Lost River Model for TMDL Development

August 2005

Prepared for:

U.S. Environmental Protection Agency Region 10
U.S. Environmental Protection Agency Region 9
Oregon Department of Environmental Quality
North Coast Regional Water Quality Control Board

Prepared by:
Water Resources and TMDL Center
Tetra Tech, Inc.

Model Configuration and Results

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1.0 INTRODUCTION

The Oregon DEQ (ODEQ) and the North Coast RWQCB (NCRWQCB) have both included the Lost River on their corresponding 303d Lists as a result of observed water quality criteria exceedances. The Lost River is actually composed of a series of riverine segments, impoundments, drains, and canals that straddle the Oregon-California border from Clear Lake Reservoir to the Klamath River. Impairments include dissolved oxygen, chlorophyll a, temperature, fecal coliform, pH, and ammonia for various portions of the Lost River system (including the Klamath Straits Drain) in Oregon and nutrients, temperature, and pH for segments of the system in California. As such, the states are required to develop TMDLs for applicable water quality parameters. The first steps in the TMDL development process have already been conducted and included compilation of available data; evaluation of monitoring data to identify the extent, location, and timing of water quality impairments; and development of a technical approach to analyze the relationship between source pollutant loading contributions and in-stream response. These steps were detailed in “Data Review and Modeling Approach – Klamath and Lost Rivers TMDL Development,” dated April 23, 2004. Subsequent steps include model configuration, model testing (calibration and corroboration), and scenario analysis. This document discusses the configuration of the Lost River model and presents modeling results for the Lost River from Malone Dam through Klamath Straits Drain to the Klamath River for 1999 and 2004.

The Lost River originates at Clear Lake Reservoir in Northern California. It flows in a northwesterly direction into Oregon, to the town of Bonanza. The river then returns south, passes in close proximity to the city of Klamath Falls, and ultimately flows back into California. In California, the Lost River flows into Tule Lake, the river’s natural hydrologic termination. Since the early 1900’s, extensive flood diversion and irrigation facilities have been constructed throughout the Lost River Basin, known as the U.S. Bureau of Reclamation’s (BOR) “Klamath Project” (WRE 1965). The “Klamath Project” has a significant impact on the hydrology and water quality of the Lost River, because it essentially creates a series of impoundments (including those at Malone Dam, Harpold Dam, Wilson Dam, and Anderson-Rose Dam) and free-flowing river segments. Flow magnitudes change dramatically throughout the year along the entire length of the Lost River due to irrigation practices and operation of the “Klamath Project.” Modification of the natural hydrology has also enabled the Lost River to be hydrologically-connected to the Klamath River for the past century through a series of pumps, canals, drains, and impoundments (from Tule Lake, through the P Canal, into the Lower Klamath Lake, and through the Klamath Straits Drain).

Due to the complex physical nature of the Lost River and its profound influence on water chemistry and biology, every attempt was made to obtain the most current and comprehensive data to support model development, application, and analysis. Although data were accessed from numerous sources and multiple, focused water quality monitoring efforts were conducted during the summer of 2004, there are still extensive data limitations. The monitoring efforts demonstrated that flow and water quality conditions can change dramatically from one day to the next at different locations in the system (even without significant atmospheric changes). These conditions imply that a detailed understanding of the time-variable nature of irrigation return flows and withdrawals along the entire length of the Lost River (and associated water quality characteristics), is critical. Unfortunately, these data sets are not currently available. The modeling approach that was pursued made the best use of available data and provides a framework which can be readily updated in the future as more data become available. While the model may not be able to predict sudden, localized changes in the system or flawlessly reproduce the temporal variability of every water quality parameter, it can be used to evaluate temporal and spatial trends and perform allocation analysis for TMDL development.

2.0 MODELING APPROACH

2.1 Model Selection

In order to support TMDL development for the Lost River system, the need for an integrated receiving water hydrodynamic and water quality modeling system was identified. The "Data Review and Modeling Approach – Klamath and Lost Rivers TMDL Development" proposed implementing the U.S. Army Corps of Engineers' CE-QUAL-W2 (W2) model for the entire Lost River system from Malone Dam through the Lower Klamath Lake, as well as the Klamath Straits Drain. This approach was approved by EPA Region 10, EPA Region 9, ODEQ, and NCRWQCB in May, 2004.

W2 is a two-dimensional, longitudinal/vertical (laterally averaged), hydrodynamic and water quality model (Cole and Wells 2003). The model is applicable to lakes, rivers, and estuaries that do not exhibit significant lateral variability in water quality conditions. It allows application to multiple branches for geometrically complex waterbodies with variable grid spacing, time-variable boundary conditions, and multiple inflows and outflows from point/nonpoint sources and precipitation.

The two major components of the W2 model include hydrodynamics and water quality kinetics. Both of these components are coupled, i.e. the hydrodynamic output is used to drive the water quality at every timestep. This makes it very efficient to execute model runs. The hydrodynamic portion of the model predicts water surface elevations, velocities, and temperature. The W2 model uses the ULTIMATE-QUICKEST numerical scheme for advection computation. The ULTIMATE-QUICKEST numerical scheme is a third order finite difference scheme. This method reduces numerical diffusion in the vertical and horizontal directions to a minimum. In areas of high gradients this scheme eliminates undershoots and overshoots which may produce small negative concentrations. The water quality portion of W2 can simulate the constituents required for Lost River TMDL development, including dissolved oxygen (DO), nutrients, phytoplankton interactions, macrophytes, and pH. In addition, the model is equipped to simulate other generic constituents.

2.2 Model Enhancements

The Lost River is a highly hydro-modified system that is predominantly fed by lake diversions. It contains multiple impoundments along its length that cause the river to exhibit highly variable hydraulic conditions, including free-flowing riverine segments and relatively stagnant reservoirs/ponds. These conditions, along with significant return flow and withdrawal from adjacent agricultural lands, lead to significant variability within short time periods. These dynamics have a dramatic effect on water quality and lead to a unique, highly biologically-active system that is inundated with phytoplankton and macrophytes during the spring, summer, and fall. Although the W2 model is capable of addressing the issues identified above, a number of enhancements to W2 version 3.2 were deemed necessary to expedite and strengthen the model for the rigors of Lost River TMDL development. These are described below.

2.2.1 Piecewise Simulation

The W2 code was modified to enable piecewise (i.e., waterbody-by-waterbody) simulation. This modification was instituted primarily to improve computational efficiency during the model calibration process. The Lost River is a complex hydraulic system that is divided into sections by a series of dams and other physical features (e.g., tunnels and pumps). To most accurately represent the system using W2, it needs to be divided into smaller "sections" composed of discrete computational segments. This is described in subsequent sections. Because the system is so large and is broken up into a large number of segments, it is extremely time-consuming to run the entire model throughout the testing process. The simulation of an upstream waterbody, for example, does not need the information for downstream segments (unless they are linked using an internal head boundary). In the existing W2 framework, even if modelers and decision makers are only concerned with the most upstream waterbody, the model would have to solve the governing equations for all waterbodies. Additionally, when all waterbodies are simulated together, any time step constraints that apply to one waterbody (such as the need to use an extremely short timestep to avoid numerical instability), would apply to all of them, and this can significantly lengthen the simulation time. To achieve more efficient model calibration and scenario evaluation, a piecewise modeling capability was incorporated into W2 which allows the user to setup a model for all waterbodies of interest, but only run select waterbodies. The model tracks and stores previous runs and enables the user to incorporate these results as boundary conditions (when interested only in downstream segments). And it essentially disconnects unnecessary downstream segments when the user is interested only in upstream segments.

2.2.2 Tributary Partitioning

A user-defined, distributed tributary partitioning function was incorporated into the W2 code to more accurately represent diffuse flows (e.g., surface runoff, return flows, and withdrawals) into and out of the river. In the existing W2 model, distributed flows (i.e., any lateral flow not represented by a discrete tributary) are applied to each modeled segment based on the segment's length. While this is typically a reasonable assumption, the Lost River's land-based inflows and withdrawals are highly managed and thus cannot be represented based on segment length (or even watershed area). To allow for a more flexible distribution of the distributed flow, a function was incorporated into W2 to provide users the ability to specify a spatial distribution pattern for the distributed flows at each branch.

2.2.3 Sediment Oxygen Demand

To improve W2's representation of SOD, a Monod type SOD formulation was incorporated into the code, as presented by Chapra (1997). Chapra suggested that SOD is nonlinearly related to the water column DO concentration, such that the higher the DO, the higher the SOD. This formulation more accurately represents the dependence of SOD on water column DO concentration. In the existing W2 model, SOD is related to water column DO such that when DO is lower than a threshold, SOD is "turned off" until the DO recovers (above the threshold). SOD is then suddenly turned on at that point. The current formulation introduces abrupt SOD behavior into the system. Therefore, it was improved upon using a Monod type formulation to achieve a smooth transition. The formulation is as follows:

$$SOD = DO/(DO + DO_{half\_saturation})*SODC \qquad \text{(Eq. 2-1)}$$

where: *SOD* is the effective SOD in g/m2/day
DO is the water column dissolved oxygen concentration
$DO_{half\_saturation}$ is the half saturation coefficient that represents the oxygen level at which SOD becomes half of the specified zero-order *SODC* coefficient.

With this formulation, the effective SOD changes continuously with the overlying water column DO and provides for a more reasonable approximation of natural processes.

2.2.4 Aquatic Vegetation

The Lost River is a biologically productive system that exhibits excessive growth of floating (phytoplankton) and rooted aquatic vegetation (macrophytes – which for the purpose of this discussion include epiphyton and periphyton). A recent survey of the Lost River during July 2004 by MaxDepth Aquatics indicated that the dominant taxon present in the river system was Ceratophyllum demersum (coontail). Other common species included Lemna minor (duckweed), several species of pondweed (Potomogeton pectinatus, P. crispus, and P. nodosus), Elodea canadensis, Heteranthera dubia, and Cladophora sp. All of these taxa are tolerant of high turbidity and are common species found in eutrophic lakes and slow-moving waters. Because the macrophytes, in particular, play such an integral role in the dynamics of the river, it is critical that they are properly addressed in the modeling framework. The formula incorporated is the same as in the EFDC model (Park et al.1995) and the WASP model (Shanahan and Alam 2001).

The current version of W2 is capable of simulating phytoplankton and epiphyton/periphyton (macrophytes). The current representation of macrophytes does not consider substrate availability or flow velocity limitation. Additionally, light conditions are calculated on a layer-average basis and the impact of macrophyte growth on hydrodynamic simulation is not handled. In an effort to more accurately represent macrophyte dynamics, a series of enhancements were made to W2 to address these limitations. No modifications were made to the phytoplankton representation, and it was used for this application.

Substrate availability limitation was added to the model. The substrate availability limitation accounts for the impact of bed composition on macrophyte communities. With this factor considered, macrophyte growth can be limited by bed type (i.e., the specified bed particle size distribution must be suitable for growth). In general, periphyton growth is limited in areas dominated by fine sediments whereas macrophytes (generally more prevalent in this system) may exhibit limited or no growth in areas characterized by cobbles and large particles. The fraction of mud reported in the MaxDepth Aquatics survey was used to characterize substrate availability throughout the system.

Hydrodynamic interactions with macrophyte growth were considered in this modeling effort. High in-stream velocities can have a limiting effect on the macrophyte community. The magnitude of the limiting effect was represented using the half saturation coefficient specified in the model input file. In general, the higher the value for the half saturation coefficient, the smaller the impact of velocity on macrophyte growth. The growth of macrophyte communities can increase the bottom roughness of river channels, and thus has an effect on hydrodynamic behavior. A simplified Monod-type formulation was used in the model to relate the density of the macrophytes to the stream bottom roughness coefficients. The half saturation coefficients for this relationship are obtained through calibration where sufficient data were available. To most accurately simulate the impact of macrophyte growth on hydrodynamics, detailed numerical representation of their physical characteristics would be required, and this is outside the scope of the current study.

Growth thickness was also included in the model to better represent the actual light conditions affecting macrophyte growth. The plant (mattress) height is specified in the updated model input file, and the model calculates the vertical average light condition for the specified height/length of the macrophytes. This is used in the growth calculation. The formulation itself is equivalent to the original W2 formulation for the case when the macrophyte occupies the entire layer. It improves predictions when macrophytes occupy only a portion of the layer and is especially useful for periphyton simulation (since periphyton tend to grow on the bottom only).

A single macrophyte category was used in the model to represent all macrophyte species present in the river. Representation of all species as a single category is supported by results of the recent survey that indicate present species generally obtain most of their nutrients from the water column in a similar manner. Ideally, a comprehensive ecological model could be incorporated into the system to study inter-species competition and co-evolution, but this is precluded by data, time, and resource constraints. It should be noted that phytoplankton was also simulated for the Lost River, and this was done using the existing W2 algorithms.

2.2.5 Slope Impacts

The model's ability to represent SOD and macrophytes for a significantly sloping channel (i.e., in the longitudinal direction – from upstream to downstream) was also improved. Using the original W2 code, the impact of SOD and macrophytes on DO can be significantly under-predicted in some sections of a sloping channel due to the heterogeneity in layer subtraction/addition for a long, sloping channel. For example, in the Lost River section from Malone Dam to Harpold Dam, the upstream segments may become very shallow during low flow conditions, however downstream segments may maintain considerable depth (due to return flows and damming). Under such a circumstance, the original W2 model would implement layer subtraction based on the upstream segments (i.e., reduce the number of vertical layers in the model). This would result in only one active layer throughout the entire modeling segment. Unfortunately, W2 currently would not be able to change the bed area for this layer to accurately represent the bed dimensions of this "new" artificial layer. Thus, the bed's impact on SOD and macrophyte prediction would not be accurately represented. To better represent potential variability, bed area associated with SOD and macrophytes is tracked in the updated model throughout the built-in layer subtraction and addition process. Therefore, the impact of SOD and macrophytes is better represented. It should be noted that the original W2 can generate reasonable results when the width of each vertical model layer varies gradually (i.e., there is not an abrupt change in segment width between any model layers in the vertical direction). However, when a narrow bottom layer is used to contain low flow, the error in SOD and macrophytes is significant.

