Near-field loading dynamics of total phosphorus and short-term water quality variations at a rainbow trout cage farm in Lake Huron

Gregor K. Reid a, Ian McMillan b and Richard D. Moccia* c

a Aquaculture Centre, Department of Animal and Poultry Science University of Guelph, Guelph, Ontario, Canada N1G 2W1. E-mail: rmoccia@uoguelph.ca; Fax: (519) 767-0573; Tel: (519) 824-4120 x52689
b Centre for Genetic Improvement of Livestock, Department of Animal and Poultry Science University of Guelph, Guelph, Ontario, Canada N1G 2W1

c Aquaculture Centre, Department of Animal and Poultry Science University of Guelph, Guelph, Ontario, Canada N1G 2W1

Received 19th December 2005, Accepted 2nd June 2006

First published on the web 13th June 2006

Aquatic total phosphorus (Tot-P) is measured at fish-cages in Lake Huron for environmental regulatory compliance. An improved understanding of how Tot-P is manifested in the near-field (∼30 m) water column relative to reference sites within the same water body, current movement and farm structures is required to help interpret sample results and refine monitoring protocols where necessary. The primary aim of this study is to investigate spatial and temporal concentrations of Tot-P at a commercial fish farm. A secondary aim investigates the utility of automated dissolved oxygen (DO) and pH monitoring to assist with Tot-P monitoring. Near-field TP at a commercial rainbow trout (Oncorhynchus mykiss) cage-farm in the North Channel of Lake Huron was intensively sampled for six multi-day periods of differing environmental and fish production scenarios. Current profiles were measured by acoustical Doppler current profilers for five periods, and multi-probes continuously measured temperature, pH and dissolved oxygen, at the farm centre and 30 m north/south for two sampling periods. Near-field Tot-P data was non-normally distributed. Differences between parametric and non-parametric measures were minor. Phosphorus depth profiles appeared to be influenced by the locations of cages, manure collectors and the lake bottom. Near-field lateral Tot-P concentrations were elevated above background only in down-current locations except during one period of high production and slow current velocity; suggesting adequately flushed cages will have background concentrations at up-current locations. Variation of DO, pH and Tot-P and the
correlations among these parameters, increased from the up-current, down-current and the site centre locations, respectively. These relationships suggest some limited utility for the use of multi-probes deployed around fish cages to determine nutrient flow direction, thereby inferring short-term trends of Tot-P concentrations adjacent to the farm. Implications for present monitoring practices are discussed.

1. Introduction

Most cage-based aquaculture in the Great Lakes is rainbow trout (*Oncorhynchus mykiss*) culture, located off the north and north east shores of Lake Huron. Due to the potential for excessive phosphorus loading to trigger eutrophication in freshwaters, Tot-P concentrations are monitored at fish-cages. The present phosphorus-loading target for Lake Huron is 2800 metric tonnes per year, established by the Great Lakes water quality agreement between Canada and the United States. Present fish production in Lake Huron is estimated at approximately 3100 metric tonnes. If one tonne of commercial rainbow trout produced in Lake Huron generates approximately 7.5 kg of phosphorus, the total phosphorus input from cage aquaculture for one year would be less than 1 percent of the Lake’s loading target. No lake-wide eutrophication effects from aquaculture would therefore be expected. However, poorly situated freshwater cage farms with limited flushing may result in localized eutrophication or hypolimnetic hypoxia. Such an incident is reported to have occurred at a fish farm in a restricted embayment of Lake Huron’s LaCloche Channel, and was in part responsible for the development of new regulatory guidelines.

Environmental jurisdiction of Lake Huron fish farms is largely the responsibility of the province of Ontario, Canada. The province imposes near-field compliance limits for dissolved oxygen (DO) and Tot-P as a mechanism to identify and warn of impending water quality problems. Although there are some requirements for benthic monitoring, most regulatory efforts are focused on the water column at this time. This is due to the dimictic nature of the water body, where benthic phosphorus release would theoretically be reflected in the water column during spring or fall turnover (isothermal mixing). As a result, temporal requirements for ice-free monitoring occur three times each, during spring and fall isothermal periods as well as five times during summer stratification. Spatially, depth integrated samples (depth of the cages) are taken 30 m at each side not attached to shore. The median of all 30 m Tot-P measurements for each period is required to remain below 10 µg L⁻¹ (parts per billion). A 10 µg L⁻¹ Tot-P threshold has been chosen by the Ontario Ministry of the Environment to manage for nuisance algae and to accommodate the minimum level of quantification for most commercial laboratories. The natural ice-free background concentration in Lake Huron is less than 5 µg L⁻¹. The only phosphorus form monitored is Tot-P; the rational that aquatic orthophosphate can cycle rapidly and Tot-P is an appropriate indicator of the overall potential for water quality impact.

