Coherence of Nutrient Loads and AFWO Klamath River Grab Sample Water Quality Database

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1.0 INTRODUCTION

The purpose of this task was to determine the coherence (or relation) between in-stream concentrations of nutrients (and related parameters) and the identified point and nonpoint loads of nutrients, a relationship that will, in part, depend upon river flow conditions. Grab sample data were summarized and, coupled with stream flows, compared to the estimates of nutrient loads developed by Ward and Armstrong (2007), for each time period and site for which AFWO grab sample data are available. (Note: grab sample data from other sources may be included in portions of the evaluations, for cross-comparison and to better fill the data record where necessary. It was assumed that such data were already in database form and readily accessible to this project.) Concentrations in excess of those estimated by river dilution of known loads can be indicative of either underestimates (or incomplete identification) of loads or the operation of an additional nutrient source, such as resuspension from bed sediments. Concentrations substantially lower than those estimated from known loads can be diagnostic of high rates of nutrient assimilation. Either provides insights into the nutrient budget of the river.

2.0 APPROACH

In water quality management, the most compelling way to determine relationships between in-stream concentrations of nutrients and point and non-point loads is through mass balances and through mass balance-based water quality modeling. Based on the principle of conservation of mass and continuity of flow, a mass balance for some constituent such as a nutrient assumes that the mass flux downstream from the confluence of two or more inputs is the sum of the individual mass fluxes from those inputs. For water quality constituents, the mass flux is the product of flow times constituent concentration, so by determining flows and concentrations for the inputs as well as downstream, it is possible to estimate the influence of an input constituent concentration on the downstream concentration of that same constituent.

The practical application of this concept for the Klamath River was to determine concentrations of constituents like phosphorus and nitrogen in the Klamath River below the confluence of a tributary and the mainstem or a waste discharge to a tributary. By determining the flows and concentrations of phosphorus in the tributary and in the Klamath River upstream of the confluence point, it was possible to calculate the phosphorus concentration downstream of that point. In addition to calculating downstream constituent concentrations immediately below the confluence of the mainstem and a tributary, it was also desirable to calculate the constituent concentrations at desired points downstream from the confluence. For substances like phosphorus and nitrogen that are known to interact with living and nonliving components of a riverine environment, there may be a net loss of phosphorus mass from the water column as it is taken up by vegetation, adsorbed to sediments and other surfaces, and perhaps lost in other ways. This mass loss must be accounted for in a mass balance-based model, and it is generally represented as a first order reaction encompassing a number of mechanisms unless the kinetics of the phenomena causing the losses are well known and can be described in more detail.

Water quality models based on mass balances vary in complexity, from steady-state simplified models to steady-state segmented models to dynamic segmented and networked models. A thorough review of these models and their applications may be found in textbooks such as

Thomann and Mueller (1987) and Chapra and Reckow (1983). Steady-state simplified models incorporate mass-balance and flow balance principles and reasonable representation of natural systems, and they may be used for first approximations of constituent concentrations in natural systems. Such simplified models include continuously stirred reactor (CSTR) models, plug flow models, and dispersive flow models. The first two have been used in chemical engineering for many years, and there is a great body of literature and practice with such models. Dispersive flow models have been more commonly applied to natural systems. CSTR models have been used most often to represent lake and some non-linear estuarine systems, while plug flow and dispersive flow models have been used to represent fast moving and slow moving riverine systems, respectively, as well as linear estuarine systems. It is the steady-state plug flow model that is used here to represent constituents in the lower Klamath River. Details about this model and how it is applied to the lower Klamath River are given below.

3.0 SIMPLIFIED RIVERINE WATER QUALITY MODELING

As detailed in Thomann and Mueller (1987), there are two areas of interest in modeling riverine systems with plug-flow models. The first is the point of discharge of residuals whether they be from point sources (e.g., wastewater discharges) or tributaries, while the second is downstream of that point of discharge. At the point of discharge, several assumptions apply in plug-flow models:

1. Water quality constituents are homogeneous in the cross-section of the river so that there are no lateral or vertical concentration gradients – the consequences of this assumption is that constituents discharged to a river are instantaneously mixed laterally and vertically in the river cross-section and no plume exists, an assumption that obviously only approximates what actually occurs;
2. There is no mixing of water in the longitudinal direction downstream, i.e., each element of water and its associated water quality flows downstream in a unique, discrete fashion – the consequence of this assumption is that there is no longitudinal mixing of water or constituents due to dispersion or velocity gradients so that a pulse discharge of some constituent is mixed throughout the river cross-section at the point of discharge (per the first assumption) and the water that received the constituent stays intact as it carries the constituent downstream.

While these assumptions may appear to constrain the use of the plug flow model for riverine systems like the lower Klamath River, they in fact do not. The first assumption, for example, affects only the portion of the river immediately below the confluence of a tributary and the mainstem. The second has little consequence for riverine systems in which advective transport is significantly greater than dispersive transport, as is the case for the lower Klamath River.

Constituent concentrations are calculated for plug flow models at discharge points and downstream from those discharge points based on mass balances calculated at the point of discharge and at distances downstream as an element of water and its associated constituents passes through those points downstream.

3.1 Discharge Point Mass Balance

At a discharge point, the constituent concentration in the river resulting from a waste discharge or tributary input is calculated by mass balance which may be stated in the following way:

Mass rate of constituent from just upstream of the discharge point
+ mass rate of constituent added by source at the discharge point
= mass rate of constituent immediately downstream of discharge point.

Because the mass rate of a water quality constituent is calculated as flow times concentration, the mass rate of constituent from just upstream of the discharge point is calculated as $Q_u\ s_u$ where Q_u is the upstream flow (L^3/T) and s_u is the upstream constituent concentration (M/L^3). The subscript and dimensions nomenclature used here is u = upstream, L = length unit, and M = mass unit and where L^3 = volume. Note that the product of flow times concentration yields units of mass per time, or $(L^3/T)\ (M/L^3) = M/T$, which is the upstream constituent load, W_u.

Similarly, the mass rate (M/T) of constituent added by the discharge or tributary is calculated as Q_e times s_e where Q_e is the discharge or tributary flow and s_e is the discharge or tributary constituent concentration. This mass rate is also termed the discharge load, W_e.

Finally, the mass rate of constituent flux immediately downstream of the discharge point is $(Q_u+Q_e)\ s_0$. Note that the flow immediately downstream of the discharge is the sum of the upstream flow and the discharge flow. Also, the constituent concentration just downstream of the discharge point is termed s_0 signifying the concentration at x = 0 where x = distance downstream and x = 0 is the starting point.

Mathematically, the mass balance equation is given by

$$Q_u s_u + Q_e s_e = (Q_u + Q_e)\ s_0 \qquad (1)$$

or

$$= Q\ s_0$$

where $Q = Q_u + Q_e$. Finally, the concentration, s_0, can be calculated by solving Equation 1 for s_0, and doing so yields

$$s_0 = \frac{Q_u s_u + Q_e s_e}{Q_u + Q_e} = \frac{W_u + W_e}{Q} \qquad (2)$$

Note that dimensionally the units for s_0 are M/L^3.

3.2 Downstream Concentrations

Downstream constituent concentrations may be calculated using the first-order differential equation for a steady state distribution of a reactive substance in a stream or river. The derivation of such an equation is given by Thomann and Mueller (1987, Section 2.5) and assumes a thin "slice" or differential water element of the river downstream about which a mass balance is taken for the constituent. Water flow into and out of this element and mass rate of flux into and out of the element are calculated as is the rate of change of constituent mass in the element due to a variety of physical, chemical, or biological reactions which may be approximated by first-order kinetics. The resulting partial differential equation is

$$\frac{\partial s}{\partial t} = \frac{1}{A}\frac{\partial}{\partial x}(Qs) - Ks \tag{3}$$

where $\partial s/\partial t$ represents the change in constituent concentration over time at some distance x downstream, A is the cross-sectional area of the stream, and K is the decay rate (M/T/M) of the constituent. Note that the units for the decay rate represent the mass (M) of constituent lost per unit time (T) or M/T per unit mass (M) of constituent present with resulting units of 1/T. Common units for K are mass of constituent lost through decay, uptake, transformation, etc. per day per mass present or mg/day/mg or 1/day.

Now, with boundary conditions $s = s_0$ at $x = 0$ where s_0 is calculated as shown in Equation 2 above, assuming steady-state conditions so that $\partial s/\partial t = 0$, steady flow conditions so that $\partial Q/\partial x = 0$, and a uniform cross-section so that $\partial A/\partial x = 0$, then the resulting ordinary differential equation is

$$U\frac{ds}{dx} = -Ks \tag{4}$$

where ds/dx is the constituent concentration change with distance downstream, x, and U is the average river velocity calculated as Q/A. The solution to this equation is (with the boundary condition above):

$$s = s_0 e^{\left(\frac{-Kx}{U}\right)}. \tag{5}$$

Note that this constituent concentration change downstream from a point source or tributary discharge can be expected to decrease exponentially from a concentration of s_0 at the point of discharge to some concentration s at distance x downstream. The rate of concentration change downstream is dependent on the relative magnitudes of K and U. That is, the larger the decay rate (and hence the larger the magnitude of the exponential), the faster the concentration will decrease. On the other hand, the higher the river velocity (and hence the smaller the exponential), the slower the downstream concentration will decrease.

This development of the plug flow model for water quality constituents in rivers shows that concentrations of those constituents can be easily calculated downstream from a headwater input with known flow and constituent concentration or from a discharge by first calculating the concentration of the constituent in the river following the discharge (i.e., s_0) and then by calculating concentrations downstream, s, knowing the average river velocity and the decay rate of the constituent. This also means that estimates of the average river velocity, U, and the decay rate, K, must be known or determined in some way, and there are indeed ways to estimate these two values. Also needed are the flows and constituent concentrations upstream and in the discharge itself. How these are determined in the Klamath River is described below.

3.3 Model Error

Mathematical models for water quality are representations of the physical, chemical, and biological mechanisms that affect constituent concentrations in water bodies such as lakes and reservoirs, rivers and streams, estuaries, coastal waters, and oceans. They begin with the conceptualization of the mechanisms and relationships that affect water quality, continue with the specification of the mathematical relationships that characterize them and the estimation of the model parameters (e.g., decay rates), and move to the validation of the model as a reliable representation of the system and constituent(s) modeled. The validation step may be the most important because it provides confirmation that the previous steps resulted in a reliable model. When water quality models are used to develop water quality management plans, there needs to be a high level of acceptability of the model as a tool to represent water quality and to forecast water quality under a variety of conditions (Chapra and Reckhow, 1983, pp. 435-436).

While the focus of this study has been to show the coherence of nutrient loading to the lower Klamath River and nutrient concentrations in the river using a simplified plug flow water quality model, there also needs to be some measure provided of how well the model results represent measured nutrient concentrations in the river, specifically those of the AFWO grab sample database. One of the ways to estimate confirmation using statistical methods is to calculate the relative error of each estimate (Chapra and Reckhow, 1983, pp. 447-448), i.e.,

$$\text{relative error} = \frac{\left| x_{obs} - x_{pred} \right|}{x_{obs}} \tag{6}$$

where x_{obs} is the measured nutrient concentration at some station downstream of the Iron Gate reservoir in the lower Klamath River and x_{pred} is the predicted or calculated concentration using the simplified plug flow water quality model for a given month in a given year. This relative error estimate can be converted from a fraction to a percentage by multiplying by 100. One can do this for each station where a pair of values for x_{obs} and x_{pred} exist and then calculate the average relative error of all available values for that month and year. This average relative error was calculated for each of the months that TDS, total nitrogen, and total phosphorus were modeled. The calculated relative errors will be presented later.

The relative error is estimating the error between measured and calculated concentrations. Calculation errors derive from the extent to which the mathematical model being used represents the natural system and the assumptions that go into construction of the model itself, and those assumptions have been enumerated above. For simplified models, those errors can be estimated to some extent through sensitivity analyses to determine how sensitive outputs from the model, i.e., constituent concentrations, are to changes in the inputs such as inflows and constituent concentrations in those flows as well as to the overall decay rate used.

Several factors contribute to the errors in the measured values against which the calculated values are being compared. The first factor is the analytical error inherent in the methods used (including the variability of using the methodology by the laboratory technicians performing the analyses) to analyze for constituent concentrations. For given analytical methods, the analytical error is usually known through the many quality control tests that are performed in an analytical laboratory, and it is not usual for total nitrogen and total phosphorus methods to have a 20-30% analytical error. This error is to some extent dependent on the concentrations being determined and how close they are to the detection limits of the methods. Typically, the closer the determined concentration is to the detection limit, the higher the analytical error, and it is not uncommon for the analytical error to approach 100% near the detection limit.

In addition to the analytical error, there is sampling error, i.e., how representative is the sample taken of the water in the river at the time of sampling. Samples taken in such a way as to represent vertical and horizontal variations in constituent concentrations such as occur immediately downstream of waste or tributary inputs can overcome the highly variable concentrations in a river cross-section in which concentration gradients are high. Single grab samples on the other hand must be taken carefully to represent as best as possible the constituent concentrations in the stream cross-section. To the extent that they do not, sampling error is incurred.

Also there is the error caused by assumptions about the actual constituent concentration represented by a below detection level determination. These assumptions can include representing a below detection determination as zero concentration, detection level concentration, or as is commonly done one-half the detection level concentration. Clearly, the extent to which the assumed value deviates from the measured value - had it been measured – creates error.

There is also the error or really variability that shows up as error here caused by averaging measured concentrations at a station over a month and comparing those averaged values to calculated values that represent monthly averages as well. The latter assumes that the average inflows and average constituent concentrations for those inflows vary little over the month considered. The error in the model calculations was noted above, but the variability in the measured values can be determined as their variance or standard deviation.

Finally, an additional problem was the availability of constituent concentrations in the inflows as well as in the Klamath River for certain months modeled. For some months in the 2001 through 2005 period there were no constituent concentrations, and hence the measured values against which calculated values were compared were actually the averages of those monthly constituent concentration averages for the years sampled in the 2001 through 2005 period. This resulted in station average concentrations being used to approximate inflow concentrations for those months or no observed values being available downstream for comparison to calculated concentrations.

All of these various types of error potentially affecting the magnitude of the relative error should be kept in mind in examining the modeling results.

4.0 SIMPLIFIED LOWER KLAMATH RIVER NUTRIENT MODEL

To apply the plug flow model derived above to the Klamath River, one needs to assume that the constituent of concern is a nutrient like phosphorus or nitrogen, to segment the river into reaches so that the head of each reach is a discharge point (such as a tributary or the inflow from Iron Gate Reservoir), to develop estimates of river velocity directly from field measurements or indirectly through flow vs. velocity relationships (see Thomann and Mueller, 1987 Section 2.1.3), to develop estimates of the decay rate, K, and to estimate mass rates of nutrient load from discharge points and in the river itself. How these values were developed as well as the structure of the model itself are described below.

4.1 Model Structure

The basic plug flow model for the lower Klamath River nutrient concentrations consists of a Microsoft Excel workbook with five worksheets. The first worksheet is a title page, while flows and constituent load estimates are in the second through fourth worksheets which are linked to the fifth worksheet, the water quality worksheet. Of the three worksheets for discharges, the first is for wastewater discharges (i.e., point sources; none are specified at this point), the second is for the major tributaries (i.e., the Klamath River below Iron Gate – actually a “headwater” inflow, the Shasta River, the Scott River, the Salmon River, and the Trinity River), and the third is for the 30 minor tributaries which are listed in Kier Associates and Aquatic Ecosystem Sciences LLC (2006, Table 8). The fifth worksheet is the water quality model in which the flows and nutrient loads calculated in the previous three worksheets are combined with calculations of nutrient concentrations in the Klamath River in tabular format at various river mile points downstream from the Iron Gate Reservoir dam. Graphs of flows and nutrient concentrations vs. distance downstream from Iron Gate Reservoir are included.

4.1.1 Worksheets

The five worksheets in the lower Klamath River simplified water quality model workbook are described in more detail here. The first worksheet is the title page and lists the constituent for which the simplified model is prepared as well as the month and year for which it is modeled (see Figure 1). The subsequent worksheets link to this page for constituent name, month and year, so once the user enters the constituent modeled, the month and the year, each of the subsequent spreadsheets are immediately updated with this information.

The second worksheet, shown in Figure 2, is reserved for point source discharges to the lower Klamath River if and when such discharges are identified. Flows for these discharges are entered by the user as million gallons per day (mgd) as they are normally given in wastewater discharge permits, and flows in units of ft^3/s (cfs) and m^3/s (cms) are automatically calculated. The average monthly constituent concentration is also entered by the user which is then multiplied in the spreadsheet by the flow (cms) and appropriate conversion factor to yield constituent load in kg/d. This load is then to be transferred to the fifth spreadsheet at the position in the table representing the distance downstream from Iron Gate Reservoir where the point source would enter the river.

The worksheet for major tributaries (see Figure 3) contains for each tributary its drainage area (mi^2 and km^2) which is entered as mi^2 as taken from the source and converted to km^2 by the spreadsheet, average monthly flow (cfs and calculated cms), and average monthly constituent concentration (mg/L) and calculated total constituent loads (kg/d). Drainage areas and flows were taken from Ward and Armstrong (2006) which consist of analyses of USGS data, while average monthly constituent concentrations were calculated from the AFWO database (Armstrong and Ward, 2007). Where monthly average constituent concentrations were not available, monthly station averages over the 2001 through 2005 period were entered and noted in the spreadsheet. Total constituent loads were calculated as flow times concentration as described above. Flows and constituent concentration data provided by the user are outlined in the spreadsheet shown in Figure 3. Again the tributary flows and constituent loads are transferred to the appropriate columns and rows in the water quality model in the fifth spreadsheet.

Data for the minor tributaries in the fourth spreadsheet were taken from Kier Associates and Aquatic Ecosystem Sciences LLC (2006, Table 8) (see Figure 4). This information included the tributary name, river mile (from the coast), major section (termed “reach” in the report) of the river, and watershed area (km^2). Watershed area (mi^2) was derived from the area in km^2. Flow information for the worksheet month of interest was derived from flow yield (in/mo) values developed by Ward and Armstrong (2006) for the major sections of the lower Klamath River. These in/mo flow yield values were converted in the spreadsheet to m^3/m^2/mo (same as m^3/mo/m^2) values and multiplied by drainage areas (m^2) to yield cfs and m^3/s flow values for each minor tributary for the month and year modeled. The m^3/s flows were multiplied by monthly average constituent concentrations to yield loads (kg/d) which were then transferred to the water quality model spreadsheet. During the early calibration process of developing the model, it was noticed that calculated river flows (i.e., those determined from flow balances moving downstream from Iron Gate Reservoir) did not quite equal those of measured flows at the main USGS stations in the river as they should have based on the Ward and Armstrong (2006) methodology. Comparing the watershed areas from the Yurok Tribe report to those used by Ward and Armstrong (2006) and derived from USGS data, it was clear that the total watershed of creeks surveyed in the Yurok Tribe report was less than the total intervening watershed between the gauges Each of the minor tributaries drainage areas was adjusted by an amount needed (around 1.3 to 1.4) to adjust the total of these watersheds for a section of the river to the ungauged USGS watershed drainage area for the same section. The adjusted watershed areas are shown in the fourth worksheet, and it was the adjusted watershed areas that were multiplied by the flow yield to get the monthly average flows used in the water quality model. Adjusting the watershed drainage areas resulted in higher river flows, and those adjusted river flows then matched the measured flows at the USGS stations. Monthly constituent concentrations were the same concentrations used to estimate monthly loads in Armstrong and Ward (2007).

The fifth worksheet, shown in part in Figures 5a and 5b, is the water quality model worksheet and contains information on the upstream or headwater discharge, all point source discharges, and major and minor tributary flows and constituent loads, estimates of river velocity and water depth, and constituent concentrations calculated from mass balances and constituent decay using three values for the decay rate, K, to get a sense of the sensitivity of the calculated concentrations to decay rate. Figure 5a shows the upper left half of this spreadsheet while Figure 5b shows the upper right half with slight overlap with Figure 5a. Lists of the major and minor tributaries were entered with distances upstream from the coast and downstream from Iron Gate Reservoir (on 1 mile intervals) so that each tributary was placed in the table in the spreadsheet at the exact or approximate location where it enters the lower Klamath River. Linkages with flows and constituent loads from the first three worksheets were made so that flows and loads from each upstream (i.e., Iron Gate Reservoir outflow) source and major and minor tributary appear in the appropriate columns for those classes of inflows, i.e., upstream flow and loading, point source flow and loading, tributary flow and loading, and nonpoint source (minor tributaries) flow and loading. Total flows and total constituent loads are calculated as the sum of the individual flows and constituent loads for each source. For those cases where two tributaries join the river at approximately the same river mile from opposite sides of the river and also where there was significant tributary drainage area below a USGS gauging station on a major tributary, a total load was calculated and entered as a single source. Cumulative flows were calculated from all sources with distance downstream.

Constituent concentrations were calculated at each 1 mile distance interval. At each distance “step” downstream, a check was made for the presence of a major and/or minor tributary and its associated discharge flow and constituent load. If a discharge was detected, then a flow balance and constituent mass balance was performed and the constituent concentration after the discharge calculated; this would be the s_0 value of Equation 2. If a discharge was not detected, then the total phosphorus concentration was calculated using Equation 5 where s_0 came from the previous distance interval upstream, U was calculated using velocity vs. flow relationships (see below), and K was determined through a subjective visual best fit estimate of K for each month and year, a common method used to estimate such a decay rate during the model calibration process. Once K was determined, then values usually 50% higher and 50% lower were calculated (although other ranges were used in some cases) and all three values of K used to estimate total constituent concentrations. The three values of K provided an estimate of sensitivity of the concentrations to the decay rate. The entire calculation procedure was checked to assure that flow balances and constituent mass balances were being calculated properly.

Finally, values of cumulative flow and constituent concentrations were plotted vs. distance downstream so that changes in both could be viewed and relationships between instream concentrations and external loads noted. Measured flows and constituent concentrations at the USGS stations in the river are also plotted so that calculated values can be compared to measured values to get a sense of goodness of fit. These graphs are not shown in Figures 5a or 5b but were used to produce Figures 10 to 30.

Seventy-five workbooks were prepared for this project for each month between June and October for each year during 2001 through 2005 and for three constituent: total dissolved solids, total nitrogen, and total phosphorus to demonstrate the performance of the simplified nutrient model under different flows and times of the year.

4.1.2 Flow Relationships

As noted above, it was necessary to estimate river velocity to be able to calculate constituent concentrations downstream. Further it was necessary to be able to determine average river velocities for whatever average flows existed at the time water quality modeling was to be done. Fortunately, USGS personnel discovered in the 1950’s that relationships existed between velocity, depth, and stream width and flow and that those relationships could be described by:

$$H = a\,Q^{b} \tag{7}$$

$$U = c\,Q^{d} \tag{8}$$

$$B = e\,Q^{f} \tag{9}$$

where H = average depth, U = average velocity, and B = average stream width. Also, a, c, and e are coefficients, and b, d, and f are exponents. Further, $a \cdot c \cdot e = 1$ and $b + d + f = 1$. Thus, if one had available relationships between two of the three of these variables, the third could be obtained by calculation. See Thomann and Mueller (1987, pp. 43-44) for more information on these relationships.

The basic data needed to develop the velocity vs. flow relationship were available at the four USGS gauging stations in the lower Klamath River on the USGS web site. Each time the stage vs. flow relationship is checked at a gauging station, an extensive set of measurements of velocity, flow, depth, and stream width are taken, and these data can be analyzed to determine the coefficients and exponents in the above equations. Such data are available through the USGS web site for these four stations (Iron Gate, Seiad Valley, Orleans, and near Klamath), and they were used to develop the relationships shown in Equations 7 and 8 (see USGS 2005).

The graphs shown in Figures 6 through 9 illustrate that relationships do exist between velocity and flow and depth and flow for these four stations. Except for the Iron Gate station, it was possible to use the entire record of measurements at each station to develop the relationships which are given on each graph along with the R^2 value. At Iron Gate, there were two distinct relationships for velocity vs. flow manifest in the full record as if the gauge site had been moved or the cross-section had changed or the measurement process had been altered some years ago. Thus, only very recent data were used for that particular station.

The values for the coefficients and exponents on depth vs. flow and velocity vs. flow for the four USGS stations are as follows:

Station	Depth vs. Flow		Velocity vs. Flow	
	a	b	c	d
Iron Gate	0.2045	0.4627	0.1342	0.4552
Seiad Valley	0.1922	0.4494	0.1446	0.4467
Orleans	0.4948	0.3448	0.0378	0.5726
Klamath	0.3512	0.3098	0.0421	0.5025

Except for the Klamath River near Klamath station, all of the R^2 values for the velocity vs. flow relationship are above 0.9 indicating strong relationships.

The values for the exponents are not dissimilar from those summarized by Thomann and Mueller (1987, Table 2.7) for rivers primarily on the East coast and one on the West coast. It should be noted that the value for the exponent "f" on the stream width vs. flow relationship if calculated would be 0.2 or less for each of the stations which implies steep banks. If f = 0, for example, the bank is vertical.

The velocity vs. flow relationships were inserted into the fifth worksheet and used to calculate river velocity at any given distance downstream based on the cumulative flow to that point. Because slightly different relationships were developed at each of the four stations, each relationship was assumed to apply for the portion of the river encompassing that gauging stations. There is some unevenness in the velocities and depths calculated, particularly at the interfaces between stretches of the river where one velocity vs. flow relationship transitions to another. Depth was also calculated for information purposes.

4.2 Modeling Results

Three constituents were modeled: total dissolved solids; total phosphorus; and total nitrogen. Total dissolved solids values were determined directly from laboratory analyses of samples taken at the stations indicated and during the months for which averages were calculated. Likewise, total phosphorus values were taken from the total phosphorus colorimetric test. Total nitrogen on the other hand was calculated as the sum of total organic nitrogen and total inorganic nitrogen; total organic nitrogen was calculated as total Kjeldahl nitrogen minus ammonia nitrogen while total inorganic nitrogen was calculated as the sum of ammonia nitrogen, nitrite nitrogen, and nitrate nitrogen. Because of the variability in availability of values for these various components of total nitrogen, some estimates of total nitrogen had to be determined in other ways. Further, the problem of below detection values was particularly acute in nitrogen determinations, and the assumption was made that a less than detection value was approximated by one-half the detection level – a commonly used approximation. Both the method of total nitrogen calculation and how less than detection values were handled affected significantly the accuracy of the total nitrogen values (see Armstrong and Ward, 2007) for further information), and this should be kept in mind in examining the modeling results.

An additional problem was the availability of constituent concentrations in the inflows as well as in the Klamath River for certain months modeled. This resulted in station average concentrations being used to approximate inflow concentrations for those months or no observed values being available downstream for comparison to calculated concentrations. These will be pointed out below.

Following entry of the major and minor tributary flows and total dissolved solids, total phosphorus, and total nitrogen concentration data into the appropriate worksheets for a given month and year, the cumulative flows and concentrations downstream were calculated on the water quality worksheet and graphed. Results of modeling flows and constituent concentrations are given below and presented in Figures 10 through 30.

4.2.1 Flows

Average monthly flows in the lower Klamath River near Iron Gate and near Klamath for the periods used are given in Table 1. The dramatic increase in flows downstream in June, particularly in 2003 and 2005, compared to the much reduced increases in the following months permits one to see the impact of increased major and minor tributary flows on downstream constituent concentrations, and the lower flows of September, for example, at Iron Gate and downstream demonstrate the impact primarily from the releases from Iron Gate on the river downstream.

Flows in the lower Klamath River exhibited distinct downstream as well as seasonal patterns in 2001 through 2005. Flows out of Iron Gate Reservoir averaged about 30 cms over the entire period modeled and changed little from month to month (see flows in Table 1). Downstream, flows were generally rather constant or increased only slowly for the first 230 km even with the entrance of the Shasta River 23.7 km downstream and the Scott River 86.7 km downstream. It was not until the Salmon River entered at 230 km and the Trinity River at 272 km downstream that significant flow changes were observed. This was especially true from August through October for each year of 2001 through 2005. Significantly greater increases were observed, however, downstream in June and to a lesser extent July due to high inflows from the tributaries.

Releases from Iron Gate Reservoir in June 2001 averaged 53.7 cms, the highest during the entire period modeled, and averaged about 35.5 cms from July through October (see Table 1 and Figure 10). Downstream flows in June increased significantly below the 230 km point where the Salmon River enters the Klamath River and at the 272 km point where the Trinity River enters reaching 170.1 cms near Klamath (considered to be same as Terwer here). Monthly flows from July through October averaged between 73.7 and 97.6 cms (see Table 1 and Figure 10). The higher rainfalls nearer the coast in June accounted for the increased runoff, particularly in the Trinity River.

The flows in 2002 were similar to 2001 although the June release from Iron Gate was about half that of June 2001 (Table 1). Again, major flow increases occurred downstream at the confluences with the Salmon and Trinity Rivers (Figure 11).

In 2003 these patterns were repeated except that June and July downstream flows increased significantly more than in 2001 and 2002 (see Table 1 and Figure 12). Inflows from the Scott, Salmon, and Trinity Rivers were particularly significant as were those from the minor tributaries due to high rainfalls. From August through October flows downstream were reduced and similar from month to month.

Flows in 2004 were close to those in 2003 except in June and July. Releases from Iron Gate in June were 27.0 cms while those in July were 19.1, and flows at Terwer were almost 10 times those at Iron Gate in June and over just three times those at Iron Gate in August through October (Table 1). Clearly significant inflows occurred downstream in June and July (Table 1 and Figure 13).

In 2005, releases from Iron Gate Reservoir again averaged around 32 cms shown in Table 1 and Figure 14. The downstream flows in June increased dramatically with inflows from the major and minor tributaries, particularly the Salmon River and especially the Trinity River, reaching 409 cms near Klamath. As in 2003, flows were significantly reduced in July then from August through October were reduced and similar from month to month.