2.2.6 Flow Control Structures

To more accurately simulate flow downstream of impoundments and to avoid numerical instability during the low-flow season, the existing W2 flow control structure equation was enhanced to include a leakage term. This added leakage term allows some water to flow from upstream segments to downstream segments, even when the upstream water level is lower than the dam crest. Dam leakage allows downstream segments to realistically remain wet during low impoundment water surface elevation periods. This function was added because there is always a small amount of leakage water downstream of impoundments in the Lost River (personal communication with BOR). Additionally, the hydrodynamic model will not run when there is no water, thus a minimum flow must be maintained in the system.

2.2.7 TMDL Development Tool

To expedite TMDL development, a TMDL Development Tool was developed and incorporated into the W2 model. The tool allows the user to specify the load reduction ratio for each loading source and constituent in an external control file. The model then directly uses this information to adjust the boundary conditions for scenario analysis.

2.3 Model Configuration

Model configuration involved setting up the model computational grid (bathymetry) using available geometric data, designating the model's state variables, and setting boundary conditions, initial conditions, and hydraulic and kinetic parameters for the hydrodynamic and water quality simulations. This section describes the configuration process and key components of the model in greater detail.

2.3.1 Segmentation/Computational Grid Setup

The computational grid setup defines the process of segmenting the entire Lost River into smaller computational segments for application of the W2 finite difference scheme. In general, bathymetry is the most critical component in developing the grid for the system.

For this modeling study, the Lost River was divided into 12 waterbodies based on the presence of major hydraulic features and the location of monitoring data in the system. Each of these waterbodies, which are listed in Table 2-1 and shown graphically in Figure 2-1, was represented using unique geometric and hydrological characteristics in the model. It should be noted that all longitudinal dimensions (in meters) in the table are approximate values, as measured using GIS. Longitudinal dimensions presented for waterbodies 7 through 12 are estimates, because waterbodies 7 and 9 are wide lakes that do not necessarily have a finite length. A combination of USGS quadrangle maps for Oregon and California and RF3 reach file layers in GIS were used to establish the longitudinal dimensions of the system.

Table 2-1. Lost River Model Waterbodies

Waterbody #	Description	Starting River Meter (m)	Ending River Meter (m)	Number of Segments	Segment Length (m)	Number of Layers	Layer Thickness (m)
1	Malone-Harpold	0	38,638	80	483.0	5	1.0
2	Harpold-Ranch	38,638	43,535	10	489.7	4	0.96
3	Ranch-Wilson Reservoir	43,535	58,695	30	505.3	4	0.84
4	Wilson Reservoir	58,695	63,253	9	506.4	5	1.0
5	Wilson Dam to Anderson Rose Dam	63,253	92,653	55	534.5	5	1.0
6	Anderson Rose Dam to Tule Lake	92,653	104,722	24	502.9	4	1.0
7	Tule Lake	104,722	112,732	1	8008.0	2	1.0
8	P-Canal	112,732	116,757	8	502.6	3	1.0
9	Lower Klamath Lake	116,757	128,655	1	11898.0	2	1.0
10	Klamath Straits Drain before Pump E	128,655	135,252	13	507.2	5	1.15
11	Klamath Straits Drain before Pump F	135,255	143,327	15	538.1	5	0.93
12	Klamath Straits Drain after Pump F	143,327	146,346	6	503.2	5	0.93

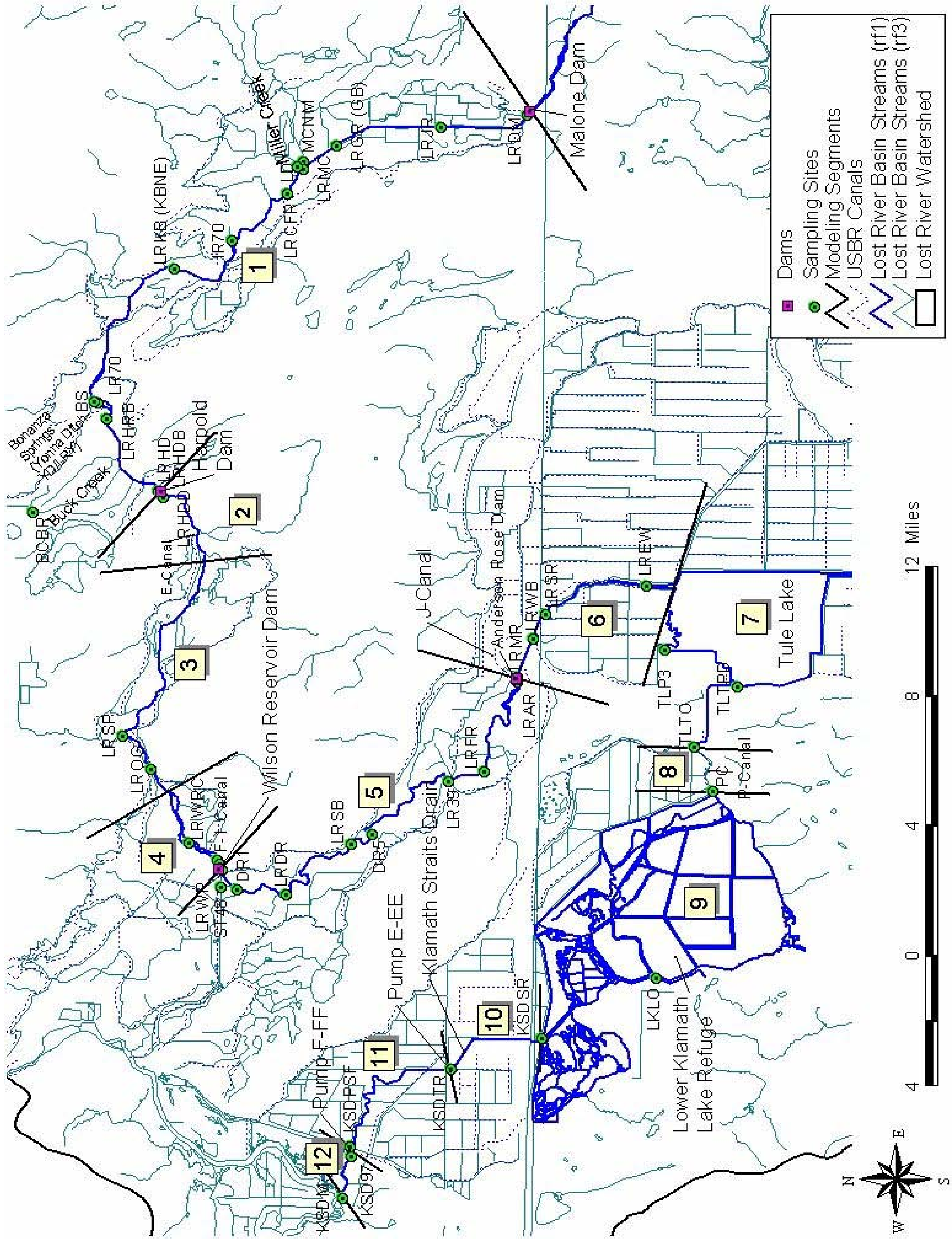

Figure 2-1. Lost River Model Water bodies

Each of the 12 modeling waterbodies was further divided into computational segments (a.k.a. segments) for greater detail in modeling. The number of segments and lengths of each segment varied by modeling waterbody, however each segment was approximately 500 meters in length (with the exception of Tule Lake and the Lower Klamath Lake which were each represented as a single computational segment). This resulted in a whole number of segments for each segment. It should be emphasized that Tule Lake and the Lower Klamath Lake are very complex features, however due to the scope of the study and geometric, hydrologic, and water quality data limitations, representation using a single computational segment for each was deemed appropriate. Major data limitations precluding a more detailed representation of these lakes include absence of bathymetric data and lack of spatially- and temporally-variable loading data. These lakes can be further segmented in the future to examine spatial variability of water quality, in the event that sufficient additional data are obtained. Table 2-1 also summarizes the lengths and numbers of computational segments for each of the 12 waterbodies.

Within the W2 model, each computational segment can have multiple layers associated with it. The number of layers and layer thickness for each computational segment is designated based on physical characteristics and the need to adequately represent the vertical variation of water quality while maintaining computational stability and limiting simulation time. The number of vertical layers varied for each of the modeling waterbodies from 2 to 5 layers. Previous W2 applications have used a vertical grid spacing (layer thickness) of 0.2 meters to 5 meters (Cole and Wells 2003). For this study, layer thicknesses were set to approximately 1 meter (and ranged from 0.84 meters to 1.15 meters) for the 12 waterbodies (Table 2-1).

The average width of each computational segment varied significantly for each waterbody (and each layer) used to represent the Lost River system. Depth-variable widths were specified using a combination of USGS quad maps; Lost River Channel Improvements Plans from the early 1900's (from BOR) for several locations on the Lost River - Poe Valley, Langell Valley, Klamath Straits Drain, and the Lower Lost River; and physical measurements conducted by NCRWQCB and BOR in late 2003 and early 2004. The NCRWQCB and BOR physical measurement locations are presented in Table 2-2.

Table 2-2. Physical Measurement Locations

Site ID	Site Name
LRDM	Lost River downstream of Malone Dam
LRGR	Lost River at Gift Road Bridge
MCEL	Miller Creek at East Langell Valley Road
LRCR	Lost River at Cheese Factory Road Bridge
LRKB	Lost River at Keller Bridge
LR70	Lost River at Highway 70 Bridge in Bonanza
BC	Buck Creek @ Burgdorf Road/Casebeer Road
LRHDB	Lost River downstream of Harpold Dam @ bridge
LRPV	Lost River @ Poe Valley, Lost River Ranch @ bridge
LROG	Lost River @ Olene Gap
LRWRC	Lost River in Wilson Reservoir @ Crystal Springs Road Bridge
DR1	Drain #1 (downstream of Lost River Diversion Channel)
LRDCTR	Lost River Diversion Channel @ Tingley Road Bridge
LRDR	Lost River @ Dehlinger Road
LRSB	Lost River @ Stukel Bridge (Matney Way)
DR5	Drain #5 (Wong Road)

Site ID	Site Name
LR39	Lost River @ Highway 39 Bridge
LRFR	Lost River @ Falvey Road Bridge
LRMB	Lost River @ S. Merrill Road Bridge
LRARB	Lost River downstream of Anderson-Rose Dam @ Bridge
LREW	Lost River @ East/West Road Bridge
PC	P Canal
KSDM	Klamath Straits Drain West of Rail Road Tracks
NNC	North Canal section between RR tracks and Hwy 97
ADY	ADY Canal section, east side of Hwy 97 Bridge

Once the dimensions of the computational segments had been defined for the grid, the segment orientation was specified. These values were specified in radians, with north represented as zero radians. The segment orientation was measured for each segment in each waterbody and stored in the bathymetry files.

2.3.2 State Variables

Selection of appropriate model state variables to represent processes and hydrodynamic and water quality processes of concern is a critical factor in model configuration. For this study, state variables were selected to most accurately predict TMDL impairments and related physical, chemical, and biological processes. The following constituents were configured for the Lost River model in W2. Refer to Cole and Wells (2003) for details regarding equations utilized and interactions represented.

1) Conductivity
2) Temperature
3) ISS (inorganic suspended solids)
4) PO_4 (dissolved inorganic phosphorus)
5) NH_4 (ammonium)
6) NO_3/NO_2
7) LDOM (labile dissolved organic matter)
8) RDOM (refractory dissolved organic matter)
9) LPOM (labile particulate organic matter)
10) RPOM (refractory particulate organic matter)
11) DO (Dissolved Oxygen)
12) CBOD (Carbonaceous Biochemical Oxygen Demand)
13) Alkalinity
14) TIC (total inorganic carbon)
15) Phytoplankton
16) Macrophytes (epiphyton/periphyton)

2.3.3 Boundary Conditions/Linkages

To run the dynamic W2 model external forcing factors, known as boundary conditions, and internal linkages must be specified for the system. These forcing factors are a critical component in the modeling process and have direct implications on the quality of the model’s predictions. External factors include a wide range of dynamic information:

- Upstream external inflows, temperature, and constituent boundary conditions (US);
- Tributary inflows, temperature, and constituent boundary conditions (TRIB);
- Distributed tributary inflows, temperature, and constituent boundary conditions (DST);
- Withdrawals (WD); and
- Atmospheric conditions (including wind, air temperature, solar radiation).

Upstream external inflows essentially represent the inflow at the model's "starting" point. Tributary inflows represent the major tributaries that feed into the Lost River. Distributed tributary inflows represent the combination of all diffuse contributions to each of the waterbodies (i.e., anything that is not considered a major tributary inflow, such as irrigation return flow). All water removed from the system is combined within the Withdrawals category. The US, TRIB, DST, and WD boundary conditions were specified for the Lost River model based on all available data. The available data are sufficient to provide limited spatially- and temporally-variable inputs. Thus, the boundary conditions generally represent "smoothed" or averaged conditions over a period of time. Ideally, high-resolution time-variable inputs should be used to drive the model, however, these inputs are currently not available. "Smoothed" conditions limit the model's ability to predict localized and short-term effects, however, they enable the model to reasonably predict trends.

Meteorological data are an important component of the W2 model. The surface boundary conditions are determined by the meteorological conditions. The meteorological data required by the W2 model are air temperature, dewpoint temperature, wind speed, wind direction, and cloud cover. In general, hourly data are recommended (expressed in Julian Day) (Cole and Wells 2003). Hourly, unedited local climatological data were used from the Klamath Falls Airport for the entire Lost River system. These data provided the most complete data set of required meteorological parameters for the W2 model meteorological file. Cloud cover was calculated using hourly sky conditions reported at this site (which are based on a scale from 0 to 8). Table 2-3 shows the lookup table used for calculating the cloud cover. The sky conditions reported were converted to a scale of ten based on W2's meteorological data file requirements for cloud cover.

