Estimating aquatic phosphorus concentrations 30 metres down-current from a rainbow trout cage array

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Aquatic total phosphorus (*Tot-P*) is measured 30 m distant from rainbow trout (*Oncorhynchus mykiss*) cages, for regulatory compliance on the Canadian side of Lake Huron. The ability to predict changes in near-field *Tot-P* concentrations from changes in production, or to explain near-field concentrations in the event of compromised reference sites, would be very useful for managers and farmers. A logical first step in the development of a near-field model is the estimation of down-current *Tot-P* concentrations. A nutritional mass balance approach was used to calculate the amount of non-settleable *Tot-P* which was divided by the corresponding flushing volume over four separate production periods. Despite a number of uncertainties, such as cage effects on flushing volume, the contribution of particulate phosphorus, fish distribution, feed conversion ratio, and ingestion–excretion time; accuracy (slope = 1.06) and precision ($r^2 = 0.75$) of modelled estimates fit well with empirical results. It was concluded that 30 m down-current *Tot-P* concentrations could be modelled under a diverse set of culture and environmental conditions, suggesting typical ‘near-field’ concentrations of *Tot-P* can be explained on the basis of farm activities.

Introduction

Measurements of aquatic *Tot-P* concentrations, 30 m distant from rainbow trout cage farms, are necessary for regulatory compliance in Lake Huron.¹ The ability to model near-field concentrations of *Tot-P*, would assist in fish production decisions and improve our understanding of system dynamics.

Since phosphorus is typically a limiting nutrient in freshwater ecosystems,² phosphorus loading from open water cage-aquaculture has the potential to influence water quality. Indigestible phosphorus is egested in feces, while digestible phosphorus will be retained in the fish carcass, or excreted as orthophosphate.³ This is illustrated in Fig. 1. Knowledge of nutrient fractionation by cultured fish typically forms the basis of model inputs for predicting aquaculture’s impacts.

Environmental impact modelling of cage-based aquaculture in freshwater is much less developed than in mariculture settings. Most published modelling efforts have focused on variants of traditional lake phosphorus models^{4–7} like Dillon–Rigler,⁸ Vollenweider⁹ and the OECD¹⁰ models; or mass balance, mechanistic approaches.^{11,12} While there has been some limited success using the Dillon–Rigler model to predict *Tot-P* in small Scottish lochs where a fish farm was the major contributor of phosphorus,⁴ most iterations of the traditional lake phosphorus models usually over-predict water body concentrations by two fold.⁷ But there has been some success, mathematically correcting a variant of the OECD

model improved predictions of *Tot-P* for some Swedish lakes with fish cages.⁷

Regardless of the successes or failures, these models were designed to predict the mean phosphorus concentration of an entire water body in response to fish farm inputs. This approach is not necessarily practical in very large water bodies like the Great Lakes, where the potential for lake-wide eutrophication from aquaculture is negligible, and where it is the near-field concentrations of phosphorus that are of regulatory significance. Regulatory monitoring of fish cages in Ontario (Canada) reflects this approach, with sampling protocols designed to detect localized impacts. Ice-free, seasonal phosphorus sampling is required at distances 30 m from fish cage arrays, within the depths of the cages, at every side not attached to shore.¹

Fig. 1 Schematic of phosphorus (P) partitioning in salmonid culture.

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Reference sites for aquaculture monitoring are locations assumed to be representative of 'normal' or background water quality conditions either in similar, but unfarmed water bodies,⁷ or from within the same water body.¹ There is some subjectivity in the choice of suitable reference sites for assessing water quality impacts from cage fish farms within large water bodies. If the reference site is too close to the cages, there is a risk the farm may influence the very waters intended to be a basis for comparison.¹ If the reference site is too far removed, it may not be representative of localized conditions around the farm, and could be influenced by non-farm related nutrient inputs. Failure to credibly explain *Tot-P* measurements in the event of compromised reference sites could make regulatory enforcement, legal liability, or farm management decisions extremely difficult.

