	21.27	6.44
27-Jul-15	6.96	621.47	20.78	4.17
27-Jul-15	7.09	621.34	20.59	4.33
27-Jul-15	8.04	620.39	15.51	0.49
27-Jul-15	9.01	619.42	11.15	0.00
27-Jul-15	10.06	618.37	9.25	0.00
27-Jul-15	10.99	617.44	8.81	0.00
27-Jul-15	12.01	616.42	8.62	0.00
27-Jul-15	12.99	615.44	8.52	0.00
27-Jul-15	13.99	614.44	8.45	0.00
27-Jul-15	15.00	613.43	8.41	0.00
27-Jul-15	15.98	612.45	8.34	0.00
27-Jul-15	16.99	611.44	8.29	0.00
27-Jul-15	18.03	610.40	8.25	0.00
27-Jul-15	18.97	609.46	8.19	0.00
27-Jul-15	20.01	608.42	8.18	0.00
27-Jul-15	20.64	607.79	8.15	0.00

Table C.1. continued

Date	Depth (m)	Depth (m a.s.l.)	Temp (°C)	DO (mg/L)
11-Aug-15	0.32	626.96	21.77	8.10
11-Aug-15	1.00	626.28	21.80	7.96
11-Aug-15	2.01	625.27	21.79	7.70
11-Aug-15	3.03	624.25	21.76	7.41
11-Aug-15	3.97	623.31	21.47	6.27
11-Aug-15	5.00	622.28	21.20	5.64
11-Aug-15	5.98	621.30	20.95	4.56
11-Aug-15	7.05	620.23	17.24	0.30
11-Aug-15	8.03	619.25	12.13	0.00
11-Aug-15	9.06	618.22	9.71	0.00
11-Aug-15	10.05	617.23	9.08	0.00
11-Aug-15	11.02	616.26	8.82	0.00
11-Aug-15	11.99	615.29	8.69	0.00
11-Aug-15	13.14	614.14	8.57	0.00
11-Aug-15	14.11	613.17	8.53	0.00
11-Aug-15	15.02	612.26	8.48	0.00
11-Aug-15	16.02	611.26	8.42	0.00
11-Aug-15	16.99	610.29	8.34	0.00
11-Aug-15	18.05	609.23	8.25	0.00
11-Aug-15	19.00	608.28	8.21	0.00
11-Aug-15	20.00	607.28	8.20	0.00
11-Aug-15	20.71	606.57	8.17	0.00

Table C.1. continued

Date	Depth (m)	Depth (m a.s.l.)	Temp (°C)	DO (mg/L)
25-Aug-15	0.31	625.86	21.08	10.45
25-Aug-15	0.99	625.18	21.04	10.47
25-Aug-15	1.97	624.20	20.89	9.84
25-Aug-15	3.04	623.13	20.68	8.83
25-Aug-15	4.03	622.14	20.34	7.26
25-Aug-15	5.00	621.17	20.13	6.31
25-Aug-15	6.03	620.14	19.15	4.00
25-Aug-15	6.99	619.18	13.91	0.29
25-Aug-15	8.03	618.14	10.22	0.12
25-Aug-15	8.91	617.26	9.24	0.00
25-Aug-15	10.05	616.12	8.80	0.00
25-Aug-15	11.00	615.17	8.61	0.00
25-Aug-15	12.04	614.13	8.56	0.00
25-Aug-15	12.99	613.18	8.50	0.00
25-Aug-15	13.98	612.19	8.45	0.00
25-Aug-15	15.03	611.14	8.38	0.00
25-Aug-15	16.00	610.17	8.30	0.00
25-Aug-15	17.06	609.11	8.27	0.00
25-Aug-15	18.06	608.11	8.25	0.00
25-Aug-15	18.98	607.19	8.24	0.00
8-Sep-15	0.34	624.82	17.81	11.67
8-Sep-15	1.01	624.15	17.52	11.33
8-Sep-15	2.05	623.11	17.25	10.23
8-Sep-15	3.00	622.16	17.03	8.75
8-Sep-15	4.04	621.12	16.91	8.03
8-Sep-15	5.00	620.16	16.78	6.71
8-Sep-15	5.99	619.17	16.36	5.17
8-Sep-15	7.03	618.13	12.18	0.29
8-Sep-15	7.98	617.18	9.44	0.00
8-Sep-15	9.14	616.02	8.97	0.00
8-Sep-15	10.04	615.12	8.74	0.00
8-Sep-15	11.05	614.11	8.70	0.00
8-Sep-15	12.00	613.16	8.61	0.00
8-Sep-15	12.97	612.19	8.59	0.00
8-Sep-15	14.02	611.14	8.53	0.00
8-Sep-15	15.09	610.07	8.42	0.00
8-Sep-15	15.66	609.50	8.40	0.00

Table C.1. continued

Date	Depth (m)	Depth (m a.s.l.)	Temp (°C)	DO (mg/L)
5-Oct-15	0.34	623.87	15.10	8.27
5-Oct-15	0.95	623.26	14.97	8.06
5-Oct-15	3.00	621.21	14.82	7.23
5-Oct-15	3.98	620.23	14.78	6.95
5-Oct-15	4.99	619.22	14.69	6.23
5-Oct-15	5.99	618.22	14.08	2.08
5-Oct-15	7.01	617.20	11.82	0.25
5-Oct-15	8.03	616.18	9.42	0.01
5-Oct-15	9.00	615.21	9.02	0.00
5-Oct-15	10.04	614.17	8.83	0.00
5-Oct-15	11.00	613.21	8.77	0.00
5-Oct-15	12.00	612.21	8.72	0.00
5-Oct-15	12.05	612.16	8.71	0.00
5-Oct-15	13.11	611.10	8.67	0.00
5-Oct-15	14.03	610.18	8.63	0.00
5-Oct-15	15.05	609.16	8.55	0.00
5-Oct-15	15.97	608.24	8.49	0.00
5-Oct-15	17.02	607.19	8.48	0.00
18-Oct-15	0.18	623.63	14.86	9.17
18-Oct-15	1.01	622.80	14.84	8.93
18-Oct-15	1.99	621.82	14.82	8.58
18-Oct-15	3.01	620.80	14.64	6.88
18-Oct-15	4.06	619.75	14.23	4.26
18-Oct-15	4.97	618.84	13.89	2.44
18-Oct-15	5.95	617.86	13.49	0.68
18-Oct-15	7.00	616.81	11.78	0.07
18-Oct-15	8.12	615.69	9.64	0.00
18-Oct-15	9.02	614.79	9.40	0.00
18-Oct-15	10.00	613.81	9.24	0.00
18-Oct-15	11.00	612.81	9.02	0.00
18-Oct-15	12.00	611.81	8.80	0.00
18-Oct-15	13.04	610.77	8.76	0.00
18-Oct-15	13.99	609.82	8.75	0.00
18-Oct-15	14.48	609.33	8.69	0.00

Table C.1. continued

Date	Depth (m)	Depth (m a.s.l.)	Temp (°C)	DO (mg/L)
9-Nov-15	0.25	623.38	10.12	7.60
9-Nov-15	1.00	622.63	10.12	6.64
9-Nov-15	1.95	621.68	10.12	6.39
9-Nov-15	3.01	620.62	10.11	6.08
9-Nov-15	4.00	619.63	10.11	5.76
9-Nov-15	4.98	618.65	10.11	5.56
9-Nov-15	6.03	617.60	10.10	5.28
9-Nov-15	7.01	616.62	10.10	5.00
9-Nov-15	8.05	615.58	10.09	4.73
9-Nov-15	8.99	614.64	10.09	4.50
9-Nov-15	10.07	613.56	10.07	4.32
9-Nov-15	10.98	612.65	10.02	4.25
9-Nov-15	12.02	611.61	9.93	1.89
9-Nov-15	13.01	610.62	9.82	0.17
9-Nov-15	14.00	609.63	9.48	0.00

Appendix D

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

Annual sub-catchment total phosphorus (TP) loading was calculated using the nonparametric smearing approach (Duan 1983, Colin 1995, Helsel and Hirsch 2002) provided in Appendix G of Rajkovich (2014). Using this approach, loads from Willow Creek inflow and outflow collected by Adams (2012), Rajkovich (2014), and USGS (2015) were individually 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 were 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.

Annual TP (FigureD.1-D.2) loads were graphed versus discharge and a nutrient-specific linear relationship was determined for the inflow and outflow. The fitted parameters, bias correction factor and corresponding R^2 values for TP loading are presented Table D.1, respectively. Linear relationships were then applied to continuous discharge data to estimate 15 minute interval TP loading for inflow and outflow of Willow Creek Reservoir.

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Table D.1. Fitted parameters, bias-correct factor and corresponding R^2 values used to calculate specific TP loads for Willow Creek inflow and outflow located at Willow Creek Reservoir, Heppner, OR.

Location	b_0	b1	bias-correction factor	R^2
Willow Creek inflow	11.51	1.12	1.11	0.93
Willow Creek outflow	10.89	0.93	1.06	0.85

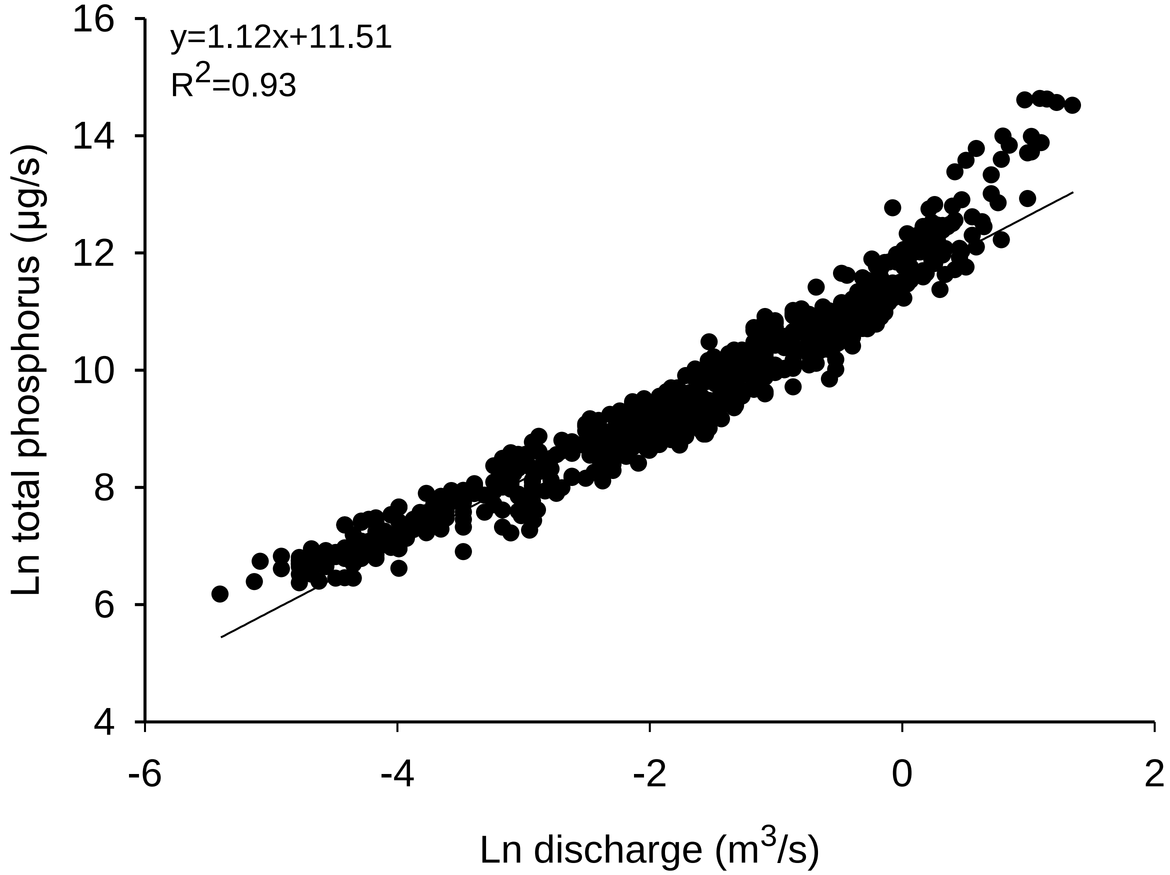

Figure D.1. Ln total phosphorus as a function of Ln discharge for the Willow Creek inflow at Willow Creek Reservoir, Heppner, OR. Values for curve provided by samples collected from Adams (2012) and Rajkovich (2014).

