Effects of Zosel Dam Water Regulation on Osoyoos Lake Water Quality (Study 4)

FINAL

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Executive Summary

The State of Washington Water Research Center was tasked by the Washington State Department of Ecology to assess the effects of Zosel Dam on water quality in Osoyoos Lake. The purpose of this Study 4 is to inform the development of a new Order of Approval, which will prescribe dam operations starting in 2013. Zosel Dam is located on the southern end of Osoyoos Lake and is capable of storing around 20,000 acre-feet (24 million m^3) by raising the lake's elevation from around 909 feet, the minimum elevation of the dam, to 912.5 feet, the maximum elevation of the dam. The dam plays little role in regulating flow rates through the lake – its main role is to maintain summer and fall lake elevations around 911.5 feet during most non-drought "normal" years, around 912.5 feet during most "drought" years, and around 909.5 feet in most winters.

Primary uses of the lake include recreation, irrigation, drinking water, and habitat for aquatic life, including Kokanee Salmon (*Oncorhynchus nerka*). Nutrient control efforts since the early 1970s have resulted in an order of magnitude decrease in phosphorus loading to lakes in the Okanagan River Basin, including Osoyoos Lake. Decreases in external phosphorus loading from point sources to Osoyoos Lake has led to lower phosphorus levels in the lake. Between 1999 and 2009, Secchi depths in the lake have generally ranged from two to six meters, with depths tending to be greatest in the north basin (3-6 m) and lowest in the south basin (2-4 m). Chlorophyll a levels range from 0-0.015 mg/L, with the lowest concentrations typically measured in the North Basin. Total phosphorus (TP) levels are generally below 0.02 mg-P/L and are commonly below water quality objectives of 0.015 mg-P/L to protect recreation and aesthetic uses. The lake's trophic status has improved from eutrophic in the 1970s to mesotrophic presently. All three basins exhibit declines in bottom water dissolved oxygen levels after thermal stratification. Bottom waters in the central and south basins are void of oxygen for much of the late summer and fall.

Data analyses in this study suggest that nutrient and phytoplankton levels in the lake are related to, and partly controlled by, inflow to Osoyoos Lake from the Okanagan River. Nutrient and phytoplankton levels were slightly higher during normal flow versus drought years having typically lower inflows. For example, summer TP in normal versus drought years averaged 0.020

versus 0.016 mg-P/L for the north basin, 0.051 versus 0.033 mg-P/L for the central basin, and 0.044 versus 0.025 mg-P/L for the south basin. Seasonal inflows also tended to positively correlate with average summer TP and chlorophyll a. Strong correlations were found between spring inflows and summer TP and chlorophyll a in the north basin, and between spring and summer flows and TP in the central and south basins. The strongest relationships were found in the central basin, where the r^2 for the linear correlation between average spring and summer inflows and TP was around 0.5.

Zosel Dam exerts no control on lake inflow and only effects lake elevation and water depth minimally from year to year (i.e., differences of a few feet). Therefore, we are unable to suggest changes in dam operation that would directly and knowingly affect water quality in Osoyoos Lake. Rather than relying on changes in dam operations to impact water quality, we suggest that lake managers focus on the continued control of nutrient loading to the lake. We also identified internal nutrient loading as a potentially important controller of summer productivity, particularly in the central and south basins. As a result, lake managers should evaluate the significance of internal nutrient loading on water quality in Osoyoos Lake. The impact of summer bottom water anoxia on cold water fisheries also warrants further examination. One potential management strategy to ameliorate both internal nutrient loading and bottom water anoxia is lake oxygenation. Lake oxygenation is an engineered system that uses pure oxygen gas to enhance the oxygen content of bottom waters. These systems have been successfully operated elsewhere in the region and country, and could be a component of further improving water quality in Osoyoos Lake.

1 Introduction

The Washington State Department of Ecology (Ecology) is responsible for Zosel Dam, which regulates Osoyoos Lake's water elevation and discharge. Under the Boundary Water Treaty of 1909, the International Joint Commission uses an Order of Approval to prescribe the allowable levels of Osoyoos Lake in both Canada and the United States. The International Osoyoos Lake Board of Control is appointed by the International Joint Commission and supervises the implementation of the provisions of the Order of Approval. The current Order of Approval will terminate on February 22, 2013. A number of studies are being conducted to evaluate whether provisional changes are necessary for the new Order of Approval. In this Study 4, the State of Washington Water Research Center assessed the effects of Zosel Dam operation on water quality in Osoyoos Lake. This assessment is part of the comprehensive Osoyoos Lake Drought Study undertaken to inform the development of a new Order of Approval.

1.1 Objectives

The overall objective of this study, specified in the original scope of work, was to analyze existing information to answer key questions related to Osoyoos Lake's water quality, elevation, and discharge. After a background section on the historical water quality of Osoyoos Lake, these specific questions are addressed in individual sections as follows:

- What are the water quality parameters of concern in the lake?
- Which factors control these parameters of concern?
- How are these factors affected by lake level or discharge?
- Can changes to the current dam regulation plan improve lake water quality?

1.2 Background

Osoyoos Lake is situated the farthest south in a chain of lakes located along the Okanagan River. The Okanagan River flows from the southern interior of British Columbia to the US border. It then continues south as the Okanogan River and discharges into the Columbia River downstream of Chief Joseph Dan (Figure 1). The lake includes a deep large north basin, a smaller central basin, and a large but relatively shallow south basin (Figure 2 and 3). It is important to note that at this scale, Figure 3 does not show the small but deeper pocket of water in the central basin. Primary uses of the lake include recreation, irrigation, drinking water, and habitat for aquatic life, including Kokanee Salmon (*Oncorhynchus nerka*), a landlocked form of Sockeye. Human population growth in the Okanagan River Basin has corresponded with the degradation of water quality in many of the basin's lakes (Jensen and Epp, 2002). Increases in the discharge of wastewater effluent, rich in phosphorus (P), to surface waters has been identified as the primary factor in this degradation. Other sources of nutrients to Okanagan lakes that have increased over the years include agricultural activities, forest harvesting, septic tanks, and soil erosion.

In the 1970s, Canadian authorities began implementing strategies for decreasing the nutrient loading from wastewater treatment plants to lakes in the Okanagan River Basin. These management activities and their impacts on water quality are presented in a comprehensive study by the British Columbia Ministry of Water, Land and Air Protection (Jensen and Epp, 2002). Based on data presented in Jenen and Epp (2002) nutrient control efforts have resulted in an order of magnitude decrease in P loading to Okanagan lakes since the early 1970s. In the north basin of Osoyoos Lake, springtime total P (TP) in surface waters has decreased from > 25 µg-P/L prior to the late 1980s to < 20 µg-P/L since the mid 1990s. Levels of TP in surface waters of the north basin in the fall also appear to have dropped slightly, though trends are less clear. Fall TP levels in bottom waters of the north basin show a significant downward trend from the 1970s to 2001, although levels are more than two to three times those of north basin surface waters. This finding suggests that hypolimnetic accumulation of P is still occurring in the lake during this time of year. Concurrently, levels of dissolved oxygen have improved in the bottom waters of the north basin. In the fall, dissolved oxygen levels in bottom waters have increased from < 3 mg/L prior to the mid 1980s to > 3.5 mg/L in the 1990s (Jenen and Epp, 2002).

Data also indicate improvements in phytoplankton levels and water clarity. The trophic status indexes for Secchi depth, TP and chlorophyll a for the north basin have dropped from 45-60 in 1971 (eutrophic) to 34-46 in 2006 (mesotrophic), indicating a long-term improvement in water quality (Jensen, personal communications, 2007). Limited historical data compiled by the

Washington Department of Ecology (1999) suggests that the water quality in the south basin of Osoyoos Lake has also improved since the 1970s and 1980s. TP and chlorophyll a concentrations in surface waters before 1989 ranged from 12-21 µg-P/L and 3.3-6.0 µg/L, respectively (n = 3-4). Levels in 1992 and 1993 ranged from 12-15 µg-P/L (n = 5) for TP and 0.8-4.7 µg/L for chlorophyll a (n = 4). Trophic state indexes for Secchi depth, TP and chlorophyll a in 1993 ranged from 40-45 (mesotrophic). Anoxic conditions and elevated TP were observed in bottom waters of the south basin in 1993, the only year for which oxygen profiles were reported by the Washington Department of Ecology. This suggests that P was internally recycling from lake sediments to overlaying water.

Previous studies have also discussed the influences of hydrologic conditions on water quality in Osoyoos Lake. Jensen and Epp (2002) make the cogent point that wet conditions potentially affect the lakes of the Okanagan Basin differently now that point sources are largely under control. They suggest that before the control of P loading from point sources, wet years would result in the dilution of nutrients and lower algal productivity relative to dry years. After the control of P loading from point sources, relative to dry years, wet years should result in higher P loading to water bodies now dominated by non-point source inputs. This is because greater rainfall on watersheds tends to result in larger non-point source nutrient loading to lakes. Indeed, wet periods during the early 1980s and late 1990s correlated with increased TP levels in the surface waters of Okanagan Lake (Jensen and Epp, 2002). Hyatt et al. (personal communications, 2007) report that summer TP levels in the north basin of Osoyoos Lake correlate with summer inflow from the Okanagan River. Furthermore, summer inflow tends to have greater TP levels than the lake; summer levels in inflow ranged from 10-30 µg-P/L while levels in the north basin ranged from 10-20 µg-P/L. They concluded that upstream factors including flow regulation at Penticton, the discharge point from Okanagan Lake, may be an important regulator of nutrient levels and algal productivity in Osoyoos Lake's north basin. Hyatt et al. (personal communications, 2007) also concluded that regulation of lake level and discharge at Zosel Dam likely plays little role in regulating water quality in Osoyoos Lake.

Data used in this study was mainly from three sources, the Osoyoos Lake Water Quality Society, the Okanagan Nation Alliance, and the BC Ministry of the Environment. Data obtained from the Osoyoos Lake Water Quality Society was for 2004-2009 for five stations: three stations in the north basin (north end, middle, and south end), one station in the middle of the central basin, and one station in the south basin at the US-Canada border. It included weekly to bi-monthly data from around April through October. Monitored parameters included: Secchi depth; surface and bottom temperature, dissolved oxygen, specific conductance, and pH; and temperature and dissolved oxygen profiles for 2006-2009. For the north basin, bottom water data was for a depth of 28 m and profiles were only down to 28 m (maximum depth in north basin is around 63 m), the length of the probe cable used by the Society. Data obtained from the BC Ministry of the Environment was for 1976-2009 for three stations: middle of the north basin (49.0544 latitude, 119.4845 longitude), middle of the central basin (49.0204 latitude, 119.4561 longitude), and north end of the south basin just north of the US-Canada border (49.0033 latitude, 119.4424 longitude). While there is some variability between years, the data set included monthly values for nutrients (including total P, total dissolved P, dissolved orthophosphate, nitrate plus nitrite and total nitrogen) from around May through November. The north basin includes nutrient data for depths of 1, 20 and 45 m, while the central and south basin includes nutrient data for depths ranging between 1 and 20 meters. Typically, the BC Ministry of the Environment and the Okanagan Nation Alliance sample a 1-10 m surface composite at 1, 5 and 10 m depths. The BC Ministry of the Environment also collects a hypolimnetic composite of 20 m, 2 off the bottom, and some intermediate depth or 45 m if deeper. There are also a couple of site specific variations that do not warrant detailed discussion Chlorophyll a in surface waster was also collected at each station approximately monthly. Since around 1999, the data set has also consistently included temperature and dissolved oxygen profiles.

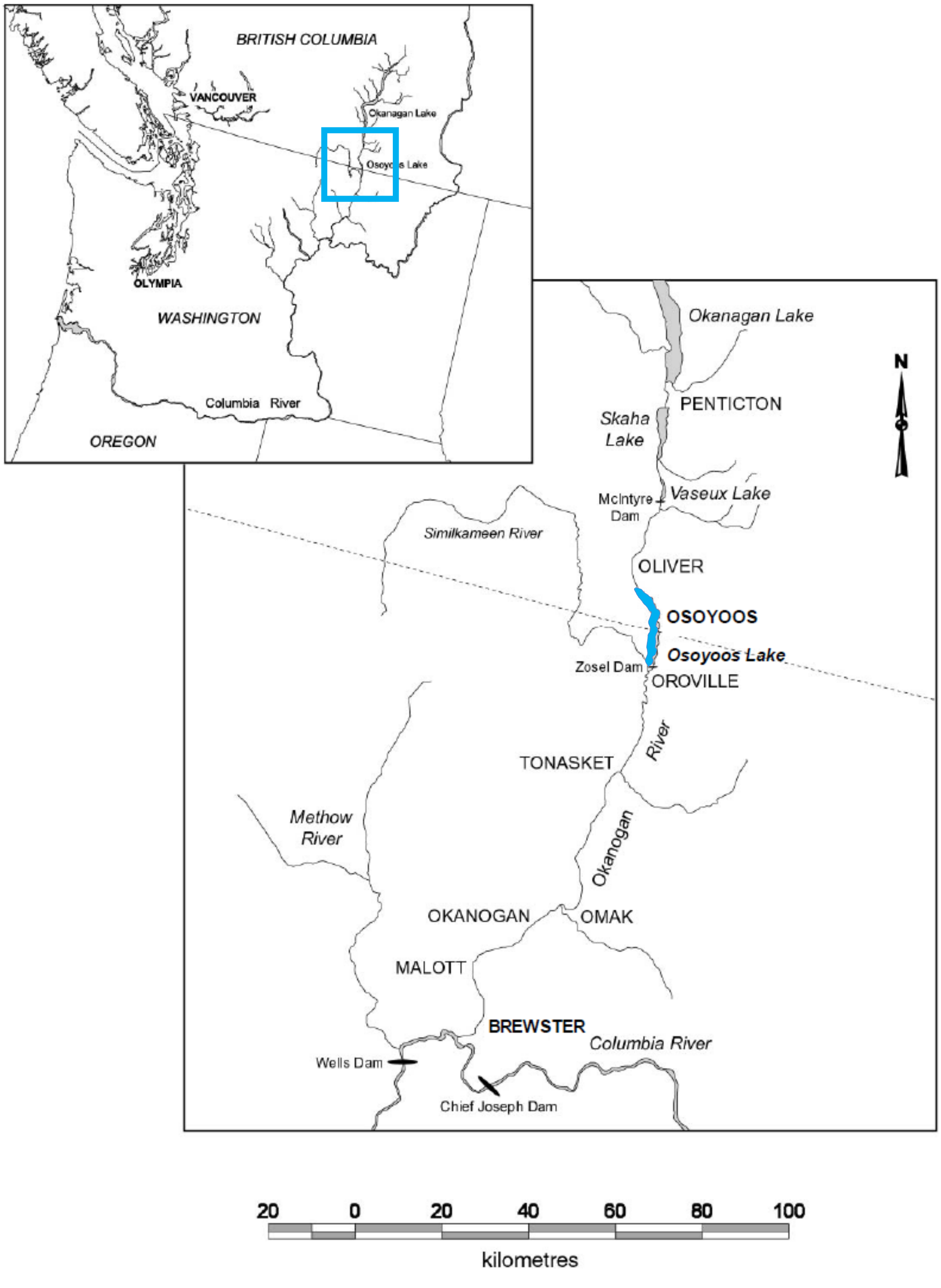


Figure 1. Map of Osoyoos Lake including Okanagan River (BC), Okanogan River (US), and Similkameen River (Glenfir Resources, 2006).

