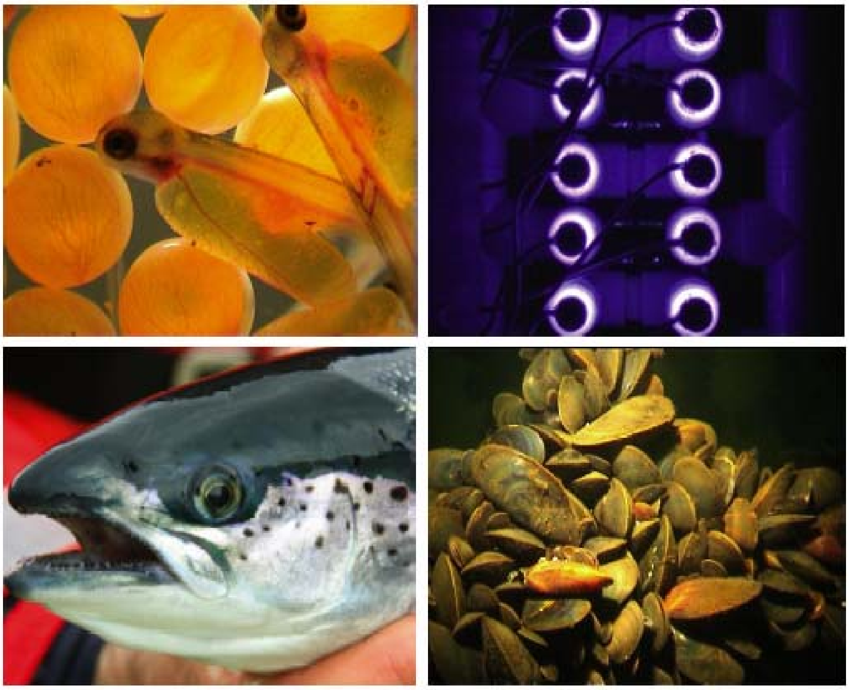
Validation Of Oecd-Model For Predicted Impact Of Freshwater Cage Production On In-Loch Total Phosphorus Concentration.

SARF055



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Validation of OECD-model for predicted impact of freshwater cage production on in-loch total phosphorus concentration.

On behalf of the Scottish Aquaculture Research Forum

Map and Marine Ltd., Namara Projects and Viking Fish Farms Ardtoe Marine Laboratory

Cromey, C.J., Rodger, A.N.S., Treasurer, J.W.

April 2010, reviewer comments added August 2010

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SARF055 - VALIDATION OF THE OECD - MODEL FOR PREDICTED IMPACT OF FRESHWATER CAGE PRODUCTION ON INLOCH TOTAL PHOSPHORUS CONTENT

1.0 EXECUTIVE SUMMARY

The regulatory framework for freshwater aquaculture in Scotland requires that, when establishing or augmenting a fish farm, an assessment of the likely impacts of the associated total phosphorus (TP) release be undertaken. The assessment requires the effect of the proposed additional phosphorus loading on in-loch total phosphorus concentration to be considered, thus ensuring that the new or additional production does not cause TP levels to lead to deterioration in ecological status, as defined by the Water Framework Directive.

The OECD equation (OECD, 1982) can be used to predict the change in total phosphorus (TP) concentration in a freshwater loch, using loch-specific information on mean depth, annual mean loch outflow, surface area and phosphorus loading. The equation is empirically based and derived from a large data set of temperate freshwaters (OECD, 1982), including Nordic and Alpine water bodies. The Scottish Environment Protection Agency (SEPA) applies the OECD equation in the regulation of aquaculture in freshwater lochs, normally where a producer applies for an increase in annual production. Loch-specific information is entered into the equation, as well as the expected annual increase in TP loading calculated from the applied-for increase in annual production using, as a default, 10 kg TP discharged per tonne fish produced per year. However, SEPA only uses this figure in the absence of a calculated figure for the site. In this regulatory process, loch-specific information is taken from the *GB Lakes inventory*, *A Bathymetrical Survey of the Freshwater Lochs of Scotland* (Murray, 1910), and the hydrological model *Low Flows 2000*.

A primary objective of the project was to test the OECD equation, by comparing predicted changes in TP with observed changes from the SEPA monitoring data set.

Twenty three study sites were shortlisted, comprising those with significant aquaculture presence, a range of lochs in terms of Water Framework Directive classification (though all were either oligo- or meso-trophic) and of physical parameters ranging across mean loch depth (range 5 to 132 m), annual mean loch outflow (0.2 to 90 $m^3 s^{-1}$), surface area (0.6 to 55 km^2) and residence time (0.2 to 6.5 year). Aquaculture production data were collated either directly from farmers or from SEPA and complete data sets were available for 15 of the 23 study sites.

Historical observations of TP were obtained from SEPA monitoring data sets for the study sites and 1 and 3 year geometric means were calculated. As TP monthly samples were highly variable at some sites, geometric means were used instead of arithmetic means, consistent with the approach used in the Loch Earn study SEPA (2004). This resulted in a time series for most sites from 2003 to 2009, with some data pre-2003. From 2003 onwards, one-year geometric means varied from 2.3 to 22.1 µg l^{-1}, and on average were calculated from 9.4 observations per year. Three-year geometric means varied from 2.6 to 20.5 µg l^{-1}, and on average were calculated from 24.3 observations over 3 year periods. TP observations measured from operators' commissioned studies were not available to the project to further test the equation performance.

Assessment of TP release from fish farm production was undertaken using the Fish-PrFEQ (Production, Feeding & Effluent Quality) model (Bureau, 2003), allowing fish growth and waste to be modelled. A predictive approach was necessary in the absence of seasonal production data. Predictive methods for assessment of waste releases are well established and offer a cost and time effective approach for assessing outputs.

Six production modes were assumed for growth and waste release modelling and covered production of single and multiple inputs of rainbow trout and S1 and SO salmon smolts. Four diets and two waste feed scenarios were considered for each. Predicted mean TP release ranged from 7.8 – 12.3 kg t^{-1} production for rainbow trout, and 10.81 – 14.35 kg t^{-1} production for Atlantic salmon.

Sensitivity of loch parameters in the OECD equation was found to be insignificant compared to variation in TP observations. Variation in equation parameters of loch depth (± 10%), surface area (± 10%), outflow (± 20%) and kg P discharged per tonne produced (± 10%) were tested for Loch Arkaig and Loch Arienas. A single and multiple parameter test (where 10,000 predictions were undertaken using different parameters within reasonable bounds), resulted in differences in predictions of less than 0.2 µg l^{-1} for all tests and both lochs.

For each loch, a timeline was constructed consisting of TP monitoring data and annual production data; fluctuations in production data were calculated between years. These fluctuations were changes in consent production, or fluctuations between periods within the existing consented production. The OECD equation was used to predict the expected change in in-loch TP concentration where there was an increase in production, and this was then compared to the one- and three-year geometric means of the TP monitoring data. Mass budgets for each loch were also determined using the PLUS model (Plus Model, Macaulay Institute, Aberdeen, UK) and information on point sources including aquaculture. Predicted in-loch TP was compared to five-year observed geometric means.

Further tests with the equation included use of extreme parameter values and site-specific parameters on kg P discharged per tonne produced depending on production mode.

Model performance was low for the majority of tests where predicted changes in TP were compared with observed (coefficient of determination $r^2 < 0.12$, n ranged from 8 to 20 tests). Model performance was defined as 'poor' when using methodology which categorises model performance by examining the statistical significance of r^2 and the gradient and intercept of the linear regression between predictions and observations (Portilla and Tett, 2008; Jusup et al. 2009). Using the OECD equation in the mass budget approach, with predictions from the PLUS model, resulted in a performance of 'fair'.

The present study finds low performance of the OECD equation when used in a similar manner to the consenting process; i.e. used to predict a change in TP according to an increase in TP loading from aquaculture. This finding implies that the current regulatory method using the OECD equation is inadequate and should be extensively reviewed.

Developing a mass budget approach for all aquaculturally important lochs, including PLUS model predictions, regulatory information on point source discharges and operator-returned aquaculture production, would be a useful step towards improving predictive capability for in-loch TP concentration.

The use of a fixed figure for TP release estimates from fish farms needs further assessment. The figure of 10 kg t^{-1} produced is used as a default in the absence of site-specific information which is used when available. The rates of feed waste on farm are not well understood and the existing consenting process, in the main, limits fish farming activity on biomass, which is not necessarily as useful a predictor of TP release as is fish production. Ideally, data on feed input and fish production per quarter would give the minimum level of information necessary to describe the cycle of fish farm TP release effectively.

TP from fish farms should however be viewed within the broader context of all nutrient inputs into any given loch system and the rigour to be applied in collection of fish farm data should be proportional to the overall status of the loch and significance of other non-aquaculture nutrient inputs.

It was evident during the study that statutory returns from freshwater fish farms on production data, feed use and FCR (Feed Conversion Ratio) were not available for several salmon farms. This excluded a number of the case examples from the validation process. There should be more critical evaluation of fish farm returns. It is also important that data on fish farms obtained in public surveys and held by government should be readily available to researchers working on behalf of public organisations.

A fish farming monitoring and reporting system called “Sentinel Fish Farms” has been set up on a trial basis and enables data to be entered into a reporting package that can be seen remotely (Prof J. Turnbull, Institute of Aquaculture, University of Stirling). Use of such a system may make the reporting of fish farming activity data more efficient, the information more readily available, and would save time for the farm staff and prevent duplication of the reporting of information to various sources.

2.0 ACKNOWLEDGEMENT

Many thanks go to Ian Milne and Malcolm Smith (SEPA) for assistance with collation of TP monitoring data, production data and the method of use of the OECD equation. Thanks go to John Carmichael (Dawnfresh), Mark Weir (Skretting Ltd) and David Bassett (BTA) for information and guidance at project meetings. Also, we thank Lighthouse Caledonia, Scottish Sea Farms and Marine Scotland for providing information. Six other anonymous producers participated in discussions. We thank the external reviewers for their extensive comments and reviews.

3.0 STUDY OBJECTIVES

The specific objectives of the project were:

(1) Review the current knowledge on the transport pathway of phosphorus in feed and faecal material from freshwater production in Scotland and, in particular, determine whether existing information is representative of modern feeds in use and feeds new to market

(2) Review current use of the OECD equation and similar models in the context of freshwater lochs in Scotland

(3) Review the existing monitoring survey data sets of freshwater lochs containing aquaculture production with respect to phosphorus; with assistance from SEPA obtain a shortlist (approximately 10 lochs)

(4) Laboratory determinations of physical and chemical characteristics of feed and faeces with respect to phosphorus, using a range of modern diets, complementing current information available

(5) By including results from laboratory investigations and the reviews, compare predictions of OECD type models with observations from monitoring surveys and refine as necessary

(6) Inform the SEPA freshwater fish farming manual which is currently being developed by the regulator

Extent to which the objectives have been met

Objectives 1 and 2 – review of the waste pathways and models

These objectives were met by undertaking a review of the scientific literature and reporting on waste transport pathways and use of models.

The literature on TP release implied that, by using mass balance and bioenergetic modelling approaches, sufficient reliability in TP release rates to allow OECD validation could be achieved. The project then used these predictive approaches with pragmatism and economics in mind.

Several examples of use of the OECD model were found in the peer reviewed literature. Many of these studies made comparisons with other similar ‘static’ and dynamic TP models. Some studies had also calibrated coefficients on a site-specific basis. Examples of dynamic models were also found, as well as complex models applied to whole lochs that aimed to predict circulation and residence time in the lochs. It was apparent from the review that most assessments included attempts at a whole lake budget.

This review informed partners that recent up-to-date information on feed and faeces has been reported by Canadian scientists. This finding influenced objective 4, in that laboratory determinations would largely be a repeat of Canadian studies.

Objective 3 – review monitoring data sets and shortlist sites

This objective was achieved by short listing 23 sites and analysing SEPA monitoring data for these sites. The number of sites exceeded the number of ten specified in the project proposal. This data set provided a good basis for testing the OECD equation in objective 5.

Objective 4 – laboratory determinations of waste characteristics of feed and faeces in relation to P

The literature review provided up-to-date information on modern feeds, mostly from Canadian studies, improving on the information that was currently used in the regulatory process based on historical data. Further, collaboration with Bureau and the project partners resulted in a growth and waste estimation model validated in Canada. Low sensitivity of the equation to some waste parameters meant that extensive experimentation to determine minor differences between Canadian and Scottish feeds would result in only minor variation.

As a result of these findings, laboratory determinations were deemed unnecessary early on in the project (partner meeting 26th June 2009). Instead, waste estimation and growth models validated in Canada would be tested with Scottish feeds and results summarised in a context useful for use in the OECD equation. These models would provide all the necessary information.

From the extensive literature search and contact with Canadian freshwater modellers it was apparent that all the parameters for testing the OECD model were available in the literature, so extensive testing of fish in laboratory tanks to assess the waste budget were unnecessary and would have detracted from the modelling work. The suggestion to examine TP levels in selected lochs was also difficult in the time available. It was agreed at a meeting of the partners on 26th June 2009 that there would be more benefit in assessing the extensive monthly TP data sets held by SEPA and the analyses could be done on a wider selection of lochs with aquaculture operations. This was finally agreed as 23 lochs representing a wide range of localities, sizes, depths, and with both salmon and trout.

Assessment of TP waste release from fish farms was conducted using a basic mass balance approach and more advanced bioenergetic modelling (Fish-PrFEQ). The findings partitioned dissolved and solid TP for two species, six production modes, two feed wastage rates and four diets.

Objective 5 – testing of the OECD equation

This objective was achieved by testing the equation for nine complete loch data sets, and by making a statistical assessment of model performance. A sensitivity analysis determined which model parameters were important, by taking account of possible error in model input loch and waste parameters. This objective could have been more satisfactorily achieved if production data for all study sites had been made available.

Testing of the Dillon-Rigler (Dillon-Rigler, 1974) model and dilution models was discouraged by SEPA and so was not undertaken.

Objective 6 – informing the freshwater fish farming manual

Although a freshwater fish farming manual is not currently being written by the SEPA, this objective was achieved by making specific recommendations on annual production and feed returns, husbandry practices, model input parameterisation and OECD equation use. These are the primary recommendations from the findings of the research.

4.0 LITERATURE AND DATA REVIEW

4.1 OECD equation and project background

The project was commissioned by the Scottish Aquaculture Research Forum (SARF) to validate the existing OECD equation (Vollenweider, 1980; OECD, 1982; Phillips, 1985) for its use in managing the phosphorus-associated impact of fish cage production in Scottish freshwater (fresh water) lochs. The OECD equation predicts the change in total phosphorus (TP) concentration in a defined water body from a limited number of loch and fish production specific variables. The predicted change in TP concentration can then be used to assess the likely consequences on trophic status of the water body and hence define required management measures.

Since the early days of fish farming in Scotland, changes in fish feed specification, scale of fish production as well as husbandry practices have all occurred and, as a consequence, the way the OECD equation is used is also in need of review. This project has therefore considered the contemporary understanding of waste streams from freshwater aquaculture, looked at representative freshwater systems and their response to reported waste inputs, and explored the sensitivity and validity of the OECD equation.

Following contemporary terminology (eq. 2a, p197 in Johansson and Nordvarg (2002)) and specifically for fish farm emissions resolved over an annual time scale, change in TP using the OECD equation is defined as: $\Delta TP = a\left(\frac{\Delta TP_{in}}{1+\sqrt{T}}\right)^{b}$

(1)

where

ΔTP = predicted effect of annual fish farm emission on in-loch TP concentration (µg l^{-1}), ΔTP_{in} is the predicted effect of farm emissions on inflow concentration,

T = loch residence time (year)a = 1.55 and b = 0.82 are empirical constants from the OECD combined data set (OECD, 1982).

Residence time is dependent on loch outflow Q (m^3 s^{-1}), loch surface area A (km^2) and mean loch depth D_m (metres):

$$T = \frac{A * 10^6 * D_m}{Q * 3600 * 24 * 365.25} \qquad (2)$$

The effect on the inflow concentration (ΔTP_{in}) is calculated from the annual TP load (TP_{load} (kg year^{-1})) and Q as follows:

$$\Delta TP_{in} = \frac{TP_{load}}{Q} \quad (3)$$

4.2 Fish Farm Wastes

Fish farm wastes of interest to this study are those which will contribute to the TP load. These are predominantly by-products of the feeding and metabolic processes and can be both solid and dissolved, potentially degrading the receiving environment when the quantities released are above what can be readily assimilated within existing trophic structures.

Wastes from fish farming more generally contain nitrogen, phosphorus and potentially all have transient, long term or both effects upon the chemistry and species mix of water column and benthic sediments (Kelly, 2001), depending on the quantities released and conditions of the receiving environment.

In fresh water systems phosphorus is assumed to be the primary limiting factor for algal growth (Schindler, 1978; Weltch, 1992; Gibson, 1997), on account of it's occurring in the least amount relative to the needs of plants. It is therefore the potential output of phosphorus from fish farms that is primarily regulated in the management of fresh water systems, and management measures are derived in Scotland for given water bodies by use of the OECD equation. Within the equation the rate of release of TP per tonne of fish produced, is set to a default of 10 kg t^{-1} production for both Atlantic salmon and rainbow trout, when no other evidence of farm specific release rates can be provided. The use of TP release rates within the OECD equation assumes fish production per annum, as concentrations are based on annualised figures.