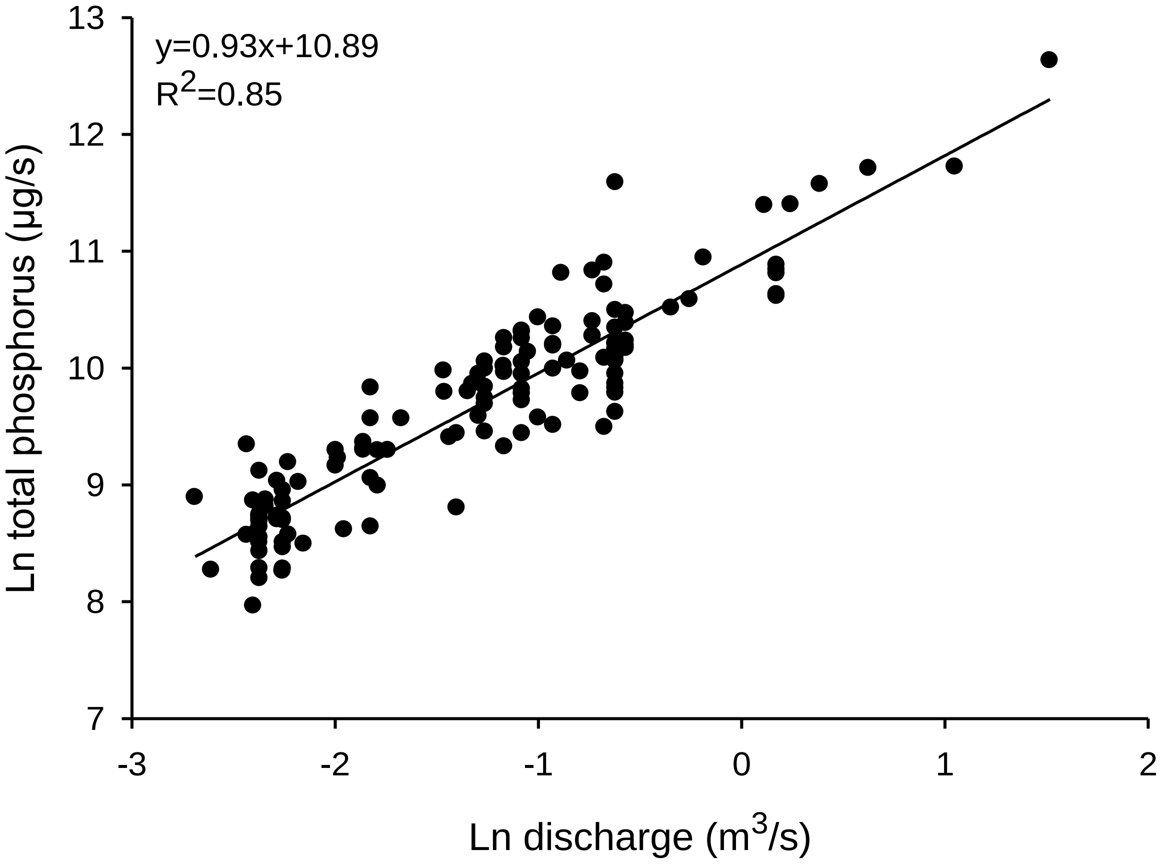

Figure D.2. Ln total phosphorus as a function of Ln discharge for the Willow Creek outflow at Willow Creek Reservoir, Heppner, OR. Values for curve provided by samples collected from Adams (2012), Rajkovich (2014), and USGS (2015).

Appendix E

Annual water budget of Willow Creek Reservoir, OR

Annual water budget for Willow Creek Reservoir during the 2014-2015 study period. Positive values in groundwater column represent a loss from the reservoir to groundwater.

Table E.1. Annual water budget for Willow Creek Reservoir during 2014-2015 study period. Positive values in groundwater represent a loss from the reservoir to groundwater.

Inputs	2014 (m^3/y)	2015 (m^3/y)	Source
Willow Creek	$1.28 \cdot 10^7$	$7.23 \cdot 10^6$	This study
Balm Fork Creek	$6.38 \cdot 10^5$	$3.62 \cdot 10^5$	Estimated from Adams (2012)
Precipitation	$1.56 \cdot 10^5$	$1.02 \cdot 10^5$	This study
Groundwater gain/loss	$1.15 \cdot 10^6$	$4.58 \cdot 10^5$	This study
Outputs			
Willow Creek Dam	$1.33 \cdot 10^7$	$7.42 \cdot 10^6$	This study
Evaporation	$6.53 \cdot 10^5$	$6.19 \cdot 10^5$	Regional averages (see Appendix A)

Appendix F

Annual total phosphorus budget for Willow Creek Reservoir, OR for 2014 and 2015 of water column data

Internal loading values were estimated from water column sampling (see methods Chapter 2). Positive values indicate a retention of total phosphorus while negative values indicate a loss from Willow Creek Reservoir. Positive values in groundwater represent a loss from the reservoir to groundwater.

Table F.1. Annual total phosphorus budget for Willow Creek Reservoir, OR for 2014 and 2015 of water column data. Internal loading values were estimated from water column sampling (see methods Chapter 2). Positive values indicate a retention of total phosphorus while negatives indicate a loss.

	2014				2015				
	Annual		**Anoxic**		**Annual**		**Anoxic**		
Inputs	Mass (kg/y)	%	Mass (kg/y)	%	Mass (kg/y)	%	Mass (kg/y)	%	Source
Willow Creek	1420	86	36	21	729	66	20	6	This study
Balm Fork Creek	54	3	None	None	28	2	None	None	Estimated from Adams (2012)
Dry deposition	9	1	4	2	10	1	4	1	Jassby et al. 1994
Wet deposition	43	3	6	4	28	3	2	0	Jassby et al. 1994; Ellis et al. 2015
Internal loading	124	8	124	73	318	29	318	93	This study
Outputs									
Willow Creek Dam	779	-	206	-	457	-	207	-	This study
Δ P Storage	871	-	-36	-	655	-	136	-	This study

Appendix G

Lake elevations and corresponding volumes and surface areas

Lake volume and surface areas were calculated using 15 minute forebay elevations (in meters above sea level – a.sl.) recorded by the US Geological Survey (USGS; Willow Creek station ID 14034490) at Willow Creek dam. The 15 minute forebay elevations were averaged for each day and used to calculate the elevation of the reservoir on each day. Any missing 15 min interval data were linearly interpolated from adjacent data (Missing forebay data: 16-Apr to 30-Apr-2014, 23-May to 29-May-2014, 21-Aug to 31-Aug-2014, 16-Dec to 31-Dec-2014, 16-Apr to 30-Apr-2015, 14-Aug to 31-Aug-2015, 15-Dec to 31-Dec-2015) after inspecting the data set to ensure elevations before and after the missing period were similar. USGS hydrographic survey data from WCR collected in 2007 (K. Tackley, USACE personal communication) were combined with daily forebay elevations to calculate reservoir volumes (m^3) as well as 2D and 3D surface areas (m^2) using the model builder function in ESRI© ArcMap 10.3.

To determine the depth of the anoxic boundary from bi-weekly profiles of temperature and DO data, I used a relative thermal resistance to mixing (RTRM) spreadsheet (Kortmann, Ecosystem Consulting Service, Inc.). Daily forebay elevations (in meters above sea level – a.sl.) were obtained from the USGS gauging station (USGS; Willow Creek station ID 14034490) and the depth of the anoxic boundary was subtracted to determine the depth of the anoxic layer. To calculate the anoxic volumes and surface areas, I used 2007 USGS hydrographic survey data from WCR (Kathryn Tackley, USACE personal communication) and ESRI© ArcMap 10.3 GIS software. The software's Model Builder function was used with the daily depth of the anoxic boundary layer to calculate the reservoir volumes (m^3) as well as 2D and 3D surface areas (m^2) below the anoxic boundary.

References

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Table G.1. Reservoir elevation and associated surface areas and volumes.

Date	Lake Elevation (m a.s.l.)	2D Surface area (m^2)	3D Surface area (m^2)	Volume (m^3)
1-Jan-14	627.52	464637.27	478910.21	4485353.47
2-Jan-14	627.53	464777.14	479059.89	4489602.75
3-Jan-14	627.54	464963.78	479259.60	4495270.45
4-Jan-14	627.54	465010.46	479309.56	4496687.73
5-Jan-14	627.55	465057.16	479359.52	4498105.15
6-Jan-14	627.54	465010.46	479309.56	4496687.73
7-Jan-14	627.55	465057.16	479359.52	4498105.15
8-Jan-14	627.57	465384.30	479709.55	4508031.10
9-Jan-14	627.58	465618.28	479959.87	4515125.34
10-Jan-14	627.60	465852.50	480210.44	4522223.15
11-Jan-14	627.62	466227.79	480611.87	4533587.07
12-Jan-14	627.62	466133.91	480511.46	4530745.23
13-Jan-14	627.64	466556.69	480963.66	4543538.02
14-Jan-14	627.66	466744.86	481164.89	4549227.42
15-Jan-14	627.67	466980.29	481416.67	4556342.41
16-Jan-14	627.68	467168.82	481618.27	4562036.98
17-Jan-14	627.69	467310.32	481769.57	4566309.42
18-Jan-14	627.70	467404.70	481870.49	4569158.43
19-Jan-14	627.71	467499.13	481971.45	4572008.02
20-Jan-14	627.71	467640.84	482122.97	4576283.48
21-Jan-14	627.72	467735.36	482224.03	4579134.50
22-Jan-14	627.72	467782.64	482274.57	4580560.23
23-Jan-14	627.73	467877.23	482375.69	4583412.12
24-Jan-14	627.74	467971.85	482476.85	4586264.59
25-Jan-14	627.73	467924.53	482426.27	4584838.28
26-Jan-14	627.73	467877.23	482375.69	4583412.12
27-Jan-14	627.73	467877.23	482375.69	4583412.12
28-Jan-14	627.73	467924.53	482426.27	4584838.28
29-Jan-14	627.74	468066.52	482578.05	4589117.64
30-Jan-14	627.79	468825.29	483389.10	4611962.80
31-Jan-14	627.84	469538.97	484151.78	4633413.79
1-Feb-14	627.87	470063.78	484712.52	4649165.29
2-Feb-14	627.90	470494.07	485172.20	4662065.98
3-Feb-14	627.92	470781.39	485479.11	4670673.00
4-Feb-14	627.95	471261.05	485991.43	4685029.73
5-Feb-14	627.96	471501.25	486247.96	4692213.58
6-Feb-14	627.96	471549.33	486299.30	4693650.78
7-Feb-14	627.98	471789.83	486556.13	4700839.03
8-Feb-14	628.00	472078.78	486864.66	4709469.76

Table G.1. continued

Date	Lake Elevation (m a.s.l.)	2D Surface area (m^2)	3D Surface area (m^2)	Volume (m^3)
9-Feb-14	628.03	472609.44	487431.24	4725306.51
10-Feb-14	628.06	472996.14	487844.06	4736835.33
11-Feb-14	628.09	473480.43	488360.98	4751259.63
12-Feb-14	628.13	474208.74	489138.25	4772923.80
13-Feb-14	628.35	477686.75	492847.90	4875921.79
14-Feb-14	628.67	482973.57	498480.26	5031107.66
15-Feb-14	628.96	487756.36	503569.18	5170168.42
16-Feb-14	629.23	492418.84	508524.53	5304607.39
17-Feb-14	629.50	497109.58	513504.64	5438821.27
18-Feb-14	629.72	500908.72	517534.46	5546809.93
19-Feb-14	629.90	504104.29	520921.60	5637176.16
20-Feb-14	630.05	506839.79	523819.38	5714209.78
21-Feb-14	630.15	508603.70	525687.10	5763730.84
22-Feb-14	630.22	509933.39	527094.62	5800984.82
23-Feb-14	630.28	511045.88	528271.97	5832104.24
24-Feb-14	630.34	511994.66	529275.86	5858609.17
25-Feb-14	630.38	512890.28	530223.35	5883599.95
26-Feb-14	630.44	513844.70	531232.87	5910200.59
27-Feb-14	630.48	514745.63	532185.65	5935281.72
28-Feb-14	630.54	515818.83	533320.41	5965122.73
1-Mar-14	630.61	517066.01	534638.86	5999753.27
2-Mar-14	630.69	518489.16	536142.98	6039207.88
3-Mar-14	630.77	520090.55	537835.04	6083526.10
4-Mar-14	630.93	523085.47	540998.27	6166195.35
5-Mar-14	631.11	526574.92	544681.83	6262175.75
6-Mar-14	631.23	528744.78	546971.33	6321682.98
7-Mar-14	631.28	529746.36	548027.87	6349106.36
8-Mar-14	631.25	529156.84	547406.03	6332968.68
9-Mar-14	631.19	528039.53	546227.29	6302356.52
10-Mar-14	631.13	526867.34	544990.42	6270202.98
11-Mar-14	631.79	539861.17	558688.57	6624577.87
12-Mar-14	632.09	545858.06	565001.61	6786729.81
13-Mar-14	631.97	543459.98	562477.75	6721985.25
14-Mar-14	631.80	539921.88	558752.50	6626223.46
15-Mar-14	631.76	539133.49	557922.16	6604845.22
16-Mar-14	631.88	541686.70	560610.91	6674026.17
17-Mar-14	631.83	540590.30	559456.42	6644337.17
18-Mar-14	631.75	539072.92	557858.35	6603202.04
19-Mar-14	631.70	537984.29	556711.62	6573656.22

Table G.1. continued

Date	Lake Elevation (m a.s.l.)	2D Surface area (m^2)	3D Surface area (m^2)	Volume (m^3)
20-Mar-14	631.70	537984.29	556711.62	6573656.22
21-Mar-14	631.74	538770.20	557539.49	6594988.87
22-Mar-14	631.81	540286.32	559136.31	6636100.89
23-Mar-14	631.89	541869.75	560803.64	6678980.19
24-Mar-14	631.95	543092.40	562090.82	6712049.82
25-Mar-14	632.01	544134.82	563188.07	6740217.69
26-Mar-14	632.06	545180.13	564288.21	6768439.65
27-Mar-14	632.12	546351.87	565521.21	6800046.03
28-Mar-14	632.17	547465.28	566692.66	6830051.61
29-Mar-14	632.24	548892.71	568194.23	6868481.12
30-Mar-14	632.34	550887.54	570292.18	6922115.12
31-Mar-14	632.46	553395.55	572929.06	6989432.05
1-Apr-14	632.58	555856.35	575515.46	7055361.40
2-Apr-14	632.66	557632.50	577381.75	7102876.14
3-Apr-14	632.69	558205.08	577983.30	7118180.96
4-Apr-14	632.70	558396.12	578184.00	7123286.06
5-Apr-14	632.71	558650.99	578451.74	7130095.58
6-Apr-14	632.72	558842.24	578652.64	7135204.76
7-Apr-14	632.76	559608.15	579457.17	7155658.98
8-Apr-14	632.80	560567.58	580464.87	7181266.19
9-Apr-14	632.84	561400.91	581340.03	7203494.62
10-Apr-14	632.85	561593.46	581542.23	7208628.95
11-Apr-14	632.82	560887.89	580801.27	7189811.68
12-Apr-14	632.81	560631.62	580532.13	7182974.89
13-Apr-14	632.83	561016.08	580935.90	7193231.24
14-Apr-14	632.86	561657.66	581609.65	7210340.79
15-Apr-14	632.87	561850.33	581811.97	7215477.46
16-Apr-14	632.87	561950.72	581917.39	7218153.80
17-Apr-14	632.87	562051.12	582022.81	7220830.04
18-Apr-14	632.88	562151.55	582128.26	7223506.77
19-Apr-14	632.88	562252.01	582233.76	7226184.54
20-Apr-14	632.89	562352.51	582339.28	7228862.78
21-Apr-14	632.89	562453.00	582444.80	7231540.95
22-Apr-14	632.90	562553.52	582550.35	7234219.59
23-Apr-14	632.90	562654.09	582655.94	7236899.27
24-Apr-14	632.91	562754.68	582761.56	7239579.43
25-Apr-14	632.91	562855.28	582867.18	7242259.51
26-Apr-14	632.92	562955.90	582972.82	7244940.06
27-Apr-14	632.92	563056.56	583078.51	7247621.66