Methods that can predict or explain near-field water quality changes at cage sites would be of use, especially where the reliability of reference sites is questionable. If near-field concentrations of *Tot-P* at a cage site can be successfully modelled, it follows that measured concentrations may be explained on the basis of farm activities. The ability to successfully model these concentrations may also enable the estimation of flushing rates necessary to ensure that proposed changes in production level and phosphorus load does not exceed near-field *Tot-P* compliance limits.

In order to estimate near-field *Tot-P* concentration in waters around fish cages, the mass of non-settleable *Tot-P* produced, and the dilution factor caused by volume and flushing rates needs to be determined. There has been some success applying a similar approach to estimate nutrient concentrations in rivers that receive effluent discharges from land-based rainbow trout farms.¹³ However, while nutritional mass balance models are reasonably well developed,^{13,14} determining water volume flushed through fish cages can be difficult, due to the affects of cages on hydrodynamics. Drag is produced as water flows through the cage netting and around cage structures,^{15,16} thereby reducing the flow velocity and increasing turbulence in adjacent waters. Drag and turbulence are affected by: the ratio of net thread to space, referred to as solidity¹⁵ or porosity,¹⁷ flexibility of the cage,¹⁸ angle of attack,^{15,17} number of net

panel crossings,¹⁵ lift;¹⁹ space between cages;^{15,16} the drag coefficient (or roughness) of the individual net threads;^{15,16} and current velocity.²⁰ Wakes can be generated at multiple scales, ranging from individual net threads^{15,16} to vortical flow generated by the general obstruction of water flow caused by the cages;¹⁷ the amount of spread a function of the distance travelled.^{15,16} These parameters are seldom constant. Fouling of the mesh can alter the thread drag coefficients and change the porosity. The affect of several dozen tonnes of fish on flow fields appears to be largely unknown.

Modelling cage-affects on flushing volume would be extremely complex and the necessary data inputs would be arguably impractical to acquire at functional commercial fish farms. However, reviewing the precision and accuracy of near-field *Tot-P* estimates made without attempting to correct for cage affects on flushing volume, may be one method to help determine how such influences affect model estimates and what, if any, correction factors should be investigated.

Therefore, this study aimed to estimate mean daily *Tot-P* concentrations, 30 m down-current of a rainbow trout farm in Lake Huron, combining estimates of nutrient loading with 'uncorrected' flushing volumes, as a first step to modelling 'near-field' *Tot-P* concentrations. A mass balance waste estimation model¹⁴ was modified and combined with a one-dimensional flushing calculation to estimate down-current concentrations of *Tot-P* during four separate production periods.

Experimental

The modelling and field validation was tested at an operating commercial fish farm where variations in animal husbandry and environmental conditions are dynamic. Four modelling periods (T1–T4) of differing environmental, husbandry and production outputs were chosen to ensure a number of diverse conditions for testing.

Total phosphorus and current measurements

Tot-P water sampling details and current profiling specifics are detailed in Table 1. To avoid entangling the vertical point

Table 1 Total phosphorus sampling and current profiling details

Period	Total phosphorus sampling (6.1 m depth)	ADCP current profiler
T1 01/07/07 21:00–01/07/10	Grab samples (3 sub-samples per sample) every 3 h with a vertical point sampler. South (30 m) <i>n</i> = 25, north (30 m) <i>n</i> = 25	28.5 m depth, sounding at 1 m intervals to the surface 1 sample h ^{−1}
T2 01/09/02 21:00–01/09/05	Grab samples (3 sub-samples per sample) every 3 h with a vertical point sampler. South (30 m) <i>n</i> = 25, north (30 m) <i>n</i> = 25	28.5 m depth, sounding 1 m intervals to the surface 1 ensemble 20 min ^{−1}
T3 ^a 02/06/25 5:00–02/06/29	Grab samples every 8 h; two samples per time. South (30 m) <i>n</i> = 30, north (30 m) <i>n</i> = 30	37 m depth, sounding 1 m intervals to 5 m 1 sample 30 min ^{−1}
T4 ^b 02/10/15 21:00–02/10/18	Samples were vacuum pumped every 3 h through a polyvinyl hose into a flask (3 sub-samples per sample). Hose intakes were moored at a 6.1 m depth South (30 m) <i>n</i> = 24, north (30 m) <i>n</i> = 24	38 m depth, sounding 1 m intervals to the surface 1 sample 30 min ^{−1}