The use of change in TP as the regulatory measure assumes that all phosphorus released from fish farming is potentially plant available. The majority of plant available phosphorus, orthophosphate (or dissolved reactive phosphorus) released directly by fish is a by-product of metabolism, derived from absorbed and utilized dietary phosphorus and excreted via brachial and urinary pathways. Orthophosphates also leach from waste feeds as they fall through the water column and, as shown in tank based experiments (Coloso, 2003), approximately 80% of feed origin orthophosphates can be released with 30 minutes of immersion. Figure 1 illustrates the assumed pathways for in-feed phosphorus.

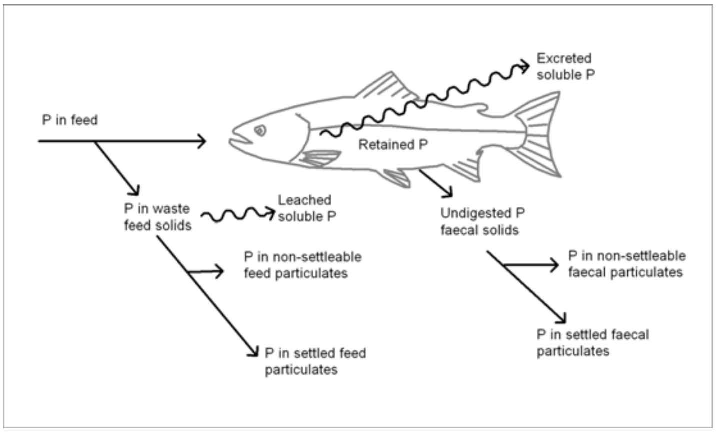

Figure 1 – assumed main pathways and partitioning of phosphorus from fish feed (Reid, 2007) adapted.

Nitrogen in the form of ammonia is the other directly released dissolved metabolic fish waste, being derived from the oxidation of dietary protein (Bureau, 2009). The influence of nitrogen with phosphorus (Elser, 2007) has been shown to be of significance in phytoplankton enhancement in fresh water systems and therefore - although not the focus of this study - nitrogen should not be dismissed in management of fresh water systems.

Solids wastes from fish generally originate from undigested (faecal material) or administered but non-consumed (waste) feed. Faecal material is mostly composed of minerals, carbohydrate, fibre and small amounts of protein and fat. Wasted feed is obviously more labile and rapid water absorption enables leaching of soluble components.

Commercial fish feeds usually contain more phosphorus than is required for growth alone and therefore the unavailable or surplus phosphorus is excreted in dissolved and solid forms (Coloso, 2003). Indigestible phosphorus is egested in faeces, while digestible phosphorus is retained in the fish carcass or excreted as soluble orthophosphate (Bureau et al., 1999; Reid, 2007), via the urinary or brachial pathways.

Faeces and waste feed settle rapidly to the sediment in most Scottish fresh water loch scenarios, following settling velocities reflective of particulate density and size. The settling rates of these particulates, when combined with knowledge of horizontal waterborne currents and localized bathymetry, enable prediction of areas and fluxes of deposition.

From a basic mass balance approach (Cho, 1991; Kelly, 1996), Table 1 shows the TP released from production of Atlantic salmon, grown using an average food conversion ratio (FCR) of 1.2, approximately 73% of the phosphorus administered or 9.5 kg t^{-1} fish produced.

Table 1 – Basic mass balance for phosphorus in production of 5 t of Atlantic salmon, where ww = wet weight.

Feed used, kg,ww	6000
FCR	1.20
Fish Produced, kg, ww	5000
Feed wastage rate, %	10.00
Phosphorus content feed, %	1.20
Phosphorus retained in fish, %, ww	0.49
Phosphorous in feed, kg	72.00
Phosphorous retained in fish, kg	24.50
Phosphorus in waste feed, kg	7.20
TP discharge, kg	47.50
TP discharge, kg/t fish produced	9.50

The scenario illustrated in Table 1 shows TP discharge close to the values used in regulation, e.g. 10 kg t^{-1} production. In the literature, values for phosphorus retained in fish are reported to vary between 0.5% (Kelly, 1996) to 0.36% (Bureau, 2003) of wet fish weight. TP release, from empirical study (Foy, 1991; Hennesey, 1996; Kelly, 1996; Reid, 2006), ranges from 9 – 11 kg t^{-1} production for Atlantic salmon and 9 - 25 kg t^{-1} production for rainbow trout. As measurement of TP release has its difficulties, and with the drive to find more effective feeds, models which explore feed effectiveness in relation to growth and waste release have been developed (Cho, 1991; Cho et al., 1998; Bureau, 1999; Bureau et al., 1999; Cho, 2001). TP levels in the effluent can be reduced by lowering phosphorus levels in fish feed, or by improving the utilization of dietary phosphorus by the fish (Coloso, 2001; Coloso, 2003), or both.

The theoretical partitioning of TP wastes into solids and dissolved forms as a function of daily fish growth and diet specification is now fairly well understood through the use of mass balance modelling (Cho et al., 1998; Bureau et al., 1999; Papatryphon et al., 2005). This has enabled the development of experiments which have considered the influence of localised currents and their effect on dissolved or non-settling particulates (Reid, 2006;

Reid, 2007), and thermoclines which act to retain solid phosphorus in the hypolimnion (Bristow, 2008).

Figures for waste feed from fresh water aquaculture are not readily accessible, with no recent studies of contemporary Scottish practice being available. Discussion for this study with farm operators revealed a range between 5 - 20% of administered feed being wasted. This is significantly higher than for marine operations where researchers have observed losses between 3 – 10% (Cromey et al., 2002; Davies, 2002; SEPA, 2005). The higher waste feed rate in fresh water is attributed mainly to the ‘messy’ feeding of juveniles, the lack of surface visible feeding response in salmon (particularly during winter) and the comparatively small amounts of feed involved when compared to marine systems, meaning operators are less focused on economics-driven feed efficiency. In contrast to salmon production, trout farmers argue that their feed wastage is at the lower end of the range, on account of trout being predominantly surface feeders, and therefore staff are better able to gauge feed rates.

Phosphorus in faeces and waste feed is not directly plant-available, though release of plant-available orthophosphate from laboratory based samples collected from sediments augmented with waste feed and faeces has been shown to be up to an order of magnitude greater than background releases for low nutrient status lochs, in aerobic conditions (Kelly, 1992). Maximal figures from this Scottish study were 57 mg m^{-2} d^{-1} release of orthophosphate from settled waste materials which, if extrapolated, equates to 0.02 kg m^{-2} per annum. Such orthophosphate releases from the sediments have the potential to enhance algal production and, where anoxic conditions develop, the rate of release of orthophosphates can be greater (Lee, 1977; Cerco, 1989). Recent work on effects of sediment released orthophosphate have shown thermal stratification of the water column to be a significant factor (Bristow, 2008). On average Bristow showed, 88% of the input phosphorus was retained in the sediments during aquaculture, with 7% accumulating in loch water and 5% exported by the outflow.

Fish faeces have been shown to have a higher percentage, by dry weight, of phosphorus than the ingested feed (Kibria et al., 1997). For salmonids the phosphorus content of faeces has been shown to be of the order of 4.8% by dry weight (Reid, 2008). Rapid release of orthophosphates from fish faeces has been shown to occur in the first 1-4 days, with release rate reducing thereafter as bacterial growth accelerates (Kibria et al., 1997).

4.3 Regulatory context

The Water Framework Directive (WFD) 2000/60/EC seeks to establish a framework for Community action on water policy across Europe and broadly aims to maintain waters in, or return them to, conditions which exhibit good ecological status. The delivery of water management actions is to be focused at a catchment level, extending to 3 nautical miles or more seaward, and such bound areas have become subject to River Basin Management Plans. Within Scotland the Water Services Water Environment Act implements the WFD and requires the Scottish Environment Protection Agency (SEPA) to develop policies and methods, in partnership with others, to respond to the directive.

As a premise to the WFD, the quality status of many aquatic systems in Europe is assumed to be in decline. The pressures which drive such decline are generally well understood, though the associated environmental responses may be less predictable, leading to difficulties in managing aquatic resources most effectively.

Within this context, the management of existing and new fresh water aquaculture as a pressure on aquatic systems is required. In Scotland the management of freshwater aquaculture discharges is undertaken by SEPA. The assessment methods used by SEPA are currently being revised to render them compliant with the requirements of the WFD: that no deterioration in ecological status occurs.

Currently SEPA manages freshwater aquaculture discharges on the presumption of maintaining ecological status of the standing waters (as defined under the WFD), and ultimately achieving Good Ecological Status. Changes in trophic status are assumed to be detectable when deviations of more than 20% from mean baseline total phosphorus (TP) value are experienced (Maki A.W., 1984; Stauffer, 1986).

Assessments of trophic status of standing waters are based on methods described in the publication “Eutrophication of waters: monitoring assessment and control” (OECD, 1982), where TP value is the primary determinand. This method uses geometric rather than arithmetic means when assessing annual TP concentrations in systems and allows for the removal of extreme data points, when greater than 2 standard deviations from the mean. SEPA formerly followed the OECD recommendations for setting water quality standards (WQS) thresholds and uses the values shown in Table 2 in assessment of a loch’s potential to assimilate further TP discharges.

Management of TP in standing waters is therefore undertaken in respect of an assumed static trophic status for a given aquatic system and changes in TP which can be regulated are assessed against a possible deviation window (± 20% of mean TP) which, once breached, will potentially lead to a change of trophic status.

Table 2- OECD trophic status categories and water quality standards formerly used by SEPA (the current classification is driven by the WFD).

	Trophic Status				
	ultraoligotrophic	oligotrophic	mesotrophic	eutrophic	hypertrophic
Total phosphorus (µg/l)	<=4	<=10	<=35	<=100	>100
Chlorophyll (µg/l)	<=1	<=2.5	<=8	<=25	>25
Secchi disc (m)	>=12	>=6	>=3	>=1.5	<1.5

	Water Quality Standard per trophic status			
Total phosphorus (µg/l)	<=2.5	<=8	<=25	<=80

Note: limits are annual geometric means after the exclusion of all data points beyond the two standard deviation range (prior to transformation).
(SEPA, 2002, OECD, 1982)

How effectively nutrients are transformed into phytoplankton biomass depends on a number of different ‘sensitivity’ factors, such as depth, retention, and water colour. In general, the impact of nutrients is likely to be less in deep, rapidly flushed, peaty waters compared with shallow, poorly flushed, non-peat-stained waters (Carvalho, 2005). High phytoplankton biomass may not always lead to eutrophic conditions, but from a management perspective the risk of eutrophication is greater and thus policy and regulation must act to manage the risk within acceptable or Directive defined levels.

4.4 Description of the FRESH WATER aquaculture sector

Cage based FRESH WATER fish aquaculture is the primary interest in this study. Four species, *Oncorhynchus mykiss* (Rainbow trout), *Salmo salar* (Atlantic salmon), *Salmo trutta* (Brown trout) and *Salvelinus alpinus* (*Arctic charr*), feature in the Scottish Annual Production Survey (FRS, 2008) as being produced using cage culture methods. Comparative values for these species in Scottish lochs are given in Table 3.

Table 3 - Comparative values of fish produced for harvest/transfer in Scottish FRESH WATER cage systems, 2007 (FRS, 2008)

Species	No. of cage sites	Weight at harvest/transfer	Period to harvest/transfer	Production, t / year
Rainbow trout	8	340 - 900 g	12-24 months	2704
Atlantic salmon	56	60 - 100 g	6 or 12 months	1166-2333*
Brown trout	?			124
Arctic charr	?			6.5

* based on variable transfer weights

Rainbow trout was the primary species in terms of production mass from cage culture in FRESH WATER in 2007, with five out of the eight sites each accounting for more than 100 tonnes of production. Rainbow trout were also produced for restocking of sport fisheries and in the same year 845 tonnes were released for this purpose, though how much was produced in cage culture is not specified.

In comparison, salmon was produced at a much greater number of sites than rainbow trout, but at a slightly lesser production mass. The statistics refer to numbers of produced smolts and the range in production mass shown in Table 3 is derived from the product of the possible smolt weights at transfer and the total reported smolt numbers. The actual production period for salmon may be half that of rainbow trout, if produced using photoperiod manipulation (termed S_0) and thus will have significance in respect of the timing and production quantities of metabolic wastes.

The other species produced in freshwater are of minimal comparative mass, being 4.5% and 0.2% of the rainbow trout figure, for brown trout and Arctic charr respectively. The study therefore focused primarily on rainbow trout and Atlantic salmon.

The figures in Table 3 refer to the masses of fish removed for harvest or transfer in the respective categories and do not include fish held for ongrowing on site in their second year. The table therefore illustrates purely ‘harvest type’ production and not onsite biological production. The latter must be considered when estimating waste budgets and, without the availability of these data from farm records, predictive methods must be employed.

4.5 Regulatory TP monitoring data

SEPA takes water column samples for TP determination near the loch outflow and analytical determination is via manual colorimetric chemistry (SEPA, 2008 - summary in Annex). The sampling strategy assumes that sampling at the outflow provides an integrated sample of the loch water. This strategy will not capture heterogeneity caused by wind effects, local point sources of TP or lochs upstream of the sampling point. The sample will contain dissolved and suspended particulate TP and the analytical determination includes all inorganic and organic forms of phosphorus.

Operators wishing to compare TP at different depths and locations within lochs to values observed by SEPA at the loch outlet sampling point have commissioned studies in this regard. Unfortunately none of these studies were made available to this project to test the OECD equations. A SEPA internal publication for Loch Earn (SEPA, 2004) has considered possible localised effects and found no significant differences between TP observations at 20 m sampling intervals down to 80 m when compared with surface and 10 m depth (SEPA).

Table 4 - Number of TP observations per year for each site

Loch name	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009
Arienas					11	10	5	11	9			
Arkaig					10	12	10	11	10			
Avich			4	7	1		1	6	6			
Awe(N)							1	11	6	11	12	9
Awe(S)							1	10	7	11	12	9
Ba			4	4	3	2		9	1	13	12	11
Caravat					7	11	8	11	6	11	8	9
Damh					9	8	8	10	10	10	9	11
Earn	3	7	3	5	2	11	10	12	11	10	12	12
Frisa			2	4	3		2	9	8	11	11	9
Garry							10	12	11			
Loch of Cliff			2	3	3	3	5	6	4	12	12	10
Lochy							7	11	11	11	13	11
Merkland					8	11	8	9	7	11	12	11
Migdale					6	11	8	11	10	11	12	10
Ness					11	11	8	11	9	11	10	10
Scadavay(N)					7	11	11	11	8	12	9	9
Scadavay(S)					7	11	9	11	6	10	9	11
Sgamhain		3	7	5	5					8	10	9
Shiel					9	12	9	12	10	10	12	9
Shin					7	12	8	10	10	11	12	11
Tay	7	3				5	6	6	6	12	12	12
Tralaig			4	6	1		2	10	11			

As the SEPA monitoring data set has largely been consistent in terms of sampling location and analytical method since 2003, it is the most useful available data set for testing the equation across the study sites.

4.6 Synthesis of review information: key research questions

- The OECD equation has a small number of input terms whose relative importance requires evaluation. A sensitivity analysis was therefore required.
- Based on the regulatory assumptions for TP release from fish farms, the equation's predictions required testing against observed TP at regulatory sampling stations.
- An evaluation of the actual fish production per loch was required to quantify TP released.
- Assessment of the effect of different species, feeds, production modes and feed wastage rates on TP release was required.

5.0 METHODS

5.1 Site selection

All available data describing geographical characteristics of lochs and fish farm activity were pooled and input to a geographical information system (GIS) (Mapinfo). Figure 2 illustrates the geographical spread of the sites considered and Table 5 outlines the broad descriptive statistics of the farms, the lochs and the TP sampling points considered in the study.