A concern expressed by the aquaculture industry with monitoring near-field Tot-P, is that in a dynamic multi-user environment such as the Great Lakes, these measurements may only partially reflect loading from a fish farm. It can be difficult to differentiate farm-loaded phosphorus from natural or other anthropogenic sources and therefore difficult to explain near-field concentrations for regulatory compliance or farm management. The present method used by the province for differentiating farm impacts in the Great Lakes from other sources, is by the use of reference sites. These are used to quantify local
Near-field loading dynamics of total phosphorus and short-term water quality var... (DOI: 10.1039/b517972f)

There is some subjectivity in the choice of reference sites for assessing water quality impacts from cage fish farms in large water bodies. If the reference site is too close to the cages, there is a risk that the farm may influence the very waters intended as a basis for comparison. Far-field effects of aquaculture are not well understood at this time. Another concern is that reference sites may be too distant to reflect the localized water quality around the residing fish farm. This is of particular concern in the North Channel area of Lake Huron with numerous bays, channels and embayments, which may have their own unique water quality characteristics. Therefore, the investigation of alternative monitoring techniques to infer farm impacts in the event of compromised reference sites, is warranted.

Several jurisdictions have invoked the concept of a ‘mixing zone’ or ‘allowable zone of effect’ around cages, where water quality is sampled for regulatory compliance at a declared boundary. Understanding how near-field nutrient concentrations are manifested spatially and temporally is therefore important for the design of such monitoring protocols. To the best of the authors’ knowledge there are no detailed studies in the scientific literature describing how phosphorus concentrations are manifested in the near-field water column at fish-cages. As such, reviews on the suitability of regulatory Tot-P monitoring protocols would benefit from detailed research in this area. The primary goal of this study therefore, aims to describe near-field loading dynamics of Tot-P at a cage-based rainbow trout farm and to determine how concentrations are manifested relative to references sites, water movement, location and depth. The specific objectives for Tot-P sampling are as follows:

1. Describe lateral, near field (30 m) Tot-P concentrations in the context of current movement.
2. Describe near field Tot-P depth profiles over a multi-day period of peak seasonal fish production.
3. Compare mean ice-free depth profiles of Tot-P between reference sites and at the farm site centre (determine suitability of references sites).
4. Examine site centre Tot-P depth profiles relative to farm structures, such as cages, manure collectors and the lake bottom.
5. Determine the variation associated with a range of near-field Tot-P concentrations.
6. Examine a parametric (means and standard error) and a non-parametric (medians and interquartile ranges) approach to interpreting near-field Tot-P concentrations.

Depth profiles of Tot-P taken at the farm site centre are located within the ‘allowable zone of influence’ and as such are not typically recorded for regulatory purposes in Lake Huron. However, a site centre Tot-P profile can provide useful insight into the response of water quality to nutrient loading from a farm. Tot-P is arguably the most important nutrient to monitor in freshwater but is ironically the most difficult to measure, particularly at concentrations below 10 µg L⁻¹. DO and pH can be measured relatively easily in situ with multi-probes; much less labour intensive than Tot-P sample collection and analysis. Potential relationships between these parameters may have some utility to infer trends of phosphorus concentrations in the absence of physical sample collection. A secondary study goal therefore, is to determine if monitoring the variation of near-field DO and pH can provide insight into trends of near-field Tot-P concentrations to assist in regulatory interpretation or reduce the number of Tot-P samples required.

Experimental

The study was conducted at a commercial cage-aquaculture rainbow trout farm that produces an average of 250 metric tonne per annum production cycle. The farm is located in the Waubuno Channel off the north
Near-field loading dynamics of total phosphorus and short-term water quality var..... (DOI: 10.1039/b517972f)

shore of Lake Huron. The depth of the site ranges from 26 m at the near-shore side (east) to 36 m at the open channel side (west). The farm cages are cubic with each dimension 15.25 m (50 feet) and a 1.5 m height above the water line (approximately 3200 m³ below the waterline). A nylon mesh (2 mm, square mesh) manure collector in the shape of an inverted pyramid with 31° pitch sides hangs below each of the site’s 6 cages. The farm site orientation and sampling locations are illustrated in Fig. 1. Hand feeding at the farm occurs twice daily under typical feeding regimens.