It is important to note in Figures 10 through 14 that the calculated monthly flows from Iron Gate Reservoir to Klamath (Terwer) matched the observed average monthly flows at the four Klamath River USGS gauging stations almost exactly. This, of course, was expected because the inflows from Iron Gate and the major tributaries downstream were based on gauged flows and the flows from minor tributaries were based on extrapolated estimates of flow yields calculated as the difference between observed flows between USGS stations in the Klamath River and the gauged inflows from the major tributaries as calculated by Ward and Armstrong (2006). Indeed, the lack of a match between the calculated and observed flows was an indication that flows had not been accounted for correctly. The fact that the calculated and observed flows do match indicates that the simplified water quality model is accounting for flows correctly, and any differences between calculated constituent concentrations and calculated concentrations are not due to errors in flows.

4.2.2 Total Dissolved Solids

In any water quality modeling effort, it is important to determine that the mass balance-based model is indeed conserving mass, i.e., the mass balances are working. One way to check this is to enter constant concentrations of a fictional conservative material (i.e., K = 0) into each of the sources and to determine if the simplified water quality model reproduces those concentrations downstream. Using the flows for one of the months to be modeled, concentrations of 100 mg/L were entered for each of the sources and downstream concentrations calculated by the simplified model; the model did indeed calculate concentrations of 100 mg/L at every calculation point confirming that the mass balance calculations in the simplified water quality model were correctly entered.

To determine then how well the simplified model can represent actual water quality in the system to be modeled, one models a natural conservative material like total dissolved solids (TDS) again to check the mass-balance characteristics of the model as well as to determine how well observed concentrations of the constituent are represented. Calculated concentrations of the constituent should reflect the effects of flows only through the mass balances calculated, for with a conservative material there is no decay and thus no mass lost due to decay. Assuming the TDS samples have been taken and analyses conducted carefully similar to the other constituents to be modeled, how well the model represents TDS provides some indication of its ability to represent water quality in general and some estimate of base level accuracy of representing non-conservative materials in particular. Thus, TDS was modeled in the lower Klamath River for June through October for 2001 through 2005.

Results of TDS modeling for 2001 are shown in Figure 15. Note that the TDS concentrations calculated are shown by the solid line while average monthly measured values are shown by the solid points. Further, concentration changes downstream are due strictly to mass loadings and flow changes (i.e., dilution), not to decay. There is a very good match of calculated values to observed values for each month during June through October although the calculated values do not match exactly some of the observed values as might be expected. Because the observed values are monthly averages, some statistical variation is expected. Further, each measurement will embody sampling error as well as analytical error. For TDS, the analytical error should be small because the analytical method is a simple gravimetric method with minimal error. The sampling error is a measure of how representative the water sample is for the river over that month period. For months in which flows and concentrations are fairly constant, this error should be small; for months with flow and concentration variations, the error will be higher. Both errors combined with the statistical variation will produce large enough error bars on the observed average concentrations that calculated values will normally fall well within those boundaries.

For 2001, the calculated and measured values of TDS are relatively constant from Iron Gate downstream to Klamath in June and July with calculated and measured values staying within the range of 90 mg/L to 120 mg/L with the concentration in the Iron Gate release of 100 mg/L (see Figure 15). By August, the TDS concentration in the Iron Gate release had risen to just below 125 mg/L, and concentrations downstream varied more caused primarily by tributary inflows. Calculated and measured concentrations ranged from about 90 mg/L to 125 mg/L. This pattern was closely replicated in September, and then measured October concentrations in the Iron Gate release increased further to about 150 mg/L and calculated concentrations downstream rose to about 160 mg/L due to the Shasta River inflow then decreased downstream with the Trinity River inflow and smaller tributaries just upstream. Based on the calculated and measured concentrations the average relative errors calculated for June through October, as given in Table 2, were 6.6%, 1.5%, 5.3%, 5.1%, and 2.1%, respectively. Considering that these are monthly average calculated estimates compared to monthly average measured values using a simplified plug flow model, these error estimates are very low and the simplified model can be considered to provide an excellent fit to observed data.

In 2002, the lower flows in the Iron Gate releases coupled with the rapid increase in flow downstream in June especially and somewhat less in July and August produced a significantly different concentration vs. distance profile than in 2001. TDS concentrations in the Iron Gate release were 135 mg/L (see Figure 16) and decreased steadily downstream to around 70 mg/L at Klamath due to the diluting effect of lower TDS concentrations in the inflowing tributaries. By July, the TDS concentration vs. distance profile was similar to that of 2001, and they stayed that way through October. Relative errors for June through October are 6.2%, 12.9%, 2.7%, 6.2%, and 5.9%, respectively, as given in Table 2.

TDS modeling for 2003 shows the significant diluting effect of the high flows downstream of Iron Gate Reservoir in June and the reduced flows in August, September, and October (see Figure 17). For June, TDS concentration in the Iron Gate release was again 130 mg/L, and concentrations in the Scott, Salmon, and Trinity Rivers had to be estimated in the absence of measured values, so station averages were used. Even with this substitution, measured values at Klamath were matched closely, and the average relative error was 1.7%. For July through September, measured values were available for all inputs and a number of stations downstream in the Klamath River so that errors of 9.6%, 4.9%, and 31.2%, respectively, could be calculated (Table 2). For September, the high error value is due primarily to a single monthly average in the river at Terwer. For October, all input values had to be estimated in the absence of any measured values, and there were no measured values in the river against which comparisons could be made and average relative error calculated.

Flow changes from June to October in 2004 were similar to those in 2003, but the flows themselves were slightly lower as shown in Table 1 and Figure 13. As a consequence, the calculated TDS concentrations downstream of Iron Gate reflected these flow patterns and the TDS concentrations in the tributaries (see Figure 18). Flows leaving Iron Gate had TDS concentrations from about 100 mg/L to 140 mg/L from June through October except for the higher concentration in July of 160 mg/L. These concentrations dropped steadily each month to near 100 mg/L at Klamath except for June when the lowest values were near 80 mg/L. Model errors were 4.1%, 2.4%, 3.2%, 4.8%, and 3.3% for June through October, respectively (see Table 2) – very low relative error levels.

Finally, TDS modeling results for 2005 are given in Figure 19. TDS concentrations leaving Iron Gate were measured only for June at 120 mg/L; all of the other concentrations at Iron Gate were estimated. While calculated concentrations dropped steady downstream in June when there was significant flow increase downstream, during other months the concentrations dropped only slightly or not at all. For June, predicted TDS concentrations matched observed values very closely (average relative error of 7.9%), while for August significant deviations are found at stations downstream (average relative error of 32.7%). The low values in the Klamath River at Orleans and Terwer are based on single samples, and the concentration in the outflow from Iron Gate Reservoir is based on a station average. For October, station averages were again used for Iron Gate, the Salmon River, and Trinity River in the absence of measured values, and the deviation of the predicted and measured values above Shasta is likely due to the assumed value for waters leaving Iron Gate. Overall, the modeling error for October was 15.1%. Other model error values for July and September were 10.0% and 10.7%, respectively.

In summary, TDS concentrations leaving Iron Gate reservoir were typically between 100 mg/L and 140 mg/L – occasionally higher – and concentrations then decreased downstream in proportion to the flows of the lower TDS waters entering the lower Klamath River. Because of its higher TDS concentrations (overall, i.e., over all months and years used in this study, average of 345 mg/L), the Shasta River caused concentrations in the Klamath to rise while the lower TDS inflows from the Scott (overall average of 134 mg/L), Salmon (overall average of 70 mg/L), and Trinity Rivers (overall average of 70 mg/L) caused decreases. Thus, the typical concentration profile was a steady decrease downstream punctuated by drops in concentrations where major tributaries entered. The rate of decrease downstream was determined primarily by inflows.

TDS modeling was considered to be successful overall, and the comparison of predicted values to measured values as relative error was considered to be excellent in 2001 and 2004. For 2002, 2003, and 2005, the comparisons of predicted and observed was considered to be less successful when observed values for inputs were missing and station averages had to be used. TDS modeling did demonstrate the simplified water quality model could be considered to be very satisfactory for constituent water quality modeling in the lower Klamath River.

4.2.3 Total Phosphorus

The simplified water quality model was used to model total phosphorus in the lower Klamath River, and several patterns emerged while doing so. First, total phosphorus behaved as a non-conservative material as expected, with temperature having a significant effect on decay rates as would be expected. During the warmer months of July and August, decay rates were significantly higher than in the cooler months of September and October when the decay rates were so low that total phosphorus behaved almost as a conservative material. Second, during the very high flow months of June and sometimes July, total phosphorus decay rates were somewhat insensitive to decay rate as hydraulic transport rates overwhelmed decay rates. Third, total phosphorus concentrations downstream from Iron Gate were driven largely by the concentration leaving Iron Gate, and that concentration tended to increase from June through August and then decline thereafter.

Total phosphorus concentrations in June 2001 start at 0.128 mg/L at Iron Gate and decline only to 0.10 mg/L downstream near Klamath (see Figure 20). In July the Iron Gate concentration increases to 0.180 mg/L, and in August it is 0.397 mg/L. By September the concentration at Iron Gate has decreased to 0.255 mg/L at Iron Gate and downstream concentrations decline slowly downstream until the confluences with the Salmon River, Trinity River, and the many minor tributaries in the area bring the concentrations down sharply to near 0.1 mg/L near Klamath. In October the Iron Gate total phosphorus concentration is 0.187 mg/L and it decreases to 0.10 mg/L at Klamath. Model accuracy based on the average relative error is the following: June 12.2%; July 8.2%; August 15.0%; September 7.2%; and October 15.7%. Total phosphorus concentrations were less well simulated with concentrations overestimated in June (although the calculated concentration near Klamath was close to that measured). Calculated total phosphorus concentrations in September matched well the measured concentration near Klamath but only approximated measured concentrations at Seiad Valley and Orleans. Model predictions were poorest in October.

Total phosphorus concentrations in the Iron Gate release in 2002 increased from 0.130 mg/L in June to about 0.19 mg/L in July and August, to 0.260 mg/L in September, and finally to 0.280 mg/L in October as shown in Figure 21. Concentrations decrease steadily downstream each month so that concentrations at Terwer range from 0.04 mg/L in June to 0.10 mg/L in October. Decay rates are estimated to be about 0.005/day in June and August and near 0.05/day – 0.075/day the rest of the time. The only increases in concentration downstream are at the confluence of the Shasta River with the Klamath due to the higher total phosphorus concentrations in the Shasta, and decreases in total phosphorus are found where the Scott, Salmon, and Trinity Rivers inflow because of their lower total phosphorus concentrations. Model accuracy based on the average relative error is the following (see Table 2): June 7.4%; July 9.3%; August 10.6%; September 10.0%; and October 11.3%. In general there was very good fit of calculated total phosphorus concentrations to measured.

Modeling of total phosphorus in 2003 was similar to that in 2001 except that higher flows caused by tributary inflows in June and July accounted for a more rapid decrease in concentrations downstream due to dilution as well as decay (see Figure 22). Again, hydraulic transport rates were large compared to decay rates. In the lower flow and warmer month of August, decay rates were higher before decreasing back to very low values in September and October. Average relative error values were the following for 2003 (see Table 2): June 14.3%; July 5.0%; August 4.7%; September 8.6%; and undetermined for October because of no available measured values. Again, Iron Gate concentration rose from 0.190 mg/L in June to 0.310 mg/L July but declined only slightly thereafter to about 0.2 mg/L.

As shown in Figure 23, total phosphorus concentrations again followed a concentration profile that was similar to previous years. Concentrations in the Iron Gate release, shown in Figure 23, increase from 0.12 mg/L to 0.27 mg/L from June through September. The 0.155 mg/L concentration given for October is based on the average of values in other years. As in previous years, total phosphorus concentrations then decrease steadily downstream with decay rates of about 0.005/day except for August when the decay rate estimated was about 0.125/day. The relative error of calculated concentrations compared to measured values were 11.3%, 22.4%, 13.6%, and 14.9% for June through September, respectively (see Table 2). No relative error estimate was calculated for October as there were no measured values for comparison.

Total phosphorus concentrations in the Iron Gate Reservoir release in June 2005 averaged only 0.088 mg/L (see Figure 24) and rose steadily to 0.175 mg/L in September before declining in October to 0.158 mg/L. Concentrations of total phosphorus dropped steadily downstream in the lower Klamath River with the highest decay rates occurring in July and September. Calculated total phosphorus concentrations compare very closely with the measured concentrations. Average relative error values were the following for 2003 (from Table 2): June 10.0%; July 7.8%; August 18.8%; September 2.7%; and October 10.8% indicating very good fit of the simplified water quality model for total phosphorus.

The typical pattern for total phosphorus concentrations in the lower Klamath River was a decreasing concentration in the river downstream from Iron Gate reservoir. Total phosphorus concentrations in the Iron Gate release determine the overall concentration profile downstream. This is evident in Figure 25 in which the July 2001 total phosphorus simplified model was modified to represent only the middle decay rate, the measured concentrations were deleted, and the total phosphorus concentration in the Iron Gate release was held at 100% of the July 2001 concentration, 50% of that value, and 25% of that value. It is clear from the figure that the phosphorus concentration profile is reduced proportionately. This influence of the Iron Gate release total phosphorus concentration is due to the fact that the total phosphorus loading from Iron Gate Reservoir is far more than the loading of any other input downstream of Iron Gate. In essence, the loading of total phosphorus from Iron Gate Reservoir drives the concentrations downstream.

4.2.4 Total Nitrogen

Total nitrogen was modeled for June through October of 2001 through 2005, and calculated total nitrogen values were compared to measured values at stations downstream from Iron Gate Reservoir where data were available. Total nitrogen behaved like total phosphorus in many respects in that it is a non-conservative material, decay rates appeared to be related to temperature, concentrations downstream are driven by the total nitrogen concentration leaving Iron Gate Reservoir, and those concentrations increased from June through October.

Predicted total nitrogen values for 2001 are shown in Figure 26 and reflect all of these patterns noted above. Concentrations in the Iron Gate release increased from 0.80 mg/L in June to 1.91 mg/L in October. Downstream concentrations decrease as total nitrogen is lost from the water column with increasing rates in August and September compared to June, July, and October as well as by dilution from the Salmon River and minor tributaries and particularly the Trinity River. The simplified water quality model represented observed monthly averages fairly well with the following average relative errors: June 12.4%; July 9.9%; August 17.7%; September 17.6%, and October 7.8% (from Table 2).

In 2002, total nitrogen concentrations in the Iron Gate release increased from 0.55 mg/L in June to about 1.14 mg/L in July and August then down to about 1.0 mg/L in September and October (see Figure 27). Decay rates similarly rose from a low of 0.005/day in June to a high of 0.125/day in August and September. Model average relative errors for June through October were 18.6%, 17.9%, 25.5%, 7.9%, and 18.7% (from Table 2). Overall concentration profile patters were similar to 2001 and calculated values matched measured values fairly well.

Predicted values in 2003 are lower due to higher flows and lower concentrations in the Iron Gate release (see Figure 28). Total nitrogen concentrations in Iron Gate release increase from 0.66 mg/L in June to 0.98 mg/L in September. Concentrations downstream decrease only slightly, and decay rates were estimated to be much lower than in 2001. Surprisingly, August decay rates are much lower than they were in 2001. With few observed values in June for inflows to the Klamath River as well as observed values in the River and none in October, it was difficult to determine just how well the simplified water quality model represented observed monthly averages, but the match in August showed that the model was performing very well with the following average relative errors: June 20.5%; July 18.7%; August 2.2%; and September 6.6% (see Table 2). It should be noted, however, that one or more of the measured values for June, July, and September were averages of monthly values from other years which were used in the absence of values for 2003.

Total nitrogen concentrations in the Iron Gate release again were 0.66 mg/L in June and increased to 0.92 mg/L in August before decreasing thereafter. While the calculated values of total nitrogen for 2004 were similar to those of previous years, the measured values include multiple incidences of missing components of total nitrogen, substitutions for below detection values, and for October the use of average monthly values from other years. Thus, the relative errors calculated for the monthly results are very high, i.e., values of 16.8%, 28.1%, 48.6%, 28.2%, and 30.1% for June through October (Table 2). Given the uncertainty in the measured values, it is difficult to discern the accuracy of the modeling for 2004 shown in Figure 29.

As shown in Figure 30, observed total nitrogen values in 2005 appeared to follow much the same pattern as in 2001 with increasing concentrations in the Iron Gate release from 0.69 mg/L in June to 1.33 mg/L in October, large decay rates in June and August, and significant decreases in concentrations with inflows from the major tributaries further downstream. The simplified water quality model represented observed monthly averages fairly well with the following average relative errors: June 24.7%; July 102.5%; August 41.1%; September 9.2%, and October 42.5% (Table 2). Again, the October relative error was calculated with one or more of the measured values being monthly averages from other years.

Like total phosphorus, there were patters of total nitrogen concentrations at Iron Gate and downstream that were typical for all years. Concentrations in the Iron Gate release were between 0.5 mg/L and 1.9 mg/L for all five years, and there was often an increase in concentration from June to later summer months then a decrease by October. Concentration profiles downstream also showed a steady decrease due to dilution with the inflows downstream that had lower total nitrogen concentrations than the lower Klamath River. Like total phosphorus, the total nitrogen loading from Iron Gate Reservoir was significantly higher than any inflow loads downstream, and hence the total nitrogen loads coming from Iron Gate Reservoir drive the concentrations downstream. As total nitrogen concentrations in the Iron Gate releases increase or decrease, one would expect the downstream concentrations to increase and decrease as well.

4.3 Sensitivity Analyses

Two types of sensitivity analyses were conducted. One concerned the sensitivity of calculated concentrations to the decay rate, K. In each workbook, the worksheet for calculating constituent concentrations included the capability of calculating those concentrations with three values of K. For each year and month used, values of K generally equal to 50% above and 50% below the value of K selected were used, and the constituent concentrations resulting plotted. It can be observed in Figures 20-30 for total phosphorus and total nitrogen that during the colder months – June, September, and October - the variation in the decay coefficient has little effect on the calculated total phosphorus concentrations. This is due in part to the very low decay rate found to be appropriate for total phosphorus and total nitrogen in the lower Klamath River during those months but also due to the dominance of advective transport over decay during the high flow months of June and to some extent July. During the warmer months – July and August – the decay rates usually increased significantly due to the increased biological activity that would affect nutrient concentrations. Although other mechanisms may be involved causing the loss of phosphorus and nitrogen from the water column during downstream transport, biological mechanisms are assumed to be the dominant ones.

The other sensitivity analysis was on the boundary condition at Iron Gate Reservoir, namely the concentration of total phosphorus leaving the reservoir. As shown in Figure 31, changes in downstream total phosphorus concentrations matched almost proportionately the changes at Iron Gate. This would be expected in an advective transport dominated system, and it confirms the expectations noted above that releases from Iron Gate Reservoir drive total phosphorus and total nitrogen concentrations downstream.

4.4 Temperature Effects

It is well known that most reactions increase with temperature increases in natural waters , and, to the extent that total nitrogen and total phosphorus decay rates are comprised of decay mechanisms that are temperature-dependent, those decay rates will be affected by temperature. Temperature effects on reaction rates can be expressed by the modified van’t Hoff-Arrhenius equation (Chapra and Reckhow, 1983), namely:

$$K_T = K_{20}\ \theta^{(T-20)} \tag{10}$$

where K_T = rate at temperature, T, K_{20} = rate at 20° C, and θ = temperature coefficient derived from the van’t Hoff-Arrhenius equation. Biologists typically use the concept of Q_{10},which is defined as the ratio of the rate at 20° C to the rate at 10° C. It is easy to show from Equation 10 that $Q_{10} = \theta^{10}$.

The value of θ for many biological reactions, including the nitrification rate of nitrogen, is around 1.07-1.08 (Thomann and Mueller, 1987) which is equivalent to Q_{10} values of 1.97-2.16. Indeed, a Q_{10} value of 2 is equivalent to a θ value of 1.072.

Based on Equation 10, the influence of temperature on reaction rates in the lower Klamath River was estimated by examining the ratio K_T/K_{20} (using a θ of 1.07) which will indicate the magnitude of the increase or decrease in rates from those at 20° C. Monthly average temperatures in the lower Klamath River for 2001 through 2005 are shown in Figure 32. Monthly averages over this five year period reflect the seasonal changes as expected and are as follows: June 18.5° C; July 22.5° C, August 22.4° C; September 19.2° C; and October 15.4° C. Also shown in Figure 32 are the ratios of K_T/K_{20} based on the calculation using $1.07^{(T-20)}$, and again the seasonal changes in temperature values less than K_{20} in June, values greater in July and August, and then values less than in September and significantly less than in October. Average monthly values over the five-year period are: June 0.90; July 1.19; August 1.18; September 0.95; and October 0.74. Thus, from July to October, there is an estimated factor of 1.6 change in reaction rates over this period due to change in temperature.

Estimated temperature effects on the total nitrogen and total phosphorus decay rates in the lower Klamath River can be seen in the monthly decay rates estimated from the simplified modeling in Figure 33. These seasonal changes seem clear for total nitrogen in 2001, 2003, and 2004. Total phosphorus decay rates seem to follow seasonal changes in 2001, 2002, 2004, and 2005. The overall changes in these rates for both total nitrogen and total phosphorus are greater than the factor of 1.6 which could be related to temperature alone suggesting that other loss mechanisms may be involved. However, as Chapra and Reckow (1983) caution, for some reactions in natural waters θ can vary significantly within the temperature fluctuations encountered. Thus, these results should be used with caution, and further work is needed to clarify the role of temperature on these temperature-dependent decay rates.

5.0 ANALYSIS OF RESULTS

The coherence of nutrient loads to the lower Klamath River and the nutrient concentrations in the River as contained in the AFWO grab sample water quality database has been tested using a mass balance approach, i.e., the in-stream concentrations of nutrients in the lower Klamath River are a result of the balance of mass inputs from headwaters (Iron Gate Reservoir), major gauged tributaries (Shasta, Scott, Salmon, and Trinity Rivers), and minor ungauged tributaries. They are also the result of nutrient mass loss mechanisms that cause concentrations in the river to decrease with distance downstream from these mass input points. This mass balance approach is embodied in mass balance-based water quality models, and one of those models appropriate to the lower Klamath River is the plug flow model which is useful for general assessment of the impact of nutrient loads to an advective riverine system. Its assumptions of mass balances at points of discharge, the dominance of advective transport over dispersive transport in transporting materials downstream in fast moving rivers like the lower Klamath River, and mass loss mechanisms being accounted for by an overall decay coefficient are appropriate. A model of this nature can provide very useful insights about how a system like the lower Klamath River will respond to flow changes and constituent loads in a quick and relatively inexpensive way compared to more sophisticated and complex water quality models.

The plug flow model for total phosphorus appears to be appropriate for the lower Klamath River and to represent flows, total dissolved solids, total phosphorus, and total nitrogen concentrations successfully under a variety of flow and constituent loading conditions. Calculated cumulative flows match measured flows in the River very accurately, and calculated constituent concentrations match measured concentrations fairly well in 2001 and in 2005. The measured values for 2001 may have been influenced by some of the factors noted in Armstrong and Ward (2007); they and the 2005 measured values could also be influenced by the averaging of data from several sources to arrive at monthly averages.

From the presentation of data and modeling results above, it is evident that there are two dominant influences on water quality in the lower Klamath River. The first is the release from Iron Gate Reservoir. While the flows out of Iron Gate Reservoir in the months and years studied are not particularly large, the concentrations of total phosphorus and total nitrogen are. These concentrations drop downstream due primarily to diluting flows from the major and minor tributaries as well as biological activity during the warmer months. If the total phosphorus or total nitrogen concentration in the Iron Gate release is high, then their concentrations tend to stay high downstream until they are diluted by lower nutrient content inflows from major and minor tributaries. If the total phosphorus or total nitrogen concentration in the Iron Gate release is low, then concentrations are low throughout the lower Klamath River.

It was also noted that total phosphorus and total nitrogen concentrations typically increase in the Iron Gate release between June and October while flows decreased from June to July then increased again through October. Whether this is a consistent pattern from year to year beyond 2001 through 2005 has not been determined. If it is a consistent pattern, then water quality characteristics in the reservoir and operation of the reservoir need to be examined for causative effects on release water quality.

6.0 CONCLUSIONS

The following conclusions may be drawn from this study:

1. A simplified plug flow water quality model has been applied successfully to the lower Klamath River to represent flows, total dissolved solids, total phosphorus, and total nitrogen concentrations;
2. The plug flow model has been applied to total dissolved solids, total nitrogen, and total phosphorus for June through October for 2001 through 2005 – a total of 75 different workbooks were created in the process;
3. Through calibration and sensitivity analyses, the apparent decay rate for total phosphorus and total nitrogen was very low during the cooler months of June, September, and October and significantly higher during the warmer months of July and August;
4. Through further sensitivity analyses, it was apparent that constituent concentrations in the lower Klamath River overall are driven by the releases from the Iron Gate Reservoir, that the upper portion of the lower Klamath River is heavily influenced by the total phosphorus and total nitrogen concentration in the release from the Iron Gate Reservoir and that the lower portion of the river is heavily influenced, primarily via dilution, by the inflows from the major and minor tributaries;
5. Water quality characteristics in Iron Gate Reservoir and/or operational patterns may influence the decrease in release flows and increase in total phosphorus and total nitrogen concentration noted between June and September in each of 2001 through 2005; and
6. The total phosphorus and total nitrogen water quality models appear to be useful for addressing water resources and water quality management plans in the lower Klamath River.

7.0 RECOMMENDATIONS

Based on the results and conclusions of this study, it is recommended that:

1. The utility of the simplified model for addressing water resources and water quality management issues be assessed; and
2. Factors that influence water releases and the water quality, specifically total phosphorus and total nitrogen concentrations, leaving Iron Gate Reservoir be determined for possible consideration in water resources and water quality management plans for the Reservoir.

8.0 REFERENCES

Armstrong, Neal E. and George H. Ward. 2007. Evaluation of Nutrient Loading. Prepared for: Paul Zedonis, U.S. Fish and Wildlife Service, Arcata Fish and Wildlife Office, 1655 Heindon Rd., Arcata, CA 95521.

Armstrong, Neal E. and George H. Ward. 2005. Review of the AFWO Klamath River Grab Sample Water Quality Database. Prepared for: Paul Zedonis, U.S. Fish and Wildlife Service, Arcata Fish and Wildlife Office, 1655 Heindon Rd., Arcata, CA 95521.

Chapra, Steven C. and Kenneth H. Reckow. 1983. Engineering Approaches for Lake Management, Volume 2: Mechanistic Modeling. Butterworth Publishers, Boston.

Kier Associates and Aquatic Ecosystem Sciences LLC. 2006. Analysis of Klamath River Nutrient Loads, 1996-2004. Prepared for the Yurok Tribe Environmental Program, June.

Thomann, Robert V. and John A. Mueller. 1987. Principles of Surface Water Quality Modeling and Control. Harper & Row, Publishers, New York.

U.S. Geological Survey. 2005. USGS Surface Water – Data for the Nation at http://waterdata.usgs.gov/nwis/sw, see Field Measurements.

Ward, George H. and Neal E. Armstrong. 2006. Hydrological features of Lower Klamath River and tributaries. Memorandum to U.S. Fish and Wildlife Service, Arcata Office, January 15.

Table 1 Monthly average flows used for simplified water quality modeling in the lower Klamath River at Iron Gate and at Terwer for June through October of 2001 through 2005.

Year	Month	Monthly Average Flow at Iron Gate (cfs)	Monthly Average Flow at Iron Gate (cms)	Monthly Average Flow near Klamath (plotted as Terwer) (cfs)	Monthly Average Flow near Klamath (plotted as Terwer) (cms)	Ratio of Flows at Terwer and Iron Gate
2001	June	1,897	53.7	6,006	170.1	3.17
	July	1,012	28.7	3,271	92.6	3.23
	August	1,023	29.0	2,713	76.8	2.65
	September	1,026	29.1	2,601	73.7	2.54
	October	1,308	37.0	3,447	97.6	2.64
2002	June	993	28.1	6,528	184.9	6.57
	July	837	23.7	3,187	90.3	3.81
	August	666	18.9	2,327	65.9	3.49
	September	813	23.0	1,993	56.4	2.45
	October	1,047	29.7	2,405	68.1	2.30
2003	June	1,304	36.9	12,902	365.4	9.89
	July	827	23.4	5,201	147.3	6.29
	August	996	28.2	3,463	98.1	3.48
	September	1,254	35.5	3,383	95.8	2.70
	October	1,366	38.7	3,057	86.6	2.24
2004	June	953	27.0	9,473	268.3	9.94
	July	674	19.1	4,382	124.1	6.50
	August	752	21.3	2,964	83.9	3.94
	September	913	25.9	3,049	86.3	3.34
	October	926	26.2	3,087	87.4	3.33
2005	June	1,222	34.6	14,443	409.0	11.82
	July	925	26.2	6,487	183.7	7.01
	August	999	28.3	3,647	103.3	3.65
	September	1,179	33.4	3,123	88.4	2.65
	October	1,357	38.4	3,584	101.5	2.64

Table 2. Relative errors for modeling of flow, total dissolved solids, total nitrogen and total phosphorus in the lower Klamath River for June through October and 2001 through 2005.

