THE STATE OF LAKE WOLSEY

PART II: SOURCE LOADING ASSESSMENT

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1 Introduction

Lake Wolsey is a large dimictic embayment of the Great Lakes located on Manitoulin Island, the world's largest freshwater island (712 000 acres) (Hoffman *et al*, 1959) situated in the North Channel of Lake Huron (Figure 1). Tourism, trucking, commercial-scale cage aquaculture (Gale, 1999) and agriculture are the main anthropogenic activities on the island. In Part I of this report series, we documented the degraded water quality conditions of the Lake Wolsey embayment (Diep & Boyd, 2016). Our summary of the historical and current limnological conditions indicate that though this is a clear water, mesotrophic system with moderate productivity, it is experiencing significant eutrophication effects with the recent and severe dissolved oxygen depletion and extensive hypolimnetic anoxia not observed historically (Diep & Boyd, 2016). In this report we examined the factors at the landscape, both anthropogenic and allochthonous, which are potentially contributing to the dissolved oxygen depletion observed in this system.

DO is an essential component of aquatic ecosystems and significant depletion of DO can compromise the ability of a waterbody to support aerobic aquatic communities. Hypolimnetic dissolved oxygen (DO) depletion leading to anoxia, or the near absence of DO, can lead to degradation or loss of benthic environment which can have an impact on sediment-dwelling biota. Hypolimnetic anoxia is typically associated with high nutrient concentrations (e.g., > 20 $\mu g\ P\ L^{-1}$; CCME, 1999) or eutrophication particularly for waterbodies affected by urbanization, agriculture, or where there is significant industrial activity. Adverse effects as a result of significant DO depletion include both acute (i.e., lethal) and chronic (i.e., sublethal) effects, depending on the magnitude of the depletion and the sensitivity of the organism/communities. This occurs when DO levels fall below a threshold and the aquatic organism is unable to escape or adapt. Maintaining a sufficient level of DO to support these communities is a common goal in environmental protection programs and initiatives (e.g., MOE, 1994; CCME, 1999).

Determination of the factors exacerbating the DO condition of this embayment requires an understanding of the characteristics of this waterbody and its watershed along with identification of the relative nutrient and organic/BOD loads contributing to the degraded hypolimnetic DO condition. Excessive inputs of phosphorus originating from the watershed (e.g., Cooke & Prepas, 1998; Chambers *et al*, 2001), shoreline development (MOE, 2010), agriculture and cage aquaculture (Yan, 2005) have the potential to indirectly affect the hypolimnetic dissolved oxygen condition by stimulating algal productivity and increasing the biomass of oxidizable organic material in the water column. Excessive inputs of oxygen-consuming organic materials (i.e., high BOD) to a receiving waterbody will directly consume dissolved oxygen through microbial degradation/respiration processes (Epping *et al*, 1999). The greater the BOD and organic loading, the greater the amount of oxygen consumed and this may lead to measurable decreases in dissolved oxygen concentrations in the water column.

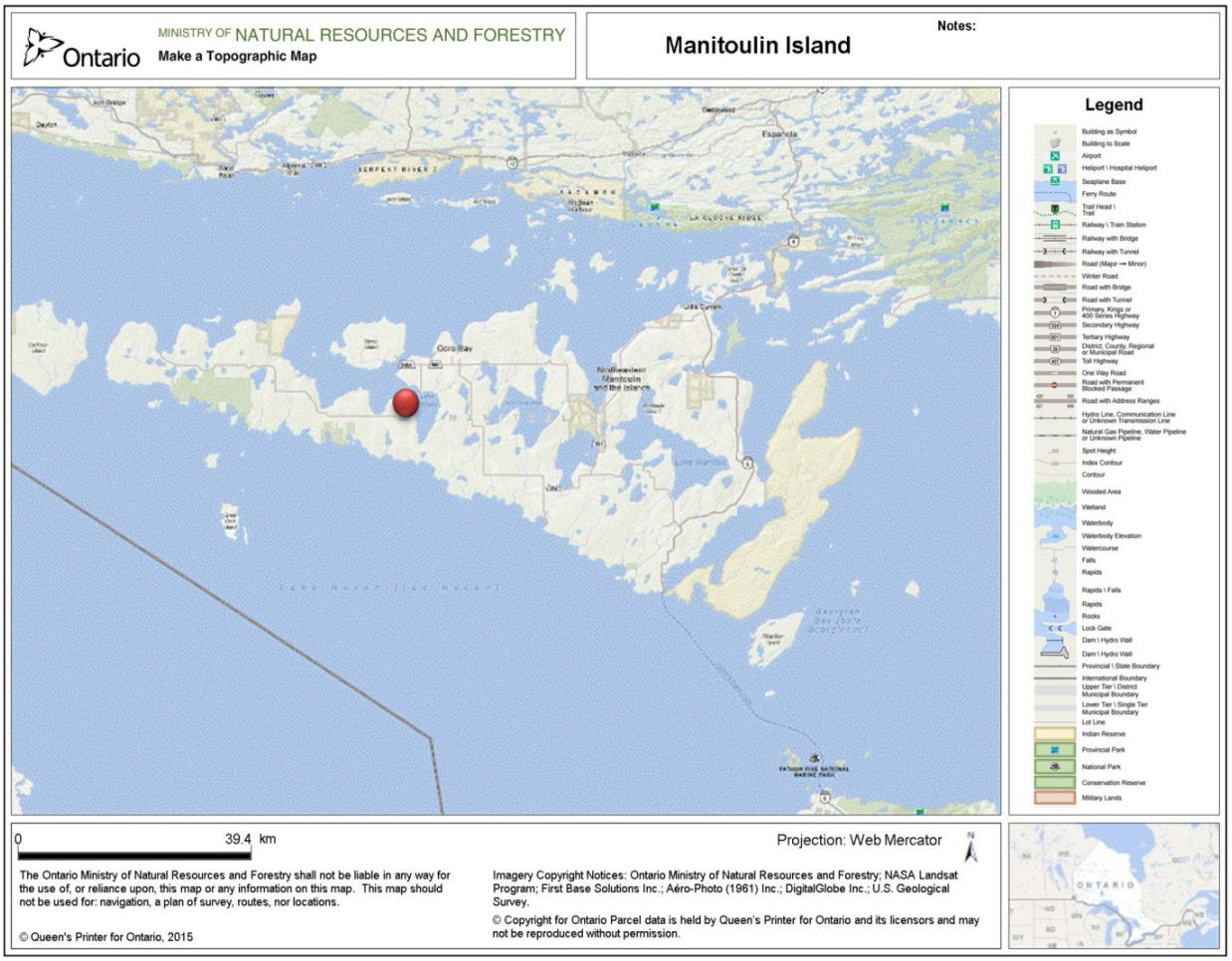


Figure 1 Map of Manitoulin Island, North Channel of the Great Lakes. (●) indicates Lake Wolsey embayment

Eutrophication studies typically focus on phosphorus (P) loading because it is generally a good indicator of the trophic status of a waterbody. However, P levels in Lake Wolsey are moderately low, particularly in the spring (< 10 µg L^{-1}) (Hamblin & Gale, 2002; Diep & Boyd, 2016), increasing in the summer and fall (Diep & Boyd, 2016). Ice-free averaged P concentrations remain well below the interim PWQO of 20 µg L^{-1} and this embayment is considered mesotrophic (Diep & Boyd, 2016).

Few studies examined the relationship between organic material (e.g., DOC, POC, TOC, particulate) and DO depletion primarily because levels are generally low. However, for some lakes subject to high inputs of allochthonous DOC, hypolimnetic anoxia and elevated methane levels can occur (Houser *et al*, 2003). Houser *et al* (2003) observed severe hypolimnetic dissolved oxygen depletion in a number of Wisconsin lakes, in the absence of significant primary productivity, and attributed it to the high DOC levels observed in these lakes. While in-lake production of organic material (e.g., algae) will also consume oxygen, Prairie *et al* (2002)

found allochthonous organic material tend to be more bioavailable and chromophoric (capable of light absorption) than authochthonous materials. According to Prairie *et al*'s (2002) study, clear-water water low-DOC waterbodies are generally not susceptible to natural DO depletion, yet for the Lake Wolsey embayment DOC levels are low and generally at or below 3 mg L^{-1} (Diep & Boyd, 2016).

Historical records indicate susceptibility to DO depletion, exacerberated by deforestation and initial settlement in the 1800s/1900s and construction of the causeway, which have reduced the resiliency and assimilative capacity of Lake Wolsey (Clerk, 2001). This system's sensitivity to DO depletion is not surprising given the large surface area and small hypolimnetic volume, however the progressive deterioration in the DO condition of this embayment in the mid-1980s and 1990s (Clerk, 2001) and the wide-spread hypolimnetic anoxia since the mid-2000s (Diep & Boyd, 2016) is of concern. In Part 1 of this report series, changes in the environmental condition of Lake Wolsey between 1986 to 2014 were notable with severe DO depletion observed since the mid-2000s with volume-weighted average DO concentrations below 1 mg L^{-1} and below the Provincial Water Quality Objectives (PWQOs) (Diep & Boyd, 2016). Other eutrophication effects include occurrences of harmful algal blooms (HABs) which have occurred regularly since 2006 (Diep & Boyd, 2016). Waterbodies where the water quality does not meet the PWQOs, such as Lake Wolsey, are classified as Policy 2 waterbodies and "*shall not be degraded further and all practical measures shall be taken to upgrade water quality to the Objective"* (MOE, 1994). Analysis of historical and recent water quality data indicate the mid-2000s likely represents a tipping point for this system (Diep & Boyd, 2016).

The progressive deterioration in DO conditions with anoxic conditions throughout the entire hypolimnion and the occurrences of HABs is concerning and highilights the need to better understand the key contributors to this hypolimnetic eutrophication effect. Potential allochthonous or anthropogenic contributors to the hypolimnetic dissolved oxygen condition in Lake Wolsey include the watershed, agriculture, aquaculture, urbanization and shoreline development..

This source loading assessment report provides:

- An overview of the available land-use features and characteristics of the Lake Wolsey watershed
- Identification and characterization of the anthropogenic activities in the watershed
- Identification of the primary sources of phosphorus and organic and total biochemical oxygen demand (BOD) to Lake Wolsey
- Total and relative load estimates of the anthropogenic and allochthonous sources of phosphorus and organic/BOD to the embayment

This report provides a summary analysis of the allochthonous and anthropogenic sources of materials to the watershed that are potentially contributing to the severe dissolved oxygen depletion observed in the embayment. It provides important background information for resource managers and interested stakeholders which can be used to identify management options for mitigating, restoring or maintaining water quality or to predict the potential effects further develoopment or industrial activity may have on this waterbody.

2 Datasets

Loading estimates are based on site-specific data collected by the Ontario Ministry of Environment and Climate Change (MOECC), Ontario Ministry of Agriculture and Food and Rural Affairs (OMAFRA) and Ontario Ministry of Natural Resources and Forestry (MNRF). OMAFRA inventoried the Lake Wolsey watershed in 2009 using field observation methods and collected information on tillage, crop type, irrigation type, fertilizer type and livestock type and this GIS-referenced land-use data was included along with bathymetry data (MNRF and MOE), water and sediment quality data (MOECC) and production data from Blue Goose / Meeker's Aquaculture. Site-specific data on Lake Wolsey from the literature (e.g., Milne *et al*, 2015; Hamblin & Gale, 2002; Clerk, 2001), and from our dataset (Diep & Boyd, 2016) were included where possible.

We reviewed the literature for applicable export coefficients and industry-relevant data, which have been combined with the site-specific land use data to calculate load estimates for allochthonous and anthropogenic sources. Literature-based export coefficients for the watershed, natural land-use features, agriculture, shoreline development and urbanization were reviewed and considered. We did not include atmospheric deposition load estimates as Milne *et al* (2015) found this to be negligible. We applied industry-relevant data, primarily from the University of Guelph (e.g., Bureau *et al*, 2003; D. Bureau, pers. comm.) and other published literature.

3 Watershed Characteristics

The watershed of Lake Wolsey, including Lake Wolsey, is 12 037 hectares (ha) in size. According to the land-use data Lake Wolsey itself is ~ 2212 ha and accounts for approximately for one-fifth of the watershed area. The watershed of Lake Wolsey has poor drainage due to slow water percolation and the flatness of the land, therefore land run-off is low with water collecting at or near the surface (Hoffman *et al*, 1959). Although there are ephemeral streams (Milne, 2012), there are no significant tributaries to Lake Wolsey (Clerk, 2001).

Lake Wolsey possesses a large littoral zone with fringing wetlands dominating the northern shoreline and limited shoreline development in the south. It is moderately deep, with a maximum depth of 24 m (Hamblin & Gale, 2002). The deep basin is located in the south-west region of the embayment in close proximity to a cattle farm and a commercial-scale cage

aquaculture operation (Figure 2). Rock bluffs occur along the southeast and southwest shores of Lake Wolsey where water depths drop rapidly.

Table 1 Summary table of the Lake Wolsey watershed land-use types, 2009

Land Use Category	Area (ha)	% Land Use
Woodlot	5914.0	60.2%
Agricultural Fields	2502.8	25.5%
Rough Land	423.3	4.3%
Water	314.0	3.2%
Riparian	283.5	2.9%
Ditches	106.2	1.1%
Farmstead	103.7	1.1%
Fencerow	75.5	0.8%
Road	55.7	0.6%
Recreation	33.2	0.3%
Urban	7.3	0.1%

We used the 2009 OMAFRA land-use data to determine the total and percent area of the various land-use components. We found Lake Wolsey's watershed to be relatively undeveloped with woodlot as the main land-use type, occupying 60% (~5900 ha) of this watershed and this is consistent with Milne *et al*'s (2015) assessment. Elm, alder and spruce are the dominant tree types in these woodlots. Milne *et al* (2015) further partitioned this land-use category and found woodlot comprised of 50% dense and 12% sparse forested lands. Other natural land-use features include rough land, which accounts for 4.3% (~420 ha) of the watershed and ditches comprising another 1.1% (~106 ha) (Table 1, Figure 2). Fencerows exceed road area, both of which account for < 1% of the total watershed area.

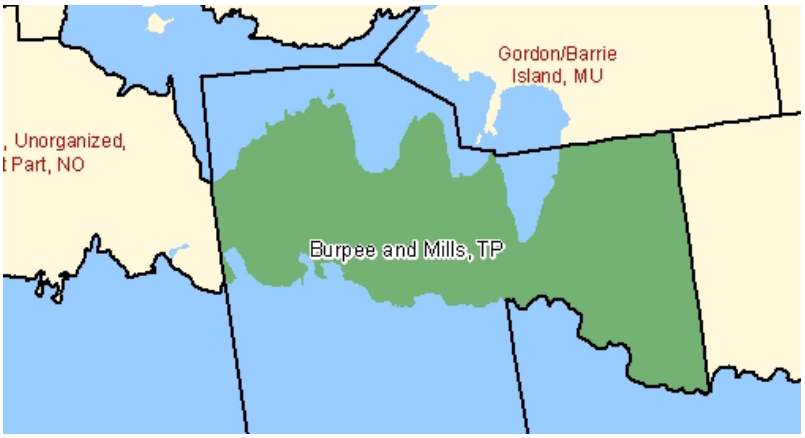


Figure 2 Burpee and Mills Township, Ontario (from Statistics Canada, 2013)

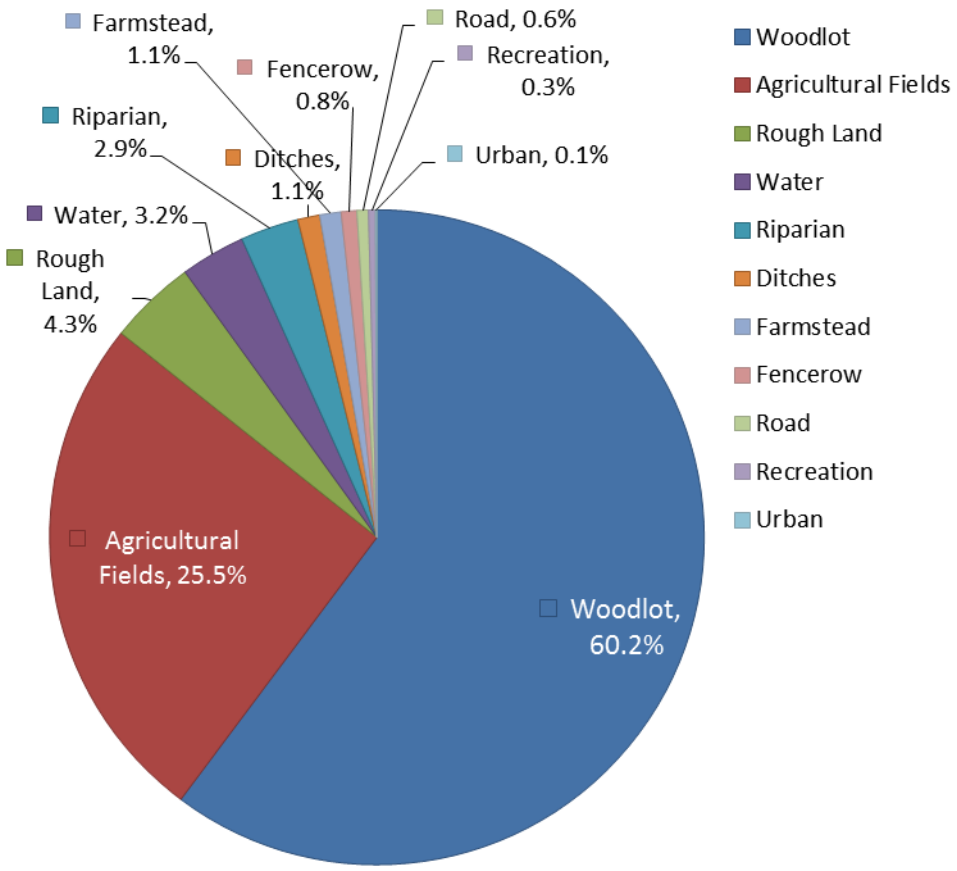


Figure 3 Lake Wolsey watershed land-use categories based on 2009 watershed inventory (data from OMAFRA)

A)

B)

Figure 4 Aerial photograph of a) agricultural fields along the western shoreline and b)) woodlots along the eastern shoreline of Lake Wolsey, taken on October 14, 2015.

According to the 2009 land-use information anthropogenic activity is low in this watershed (Table 1, Figure 3). Urbanization and recreation combined accounts for less than 0.5% (~40 ha) of the watershed area. Urbanization occurs primarily along the south-western shoreline of Lake Wolsey. Natural land features such as ditches, fencerow and rough land area exceed the urbanized and recreational areas of the Lake Wolsey watershed (Table 1, Figure 2).