Table G.1. continued

Date	Lake Elevation (m a.s.l.)	2D Surface area (m^2)	3D Surface area (m^2)	Volume (m^3)
28-Apr-14	632.93	563157.25	583184.23	7250303.74
29-Apr-14	632.93	563257.94	583289.95	7252985.73
30-Apr-14	632.94	563358.68	583395.71	7255668.77
1-May-14	632.94	563459.42	583501.48	7258351.73
2-May-14	632.96	616806.39	636857.34	7271063.04
3-May-14	632.97	616806.39	636857.34	7272943.07
4-May-14	632.97	616806.39	636857.34	7272943.07
5-May-14	632.97	616806.39	636857.34	7274823.09
6-May-14	632.97	616806.39	636857.34	7274823.09
7-May-14	632.96	616806.39	636857.34	7271063.04
8-May-14	632.98	616806.39	636857.34	7280463.17
9-May-14	632.97	616806.39	636857.34	7274823.09
10-May-14	632.97	616806.39	636857.34	7276703.12
11-May-14	632.98	616806.39	636857.34	7278583.14
12-May-14	632.98	616806.39	636857.34	7280463.17
13-May-14	632.97	616806.39	636857.34	7276703.12
14-May-14	632.96	616806.39	636857.34	7267302.99
15-May-14	632.94	563394.94	583433.78	7256634.40
16-May-14	632.93	563201.55	583230.73	7251483.60
17-May-14	632.92	562943.83	582960.15	7244618.62
18-May-14	632.90	562621.91	582622.15	7236041.81
19-May-14	632.90	562621.91	582622.15	7236041.81
20-May-14	632.91	562686.27	582689.73	7237756.78
21-May-14	632.90	562557.56	582554.58	7234327.03
22-May-14	632.89	562428.88	582419.47	7230898.08
23-May-14	632.88	562187.72	582166.24	7224470.89
24-May-14	632.87	561946.70	581913.16	7218046.46
25-May-14	632.86	561705.82	581660.22	7211624.79
26-May-14	632.85	561465.08	581407.42	7205205.87
27-May-14	632.84	561224.49	581154.76	7198789.70
28-May-14	632.82	560984.03	580902.24	7192376.28
29-May-14	632.81	560743.72	580649.86	7185965.60
30-May-14	632.80	560503.55	580397.62	7179557.67
31-May-14	632.80	560439.52	580330.38	7177849.36
1-Jun-14	632.79	560311.51	580195.93	7174433.31
2-Jun-14	632.79	560183.54	580061.52	7171018.04
3-Jun-14	632.78	559991.65	579859.98	7165896.60
4-Jun-14	632.76	559672.04	579524.28	7157364.76
5-Jun-14	632.75	559352.69	579188.84	7148837.79

Table G.1. continued

Date	Lake Elevation (m a.s.l.)	2D Surface area (m^2)	3D Surface area (m^2)	Volume (m^3)
6-Jun-14	632.73	558969.79	578786.63	7138611.85
7-Jun-14	632.71	558523.54	578317.85	7126690.44
8-Jun-14	632.68	557950.50	577715.85	7111376.88
9-Jun-14	632.65	557314.76	577047.91	7094380.24
10-Jun-14	632.62	556680.01	576380.97	7077402.96
11-Jun-14	632.59	556109.60	575781.59	7062139.94
12-Jun-14	632.57	555603.26	575249.48	7048585.94
13-Jun-14	632.53	554908.08	574518.89	7029969.33
14-Jun-14	632.51	554529.41	574120.89	7019824.63
15-Jun-14	632.50	554277.16	573855.76	7013065.35
16-Jun-14	632.48	553710.19	573259.80	6997868.20
17-Jun-14	632.44	553018.33	572532.51	6979315.00
18-Jun-14	632.42	552578.68	572070.32	6967520.50
19-Jun-14	632.40	552202.24	571674.55	6957418.38
20-Jun-14	632.38	551700.88	571147.41	6943959.59
21-Jun-14	632.35	551075.08	570489.39	6927153.29
22-Jun-14	632.31	550387.87	569766.73	6908688.37
23-Jun-14	632.28	549701.86	569045.28	6890246.47
24-Jun-14	632.25	549017.08	568325.05	6871827.55
25-Jun-14	632.21	548271.43	567540.72	6851760.34
26-Jun-14	632.18	547589.19	566823.02	6833389.34
27-Jun-14	632.16	547217.57	566432.06	6823378.42
28-Jun-14	632.15	546970.03	566171.61	6816708.26
29-Jun-14	632.12	546475.42	565651.21	6803376.97
30-Jun-14	632.08	545673.05	564806.93	6781739.33
1-Jul-14	632.04	544872.39	563964.34	6760133.45
2-Jul-14	632.01	544134.82	563188.07	6740217.69
3-Jul-14	631.97	543459.98	562477.75	6721985.25
4-Jul-14	631.93	542664.02	561639.85	6700466.97
5-Jul-14	631.90	541930.79	560867.91	6680631.91
6-Jul-14	631.86	541259.94	560161.56	6662473.30
7-Jul-14	631.82	540407.88	559264.32	6639394.84
8-Jul-14	631.78	539557.80	558369.05	6616352.70
9-Jul-14	631.73	538649.18	557412.02	6591704.90
10-Jul-14	631.68	537622.14	556330.10	6563820.87
11-Jul-14	631.63	536598.01	555251.08	6535989.99
12-Jul-14	631.58	535576.79	554174.95	6508212.10
13-Jul-14	631.53	534618.29	553164.77	6482116.47
14-Jul-14	631.48	533602.70	552094.27	6454441.02

Table G.1. continued

Date	Lake Elevation (m a.s.l.)	2D Surface area (m^2)	3D Surface area (m^2)	Volume (m^3)
15-Jul-14	631.42	532590.02	551026.66	6426818.11
16-Jul-14	631.36	531402.34	549774.36	6394387.64
17-Jul-14	631.28	529864.38	548152.36	6352336.05
18-Jul-14	631.20	528215.71	546413.16	6307185.72
19-Jul-14	631.12	526633.38	544743.52	6263780.84
20-Jul-14	631.03	525058.38	543081.19	6220505.87
21-Jul-14	630.95	523548.64	541487.33	6178955.91
22-Jul-14	630.88	522103.37	539961.16	6139116.61
23-Jul-14	630.80	520721.83	538501.93	6100974.27
24-Jul-14	630.73	519288.87	536988.03	6061349.90
25-Jul-14	630.66	517919.15	535540.58	6023413.02
26-Jul-14	630.58	516498.50	534038.96	5984001.75
27-Jul-14	630.50	515084.14	532543.60	5944698.49
28-Jul-14	630.43	513732.27	531113.95	5907068.53
29-Jul-14	630.35	512274.27	529571.68	5866414.10
30-Jul-14	630.27	510878.75	528095.11	5827432.01
31-Jul-14	630.19	509378.65	526507.45	5785450.50
1-Aug-14	630.11	507885.87	524927.10	5743592.15
2-Aug-14	630.03	506455.31	523412.18	5703399.94
3-Aug-14	629.95	505031.54	521904.04	5663320.83
4-Aug-14	629.87	503614.57	520402.67	5623354.29
5-Aug-14	629.80	502258.50	518965.43	5585030.56
6-Aug-14	629.73	501016.47	517648.70	5549863.80
7-Aug-14	629.66	499940.76	516508.03	5519354.64
8-Aug-14	629.60	498869.07	515371.37	5488910.94
9-Aug-14	629.54	497801.41	514238.72	5458532.44
10-Aug-14	629.49	496843.95	513222.76	5431247.35
11-Aug-14	629.45	496101.50	512434.81	5410061.87
12-Aug-14	629.40	495308.22	511592.76	5387398.25
13-Aug-14	629.34	494359.26	510585.27	5360249.71
14-Aug-14	629.28	493256.25	509413.98	5328642.09
15-Aug-14	629.22	492262.12	508358.05	5300105.43
16-Aug-14	629.16	491115.54	507139.90	5267134.77
17-Aug-14	629.09	489973.83	505926.61	5234240.84
18-Aug-14	629.02	488785.43	504663.36	5199933.40
19-Aug-14	628.94	487499.72	503296.27	5162736.97
20-Aug-14	628.87	486220.29	501935.44	5125638.28
21-Aug-14	628.78	484777.86	500400.74	5083710.64
22-Aug-14	628.69	483343.50	498874.08	5041907.22

Table G.1. continued

Date	Lake Elevation (m a.s.l.)	2D Surface area (m^2)	3D Surface area (m^2)	Volume (m^3)
23-Aug-14	628.61	481917.21	497355.47	5000227.32
24-Aug-14	628.52	480498.99	495844.90	4958670.24
25-Aug-14	628.43	479088.84	494342.38	4917235.30
26-Aug-14	628.35	477686.75	492847.90	4875921.79
27-Aug-14	628.26	476292.74	491361.47	4834729.01
28-Aug-14	628.18	474906.79	489883.08	4793656.27
29-Aug-14	628.09	473528.91	488412.73	4752702.88
30-Aug-14	628.00	472159.10	486950.43	4711868.13
31-Aug-14	627.92	470797.36	485496.17	4671151.32
1-Sep-14	627.83	469443.69	484049.96	4630551.77
2-Sep-14	627.74	468066.52	482578.05	4589117.64
3-Sep-14	627.65	466603.72	481013.95	4544960.15
4-Sep-14	627.55	465150.58	479459.48	4500940.43
5-Sep-14	627.46	463660.69	477864.96	4455644.24
6-Sep-14	627.35	462125.48	476221.74	4409084.31
7-Sep-14	627.25	460175.12	474163.18	4362695.68
8-Sep-14	627.15	458011.01	471887.82	4315117.71
9-Sep-14	627.04	455636.19	469397.35	4266382.63
10-Sep-14	626.94	453169.13	466817.49	4219290.99
11-Sep-14	626.83	450599.35	464132.81	4171082.67
12-Sep-14	626.74	448401.27	461833.45	4128612.58
13-Sep-14	626.66	446614.74	459959.27	4091784.72
14-Sep-14	626.58	444932.15	458192.57	4056458.51
15-Sep-14	626.50	443274.93	456451.65	4021264.22
16-Sep-14	626.42	441519.40	454609.50	3984856.17
17-Sep-14	626.34	439785.15	452791.84	3949935.11
18-Sep-14	626.25	437918.78	450839.41	3913818.81
19-Sep-14	626.19	436343.11	449193.87	3884506.22
20-Sep-14	626.15	435449.12	448262.03	3868562.84
21-Sep-14	626.11	434465.23	447237.33	3851328.03
22-Sep-14	626.07	433535.97	446270.53	3835453.95
23-Sep-14	626.03	432503.34	445197.40	3818296.00
24-Sep-14	626.00	431555.80	444212.80	3802494.07
25-Sep-14	625.96	430688.55	443311.60	3788039.43
26-Sep-14	625.93	429681.82	442264.81	3770993.83
27-Sep-14	625.88	428616.89	441156.82	3752681.22
28-Sep-14	625.83	427377.29	439868.04	3731808.69
29-Sep-14	625.79	426268.67	438716.47	3713595.41
30-Sep-14	625.74	424898.03	437293.86	3691543.16

Table G.1. continued

Date	Lake Elevation (m a.s.l.)	2D Surface area (m^2)	3D Surface area (m^2)	Volume (m^3)
1-Oct-14	625.68	423448.04	435788.79	3668271.60
2-Oct-14	625.63	422082.45	434371.37	3646365.47
3-Oct-14	625.60	421104.57	433356.92	3630945.18
4-Oct-14	625.57	420256.13	432480.79	3619404.70
5-Oct-14	625.54	419458.05	431655.18	3607887.42
6-Oct-14	625.52	418787.45	430960.22	3597667.63
7-Oct-14	625.49	418045.46	430190.81	3586189.57
8-Oct-14	625.46	417322.30	429440.29	3574731.74
9-Oct-14	625.43	416528.34	428615.88	3562023.82
10-Oct-14	625.40	415719.87	427777.00	3549340.30
11-Oct-14	625.38	415077.38	427110.21	3539211.24
12-Oct-14	625.34	414189.87	426189.37	3525309.38
13-Oct-14	625.32	413536.18	425511.41	3515217.76
14-Oct-14	625.29	412898.06	424849.06	3505141.95
15-Oct-14	625.27	412277.18	424204.01	3495081.44
16-Oct-14	625.25	411817.26	423725.97	3487545.92
17-Oct-14	625.23	411281.78	423169.45	3478765.10
18-Oct-14	625.22	410977.32	422852.98	3473752.61
19-Oct-14	625.20	410600.35	422461.01	3467492.20
20-Oct-14	625.19	410226.02	422071.71	3461237.50
21-Oct-14	625.18	410151.12	421993.82	3459987.25
22-Oct-14	625.17	409701.99	421526.77	3452490.51
23-Oct-14	625.15	409251.40	421058.27	3445002.00
24-Oct-14	625.12	408645.63	420428.66	3435030.18
25-Oct-14	625.11	408185.63	419950.78	3427561.07
26-Oct-14	625.09	407798.18	419548.44	3421343.26
27-Oct-14	625.06	407092.04	418815.55	3410166.21
28-Oct-14	625.04	406614.37	418320.07	3402725.66
29-Oct-14	625.03	406290.75	417984.58	3397770.19
30-Oct-14	625.02	406044.39	417729.33	3394056.19
31-Oct-14	625.02	405878.07	417557.08	3391581.45
1-Nov-14	625.01	405627.09	417297.22	3387871.24
2-Nov-14	625.00	405459.53	417123.74	3385399.05
3-Nov-14	625.00	405459.53	417123.74	3385399.05
4-Nov-14	625.00	405375.54	417036.80	3384163.34
5-Nov-14	624.99	405207.14	416862.48	3381692.68
6-Nov-14	625.00	405375.54	417036.80	3384163.34
7-Nov-14	624.98	404783.63	416424.17	3375520.55
8-Nov-14	624.96	404356.51	415982.22	3369354.90