Fig. 1 Site configuration, sampling locations and current profiler (ADCP) locations at the commercial field site in the Wabauno Channel (North Channel, Lake Huron).

Near-field water quality sampling procedures are outlined in Table 1. Near-field Tot-P was measured during all six sampling periods. The sampling methodology varied between periods due to the objectives of the particular investigation and environmental or logistical constraints. Ice-free seasonal Tot-P sampling at the site centre and the two reference sites, are detailed in Table 2. The farm operator measured hypolimnetic DO, thermocline and secchi depths once during each sampling period.

Table 1 Near-field sampling procedures and data collection

<table>
<thead>
<tr>
<th>Period</th>
<th>Total phosphorus sampling</th>
<th>Current profiler</th>
<th>Multi-probes</th>
</tr>
</thead>
<tbody>
<tr>
<td>P1</td>
<td>Point samples (3 sub-samples per sample) at 3 hour intervals with a vertical point sampler at 6.1 m</td>
<td>Not deployed</td>
<td>Not deployed, equipment unavailable</td>
</tr>
<tr>
<td>01/05/05 21:00–01/05/06 21:00</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>01/05/09 0:00–01/05/09 18:00</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Date Range</td>
<td>Sampling Details</td>
<td>Depth</td>
</tr>
<tr>
<td>---</td>
<td>------------------------</td>
<td>----------------------------------------------------------------------------------</td>
<td>-------</td>
</tr>
<tr>
<td>P2</td>
<td>01/07/07 21:00–01/07/10 21:00</td>
<td>Point samples (3 sub-samples per sample) every 3 hours with a vertical point sampler at 6.1 m, South (30 m) ( n = 25 ), north (30 m) ( n = 25 ), site centre ( n = 25 )</td>
<td>28.5 m depth, sounding at 1 m intervals to the surface</td>
</tr>
<tr>
<td>P3</td>
<td>01/09/02 21:00–01/09/05 21:00</td>
<td>Point samples (3 sub-samples per sample) every 3 hours with a vertical point sampler at 6.1 m, South (30 m) ( n = 25 ), north (30 m) ( n = 25 ) and site centre ( n = 25 )</td>
<td>28.5 m depth, sounding 1 m intervals to the surface</td>
</tr>
<tr>
<td>P4</td>
<td>01/10/15 21:00–01/10/18 21:00</td>
<td>Point samples (3 sub-samples per sample) every 3 hours with a vertical point sampler at 6.1 m, South (30 m) ( n = 13 ), north (30 m) ( n = 12 ) and site centre ( n = 24 )</td>
<td>28.5 m depth sounding 1 m intervals to the surface</td>
</tr>
<tr>
<td>P5</td>
<td>02/06/25 5:00–02/06/29 21:00</td>
<td>Point samples every 8 hour; two samples per time at 6 depths per location (from the surface to 30.5 m, at 6.1 m increments), South (30 m) ( n = 180 ), north (30 m) ( n = 178 ), site centre ( n = 269 )</td>
<td>37 m depth, sounding 1 m intervals to 5 m</td>
</tr>
</tbody>
</table>
Point samples were vacuum pumped every 3 hours through a polyvinyl hose into a flask (3 sub-samples per sample). Hose intakes were moored adjacent to the multi-probe sensors (6.1 m depth) South (30 m) \( n = 24 \), north (30 m) \( n = 24 \) and site centre \( n = 24 \)

\(^a\) A point sample is defined as a water sample collected at a specific location in the water column. \(^b\) At each depth and time, 3 samples were taken at site centre for this period.