Relative Error

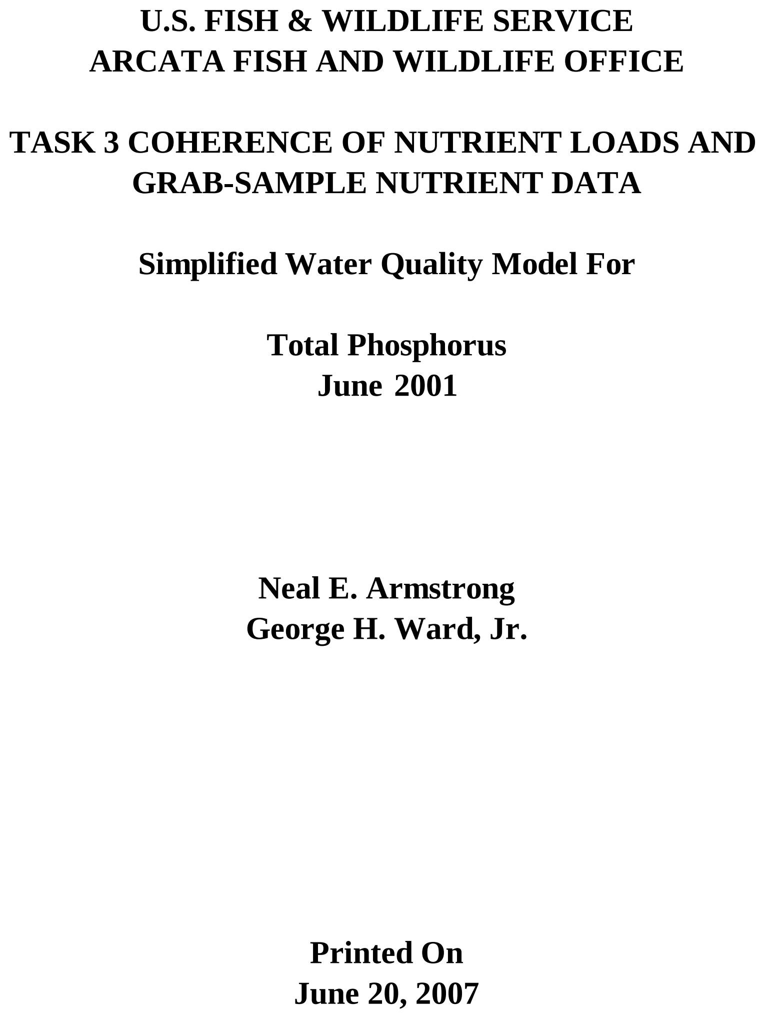
Year	Month	Flow	Total Dissolved Solids	Total Nitrogen	Total Phosphorus	Comments
2001	June	0.16	6.6	12.4	12.2	
	July	0.26	1.5	9.9	8.2	
	August	0.12	5.3	17.7	15.0	
	September	0.34	5.1	17.6	7.2	
	October	0.20	2.1	7.9	15.7	
2002	June	0.28	6.2	18.6	7.4	
	July	0.32	12.9	17.9	9.3	
	August	0.36	2.7	25.5	10.6	
	September	0.17	6.2	7.9	10.0	
	October	0.21	5.9	18.7	11.3	
2003	June	0.30	1.7	20.5	14.3	* TN
	July	0.38	9.6	18.7	5.0	* TN
	August	0.35	4.9	2.2	4.7	
	September	0.16	31.2	6.6	8.6	* TN
	October	0.23				** TDS, TN, TP
2004	June	0.32	4.1	16.8	11.3	
	July	0.38	2.4	28.1	22.4	
	August	0.31	3.2	48.6	13.6	
	September	0.21	4.8	28.2	14.9	
	October	1.18	3.3	30.1		* TN, ** TP, negative tributary flows
2005	June	0.34	7.9	24.7	10.0	
	July	0.41	10.0	102.5	7.8	
	August	0.37	32.7	41.1	18.8	
	September	0.20	10.7	9.2	2.7	
	October	0.28	15.1	42.5	10.8	* TN

Legend:

* One or more comparative values are averages of monthly average values

** No measured values for comparison

Relative error (%) calculated as: $\text{relative error} = \frac{\left|x_{obs} - x_{pred}\right|}{x_{obs}} \text{x} 100$



U.S. FISH & WILDLIFE SERVICE
ARCATA FISH AND WILDLIFE OFFICE

TASK 3 COHERENCE OF NUTRIENT LOADS AND
GRAB-SAMPLE NUTRIENT DATA

Simplified Water Quality Model For

Total Phosphorus
June 2001

Neal E. Armstrong
George H. Ward, Jr.

Printed On
June 20, 2007

Figure 1. Title page spreadsheet of the simplified water quality model workbook for the lower Klamath River.

SIMPLIFIED WATER QUALITY MODEL FOR THE KLAMATH RIVER
POINT SOURCE LOADING
Total Phosphorus
June 2001

Location	Permit No.	Point Source Inflow (mgd)	(cfs)	(cms)	Constit. Conc. (mg/L)	Constit. Load (kg/d)

(As point sources are identified, they will be added to this worksheet)

Figure 2. Point source wastewater discharge spreadsheet of the simplified water quality model workbook for the lower Klamath River.

SIMPLIFIED WATER QUALITY MODEL FOR THE KLAMATH RIVER
TRIBUTARY LOADING
Total Phosphorus
June 2001

USGS Station No.	Station Name	Drainage Area (mi^2)	Drainage Area (km^2)	Flow (cfs)	Flow (cms)	Constit. Conc. (mg/L)	Constit. Load (kg/d)
11516530	Klamath River below Iron Gate Da	4,630	11,992	1,897	53.7	0.128	594.1
11517500	Shasta River near Yreka	793	2,054	26	0.7	0.41	26.1
11519500	Scott River near Fort Jones	653	1,691	50	1.4	0.04	4.9
11522500	Salmon River at Somes Bar	751	1,945	408	11.6	0.02	20.0
11530000	Trinity River at Hoopa	2,853	7,389	1,569	44.4	0.185	710.2

Figure 3. Major tributary spreadsheet of the simplified water quality model workbook for the lower Klamath River.

SIMPLIFIED WATER QUALITY MODEL FOR THE KLAMATH RIVER
NONPOINT SOURCE LOADING
Total Phosphorus
June 2001

Creek Name	River Mile	Reach	Watershed Area (mi^2)	Watershed Area (km^2)	Adjusted Watershed Area (km^2)	Flow Yield (in/mo)	Flow Yield (m^3/m^2/mo)	Flow (m^3/mo)	Flow (cfs)	Flow (m^3/s)	Constit. Avg. Conc. (mg/L)
Little Bogus	187.00	Iron Gate to Seiad	20.8	38.4	53.8	0.16	0.0041	218,481	2.9	0.1	0.013
Willow Cr.	185.00	Iron Gate to Seiad	81.7	151.1	211.5	0.16	0.0041	859,699	11.6	0.3	0.013
Cottonwood Cr.	182.00	Iron Gate to Seiad	138.9	257.0	359.8	0.16	0.0041	1,462,227	19.6	0.6	0.013
Humburg Cr.	171.48	Iron Gate to Seiad	51.6	95.5	133.7	0.16	0.0041	543,357	7.3	0.2	0.013
Beaver Cr.	161.00	Iron Gate to Seiad	151.2	279.8	391.7	0.16	0.0041	1,591,950	21.4	0.6	0.015
Barkhouse Cr.	157.31	Iron Gate to Seiad	22.4	41.5	58.1	0.16	0.0041	236,118	3.2	0.1	0.013
Horse Cr.	147.40	Iron Gate to Seiad	85.2	157.7	220.8	0.16	0.0041	897,250	12.1	0.3	0.013
Scott Tribs	143.00	Iron Gate to Seiad	213.8	395.5	553.7	0.16	0.0041	2,250,237	30.2	0.9	0.013
Grider Cr.	130.29	Iron Gate to Seiad	64.5	119.4	167.2	0.16	0.0041	679,338	9.1	0.3	0.013
Seiad Cr.	130.06	Iron Gate to Seiad	38.1	70.4	98.6	0.16	0.0041	400,548	5.4	0.2	0.013
Thompson Cr.	123.00	Seiad to Orleans	55.0	94.1	142.6	0.36	0.0091	1,303,582	17.5	0.5	0.013
Indian Cr.	106.73	Seiad to Orleans	179.6	307.0	465.1	0.36	0.0091	4,252,920	57.1	1.6	0.013
Elk Cr.	105.46	Seiad to Orleans	143.7	245.7	372.2	0.36	0.0091	3,403,721	45.7	1.3	0.013
Clear Cr.	98.57	Seiad to Orleans	166.9	285.4	432.4	0.36	0.0091	3,953,692	53.1	1.5	0.013
Independence Cr.	94.00	Seiad to Orleans	27.3	46.7	70.8	0.36	0.0091	646,943	8.7	0.2	0.013
Ukonom Cr.	89.88	Seiad to Orleans	49.5	84.6	128.2	0.36	0.0091	1,171,977	15.7	0.4	0.013
Dillon Cr.	84.00	Seiad to Orleans	109.6	187.3	283.8	0.36	0.0091	2,594,697	34.9	1.0	0.013
Rock Cr.	79.04	Seiad to Orleans	50.4	86.1	130.4	0.36	0.0091	1,192,757	16.0	0.5	0.013
Camp Cr.	56.94	Orleans to Klamath Glen	55.2	108.9	143.1	2.43	0.0617	8,832,085	118.7	3.4	0.013
Boise Cr.	55.53	Orleans to Klamath Glen	20.4	40.2	52.8	2.43	0.0617	3,260,329	43.8	1.2	0.013
Red Cap Cr.	52.71	Orleans to Klamath Glen	80.2	158.0	207.6	2.43	0.0617	12,814,228	172.2	4.9	0.013
Bluff Cr.	49.54	Orleans to Klamath Glen	97.5	192.2	252.6	2.43	0.0617	15,587,940	209.4	5.9	0.013
Trinity Trib.	43.42	Orleans to Klamath Glen	152.4	300.3	394.6	2.43	0.0617	24,355,143	327.2	9.3	0.013
Little Pine	40.75	Orleans to Klamath Glen	60.7	119.7	157.3	2.43	0.0617	9,707,994	130.4	3.7	0.013
Tully Cr.	38.54	Orleans to Klamath Glen	22.5	44.3	58.2	2.43	0.0617	3,592,850	48.3	1.4	0.013
Roach Cr.	31.49	Orleans to Klamath Glen	37.9	74.7	98.2	2.43	0.0617	6,058,372	81.4	2.3	0.013
Pecwan Cr.	25.37	Orleans to Klamath Glen	36.3	71.6	94.1	2.43	0.0617	5,806,954	78.0	2.2	0.013
Tectah Cr.	22.00	Orleans to Klamath Glen	25.2	49.6	65.2	2.43	0.0617	4,022,694	54.0	1.5	0.013
Ah Pah Cr.	17.17	Orleans to Klamath Glen	20.1	39.7	52.2	2.43	0.0617	3,219,778	43.3	1.2	0.013
Blue Cr.	16.28	Orleans to Klamath Glen	164.0	323.2	424.7	2.43	0.0617	26,212,395	352.2	10.0	0.013
		Iron Gate to Seiad	868.3	1,606.3	2,248.8						
		Seiad to Orleans	782.0	1,336.9	2,025.4						
		Orleans to Klamath Glen	772.4	1,522.4	2,000.4						
			2,422.6								
Water-Budget Areas		Iron Gate to Seiad	864								
		Seiad to Orleans	784								
		Orleans to Klamath Glen	772								
			2420								
Adjustment Factor		Iron Gate to Seiad	0.4								
		Seiad to Orleans	0.515								
		Orleans to Klamath Glen	0.314								

Figure 4. Minor tributary spreadsheet of the simplified water quality model workbook for the lower Klamath River.

SIMPLIFIED WATER QUALITY MODEL FOR THE KLAMATH RIVER
Total Phosphorus
June 2001

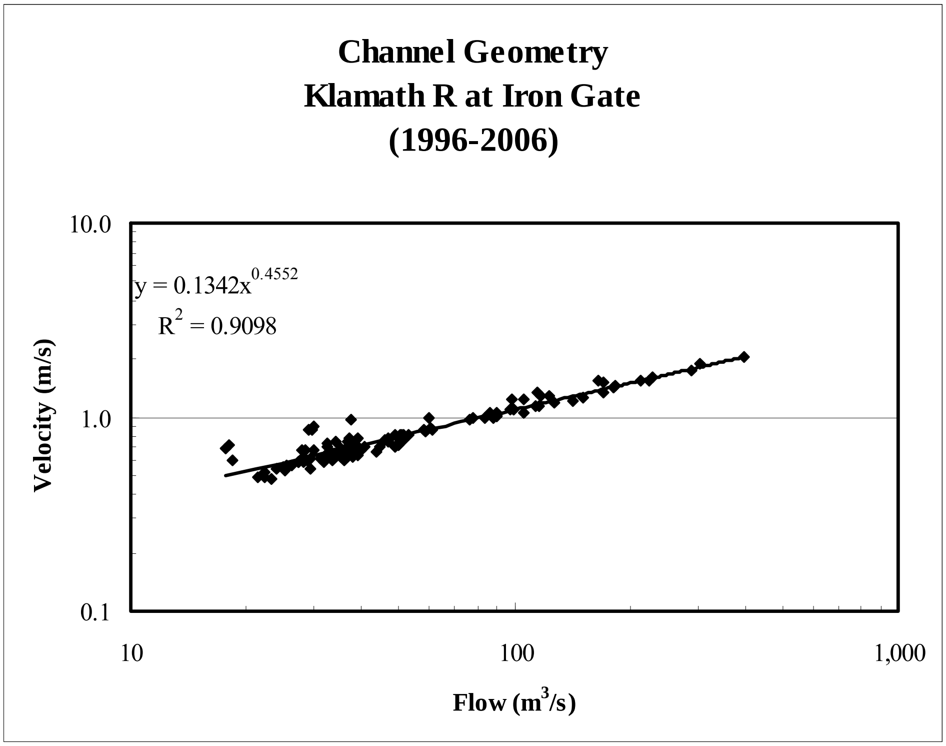
Location	Distance Above Mouth		Dist. Dnstrm.	Incr. Dist. Dnstrm.	Upstream Flow	Upstream Loading	Point Source Flow	Point Source Loading	Trib Flow	Trib Load	Nonpoint Source Flow	Nonpoint Source Loading	Total Flow
	(mi)	(km)	(km)	(km)	(cms)	(kg/d)	(cms)	(kg/d)	(cms)	(kg/d)	(cms)	(kg/d)	(cms)
KLAMATH R. AT IRON GATE	189.8	351.7	0.0	0.0	53.7	594.1							53.72
	189.0	350.2	1.5	1.5									
	188.0	348.4	3.3	1.9									
Little Bogus Cr.	187.0	346.5	5.2	1.9							0.08	0.09	0.08
	186.0	344.7	7.0	1.9									
Willow Cr.	185.0	342.8	8.9	1.9							0.33	0.37	0.33
	184.0	341.0	10.7	1.9									
	183.0	339.1	12.6	1.9									
Cottonwood Cr.	182.0	337.2	14.5	1.9							0.56	0.62	0.56
	181.0	335.4	16.3	1.9									
	180.0	333.5	18.2	1.9									
	179.0	331.7	20.0	1.9									
KLAMATH R. ABOVE SHASTA	178.0	329.8	21.9	1.9									
Shasta River	177.0	328.0	23.7	1.9					0.74	26.1			0.74
	176.0	326.1	25.6	1.9									

Figure 5a. Upper left portion of the water quality model spreadsheet of the simplified water quality model workbook for the lower Klamath River.

R THE KLAMATH RIVER

								k (1/d) =	**0.005**	**0.050**	**0.100**			
Nonpoint Source Flow (cms)	**Nonpoint Source Loading (kg/d)**	**Total Flow (cms)**	**Cum Flow (cms)**	**Total Load (kg/d)**	**Average Velocity (m/s)**	**(km/d)**	**Avg. Depth (m)**	**Constit. Conc. (mg/L)**	**Constit. Conc. (mg/L)**	**Constit. Conc. (mg/L)**	**Cum Flow in Klamath River (cfs)**	**Cum Flow in Klamath River (cms)**	**Constit. Conc. in Klamath River (mg/L)**	
		53.72	53.7	594.1	0.82	71.10	0.81	0.128	0.128	0.128	1,897	54	0.128	
			53.7		0.82	71.10	0.81	0.128	0.128	0.128				
			53.7		0.82	71.10	0.81	0.128	0.128	0.127				
0.08	0.09	0.08	53.8	0.1	0.82	71.15	0.81	0.128	0.127	0.127				
			53.8		0.82	71.15	0.81	0.128	0.127	0.127				
0.33	0.37	0.33	54.1	0.4	0.83	71.34	0.82	0.127	0.126	0.126				
			54.1		0.83	71.34	0.82	0.127	0.126	0.125				
			54.1		0.83	71.34	0.82	0.127	0.126	0.125				
0.56	0.62	0.56	54.7	0.6	0.83	71.67	0.82	0.126	0.125	0.123				
			54.7		0.83	71.67	0.82	0.126	0.125	0.123				
			54.7		0.83	71.67	0.82	0.126	0.124	0.123				
			54.7		0.83	71.67	0.82	0.126	0.124	0.122				
			54.7		0.83	71.67	0.82	0.126	0.124	0.122				
		0.74	55.4	26.1	0.83	72.11	0.82	0.130	0.128	0.126				
			55.4		0.83	72.11	0.82	0.130	0.128	0.125				

Figure 5b. Upper right portion of the water quality model spreadsheet of the simplified water quality model workbook for the lower Klamath River.



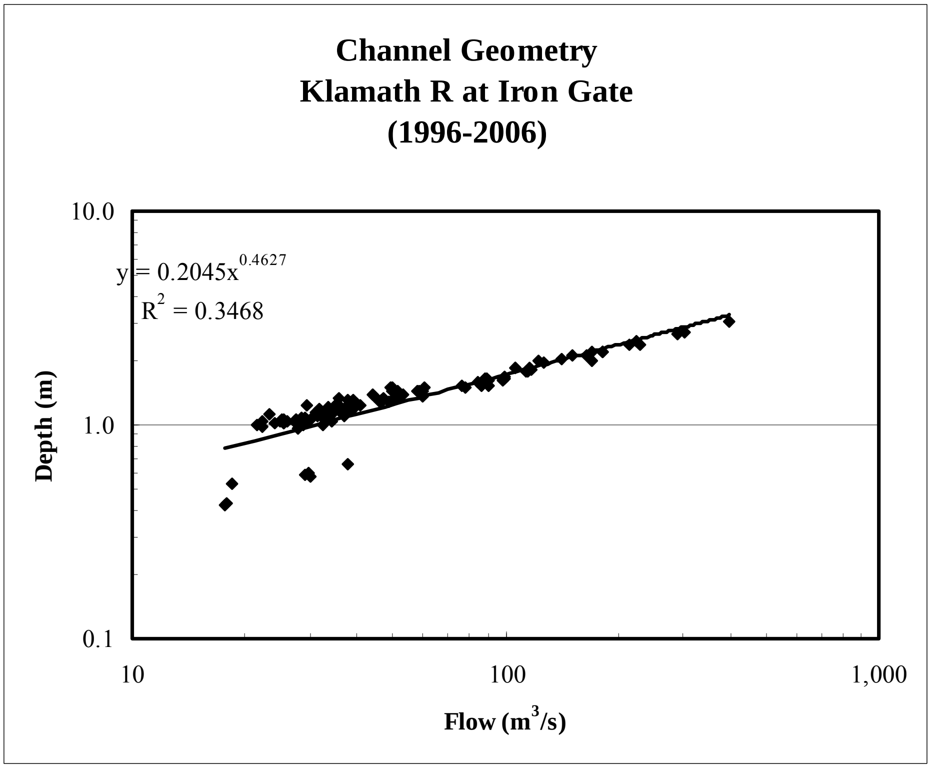
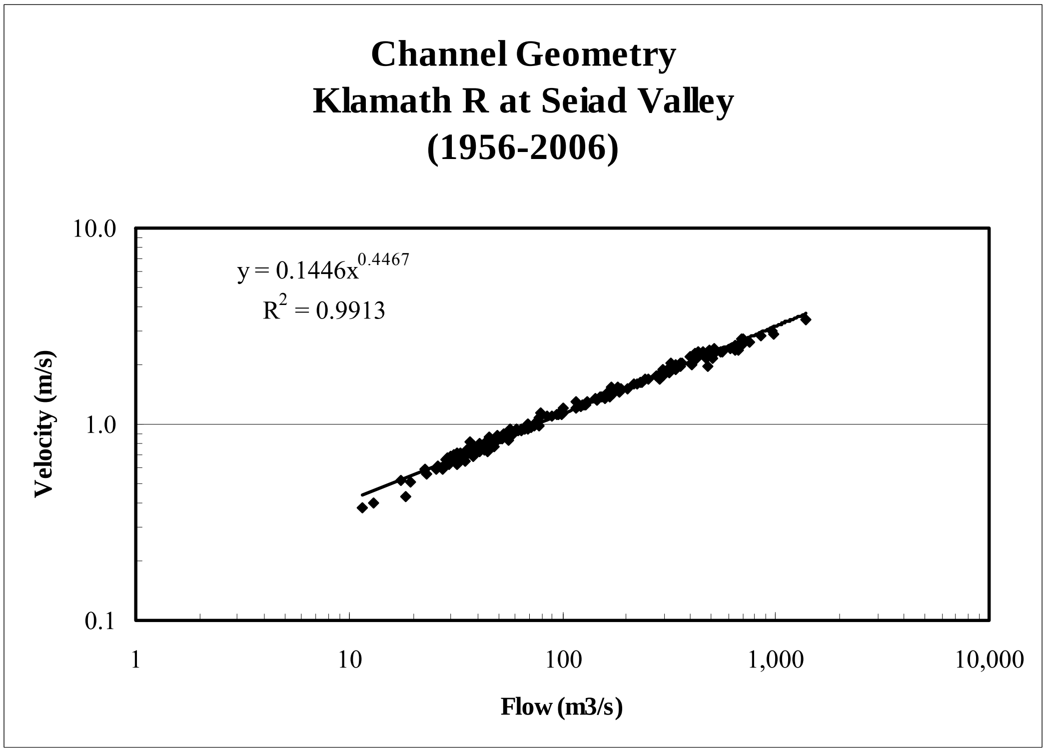


Figure 6. Flow relations in the lower Klamath River at Iron Gate, 1996-2006



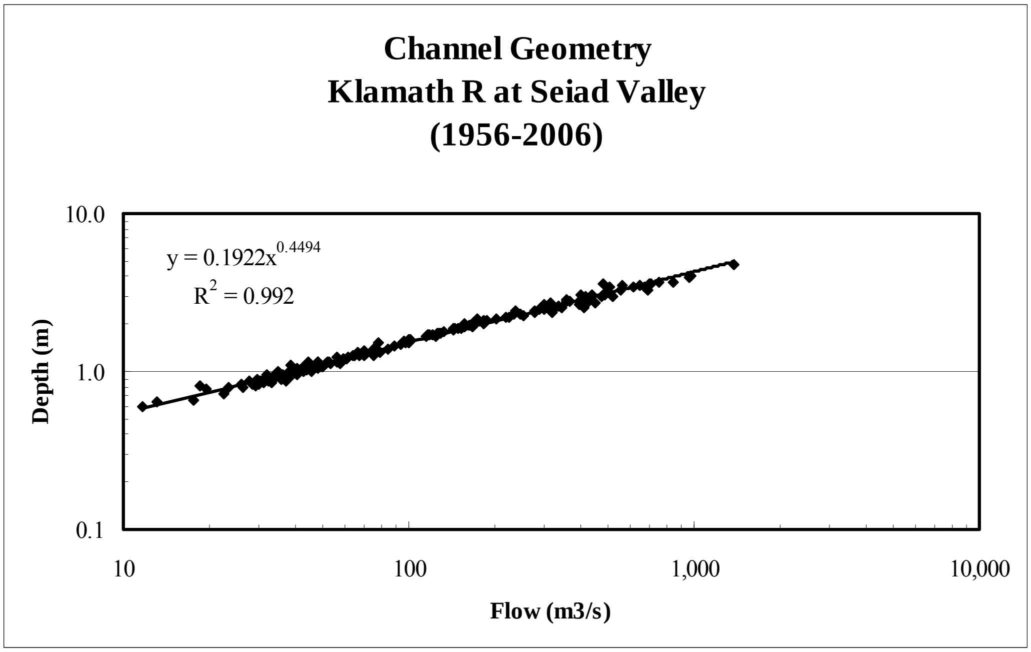
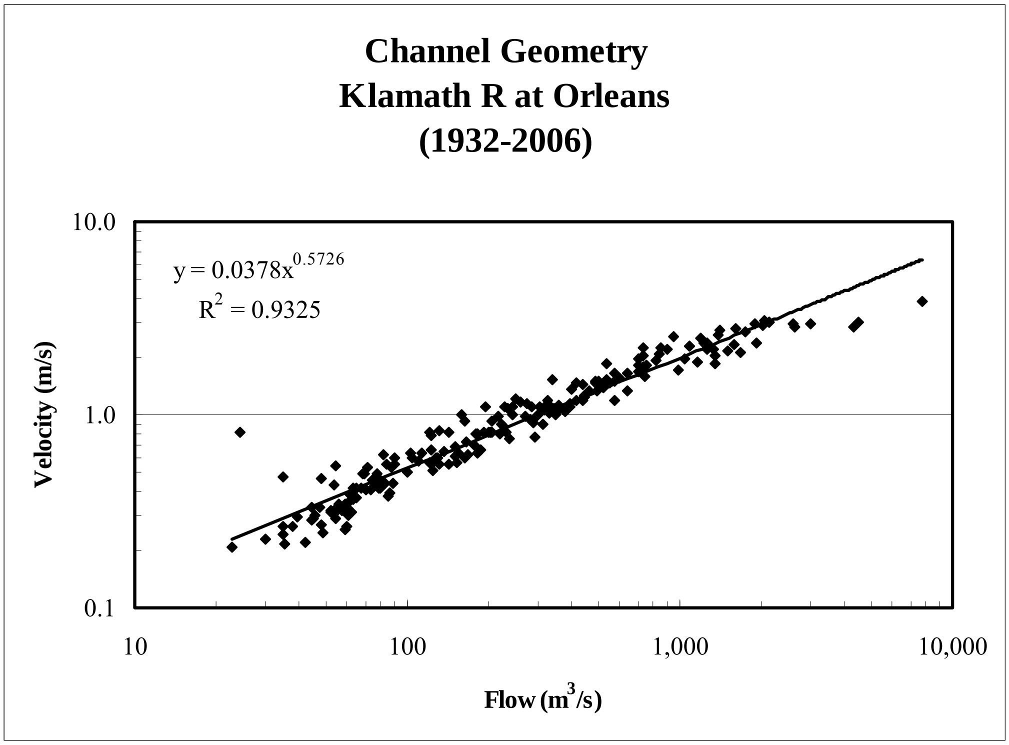


Figure 7. Flow relations in the lower Klamath River at Seiad Valley, 1956-2006.



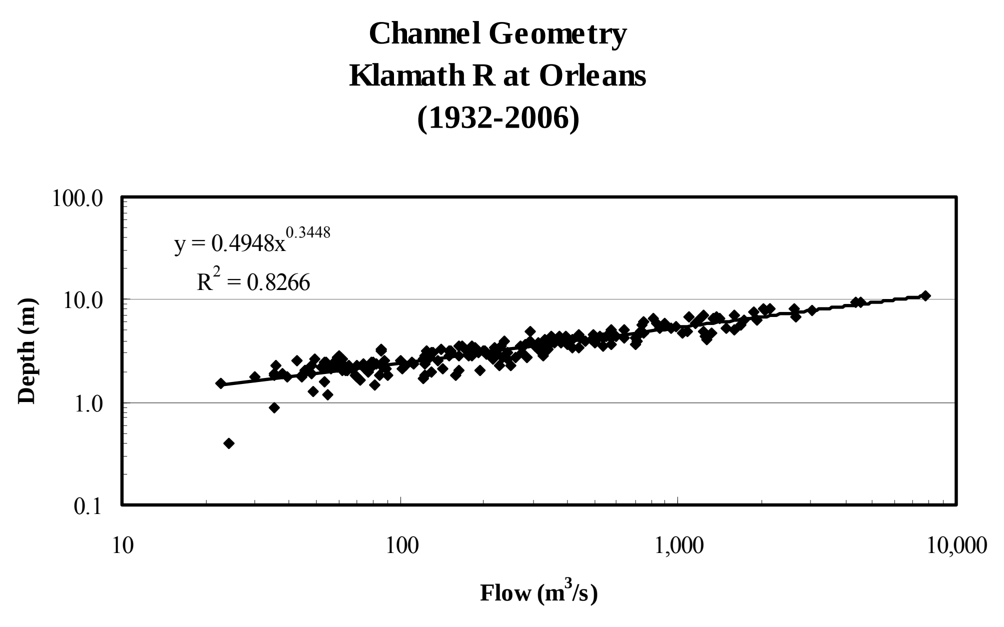
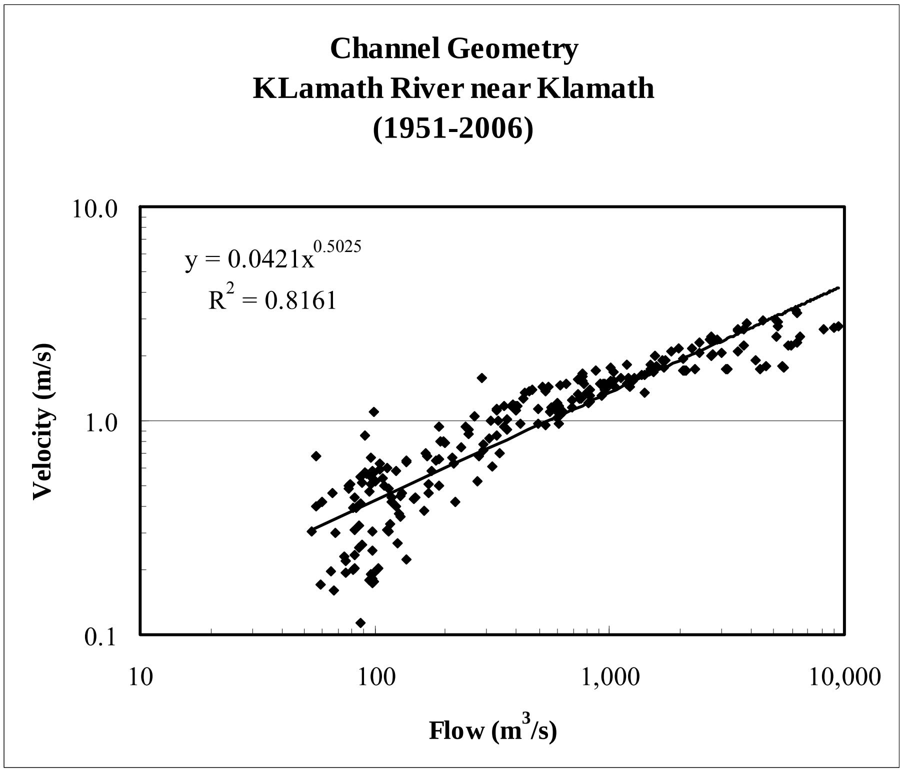


Figure 8. Flow relations in the lower Klamath River at Orleans, 1932-2006.