^a A 5 day period was chosen because feeding was reduced by 90% for two days, and this was an opportunity to test the model's response to large changes in phosphorus loading. ^b Sampling methodology was modified for this period (see table) to eliminate boat use due to safety concerns of night sampling.

Fig. 2 (a) Site configuration, sampling locations and acoustical Doppler current profiler (ADCP) locations at the commercial farm site in the Wabau Channel (North Channel, Lake Huron). (b) Schematic showing cage dimensions.

sampler with mooring cables, the 30 m sampling locations were moved slightly west of the centre of the farm (Fig. 2a). Reference sites were sampled a minimum of two times during each modelling period. *Tot-P* was analyzed using a colorimetric procedure for low concentration *Tot-P*.²¹ Samples were digested for 30 min in sulfuric acid–persulfate media at 121 °C. The lower level of detection for the analytical procedure was $1 \pm 0.3 \mu\text{g L}^{-1}$ or less (analytical level of quantification was $5 \pm 1 \mu\text{g L}^{-1}$ 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.²² For quality assurance, calibration standards and certified reference material for *Tot-P* (from the National Water Research Institute of Canada) were analyzed throughout the entire procedure (assays on CRMs were within $\pm 0.5 \mu\text{g L}^{-1}$ of certified values).

Current velocities and directions were measured with an acoustical Doppler current profiler (ADCP, RDI work horse model, 600 kHz) positioned on the lake bottom. Deployment and data collection details are shown in Fig. 2 and Table 1. Given the position of 30 m sampling locations, and assuming that the current direction travels more or less linearly through the cage array, the sampling locations would be within down-current waters when flow direction traveled within 22° east of either a north or south vector, and 45° west of a north or south vector. Consequently, samples taken when water flow was travelling within these parameters were classified as either up-current or down-current flow through the site, respectively. Since ADCPs were deployed some distance beyond the 30 m monitoring locations, up and down-current classifications are considered approximations, since direct measures of current flow between the cage array and the 30 m monitoring point were not possible. Times in which the current flow was less

than 1 cm s^{-1} were omitted, since these flows approached the measurement error of the ADCP. Samples taken where the current direction changed during sample collection were also omitted.

Estimation of total phosphorus loading

The farm operator recorded daily feed inputs for each fish cage. Waste estimates were made using a modified waste estimation model.¹⁴ Estimation of non-settleable *Tot-P* is detailed in Eqns (1). The mass of soluble phosphorus excreted is simply the estimate of phosphorus digested by the fish minus the amount of phosphorus retained in the carcass (eqn (1i)). It is assumed that the soluble phosphorous (*Sol-P*) loading from an entire cage is the g fish^{-1} value multiplied by the number of fish in the cage. Fecal phosphorus equals phosphorus ingested minus the phosphorus digested (eqn (1ii)). *Tot-P* in these estimates does not include contribution from waste feed because it is assumed that feed pellets will not travel 30 m distance (within the cage depth) under typical current regimens, but instead includes all soluble excreted phosphorus and non-settleable fecal phosphorus (eqn (1iii)). The amount of non-settleable phosphorus (as fine, fecal particulates) is calculated (eqn (1iv)) as a percentage of the total phosphorus loaded.²³ Retained phosphorus is the difference between the total carcass phosphorous of the initial and final body weights (eqn (1v)) over the period of interest. The carcass phosphorus content (as a percent) is determined by a regression equation²² where phosphorus in the carcass is a function of body weight (eqn (1vi)). This regression for phosphorus carcass composition was developed with trout from the same commercial farm used in this study and one other Ontario cage-farm.²⁴ The estimated final body weight is calculated by dividing the FCR (wt feed/wt fish gain) by total weight of the feed consumed (eqn (1vii)).

