APPENDIX 3

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MEMORANDUM

To:	Klamath TMDL Technical Team	**Date:**	February 12, 2008
From:	Jonathan Butcher	**Project:**	Klamath
Subject:	Nutrient Dynamics in the Klamath	**Tt Pjn:**	20729-02

Oregon DEQ (DEQ) and California's North Coast Regional Water Quality Control Board (Board) are developing Total Maximum Daily Loads (TMDLs) for the Klamath River to address impairments associated with dissolved oxygen, temperature, nutrients, pH, and chlorophyll *a* – all of which are ultimately affected by the dynamics of nutrients, algal growth, and organic matter transport in the system. The river begins at Upper Klamath Lake in Oregon and encompasses 15,722 square miles in the states of Oregon and California, flowing from the Cascades in Oregon westerly and southerly to the Pacific Ocean in Del Norte, CA. The system has several unusual characteristics. First, the gradient increases downstream. Second, the source of the river is an aging eutrophic lake, which leads to nutrient concentrations that are highest in the headwaters, while downstream tributaries generally have lower nutrient concentrations than the mainstem. Finally, there are a series of dams in the upper third of the watershed, forming a segmented system.

The Klamath is one of the major salmon rivers of the western United States, so interest in the protection, management, and restoration of the system is high. Nutrients in the system are dominated by the loading leaving Upper Klamath Lake, which cannot easily be controlled. The temporal and spatial pattern of water quality downstream is largely controlled by processes that retain, transform, or release nutrients within the impounded and free-flowing reaches, including growth of planktonic algae (primarily in impoundments), settling of nutrients to and regeneration of nutrients from the sediment (also primarily in impoundments), and uptake/release of nutrients by periphytic algae (primarily in free-flowing reaches).

PacifiCorp, which operates federally-licensed hydroelectric projects on the river, developed a simulation model of the river, linking CE-QUAL-W2 models of the impoundments with an RMA-11 model of the free-flowing reaches (PacifiCorp, 2005). This model was subsequently updated and recalibrated by Tetra Tech for USEPA, DEQ, and the Board, and forms a basis for developing the TMDL and potential management scenarios to meet the TMDL. While Tetra Tech has developed a draft model calibration report, a final public version of the report has not yet been released. Stakeholder review of the modeling effort has, however, provoked some questions regarding the processes controlling nutrient dynamics in the impounded and free-flowing reaches (particularly their relative importance), and whether the model accurately represents these processes (Asarian, 2007; PacifiCorp, 2007). In addition, several reports have been published on nutrient dynamics in the system.

To help resolve these issues, the Board and USEPA requested a review of the reports that analyze nutrient dynamics in the Klamath River system, with particular emphasis on evaluation of the effects of reservoirs in California on water quality relative to free-flowing reaches. The review was conducted by Dr. Jonathan Butcher, who is familiar with the Klamath River system, but was not directly involved in the model development effort.

1 Key Issues

The disputes over nutrient dynamics in the Klamath River system are intimately tied to the policy debate over the potential removal of hydropower dams in the Upper Klamath. PacifiCorp (2005) created the original linked water quality simulation models of the system (RMA-11 for the free-flowing reaches and CE-QUAL-W2 for the impoundments), and applied them to the 2000-2004 period, with calibration based on more intensive data collected in 2000. In a series of reports, Asarian and Kann (working variously on behalf of the Yurok and Karuk tribes) raised concerns that the model overestimated nutrient retention rates in the impoundments, while underestimating nutrient retention rates in the free-flowing reaches, resulting in an unrealistic estimate of benefits of the impoundments in controlling downstream nutrient concentrations (see Asarian and Kann, 2006a, 2006b).

Tetra Tech, for USEPA, subsequently recalibrated the PacifiCorp models for year 2000 (with validation application to the reaches above Iron Gate Dam for 2002). The recalibration effort did result in lower nutrient retention rates within the reservoirs and higher retention rates within the free-flowing segments – suggesting that some of the original criticisms of the model were correct. Asarian (2007) has continued to express concerns that the model under-represents nutrient retention in the free-flowing reaches of the river downstream of Iron Gate Dam – and thus does not provide a fair evaluation of the conditions that would result from conversion of impoundments back to free-flowing reaches. On the other side, PacifiCorp (2007) has contended that the analyses of Asarian and Kann are flawed in a variety of ways, while defending the model results.

The truth of the matter is that water quality data are fairly sparse in this system – which lends considerable uncertainty to both direct evaluations of observations and model setup and calibration. The station immediately below Iron Gate Dam (RM 189.73) has samples from 1996-2004, on a biweekly basis for 1998-2002 and monthly in other years. The key downstream station for evaluating nutrient retention at Seiad Valley (RM 130.85) has a similar density of samples only for 1998-2001. Further, samples have generally not been collected in January through April, meaning that a large portion of the total annual flow has not been sampled (see Figure 1). As a result, the mass balance and retention calculations of Asarian and Kann (2006a) are based on June through October, not complete years, preventing full closure of the mass balance.

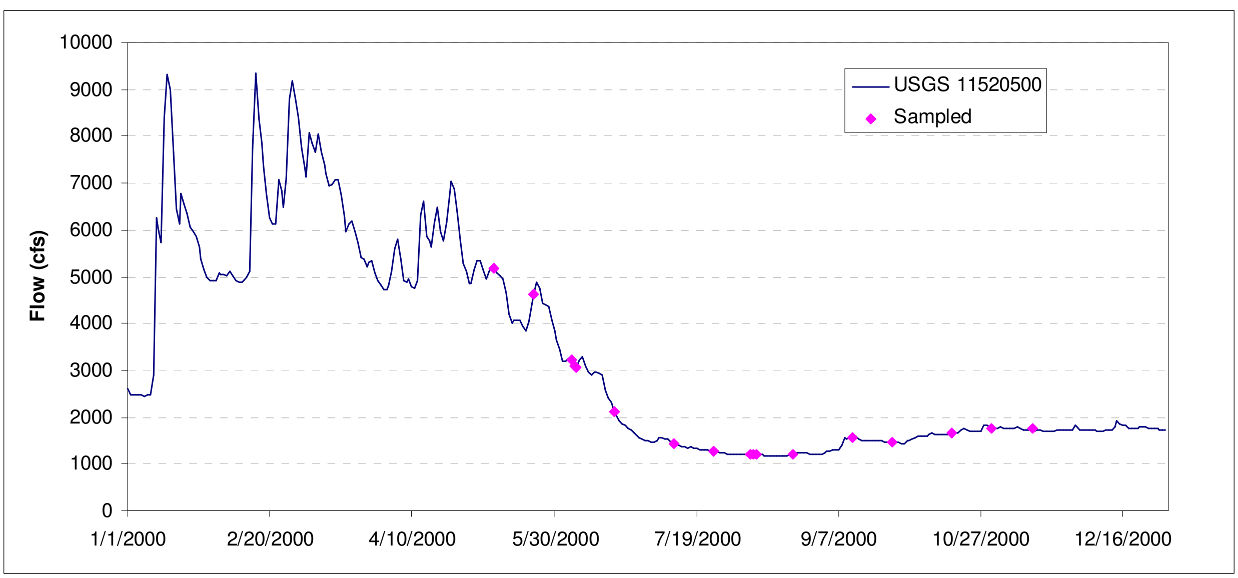

Figure 1. Daily Flows and Water Quality Samples, Klamath River at Seiad Valley, 2000

For the modeling, focus has been on 2000, as this is the year with the best information on tributary loads. Tetra Tech has run the complete, recalibrated model *only* for 2000. Indeed, due to the short residence time and elevated loads from the headwaters at Upper Klamath Lake, the model predictions are strongly determined by the boundary conditions (upstream load and relative dilution provided by the downstream tributaries), and results for years in which the boundary conditions are not well-defined are largely speculative.

It is also important to recognize that the patterns of nutrient retention are likely to vary significantly from year to year. The data analyzed by Asarian and Kann (2006a) show consistent seasonal retention of total Nitrogen between Iron Gate and Seiad Valley in some years (e.g., 2001 and 2002), but not in others. Notably, for 2000 the retention calculated for most sample dates appears to be close to the expected range of uncertainty for nitrogen concentration measurements[1] except for one date, which results in an estimation of net retention over the June-October period. The authors note (p. 42): "most of the positive retention in the Iron Gate (KR18973) to Seiad Valley (KR12858) reach for the 2000 season was due to a single high sample on 7/11/2000 at Iron Gate, when TKN was 4.5 mg/L… There are 313 TKN samples in the database below Iron Gate taken from 1971 to 2004 and this was the highest measurement, with no other samples above 2.0 mg/L…"

Both the empirical analyses of nutrient trend and the model predictions are uncertain as a direct result of the sparse data. Biweekly or monthly samples are likely to provide an inaccurate estimate of the nutrient mass entering or leaving a reach, introducing uncertainty into direct estimates of load, while similarly creating uncertainty in model forcing functions. Further, it is not appropriate to compare long term trends from the data to model results from a single year, as year-to-year variability is likely significant.

In sum, the empirical work of Asarian and Kann is most appropriate as a long-term, statistical estimate of typical removal rates. The model output, while also uncertain, provides an estimate for a specific set of flow and boundary conditions. The two should be qualitatively similar, but not identical.

2 River Retention of Nutrients

Physical and biological processes in river reaches can result in net removal or temporary retention of nutrients. One of the major processes for temporary retention is uptake of nutrients by periphyton. Periphytic algae, as well as heterotrophic organisms, require nutrients for growth and remove inorganic nutrients from the water column, converting them to organic biomass. Heterotrophs also remove organic matter as foodstock. This storage, however, is temporary. In addition to normal dieoff and predation, periphyton is subject to scour and transport downstream during high flow events.