The Lake Wolsey watershed is located in both Burpee/Mills and Gordon Townships. The southern portion of the Lake Wolsey watershed is situated in Burpee and Mills Township (Figure 2) with the northern portion located in Gordon township. Based on the Statistics Canada census data, the population of Burpee and Mills Township is low, with 362, 329 and 308 people in 2001, 2006 and 2011, respectively, resulting in a population density ranging from 1.4 to 1.7 per km^2 (Statistics Canada, 2007; Statistics Canada, 2013), indicating a progressive decline in urbanization and anthropogenic activity within this watershed. Gordon Township is slightly more populated with a population of 473, 412 and 491 in 2001, 2006 and 2011, respectively, (Statistics Canada, 2007; Statistics Canada 2013) and this data reflects the recent almagation of the townships of Gordon and Barrie Island in 2007(Statistics Canada, 2013). Recent census data indicates a slight increase in population density, however overall density remains low at 2.6 people per per km^2 and is below the national average and Ontario average of 3.7 and 13.4 people per per km^2, respectively (Statistics Canada, 2013; Statistics Canada, 2007). The low overall population density is consistent with the watershed land-use data, where we found anthropogenic activity to be < 1% in this watershed (Table 1).

This watershed is not intensively farmed. Agricultural activity is moderate, with farmsteads accounting for 1.1% (~100 ha) of the watershed while fields accounted for another 25.5% (~2500 ha) (Table 1). These estimates are lower than Milne *et al* (2015) estimate of 32% for agricultural lands. The agricultural fields and farmsteads are situated mainly on the north and southwest ends of the watershed. Most of the agricultural lands on the north end are comprised of fields and these agricultural lands likely drain into Lake Wolsey via a small ephemeral creek (Clerk, 2001). The agricultural fields and farmsteads along the south-western portion of Lake Wolsey appear to be a mixture of hay and pasture with limited poultry and barley production.

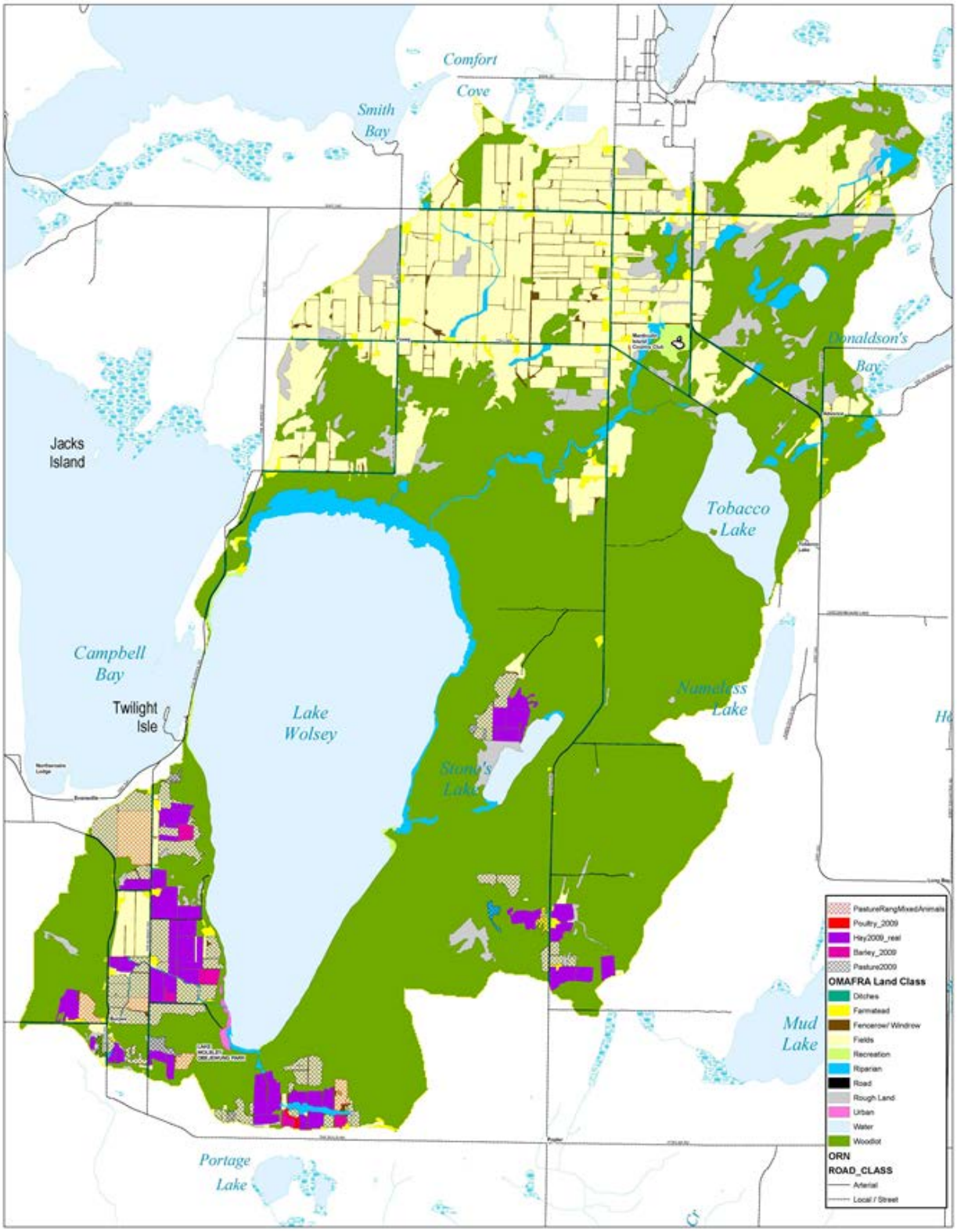


Figure 5 Map of the Lake Wolsey watershed and land-use features (2009 data from OMAFRA 2009

4 Industry: Cage Aquaculture

In the past, sawmills were the primary industry (ca 1900) in Lake Wolsey during the logging and deforestation era, (Clerk, 2001; references therein). Today, the primary industry present in Lake Wolsey is the commercial-scale cage aquaculture operation. It is one of six licenced commercial-scale cage aquaculture operation in the Great Lakes and the only site located in a Type 2 location (i.e., bounded hypolimnion) (Boyd *et al*, 2001).

Cages are stocked typically with 50 g fish that are grown to market size (1 kg) for human consumption within 18 months (Milne *et al*, 2015). Cage aquaculture operations typically have two peak feeding seasons, generally in the spring and fall when water temperatures are optimal. Substitence feeding occurs when water temperatures are suboptimal, generally in late-summer and winter.

Cage aquaculture operations rely on the natural environment to disperse wastes from the facility and the net design of the cages allows for water flow between the cage structure and the receiving waterbody. As such, wastes generated by the facility are rapidly dispersed in the water column or settle to the lakebed, generally in the immediate vicinity fo the cages.

Figure 6 Aerial photograph of Blue Goose / MTM cage aquaculture operation in Lake Wolsey with 16 square cages and one experimental hexagon cage, taken on October 14, 2015.

Figure 7 Aerial photograph of Blue Goose / MTM cage aquaculture operation and land-based composting facility in Lake Wolsey taken on October 14, 2015.

In 1986, initial production scale was small producing < 10 metric tonnes (or 10 000 kg) of rainbow trout annually from 1986 to 1989 (Table 2, Figure 4). Rapid expansion occurred between 1990 and 1996 with a ~ 30-fold increase in operational scale from ~ 9 to ~320 tonnes (Table 2, Figure 4). Currently, this operation is licenced with a feed allocation quota of 510 tonnes. The operational scale of the cage aquaculture facility has varied from year to year with peak production of 405 tonnes of rainbow trout produced and 460 tonnes of feed used in 2014 (Table 2). Milne *et al* (2015) cited eight permanent and eight seasonal cages producing 280 tonnes of rainbow trout in 2007, while Hille (2008) report 18 functional cages producing 295 tonnes of fish annually. More recently, during a 2015 aerial survey of the cage aquaculture facilities in the Great Lakes we noted that this operation currently posseses 16 square cages and one large hexagon cage (Figure 6). This operation occupies a water lot that is 160 m by 90 m and the square cages are typically 15 m by 15 m. With the new hexagon structure at the end of the structure, this cage array extends out to the land tenure boundary. Cages are typically 15 m deep (Reid *et al*, 2006) and though some of the cages are sited over shallow depths, the majority of the cage structure is site over water depths 15 m and greater. The Blue Goose / MTM aquaculture operation also includes a land-based composting facility which Daynard (2012) reports uses 4.5 million pounds of fish processing byproduct, mainly offal, and by-products of forestry industry (sawdust) to produce the compost material.

Table 2 Annual rainbow trout cage aquaculture production (kg), feed usage (kg) and feed conversion ratio (FCR), Lake Wolsey (1986 - 2014)

Year	Production (kg)	Feed Usage (kg)	FCR
1986	1,624	4,000	2.46
1987	1,882	5,447	2.89
1988	5,903	8,442	1.43
1989	5,230		
1990	9,318	6,685	0.72
1993	43,403		
1994	119,099		
1995	235,000		
1996	323,546		
1997	114,480	249,275	2.18
1998	240,725	462,712	1.92
1999	352,336	380,112	1.08
2000	278,361	428,772	1.54
2001	301,018	450,462	1.50
2002	313,067	468,000	1.49
2003	189,655	418,000	2.20
2004	285,844	460,708	1.61
2005	259,002	316,221	1.22
2006	281,307	311,884	1.11
2007 *	272,938	354,820	1.30
2008	292,001	354,800	1.22
2009	368,212	457,112	1.24
2010	356,366	401,524	1.13
2011	195,220	212,900	1.09
2012	171,120	340,693	1.99 **
2013	220,544	389,109	1.76
2014	405,400	460,295	1.14

* 2007 fish production and FCR data from Milne *et al* (2015)

** In 2012, the cage aquaculture operation experienced weather-related fish loss, resulting in a high feed conversion ratio (FCR)

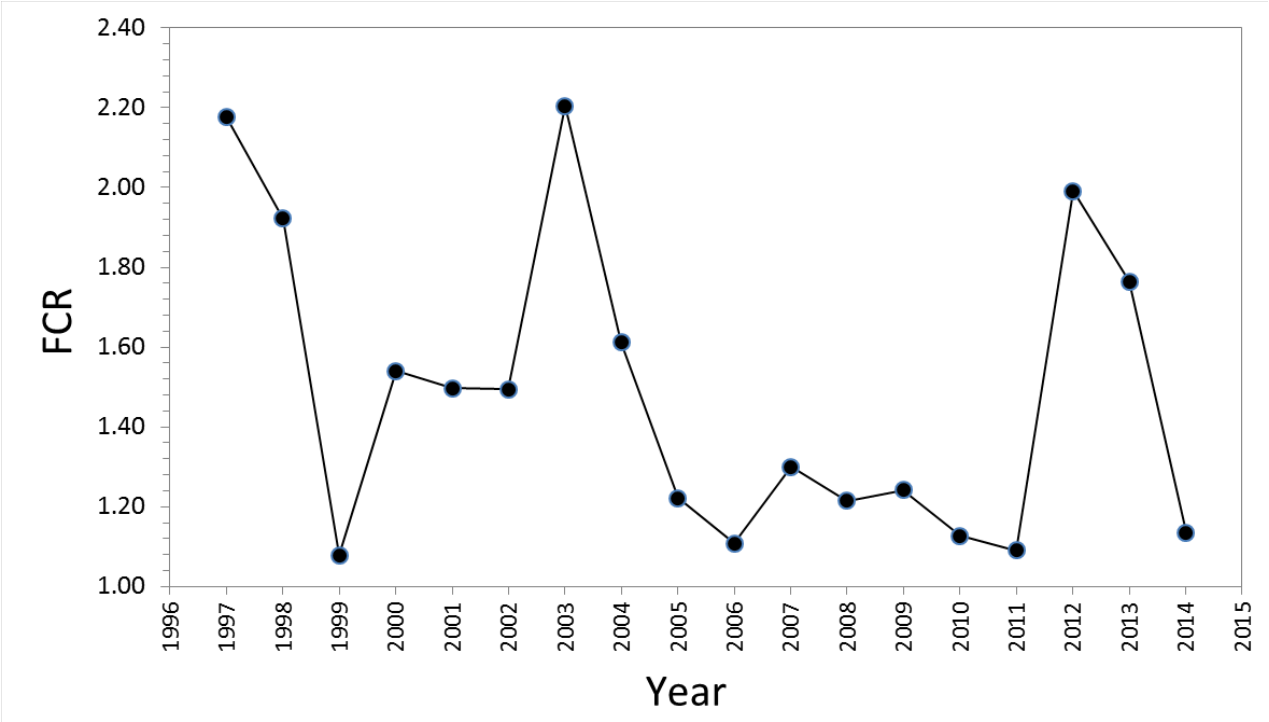


Figure 8 Economical feed conversion ratios (FCRs), amount of feed used to fish produced, for the aquaculture operation in Lake Wolsey from 1997 – 2014. (2007 production data from Milne *et al*, 2015) * Aquaculture operation experienced weather-related fish loss in 2012.

This operation is currently the only organically certified cage aquaculture operation in the Great Lakes, certified by Ocean Trust Ireland (CleanFish, 2016). Stocking densities are maintained below 15 kg m^{-3} (CleanFish, 2016) and can be as low as 10 kg m^{-3}. Although feed conversion ratios (FCRs), which is the weight of food fed to weight gained, can be as low as 1.14 (Bureau *et al*, 2003), we found the economical FCR, which is the total feed purchased to fish produced, ranged widely for this operation. Prior to 1999, FCRs commonly exceeded 2.0, however improvements in the FCRs occurred since the mid-2000s and FCRs are generally low, except in 2012 and 2013 where FCRs were as high as 1.99 and 1.76, respectively. Weather-related fish loss resulted in a high FCR in 2012. Milne *et al* (2015) reported a FCR of 1.3 during the 2007 operational year and if we exclude the 2012/13 data, this operation's more recent economical FCRs are generally below this value, but are consistent with reported economical FCR's of 1.05 and 1.18 for fall-stocked and spring-stocked fish, respectively (Bureau *et al*, 2003).

5 Phosphorus Loading Assessment

5.1 Watershed-based Phosphorus Inputs: Natural Features

Wetlands compromise a small proportion of the watershed, occupying 512.8 ha or 4.3% of the total watershed area. There are with 45 wetland areas ranging from 2.3 m^2 to 95 ha. Fringing wetlands also occur along the northern shoreline of Lake Wolsey (Figure 9). The marginal

vegetation that surrounds this embayment is similar to that found in other sheltered embayments and those along the northern shores of Lake Wolsey represent the largest riparian zone (~ 155 ha). There are ~ 30 smaller riparian areas, ranging from 24.3 m^2 to 15.6 ha, located mainly on the northside of the watershed. Combined the riparian areas occupy 3% of the total watershed area. Wetlands in Florida and Wisconsin can export as much as 0.66 kg P ha^{-1} (Harper, 1998) and 0.11 kg P ha^{-1} per year (Garn *et al*, 2006), respectively, however in Ontario, the P export coefficients for wetlands are lower ranging from 0 to 0.05 kg P ha^{-1} (MOE, 2010). When we applied the Ontario P export coefficients for wetlands to the Lake Wolsey watershed we found wetlands contributed a maximum of 25.6 kg P per year; while riparian areas contribute a maximum of 14.2 kg P per year and combined they contribute ~ 40 kg P per year.

Figure 9 Aerial photograph of fringing wetlands located along the north shores of Lake Wolsey, taken on October 14, 2015.

There are over 110 rough land areas varying in size from ~ 110 m^2 to 37.4 ha. These rough land areas occur primarily on the northside of the watershed. Between these rough land features and the embayment are large areas of woodlot, which would likely mitigate some overland runoff. P export coefficients are not available for rough land, however because rough land areas are impermeable, they may be more similar to industrial areas where percent impervious is > 85% (Harper, 1998). Loehr *et al* (1989) calculated P export coefficients for industrial areas ranges from 0.4 kg P ha^{-1} to 4.1 kg P ha^{-1} and Harper (1998) identified a P export coefficient of 3.7 kg P ha^{-1} (Harper, 1998), which is within the range of export coefficients identified by Loehr *et al* (1989). If we apply the minimum export coefficient, which is likely more suitable for these rough land areas, the potential phosphorus loading from rough land areas is 169.3 kg P per year.

Ditches typically retain water, but will contribute to overland flows during storm events, however we were unable to find P export loading coefficients for this land type. We expect P loading from this land type to be low since these ditches are not in close proximity to Lake Wolsey. Phosphorus loading from rough land areas and ditches are expected to be episodic, corresponding to storm events, therefore contributions from this land use type are expected to be highest in the spring.

Table 3 Lake Wolsey watershed land-use characteristics (based on OMAFRA land-use inventory data, 2009)

Land Use Category	Number	Minimum	Maximum	Average	Total area
		m^2	ha	ha	ha
Woodlots	65	422	2032	91.0	5914.0
Waterbodies[1]	5	497	2218	506.3	2531.5
Fields	458	8	115	5.5	2502.8
Rough Land	111	110	37	3.8	423.3
Riparian	31	24	155	9.1	283.5
Farmstead	115	2	4	0.9	103.7
Ditches	30	26	13	3.5	106.2
Fencerow	149	18	12	0.5	75.5
Road	2	300	56	27.8	55.7
Recreation	5	4584	23	6.6	33.2
Urban	3	2030	6	2.4	7.3

[1] Includes Lake Wolsey (2218 ha)

This watershed is mostly forested (~60%) with 65 stands of woodlot, ranging in size from 422 m^2 to 2,032 ha. P export coefficients can be as low as < 0.1 kg ha^{-1} yr^{-1} (Reckhow *et al*, 1980; Rast & Lee, 1978); Loehr *et al*, 1989) or > 0.8 kg ha^{-1} yr^{-1} (Reckhow *et al*, 1980; Loehr *et al*, 1989) and when applied to Lake Wolsey results in an annual P load ranging from less than 203 kg to greater than 1 626 kg. However, the average P coefficient for forested land is ~ 0.2 kg ha^{-1} yr^{-1} (Reckhow *et al*, 1980; McFarland & Hauck, 2001; Clesceri *et al*, 1986) and if we apply this P export coefficient to the Lake Wolsey watershed we find woodlots potentially contribute an average of 1 183 kg of P per year. This estimate appears realistic given the tree type coverage (e.g., elm, alder and spruce) and soil composition (e.g., clay loam till and lacustrine silt loam).

Given high woodlot coverage in this watershed, it is not surprisig that woodlots dominate the natural-land use featuress with a P load of 1 183 kg. Combined with P loads from wetlands/riparian, rough land and forested area, these natural land use features contribute a total of 1 392 kg P to the watershed annually.