Eqns (1): Estimation of non-settleable total phosphorus loading

$$\text{Mass of soluble phosphorus } Sol-P = ((FA - AFW) \times P_{\text{feed}} \times P_{\text{di}}) - RP \text{ (g)} \quad (1i)$$

where $(FA - AFW)$ = amount of feed ingested and $((FA - AFW) \times P_{\text{feed}} \times P_{\text{di}})$ = amount of phosphorus digested

$$P_{\text{fecal}} = (FA - AFW) \times P_{\text{feed}} \times (1 - P_{\text{di}}) \text{ (g fish}^{-1}) \quad (1ii)$$

$$Tot-P = P_{\text{fecal}} + Sol-P \text{ (g fish}^{-1}) \quad (1iii)$$

$$P_{\text{ns,fecal}} = Tot-P \times NSet-P \text{ (g fish}^{-1}) \quad (1iv)$$

$$RP = FBW \times P_{\text{carcass}} - IBW \times P_{\text{carcass}} \text{ (g fish}^{-1}) \quad (1v)$$

$$P_{\text{carcass}} = 0.0035 \text{ (g fish}^{-1}) + 0.1076 \text{ (g fish}^{-1}) \quad (1vi)$$

$$FBW = (1/FCR)(\text{Feed} - AFW) \text{ (g fish}^{-1}) \quad (1vii)$$

$$Tot-P_{\text{ns}} = P_{\text{ns,fecal}} + Sol-P \text{ (g fish}^{-1}) \quad (1viii)$$

Feed conversion ratios (FCRs) were calculated from farm weight and growth data collected by the farm operator over two production seasons. Model constants are shown in Table 2.

Estimation of aquatic *Tot-P* concentration is detailed in Eqns (2). The non-settleable total phosphorus output (as

Table 2 Model constants^a

Constant	Source
$AFW = 0.05$	Cho and Bureau ¹⁴
$P_{\text{feed}} = 0.0112$	Analysis (Laboratory Services, University of Guelph, Guelph, ON, Canada)
$P_{\text{di}} = 0.45$	K. Were, Skretting (then, Moore Clark), personal communication, 2003
$NSet-P = 0.10$	Derived from Coloso <i>et al.</i> ²³
$(t-1) = 12 \text{ h}$	Reid ²⁵

^a Estimation of total phosphorus concentration in the site down-current at 30 m.

mass) is divided by the estimated daily flushing volume (uncorrected) and added to the measured *Tot-P* concentration up-current; to estimate the down-current concentration (eqn (2i)). This approach is sometimes referred to as uptake-clearance.²⁶ An uncorrected, one dimensional flushing equation was approximated using 6 m depth current velocity data. This depth is just above the mid-depth of the cages, and is the same depth as *Tot-P* sample collection. The inter-cage volume between east–west adjacent cages was included in the flushing calculation.

For ease of description, the orientation of adjacent cages along the direction of current flow will be referred to as a column. The farm *Tot-P* contribution is subsequently a mean of the exiting down-current concentrations from all columns (eqn (2iii)). The resulting down-current phosphorus concentrations are assumed to be additive across adjacent cages (eqn (2iv)). The non-settleable *Tot-P* contribution from an individual cage is a function of the soluble phosphorus and non-settleable fecal particulates (eqn (2v)). The non-settleable fecal fraction is included since it is assumed that it will travel with *Sol-P* to 30 m. The $(t-1)$ value accounts for the ingestion–excretion time delay. With the value used in this model (Table 2), *Sol-P* generated from the afternoon feeding (one morning and afternoon feed daily) is included in the following day's loading value.