Tanner and Anderson (1996) demonstrated that periphyton (dominantly *Cladophora*) were very effective in reducing dissolved inorganic nitrogen loads downstream of wastewater treatment plants in the South

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[1] Total nitrogen is estimated as the sum of total Kjeldahl nitrogen (TKN) and nitrite-plus-nitrate nitrogen. For USGS analyses, relative standard deviations (RSDs) for these measurements in natural waters are typically in the range of 8 to 10 percent (e.g., Lambing and Cleasby, 2006), although Campbell (2001) reported RSD's less than 5 percent for Klamath River nutrient samples. Other laboratories may achieve differing levels of precision. More importantly, TKN is reported to the nearest 0.1 mg/L, while nitrite and nitrate nitrogen are reported to the nearest 0.01 mg/L, reflecting the underlying precision in the analytical methods. In the Klamath below Iron Gate, TKN often constitutes about 90 percent of total nitrogen. At a typical total nitrogen concentration of about 0.8 mg/L, there is thus a built in reporting uncertainty (reflecting the underlying analytical uncertainty) of around ±14 percent. Additional uncertainty is introduced by sampling procedures, as samples may not be fully representative of the complete flow-weighted average concentration passing a given point, and there may also be systematic changes in nutrient concentrations over the diurnal cycle due to algal influences. Finally, calculation of nutrient retention requires use of flows, which are also subject to measurement uncertainty, further decreasing the precision of mass transport estimates obtained by multiplying flow times concentration.

Umpqua River, OR. Similarly, locations in the Bow River in Alberta supported dense *Cladophora* and macrophyte growths that were sensitive to nitrogen load and effective in removing inorganic N from the water column (Sosiak, 2002). Such biological uptake is, however, largely temporary in nature, as biomass follows seasonal cycles with release of nutrients as biomass declines in the fall. Decaying periphyton mats may also promote anoxic conditions that lead to denitrification and loss of nitrogen from the system. Dodds (2003) summarized the role of periphyton in removing phosphorus from aquatic systems. Some of this storage is also temporary; however, Dodds also points out that localized increases in pH during photosynthesis can lead to increased precipitation of calcium phosphate, concurrent deposition of carbonate-phosphate complexes, and long term burial losses of phosphorus.

Temporary retention in river reaches also occurs as a result of settling and storage of particulate matter, including organic detritus. Inorganic orthophosphate and, to a lesser extent, ammonium can also sorb to sediment particles and settle out. These processes also largely constitute temporary retention, as the stored particulate matter can be remobilized by scouring flows.

Permanent removal of nutrient mass can also occur in several ways. For nitrogen, denitrification and conversion to nitrogen gas results in a loss of nitrogen from the water to the air. This may be balanced by fixation of atmospheric nitrogen by certain types of cyanophytes, but these are usually not dominant in flowing waters. Water lost to deep groundwater, agricultural diversions, or riparian wells can remove nutrients, and is more important for nitrogen, which is more soluble than phosphorus. Effective removal of phosphorus may also occur due to burial in deposits that are not readily remobilized (due, for instance, to stream meander and cutoffs), export to the floodplain, or conversion to tightly bound, insoluble mineral forms. These latter processes tend to be of less importance in higher gradient systems, so net rates of removal for TP are expected to be less than net rates of removal for TN in a system like the Klamath.

In general, temporary retention is most important during lower flow periods, which tend to coincide with the growing season. Temporary retention does not, in the end, change the nutrient load that is delivered downstream; however, it can significantly affect both the timing and bioavailability of load delivery. While extensive periphyton communities remain intact below a source area, they may substantially reduce the nutrients available to support algal growth downstream – as appears to be observed in the Klamath. High flows in the Klamath typically occur in the winter and spring. The net effect of temporary retention should thus be to shift much of the nutrient load from the summer and fall to the winter and early spring – a period for which there are very few water quality observations.

The likelihood of significant scour of periphyton can be evaluated in terms of days of accrual, using the relationship of Biggs (2000), where accrual time is defined as the number of days between events three-times the median flow. Accrual time was analyzed at each of the USGS gages. Because the Klamath is a large river with a multi-day response time, the number of events per year was estimated based on the count of times the hydrograph crossed the three-times-median threshold, rather than the number of individual days above the threshold. Resulting estimates (Table 1) show a pattern of decreasing time between scouring events with distance downstream as additional major tributaries join.

Table 1. Estimated Days of Accrual (1985-2005 Data)

USGS Gage	Average Days of Accrual
11516530: Klamath River below Iron Gate	185.7
11520500: Klamath River near Seiad Valley	122.8
11523000: Klamath River above Shasta River	81.9
11530500: Klamath River at Klamath	69.1

Nutrient concentrations measured in the Klamath tend to decrease with distance downstream from Iron Gate Dam, as has been noted by various authors. It is important to note, however, that nutrient retention needs to be evaluated as a mass balance, based on loads, not concentration trends. In the Klamath below Iron Gate, the concentrations of nutrients in many of the tributaries are generally lower than those in the mainstem; thus a reduction in mainstem concentration is expected solely as a result of dilution, regardless of whether there is any true retention.

2.1 Review of Nutrient Mass Balance Estimates for the Lower Klamath

Asarian and Kann (2006b) evaluated the PacifiCorp modeling and contended that it overestimated retention in the reservoirs, while underestimating retention in flowing reaches. This analysis, however, is based primarily on comparison of longitudinal concentration distributions in the Klamath mainstem. This is potentially misleading for two reasons. First, the rate of change in concentration along the length of the river is in large part a function of nutrient concentrations in incremental tributary flow, which is not well characterized. Second, the sparseness of the monitoring data introduces considerable uncertainty into the analysis.

Asarian and Kann (2006a) do provide a mass balance evaluation in terms of loads, again concluding that retention in flowing reaches is underestimated by the model. The conclusions of this effort depend in part on how loads are estimated, which can be problematic for sparse data. Asarian and Kann did this as follows:

- Total N is calculated as the sum of Total Kjeldahl Nitrogen (TKN) and NO_3-N+NO_2-N.
- The biweekly (or monthly) concentration data were used to create a continuous daily estimate using linear interpolation between points.
- Resulting daily TN concentration was multiplied by flow to obtain load.
- Retention rates between stations were calculated for June-October, the period for which most monitoring is available.

As noted above, because only a seasonal estimate can be made, the approach measures net retention, not removal, and a significant portion of the retained load may be mobilized and moved downstream by winter flows. Methodologically, the other major concern is the use of linear interpolation.

Estimating constituent mass loads from point-in-time measurements of water-column concentrations presents many difficulties. Load is determined from concentration multiplied by flow, and while measurements of flow are continuous, only intermittent measurements of concentration are available. Calculating total load therefore requires "filling in" concentration estimates for days without samples. The process is further complicated by the fact that concentration and flow are often highly correlated with one another, and many different types of correlation may apply. For instance, if a load occurs primarily as a result of nonpoint soil erosion, flow and concentration will tend to be positively correlated; that is, concentrations will increase during high flows, which correspond to precipitation-washoff events. On the other hand, if load is attributable to a relatively constant point discharge, concentration will decrease as additional flow dilutes the constant load. In most cases, a combination of processes is found.

Preston et al. (1989) undertook a detailed study of advantages and disadvantages of various methods for calculating annual loads from tributary concentration and flow data. Their study demonstrates that simply calculating loads for days when both flow and concentration have been measured and using results as a basis for averaging is seldom a good choice. A method dependent on interpolation between measured concentrations is likely to have similar problems. Depending on the nature of the relationship between flow and concentration, more reliable results may be obtained by one of three approaches:

- Averaging Methods: An average (e.g., yearly, seasonal, or monthly) concentration value is combined with the complete time series of daily average flows
- Regression Methods: A linear, log-linear, or exponential relationship is assumed to hold between concentration and flow, thus yielding a rating-curve approach
- Ratio Methods: Adapted from sampling theory, load estimates by this method are based on the flow-weighted average concentration times the mean flow over the averaging period and performs best when flow and concentration are only weakly related.

No single method provided superior results in all cases examined by Preston et al.; the best method for extrapolating from limited sample data depends on the nature of the relationship between flow and concentration, which is typically not known in detail.

Thus, the accuracy of the interpolation approach will depend in large part on whether there is correlation between flow and concentration. If the two variables are truly independent, then no error will be introduced by this approach. If they are correlated, the approach is sub-optimal.

Reducing the potential impact of these issues is the fact that the Upper Klamath is a highly controlled system, with multiple reservoirs. These reservoirs should serve to damp out correlations between flow and concentration, particularly for the reach between Iron Gate and Seiad. As the river accumulates more uncontrolled tributary flow downstream, correlation may reemerge, rendering the load estimates suspect. (Indeed, this might be why Kann and Assarian detected no nitrogen retention below Orleans).

Campbell (2001) analyzed monitoring data from 1996 through 1998 from Keno Dam to Seiad Valley, and concluded that there was a negative correlation between flow and concentration for all nutrient species, and that this negative correlation became stronger downstream (as far as Seiad Valley). This type of situation can arise when nutrient loads are dominated by lake sources, and tributary stormflow contributions – even if elevated relative to baseflow – serve to dilute the mainstem concentration. Reexamination of the detailed 2000 USGS monitoring at Seiad Valley confirmed a negative correlation between TKN and flow, but showed essentially no correlation between TP and flow.