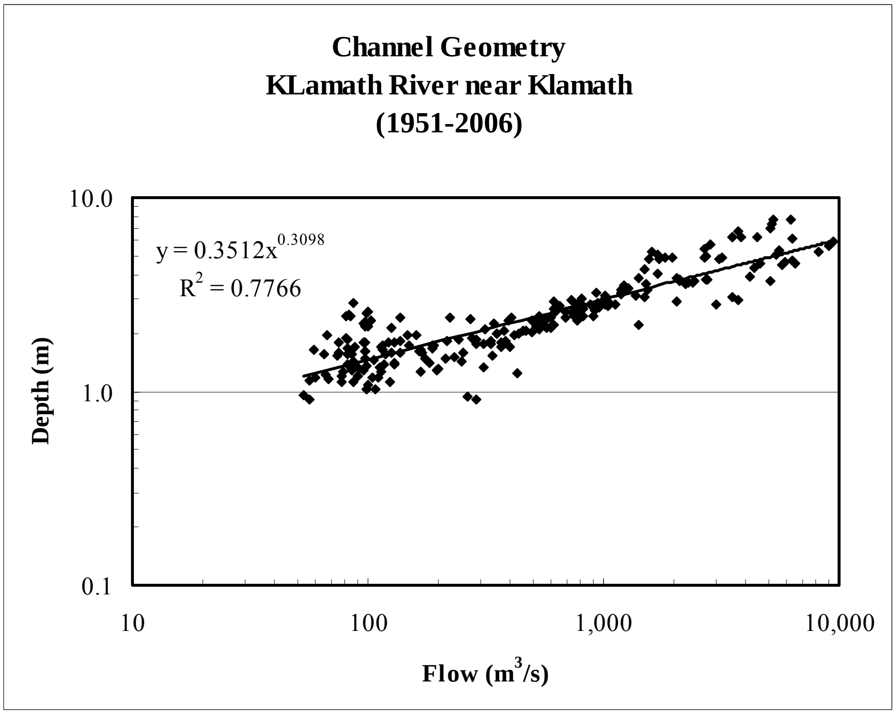
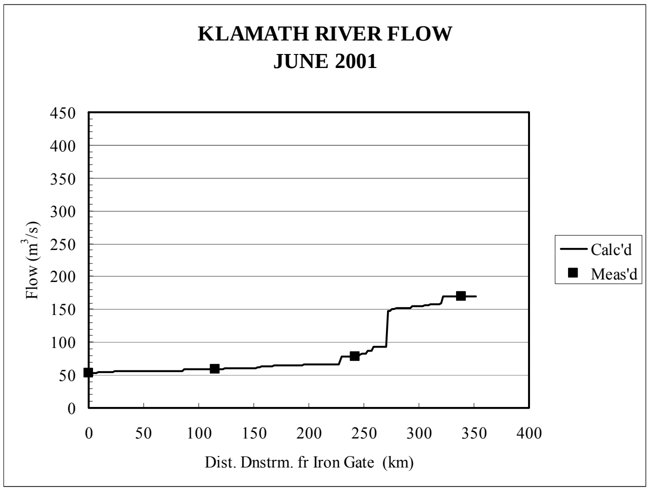
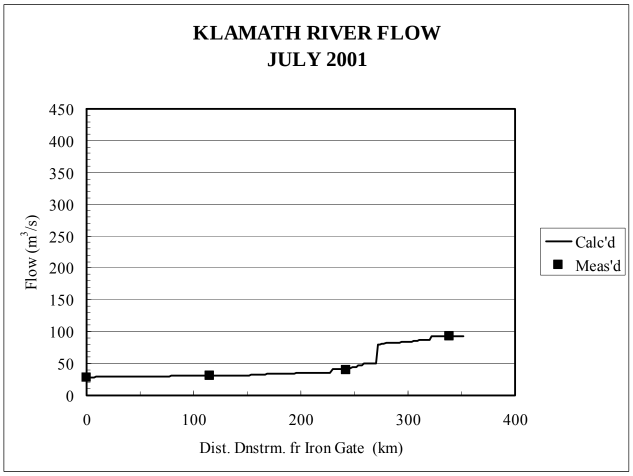
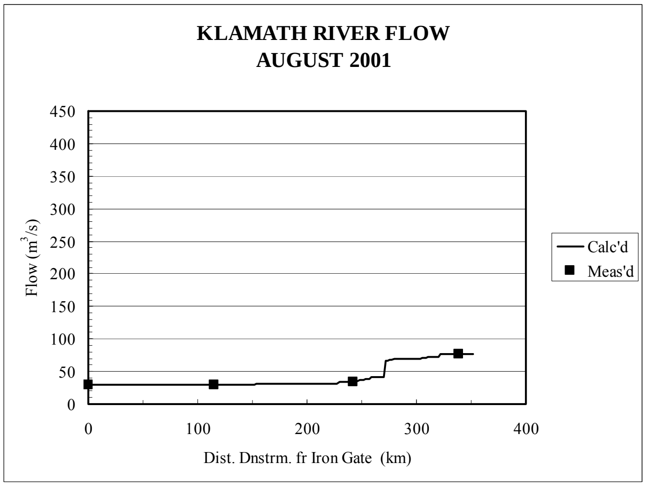
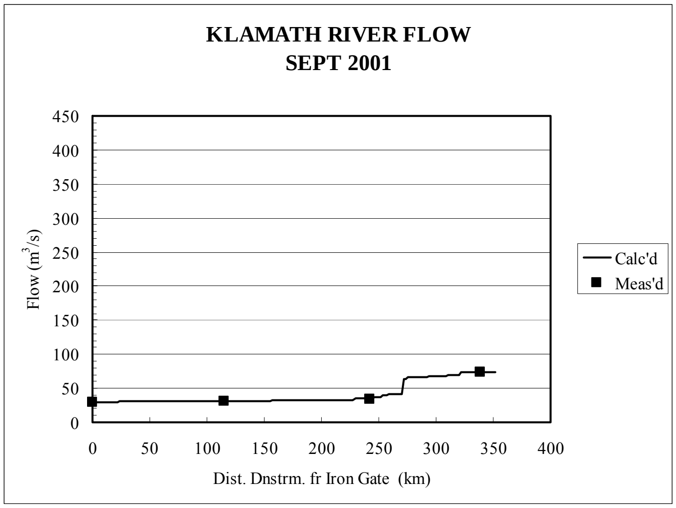


Figure 9. Flow relations in the lower Klamath River near Klamath, 1951-2006.


KLAMATH RIVER FLOW
JUNE 2001
Flow (m3/s)
450
400
350
300
250
200
150
100
50
0
0
50
100
150
200
250
300
350
400
Dist. Dnstrm. fr Iron Gate (km)
Calc'd
Meas'd


KLAMATH RIVER FLOW
JULY 2001
Flow (m3/s)
450
400
350
300
250
200
150
100
50
0
0
100
200
300
400
Dist. Dnstrm. fr Iron Gate (km)
Calc'd
Meas'd


KLAMATH RIVER FLOW
AUGUST 2001
Flow (m3/s)
450
400
350
300
250
200
150
100
50
0
0
100
200
300
400
Dist. Dnstrm. fr Iron Gate (km)
Calc'd
Meas'd



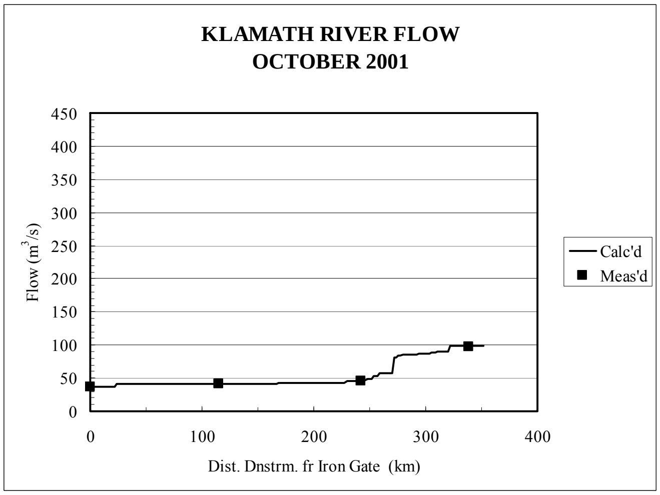
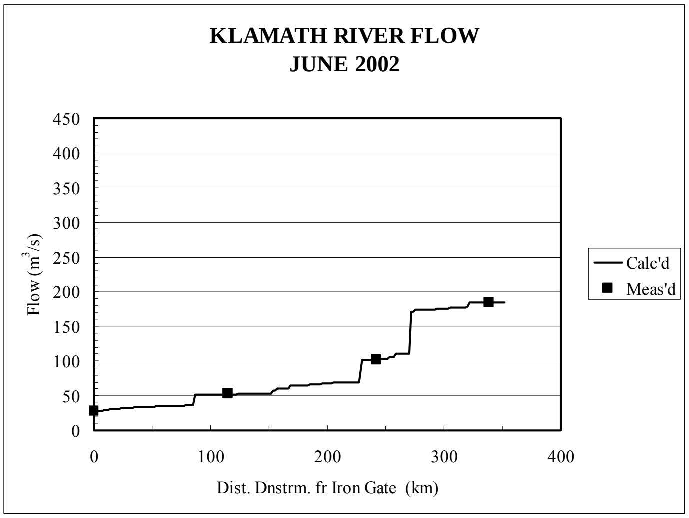
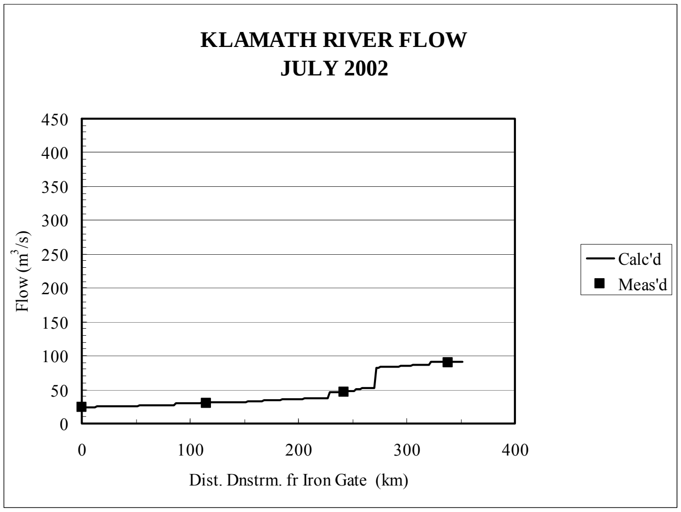
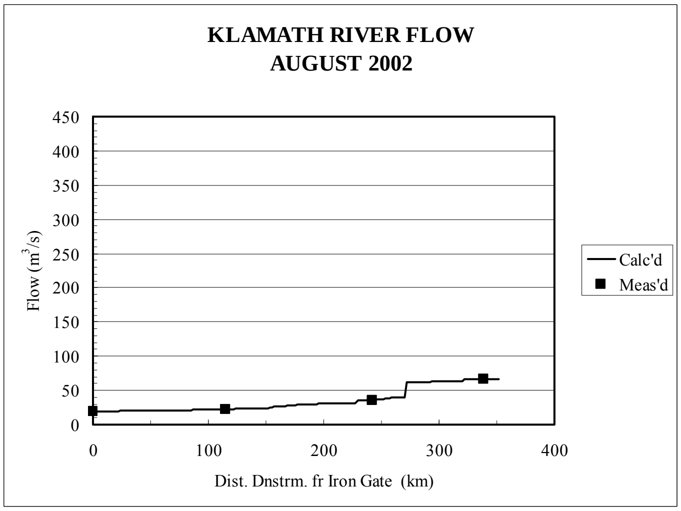
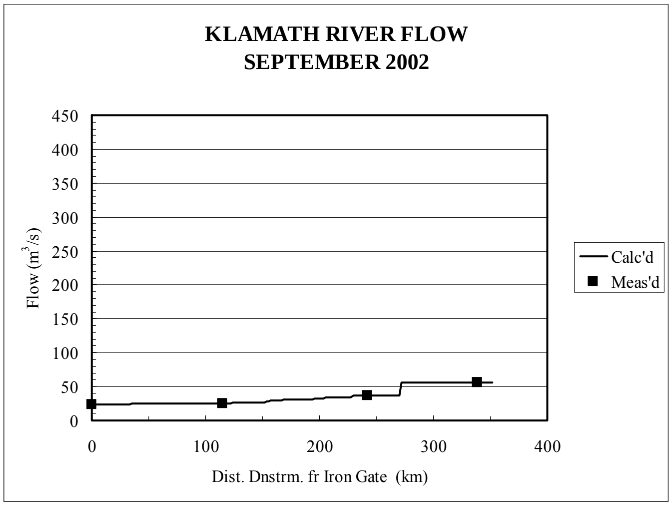


Figure 10. Measured and calculated flows in the Klamath River, June through October 2001.


KLAMATH RIVER FLOW
JUNE 2002
Flow (m^3/s)
450
400
350
300
250
200
150
100
50
0
0
100
200
300
400
Dist. Dnstrm. fr Iron Gate (km)
Calc'd
Meas'd


KLAMATH RIVER FLOW
JULY 2002
Flow (m^3/s)
450
400
350
300
250
200
150
100
50
0
0
100
200
300
400
Dist. Dnstrm. fr Iron Gate (km)
Calc'd
Meas'd


KLAMATH RIVER FLOW
AUGUST 2002
Flow (m^3/s)
450
400
350
300
250
200
150
100
50
0
0
100
200
300
400
Dist. Dnstrm. fr Iron Gate (km)
Calc'd
Meas'd



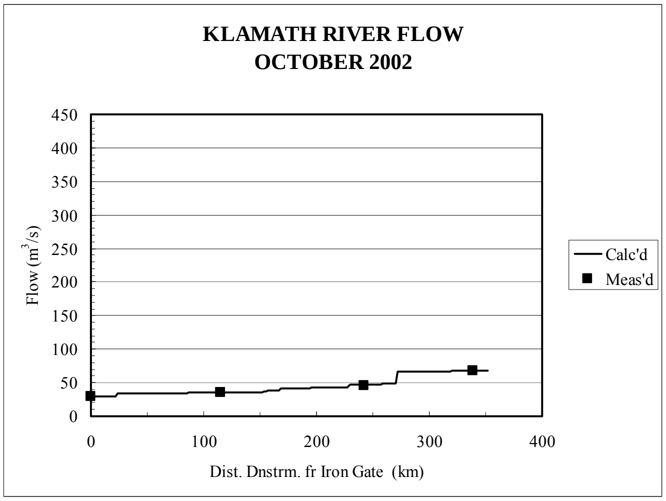
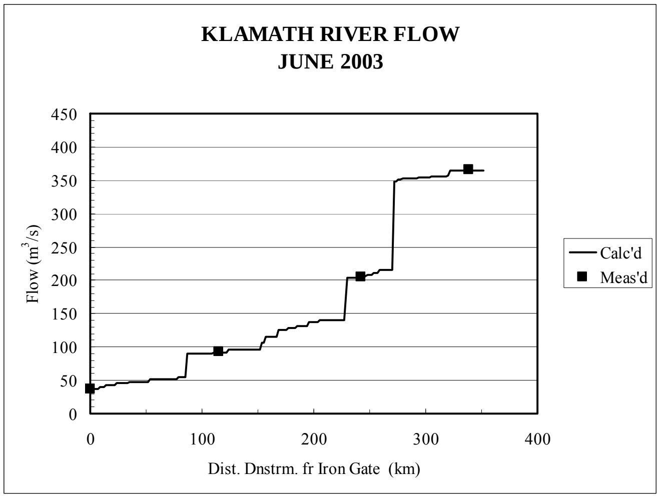
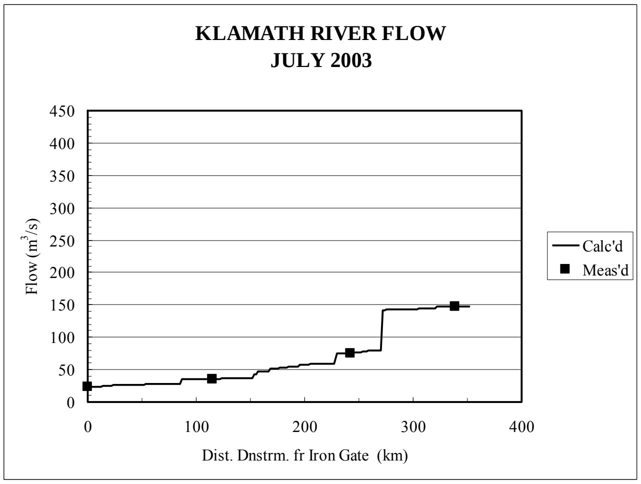
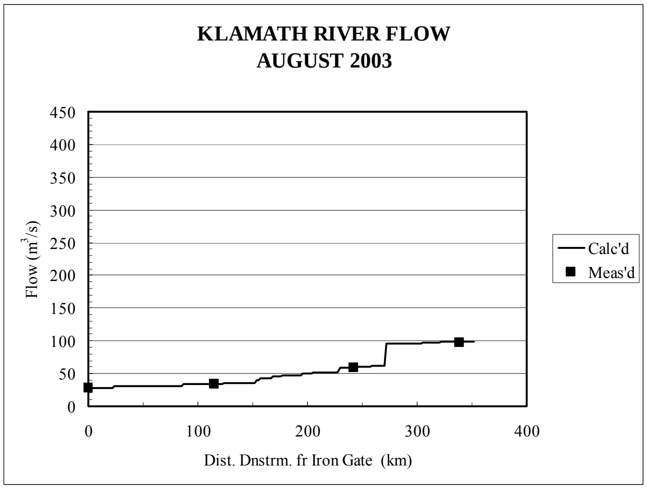
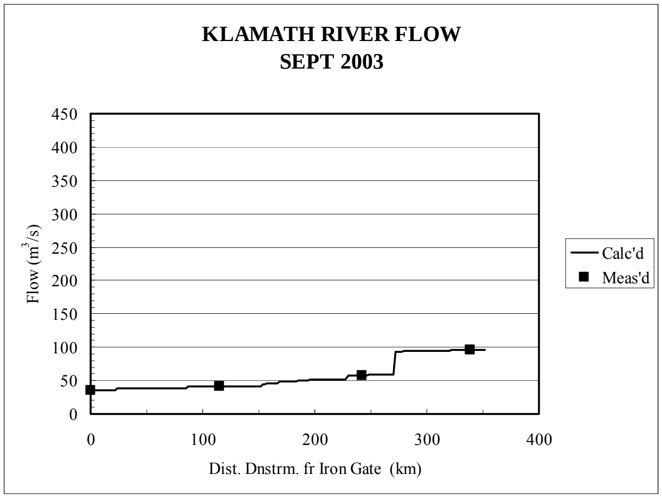


Figure 11. Measured and calculated flows in the Klamath River, June through October 2002.


KLAMATH RIVER FLOW
JUNE 2003
Flow (m^3/s)
0
50
100
150
200
250
300
350
400
450
0
100
200
300
400
Dist. Dnstrm. fr Iron Gate (km)
Calc'd
■ Meas'd


KLAMATH RIVER FLOW
JULY 2003
Flow (m^3/s)
0
50
100
150
200
250
300
350
400
450
0
100
200
300
400
Dist. Dnstrm. fr Iron Gate (km)
Calc'd
■ Meas'd


KLAMATH RIVER FLOW
AUGUST 2003
Flow (m^3/s)
0
50
100
150
200
250
300
350
400
450
0
100
200
300
400
Dist. Dnstrm. fr Iron Gate (km)
Calc'd
■ Meas'd



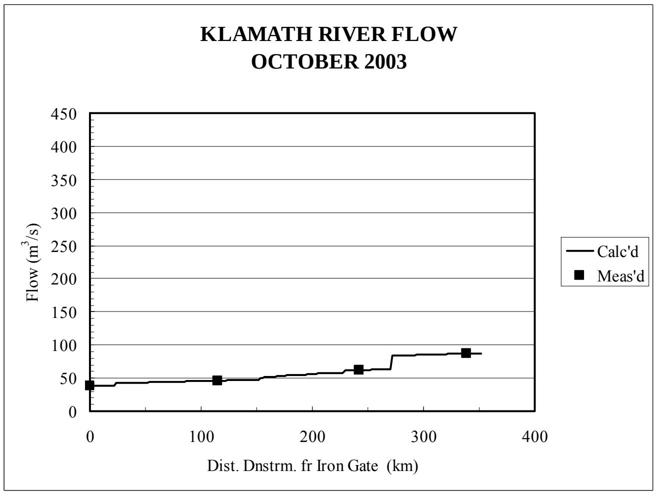
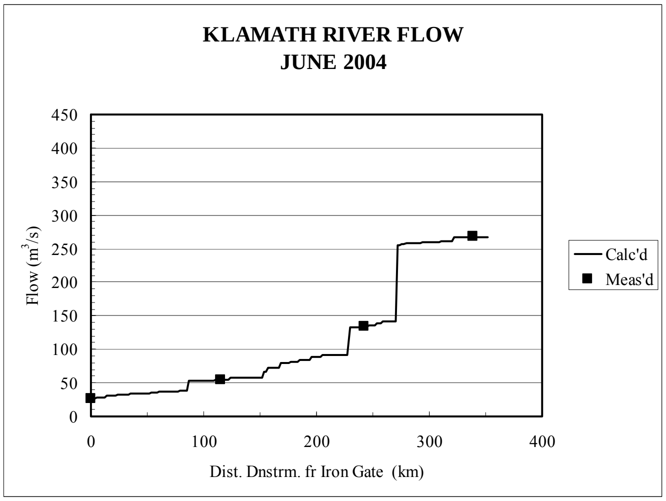
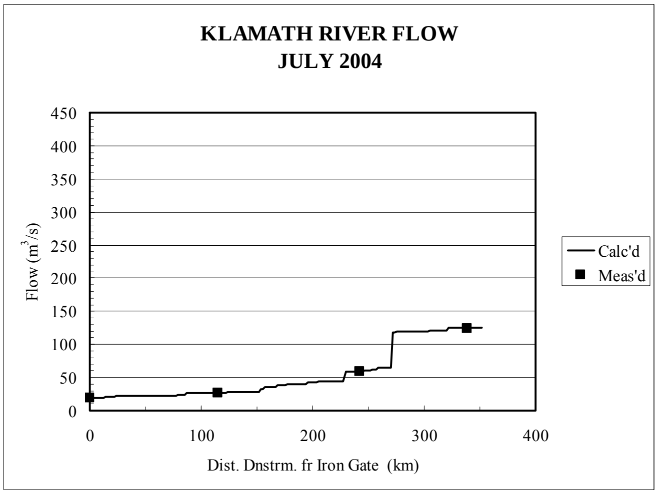
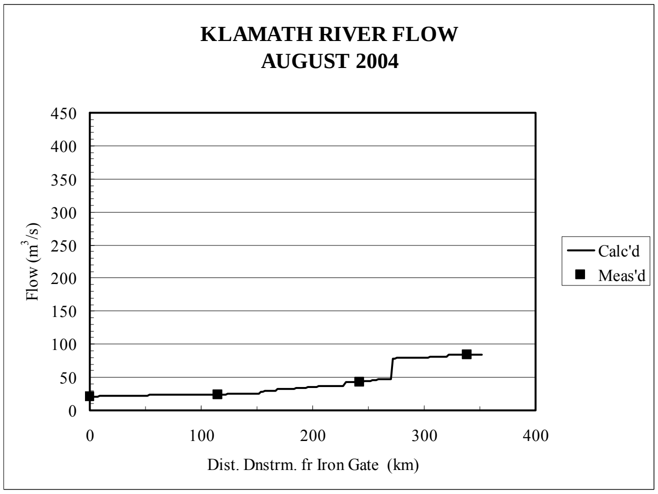
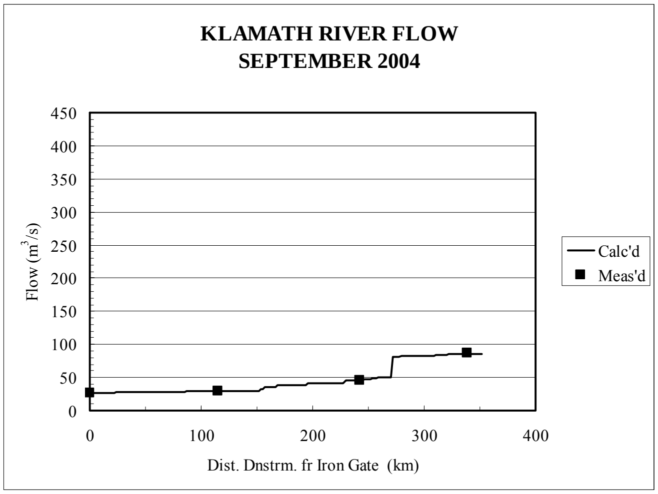


Figure 12. Measured and calculated flows in the Klamath River, June through October, 2003.


KLAMATH RIVER FLOW
JUNE 2004
Flow (m³/s)
0
50
100
150
200
250
300
350
400
450
0
100
200
300
400
Dist. Dnstrm. fr Iron Gate (km)
Calc'd
Meas'd


KLAMATH RIVER FLOW
JULY 2004
Flow (m³/s)
0
50
100
150
200
250
300
350
400
450
0
100
200
300
400
Dist. Dnstrm. fr Iron Gate (km)
Calc'd
Meas'd


KLAMATH RIVER FLOW
AUGUST 2004
Flow (m³/s)
0
50
100
150
200
250
300
350
400
450
0
100
200
300
400
Dist. Dnstrm. fr Iron Gate (km)
Calc'd
Meas'd



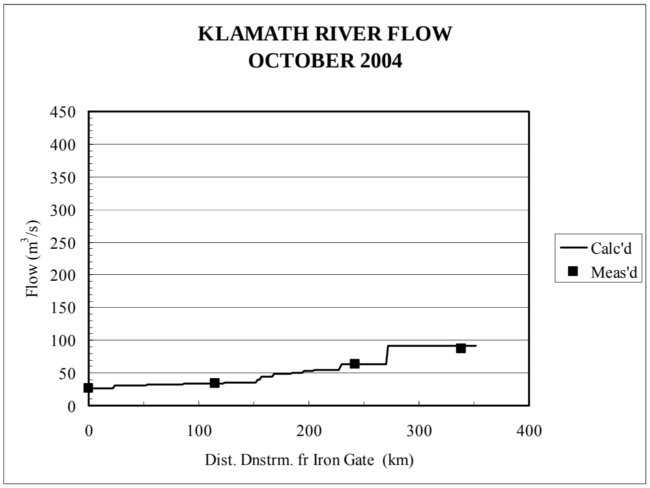
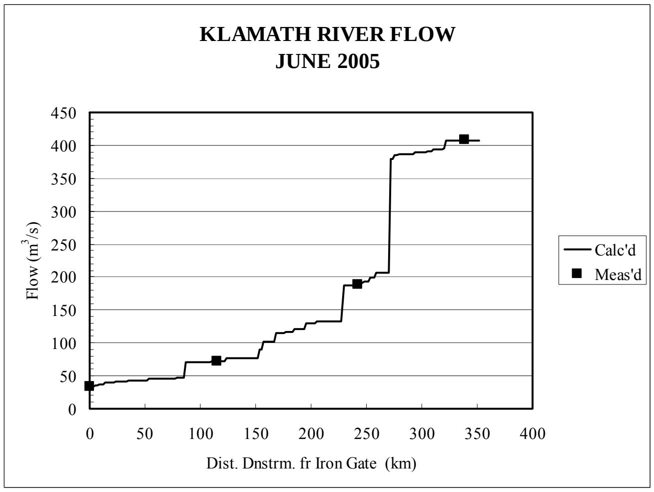
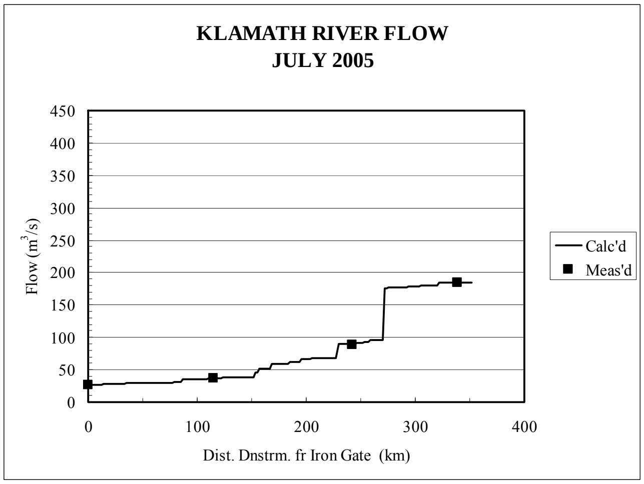
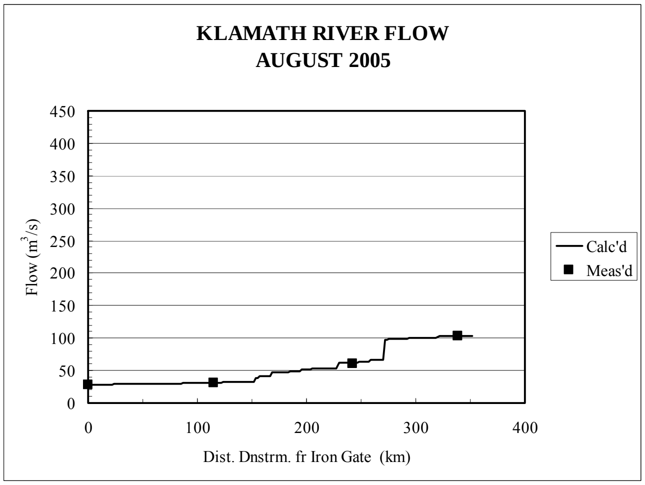
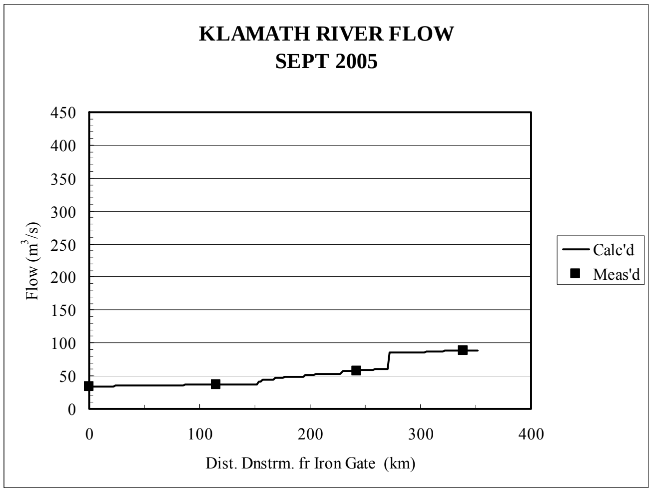


Figure 13. Measured and calculated flows in the Klamath River, June through October, 2004.