Table 2-3. Cloud Cover Lookup Table

Cloud Cover Condition	Cloud Cover
CLR (Clear)	0.05
FEW (Few)	0.25
SCT (Scattered)	0.50
BKN (Broken)	0.75
VV (Vertical Visibility into fog or snow)	0.90
OVC (Overcast)	0.95

Precipitation and evaporation inputs are not directly considered for the river sections in the Lost River model formulations. They were assumed to be equivalent, on an annual basis, due to their relatively small surface areas. For Tule Lake and Lower Klamath Lake evaporation is simulated using the default parameters and equations in CE-QUAL-W2. It should be noted, however, that although the model does not explicitly consider precipitation or evaporation inputs for the riverine sections, it does simulate the impact of evaporation on heat balance.

Internal linkages that must be specified include:

- Downstream weir-based boundary conditions (DSW);
- Upstream internal flow, temperature and constituent boundary conditions (USIFB);
- Downstream internal head boundary conditions (DSIH); and
- Upstream internal head boundary conditions (USIH).

Dams (e.g., Harpold and Anderson Rose), which represent the most downstream portion of many Lost River waterbodies, are represented using downstream weir-based boundary conditions. The equations instituted are described below. Internal boundary conditions for waterbodies that are downstream of a dam (or segment represented with DSW) are represented using upstream internal boundary conditions (or essentially, the outflows based on the DSW equations). Downstream and upstream internal head boundary conditions are used to link free-flowing waterbodies (i.e., those not divided by a physical structure).

The model was first configured and calibrated (tested) for 1999 due to data availability and the exhibition of water quality criteria exceedences. The calibration was corroborated using 2004 data. The model boundary conditions primarily utilized information from 1999 (for both the 1999 and 2004 runs). Any exceptions are discussed in subsequent sections (*in italics*). Figure 2-2 presents a diagram of the modeling environment and relative locations of boundary conditions. Yellow circles represent divisions between the 12 modeling waterbodies. Blue arrows represent TRIB inputs and the one US input. Red arrows represent DST inputs, which are not at a single location, but rather distributed along the entire waterbody length. WDs are represented with green arrows. Table 2-4 lists the primary boundary conditions and linkages by waterbody.

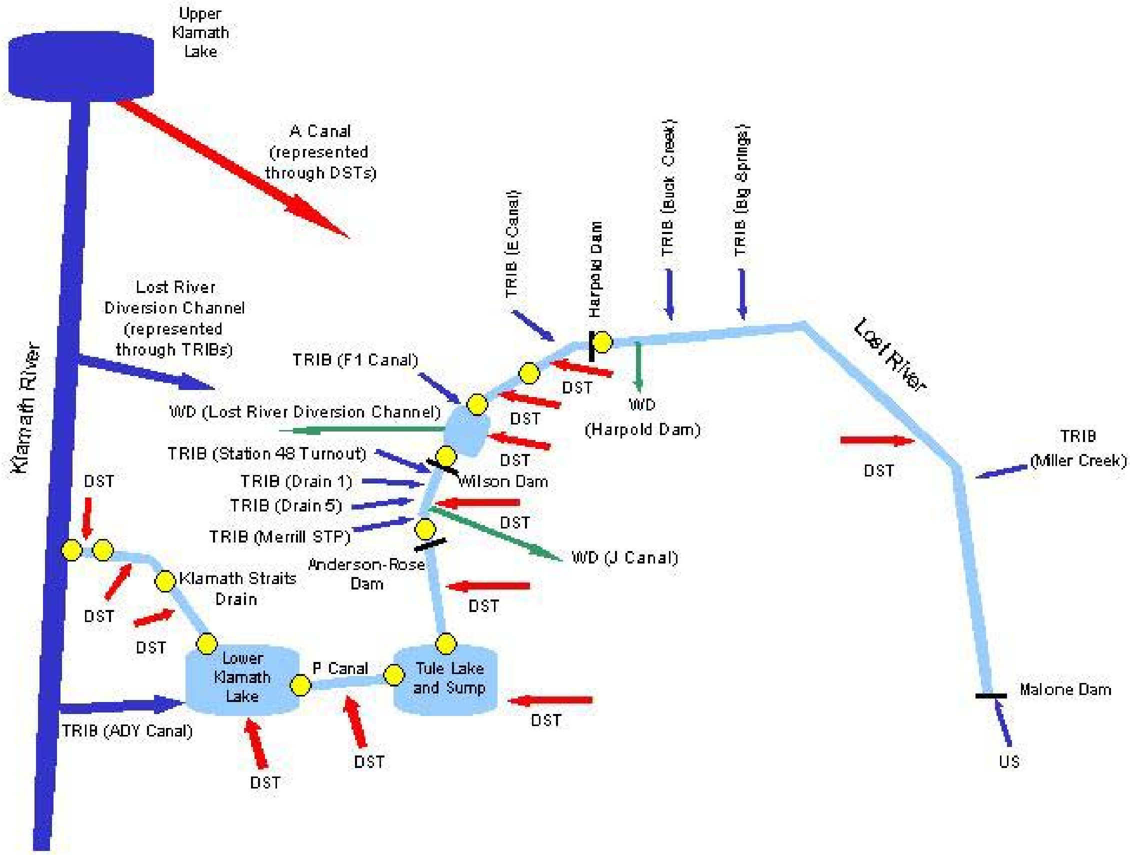

Figure 2-2. Lost River Model

Table 2-4. Boundary conditions and Linkages for the Lost River Waterbodies

Waterbody	Location	Boundary Condition
1	Malone Dam	US
1	From Malone to Harpold Dam	DST
1	Miller Creek	TRIB
1	Big Springs	TRIB
1	Buck Creek	TRIB
1	Lost River (LR) before Harpold Dam	WD
1	LR at Harpold Dam	DSW
2	LR downstream of Harpold Dam	USIFB
2	LR from Harpold to RM 27	DST
2	E Canal	TRIB
2	LR at RM 27	DSIH
3	LR downstream of RM 27	USIH
3	LR from Ranch to Wilson Res	DST
3	LR before entering Wilson Res	DSIH
4	LR entering Wilson Res	USIH
4	LR at Wilson Reservoir	DST
4	LR upstream of Wilson Dam	WD
4	F-1 Canal	TRIB

Waterbody	Location	Boundary Condition
4	LR at Wilson Dam	DSW
5	LR downstream of Wilson Dam	USIFB
5	LR from Wilson Dam to Anderson Rose Dam	DST
5	LR at J-Canal	WD
5	LR at Anderson Rose Dam	DSW
5	Station 48 Turnout	TRIB
5	Drain #1	TRIB
5	Drain #5	TRIB
5	City of Merrill STP	TRIB
6	LR downstream of Anderson Rose Dam	USIFB
6	LR from Anderson Rose Dam to Tule Lake	DST
6	LR before entering Tule Lake	DSW
7	LR entering Tule Lake	USIFB
7	LR at Tule Lake	DST
7	LR at Tule Lake outlet	DSW
8	P Canal downstream of Tule Lake	USIFB
8	P Canal	DST
8	LR before entering Tule Lake	DSW
9	P canal entering Lower Klamath Lake	USIFB
9	Lower Klamath Lake	DST
9	ADY Canal	TRIB
9	Lower Klamath Lake entering Klamath Straits Drain	DSW
10	Klamath Straits Drain leaving Lower Klamath Lake	USIFB
10	Klamath Straits Drain from Lower Klamath Lake to Pump E	DST
10	Klamath Straits Drain at Pump E	DSW
11	Klamath Straits Drain leaving Pump E	USIFB
11	Klamath Straits Drain from Pump E to Pump F	DST
11	Klamath Straits Drain at Pumps F	DSW
12	Klamath Straits Drain leaving Pump F	USIFB
12	Klamath Straits Drain from Pump F to Discharge at Klamath	DST
12	Klamath Straits Drain at Klamath River	DSW

The following sub-sections provide a detailed description of the boundary conditions used to represent each waterbody.

2.3.3.1 Waterbody #1: Malone Dam to Harpold Dam

US: The 1999 daily flow data downstream of Malone Dam from the BOR database were used to form the upstream inflow boundary condition. During the irrigation period Malone Dam discharge into the Lost River is effectively zero, with the exception of dam leakage (which was represented in the model as 0.2 cms for the sake of model stability). Time-variable temperature, monitored at LRDM (downstream of the Malone Dam diversion), were also used. Since the temperature data are relatively sparse, dates without data were obtained through linear interpolation using the measured data.

With regard to water quality parameters, the measured data do not cover the complete list of the model state variables, so certain assumptions were made in initially setting the boundary conditions. It should be noted that the final values for these parameters were determined through the calibration process. The constituents with measured data include NH_4, NO_3/NO_2, phytoplankton (in terms of chlorophyll-a), PO_4, alkalinity, and conductivity. These values were directly incorporated into the concentration boundary condition file. There are no 1999 data available to specify boundary conditions for ISS, CBOD, LDOM, RDOM, LPOM, RPOM, periphyton/macrophytes, or TIC. In the W2 model the LDOM, RDOM, LPOM, and RPOM are used to track the organic matter internally generated by algae death, so the boundary concentrations for these four organic matter constituents were set to 0.0 for all the dates. Periphyton/macrophytes were set to 0.0 g/m^2 since they are assumed to be non-transportable (and represented as such in the model). CBOD and TIC are two important constituents for which no data were available. Therefore their values were estimated to be equal to 4.0 mg/L through the calibration process. This value is within the range of the 2004 monitoring data. Since no data are available to characterize the temporal trends of CBOD and TIC concentrations for the boundary conditions, they were set constant throughout the year. TIC was obtained through model calibration for pH. No data were available for ISS either, therefore it was set to 6.0 mg/L, which is within the range of the 2004 monitoring data.

For the 2004 simulation, 2004 monitoring data at station LRDM were used. The CBOD concentration was derived from monitored BOD5 data and a calibrated decay rate. Flow data at Malone Dam were only available after April 29, 2004. Data for the remaining period were derived from available data at Harpold Dam for 2004 and 1999. This derivation involved calculating the ratio between concurrently available flows at Harpold and Malone Dams. This ratio was also used to derive flows for Miller Creek, Big Springs, and Buck Creek.

<u>DSW:</u> Although outflow rates are available at Harpold Dam (only in winter months due to backwater effects from Lost River Ranch dam in other months), they were not directly applied as a flow boundary condition in the model, because the goal of the effort is to develop a predictive modeling system (that is able to route flow from upstream to downstream). Since the discharge flow at Harpold Dam is generally stage-dependent, a stage-discharge relationship was derived based on the observed flow and water surface elevation data. The equation is as follows:

$$Q = aH^b + c \qquad \text{(Eq. 2-2)}$$

where: Q is the spillway flow rate (m^3/s)
H is the water depth above the spillway crest (m)
a, and b are the derived coefficient and exponent, respectively
c is a leakage term

For Harpold Dam, the values of a, b, and c are: 28.3, 1.95, and 0.1, respectively.

<u>TRIB:</u> In total, three tributaries were represented for waterbody #1. These include Miller Creek, Bonanza Springs, and Buck Creek. Although Bonanza Springs is not a direct surface tributary to the Lost River, past reports identify that it contributes significant flow to the river.

There are no data available to specify time series flow for Miller Creek, although a qualitative description in a historical report stated that the flow in Miller Creek into the Lost River is insignificant (USGS, 1999). Three flow data points are available from the USGS report, and the average of these flows is 0.2 cms. Therefore, this value was assumed for the entire year in the flow boundary condition file. Observed temperature and water quality constituent concentrations for Miller Creek (using LRMC) were used to set up the temperature and concentration boundary condition files. For the constituents without observed data for 1999 (ISS, CBOD, LDOM, RDOM, LPOM, RPOM, macrophytes, and TIC), the same convention used for the US was applied.

There are also insufficient data available to specify a complete flow time series from Bonanza Springs. Woods and Orlob (1963) stated that Bonanza Springs contributes to the Lost River at an average flow rate of 1.97 cms. Therefore, this flow rate was used for the entire year as the flow boundary condition. The temperature and concentration boundary conditions were specified utilizing observed data at BS. For the constituents without observed data (which are the same as those listed for US), the same convention used for the US was applied.

No time series flow data are available for Buck Creek either, although three flow values from USGS (1999) are available. The average of the three flow data points is 0.30 cms, thus this value was assigned as the boundary condition for the entire year. The temperature and concentration boundary conditions were specified based on observed data at BCBR. For the constituents without observed data (same as above), the same convention used for the US was applied.

TRIB data were derived from the monitoring data at the Miller Creek station for 2004. These data were applied to an extended period preceding and following (30 days in each direction) the monitoring data. The BOD was calculated in the same way as for the US boundary. Flow measurements for 2004 were averaged and used for the entire 2004 simulation period. TRIB data for Big Springs and Buck Creek also used 2004 monitoring data. Once again the data were extended backward for 30 days and forward for 30 days to create a relatively stable environment. The 2004 measured flow data for Buck Creek were averaged to update the flow file with a constant value for the 2004 simulation period.

<u>DST:</u> In general, the major sources of the distributed flows are agricultural irrigation withdrawals, return flows, watershed runoff, groundwater interaction, and other unaccounted for flows. In some cases these flows were negative and represented withdrawals from the system. Ideally, these sources would be treated separately in the model since they represent different spatial and temporal, as well as bio-chemical features. However, since no data are available to support a detailed characterization/differentiation of these impacts, a “combined” approach was applied to derive and configure the distributed flows. Using the “combined” approach, all the distributed flow and pollutant sources were lumped together to form a single source/sink for the waterbody.