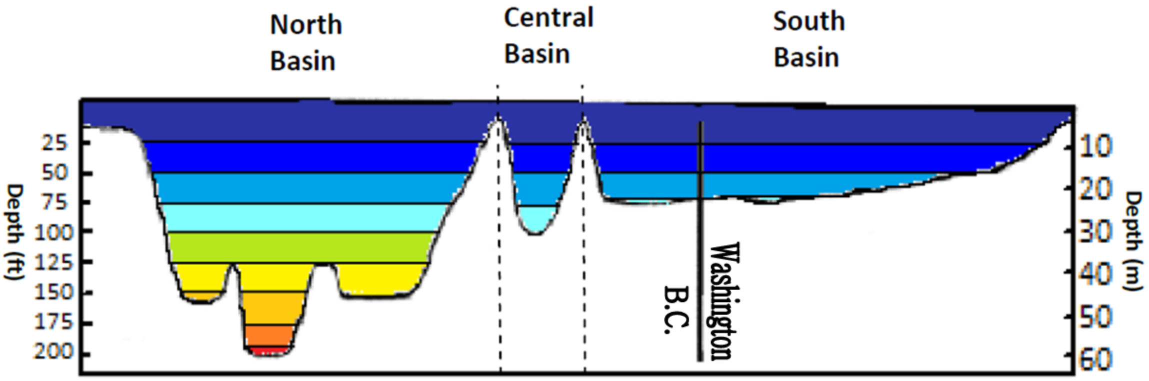


Figure 2. Cross-sectional view of Osoyoos Lake, illustrating depths for the north basin, central basin, and south basin. Modified from Hyatt et al. (personal communications, 2007). Note that the south basin is shallower here than in Figure 3, which was based on earlier bathymetric data.

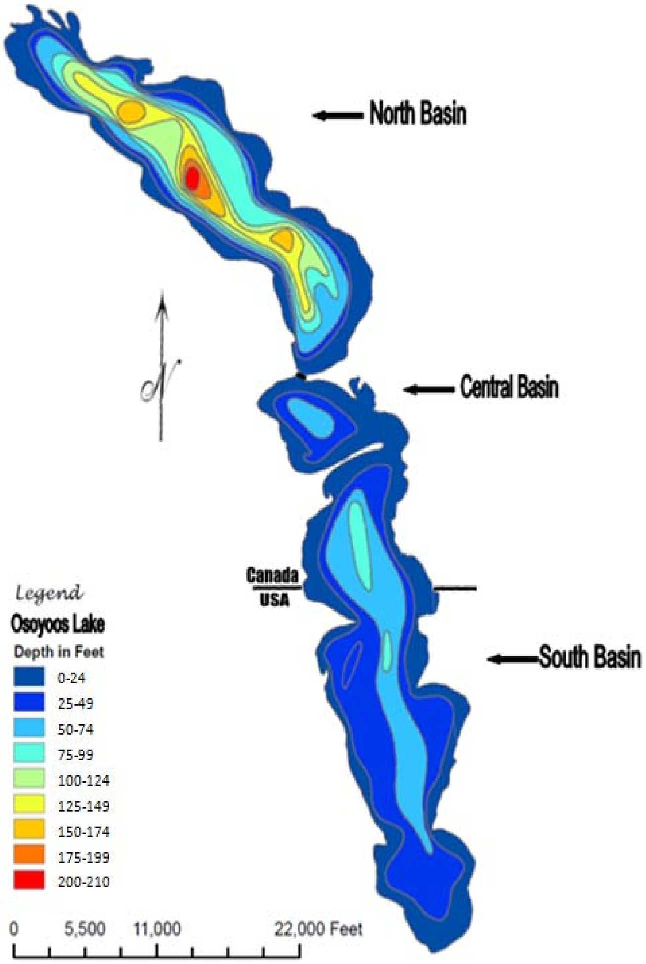


Figure 3. Bathymetry contour map of Osoyoos Lake. Updated from ArcGIS and Anglers Atlas, 2002. Map survey conducted August 1966 by the Province of British Columbia.

2 Water Quality Parameters of Concern

Good water quality is critical to the economic viability of the Osoyoos Lake region, which greatly depends on lake recreation and the aesthetic experience of lakeside residents. The importance of water quality is encapsulated in the following statement by the Osoyoos Lake Water Quality Society (Glenfir Resources, 2006):

> *Osoyoos Lake is the focal point of the beauty of our Town and of our tourism industry. Without a healthy and attractive lake, our Town could very well become a "ghost" town. The water of Osoyoos Lake is, in fact, the lifeblood and the essence of our community's future.*

The core water quality parameters of concern in Osoyoos Lake include: (1) P - P is the nutrient that limits algal growth in most freshwater lakes and excessive levels can lead to high phytoplankton growth; (2) phytoplankton - heavy blooms of algae, in particular blue-green algae, can impact aesthetics, cause low water transparency, and lead to low oxygen levels upon decay; (3) water transparency - transparency impacts aesthetics as well as water safety from the standpoint of being able to see children underwater; and (4) dissolved oxygen - low levels of dissolved oxygen can negatively impact aquatic biota and enhance internal recycling of P. These parameters are interrelated because they influence each other. In general, for example, the more P loading in the spring, the higher the concentrations of phytoplankton in the summer. In turn, higher concentrations of phytoplankton can reduce water clarity. Decay of dead phytoplankton in bottom waters can lead to low dissolved oxygen levels in the summer and fall, negatively impacting lake biota, including cold water fish. Low oxygen conditions can also promote the internal recycling of nutrients (this phenomenon is discussed in detail in Section 3.3).

Data for Secchi depth, chlorophyll a, and TP over the past 10 to 20 years for Osoyoos Lake's three basins are shown in Figure 4. Secchi depth data in Figure 4 starts in 1999, when consistent data collection of this parameter began; chlorophyll a and TP data start in 1990. The year 1990 was selected as a starting point since it is after the water quality improvements resulting of P point source controls in the 1970s. Thus, this data set represents water quality for the lake in its current "steady state", post point-source control condition. Secchi depth data in the lake generally ranges from two to six meters with depths typically greatest in the north basin (3-6 m) and lowest in the south basin (2-4 m). Secchi depth, a very simple measurement that encompasses the water quality effects of P loading and phytoplankton, can be used as a general criterion for lake water quality. A Secchi depth below 2 m is an indicator of eutrophic conditions, and a minimum Secchi disk of 2 m is commonly used as a criterion for recreational and aesthetic uses in lakes (Cooke et al., 2005; Horne and Goldman, 1994, Dr. Alex Horne, personal communications). Based on this criterion, Osoyoos Lake has reasonable water quality. Chlorophyll a generally ranges from 0-0.015 mg/L, with the lowest levels since 2001 in the north basin. TP levels are generally below 0.02 mg-P/L and are commonly below the water quality objectives of 0.015 mg-P/L in the spring set to protect recreation and aesthetic uses (Jensen and Epp, 2002).

Temperature and dissolved oxygen profiles for the three basins during the example year 2007 are shown in Figure 5. During the summer, all three basins exhibit thermal stratification, when warm surface waters float on top of a cold, denser layer of bottom water. All three basins also experience declines in bottom water dissolved oxygen levels after thermal stratification. Summertime oxygen depletion is especially apparent in the two smaller central and south basins. An examination of data from 2000 to the present shows that these spatial and temporal patterns of temperature and oxygen were common in these years. Oxygen is consumed through the decay of both "fresh" phytoplankton that sinks into bottom waters and "old" organic matter that accumulates in bottom sediments with time. Anoxic conditions are a particular concern for resident Kokanee salmon, which prefer cold, well-oxygenated waters. In general, waters having temperatures below 20 ^{o}C and dissolved oxygen concentrations greater than 5 mg/L create optimal habitat conditions for lake salmon and trout.

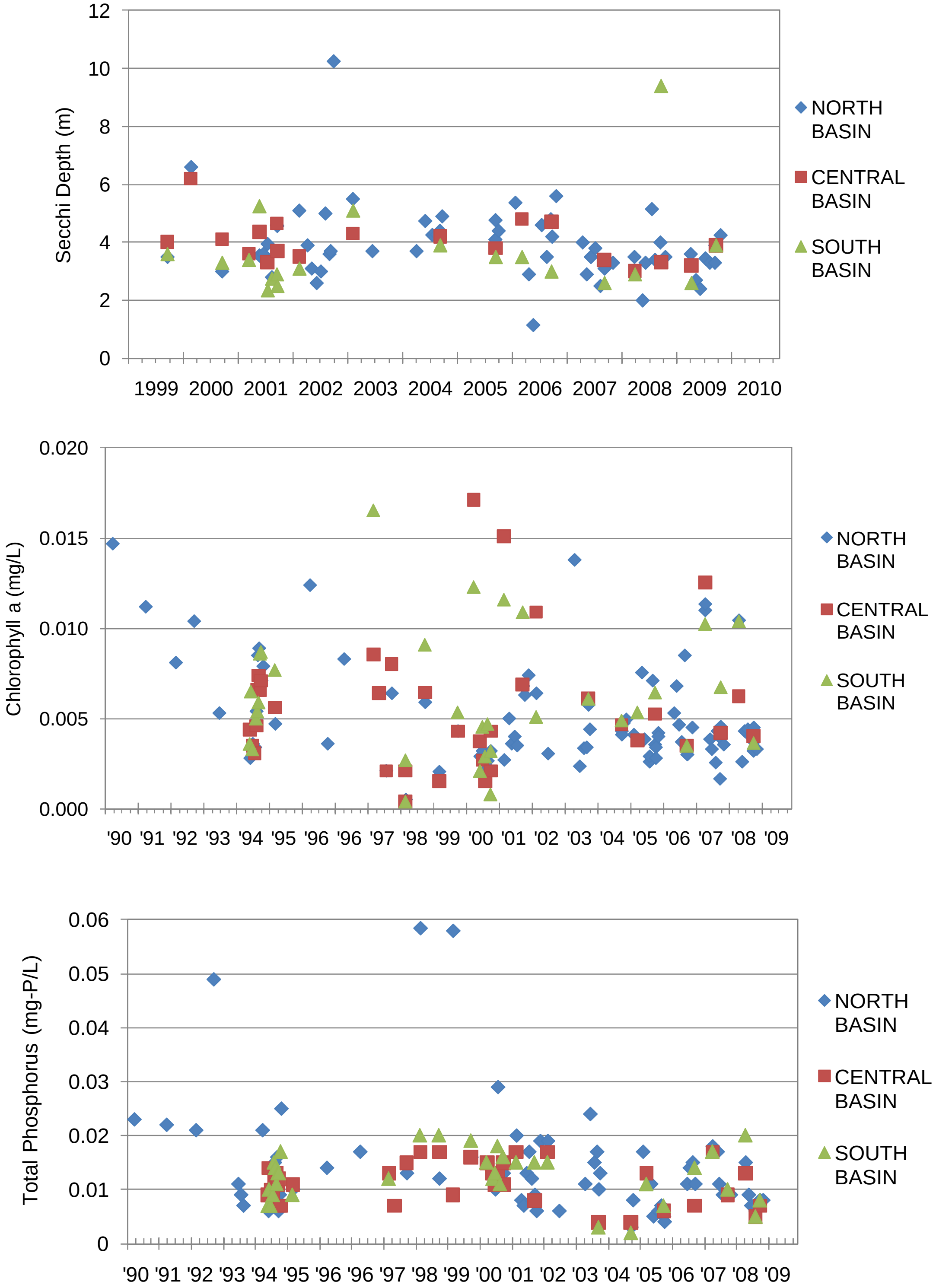
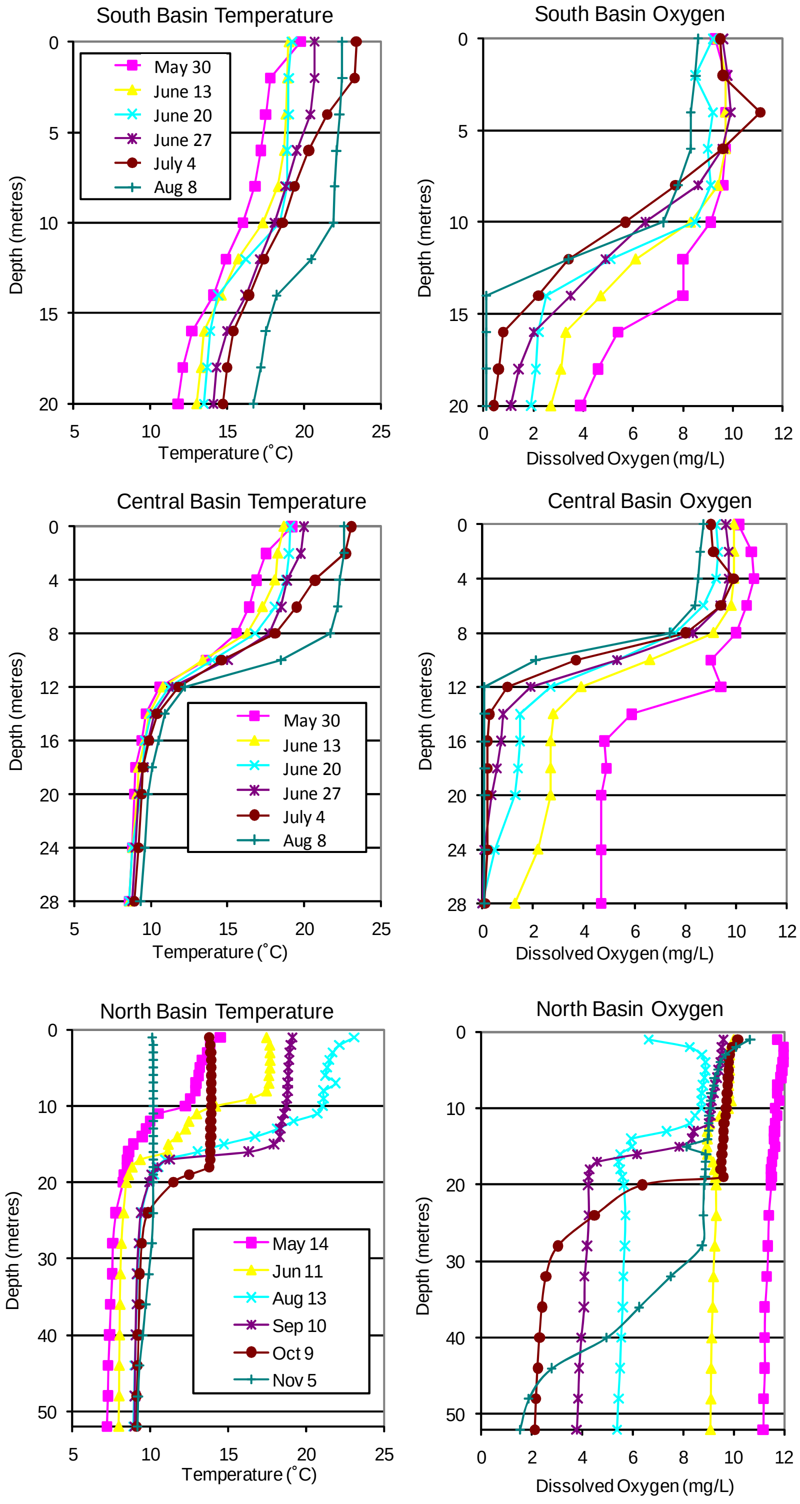