KLAMATH RIVER FLOW
JUNE 2005
Flow (m3/s)
450
400
350
300
250
200
150
100
50
0
0
50
100
150
200
250
300
350
400
Dist. Dnstrm. fr Iron Gate (km)
Calc'd
Meas'd


KLAMATH RIVER FLOW
JULY 2005
Flow (m3/s)
450
400
350
300
250
200
150
100
50
0
0
100
200
300
400
Dist. Dnstrm. fr Iron Gate (km)
Calc'd
Meas'd


KLAMATH RIVER FLOW
AUGUST 2005
Flow (m3/s)
450
400
350
300
250
200
150
100
50
0
0
100
200
300
400
Dist. Dnstrm. fr Iron Gate (km)
Calc'd
Meas'd



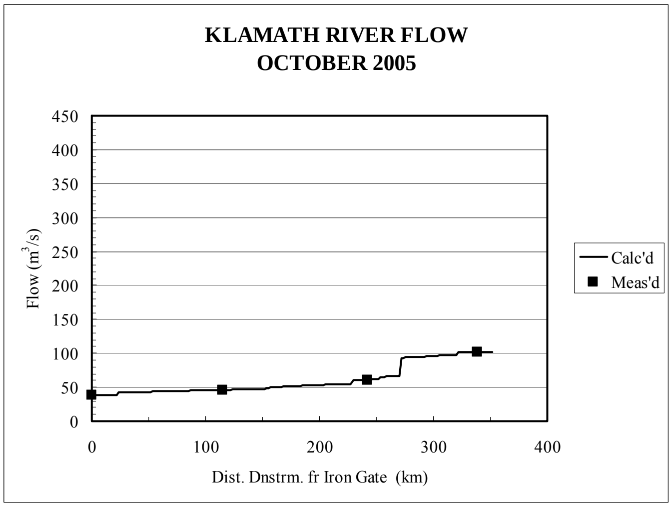
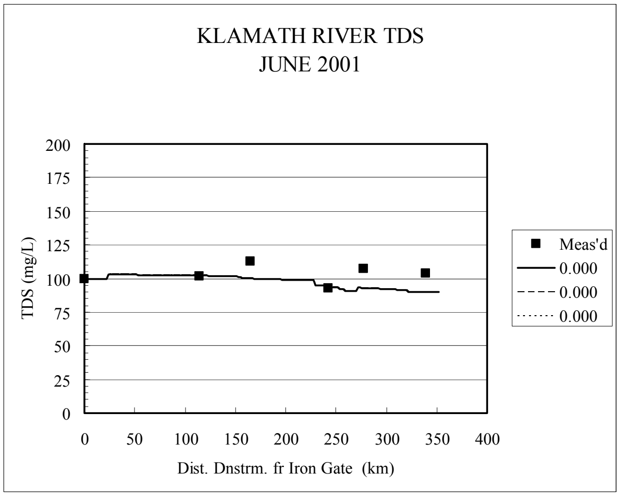
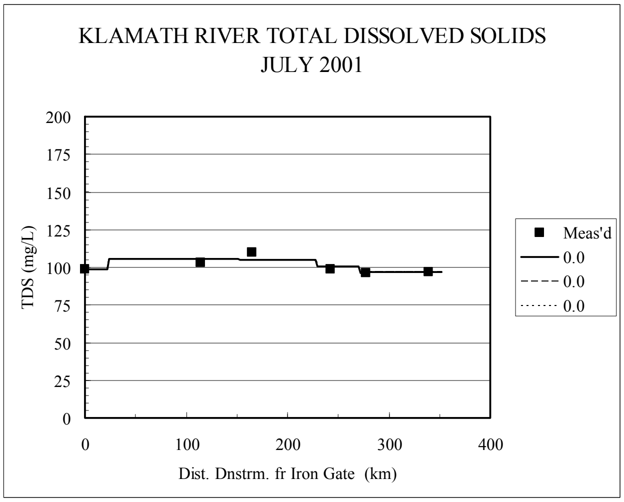
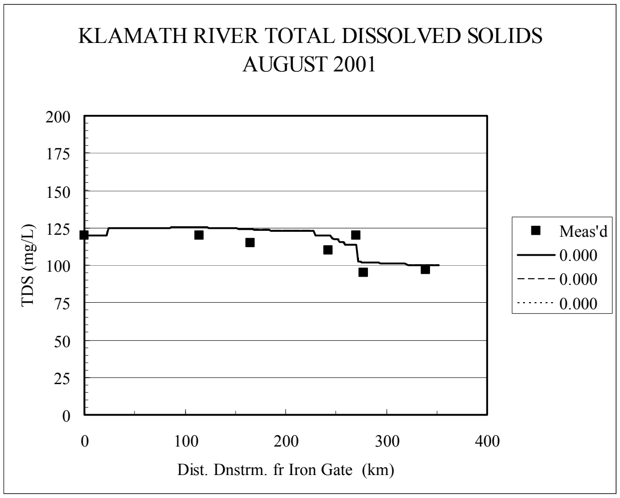
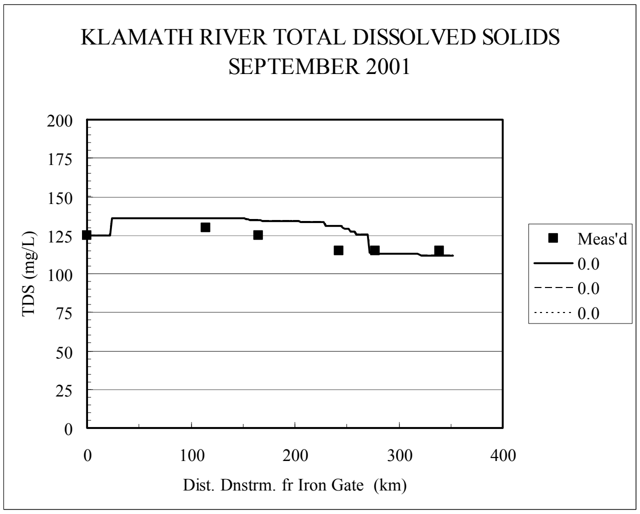


Figure 14. Measured and calculated flows in the Klamath River, June through October 2005.


KLAMATH RIVER TDS
JUNE 2001
TDS (mg/L)
0
25
50
75
100
125
150
175
200
0
50
100
150
200
250
300
350
400
Dist. Dnstrm. fr Iron Gate (km)
■ Meas'd
0.000
0.000
0.000


KLAMATH RIVER TOTAL DISSOLVED SOLIDS
JULY 2001
TDS (mg/L)
0
25
50
75
100
125
150
175
200
0
100
200
300
400
Dist. Dnstrm. fr Iron Gate (km)
■ Meas'd
0.0
0.0
0.0


KLAMATH RIVER TOTAL DISSOLVED SOLIDS
AUGUST 2001
TDS (mg/L)
0
25
50
75
100
125
150
175
200
0
100
200
300
400
Dist. Dnstrm. fr Iron Gate (km)
■ Meas'd
0.000
0.000
0.000



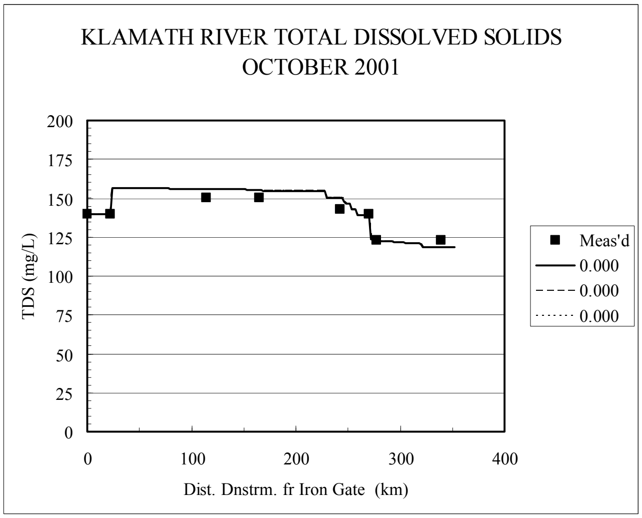
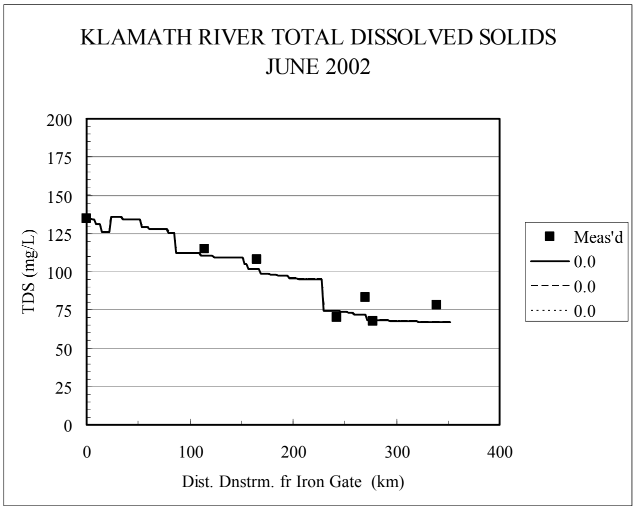
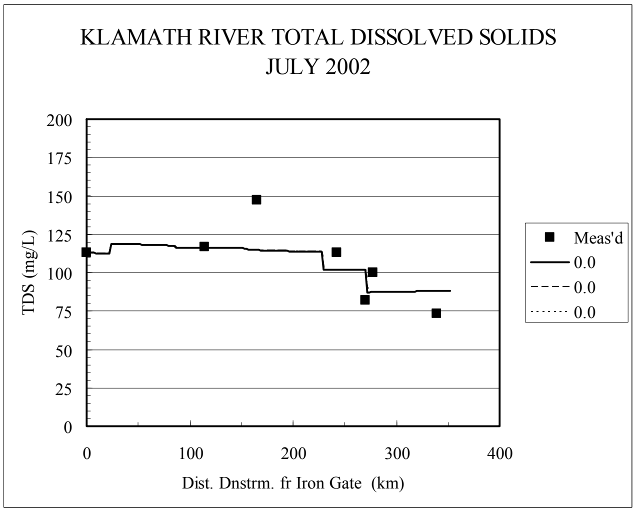
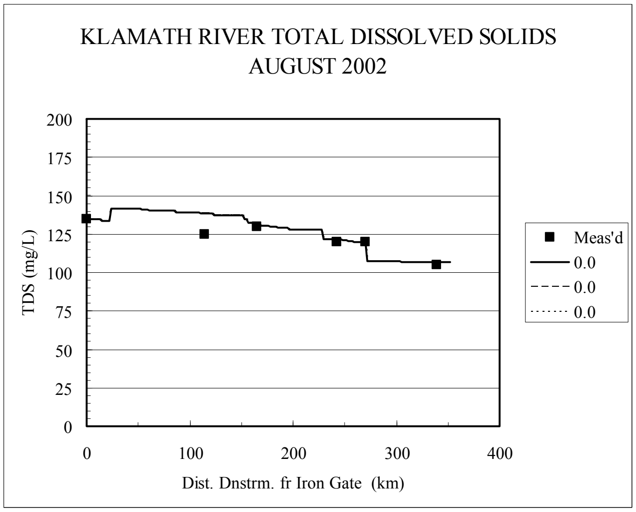
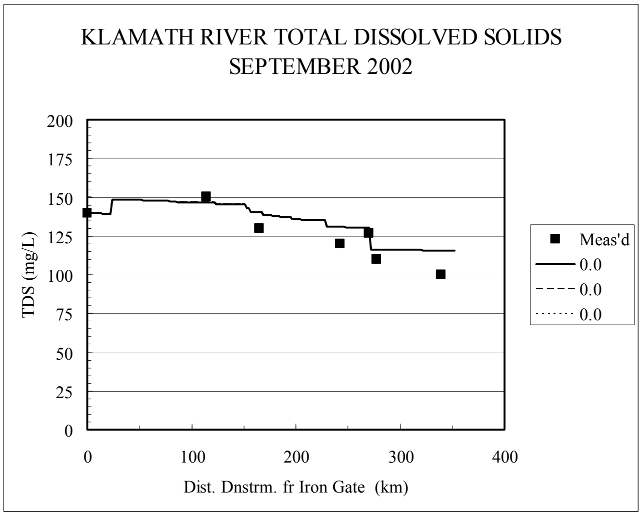


Figure 15. Klamath River Total Dissolved Solids, June, August, and October, 2001.


KLAMATH RIVER TOTAL DISSOLVED SOLIDS
JUNE 2002
TDS (mg/L)
200
175
150
125
100
75
50
25
0
0
100
200
300
400
Dist. Dnstrm. fr Iron Gate (km)
Meas'd
0.0
0.0
0.0


KLAMATH RIVER TOTAL DISSOLVED SOLIDS
JULY 2002
TDS (mg/L)
200
175
150
125
100
75
50
25
0
0
100
200
300
400
Dist. Dnstrm. fr Iron Gate (km)
Meas'd
0.0
0.0
0.0


KLAMATH RIVER TOTAL DISSOLVED SOLIDS
AUGUST 2002
TDS (mg/L)
200
175
150
125
100
75
50
25
0
0
100
200
300
400
Dist. Dnstrm. fr Iron Gate (km)
Meas'd
0.0
0.0
0.0



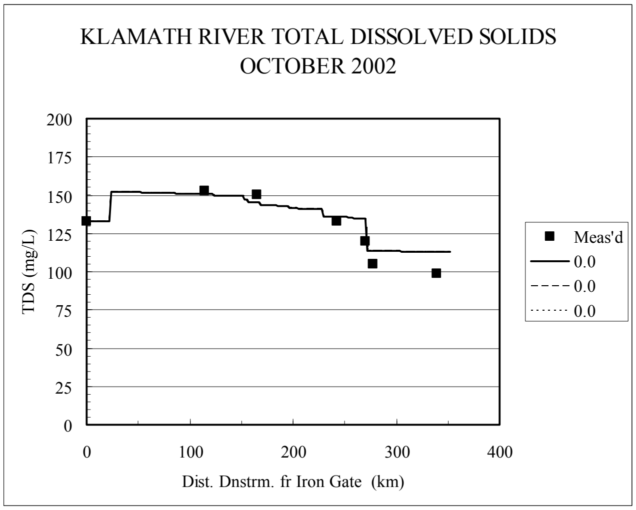
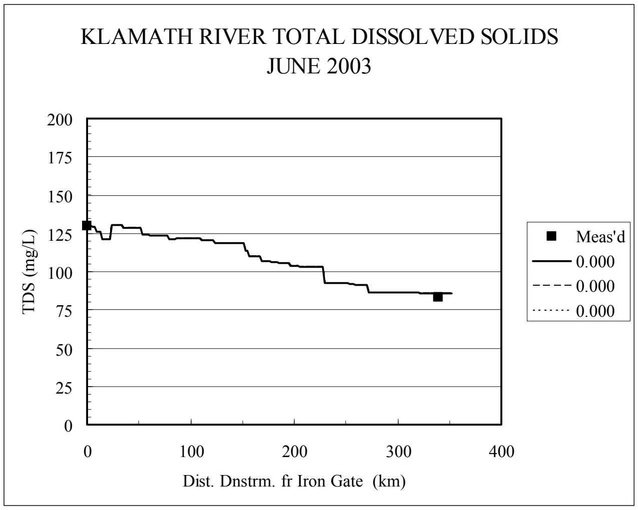
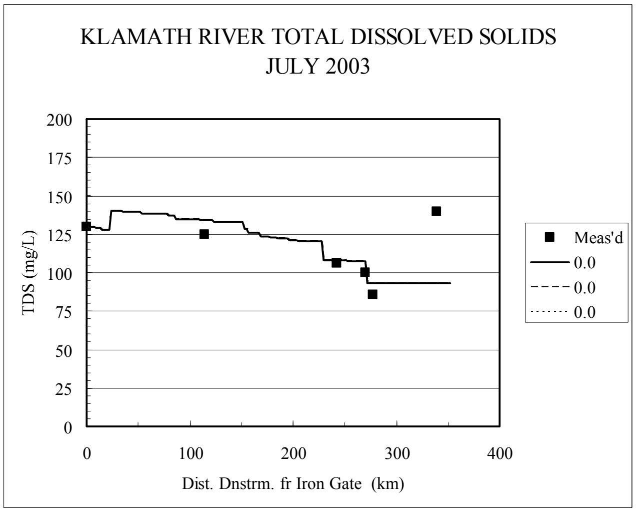
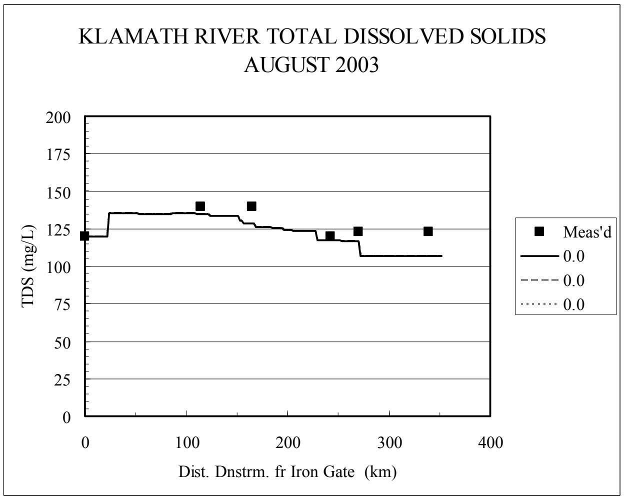
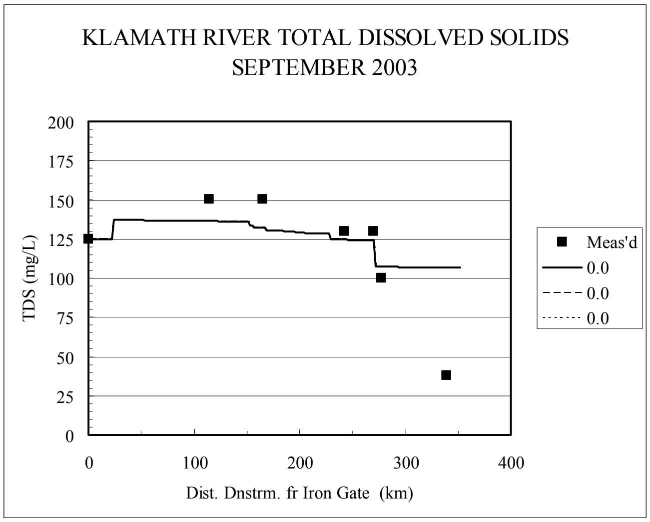


Figure 16. Klamath River Total Dissolved Solids, June through October, 2002.


KLAMATH RIVER TOTAL DISSOLVED SOLIDS
JUNE 2003
TDS (mg/L)
200
175
150
125
100
75
50
25
0
0
100
200
300
400
Dist. Dnstrm. fr Iron Gate (km)
Meas'd
0.000
0.000
0.000


KLAMATH RIVER TOTAL DISSOLVED SOLIDS
JULY 2003
TDS (mg/L)
200
175
150
125
100
75
50
25
0
0
100
200
300
400
Dist. Dnstrm. fr Iron Gate (km)
Meas'd
0.0
0.0
0.0


KLAMATH RIVER TOTAL DISSOLVED SOLIDS
AUGUST 2003
TDS (mg/L)
200
175
150
125
100
75
50
25
0
0
100
200
300
400
Dist. Dnstrm. fr Iron Gate (km)
Meas'd
0.0
0.0
0.0



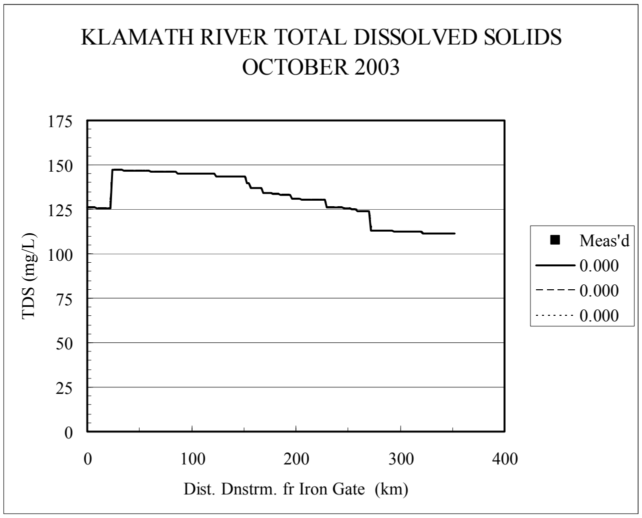
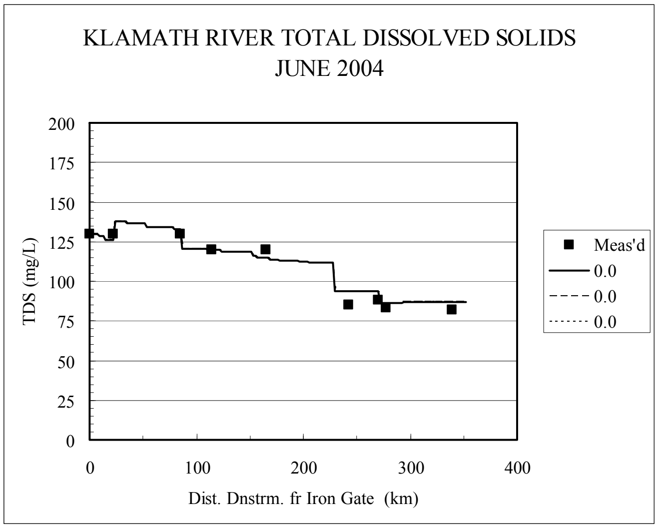
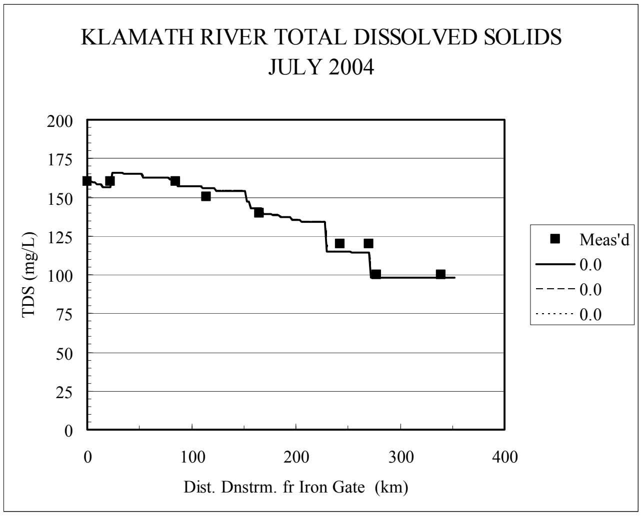
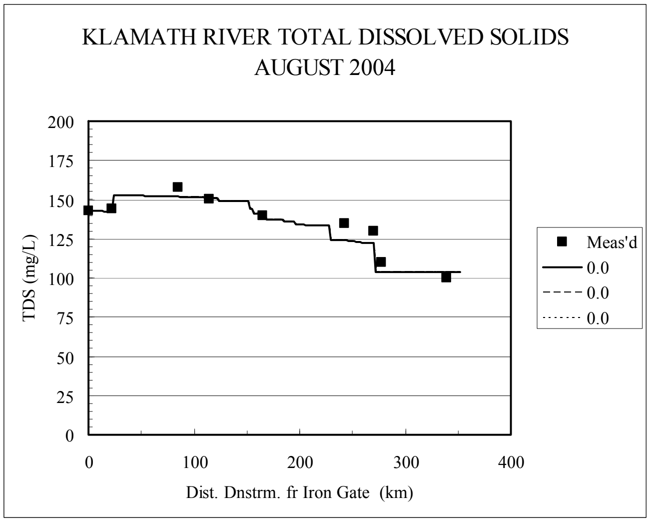
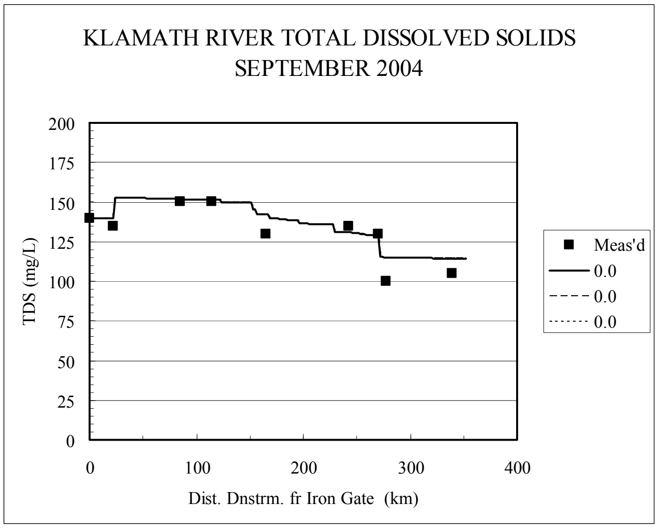


Figure 17. Klamath River Total Dissolved Solids, June through October, 2003.


KLAMATH RIVER TOTAL DISSOLVED SOLIDS
JUNE 2004
TDS (mg/L)
200
175
150
125
100
75
50
25
0
0
100
200
300
400
Dist. Dnstrm. fr Iron Gate (km)
■ Meas'd
0.0
0.0
0.0


KLAMATH RIVER TOTAL DISSOLVED SOLIDS
JULY 2004
TDS (mg/L)
200
175
150
125
100
75
50
25
0
0
100
200
300
400
Dist. Dnstrm. fr Iron Gate (km)
■ Meas'd
0.0
0.0
0.0


KLAMATH RIVER TOTAL DISSOLVED SOLIDS
AUGUST 2004
TDS (mg/L)
200
175
150
125
100
75
50
25
0
0
100
200
300
400
Dist. Dnstrm. fr Iron Gate (km)
■ Meas'd
0.0
0.0
0.0



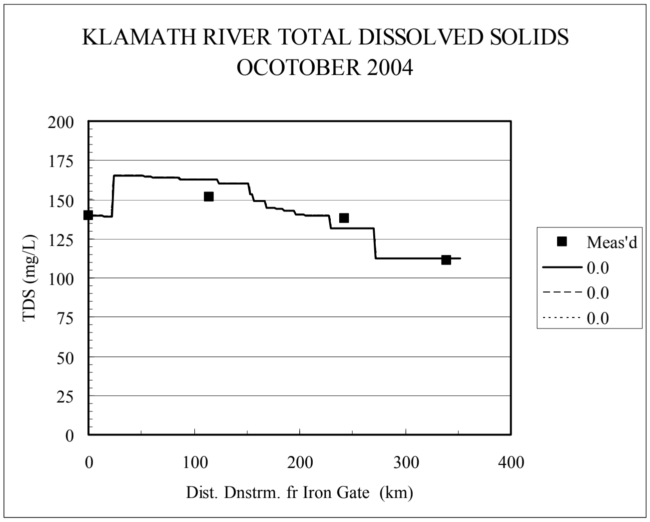
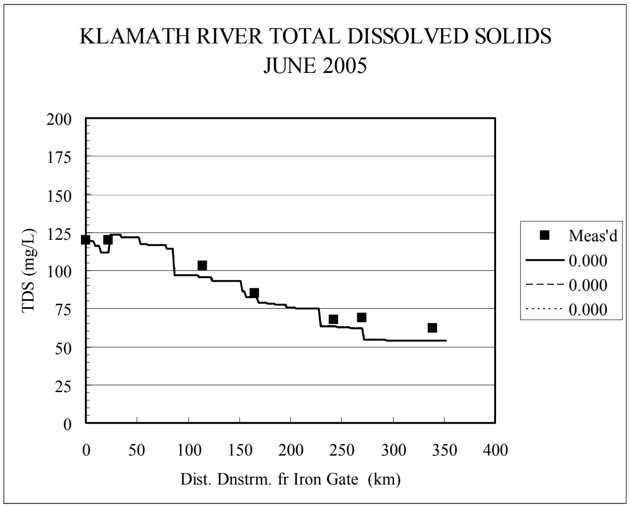
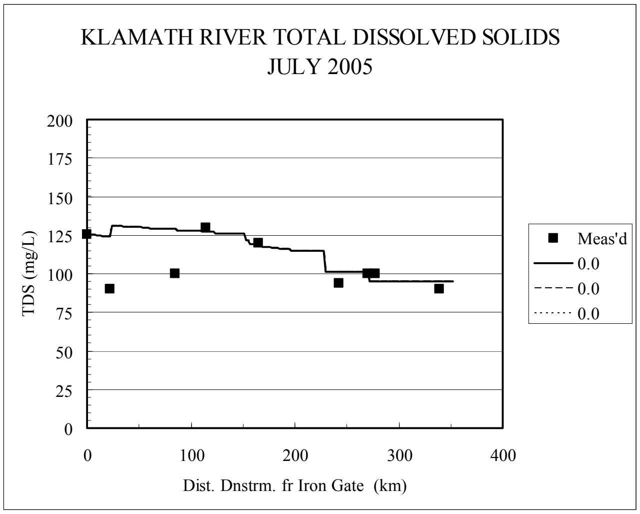
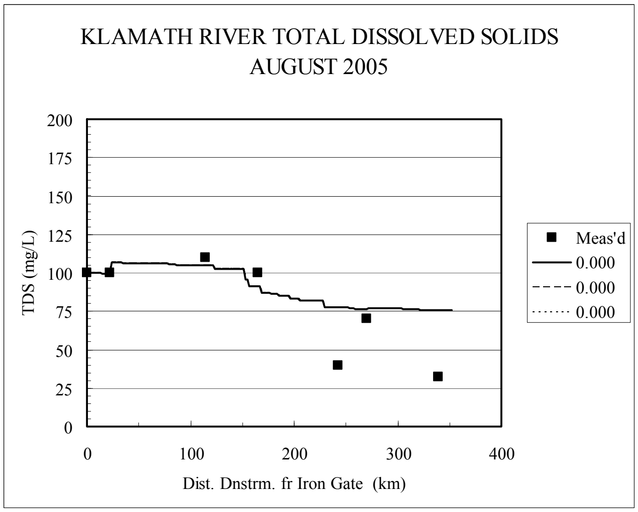
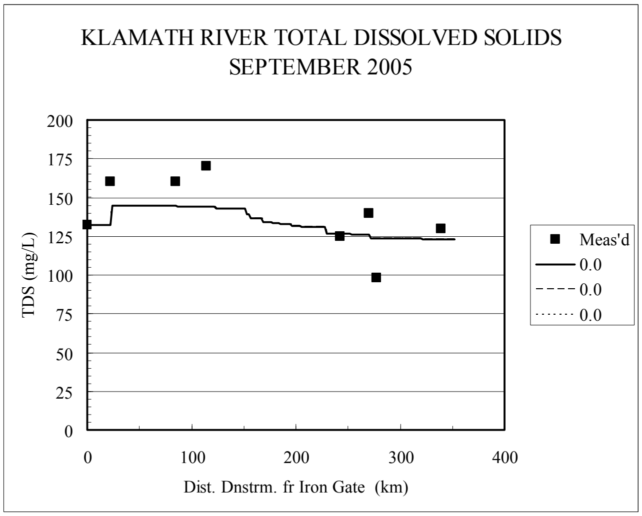


Figure 18. Klamath River Total Dissolved Solids, June through October, 2004.