Table G.1. continued

Date	Lake Elevation (m a.s.l.)	2D Surface area (m^2)	3D Surface area (m^2)	Volume (m^3)
9-Nov-14	624.96	404183.53	415803.30	3366890.46
10-Nov-14	624.94	403749.00	415353.92	3360734.02
11-Nov-14	624.93	403399.71	414992.75	3355813.64
12-Nov-14	624.92	403047.44	414628.61	3350897.53
13-Nov-14	624.90	402603.95	414170.29	3344758.46
14-Nov-14	624.89	402425.69	413986.10	3342304.73
15-Nov-14	624.88	402067.33	413615.88	3337400.54
16-Nov-14	624.87	401706.29	413243.00	3332500.73
17-Nov-14	624.87	401614.97	413148.72	3331276.47
18-Nov-14	624.86	401523.12	413053.92	3330052.49
19-Nov-14	624.86	401337.11	412861.98	3327605.37
20-Nov-14	624.86	401242.53	412764.44	3326382.24
21-Nov-14	624.85	401147.88	412666.83	3325159.39
22-Nov-14	624.88	401887.19	413429.82	3334950.09
23-Nov-14	624.92	403135.84	414719.97	3352126.15
24-Nov-14	624.95	403922.95	415533.80	3363195.80
25-Nov-14	624.96	404270.31	415893.05	3368122.55
26-Nov-14	624.96	404270.31	415893.05	3368122.55
27-Nov-14	624.97	404527.85	416159.50	3371820.37
28-Nov-14	624.98	404868.61	416512.11	3376754.46
29-Nov-14	624.99	405038.16	416687.59	3379223.05
30-Nov-14	625.00	405459.53	417123.74	3385399.05
1-Dec-14	625.00	405543.34	417210.51	3386635.02
2-Dec-14	625.00	405291.38	416949.68	3382927.88
3-Dec-14	624.99	405038.16	416687.59	3379223.05
4-Dec-14	624.97	404698.53	416336.10	3374286.90
5-Dec-14	624.97	404527.85	416159.50	3371820.37
6-Dec-14	624.97	404613.30	416247.91	3373053.51
7-Dec-14	624.99	405038.16	416687.59	3379223.05
8-Dec-14	624.99	405207.14	416862.48	3381692.68
9-Dec-14	625.00	405375.54	417036.80	3384163.34
10-Dec-14	625.01	405794.47	417470.51	3390344.46
11-Dec-14	625.02	405878.07	417557.08	3391581.45
12-Dec-14	625.02	405878.07	417557.08	3391581.45
13-Dec-14	625.03	406126.87	417814.77	3395293.94
14-Dec-14	625.05	406694.68	418403.35	3403965.14
15-Dec-14	625.08	407546.71	419287.39	3417339.51
16-Dec-14	625.11	408382.11	420154.87	3430741.19
17-Dec-14	625.15	409201.26	421006.14	3444170.45

Table G.1. continued

Date	Lake Elevation (m a.s.l.)	2D Surface area (m^2)	3D Surface area (m^2)	Volume (m^3)
18-Dec-14	625.18	410009.58	421846.64	3457626.41
19-Dec-14	625.21	410817.64	422686.96	3471108.49
20-Dec-14	625.24	411638.52	423540.21	3484617.71
21-Dec-14	625.28	412465.46	424399.67	3498154.02
22-Dec-14	625.31	413310.55	425277.36	3511717.31
23-Dec-14	625.34	414189.87	426189.37	3525309.38
24-Dec-14	625.38	415059.54	427091.69	3538930.24
25-Dec-14	625.41	415927.51	427992.44	3552579.15
26-Dec-14	625.44	416795.43	428893.11	3566257.10
27-Dec-14	625.47	417648.72	429779.20	3579963.24
28-Dec-14	625.51	418533.14	430696.44	3593697.48
29-Dec-14	625.54	419429.83	431625.93	3607461.27
30-Dec-14	625.57	420402.02	432631.13	3621255.41
31-Dec-14	625.61	421370.82	433632.97	3635082.16
1-Jan-15	625.64	422244.48	434539.50	3648938.98
2-Jan-15	625.68	423209.13	435540.75	3664400.68
3-Jan-15	625.72	424490.99	436871.49	3685070.81
4-Jan-15	625.79	426268.67	438716.47	3713595.41
5-Jan-15	625.86	428149.67	440671.17	3744846.94
6-Jan-15	626.13	434997.30	447791.37	3860603.47
7-Jan-15	626.51	443593.66	456786.47	4028022.16
8-Jan-15	626.83	450523.49	464053.67	4169709.36
9-Jan-15	627.07	456260.36	470051.41	4278890.24
10-Jan-15	627.27	460495.09	474499.50	4369711.19
11-Jan-15	627.43	463336.15	477517.53	4445755.04
12-Jan-15	627.58	465524.66	479859.71	4512287.22
13-Jan-15	627.71	467499.13	481971.45	4572008.02
14-Jan-15	627.81	469205.64	483795.58	4623399.27
15-Jan-15	627.91	470733.48	485427.94	4669238.13
16-Jan-15	628.00	472175.17	486967.59	4712347.85
17-Jan-15	628.08	473431.95	488309.25	4749816.54
18-Jan-15	628.19	475183.33	490178.11	4801861.25
19-Jan-15	628.31	477046.15	492164.89	4857006.62
20-Jan-15	628.44	479121.93	494377.64	4918208.84
21-Jan-15	628.55	480965.28	496341.61	4972346.11
22-Jan-15	628.65	482620.96	498104.84	5020806.70
23-Jan-15	628.74	484135.62	499717.24	5065006.74
24-Jan-15	628.83	485557.47	501230.28	5106385.43
25-Jan-15	628.90	486731.31	502479.02	5140466.06

Table G.1. continued

Date	Lake Elevation (m a.s.l.)	2D Surface area (m^2)	3D Surface area (m^2)	Volume (m^3)
26-Jan-15	628.97	487910.46	503733.05	5174629.17
27-Jan-15	629.04	489146.56	505047.26	5210365.98
28-Jan-15	629.12	490440.31	506422.37	5247688.19
29-Jan-15	629.19	491636.11	507693.00	5282111.91
30-Jan-15	629.25	492784.89	508913.35	5315117.55
31-Jan-15	629.32	493886.00	510082.75	5346694.94
1-Feb-15	629.37	494833.33	511088.61	5373817.47
2-Feb-15	629.44	495942.66	512266.22	5405526.24
3-Feb-15	629.51	497215.90	513617.47	5441851.98
4-Feb-15	629.58	498388.13	514861.18	5475232.56
5-Feb-15	629.65	499672.46	516223.49	5511737.59
6-Feb-15	629.73	501124.26	517762.99	5552918.32
7-Feb-15	629.80	502312.63	519022.80	5586561.53
8-Feb-15	629.89	503995.39	520806.21	5634103.47
9-Feb-15	630.00	505852.12	522773.29	5686429.63
10-Feb-15	630.10	507665.34	524693.59	5737401.35
11-Feb-15	630.22	509822.36	526977.11	5797876.60
12-Feb-15	630.34	512106.47	529394.16	5861730.63
13-Feb-15	630.45	514182.25	531589.86	5919600.87
14-Feb-15	630.56	516045.22	533559.77	5971412.97
15-Feb-15	630.64	517691.42	535299.90	6017099.94
16-Feb-15	630.72	519174.51	536867.19	6058184.67
17-Feb-15	630.79	520492.13	538259.28	6094627.03
18-Feb-15	630.86	521757.45	539595.81	6129571.55
19-Feb-15	630.92	522854.13	540753.98	6159819.30
20-Feb-15	630.97	523896.44	541854.54	6188533.75
21-Feb-15	631.02	524825.67	542835.54	6214105.78
22-Feb-15	631.06	525640.86	543696.02	6236518.53
23-Feb-15	631.10	526282.75	544373.49	6254152.97
24-Feb-15	631.12	526691.86	544805.23	6265386.10
25-Feb-15	631.16	527394.33	545546.51	6284663.23
26-Feb-15	631.19	527980.83	546165.35	6300747.14
27-Feb-15	631.22	528568.33	546785.19	6316848.95
28-Feb-15	631.27	529510.43	547779.01	6342649.13
1-Mar-15	631.30	530277.78	548588.38	6363645.65
2-Mar-15	631.34	530869.20	549212.13	6379817.53
3-Mar-15	631.37	531580.24	549961.95	6399247.60
4-Mar-15	631.40	532173.87	550587.90	6415459.21
5-Mar-15	631.43	532649.51	551089.38	6428441.53

Table G.1. continued

Date	Lake Elevation (m a.s.l.)	2D Surface area (m^2)	3D Surface area (m^2)	Volume (m^3)
6-Mar-15	631.46	533364.16	551842.80	6447936.79
7-Mar-15	631.50	534080.26	552597.67	6467458.21
8-Mar-15	631.53	534737.96	553290.90	6485375.87
9-Mar-15	631.56	535336.92	553922.16	6501683.81
10-Mar-15	631.60	535996.94	554617.71	6519643.65
11-Mar-15	631.63	536598.01	555251.08	6535989.99
12-Mar-15	631.66	537200.09	555885.44	6552354.67
13-Mar-15	631.69	537803.17	556520.81	6568737.72
14-Mar-15	631.72	538467.72	557220.88	6586780.32
15-Mar-15	631.74	538770.20	557539.49	6594988.87
16-Mar-15	631.76	539133.49	557922.16	6604845.22
17-Mar-15	631.77	539497.15	558305.18	6614708.22
18-Mar-15	631.80	539982.59	558816.44	6627869.24
19-Mar-15	631.82	540407.88	559264.32	6639394.84
20-Mar-15	631.84	540711.96	559584.54	6647632.98
21-Mar-15	631.86	541138.09	560033.26	6659174.15
22-Mar-15	631.88	541625.71	560546.69	6672375.21
23-Mar-15	631.92	542358.33	561318.03	6692199.10
24-Mar-15	631.98	543643.91	562671.35	6726955.49
25-Mar-15	632.02	544380.51	563446.66	6746853.28
26-Mar-15	632.08	545611.40	564742.05	6780076.21
27-Mar-15	632.13	546660.82	565846.29	6808374.79
28-Mar-15	632.19	547837.14	567083.86	6840067.05
29-Mar-15	632.25	549141.50	568455.91	6875174.74
30-Mar-15	632.33	550762.56	570160.76	6918757.29
31-Mar-15	632.41	552390.42	571872.39	6962468.58
1-Apr-15	632.48	553899.09	573458.36	7002932.19
2-Apr-15	632.56	555476.77	575116.56	7045199.37
3-Apr-15	632.63	556997.26	576714.32	7085889.18
4-Apr-15	632.70	558459.83	578250.92	7124988.15
5-Apr-15	632.78	559991.65	579859.98	7165896.60
6-Apr-15	632.86	561786.10	581744.52	7213765.04
7-Apr-15	632.95	563588.42	583636.91	7261786.97
8-Apr-15	632.98	616806.39	636857.34	7280463.17
9-Apr-15	632.98	616806.39	636857.34	7280463.17
10-Apr-15	632.98	616806.39	636857.34	7282343.19
11-Apr-15	632.98	616806.39	636857.34	7282343.19
12-Apr-15	632.98	616806.39	636857.34	7282343.19
13-Apr-15	632.98	616806.39	636857.34	7282343.19

Table G.1. continued

Date	Lake Elevation (m a.s.l.)	2D Surface area (m^2)	3D Surface area (m^2)	Volume (m^3)
14-Apr-15	632.98	616806.39	636857.34	7282343.19
15-Apr-15	632.98	616806.39	636857.34	7280463.17
16-Apr-15	632.96	616806.39	636857.34	7268243.00
17-Apr-15	632.94	563394.94	583433.78	7256634.40
18-Apr-15	632.92	562976.04	582993.97	7245476.57
19-Apr-15	632.90	562557.56	582554.58	7234327.03
20-Apr-15	632.88	562139.50	582115.62	7223185.79
21-Apr-15	632.86	561721.87	581677.08	7212052.82
22-Apr-15	632.84	561304.67	581238.96	7200928.12
23-Apr-15	632.82	560887.89	580801.27	7189811.68
24-Apr-15	632.80	560471.53	580364.00	7178703.49
25-Apr-15	632.78	560055.60	579927.15	7167603.55
26-Apr-15	632.76	559640.10	579490.73	7156511.85
27-Apr-15	632.74	559225.01	579054.73	7145428.37
28-Apr-15	632.72	558810.36	578619.15	7134353.11
29-Apr-15	632.70	558396.12	578184.00	7123286.06
30-Apr-15	632.68	557982.32	577749.27	7112227.22
1-May-15	632.66	557568.93	577314.96	7101176.57
2-May-15	632.63	556997.26	576714.32	7085889.18
3-May-15	632.59	556172.94	575848.15	7063835.06
4-May-15	632.55	555350.32	574983.67	7041813.57
5-May-15	632.52	554718.70	574319.84	7024896.12
6-May-15	632.50	554277.16	573855.76	7013065.35
7-May-15	632.48	553899.09	573458.36	7002932.19
8-May-15	632.46	553458.46	572995.19	6991118.90
9-May-15	632.43	552767.04	572268.34	6972574.14
10-May-15	632.40	552139.54	571608.62	6955735.36
11-May-15	632.38	551700.88	571147.41	6943959.59
12-May-15	632.36	551325.28	570752.48	6933873.52
13-May-15	632.34	551012.56	570423.65	6925473.71
14-May-15	632.37	551638.25	571081.56	6942278.11
15-May-15	632.36	551325.28	570752.48	6933873.52
16-May-15	632.31	550325.45	569701.10	6907010.88
17-May-15	632.26	549265.95	568586.81	6878522.68
18-May-15	632.21	548271.43	567540.72	6851760.34
19-May-15	632.16	547155.67	566366.93	6821710.60
20-May-15	632.11	546290.11	565456.23	6798380.85
21-May-15	632.08	545611.40	564742.05	6780076.21
22-May-15	632.06	545180.13	564288.21	6768439.65