Figure 4. Secchi depth (top), chlorophyll a (middle) and TP (bottom) in the north, central and south basins of Osoyoos Lake. Data from the BC Ministry of the Environment.



South Basin Temperature

South Basin Oxygen

Central Basin Temperature

Central Basin Oxygen

North Basin Temperature

North Basin Oxygen

Figure 5. Temperature and dissolved oxygen profiles for the south, central and north basins of Osoyoos Lake during the year 2007. North basin data from the BC Ministry of the Environment. Central and south basin data from the Osoyoos Lake Water Quality Society.

3 Factors that Control Water Quality

3.1 Water depth and External Nutrient Loading

Fundamentally, two factors, water depth and external P loading, control the trophic status of a lake. The Canadian limnologist, Richard Vollenweider, used these two factors to develop one of the first models of lake eutrophication – the Vollenweider Plot (Figure 6) (Vollenweider, 1975). The model is generally used to establish a lake's initial trophic status and to track changes in trophic status as P loading is substantially decreased. Conditions of high P loading combined with shallow depth enhance internal recycling of P and results in greater phytoplankton productivity. Therefore, according to the Vollenweider Plot, lakes with higher external P loading and shallower depths fall into the "eutrophic" classification. The past and present state of Osoyoos Lake is shown on Figure 6. Based on data from Jensen and Epp (2002), annual P loading in the 1970s to Osoyoos Lake was on the order of 30,000 kg, with roughly half the loading from sewage treatment plants and half from non-point sources in the watershed. This is equivalent to an aerial loading of around 0.5 $g/m^2/yr$ to the lake. By 2000, nearly all P loading from P sewage treatment plants was controlled (Jensen and Epp, 2002). Assuming some improvements in non-point source P loading as well, the aerial P loading to Osoyoos Lake dropped to around 0.2 $g/m^2/yr$. Based on Figure 6, the Vollenweider Plot predicts that this drop in P loading will result in a shift in trophic status from eutrophic to mesotrophic. This correlates well with observations that indicate the lake's trophic status has improved, moving from eutrophic in the 1970s to its current mesotrophic classification. Note also based on Figure 6, changing the elevation of Osoyoos Lake by a few meters would have little or no meaningful effect on the lake's actual water depth and trophic status.

The fact that a minor change in lake depth does not affect trophic status has some bearing on the question: would water quality improve if there was no dam? The bottom elevation of the natural outlet is 906 feet, compared to 909 feet, which is the bottom elevation of the dam, and 912.5 feet, which is the upper operating elevation of the dam. Also recall that the dam does not dramatically affect flow rate. Thus, without a dam the lake depth would be a few feet lower but flow through the lake would be similar to current conditions with the dam. This suggests that there would not be a dramatic change in lake water quality if there was no dam.

Another simple model used to evaluate eutrophication relates spring TP concentration to summer phytoplankton levels, measured as chlorophyll a concentration, and summer phytoplankton levels to summer water transparency (Horne and Goldman, 1994). Other models relate summer TP concentration to both chlorophyll a concentration and water transparency (Nürnberg, 1996; Figure 7). In these models, P concentration is assumed to control phytoplankton productivity, and phytoplankton productivity is assumed to control water transparency. If phytoplankton productivity is also controlled by nitrogen or sunlight availability, or water transparency is controlled by suspended sediments, these models may not be appropriate.

Figures 8-10 illustrate the following relationships in the three basins of Osoyoos Lake: (1) TP versus chlorophyll a, (2) TP versus Secchi depth, and (3) chlorophyll a versus Secchi depth. The conventional relationships depicted in Figure 7 do not hold from year to year in Osoyoos Lake, with the exception of decreasing clarity with increasing phytoplankton in the north basin (bottom plot of Figure 8). Whereas Figure 7 represents data collected from many temperate lakes worldwide, Figures 8-10 present data from a single lake across multiple years. However, the general magnitude of TP (~0.1 mg-P/L), chlorophyll a (~0.003 mg/L) and Secchi depth (~3.5 m) observed in the three basins of Osoyoos Lake are similar to values predicted by the model in Figure 7. So, Osoyoos Lake acts similar to other lakes. But, inter-annual variations in TP levels failed to predict phytoplankton concentration or transparency. Hyatt et al. (personal communications, 2007) noted a similar lack of relationship between summertime TP, chlorophyll a and Secchi depth in Osoyoos Lake.

3.2 Hydraulic Residence Time

A related environmental factor that affects trophic status, and in turn, water quality, is hydraulic residence time. Residence time is defined as the amount of time an average water particle spends in a lake. In lakes having a constant external loading source, shorter residence time generally improves trophic status. Greater flushing is associated with shorter residence time, which results in the dilution of nutrients and lower algal growth (Cooke et al., 2005). However, as noted in Section 1.2, in lakes such as Osoyoos Lake in which non-point nutrient loading is relatively high compared to point source loading (i.e., wastewater treatment plant discharges), shorter residence time may be associated with greater nutrient loading. This opposite effect is due to wet conditions that lead to greater non-point source nutrient loading to the lake. In this case, shorter residence time can correlate with impaired rather than improved water quality. Dilution, by decreasing resident time, has been used successfully in some lakes and reservoirs to improve water quality (Cooke et al., 2005). To be successful, hydraulic residence time should be reduced from years to months, and the incoming water used for dilution should be low in nutrients. At extremely low residence times, on the order of days, flushing can wash the phytoplankton out of the lake, quickly improving water quality (Cooke et al., 2005). However, these strategies may be ineffective if applied to Osoyoos Lake because the incoming water lacks both the quality and quantity required for successful dilution and/or flushing. For example, to drop the lake's residence time from 0.7 years to 0.2 years would require over 900,000 acre-ft (1,100 million m^3) of low-P water every year. This was calculated as follows. Annual inflow to the lake can be estimated as the lake volume (320 million m^3) divided by the lake's retention time (0.7 years), and is around 460 million m^3/yr. The flow required to achieve a retention time of 0.2 years can be estimated as the lake volume (320 million m^3) divided by 0.2 years, or 1,600 million m^3/yr. The difference between the two flows, or the additional flow needed to drop the lake's residence time from 0.7 to 0.2 years, is around 1,100 million m^3.

3.3 Internal Nutrient Loading

Nutrient loading to a lake can be external or internal. External loading includes point sources such as wastewater treatment plant discharges and non-point sources such as agricultural runoff. Great efforts have been made to control external point sources of nutrient loading to lakes in the Okanagan Basin. In contrast, internal nutrient loading refers to the recycling of nutrients that have accumulated in the lake – typically in bottom sediments – into the water column, where the nutrients can stimulate phytoplankton growth. In shallow lakes, a common internal loading mechanism is wind resuspension of nutrient-rich sediments directly into warm and sunny surface waters.

Internal nutrient loading in deep lakes is more complex. For internal nutrient loading to occur in deep lakes, bottom waters must be devoid of oxygen and must be mixed upward. Under anoxic conditions, sediments tend to release dissolved and highly bioavailable forms of P and N, phosphate and ammonia, to overlying water. When this nutrient-rich bottom water becomes entrained into surface waters, either through summer wind mixing or fall turnover, nutrients can stimulate phytoplankton growth. Productive lakes, having anaerobic bottom waters, moderate depth, and high surface area are susceptible to wind mixing and are particularly vulnerable to internal nutrient loading. The Osgood Index, mean depth (m) divided by the square root of surface area (km^2), is a simple measurement of a lake's vulnerability to internal loading. Values below 6, coupled with elevated trophic status, indicate a high probability of internal nutrient loading. In such lakes, poor water quality may continue for years after external nutrient loading is controlled, because internal nutrient loading will continue to exacerbate eutrophic conditions.

Because of the variability in their depth, volume, and surface area, the three basins of Osoyoos Lake provide a unique case study in basin morphometry's influence on internal nutrient loading potential (Table 1). The north basin is very deep and large in volume, whereas the central basin is less deep than the north basin and relatively small in volume and surface area. Except for a small deep pocket in the central basin (Figure 2), the south basin is overall a bit deeper than the central basin and relatively large (Figure 3). The south basin's volume is around 60% that of the north basin, but the south basin has greater area, length, width, and shoreline. The shallower depths in the south and central basins, relative to the north basin, may be in part the effect of historical backflows into the lake during high flows of the Similkameen River. Because of the river's location, these backflows would have deposited sediments primarily in the south and central basins, decreasing their depths.

Because all three basins have comparatively low Osgood Index values and a mesotrophic tropic status, they are susceptible to internal nutrient loading. The central and south basins may be particularly susceptible, having Osgood Index values of 5.0 and 3.1, respectively. Water quality data from Osoyoos Lake confirms the lake's susceptibility to internal nutrient loading. All basins appear to accumulate P in bottom waters during some summers (Figure 11). In 1994, for example, TP levels in bottom waters of all basins increased from below 0.01 mg-P/L in May to 0.04-0.05 mg-P/L in September-October. This accumulation occurred because the bottom waters of the basins, particularly the smaller central and south basins, were anoxic. As TP levels increase in bottom waters, they also increase in surface waters (Figure 11). In both the central and south basins, which have the greater potential for internal nutrient loading, TP levels in surface waters increased from around 0.005 mg-P/L in June and July, to 0.01 mg-P/L in August, and to 0.014 mg-P/L in September. This increase in TP is likely the result of the entrainment of P-rich bottom waters into surface water via wind mixing.

The strength of thermal stratification and timing of entrainment of P into surface waters also correlates with each basin's Osgood Index value. The south basin (Osgood Index of 3.1) exhibited fairly weak stratification, as indicated by the moderate temperature differential between surface and bottom waters (Figure 5). In contrast, the central and north basins (Osgood Index of 5.0 and 6.4, respectively) exhibited strong thermal stratification. The earliest overturn in 1994, as indicated by the convergence of bottom and surface water TP levels, also occurred in the south basin, the basin with the lowest Osgood Index (Figure 11).