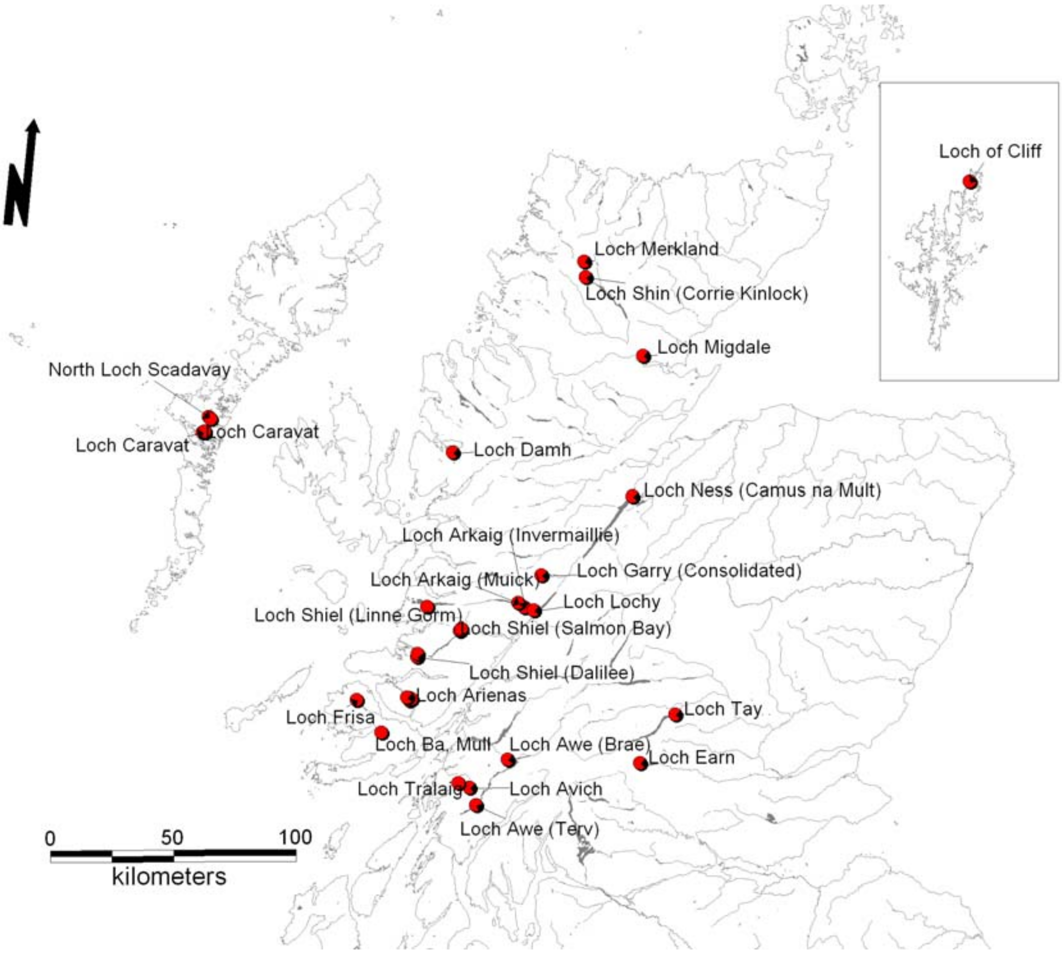

Figure 2 – Map of selected sites

Table 5 – Broad descriptive statistics for fish farm, loch and sampling points.

Farms	No. farm sites	37
	No. trout	5
	No. salmon	32
	Biomass, max, t	400
	Biomass, min, t	7.5
	Production, max,t	425
	Production, min, t	4

Lochs	No. Lochs	21
	Max depth,m	132
	Min depth, m	3
	Mean flow rate max, m3/s	89.84
	Mean flow rate min, m3/s	0.185
	Residence time, max, yr	6.51
	Residence time, min, yr	0.15

Sampling	Cages to sampling, max, km	24.01
	Cages to sampling, min, km	0.09
	Cages to outflow, max, km	24.26
	Cages to outflow, min, km	0.64

From these data it was then possible to select the most appropriate lochs, farms and sampling data sets to consider in the OECD testing process.

5.2 Production data

At project start-up it was assumed that sufficient farm production data would be available to consider monthly changes in TP release from fish farms in a number of representative lochs. A limited response, until very late in the project from mainly Atlantic salmon producers, forced the project to consider predictive methods for assessing production. To enable the development of robust assumptions for predicting production and related waste outputs, it was necessary to describe 'idealised' production thought to be in operation in contemporary Scotland. These have been developed from the limited production data made available to the project as well as the information from a number of farmers who were interviewed in confidence. This process enabled the description of 'idealised' operating parameters which, amongst others, included: production period, temperature, feed specifications, feed wastage, feed rate, growth rate, grading culls, mortalities etc.

Six broad idealised production modes were derived to support the modelling process. These were:

a) RBT_sg, rainbow trout produced using a single generation of fish, with maximum biomass being reached for the final period of growout prior to complete harvesting out.

b) RBT_mt, rainbow trout produced from multiple generations of fish, constantly operated at near maximum biomass, with harvested biomass being replenished with new stock.
c) AS_S1 – Atlantic salmon produced as a single naturally smolting generation, with maximum biomass being reached towards the end of growth period.
d) AS_S0a – Atlantic salmon produced using adjusted smolting periods, with spring stocking, with maximum biomass being reached towards the end of growth period.
e) AS_S0b – Atlantic salmon produced using adjusted smolting periods, with autumn stocking, with maximum biomass being reached towards the end of growth period.
f) AS_SOab - Atlantic salmon produced using adjusted smolting periods, with spring and autumn stocking with maximum biomass being reached twice within the entire stocking period, though approximately 1 month is fallow mid cycle.

The ranges of assumed parameters per production mode are detailed in Table 6.

Table 6 – Assumed parameters per production mode, showing stocking and fallowing time, production period, start and end weights (wet weight), average feed wastage and thermal-unit growth coefficient (TGC).

Production Mode	Stocked	Fallowed	Prod. Period, d	Start wt, g	Finish wt, g	Av. Feed Wastage, %	TGC
RBT_sg	July	June	360	25	1000	7.5	0.2
RBT_mt	continuous	never	169-190	25	400	7.5	0.2
AS_S1	July	April	301	5	70	12.5	0.087
AS_S0a	April	September	175	10	65	12.5	0.087
AS_S0b	October	March	182	30	75	12.5	0.087
AS_S0ab	combined AS_S0a and AS_S0b						

The complexity of modelling grading culls and mortalities was not considered in the basic modelling of fish growth and waste production. The model was run for scenarios with individual fish subjected to the respective produce mode category parameters, then growth and outputs were expressed relative to production and feed input per kilogram, to offer greatest utility for running OECD scenarios.

5.3 Modelling fish farm waste production in FRESH WATER

Further to discussion with researchers working in fish nutrition in Canada (Bureau_*pers comms*, 2009), the bioenergetics model Fish-PrFEQ (Cho et al., 1998) was used to assist predictions for waste estimations for both RBT and Atlantic salmon, following the production modes described in Table 6. The model has been validated for use in Ontario for RBT but, as used in the context of the present study, local diet specifications and species specific Thermal-unit Growth Coefficients (TGC) were used and the outputs are assumed to be robust. Thermal-unit Growth Coefficient is defined in this context as:

$$TCG = 100 \left[W_2^{1/3} - W_1^{1/3} \right] / \left[T \;\; D \right]$$

where W_1 and W_2 are fish weight at start and finish of reference period, T is the average temperature and D the number of days in the reference period.

The model uses empirically based energy utilisation coefficients to estimate uptake and outputs, as shown in Figure 3.

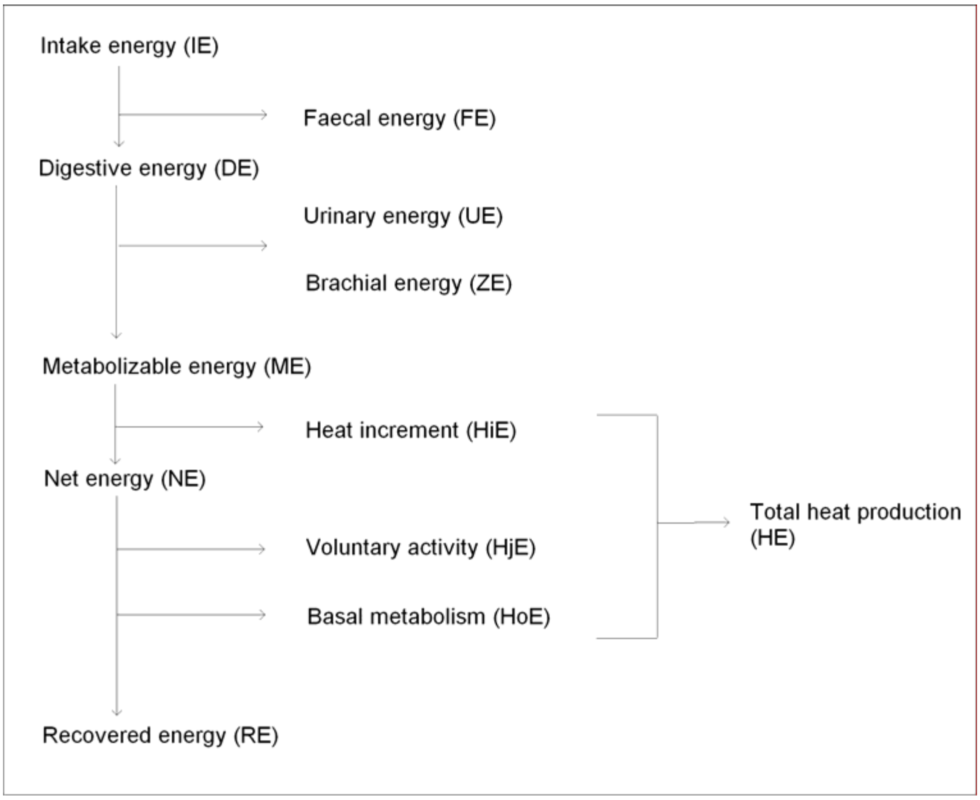

Figure 3 – Energy pathways used in calculating waste partitioning in Fish-PrFEQ model.

Model outputs per production mode are given in Annex 2 to this report.

A comparison of details of proximal composition of feeds that were considered is given in Annex 3. Commercially available feeds from Skretting and EWOS in Scotland were considered within the study. Data were also provided by Biomar towards the end of the project but as the compositions of their feeds were similar to the ones already modelled, inclusion in the study was not considered necessary.

The range of calculated digestible energy (DE) was 18.34 – 21.89 kJ g^{-1}, for the majority of standard feeds. Floating feeds for trout were the exception, with DE values at 14.7 KJ/g.

The TP in the feed was in the range from 1.0 to 1.7%, the organic feeds having the highest phosphorus on account of the higher proportions of animal origin constituents in these feeds.

Partition of TP released between solids and dissolved was explored for each of the production modes and diets. Table 7 illustrates the partitions for Atlantic salmon grown under the S1 production mode.

Table 7 – Partitioning of TP release between solids and dissolved for 4 diets for the AS_S1 production mode.

For TP release of range 10.8-13.87 kg/t production

	% of TP released	
Diet	Solids	Dissolved
1	64.73	35.27
2	63.64	36.36
3	63.64	36.36
4	58.34	41.66

Differences in TP released over time were considered important and changes in monthly outputs were derived for each production mode. Figure 4 illustrates the monthly release rate for production modes AS_S1 and AS_SOab, both fed on diet 1.

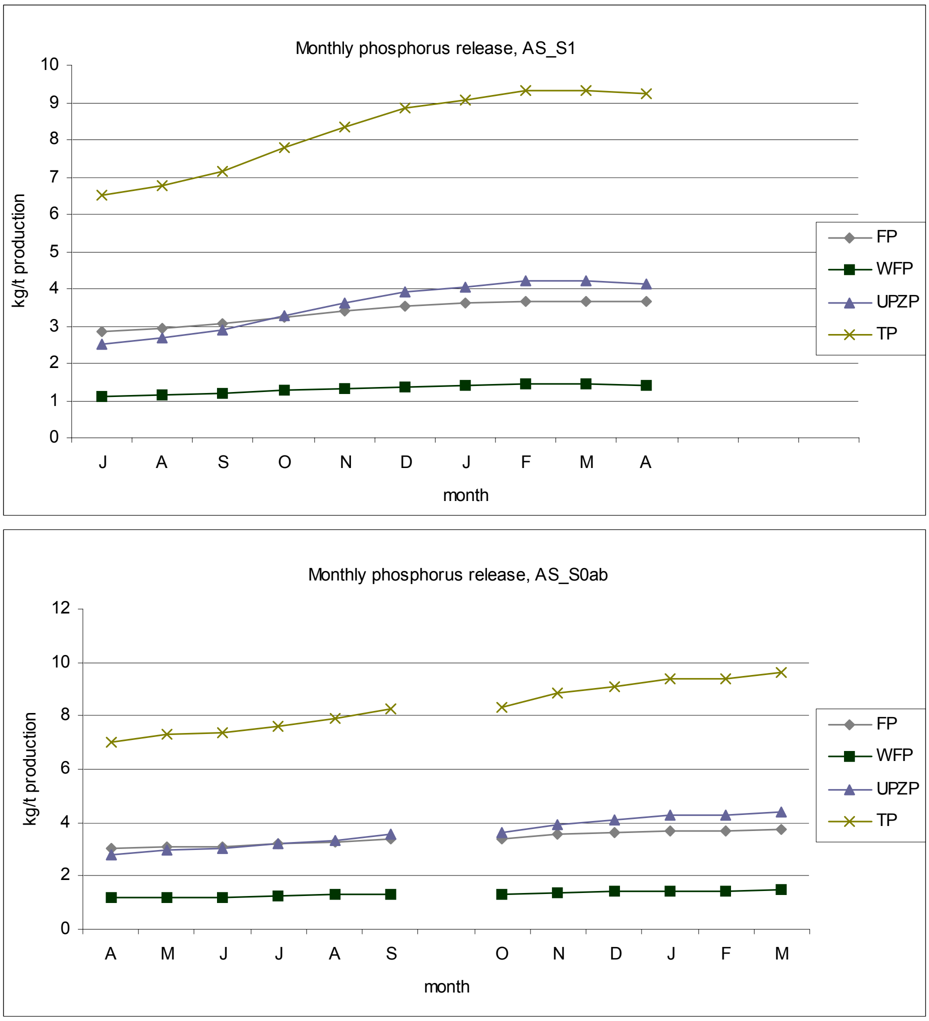

Figure 4 - Monthly TP release rate for production modes AS_S1 and AS_SOab, both fed on diet 1, where legends refer to phosphorus types: FP – faecal, WFP – waste feed, UPZP – brachial and urinary, TP- total.

The ranges of TP release rates for all considered production modes were calculated. These were generated for standard and extreme feed wastage rates. Table 8 illustrates the modelling outcomes.

Table 8 – Comparison of predicted ranges of TP release rate for production modes considered in study.

Feed wastage rate		std	extreme
TP release rate		kg/t prod	kg/t prod
RBT_sg	min	6.70	8.83
	max	13.07	15.78
	mean	9.88	12.30
RBT_mt	min	5.19	6.62
	max	10.42	12.70
	mean	7.80	9.66
AS_S1	min	8.24	10.08
	max	13.38	16.12
	mean	10.81	13.10
AS_S0a	min	7.57	9.31
	max	12.50	15.00
	mean	10.04	12.16
AS_S0b	min	9.11	11.09
	max	14.76	17.61
	mean	11.94	14.35
AS_S0ab	min	8.34	10.20
	max	13.36	16.31
	mean	10.85	13.25

Table 9 – Comparison of predicted ranges of TP release rate for generalised production modes used in modelling, covering all modes rainbow trout, all modes Atlantic salmon and figures covering both species.

Feed wastage rate		std	extreme
TP release rate		kg/t prod	kg/t prod
RBT_gen	min	5.94	7.72
	max	11.74	14.24
	mean	8.84	10.98
AS_gen	min	8.32	10.17
	max	13.50	16.26
	mean	10.91	13.22
RBTAS_gen	min	7.53	9.36
	max	12.91	15.59
	mean	10.22	12.47

5.4 Observed TP data for the lochs

One and three year geometric means were calculated for TP observations between 2003 and 2009 for all study sites, with some pre-2003 data included. Where an observation was below the limit of detection (LOD), 50%of the LOD value was used in the calculations. Three year geometric means use TP measurements for the current year and the previous two years. Five year geometric means used in test 2 were calculated from the most recent five years of data, except for Lochs Avich, Garry and Tralaig where three years were used.

5.5 OECD equation

In the literature, examples of three approaches can be found with regards to use of the OECD equation in fish farm emissions.

Approach 1 – predicting the effect of an increase in aquaculture production

This is used by SEPA in a regulatory context (examples can be found in SEPA consent assessments and operator commissioned reports). For example, a producer wishes to increase production by *x* tonnes in the year *t*. Assuming the loch is in steady state and that the loch will reach its new steady state after *s* years in the year *t*+*s*, the additional annual load to the loch attributed to the fish farm is

$$TP_{load} = x * TP_{prod} \tag{4}$$

where TP_{prod} = amount of TP discharged from the fish farm per tonne produced (kg TP tonne^{-1} production). The time to reach steady state (*s* years) is considered to be at least equal to the residence time (Johansson, 2002).

ΔTP (Eq. 1) is then calculated using equations 2 and 3, and this is the predicted effect of the fish farm on in-loch TP concentration. Then, predicted ΔTP is added to observed TP for the current year (denoted $TP_{obs}(t)$ with units µg l^{-1}) to predict the new steady state concentration in year *t*+*s* (denoted TP(t+s) - µg l^{-1}):

$$TP\ (t+s) = TP_{obs}\ (t) + \Delta TP \tag{5}$$

Importantly, this approach relies on confidence in $TP_{obs}(t)$, as the predicted TP at the new steady state is directly dependent on the observed data used in the assessment (equation

5). This leads to considerable debate as to what value of $TP_{obs}(t)$ should be used in the assessment, including sampling point, depth of sampling, methodology and method of averaging data (arithmetic or geometric).

If the model is correct in predicting the change in TP between the years *t* and *t+s* then it should equal the observed change in TP between the years *t* and *t+s*. i.e.

$$\Delta \mathrm{TP} = \Delta \mathrm{TP}_{\mathrm{obs}} \qquad (6)$$

where

$$\Delta TP_{obs} = TP_{obs}(t+s) - TP_{obs}(t) \qquad (7)$$

The example calculation shows observed TP for the year of interest of 10.5 µg l^{-1} and predicted TP for that year of 11.5 µg l^{-1} (Table 10), where the predicted TP is dependent on TP_{obs} from an earlier period (year *t*).