Table G.1. continued

Date	Lake Elevation (m a.s.l.)	2D Surface area (m^2)	3D Surface area (m^2)	Volume (m^3)
23-May-15	632.03	544564.89	563640.72	6751831.94
24-May-15	632.00	544073.42	563123.44	6738559.26
25-May-15	631.98	543582.59	562606.81	6725298.56
26-May-15	631.95	542969.96	561961.92	6708739.50
27-May-15	631.92	542358.33	561318.03	6692199.10
28-May-15	631.88	541625.71	560546.69	6672375.21
29-May-15	631.84	540894.53	559776.79	6652578.08
30-May-15	631.81	540164.80	559008.33	6632807.67
31-May-15	631.76	539254.67	558049.79	6608132.15
1-Jun-15	631.72	538346.81	557093.50	6583498.19
2-Jun-15	631.67	537380.91	556075.95	6557267.66
3-Jun-15	631.62	536417.58	555060.96	6531084.16
4-Jun-15	631.58	535696.78	554301.40	6511477.34
5-Jun-15	631.55	535157.13	553732.68	6496789.51
6-Jun-15	631.53	534678.12	553227.83	6483746.08
7-Jun-15	631.50	534140.00	552660.64	6469086.17
8-Jun-15	631.47	533543.05	552031.39	6452814.69
9-Jun-15	631.44	532887.56	551340.36	6434937.05
10-Jun-15	631.40	532173.87	550587.90	6415459.21
11-Jun-15	631.36	531402.34	549774.36	6394387.64
12-Jun-15	631.32	530632.51	548962.51	6373346.61
13-Jun-15	631.28	529864.38	548152.36	6352336.05
14-Jun-15	631.24	529097.95	547343.90	6331355.90
15-Jun-15	631.21	528391.98	546599.13	6312016.53
16-Jun-15	631.17	527687.45	545855.81	6292702.95
17-Jun-15	631.12	526691.86	544805.23	6265386.10
18-Jun-15	631.05	525407.75	543449.97	6230111.33
19-Jun-15	630.98	524070.48	542038.28	6193325.05
20-Jun-15	630.91	522738.52	540631.90	6156632.34
21-Jun-15	630.85	521527.03	539352.44	6123211.69
22-Jun-15	630.78	520262.60	538016.80	6088282.59
23-Jun-15	630.71	519003.04	536686.00	6053438.12
24-Jun-15	630.65	517748.34	535360.06	6018677.95
25-Jun-15	630.58	516441.81	533979.03	5982427.54
26-Jun-15	630.51	515197.06	532663.00	5947838.78
27-Jun-15	630.44	513957.18	531351.83	5913333.33
28-Jun-15	630.38	512722.16	530045.50	5878910.85
29-Jun-15	630.31	511492.00	528744.03	5844571.03
30-Jun-15	630.25	510433.51	527623.93	5814980.17

Table G.1. continued

Date	Lake Elevation (m a.s.l.)	2D Surface area (m^2)	3D Surface area (m^2)	Volume (m^3)
1-Jul-15	630.20	509544.96	526683.50	5790109.02
2-Jul-15	630.15	508658.99	525745.63	5765281.15
3-Jul-15	630.09	507610.24	524635.24	5735854.07
4-Jul-15	630.03	506510.21	523470.32	5704943.70
5-Jul-15	629.97	505359.50	522251.47	5672559.85
6-Jul-15	629.91	504267.71	521094.76	5641786.43
7-Jul-15	629.84	503071.39	519827.02	5608012.39
8-Jul-15	629.77	501771.86	518449.56	5571259.28
9-Jul-15	629.70	500531.90	517134.91	5536126.56
10-Jul-15	629.63	499243.71	515768.75	5499558.80
11-Jul-15	629.55	497907.99	514351.80	5461567.36
12-Jul-15	629.48	496684.68	513053.74	5426704.93
13-Jul-15	629.42	495572.39	511873.19	5394948.76
14-Jul-15	629.39	495149.83	511424.62	5382869.88
15-Jul-15	629.32	493938.54	510138.55	5348200.38
16-Jul-15	629.25	492680.26	508802.21	5312113.85
17-Jul-15	629.18	491584.01	507637.65	5280613.48
18-Jul-15	629.12	490492.19	506477.51	5249183.14
19-Jul-15	629.06	489404.80	505321.79	5217822.54
20-Jul-15	628.99	488321.85	504170.48	5186531.40
21-Jul-15	628.92	487140.85	502914.60	5152339.51
22-Jul-15	628.85	485914.16	501609.77	5116749.08
23-Jul-15	628.77	484642.52	500256.71	5079770.91
24-Jul-15	628.69	483225.74	498748.71	5038470.10
25-Jul-15	628.60	481816.84	497248.58	4997289.86
26-Jul-15	628.52	480415.82	495756.29	4956229.52
27-Jul-15	628.43	478973.07	494219.00	4913828.43
28-Jul-15	628.34	477588.09	492742.71	4873010.11
29-Jul-15	628.26	476210.99	491274.28	4832309.65
30-Jul-15	628.17	474890.53	489865.73	4793173.78
31-Jul-15	628.09	473528.91	488412.73	4752702.88
1-Aug-15	628.00	472175.17	486967.59	4712347.85
2-Aug-15	627.92	470829.31	485530.30	4672108.02
3-Aug-15	627.83	469443.69	484049.96	4630551.77
4-Aug-15	627.74	468066.52	482578.05	4589117.64
5-Aug-15	627.66	466791.92	481215.23	4550650.13
6-Aug-15	627.59	465665.10	480009.96	4516544.62
7-Aug-15	627.53	464730.51	479009.98	4488186.18
8-Aug-15	627.46	463799.93	478014.01	4459884.59

Table G.1. continued

Date	Lake Elevation (m a.s.l.)	2D Surface area (m^2)	3D Surface area (m^2)	Volume (m^3)
9-Aug-15	627.40	462827.15	476972.56	4430228.84
10-Aug-15	627.35	461977.06	476063.46	4404859.31
11-Aug-15	627.28	460814.50	474835.26	4376731.57
12-Aug-15	627.22	459550.90	473506.28	4348679.10
13-Aug-15	627.16	458273.74	472163.66	4320703.39
14-Aug-15	627.08	456458.70	470259.32	4282916.70
15-Aug-15	627.00	454549.37	468259.89	4245283.37
16-Aug-15	626.91	452568.30	466189.32	4207812.13
17-Aug-15	626.83	450567.42	464099.51	4170504.58
18-Aug-15	626.75	448634.40	462077.92	4133361.48
19-Aug-15	626.67	446836.16	460191.58	4096371.25
20-Aug-15	626.58	445076.69	458344.44	4059528.15
21-Aug-15	626.50	443348.83	456529.28	4022828.67
22-Aug-15	626.42	441589.16	454682.63	3986272.67
23-Aug-15	626.34	439781.62	452788.13	3949864.74
24-Aug-15	626.25	437907.65	450827.78	3913608.17
25-Aug-15	626.17	435952.58	448786.70	3877509.53
26-Aug-15	626.09	433897.99	446647.01	3841576.73
27-Aug-15	626.01	431755.86	444420.66	3805817.82
28-Aug-15	625.92	429637.35	442218.55	3770235.48
29-Aug-15	625.84	427557.93	440055.79	3734826.19
30-Aug-15	625.76	425404.96	437819.75	3699591.29
31-Aug-15	625.68	423217.53	435549.47	3664536.54
1-Sep-15	625.59	421020.06	433269.37	3629661.78
2-Sep-15	625.51	418623.99	430790.68	3595115.20
3-Sep-15	625.43	416368.21	428449.67	3559485.15
4-Sep-15	625.34	414108.89	426105.35	3524047.05
5-Sep-15	625.27	412354.11	424283.96	3496338.18
6-Sep-15	625.23	411358.22	423248.89	3480018.81
7-Sep-15	625.19	410375.69	422227.36	3463738.69
8-Sep-15	625.16	409551.93	421370.73	3449993.42
9-Sep-15	625.12	408645.63	420428.66	3435030.18
10-Sep-15	625.09	407720.21	419467.50	3420100.41
11-Sep-15	625.05	406774.85	418486.48	3405204.87
12-Sep-15	625.01	405794.47	417470.51	3390344.46
13-Sep-15	624.98	404783.63	416424.17	3375520.55
14-Sep-15	624.93	403487.30	415083.30	3357043.33
15-Sep-15	624.89	402336.41	413893.85	3341078.27
16-Sep-15	624.85	401147.88	412666.83	3325159.39

Table G.1. continued

Date	Lake Elevation (m a.s.l.)	2D Surface area (m^2)	3D Surface area (m^2)	Volume (m^3)
17-Sep-15	624.82	399965.30	411448.42	3310508.45
18-Sep-15	624.78	398750.68	410197.80	3295901.34
19-Sep-15	624.74	397460.10	408868.46	3280126.93
20-Sep-15	624.71	396491.34	407869.92	3268027.18
21-Sep-15	624.67	395386.05	406728.90	3253545.54
22-Sep-15	624.64	394522.30	405835.41	3241507.46
23-Sep-15	624.61	393515.58	404793.04	3227095.89
24-Sep-15	624.57	392620.75	403865.50	3213917.15
25-Sep-15	624.54	391744.53	402956.57	3200768.09
26-Sep-15	624.50	390883.52	402062.79	3187648.17
27-Sep-15	624.47	389955.06	401098.53	3173368.17
28-Sep-15	624.43	389017.91	400125.51	3159122.29
29-Sep-15	624.39	388075.63	399147.30	3144910.78
30-Sep-15	624.36	387288.22	398329.92	3133094.26
1-Oct-15	624.33	386424.53	397433.23	3120123.72
2-Oct-15	624.29	385472.50	396445.18	3106007.19
3-Oct-15	624.26	384593.97	395533.77	3093097.82
4-Oct-15	624.23	383799.13	394709.20	3081387.53
5-Oct-15	624.21	383174.39	394060.69	3072036.62
6-Oct-15	624.18	382556.40	393418.90	3062700.83
7-Oct-15	624.15	381705.77	392535.45	3049888.73
8-Oct-15	624.12	380925.33	391725.17	3038266.22
9-Oct-15	624.09	380148.49	390918.54	3026667.47
10-Oct-15	624.06	379374.64	390114.85	3015092.35
11-Oct-15	624.02	378457.70	389162.03	3001233.17
12-Oct-15	624.01	378155.53	388847.95	2996620.86
13-Oct-15	623.97	377254.89	387911.56	2982805.93
14-Oct-15	623.94	376506.35	387133.23	2971318.62
15-Oct-15	623.91	375685.48	386279.64	2958708.87
16-Oct-15	623.87	374857.21	385418.68	2946126.74
17-Oct-15	623.84	374022.63	384551.42	2933572.51
18-Oct-15	623.81	373324.15	383826.15	2923321.86
19-Oct-15	623.78	372444.67	382914.02	2910819.80
20-Oct-15	623.75	371660.60	382100.39	2899479.63
21-Oct-15	623.72	370785.59	381192.77	2887033.27
22-Oct-15	623.68	369993.79	380371.32	2875743.83
23-Oct-15	623.66	369448.08	379804.91	2867855.48
24-Oct-15	623.65	369219.17	379567.13	2864478.30
25-Oct-15	623.65	368995.24	379334.34	2861103.19

Table G.1. continued

Date	Lake Elevation (m a.s.l.)	2D Surface area (m^2)	3D Surface area (m^2)	Volume (m^3)
26-Oct-15	623.64	368921.50	379257.65	2859978.61
27-Oct-15	623.63	368701.69	379029.01	2856606.19
28-Oct-15	623.63	368556.14	378877.60	2854359.03
29-Oct-15	623.63	368556.14	378877.60	2854359.03
30-Oct-15	623.62	368483.61	378802.14	2853235.78
31-Oct-15	623.62	368411.15	378726.75	2852112.76
1-Nov-15	623.63	368556.14	378877.60	2854359.03
2-Nov-15	623.63	368556.14	378877.60	2854359.03
3-Nov-15	623.63	368556.14	378877.60	2854359.03
4-Nov-15	623.62	368483.61	378802.14	2853235.78
5-Nov-15	623.62	368483.61	378802.14	2853235.78
6-Nov-15	623.62	368483.61	378802.14	2853235.78
7-Nov-15	623.62	368483.61	378802.14	2853235.78
8-Nov-15	623.62	368411.15	378726.75	2852112.76
9-Nov-15	623.63	368556.14	378877.60	2854359.03
10-Nov-15	623.63	368628.74	378953.12	2855482.50
11-Nov-15	623.63	368701.69	379029.01	2856606.19
12-Nov-15	623.64	368847.95	379181.16	2858854.25
13-Nov-15	623.64	368774.76	379105.02	2857730.11
14-Nov-15	623.64	368774.76	379105.02	2857730.11
15-Nov-15	623.63	368628.74	378953.12	2855482.50
16-Nov-15	623.64	368847.95	379181.16	2858854.25
17-Nov-15	623.64	368774.76	379105.02	2857730.11
18-Nov-15	623.63	368628.74	378953.12	2855482.50
19-Nov-15	623.66	369294.68	379645.59	2865603.80
20-Nov-15	623.67	369602.82	379965.56	2870108.11
21-Nov-15	623.68	369758.36	380127.02	2872361.68
22-Nov-15	623.68	369758.36	380127.02	2872361.68
23-Nov-15	623.68	369915.03	380289.61	2874616.21
24-Nov-15	623.70	370466.84	380862.16	2882514.59
25-Nov-15	623.71	370546.20	380944.48	2883643.90
26-Nov-15	623.70	370387.61	380779.96	2881385.53
27-Nov-15	623.70	370387.61	380779.96	2881385.53
28-Nov-15	623.70	370387.61	380779.96	2881385.53
29-Nov-15	623.70	370308.49	380697.88	2880256.71
30-Nov-15	623.69	370229.90	380616.32	2879128.13
1-Dec-15	623.69	370151.51	380534.97	2877999.79
2-Dec-15	623.70	370308.49	380697.88	2880256.71
3-Dec-15	623.72	370865.37	381275.53	2888163.54