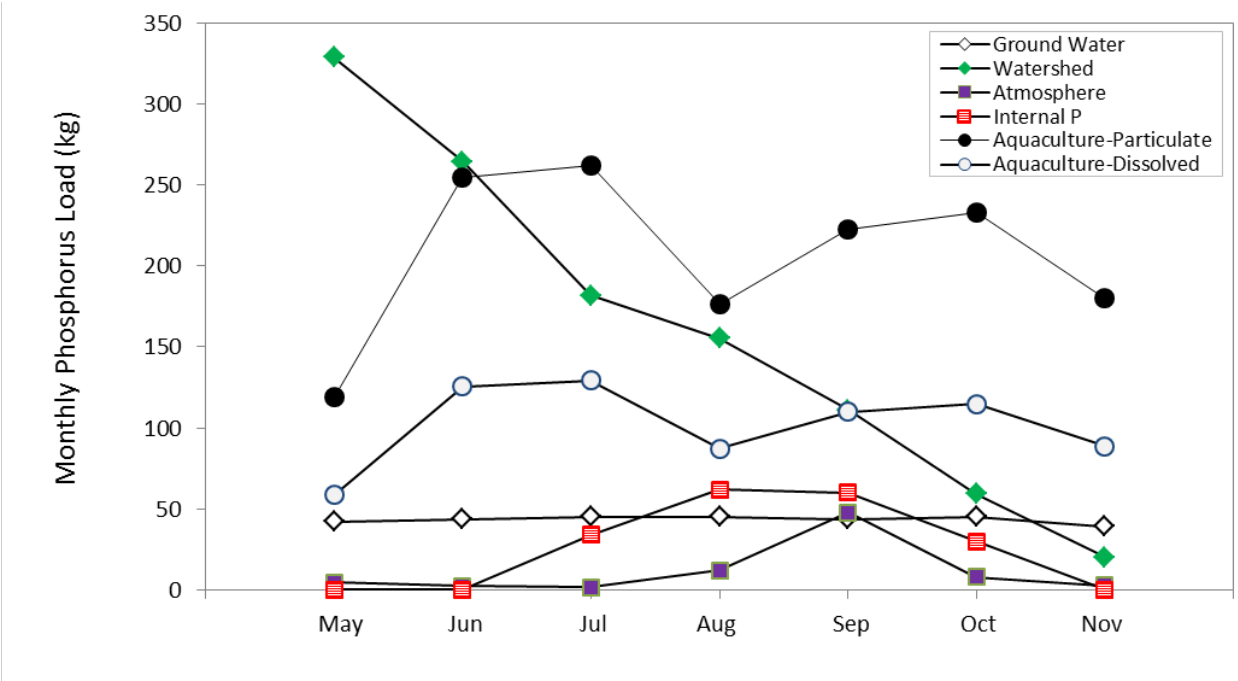


Figure 10. Monthly phosphorus loads (kg) from the watershed (◆), groundwater (◇), atmosphere (■), internal loading (■), and total dissolved (○) and particulate (●) P from cage aquaculture operation (Data from Milne, 2012)

Milne *et al* (2015), based on sampling of ephmeral streams and using a water balance approach, estimated non-point sources contributed a maximum of 5 kg day^{-1} of P, with an average contribution of 0.33 kg day^{-1} of P, resulting in a total P load of 1120 kg from watershed sources. The low average P load rate of 0.33 kg day^{-1} is likely due to many of the ephemeral streams drying up during the ice-free season.

Milne et al's (2015) P load estimate of 1.1 tonnes is equivalent to our P load estimates for the watershed's natural land-use features (i.e., woodlot) and is nearly half the P load when we factor in agricultural sources of P. Their estimate is only for the the May to November period (Milne *et al,* 2015) and when we normalize this estimate to arrive at an annual P load, we find the the total P load from the watershed is 1920 kg (Jan – Dec), or 1825 kg when we apply the maximum P load rate of 5 kg day^{-1}.

Watershed input is highest in the spring (Figure 10; Milne *et al*, 2015), as is generally observed in other waterbodies. There is a progressive decline in watershed-based P load with May exhibiting the highest P load of over 300 kg per month and declining to less than 50 kg per month by November. This trend is sharp contrast to the increasing ambient P concentrations trend over the ice-free seen observed in Lake Wolsey (Figure 11; Diep & Boyd, 2016), which suggests non-watershed based sources are contributing to the elevated P levels observed in this embayment.

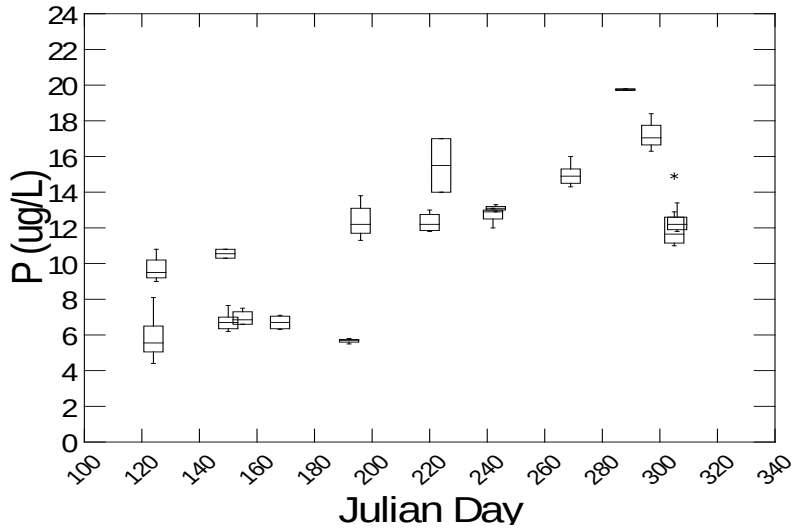


Figure 11 Total phosphorus concentrations (µg L^{-1}) as a function of Julian day over the ice-free season, Lake Wolsey (MOECC data, 2008 – 2011) (from Diep & Boyd, 2016)

From our evaluation of the watershed data and available P export coeffients, we find woodlots to be the primary "Natural Feature" source of P to Lake Wolsey with additional minor inputs from wetland/riparian, rough land and ditches. Wetlands/riparian, rough land and forested areas potentially contribute 40 kg P, 169 kg P and 1 183 kg P per year, respectively yielding an estimated total of 1 392 kg P to the watershed annually.

5.2 Agricultural-based Phosphorus Inputs

Agricultural activities can be a significant non-point source of nutrients (e.g., Hobbie & Likens, 1973; Cooke & Prepas, 1998). The percentage of the watershed that is intensively farmed and the type of agricultural activity will determine total P loads from this source and the relative contribution this activity has on the trophic status of the waterbody. On Manitoulin Island, approximately 40% of the island is farmed, however the soils of the island limits the agricultural potential, therefore much of the farmed areas are used for livestock grazing (Hoffman *et al*, 1959).

The agricultural intensity in the Lake Wolsey watershed is moderate to moderately low with just over a quarter of the watershed (~ 2500 ha) being farmed (Table 1, Figure 3). There are ~ 458

agricultural fields in the Lake Wolsey watershed, averaging 5.5 ha in size with a maximum of 115.3 ha. In 2009, a more detailed agricultural assessment of the agricultural lands located in the southern half of the Lake Wolsey watershed was undertaken by OMAFRA. Approximately a quarter of the fields (~ 660 ha) were assessed providing additional detailed agricultural data.

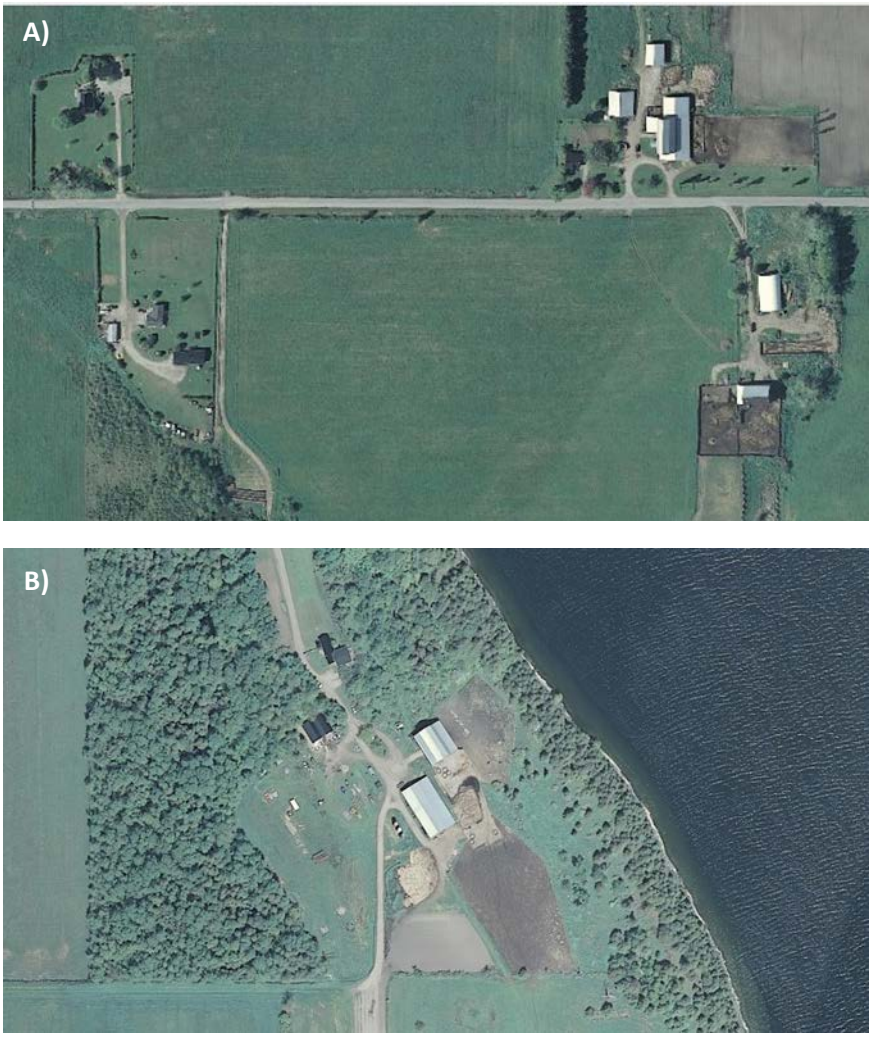


Figure 12 Satellite images of farmsteads in a) Gordon Township, ~ 3 km from Lake Wolsey north shore and b) Burpee/Mills Township along the western shoreline of Lake Wolsey. Imagery Copyright Notices: Data provided by Ontario Ministry of Natural Resources and Forestry © Copyright: NASA Landsat Program. All Rights Reserved

From this detailed assessment over 50% of the agricultural lands were identified as pasture land. Hay was the second highest agricultural land type (~ 299.5 ha) followed by barley (23.4 ha). Based on this detailed assessment we assumed that 51.1%, 45.3% and 3.5% of the agricultural lands in the Lake Wolsey watershed were used for pasture, hay production and barley production, respectively. Of the agricultural lands surveyed, only 17.3 ha apply conservation tillage methods with the remainder applying conventional tillage. Conventional

tillage methods will generally result in higher export of nutrients compared to conservation tillage methods (Reckhow *et al*, 1980).

Literature-based agricultural P export coefficients vary widely. For pasture land, P export coefficients were dependent on the fertilizer application, grazing intensity and cover type (Reckhow *et al*, 1980). Loehr *et al* (1989) P export coefficient for pasture land ranged from 0.1 kg ha^{-1} yr^{-1} to 0.6 kg ha^{-1} yr^{-1} and Reckhow *et al* (1980) identified P export coefficients as low as 0.1 kg ha^{-1} yr^{-1} and as high as 4.9 kg ha^{-1} yr^{-1}, with an average P export coefficient of 1.5 kg ha^{-1} yr^{-1}. The P export coefficient identified in the MOE Lakeshore Capacity Assessment Handbook MOE (2010) P ~ 0.1 kg ha^{-1} yr^{-1}, falls at the lower end of the P export coefficient spectrum identified by both Reckhow *et al* (1980) and Loehr *et al* (1989). Reckhow *et al* (1980) export coefficients are substantially higher than the range identified by Loehr *et al* (1989) and MOE (2010), likely because their assessment included areas with various grazing level intensities and therefor included intensive agricultural lands. The P export coefficient commonly used in Ontario is consistent with the minimum identified by Reckhow *et al* (1980) and Loehr *et al* (1989), and is likely more applicable to the Lake Wolsey watershed. Therefore, for the Lake Wolsey watershed, we have chosen to apply the MOE (2010) P export coefficient of 0.1 kg ha^{-1} yr^{-1} resulting in a potential annual P load of 128 kg from pasture land.

Agricultural lands used for hay production contributes substantially more P load per unit area than pasture land. The P export coefficient for hay production is 0.64 kg ha^{-1} yr^{-1} (Reckhow *et al*, 1980; references therein), which is over six times the P export coefficient for pasture land. P export coefficient data was not available for barley, but is likely < 1.0 kg ha^{-1} yr^{-1}. If we apply the P export coefficient of 0.64 kg ha^{-1} yr^{-1} to the remainder the agricultural lands in the watershed, assuming it is primarily used for hay production, these agricultural lands potentially contribute 782 kg P yr^{-1}. Combining both pasture land and hay, the agricultural fields potentially contribute 910 kg P annually to the natural receiving environment.

There are 115 farmsteads in the Lake Wolsey watershed, averaging ~ 0.9 ha in size (to a maximum size of 4.2 ha) accounting for 104 ha or 1.1% of the total watershed area. Although there is some livestock information it is limited to the Burpee/Mills Township area, with some of the lands identified as rough land, riparian, woodlot and farmsteads were re-designated as mixed animal agriculture. Five areas ranging from 0.5 ha to 40.3 ha in size, for a total area of 70.2 ha were identified as mixed animal range agricultural use.

The P export coefficients for farmsteads/livestock can vary widely depending on the presence and or number of feedlots and manure storage areas, livestock quantity and type. Although literature-based P export coefficients for agricultural lands can be low, ranging from 0.26 to 0.99 kg ha^{-1} yr^{-1} (Clersceri *et al*, 1986; Rast & Lee, 1978; Dodd *et al*, 1992), Loehr *et al's* (1989) estimated P export coefficients of 0.08 kg ha^{-1} yr^{-1} to 3.25 kg ha^{-1} yr^{-1} for mixed agriculture, with an average P export coefficient of 1.13 kg ha^{-1} yr^{-1}. If we assume 104 ha is used for mixed

agriculture, this results in a P load ranging from 8.3 kg to 338 kg. However, feedlots in particular are significant sources of P with export coefficients ranging from 70 to 308 kg P ha^{-1} based on large feedlots with 100 to 500 heads, or 80 to 550 animal units (455 kg live weight) (Coote & Hore, 1977; Coote & Hore, 1978). These feedlot sizes are larger than what is expected in the Lake Wolsey watershed. For example, in 2005 there were 174 farms on Manitoulin Island raising a total of 7 627 heads of cattle, for an average of 44 heads per farm (Cummings, 2011). Waste export coefficients on a per animal unit basis (455 kg live weight) is likely more appropriate and for cattle, P export coefficients ranged from 0.11 kg to 0.38 per animal unit (Coote & Hore, 1978). We applied these P export coefficients and assumed that there are, on average, ten cattle per feedlot/farmstead for a total of 1150 cattle in the Lake Wolsey watershed. This results in a total P load ranging from 127 kg to 437 kg for livestock, which is higher than that estimated based on mixed agriculture land use. In 2014, the Manitoulin Cattle Exchange (MCE) reported only 800 cattle were processed on Manitoulin Island (McCutcheon, 2014) and given that Manitoulin Island is approximately 288 000 ha (Hoffman et al, 1959) and the Lake Wolsey watershed (12 037 ha) is approximately 4% of the total Manitoulin Island area, the P load attributable to livestock likely represents the maximum for this agricultural source.

These estimates can be further refined with detailed farm information including presence of manure storage areas, livestock type and quantity and paved or unpaved feedlots. For example, poultry is identified as one of the livestock types in Burpee/Mills Township. Although, poultry manure generally has a higher phosphorus content than cattle manure (Udeigwe & Wang, 2010), the amount of waste produced is much lower. Based on our assessment the total P load from agriculture is up to 1 347 kg of P from pasture land, hay production and livestock.

Milne *et al* (2015) in their 2007 assessment of Lake Wolsey, estimated non-point sources contributed 1.1 tonnes of P from the watershed, which represents the combined inputs of natural land-use features (e.g., woodlots) and agricultural lands. If we assume this P load is equally attributable to the natural land-use features and agricultural lands, then Milne et al's (2015) estimate is approximately half of our land-use based estimate for agricultural lands, due in part to the estimate covering only the ice-free season (May – November). When we normalized Milne *et al's* (2015) estimate to arrive at an annual P load we find the total P load from non-point sources to be 1.9 tonnes, which remains well below our watershed (natural land use and agricultural) annual P load of 2.7 tonnes, which suggests tributary-based monitoring of the ephemeral streams of Lake Wolsey indicates lower P loads from agricultural and the natural land-use features of the watershed.

Nutrient inputs from agriculture activities originating on the northside of the watershed are likely mitigated and buffered as it is transported through the large woodlot areas separating these agriculture fields from Lake Wolsey (Figure 12). The agriculture field and farmsteads on the southwestern side of the watershed are in closer proximity to Lake Wolsey and phosphorus

inputs are likely more direct and are expected to have a larger impact on the natural receiving environment (Figure 12).

Phosphorus inputs from agricultural activity can be significant, with estimated P load of 1.3 tonnes. In Ontario, the Ontario Ministry of Agriculture and Rural Affairs (OMAFRA) have developed a number of nutrient management tools and resources through the Best Management Practices Program to help farmers optimize operational practices and reduce potential nutrient and organic loads. This program provides practical solutions through the use of worksheets on field management, manure storage and nutrient application rates of manure, biosolids or fertilizer (OMAFRA, 2015a & 2015b).

By using tools such as the Agricultural Planning Tools Suite (AgriSuite), which is a provincial nutrient management planning software, farmers can determine the phosphorus (P) index of their land parcels. The P index is based on soil erosion, water runoff, soil P levels, commercial fertilizer application rate and method and manure/biosolid (organic P) application rate and method (OMAFRA, 2015c). This index is then used to determine the optimal phosphorus application rate for their crops which would minimize P loss while maintaining soil productivity and reduce soil erosion (OMAFRA, 2015b,c,d). For example, a P index of greater than 30 ppm indicates a higher risk of P loss, resulting in higher recommended setback distances from the P application area and shoreline and a lower maximum P application rate (OMAFRA, 2015c). AgriSuite can be also used to determine if agronomic requirements are being met as well as how fertilizer type and blend, application timing/method and application rate will affect the economics of the farm by estimating the costs associated with the fertilizer/manure application.

In AgriSuite, cropping and field management information, such as crop type, background soil P levels, tillage method and practice and yield are used to determine crop nutrient balances and nutrient application rate (OMAFRA, 2015d,e). In the Lake Wolsey watershed, the agricultural fields used for pasture, hay, wheat or barley production would require 180, 180, 70 and 110 kg P ha^{-1}, respectively. This would generate typical yields of 4.9, 3.0, 5.1 and 4 tonne per hectare for hay (pasture land), hay, winter wheat and spring barley, respectively, assuming no-till.