In terms of changes in TP, the predicted change (ΔTP) is 0.5 µg l^{-1} and the observed change (ΔTP_{obs}) is -0.5 µg l^{-1}.

Table 10. Example calculations for uses of Equations 5 – 7.

	Year t	Year t+s
Observed TP	TP obs (t) = 11.0 µg l^{-1}	TP obs (t+s) = 10.5 µg l^{-1}
Predicted TP (ΔTP = 0.5 µg l^{-1} which is the predicted effect of the fish farm emission)		TP(t+s) = 11.0 + 0.5 = 11.5 µg l^{-1}

In this study we assess model performance on ΔTP and ΔTP_{obs}, as this gives a true assessment of model performance consistent with Johansson and Nordvarg (2002). That is, we compare the predicted change in TP (ΔTP) with the observed change in TP (ΔTP_{obs}). This means that predictions under scrutiny do not depend on previous years' observations.

Approach 2 – prediction of TP in loch concentration from a loch mass budget

This approach evaluates the annual load of all sources of TP to a water body, and then uses the OECD equation to predict in-loch TP (ICIT, 2004; SEPA, 2004) (SEPA, 2004 for

Loch Earn, ICIT (2004) for a non-aquacultural loch). For this approach, TP_{load} is the sum of all the diffuse and point sources. Once this is evaluated, Eq. 1 is then used to predict in-loch TP which is then compared with observations. In the case of SEPA (2004) for the Earn study, the observed data used for comparison were five-year geometric means.

Approach 3 – predicting the effect of fish farming emissions – before and after farming started

In the first instance this requires pre-fish farming observed data or some method for predicting the in-loch TP before fish farming commenced. Then, the total annual load of TP from the fish farm is used in the OECD equation to predict the contribution to in-loch TP from fish farming. This approach is used by Johansson and Nordvarg (2002). In Scotland, within the regulatory consenting process of fish farms, this has led to some debate as to the ‘reference’ background TP of lochs. This may be calculated from either the MEI method (Cardoso, 2007) or from assessment of subfossil diatoms (Bennion, 2004).

Approach used in this study

As a primary objective was to assess the OECD equation with reference to freshwater aquaculture, the project focused on Approach 1, as this approach is used in regulation. Examination of production data showed cyclical and significant variation in production over time within consent limits. Therefore, we used these variations as tests of the model performance along with consented increases. We also used Approach 2 for all sites, as this approach made use of existing modelling tools such as the PLUS model, as well as five-year geometric observed means that could be calculated from the monitoring data set.

Both Approach 1 and 2 were applied to a reasonably large data set of 23 aquaculture important lochs. This meant that within this data set the influence of non-aquacultural TP was likely to vary from low to high.

Calculations with the OECD equation were undertaken both in spreadsheet based tools and software written specifically for this project in Delphi 7. This software allowed more parameters to be changed consistently and the whole data set to be reassessed at once. Predictions from this software were regularly cross checked with spreadsheet calculations. These spreadsheet calculations were cross checked with SEPA spreadsheet tools, an operator commissioned assessment using the equation, and other literature (ICIT, 2004; SEPA, 2004)

5.6 Sensitivity analysis

The objective of this sensitivity analysis was to determine the sensitivity of the OECD equation parameters, thereby allowing an assessment of the importance of parameter accuracy. This analysis was undertaken for two lochs, widely different in terms of residence time and production: a high volume loch with long residence time (Loch Arkaig) and a low volume loch with a short residence time (Loch Arienas) (Table 11). The sensitivity of parameters of loch depth (± 10%), surface area (± 10%), outflow (± 20%) and P discharged per tonne aquaculture production (± 10%) were tested for a hypothetical increase in production. These ranges are expected to represent a reasonable amount of expected parameter inaccuracy or variance. Gosling (Personal communication) found that mean rainfall at 6 meteorological stations over 20 years (Braemar, Lerwick, Leuchars, Paisley, Stornoway & Tiree) varied by ±14% and predictions of loch outflow using *Low Flows 2000* varied by ±11%. Thus, to make a stringent test, ±20% outflow was chosen.

Table 11. Model parameters for lochs used in the sensitivity analysis.

	Loch Arkaig	Loch Arienas
Hypothetical increase in production (t)	54.4	5.3
Loch residence time (year)	3.78	0.67
Loch volume (m^3)	$2.09*10^9$	$2.94*10^7$
Loch surface area (km^2)	44.6	1.73
Average loch depth (m)	47	17
Average annual outflow ($m^3\ s^{-1}$)	17.540	1.395
kg P discharged per tonne production	10	10

A multi-parameter sensitivity exercise tested the effect on predictions by running the model with many different combinations of parameters within the defined limits (n = 10,000 scenarios). This provides a realistic assessment of sensitivity, as in real terms a number of parameters may be inaccurate and we wish to know the combined effect on model performance of these inaccurate parameters. The value of parameters used in each scenario was determined either by using a) normal, or b) random, distributions (Table 12). Selecting parameters from a normal distribution results in many scenarios where parameters are close to the mean, and only a few scenarios have extreme values (Figure 5). By this method, the likelihood of selecting an extreme for more than one parameter in any single test is realistically low. Determining parameter value randomly means that there is an equal chance of using a parameter within its specified range.

Figure 5. Depth parameter distribution for Loch Arienas used in the multi-parameter sensitivity test.

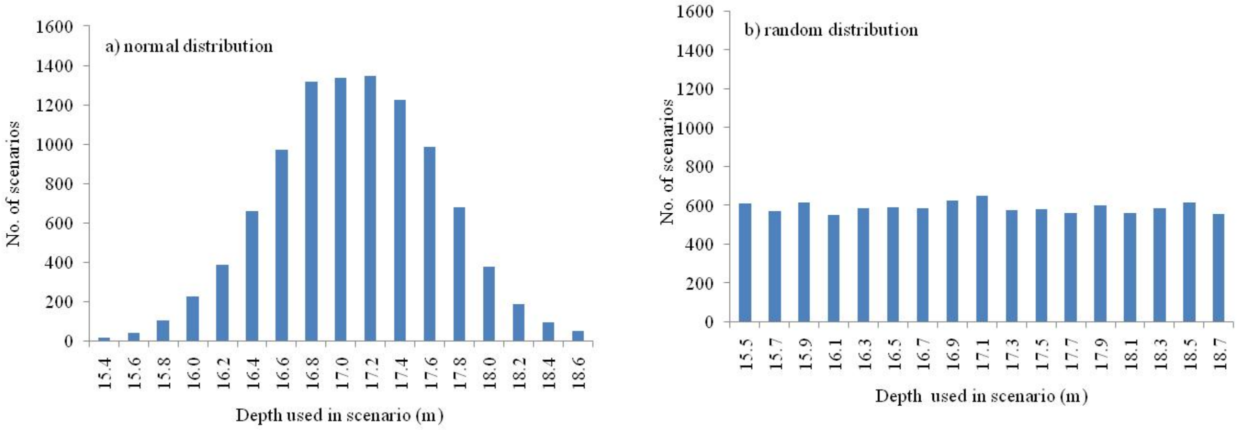

Table12. Mean and standard deviation of loch parameters used in the multi-parameter sensitivity test to define a Normal distribution (6 times the standard deviation was used).

	Average loch depth (m)	Loch surface area (km^2)	Outflow (m^3 s^{-1})	kg P discharged per tonne prod.
Loch Arkaig	47.0, 1.56	4.56, 1.485	17.54, 1.169	10.0, 0.33
Loch Arenias	17.0, 0.57	1.73, 0.058	1.395, 0.093	10.0, 0.33

5.7 Validation

Mean loch depth was taken from Murray and Pullar, 1910 and GB Lakes database; loch surface area and loch outflow (*Low Flows 2000*) were provided for each loch by SEPA. Monthly loch outflow data were available for Lochs Arienas, Arkaig, Awe, Lochy and Ness and were used where appropriate.

Annual production figures were provided by SEPA from returns by operators for 5 of the study sites. Annual and quarterly production and feed input figures were calculated for sites where detailed data were available for 10 sites (4 trout, 6 salmon). For 8 of the 23 study sites, the OECD equation could not be extensively tested as annual production data were not made available. Consented production was used in a loch budget In the case of these 8 sites (test 2), and the model performance was assessed with and without these 8 sites.

With regards to the TP discharged from the fish farm, most tests used production mode *RBTAS_gen*, which was a mean of all the production modes (Table 9). This was consistent with the approach normally used for site assessments. Where mass budgets were calculated for each loch, the mean of all production modes was also used. Where production mode was tested (test 4), *RBT_mt* was used for trout production in Lochs Awe, Earn, Lochy and Tay, and *AS_gen* was an average of four salmon production modes used for all salmon sites (Table 13). Where feed input was used as the main driver for TP discharge, general figures were used for trout and salmon farms and no account was taken of production mode. Both observed and predicted TP refer to total TP (particulate and dissolved) and no distinction is made between these fractions in use of the OECD equation.

Table 13. Parameters used in the OECD equation for calculating TP discharged from the fish farms for each test.

Test	Mean (kg TP t-1 fish produced)	Extreme (kg TP t-1 fish produced)
1	10.2	12.5
2	10.2	N/A
3, 6	10.2	N/A
4	7.8 (trout)	N/A
	10.9 (salmon)	

	Mean (kg TP t-1 feed input)	Extreme (kg TP t-1 feed input)
5	9.2 (trout)	N/A
	11.2 (salmon)	

A variety of tests was undertaken to test the OECD equation for a range of scenarios.

Table 14. Tests of the OECD equation undertaken for the study sites.

Test	Objective	How TP load calculated	Observed data used for comparison (geometric means)
1	Test increase in production	Production data	1 and 3 year
2	Test using loch	Production data, PLUS	5 year of most recent observations

	mass budgets	model, estimated point sources	(except Lochs Avich, Garry and Tralaig – 3 year)
3	Test reduced mixing zone	Production data	1 and 3 year
4	Test production mode	Production data	1 and 3 year
5	Test changes in feed input	Feed input data	1 and 3 year
6	Test reduction in production	Production data	1 and 3 year

Tests 1 and 6 - Annual production data were examined to determine years where there was an increase or decrease in production; these variations in production were within the consented production and were not insignificant. The change in production was used to calculate TP_{load} in Eq. 4.

Test 2 - A phosphorus mass budget was attempted for each site using predictions from the PLUS model and consented production data, similar to the approach used for Loch Earn (Weller, 2000; SEPA, 2004) (Malcolm and Ferrier, 2003). The PLUS model was used to predict annual loading of TP to each of the sites from diffuse sources. It simulates the effects of catchment inputs from TP using the PLUS coefficients and human inputs based on the 2001 Land use census (Futter, Personal communication). An export coefficient for P dependent on land use and slope was used for each loch catchment area. According to population density in the 2001 survey, a contribution of P from human population was applied (if population density exceeds 0.3 people per ha then urban (0.9125 kg P year^{-1} PE^{-1}), otherwise rural (0.25 kg P year^{-1} PE^{-1}), where PE is population equivalent). For a chain of lochs, these calculations were undertaken firstly for the headwater loch and then repeated for lochs downstream. Export of P between each loch in the chain is therefore calculated in this approach, from first order loch (headwater loch) to the loch of interest. In addition to the predictions from the PLUS model, point sources of TP were calculated. These were primarily from aquaculture but other point sources were included where known. The project experienced difficulty in gathering information on non-aquaculture TP point sources, as this did not appear to be centrally available. Significance of these unknown point sources varies in importance between lochs and influences the final predicted TP from the equation. In the Loch Earn budget, point sources from septic tanks and caravan parks were estimated at 356 kg TP year^{-1}, approximately 6% of total budget (SEPA, 2004). In addition, for Loch Earn, SEPA (2004) reports the importance of Loch

Lednock as a point source of TP, and this was incorporated using a flushing time of one year. Predicted in-loch TP concentration was then compared with five-year geometric means as undertaken in the Loch Earn study. Additionally, for each loch the balance of TP annual load required to obtain complete agreement between predicted TP from the OECD equation and observed TP was also calculated for discussion. For Lochs Awe, Caravat, Damh, Loch of Cliff and Scadavay, the PLUS model predicted TP concentration lower than the reference TP calculated by the MEI method (Cardoso, 2007) In these lochs, the predicted TP from the PLUS model and associated load was adjusted to equal the reference value. Point sources were then added as described.

Test 3 – the OECD equation uses the whole loch volume to determine the residence time (T in Eq. 2) and therefore assumes mixing over the whole loch – this is likely to be an over simplification given the complex mixing and variable stratification shown for some lochs (Duwe et al. (2003)). The effect of local mixing was tested in a simple modification of the method. As the proximity of the farm to the sampling point for the TP monitoring data varies between lochs, a mixing volume was calculated to represent the potential mixing volume between the cages and the downstream sampling point. Therefore, the loch surface area between the cages and the sampling point was used with mean depth to calculate volume. In all lochs, this would result in the same load being discharged to a smaller volume, so predicted TP was higher as expected (Eqs. 1 and 2).

Test 4 – the species being farmed and production mode results in different amounts of discharged TP from the farm. Thus, by including the detail of production mode the effect on model performance could be assessed.

Test 5 – as TP discharged is largely influenced by feed type, feed input and feed characteristics such as digestibility, this test was undertaken to determine whether feed input rather than production was a more useful parameter for using in the OECD equation.

5.8 Comparison of predicted and observed

Both one- and three-year geometric observed means were compared with predictions. An underlying assumption of static models is that at least one residence time is required to reach steady state. Therefore, three-year geometric means were also used in comparisons as 82% of the sites had residence times of less than 3 years.

For example, if a change in production was modelled for the year 2005, then predicted changes in TP were compared with the difference between the observed one-year geometric means for 2004 and 2005. To account for longer residence times, predicted changes in TP were also compared with the difference between three-year geometric means covering the periods 2002-2004 and 2005-2008. In test 1, an additional test was undertaken with one-year observed geometric means. In this case, the changes in observed TP for the previous year and next year were used; e.g. if a change in production was modelled for the year 2005, then observed means for 2004 and 2006 were used to calculate the change in observed loch concentration.

5.9 Benefits and limitations of the different tests

A benefit of using the OECD equation is that it is a simple management model which has been used historically for assessing TP inputs to water bodies. It is an example of numerous similar so called ‘static’ models, which have been applied to lakes with and without aquaculture and with varying degrees of success (Johansson, 2002; Bryhn, 2007). The primary assumption with static models is that they assume the water body is in steady-state and the water body has adjusted to the TP load. Steady state may be achieved after about one residence time and this has to be taken into account when assessing model performance. A further limitation is that static models also assume that where the change in TP loading from a particular source is being assessed, all other TP sources remain constant.

Table 15. Specific benefits and limitations of the different tests.

Test	Benefits	Limitations
1 – increase in production	Directly tests the manner in which the OECD equation is used in regulation	By comparing differences between years, the increase in production may not be sufficiently long enough to result in a change in the steady state
2 – mass budget	Tests whether a mass budget approach can predict TP; gross budgets and use of a 5 year observed means longer term trends are being investigated	Some unquantified point sources; uncertainty with PLUS model parameters
3 – distance to sampling point considered	As sampling points are downstream of cages, tests possibility of localised mixing of TP	Localised water exchange highly complex (e.g. Duwe et al. (2003) found residence time varied from a few days to several years in different basins of Loch Lomond)

4 – production mode	Different species and husbandry practices result in different TP discharge rates – by including this detail improved model performance can be determined	Information not readily available for all sites
5 – feed input	Optimisation of feed use is an important husbandry practice – is model performance improved when using feed input	Feed input data not readily available and not collected as part of returns from farmer
6 – reduction in production	Tests whether the equation can predict reductions in TP load from aquaculture	As for test 1

5.10 Statistical tests and assessment of model performance

Importantly, in all tests except test 2 (mass budget), the predicted change in TP in-loch concentration was compared with the observed change in TP in-loch concentration (similar to Johannsson and Nordvarg (2002)) and this comparison was used to assess model performance.

Model performance was statistically tested following the method proposed by (Portilla, 2007) and applied by (Jusup et al., 2009), where model predictions were placed on the x-axis and observed values on the y-axis. Advice was sought Jusup (pers. comm.) on the application of the method to this data set. The primary reason for plotting predictions on the x-axis, is that the predicted change in TP for each scenario is under the sole control of the modeller. It is likely to show less variation than observed changes in TP.

Models were assessed using the linear regression of $Y_i = \beta_0 + \beta_1 X_i$ for observed (Y_i) and predicted (X_i) values, where β_0 is the intercept and β_1 the slope. A Student's t-test was undertaken for r^2, β_0, β_1 (α=0.05, n-2 degrees of freedom) to test if r^2, β_0 and β_1 were significantly different from 1, 0 and 1 respectively (Mesple, 1996). Model performance was classified according to the outcome of these tests (Oreskes, 1994) (Table 16).

Table 16. Classification of model performance according to the linear regression between observed and predicted TP.