3.4 Shoreline Erosion

Unconsolidated materials such as sands, gravels, and clays along the lake shoreline are susceptible to erosion via natural and anthropogenic pathways. The severity of shoreline erosion depends on several factors including shoreline slope, vegetation, soil composition, and intensity of human activity. Impacts of erosion include water quality impairment due to increased sediment loading and sediment-associated nutrient addition, as well as loss of waterfront property. Wave action from wind or boats can facilitate shoreline erosion, and near-bank wave heights around 0.4-0.5 feet mark the onset of bank sediment motion (Glamore, 2009). However, correlating characteristics of wave action into quantifiable measures of shoreline erosion has proven difficult, and separating boat wake erosion from other sources of erosion is also tenuous. Moreover, many existing studies have focused on boat traffic in river environments, which have significant longitudinal currents compared to lake environments. As a result, the impact of boat wakes on shoreline erosion in lakes is not well understood (Asplund, 2000). The erosive power of waves is commonly modeled proportional to the wave height raised to a power. As a result, small increases in height rapidly increase the erosion potential.

Both lake elevation and boat size and speed affect the magnitude of shoreline erosion. Lake elevation can have a significant impact on erosion depending on near shore bathymetry.

Waves breaking on flatter slopes at lower lake levels generally produce less erosion than the same waves hitting steeper slopes at higher water levels (Figure 12). The size of boat wake is a function of hull size, boat speed, water depth and distance from shore. To alleviate boat wake impacts, many lake managers and state governments are beginning to impose no-wake zones (low boat speeds) in near-shore regions. For example, in July of 2009, Wisconsin Governor Doyle signed into law a bill that created a 100-foot no-wake zone along all lake shores in the state. Other lakes have more restrictive criteria. For example, Big Payette Lake in Idaho has a no wake zone within 300 feet of the shore.

Homeowners along the shore of Osoyoos Lake are keenly aware of the potential for shorelines to erode as a result of wave action, and concerns have been raised about shoreline erosion at lake elevations above 912.5 feet. From the standpoint of dam operation, managers can control the relative location of shoreline erosion by controlling lake elevation. However, this can only be done in non-wet years, since in wet years the elevation of the lake can rise uncontrollably due to increasing flows and water elevation in the Similkameen River. Thus, some erosion due to high water (elevations above 912.5 feet) is unavoidable in some years. Assuming shoreline slope is relatively constant at typical lake elevations (911-912 feet), dam operations has little effect on the magnitude of erosion. As noted above, other control strategies may need to be implemented to control the magnitude of erosion, such as the implementation of no-wake zones.

Table 1. Characteristics of Osoyoos Lake's three basins. Data partly based on map survey conducted August 1966 by the Province of British Columbia.

Parameter	**North Basin**	**Central Basin**	**South Basin**
Maximum depth, ft (m)	208 (63.4)	102 (31.0)	86 (26.2)
Mean depth, ft (m)	65.6 (20.0)	23.7 (7.2)	33.9 (10.3)
Area, acres (ha)	2,420 (980)	529 (214)	2,770 (1,120)
Length, ft (m)	23,180 (7,070)	5,800 (1,770)	25,010 (7,620)
Width, ft (m)	5,660 (1,730)	5,150 (1,570)	6,830 (2,080)
Shoreline, ft (m)	66,480 (20,260)	16,880 (5,150)	70,850 (21,590)
Total volume, acre-feet (10^6 m^3)	158,840 (196)	12,460 (15.4)	93,980 (116)
Normal year residence time, yr	0.27	0.02	0.16
Drought year residence time, yr	0.50	0.04	0.30
Osgood Index	6.4	5.0	3.1

Residence times calculated based on annual flow near Oliver, BC: normal year average of ~840 cfs (years 1989-1991, 1995-2000, 2002, 2004, 2006-2007); drought years average of ~440 cfs (1988, 1992-1994, 2001, 2003, 2005).

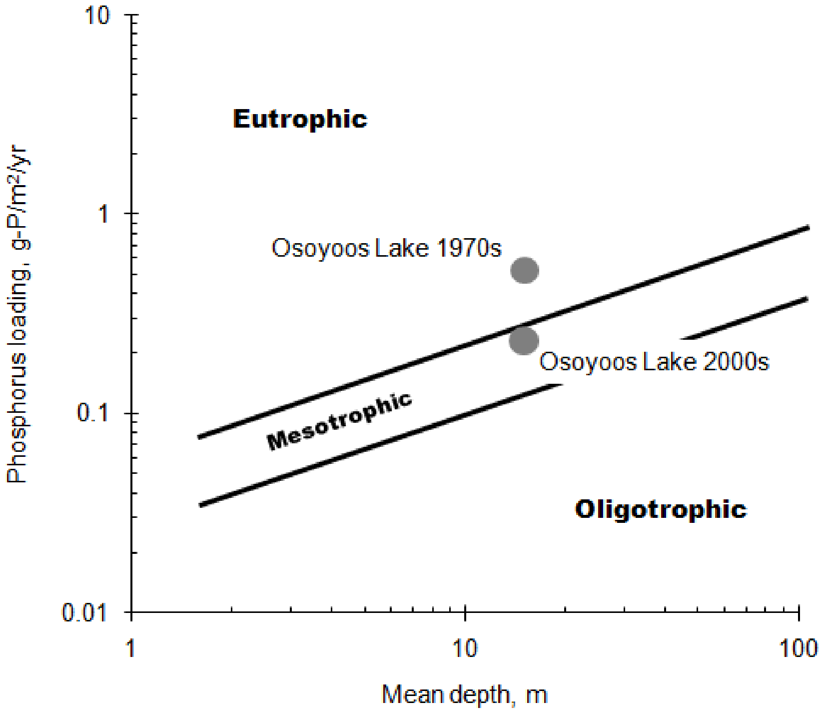


Figure 6. The Vollenweider Plot. Lakes above the upper line (high loading and low depth) are classified as eutrophic while lakes below the lower line (low loading and high depth) are classified as oligotrophic. Lakes between the two lines are classified as mesotrophic. Osoyoos Lake has a mean depth of 14.1 m. Arial loading has decreased from around 0.5 g-P/m^2/yr in the 1970s to a present level of around 0.2 g-P/m^2/yr. The Vollenweider Plot predicts a shift in trophic status from eutrophic to mesotrophic, and this indeed has been observed. Modified from Horne and Goldman (1994).

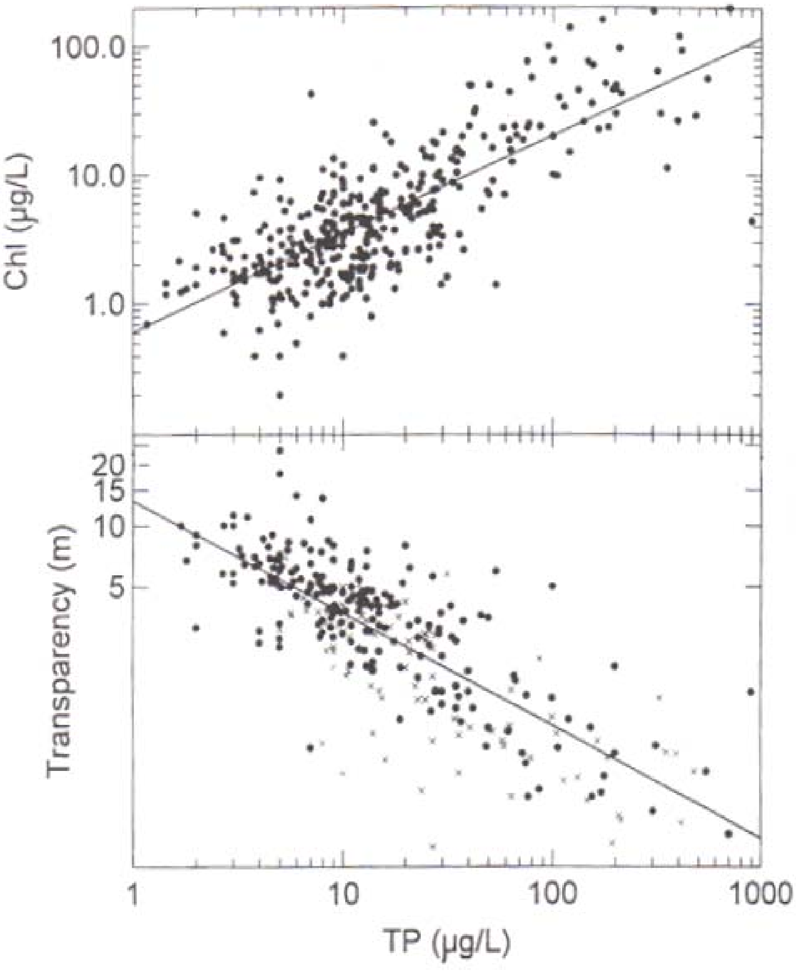


Figure 7. Example of lake water quality model relating summer average total phosphorus (TP) to summer average chlorophyll a (Chl) and Secchi depth transparency. Data set is for temperate lakes from around the world compiled by Nürnberg (1996). Note log scales on all axes.

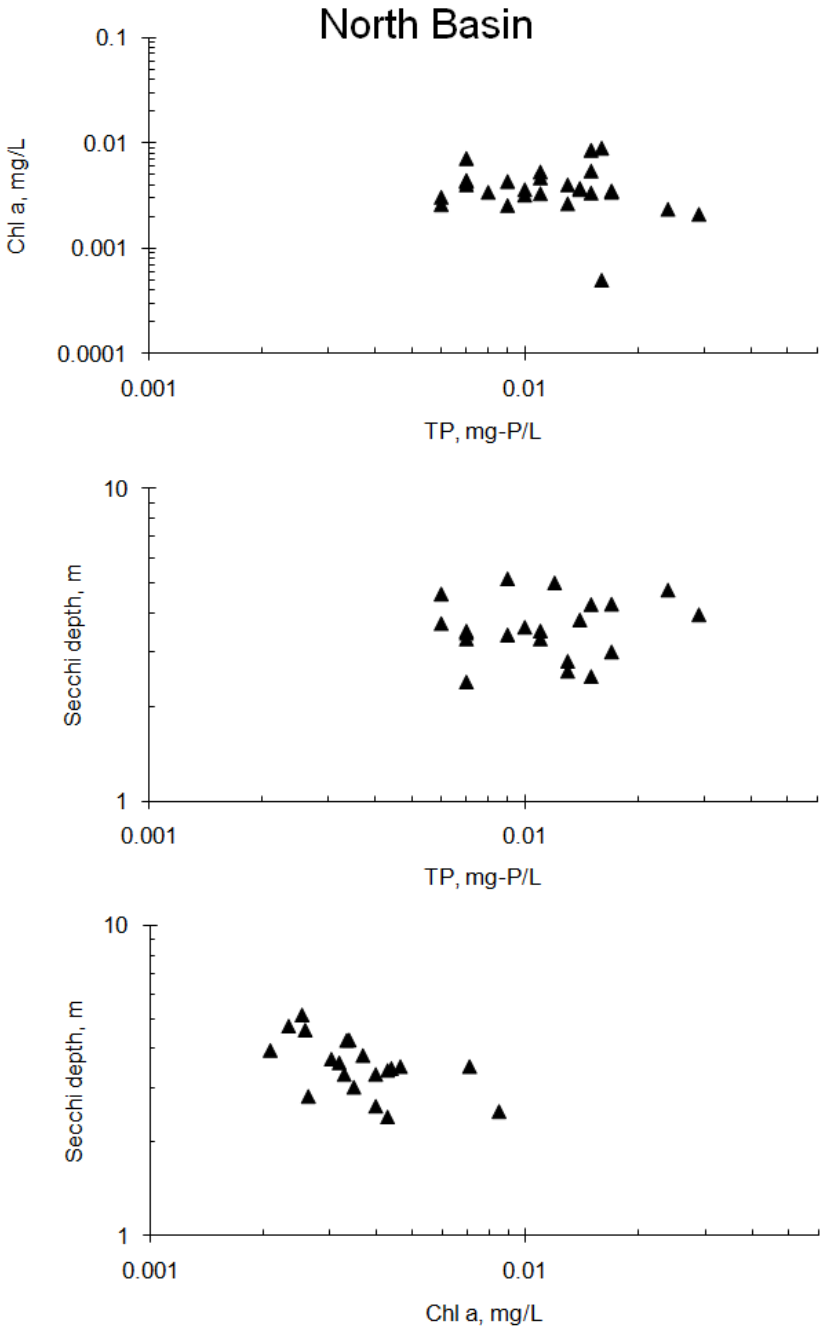


Figure 8. Relationships between summer (June, July and August) total phosphorus (TP), chlorophyll a, and transparency for the north basin of Osoyoos Lake. Data is from 1990-2009. Note there are no clear relationships in the data. Data from the BC Ministry of the Environment.