Table G.1. continued

Date	Lake Elevation (m a.s.l.)	2D Surface area (m^2)	3D Surface area (m^2)	Volume (m^3)
4-Dec-15	623.74	371342.10	381770.05	2894950.28
5-Dec-15	623.77	372209.60	382670.09	2907415.24
6-Dec-15	623.77	372131.32	382588.85	2906280.86
7-Dec-15	623.79	372843.77	383327.94	2916498.89
8-Dec-15	623.86	374402.59	384946.24	2939275.51
9-Dec-15	623.87	374781.45	385339.95	2944984.29
10-Dec-15	623.92	376058.67	386667.69	2964437.16
11-Dec-15	623.97	377179.88	387833.57	2981656.17
12-Dec-15	624.01	378230.98	388926.38	2997773.59
13-Dec-15	624.05	379144.13	389875.35	3011624.40
14-Dec-15	624.08	379993.33	390757.41	3024350.55
15-Dec-15	624.11	380769.42	391563.30	3035944.57
16-Dec-15	624.14	381550.24	392373.95	3047562.33
17-Dec-15	624.18	382633.71	393499.18	3063866.98
18-Dec-15	624.23	383878.12	394791.15	3082557.47
19-Dec-15	624.31	385872.71	396860.38	3111884.84
20-Dec-15	624.38	387759.08	398818.76	3140181.29
21-Dec-15	624.44	389174.50	400288.09	3161494.22
22-Dec-15	624.48	390342.89	401501.29	3179314.04
23-Dec-15	624.53	391429.13	402629.27	3195993.87
24-Dec-15	624.55	392141.26	403368.17	3206741.30
25-Dec-15	624.58	392944.21	404200.86	3218705.96
26-Dec-15	624.61	393597.95	404878.39	3228295.46
27-Dec-15	624.64	394353.56	405660.73	3239102.97
28-Dec-15	624.66	395121.25	406455.16	3249931.35
29-Dec-15	624.69	395837.72	407195.46	3259574.66
30-Dec-15	624.71	396396.97	407772.57	3266818.81
31-Dec-15	624.71	396586.77	407968.32	3269235.83

Table G.2. Anoxic (<1 mg/L dissolved oxygen) elevation and associated surface areas and volumes.

Date	Lake Elevation (m a.s.l.)	2D Surface area (m^2)	3D Surface area (m^2)	Volume (m^3)
1-Jul-14	606.37	0.00	0.00	0.00
2-Jul-14	607.05	2654.59	2673.50	309.21
3-Jul-14	607.72	9088.05	9165.92	4335.61
4-Jul-14	608.40	22884.03	23082.96	14132.88
5-Jul-14	609.07	43341.73	43731.27	35823.34
6-Jul-14	609.75	61903.11	62577.10	72514.07
7-Jul-14	610.42	73686.20	74652.84	118105.47
8-Jul-14	611.09	84993.20	86261.22	171072.46
9-Jul-14	611.76	94887.36	96466.35	231140.54
10-Jul-14	612.42	106383.66	108279.18	297418.53
11-Jul-14	613.08	118980.11	121219.79	371835.08
12-Jul-14	613.74	128745.40	131351.84	453683.04
13-Jul-14	614.40	139980.85	142972.10	542689.97
14-Jul-14	615.06	152855.55	156254.69	639477.43
15-Jul-14	615.72	166628.09	170464.04	744724.34
16-Jul-14	615.88	170450.25	174393.37	771773.06
17-Jul-14	616.03	174352.56	178389.76	796274.98
18-Jul-14	616.16	178003.35	182128.69	820262.31
19-Jul-14	616.30	181210.95	185426.61	845252.84
20-Jul-14	616.44	184409.84	188716.84	870687.19
21-Jul-14	616.58	187662.72	192064.39	897137.94
22-Jul-14	616.73	190895.25	195394.27	924626.81
23-Jul-14	616.88	194377.32	198976.60	953188.20
24-Jul-14	617.02	198021.69	202721.31	981680.72
25-Jul-14	617.17	201660.97	206465.82	1011317.67
26-Jul-14	617.32	204941.85	209849.73	1040842.87
27-Jul-14	617.46	208120.28	213130.87	1070838.70
28-Jul-14	617.61	211317.00	216431.81	1101934.53
29-Jul-14	617.75	214421.62	219635.72	1132198.56
30-Jul-14	618.04	221078.14	226492.63	1194929.49
31-Jul-14	618.32	227911.79	233528.82	1258253.86
1-Aug-14	618.60	233830.67	239655.17	1323362.81
2-Aug-14	618.89	240371.22	246415.15	1390908.57
3-Aug-14	619.17	248974.15	255245.29	1460567.78
4-Aug-14	619.46	258347.16	264857.24	1532928.96
5-Aug-14	619.75	267665.99	274427.06	1608691.94

Table G.2 continued

Date	Lake Elevation (m a.s.l.)	2D Surface area (m^2)	3D Surface area (m^2)	Volume (m^3)
6-Aug-14	620.04	276790.42	283810.17	1688759.23
7-Aug-14	620.34	286480.41	293775.75	1774187.50
8-Aug-14	620.65	296515.68	304090.68	1862651.64
9-Aug-14	620.95	305248.03	313099.49	1953952.34
10-Aug-14	621.26	312922.61	321053.73	2049607.65
11-Aug-14	621.58	319706.30	328128.40	2151334.87
12-Aug-14	621.90	326534.41	335250.18	2254273.87
13-Aug-14	621.82	324917.79	333563.01	2229423.54
14-Aug-14	621.74	323083.90	331649.85	2201741.81
15-Aug-14	621.66	321379.81	329872.68	2176175.80
16-Aug-14	621.57	319471.55	327883.64	2147823.22
17-Aug-14	621.48	317593.11	325924.76	2119637.86
18-Aug-14	621.39	315657.61	323906.28	2090656.65
19-Aug-14	621.29	313621.51	321782.35	2059939.15
20-Aug-14	621.19	311431.30	319504.25	2029424.66
21-Aug-14	621.09	308704.11	316679.34	1996001.30
22-Aug-14	620.98	305979.72	313857.62	1962874.80
23-Aug-14	620.87	303124.58	310904.81	1930044.17
24-Aug-14	620.76	300027.37	307709.55	1897536.27
25-Aug-14	620.66	296805.39	304388.83	1865367.87
26-Aug-14	620.55	293523.99	301007.21	1833554.91
27-Aug-14	620.41	288783.10	296141.01	1793840.32
28-Aug-14	620.28	284360.44	291593.40	1754770.97
29-Aug-14	620.14	279916.79	287025.00	1716299.67
30-Aug-14	620.00	275582.16	282568.71	1678423.77
31-Aug-14	619.87	271322.22	278188.36	1641139.02
1-Sep-14	619.73	267176.45	273923.65	1604423.89
2-Sep-14	619.59	262598.41	269224.76	1567758.22
3-Sep-14	619.45	258012.81	264513.54	1530152.49
4-Sep-14	619.30	253547.53	259926.42	1493193.98
5-Sep-14	619.16	248329.02	254585.62	1456156.52
6-Sep-14	619.00	243499.13	249635.16	1419139.85
7-Sep-14	618.85	239521.33	245538.82	1382781.38
8-Sep-14	618.70	235883.03	241781.81	1346268.35
9-Sep-14	618.54	232593.13	238373.71	1309569.37
10-Sep-14	618.55	232652.05	238434.70	1310220.02
11-Sep-14	618.55	232646.73	238429.19	1310161.39

Table G.2 continued

Date	Lake Elevation (m a.s.l.)	2D Surface area (m^2)	3D Surface area (m^2)	Volume (m^3)
12-Sep-14	618.56	232899.26	238690.54	1312940.94
13-Sep-14	618.58	233403.63	239212.80	1318567.35
14-Sep-14	618.61	233968.50	239798.00	1324919.18
15-Sep-14	618.64	234528.89	240378.92	1331286.05
16-Sep-14	618.66	235030.74	240899.13	1336951.99
17-Sep-14	618.69	235609.74	241498.99	1343348.17
18-Sep-14	618.71	236144.99	242052.83	1349040.33
19-Sep-14	618.75	237042.56	242980.73	1358355.63
20-Sep-14	618.82	238718.84	244710.95	1374971.27
21-Sep-14	618.89	240378.08	246422.22	1390973.95
22-Sep-14	618.96	242174.95	248273.91	1407826.69
23-Sep-14	619.02	244094.70	250246.79	1424068.44
24-Sep-14	618.92	241114.92	247182.06	1398043.92
25-Sep-14	618.81	238519.64	244505.52	1373045.37
26-Sep-14	618.70	235939.89	241840.64	1346872.52
27-Sep-14	618.59	233554.51	239369.07	1320257.04
28-Sep-14	618.47	231069.66	236795.87	1292500.40
29-Sep-14	618.36	228684.98	234328.23	1266434.05
30-Sep-14	618.23	225958.91	231513.20	1238577.92
1-Oct-14	618.11	222796.34	228259.84	1210400.56
2-Oct-14	617.99	219850.30	225227.86	1183284.70
3-Oct-14	617.88	217388.96	222691.87	1159828.51
4-Oct-14	617.78	215102.56	220337.46	1138605.08
5-Oct-14	617.68	212909.53	218076.05	1117602.11
6-Oct-14	617.59	210857.08	215956.99	1097452.51
7-Oct-14	617.49	208739.70	213770.62	1076861.69
8-Oct-14	617.40	206915.06	211886.37	1059284.42
9-Oct-14	617.32	204985.37	209894.62	1041238.04
10-Oct-14	617.23	203003.96	207851.09	1023363.35
11-Oct-14	617.15	201159.75	205948.94	1006888.05
12-Oct-14	617.06	198901.35	203625.93	988748.39
13-Oct-14	616.98	196894.66	201562.16	972614.71
14-Oct-14	616.89	194804.51	199415.87	956649.37
15-Oct-14	616.81	192847.55	197403.37	940847.46
16-Oct-14	616.74	191107.62	195612.77	926366.06
17-Oct-14	616.66	189348.55	193800.96	911437.81

Table G.2 continued

Date	Lake Elevation (m a.s.l.)	2D Surface area (m^2)	3D Surface area (m^2)	Volume (m^3)
18-Oct-14	616.59	187813.54	192219.57	898362.36
19-Oct-14	616.52	186156.80	190514.52	884828.06
20-Oct-14	616.44	184501.44	188811.05	871413.21
21-Oct-14	616.38	183110.65	187380.59	860349.90
22-Oct-14	616.14	177575.72	181689.66	817114.17
23-Oct-14	615.90	170971.36	174928.42	775330.98
24-Oct-14	615.66	165051.71	168844.37	734028.07
25-Oct-14	615.42	159596.58	163230.48	695120.19
26-Oct-14	615.18	155059.13	158537.45	657892.63
27-Oct-14	614.93	150437.67	153754.04	619878.18
28-Oct-14	614.69	145874.22	149042.03	584362.07
29-Oct-14	614.46	141152.12	144178.39	550831.26
30-Oct-14	614.23	136720.46	139607.61	518810.02
31-Oct-14	614.00	132938.00	135692.74	488138.90
1-Nov-14	613.77	129257.37	131882.22	457913.42
2-Nov-14	613.54	125843.67	128341.22	428893.02
3-Nov-14	613.32	122699.00	125073.92	401379.55
4-Nov-14	613.10	119330.29	121581.07	374201.97
5-Nov-14	612.88	115591.87	117724.47	348882.16
6-Nov-14	612.68	111051.47	113075.31	325839.15
7-Nov-14	612.45	106941.75	108852.16	300704.10
8-Nov-14	612.22	102552.55	104353.08	277165.93
9-Nov-14	612.01	98879.51	100575.92	255463.64
10-Nov-14	611.78	95275.45	96866.71	233660.46
11-Nov-14	611.56	92204.68	93692.09	212891.39
12-Nov-14	611.34	88979.36	90362.61	192818.36
13-Nov-14	611.12	85402.79	86682.44	173223.76
14-Nov-14	610.90	81678.59	82857.78	155209.56
15-Nov-14	610.68	77337.82	78415.67	137579.44
16-Nov-14	610.46	74237.48	75219.89	120782.07
17-Nov-14	610.25	70949.32	71839.69	105357.93
18-Nov-14	610.03	67317.99	68115.83	90661.72
19-Nov-14	609.82	63153.15	63856.64	76604.42
20-Nov-14	609.60	59063.55	59672.35	63622.69
21-Nov-14	609.39	53834.57	54352.70	51612.39
22-Nov-14	609.21	49169.70	49613.94	42065.96
23-Nov-14	609.04	41896.85	42273.69	34440.18