### Table 2 (a) Sample collection for total phosphorus depth profiles at reference sites and the farm site centre, over one full ice-free season. (b) Dates of sample collection

<table>
<thead>
<tr>
<th>(a)</th>
<th>Depth/m</th>
<th>Samples collected(^a)</th>
</tr>
</thead>
<tbody>
<tr>
<td>North reference site (2 km)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.2</td>
<td>50</td>
<td></td>
</tr>
<tr>
<td>6.1</td>
<td>50</td>
<td></td>
</tr>
<tr>
<td>12.2</td>
<td>49</td>
<td></td>
</tr>
<tr>
<td>18.3</td>
<td>49</td>
<td></td>
</tr>
<tr>
<td>24.4</td>
<td>50</td>
<td></td>
</tr>
<tr>
<td>30.5</td>
<td>48</td>
<td></td>
</tr>
<tr>
<td>South reference site (2.5 km)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.2</td>
<td>49</td>
<td></td>
</tr>
<tr>
<td>6.1</td>
<td>50</td>
<td></td>
</tr>
<tr>
<td>12.2</td>
<td>48</td>
<td></td>
</tr>
<tr>
<td>18.3</td>
<td>49</td>
<td></td>
</tr>
<tr>
<td>24.4</td>
<td>49</td>
<td></td>
</tr>
<tr>
<td>30.5</td>
<td>48</td>
<td></td>
</tr>
<tr>
<td>Site centre(^b)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.2</td>
<td>67</td>
<td></td>
</tr>
<tr>
<td>6.1</td>
<td>66</td>
<td></td>
</tr>
<tr>
<td>12.2</td>
<td>67</td>
<td></td>
</tr>
<tr>
<td>18.3</td>
<td>66</td>
<td></td>
</tr>
</tbody>
</table>
Near-field loading dynamics of total phosphorus and short-term water quality var.... (DOI: 10.1039/b517972f)

| April 27 | June 15 | August 29 |
| April 28 | June 25<sup>d</sup> | August 30<sup>e</sup> |
| May 1    | June 26<sup>d</sup> | September 27 |
| May 2    | June 27<sup>d</sup> | September 28 |
| May 14   | June 28<sup>d</sup> | October 17 |
| May 15   | June 29<sup>d</sup> | October 18 |
| May 16   | July 16 | November 13<sup>e</sup> |
| June 16  | July 17 |
| June 17  | August 13 |

(a) Samples collected are the number of point sampler drops to a given depth.  
(b) A greater number of samples were collected at the site centre to compensate for the expected increase in variability at this location.  
(c) Samples were taken over the 2002 ice-free season.  
(d) Sampling occurred six times at both the north and south references sites and nine times at the site centre.  
(e) Sampling occurred two times at each location.

ADCPs (acoustical Doppler current profilers. Workhorse Sentinel, 600 kHz, RD Instruments, Inc.) were bottom-deployed by Environment Canada researchers (Fig. 1, Table 1) for 5 of the 6 sampling periods. Multi-probes were deployed for the last 2 sampling periods just above the cage mid-depth at 6.1 m and measured DO, temperature and pH. Multi-probe sensors were calibrated in accordance with YSI operating protocols. The units were bound together and logged simultaneously to ensure identical calibration and functionality; prior to and post-deployment. Tot-P was analyzed manually using a colorometric procedure for low concentration Tot-P. Samples were digested for 30 minutes in sulfuric acid-persulfate media at 121 °C. The lower level of detection for the analytical procedure was 1 ± 0.3 µg L<sup>-1</sup> or less (analytical level of quantification was 5 ± 1 µg L<sup>-1</sup> or less). Lower levels of detection and quantification were determined in accordance with procedures from Standard Methods for the Examination of Water and Waste Water. For quality assurance, calibration standards and certified material reference for Tot-P (from the National Water Research Institute of Canada) were run through the entire procedure. Tot-P sample values were derived from sub-sample means. Sub-sample Tot-P concentrations greater than 10 standard deviations from the overall study mean were considered outliers and omitted (these made up less than 0.5% of all Tot-P measurements in the study). PROC UNIVARIATE, SAS GLM software was used to test the normality (Sharpiow–Wilk and Kolmogorov–Smirnov procedures) of near-field phosphorus
Near-field loading dynamics of total phosphorus and short-term water quality var..... (DOI: 10.1039/b517972f)

concentrations. Where data distributions were non-normal, Tot-P data was log transformation and t-tests were used to assess significant differences ($P < 0.05$) between up/down-current and locations at specific depths. Where transformations did not fully normalize the data distribution a Wilcoxon–Mann–Whitney test was used to confirm $t$-test results.

For classifying samples relative to current direction, samples taken at the near-field north/south sampling locations during times corresponding to current flowing within 45° either side of a north or south declination, were classified as up-current or down-current samples. A north current is defined here as a north heading current. If these samples were taken when the current was flowing east/west, when current magnitude was less than 1 cm s$^{-1}$ (these values approached the measurement error of the ADCPs), or when current direction moved out of the up-current and down-current classification during the time required to complete Tot-P sampling, they were omitted. The number of sampling times in each period meeting the up-current or down-current classification criteria are shown in Table 4.