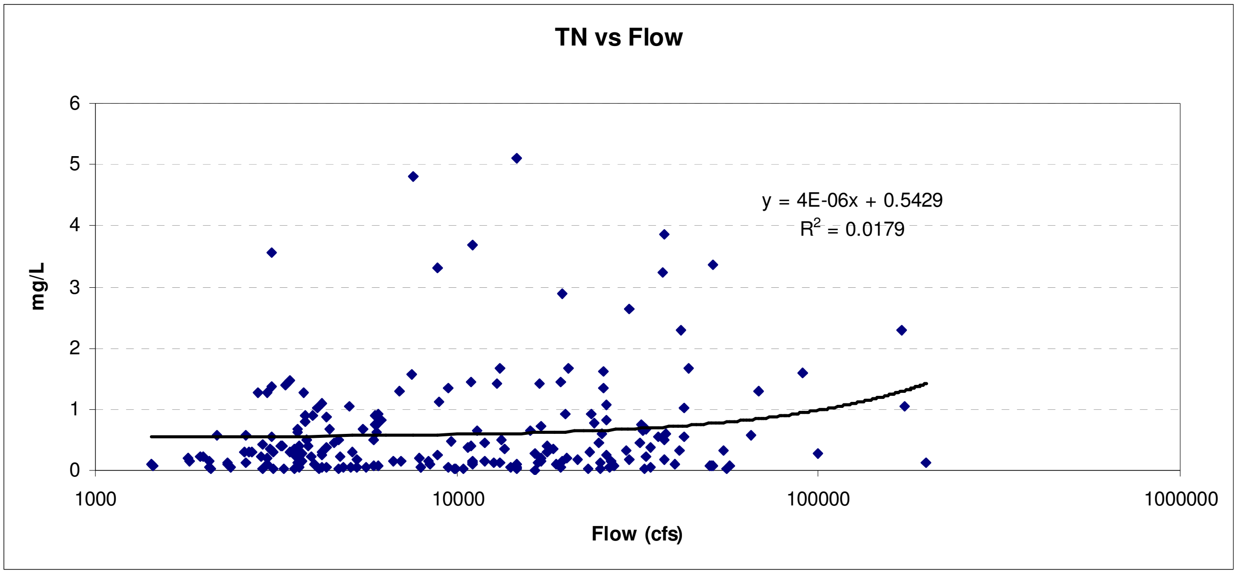
Further downstream, USGS nutrient water quality monitoring from 1973 to 2003 is available at Klamath, CA (USGS gage 11530500), and these data were examined as a check. As shown in Figure 2, concentration is only weakly related to flow at this station, and, while the slope is positive, it is not significant. The relationships remain weak if results are stratified into summer and winter seasons.

To the extent that flow and concentration are truly independent of one another, the simple interpolation method used by Asarian and Kann will not introduce error. However, where and when a negative correlation between flow and concentration exists, the interpolation approach will tend to overerestimate total load – because concentrations that are too high will tend to be applied to the high flow events that constitute the bulk of the total movement of mass. If, as expected, the negative correlation is strongest immediately downstream of Iron Gate and decreases downstream, this could introduce a bias that results in overestimation of the nutrient retention between Iron Gate and Seiad Valley.

Despite these caveats, the approach taken by Asarian and Kann seems likely to provide reasonable estimates of seasonal nutrient retention over the long term (although not removal, as full-year mass balances are not available). Asarian and Kann, however, attempt to take the analysis further, evaluating retention by reach first on a yearly, and then on a monthly basis. As each month is represented by only one or two sampling events (and these events likely did not sample the same parcel of water), this is asking too much of the sparse data. Due to the uncertainty present in the data and the method, the best that can be hoped for is a statistical convergence to a reasonable estimate. Interpretations of the magnitude of retention for individual months are at best suspect.

Due to changes in sample locations, more than two years of data are available only for the reach Iron Gate to Seiad Valley. For the whole analysis period evaluated by Asarian and Kann (1998-2002), the June-

October net retention of TN is 18.6 percent, or 0.31 percent per mile. It should be remembered that this seasonal estimate is likely an upper bound on the annual retention, as it includes temporary storage that will be flushed downstream during winter high flows.



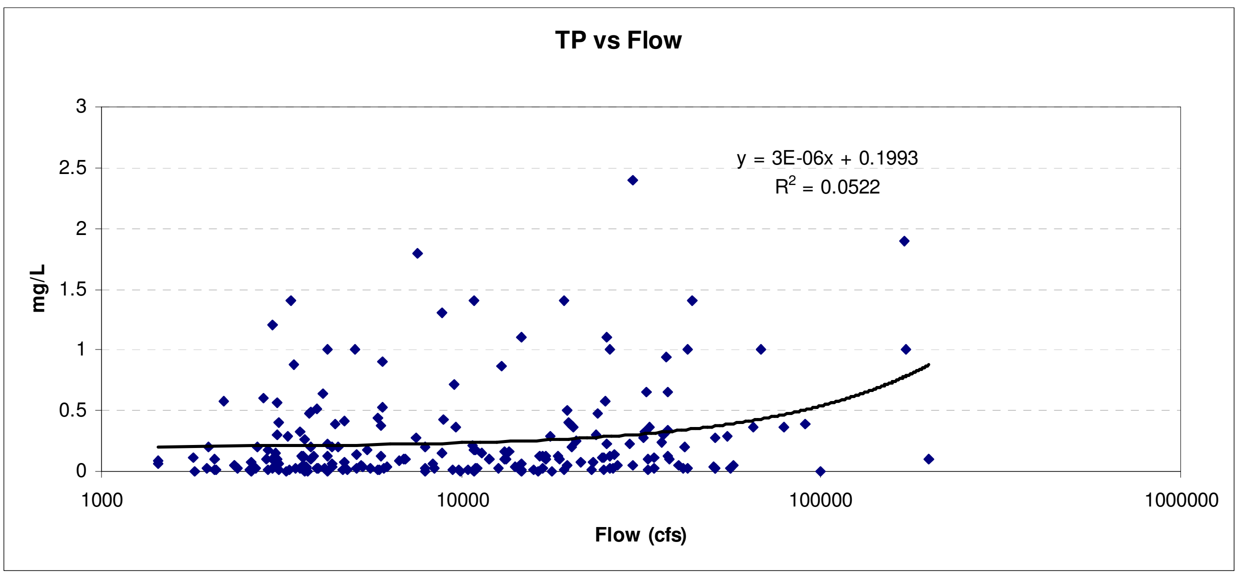


Figure 2. Relation of Nutrient Concentration to Flow, Klamath River at Klamath, CA

2.2 Expected Range of River Retention Estimates

USGS, as part of its Spatially Referenced Regressions on Watershed Attributes (SPARROW) project had developed generalized reach removal coefficients for TN and TP based on analysis of monitoring records of 381 USGS National Stream Quality Accounting Network (NASQAN) monitoring sites throughout the US (Smith et al., 1997). Removal is represented as an exponential decay process, such that the retention in a reach is given by

$$\text{Retention} = 1 - \exp(-\delta t),$$

where δ is a loss coefficient (day^{-1}) and t is travel time in days. The national coefficients originally developed by Smith et al. (1997) were revised by Smith et al. (2003a), as reported in Smith et al. (2003b). Median flows in the Klamath downstream of Iron Gate are greater than 1000 cfs, but less than 10,000 cfs, so the relevant national decay coefficients are 0.118 day^{-1} for TN and 0.098 day^{-1} for TP. The mean travel time from Iron Gate to Seiad is on the order of 2 days, so we would expect, as a long-term average, loss rates of about 21 percent for TN and 17 percent for TP. The growing season TN retention estimates for this reach given by Asarian and Kann range from 20 to 61 percent – but retention over the growing season is likely to be higher than annual net retention due to temporary storage in periphyton.

The SPARROW estimates of loss depend entirely on the decay coefficients, which are subject to considerable uncertainty and vary as a result of site-specific conditions. Other evidence is available in recently completed work of Armstrong and Ward (2008), who developed a simplified model of Klamath summer monitoring data for 2001-2005. Their application is a spreadsheet plug-flow model in which the decay rates for TN and TP are taken as calibration parameters. The methodology has some potential problems: First, it is sensitive to assumptions about tributary loads, which are poorly characterized for many of these years. Second, the approach fits individual decay rate estimates for each month in the dataset, which likely leads to over-fitting of the data. Finally, a single decay rate is applied for each month to the entire distance between Iron Gate and Turwar. However, the results are useful in providing another independent estimate of potential retention / loss rates in the Klamath River. Finally, the analyses cover only the June through October period, so one can examine only seasonal retention, not ultimate loss.

The decay rates fit by Armstrong and Ward range between 0.005 and 0.15 day^{-1} for both TN and TP, and are generally higher in the summer, suggesting that periphyton uptake may be a significant component of the retention. The authors do not provide an integrated summary of their decay rate estimates; however, examination of their Figure 33 suggests that the median decay rates were 0.005 day^{-1} for TN and 0.075 day^{-1} for TP. For two day travel between Iron Gate and Seiad, this would imply nitrogen retention of only 1 percent and phosphorus retention of 14 percent. (For individual months in which the estimated decay rate reached 0.15 day^{-1} the retention would be 26 percent.) These results suggest that the seasonal retention rate for TN in the Klamath could well be much less than predicted by SPARROW; however, they do not preclude the possibility that retention rates are much higher between Iron Gate and Seiad Valley than between Seiad Valley and Turwar, as suggested by Asarian and Kann (2006a). The results of Armstrong and Ward are also subject to considerable uncertainty. They report relative percent error on model-predicted concentration by month, ranging from 2 to 102 percent for total nitrogen (with median of 19 percent) and 3 to 22 percent for total phosphorus (with median of 11 percent).

2.3 RMA-11 Implementation

RMA-11 (King, 1998) simulates four state variables for nitrogen (nitrate, nitrite, ammonia, and organic N) and two state variables for phosphorus (dissolved P and organic P). Algal biomass also acts as a store of nutrients. Sorption of inorganic P to suspended sediment is represented as a sink, not a state variable, and thus forms a loss pathway from the system. Settling rates can be specified for organic N and organic P, again representing losses. While both deposition and scour of sediment are simulated by the model, the sediment mass balance is not directly linked to the nutrient mass balance (except through sorption of inorganic P). Algae take up inorganic nutrients during photosynthesis and convert them to organic nutrients, which are released during respiration (as inorganic nutrients) or decay (as organic nutrients). Algae can settle to the sediment, creating a sink for nutrients. (While the model documentation also discusses algal losses to grazing, this is apparently not implemented in the version of the model used for the Klamath.)

Thus, RMA-11 can potentially simulate internal nutrient losses (other than advection out of the system) in four ways: settling or grazing of algae, settling of organic N, settling of organic P, and sorption of inorganic P. RMA-11 can also simulate releases from the sediment of inorganic P and ammonium. Within the model, the phytoplankton settling rate was initially set to zero (PacifiCorp, 2005), but subsequently revised by Tetra Tech to match organic matter settling rates (0.05 m/day). PacifiCorp does not document the values for the other relevant rate constants; however, inspection of the model input shows that sorption losses of inorganic P are not simulated because TSS is not simulated. Net settling of organic N and organic P occurs in accordance with an organic matter settling velocity of 0.05 m/day (a very low value based on assumptions that net settling will be minimal in a fast-flowing river). No sediment releases of inorganic P or ammonium are specified.