For Waterbody #1, the initial estimate of the distributed flow rate was obtained by subtracting the Malone Dam outflow and tributary flows from the Harpold Dam outflow. This initial estimated flow was then iteratively refined through a comparison of the observed and simulated elevations at the Harpold Dam, until a reasonable match between the data and model results were achieved. There are no data available for assigning the time series of temperature and water quality concentration to the distributed flow. It was assumed that during the summer low flow period (which has been the focus of the study to date), the water quality at Lost River at Keller Bridge (LRKB) is largely a direct reflection of the distributed flow water quality. During summer periods, the flow from Malone Dam is generally insignificant since most of the water is used for irrigation. Therefore, the LRKB monitoring data for temperature and constituent concentrations were used to represent the DST.

For 2004, LRKB data were also used as the basis for DST. The data were extended backward for 30 days and forward for 30 days to create a relatively stable environment (reducing the impact of the 1999 boundary). The BOD and RPOM were calculated similarly to that for the US boundary.

WD: One withdrawal was configured for Waterbody #1, and this was the withdrawal at Harpold Dam. The Harpold Dam withdrawal represents the pump-out operation, which is located upstream of Harpold Dam, and all the pumping operations in the region. This pumping was obtained through the model calibration process (since no pumping data were readily available), with an aim at maintaining computational stability. A value of 4.0 cms was used in the model during the irrigation season while a value of 0.0 cms was used for the remainder of the year.

2.3.3.2 Waterbody #2: Harpold Dam to RM 27 (Poe Valley Bridge)

USIFB: The upstream inflow, temperature, and constituents for Waterbody #2 are provided by the flow from Waterbody #1 at Harpold Dam. In this study, Waterbody #1 was simulated independently, and the resulting dam discharge flow rate, as well as the simulated temperature and water quality, were saved in separate files. These were then read when simulating Waterbodies #2 through #4.

DSIH: For Waterbody #2, the downstream boundary condition was set as an internal head boundary condition at the Poe Valley Bridge (RM 27). This was continuously calculated and updated throughout the model simulation process.

TRIB: One tributary was represented in the model for Waterbody #2, in order to account for the contribution from the E Canal. Based on communication with ODEQ, there was assumed to be relatively insignificant flow from the E Canal. Therefore, a 0.1 cms flow was assumed for this inflow. The temperature and concentration boundary conditions were similar to those used for upstream TRIB inputs. Considering the low flow rate from the E canal, this temperature and concentration boundary condition do not have a significant impact on model results. The reason for keeping this tributary as a boundary condition is for scenario evaluation, where the flow from E Canal may require further evaluation.

DST: The distributed flow for Waterbody #2 was estimated in combination with Waterbodies #3 and #4. The distributed flow for Waterbodies #2, #3, and #4 were derived simultaneously, because the only available water surface elevation data for flow balance calculation were available for Wilson Reservoir. The initial estimate of the distributed flow rates for the three waterbodies were obtained by scaling the distributed flow for Waterbody #1, using the segment-length ratio between Waterbody #1 and Waterbodies #2, #3 and #4. These initial estimated flows were then iteratively refined by comparing the observed and simulated elevations at Wilson Dam, until a reasonable match between the data and model results were achieved. It was found that for most of the dates negative flows needed to be assigned to distributed flows for Waterbodies #2, #3, and #4, in order to achieve a reasonable match between observed and simulated surface water elevation for Wilson Reservoir. These negative flow rates represent pumping activities, vegetative evapotranspiration, seepage, measurement uncertainties, and other factors which are not explicitly represented. Because using negative flows for the distributed inputs misrepresents the load actually contributed by the watershed, the negative flows were removed from the DST file and added to the withdrawal file (WD) for the Lost River Diversion Dam described for Waterbody #4.

There are no data available for assigning a time series of temperature and water quality concentrations to the distributed flows, so it was assumed that the watershed runoff, agricultural return flow, and ground water concentrations for Waterbody #2 are similar to those of Waterbody #1.

WD: No withdrawals were configured for this waterbody.

2.3.3.3 Waterbody #3: RM 27 to Lost River before Wilson Reservoir

USIH: The upstream boundary condition for Waterbody #3 was provided through the internal head boundary condition between Waterbodies #2 and #3 at Poe Valley Bridge (RM 27). This is continuously calculated and updated throughout the model simulation process.

DSIH: For Waterbody #3, the downstream boundary condition was set as an internal head boundary condition at the point before entering Wilson Reservoir. This was continuously calculated and updated throughout the model simulation process.

TRIB: No tributary boundary conditions were configured for this waterbody.

DST: The derivation of distributed flow, temperature, and constituent boundary conditions for Waterbody #3 were described in the section for Waterbody #2.

WD: No withdrawals were configured for this waterbody.

2.3.3.4 Waterbody #4: Lost River before Wilson Reservoir to Wilson Dam

USIH: The upstream boundary condition for Waterbody #4 was provided through the internal head boundary condition between Waterbodies #3 and #4 at the Lost River before entering Wilson Reservoir. This is continuously calculated and updated throughout the model simulation process.

DSW: Historical data show that no spillage occurred at Wilson Dam during 1999, therefore a constant downstream boundary condition was configured to represent leakage of 0.1 cms.

TRIB: One tributary, the F-1 Canal, was represented in the model for Waterbody #4. Based on communication with ODEQ, flow from the F-1 Canal was assumed to be relatively insignificant, therefore, a 0.1 cms flow was assumed. The temperature and concentration boundary conditions were assigned based on upstream TRIB inputs. Considering the low flow rate from the F-1 canal, this temperature and concentration boundary condition do not have a significant impact on model results. The reason for keeping this tributary as a boundary condition is for scenario evaluation, where the flow from F-1 Canal may require further evaluation.

DST: The derivation of distributed flow, temperature, and constituent boundary conditions for Waterbody #4 were described in the section for Waterbody #2.

WD: One withdrawal was configured for Waterbody #4 to represent the diversion to the Lost River Diversion Channel. The historical observed diversion flow rate was converted into the format required by W2 to form the corresponding boundary condition. This flow was adjusted using the approach described in DST for Waterbody #2.

The historical observed diversion flow rate for 2004 was used and adjusted as for 1999.

2.3.3.5 Waterbody #5: Wilson Dam to Anderson Rose Dam

USIFB: The upstream inflow, temperature, and constituents for Waterbody #5 are provided by the flow from Waterbody #4 at Wilson Dam. In this study, Waterbodies #2, #3, and #4 were simulated simultaneously, and the simulated temperature and water quality immediately upstream of the dam were saved in separate files. These were then read during simulation of Waterbody #5 as the upstream boundary condition. The upstream flow boundary condition for Waterbody #5 was set the same as the DSW for Waterbody #4.

DSW: The downstream boundary condition for Waterbody #5 (at Anderson Rose Dam) was defined using a rectangular weir equation. This was done because dimensions of Anderson Rose Dam were available and thus flow could be related to crest length. A stage-storage relationship wasn't available as was the case for Harpold Dam.

$$Q = 2/3 \cdot C_d \cdot L \cdot \sqrt{2g} \cdot H^{1.5} \qquad \text{(Eq. 2-3)}$$

where: C_d is the coefficient of discharge (~0.62)
L is the crest length

It should be noted that if one adds the seepage term c to Eq. 2-3, it is equivalent to Eq. 2-2. The coefficients *a* and *b* in Eq.2-2 are the same as $2/3 \cdot C_d \cdot L \cdot \sqrt{2g}$ and 1.5, respectively, in Eq. 2-3. Using the crest length of the Anderson Rose Dam (324 ft) and the coefficient of discharge (0.62) results in values for a and b equal to 180.72 and 1.5, respectively. A leakage term of 0.1 was used to account for leakage when water is below the dam crest.

TRIB: Four tributaries were represented in the Lost River model for Waterbody #5, including the Station 48 turnout, Drain #1, Drain #5, and the City of Merrill STP.

Daily flow data are available for the Station 48 turnout and were used to specify the time series boundary condition at this location. The temperature and concentration boundary conditions were also specified based on observed data (at Station 48). For the constituents without observed data (similar to those identified for upstream waterbodies), the same convention for setting up the upstream boundary condition was followed.

It should be noted that the Station 48 turnout flow includes contributions from the Klamath River and from the Lost River Diversion Dam (Wilson Reservoir contributions). For TMDL development, distinguishing between these sources is important. If it is assumed that all the Lost River Diversion Dam water goes into Station 48 and the remainder of water at Station 48 is from the Klamath River (taking into account the contribution of the net flow from the Miller Hill pump), the net flow provides an estimate of the amount of water from either the Klamath River (when net flow is negative) or Lost River Diversion Dam (when net flow is positive) (BOR personal communication). The equation below (Eq. 2-4) illustrates this:

$$NetFlow = LostRiverDiversionDam - Station48 - MillerHillNet \qquad \text{(Eq. 2-4)}$$

All the negative net flow, along with the corresponding constituent boundary conditions, at Station 48 provide an estimate of the loading from the Klamath River. Figure 2-3 presents the USGS Quads for this region.

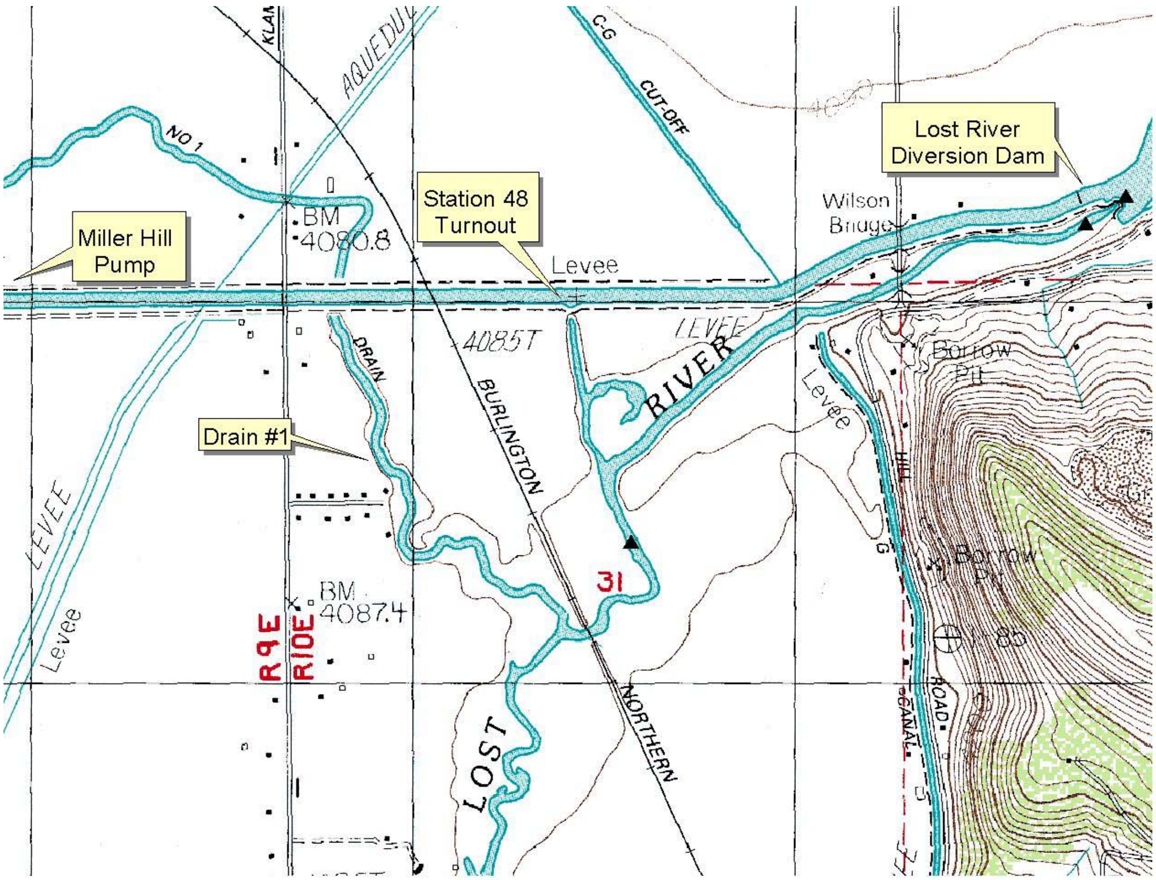

Figure 2-3. Junction of the Lost River, Lost River Diversion Channel, Drain #1, and Station 48 Turnout

No time-series flow data were available for Drain #1. The flow was therefore set equal to Drain #5. The temperature and concentration boundary conditions were specified based on observed data for Drain #1 (at DR1). For the constituents without observed data, the same convention for setting up the upstream boundary condition was followed.

Four flow data points were available for Drain #5 during the 1999 irrigation period (USGS 1999). The data points were averaged to generate the flow rate for Drain #5 in the model.

The temperature and concentration boundary conditions were specified based on observed data for Drain #5 (at DR5). For the constituents without observed data, the same convention for setting up the upstream boundary condition was followed.

The City of Merrill STP was also configured as a TRIB in the Lost River model. Temporally-variable data were not available for this point source, therefore its contribution was represented using an average flow of 0.14 mgd (0.006 cms) and water quality concentrations of 1.8 mg/L, 9.1 mg/L, 1.8 mg/L, 12.7 mg/L, 6.0 mg/L, and 830 uOhm/cm for PO_4, NH_4, NO_2/NO_3, CBOD, ISS, and conductivity, respectively (personal communication with ODEQ). Flow from this STP is generally small compared to other contributing sources to the river at this location.

For 2004, daily flow data for the Station 48 turnout were used to specify the time series boundary condition at this location. Monitoring data at this location were also used. The data were extended backward for 30 days and forward for 30 days to create a relatively stable environment.

Drain #1 flow values (three) for 2004 were averaged and set for the 2004 simulation period. The constituent and temperature data were updated with 2004 data collected at DR1.