AgriSuite can also be used to predict how changes in farming practices will affect fertilizer/manure application and P index. For example, if barley is used as a cover crop and this cover crop is harvested, no additional fertilizer/manure application is required and this crop would yield up to 2.5 tonne per hectare of barley and remove 6 kg ha^{-1} of P. However, if this barley is used as a spring crop with a yield of 4 tonne ha^{-1}, it would require a P application rate of 110 kg ha^{-1} and remove 33 kg ha^{-1} P upon harvest. Changing the tillage method from no-till to plough increases the P index, particularly if it is done in the fall. The OMAFRA tools and resources can be used to identify best farming practices to optimize yields while also minimizing P inputs.

From our literature review and evaluation of the Lake Wolsey agricultural land-use data, pasture land and hay production were the dominant agricultural land types and were the main agricultural contributors of P, followed by farmsteads and mixed animal range, resulting in a total P load of 1.3 tonnes. On a per unit area basis, farmsteads have the potential to contribute significantly to the P load, however the total area is small and detailed agricultural practices (e.g., feedlots, manure storage areas etc) are unknown. The Best Management Practices Program administered through OMAFRA, is an Ontario-based resource for farmers that provides not only practical solutions to farmers on how to optimize their farming practices to increase yields, but the data used in the program can also be used to refine loading estimates for agricultural sources of P to Lake Wolsey. If information on fertilizer/manure application rates, background soil P, crop type, livestock type and density is provided along with improved assessment of the watershed, such as identifying the number and type of livestock and number of manure storage areas, can be used to better estimate the agricultural P to the Lake Wolsey system.

5.3 Industrial-based Phosphorus Inputs

Industrial activity, such as commercial-scale cage aquaculture can contribute significant amounts of nutrients and organic material to waterbody (Yan, 2005; Hamblin & Gale, 2002; Chambers *et al*, 2001; Bristow *et al*, 2008). Historically waste feed represented a significant proportion of the total solid waste discharged from cage aquaculture operations (e.g., Yeo *et al*, 2004; Reid *et al*, 2008). Recent advances in feed formulation with improvements in feeding strategies have dramatically reduced the amount of feed required. Standard feed waste rate of 5% is commonly used (Bureau *et al*, 2003; Stechey *et al*, 2005) and at the experimental cage aquaculture facility in the Experimental Lakes Area (ELA) the feed waste accounted for less than 4% of the total settled aquaculture wastes underneath the cages, the rest dominated by faecal material (91% - 98%), (Findlay *et al*, 2009). More recently, DFO (2015) reported feed waste of $\leq$ 1%, as such the majority of the wastes produced is fish faecal waste and this waste has high nutrient content. Naylor *et al* (1999) determined a phosphorus (P) and nitrogen (N) content of 2.54% and 2.83%, respectively for fish faecal waste for feed commonly used at the time. More recent literature reports an average phosphorus and nitrogen content of 2.87% and 3.97% for rainbow trout faecal waste (Moccia *et al*, 2007). Yeo *et al* (2004) in their review of aquaculture wastes and waste by-products found the N and P content of fish faecal waste to be similar to livestock manure and both generally represented the upper limit in nutrient content.

Standard Ontario commericial feeds result in feed conversion ratios (FCR, kg of dry weight feed required to grow a kg of wet weight fish) ranging from 1 .14 to 1.29 with phosphorus outputs of 7.5 kg to 15.2 kg per tonne fish produced with feed types A and C being the two most commonly used fish feed types in Ontario (Bureau *et al*, 2003). These estimates are based on a standard 5% feed waste rate (Bureau *et al*, 2003; Stechey *et al*, 2005). We updated these estimates to 1% feed waste rate (DFO, 2015) to reflect current conditions and normalized the estimates to

feed usage (kg waste per metric tonne feed used) in Table 4. The FCRs, adjusted to 1% feed waste, ranged from 1.09 to 1.21 (Table 4). Cage aquaculture operations potentially release 4.7 kg to 7.3 kg of particulate P and 1.4 kg to 4.1 kg of dissolved P per tonne of feed used, resulting in a total P load of 6.2 to 11.3 kg P per tonne feed used (Table 4). Nitrogenous waste loadings are high, with 32 to 44 kg dissolved N per tonne feed used and 7.8 to 7.9 kg particulate N per tonne feed used. The particulate P dominates the P total, ranging from 64 % to 78%, while the dissolved fraction represents at least 80% of the N pool.

Table 4 Estimated waste outputs (kg per metric tonne of feed used) of rainbow trout fed standard Ontario commercial fish feed, assuming 1% feed waste rate (adapted from Bureau *et al*, 2003)

Parameter	**Feed Type**		
	A	**B**	**C**
FCR	1.09	1.21	1.17
Total solid waste	202	237	207
Solid N waste	7.8	9.2	7.9
Solid P waste	4.9	7.3	4.7
Dissolved N waste	32.0	43.8	33.5
Dissolved P waste	1.4	4.1	1.5
Total N waste (solid + dissolved)	39.8	52.9	41.4
Total P waste (solid + dissolved)	6.3	11.3	6.2
Total BOD[1, 2]	317	400	327
Total BOD per tonne feed used [3]	*352 mg per kg feed used*		
Total BOD per tonne feed used [4]	*266 - 293 mg per kg feed used*		

[1] BOD is estimated according to Volpe *et al* (2010) where BOD = (total N in feed − total N in fish) × 4.57 + (total C in feed − total C in fish) × 2.67 and using Bureau et al's (2003) waste output coefficients for the commonly used commercial feeds in Ontario
[2] BOD estimates assumes 250 mg/g total organic carbon content for faecal waste
[3] Dalsgaard and Pedersen's (2011) measured BOD estimates of 352 kg per tonne feed for faecal waste (Danish fish feed)
[4] Bureau & Cole (unpublished) theoretical BOD estimates of 266 kg to 293 kg per tonne feed for faecal waste (standard Ontario feed)
** Total BOD is represented by chemical oxygen demand (COD) and the 5-day biochemical oxygen demand (BOD_5)

Although P loadings from cage aquaculture operations were historically high, these have dramatically decreased over time. Phosphorus content in feed can be as low as < 1% (Milne *et al*, 2015; DFO, 2015) and current operations now release two to three-fold less phosphorus into the natural environment annually as a result of improved feed formulations and reduced feed wastage.

Production scale of the cage aquaculture operation has varied widely during the operational life of the facility. Recent data indicates an increase in feed usage and it is expected that there will

be a corresponding increase in P loading from the aquaculture facility. Since 2009 feed usage fluctuated from 213 tonnes to 460 tonnes per year, with an average feed usage of 377 tonnes per year and the facility is permitted a maximum feed allocation of 510 tonnes. We provide waste output estimates for three production scales including 250, 375 and 500 tonnes feed usage and for the purposes of this source loading assessment we have assumed the average production scale of 375 tonnes of feed. These estimates assume a 1% feed waste rate and are based on the estimated waste output for a standard commercial feed (Feed A) commonly used in Ontario (Table 5).

Table 5 Estimated waste outputs of a cage aquaculture operation utilizing 250, 375 and 500 metric tonnes of fish feed, assuming 1% feed waste rate and using a standard commercial Ontario fish feed (Feed A; FCR 1.09) (based on Bureau *et al*, 2003; Dalsgaard & Pedersen, 2011; and Volpe *et al*, 2010)

Parameter	**Feed Usage (metric tonnes)**		
	250	**375**	**500**
Total solid waste	51	76	101
Solid N waste	2.0	2.9	3.9
Solid P waste	1.2	1.8	2.4
Dissolved N waste	8.0	12.0	16.0
Dissolved P waste	0.4	0.5	0.7
Total N waste (solid + dissolved)	10.0	14.9	19.9
Total P waste (solid + dissolved)	1.6	2.4	3.2
Total BOD[1, 2] (Volpe *et al*, 2010)	79	119	158
Total BOD [3] (Dalsgaard & Pedersen, 2011)	88	132	176
Total BOD [4] (Bureau & Cole, unpublished)	67 - 73	100 - 110	133 - 147

[1] BOD is estimated according to Volpe *et al* (2010) where BOD = (total N in feed − total N in fish) × 4.57 + (total C in feed − total C in fish) × 2.67 and using Bureau et al's (2003) waste output coefficients for the commonly used commercial feeds in Ontario
[2] BOD estimates assumes 250 mg/g total organic carbon content for faecal waste
[3] Dalsgaard and Pedersen's (2011) measured BOD estimates of 352 kg per tonne feed for faecal waste (Danish fish feed)
[4] Bureau & Cole (unpublished) theoretical BOD estimates of 266 kg to 293 kg per tonne feed for faecal waste (standard Ontario feed)

On average, the aquaculture operation in Lake Wolsey, assuming an annual 375 tonne feed usage, will discharge 537 kg of dissolved P and 1 832 kg of particulate P to the natural environment annually (Table 5). Waste outputs for nitrogeneous waste is high and for an

operation utilizing 375 tonnes of feed will discharge 12 tonnes of dissolved N and 2.9 tonnes of particulate N wastes. Combined this operation discharges 2.4 tonnes of P and 14.9 tonnes of N, annually to this embayment.

Table 6 Summary table of total phosphorus (mg g^{-1} d.w.) and total Kjeldahl nitrogen (mg g^{-1}) concentrations of sediment at varying distances from the cage aquaculture operation in Lake Wolsey, collected by the Ontario Ministry of Environment and Climate Change (MOECC), 1986 to 2005

Year	Distance from cages	N	TP (mg g^{-1} d.w.)					TKN (m g^{-1} d.w.)				
			Mean	Median	Min	Max	Std dev.	Mean	Median	Min	Max	Std dev.
1986	0 - 5 m	6	0.7	0.6	0.5	1.4	0.3	1.8	1.4	1.3	3.7	0.9
	30 m	1	-	0.2	-	-	-	-	0.4	-	-	-
1987	0 - 5 m	5	0.5	0.4	0.3	0.9	0.2	1.2	0.8	9.9	2.1	0.7
	30 m	1	-	0.5	-	-	-	-	1.2	-	-	-
2000	0 - 5 m	3	**14.1**	**15.0**	1.6	25.7	12.1	**14.1**	**15.0**	3.0	28.7	12.9
	≥ 1000 m	2	0.8	-	0.8	0.8	-	4.0	-	4.0	4.1	-
2003	0 - 5 m	1	4.1	-	-	-	-	3.8	-	-	-	-
	≥ 1000 m	1	0.8	-	-	-	-	3.6	-	-	-	-
2004	0 - 5 m	4	**12.1**	**12.2**	0.8	23.0	10.1	**5.6**	**5.9**	2.4	8.1	3.0
	25 - 30 m	3	**5.3**	**5.9**	1.2	8.7	3.8	3.0	3.4	1.9	3.8	1.0
	≥ 1000 m	2	0.7	-	0.6	0.8	0.1	2.8	2.8	2.7	2.8	0.1
2005	10 - 20 m	3	**3.7**	**2.6**	2.5	6.0	2.0	3.2	2.4	2.3	4.8	1.4
	30 m	15	**2.5**	**2.6**	0.8	5.9	1.3	3.1	3.0	1.8	5.4	0.9
	500 - 800 m	7	0.8	0.8	0.6	0.9	0.1	3.6	3.7	2.8	4.0	0.4
	≥ 1000 m	14	0.8	0.8	0.3	2.2	0.5	2.8	3.1	0.3	5.9	1.5

* Bold numbers indicate average concentrations exceed the Provincial Sediment Quality Guideline severe-effect-levels (PSQG) of 2.0 mg g^{-1} and 4.8 mg g^{-1} for total phosphorus and total Kjeldahl nitrogen, respectively (MOE, 2008)

Combined this operation discharges 2.4 tonnes of P and 14.9 tonnes of N, annually to this embayment. This phosphorus loading estimate is slightly higher than Milne *et al*'s (2015) estimate of 2.2 tonnes for total P (or 1.1 tonnes P when only 10% of the particulate P is included). Milne *et al* (2015), based on detailed 2007 production data and using the bioenergetics mass-balance model, estimated1 383 kg of particulate P and 714 kg of dissolved P, for a total P load of 2 160kg was discharged to the embayment in 2007. The dissolved P component accounted for 33% (or 714 kg) of the total P load which is higher than our estimate of 23% or 537 kg. Milne *et al* (2015) also assumed a higher feed waste rate of 2% which resulted in 63 kg of P from feed waste. For the purposes of their mass-balance study, Milne *et al* (2015) assumed only 10% of the 1383 kg particulate P is available and therefore only 138 kg

particulate P is accounted for in the reported P load of 1.1 tonnes. Our estimate is higher than Milne *et al* (2015) for total P load, in part due to the higher feed use (375 tonnes vs 355 tonnes), but aligns well with Milne *et al's* (2015) estimate, when normalized to the 2007 production scale (feed usage) and when factoring in total particulate P.

Although dissolved P loadings from the cage aquaculture facility may account for a high proportion of the total P (Persson, 1991; Cho & Bureau, 2001), the most recent data suggests that for standard Ontario feed, dissolved P can be as low as 22% of total P (Bureau *et al*, 2003; Table 4). Therefore a significant proportion of the phosphorus from a cage aquaculture operation will rapidly settle out of the water column (Moccia & Bevan, 2010; Elberzion & Kelly, 1998).

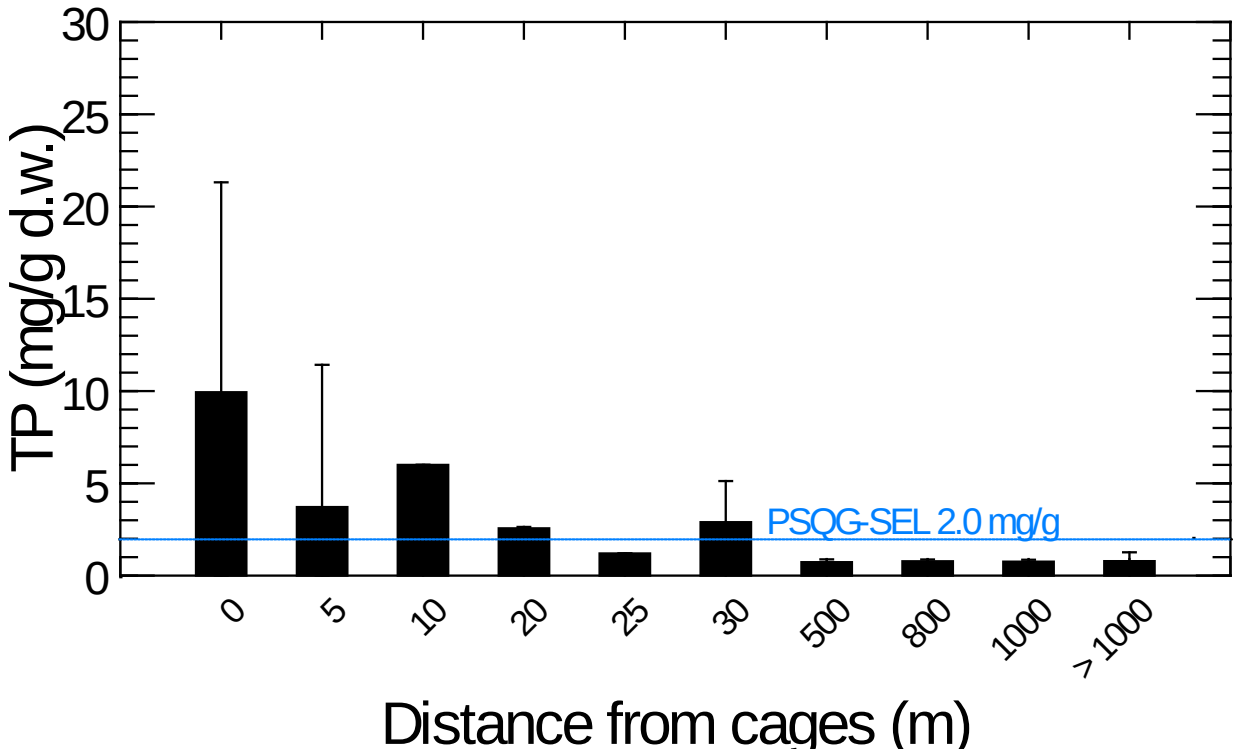


Figure 13 Concentrations of total phosphorus (mg g^{-1} d.w.) of sediment at at varying distances from the the cage aquaculture operation in Lake Wolsey, collected by the Ontario Ministry of Environment and Climate Change (MOECC) between 1986 to 2005

Sediment surveys conducted by the Ontario Ministry of Environment and Climate Change (MOECC) between 1986 to 2005 indicate nutrient-enriched sediment conditions in the immediate vicinity of the cage aquaculture operation (within 30 m) (Table 6, Figure 13) post-1987. In 1986/87, when operational scale was less than 50 tonnes (Table 2), phosphorus (TP) and total Kjeldahl nitrogen (TKN) levels were approximately 0.6 mg g^{-1} and 1.4 mg g^{-1} in the immediate vicinity of the cage aquaculture operation (near-cage stations) (Table 6) and did not exceed the Provincial Sediment Quality Guidelines severe-effects-levels (PSQG-SELs) of 2.0

mg g^{-1} and 4.8 mg g^{-1}, respectively (MOE, 2008). Since 2000, phosphorus levels in sediment regularly exceeded the PSQG-SEL at the majority of the near-cage stations with the maximum concentration of 25.7 mg g^{-1} observed in 2000 (Table 6). Reference stations TP levels remained well below the PSQG-SEL, with TP concentrations generally below 1 mg g^{-1} (Table 6**.**). These data support the observation that phosphorus loadings from the cage aquaculture facility are resulting in nutrient-enriched sediment conditions in the immediate vicinity of the facility, in large part due to the high proportion of particulate-bound P in the fish waste.