Within the Klamath, periphytic algae can play an important role in nutrient cycling although quantitative data are limited and have been cited as a significant data gap (Flint et al., 2005). RMA-11 (King, 1998) has a rather simplistic representation of periphytic algae and algal-related nutrient cycling. This was somewhat remedied by project-motivated modifications to the RMA-11 (v41) code that separated algal respiration and death and added organic matter as a state component. Benthic algae are simulated as if they were planktonic algae, except not subject to advection or settling.

Despite the modifications to the algal code for the Klamath project, RMA-11 omits various processes that could potentially reduce its ability to accurately represent nutrient cycling in the free-flowing reaches of the Klamath. The importance of these processes is generally not known for the Klamath, so they can only be discussed in a speculative context. The majority of these processes are omitted from most other river water quality models as well. Among these are the following:

- RMA-11 does not simulate **denitrification**, the rationale being that this is not a significant pathway in free-flowing, relatively shallow rivers since denitrification bacteria require hypoxic conditions, as well as ample fixed carbon and nitrate supplies. In some rivers, however, there is evidence of significant denitrification occurring within the bed. The general thinking is that denitrification is of little significance in the well-oxygenated sediments of gravel-bed streams (Allan, 1995), and gravel-bed streams are more likely to convert ammonium to nitrate (e.g., research in the Williamette reported by Fernald et al., 2006). Denitrification in the Klamath mainstem is likely limited by the availability of organic matter in the bed. Anoxia under decaying periphyton mats could, however, form a locus for denitrification (Triska and Oremland, 1981). Omission of this pathway may cause the RMA-11 model to underestimate nitrogen loss rates in the river; however, the magnitude of this error is not known. Similarly, RMA-11 (like most other river water quality models) does not simulate chemical reactions that may precipitate inorganic phosphorus in inorganic forms.
- RMA-11 does not simulate **luxury uptake** of nutrients by periphytic algae. In many cases, algae may be able to uptake and store excess nutrients against future growth requirements (Droop, 1983). This phenomenon is more likely to be a significant factor when there is strong temporal variability in nutrient availability. The presence of upstream impoundments tends to smooth out temporal variability in the lower Klamath, and may thus reduce the impact of luxury uptake on retention.
- The Klamath version of RMA-11 simulates respiration as the inverse of photosynthesis. That is, while photosynthesis involves the uptake of inorganic nutrients and inorganic carbon to form biomass, respiration is assumed to release equal amounts of inorganic nutrients and carbon (PacifiCorp, 2005, Appendix A). In reality, the releases of nutrients (if they occur) are likely to be at least in part in organic form. Related to the previous bullet, there is no provision for intracellular storage of nutrients as fixed-carbon energy sources are oxidized. The result is that the model simulation of diurnal ammonium concentrations shows greater variability than

observed data during the growing season, with concentrations depressed during periods of photosynthesis, then enhanced during night-time respiration.

- The RMA-11 model, like most other river models, does not consider the interaction of stream nutrients with riparian perennial vegetation, which may provide for long term sequestration of nutrients. Riparian vegetation is most often thought to intercept nutrients derived from upland sources. However, in a gravel bed river nitrogen in the hyporheic zone derived from the river can be taken up directly by the roots of woody vegetation (Peterjohn and Correll, 1994; Naiman et al., 2000). Species such as alder may act as net nitrogen sources, however, due to their ability to fix atmospheric nitrogen. The net balance of these processes is unknown for the Klamath.

Together, these simplifying assumptions in RMA-11 would tend to result in an underestimate of retention and an over-estimation of the downstream transport of inorganic nutrients during the algal growing season. Denitrification seems likely to be the most significant omitted factor in the Klamath, but its impact is not known for this system.

As implemented for the Klamath, there are very few ultimate sinks for nutrients in RMA-11. Settling of organic nutrients and algae will constitute a loss, but this loss will be small, given the low settling velocity and short travel times. Nutrients taken up by periphyton will be temporarily retained, but will be re-released as periphyton dies off or is scoured. The simulation of periphyton in the model indeed begins with low periphyton biomass, increases to higher biomass in summer, then declines back toward zero (Figure 3).

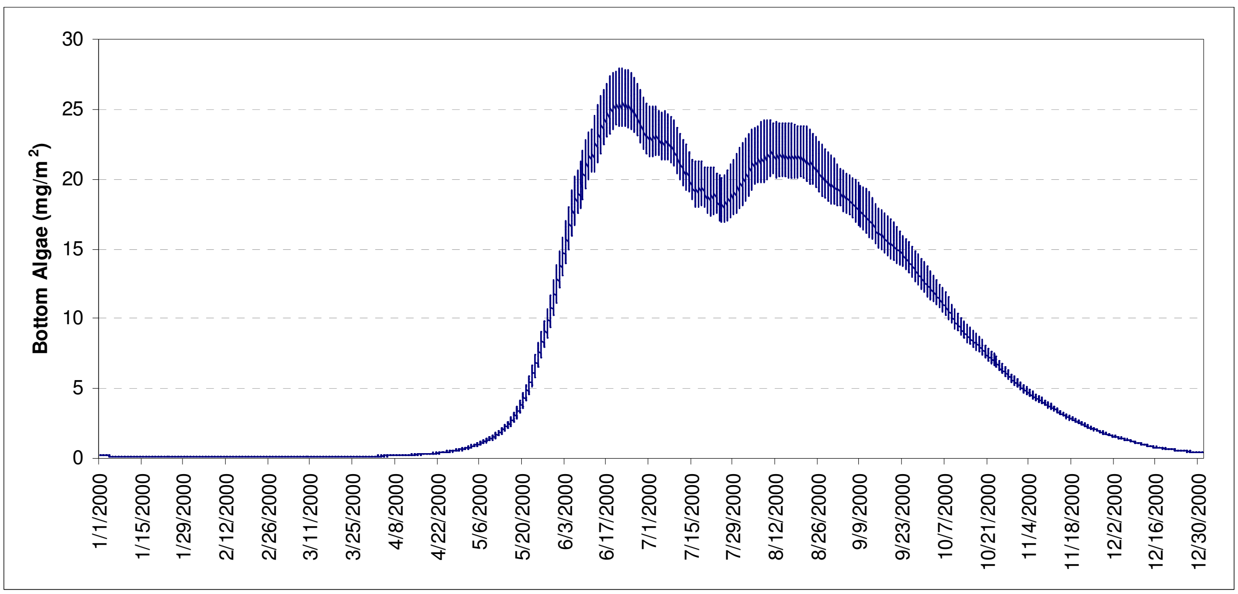


Figure 3. Periphyton Biomass Concentration Simulated for Klamath Upstream of Scott River

From Figure 3 we can conclude that periphyton, as simulated in the model, do not represent a significant net sink of nutrients, because the biomass declines back toward zero by the end of the year. It is also of interest to note that there is only one brief period (late May to early June) in which rapid accrual of periphyton biomass is simulated. Only during this period would we expect to see significant nutrient retention predicted for periphyton. During other periods, the periphyton are simulated as remaining at approximately steady biomass (in which case inorganic nutrient uptake should be balanced by output of inorganic and organic nutrients), or declining (in which case they will be creating a net increase in nutrient loads.)

Given the limitations of the RMA-11 code and the way it is parameterized for the Klamath, it appears clear that the model would not be expected to predict net removal of more than a few percent of total nutrient loads in free-flowing reaches of the river over the course of a year.

To test model behavior, a mass balance was constructed from the river and boundary flow and concentration data in the model. Loads were estimated on a monthly basis for TN, TP, NO_2+NO_3, PO_4, organic N, and organic P. The organic N and P components of non-living organic matter were calculated from organic matter concentrations according to the stoichiometry described in the model calibration report (organic N = 0.07 x organic matter; organic P = 0.0055 x organic matter). Within the Klamath, a noticeable fraction of the nutrient load may be transported in the form of living planktonic algae. Therefore, the planktonic algal biomass was also converted to organic N and organic P, using the same stoichiometry.

Model mass balance results were calculated for each river reach from Iron Gate to Seiad, but the net results over this whole distance are most informative (Table 2 and Table 3). For 2000, the model predicts TN loss/retention of 0.37 percent and TP loss/retention of 0.52 percent. For the period of June – September analyzed by Asarian and Kann (2006a), the TN retention predicted by the model is 1.05 percent. These results are less than estimated from the SPARROW methods or by the analyses of Asarian and Kann. They are, however, generally consistent with the analyses of the 2001-2005 data by Armstrong and Ward (2008), which suggest a TN retention rate of approximately 1 percent between Iron Gate and Seiad. As noted above, all these estimates of retention are subject to considerable uncertainty. This is an unavoidable result of the sparse data available. It is possible that RMA-11 would tend to underestimate seasonal nutrient retention rates due to the omission of various processes that can enhance nutrient retention and loss. However, the data are not sufficient to determine whether such an underestimation exists or is statistically significant. A comparison of nutrient losses on a full-year basis cannot be made, because both Asarian and Kann (2006a) and Ward and Armstrong (2008) worked with only seasonal nutrient data.

Table 2. Total P Mass Balance (kg) for RMA-11 Application for Year 2000, Klamath River from Iron Gate Dam to Seiad, CA

Month	IN	OUT	Change	Retention
1	37,751	36,027	-1,724	4.57%
2	68,409	68,106	-303	0.44%
3	72,501	72,325	-176	0.24%
4	55,820	55,551	-270	0.48%
5	56,498	56,220	-277	0.49%
6	38,889	39,155	266	-0.68%
7	23,875	23,416	-460	1.93%
8	27,364	26,949	-416	1.52%
9	25,776	26,123	348	-1.35%
10	23,951	24,095	143	-0.60%
11	19,410	19,746	337	-1.73%
12	15,159	15,288	129	-0.85%
Whole Year	465,403	462,999	-2,404	0.52%

Table 3. Total N Mass Balance (kg) for RMA-11 Application for Year 2000, Klamath River from Iron Gate Dam to Seiad, CA

Month	IN	OUT	Change	Retention
1	260,614	260,409	-205	0.08%
2	264,131	261,344	-2,787	1.06%
3	281,346	278,604	-2,742	0.97%
4	244,653	243,079	-1,573	0.64%
5	154,400	156,288	1,888	-1.22%
6	105,152	105,184	32	-0.03%
7	62,008	59,356	-2,652	4.28%
8	73,882	71,031	-2,852	3.86%
9	78,354	80,464	2,110	-2.69%
10	86,365	87,557	1,192	-1.38%
11	83,931	84,289	357	-0.43%
12	88,934	89,489	555	-0.62%
Whole Year	1,783,771	1,777,092	-6,679	0.37%

The model does predict a seasonal pattern of temporary retention in the spring and summer, followed by releases in the fall as periphyton densities decline. Plots of the cumulative changes in nitrogen and phosphorus component loads over the simulation year 2000 (Figure 4 and Figure 5) suggest that the spring to early summer period is dominated by the decay of organic matter to inorganic nutrients, followed by uptake of ammonium and inorganic P as periphyton growth accelerates in May and release of organic nutrients as the periphyton reaches senescence.