Four flow values were available for Drain #5. These values were averaged to specify the flow rate at Drain #5. The constituent concentrations and temperature at Drain #5 were updated using 2004 data following the same method for deriving other updated boundary conditions.

DST: The distributed flows for Waterbody #5 were first derived using the same scaling approach as for Waterbodies #2 through #4. This was then adjusted iteratively until the predicted Anderson Rose Dam spillage matched the observed flow (namely in terms of average flow from May through October). There are no data available for assigning the temperature and water quality time series concentrations to the distributed flows, so it was assumed that the watershed runoff, agricultural return flow and ground water concentrations for Waterbody #5 are similar to conditions at Anderson Rose Dam. These conditions were therefore represented by the monitoring data at the dam. It should be noted that for the entire stretch from Wilson Dam to the Anderson Rose Dam, the ARDMUS station was the only station with considerable data. With this configuration, the model tended to significantly underpredict the nitrate/nitrite for the summer. To reduce this underprediction, the distributed boundary for nitrate/nitrite was iteratively altered until the model reasonably reproduced the observed nitrate/nitrate at ARDMUS.

A small A-canal contribution exists via the C-canal (approximately 0.08-0.42 cms) that feeds into the downstream portion of this Waterbody (personal communication with BOR). According to BOR an estimate of these spills may be available from the Klamath Irrigation District (KID). Currently this contribution is considered within the DST. For TMDL analysis, the A-canal contribution can be separated, if data can be obtained for the C-canal.

WD: One withdrawal was configured for this waterbody to represent the water diversion to the J Canal. The historical observed diversion flow rate was converted into the format required by W2 to form the corresponding boundary condition.

The observed diversion flow rate in 2004 was converted into the format required by W2 to form the corresponding boundary condition.

2.3.3.6 Waterbody #6: Anderson Rose Dam to Lost River before Tule Lake

USIFB: The upstream boundary condition for Waterbody #6 was provided by the internal flow boundary condition between Waterbody #5 and #6 at Anderson Rose Dam.

DSW: The downstream boundary condition for Waterbody #6 (from Anderson Rose Dam to Tule Lake), was set using a hypothetical flow control structure (using Eq. 2-2). An internal head boundary was initially defined, however the abrupt change in the river's dimensions at this point (i.e., from the Lost River to Tule Lake – since Tule Lake was represented as a single computational segment) caused model instability. As such, a hypothetical flow control structure was used to essentially regulate flow into Tule Lake, yet still predict realistic flows into the lake. The values for "a" and "b" were initially derived based on Manning's equation, and then refined through calibration, in an effort to avoid computational instability. The final values were as follows: a = 20.0, b = 1.67, and c = 0.0.

TRIB: No tributary boundary conditions were configured for this waterbody.

DST: The distributed flows for Waterbody #6 were derived based on the Tule Lake water balance data in Tim Mayer's (2004) technical memorandum. It indicated that the average May to October contribution to Tule Lake from Anderson Rose Dam spill is about 0.69 cms. Since the simulated Waterbody #5 spill flow for the same period was 0.53 cms (close to, but smaller than 0.69 cms), a constant flow of 0.16 cms was assigned to the distributed flow boundary condition for Waterbody #6 during this period. For other periods, the flow was obtained by scaling the distributed flow for Waterbody #5 based on a segment length ratio. The temperature and concentration boundary conditions were set based on monitoring data at station LREW.

WD: No withdrawals were configured for this waterbody.

2.3.3.7 Waterbody #7: Tule Lake

USIFB: The upstream boundary condition for Waterbody #7 was provided by the internal flow boundary condition between Waterbodies #6 and #7.

DSW: Tule Lake was configured as a very coarse, one-segment model, with inflow and outflow occurring in the same segment. The major outflow from Tule Lake includes irrigation diversions through pumps R and 26, N-12 canal, Q and R canals, D plant pump, and evaporation (Mayer, 2004). However, no information was available to distinguish between rates for each of these diversions. Since the primary outflow from Tule Lake to downstream Lost River segments is through the D plant pump, the daily flow data at the D plant pump were used to represent the outflow boundary condition. The remaining outflows were therefore implicitly represented in the lumped DST.

The 2004 daily flow data at the D plant pump were used to set up an outflow boundary condition for Tule Lake.

TRIB: No tributary boundary conditions were configured for this waterbody.

DST: The initial estimate of the distributed flows for waterbody #7 were derived based on the Tule Lake water balance data in Tim Mayers' (2004) technical memorandum. This report listed the monthly distributed inflow rate for Tule Lake for the period 1989 to 1998. These flow rates were converted into cms and the monthly average values were used for each day of the month in the flow time series. The initial estimate of the DST was iteratively adjusted to account for ungaged outflow and inflow, and the final estimates were obtained once the simulated Tule Lake surface water elevation correlated well with the measured elevation.

The DST also inherently includes contributions from the City of Tulelake STP. The STP discharges to a normally dry drainage ditch adjacent to the plant, which is located approximately 10 miles from the Tule Lake Sump. Although the drainage ditch is hydrologically-connected to the Tule Lake Sump, flows from the STP are relatively low and the discharge path to the sump is not well-defined (personal communication with NCRWQCB). Therefore, it was deemed appropriate to consider the STP's contribution as a component of the DST for this waterbody. The water quality and temperature of the DST was set to be the same as that of Waterbody #6, considering their geographical proximity.

WD: No withdrawals were configured for this waterbody.

2.3.3.8 Waterbody #8: P-Canal

USIFB: The upstream boundary condition for Waterbody #8 was provided by the internal flow boundary condition between Waterbody #7 and Waterbody #8, which is equivalent to the flow at the D plant pump. Considering that Tule Lake was represented with extremely coarse spatial resolution, the model result of Tule Lake is not considered to be sufficiently accurate to represent the upstream boundary condition for Waterbody #8. Instead, the monitored data at station TLTO is used to configure the USIFB water quality boundary condition to avoid transferring the uncertainty in Tule Lake model result to downstream segments.

DSW: The downstream boundary condition for Waterbody #8 was set using a hypothetical flow control structure (using Eq. 2-2). The values for "a", "b", and "c" were derived based on Manning's equation as: a = 1.67, b = 1.72, and c = 0.0.

TRIB: No tributary boundary conditions were configured for this waterbody.

DST: The distributed flows for Waterbody #8 were set to zero based on the assumption that the return flow, groundwater recharge, and other runoff in this relatively small drainage area are discharged into either Tule Lake or Lower Klamath Lake.

WD: No withdrawals were configured for this waterbody.

2.3.3.9 Waterbody #9: Lower Klamath Lake

USIFB: The upstream flow and water quality boundary condition for Waterbody #9 was provided by the internal boundary condition between Waterbodies #8 and #9.

DSW: Lower Klamath Lake was configured as a coarse, single-segment model with inflow and outflow occurring in the same segment. Insufficient information was available for further discretizing this water body into a higher resolution grid (to better represent spatial variability). The major outflow from Lower Klamath Lake was represented by the discharge into Klamath Straits Drain. Other withdrawals for irrigation were lumped into the DST since data were not available for a detailed representation.

Flow was derived for 2004 based on the assumption that the outflow from Lower Klamath Lake to Klamath Straits Drain is proportional to the pump rate at the E and EE pumps. Therefore, ratios derived from 1999 data were applied to available 2004 data.

TRIB: ADY canal was the only tributary explicitly represented for Lower Klamath Lake. Flow data provided by BOR were used to represent this tributary inflow. The concentration of NH_4, PO_4, and NO_3 were assigned based on Mayer, 2004. For other constituents, concentrations were assumed to be similar to those for the Station 48 turnout (since contributions to both locations originate in the Klamath River during the irrigation season).

2004 flow data provided by BOR were used to represent this tributary flow. The concentration and temperature data for ADY inflow was updated based on 2004 data using the same method previously discussed.

DST: Distributed flow was used to balance the flow into and out of the lake. An iterative process was implemented to estimate the distributed flow rate based on the time variable storage for Lower Klamath Lake as reported in Burt and Freeman's report (Burt and Freeman, 2003). Although this process resulted in some negative distributed flows, the flows were not assigned to the outflows, as was the case for upstream segments. This is based on the assumption that the negative flows are largely caused by withdrawals from the lake. Since the outflow from the lake is used as the inflow for the downstream waterbody, the negative flows were not added to the outflow in order to prevent introducing uncertainty in the downstream segment simulation. Constituent concentrations and temperature for the distributed flow were set equal to those for Waterbody #7, based on the assumption that return flow and groundwater recharge in this area are similar to that of the Tule Lake area.

Distributed flow for 2004 was set to be the same as that of the 1999 since no data is available to derive the flow balance for 2004. The water quality concentration was configured based on the 1999 condition but updated with the monitoring data at P-Canal for the summer period using the same convention previously discussed. The temperature time series is set to be equal to that of water body #7.

WD: No lateral withdrawals were configured for this waterbody.

2.3.3.10 Waterbody #10: Klamath Straits Drain at Pump E

USIFB: The upstream boundary condition for Waterbody #10 was provided by the internal flow boundary condition between Waterbodies #9 and #10. . Considering that Lower Klamath Lake was represented with extremely coarse spatial resolution, the model result of the Lake is not considered to be sufficiently accurate to represent the upstream boundary condition for Waterbody #10. Instead, the monitored data at station KSDSR is used to configure the USIFB water quality boundary condition to avoid transferring the uncertainty in Lower Klamath Lake model result to downstream segments.

DSW: The downstream boundary condition for Waterbody #10 was set using the flow time series at pump E provided by BOR.

The downstream boundary condition for Waterbody #10 was set using the 2004 flow time series at pump E provided by BOR.

TRIB: No tributary boundary conditions were configured for this waterbody.

DST: The distributed flow for Waterbody #10 was derived from the USIFB and DSW flows. This was assumed to be an acceptable approach since monitoring data for distributed flows and river stage were not readily available. The concentrations of the distributed flow were set based on the data at KSDTR, and temperature is set to be the same as in the DST for waterbody #9.

The 2004 concentration time series is configured by using he monitoring data at KSDSR to update the time series for 1999 model to represent the summer condition. The temperature time series is set to be the same as for water body #9.

WD: No lateral withdrawals were configured for this waterbody.

2.3.3.11 Waterbody #11: Klamath Straits Drain between E and F Pumps

USIFB: The upstream boundary condition for Waterbody #11 was provided by the internal flow boundary condition between Waterbody #10 and #11. The simulated water quality and temperature in Waterbody #10 were used directly as water quality and temperature boundary conditions.

DSW: The downstream boundary condition for Waterbody #11 was set using the flow time series at pump F provided by BOR.

The downstream boundary condition for Waterbody #11 was set using the 2004 flow time series at pump F provided by BOR.

TRIB: No tributary boundary conditions were configured for this waterbody.

DST: The distributed flow for Waterbody #11 was derived from the USIFB and DSW flows. This was assumed to be an acceptable approach since monitoring data for distributed flows and river stage were not readily available. The concentration of the distributed flow were configured based on the monitoring data at KSDPSF, and the temperature is set to be the same as waterbody #10.

The 2004 concentration time series is configured by using the monitoring data at KSDM to update the time series for 1999 model to represent the summer condition. The temperature time series is set to be the same as for water body #10.

WD: No lateral withdrawals were configured for this waterbody.

2.3.3.12 Waterbody #12: Klamath Straits Drain between F Pump and Klamath River

USIFB: The upstream boundary condition for Waterbody #12 was provided by the internal flow boundary condition between Waterbodies #11 and #12. The simulated water quality and temperature at the last segment in Waterbody #11 were used directly as water quality and temperature boundary conditions.

DSW: The downstream boundary condition for Waterbody #12 was set using a hypothetical flow control structure (using Eq. 2-2). The values for “a”, “b”, and “c” were derived based on Manning’s equation as: $a = 1.696$, $b = 1.72$, and $c = 0.0$.

TRIB: No tributary boundary conditions were configured for this waterbody.

DST: The distributed flows for Waterbody #12 were derived by scaling the distributed flow for Waterbody #11 using the ratio between the lengths of Waterbodies #12 and #11. This assumes that these two sections of the Klamath Straits Drain share similar flow generation and discharge characteristics. The concentration of the distributed flow were configured based on the monitoring data at KSD97, and the temperature is set to be the same as waterbody #11.

The 2004 concentration and temperature time series were set to be the same as for waterbody #12 since no data is available to derive the waterbody specific time series, and they two water bodies are close to each other to warrant using the similar DST concentration and temperature time series.

WD: No lateral withdrawals were configured for this waterbody.

2.3.3.13 Boundary Conditions Summary Table

Table 2-5 is presented below to summarize the extensive information presented in Sections 2.3.3.1 through 2.3.3.13. The Flow and Water Quality columns indicate the method used to characterize the boundary conditions. "Data" refers to monitoring data. If presented alone, then sufficient time-variable monitoring data were available to characterize conditions. "Interpolation" indicates that limited monitoring data were available and thus values were interpolated from available data. "Calibration" indicates that values were arrived at through model calibration. In many situations, a combination of these methods was used. "Literature" indicates that values were derived from the literature. "Weir Equation" denotes that an equation was used to derive flow conditions. "Local Knowledge" indicates that values were designated based on conversations with local experts and professionals familiar with the area and conditions. "Model" indicates that the model generated values (typically for linkage between Waterbodies).