KLAMATH RIVER TOTAL DISSOLVED SOLIDS
JUNE 2005
TDS (mg/L)
200
175
150
125
100
75
50
25
0
0
50
100
150
200
250
300
350
400
Dist. Dnstrm. fr Iron Gate (km)
■ Meas'd
0.000
0.000
0.000


KLAMATH RIVER TOTAL DISSOLVED SOLIDS
JULY 2005
TDS (mg/L)
200
175
150
125
100
75
50
25
0
0
100
200
300
400
Dist. Dnstrm. fr Iron Gate (km)
■ Meas'd
0.0
0.0
0.0


KLAMATH RIVER TOTAL DISSOLVED SOLIDS
AUGUST 2005
TDS (mg/L)
200
175
150
125
100
75
50
25
0
0
100
200
300
400
Dist. Dnstrm. fr Iron Gate (km)
■ Meas'd
0.000
0.000
0.000



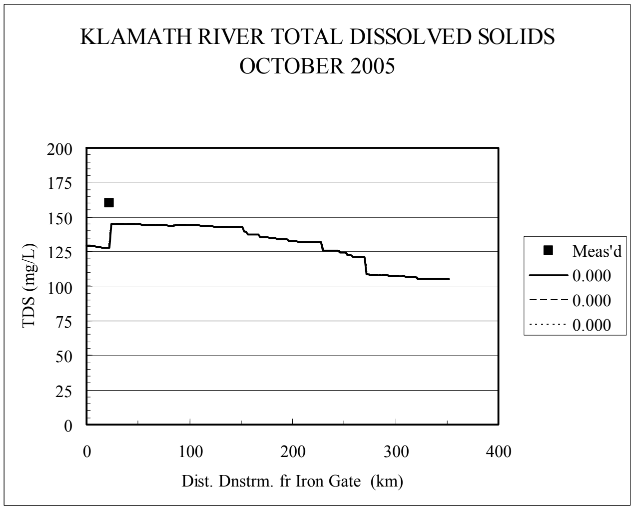
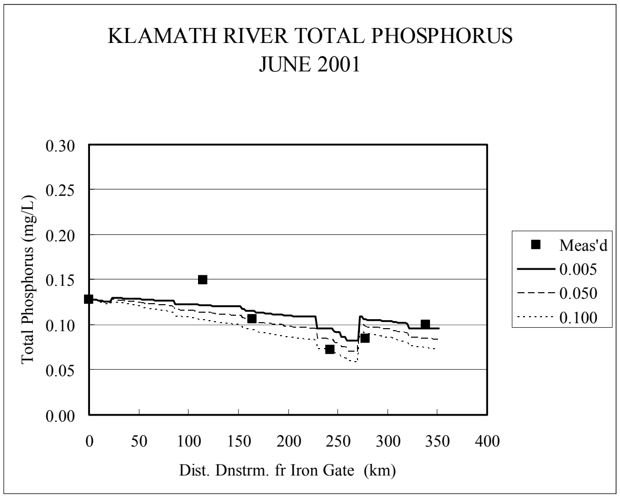
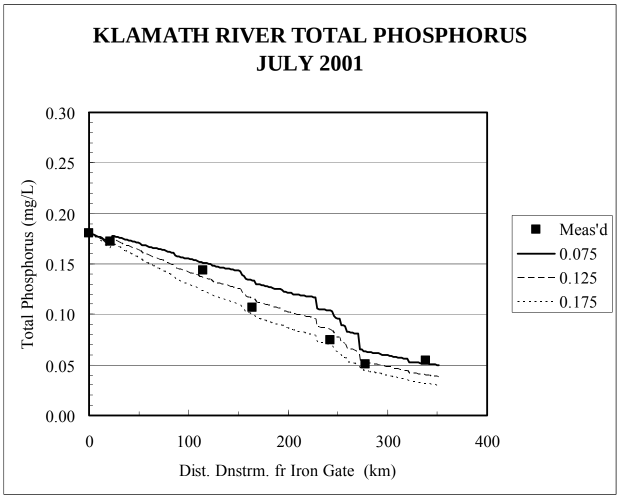
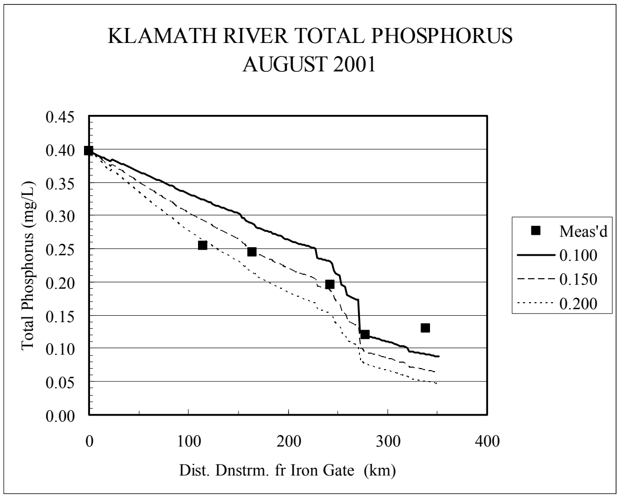
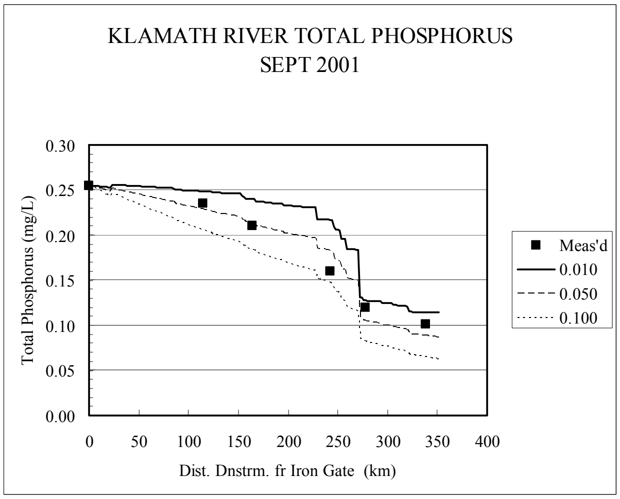


Figure 19. Klamath River Total Dissolved Solids, June through October, 2005.


KLAMATH RIVER TOTAL PHOSPHORUS
JUNE 2001
Total Phosphorus (mg/L)
0.30
0.25
0.20
0.15
0.10
0.05
0.00
0
50
100
150
200
250
300
350
400
Dist. Dnstrm. fr Iron Gate (km)
Meas'd
0.005
0.050
0.100


KLAMATH RIVER TOTAL PHOSPHORUS
JULY 2001
Total Phosphorus (mg/L)
0.30
0.25
0.20
0.15
0.10
0.05
0.00
0
100
200
300
400
Dist. Dnstrm. fr Iron Gate (km)
Meas'd
0.075
0.125
0.175


KLAMATH RIVER TOTAL PHOSPHORUS
AUGUST 2001
Total Phosphorus (mg/L)
0.45
0.40
0.35
0.30
0.25
0.20
0.15
0.10
0.05
0.00
0
100
200
300
400
Dist. Dnstrm. fr Iron Gate (km)
Meas'd
0.100
0.150
0.200



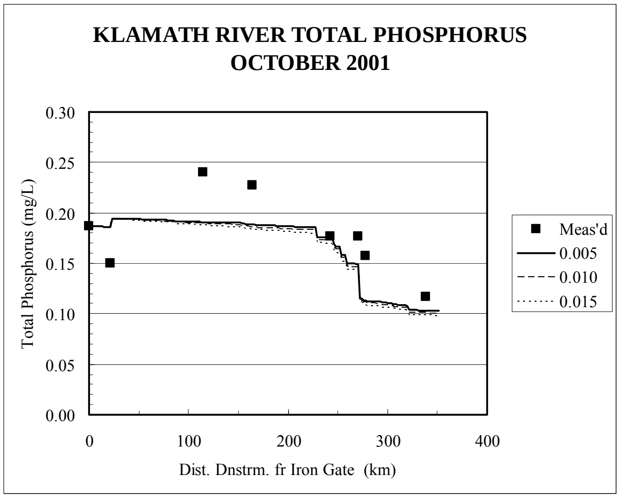
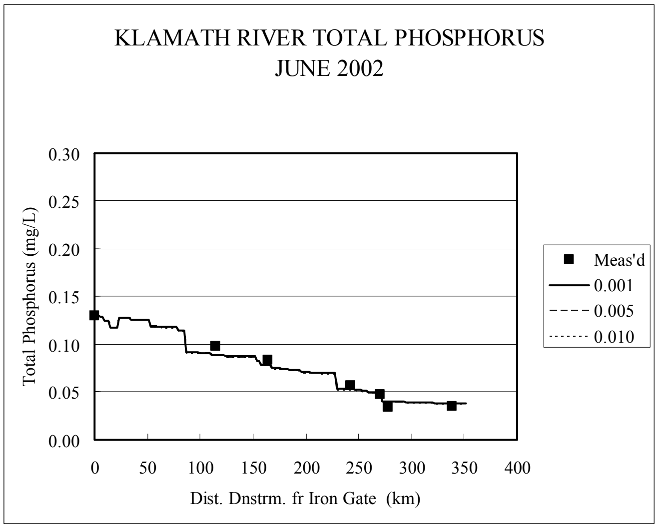
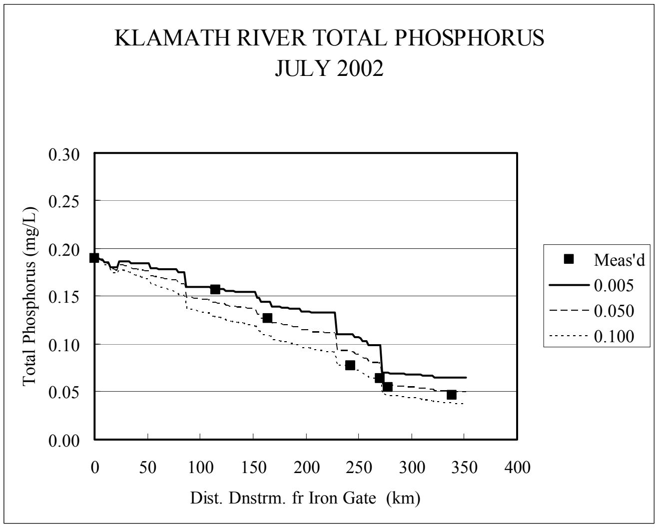
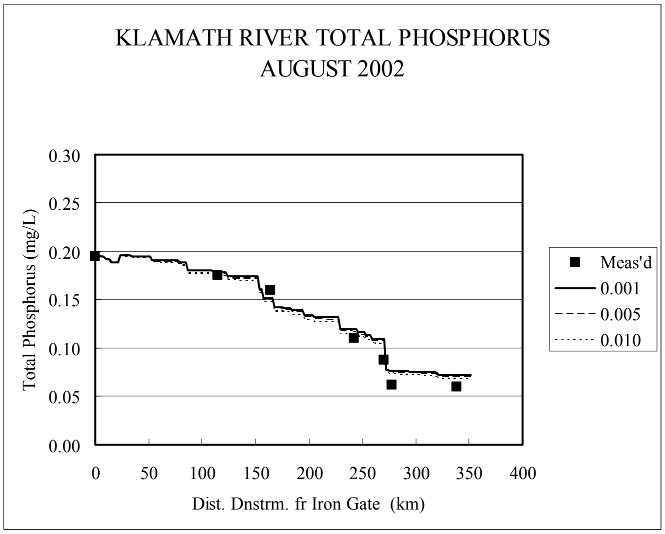
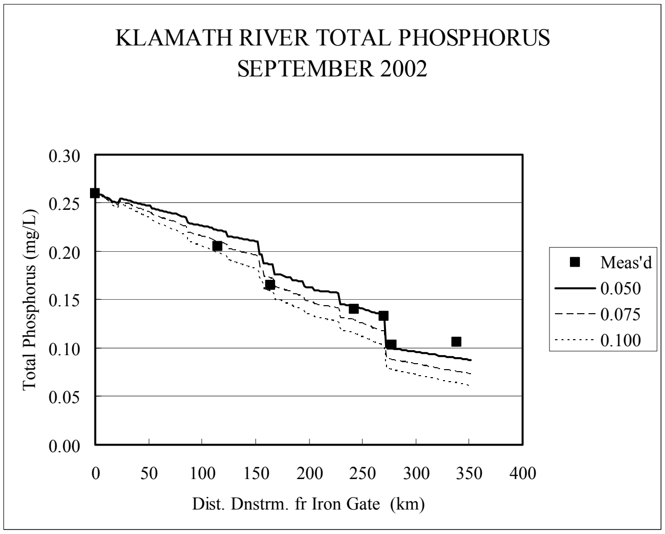


Figure 20. Klamath River Total Phosphorus, June through October, 2001


KLAMATH RIVER TOTAL PHOSPHORUS
JUNE 2002
Total Phosphorus (mg/L)
0.30
0.25
0.20
0.15
0.10
0.05
0.00
0
50
100
150
200
250
300
350
400
Dist. Dnstrm. fr Iron Gate (km)
■ Meas'd
0.001
0.005
0.010


KLAMATH RIVER TOTAL PHOSPHORUS
JULY 2002
Total Phosphorus (mg/L)
0.30
0.25
0.20
0.15
0.10
0.05
0.00
0
50
100
150
200
250
300
350
400
Dist. Dnstrm. fr Iron Gate (km)
■ Meas'd
0.005
0.050
0.100


KLAMATH RIVER TOTAL PHOSPHORUS
AUGUST 2002
Total Phosphorus (mg/L)
0.30
0.25
0.20
0.15
0.10
0.05
0.00
0
50
100
150
200
250
300
350
400
Dist. Dnstrm. fr Iron Gate (km)
■ Meas'd
0.001
0.005
0.010



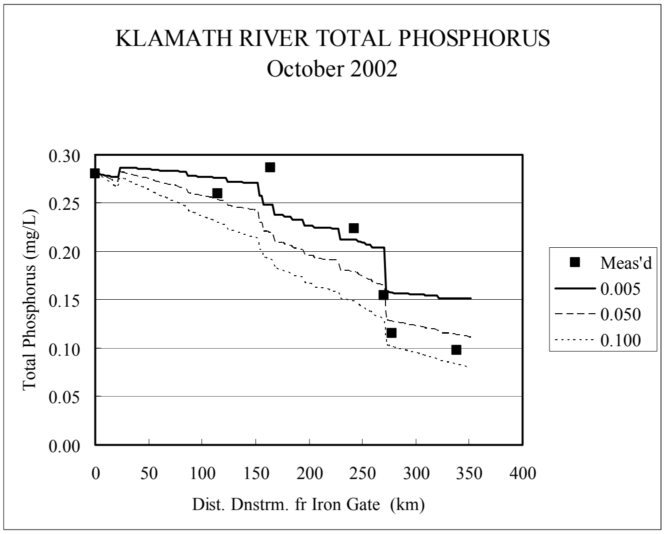
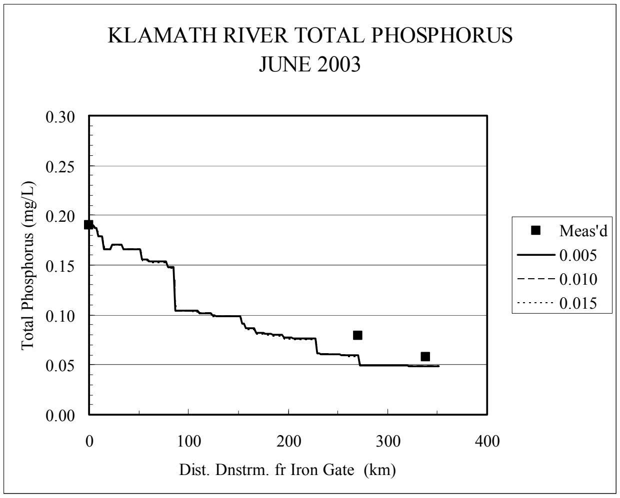
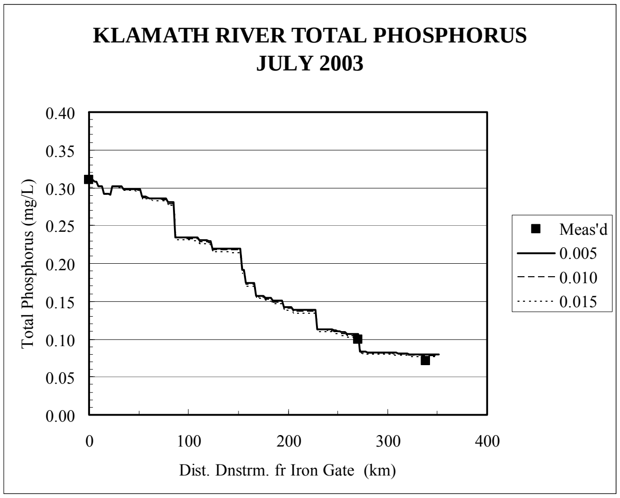
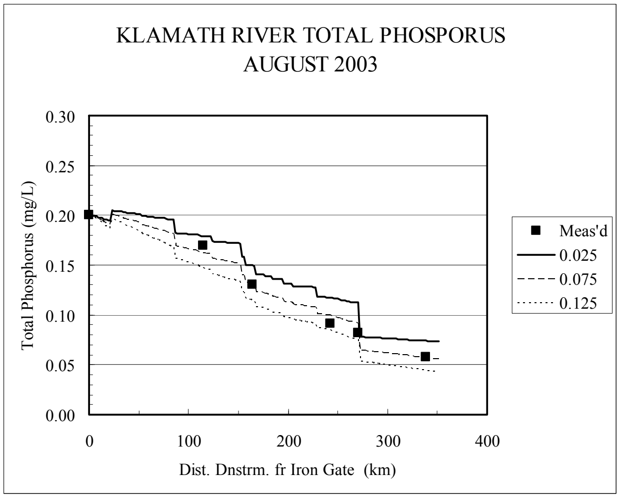
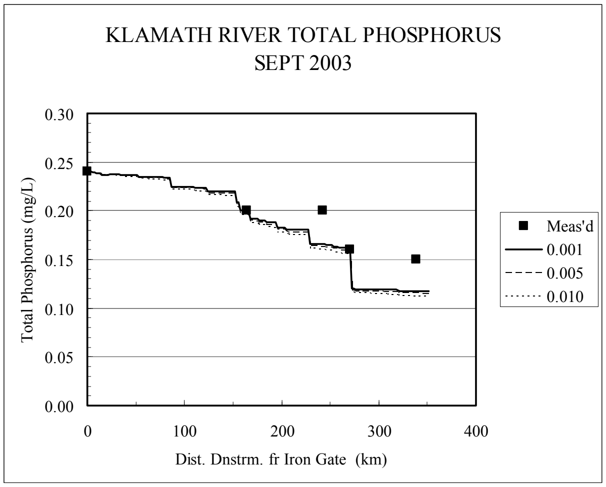


Figure 21. Klamath River Total Phosphorus, June through October, 2002


KLAMATH RIVER TOTAL PHOSPHORUS
JUNE 2003
Total Phosphorus (mg/L)
0.30
0.25
0.20
0.15
0.10
0.05
0.00
0
100
200
300
400
Dist. Dnstrm. fr Iron Gate (km)
Meas'd
0.005
0.010
0.015


KLAMATH RIVER TOTAL PHOSPHORUS
JULY 2003
Total Phosphorus (mg/L)
0.40
0.35
0.30
0.25
0.20
0.15
0.10
0.05
0.00
0
100
200
300
400
Dist. Dnstrm. fr Iron Gate (km)
Meas'd
0.005
0.010
0.015


KLAMATH RIVER TOTAL PHOSPORUS
AUGUST 2003
Total Phosphorus (mg/L)
0.30
0.25
0.20
0.15
0.10
0.05
0.00
0
100
200
300
400
Dist. Dnstrm. fr Iron Gate (km)
Meas'd
0.025
0.075
0.125



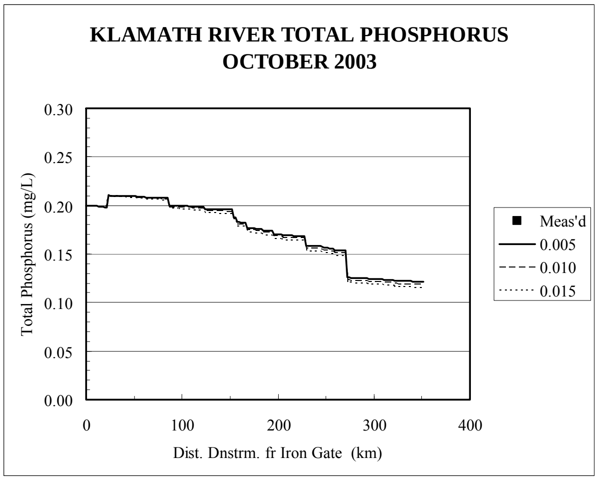
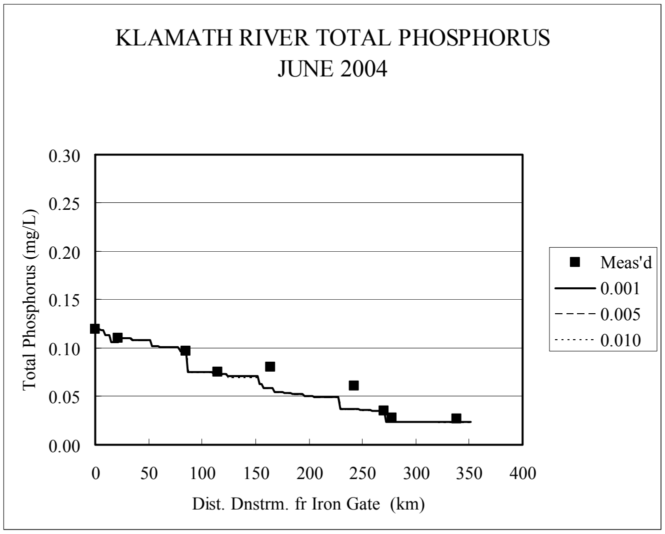
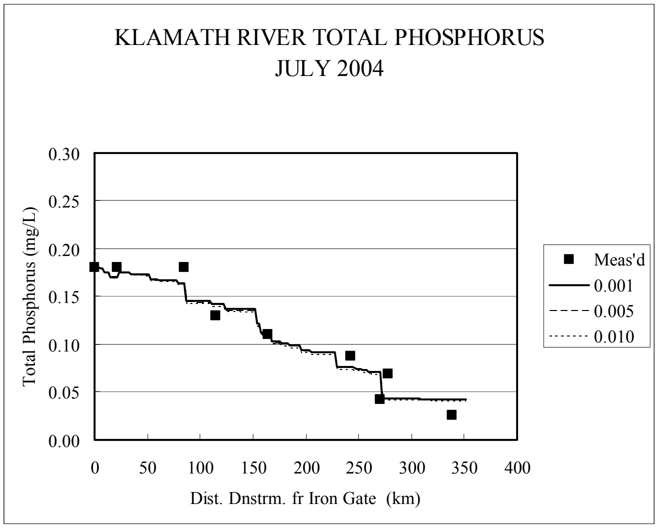
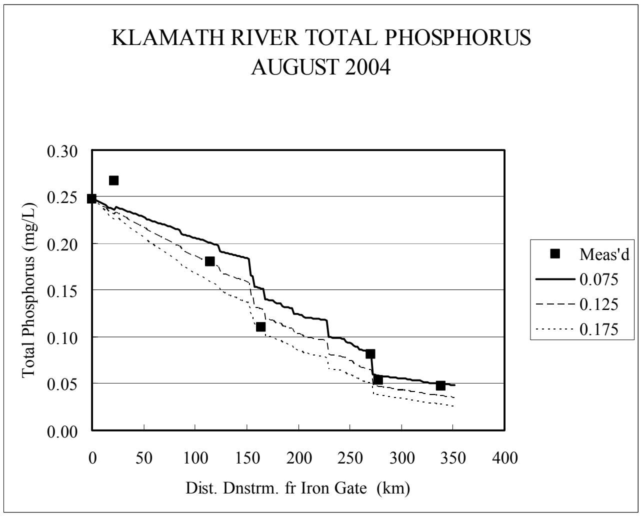
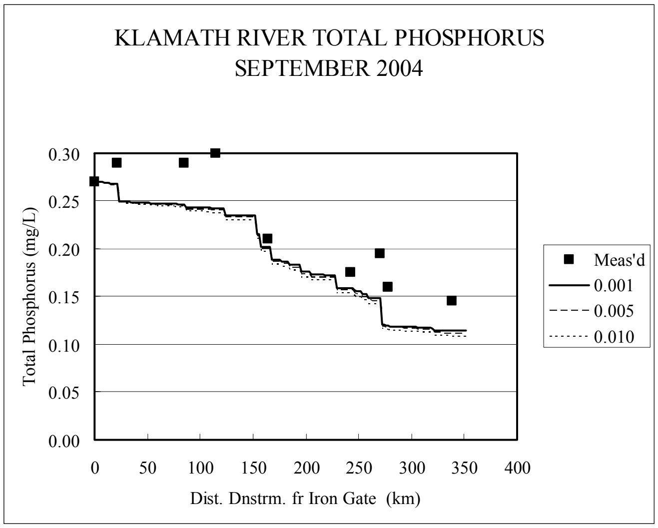


Figure 22. Klamath River Total Phosphorus, June through October, 2003


KLAMATH RIVER TOTAL PHOSPHORUS
JUNE 2004
Total Phosphorus (mg/L)
0.30
0.25
0.20
0.15
0.10
0.05
0.00
0
50
100
150
200
250
300
350
400
Dist. Dnstrm. fr Iron Gate (km)
■ Meas'd
0.001
0.005
0.010


KLAMATH RIVER TOTAL PHOSPHORUS
JULY 2004
Total Phosphorus (mg/L)
0.30
0.25
0.20
0.15
0.10
0.05
0.00
0
50
100
150
200
250
300
350
400
Dist. Dnstrm. fr Iron Gate (km)
■ Meas'd
0.001
0.005
0.010


KLAMATH RIVER TOTAL PHOSPHORUS
AUGUST 2004
Total Phosphorus (mg/L)
0.30
0.25
0.20
0.15
0.10
0.05
0.00
0
50
100
150
200
250
300
350
400
Dist. Dnstrm. fr Iron Gate (km)
■ Meas'd
0.075
0.125
0.175