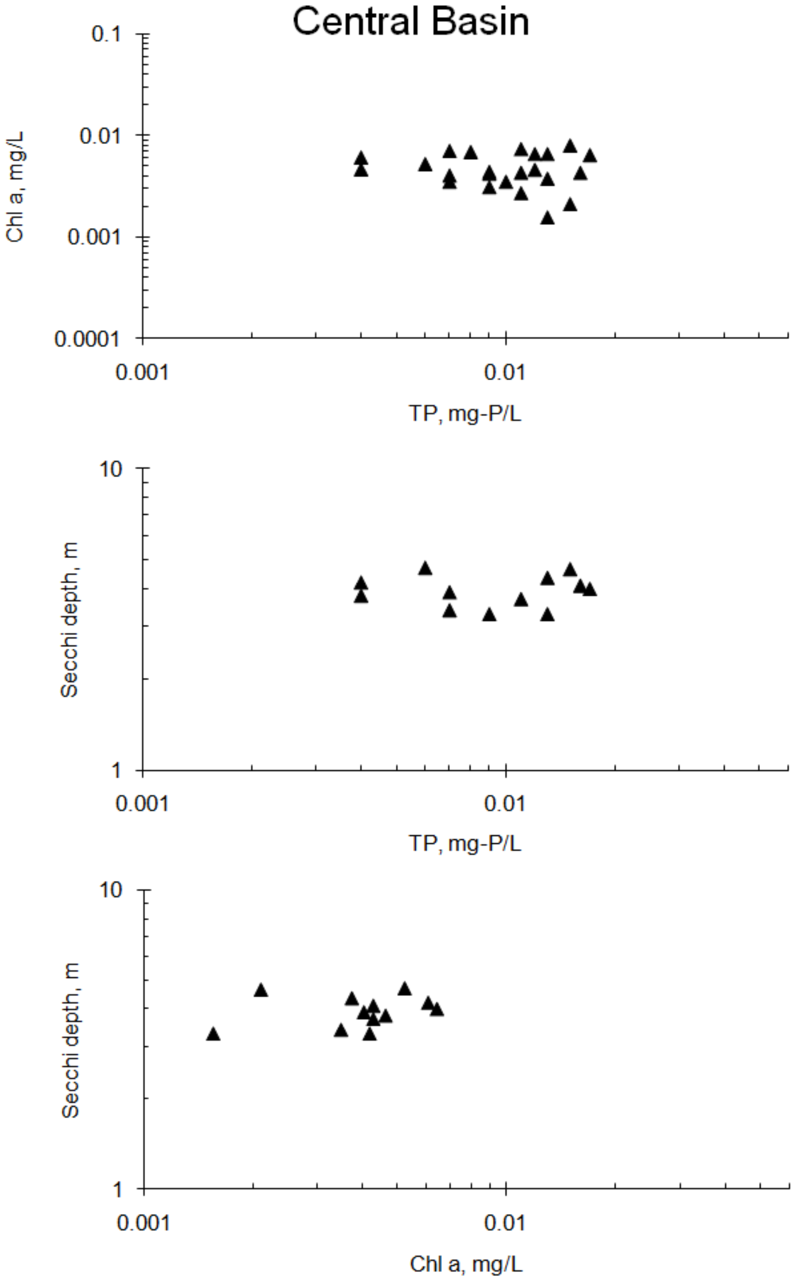


Figure 9. Relationships between summer (May-September) total phosphorus (TP), chlorophyll a, and transparency for the central basin of Osoyoos Lake. Data is from 1990-2009. Note there are no clear relationships in the data. Data from the BC Ministry of the Environment.

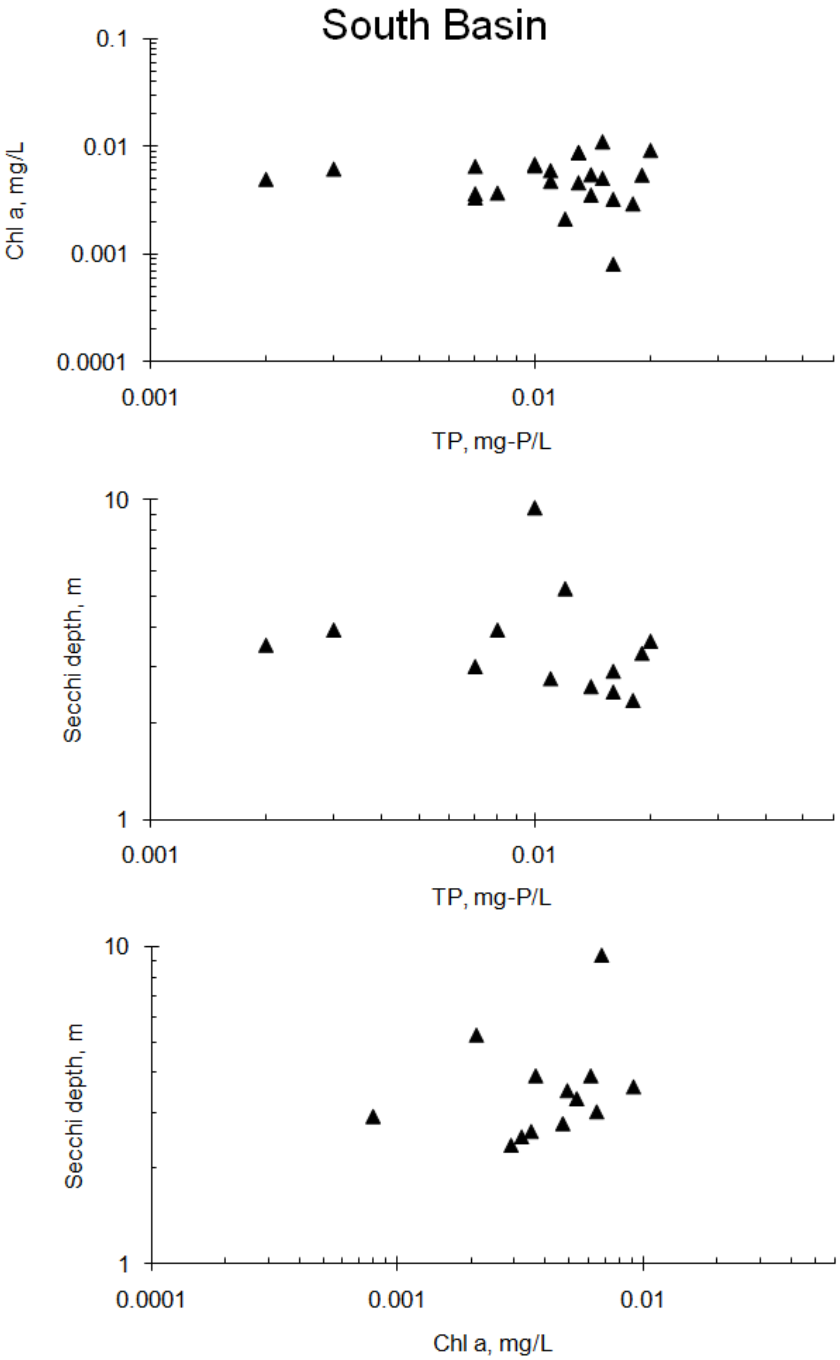
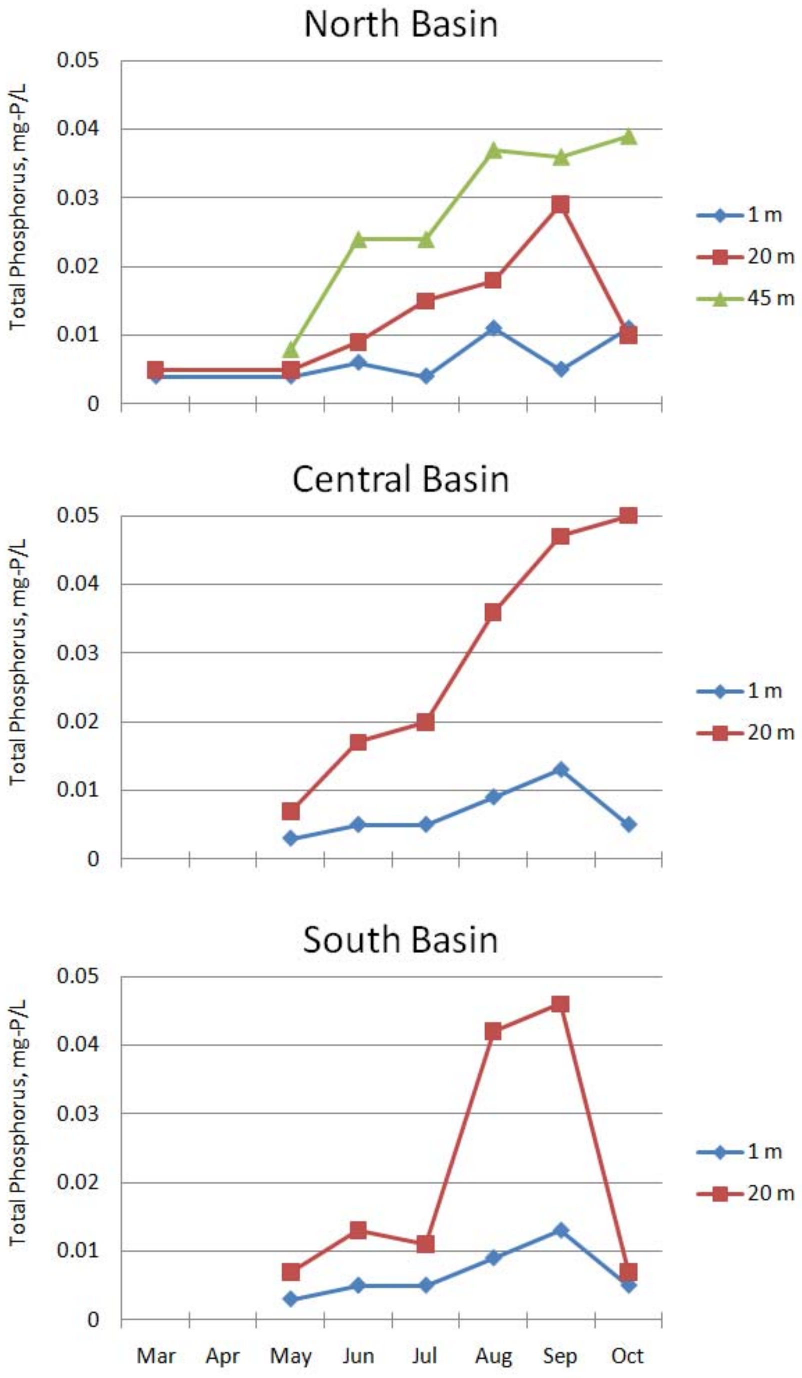


Figure 10. Relationships between summer (May-September) total phosphorus (TP), chlorophyll a, and transparency for the south basin of Osoyoos Lake. Data is from 1990-2009. Note there are no clear relationships in the data. Data from the BC Ministry of the Environment.



North Basin

Central Basin

South Basin

Figure 11. Total phosphorus in surface and bottom waters in Osoyoos Lake's three basins in example year 1994. Bottom waters in each basin accumulate P as the summer progresses as a result of P release from anaerobic sediments. 1994 was a drought year with fairly low summer flow (see Table 2). The upward trend in P in surface waters in all basins in the late summer and fall is likely the result of internal nutrient loading. Data from the BC Ministry of the Environment.

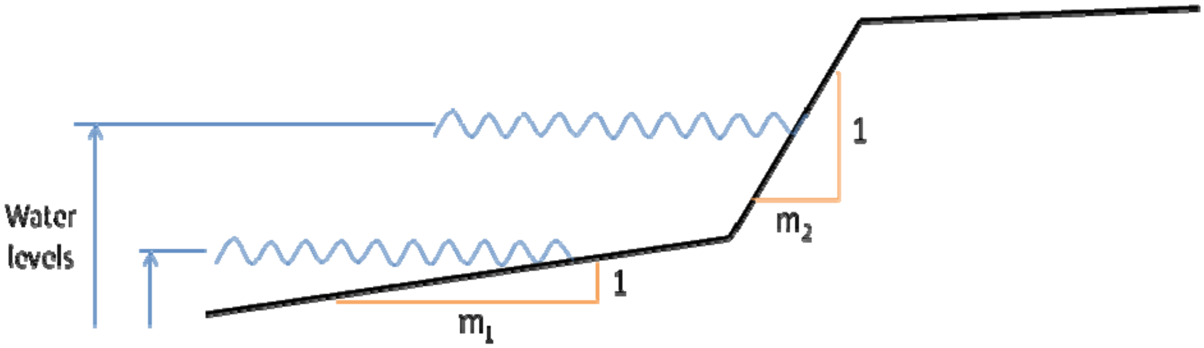


Figure 12. Schematic of water level impact on shoreline erosion. Waves breaking on the flatter slope (m1) at lower lake levels generally produce less erosion than the same waves hitting a steeper slope (m2) at higher water levels.

4 Effects of Lake Depth and Inflow on Water Quality

Natural fluctuation of lake elevation and water depth plays an important role in the ecological functioning of a lake. Lake elevation stabilization, through the use of dams, is a widespread practice to minimize flooding of shoreline development during the wet season and to maintain human access during the dry season (NRC, 1992). When lake level is stabilized by humans, some ecological function is lost or altered. For example, loss of ecological function is associated with human-induced lake elevation fluctuations that unnaturally flood or dry natural wetlands situated on the lake's edge. These wetlands provide key habitat to birds, fish and other aquatic biota. Wetlands can also act as important water quality buffers between aquatic and terrestrial systems by removing sediment and nutrients from inflowing waters. Other important ecological functions that can be negatively affected relate to reproduction and growth of fish and aquatic plants in littoral areas.