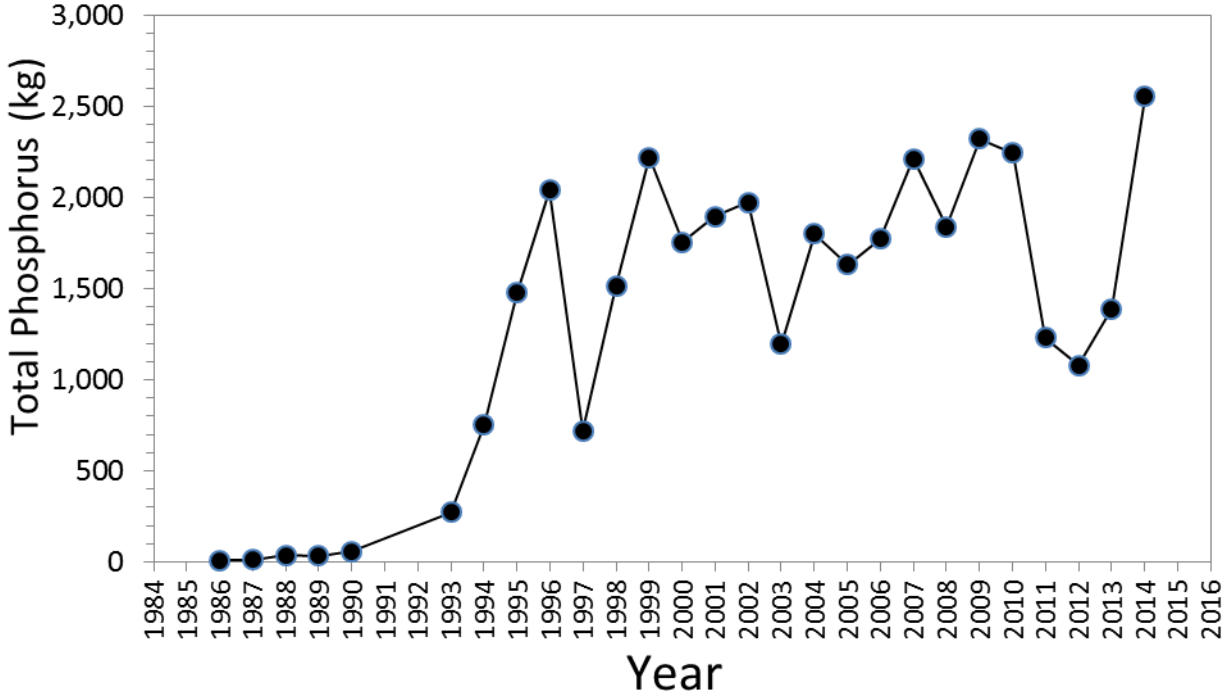


Figure 14 Annual total phosphorus load (kg) from the cage aquaculture operation to Lake Wolsey based on annual fish production data (1986 - 2014) and assuming 6.3 kg P per tonne feed used, assuming a 1% feed waste rate and using standard commercial Ontario fish feed (Feed A; FCR 1.09) (adapted from Bureau *et al*, 2003) (2007 feed usage data from Milne *et al*, 2015)

Particulate phosphorus is generally not available for algal uptake, unless reduced conditions occur in the bottom waters (e.g., Nurnberg, 1995) or during resuspension events. Internal loading occurs when bottom water are anoxic (e.g., Nurnberg, 1995; Temporetti & Pedrozo, 2000) and enriched organic or calcium conditions in the sediment (Temporetti & Pedrozo, 2000) facilitate the release of dissolved P back to the water column. Since the mid-2000s Lake Wolsey experienced wide-spread hypolimnetic anoxia during the summer stratified (Diep & Boyd, 2016) and these conditions are conducive to internal P loading effects. P release rates from sediment vary according to dissolved oxygen conditions and the operational life of the facility, with higher P release rates observed at more established farms and under anoxic

conditions (Temporetti & Pedrozo, 2000). Temporetti & Pedrozo (2000) found P release rates as high as 815 and 2331 mg P m^{-2} day^{-1} under oxic and anoxic conditions, respectively, for sediments collected under an established rainbow trout aquaculture facility which indicates exceedance of its P fixation capacity. These P release rates greatly exceed the 12 mg P m^{-2} day^{-1} (Nurnberg, 1984) used by Milne *et al* (2015) to estimate internal P loading for Lake Wolsey. The localized nature of waste accumulations suggests there is likely spatial variability in P release rates, with high rates observed near the cage aquaculture facility.

Historically, P loadings were well below 0.5 tonnes prior to the mid-1990s. Rapid expansion between 1994 and 1996 resulted in P loadings generally above 2.0 tonnes, with wide variation in annual feed usage and hence annual P loads (Figure 14, Table 2). Although P loads from the cage aquaculture operation can be large, water quality effects from cage aquaculture are generally localized and elevated phosphorus is generally confined within 30m of the cage aquaculture facility (Reid *et al*, 2006), in part due to the large proportion of particulate P that settle from the water column. Aquaculture-based P loads are temporally dependent and generally tied to operational practices. The primary waste material is fish faeces and associated with feeding, therefore the majority of the waste production coincide with peak feeding times which are associated with water temperature. Most of the P load is expected to enter the system during the spring and fall when growing conditions are optimal. For Lake Wolsey, monthly P loads from the aquaculture occurred in early summer (June/July) and in the fall (September/October) in 2007 (Figure 10; Milne *et al*, 2015), which suggests ongoing contribution of P during the summer stratifed season.

In our source loading assessment we found the cage aquaculture operation to be a significant source of phosphorus, discharging 2.4 tonnes of P annually to this embayment. Over two-thirds of this P is in particulate form and will settle out of the water column in the immediate vicinity of the operation and is not available for phytoplankton uptake unless physical factors such as resuspension events or bottom-water anoxia (i.e., internal P loading) re-introduce the P back into the water column.

5.4 Shoreline Development and Urbanization Phosphorus Inputs

In highly developed watersheds and shorelines, shoreline development and urbanization can be major anthropogenic sources of phosphorus to a waterbody (e.g., MOE, 2010). However, with less than 1000 people or ~ 2 individuals per square kilometre (Statistics Canada, 2007), this watershed is minimally populated. We currently do not have information on the number of residential homes, however based on the number of farmsteads which can be used as a surrogate for number of residential homes, there is a minimum of 115 residential homes in the Lake Wolsey watershed. According to the 2009 land-use data there are three urban areas in this watershed ranging from 0.2 ha to 5.6 ha, accounting for < 0.1% of the total watershed area.

Recreational areas in this watershed are also minimal with only 5 identified in the watershed ranging from 0.5 ha to 22.6 ha in size.

P export coefficients for residential or urban areas vary widely from 0.19 kg P ha^{-1} yr^{-1} for large residential lots to 2.7 kg P ha^{-1} yr^{-1} for small residential lots (Reckhow *et al*, 1980). Other studies have identified a P export coefficients ranging from ~ 1 kg P ha^{-1} yr^{-1} (Rast & Lee, 1978; Loehr *et al*, 1989; Dodd *et al*, 1982) to 2.2 kg P ha^{-1} yr^{-1} (Loehr *et al*, 1989; McFarland & Hauck, 2001). In the Lake Simcoe watershed, urbanized areas were found to contribute 132 kg P km^{-2} yr^{-1} (Scott *et al*, 2001) or 1.3 kg P ha^{-1} yr^{-1}, which falls at the low end of the spectrum identified in the literature.

The urban areas of the Lake Wolsey watershed are likely single dwelling homes with large lots, thus the applicable P export coefficient likely fall at the lower end of the coefficient spectrum, these residential homes likely use septic tanks which will result in higher P export coefficients. Therefore we applied the P export coefficients identified by Reckhow *et al* (1980) for the urbanized areas of this watershed and estimated a contribution of 1.4 kg to 19.7 kg of P annually.

Shoreline development is minimal and confined mainly to the southwest shores of Lake Wolsey. There are only 27 cottages, 10 year-round residences and two campsites (Gale, 1999). The amount of P contributed by shoreline residences is dependent on the distance from shoreline, usage rate, or relative occupation rate. The Lakeshore Capacity Handbook recommends a 100% loading coefficient be used if the septic system is within 300m of the shoreline. This assumption is reasonable, especially given the areas along the Lake Wolsey shoreline are composed mainly of rock bluffs and bedrock likely overlain with thin soils that retain very little nutrients.

The Lakeshore Capacity Handbook assumes that a seasonal residence (e.g., cottages) will contribute 0.69 kg of P yr^{-1} while year-round or permanent residences will contribute 2.56 kg of P yr^{-1}. Cottages and permanent residences along the Lake Wolsey shoreline therefore potentially contribute 18.6 kg to 25.6 kg P, respectively, annually to this embayment. Full-service campsites contribute 0.37 kg of P yr^{-1} (MOE, 2010) and therefore the two campsites in Lake Wolsey potentially contribute only 0.7 kg of P to this embayment. Our land-use data indicates that there are five recreational areas in the Lake Wolsey watershed. If we assume that the P loading from these recreational areas is similar to resorts and we apply the MOE (2010) resort P export coefficient of 1.18 kg capita years per year, then these recreational areas potentially contribute 5.9 kg of P, annually.

Although we did not have detailed population and septic system information, based on the available data we found shoreline development, recreational use and urbanization were minor contributors of phosphorus, contributing less 0.1 tonnes of phosphorus annually to Lake

Wolsey. These estimated P loads are well below the P loads estimated for the watershed, agriculture and cage aquaculture and indicates that this land-use type is not a significant source of P to Lake Wolsey.

5.5 Other Factors

Campbell Bay and the North Channel Inputs

A small causeway connects Lake Wolsey to Campbell Bay/North Channel, allowing for water exchange between the two waterbodies. Although flows between the embayment and North Channel waters are restricted by the causeway (4 m depth), it remains an energetic system with hydrological connectivity to the Great Lakes is limited to the surface layer of the water column resulting in good epilimnetic (surface layer) flushing but no hypolimnetic or bottom-water exchange (Hamblin & Gale, 2002; Milne *et al*, 2015).

On an ice-free average basis, Lake Wolsey is more nutrient-enriched than Campbell Bay (Hamblin & Gale, 2002), therefore, incursions of Campbell Bay/North Channel waters are likely to dilute the waters of Lake Wolsey, particularly in the immediate vicinity of the causeway (e.g., lake-effect zone); excursions of embayment waters represent a net export of phosphorus from Lake Wolsey. Milne *et al's* (2015) 2007 assessment concluded that while 539 kg of P entered Lake Wolsey via Campbell Bay, 802 kg P was exported out, resulting in a net P export of 262 kg from the Lake Wolsey system between May to November, 2007. While the physical dimensions of the causeway limits the dilution potential of Campbell Bay/North Channel, the energetic exchange between the two waterbodies is likely a key mitigating factor.

Internal Phosphorus Loads

The degraded dissolved oxygen condition with wide-spread hypolimnetic anoxia observed in Lake Wolsey since the mid-2000s (Diep & Boyd, 2016), result in conditions conducive to internal P loading. Internal P loads are generally considered an autochthonous sources of phosphorus as it releases P formerly sequestered in the sediment back to the water column in the dissolved form. This occurs under reduced conditions when dissolved oxygen are critically low, typically when levels are at or below 1 mg L^{-1} (Nurnberg, 1995). Phosphorus release from the sediment is not observed in well-oxygenated lakes if DO is maintained at or above 2 mg L^{-1} (Nurnberg, 1984).

Waterbodies that experienced seasonal or chronic hypoxia or anoxia, such as those subject to long-term anthropogenic pollution and anoxic hypolimnia, experience internal P loading effects with potential for leakage of P from the hypolimnion to the metalimnion. Information on the anoxic sediment surface area, the duration of the anoxic period, and the P release rate from the sediment can be used to estimate the P load from internal loading effects (Nurnberg, 1984).

This report did not include autochthonous-based sources of P in the assessment as the focus was on quantifying allochthonous and anthropogenic P sources. However, Milne *et al* (2015) estimated a P load of 186 kg attributable to internal phosphorus loading based on hypolimnetic depth of 18m and an internal load of 1.9 kg day^{-1} for Lake Wolsey in 2007. Temporal variability in hypolimnetic depth is common in Lake Wolsey with hypolimnetic depths as shallow as 12 m (Diep & Boyd, 2016), suggesting internal P loads will vary interannually. Other factors include the particulate P contribution by the cage aquaculture operation, resulting in localized nutrient enrichment in sediment collected in the immediate vicinity of the cage aquaculture operation with P concentrations typically exceeding the PSQG-SEL. Aquaculture wastes has the potential to increase P release rates from the sediment, particularly under anoxic conditions (Temporetti & Pedrozo, 2000), however this will be confined to the area of the aquaculture waste footprint. Overall, Milne *et al* (2015) indicate internal P load to be a minor component (6%) of the total P load.

Invasive Species

The proliferation of dreissenid mussels has changed the lakebed landscape in Lake Wolsey and they are especially prevalent on the southside of the cage aquaculture operation. Decreases in ambient phosphorus and chlorophyll a concentrations in the surface waters may occur as a result of their filtration activities. Their preferential de-selection of cyanobacteria may result in higher proportion of cyanobacteria in the algal assemblage and occurrence of algal toxins as observed by Hille (2008) in 2006. Cyanobacteria was found to constitute a large proportion of the benthic algae attached to the dreissenid mussels with detectable levels of microcystin in the benthic algae/dreissenid samples taken in the vicinity of the cage aquaculture operations (Hille, 2008). At the end of their life-cycle or if exposed to low dissolved oxygen conditions, these mussels senesce and become sources of oxidizable organic material.

6 Organic Material and Biochemical Oxygen Demand (BOD) Loading Assessment

In eutrophic systems, phytoplankton represents a significant source of organic material and this is the reasons dissolved oxygen models focus primarily on phosphorus as the driver of hypolimnetic dissolved oxygen depletion. In the previous sections it was noted that the Lake Wolsey watershed and shoreline are relatively undeveloped and the embayment is not experiencing excessive levels of nutrients or elevated primary productivity (Diep & Boyd, 2016). The severe dissolved oxygen (DO) depletion observed since the mid-2000s are occuring at time when annual phosphorus levels are relatively constant (Diep & Boyd, 2016; Milne *et al*, 2015) and chlorophyll a levels remain moderately low (< 5 µg L^{-1}) (Diep & Boyd, 2016)

Oligotrophic and mesotrophic lakes that experience severe hypolimnetic dissolve oxygen depletion not accounted for by primary production may be experiencing significant inputs of non-algal sources of organic material to the hypolimnion as observed by Houser *et al* (2003), a factor normally not considered in eutrophication models. High inputs of allochthonous and/or anthropogenic-based organic material have the potential to exacerbate the hypolimnetic DO levels of sensitive ecosystems where microbial degradation of this organic material is the key oxygen-consuming process. Prairie *et al* (2002) found excessive levels of organic material can resulted in measurable decreases in dissolved oxygen. As with phosphorus, the sources of organic material to Lake Wolsey include the watershed, agricultural activities, aquaculture activities and shoreline development.

A common measure of dissolved oxygen consumption in water is biochemical oxygen demand (BOD) is the amount of oxygen consumed to process carbonaceous and nitrogeneous compounds in the sample. BOD is not a substance or pollutant but a characteristic of the sample. BOD can be measured as chemical oxygen demand (COD) or biochemical oxygen demand (BOD_5). Chemical oxygen demand (COD) is the total amount of oxygen required to oxidize all organic material into carbon dioxide and water, while BOD_5 is the amount of oxygen required to process the waste materials, reflecting microbial respiration demands, typically measured as the amount of oxygen consumed by microorganisms over a five-day period.

The discharge of oxygen-consuming materials (i.e., high BOD) to a receiving waterbody will consume dissolved oxygen through microbial degradation/respiration processes. The greater the BOD and organic loading, the greater the amount of oxygen consumed and excessive organic/BOD loading can lead to measurable decreases in dissolved oxygen concentrations. For the purposes of this report, we refer to the COD and BOD_5 as total BOD.

Common measures of organic material include measurements of dissolve organic carbon (DOC) and particulate organic carbon (POC) and these represent the dissolved and particulate fractions of the organic material in a waterbody. There is limited information on the relationship between DOC and DO depletion for temperate freshwater systems because most studies focused on nutrients and their indirect effects on the DO condition. Houser *et al* (2003) observed the occurrence of severe hypolimnetic dissolved oxygen depletion in a number of Wisconsin lakes, in the absence of significant primary productivity, and attributed it to allochthonous DOC, identifying it as a significant source of material for hypolimnetic microbial activity. These Wisconsin lakes with high DOC concentrations were found to be anoxic and exhibited elevated methane levels in the bottom-waters (Houser *et al*, 2003). Allochthonous organic material tend to be more bioavailable and chromophoric than authochthonous materials (Prairie *et al*, 2002) and these properties will affect the rate and degree of microbial decomposition.

In this report we have undertaken a detailed examination of the potential sources of organic material entering Lake Wolsey to provide a source loading assessment of the organic loading entering this embayment, focusing primarily on three parameters a) biochemical oxygen demand (BOD), b) suspended solids (SS) and c) organic material (OC). This will facilitate identification of the main factors or sources of organic material that are contributing to hypolimnetic eutrophication effects.

6.1 Watershed-based Organic Inputs

Watersheds can be significant non-point sources of allochthonous organic material to a waterbody. The amount and type of organic material that enters a waterbody is dependent on run-off characteristics, tributary discharge and concentrations, watershed characteristics, agricultural activity and the season. Traditionally, most studies include an evaluation of tributary discharge rates and concentrations to determine the organic loading entering a waterbody, however, as noted by Milne *et al* (2015) other than ephemeral streams, there are no tributaries in this watershed. In June 2010, Milne (2012) sampled thirteen emphemeral streams around Lake Wolsey, however only two were resampled in September with nine identified as having no flow or as being dry. Overland run-off is likely the major transport mechanism conveying organic material from the watershed to the embayment.

Limited literature-based DOC export coefficients are available and we found values to vary widely and were dependent on watershed characteristics (Hobbie & Likens, 1973), agricultural activities (Royer & David, 2005), and tributary discharge rates. Royer & David (2005), in their evaluation of the intensively farmed watersheds in Illinois, identified DOC export coefficients ranging from 3 kg ha^{-1} yr^{-1} to 23 kg ha^{-1} yr^{-1}. Rasmussen *et al* (1989) reviewed data from 287 lakes in four geographical regions of northern U.S. and Canada and arrived at an average DOC export coefficient of 3.0 g DOC m^{-2} DA yr^{-1} (or 30 kg ha^{-1} yr^{-1}) which exceeds the range identified by Royer & David (2005). Hobbie & Liken (1973) evaluation of the Hubbard Brook experiment watersheds determined a DOC export coefficient of 20.5 kg ha^{-1} yr^{-1} for both disturbed and undisturbed watersheds and this value was within the range identified by Royer & David (2005). If we apply these generic upper and lower DOC export coefficients to the natural land features including woodlot, roughland/ditches, wetland/riparian, we find that, when combined, these natural land-use features potentially contribute 20.2 to 201.8 tonnes of DOC annually to Lake Wolsey.

There is a limited export coefficient information available for suspended solids, which make estimates of the suspended solids load difficult. The amount of particulate organic material from the watershed to the lake is complex and mainly dependent on the tributary discharge rates and rainfall events (Hobbie & Likens, 1973). In systems where tributary discharge rates are high (>10 L sec^{-1}), the amount of fine particulate matter increases (Hobbie & Likens, 1973), however the only tributaries present in Lake Wolsey are ephemeral streams, these discharge rates are

highly unlikely. In general, the dissolved organic content greatly exceeds the particulate organic content in oligotrophic systems (Biddanda *et al*, 2001 and references therein). The ratio of particulate organic carbon to dissolved organic carbon (POC:DOC) can range from 0.1 and 0.25 (Rasmussen *et al*, 1989 and references therein), therefore based on the preliminary DOC loading, particulate organic loading from the watershed ranges from 2.0 to 50.5 tonnes. Forest density is expected to be low and sparse given the dolomictic limestone geography and for woodlots with this characteristic, organic loading is expected to be at the lower as observed by Engstrom (1987).