Slope (β_1)	Intercept (β_0)	linear correlation coefficient (r^2)	Classification
not significantly different from 1	Not significantly different from 0	significantly > 0	Excellent
Only one of the above criteria are satisfied		significantly > 0	Good
significantly different from 1	significantly different from 0	significantly > 0	Fair
n/a	n/a	not significantly different from 0	Poor

Efficiency (E), which is a measure of goodness of fit, was also used to assess model performance and the agreement between observations and predictions (Mayer, 1993) (Mayer and Butler, 1993):

$$E = 1 - \frac{\sum_{i=1}^{n} (\hat{Y}_i - Y_i)^2}{\sum_{i=1}^{n} (Y_i - \overline{Y})^2}$$

where $Yi = \text{observed}, \hat{Y} = \text{modelled and } \overline{Y} = \text{observed mean for n comparisons.}$

The higher the value of *E*, the higher the agreement between predictions and observations and Mayer and Butler (1993) caution against using models where *E* < 0.

6.0 RESULTS

6.1 TP monitoring data – one-year and three-year geometric means

The lochs were ranked according to observed TP, where the majority of lochs had observations between 2003 and 2009 (Figure 6). Sampling had been discontinued for Lochs Avich, Tralaig, Garry, Arienas and Arkaig from 2007 onwards. The mean difference between three-year and one-year geometric means was 1.5 µg l^{-1} between 2005 and 2009, max. difference = 7.2 µg l^{-1}, n = 97) (Figure 7).

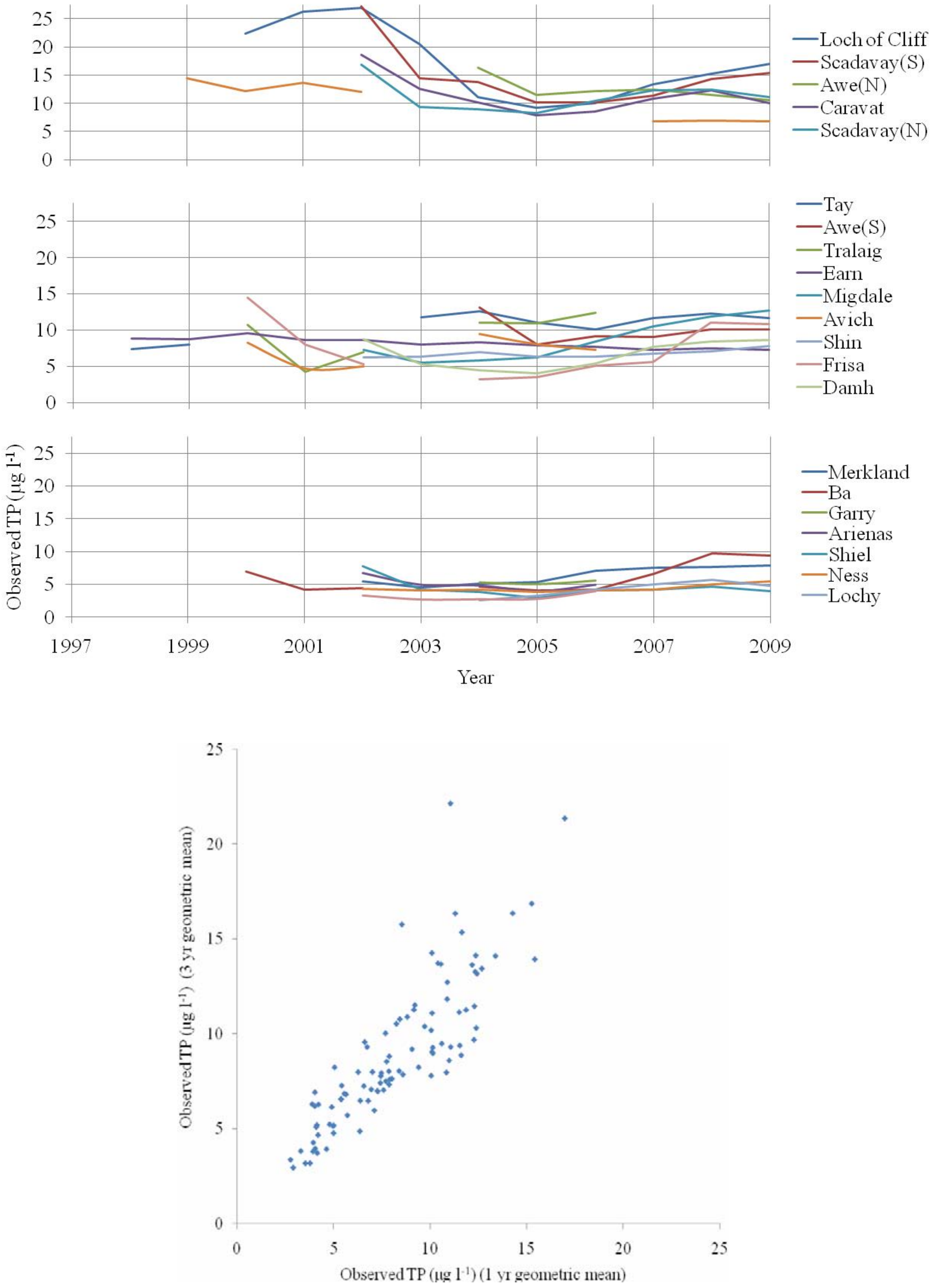

Figure 7. Three-year and one-year geometric means for observed TP.

6.2 OECD equation - sensitivity analysis

By varying loch depth (± 10%), surface area (± 10%), outflow (± 20%) and P discharged per tonne aquaculture production (± 10%), differences of less than 0.3 µg l^{-1} from the mean were found (95% were < 0.2 µg l^{-1}) (Figure 8). This implies that inaccurate parameters within these ranges could account for up to 0.3 µg l^{-1} difference in model predictions.

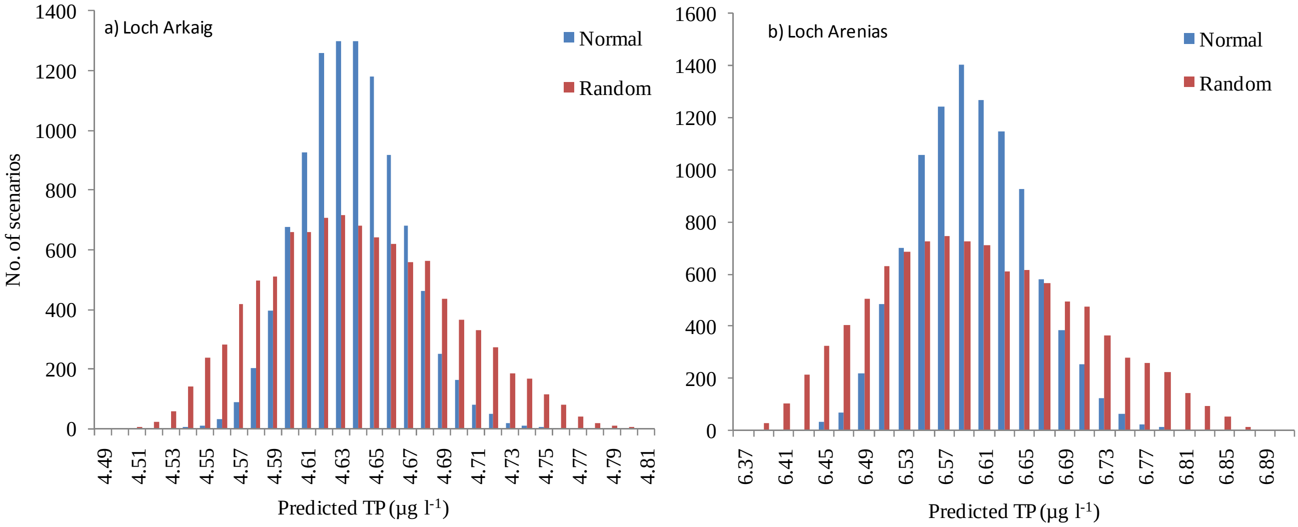

Figure 8. Predicted TP for a) Loch Arkaig and b) Loch Arienas (n=10,000 scenarios) using normally distributed and random model parameters.

The following rank of parameters was found (most sensitive first): annual mean loch outflow > kg P per tonne produced > surface area > depth.

6.3 Validation

Test 1 – increase in production

Regression between predicted ΔTP and observed ΔTP was low when using both one-year (r^2 = 0.16, n = 20) and three-year geometric means (r^2 = 0.03, n = 12) for comparisons (Figure 9). This indicates that 16% of the observed variability in one-year geometric means is explained by the model, with less than 5% of the variability in three-year geometric means explained by the model.

Where three-year observed means are used, fewer tests are possible because of the availability of production data and the time series of observed data. For example, to test an increase in production for a site in the year 2005, this requires production data for 2004 and 2005 in addition to observed TP for 2003 to 2007.

Two major outliers are apparent in Figure 9 and it is useful to determine whether excluding these from the data set improves model performance. The first arises from a large one-year and three-year observed ΔTP caused by high observations for two particular years in the same loch (ΔTP_{3year} = 7.6 μg l^{-1} in Figure 10. Examination of the original observations showed several months of elevated observed TP data in two different years, and there was an order of magnitude difference between some samples. Secondly, a high predicted ΔTP arose from an apparent large increase in production for a site (predicted ΔTP = 6.0 μg l^{-1}), but this production change is likely to be an error. Excluding these two outliers resulted in little change to model performance (r^2 = 0.06 and 0.05 respectively)
(Figure 10A, B).

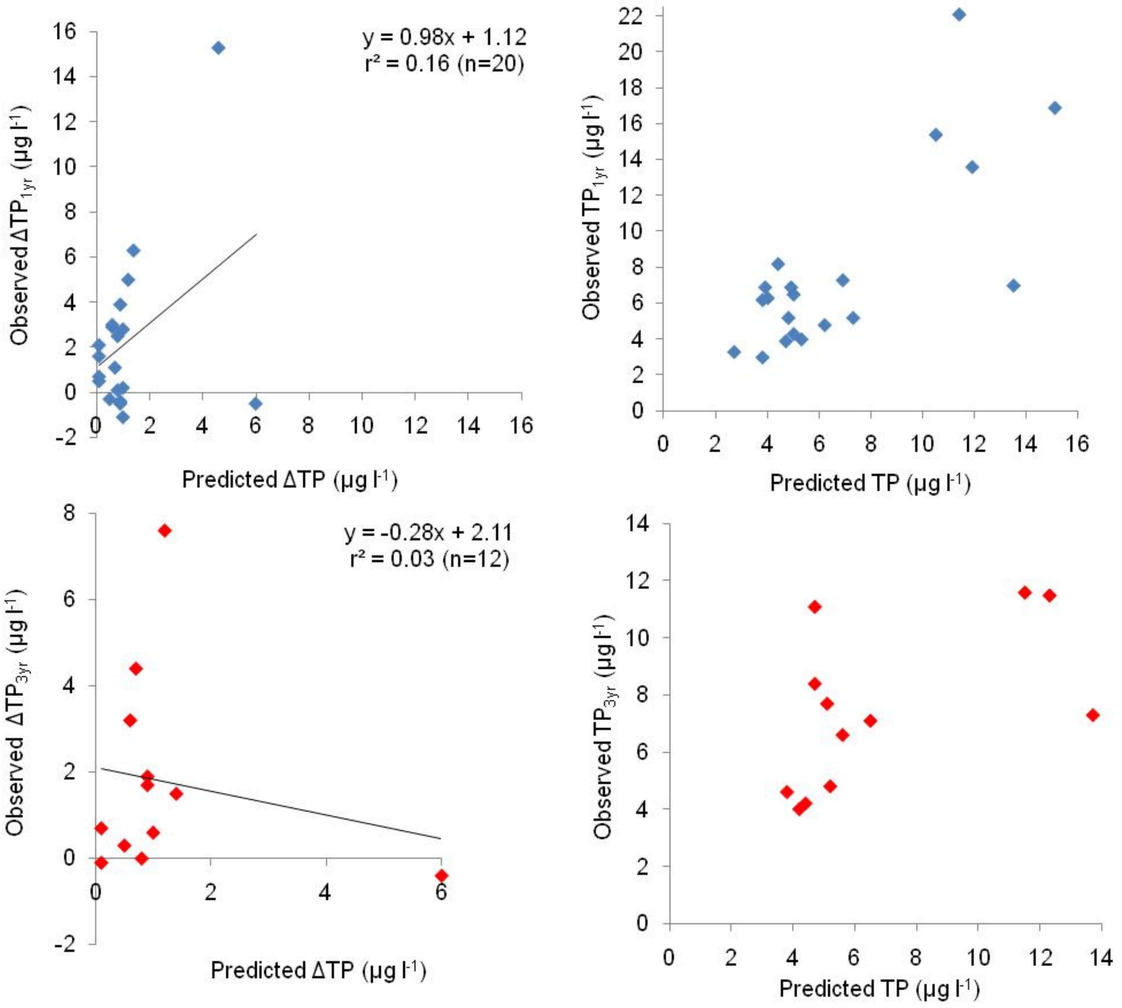

Figure 9. Model performance - predicted and observed changes in total phosphorus (ΔTP) and predicted and observed in loch TP for years where there has been an increase in production. One-year and three-year geometric means were used for observed TP and ΔTP.

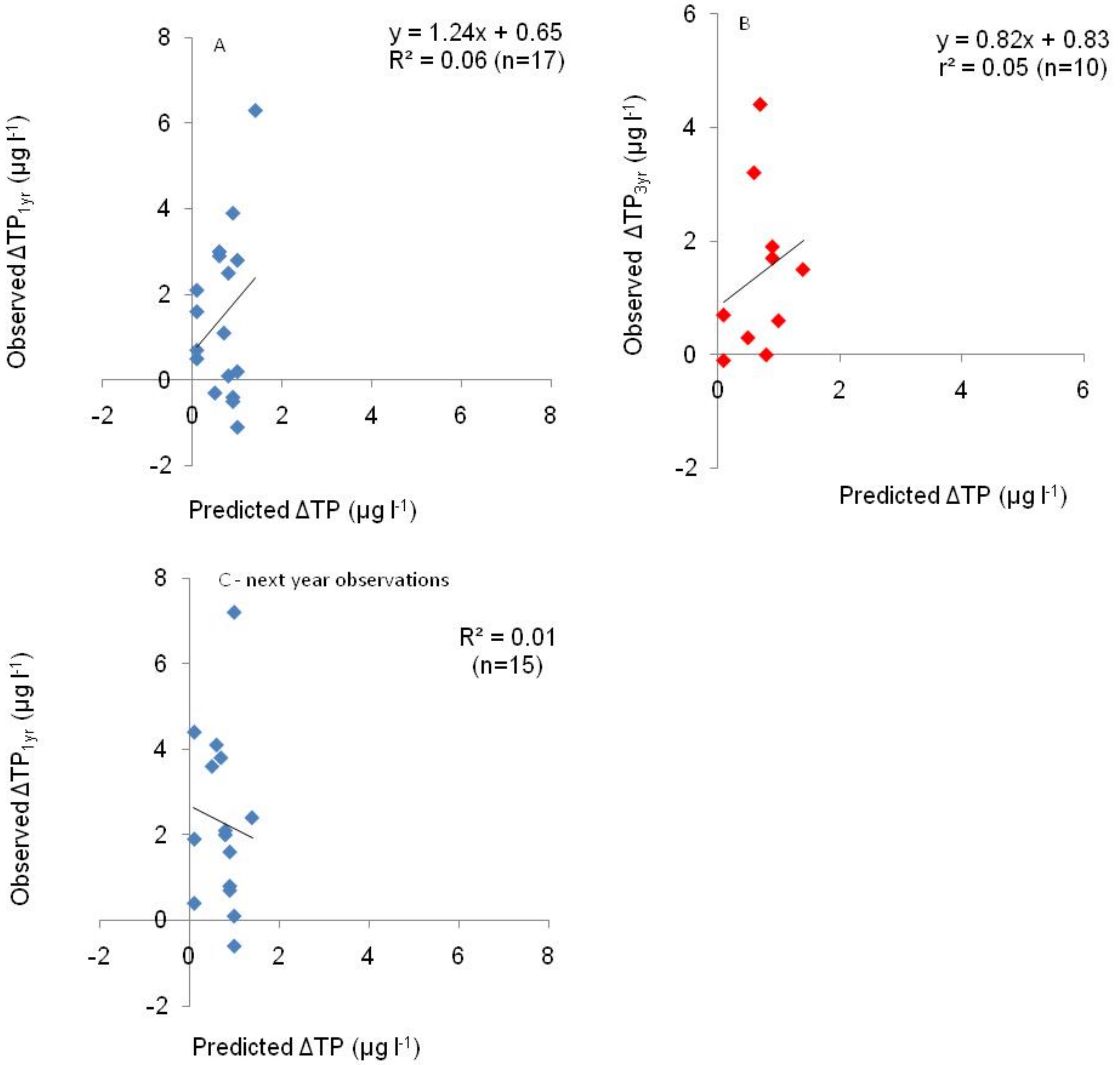

Figure 10. Model performance with two outliers excluded - predicted and observed changes in total phosphorus (ΔTP) for years where there has been an increase in production. A) One-year and B) three-year geometric means were used for observed ΔTP. In addition, C) is the one-year observed ΔTP for the year after the increase in production (see method for further explanation).

These two outliers are two different sites. Excluding these sites means that the model performance shown in Figure 10 applies to tests that were undertaken for 12 of the 15 sites for one-year comparisons, and 6 of the 15 sites for three-year comparisons. These two outliers were excluded from subsequent analyses, as they were a large influence on the data set.