**Results**

The farm and environmental conditions for each sampling period are detailed in Table 3. The hypolimnetic DO remained above 6 mg L$^{-1}$ for all sampling periods. The mean current velocity for the 2002 ice-free season is shown in Fig. 2. Vertical current movement was not measurable by the ADCPs (<1 cm$^{-1}$) except during the first two days of spring or fall turnover, and this occurrence did not correspond to any of the Tot-P sampling times. The mean down-current Tot-P was higher than ($P < 0.05$) mean up-current Tot-P for all periods except P4 (Table 4), which was not significantly different. The up-current concentrations of Tot-P were within 1 µg L$^{-1}$ of reference site concentrations except during P2.

![Fig. 2](image) Depth profile of mean current velocities. Measured every half hour from May 30 to November 6, 2002. Standard error at each depth is <0.05 cm s$^{-1}$ ($n = 1694$ at each depth). Deployment details are described in Table 1 and Fig. 1.

**Table 3** Farm and environmental conditions for each sampling period
<table>
<thead>
<tr>
<th>Period</th>
<th>Environmental</th>
<th>Farm</th>
</tr>
</thead>
</table>
| P1     | Onset of stratification<sup>a</sup>  
01/05/05 21:00–01/05/06 21:00  
01/05/09 0:00–01/05/09 18:00  
Reference site Tot-P<sup>e</sup> = 5.4 ± 0.3 µg L<sup>-1</sup>  
(median Tot-P = 5.4 µg L<sup>-1</sup>) | Cages 1, 2 and 4 stocked<sup>d</sup>  
Mean feed = 270 kg d<sup>-1</sup>  
Biomass<sup>c</sup> ≈ 49 MT |
| P2     | Thermocline ≈ 22 m  
01/07/07 21:00–01/07/10 21:00  
Water temperature = 18 °C  
Secchi depth ≈ 6 m  
Reference site Tot-P<sup>e</sup> = 5.5 ± 0.4 µg L<sup>-1</sup>  
(median Tot-P = 5.5 µg L<sup>-1</sup>) | All cages stocked  
Mean feed = 1890 kg d<sup>-1</sup>  
Biomass ≈ 148 MT |
| P3     | Thermocline ≈ 14 m  
01/09/02 21:00–01/09/05 21:00  
Water temperature = 18 °C  
Secchi depth ≈ 6 m  
Reference site Tot-P = 5.1 ± 0.3 µg L<sup>-1</sup>  
(median Tot-P = 4.6 µg L<sup>-1</sup>) | Cages 5 and 6 stocked  
Mean feed = 750 kg d<sup>-1</sup>  
Biomass ≈ 61 MT |
| P4     | Isothermal  
01/10/15 21:00–01/10/18 21:00  
Water temperature = 13 °C  
Secchi depth ≈ 9.5 m  
Reference site Tot-P = 3.5 ± 0.2 µg L<sup>-1</sup>  
(median Tot-P = 3.7 µg L<sup>-1</sup>) | Cages 3, 4, 6 stocked  
Mean feed = 750 kg d<sup>-1</sup>  
Biomass ≈ 93 MT |
| P5     | Thermocline ≈ 12 m  
02/06/25 5:00–02/06/29 21:00  
Water temperature = 16 °C  
Secchi depth ≈ 6.5 m  
Reference site Tot-P = 4.0 ± 0.1 µg L<sup>-1</sup>  
(median Tot-P = 3.8 µg L<sup>-1</sup>) | All cages stocked  
85% feed reduction on day 2 and 3  
Feed = 220-1840 kg d<sup>-1</sup>  
Biomass ≈ 118 MT |
Near-field loading dynamics of total phosphorus and short-term water quality var..... (DOI: 10.1039/b517972f)

P6 Isothermal Cages 2, 4, 5 and 6 stocked
02/10/15 21:00–02/10/18 21:00
Water temperature = 14 °C
Mean feed = 1095 kg d–1
Biomass ≈ 73 MT
Secchi depth ≈ 7 m
Reference site Tot-P = 4.6 ± 0.3 µg L–1
(median Tot-P = 4.7 µg L–1)

\[ a \] A difference of 4 °C between the surface and lake bottom at the site. \[ b \] Temperature is averaged over the number of days in the sampling period and throughout the cage depth. \[ c \] Reference site samples (three sub-samples per sample) were taken at 6.1 m, a minimum of two separate days during the sampling period. North and south reference site samples pooled. \[ d \] Cage numbers are shown in Fig. 1. \[ e \] Estimated by the farm operator using mean feed conversion and fish sample weights. \[ f \] One set of reference site samples was taken 3 days after the sampling period. \[ g \] Taken a week prior to the sampling period.