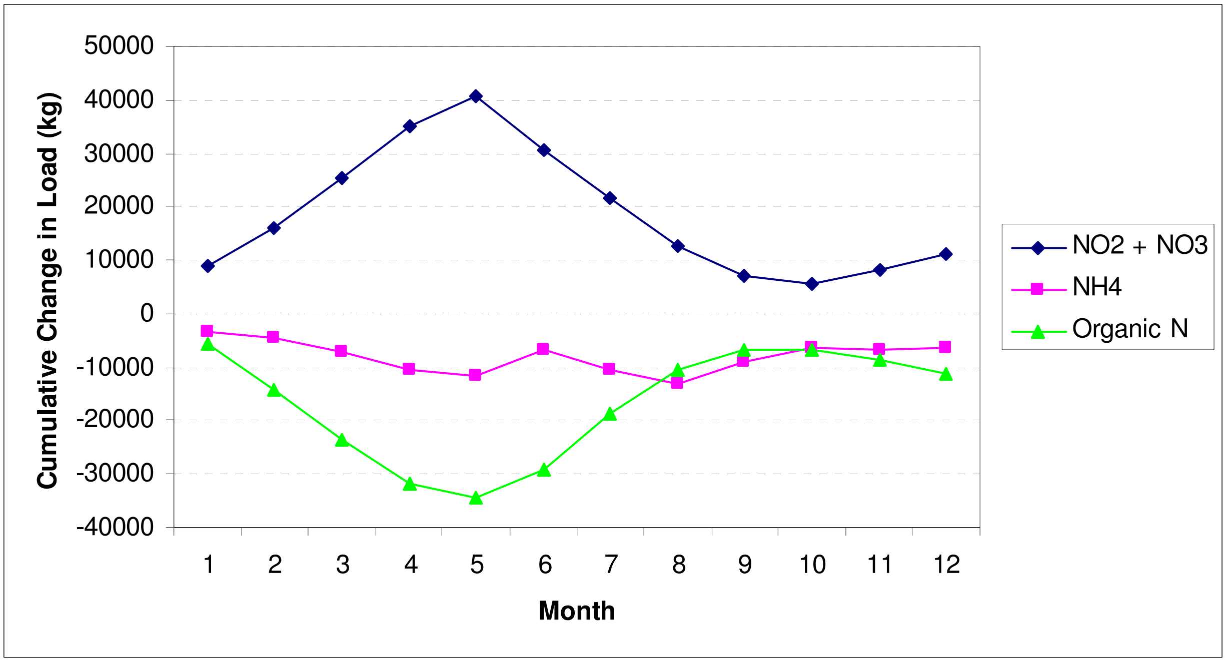


Figure 4. Cumulative Change in Nitrogen Load Predicted by Klamath River Model, Iron Gate to Seiad, for Year 2000

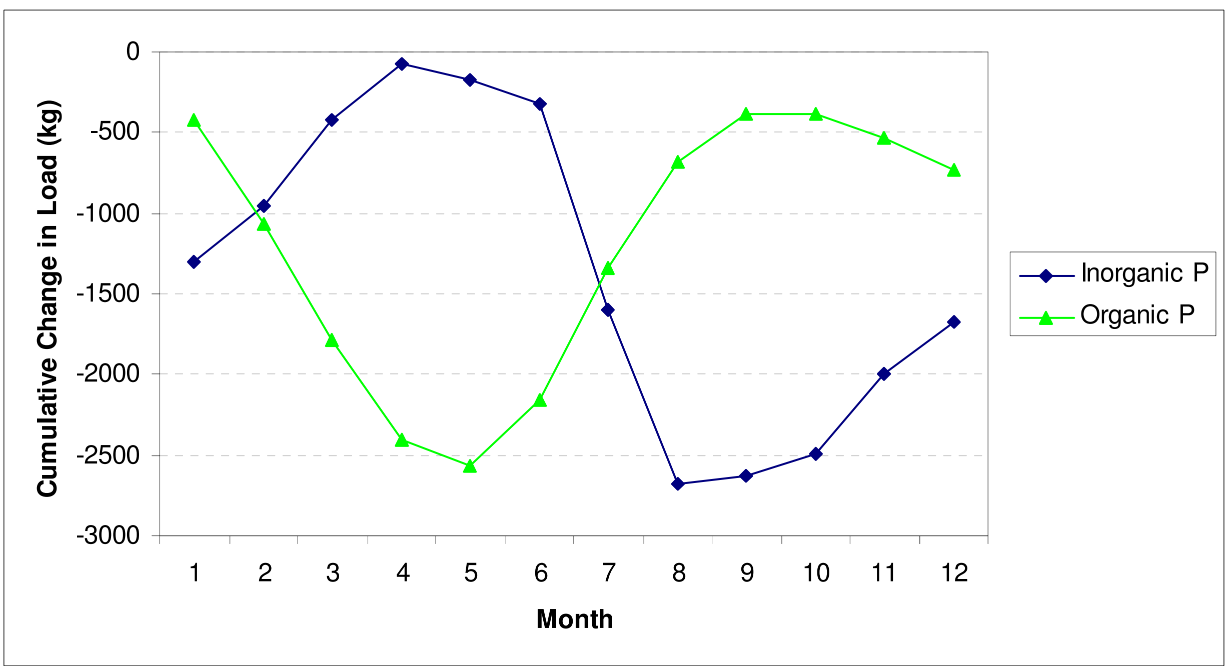


Figure 5. Cumulative Change in Phosphorus Load Predicted by Klamath River Model, Iron Gate to Seiad, for Year 2000

While the model predicts little change in total loads over the course of a year during transit from Iron Gate to Seiad Valley, the annual flow-weighted concentration does decline, by about 17 percent for TN and 19.5 percent for TP (Figure 6). This decline is almost entirely due to accumulation of flow from cleaner tributaries, which dilutes the load originating above Iron Gate dam – and points out the pitfalls inherent in trying to assess retention based only on concentration.

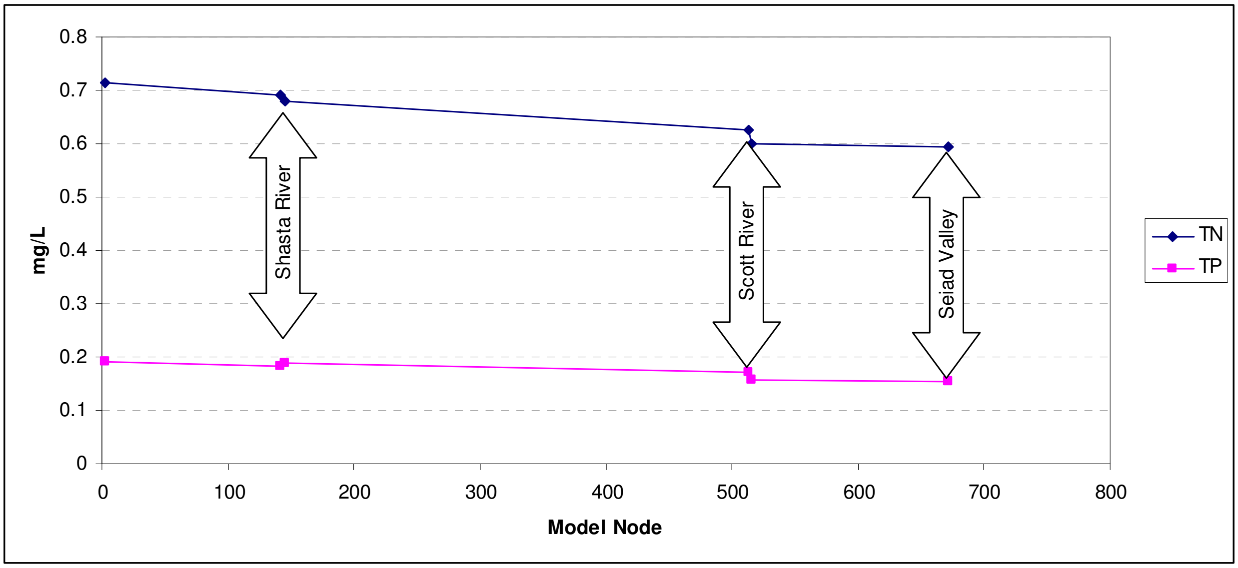


Figure 6. Annual Flow-Weighted Concentrations for 2000 Model Run

In sum, the RMA-11 model application predicts little nutrient loss in the free-flowing reaches of the Klamath, although there is seasonal retention. Even adjusted for partial year estimates, this is at odds with the estimates of Asarian and Kann (2006a), as well as estimates from the USGS SPARROW model. The result is not unexpected, given that RMA-11 provides few permanent sinks for nutrients. The importance of potential sinks (such as denitrification) is unclear, and the estimates from Asarian and Kann (based on limited data) and SPARROW (an approximate, national-scale method) are subject to considerable uncertainty. However, it does appear that the RMA-11 model may have some tendency to underestimate nutrient losses in the free-flowing reaches of the Klamath. The data are not sufficient to resolve whether these factors are significant relative to the overall mass balance, and the magnitude of any such effect cannot be fully resolved without more intensive sampling, coupled with model application to intensively sampled years.