Using the next years’ observations to calculate the change in observed TP (Figure 10C) degraded model performance.

Extreme values of 12.5 kg TP discharged t^{-1} production were used to determine whether this improved model performance. This higher value represents the extreme scenario where FCR's are higher. Model performance was not improved when this higher value was used (Figure 11).

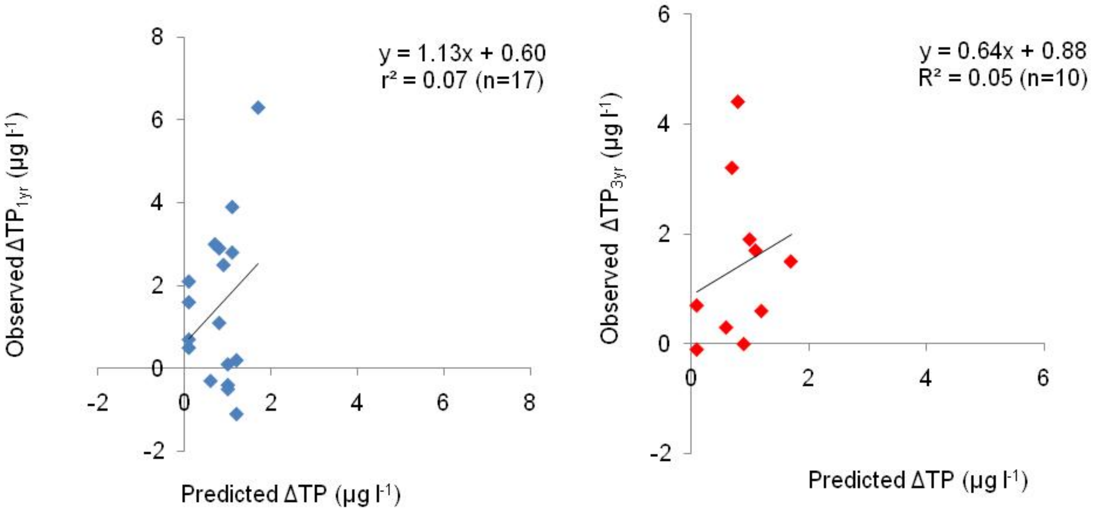

Figure 11. Model performance where an extreme value of 12.5 kg TP discharged t^{-1} production was used (compare Figure 9). One-year and three-year geometric means were used for observed ΔTP.

Test 2 – mass budgets

Using the OECD equation and PLUS model to predict TP from mass budgets for all lochs resulted in r^2 = 0.26 (n=23) (Figure 12A). Model performance does not appear to depend on whether there is high or low contribution from aquaculture TP (Figure 12B); i.e. both types of lochs fit into the general trend, with the exception of one outlier from each. For 8 of the sites where only consent production data were used (as actual figures were not available), when these sites were excluded r^2 increased to 0.42 (n = 15).

The Envelope of Acceptable Precision (EAP) was set to 80%. By ranking the sites in terms of mean absolute relative error (MARE – Portilla and Tett, 2007), 20% of the sites were excluded from the regression (Figure 12C, r^2 = 0.59, n=18).

To obtain exact agreement between OECD equation predicted TP and observed TP, the annual load required to achieve this was calculated (shown in the Balance column in Table 16). If the OECD equation had high predictive capability, then this balance figure would be the missing load from the budget. To put the balance figures into perspective, based on 0.75 kg TP $year^{-1}$ PE^{-1} discharged from a sewage treatment works (SEPA, 2005), 100 kg

TP year^{-1} corresponds to 133 PE. Many of the balance figures are high. The differences between observed and predicted TP for this test are a combination of the OECD equation and PLUS model predictions, and missing or approximated components of the mass budget.

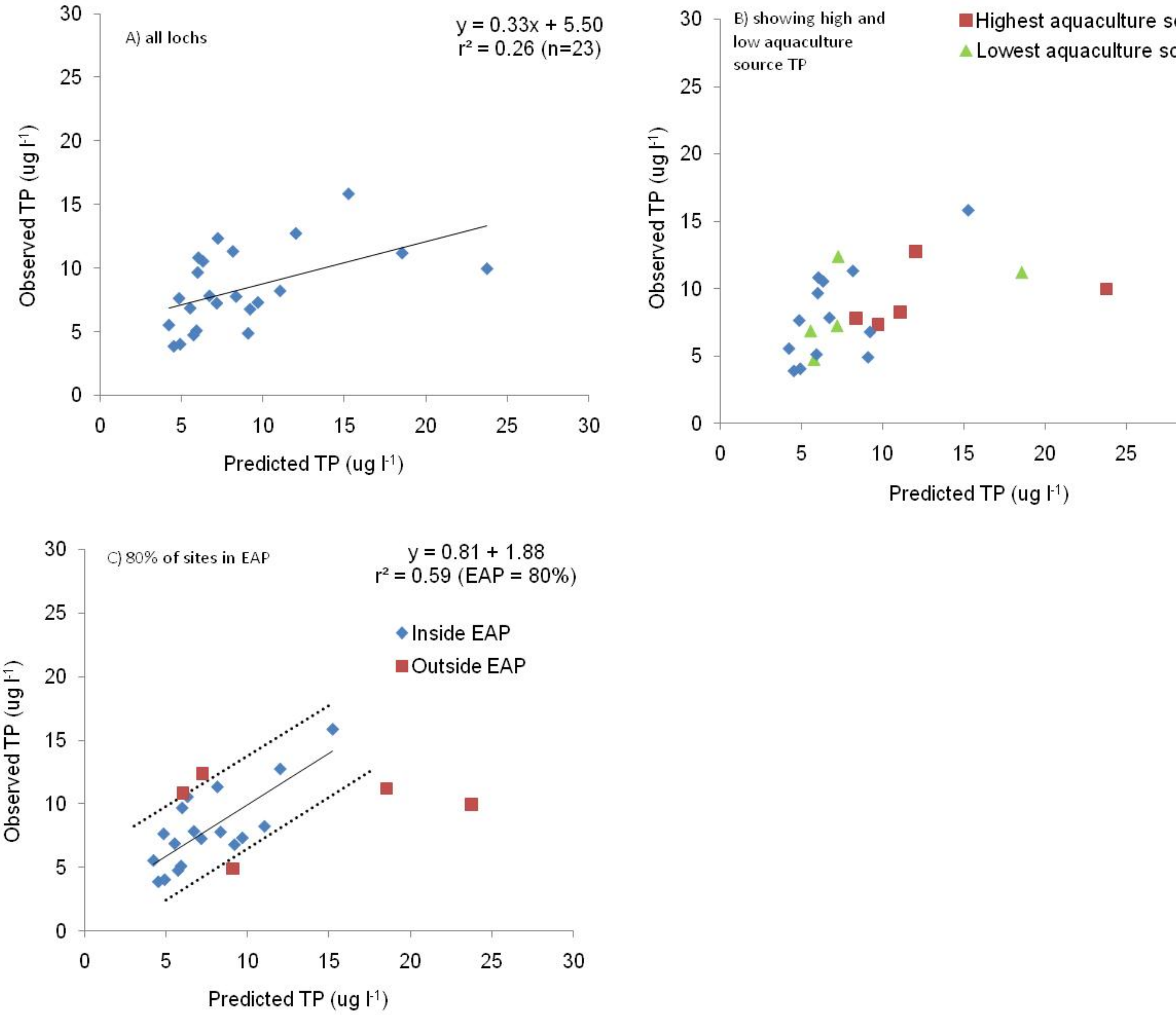

Figure 12. Predicted TP from mass budgets for the sites using PLUS model and consented production for compared with observed TP for A) all lochs and B) highest and lowest % sources of aquaculture TP. C) shows 80% of the sites in the Envelope of Acceptable Precision (EAP). The PLUS model uses 2001 land survey data and observed data are five-year geometric means. Note that in-loch concentration is shown, not ΔTP as for other tests.

Table 16. Mass budgets for the sites using PLUS model and consented production for each loch. PLUS model uses 2001 land survey data and observed data are five-year geometric means. Balance is the amount of adjustment required to the total budget to obtain exact agreement between predicted and observed (e.g. negative values mean over prediction of TP).

	Annual load (kg/yr)				Pred TP	Obs TP	Prod.	Balance
Site name	PLUS model	Aquaculture	Other	Total	ug/l	ug/l	tonnes	kg/yr
Arienas	529	163		692	9.1	4.9	16	-370
Arkaig	4695	1326		6021	4.5	3.9	130	-1000
Avich	798	102		900	7.2	7.3	10	14
Awe(N)	12231	4080		16311	6.3	10.6	400	14500
Awe(S)	12231	3060		15291	6.0	9.7	300	12300
Ba	831	255		1086	6.7	7.8	25	220
Caravat	70	306		376	23.8	10.0	30	-245
Damh	841	734		1575	8.3	7.8	72	-120
Earn	3276	4335	356	7611	9.7	7.3	425	-2600
Frisa	326	275		602	11.1	8.2	27	-185
Garry	3296	867		4163	4.2	5.6	85	1700
LochofCliff	410	89		499	15.3	15.9	8.7	25
Lochy	5774	3570		9344	5.9	5.1	350	-1500
Merkland	441	102		543	4.9	7.6	10	400
Migdale	357	61		417	18.5	11.2	5.98	-193
Ness	35299	1142		36441	5.7	4.8	112	-7200
Scadavay(N)	246	51		297	8.2	11.3	5	145
Scadavay(S)	66	61		127	12.0	12.7	6	9
Sgamhain	157	113		270	9.2	6.8	11.1	-85
Shiel	4689	1010		5699	4.9	4.0	99	-1300
Shin	5757	612		6369	5.5	6.9	60	2000
Tay	12183	3570		15753	6.0	10.8	350	16200
Tralaig	315	51		366	7.2	12.4	5	340

Test 3 – distance to sampling point

This test was designed to take account of the distance between cages and sampling point, as this varies between all lochs (Figure 13). These results show that modifying the mixing volume according to the proximity of the cages to sampling point does not improve model performance.

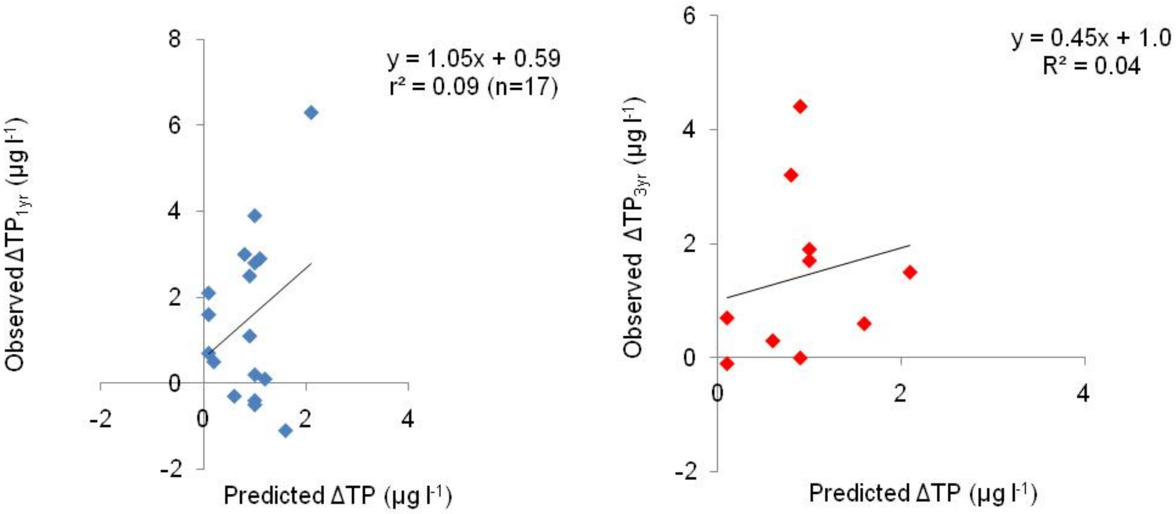

Figure 13. Model performance – predicted and observed ΔTP using a modified mixing volume. The distance between the cages to the sampling point and loch width are used as the mixing volume. One-year and three-year geometric means were used for observed ΔTP.

Test 4 - use of production mode

This test included detail for each site on the production mode, allowing the TP discharged to be varied between sites depending on species and mode of production (Figure 14), and the test results can be compared directly to test 1 (Figure 10).

Model performance was slightly improved when comparisons were made with three-year observed means, and no change to model performance was found when comparisons were made with one-year means.

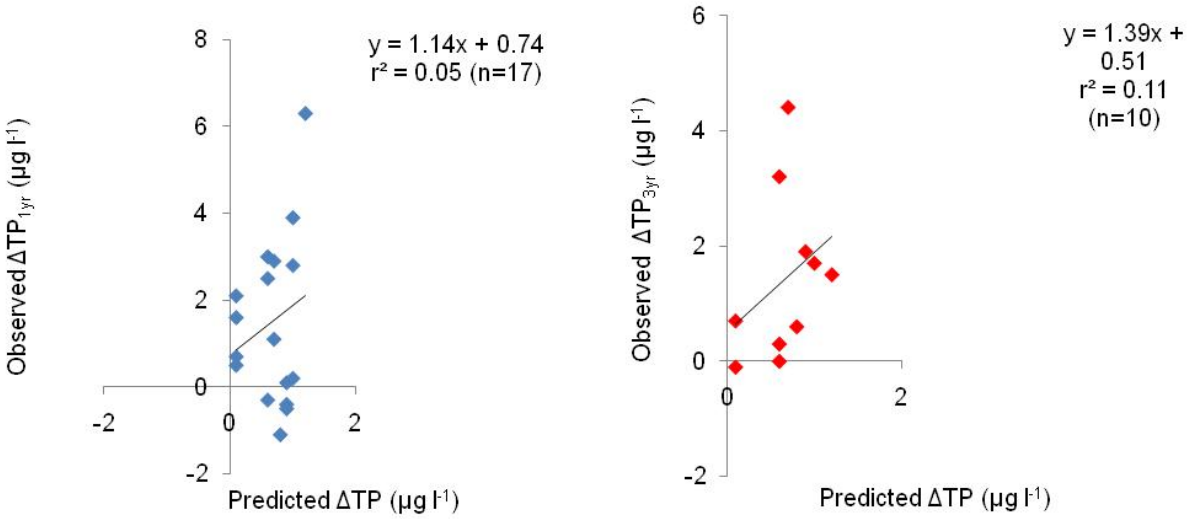

Figure 14 Model performance - predicted and observed ΔTP using production mode information as the driver for phosphorus loading. One-year and three-year geometric means were used for observed ΔTP.

Test 5 – use of feed input data to calculate phosphorus loading

This tested the equation using phosphorus loading calculated from feed input rather than production, where feed input was the driving model parameter rather than production. As most operators make returns to SEPA of production rather than feed input, this test used some of the detailed husbandry data provided by farmers. Fewer tests were possible than with production data.

Performance of the OECD equation was not improved when using feed input rather than production data (Figure 15). There was no correlation between predicted and observed ΔTP in this test.

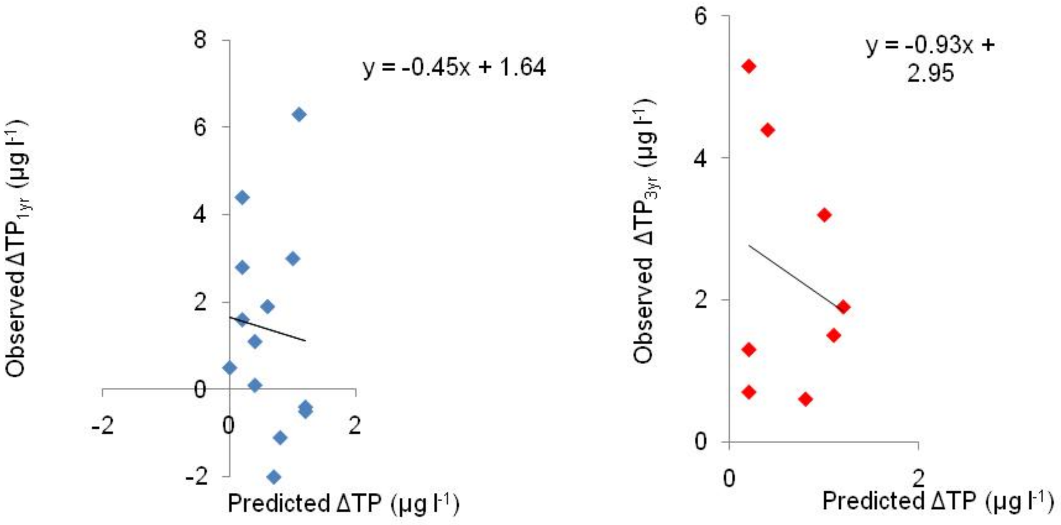

Figure 15. Model performance using feed input as the main driver for TP loading rather than production. One-year and three-year geometric means were used for observed ΔTP.

Test 6 – reductions in production between years

The OCED equation was used to predict the change in TP for years where there was a decrease in production; the equation is not used in this manner for regulatory purposes. The equation did not predict observed changes in TP (Figure 16).