Table 4 Lateral Tot-P concentrations at 30 m relative to current direction at a 6.1 m depth

<table>
<thead>
<tr>
<th>Period</th>
<th>Mean current velocity/cm s (^{-1})</th>
<th>Near field (30 m), up-current [Tot-P]/µg L–1</th>
<th>Near field (30 m), down-current [Tot-P]/µg L–1</th>
</tr>
</thead>
<tbody>
<tr>
<td>P2</td>
<td>11 2.5 ± 0.2</td>
<td>7.7 ± 0.7</td>
<td>11.3 ± 1.3</td>
</tr>
<tr>
<td>P3</td>
<td>11 3.4 ± 0.5</td>
<td>4.1 ± 0.3</td>
<td>5.2 ± 0.4</td>
</tr>
<tr>
<td>P4</td>
<td>8 4.3 ± 0.1</td>
<td>4.6 ± 0.1</td>
<td>5.7 ± 0.6</td>
</tr>
<tr>
<td>P5</td>
<td>10 5.8 ± 0.9</td>
<td>4.0 ± 0.3</td>
<td>5.8 ± 0.5</td>
</tr>
<tr>
<td>P6</td>
<td>22 4.1 ± 0.1</td>
<td>4.5 ± 0.2</td>
<td>7.5 ± 0.5</td>
</tr>
</tbody>
</table>

\[ a \] ± values are standard error. \[ b \] All up-current and down current Tot-P means during the same period are significantly different (\( P < 0.05 \)) except for P4.

The mean of all near-field Tot-P measurements from all periods was 6.5 ± 0.1 µg L–1 (5.6 µg L–1 median). The mean study background Tot-P concentration of 4.5 ± 0.1 µg L–1 (3.9 µg L–1 median) was derived from reference site samples (all depths, sampling periods and reference sites pooled). Variation in near-field Tot-P concentrations was observed (Fig. 3 to 7). Mean seasonal ice-free Tot-P at the site centre was significantly higher (\( P < 0.05 \)) than both reference sites at all depths (Fig. 3). Within the depth of the cages, Tot-P values at 30 m were less than site centre values (\( P < 0.05 \)) with mean 30 m Tot-P concentrations approaching reference site values (Fig. 4). The study’s data distribution of near-field Tot-P values was non-normal (\textit{i.e.} all near-field values pooled), although differences between parametric and non-parametric measures were minor (Fig. 5). The CV (coefficient of variation, the standard deviation divided by the mean) of Tot-P, DO and pH increased from the up-current (30 m) to the down-current (30 m) and site...
centre, respectively (Fig. 6). DO, Tot-P and pH varied together, the magnitude of the correlation also significantly ($P < 0.05$) increasing in this manner. These correlations are illustrated in Fig. 7 with data from P6. During P5, the other sampling period with multi-probe deployment, correlations between DO (% saturation) and pH were $r^2 = 0.36$ at 30 m up-current and $r^2 = 0.52$ at the 30 m down-current location.

**Fig. 3** Tot-P site centre depth profiles relative to farm structures and reference sites during 2002. Error bars represent the range of ± one standard error. Lake bottom depth at reference sites was 53 m. An east-west cross section (site width) of the site is viewed in the schematic. Sampling details are in Table 2.
Fig. 4 Mean, five-day Tot-P depth profiles during peak annual production in 2002. The range of one standard error is shown only on a single side of each mean to facilitate figure viewing.