Eqns (2): Estimation of total phosphorus concentration in the site down-current at 30 m.

$$[Tot-P]_{\text{Down-current},t} = [Tot-P]_{\text{ns,farm}} + [Tot-P]_{\text{In}} (\mu\text{g L}^{-1}) \quad (2i)$$

$$F_{\text{cage}} = \text{number of flushings}_t \times \text{cage volume (m}^3\text{)} \quad (2ii)$$

where number of flushings_{*t*} = $t/(\text{cage length/current magnitude})$

$$[Tot-P]_{\text{ns,farm}} = \text{Mean } [Tot-P]_{\text{ns,Column}} (\mu\text{g L}^{-1}) \quad (2iii)$$

$$[Tot-P]_{\text{ns,column}} = \sum [Tot-P]_{\text{ns,cage}} (\mu\text{g L}^{-1}) \quad (2iv)$$

$$[Tot-P]_{\text{ns,cage}} = Tot-P_{\text{ns}(t-1)} F_{\text{cage}}^{-1} (\mu\text{g L}^{-1}) \quad (2v)$$

Table 3 Environmental conditions

Period	Thermocline/m	Temperature ^a /°C	Secchi depth/m	Reference site <i>Tot-P</i> ^b /μg L ⁻¹
T1	≈ 22	18	≈ 6.0 m	5.5 ± 0.4 (median = 5.5)
T2	≈ 14	18	≈ 6.0 m	5.1 ± 0.3 (median = 4.6)
T3	≈ 12	16	≈ 6.5 m	4.0 ± 0.1 (median = 3.8)
T4	Isothermal	14	≈ 7.0 m	4.6 ± 0.3 (median = 4.7)

^a All water temperatures are averaged over the number of days in the sampling periods and through out the cage depth. ^b Reference site samples (three sub-samples per sample) were taken at 6.1 m, a minimum of two separate days during the sampling period. There was no significant difference between north and south reference sites ($P < 0.05$), so all samples were pooled.

Fig. 3 Mean feed conversion ratios (FCR) for fish sizes 39–189 g, 202–574 g and 642–1032 g are 0.79, 1.05 and 1.49, respectively.

Results

Environmental conditions, production details, and reference site *Tot-P* concentrations are listed in Table 3. Farm FCRs are detailed in Fig. 3. Production and husbandry details and *Tot-P* loading estimates are detailed in Table 4. Empirical measurements of current magnitude, *Tot-P* in the site both up-current and down-current, and the number of samples that fall into this category are listed in Table 5. Results of individual modelling periods comparing estimated and measured means are detailed in Fig. 4. Estimated phosphorus concentrations had a reasonably good fit with measured values (Fig. 5; $R^2 = 0.75$ and a slope of 1.06).

Discussion

Despite a reasonably good fit between the model predicted concentrations and the measured values, there are several limitations that should be discussed. These are as follows:

- The estimation of particulate phosphorus reaching 30 m.
- Current flow and flushing estimates.
- FCR assumptions.
- Estimates of the delay time between ingestion and excretion.

Table 4 Husbandry specifics and phosphorus loading estimates for individual cages

Period	Cage number ^a	Estimated biomass ^b (mt)	Mean fish size/g	Mean feed use ^d /kg day ⁻¹	Non-settleable total phosphorus ^e /g day ⁻¹
T1	1	31	1040	350	1059.7
	2	28	890	350	1209.4
	3	34	980	350	1059.7
	4	31	995	450	1387.8
	5	12	190	175	195.2
	6	12	90	175	108.9
T2	5	28	450	400	773.4
	6	33	280	400	722.9
T3	1	29	910	0–500	0–1129.0
	2	15	1070	0–300	0–620.9
	3	36	735	0–500	0–677.4
	4	17	1150	0–300	0–1110.2
	5	7	105	125	79.3
	6	4–14 ^c	70	120	72.2
T4	2	15	290	275	0–354.0
	4	22	335	450	590.5
	5	28	478	500	696.8
	6	8	290	75	94.5

^a Only stocked cages are listed. ^b Estimated by operator using mean feed conversion and fish sample weight. ^c The range indicates a biomass change over the period (*i.e.* fish removed or added). ^d Where a range occurs, the zero indicates at least one day without feeding. The upper value is a mean derived from fed days only. ^e Where a range occurs, the zero indicates at least one day without theoretical excretion. The upper value is a mean estimate using fed days only.