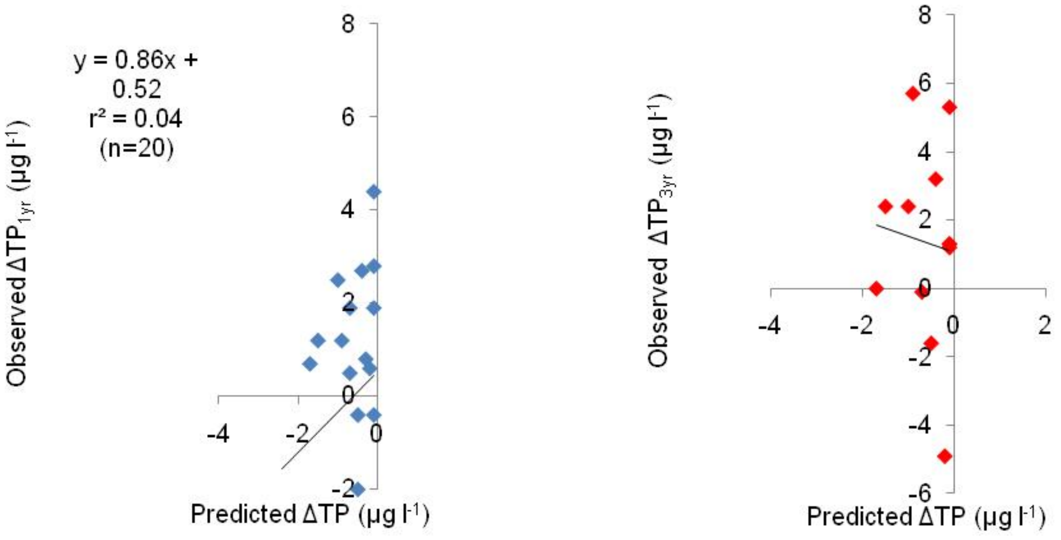

Figure 16. Model performance - predicted and observed ΔTP for years where there has been a decrease in production. One-year and three-year geometric means were used for observed ΔTP.

6.4 Statistical tests of model performance

Statistical testing following the method of Portilla and Tett (2008) and Jusup et al. (2009) resulted in $r^2 < 0.12$ and model classification of ‘poor’ for all tests except test 2 (Table 16). These tests show that where TP loading is increased to a loch through increased production, the OECD equation does not predict the change in in-loch TP. Model performance is ‘poor’, regardless of whether one-year or three-year geometric observed means are used for comparisons. Undertaking some modifications in the equation application and using more detailed information in the model parameters, such as using extreme parameter values, accounting for the distance from cages to sampling point, accounting for production mode and using feed input as a driver for TP loading did not improve model performance.

Where mass balances were constructed from the PLUS model and estimates were made of point source TP (test 2), a higher r^2 of 0.26 was found. As r^2 was tested as significantly different from zero, this resulted in a model classification of ‘fair’ (see Table 17 for definitions), but the intercept and the gradient were significantly different from zero and 1 respectively. In all tests, Efficiency was less than 0, and Mayer and Butler (1993) caution against using models where *E* is less than 0.

Table 17. Model performance showing regression coefficient (r^2) and the regression line $Y_i = \beta_0 + \beta_1 X_i$ for observed (Y_i) and predicted (X_i) values where β_0 is the intercept and β_1 the slope for each test. S.E. is standard error. *E* is Efficiency, a measure of goodness of fit, and *n* is number of tests. *Obs.* is the geometric mean of the observed data used for model comparisons. Test 1b is using extreme parameter values for kg TP discharged t^{-1} production.

				Estimate		S.E.				
Test		**Obs.**	**r^2**	**β_0**	**β_1**	**β_0**	**β_1**	**E**	**n**	**Class**
1	Increase in prod.	1 yr	0.06	0.7	1.24	1.1	1.37	-0.13	17	Poor
1		3 yr	0.05	0.8	0.82	1.1	1.42	-0.22	10	Poor
1b		1 yr	0.07	0.6	1.13	1	1.1	-0.07	17	Poor
1b		3 yr	0.05	0.9	0.64	1.1	1.13	-0.15	10	Poor
2	Mass balance	5 yr	0.26	5.5	0.33	1.9	0.19	-0.82	23	Fair
3	Dist. to sampling point	1 yr	0.09	0.6	1.05	0.9	0.94	-0.03	17	Poor
3		3 yr	0.04	1	0.45	1	0.91	-0.14	10	Poor
4	Use of production mode	1 yr	0.05	0.7	1.14	1.1	1.47	-0.15	17	Poor
4		3 yr	0.11	0.5	1.39	1.2	1.6	-0.19	10	Poor
5	Feed input data	1 yr	0.01	1.6	-0.45	1.3	1.82	-0.17	13	Poor
5		3 yr	0.05	2.9	-0.93	1.9	2.48	-0.66	8	Poor
6	Reduction in prod.	1 yr	0.04	0.5	0.86	0.9	1.03	-0.02	20	Poor
6		3 yr	0.01	1.2	-0.24	1.7	2.03	-0.25	12	Poor

Note: Test 2 – r^2 increased to 0.42 when excluding the 8 sites where consent production data were used instead of actual data.

6.5 Discussion of the results and their reliability

Performance of the OECD equation for predicting the change in in-loch TP as a result of increases in production was defined as ‘poor’, where less than 12% of the variability was explained by the model. In all tests except the mass budget (test 2), r^2 was not significantly different from zero. Portilla and Tett (2008) define the ‘poor’ category as “it corresponds to a value of r^2 that is indistinguishable from zero, and which could have been obtained by comparing observations with numbers picked at random from those predicted by the model.” The number of different scenarios that the OECD equation could be tested for varied between 8 to 20, depending on the test. Although 8 lochs of the 23 lochs chosen did not have complete production data sets, the 15 lochs that did have complete production data sets are reasonably representative of the aquaculturally important lochs in Scotland. Given the consistently low performance of the OECD equation in this validation study, it appears unlikely that further testing with more scenarios will yield a different result. The present findings of the project are therefore reliable from this viewpoint.

When the OECD equation was used in conjunction with the PLUS model to predict in-loch TP from mass budgets, performance of the OECD equation improved to ‘fair’. This means that the regression coefficient is significantly different from zero, but the intercept and gradient of the regression line of predicted and observed TP are significantly different from zero and 1 respectively. This indicates that further development of this mass budget approach for all the aquaculture lochs may yield better predictive capability, particularly if other ‘static’ models similar to the OECD equation are tested with this approach (e.g. see Johansson and Nordvarg, 2002). r^2 was further improved for this test when excluding the 8 sites for which actual production data were not available. The loch mass budgets used in test 2 were reasonably reliable, as they were based on predictions from the PLUS model using standard parameters and consented aquaculture production information. To improve reliability of this mass budget approach, specific recommendations are made in section 6.7.

The sensitivity analysis showed that the OECD equation predictions are relatively insensitive to minor changes in model parameters, when compared to the variation seen in observations. These findings are reliable as the method used for the analysis is standard for a model validation exercise, and loch parameters were varied within reasonable bounds. The importance of sensitivity analysis cannot be overemphasized throughout model validation, as this determines which input parameters are important and why. It occasionally demonstrates, as was the case for this exercise, that relatively minor inaccuracies in input parameters are unimportant when model performance is so low.

The predictions for TP release are from a model validated for rainbow trout in Canada. The use of the model with diets specific to the region and using TGC which reflect observed growth for given temperature conditions in Scotland, implies predictions are highly likely to be of similar accuracy to those achieved by the developers. The Fish-PrFEQ model does however work in idealised conditions of nutrition and other factors such as fish strain, water quality, fish health and other stressors likely to reduce the efficiency of food conversion to fish tissue. The theoretical FCRs which the model predicted were therefore low, sometimes approaching 1, which is assumed to be unrepresentative of real conditions on fish farms in Scotland.

6.6 Implications of the findings

Variability of the observed TP both between years and within years at some lochs was high, demonstrating that these lochs are highly dynamic and will not easily be represented with a steady-state model such as the OECD equation. The observed variability however, reflects reality and so the usefulness and performance of any model has to be tested against this.

The performance of the OECD equation was low when used in a similar manner to the consenting process; i.e. used to predict a change in TP according to an increase in TP loading from aquaculture. This finding implies the current regulatory method using the OECD equation should be reviewed.

Improved performance (defined ‘fair’) of the OECD equation was achieved when a mass budget was constructed for each loch using the PLUS model and comparisons made with five-year observed means. This implies that this approach, with further validation and detailed budget, could be a more reliable approach for predicting in-loch TP concentration. Various approaches were investigated with the OECD equation, including using more detailed information on production mode and representing localised mixing by taking account of the distance between cages and outflow point. These variations in methodology did not improve model performance. In-loch parameters used in the OECD equation were found to have low sensitivity (<0.2 µg l^{-1}) when changes in loch depth (± 10%), surface area (± 10%) and outflow (± 20%) were tested. Loch outflow was the most sensitive and potentially the most variable. This change in predicted TP is insignificant when compared to variation in observed data. This finding implies that minor inaccuracies in loch parameters are not a factor in the low predictive capability of the OECD equation.

A large variation in observed TP was found even when three year geometric means were calculated. Such variations in observations creates difficulties for model validation and further infers that the use of observed TP as a model parameter is inappropriate when calculating change in TP on account of aquaculture.

In the further development of a modellng framework for freshwater aquaculture production, use of observed TP data as a model parameter should be avoided. Predicted change in TP should be generated using a set of parameters which do not include observed TP, though reliable TP is necessary for model validation. The range of variability of observed TP should form the boundaries within which model predictions and performance are assessed.

Despite the welcomed cooperation of the majority of the freshwater aquaculture industry, large data requirements were left unfulfilled despite efforts to describe transparent objectives and methods, and provide a confidentiality agreement as part of an independent study. The implications of this are that for lochs where detailed data sets were provided, the overall conclusion that the OECD equation has limited use for assessing changes in aquacultural production, is valid. On the contrary, for the sites where data were lacking, it is not possible to conclude this finding with such certainty; i.e. the OECD equation may well have better performance for these sites, but this study could not test this so rigorously.

A reporting system for aquaculture called “Sentinel Fish Farms” has been set up on a trial basis and enables data to be entered into a reporting package that can be viewed remotely (Prof J. Turnbull, Institute of Aquaculture, University of Stirling). A system such as this would make the reporting of fish farming activity data more efficient, would make the information more readily available, and would save time for the farm staff and prevent duplication of the reporting of information to various sources.

Predictions of TP release, where partitioning of solids and dissolved wastes is conducted, offer data which can be subsequently used in dispersion modelling, where local currents and thermal stratification are describable. The significance of this process in avoidance of eutrophication should however be set against the considerable costs associated with establishing data on localised physical characteristics.

The fish growth and waste production modelling exercise illustrated that the different production modes and diets produce significantly different amounts of TP within an annual production reporting period. It is obvious, but not recognised within the regulatory framework, that for example an organic farmer using organic feed to produce S1 salmon will work at the highest rate of TP per kg production. However, over the annual TP reporting period a salmon farmer producing nearly two crops of SO salmon (in our examples (a + b)), may do so using a low phosphorus feed, but is likely to release equal or possibly greater amount of total TP than the organic farmer, for a given consented maximum biomass.

Additionally the timing of high end TP releases is likely to be of significance, where seasonal differences in rainfall and irradiance will affect, respectively, loch volume (and nutrient dilution) and phytoplankton production.

It is likely that phasing maximum fish production, and hence TP release, with periods of high dilution and lower irradiance may assist with avoidance of eutrophication.

6.7 Recommendation for further validation of the mass budget approach using the PLUS model

The PLUS model was not available to use directly in the present study, as the model was in the final stages of handover from MLURI to SEPA. The project partners therefore were requesting model runs through MLURI, which provided data in kind. A more detailed study using the PLUS model and the sites in the present study should be undertaken.

Objectives

1. To validate the mass budget approach for all 23 study sites using the PLUS model and findings from this project.

Specifically:

2. to predict observed TP for the current situation for each loch

3. to predict the change in TP (ΔTP) before and after aquaculture for each loch

4. and to determine sensitivity of the most important parameters in the PLUS model predictions.

Outline method

1. Rerun the PLUS model to predict TP loading from diffuse sources, specifying a range of export coefficients and using more recent information on land use than 2001 data, if available. Determine sensitivity of parameters

2. Use 3 or 5 year averaged actual production data for all the lochs, using mean and extreme parameter values for kg TP t^{-1} production from this study. Production data from 8 sites are currently missing

3. Evaluate other point sources for each loch – this information was surprisingly difficult to find, despite assistance from SEPA

4. Use the predicted TP loading from diffuse and point sources in a range of ‘static’ models (including the OECD equation) to refine the predictions of in-loch TP concentration

5. Compare predictions with 3 or 5 year geometric observed means to assess model performance using similar statistical tests to those used in the present study - this may result in some useful loch-specific empirical constants. A general set of empirical constants which applies to all lochs appears unlikely given the findings of this study

6. To achieve objective 3, calculate observed ΔTP for before and after aquaculture (using reference TP from MEI method or from other studies). Compare this with predicted ΔTP

7. Developing such a framework on a loch by loch basis would help to establish a more reliable and fairer method for consenting of freshwater production in Scottish lochs.

7.0 CONCLUSIONS AND RECOMMENDATIONS

This study concluded that the OECD equation had limited predictive capability for assessing change in loch TP on account of aquaculture production, in the context of the TP and fish farm production data explored. High variability in the observed TP for some sites contributed to the underperformance of the model on the whole. The current consenting approach, which uses the OECD equation, should therefore be extensively reviewed.

Developing a mass budget approach for all aquaculturally important lochs including the PLUS model, regulatory information on point source discharges, and operator-returned aquaculture production, would be a logical first step to improving predictive capability for in-loch TP concentration (recommendation 6.7).

Once a mass budget has been completed, it is recommended that other static as well as dynamic TP prediction models should be used to predict in-loch TP concentration (see for example Bryhn and Håkanson, 2007 who compare 12 static and 3 dynamic models). These predictions should then be compared with the SEPA monitoring TP data sets and other data sets such as those held by the Institute of Aquaculture, Stirling University and within operator commissioned reports. Inclusion of these additional non-SEPA data sets would be essential for such a study.

Of the 23 lochs that were chosen for their importance relating to aquaculture, 8 lochs had incomplete data sets, where accurate fish production information was the single most lacking piece of vital information. It is recommended that centralisation of information on production returns at SEPA should be undertaken (i.e. in a database), so that time series of production returns for each loch can be easily obtained. Similarly, it is recommended that SEPA insist on production returns from farmers when requested, as part of the license conditions of the consent.

For a scientific model validation study to achieve its objectives, its reliability depends on the accuracy of information and the willingness to provide data by stakeholders – in the context of this project this includes the industry and its contractors and regulatory bodies (SEPA, Marine Scotland, formerly FRS). It is respected that sharing of sensitive information even within a confidentiality agreement is the choice of stakeholders. It is recommended that more open dialogue is encouraged between stakeholders when planning and undertaking scientific studies. Such dialogue has greatly improved in marine aquaculture in the last 15 years, and this has been fundamental in progressing the scientific validation of the models used in regulation.

Six production modes were assumed for growth and waste release modelling and covered production of single and multiple inputs of rainbow trout and S1 and SO salmon smolts. Four diets and 2 waste feed scenarios were considered for each. Predicted mean TP release ranged from 7.8 – 12.3 kg t^{-1} production for rainbow trout and 10.81 – 14.35 kg t^{-1} production for Atlantic salmon.

Predictions for TP release rate were highest for organic feeds, based on their high percentage phosphorus composition. It is thought likely that farmers using this feed will be following a production mode similar to the reported S1 scenario, with maximum TP output per fish occurring in the months of October to December. For comparison of this effect, Figure 17 shows TP release per fish for theoretical S0 and S1 production with low and high P feeds. Broadly, the combined S0a + S0b (low P) mass of TP released equates to total TP released for the S1 (high P) release but, depending on the dates of the administrative annual period, comparative TP release will vary.

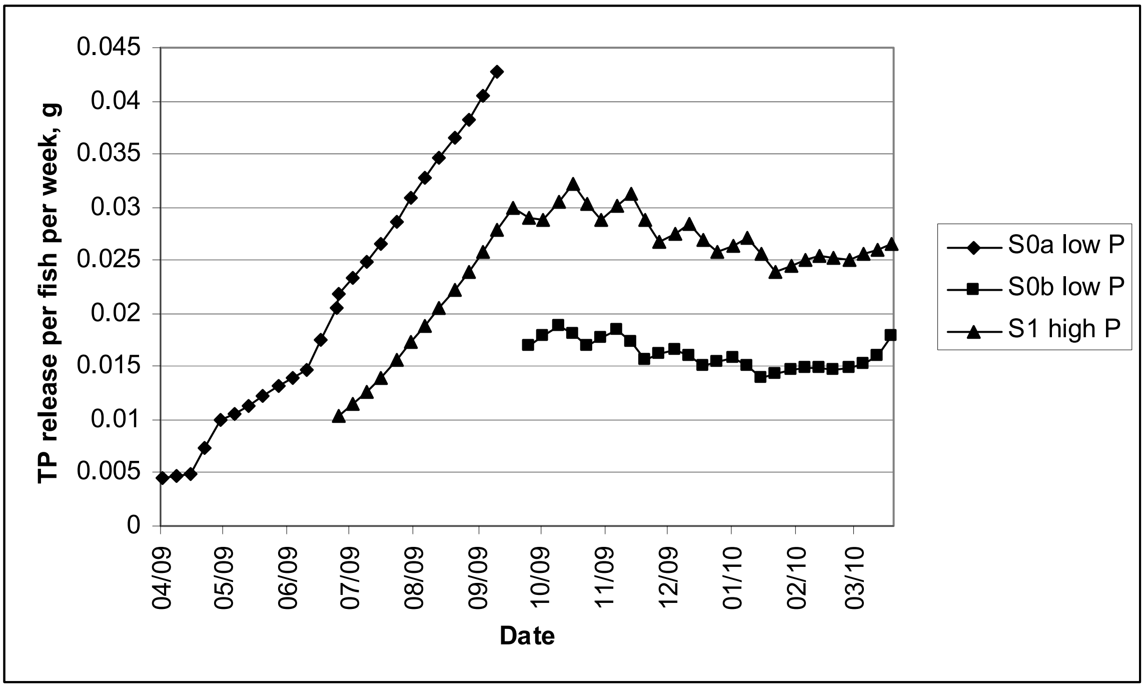

Figure 17 – Comparison of TP release per fish in SO and S1 production modes with low and high P feeds.