To examine the effects of changes in lake water depth and inflow from the Okanagan River on water quality in Osoyoos Lake, we first examined average summer TP and chlorophyll a levels in "normal" versus "drought" years in all three lake basins (Figures 13 and 14). A drought year is declared when one of the following criteria are met: (1) the volume of flow in the Similkameen River for April-July is <1.0 million acre-feet (1.2 billion m^3); (2) the net inflow to Okanogan Lake for April-July is less <195,000 acre-feet (240 million m^3); or (3) the level of Okanogan Lake for June-July fails to reach 1122.8 feet (342.23 m). None of the "normal" years include a backflow event in which river water reverse-flowed into the south end of the lake. The data suggest that nutrient and phytoplankton levels are slightly lower during drought versus normal years. For example, summer average TP in drought versus normal years averaged 0.016 mg-P/L versus 0.020 mg-P/L for the north basin, 0.033 mg-P/L versus 0.051 mg-P/L for the central basin, and 0.025 mg-P/L versus 0.044 mg-P/L for the south basin. Differences were less obvious for phytoplankton data. These results suggest that water depth and inflows associated with normal years (i.e., lower and more stable lake water depths and higher inflow) correlate with, and potentially cause, slightly higher levels of P and productivity in the three basins of Osoyoos Lake.

To further explore how inflows from the Okanagan River affect water quality, we developed a dataset of average values for the following parameters in each basin: (1) winter inflow, (2) spring inflow, (3) summer inflow, (4) summer TP, (5) summer chlorophyll a, and (6) summer Secchi depth (Table 2). The dataset included information from 1994 to 2008. The start date of 1994 was the first year with comprehensive data from the central and south basins. Excluded from the dataset were earlier measurements taken in the north basin prior to external point source nutrient control.

We evaluated linear correlations between summer and spring inflows and summer water quality variables (TP, chlorophyll a, Secchi depth) for each basin. Figure 15 shows correlations for spring inflow and Figure 16 shows correlations for summer inflow. A qualitative summary of the strength of linear correlations between flow and water quality is included in Table 3. Flows tended to positively correlate with TP and chlorophyll a. The strongest correlations were between spring flows and summer TP and chlorophyll a in the north basin, and between spring and summer flows and TP in the central and south basins. In the central basin, for example, the r^2 for the correlations between spring and summer flows and TP was approximately 0.5. That is, 50% of the variability in summer TP was explained by observed variability in flows. Such a high r^2 suggests that higher inflows may lead to higher TP levels. The weakest correlations were between Secchi depth and flows. Results suggest that spring inflow, and the associated inflowing nutrients, is a strong controller of summer productivity as measured by chlorophyll a in the north basin. Both spring and summer inflows appear to control summer TP in the central and south basins, but correlations are weak between these inflows and summer chlorophyll a.

We qualitatively examined the relationship between lake water depth and water quality using TP and elevation measurements for recent years in the north basin (Figure 17). The evaluation was limited to 2003-2007 since it included both drought and wet years, and the temporal resolution was such that it allowed for visual inspection of seasonal trends. In addition, the analysis was limited to the north basin since datasets from the Central and South Basins were too sparse for meaningful evaluation. The north basin dataset includes two drought years (2003 and 2005; elevations around 912-912.5 feet), two normal years (2006 and 2007; elevations around 911.5 feet), and one year that was initially managed as a drought year and then as a normal year (2004; elevation at 912.5 for first two months and 911.5 feet for next four months).

TP levels between the years appear to show little difference, all ranging from around 0 to 0.04 mg-P/L. However, differences in annual average TP values between years suggest that normal years had higher TP levels than drought years. Average annual TP levels for drought years were 0.010 mg-P/L (2003) and 0.014 mg-P/L (2005). Levels in normal years were 0.017 mg-P/L (2004), 0.012 mg-P/L (2006) and 0.016 mg-P/L (2007). Whereas the data show some inter-annual variability, a seasonal pattern in TP is reasonably clear. TP levels generally peaked in the fall, further suggesting an influence of internal nutrient loading on TP in the surface waters of Osoyoos Lake.

There is interest by water managers in the Okanagan Basin to use flows to flush Osoyoos Lake to improve water quality. Flushing of surface waters could possibly be used to dilute nutrients in surface waters, thereby decreasing phytoplankton productivity and improving surface water quality. Flushing of bottom waters could potentially be used to improve dissolved oxygen concentration in bottom waters, thereby improving fish habitat and possibly impeding internal P loading. Flushing surface waters during the fall, when the influence of internal nutrient loading is substantial, might improve water quality during this period. But, as noted in Section 4, higher inflow is generally associated with poorer water quality. Thus flushing could inadvertently degrade water quality. Also, as noted in Section 3.2, for flushing to be effective high volumes of low nutrient water are needed, and this may be in low supply in the Okanagan River Basin. In addition to the implementation of any potential flushing scheme, lake managers should consider addressing internal nutrient loading directly through in-lake management strategies, such as lake oxygenation which is described in Section 5.

Table 2. Water inflow and water quality data for Osoyoos Lake. Shaded rows are drought years; unshaded rows are normal years. These data are graphically illustrated in Figures 15 and 16. TP and chlorophyll a data from surface waters. Data from the BC Ministry of the Environment.

	Average Flow (cfs) at Oliver, BC			Average Summer Data (June- Sep)								
				NORTH BASIN			CENTRAL BASIN			SOUTH BASIN		
Years	Winter flow (Dec-Feb)	Spring flow (Mar-May)	Summer flow (June-Sep)	TP (mg-P /L)	Chl a (mg/L)	Secchi Depth (m)	TP (mg-P /L)	Chl a (mg/L)	Secchi Depth (m)	TP (mg-P /L)	Chl a (mg/L)	Secchi Depth (m)
1994	452	1048	538	0.025	0.006	3.8	0.033	0.006	3.2	0.031	0.006	3.1
1995	449	1369	605	0.034		3.8			3.1			3.2
1996	800	1940	1667			4.3			3.8			3.7
1997	910	2226	2649									
1998	653	1344	812	0.023	0.004	3.6	0.063	0.006	3.2		0.001	2.9
1999	735	1816	1288	0.024	0.006	3.7	0.064	0.007	3.7	0.054	0.009	3.5
2000	484	971	1020	0.022	0.003	4.2	0.037	0.003	3.9	0.055	0.005	3.2
2001	221	264	367	0.017	0.003	3.8	0.032	0.003	3.8	0.026	0.003	3.1
2002	264	936	895	0.014	0.005	3.8	0.045	0.007	3.7	0.041	0.011	3.2
2003	206	334	350	0.013	0.004	3.6	0.021	0.005	3.6			3.6
2004	365	291	429	0.018	0.004	3.8	0.022	0.006	3.4	0.016	0.006	3.0
2005	673	809	759	0.009	0.004	4.1	0.045	0.005	3.8	0.019	0.005	3.5
2006	376	1097	1028	0.014	0.004	3.7	0.088	0.005	2.9	0.055	0.007	2.5
2007	230	674	401	0.016	0.005	3.4	0.040	0.004	3.4	0.053	0.004	2.6
2008	212	488	718	0.012	0.003	4.0	0.050	0.004	3.3	0.038	0.007	

Table 3. Summary of correlation strength between average seasonal inflow and average summer water quality in the three basins of Osoyoos Lake.

Flow Parameter	Correlation		
	TP	Chl a	Secchi Depth
NORTH BASIN			
Average Winter Flow	+	+	+
Average Spring Flow	++	++	0
Average Summer Flow	0	0	+
CENTRAL BASIN			
Average Winter Flow	+	+	0
Average Spring Flow	++	+	0
Average Summer Flow	++	+	0
SOUTH BASIN			
Average Winter Flow	0	0	+
Average Spring Flow	++	0	0
Average Summer Flow	++	+	+

Note: Winter is December through February; spring is March through May; summer is June through September. Results based on analysis of data from 1994 through 2008 (see Table 2 and Figures 15 and 16). 0 indicates no correlation (r^2 of linear regression < 0.1); + indicates a very weak positive correlation (r^2 of linear regression = 0.1-0.3); ++ indicates a weak correlation (r^2 of linear regression = 0.3-0.6); See corresponding Figures 15 and 16.

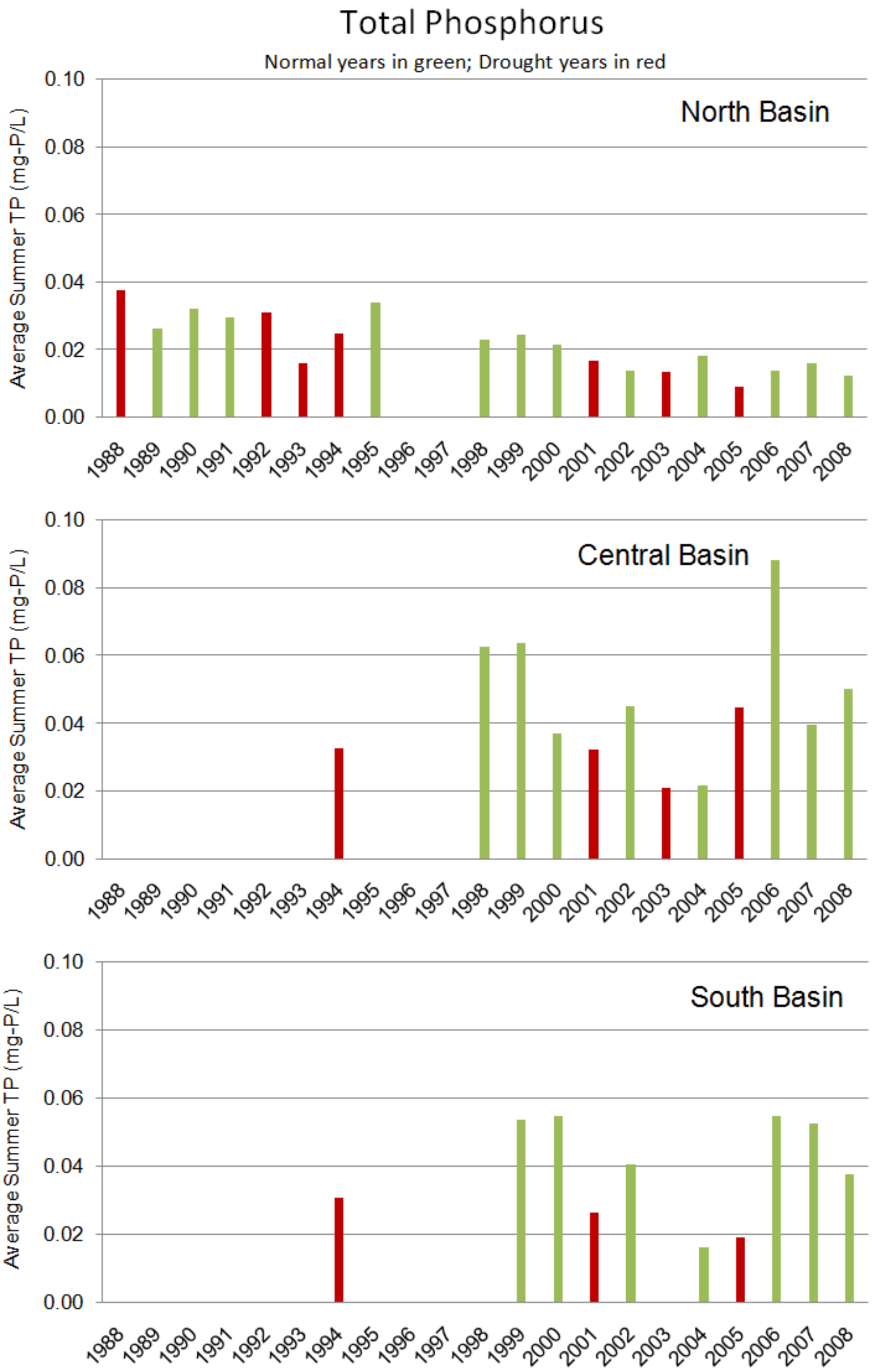


Figure 13. Average summer (June through September) total phosphorus (TP) in the surface waters of the north basin (top), central basin (middle), and south basin (bottom) of Osoyoos Lake. Green bars are normal years and red bars are drought years. P levels appear to generally be lower in drought versus normal years. Numerical data is shown in Table 2. Also note the downward trend in P levels in the north basin over time.