(v) Vertical fish distribution.

(vi) Up-current *vs.* background *Tot-P*.

Dispersion and measurement of particulate phosphorus

Coloso *et al.*²³ reported that 5–10% of *Tot-P* is present as non-settleable solids (particulates <200 µm) in rainbow trout culture, depending on diet type. The upper limit of 10% was used as a crude estimator in the absence of settleable particulate advection data to account for an unknown, but assumed intermittent amount of settleable particulates advecting to near-field monitoring locations. While it was not possible to accurately determine the amount of settleable particulate phosphorus advecting to 30 m; it is reasonable to assume this amount would be limited under typical current regimens. At a median settling rate of 1.15 cm s⁻¹,²⁷ a current speed of 5.6 cm s⁻¹ would be needed to transport feces released from the

surface at the closest cage edge to a 6.1 m depth, 30 m distant. Feces released farther (65 m maximum) in the cage-array, would require greater speeds to reach this location. Feces released below 6.1 m anywhere within the array would presumably not reach this location. Current speeds at the site did exceed 5.6 cm s⁻¹ for 3 of the 13 sampling days, suggesting that phosphorus in some settleable particulates could occasionally contribute to *Tot-P* measurements along with, *Sol-P* and non-settleable phosphorus particulates.

Current flow data and flushing estimates

Since ADCPs were not deployed directly beneath the cages at the site, current vectors and velocities between the cages and 30 m down-current are approximations derived from more distant measurements. There will be some inaccuracies in these estimates given cage structural influences described previously.

Table 5 Daily mean current magnitudes and measured total phosphorus concentrations up/down-current at 30 m

Period	Day	Daily mean current velocity/cm s ⁻¹		Daily mean <i>Tot-P</i> /µg L ⁻¹		
		<i>n</i>		<i>n</i>	Up-current (30 m)	Down-current (30 m)
T1	1	2	2.75 ± 0.95	2	6.47 ± 0.44	9.67 ± 3.34
	2	4	2.63 ± 1.14	4	7.35 ± 0.49	10.26 ± 2.18
	3	3	2.20 ± 0.26	3	6.60 ± 1.20	10.26 ± 0.91
T2	1	1	3.90 ^a	1 ^b	4.82 ± 0.09	5.44 ± 0.43
	2	8	4.74 ± 1.52	8	4.05 ± 0.24	4.53 ± 0.26
	3	2	2.40 ± 1.30	2	5.18 ± 0.42	5.64 ± 0.62
T3	1 ^c	0	N/A	0	N/A	N/A
	2	9	7.27 ± 1.35	6	4.24 ± 0.52	6.30 ± 1.09
	3	9	8.54 ± 0.40	6	3.57 ± 0.20	5.23 ± 0.15
	4	3	8.97 ± 0.73	2	4.06 ± 0.28	5.80 ± 0.34
T4	5	3	3.70 ± 0.56	2	5.05 ± 0.54	7.41 ± 1.26
	1	5	3.60 ± 0.42	5	4.26 ± 0.23	5.80 ± 0.27
	2	6	4.78 ± 1.09	6	4.82 ± 0.14	6.76 ± 0.38
	3	9	4.76 ± 0.78	9	4.32 ± 0.20	8.57 ± 0.34

^a All ± values are standard error. Single sample, no standard error. ^b Standard error for the up and down-current samples were calculated from three, sub-samples. ^c No samples could be categorized up/down-current for this day.

Fig. 4 Measured vs. estimated *Tot-P* concentrations 30 m down-current for individual sampling periods (T1–T4). Error bars are $\pm$ one standard error.

However, in all cases, daily average down-current *Tot-P* concentrations were higher or the same as up-current concentrations. Results from a simultaneous study by the authors using the same current data found variations and correlations between daily mean *Tot-P*, dissolved oxygen (% saturation) and pH increased from the up-current to down-current locations.²⁸ This is what would be expected if mean current flow was generally linear with a reasonable approximation of up/down current locations.