Harper (1998) provided suspended solid export coefficients of 18.8 kg ha^{-1} yr^{-1} and 27.7 kg ha^{-1} yr^{-1} for open-space areas and wetlands, respectively. Although the suspended solids export coefficient for wetlands is higher, wetlands only comprise ~3% of the total watershed area and potentially contribute only 7.9 tonnes of suspended solids annually to Lake Wolsey. When we apply the open-space export coefficient to the woodlot, roughland, and ditch areas of this watershed, we find these natural land-use features potentially contribute 121.1 tonnes of suspended solids annually to Lake Wolsey. Combined, the natural land-use features of this watershed potentially contribute ~ 129 tonnes of suspended solids annually to this embayment.

The BOD export coefficients for open space and wetlands are 2.4 kg ha^{-1} yr^{-1} and 12.3 kg ha^{-1} yr^{-1}, respectively (Harper, 1998). These BOD export coefficients are low. Although the BOD export coefficient for wetlands is five-fold higher than open-space, wetlands constitute only ~3% of the total watershed area, thus only contribute an annual BOD loading of 3.5T. When we apply the open-space BOD export coefficient to the woodlot, roughland, and ditch areas of this watershed, we find these natural land-use features potentially contribute an annual BOD loading of 15.5T.

There is a seasonal component to watershed-based loadings of organic and BOD materials to Lake Wolsey (data from Milne *et al*, 2015; Figure 10). As seen in Figure 10, watershed inputs are highest in the May and declines progressively over the ice-free season, with over 50% of the loading from the watershed entering Lake Wolsey in May/June. If we assume that watershed organic and BOD loading exhibits the same trend, then likely most of the diffuse non-point sources of organic and BOD materials enters the embayment in late spring and early summer.

Urbanization can be a significant source of organic/BOD materials in areas that are heavily developed with export coefficients as high as 2625 kg ha^{-1} yr^{-1} SS and 1232 kg ha^{-1} yr^{-1} BOD for high density residential areas (Jeje, 2006). For this watershed, with its minimal urbanization and single-dwelling residences, the low and medium density residential land use export coefficient are more applicable. Based on the Jeje (2006) export coefficients of 63 kg ha^{-1} yr^{-1} SS and 81 kg ha^{-1} yr^{-1} BOD, the urban areas of watershed potentially contributes 456 kg SS and 593 kg BOD annually to Lake Wolsey.

We found DOC loadings to vary ten-fold, ranging from 20 to 202 tonnes of DOC. Although suspended solids loading from the natural land-use features were as high as 129 tonnes, the POC loading is likely lower (< 51 tonnes). The BOD loading associated with the natural land use features is 19 tonnes annually. These estimates suggest that though the DOC and suspended solids loading can be potentially high, the associated BOD load is low. These estimates based on the available literature and data could be refined with additional site-specific data including hydrological characteristics of this watershed and measured concentrations of DOC, suspended solids or BOD from these land-use features.

6.2 Agricultural-based Organic Inputs

Agricultural activity is a key anthropogenic source of organic material. Intensively farmed watersheds have the potential to contribute significant loads of oxygen-consuming organic material to the receiving waterbody (Royer & David, 2005). However, few studies focus on quantifying organic inputs from agricultural sources focusing rather on nutrients and bacterial contamination on water quality. The studies that provide the relevant export coefficient data are limited to the 1970s PLUARG era and/or focus on tributaries as the primary conveyors of agricultural-based organic material.

Quantitative estimates of the organic loading from agricultural lands is dependent on activity type (e.g., pasture, livestock etc), farming practices, presence and intensity of feedlots, export coefficients (DOC, POC and BOD), size of manure storage areas and proximity to the embayment. Most of this information is not available for the Lake Wolsey watershed, therefore for this section; we provide a qualitative overview of the potential loading this activity contributes to in Lake Wolsey. In the absence of tributaries, inputs from the agricultural lands of this watershed are dominated by subsurface flow, groundwater or surface run-off.

For intensively farmed watersheds Royer & David (2005) estimated a DOC export coefficient of 23 kg ha^{-1} yr^{-1}. If we apply the upper limit of this range (export coefficient of 23 kg ha^{-1} yr^{-1}) to the agricultural lands of Lake Wolsey watershed, including pasture and farmsteads (~ 2606 ha), these agricultural lands potentially contribute 60 tonnes of DOC to Lake Wolsey annually.

Lin (1972) characterized the characteristics of manure of a variety of livestock types and found, in general, the BOD of animal manure is higher than untreated domestic sewage (Lin, 1972). The total solids and BOD levels are highest for diary cattle compared to beef cattle (Lin, 1972 and references therein). Robinson & Draper (1978) estimated a chemical oxygen demand (COD) ranging between 12 to 55 kg COD per animal unit, but attenuation is likely high. Beef lots can also be a significant source of particulate material with total solids ranging between 7 655 to 23 900 mg L^{-1} in the runoff from paved and unpaved beef lots (Lin, 1972). Agricultural practices such as soil conservation have the potential to reduce the amount of particulate material that is carried away by runoff. According to the 2009 land-use inventory, only a small

proportion of the agricultural lands, located in the southwest regions of this watershed, are used for livestock, mostly as pasture for mixed range animals or for poultry production, therefore BOD contributions from agricultural lands with livestock is expected to be low. In order to estimate the BOD or suspended solids load from agricultural lands we require detailed feedlot and agricultural practices information, which are not currently available.

Agricultural practices will also determine the magnitude and composition of DOC inputs (e.g., Hernes *et al*, 2008) and BOD (Robinson & Draper, 1978) from agricultural lands. Summer irrigation of cropland resulted in higher export of DOC from the agricultural lands to the natural receiving environment (Hernes *et al*, 2008), while farms that apply winter manure will result in run-off with higher oxygen demand (Robinson & Draper, 1978), the effects of which will be seasonally dependent.

Agricultural sources of BOD and total solids are seasonally variable and dependent on site-specific characteristics (Coote & Hore, 1978). Higher BOD was observed in between the December – April period compared to the summer period, regardless of whether the beeflots were paved or unpaved (Coote & Hore, 1978). This is consistent with other studies where winter manure spreading typically results in higher oxygen demand in runoff (Robinson & Draper, 1978). Overland runoff resulting from storm events, typically in the spring and winter, will result in higher DOC concentrations and discharge (Hernes *et al*, 2008).

Soil permeability is another key factor which will determine the amount of organic material that enters the embayment. Paved surfaces will generally result in higher runoff and concentration of organic material compared to unpaved surfaces (Coote & Hore, 1978). For livestock lots and manure storage areas, paved surfaces resulted in higher BOD loads and total solids concentrations (Coote & Hore, 1978). However, suspended solids concentrations were similar between paved and unpaved beef lots (~7000 mg L^{-1}) (Coote & Hore, 1978). While the agricultural lands and livestock areas within Lake Wolsey are likely unpaved, soil permeability is expected to be low due to the rock-dominated surfaces of this watershed, which is a key factor limiting the agricultural potential of this watershed.

These factors are taken into account in Ontario's Agricultural Planning Tools Suite (AgriSuite), a provincial nutrient management planning software. The MSTOR worksheet of AgriSuite can be used to determine manure output and storage requirements for various livestock types (OMAFRA, 2015a). Detailed waste output information is provided for a variety of livestock types. For example, a farm with 10 large dairy cows will generate 229 m^3 of solid manure annually and requires 102 m^2 barn for manure storage, while another farm with 10 beef cattle generates only 68.6m^3 of solid manure and therefore requires a requires a smaller barn (37 m^2). Pigs and chickens (N = 25) produce 38 m^3 and 2 m^3 of solid manure annually, therefore manure storage is minor or negligible. If the manure generated is used for field application, the AgriSuite tool can be used to identify the optimal nutrient application rate/method, fertilizer type

and blend and application timing to minimize P loss for a given crop type. This tool also has the capacity to estimate generation from other on-farm sources such as milking center washwater and silo seepage and treatments (anaerobic digesters) (OMAFRA, 2015a).

Generally, the BOD of poultry manure is nearly two-fold higher than cattle manure (Udeigwe & Wang, 2010), however poultry manure production is much lower. Compared to fish faecal waste, Yeo *et al* (2004) found the BOD to be similar to livestock manure. Currently, we do not have detailed information on the types or quantity of livestock in the Lake Wolsey watershed. If a farm raises five dairy cows, five beef cattle and 25 chickens, 129 tonnes of solid manure is produced annually, according to AgriSuite/MSTOR. Although this solid manure production from livestock is greater than an average-sized cage aquaculture operation, it is unrealistic to assume that this, or any, solid manure loading enters the natural receiving waterbody in its entirety, particularly in the presence of properly sized and constructed manure storage areas.

However, runoff waters from feedlots represent a mechanism for conveying of nutrients and organic/BOD materials to the natural receiving waterbody. Coote & Hore (1977 & 1978) estimated the BOD loading on a per unit area and per unit animal basis (455 kg live weight). Coote & Hore (1977) found high BOD levels in the runoff waters from manure storage areas with lower BOD values observed at the smaller operational scales (100 cattle) and unpaved feedlots. The amount of BOD produced per animal unit can be as high as 7.3 kg per animal unit for large paved feedlots and as low as 2.89 kg per animal unit for smaller feedlots with semi-solid manure storage (Coote & Hore, 1977; Coote & Hore, 1978). Farms with solid manure storage result in a BOD export coefficient of 3.9 kg per animal unit. On a per unit area basis, feed lots contributed 2.9 to 15.8 tonnes BOD per hectare for feedlots ranging from 100 - 500 heads or 80 to 550 animal units (455 kg live weight) (Coote & Hore, 1977; Coote & Hore, 1978).

However, feedlots in the Lake Wolsey watershed are expected to be small, therefore we applied the per animal unit export coefficients. Based on our land-use inventory data there are 115 farmsteads and if we assume there are, on average, ten cattle for each farmstead, this results in a total BOD load ranging from 3 324 kg to 8 418 kg per year for 1150 animal units. However, with properly sized and constructed manure storage facility it is expected that the organic/BOD inputs will be minimized. The Manitoulin Cattle Exchange (MCE) reported over 800 cattle were processed on Manitoulin Island in 2014 (McCutcheon, 2014), which suggests the assumed 1150 cattle for the Wolsey watershed alone (Burpee/Mills and Gordon township) may be an overestimate.

Solids and suspended solids from feedlot runoff can be also be high (Coote & Hore, 1977; Coote & Hore, 1978). Solids and suspended solids (SS) export coefficients range from 9.7 to 36.2 kg per animal unit and 3.2 and 19.8 kg per animal unit, respectively. Assuming there are, on average, 10 cattle per farmstead, this results in total solids and suspended solids load ranging from 11.2 to 41.4 tonnes and 3.7 to 22.8 tonnes, respectively, for livestock. If we

assume the solids discharged from the feedlots has an organic carbon (OC) content of 250 mg g^{-1} (d.w), then this results in an OC load of 2.8 to 10.4 tonnes from feedlots. Detailed farming information such as the livestock type and quantity, paved or unpaved feedlots and presence of manure storage facilities will result in more accurate and likely lower organic (solids, OC, SS) and BOD load estimates for this agricultural source.

Organic loading from agricultural lands is dependent on farming practices (e.g., winter manure spreading), soil permeability (e.g., paved, unpaved), activity type (e.g., cropland, pasture), feedlot intensity and quantity and season. The agricultural activity in this watershed is relatively low occupying only a quarter of the total watershed area. Most of the lands are used for pasture and hay production, with minimal mixed range and poultry production. Therefore, the organic loading from these agricultural lands is expected to be low. We estimated the organic carbon loading from agricultural lands to be 60 tonnes and for livestock, the BOD load can be as high as 3.3 tonnes, assuming livestock ten cattle per farmstead. The tools and resources such as AgriSuite/MSTOR provided through Ontario's Best Management Practices Program for the management of livestock wastes can be used to estimate on-farm generation of waste and this information can be used to further refine the organic and BOD load estimates from agricultural sources.

6.3 Industrial-based Organic Inputs

In Ontario, cage aquaculture operations do not collect and treat their waste, but rely on the natural environment to assimilate the excretory and feed waste material. Particulate waste accounts for significant proportion of the aquaculture waste material. The total organic carbon (TOC) content of rainbow trout faeces is 25% (or 250 mg g^{-1}) and the loss on ignition (LOI), which represents the organic fraction of the solids, is 67% (or 670 mg g^{-1}) (N. Diep *Pers. Comm*.), however Moccia et al's (2007) faecal waste assessment determined a TOC content of 41% or 409 mg g^{-1}, which is much higher than our estimate. Bureau *et al* (2003) determined that for every metric ton of fish produced 240 to 318 kg of total solids are discharged annually in the form of excretory wastes based on 5% feed waste rate. We updated their waste output coefficients to reflect the current 1% feed waste rate (DFO, 2015) and this resulted in lower waste outputs based on amount of feed used (Table 4).

Assuming a 1% feed waste rate, the amount of solid wastes generated by cage aquaculture operations ranges from 202 to 237 kg per tonne feed used (Table 4) and if we assume an organic carbon content of 250 mg g^{-1} (d.w.), this results in a carbon loading rate of 50.5 kg to 59.3 kg per tonne feed. An operation utilizing 375 tonnes of feed, will generate 76 to 89 tonnes of solids or 18.9 to 22.2 tonnes of organic carbon annually. Faecal waste has a high settling velocity (~ 6 cm s^{-1}) (Moccia & Bevan, 2010), therefore settle quickly to the lakebed, accumulating typically in the immediate vicinity of the cage aquaculture operation. The cage array extends nearly to the extent of the permitted or land tenure area (160 m by 90 m) along

the long axis. If we average the aquaculture waste loading is over the land tenure area, and assuming 80% feed usage during the ice-free season (May - November), the resulting solids loading rate is 18.9 to 22.2 g m^{-2} day^{-1} and for carbon is 4.9 to 5.8 gC m^{-2} day^{-1}. The carbon loading rate is 1.5-fold higher if we use Moccia et al's (2007) organic carbon content of 409 mg g^{-1}. This additional loading of waste material greatly exceeds maximum background sedimentation rates of 7.4 g m^{-2} day^{-1} during the deforestation/settlement era, as inferrred by the paleolimnological study by Clerk (2001). It is also higher than Milne *et al's* (2015) estimated a background sedimentation rate of 2 g m^{-2} day^{-1}, based on a sediment trap situated in the middle of the embayment, over 1 km away from the cage aquaculture operation.

Therefore, discharges from a cage aquaculture operation utilizing 375 tonnes of feed will potentially result in a minimum three-fold increase in sedimentation rates compared to background, and is expected to be confined generally to the immediate vicinity of the operation, and this is consistent with Rooney et al's (2006) observation of a three-fold increase in the organic content of the sediment from under the experimental 10 tonne cage aquaculture operation in the Experimental Lakes Area (ELA).

Solid and dissolved nitrogenous wastes are significant components of the total excretory waste released to the environment and the breakdown of nitrogenous material can also consume oxygen through the process of nitrification. Ammonia and nitrite, nitrogeneous materials, will consume oxygen as it undergoes a series of oxidation stages (Wetzel, 2001). For example, the nitrification of ammonia to nitrate will consume 2 moles of oxygen (Wetzel, 2001). For each metric ton of feed used 40 to 53 of excretory nitrogenous waste is released to the environment (Table 5), assuming a 1% feed waste rate, hence cage aquaculture operation utilizing 375 tonnes of feed will discharge 12 tonnes of dissolved and 3 tonnes of solid nitrogeneous waste annually to Lake Wolsey (Table 5).

Unlike phosphorus, most (~ 80%) of the nitrogenous waste is in the dissolved form (Bureau *et al*, 2003; Dalsgaard & Pedersen, 2011), therefore these breakdown processes likley occur in the upper surface waters. However, we found elevated TKN levels in the sediment near the cage aquaculture operation (Figure 13), which indicate that these nitrogeneous wastes settling and are accumulating at the lakebed. In some instances, sediment collected at the edge of the cages were found to exceed the PSQG-SEL of 4.8 mg g^{-1} for TKN and can be as high as three-fold higher than reference ((Figure 13).

We examined the historical sediment chemistry data for Lake Wolsey and found that though the organic enrichment signal is not as pronounced as phosphorus ((Figure 13), the sediment in the vicinity of the cages is more organically enriched as indicated by the higher loss on ignition (LOI) and total organic carbon concentrations (TOC) (Figure 15), particularly in 2000 where LOI levels exceeded 400 mg g^{-1} (d.w.) and was five-fold higher than reference (Table 7). Other indicators of fish waste, primarily copper (Cu) and zinc (Zn), were elevated in the immediate

vicinity of the cage aquaculture facility. In 2000, averaged Cu and Zn concentrations were four-fold and over twenty-fold higher, respectively, than reference with concentrations exceeding the Provincial Sediment Quality Guidelines severe-effect-levels (PSGQ-SELs) of 110 ug g^{-1} (d.w.) and 820 ug g^{-1} (d.w.), respectively (Table 7). Exceedances were not observed in 2004/05, however Zn levels were two-fold to five-fold higher at the cage aquaculture operation compared to reference ((Table 7). It is not surprising that Zn is a good indicator of fish waste as the Zn content of fish faecal waste is above 600 ug g^{-1} (Moccia *et al*, 2007; Naylor *et al*, 1999) and exceeds the background levels (Table 7). Copper is also a good indicator, but are present at lower concentrations of approximately 40 ug g^{-1} (Moccia *et al*, 2007; Naylor *et al*, 1999).