3 Reservoir Retention of Nutrients

Reservoirs can be effective traps of influent nutrients. By design, reservoirs represent areas of a river system in which velocity is decreased and residence time increased. This encourages the settling of particulate material, including both nutrient-bearing organic detritus and nutrients sorbed to inorganic sediment. Reservoirs also encourage the growth of planktonic algae, and settling of dead algal detritus can increase loss rates.

In general, these factors would lead to increased nutrient loss in reservoirs as opposed to free-flowing reaches. The difference, however, depends on reservoir residence time (which is short in the Klamath reservoirs). In addition, there are several compensating factors. First, algal growth in deeper reservoirs is primarily planktonic, and plankton are readily advected downstream, unlike periphytic algae, so reservoirs with short retention times may provide less retention of nutrients than free-flowing reaches.

Second, under anoxic conditions there is typically significant evolution of phosphorus and ammonium from lake sediments (internal loading).

3.1 Mass Balance Analyses for Reservoir Retention in the Klamath

The first attempt at nutrient budgets for Iron Gate Reservoir was made by USEPA (1978), based on 1975 monthly sampling. They concluded that the mass of nitrogen leaving Iron Gate was 21 percent higher than inflow, while the reservoir retained 7 percent of the phosphorus mass. As noted by Kann and Asarian (2005), these estimates are based on limited data and are not corrected for changes in reservoir storage.

Kann and Asarian (2005, 2007) have produced two reports on the nutrient budgets of Iron Gate and Copco reservoirs. The first evaluated monthly sampling collected for relicensing purposes in 2002. Unfortunately, data were collected only for March through November, and do not include the full turnover period, so a full year mass balance cannot be created. As with their work on mass balances in the river, Kann and Asarian interpolated concentrations between sampling dates and attempted to evaluate the mass balance on a monthly basis. As with the river, the limited sampling basis and the associated uncertainty in mass calculations renders monthly calculations suspect. Over the period from April 1 to November 13, they estimated net retention in Copco of 36.29 metric tons of TP (26.3 percent of influent loads), and 48.20 metric tons of TN (8.1 percent of influent loads). Over the same period, Iron Gate was estimated to retain 32.4 metric tons of TP (27.3 percent of influent loads) and 65.8 metric tons of TN (12.4 percent of influent loads). Because the calculations do not include the full fall turnover or winter flushing flows, these can be taken as upper bounds on the annual retention. Both reservoirs showed a noticeable shift from inorganic N in the influent to organic N in the effluent, apparently due to algal uptake.

Kann and Asarian (2007) analyzed a complete year of biweekly data collected from May 2005 to May 2006 at several locations in Iron Gate and Copco and their tributaries. Over the entire year, Copco was estimated to retain 9.4 percent of influent phosphorus and 9.1 percent of influent nitrogen, while Iron Gate was estimated to retain 3.1 percent of influent phosphorus and 10.0 percent of influent nitrogen. The annual balances are, however, subject to considerable uncertainty due to large uncertainties in flow measurements (as well as the uncertainties in water quality sampling) over the winter high flow period. For the growing season, defined as May 18 2005 to October 5 2005, Copco was estimated to retain 3.3 percent of influent phosphorus and 18.2 percent of influent nitrogen, while Iron Gate was estimated to retain 0.5 percent of influent phosphorus and 15.3 percent of influent nitrogen. The phosphorus retention rates estimated for the 2005 growing season are dramatically lower than those obtained for 2002 data. Kann and Asarian attribute this difference to higher levels of dissolved P in inflows, coupled with internal P loading. Nitrogen retention estimates for the growing season are twice those obtained earlier for Copco and similar to the 2002 results for Iron Gate.

The differences in the retention rates estimated in the two studies may reflect actual differences in reservoir behavior from year to year. However, it is likely that much of the difference in estimates reflects uncertainties in estimation from limited data. For example, in the 2005-2006 data for Copco inflows, the coefficient of variation (standard deviation divided by the mean) is 0.29 for TP and 0.25 for TN, while the standard error on the mean is 6.2 percent of the influent mean value for TP and 5.3 percent of the influent mean value for TN. Over the summer growing period, the standard errors on the mean for both TP and TN are approximately 9 percent of the influent mean value. The retention estimates are thus generally within the range of two standard errors on the influent mean. This uncertainty or variation in the data supports the need for a modeling approach to interpolate through the limited observations.

As in the earlier report, Kann and Asarian (2007) attempted analyses of mass balances on a monthly basis, and detected periods of negative retention. As each month has only two samples, these estimates are highly uncertain, and results for any given month may be only an artifact of the data. As noted by PacifiCorp (2006), there is a lag time between nutrients entering Copco and being discharged from Iron Gate. As a result of this lag, "it is expected that at times the nutrient concentration in release waters from Iron Gate Reservoir…may be greater than in the inflowing waters to Copco reservoir on the same day, even though the reservoirs act to retain and reduce the loads from these nutrient 'events' as they move through the reservoirs."

3.2 Expected Range of Retention

As with the SPARROW estimates for stream reaches, there are simplified empirical methods for estimating nutrient retention in reservoirs that can be used to evaluate whether estimates based on limited observations are reasonable.

Under steady-state conditions,

$$\text{Retention} = 1 - \frac{C}{C_i},$$

where C is the mixed concentration at the dam, and C_i is the influent concentration. In a simple, first-order representation of sedimentation loss, this yields

$$\text{Retention} = 1 - \frac{1}{1 + BT},$$

where B is a first-order sedimentation loss coefficient and T is residence time. For TN, Bachman (1980) gives an estimate of B in terms of flushing rate, as

$$B_{TN} = 0.693\, T^{-0.55}.$$

Similarly, for TP, Vollenweider (1976) estimated

$$B_{TP} = T^{-0.5}.$$

An alternate analysis of TP retention based on an analysis of oxic lakes, exclusive of internal sources, is given by Nürnberg (1984) as

$$\text{Retention} = \frac{15}{18 + z/T},$$

where z is the average depth.

For the two downstream reservoirs in the Klamath system, Copco and Iron Gate, the relevant parameters are given in Table 4. Determination of a residence time is problematic for run-of-river reservoirs that are dominated by winter flow-through. Not only does residence time vary throughout the year, but in addition the reservoirs are not well-mixed in summer, and retention time in the hypolimnion may be much longer than in the epilimnion. For the period of May 2005 through May 2006 reported by Kann and Asarian (2007), the overall residence time in both reservoirs was on the order of 6 days, but the summer residence time of surface waters was around 20-25 days for Copco and 25-35 days for Iron Gate (but can reach as high as 50 days in Iron Gate). For this simple comparison, compromise values of 14 and 16 days were used, combined with summer mean depth.

Table 4. Hydraulic Parameters for Klamath Reservoirs (May 2004 – May 2005)

Impoundment	Residence Time (*T*, yrs)	Mean Depth (*z*, m)
Copco	0.0384	11.7
Iron Gate	0.0484	16.6

Note: Approximate values for summer growing period based on analysis of 2002 and 2004-2005 data in Kann and Asarian (2005, 2007)

Reservoir nutrient retention estimates obtained from the several empirical methods are shown in Table 5, along with the full-year estimates provided by Kann and Asarian (2007). The latter also provide a range of literature-based estimates (Kann and Asarian, 2007, Section 3.4.5.2). For short residence time lakes, the Vollenweider method gives significantly higher retention than that of Nürnberg, with the latter likely being more appropriate. The estimates of Kann and Asarian (2007) on an annual basis are in general agreement with the empirical estimates. Estimated retention is perhaps a little higher than predicted in Copco and lower in Iron Gate – which may reflect the fact that these two reservoirs are in series, with more easily removable material being retained upstream in Copco.

Table 5. Estimated Nutrient Retention for Copco and Iron Gate Reservoirs, 2004-2005

Parameter	Method	Copco	Iron Gate
TP	Vollenweider (1976)	16.4%	17.3%
TP	Nürnberg (1984)	4.6%	3.8%
TP	Range of 5 methods cited by Kann and Asarian (2007)	1.4% - 29%	-1.9% - 29%
TP – 2004-2005 data	Kann and Asarian (2007)	9.4%	3.1%
TN	Bachman (1980)	13.8%	14.5%
TN	Range of 2 methods cited by Kann and Asarian (2007)	8.7% - 10.3%	9.4% - 10.0%
TN – 2004-2005 data	Kann and Asarian (2007)	9.1%	10.0%

3.3 CE-QUAL-W2 IMPLEMENTATION

The CE-QUAL-W2 model (Cole and Wells, 2005) is a two-dimensional, longitudinal/vertical (laterally averaged) hydrodynamic and water quality model that is frequently applied to reservoirs. The model simulates inorganic nutrients (orthophosphate, ammonium, nitrite/nitrate) along with organic matter (labile and refractory, dissolved and particulate) and algae. Decay of organic matter and respiration/death of algae releases inorganic nutrients, while algal growth converts inorganic nutrients to organic matter. In addition to inflow and outflow, the model represents the following internal sources and sinks of nutrients:

Sources	Sinks
Release of PO_4 from sediment under anaerobic conditions	Settling of PO_4
Release of NH_4 from sediment under anaerobic conditions	Settling of organic matter
	Settling of algae
	Denitrification (loss to atmosphere)

Unlike RMA-11 applications to rivers, the nutrient sinks in CE-QUAL-W2 can be significant. The current version of the model also has the ability to simulate macrophytes with direct uptake of nutrients from the sediment; however, this pathway is not considered important and is not implemented in the Klamath models.

Several other potential source/sink pathways are not included in the model, including:

- Release of inorganic nutrients from the sediment under aerobic conditions (usually not a significant process except in shallow lakes where wind-induced scour can redistribute sediment-sorbed nutrients into the water column).
- Release of organic matter from the sediment.
- Settling of NH_4 (like phosphorus, ammonium can sorb to particulate matter and settle out of the water column).
- Nitrogen fixation (some cyanophytes can fix gaseous nitrogen, resulting in a net input of nitrogen to the system).