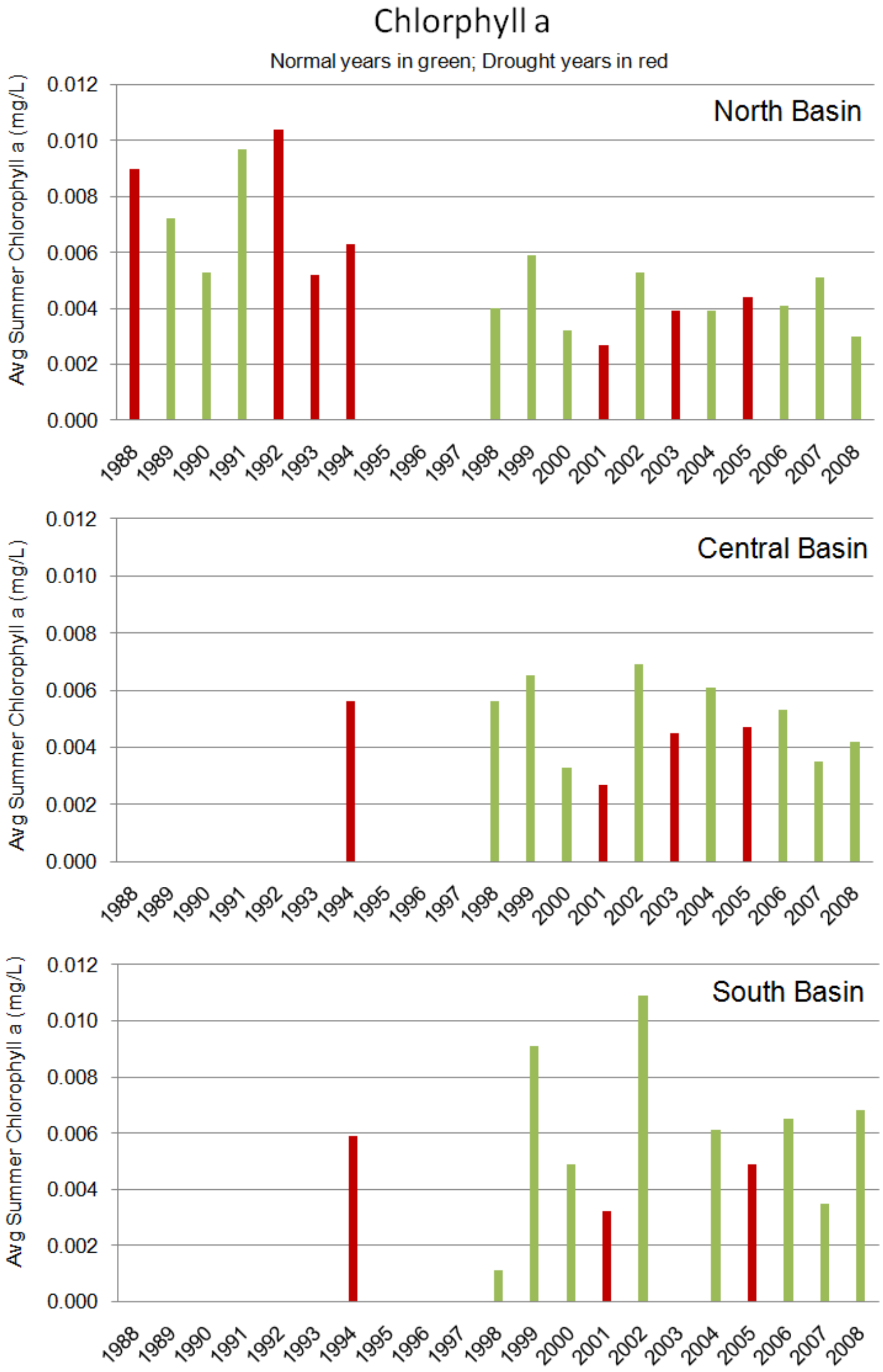


Figure 14. Average summer (June through September) chlorophyll a in the surface waters of the north basin (top), central basin (middle), and south basin (bottom) of Osoyoos Lake. Green bars are normal years and red bars are drought years. Levels appear to generally be lower in drought versus normal years. Numerical data is shown in Table 2. Also note the downward trend in chlorophyll a levels in the north basin over time.

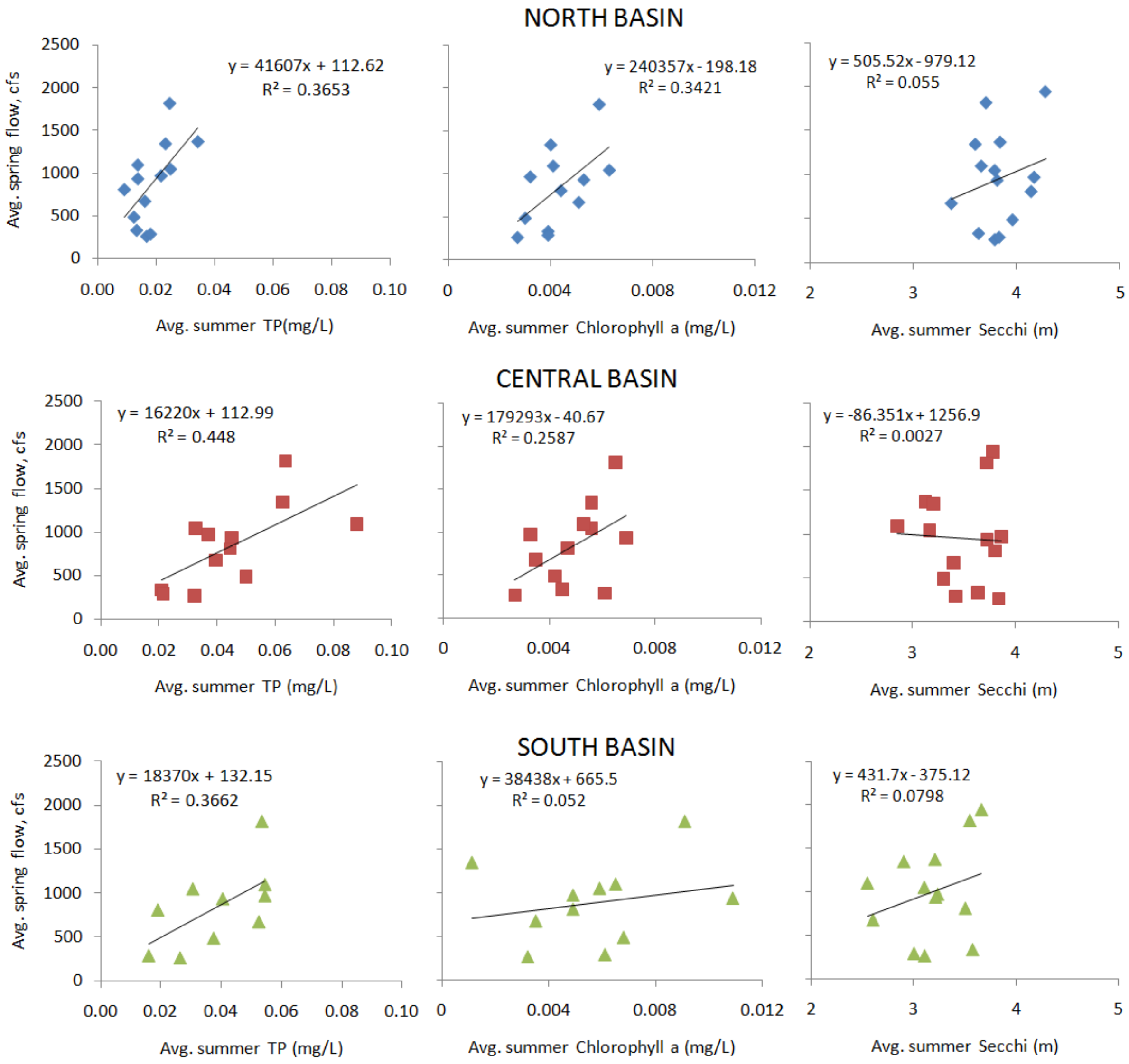


Figure 15. Correlations between average spring inflow to Osoyoos Lake and average summer total phosphorus (TP), chlorophyll a, and Secchi depth in the surface waters of the lake's three basins for 1994-2008. Spring is March through May and summer is June through September. Numerical data shown in Table 2. Note the general trend in which increasing spring inflow weakly correlates with increased P and phytoplankton in lake surface waters.

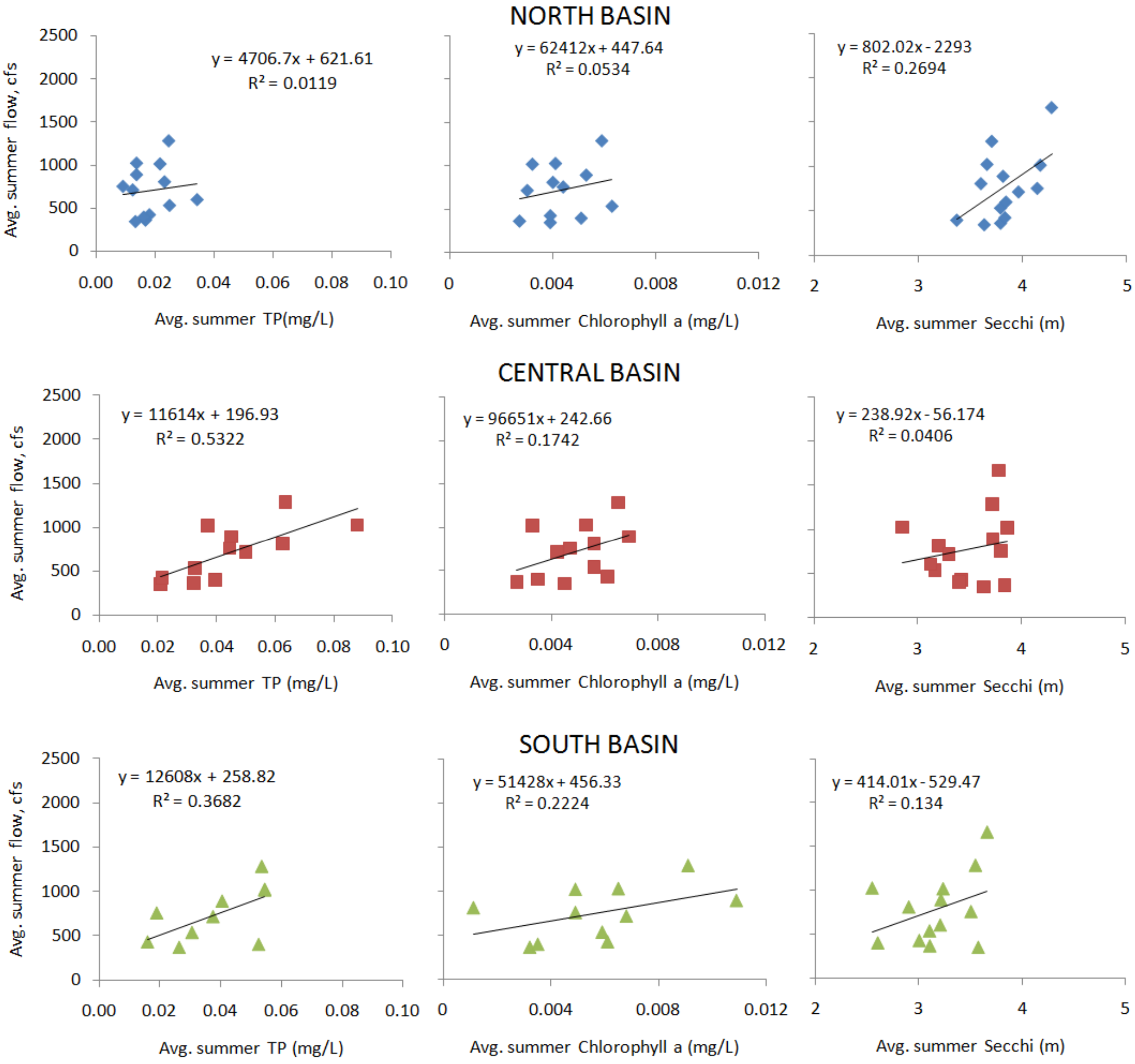


Figure 16. Correlations between average summer inflow to Osoyoos Lake and average summer total phosphorus (TP), chlorophyll a, and Secchi depth in the surface waters of the lake's three basins for 1994-2008. Summer is June through September. Numerical data is shown in Table 2. Note the general trend in which increasing summer inflow weakly correlates with increased P and phytoplankton in lake surface waters.

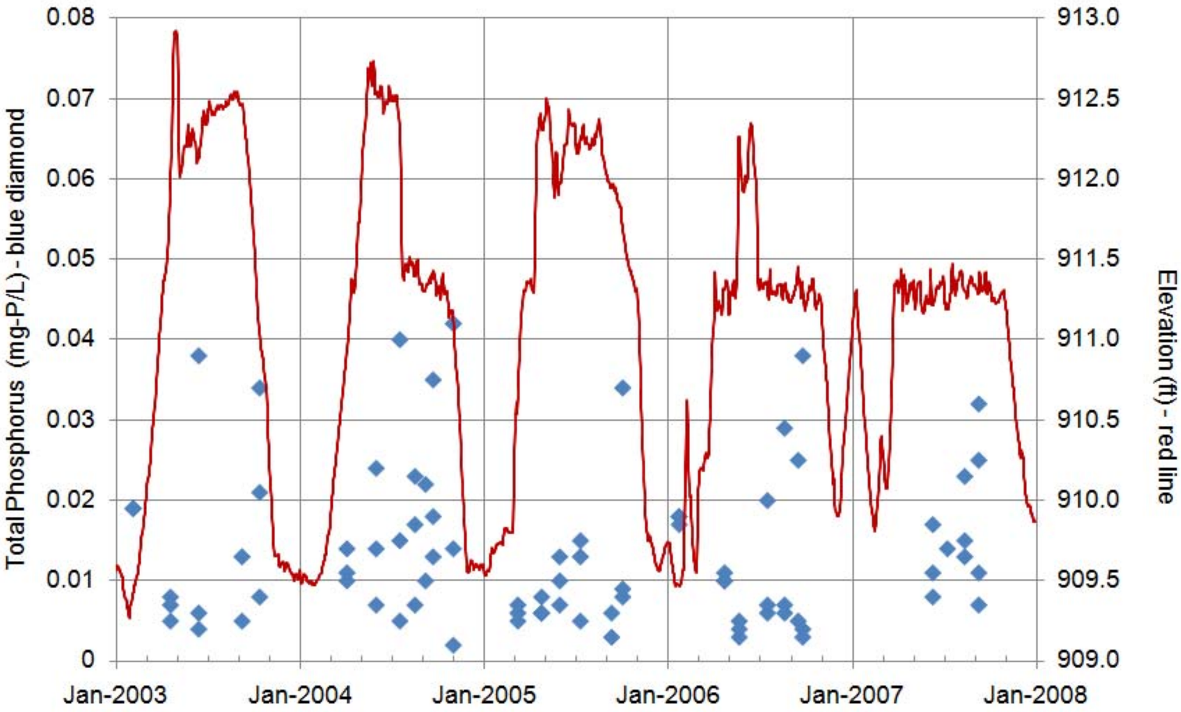


Figure 17. Lake elevation and total phosphorus (TP) in the north basin of Osoyoos Lake. Elevation, which controls water depth, appears to have little correlation with lake TP levels, though on average TP levels tended to be higher in normal versus drought years. Note the seasonal pattern of higher TP levels in the fall. This pattern may be indicative of internal nutrient loading, where bottom waters rich in P are mixed into surface waters as the lake destratifies in the fall.