Table 7 Summary table of loss on ignition (LOI; mg g^{-1} d.w.), total organic carbon (TOC; mg g^{-1} d.w.), copper (Cu; mg g^{-1} d.w.) and zinc (Zn; mg g^{-1} d.w.) concentrations of sediment at varying distances from the cage aquaculture operation in Lake Wolsey, collected by the Ontario Ministry of Environment and Climate Change (MOECC) between 1986 to 2005

Year	Distance from cages	N	LOI (mg g^{-1} d.w.)					TOC (mg g^{-1} d.w.)					Cu (µg g^{-1} d.w.)					Zinc (µg g^{-1} d.w.)				
			Mean	Median	Min	Max	Std dev.	Mean	Median	Min	Max	Std dev.	Mean	Median	Min	Max	Std dev.	Mean	Median	Min	Max	Std dev.
1986	0 - 5 m	6	31	31	25	37	3.8	-	-	-	-	-	16	17	12	19	2.3	42	43	33	47	4.8
	30 m	1	10	-	-	-	-	-	-	-	-	-	5	-	-	-	-	13	-	-	-	-
1987	0 - 5 m	5	24	15	12	40	14.3	-	-	-	-	-	13	9	7	21	6.7	33	25	19	55	15.7
	30 m	1	15	-	-	-	-	-	-	-	-	-	14	-	-	-	-	35	-	-	-	-
2000	0 - 5 m	3	258	277	61	437	188.3	-	-	-	-	-	134	101	28	273	125.9	1787	1280	113	3967	1976
	≥ 1000 m	2	80	-	77	83	-	-	-	-	-	-	33	-	33	33	-	76	-	74	78	-
2003	0 - 5 m	1	73	-	-	-	-	73	-	-	-	-	47	-	-	-	-	270	-	-	-	-
	≥ 1000 m	1	70	-	-	-	-	70	-	-	-	-	32	-	-	-	-	76	-	-	-	-
2004	0 - 5 m	4	107	107	63	153	45.9	55	54	30	81	24.9	65	54	41	113	33.0	413	400	87	767	307.1
	25 - 30 m	3	63	67	51	71	10.6	32	34	25	37	6.2	41	26	24	74	28.3	180	200	100	240	72.1
	≥ 1000 m	2	67	67	66	67	0.7	32	32	31	33	1.4	35	35	33	36	2.1	81	81	78	84	4.2
2005	10 - 20 m	3	62	49	48	88	22.8	34	26	25	50	14.2	30	23	21	46	13.9	193	130	130	320	109.7
	30 m	15	62	62	44	93	12.7	33	33	21	54	8.2	32	32	20	47	7.3	165	150	76	300	61.0
	500 - 800 m	7	70	71	60	74	4.6	36	36	32	37	1.8	33	33	31	35	1.3	75	74	71	83	4.0
	≥ 1000 m	14	49	59	7	68	23.2	25	30	4	34	11.3	23	29	2	33	11.5	56	70	9	76	26.0

Based on the more recent 2004/05 data, we found the there was a strong positive relationship between phosphorus (P) and Zn, with Zn explaining 85% of the variability in P concentrations, while TOC explained only 57% of the variability (Figure 16). These data suggests that Zn is a more sensitive indicator of fish waste than the organic matter indicators (i.e., LOI, TOC), likely due to the assimilation of the organic waste materials by local benthic biota.

The sediment chemistry data supports the general observation that wastes from the cage aquaculture operation are settling in the immediate vicinity of the opreration. P and Zn are

sensitive indicators of the fish waste material and the elevated levels observed at sites 30 m from the cage aquaculture operation, suggests the depositional waste footprint of the aquaculture operation extends out 30 m from the facility. At locations distal to the operation (> 500 m) sediment conditions exhibit low P and Zn levels (Table 7).

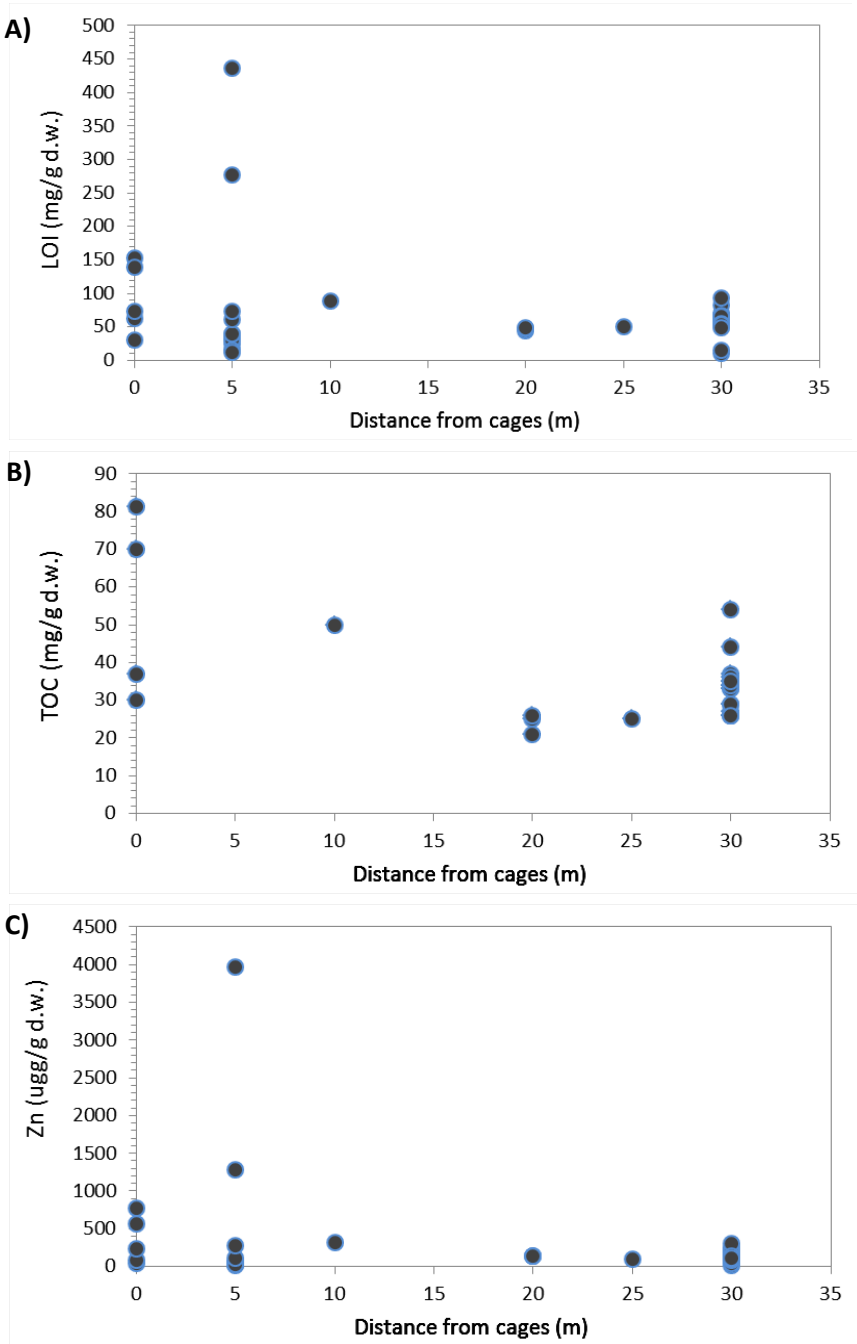


Figure 15 Concentrations of a) loss on ignition (LOI; mg g^{-1} d.w.) b) total organic carbon (TOC; mg g^{-1} d.w.) c) copper (Cu; mg g^{-1} d.w.) and d) zinc (Zn; mg g^{-1} d.w.) concentrations of sediment at varying distances from the cage aquaculture operation in Lake Wolsey, collected by the Ontario Ministry of Environment and Climate Change (MOECC) between 1986 to 2005

This excretory waste has high biochemical oxygen demand (BOD) (Bureau & Cole, unpublished; Dalsgaard & Pedersen, 2011) and is composed primarily of organic material. In Yeo et al's (2004) review of the BOD characteristics of a broad spectrum of waste by-products and aquaculture effluent, the BOD of fish faecal waste was found to be similar to that of livestock manure. Since much of the waste from the cage aquaculture operation is particulate bound (e.g., Bureau *et al*, 2003) and will rapidly settle out of the water column (e.g., Elberzion & Kelly, 2001; Moccia & Bevan, 2010) to the lakebed, typically under or in close proximity ot the cage aquaculture operation and effects are likely confined to the bottom-waters (Bristow *et al*, 2008).

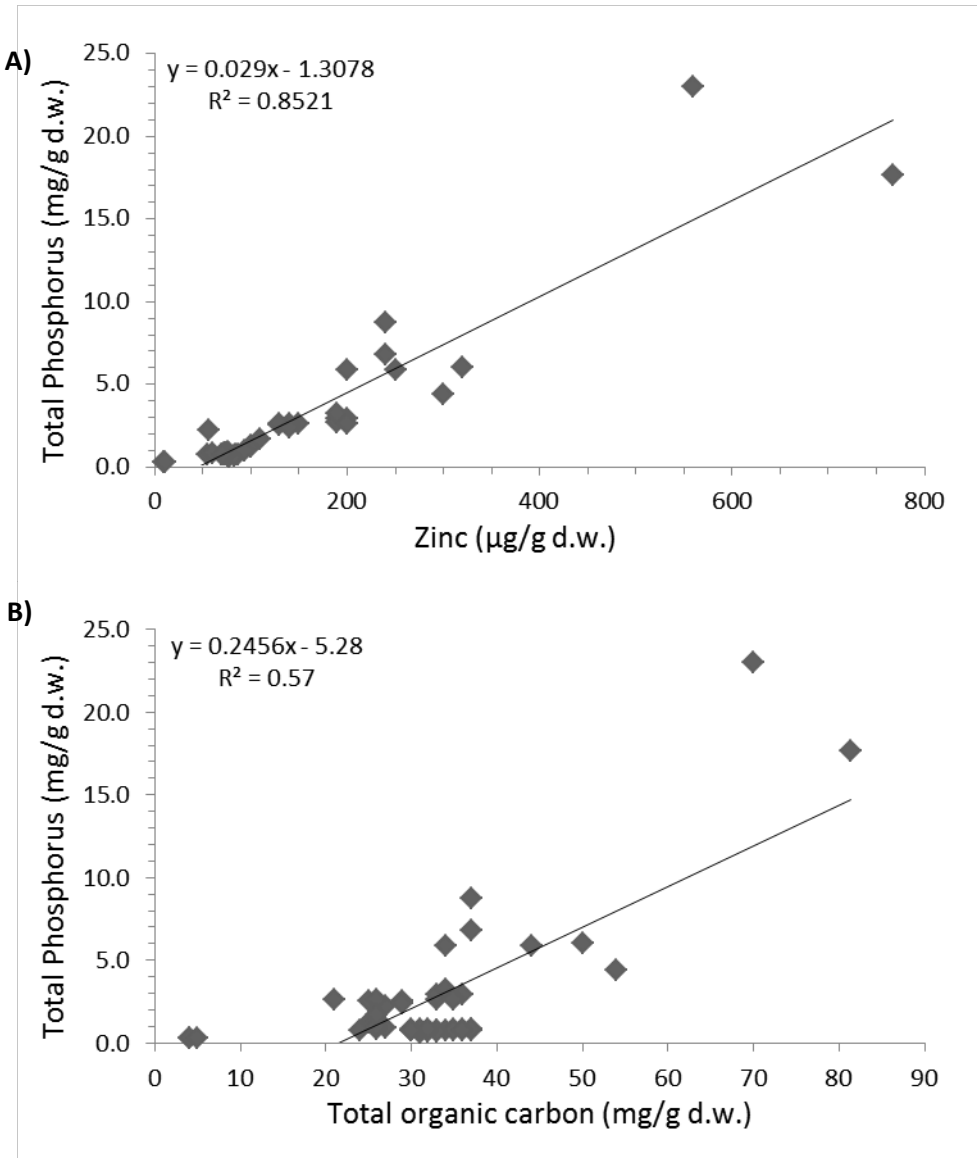


Figure 16 Total phosphorus (ug g^{-1} d.w.) as a function of a) zinc (ug g^{-1} d.w.) and b) total organic carbon (mg g^{-1} d.w.) of sediment at varying distances from the cage aquaculture operation in Lake Wolsey, collected by the Ontario Ministry of Environment and Climate Change (MOECC) between 2003 - 2005

There are multiple approaches to estimating the BOD (COD/BOD_5) waste output from rainbow trout. The total BOD of fish faecal waste can be theoretically estimated based on its carbon and nitrogen content, where the amount of oxygen requried to oxidize 1 kg of carbon and 1 kg of nitrogen is 2.67 kg and 4.57 kg, respectively (Boyd, 2009; Volpe *et al*, 2010). BOD was estimated from the undigested nitrogen and carbon waste loads from Table 4 (adapted from Bureau *et al*, 2003), which assumed a 1% feed waste rate, and by applying the Volpe *et al* (2010) and Boyd (2009) approach (see below):

Equation 1. BOD = (total N in feed − total N in fish) × 4.57 + (total C in feed − total C in fish) × 2.67

(Volpe *et al*, 2010; Boyd, 2009)

This yielded BOD estimates of 317 kg to 400 kg per tonne feed used based on 1% feed waste rate and assuming 250 mg g^{-1} carbon content of faecal matter (Table 4). This exceeds the range of 266 to 293 kg per tonne feed, identified by Bureau & Cole (unpublished), however is consistent with Dalsgaard & Pedersen's (2011) measurements of 352 kg per tonne feed used. Dalsgaard & Pedersen (2011) further partitioned the BOD components into dissolved/suspended or solids and into biological (BOD_5) or chemical (COD) components. The solids component constitute ~71% of the COD and only ~44% of the BOD_5 with the latter representing the more bioavailable component of the waste material (Dalsgaard & Pedersen, 2011).

This operation discharges, on average and assuming 375 tonne feed use, 76 tonnes of solid waste, of which 19 tonnes is organic carbon and a BOD load of 100 to 132 tonnes annually to Lake Wolsey (Table 5). This operation is permitted a feed allocation of 510 tonnes and if the operational scale were to increase feed use from 375 tonnes to 500 tonnes, this will result in a corresponding waste load increase of 101 tonnes of solid waste and 133 to 176 tonnes of BOD wastes (Table 5).

We established previously that wastes from the aquaculture facility results in a localized waste depositional pattern with effects observed within 30 m of the cages (Figure 13, Table 7). If we assume the BOD waste load is spread over the entire land tenure area (160 m x 90 m), and assuming 375 tonnes of feed usage, this results in an average BOD loading rate of 26 to 34 g BOD m^{-2} day^{-1}, during the ice-free season assuming 80% feed use between May – November. In comparison, the sediment oxygen demand of Lake Erie sediment is well-below 1 g m^{-2} day^{-1} (Snodgrass, 1987; Smith, 2008 and references therein), which is much lower than the estimated BOD loading from the cage aquaculture operation.

The use of waste coefficients based on feed usage, removes the need to factor in feed conversion ratios (FCR) and for the purposes of this report, we applied the waste coefficients of Feed type A, one of the commonly used Ontario feeds with the lowest solids waste output.

Annual feed use has fluctuated from 213 to 468 tonnes from 1997 to 2014, resulting in an annual BOD load ranging from 67 to 148 tonnes (Figure 17). Since 2011, there has been a steady increase in the amount of BOD discharged to the Lake Wolsey system, reflecting an increase in feed usage. To better understand the timing of these inputs, we plotted the monthly BOD input based on the detailed 2007 feed usage information from Milne *et al* (2015) (Figure 18). BOD inputs from the cage aquaculture operation is highest in early to mid-summer (Jun/Jul) with approximately 18 tonnes of BOD per month, with lower inputs in August (Figure 18). BOD inputs in the September and October are slightly lower, approximately 15 tonnes per month. Over 60% of the BOD waste materials is discharge to Lake Wolsey during the summer stratified season, typically June to September.

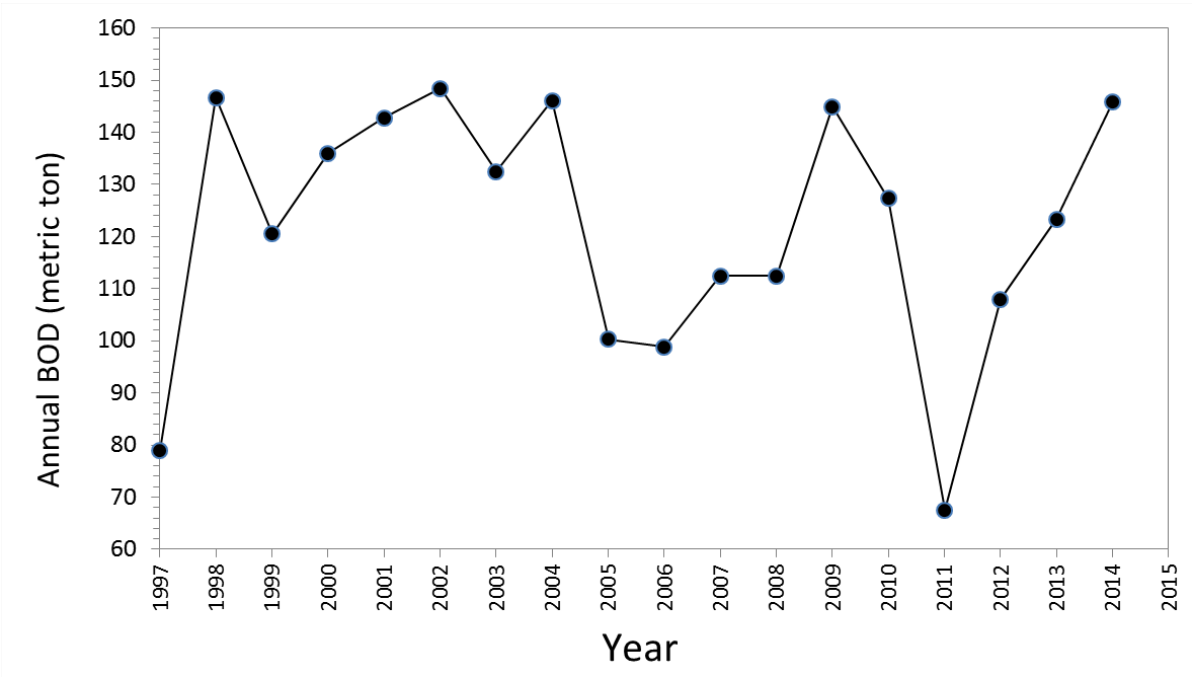


Figure 17 Annual total biochemical oxygen demand BOD (BOD_5/COD) load (metric tonnes) from the cage aquaculture operation to Lake Wolsey based on feed usage data from 1997 to 2014, assuming 317 kg BOD per tonne feed used, 1% feed waste rate and using standard commercial Ontario fish feed (Feed A; FCR 1.09) (2007 feed usage data from Milne *et al* , 2015)

Advances in feed formulation and feeding strategies have greatly reduced feed waste rates from the previous industry standard of 5% (Bureau *et al*, 2003), to less than 4% (Findlay *et al*, 2009). More recently, a 1% feed waste rate is considered the new industry performance standard (DFO, 2015). Our BOD waste output estimates are based on a 1% feed waste rate and higher rates will likely result in a disproportionately higher BOD load as waste feed exerts a higher oxygen demand than faecal waste (Dalsgaard & Pedersen, 2011; Yeo *et al*, 2004), with BOD as high as 1300 kg per tonne feed waste used, which is nearly four-fold higher than the BOD of rainbow trout faecal waste (Dalsgaard & Pedersen, 2011), while Yeo *et al* (2004) observed feed

waste had nearly an order of magnitude higher BOD than fish faecal waste. Operational strategies to minimize feed waste will reduce the solids and BOD loadings to Lake Wolsey.