Table G.2 continued

Date	Lake Elevation (m a.s.l.)	2D Surface area (m^2)	3D Surface area (m^2)	Volume (m^3)
24-Nov-14	608.86	35177.29	35488.85	27471.09
25-Nov-14	608.66	29676.17	29935.54	21105.01
26-Nov-14	608.45	24369.88	24580.76	15424.97
27-Nov-14	608.25	18545.28	18711.03	11109.11
28-Nov-14	608.05	13611.89	13737.78	8038.73
29-Nov-14	607.85	10612.08	10707.50	5580.66
30-Nov-14	607.66	8368.07	8437.80	3745.89
1-Dec-14	607.45	6465.72	6514.68	2220.73
2-Dec-14	607.23	4654.93	4685.93	1003.08
3-Dec-14	607.01	2212.55	2228.99	230.74
4-Dec-14	606.79	180.32	184.03	40.09
5-Dec-14	606.58	98.40	99.13	10.17
6-Dec-14	606.37	0.00	0.00	0.00
2-Jun-15	606.37	0.00	0.00	0.00
3-Jun-15	607.08	3089.42	3110.65	402.72
4-Jun-15	607.80	9958.27	10046.23	5040.65
5-Jun-15	608.53	26408.19	26636.50	17360.34
6-Jun-15	609.26	50668.13	51133.87	44736.38
7-Jun-15	609.99	66487.86	67267.28	87822.82
8-Jun-15	610.72	78028.73	79123.11	140495.37
9-Jun-15	611.44	90413.36	91843.03	201719.70
10-Jun-15	612.16	101451.19	103220.68	270664.98
11-Jun-15	612.88	115492.07	117621.94	348292.78
12-Jun-15	613.60	126614.96	129140.82	435309.45
13-Jun-15	614.31	138214.94	141151.56	530157.63
14-Jun-15	615.03	152229.41	155606.82	634403.38
15-Jun-15	615.75	167285.67	171139.53	749169.77
16-Jun-15	616.47	185099.93	189426.85	876233.02
17-Jun-15	616.70	190204.86	194683.25	918788.99
18-Jun-15	616.91	195166.97	199788.39	959538.08
19-Jun-15	617.12	200450.91	205218.36	1000774.82
20-Jun-15	617.33	205184.11	210099.63	1043058.37
21-Jun-15	617.54	209845.15	214912.07	1087586.01
22-Jun-15	617.75	214448.61	219663.55	1132455.24
23-Jun-15	617.96	219332.83	224694.71	1178331.81
24-Jun-15	618.18	224469.11	229980.54	1225255.33

Table G.2 continued

Date	Lake Elevation (m a.s.l.)	2D Surface area (m^2)	3D Surface area (m^2)	Volume (m^3)
25-Jun-15	618.38	229260.80	234923.65	1272568.02
26-Jun-15	618.59	233667.65	239486.26	1321526.71
27-Jun-15	618.81	238352.62	244333.28	1371430.44
28-Jun-15	619.02	243894.34	250041.04	1422411.47
29-Jun-15	619.23	251153.55	257471.84	1474724.98
30-Jun-15	619.45	258106.32	264609.66	1530924.61
1-Jul-15	619.53	260588.16	267160.70	1551621.14
2-Jul-15	619.61	263214.08	269856.31	1572519.71
3-Jul-15	619.68	265626.66	272330.76	1591204.32
4-Jul-15	619.75	267728.08	274490.91	1609235.36
5-Jul-15	619.81	269682.56	276501.50	1626583.98
6-Jul-15	619.88	271739.78	278618.07	1644887.51
7-Jul-15	619.94	273642.39	280575.01	1661661.86
8-Jul-15	620.00	275400.42	282381.99	1676875.23
9-Jul-15	620.06	277282.55	284316.00	1693032.53
10-Jul-15	620.11	279037.37	286120.30	1708448.06
11-Jul-15	620.16	280688.61	287818.86	1723104.84
12-Jul-15	620.22	282614.02	289797.59	1739571.54
13-Jul-15	620.29	284708.47	291951.48	1757886.35
14-Jul-15	620.39	288024.34	295362.82	1787719.28
15-Jul-15	620.41	288541.61	295893.38	1791902.53
16-Jul-15	620.42	288951.49	296313.75	1795212.73
17-Jul-15	620.44	289698.06	297079.18	1801174.75
18-Jul-15	620.46	290474.08	297874.06	1807152.93
19-Jul-15	620.48	291226.82	298645.66	1813146.52
20-Jul-15	620.50	291972.73	299410.46	1819155.60
21-Jul-15	620.51	292490.18	299941.28	1823396.55
22-Jul-15	620.53	292852.67	300314.35	1826751.49
23-Jul-15	620.53	293095.19	300564.67	1829216.87
24-Jul-15	620.53	293074.35	300543.16	1829003.50
25-Jul-15	620.53	293053.52	300521.65	1828789.86
26-Jul-15	620.53	293032.74	300500.20	1828576.52
27-Jul-15	620.53	292924.80	300388.75	1827469.94
28-Jul-15	620.51	292327.59	299774.30	1822004.39
29-Jul-15	620.49	291653.25	299082.79	1816550.59
30-Jul-15	620.47	291083.45	298498.68	1811996.75
31-Jul-15	620.46	290399.92	297798.05	1806566.53

Table G.2 continued

Date	Lake Elevation (m a.s.l.)	2D Surface area (m^2)	3D Surface area (m^2)	Volume (m^3)
1-Aug-15	620.44	289694.64	297075.68	1801148.96
2-Aug-15	620.42	289016.88	296380.82	1795744.75
3-Aug-15	620.40	288237.45	295581.51	1789474.28
4-Aug-15	620.38	287500.73	294824.91	1783220.12
5-Aug-15	620.36	286988.87	294298.73	1778730.80
6-Aug-15	620.35	286780.01	294083.93	1776870.35
7-Aug-15	620.36	286963.80	294272.94	1778507.24
8-Aug-15	620.36	287148.21	294462.59	1780145.47
9-Aug-15	620.37	287234.72	294551.53	1780909.11
10-Aug-15	620.38	287625.93	294953.55	1784301.36
11-Aug-15	620.38	287817.42	295150.26	1785943.38
12-Aug-15	620.33	286078.22	293361.77	1770501.37
13-Aug-15	620.28	284403.17	291637.35	1755150.34
14-Aug-15	620.20	281922.64	289087.42	1733778.03
15-Aug-15	620.13	279501.28	286597.52	1712592.41
16-Aug-15	620.05	277116.57	284145.39	1691586.93
17-Aug-15	619.97	274686.65	281648.58	1670763.51
18-Aug-15	619.90	272328.87	279224.15	1650121.16
19-Aug-15	619.82	270029.18	276858.08	1629654.13
20-Aug-15	619.75	267742.33	274505.57	1609360.13
21-Aug-15	619.67	265384.66	272082.31	1589240.63
22-Aug-15	619.60	262798.55	269430.08	1569308.14
23-Aug-15	619.52	260342.01	266907.73	1549568.41
24-Aug-15	619.45	257995.31	264495.55	1530008.01
25-Aug-15	619.37	255680.69	262116.51	1510623.71
26-Aug-15	619.28	252875.69	259236.97	1487799.04
27-Aug-15	619.19	249682.24	255968.92	1465237.39
28-Aug-15	619.10	246474.95	252688.45	1442973.53
29-Aug-15	619.01	243720.81	249862.83	1420975.45
30-Aug-15	618.92	241238.37	247309.30	1399213.39
31-Aug-15	618.83	238994.38	244995.22	1377661.27
1-Sep-15	618.74	236843.10	242774.61	1356307.02
2-Sep-15	618.65	234876.48	240739.23	1335213.57
3-Sep-15	618.56	232956.55	238749.85	1313579.16
4-Sep-15	618.47	231036.00	236761.01	1292122.86
5-Sep-15	618.39	229490.03	235160.73	1275037.48

Table G.2 continued

Date	Lake Elevation (m a.s.l.)	2D Surface area (m^2)	3D Surface area (m^2)	Volume (m^3)
6-Sep-15	618.35	228487.49	234123.99	1264328.32
7-Sep-15	618.30	227469.37	233071.75	1253666.33
8-Sep-15	618.26	226553.94	232126.91	1244433.46
9-Sep-15	618.24	225978.59	231533.49	1238768.18
10-Sep-15	618.21	225381.85	230918.61	1233117.77
11-Sep-15	618.18	224743.50	230262.11	1227482.54
12-Sep-15	618.16	224077.58	229578.05	1221864.17
13-Sep-15	618.13	223434.68	228917.04	1216261.83
14-Sep-15	618.10	222592.86	228050.75	1208638.84
15-Sep-15	618.07	221909.49	227347.60	1202396.96
16-Sep-15	618.04	221206.45	226624.89	1196174.52
17-Sep-15	618.02	220631.38	226032.28	1190643.10
18-Sep-15	617.99	220044.12	225427.51	1185126.54
19-Sep-15	617.97	219398.41	224762.26	1178955.47
20-Sep-15	617.95	218965.92	224316.61	1174803.96
21-Sep-15	617.92	218397.96	223731.21	1169328.57
22-Sep-15	617.90	217964.27	223284.32	1165195.77
23-Sep-15	617.88	217380.08	222682.73	1159745.90
24-Sep-15	617.86	216867.63	222155.04	1154971.35
25-Sep-15	617.83	216352.24	221624.39	1150208.31
26-Sep-15	617.81	215838.56	221095.47	1145456.39
27-Sep-15	617.79	215258.74	220498.33	1140059.70
28-Sep-15	617.76	214683.05	219905.21	1134677.28
`29-Sep-15	617.74	214119.84	219324.54	1129309.34
30-Sep-15	617.72	213701.39	218892.90	1125257.45
1-Oct-15	617.70	213215.89	218392.09	1120563.67
2-Oct-15	617.67	212664.86	217823.60	1115232.07
3-Oct-15	617.65	212186.87	217330.25	1110561.07
4-Oct-15	617.63	211780.96	216911.06	1106545.67
5-Oct-15	617.61	211261.31	216374.31	1101387.93
6-Oct-15	617.64	212054.43	217193.50	1109251.86
7-Oct-15	617.67	212661.49	217820.13	1115200.18
8-Oct-15	617.70	213349.72	218530.00	1121815.64
9-Oct-15	617.73	214031.10	219233.02	1128452.61
10-Oct-15	617.76	214728.94	219952.51	1135110.77
11-Oct-15	617.79	215303.68	220544.61	1140478.20

Table G.2 continued

Date	Lake Elevation (m a.s.l.)	2D Surface area (m^2)	3D Surface area (m^2)	Volume (m^3)
12-Oct-15	617.84	216452.44	221727.55	1151130.83
13-Oct-15	617.86	217036.46	222328.88	1156541.43
14-Oct-15	617.89	217760.91	223074.88	1163293.39
15-Oct-15	617.92	218405.67	223739.15	1169402.17
16-Oct-15	617.95	219040.30	224393.30	1175528.64
17-Oct-15	617.98	219682.26	225054.72	1181673.16
18-Oct-15	618.01	220473.17	225869.42	1189179.08
19-Oct-15	617.69	213139.89	218313.70	1119830.98
20-Oct-15	617.38	206291.89	211242.93	1053383.82
21-Oct-15	617.06	198875.96	203599.83	988547.71
22-Oct-15	616.74	191158.72	195665.32	926778.72
23-Oct-15	616.43	184199.06	188500.08	869023.85
24-Oct-15	616.14	177364.61	181473.02	815594.84
25-Oct-15	615.84	169445.63	173359.94	764378.99
26-Oct-15	615.55	162592.84	166313.54	716344.27
27-Oct-15	615.26	156443.07	159969.30	669251.12
28-Oct-15	614.96	150977.28	154312.07	624297.96
29-Oct-15	614.68	145526.76	148684.03	581838.55
30-Oct-15	614.39	139675.02	142657.10	540565.15
31-Oct-15	614.10	134496.96	137306.51	500918.99
1-Nov-15	613.82	130008.85	132659.37	463861.15
2-Nov-15	613.53	125652.46	128142.82	427263.32
3-Nov-15	613.25	121591.31	123923.15	391864.74
4-Nov-15	612.96	116910.64	119082.58	357331.47
5-Nov-15	612.67	110834.87	112853.35	324687.90
6-Nov-15	612.38	105726.37	107604.84	293686.12
7-Nov-15	612.10	100361.84	102100.34	264209.53
8-Nov-15	611.81	95628.40	97230.33	235858.61
9-Nov-15	611.53	91658.29	93128.75	209615.04

Appendix H

Total and dissolved phosphorus concentrations of sediment cores during anoxic trials from Willow Creek Reservoir, OR

Samples analyzed for total (TP) and dissolved (DP) phosphorus concentrations (µg/L) ± SE measured from sediment cores collected at Willow Creek Reservoir, Heppner, OR. Site names are Main Site (MS), Willow Creek (WC), Balm Fork (BF), Upper Balm Fork (UBF), Weather Buoy (BY), and Upper Willow Creek (UWC). Samples were analyzed using an AquaMate VIS spectrophotometer (ThermoFisher Scientific, Watham, MA) within 48 h using a modified ascorbic acid method in Standard Method 4500-P (Eaton et al. 2005).

References

Eaton AD, Clesceri LS, Rice EW, Franson MA. 2005. Standard methods for the examination of water and wastewater. 21st Ed. American Public Health Association, American Water Works Association, Water Environment Federation.

Table H.1. Total phosphorus (TP) concentration of each sediment core during anoxic trials. Cores analyzed during Trial 1 are designated with an "a" while Cores analyzed during Trial 2 are designated with an "b". Site names are Main Site (MS), Willow Creek (WC), Balm Fork (BF), Upper Balm Fork (UBF), Weather Buoy (BY), and Upper Willow Creek (UWC).