Though steady loch-wide annual increments of TP may contribute to change in trophic status, it is short term eutrophic events that may cause the most apparent and undesirable economic and social consequences. Therefore the ability to align maximum TP production from a fish farm with maximum dilution in the fresh water system and to avoid periods of maximum solar irradiation is an obvious management measure which could be designed through use of bioenergetic models.

The use of a fixed figure for TP release estimates from fish farms needs further assessment. The rates of feed waste on farm are not well understood and the existing consenting process, in the main, limits fish farming activity on biomass, which is not necessarily as useful a predictor of fish production and hence TP release. Ideally, small sampling periods for feed input and fish production figures would facilitate more accurate TP release predictions and where residence times are as low as 0.2 year, as in this study, quarterly averaging periods would be sufficient. Other background factors, such as riverine inputs, may however have influence over shorter timescales. It may therefore be necessary to work with shorter sampling periods for best predictions.

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ANNEX 1

Determination of Total Phosphorus in Fresh and Waste Water by Manual Colorimetric Chemistry (SEPA, 2008).

Summary - The method involves the reaction of orthophosphate ions with acidic molybdate reagents to form a reduced phosphomolybdenum blue complex, the absorbance of which is measured on a spectrophotometer at 882nm. In the determination of total phosphorus, which includes all inorganic and organic forms of phosphorus, an initial sulphuric acid - persulphate digestion is required to convert complex forms of phosphorus to orthophosphate. This method is suitable for the determination of total phosphorus in river and discharges samples.

ANNEX 2

Example Outputs from Fish-PrFEQ model per production mode

where:
SW - faecal solids
TF - total feed administered
WF - waste feed
TFP - total feed phosphorus
FP - feed phosphorus
WFP - waste feed phosphorus
UPZP - urinary and brachial phosphorus (dissolved P)
TP - total release phosphorus
sd - standard deviation
se - standard error

TGC	0.2
Feed wastage, %	7.5

Mode	Diet	Feed	FCR		SW	TF	WF	TFP	FP	WFP	UPZP	TP	TP sd	TP se
					kg/t	kg/t	kg/t	kg/t	kg/t	kg/t	kg/t	kg/t		
RBT_sg	1	Royal Hz 30	1.10	per prod	194.87	999.66	69.74	10.30	3.07	0.72	2.91	6.70	1.75	0.48
		Royal Hz 45		per feed	195.83	1000.00	69.77	10.42	3.10	0.73	2.83	6.66	0.46	0.13
	2	Sigma 50	1.14	per prod	203.04	1031.93	72.00	13.59	4.04	0.95	4.99	9.99	2.66	0.74
		Sigma 150		per feed	197.09	1000.00	69.77	13.23	3.94	0.92	4.72	9.58	0.52	0.14
	3	Royal Hz 30	1.22	per prod	245.91	1103.18	76.97	11.32	3.37	0.79	3.56	7.72	2.07	0.57
		Elite SPR 60		per feed	221.84	1000.00	69.77	10.38	3.09	0.72	3.14	6.95	0.43	0.12
	4	Harmony 20P	1.22	per prod	253.46	1100.49	76.78	16.10	4.79	1.12	6.59	12.50	2.57	0.71
		Harmony 250		per feed	229.71	1000.00	69.77	14.87	4.43	1.04	5.97	11.43	0.73	0.20

TGC	0.22
Feed wastage	7.5%

Mode	Diet	Feed	FCR		SW	TF	WF	TFP	FP	WFP	UPZP	TP	TP sd	TP se
					kg/t	kg/t	kg/t	kg/t	kg/t	kg/t	kg/t	kg/t		
RBT_sg	1	Royal Hz 30	0.80	per prod	154.55	802.04	55.96	8.02	2.39	0.56	1.47	4.42	0.22	0.06
		Royal Hz 45		per feed	192.70	1000.00	69.77	10.00	2.98	0.70	1.75	5.42	0.16	0.04
	2	Sigma 50	1.07	per prod	211.07	1073.40	74.89	14.11	4.20	0.98	5.32	10.51	3.25	0.90
		Sigma 150		per feed	196.99	1000.00	69.77	13.21	3.93	0.92	4.80	9.65	0.62	0.17
	3	Royal Hz 30	1.15	per prod	255.99	1147.79	80.08	11.77	3.50	0.82	3.84	8.17	2.54	0.71
		Elite SPR 60		per feed	221.84	1000.00	69.77	10.38	3.09	0.72	3.22	7.03	0.48	0.13
	4	Harmony 20P	1.14	per prod	263.91	1144.85	79.87	16.67	4.96	1.16	6.94	13.07	3.26	0.90
		Harmony 250		per feed	229.86	1000.00	69.77	14.81	4.41	1.03	6.02	11.46	0.63	0.18

TGC	0.087
Feed wastage, %	30.0

Mode	Diet	Feed	FCR		SW	TF	WF	TFP	FP	WFP	UPZP	TP	TP sd	TP se
					kg/t	kg/t	kg/t	kg/t	kg/t	kg/t	kg/t	kg/t		
AS_S1	1	Nutra Oly 7	1.17	per prod	200.93	1139.70	263.01	13.68	3.37	3.16	3.55	10.08	1.27	0.40
		Nutra Oly 25		per feed	176.16	1000.00	230.77	12.00	2.95	2.77	3.09	8.81	0.31	0.10
	2	Micro Start 10p	1.13	per prod	178.92	1104.94	254.99	14.36	3.54	3.31	3.91	10.76	1.35	0.43
		Micro Start 20p		per feed	161.92	1000.00	230.77	13.00	3.20	3.00	3.51	9.71	0.32	0.10
	3	Micro Start 10p	1.13	per prod	168.52	1104.94	254.99	14.36	3.54	3.31	3.91	10.76	1.35	0.43
		Transfer 20p		per feed	153.14	1000.00	230.77	13.00	3.20	3.00	3.51	9.71	0.32	0.10
	4	Harmony 10P	1.19	per prod	214.93	1160.10	267.72	19.72	4.85	4.55	6.72	16.12	1.86	0.59
		Harmony 20P		per feed	185.27	1000.00	230.77	17.00	4.18	3.92	5.76	13.87	0.31	0.10

TGC	0.087
Feed wastage, %	30.0

Mode	Diet	Feed	FCR		SW	TF	WF	TFP	FP	WFP	UPZP	TP	TP sd	TP se
					kg/t	kg/t	kg/t	kg/t	kg/t	kg/t	kg/t	kg/t		
AS_S0a	1	Nutra Oly 7	1.13	per prod	188.86	1075.96	248.30	12.91	3.18	2.98	3.15	9.31	0.53	0.17
		Nutra Oly 25		per feed	176.33	1000.00	230.77	12.00	2.95	2.77	4.19	9.91	1.65	0.52
	2	Micro Start 10p	1.10	per prod	168.77	1042.25	240.52	13.55	3.34	3.13	3.49	9.95	0.56	0.18
		Micro Start 20p		per feed	161.92	1000.00	230.77	13.00	3.20	3.00	4.64	10.84	1.70	0.54
	3	Micro Start 10p	1.10	per prod	162.54	1042.25	240.52	13.55	3.34	3.13	3.49	9.95	0.56	0.18
		Transfer 20p		per feed	152.38	1000.00	230.77	13.00	3.20	3.00	4.64	10.84	1.71	0.54
	4	Harmony 10P	1.15	per prod	202.74	1094.29	252.53	18.60	4.58	4.29	6.13	15.00	0.77	0.24
		Harmony 20P		per feed	129.69	700.00	161.54	11.90	2.93	2.75	3.91	9.58	6.61	2.09

TGC	0.087
Feed wastage	12.5

Mode	Diet	Feed	FCR		SW	TF	WF	TFP	FP	WFP	UPZP	TP	TP sd	TP se
					kg/t	kg/t	kg/t	kg/t	kg/t	kg/t	kg/t	kg/t		
AS_S0b	1	Nutra Oly 7	1.07	per prod	217.46	1059.51	117.72	12.71	3.62	1.41	4.09	9.11	0.48	0.20
		Nutra Oly 25		per feed	205.24	1000.00	111.11	12.00	3.41	1.33	3.85	8.59	0.14	0.06
	2	Micro Start 10p	1.04	per prod	192.43	1028.44	114.27	13.37	3.80	1.49	4.48	9.77	0.53	0.22
		Micro Start 20p		per feed	187.11	1000.00	111.11	13.00	3.70	1.44	4.35	9.49	0.15	0.06
	3	Micro Start 10p	1.04	per prod	174.29	1028.44	114.27	13.37	3.80	1.49	4.48	9.77	0.53	0.22
		Transfer 20p		per feed	169.47	1000.00	111.11	13.00	3.70	1.44	4.35	9.49	0.15	0.06
	4	Harmony 10P	1.09	per prod	231.17	1079.78	119.98	18.36	5.22	2.04	7.50	14.76	0.73	0.30
		Harmony 20P		per feed	214.09	1000.00	111.11	17.00	4.84	1.89	6.93	13.66	0.14	0.06

TGC	0.087
Feed wastage	12.5

Mode	Diet	Feed	FCR		SW	TF	WF	TFP	FP	WFP	UPZP	TP	TP sd	TP se
					kg/t	kg/t	kg/t	kg/t	kg/t	kg/t	kg/t	kg/t		
AS_S0ab	1	Nutra Oly 7	1.00	per prod	203.16	995.32	110.59	11.94	3.40	1.33	3.62	8.34	0.92	0.38
		Nutra Oly 25		per feed	204.01	1000.00	111.11	12.00	3.41	1.33	3.61	8.36	0.28	0.12
	2	Micro Start 10p	0.97	per prod	180.60	965.20	107.24	12.55	3.57	1.39	3.98	8.95	0.99	0.40
		Micro Start 20p		per feed	187.11	1000.00	111.11	13.00	3.70	1.44	4.10	9.24	0.30	0.12
	3	Micro Start 10p	0.97	per prod	168.41	965.20	107.24	12.55	3.57	1.39	3.98	8.95	0.99	0.40
		Transfer 20p		per feed	174.98	1000.00	111.11	13.00	3.70	1.44	4.10	9.24	0.30	0.12
	4	Harmony 10P	1.01	per prod	216.95	1013.38	112.60	17.23	4.90	1.91	6.81	13.63	1.36	0.55
		Harmony 20P		per feed	214.09	1000.00	111.11	17.00	4.84	1.89	6.70	13.42	0.28	0.12

Annex 3 – comparative proximate feed composition of feeds used in modelling

					dry matter, %	crude protein, %	lipid (oil), %	nitrogen free extract, %	%	gross energ	dig protein	dig energy		tot Phos		dig dry matter
Manufacturer	SP.	Type	size	age class,g	**DM**	**CP**	**Lipid**	**NFE**	**Ash**	**GE**	**DP %**	**DE kJ/g**	**DP/DE**	**TP%**	**DPh%**	**DDM**
Skretting	T	Elite SPR	45	100-500	92.5	40	22	22.5	8	21.955	36	18.7	19.29	1	0.68	68.19
	T		60	400-900	92.5	39	22	24.5	7	22.059	35.1	18.6	18.85	1	0.68	68.29
	T		85	800+	92.5	38	22	25.5	7	21.993	34.2	18.5	18.49	1	0.68	67.89
	T	Excel	23	8.0 - 30	92.5	45	19	20.5	8	21.61	40.5	18.4	21.97	1.2	0.82	68.84
	T		30	25 - 120	92.5	44	21	19.5	8	21.994	39.6	18.9	20.97	1.2	0.82	69.34
	T	Nutra plus	0	<.2	92.5	57	14	11.5	10	20.937	51.3	18.3	27.98	1.2	0.82	70.40
	T		1	0.2-1.5	92.5	54	18	10.5	10	21.639	48.6	19.1	25.42	1.2	0.82	71.00
	T		2	1.0 - 4	92.5	53	19	10.5	10	21.798	47.7	19.3	24.74	1.2	0.82	71.05
	T		3	3.5 - 9	92.5	53	19	10.5	10	21.798	47.7	19.3	24.74	1.2	0.82	71.05
	T	Royal Horizon	23	8.0 - 30	92.5	45	22	16.5	9	22.115	40.5	19.2	21.08	1.2	0.82	69.70
	T		30	25 - 120	92.5	44	24	15.5	9	22.499	39.6	19.7	20.13	1.2	0.82	70.20
	T		45	100-500	92.5	41	28	16.5	7	23.541	36.9	20.6	17.90	1	0.68	71.79
	T		60	400-900	92.5	39	28	18.5	7	23.409	35.1	20.4	17.24	1	0.68	70.99
	T		85	800+	92.5	38	28	19.5	7	23.343	34.2	20.2	16.90	1	0.68	70.59
	T	Std Expanded	30	25 - 120	92.5	40	8	37.5	7	18.975	36	14.7	24.51	1	0.68	62.39
	T		40	80 - 400	92.5	40	8	37.5	7	18.975	36	14.7	24.51	1	0.68	62.39
	T		60	350 - 2000	92.5	40	8	37.5	7	18.975	36	14.7	24.51	1	0.68	62.39
	T		110	> 2000	92.5	40	8	37.5	7	18.975	36	14.7	24.51	1	0.68	62.39
	S	Nutra ST	0.5	0.2 - 0.5	92.5	52	20	10.5	10	21.957	46.8	19.4	24.07	1.3	0.88	71.10
	S		0.75	0.4 - 1.0	92.5	52	20	10.5	10	21.957	46.8	19.4	24.07	1.3	0.88	71.10
	S		1	0.9 - 3.0	92.5	52	20	10.5	10	21.957	46.8	19.4	24.07	1.3	0.88	71.10
	S	Nutra Olympic	2	2.0 - 8	92.5	50	21	9.5	12	21.71	45	19.3	23.31	1.4	0.95	69.76
	S		7	7.0 - 30	92.5	49	21	11.5	11	21.814	44.1	19.3	22.89	1.2	0.82	69.86
	S		25	25 - 60	92.5	48	22	10.5	12	21.803	43.2	19.3	22.33	1.2	0.82	69.41
	S		50	>50	92.5	48	22	10.5	12	21.803	43.2	19.3	22.33	1.2	0.82	69.41
EWOS	T+S	Micro start	micro 5	5.0 - 15	93	53	20	10	10	22.108	47.7	19.6	24.32	1.3	0.88	71.75
	T+S		10p	10 - 30g	93	50	22	12	10	22.53	45	19.9	22.62	1.3	0.88	71.95
	T+S		20p	20 - 70g	93	50	22	12	10	22.53	45	19.9	22.62	1.3	0.88	71.95
	T+S		50p	50g +	93	50	22	12	10	22.53	45	19.9	22.62	1.3	0.88	71.95
	S	Transfer	20P	20-50	91	50	22	12	7	22.53	45	19.9	22.62	1.3	0.88	71.94
	S		50P	50-150	91	50	22	12	7	22.53	45	19.9	22.62	1.3	0.88	71.94
	T+S	Sigma	50	50-150	91	45	23	14	8	22.085	40.5	19.4	20.90	1.4	0.95	69.39
	T+S		150	150-600	91	43	26	13	8	22.628	38.7	20.0	19.36	1.3	0.88	69.94
	T+S		600	600 - 1500	91	40	29	14	7	23.275	36	20.6	17.50	1.1	0.75	70.59
	T+S		1500	1500 - 250	91	38	33	12	6	24.043	34.2	21.5	15.93	1	0.68	71.58
	T+S		2500	>2500	91	36	35	13	6	24.531	32.4	21.9	14.80	1	0.68	72.18
										0						
	S	Harmony	5P	5.0 - 15	93	50	20	9.7	13	21.349	45	18.9	23.75	1.7	1.16	68.92
	S		10P	10 - 30g	93	50	20	9.7	13	21.349	45	18.9	23.75	1.7	1.16	68.92
	S		20P	20 - 80g	93	50	20	9.7	13	21.349	45	18.9	23.75	1.7	1.16	68.92
	S		75P	75-250	93	48	22	9.6	13	21.65	43.2	19.3	22.42	1.6	1.09	68.97
	S		250	250-500	92	44	22	13	12	21.284	39.6	18.7	21.17	1.4	0.95	67.06

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