Table 2-5. Boundary Conditions and Linkages Summary Table

Waterbody	Location	Boundary Condition	Flow	Water Quality
1	Malone Dam	US	Data	Data, Interpolation, Calibration
1	From Malone to Harpold Dam	DST	Calibration	Calibration
1	Miller Creek	TRIB	Data, Interpolation, Calibration	Data, Interpolation, Calibration
1	Big Springs	TRIB	Literature, Interpolation, Calibration	Data, Interpolation, Calibration
1	Buck Creek	TRIB	Data, Interpolation, Calibration	Data, Interpolation, Calibration
1	Lost River (LR) before Harpold Dam	WD	Calibration	Model
1	LR at Harpold Dam	DSW	Weir Equation	Model
2	LR downstream of Harpold Dam	USIFB	Model	Model
2	LR from Harpold to RM 27	DST	Calibration	Calibration
2	E Canal	TRIB	Local Knowledge	Local Knowledge
2	LR at RM 27	DSIH	Model	Model
3	LR downstream of RM 27	USIH	Model	Model
3	LR from Ranch to Wilson Res	DST	Calibration	Calibration
3	LR before entering Wilson Res	DSIH	Model	Model

Waterbody	Location	Boundary Condition	Flow	Water Quality
4	LR entering Wilson Res	USIH	Model	Model
4	LR at Wilson Reservoir	DST	Calibration	Calibration
4	LR upstream of Wilson Dam	WD	Data	Model
4	F-1 Canal	TRIB	Local Knowledge	Local Knowledge
4	LR at Wilson Dam	DSW	Data, Local Knowledge	Model
5	LR downstream of Wilson Dam	USIFB	Model	Model
5	LR from Wilson Dam to Anderson Rose Dam	DST	Calibration	Calibration
5	LR at J-Canal	WD	Data	Model
5	LR at Anderson Rose Dam	DSW	Weir Equation	Model
5	Station 48 Turnout	TRIB	Data	Data, Interpolation, Calibration
5	Drain #1	TRIB	Data, Interpolation, Calibration	Data, Interpolation, Calibration
5	Drain #5	TRIB	Data, Interpolation, Calibration	Data, Interpolation, Calibration
5	City of Merrill STP	TRIB	Data	Data
6	LR downstream of Anderson Rose Dam	USIFB	Model	Model
6	LR from Anderson Rose Dam to Tule Lake	DST	Calibration	Calibration
6	LR before entering Tule Lake	DSW	Weir Equation	Model
7	LR entering Tule Lake	USIFB	Model	Model
7	LR at Tule Lake	DST	Calibration	Calibration
7	LR at Tule Lake outlet	DSW		
8	P Canal downstream of Tule Lake	USIFB	Model	Model
8	P Canal	DST	Calibration	Calibration
8	LR before entering Tule Lake	DSW	Data	Model
9	P canal entering Lower Klamath Lake	USIFB	Model	Model
9	Lower Klamath Lake	DST	Calibration	Calibration
9	ADY Canal	TRIB	Data	Literature, Interpolation,

Waterbody	Location	Boundary Condition	Flow	Water Quality
				Calibration
9	Lower Klamath Lake entering Klamath Straits Drain	DSW	Data, Interpolation	Model
10	Klamath Straits Drain leaving Lower Klamath Lake	USIFB	Model	Model
10	Klamath Straits Drain from Lower Klamath Lake to Pump E	DST	Calibration	Calibration
10	Klamath Straits Drain at Pump E	DSW	Data	Model
11	Klamath Straits Drain leaving Pump E	USIFB	Model	Model
11	Klamath Straits Drain from Pump E to Pump F	DST	Calibration	Calibration
11	Klamath Straits Drain at Pumps F	DSW	Data	Model
12	Klamath Straits Drain leaving Pump F	USIFB	Model	Model
12	Klamath Straits Drain from Pump F to Discharge at Klamath	DST	Calibration	Calibration
12	Klamath Straits Drain at Klamath River	DSW	Data	Model

2.3.3.14 USIFB Flows

The USIFB (internal boundary conditions) for flow are presented below in Figures 2-4 and 2-5 to demonstrate the highly variable nature of flow throughout the Lost River system throughout the year.

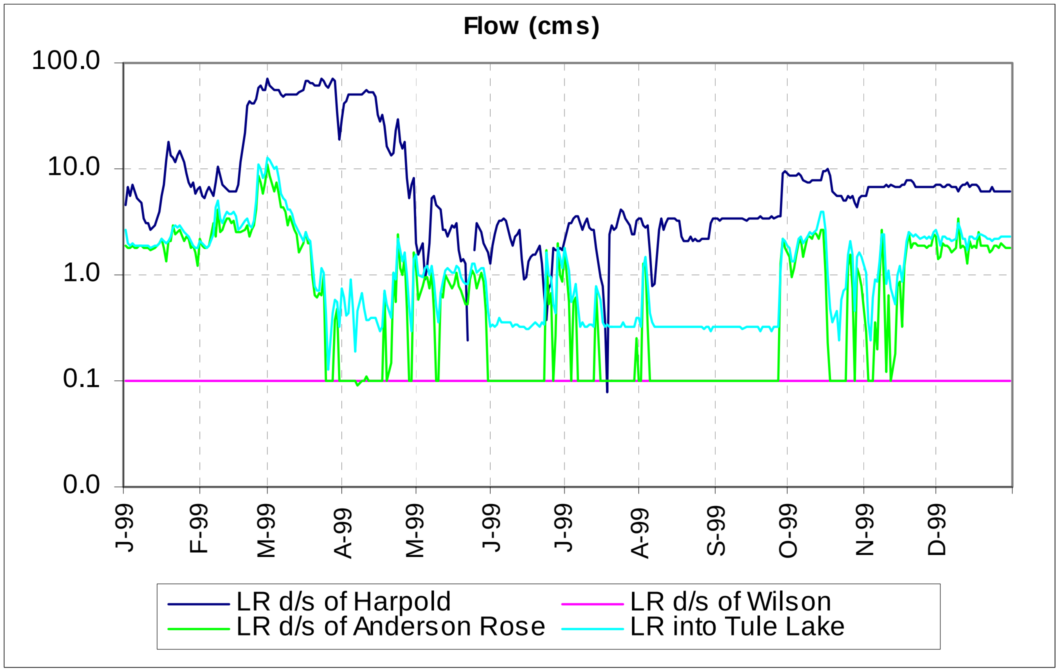

Figure 2-4. USIFB Flows from Harpold Dam to Tule Lake

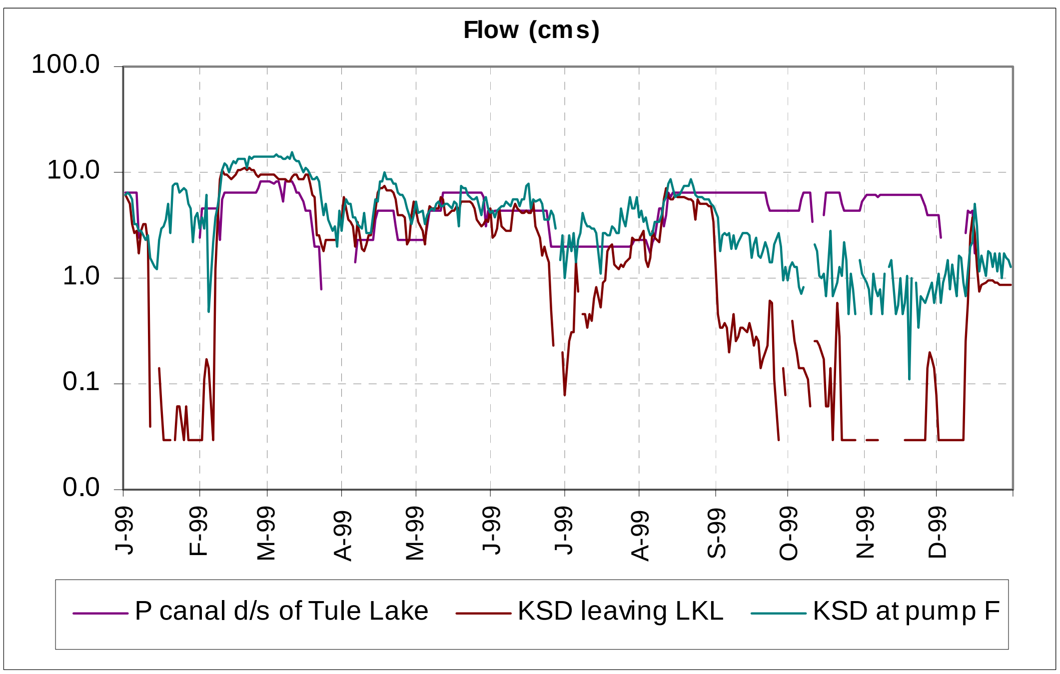

Figure 2-5. USIFB Flows from Tule Lake through the Klamath Straits Drain

2.3.4 Initial Conditions

The W2 model requires specifying initial conditions in the control and bathymetry input files. The control file specifies the initial temperature and constituents. Since there are no data available to specify the initial conditions for all the constituents and water surface elevation, they were specified based on best professional judgment. For this modeling study, the critical conditions were generally identified as the summer. Therefore, modeling to date has focused on this period. The model simulation, however, begins on January 1st (of 1999 and 2004). While all of 1999 was simulated, the end date for the 2004 simulation was day 240 (end of August). This coincided with available flow and water quality data. As such, the initial conditions do not significantly impact the model predictions during the critical period. Table 2-6 lists the initial condition for temperature and all the simulated constituents.

Table 2-6. Initial Conditions

Constituent	Initial Condition Value
Temperature	2.0 ^{o}C
PO_4	0.1 mg/L
NH_4	0.1mg/L
NO_3/NO_2	0.1 mg/L
Conductivity	300 us/cm
Bacteria	0.0 cfu
LDOM	0.2 mg/L
RDOM	0.2 mg/L
LPOM	0.2 mg/L
RPOM	0.2 mg/L
Periphyton/macrophytes	0.8 g/m2
DO	10.0 mg/L
CBOD	6.0 mg/L
ISS	0.0 mg/L
Algae	0.2 mg/L
TIC	12 mg/L
Alkalinity	100 mg/L

2.4 Modeling Assumptions and Limitations

All mathematical water quality models are a simplified representation of the very complex real world. The Lost River system is certainly no exception. It is a highly modified environmental system driven largely by irrigation operations, and it exhibits tremendous biological activity. Due to a lack of quantitative data to describe many aspects of the system, a number of key assumptions were made during model development. The combination of the lack of data and assumptions made, also lead to inherent limitations associated with the effort.

2.4.1 Assumptions

The major underlying assumptions associated with Lost River model development are as follows:

- Weather conditions do not vary significantly over the entire modeling domain. If they do, the impact on resulting water quality is assumed not to be significant.
- The impact of sediment transport and siltation on channel geometry is not significant, therefore the same bathymetric configuration can be used for different scenario simulations.
- The initial condition and the boundary conditions set for the winter and early spring period do not have a significant impact on the simulated water quality during the critical summer and early fall periods. This assumption permits assigning the initial conditions and winter/early spring boundary conditions using best professional judgment, without impairing the model performance for the critical period.
- Time series flow data were not available for all drains, tributaries, and withdrawals. Reliable time series flow data were also not available for many monitoring locations along the length of the Lost River. In light of the limitations, it was assumed that tributary flows could be reasonably represented through interpolation based on limited flow measurements. Additionally, drains and withdrawals were assumed to be reasonably derived through the calibration process. Where flow monitoring data were available along the length of the river, the data were generally assumed to be appropriate (due to the absence of data indicating otherwise), except where backwater effects were prevalent.
- The distributed flows for P-canal (Waterbody #8) were set to zero based on the assumption that the return flow, groundwater recharge, and other runoff in this relatively small drainage area are discharged into either Tule Lake or Lower Klamath Lake.
- Water quality associated with the distributed flow inputs to the model was initially specified based on monitoring data within the Lost River itself. Due to the lack of quantitative data for characterizing agricultural pumping, return flow and other unknown sources and sinks, it was assumed that the water quality associated with the distributed flow is similar to the water quality in the Lost River where the distributed flow discharges. Tetra Tech obtained data from BOR for a number of pumps in the basin (including D, E, EE, F, and FF), however data for the numerous remaining pumps in the basin could not be obtained. All irrigation districts were contacted, however data were not available.
- One phytoplankton species and one macrophyte species are sufficient for representing the overall primary production and nutrient interactions in the system.
- Topographic shading effects on water temperature and algal growth are insignificant. In scenario runs, the effects of riparian vegetation shading can be accounted for by using a scaling factor for solar radiation intensity.

- Alkalinity is conservative (as stated in CE-QUAL-W2 manual). Therefore, no internal sources or sinks were considered.
- All the organic matter in the water column (and that from other sources) has the same stochiometric ratio.
- The impact of zooplankton and benthic creatures do not have a significant impact on the algal dynamics and nutrient recycling.
- The water quality gradient within Tule Lake and Lower Klamath Lake is insignificant, therefore each can be considered as a single, mixed segment.

2.4.2 Limitations

Lost River model limitations include the following:

- The capability of a model is constrained by the availability and quality of data. Built on limited data, the Lost River model is not expected to be able to mimic the exact timing and location of all water quality conditions. However, the model can be used to represent the overall water quality trends in response to external loading and internal system dynamics.
- The model does not explicitly represent the spatial and temporal distribution of agricultural return flows and pump operation due to a lack of quantitative data. Therefore, it cannot be used to evaluate the potential impact of changing specific pumping schemes or the locations and timing of return flows. It can, however, be used to evaluate the overall impact of varied pumping flow/return flow, as well as the associated loadings (in a lumped manner). The goal of the model is to predict the general response of the river and its impoundments to spatially and temporally variable load inputs (though not necessarily discrete inputs) and to evaluate the impact of hypothetical load changes relative to current and historical conditions. The model can also be used to evaluate water quality criteria develop TMDLs.
- The winter and early spring boundary conditions for the distributed tributary flows were based on conditions for the summer (where more data are available), and thus might not be reliable. This, however, won't significantly decrease the reliability of the model for the summer critical period simulation.
- The model does not simulate multiple species for phytoplankton and macrophytes. Therefore, this model is currently not suitable for evaluating competition among multiple species or evolution of the aquatic algal communities and their interaction with nutrients.
- The model does not simulate water quality processes within the Lost River Diversion Channel, however, it can be used to transfer to and from a Klamath River model.
- Due to the lack of a direct linkage between organic matter loading and SOD and benthic nutrient flux, the model in its present stage, is not suitable for evaluating the long-term impact of load reductions on SOD.
- Neither zooplankton nor benthic animals are simulated in the model, hence, there may be some uncertainty in the simulation of algal dynamics and nutrient cycling.
- Bacteria in CE-QUAL-W2 is simulated as a general constituent with simple first-order die-off.
- Tule Lake and Lower Klamath Lake were treated as well-mixed segments, thus the model cannot be used to accurately evaluate the local water quality conditions (i.e., spatial or depth-variability) associated with the water bodies. This also introduces uncertainties in representing segments downstream of the lakes, including the P Canal and the Klamath Straits Drain.