Days sampled		Total phosphorus concentration (µg/L)							
Trial 1	Trial 2	MS.1[a]	MS.3[a]	MS.4[b]	MS.5[b]	MS.6[b]	WC.1[a]	WC.2[a]	WC.3[a]
0	0	122.08	112.50	212.41	151.91	187.66	99.72	138.05	166.79
1	1	150.85	160.43	228.86	209.61	245.36	128.49	125.30	109.33
2	2	198.76	198.76	264.61	261.86	261.86	138.08	118.92	112.54
3	3	259.30	233.75	259.09	338.84	311.34	182.65	160.30	147.52
4	4	367.87	313.58	286.59	407.59	402.09	230.55	198.61	201.80
5	5	443.04	368.79	363.59	525.84	525.84	313.11	248.14	254.33
6	6	588.53	508.09	404.85	531.35	591.85	399.81	331.74	331.74
7	7	659.66	610.16	486.64	630.64	702.64	458.56	402.88	371.94
8	8	723.66	669.66	510.62	660.62	741.62	591.66	450.66	411.66
10	10	795.59	771.59	597.64	731.42	936.03	798.59	465.59	483.59
12	11	921.71	927.71	579.58	711.58	909.58	990.71	669.71	657.71
14	13	1002.67	978.67	672.61	1020.61	1071.61	1116.67	744.67	672.67
16	15	1147.14	1044.94	754.78	891.63	1118.75	1223.78	846.94	821.40
18	17	1167.00	1135.07	835.29	1060.13	1149.13	1380.97	924.29	927.49
20	19	1272.47	1359.91	926.58	1112.94	1261.44	1442.76	991.90	974.72
22	21	1284.46	1355.85	935.28	1153.66	1258.48	1448.59	1001.57	974.98
24	23	1326.92	1398.31	923.61	1206.05	1366.20	1527.83	1027.06	1054.21
26	25	1372.21	1344.60	1033.06	1347.03	1550.69	1564.63	1094.98	1079.70
28	27	1492.45	1500.92	1027.38	1372.47	1593.10	1621.27	1175.35	1186.14
30	29	1567.44	1542.92	1144.51	1405.32	1600.49	1655.76	1220.35	1235.63
31	31	1642.43	1584.91	1237.85	1433.61	1617.46	1690.26	1265.34	1285.12
33	33	1678.40	1644.88	1404.76	1552.43	1674.06	1756.22	1307.31	1282.09
35	35	1710.32	1670.42	1336.90	1614.69	1750.46	1906.64	1341.67	1384.14

Table H.1. continued

Days sampled		Total phosphorus concentration (μg/L)						
Trial 1	Trial 2	BY.1[a]	BY.2[a]	BY.3[a]	BY.4[a]	BF.1[a]	BF.2[a]	BF.3[a]
0	0	125.27	99.72	147.63	137.73	112.42	115.60	122.08
1	1	144.46	157.23	176.39	201.94	128.49	115.72	134.88
2	2	189.18	189.18	211.54	243.47	150.86	115.73	144.47
3	3	265.68	246.52	272.07	332.75	185.85	125.17	160.30
4	4	316.77	332.74	374.26	463.68	179.45	125.16	176.26
5	5	430.67	439.95	467.79	569.89	201.73	149.14	192.45
6	6	508.09	542.12	563.78	715.37	192.53	161.59	189.43
7	7	585.41	662.75	702.97	832.91	201.78	177.03	201.78
8	8	597.66	762.66	828.66	915.66	234.66	180.66	198.66
10	10	729.59	972.59	1065.59	1113.59	255.59	237.59	252.59
12	11	846.71	1200.71	1368.71	1371.71	351.71	279.71	291.71
14	13	924.67	1380.67	1551.67	1512.67	429.67	333.67	333.67
16	15	1009.82	1613.40	1757.11	1629.36	543.56	383.88	387.07
18	17	1208.52	1780.17	1997.33	1770.58	643.26	451.65	448.46
20	19	1223.72	1687.63	2172.67	1852.75	769.11	536.73	484.04
22	21	1220.07	1840.97	2002.64	1896.86	799.82	569.44	584.46
24	23	1245.56	1979.60	2302.50	2058.12	955.42	628.87	669.35
26	25	1225.79	2022.06	2285.56	2052.49	1068.60	674.16	711.81
28	27	1361.29	2114.70	2423.71	2191.67	1185.23	776.74	856.22
30	29	1418.28	2204.69	2540.70	2304.17	1278.23	961.23	937.22
31	31	1475.27	2294.68	2657.70	2416.66	1371.22	1145.73	1018.21
33	33	1544.24	2411.65	2702.67	2434.63	1578.19	944.69	1060.18
35	35	1634.01	2444.32	2850.46	2566.11	1687.64	1017.40	1250.72

Table H.1. continued

Days sampled		Total phosphorus concentration (μg/L)						
Trial 1	Trial 2	UBF.1[b]	UBF.2[b]	UBF.3[b]	UWC.1[b]	UWC.2[b]	UWC.3[b]	UWC.4[b]
0	0	91.41	99.66	91.41	94.16	88.66	97.46	72.15
1	1	151.86	121.61	127.11	132.61	118.86	107.86	77.61
2	2	118.86	140.86	140.86	118.86	127.11	124.36	85.86
3	3	105.09	121.59	110.59	110.59	132.59	146.34	74.84
4	4	127.09	165.59	151.84	113.34	146.34	143.59	83.09
5	5	140.84	195.84	168.34	140.84	154.59	162.84	99.59
6	6	151.85	209.60	179.35	140.85	162.85	173.85	99.60
7	7	180.64	255.64	183.64	168.64	177.64	186.64	99.64
8	8	198.62	240.62	189.62	177.62	213.62	207.62	120.62
10	10	300.64	213.03	201.03	273.03	213.03	303.03	159.64
12	11	309.58	201.58	192.58	297.58	210.58	309.58	192.58
14	13	384.61	279.61	237.61	306.61	189.61	276.61	207.61
16	15	402.45	253.95	230.66	472.34	309.28	440.31	347.13
18	17	482.34	353.90	295.67	471.32	278.20	464.55	374.60
20	19	536.41	396.64	309.29	510.20	300.55	504.38	434.50
22	21	556.75	434.45	323.81	559.66	317.98	565.48	504.34
24	23	559.64	472.29	349.99	606.23	317.96	603.32	556.73
26	25	651.20	563.51	390.97	682.31	362.69	687.97	651.20
28	27	676.64	577.64	407.93	707.76	357.01	744.53	702.10
30	29	669.31	660.82	414.74	689.11	372.89	776.79	732.12
31	31	725.88	689.11	448.68	697.59	398.35	841.85	774.55
33	33	663.67	723.07	428.90	700.45	435.14	923.90	819.83
35	35	745.73	790.99	499.65	694.82	508.72	966.36	785.92

Table H.2. Dissolved phosphorus (DP) concentration of each sediment core during anoxic trials. Cores analyzed during Trial 1 are designated with an "a" while Cores analyzed during Trial 2 are designated with an "b". Site names are Main Site (MS), Willow Creek (WC), Balm Fork (BF), Upper Balm Fork (UBF), Weather Buoy (BY), and Upper Willow Creek (UWC).

Days sampled		Dissolved phosphorus concentration (µg/L)							
Trial 1	Trial 2	MS.1^{a}	MS.3^{a}	MS.4^{b}	MS.5^{b}	MS.6^{b}	WC.1^{a}	WC.2^{a}	WC.3^{a}
0	0	83.75	83.75	96.91	113.41	113.41	86.95	86.95	83.75
1	1	125.30	93.36	125.16	93.22	86.84	86.97	96.55	83.78
2	2	134.89	138.08	132.61	149.11	132.61	109.34	86.99	80.60
3	3	176.26	131.55	127.09	201.34	173.84	131.55	77.26	106.01
4	4	230.55	230.55	171.09	228.84	245.34	176.26	131.55	147.51
5	5	331.67	245.04	220.59	308.59	363.59	229.58	186.26	176.98
6	6	421.46	347.21	264.60	382.85	424.10	279.15	220.37	251.31
7	7	520.44	393.59	303.64	429.64	489.64	384.31	306.97	297.69
8	8	492.66	513.66	300.62	480.62	585.62	459.66	375.66	324.66
10	10	549.59	561.59	387.64	515.42	747.03	552.59	357.59	369.59
12	11	675.71	765.71	381.58	546.58	741.58	741.71	537.71	555.71
14	13	681.67	750.67	450.61	702.61	867.61	822.67	537.67	537.67
16	15	811.82	824.59	507.28	740.22	871.25	914.01	578.69	610.62
18	17	838.07	911.52	579.05	876.69	846.31	1068.00	675.20	703.94
20	19	864.91	1054.84	606.29	894.55	999.38	1170.56	815.60	821.05
22	21	922.58	914.83	690.69	938.19	1028.45	1089.45	804.55	723.06
24	23	939.59	912.04	702.32	990.58	1072.11	1180.00	815.90	751.38
26	25	1004.67	1050.67	744.54	1132.06	1117.91	1298.83	912.10	839.10
28	27	1120.45	1088.02	812.41	1202.76	1231.04	1255.27	886.02	899.68
30	29	1168.45	1116.52	785.28	1309.15	1212.98	1324.26	931.02	956.67
31	31	1216.44	1145.01	805.08	1130.95	1377.03	1393.26	976.01	1013.66
33	33	1336.41	1246.98	844.70	1289.37	1365.74	1426.23	1008.98	1010.63
35	35	1279.64	1287.24	867.36	1326.17	1351.63	1520.77	1055.80	1076.49

Table H.2. continued

Days sampled		Dissolved phosphorus concentration (μg/L)						
Trial 1	Trial 2	BY.1[a]	BY.2[a]	BY.3[a]	BY.4[a]	BF.1[a]	BF.2[a]	BF.3[a]
0	0	90.14	80.56	80.56	86.95	90.11	90.11	90.14
1	1	86.97	112.52	115.72	134.88	86.97	77.39	86.97
2	2	141.28	128.50	147.66	173.21	96.57	74.21	102.95
3	3	185.85	166.68	169.88	259.30	157.10	80.46	96.43
4	4	217.77	211.38	288.03	278.45	125.16	86.84	106.00
5	5	331.67	294.54	297.64	424.48	130.58	90.36	139.86
6	6	347.21	353.40	418.37	523.56	118.28	78.06	121.37
7	7	415.25	532.81	508.06	622.53	133.72	115.16	121.34
8	8	429.66	549.66	585.66	762.66	132.66	150.66	198.66
10	10	483.59	738.59	849.59	843.59	156.59	201.59	165.59
12	11	615.71	1008.71	948.71	1068.71	243.71	189.71	183.71
14	13	603.67	1062.67	1131.67	1191.67	270.67	255.67	255.67
16	15	684.07	1070.49	1252.52	1179.07	380.69	262.52	272.11
18	17	758.23	1438.46	1521.49	1224.49	483.58	362.23	320.71
20	19	796.72	1552.65	1641.51	1379.45	580.31	447.31	365.03
22	21	778.93	1556.08	1483.87	1319.98	579.08	428.69	375.52
24	23	855.34	1629.65	1616.85	1288.90	692.25	507.92	508.50
26	25	880.82	1720.20	1780.94	1469.96	802.60	536.24	584.90
28	27	982.29	1733.72	1921.40	1501.22	835.32	639.76	676.60
30	29	1018.28	1795.22	1988.90	1568.72	934.32	713.25	765.09
31	31	1054.28	1856.71	2056.39	1636.21	1033.31	786.75	853.59
33	33	1141.25	1958.68	2161.36	1663.18	1141.28	780.72	895.55
35	35	1175.51	2011.69	2288.90	1817.07	1300.98	862.14	1006.32

Table H.2. continued

Days sampled		Dissolved phosphorus concentration (μg/L)						
Trial 1	Trial 2	UBF.1[b]	UBF.2[b]	UBF.3[b]	UWC.1[b]	UWC.2[b]	UWC.3[b]	UWC.4[b]
0	0	77.66	63.91	66.66	72.16	66.66	66.66	41.96
1	1	96.42	83.64	86.84	112.39	115.58	134.74	86.84
2	2	91.36	96.86	99.61	80.36	80.36	85.86	55.61
3	3	80.34	99.59	80.34	69.34	80.34	88.59	47.34
4	4	85.84	127.09	96.84	80.34	127.09	116.09	52.84
5	5	88.59	151.84	121.59	121.59	110.59	107.84	61.09
6	6	99.60	157.35	129.85	102.35	132.60	121.60	72.10
7	7	114.64	180.64	171.64	138.64	120.64	144.64	87.64
8	8	138.62	177.62	144.62	153.62	132.62	162.62	102.62
10	10	210.64	153.03	165.03	243.03	168.03	258.03	144.64
12	11	198.58	165.58	189.58	255.58	183.58	234.58	138.58
14	13	258.61	174.61	189.61	306.61	189.61	276.61	207.61
16	15	300.54	213.19	189.90	326.75	216.10	335.48	271.43
18	17	348.39	286.93	234.52	401.44	225.78	362.64	325.10
20	19	367.53	306.38	236.50	408.29	259.79	411.20	382.08
22	21	411.16	344.19	303.42	463.57	253.92	486.86	405.34
24	23	431.52	390.76	303.40	489.76	265.55	472.29	443.17
26	25	478.66	475.83	317.43	555.03	283.49	506.94	509.77
28	27	518.24	478.64	348.53	597.44	286.30	580.47	560.67
30	29	505.25	505.25	355.34	581.62	293.69	660.82	556.75
31	31	508.08	525.05	363.82	595.77	316.32	660.82	633.12
33	33	499.62	547.70	355.36	609.93	350.29	765.50	627.49
35	35	601.48	652.39	414.79	646.73	395.57	790.99	661.46

Appendix I

Total annual and anoxic phosphorus budget for Willow Creek Reservoir, OR using sediment core data

Internal loading values were estimated from sediment core analysis (see methods Chapter 3). Positive values indicate a retention of total phosphorus while negative values indicate a loss from Willow Creek Reservoir. Positive values in groundwater represent a loss from the reservoir to groundwater.

Table I.1. Total annual and anoxic phosphorus budget for Willow Creek Reservoir, OR for 2014 and 2015 using sediment core data.

	2014				**2015**				
	Annual		**Anoxic**		**Annual**		**Anoxic**		
Inputs	Mass (kg/y)	%	Mass (kg/y)	%	Mass (kg/y)	%	Mass (kg/y)	%	Source
Willow Creek	1420	80	110	29	729	66	35	10	This study
Balm Fork Creek	54	3	-	-	28	3	-	-	Estimated from Adams (2012)
Dry deposition	9	1	5	1	10	1	5	1	Jassby et al. 1994
Wet deposition	43	2	15	4	28	3	8	2	Jassby et al. 1994; Ellis et al. 2015
Mean internal loading	246	14	246	66	305	28	305	87	This study
(Range)	108 - 429	7 - 22	108 - 429	45 - 77	133 - 531	14-40	133 - 531	74 - 92	
Outputs									
Willow Creek Dam	779	-	244	-	457	-	235	-	This study
Δ P Storage	993	-	132	-	642	-	117	-	This study
(Range)	854 - 1176	-	-7 - 314	-	470 - 868	-	-55 - 343	-	