5 Dam Regulation and Water Quality

Zosel Dam sits at the downstream southern end of Osoyoos Lake. The Dam is capable of storing around 20,000 acre-feet (24 million m^3) by raising the lake's elevation from around 909 feet to 912.5 feet. The dam has four spillway gates with a total capacity of 3,000 cubic feet per second (cfs) (85 cubic meters per second). During drought years, the lake's elevation is typically raised to around 912.5 feet and inflows and outflows are typically low (< 500 cfs) (Figures 17 and 18). In normal years, the lake is operated at an elevation of around 911.5 feet and inflows and outflows may be higher (500-1,500 cfs). During the winter, lake level is drawn down to an elevation of around 909.5 feet. In general, inflows to the lake are similar to outflows (Figures 18). Thus, the dam currently plays little role in regulating flow rates through the lake. Zosel Dam's main regulatory role is modifying the lake's summer elevation between normal years (~911.5 feet) and drought years (~912.5 feet).

Data analyses in this study suggest that TP levels in the lake are related to, and partly controlled by, inflow to Osoyoos Lake. Higher spring and summer inflows correlate with higher summer TP levels in each of the lake's basins. But, the correlations generally weaken between inflow and chlorophyll a and water transparency. Thus, decreasing inflow to the lake may not necessarily yield significant and observable improvements in water quality. In addition, adequate inflows are needed to maintain outflows that support fishery resources downstream of Zosel Dam. Zosel Dam exerts no control on lake inflow, and only affects lake water depth minimally from year to year (i.e., differences of a few feet). Therefore, we are unable to suggest changes in dam operation that would directly and knowingly affect water quality.

Rather than relying on changes in dam operations to impact water quality, we suggest that lake managers focus on the continued control of nutrient loading to the lake. Great strides have been made in controlling external nutrient loading to Osoyoos Lake. However, little attention has been paid to controlling internal nutrient loading. This study has identified internal nutrient loading as a potentially important controller of summer productivity, particularly in the central and south basins. Two common in-lake management strategies used to combat internal nutrient loading include sediment treatment with alum (aluminum sulfate) and lake aeration/oxygenation (Cooke et al., 2005). Alum treatment leads to the formation of a benign aluminum hydroxide floc at the sediment-water interface. The floc binds any phosphate released from anaerobic sediments, thereby impeding the accumulation of P in bottom waters.

The lake oxygenation approach is gaining attention because of its ability to both improve cold water habitat for lake trout and impede internal nutrient cycling of both phosphate and ammonia (Beutel and Horne, 1999; Beutel, 2006). Lake oxygenation is an engineered system that uses pure oxygen gas to enhance the oxygen content of bottom waters. These systems are extremely efficient, require fairly modest facilities, and can result in water quality improvements on a large spatial scale (Figure 19). A 8,000 kg/d oxygenation system to improve water quality for fisheries has been successfully operating in California's Camanche Reservoir since 1993. No fish kills have been observed since the project was implemented and bottom waters after oxygenation had lower levels of phosphate and ammonia (Beutel and Horne, 1999). Two smaller lake oxygenation systems are also successfully operating in regional lakes – a 1,500 kg/d system in Newman Lake near Spokane, WA and a 5,000 kg/d system in North Twin Lake on the Colville Indian Reservation near Inchelium, WA. Alum treatment is also used in conjunction with oxygenation in Newman Lake to suppress internal P loading. In Newman Lake, the volume of suitable habitat (< 20 ^{o}C and > 5 mg/L dissolved oxygen) available for lake trout has increased dramatically and decreases in internal loading of P has caused average summer volume-weighted TP concentrations to drop from > 50 µg-P/L to 15-28 µg-P/L (Moore and Christensen, 2009). Initial data analysis from the Twin Lakes system indicates that trout are using cool bottom waters for the first time in decades and internal loading of P has decreased by around half (Dr. Barry Moore, personal communications).

In the context of Osoyoos Lake, with its low Osgood Index, the south basin is especially vulnerable to internal nutrient loading. Preliminary calculations suggest that the summer oxygen demand in this basin is around 4,000 kg/d. This was calculated assuming a hypolimnion volume equal to one half of the basins total volume (hypolimnetic volume of 7.7), a typical hypolimnetic oxygen demand of 0.2 mg/L-d, and an induced oxygen demand factor of 2.5 (15.4 million m^3 x 0.5 x 0.2 mg/L-d x 2.5). The inducement factor accounts for increased oxygen demand typically observed when elevated levels of oxygen are added to hypolimnetic waters (Beutel and Horne, 1999). A system required for the central basin is comparable to the oxygenation system recently installed in North Twin Lake. A similar calculation for the larger south basin yields an oxygen demand of 30,000 kg/d. While the demand is larger, oxygenation systems of this size and larger have been implemented (Beutel and Horne, 1999). One incremental approach would be to install a pilot system in the smaller south basin for a number of years and evaluate its impacts of trout and water quality prior. Then based on the results, consider implementing an oxygenation system in the south basin. The north basin appears to not merit oxygenation since it is deeper and does not exhibit the intensity of anoxia observed in the central and south basins (see Sections 2 and Figure 5).

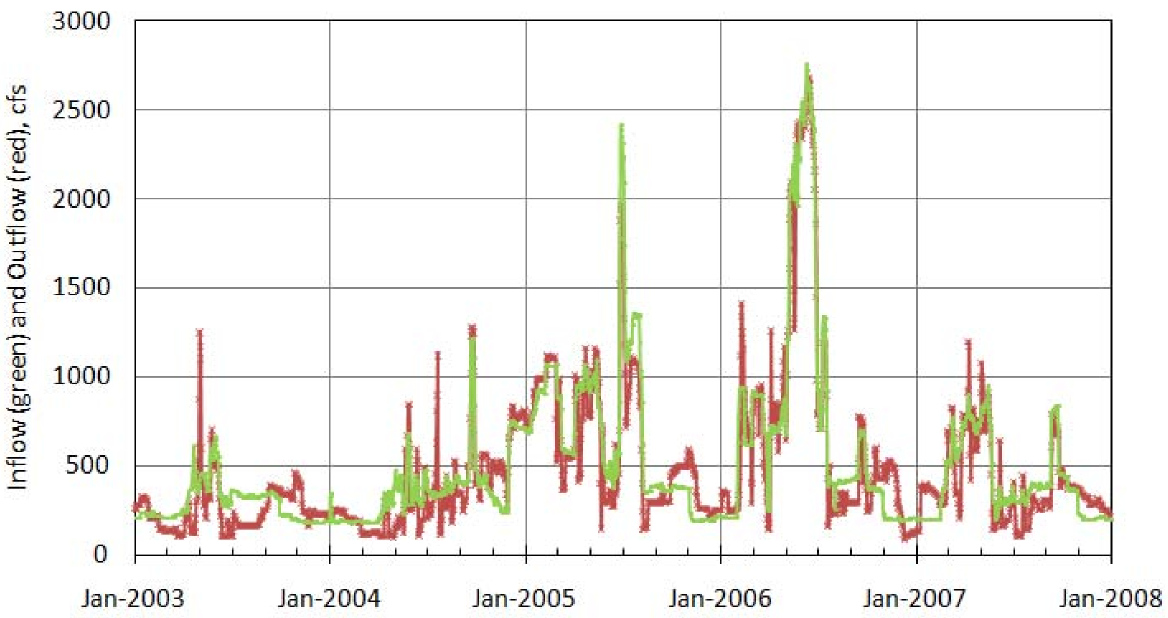


Figure 18. Inflow and outflow from Osoyoos Lake for 2003-2007. 2003 and 2005 were drought years. 2004, 2006 and 2007 were normal years.

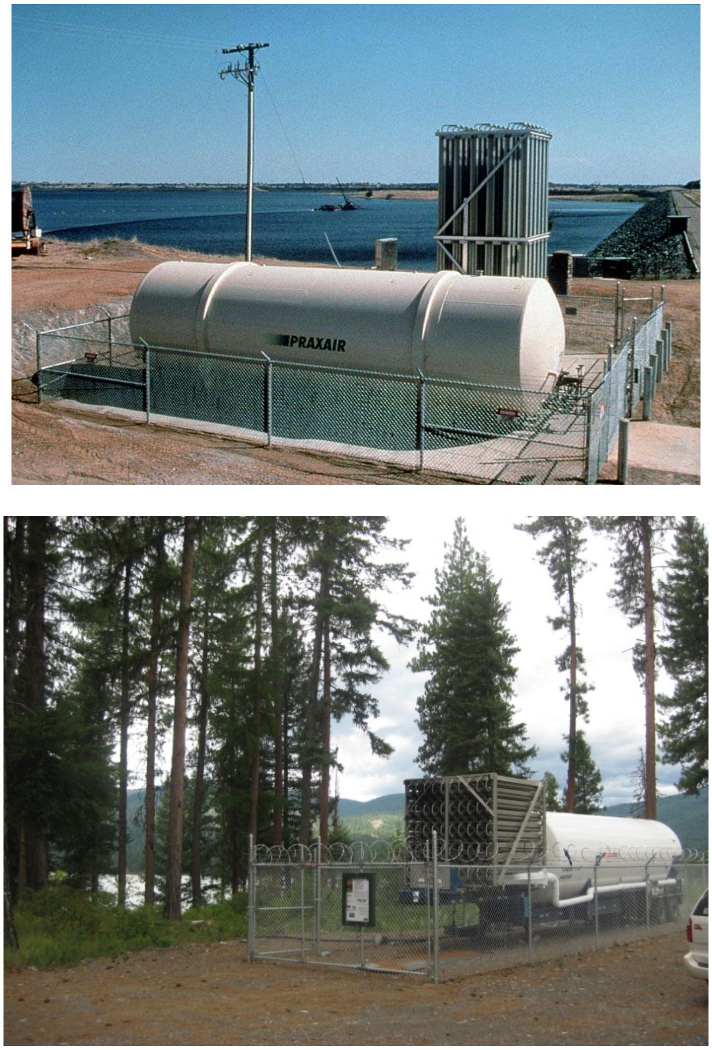


Figure 19. On-shore oxygenation facilities at Camanche Reservoir, CA (top) and Twin Lake, WA (bottom). Both systems include a liquid oxygen storage tank and an evaporator to convert the liquid to gaseous oxygen. The gas is then piped down into the bottom of the lake. The Camanche system uses a submerged contact chamber while the Twin Lakes system uses a line diffuser. See Beutel and Horne (1999) for a review of lake oxygenation technology and water quality improvements.

6 References

Asplund, T.R. 2000. The Effects of Motorized Watercraft on Aquatic Ecosystems, Wisconsin Department of Natural Resources, PUBL-SS-948-00, Madison, WI.

Beutel, M.W. 2006. Inhibition of ammonia release from anoxic profundal sediments in lakes using hypolimnetic oxygenation. *Ecological Engineering*. 28:271-279.

Beutel, M.W. and A.J. Horne. 1999. A review of the effects of hypolimnetic oxygenation on lake and reservoir water quality. *Lake and Reservoir Management*. 15(4):285-297.

Cooke, G.D., E.B. Welch, S.A. Peterson and S.A. Nichols. 2005. Restoration and Management of Lakes and Reservoirs, 3rd Edition. Taylor and Francis Group, Boca Raton, FL.

Glamore, W.C. 2009. "A Decision Support Tool for Assessing the Impact of Boat Wake Waves on Inland Waterways." http://www.pianc.org/downloads/dwa/Wglamore_DPWApaper.pdf.

Glenfir Resources. 2006. Plan of Study for the Renewal of the International Joint Commission's Osoyoos Lake Order. Prepared for Osoyoos Board of Joint Control and staff of the International Joint Commission.

Horne, A.J. and C.R. Goldman. 1994. Limnology. McGraw-Hill, Inc., New York. 576 p.

Hyatt K.D., D.J. McQueen and D.P. Rankin. 2007. Personal communications. "Controls on Osoyoos Lake Limnology and Biological Production." Osoyoos Lake Water Science Forum PowerPoint presentations: http://www.obwb.ca/fileadmin/docs/osoyoos_lake/04_Hyatt_Kim_limnology.pdf

Jensen, E.V. 2007. Personal communications. "Water quality trends in Okanagan, Skaha and Osoyoos Lakes in response to nutrient reductions and changing hydrology." Osoyoos Lake Water Science Forum PowerPoint presentations: http://www.obwb.ca/fileadmin/docs/osoyoos_lake/02_Jensen_ Vic_waterquality.pdf

Jensen, E.V. and P.F. Epp. 2002. Water quality trends in Okanagan, Skaha and Osoyoos lakes in response to nutrient reductions and hydrologic variation. B.C. Ministry of Water, Land and Air Protection.

Moore, B.C and D. Christensen. 2009. Newman Lake restoration: A case study. Part I. Chemical and biological responses to phosphorus control. Lake and Reservoir Management. 25:337-350.

National Research Council (NRC). 1992. Restoration of Aquatic Ecosystems. National Academy Press. Washington D.C.

Nürnberg, G.K. 1996. Trophic state of clear and colored, soft- and hardwater lakes with special consideration of nutrients, anoxia, phytoplankton, and fish. Lake and Reservoir Management. 12: 432-447.

Vollenweider, R.A. 1975. Input-output models with special reference to the phosphorus loading concept in limnology. Schweizerische Zeitschrift fuer Hydrologie. 37:53-83.