Fig. 5 A descriptive parametric and non-parametric comparison of the site centre total phosphorus profiles during the 2002 ice-free season. Error bars represent the range of ± one standard error about the means or interquartile ranges (the middle 50% of the data set) about the medians.
Fig. 6 Coefficient of variation for total phosphorus and dissolved oxygen as a function of nutrient loading exposure. *n* values for each sampling period (P#) are detailed in Table 4.
Discussion

Reference sites

The reference site locations used in this study and for routine regulatory monitoring were chosen by the Provincial environmental regulatory agency, in part to obtain some deepwater samples (53 m) of hypolimnetic DO (D. Glofcheiskie. North Wind Fisheries, personal communication). However, the south reference site was 3 km from a small community with an active marina. The north reference site was 2 km south of a second fish farm and 2.5 km northwest of a third fish farm. While there were some transitory differences in single depth reference site Tot-P concentrations between sampling periods (Table 3), ice-free depth integrated concentrations were not significantly different ($P < 0.05$) between the north and south reference sites (Fig. 3) or the reported historical background concentration of less than 5 $\mu$g L$^{-1}$. This suggests that there were no prolonged influences on phosphorus concentrations at reference sites by any of the fish farms or the small community. Concerns that the reference site Tot-P concentrations may not accurately reflect local background conditions appear to be unwarranted here.

Total phosphorus concentrations

Fig. 7 Correlations between total phosphorus, dissolved oxygen and pH during P6. $n$ values for P6 are detailed in Table 4.
Site centre Tot-P concentrations at specific depths could be explained in part due to sampling locations relative to the fish, manure collectors and lake bottom. The upper two Tot-P sample depths are most likely elevated as a result of sampling within the depths of fish confinement where excretion is occurring. Although interestingly the Tot-P concentration at the depth just above the cage bottom is lower (Fig. 3 and 4), despite a decrease in mean current velocity at this depth (Fig. 2) that would be expected to reduce dilution rates or advection of soluble phosphorus. This suggests that the fish do not reside at this level as much as the top two sampled depths. However, confirmation of this effect would require tracking fish depth and measuring intra- and inter-cage current velocities. Elevated concentrations occurring at the lower depths of the manure collectors (18.3 m) suggest soluble phosphorus is leached or particulate phosphorus re-suspended from captured feces or waste feed. A higher Tot-P concentration at 30.5 m than at 24.4 m may suggest a benthic loading source, possibly settled solids from the farm. However, no direct measures of manure tarp or benthic Tot-P release were made and this should be interpreted with caution. Mean Tot-P concentrations are reduced immediately adjacent (30 m) to the fish cages, relative to concentrations at the site centre. At this farm, Tot-P concentrations in the water column at 30 m during peak seasonal fish production have marginal effects, typically staying within 1 µg L–1 of the historical Lake Huron background and reference site concentrations (Fig. 4).

Current direction affected near field Tot-P concentrations as expected with the up-current concentrations lower \((P < 0.05)\) or the same as down-current concentrations (Table 4). For most sampling periods, mean up-current Tot-P concentrations were within 1 µg L–1 of reference site values. However, the period with the highest mean up-current Tot-P concentration was P2, approximately 2 µg L–1 above references site concentrations during that period. P2 had the highest production level during the study and the slowest mean current velocity. These conditions may have caused the phosphorus-loading rate to exceed the rate of phosphorus dilution or advection, resulting in increased Tot-P concentrations at both up and down-current locations. Slower current speeds, such as during P2, may also make the farm site more susceptible to the effects of current reversal. The nutrient travel distance away from the farm will be minimal at slower speeds and therefore have greater potential to return if current direction is reversed.

In addition to current movement and locations of farm structures the amount of soluble and particulate phosphorus loaded by the farm will clearly influence aquatic Tot-P concentrations. Estimating phosphorus loading from trout by mass balance modelling over a significant period of growth has been reasonably well validated. However, obtaining estimates of waste generation large enough to differentiate phosphorus retained in fish is difficult over very short time frames (e.g. days) due to little measurable growth occurring. Such short-term estimates would be necessary to juxtapose the quantity and quality of phosphorus loaded from individual cages with measured aquatic Tot-P in this study. These estimates were beyond the scope of this particular study and of limited usefulness here since this information is not typically available to regulators or farmers along with Tot-P sampling results.

**Variation and correlation of total phosphorus, pH and dissolved oxygen**

The distribution near-field Tot-P data was non-normal. Measurements of Tot-P in lakes, even in the absence of anthropogenic sources, can be highly variable and non-normal distributions are not unusual. Parametric or non-parametric methods on how to best represent Tot-P lake data have been an ongoing point of discussion. However, at the Tot-P concentrations encountered in this study, the standard errors of the means and interquartile range of the medians, overlapped (Fig. 5), suggesting that differences between...
parametric or non-parametric measures here are minor, assuming conventional measures of data spread are used. Since the background Tot-P concentrations remain relatively constant, if outliers and skewness occur, this will tend to result in the direction of increasing means; the medians typically lower than means when measuring near-field Tot-P (Fig. 5).