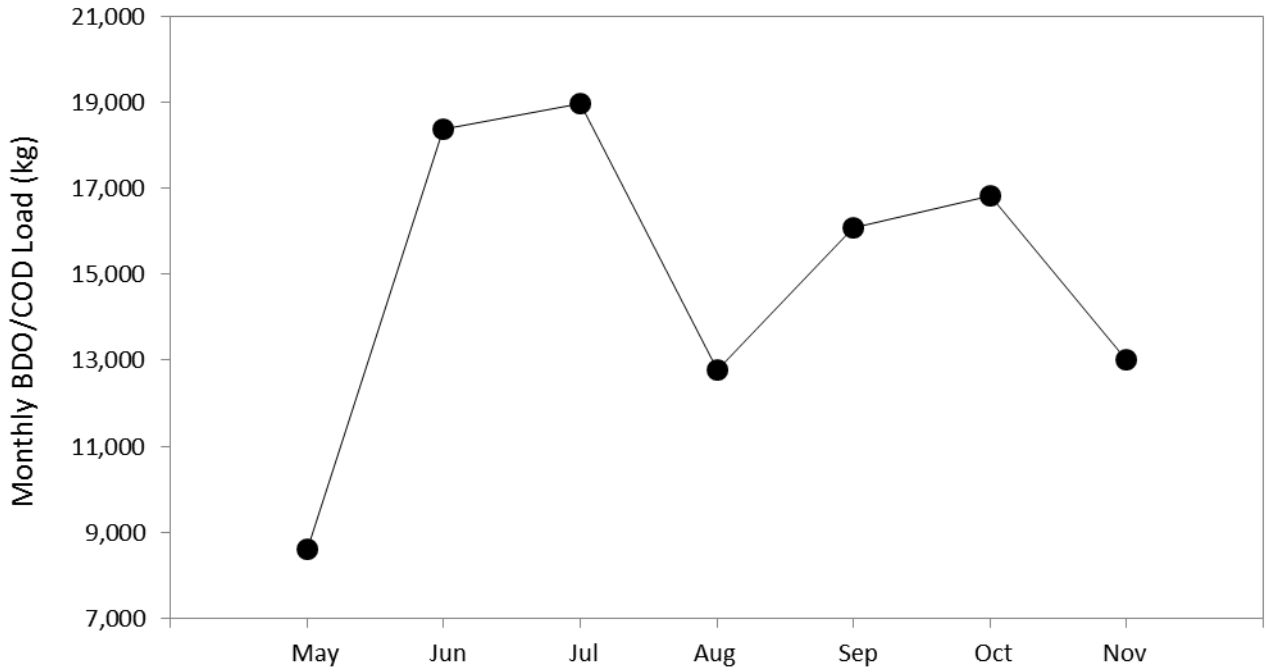


Figure 18 Monthly total biochemical oxygen demand, BOD, (BOD_5/COD) load from the cage aquaculture operation based on 2007 feed usage data from Milne *et al* (2015); assuming 202 kg BOD per tonne feed used, 1% feed waste rate and using standard commercial Ontario fish feed (Feed A; FCR 1.09)

Other factors that can influence the amount of BOD waste produced include feed composition and feeding strategies (e.g., wastage). For example, while grain-based fish feed results in lower P waste, it will also result in higher suspended solids and BOD compared to meal-based feed formulations (Davidson *et al*, 2013). Milne (2012) identified the feed used at the cage aquaculture operation as having high plant protein content and this has the potential to result in higher BOD waste compared to the standard feed used in Ontario. Lowering the protein content of feed will lead to a decrease in the BOD components (Letelier-Gordo *et al*, 2015), however increasing the digestible components will result in lower faecal energy waste and consequently solids and BOD waste (Bureau & Cole, unpublished). Experimental feeds that seek to reduce faecal energy waste have the potential to reduce solid wastes up to 40% and BOD wastes up to 45% compared to the standard feed (Bureau & Cole, unpublished).

6.4 Other Factors

Other potential contributors to the organic or BOD load in Lake Wolsey include macrophyte production and invasive species. Macrophytes can represent a significant source of oxidizable organic material and can exceed phytoplankton-derived carbon loading (Meding & Jackson,

2003) with a potential BOD of 1 mg O_2 per mg d.w. (Boyd, 1973). Lake Wolsey possesses a large littoral zone, primarily in the north and south shores, and account for ~ 30% or 608 ha of the embayment, dominated by fringing wetlands. Phytoplankton also represents an autochthonous source of organic material with a potential BOD of 1.29 mg O_2 per mg d.w. (Boyd, 1973).

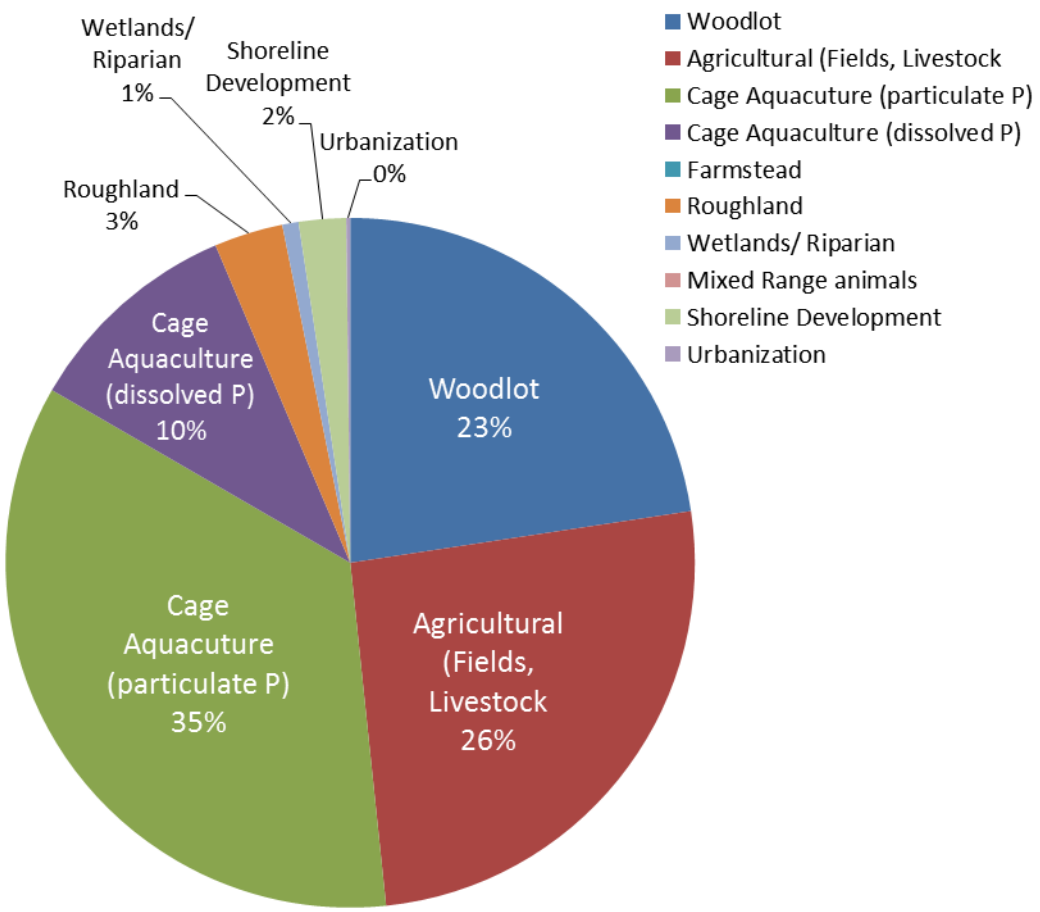
Invasive zebra mussels (Dreissenids) are present in Lake Wolsey. Zebra mussels have been found to exert an oxygen demand with every gram of zebra mussel potentially consuming ~ 42 mg O_2 d^{-1} so that in areas with intensive colonization of zebra mussels the zebra mussel oxygen demand (ZOD) can be significant (Effler & Boone, 1998) . Anoxic conditions in the hypolimnion are also lethal to Dreissenids and can result in die-off of mussel colonies.

7 Summary & Conclusions

This source loading assessment was undertaken to identify and quantify the potential anthropogenic and allochthonous sources of phosphorus, organic and BOD materials from the watershed that are potentially contributing to the severe dissolved oxygen depletion observed in the hypolimnetic waters of Lake Wolsey. From our site assessment, we found the Lake Wolsey watershed to be relatively undeveloped with woodlot occupying 60% of the watershed area, with agriculture accounting for approximately a quarter of the watershed area, most of which is used for pasture and hay production. This compares favourably to other studies for woodlot, but is slightly lower for agricultural lands (Milne *et al*, 2015). Recent land-use assessment indicates some conversion of natural land-use features to agricultural lands, however this is limited to the Burpee/Mills township area and is less than 1% of the total watershed area. We found shoreline development to be minimal and occurring mainly along the southwest shores of the embayment along with low urbanization and recreational use within the watershed. The main industrial activity in this embayment is the commercial-scale cage aquaculture operation, with historically low production (< 50 tonnes ca 1986), however recent production is much higher with feed usage ranging from 212 tonnes to 468 tonnes.

Our source loading assessment found the primary contributors of phosphorus to the Lake Wolsey embayment to be the watershed (natural features), agriculture and aquaculture. We found non-point sources of P (natural watershed features and agriculture) are the main contributors, accounting for 49% of the total P. The natural watershed features (e.g., woodlots) and agriculture contribute 1.4 tonnes and 1.3 tonnes, respectively. Our non-point P load estimate is over 2-fold higher than Milne et al's (2015) estimate of 1.1 tonnes, whose estimate is based on sampling of ephemeral streams and using a water balance approach, which suggest potentially lower P loads from agricultural and natural land-use features of this watershed. The absence of any significant tributaries in the watershed, suggests the importance of overland-flow. Seasonally, inputs from non-point sources are signficant in the spring and progressively

declines over the ice-free season and this contrasts sharply with the observed seasonal trend of increasing ambient P concentrations in the surface waters of Lake Wolsey (Diep & Boyd, 2016). Despite this seasonal pattern, overall P conditions have not changed over time (Milne *et al*, 2015), with water quality conditions in the mesotrophic range (Milne *et al*, 2015; Diep & Boyd, 2016).



[1] Assumes 375 tonne feed usage and based on 1% feed waste rate

[2] Assumes an average of 10 cattle (or animal units) per farmstead

Figure 19 Allocation of phosphorus load to land-use categories and sources in Lake Wolsey and its watershed

Shoreline development, urbanization and recreational use is low in this watershed and accounts for less than 1% of the total P load. For the aquaculture loading assessment we adjusted the waste output coefficients to reflect the lower feed waste rate of 1% and normalized it to feed usage which eliminates the need for detailed fish production and feed conversion ratio information. We assumed that, on average, the cage aquaculture operation uses 375 tonnes of

fish feed annually, resulting in 1.8 tonnes and 0.5 tonnes of particulate and dissolved P respectively. This number will fluctuate according to production needs and operational strategies and therefore the amount of P discharged to the embayment will likely vary annually We found the P load from a moderately-sized cage aquaculture operation accounts for 45% of the total P in the Lake Wolsey watershed. Our estimate of the total P load from the cage aquaculture facility is higher than Milne *et al*'s (2015) estimate due to higher production (i.e., feed usage) and inclusion of total particulate P.

Of the estimated 2.4 tonnes discharged, approximately 22% is dissolved P and the remainder is particulate P that will settle to the lakebed. Bristow et al (2008) found loadings from the cage aquaculture to be analogous to the hypolimnetic injection experiment conducted by Schindler *et al* (1980), where effects in epilimnetic waters were much lower than expected as a result of most of this waste settling to the lakebed. Our results support the general observation that most of the waste settles to the lakebed. We observed local enrichment in sediment P levels with exceedances of the Provincial Sediment Quality Guidelines severe-effect-level (PSQG-SEL) of 2.0 mg g^{-1} (MOE, 2008), however this enrichment was generally confined to the immediate vicinity of the cage aquaculture operation, with P levels well below the PSQG-SELs at sites greater than 500 m away. Although it is generally assumed that particulate-bound P is unavailable, under anoxic reduced conditions, such as that observed in Lake Wolsey (Diep & Boyd, 2016), the P release rates are much higher (Temporetti & Pedrozo, 2000), releasing P formerly sequested in the sediment back to the water column.

The agricultural lands are dominated by pasture land and hay production, resulting in total P load of 910 kg. For farmsteads with livestock, we broadly assumed that there are, on average, 10 heads of cattle per farmstead for a total of 1150 heads in the entire Wolsey watershed, resulting in a P load of up to 437 kg. This is likely an overestimate, as the Manitoulin Cattle Exchange reported only 800 cattle processed for Manitoulin Island in 2014 (McCutcheon, 2014), and the P export coefficient applied here is for large paved feedlots. Additional information on the number of livestock and presence of manure storage facilities will result in more accurate and likley lower P load from this agricultural activity.

The natural land-use features dominates this watershed and though the DOC and POC loadings can be as high as 202 tonnes and 51 tonnes, respectively, if we apply the DOC export coefficients for intensively farmed watersheds, the low ambient DOC levels and high water clarity observed in Lake Wolsey waters (< 3 mg L^{-1}) (Diep & Boyd, 2016), suggests actual loads are likely lower. Estimated suspended solids loading from natural land-use features can be as high as 129 tonnes, however the low suspended solids concentrations and low turbidity observed in Lake Wolsey waters (Diep & Boyd, 2016), suggests lower suspended solids load to the Lake Wolsey embayment. The associated BOD is estimated to be 19 tonnes for natural land-use features.

The agricultural lands of this watershed were found to potentially contribute 63 tonnes to 70 tonnes OC annually to this system, which is within the range estimated for the watershed. An estimate of the agricultural-based BOD load assumes there are, on average, ten heads of cattle per farmstead, resulting in a BOD load of up to 8 tonnes, which is half the BOD load from the watershed (Table 8).

The estimated annual solids and organic carbon loading from the cage aquaculture facility is 76 tonnes and 19 tonnes, respectively. These estimates are based on 375 tonne feed usage, 1% feed waste rate and fish manure OC content of 250 mg g^{-1}, and is expected to be higher should feed usage or the feed waste rate increase. The associated BOD load ranges from 100 to 132 tonnes from the cage aquaculture operation. Detailed feed usage information indicates production can vary annually and the operation is permitted to use up to 510 tonnes of feed annually. As with other manure types (e.g., livestock), fish faecal waste exerts a high oxygen demand (Dalsgaard & Pedersen, 2011; Yeo *et al*, 2004) and represents the maximum when compared to waste effluent and waste-byproducts (Yeo *et al*, 2004), exceeded only by fish feed (Yeo *et al*, 2004; Dalsgaard & Pedersen, 2011).

Table 8 Estimated phosphorus and organic/BOD load from natural land-use features, agriculture, aquaculture, urbanization and shoreline development to Lake Wolsey

Category	Phosphorus Load (metric tonnes)	Organic/BOD Load (metric tonnes)		
		Suspended Solids	Organic Carbon	BOD
Natural land-use features (e.g., woodlot)	1.4	129	22 to 252	19
Agriculture[2]	1.3	3 to 20	63 to 70	3 to 8
Aquaculture[1]	2.4	76	19	100 to 132
Urbanization	< 0.5	<0.5		0.6
Shoreline development	< 0.5			

[1] Assumes 375 tonne feed usage and based on 1% feed waste rate
[2] Assumes an average of 10 cattle (or animal units) per farmstead

Bristow *et al* (2008) concluded that discharges from a cage aquaculture facility are analogous to the hypolimnetic fertilization experiment conducted by Schindler *et al* (1980). Although Bristow *et al* (2008) found effects in the epilimnetic waters to be lower than expected with no significant change in surface water P concentrations until the third year of production, suspended solids in the epilimnetic and metalimnetic waters increased by the second year of production and dissolved oxygen depletion was observed with a 75% reduction by the third year. Despite the significant DO depletion in the hypolimnetic waters, Bristow *et al* (2008) found the surface epilimnetic waters maintained its oligotrophic status, which suggests effects from cage

aquaculture facilities waste loadings are expected to be most pronounced at the lakebed and in the bottom waters of aquatic systems. Our sediment surveys in Lake Wolsey confirm that these waste materials settle in the immediate vicinity of the cage aquaculture operation, resulting in enriched sediment conditions. On a per unit area and time basis, loadings from the cage aquaculture operation represents a significant anthropogenic source of solid organic/BOD materials, resulting in high sedimentation, carbon and BOD loading rates, with much of this material accumulating in the immediate vicinity of the cage array.

These estimates are based on available data and broad assumptions about livestock intensity and cage aquaculture production scale. These estimates can be further improved with detailed agricultural information, such as type and number of livestock, manure storage areas and agricultural practices (e.g., winter application of manure) as well as information on the operational practices for the cage aquaculture operation such as feed usage and feed waste rate. Loads from land-use features such as woodlots, roughlands and wetlands are considered natural and represent background loads.

There are a number of resources and options available to manage and mitigate anthropogenic sources of phosphorus and organic/BOD materials in the Lake Wolsey watershed. In Ontario, the Best Management Practices Program through the Ontario Ministry of Agriculture and Rural Affairs (OMAFRA) provides resources and tools for farmers on how to optimize farming practices to increase yields and reduce P loss. These resources can be used to identify the optimal fertilizer type and blend, application timing and method and how the fertilizer application rate will affect the economics of the farm by estimating the costs associated with the fertilizer/manure application, all of which is based on input of site-specific information. Practical solutions are provided through the use of worksheets on field management, manure storage, nutrient application rates of manure, biosolids or fertilizer (OMAFRA, 2015a & 2015b). This program provides valuable information not only to farmers but can also be useful for refining the loading estimates from agricultural sources.

For cage aquaculture operations, the Northern Ontario Aquaculture Association (NOAA) has identified a number of best management practices for aquaculture facilities which include those related to feed management (NOAA, 2011). Reducing feed waste is a key strategy for minimizing costs and environmental effects (NOAA, 2011). However, the fish waste load from cage aquaculture facilities is mainly composed of faecal waste (Reid *et al*, 2008). Therefore improvements to feed formulations that reduce the amount of waste (i.e., undigested components), has the potential to reduce waste loadings (Cho & Bureau, 2001). Cho & Bureau (2001) identified the need to reduce or remove whole grains and their by-products in order to reduce solid waste production. In the marine environment, integrated multi-trophic aquaculture systems have been identified as a potential solution to mitigating faecal waste loading from cage aquaculture operations by converting nutrient waste to harvestable biomass, thus potentially preventing eutrophication (Reid *et al*, 2008), however there are no operational models in place for the freshwater environment. Collect and treat technologies for cage aquaculture operations are limited and their efficacy will likely be dependent on faecal characteristics such as cohesiveness and stability (Reid *et al*, 2008). While altering these

characteristics will affect the waste depositional footprint size and shape, the loading is likely the same.

Our source loading assessment focused on identifying and quantifying the main sources of phosphorus and organic/BOD loads which can indirectly and directly, respectively, contribute to hypolimnetic dissolved oxygen depletion observed in Lake Wolsey. Natural land use features account for a quarter of the phosphorus loading, while anthropogenic activities, mainly agriculture and aquaculture, account for nearly three-quarters of the total P load. Though non-point source loadings (i.e., watershed and agriculture) of solids and organic material can vary widely, the loadings from the cage aquaculture operation represents the largest source of BOD materials and is potentially four to five-fold higher than non-point sources. Based on this source loading assessment, the watershed, agriculture and aquaculture are the main sources of phosphorus and organic/BOD materials to Lake Wolsey.

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