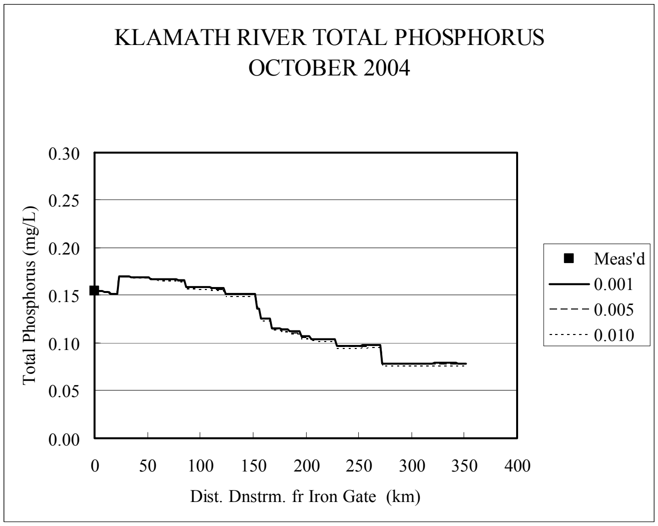
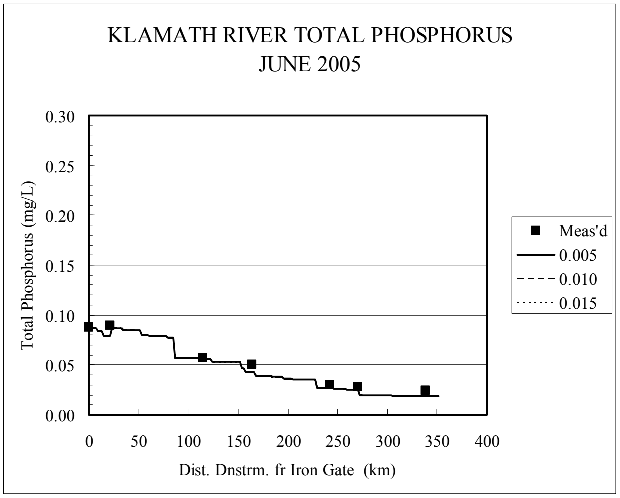
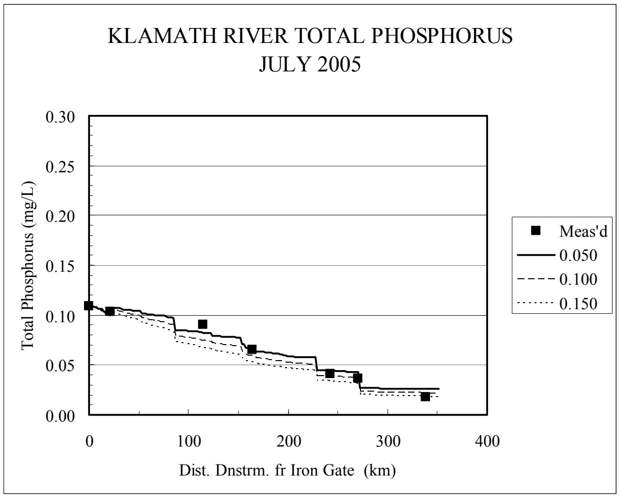
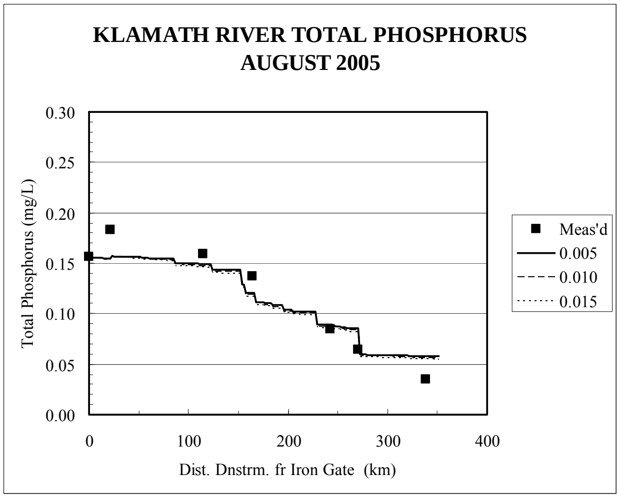
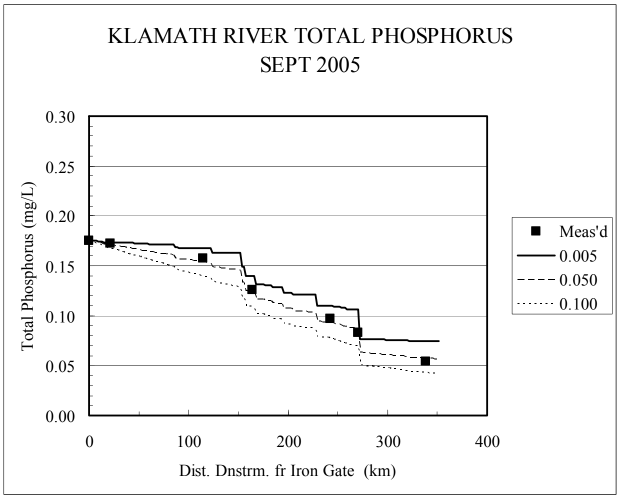


Figure 23. Klamath River Total Phosphorus, June through October, 2004


KLAMATH RIVER TOTAL PHOSPHORUS
JUNE 2005
Total Phosphorus (mg/L)
0.30
0.25
0.20
0.15
0.10
0.05
0.00
0
50
100
150
200
250
300
350
400
Dist. Dnstrm. fr Iron Gate (km)
■ Meas'd
0.005
0.010
0.015


KLAMATH RIVER TOTAL PHOSPHORUS
JULY 2005
Total Phosphorus (mg/L)
0.30
0.25
0.20
0.15
0.10
0.05
0.00
0
100
200
300
400
Dist. Dnstrm. fr Iron Gate (km)
■ Meas'd
0.050
0.100
0.150


KLAMATH RIVER TOTAL PHOSPHORUS
AUGUST 2005
Total Phosphorus (mg/L)
0.30
0.25
0.20
0.15
0.10
0.05
0.00
0
100
200
300
400
Dist. Dnstrm. fr Iron Gate (km)
■ Meas'd
0.005
0.010
0.015



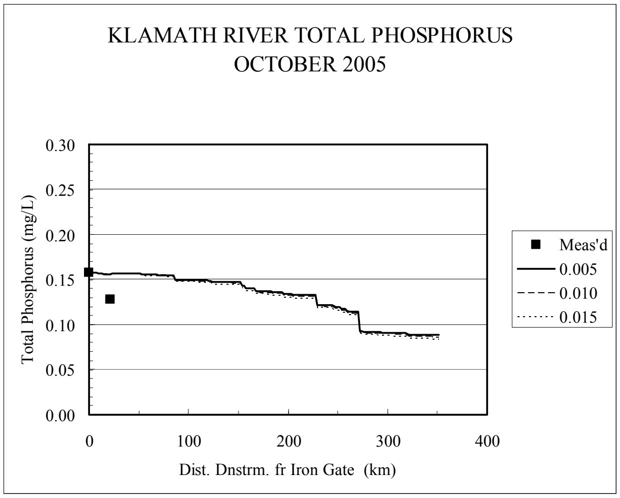
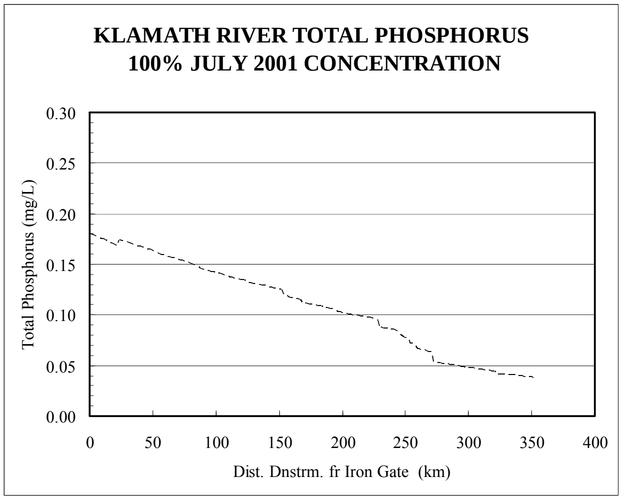
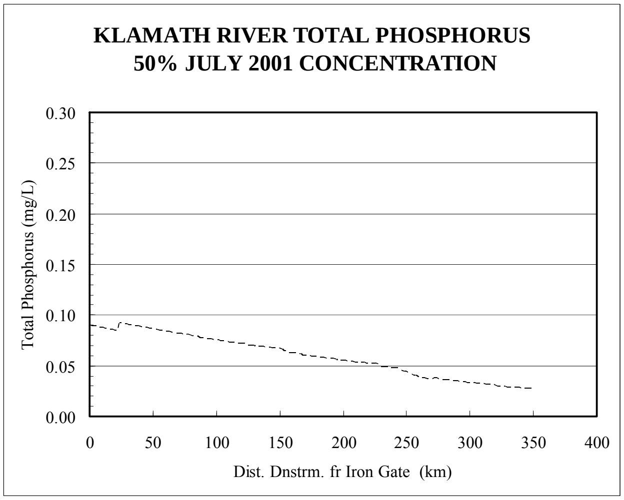


Figure 24. Klamath River Total Phosphorus, June through October, 2005





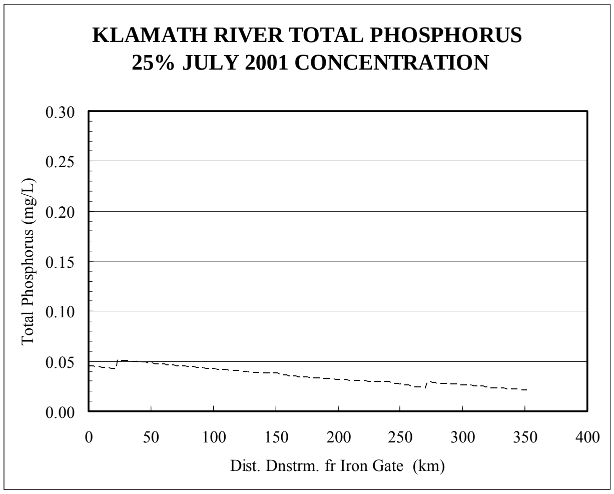
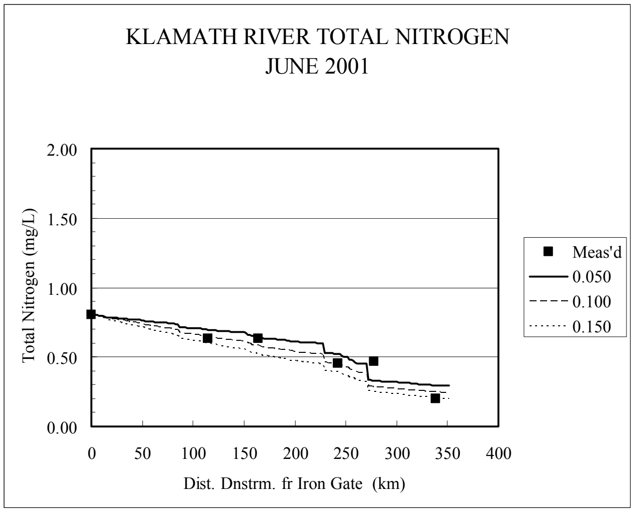
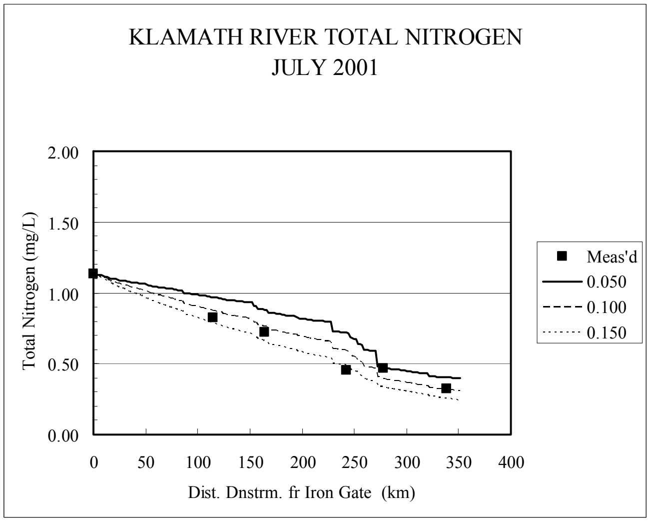
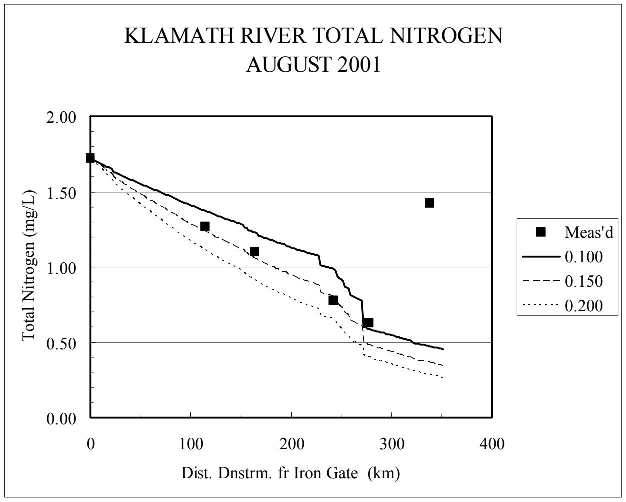
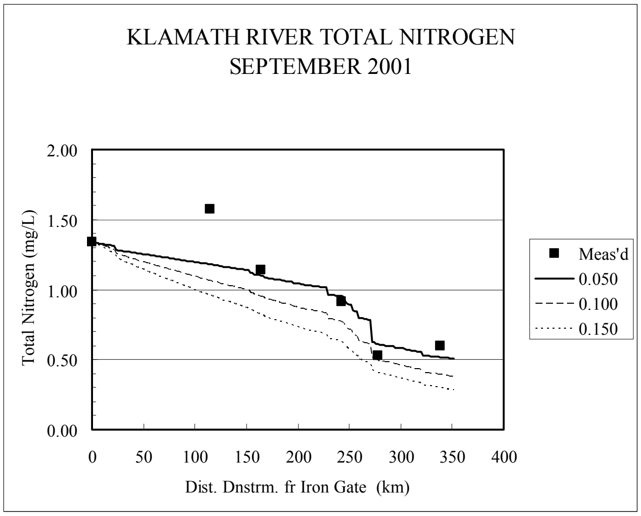


Figure 25. Effects of varying the total phosphorus concentration in the Iron Gate release.


KLAMATH RIVER TOTAL NITROGEN
JUNE 2001
Total Nitrogen (mg/L)
2.00
1.50
1.00
0.50
0.00
0
50
100
150
200
250
300
350
400
Dist. Dnstrm. fr Iron Gate (km)
■ Meas'd
0.050
0.100
0.150


KLAMATH RIVER TOTAL NITROGEN
JULY 2001
Total Nitrogen (mg/L)
2.00
1.50
1.00
0.50
0.00
0
50
100
150
200
250
300
350
400
Dist. Dnstrm. fr Iron Gate (km)
■ Meas'd
0.050
0.100
0.150


KLAMATH RIVER TOTAL NITROGEN
AUGUST 2001
Total Nitrogen (mg/L)
2.00
1.50
1.00
0.50
0.00
0
100
200
300
400
Dist. Dnstrm. fr Iron Gate (km)
■ Meas'd
0.100
0.150
0.200



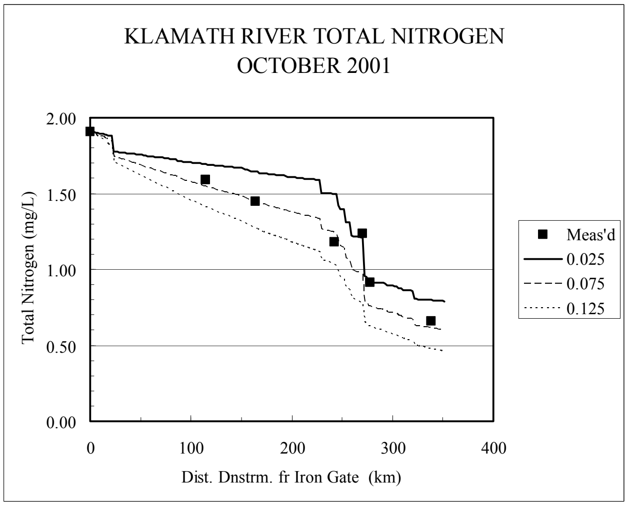
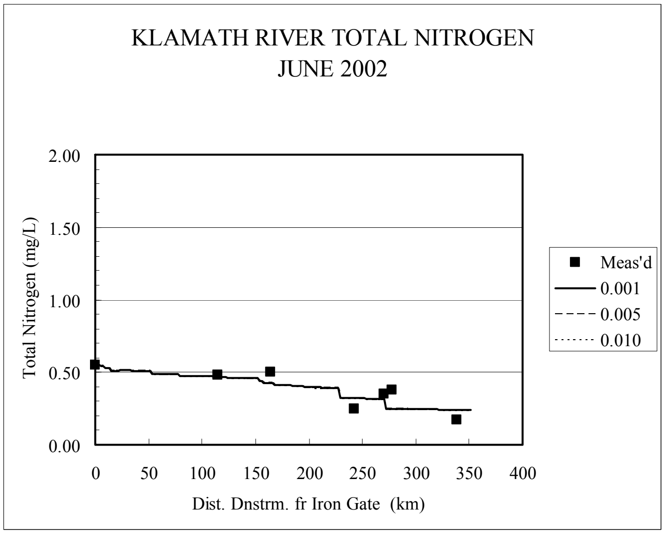
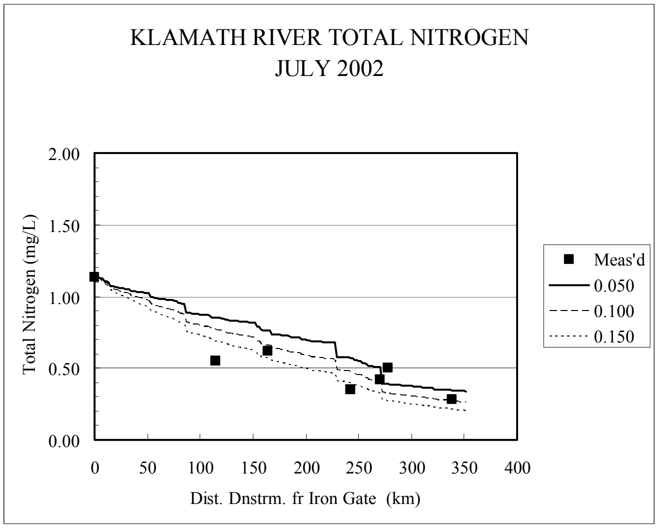
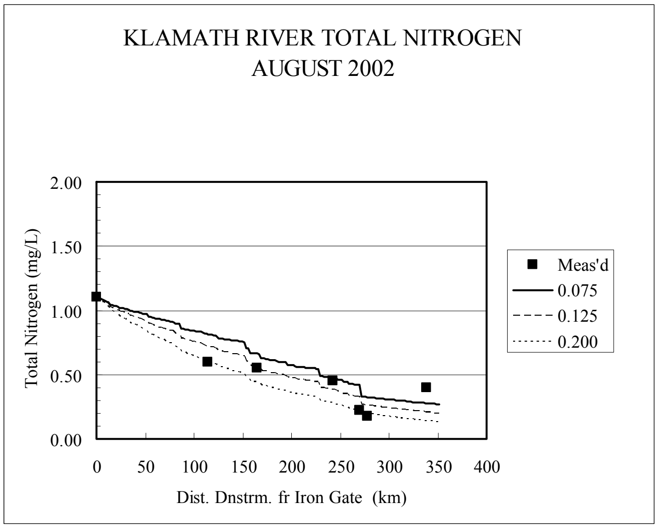
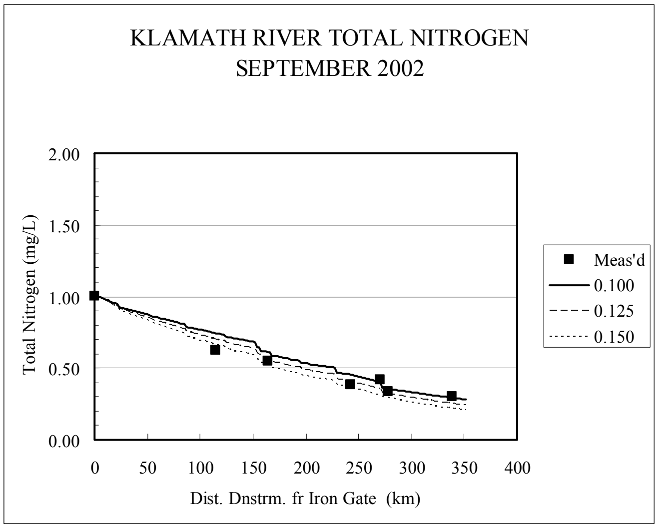


Figure 26. Klamath River total nitrogen, June through October, 2001


KLAMATH RIVER TOTAL NITROGEN
JUNE 2002
Total Nitrogen (mg/L)
2.00
1.50
1.00
0.50
0.00
0
50
100
150
200
250
300
350
400
Dist. Dnstrm. fr Iron Gate (km)
Meas'd
0.001
0.005
0.010


KLAMATH RIVER TOTAL NITROGEN
JULY 2002
Total Nitrogen (mg/L)
2.00
1.50
1.00
0.50
0.00
0
50
100
150
200
250
300
350
400
Dist. Dnstrm. fr Iron Gate (km)
Meas'd
0.050
0.100
0.150


KLAMATH RIVER TOTAL NITROGEN
AUGUST 2002
Total Nitrogen (mg/L)
2.00
1.50
1.00
0.50
0.00
0
50
100
150
200
250
300
350
400
Dist. Dnstrm. fr Iron Gate (km)
Meas'd
0.075
0.125
0.200



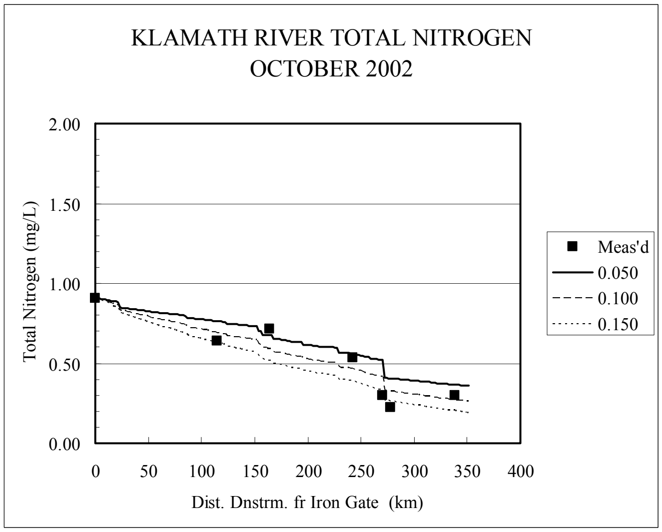
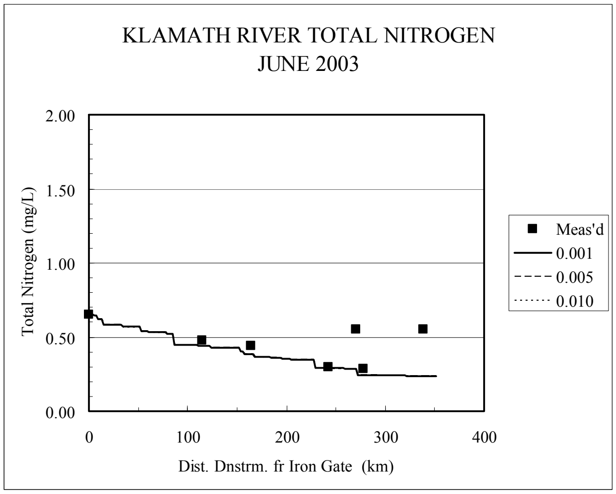
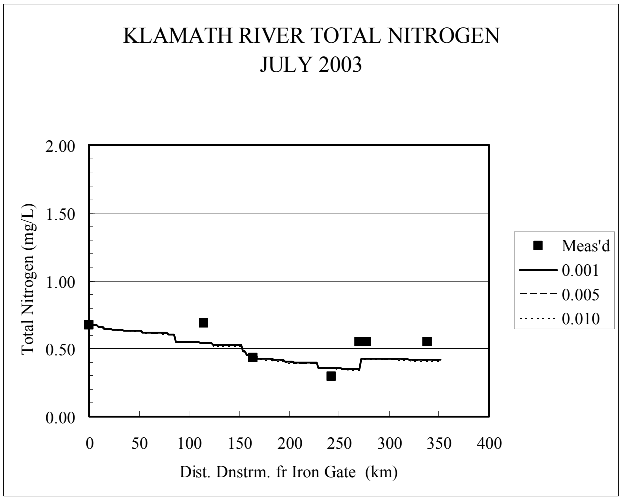
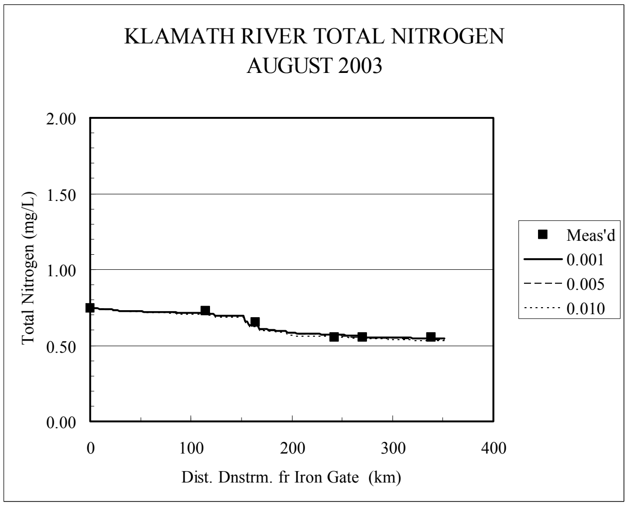
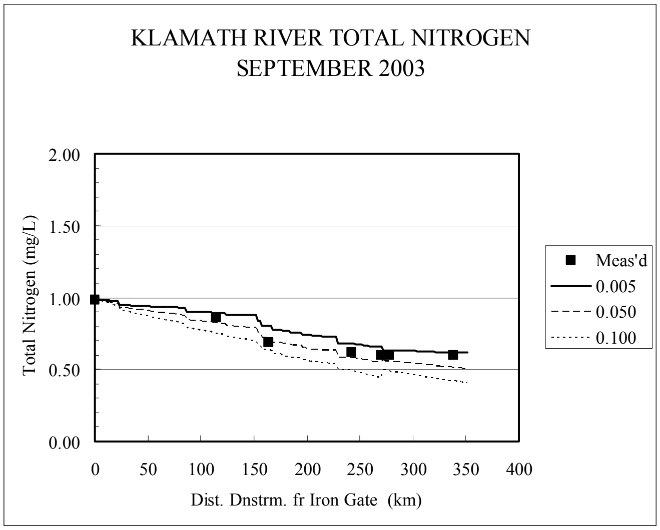


Figure 27. Klamath River total nitrogen, June through October, 2002


KLAMATH RIVER TOTAL NITROGEN
JUNE 2003
Total Nitrogen (mg/L)
2.00
1.50
1.00
0.50
0.00
0
100
200
300
400
Dist. Dnstrm. fr Iron Gate (km)
Meas'd
0.001
0.005
0.010


KLAMATH RIVER TOTAL NITROGEN
JULY 2003
Total Nitrogen (mg/L)
2.00
1.50
1.00
0.50
0.00
0
50
100
150
200
250
300
350
400
Dist. Dnstrm. fr Iron Gate (km)
Meas'd
0.001
0.005
0.010


KLAMATH RIVER TOTAL NITROGEN
AUGUST 2003
Total Nitrogen (mg/L)
2.00
1.50
1.00
0.50
0.00
0
100
200
300
400
Dist. Dnstrm. fr Iron Gate (km)
Meas'd
0.001
0.005
0.010



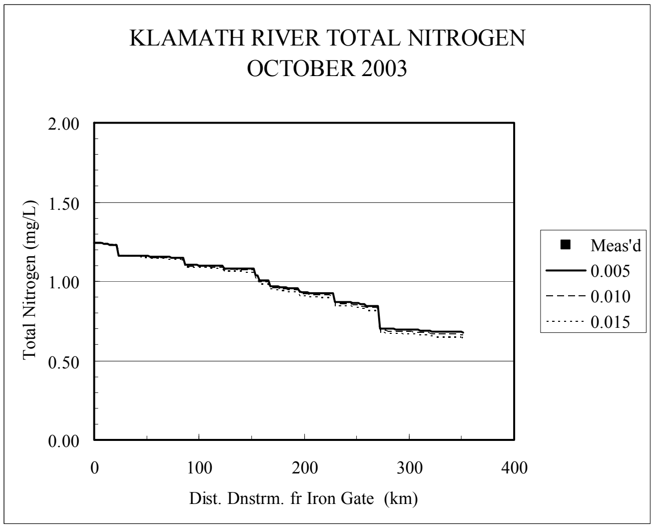
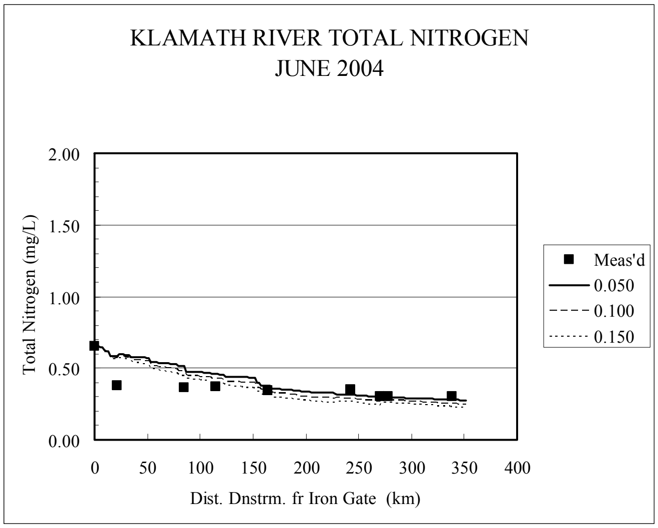
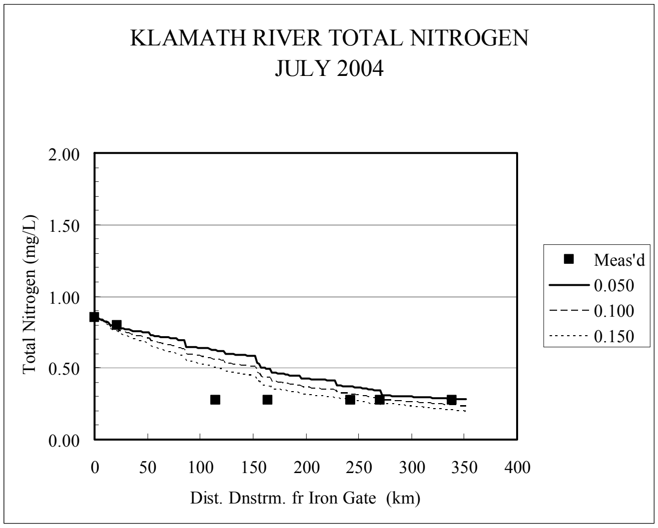
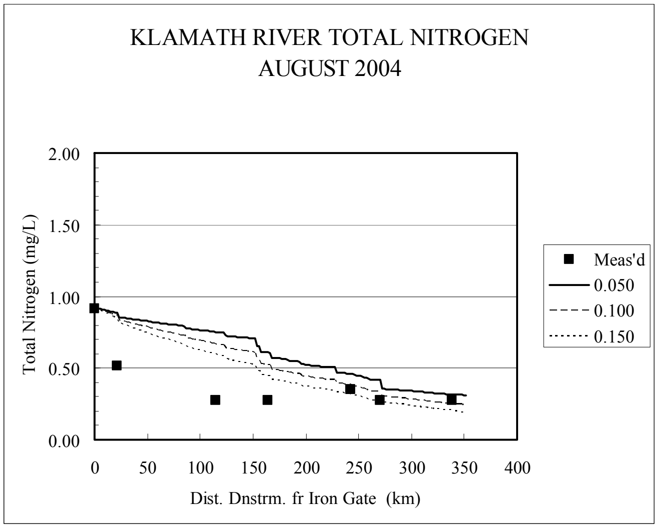
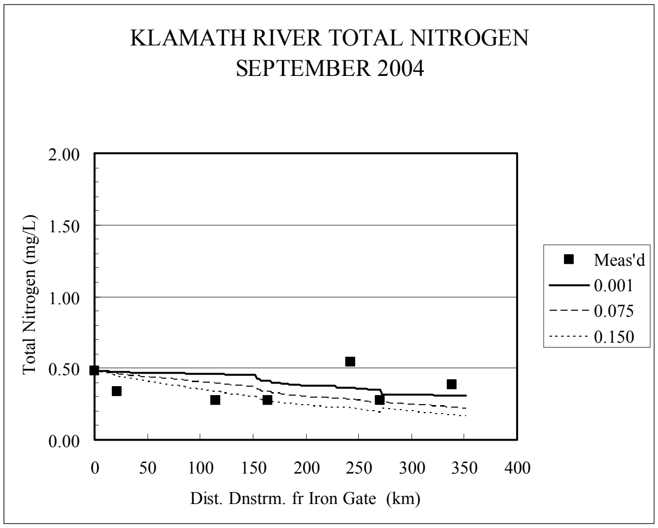