Another source of uncertainty in the modelled estimates is the increased sensitivity of *Tot-P* estimates at low current speeds. For example, a reduction in the current velocity by half, will double the concentration independent of a constant

loading rate. However, a reduction in current magnitude of 1 cm s^{-1} at a nominal current speed of 10 cm s^{-1} represents a 10% change, whereas a reduction of current magnitude by 1 cm s^{-1} at nominal velocities of 2 cm s^{-1} is a reduction of 50%. Uncertainty in current measurements therefore becomes much larger at slow current speeds, and high concentration estimates resulting from low flushing will potentially produce more error than low concentration estimates resulting from high flushing.

Vertical fish distribution

One model assumption is that the fish are uniformly distributed through the cage. However, if fish are distributed at different densities within the depth of the cage itself, varying concentrations of phosphorus could occur at these depths under the same current regimen, depending on urination and defecation locations. It is well known that fish will move to the surface during a 'feeding frenzy' and can distribute themselves according to temperature preference and social hierarchies. There is some evidence of a non-uniform vertical fish distribution at the site. In a simultaneous study by the authors, the mean ice-free season *Tot-P* profile at the site centre showed surface and 6.1 m *Tot-P* concentrations were significantly higher than the 12.2 m concentrations located just above the 13.7 m cage bottom depth.²⁸ The mean seasonal current velocity at these depths suggests that the concentration differences between various depths are not likely a reflection of current magnitude. This might indicate that fish distribution

Fig. 5 Model fit for total phosphorus concentrations.

was not as dense at the bottom of the cages. If this is the case, then the actual flushing volume containing the fish at the cage mid-depth was less than expected, resulting in higher actual concentrations at the 6.1 m depth.

Feed conversion ratio

Expected FCR's and weight of feed fed was used to estimate growth in the absence of actual fish sample weights. Mathematically, the FCR will not affect estimates of solid fecal waste, but it is essential for soluble waste estimates in the absence of actual initial and final carcass compositions. Ideally the soluble phosphorus estimation component incorporates actual carcass composition and weight gain for the mass balance estimates.¹⁴ However, the estimate resolution here is in the scale of days. Daily measurements of weight gain and carcass composition are impractical and samples would certainly fall within the error range of empirical measurements, given the relatively small daily changes in growth and nutrient deposition. However, theoretical estimates of weight gain using FCR (eqn (1vii)) to estimate nutrient retention (eqn (1v), eqn (1vi)) can accommodate this level of resolution. The FCR data measured at the farm did not easily fit a conventional regression, but the data grouping did suggest that a 'moving average' approach was one option to match FCRs to fish size. Consequently three different size ranges were assigned a mean FCR, accordingly (Fig. 3). Nevertheless, the use of theoretical FCR and approximation of FCR for a range of fish sizes has the potential to introduce some error.

Time between ingestion and excretion

Fish do not instantaneously excrete waste from ingested feed. If phosphorus loading is to be predicted over short time frames such as a single day, the time between ingestion and excretion may need to be accounted for. This may not be crucial if the day-to-day feeding regimen is frequent in terms of number of feeding events per day and consistency with respect to times of feeding. It would not likely be necessary to distinguish soluble phosphorus generated from one feeding to the next as presumably the same amount of excretion will occur from each feeding episode. However, this time-lag may need to be addressed during substantial changes in daily feeding regimen, such as in T3 of this study. Rainbow trout soluble phosphorus excretion peaks approximately 12 h (15 °C) after feed consumption.²⁵ Therefore, at the present stage of model development, this time lag was used for all periods. It was difficult to validate this approach for periods with similar daily feed inputs (T1, T2 and T4) and different temperatures. However, the relatively similar slopes between daily means of measured and estimated *Tot-P* during T3 (Fig. 4), where daily feed consumption changed dramatically and mean water temperatures were 16 °C, suggested this approach was adequate.