3.0 MODEL TESTING

Once the Lost River W2 model was configured, a calibration was performed at multiple locations throughout the system. Calibration refers to the adjustment or fine-tuning of modeling parameters to produce an adequate fit of the observations. The sequence of calibration for the Lost River W2 model involved checking the water budget first using the water surface elevation, then calibrating hydrodynamics using temperature and conductivity data, and finally calibrating water quality using available monitoring data.

In this study, the model was tested for two separate years (1999 and 2004) to increase model reliability. 1999 was the year with the most concurrent data for model configuration. The monitoring data for this year also exhibit significant water quality impairment during the summer critical period, and thus provide an excellent basis for testing the model's capability of capturing extreme conditions, which are of concern for TMDL development. 2004 was selected because a summer sampling effort was conducted by ODEQ, NCRWQCB, EPA Region 10, and EPA Region 9 to support modeling. The Lost River model was first calibrated for 1999, and then 2004 data were used to corroborate the model.

3.1 Monitoring Locations

In order to fully calibrate the Lost River model, a significant amount of time-varying monitoring data, with sufficient longitudinal resolution (and vertical resolution in the impoundments), are required. The data obtained for the Lost River are listed in Table 3-1. Stations in this list that are located on the main-stem of the Lost River and its impoundments supported model calibration. These locations are depicted in Figure 3-1 and discussed in subsequent sections. Other stations in the list were used to prescribe boundary conditions.

Table 3-1 Modeling Support Data and Data Sources

Data Type	Station/Location	Start Date	End Date	Frequency	Source
Flow	Malone Dam	2/2/87	9/11/2004	Daily	BOR
	Keller Bridge	4/17/87	5/22/02	Daily	BOR
	Harpold Dam	1/1/87	5/09/04	Daily	BOR
	Pump E-EE	1/1/87	10/17/04	Daily	BOR
	Pump F-FF	1/1/87	9/23/04	Daily	BOR
	Miller Cr	2/1/87	10/1/03	Daily	BOR
	Lost River Diversion Channel	1/1/87	3/28/04	Daily	BOR
	Station 48	1/16/87	9/12/04	Daily	BOR
	Anderson Rose Dam	1/16/87	9/12/04	Daily	BOR
	J-Canal	1/16/87	9/12/04	Daily	BOR
	Plant-D	1/16/87	9/12/04	Daily	BOR
	ADY Refuge	3/23/91	2/22/04	Daily	BOR
	KSFLOW @ Stateline	1/1/87	10/17/04	Daily	BOR
Water Quality	BCBR (BC)	3/2/99	7/27/04	Grab	BOR, ODEQ, NCRWQCB
	BS	5/12/99	6/15/04	Grab	BOR, ODEQ, NCRWQCB
	DR1	5/12/99	7/27/04	Grab	BOR, ODEQ, NCRWQCB
	DR5	1/28/99	7/27/04	Grab	BOR, ODEQ, NCRWQCB
	KSD @ Stateline	3/23/99	7/27/04	Grab	BOR, ODEQ, NCRWQCB
	KSD @Tunnel	3/23/99	11/30/99	Grab	BOR
	LRAR (ARDMUS)	3/2/99	7/27/04	Grab	BOR, ODEQ, NCRWQCB
	LREW	1/28/99	7/27/04	Grab	BOR, ODEQ, NCRWQCB
	LRHDB (LRHD)	3/2/99	7/26/04	Grab	BOR, ODEQ, NCRWQCB
	LRKB	5/12/99	7/27/04	Grab	ODEQ, NCRWQCB
	LRMD (LRDM)	5/12/99	7/27/04	Grab	BOR, ODEQ, NCRWQCB
	LRWRC (WDUS)	1/28/99	7/27/04	Grab	BOR, ODEQ
	LRMC (MC)	3/2/99	7/27/04	Grab	BOR, ODEQ
	ST48	5/12/99	7/27/04	Grab	BOR, ODEQ, NCRWQCB
	LREW	1/28/99	7/27/04	Grab	BOR, ODEQ, NCRWQCB
	TLTPD	1/13/99	06/03/03	Grab	BOR
	TLTO	3/23/99	11/14/00	Grab	BOR
	LKLO	1/13/99	09/20/00	Grab	BOR
	KSDSR	7/30/99	7/27/04	Grab	BOR, ODEQ, NCRWQCB
	KSDTR (Pump E-EE)	3/23/99	11/30/99	Grab	BOR
	KSD97 (KSDM)	1/13/99	7/27/04	Grab	BOR
	KSDPSF(Pump F-FF)	3/10/99	06/20/01	Grab	BOR, ODEQ
	GB	6/15/04	7/27/04	Grab	ODEQ, NCRWQCB

Data Type	Station/Location	Start Date	End Date	Frequency	Source
	LRCF	6/15/04	7/27/04	Grab	ODEQ, NCRWQCB
	LRKB	6/15/04	7/27/04	Grab	ODEQ, NCRWQCB
	KBNE	6/15/04	7/27/04	Grab	ODEQ, NCRWQCB
	KB	6/15/04	7/27/04	Grab	ODEQ, NCRWQCB
	WC	6/15/04	7/27/04	Grab	ODEQ, NCRWQCB
	YD	6/15/04	7/27/04	Grab	ODEQ, NCRWQCB
	LRY	6/15/04	7/27/04	Grab	ODEQ, NCRWQCB
	PC	6/15/04	7/27/04	Grab	ODEQ, NCRWQCB

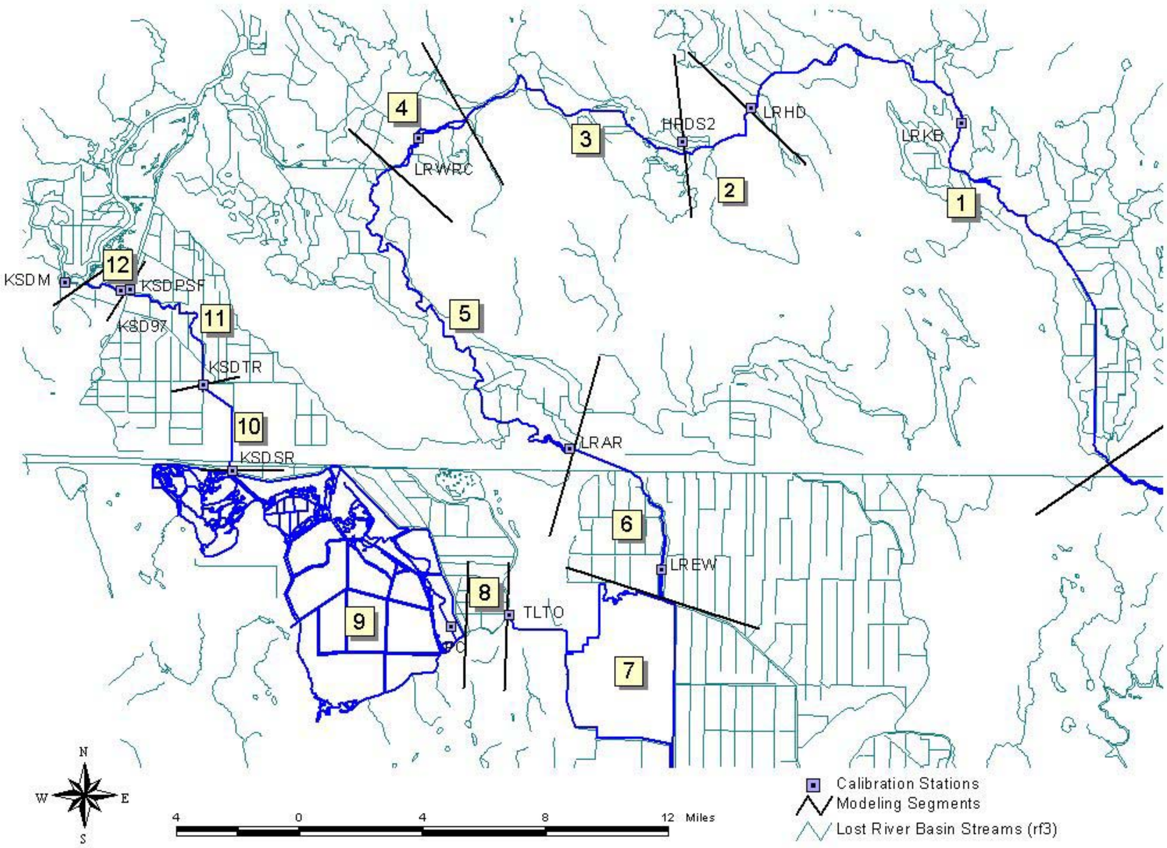

Figure 3-1. Calibration Locations for Lost River Modeling

3.2 Hydrodynamic Simulation

3.2.1 Hydraulic Parameter Designation

Default hydraulic parameters were used to run the model initially. With each model run, these parameters were adjusted to achieve a unique set of coefficients that best represented the system under all conditions. Cole and Wells (2003) reported that previous experience has shown that the default values produce remarkably accurate temperature predictions for a wide variety of systems, provided accurate geometry and boundary conditions were specified (1995). Table 3-2 shows the calibration coefficients for the hydrodynamics and temperature.

Table 3-3 Calibration Coefficients for Hydrodynamic Simulation

Coefficient	Name	Value
Longitudinal eddy viscosity	[AX]	1 m^2/s
Longitudinal eddy diffusivity	[DX]	1 m^2/s
Manning's coefficient	[MANN]	~0.02
Wind sheltering coefficient	[WSC]	0.8
Solar radiation absorbed in surface layer	[BETA]	0.45
Sediment temperature	[TSED]	11.5 ^oC
Coefficient of bottom heat exchange	[CBHE]	0.3

In general, the bathymetry and a balanced water budget for the Lost River system were the most crucial factors in the hydrodynamic simulation. Most parameters were found to have little or no effect on hydrodynamics, with the exception of Manning's Coefficient, n [MANN]. It was found that too high or too low a value for MANN caused model instability. Therefore, a moderate value or approximately 0.02 was used, and this reasonably represented the physical characteristics of the system, while maintaining model stability. The wind-sheltering coefficient [WSC] was set to a constant value since there is no visible vegetation throughout the majority of the watershed that could potentially modify the wind velocity.

3.2.2 Water Balance and Water Surface Elevation Calibration

Historical water surface elevation data (daily values) were available at Harpold Dam and Wilson Dam, therefore, these two locations were used to derive the flow balance for the first four waterbodies of the Lost River model. In addition to the water surface elevation data, data on the release rates from Harpold Dam were available from BOR. The hydrodynamic portion of the W2 model was first run to verify the water budget. This involved comparing predicted reservoir elevations with observed water surface elevations.

The simulation was implemented in a piece-wise manner. As the first step, Waterbody #1 was independently simulated using the boundary conditions described in the model configuration section. With the upstream and tributary boundary conditions and the downstream weir equation fixed, the major unknown flow sources/sinks were the distributed flows (e.g., irrigation water withdrawal or return flows, as well as watershed runoff). The major task for the flow balance calibration was thus to derive this unknown component of the flow by simulating water surface elevation at Harpold Dam and trying to match the observed elevations. Starting from the initially estimated distributed flow, the values were iteratively adjusted until a reasonable match between the simulated and observed elevation were obtained. Figures A_1999-1, A_1999-2, and A_2004-

1 (for both 1999 and 2004) in Appendices A_1999 and A_2004 display the simulated water surface elevation and dam discharge calibration versus the observed data at Harpold Dam.

After the water balance for Waterbody #1 was completed, the model simulated dam discharge at Harpold Dam was incorporated into the simulation model for Waterbodies #2 to #4 as the upstream flow boundary condition. For these three waterbodies, the major unknown sources/sinks of flow were also from the distributed flows. With the upstream inflow and tributary flows set, and the Lost River Diversion Channel withdrawal fixed, the distributed flow rates for the three waterbodies were iteratively adjusted until the simulated water surface elevation at Wilson Dam matched the observed data reasonably well. Figures A_1999-3 and A_2004-2 (for 1999 and 2004) in Appendices A_1999 and A_2004 plots the simulated Wilson Reservoir surface elevation against the observed data.

The water balances for Waterbodies #5 and #6 were calibrated using Tule Irrigation District data (for 1999) and based on Mayer's (2004) technical memorandum. Figures A_1999-4 and A_2004-3 plot the spillage at Anderson Rose Dam. For Waterbody #7, the distributed flow was obtained by calibrating the simulated water surface elevation at Tule Lake against the observed data provided by BOR. Figure A_1999-5 plots the simulated Tule Lake elevation versus the observed data.

For Waterbody #8, a special water balance calculation was not implemented. The distributed flow rate was set to zero due to the relatively small drainage area and the assumption that most distributed flow in the area is accounted for in the Tule Lake and Lower Klamath Lake modeling segments.

Major inflows for Waterbody #9 were configured using the P Canal discharge and the ADY Canal inflow. Outflow was configured using the observed flow rate at the Klamath Straits Drain (at the state line). With the known temporal variation of storage volume from the Burt and Freeman (2003) report, the distributed flow was derived by matching the simulated volume with the observation data. Figure A_1999-6 plots the comparison.