Figure 28. Klamath River total nitrogen, June through October, 2003


KLAMATH RIVER TOTAL NITROGEN
JUNE 2004
Total Nitrogen (mg/L)
2.00
1.50
1.00
0.50
0.00
0
50
100
150
200
250
300
350
400
Dist. Dnstrm. fr Iron Gate (km)
■ Meas'd
0.050
0.100
0.150


KLAMATH RIVER TOTAL NITROGEN
JULY 2004
Total Nitrogen (mg/L)
2.00
1.50
1.00
0.50
0.00
0
50
100
150
200
250
300
350
400
Dist. Dnstrm. fr Iron Gate (km)
■ Meas'd
0.050
0.100
0.150


KLAMATH RIVER TOTAL NITROGEN
AUGUST 2004
Total Nitrogen (mg/L)
2.00
1.50
1.00
0.50
0.00
0
50
100
150
200
250
300
350
400
Dist. Dnstrm. fr Iron Gate (km)
■ Meas'd
0.050
0.100
0.150



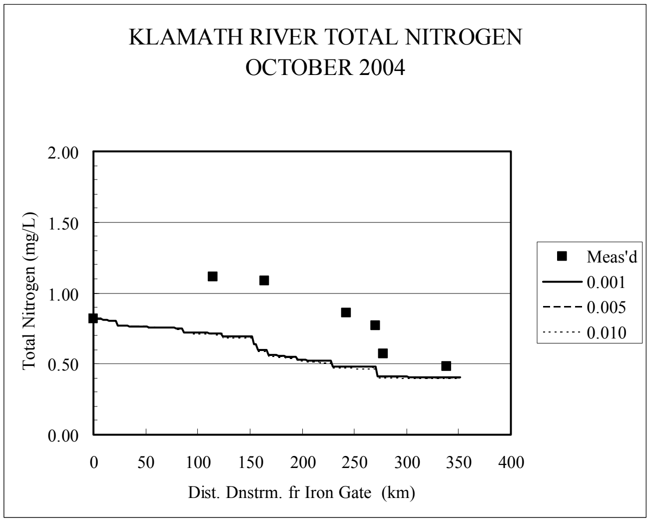
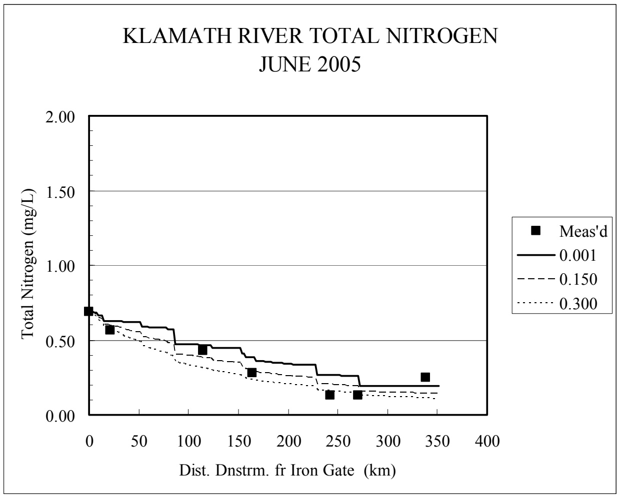
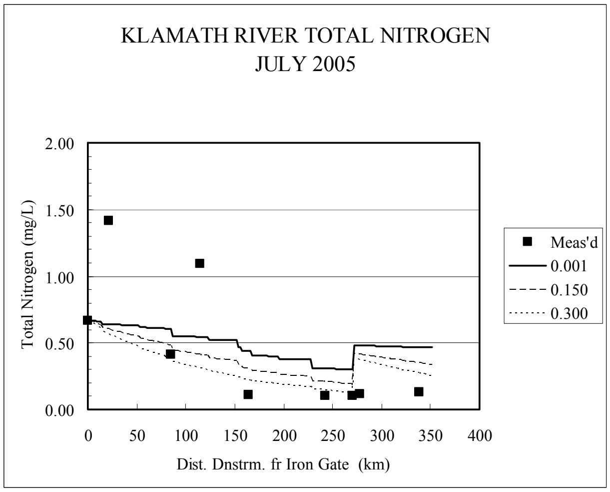
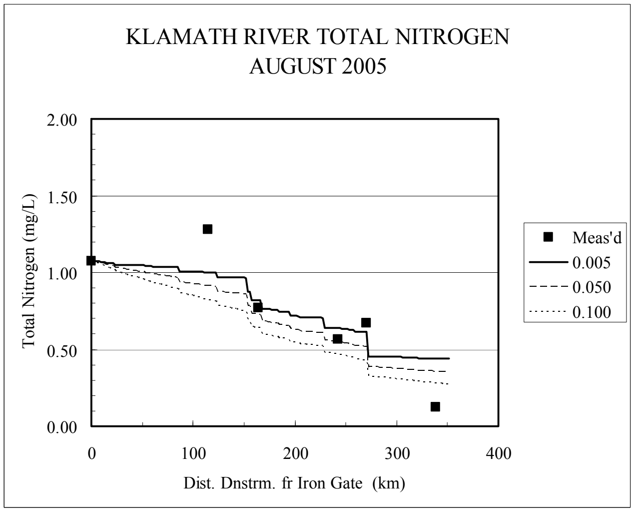
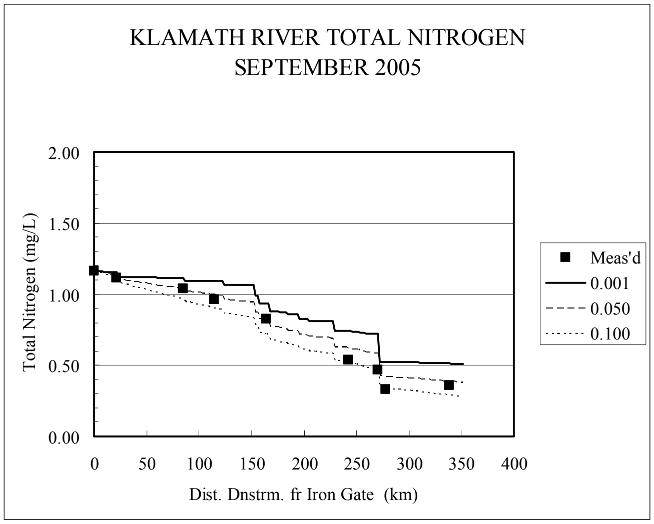


Figure 29. Klamath River total nitrogen, June through October, 2004


KLAMATH RIVER TOTAL NITROGEN
JUNE 2005
Total Nitrogen (mg/L)
2.00
1.50
1.00
0.50
0.00
0
50
100
150
200
250
300
350
400
Dist. Dnstrm. fr Iron Gate (km)
Meas'd
0.001
0.150
0.300


KLAMATH RIVER TOTAL NITROGEN
JULY 2005
Total Nitrogen (mg/L)
2.00
1.50
1.00
0.50
0.00
0
50
100
150
200
250
300
350
400
Dist. Dnstrm. fr Iron Gate (km)
Meas'd
0.001
0.150
0.300


KLAMATH RIVER TOTAL NITROGEN
AUGUST 2005
Total Nitrogen (mg/L)
2.00
1.50
1.00
0.50
0.00
0
100
200
300
400
Dist. Dnstrm. fr Iron Gate (km)
Meas'd
0.005
0.050
0.100



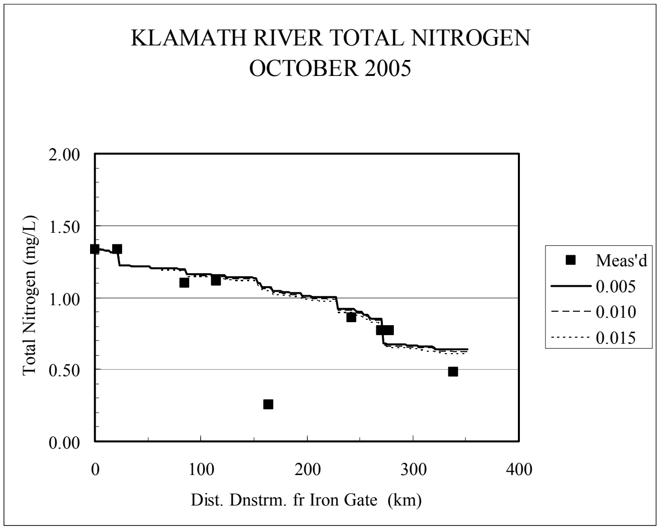


Figure 30. Klamath River total nitrogen, June through October, 2005

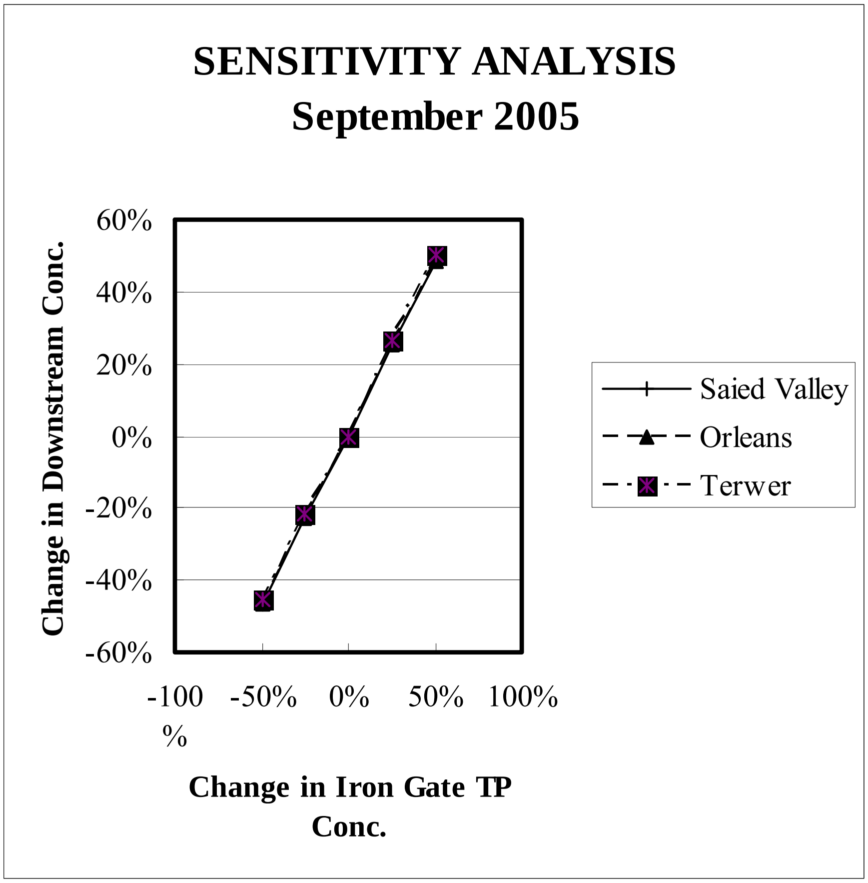
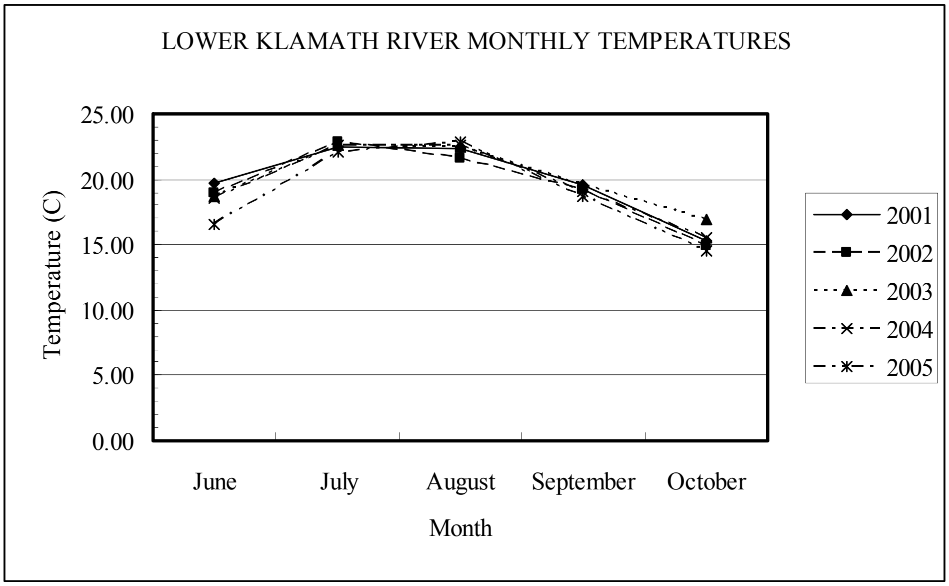


Figure 31. Sensitivity of downstream calculated total phosphorus concentrations to changes in Iron Gate total phosphorus concentrations.



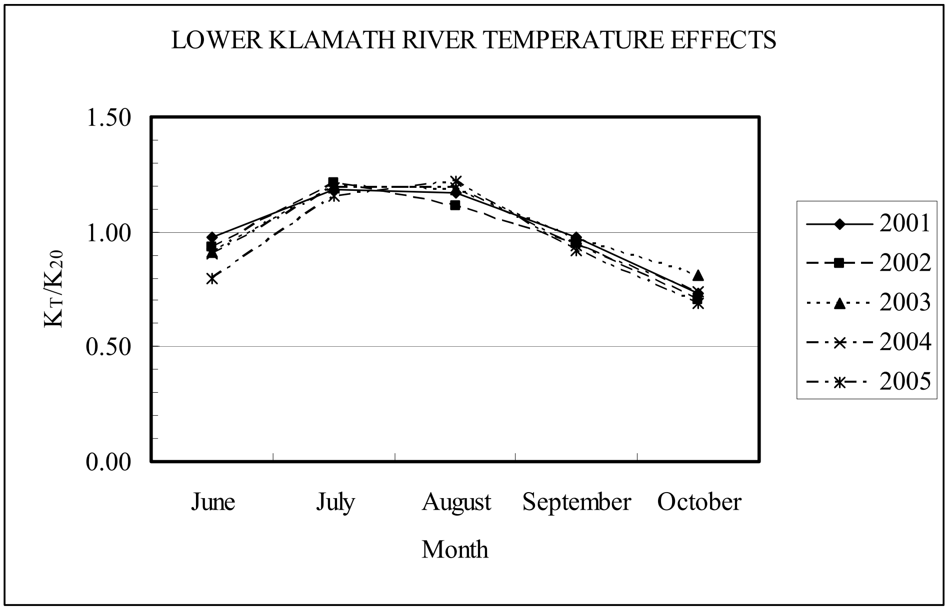
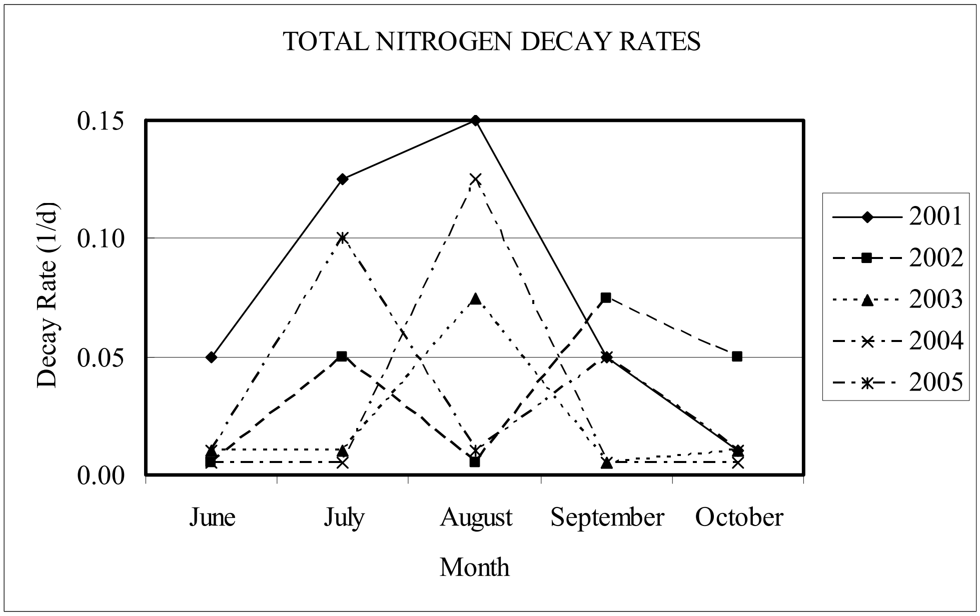


Figure 32. Average monthly temperatures in the lower Klamath River and estimated temperature effects of temperature-dependent rates assuming $\theta = 1.07$.



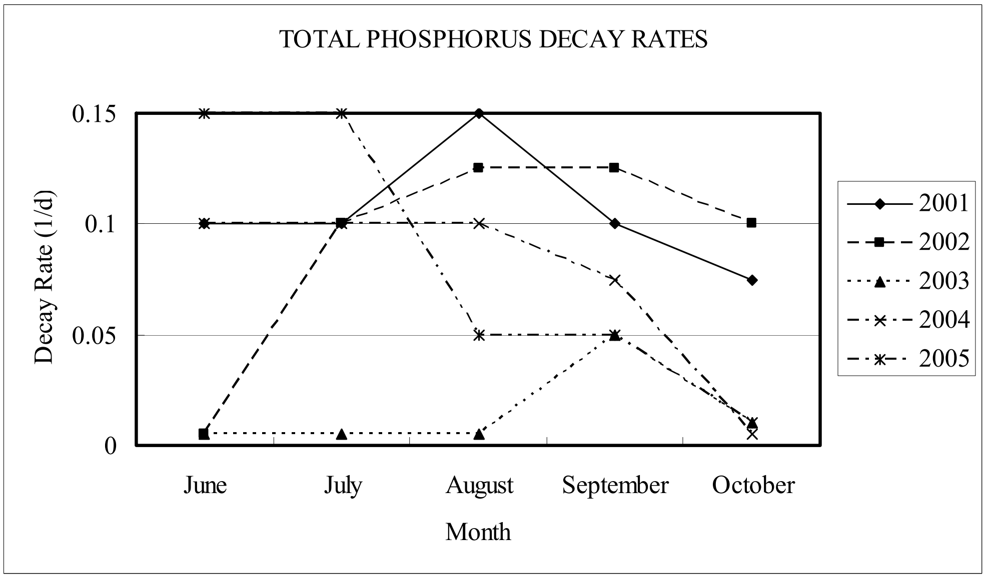


Figure 33. Monthly decay rates of Total Nitrogen and Total Phosphorus in the lower Klamath River estimated from simplified modeling.

APPENDIX I

RESPONSE TO COMMENTS BY MATT ST. JOHN, NORTH COAST REGIONAL WATER QUALITY CONTROL BOARD, STATE OF CALIFORNIA

COMMENTS FROM MATT ST. JOHN

September 24, 2007

To: Paul Zedonis, USFWS – Arcata Field Office
From: Matt St. John, NCRWQCB

Subject: Comments on “Coherence of Nutrient Loads and AFWO Klamath River Grab Sample Water Quality Database”

We appreciate the opportunity to comment on the Draft report (V.4.0 – June 30, 2007) “Coherence of Nutrient Loads and AFWO Klamath River Grab Sample Water Quality Database.” We have reviewed the draft report and provide the following comments in light of our current effort in developing total maximum daily loads (TMDLs) for the Klamath River.

- It would be useful to better define the purpose of this task in the Introduction section of the report. While the first sentence does state that “the purpose of this task was to determine the relation between in-stream concentrations of nutrients (and related parameters) and the identified point and nonpoint loads of nutrients”, it would be useful to elaborate on this. Why is it important to determine the relationship between in-stream concentrations and identified loads? Do the authors (and USFWS) suggest that the plug flow model be used to try to make water resource management decisions?
- We suggest including a section on assumptions, uncertainty, and limitations. In particular, it would be useful to acknowledge that there is uncertainty associated with the measured/observed nutrient concentration data. The fifth sentence in the Introduction section discusses possible reasons for a difference between observed and predicted nutrient concentrations, but uncertainty associated with measured/observed data is not identified.
- The fourth sentence of Section 4.3 refers to “the figures”; it would be useful to reference specific figure numbers.
- The sensitivity analysis (Section 4.3) sheds light on the significance of the decay rate as a calibration parameter. The last sentence of the first paragraph of Section 4.3 mentions that biological mechanisms are assumed to be the dominant mechanisms resulting in loss of P and N from the water column. This is certainly the case, and in our opinion highlights the fact that the plug flow model does not account for critical and dominant factors affecting nutrient concentrations in the water column.
- We think that the recommendations at the end of the report have merit. It would be useful if you could expand on the second recommendation regarding the factors that influence nutrient concentrations from Iron Gate.
- The report identifies some important observations about nutrient releases from Iron Gate Reservoir. Unfortunately the simplified plug flow model approach cannot be applied above Iron Gate to help assess nutrient dynamics in the upper reaches of the river. It could be useful to extend the scope of analysis and apply the plug flow model upstream to offer

possible explanations for the summer late summer surge of phosphorus concentration in Iron Gate discharge as suggested in conclusion number 5 of your report.

RESPONSE TO COMMENTS

The questions raised and comments made in Matt St. John's memorandum are responded to below. In each case, the question or comment is posed in italics and the response follows.

- *It would be useful to better define the purpose of this task in the Introduction section of the report. While the first sentence does state that "the purpose of this task was to determine the relation between in-stream concentrations of nutrients (and related parameters) and the identified point and nonpoint loads of nutrients", it would be useful to elaborate on this. Why is it important to determine the relationship between in-stream concentrations and identified loads? Do the authors (and USFWS) suggest that the plug flow model be used to try to make water resource management decisions?*

  The overall purpose of the project of which this task is but one of several was to enhance the value of the AFWO grab sample database. Because the database includes water quality samples taken in the lower Klamath River and its major tributaries, one of uses of the database envisioned was to provide insight into the nutrient (nitrogen and phosphorus in particular) budget of the river, and that nutrient budget accounts for the gains and losses of water quality constituents. Those gains and losses can be characterized as nutrient fluxes – nutrient loads into the river from the upstream boundary of the study area, i.e., the lower Klamath River, and from the major and minor tributaries and nutrient losses in the form of nutrients removed from the water column through various physical, chemical, and biological means. Determining those sources and understanding the impact they have on the receiving water in terms of constituent concentration changes and the subsequent impacts on biota for example are the primary reasons for determining relations between in-stream concentrations of nutrients and nutrient loads.

  As to the question about the use of plug flow models in making water resource management decisions in general and the plug flow models developed in this study in particular, it is appropriate to review a bit of history. In the field of water quality management, the methods developed to account for constituent gains and losses are mass balanced based water quality models. Such models began to be used in the 1930's as the familiar Streeter-Phelps dissolved oxygen sag equation, and this model became the basis for federal and state waste management programs throughout the United States in the 1950's, 1960's, and 1970's. It is a plug flow model and incorporated two major sets of processes – biological decomposition and the dissolved oxygen consumed in the process and reaeration, or the dissolved oxygen added to or removed from the water column through oxygen diffusion through the air water interface. The mathematical representation of biological decomposition and oxygen demand was a first order term with an overall decay or deoxygenation rate with units of mass per time per mass present or just 1/time. The Streeter-Phelps equation has since been supplanted by enhancements that incorporate biological processes that separate organic material decomposition from nitrification, oxygen addition through community photosynthesis and oxygen depletion through community respiration and benthic demand, and so forth. These enhancements may be found in DOSAG, a USEPA supported oxygen model which has been superseded by QUAL2E and derivatives thereof. Both of these are plug flow models in finite segment form.

Plug flow models such as the one used in this study have been used since the 1970's to address nutrient dynamics in streams and rivers. One has only to examine the textbooks by Robert Thomann and the many publications by Donald O'Connor and Robert Thomann to gain an appreciation for the variety of applications made of simplified models such as the plug flow model and their use for water quality management decisions.

Water quality modeling practice today typically involves the use of finite element models with numerical solutions and sophisticated output visualization means. Such models are quite sophisticated, require that they be used by individuals with significant experience in water quality modeling and interpretation of output, and be run on computers with sufficient memory and speed to achieve computational results in a reasonable period of time. Of course, such computers are readily available today, and such models are in common use. Using them to make managerial decisions has its challenges mainly because of the challenge of interpreting the complex model results and the acceptability of such complex model results by the taxpayers who must pay for the water quality management systems recommended based on those results.

Simplified models are on the other hand easy to develop and apply, and their output is easy to interpret and explain to the public. What's more, the simplified models often provide as much as 60 percent of the water quality management answer or understanding of constituent load to water quality impact one might be seeking from the finite element models.

Finite segment models are elaborations of the single segment simplified model and simply represent a series of segments whose upstream and downstream boundaries are determined by point of mass balance (e.g., tributary inflow) or by arbitrary boundaries or both. In this study, what is being called a simplified model is the finite segment model based on plug flow. Such models add a measure of sophistication that allows the user to view the impact of multiple inputs along a lengthy stretch of stream or river. Such models may add another 10 to 20 percent of understanding. It is the more sophisticated models that add the balance of understanding.

While one may argue with the percentages of understanding quoted here which are based on the authors experience and that of others in the field, the main point is that simplified models do permit the user to gain understanding quickly and easily, and that understanding may lead to a water quality management decision or it may inform the more sophisticated modeling work. The models do add value and should still be considered as tools to provide a basis for water resource management decisions just as they were in decades past by federal and state agencies. Whether they are in fact used for such purpose is a policy decision that is made for the particular situation being addressed.

- *We suggest including a section on assumptions, uncertainty, and limitations. In particular, it would be useful to acknowledge that there is uncertainty associated with the* *measured/observed nutrient concentration data. The fifth sentence in the Introduction section discusses possible reasons for a difference between observed and predicted nutrient concentrations, but uncertainty associated with measured/observed data is not identified.*

Such a section (3.3 Model Error) has been added and material presented elsewhere in the report moved into that section.

- *The fourth sentence of Section 4.3 refers to "the figures"; it would be useful to reference specific figure numbers.*

  The sentence is referring to all the figures showing calculated and measured nitrogen and phosphorus concentrations, but verbiage has been added to refer to specific figure numbers.

- *The sensitivity analysis (Section 4.3) sheds light on the significance of the decay rate as a calibration parameter. The last sentence of the first paragraph of Section 4.3 mentions that biological mechanisms are assumed to be the dominant mechanisms resulting in loss of P and N from the water column. This is certainly the case, and in our opinion highlights the fact that the plug flow model does not account for critical and dominant factors affecting nutrient concentrations in the water column.*

  Actually, the simplified plug flow model does account for critical and dominant factors present affecting nutrient concentrations in the water column represented as the lumped, simple decay rate. It just does not allow for the effects of such factors as nutrient uptake by vegetation, sorption-desorption, diffusive exchange with sediments, etc. to be discerned from the single decay rate. It is acknowledged in the report that the single decay rate accounts for all the physical, chemical, and biological mechanisms affecting constituent concentrations in the river. While one can add simultaneous plug flow equations and terms in those equations to account for constituent species and the kinetics associated with the loss and transformation of those species and eventually get to a QUAL2E type model which the USEPA has used for years in waste load allocation, the simplified model is billed as one that allows an overview of what is happening to a single constituent (or in reality the sum of species of that constituent) and how that constituent's concentrations are affected by loads to the system and overall decay that occurs. It is the easiest, effective way to address the question of the relationship between loads and in-stream concentrations, and that was the reason for using the simplified model approach. The USEPA has used simplified models (CSTR) to present lakes and reservoirs for eutrophication management for many years.

- *We think that the recommendations at the end of the report have merit. It would be useful if you could expand on the second recommendation regarding the factors that influence nutrient concentrations from Iron Gate.*

  Because the discharge from Iron Gate Reservoir is the upper boundary of the model, we have not looked upstream beyond that discharge. Flows and nutrient loads from Iron Gate become the boundary conditions for the simplified models and, as we have seen, strongly influence downstream concentrations of constituents.

- *The report identifies some important observations about nutrient releases from Iron Gate Reservoir. Unfortunately the simplified plug flow model approach cannot be applied above Iron Gate to help assess nutrient dynamics in the upper reaches of the river. It could be useful to extend the scope of analysis and apply the plug flow model upstream to offer possible explanations for the summer late summer surge of phosphorus concentration in Iron Gate discharge as suggested in conclusion number 5 of your report.*

It would be interesting to determine if the plug flow model could be applied upstream. As the comment implies, the problem might be modeling the reservoirs. Iron Gate Reservoir, for example, is a low residence time, layered reservoir which would be difficult to represent with a single layer plug flow model. If the late summer surge is being created within Iron Gate itself, then an upstream model may not add much to the picture. If, however, the surge is coming from upstream and being passed through Iron Gate, then such a model would be more useful.