Up-current vs. background total phosphorus

One limitation in applying this modelling approach is the need to determine the up-current *Tot-P* concentration entering the site. It cannot safely be assumed that the water body background concentration is always the same as the up-current concentrations. This was demonstrated during T1 where,

compared to the other periods, it had the highest production levels and the slowest current velocities. Up-current *Tot-P* was higher than the background concentration, possibly due to previously loaded phosphorus travelling back to the farm due to current oscillations. The difference between background and up-current concentrations here was unlikely due to other anthropogenic influences, since there was no significant difference ($P < 0.05$) in reference site concentrations between modelling periods. The occurrence of an up-current concentration that is higher than the background concentration poses a potential source of error for the use of this approach in predictive scenarios and caution is warranted.

Conclusions

While it is possible that model error propagated in a manner resulting in a coincidental good fit, a more logical explanation involves the sampling distance. As previously described, flow velocity and flushing rates are reduced as water travels through net panels, and wake spread increases as a function of distance traveled. One process theoretically increases solute concentration and the other process causes a theoretical decrease in solute concentration. This suggests that at some distance down-current, the effects of the two processes on solute concentrations will 'equilibrate', and concentrations would be the same as if the cage array had no effects on hydrodynamics at all. No doubt this distance will vary depending on current magnitude and other factors. However, it may have been the case that the sampling distance occurred where these effects 'averaged' under the daily mean current conditions at the study site. It is plausible that at a certain distance from the farm it may not be necessary to account for hydrodynamic influences of cages on flushing volume in model estimates. However, should estimates become sensitive to such affects; under conditions of good precision, a simple correction factor could be applied to produce accuracy. These explanations are speculative at this time and additional investigation is a logical next step for further research.

Despite the aforementioned uncertainties, this study's results suggest it is possible to estimate near-field *Tot-P* concentrations down-current from rainbow trout cages within daily time scales. Ultimately, our understanding of water quality response to cage-based rainbow trout production has improved.

Nomenclature

<i>AFW</i>	Apparent waste feed (%)
<i>FA</i>	Feed allowance/kg
<i>FBW</i>	Final body weight/g fish ⁻¹
<i>FCR</i>	Feed conversion ratio/weight feed per fish weight gain
<i>IBW</i>	Initial body weight/g fish ⁻¹
<i>NSet-P</i>	Non-settleable phosphorus coefficient (estimated percentage of particulate phosphorus less than 200 µm)
<i>P_{carcass}</i>	Total phosphorus in carcass (%)
<i>P_{di}</i>	Dietary digestible phosphorus (%)

(continued)

P_{fecal}	Total phosphorus in feces/g
$P_{\text{ns,fecal}}$	Non-settleable fecal phosphorus/g
P_{feed}	Total phosphorus in feed (%)
RP	Assumed retained phosphorus in carcass/g
$Sol-P$	Mass of soluble phosphorus/g
$Tot-P$	Mass of total phosphorus/g
$Tot-P_{\text{ns}}$	Non-settleable total phosphorus/g
F_{cage}	Total cage flushing volume/m ³
$(t-1)$	Estimated time between ingestion and excretion/h
$[Tot-P]_{\text{ns,Cage}}$	Concentration of non-settleable, Tot-P from a cage/ $\mu\text{g L}^{-1}$
$[Tot-P]_{\text{ns,Column}}$	Sum of cage Tot- P_{ns} contribution along a current vector/ $\mu\text{g L}^{-1}$
$[Tot-P]_{\text{ns,farm}}$	Non-settleable farm Tot-P contribution as a concentration/ $\mu\text{g L}^{-1}$
$[Tot-P]_{\text{In}}$	Mean up-current Tot-P/ $\mu\text{g L}^{-1}$
$[Tot-P]_{\text{Down-current}}$	Measured total phosphorus concentration 30 m down-current/ $\mu\text{g L}^{-1}$
$Tot-P_{\text{cage}}$	Mass of total phosphorus produced from a single cage/kg

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