It is expected that none of these pathways will be significant in the nutrient mass balance for the Klamath reservoirs. Nitrogen fixation is important in some systems where nitrogen supply is limited. The Klamath reservoirs, however, usually have adequate inorganic nitrogen supplies to support algal growth. Under these circumstances, N-fixing algae tend to uptake dissolved nitrogen directly from the water column as opposed to the air, as nitrogen fixation is a highly energy-demanding process (Welch and Jacoby, 2004).

As with the river simulation, the Klamath River model run output for year 2000 was used to examine the mass balance of nutrients in Iron Gate and Copco Reservoirs. The modelers provided the initial and ending storage volumes, which were combined with concentrations to estimate the change in nutrient storage over the course of the simulation. TN and TP mass balances for the two reservoirs for 2000 are summarized in Table 6 through Table 9.

For TP, the annual retention rate estimated for the model is 6.11 percent for Iron Gate and 1.22 percent for Copco. These are in the range predicted by the Nürnberg (1984) model, although the retention rate for Copco appears a bit low, and also in the range of literature estimates reported by Kann and Asarian. For TN, the annual retention rate estimated by the model is 17.63 percent for Iron Gate and 3.61 percent for Copco. The estimate for Iron Gate is similar to that from the Bachman (1980) estimator and higher than that estimated by Kann and Asarian (2007) for 2004-2005. The TN retention rate for Copco appears low relative to both the Bachman estimate and the analysis of Kann and Asarian based on 2004-2005 data. This could simply reflect differences between years. For instance, dam operations vary significantly over time and can have a major impact on nutrient retention. Another potential explanation for lower retention rates in Copco is the low concentrations of particulate organic matter in inflow to this reservoir, while the buildup of algal biomass in both Copco and Iron Gate may contribute to higher retention rates in the downstream impoundment.

Table 6. Total P Mass Balance (kg) for CE-QUAL-W2 Application for Year 2000, Iron Gate Reservoir

Month	IN	OUT	Change	Retention
1	33,813	22,900	-10,913	32.27%
2	54,050	52,012	-2,039	3.77%
3	57,213	52,394	-4,818	8.42%
4	40,121	36,947	-3,174	7.91%
5	40,596	36,641	-3,955	9.74%
6	27,439	25,963	-1,475	5.38%
7	23,515	19,633	-3,883	16.51%
8	28,110	26,485	-1,625	5.78%
9	20,355	24,417	4,062	-19.96%
10	20,773	21,126	352	-1.70%
11	11,517	16,129	4,612	-40.04%
12	11,343	11,670	327	-2.89%
Whole Year	368,845	346,318	-22,527	6.11%
Whole Year Retention (corrected for change in storage)			-22,521	6.11%

Table 7. Total N Mass Balance (kg) for CE-QUAL-W2 Application for Year 2000, Iron Gate Reservoir

Month	IN	OUT	Change	Retention
1	185,087	191,369	6,282	-3.39%
2	233,737	188,997	-44,740	19.14%
3	264,713	196,327	-68,387	25.83%
4	183,398	155,264	-28,135	15.34%
5	103,453	96,293	-7,160	6.92%
6	79,847	55,506	-24,342	30.49%
7	87,133	49,336	-37,797	43.38%
8	109,349	70,070	-39,279	35.92%
9	88,370	72,398	-15,972	18.07%
10	99,909	73,439	-26,470	26.49%
11	75,331	69,115	-6,217	8.25%
12	80,020	72,802	-7,217	9.02%
Whole Year	1,590,349	1,290,916	-299,433	18.83%
Whole Year Retention (corrected for change in storage)			-280,376	17.63%

Table 8. Total P Mass Balance (kg) for CE-QUAL-W2 Application for Year 2000, Copco Reservoir

Month	IN	OUT	Change	Retention
1	35,621	29,907	-5,714	16.04%
2	48,378	49,192	814	-1.68%
3	53,116	52,587	-529	1.00%
4	36,611	35,340	-1,270	3.47%
5	43,803	39,143	-4,659	10.64%
6	25,702	26,740	1,038	-4.04%
7	30,243	22,211	-8,033	26.56%
8	21,346	26,837	5,491	-25.72%
9	15,653	19,395	3,742	-23.90%
10	17,280	19,858	2,578	-14.92%
11	9,569	10,912	1,343	-14.04%
12	8,905	9,720	816	-9.16%
Whole Year	346,226	341,843	-4,383	1.27%
Whole Year Retention (corrected for change in storage)			-4,240	1.22%

Table 9. Total N Mass Balance (kg) for CE-QUAL-W2 Application for Year 2000, Copco Reservoir

Month	IN	OUT	Change	Retention
1	143,374	157,413	14,040	-9.79%
2	196,915	202,659	5,744	-2.92%
3	242,555	232,490	-10,065	4.15%
4	152,922	152,036	-886	0.58%
5	94,216	91,737	-2,480	2.63%
6	95,602	74,430	-21,172	22.15%
7	128,797	78,769	-50,028	38.84%
8	108,494	101,022	-7,473	6.89%
9	82,163	82,274	111	-0.14%
10	96,552	94,102	-2,450	2.54%
11	75,761	71,285	-4,476	5.91%
12	60,175	69,181	9,007	-14.97%
Whole Year	1,477,525	1,407,398	-70,127	4.75%
Whole Year Retention (corrected for change in storage)			-53,278	3.61%

Model-predicted reservoir cumulative retentions for nitrogen and phosphorus species are summarized for the two reservoirs in Figure 7 through Figure 10 (uncorrected for changes in storage). For Iron Gate, there is a steady loss of organic nutrients, accompanied by seasonal patterns in inorganic nutrient uptake and release that result in little net change over the course of the year. For Copco, the predicted cumulative loss of organic nutrients is smaller, with increases in inorganic nutrient mass in the fall.

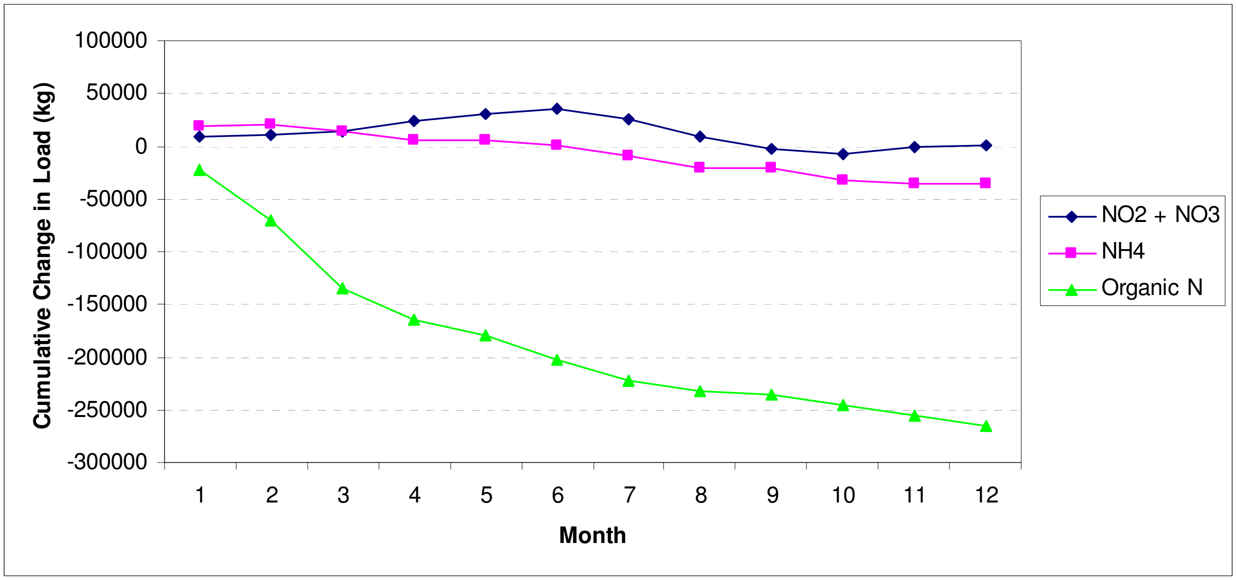


Figure 7. Cumulative Change in Nitrogen Load Predicted by Klamath River Model, Iron Gate Reservoir, for Year 2000

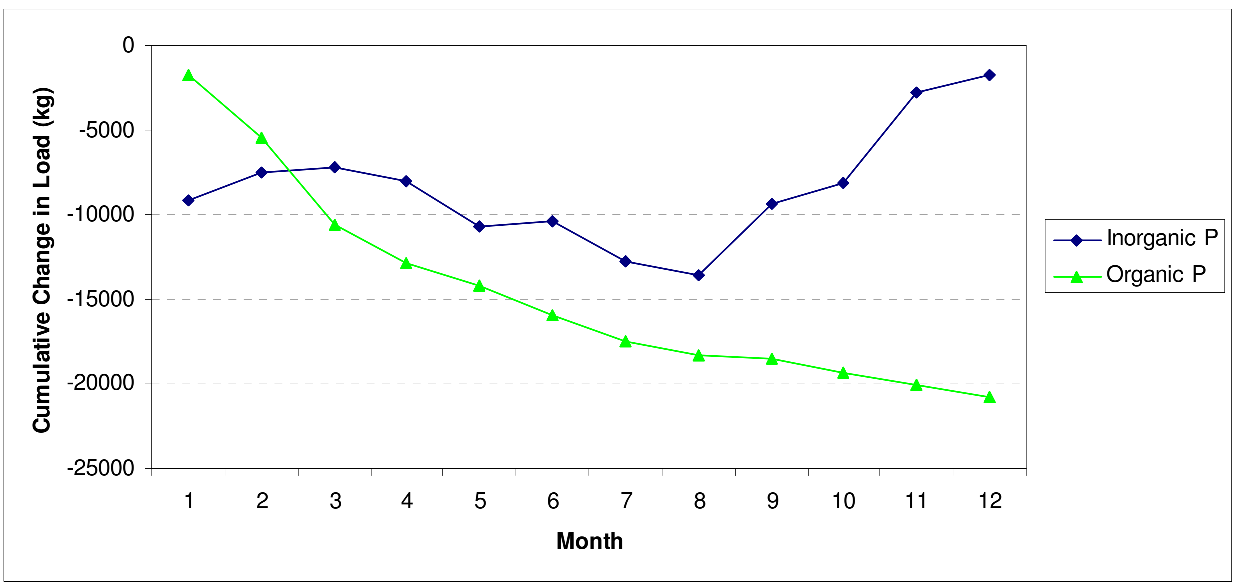


Figure 8. Cumulative Change in Phosphorus Load Predicted by Klamath River Model, Iron Gate Reservoir, for Year 2000