CV was used to report variability in order to facilitate comparisons between a wide range of concentrations.\(^1\) The CV of Tot-P, DO and pH and correlation strength between these parameters increased with exposure (i.e. up-current, down-current and site centre, respectively) to the source of nutrient loading (Fig. 6 and 7). One exception occurred with Tot-P variation between the down-current and site centre measurement during P4. However, this may have resulted from severe weather conditions reducing the number of samples collected (reducing statistical power) and the release of organic material fouled on the cage mesh due to undulation of the fish cages.

Some technical limitations should be noted. During P5, Tot-P sampling at each time interval involved two samples (drops of the point sampler) from six depths at each of the two reference and 30 m sites, in addition to three samples at all depths in the site centre. Subsequently an average of almost two hours was required to complete Tot-P sampling during each collection. A mean Tot-P value measured over two hours could not be matched with individual 30 minute data logs of DO and pH. Deriving a two hour average of DO and pH values for comparison was not a viable option since current velocity and direction often changed in less than 30 minutes and such an approach would also artificially smooth out fluctuations necessary for credible correlations at this scale. An additional problem encountered during P5 was a faulty pH sensor on the multi-probe deployed at the site centre. However, the 30 minute data logs of the two functional pH sensors could be matched with the current velocity and directional changes and those relationships between DO (% saturation) and pH were as expected, with the down-current correlation much greater than the up-current correlation.

These relationships suggest that continuous monitoring of, pH and DO with multi-probes have the potential to determine ‘near-field’ nutrient flow direction in the absence of other current flow information potentially identifying up-current and down-current samples. This is not to suggest this technique should replace existing methods of current measurement (e.g. flagging tape, drogues, current meters), but simply that there is some utility for the automated use of multi-probes to deduce some current flow conditions.

**Conclusions**

The commercial farm in this study appears to have relatively benign effects on water quality and little potential to promote eutrophication in surrounding waters. From a regulatory perspective, detailed assessment of alleged farm impacts is typically not required unless nutrient concentrations approach or exceed compliance values. Nevertheless, examination of temporal and spatial Tot-P dynamics, low impact or otherwise, can provide useful information about near-field nutrient loading at freshwater fish cages. Such information should also be applicable to sites with greater water quality impacts.

If the intent of present regulatory compliance is to prevent or advise of cumulative Tot-P increases in localized waters around the farm, this study’s findings suggest medians may be more descriptive than means. Elevated Tot-P concentrations occurring at multiple sides of the farm would suggest inadequate flushing. Whereas elevated concentrations if they occur, should manifest largely in the down-current ‘plume’ during well flushed conditions. Consequently, the use of medians would disregard a single elevated value down-current from the farm, but the measure of central tendency would respond to elevated concentrations.
on multiple sides (assuming sample collection at 3–4 sides) thereby warning of a potential problem. While automated motoring of DO and pH around fish-cages has some utility to infer the direction of nutrient flow and therefore the location of the higher nutrient concentrations, it is suggested that the use of multi-probes not be supplemental to Tot-P sampling as their use cannot viably reduce the number of Tot-P samples required. This study’s findings used in conjunction with or without the conventional use of reference sites, may provided useful ‘forensic tools’ to assess localized water quality impacts of fish culture cages for environmental assessment, farm management or regulatory compliance.

Acknowledgements

This research was funded in part by the Ontario Ministry of Agriculture, Food and Rural Affairs, The Northern Ontario Heritage Fund, Environment Canada, Department of Fisheries and Oceans, and AquaNet. This research would not have been possible without the support of Dan Glofcheskie of North Wind Fisheries and Murray Charlton of Environment Canada.

References

1 IJC (International Joint Commission), *Addressing concerns for water quality impacts from large-scale Great Lakes aquaculture (report on roundtable discussion, Co-hosted by Great Lakes Fisheries Commission and Great Lakes water quality Board of the International Joint Commission)*, University of Windsor’s Great Lakes Institute for Environmental Research, Windsor, ON, Canada, 1999.


15 OME (Ontario Ministry of the Environment), *The Determination of Total Phosphorus in Water by Colourimetry*, 1994, Laboratory Services Branch, Quality Management Office, Toronto, ON, Canada.


This journal is © The Royal Society of Chemistry 2006