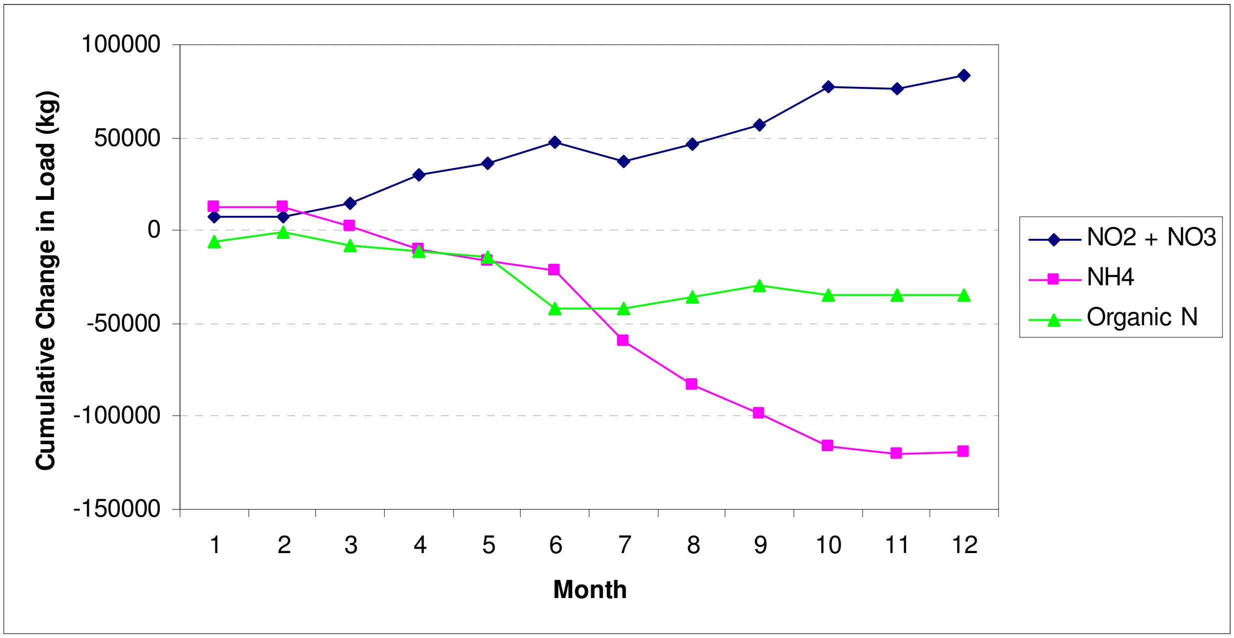


Figure 9. Cumulative Change in Nitrogen Load Predicted by Klamath River Model, Copco Reservoir, for Year 2000

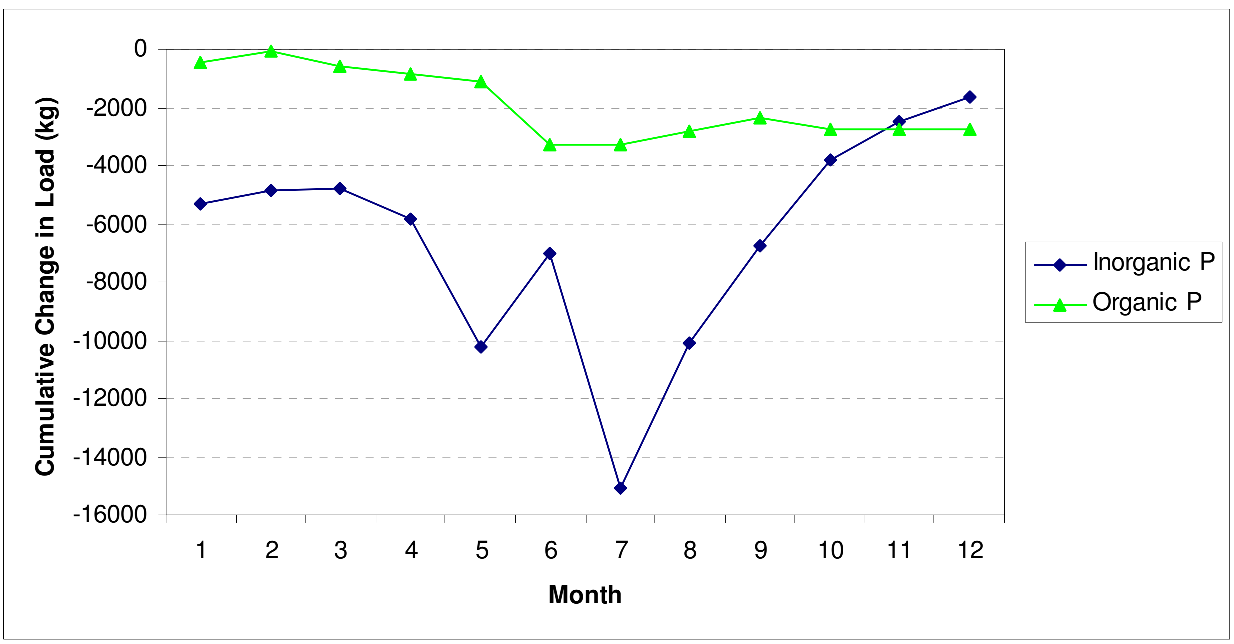


Figure 10. Cumulative Change in Phosphorus Load Predicted by Klamath River Model, Copco Reservoir, for Year 2000

4 Conclusions

The available monitoring data in the Klamath River system is not sufficient to provide a tight closure for nutrient mass balances, and estimates of nutrient retention and loss rates are thus uncertain. It is important to keep in mind the distinction between retention – which delays the transport of nutrients, but does not ultimately remove them – and loss – which results in the long-term removal of nutrients through transfer to stable sediments or the atmosphere.

Both flowing and impounded reaches of the Klamath provide opportunities for retention and loss of nutrients. The dominant process for retention in the system appears to be uptake by algae, which both delays transport downstream and converts inorganic to organic nutrient forms. Given the short residence time in the Klamath reservoirs, retention is likely more significant in flowing reaches, dominated by attached algae, than in the reservoirs, where planktonic algae may be washed downstream. Temporary retention benefits downstream reaches by reducing nutrient loads during the growing season; however, nutrient mass retained in algae is ultimately transported downstream to the estuary, largely after the end of the growing season.

Important loss pathways include denitrification with loss to the atmosphere of nitrogen and deposition of relatively insoluble forms of phosphorus to the sediment. These processes occur in both flowing and impounded reaches. Denitrification permanently removes nitrogen from the aquatic system, and is likely to be significant in the impoundments when the hypolimnion is anoxic. The argument is less clear for the flowing reaches, where oxic conditions are maintained, although some losses likely do occur in conjunction with decaying periphyton mats. For phosphorus, complexes that are insoluble under oxic conditions can often be remobilized under anoxic reducing conditions. This likely limits the annual removal of phosphorus in reservoirs where rapid deep burial is not occurring. (For the Klamath, the presence of reservoirs in series likely limits deep burial rates in the more downstream reservoirs.) For flowing reaches that maintain oxygenation, precipitated phosphorus may remain insoluble – but is prone to transport downstream sorbed to sediment.

Both the CE-QUAL-W2 model and the data analyses of Kann and Asarian (2005, 2007) predict limited amounts of TN and TP removal in Copco and Iron Gate reservoirs. Given the limitations of the available data and associated uncertainty, the model and data-based analyses appear to be in reasonable agreement with one another and with retention estimates based on empirical methods in the literature. The uncertainty in the data supports the need for a modeling approach to interpolate through the limited observations.

For the free-flowing reaches of the Klamath below Iron Gate dam, the RMA-11 model predicts some seasonal retention, but little ultimate loss of nutrients (less than 1% of annual TN and TP loads). In contrast, Asarian and Kann (2006a) contend that there is significant retention of TN between Iron Gate and Seiad. Their estimates are based on seasonal data only, so the annual rate of loss is unknown; however, the estimated seasonal retention rates are much greater than predicted by RMA-11, while appearing to be in approximate agreement with the USGS SPARROW model (Smith et al., 1997). The independent analyses of Armstrong and Ward (2008) do suggest that nutrient loss rates in the Klamath may indeed be quite low, which is consistent with the representation in the calibrated RMA-11 model. Overall, the available data are insufficient to precisely determine the true rates of annual nutrient loss in the free-flowing reaches of the Klamath. Although the RMA-11 model omits several processes such as denitrification that potentially affect nutrient loss rates, most of these processes are also omitted from most other river quality models and it is unclear if they are significant in the Klamath River.

In sum, the linked CE-QUAL-W2 and RMA-11 models of the Klamath appear to provide reasonable estimates of nutrient dynamics in the impoundments, while it is inconclusive whether or not nutrient retention and loss rates in the free-flowing reaches of the Klamath are significantly underestimated.

Despite this unresolved issue, the RMA-11 model appears to be a reasonable tool for assembling the TMDL, as long as the influence of model uncertainty on management decisions is acknowledged.

For the purposes of TMDL-based load allocations, the potential for underestimation of nutrient retention could be treated as a margin of safety (MOS). That is, the actual deleterious impacts of nutrient loads are likely to extend a lesser distance, and create less total algal biomass, than is predicted by the model. Therefore, a TMDL based on the model would include an implicit MOS insofar as the efficacy of nutrient reductions in controlling periphytic algal biomass in the river and its effect on the diurnal DO cycle is likely to be underestimated to some degree. Scenario analyses that depend on the relative retention rates of nutrients in flowing and impounded reaches (such as dam removal scenarios) must be approached with particular care, given the current level of uncertainty in the simulation of retention and loss rates. Interpretation of such scenarios will need to include an evaluation of the decision implications of model and data uncertainty. Additional, focused studies on potential nutrient loss mechanisms are recommended to further reduce uncertainty.

5 References

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