There were no water surface elevation data available for Waterbodies #10, #11, and #12. Distributed flow for these three waterbodies was derived based on the assumption that flow in the Klamath Straits Drain is approximately balanced. That is, the distributed flow for Waterbodies #10 and #11 were calculated by subtracting the downstream outflow rates from the upstream inflow rates. This difference in flow was adjusted minimally, in order to maintain computational stability. For Waterbody #12, the distributed flow was calculated by scaling the distributed flow for Waterbody #11 (based on the ratio of the lengths of each waterbody).

3.2.3 Hydrodynamic Model Evaluation with Temperature Data

After the water budget was calibrated, the next step was to reproduce the observed temperature data in the system. A piece-wise evaluation of temperature predictions was conducted as for the flow calibration process. However, for temperature, no adjustment to default parameters was necessary. The simulated water temperatures were plotted against the measured data for 1999 and 2004 and are shown in Figures B_1999-1 to B_1999-10 and B_2004-1 to B_2004-8.

3.2.4 Further Hydrodynamic Model Evaluation with Conductivity Data

The performance of the hydrodynamic model in simulating mass balance and transport was further evaluated using conductivity as a conservative tracer. The comparison of model predictions to observations is shown in Figures C_1999-1 to C_1999-10 and C_2004-1 to C_2004-8.

The relatively poor correlation for Tule Lake and other downstream stations is likely caused by the extremely coarse resolution used for Tule Lake and Lower Klamath Lake, which limit the model in predicting the flashy nature of the system. In Figure C_1999-6, the data show a peak conductivity in May and June with a decline after June. The model, however, predicts an increase in conductivity from May to October before it starts to decline. This is due to the configuration of Tule Lake as a completely mixed segment, which causes any loading entering Tule Lake to be instantly diluted by its significant volume. Therefore, when the conductivity in the distributed flow is set equal to that in Tule Lake, the simulated concentration experiences a significant time lag in reflecting the loading impact. At the same time, the summer evaporation causes the conductivity to increase, resulting in the simulated conductivity showing a rising trend. If sufficient data were available to configure a higher resolution representation of Tule Lake, the model would likely simulate a more appropriate response at locations receiving external loading.

3.3 Water Quality Simulation

Once the temperature and conductivity calibrations were completed, the next step was to perform the water quality model simulation and calibration. Water quality model results, such as observed dissolved oxygen, ammonia, nitrite/nitrate nitrogen, orthophosphate, chlorophyll a, and pH were the key calibration parameters. The water quality calibration was also a piece-wise process, which involved first calibrating the upstream waterbodies, and then using the resulting flow and predicted concentration time series (together with the watershed and other tributary inputs) to drive the downstream waterbody simulations.

The calibration of the water quality model was implemented through tuning major kinetic parameters such as algal growth rate, death rate, nitrification/denitrification rates, CBOD/organic matter decay rates, and SOD rates. The overall goal was to most accurately match observed data while maintaining consistency among all the waterbodies. As a result, the kinetic parameter values were kept the same for all the waterbodies, with the exception of Tule Lake and Lower Klamath Lake (where macrophyte kinetics and benthic flux parameters varied) and SOD rates. This approach provides confidence in applying the calibrated parameters to other time periods and for use in alternative scenarios. Tables 3-4 through 3-6 list the calibrated kinetic values for Waterbodies #1 through #12. Note that values in parentheses are for Tule and Lower Klamath Lakes.

Table 3-4. Nutrient Input Parameters Used for the Lost River

Parameter	Description	Units	Value	Typical Literature Value[1]
PO4R	Sediment release rate of phosphorous	fraction of SOD	0.0030	0.001 to 0.03
PARTP	Phosphorous partitioning coefficient for suspended solids	-	0.000	0.000
ORGP	Fraction of phosphorous in	-	0.011	0.011

Parameter	Description	Units	Value	Typical Literature Value[1]
	organic matter			
ORGN	Fraction of nitrogen in organic matter	-	0.080	0.080
NO3DK	Nitrate decay rate	day^{-1}	0.05	0.05 to 0.15
NO3T1	Lower temperature for nitrate decay	^oC	5.0	5.0
NO3T2	Upper temperature for nitrate decay	^oC	25.0	25.0
NO3K1	Lower temperature rate multiplier for nitrate decay	-	0.10	0.10
NO3K2	Upper temperature rate multiplier for nitrate decay	-	0.99	0.99
NH4DK	Ammonium decay rate	day^{-1}	0.08	0.00 to 0.80
NH4R	Sediment release rate of ammonium	fraction of SOD	0.001	0.000 to 0.400
NH4T1	Lower temperature for ammonium decay	^oC	5.0	5.0
NH4T2	Upper temperature for ammonium decay	^oC	25.0	25.0
NH4K1	Lower temperature rate multiplier for ammonium decay	-	0.10	0.10
NH4K2	Upper temperature rate multiplier for ammonium decay	-	0.99	0.99

[1] Cole and Wells (2003); Chapra, S.C. (1997)

Table 3-5. Phytoplankton Input Parameters used for the Lost River

Parameter	Description	Units	Values of Algal Groups	Typical Literature Value[1]
AG	Growth rate	day^{-1}	1.1	0.2 to 9.0
AR	Dark respiration rate	day^{-1}	0.10	0.01 to 0.92
AE	Excretion rate	day^{-1}	0.01	0.01 to 0.044
AM	Mortality rate	day^{-1}	0.03	0.03 to 0.30
AS	Settling rate	day^{-1}	0.20	0.001 to 13.20
AHSP	Phosphorous half-saturation coefficient	$g.m^{-3}$	0.002	0.001 to 1.520
AHSN	Nitrogen half-saturation coefficient	$g.m^{-3}$	0.01	0.01 to 4.32
ASAT	Light saturation	$W.m^{-3}$	100	10 to 150
AT1	Lower temperature for minimum algal rates	^oC	5.0	N/A
AT2	Lower temperature for maximum algal rates	^oC	12.0	N/A
AT3	Upper temperature for minimum algal rates	^oC	25.0	N/A
AT4	Upper temperature for maximum algal rates	^oC	30.0	N/A
AK1	Lower temperature rate multiplier for minimum algal rates	-	0.1	N/A

Parameter	Description	Units	Values of Algal Groups	Typical Literature Value[1]
AK2	Lower temperature rate multiplier for maximum algal rates	-	0.99	N/A
AK3	Upper temperature rate multiplier for minimum algal rates	-	0.99	N/A
AK4	Upper temperature rate multiplier for maximum algal rates	-	0.1	N/A
ALGP	Phosphorous to biomass ratio	-	0.011	0.011
ALGN	Nitrogen to biomass ratio	-	0.080	0.080
ALGC	Carbon to biomass ratio	-	0.45	0.45
ACHLA	Algae to chlorophyll-a ratio	-	110	110

[1] Literature values are from the CE-QUAL-W2 Users Manual which compiled data from a range of sources. The only exception is the stoichiometric coefficient, which was derived from Chapra, 1997.

Table 3-6. Macrophyte Input Parameters used for the Lost River

Parameter	Description	Units	Values of Algal Groups	Typical Literature Value[1]
EG	Growth rate	day^{-1}	0.75	N/A
ER	Dark respiration rate	day^{-1}	0.07	N/A
EE	Excretion rate	day^{-1}	0.01	N/A
EM	Mortality rate	day^{-1}	0.02	N/A
EB	burial rate	day^{-1}	0.001	N/A
EHSP	Phosphorous half-saturation coefficient	$g.m^{-3}$	0.002	N/A
EHSN	Nitrogen half-saturation coefficient	$g.m^{-3}$	0.014	N/A
ESAT	Light saturation	$W.m^{-3}$	150	75-150
ET1	Lower temperature for minimum macrophyte rates	^oC	5.0	N/A
ET2	Lower temperature for maximum macrophyte rates	^oC	18.0	N/A
ET3	Upper temperature for minimum macrophyte rates	^oC	25.0	N/A
ET4	Upper temperature for maximum macrophyte rates	^oC	30.0	N/A
EK1	Lower temperature rate multiplier for minimum macrophyte rates	-	0.1	N/A
EK2	Lower temperature rate multiplier for maximum macrophyte l rates	-	0.99	N/A
EK3	Upper temperature rate multiplier for minimum macrophyte rates	-	0.99	N/A
EK4	Upper temperature rate multiplier for maximum macrophyte rates	-	0.1	N/A

Parameter	Description	Units	Values of Algal Groups	Typical Literature Value[1]
EP	Phosphorous to biomass ratio	-	0.011	N/A
EN	Nitrogen to biomass ratio	-	0.080	N/A
EC	Carbon to biomass ratio	-	0.45	N/A
ECHLA	Algae to chlorophyll-a ratio	-	55	N/A

[1] Literature values are from the CE-QUAL-W2 Users Manual which compiled data from a range of sources and the example models. The only exception is the stoichiometric coefficient, which was derived from Chapra, 1997.

Different SOD rates were assigned for different waterbodies and refined through the calibration process. SOD monitoring data at Harpold Dam (a value of 3.8 g/m^2/day) was used to derive SOD rates from Malone Dam to Harpold Dam. It was assumed that the SOD increased linearly from upstream to downstream, with an initial value of 1.0 g/m^2/day set for the most upstream segment. The SOD rate measured at Wilson Dam (2.5 g/m^2/day) was used in a similar manner to derive SOD rates from Harpold Dam to Wilson Dam. For the remaining waterbodies, a base value of 2.0 g/m^2/day was initially estimated and then adjusted through calibration. Figure 3-2 presents the SOD rates used for each modeling segment. The waterbody divisions are indicated at the top of the plot.

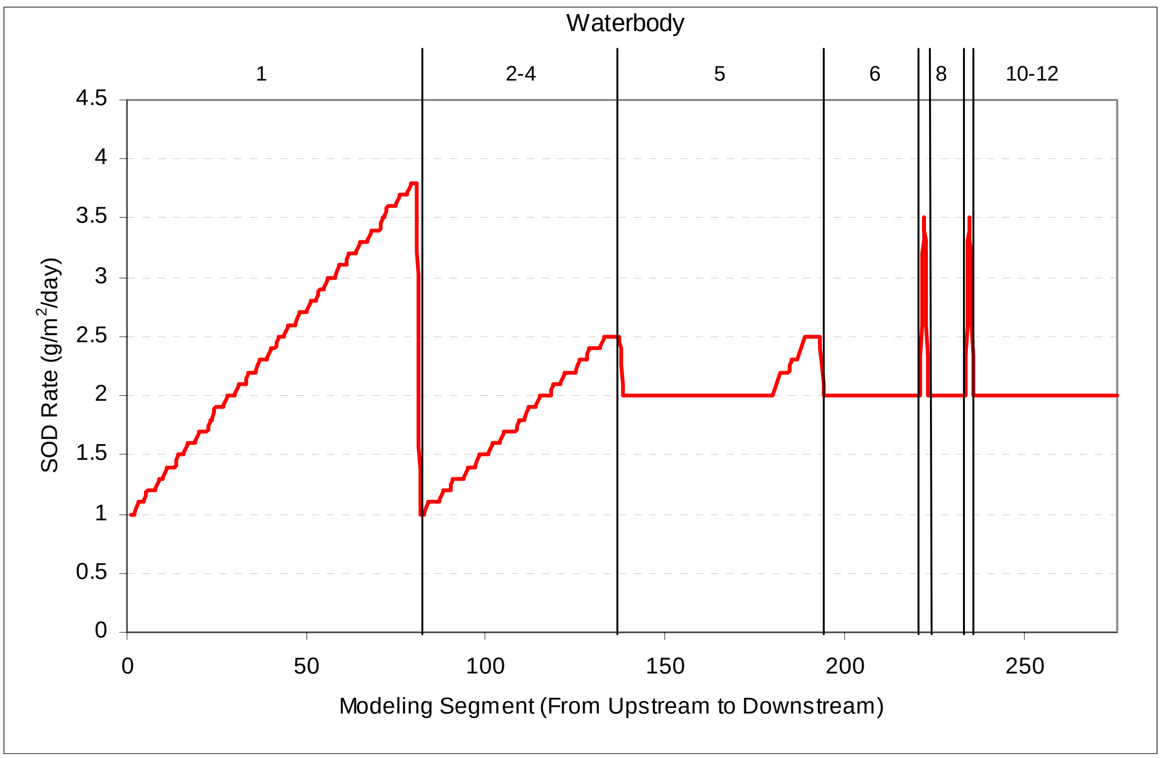

Figure 3-2. SOD Rate Variability in the Model

Appendices D_1999 and D_2004 present the model-simulated nutrient, DO, and chlorophyll a concentrations along with the observed data at the monitoring stations described above. Note in the figures that the “max”, “min”, and “mean” refer to the vertical maximum, minimum, and mean values of the corresponding constituents. If these values are indiscernible on the plots, then there is no vertical stratification occurring; otherwise, vertical stratification exists. Time-series plots of modeled versus observed data were the primary method of calibration for the Lost River

Model. They provide more insight into the nature of the system than statistical comparisons – particularly in light of the major data limitations associated with the Lost River. The following text briefly discusses the calibration performance at each station.

3.3.1 Lost River at Keller Bridge (LRKB)

As shown in Figures D_1999-1 and D_2004-1, the model results at LRKB follow the general trends demonstrated by the observation data. For DO, the model simulated relatively high concentrations during the winter, spring, and fall periods, but reached lower values during summer. Also, the model results show that there is no vertical stratification in the section. Since DO is plotted at a sub-daily frequency, the diel fluctuation is also apparent from the simulation results. Diel fluctuation at LRKB is not significant, however. The simulated nutrient, chlorophyll a, and pH values appear to follow the general observed trends very well, indicating that the model reasonably represents mass balance and water quality interactions for this section.

The simulated spikes of NO_3 and PO_4 during March (both 1999 and 2004) are due to boundary conditions at Malone Dam, where data show high concentrations of these two constituents. Due to lack of data for 2004, boundary conditions during spring and winter of the 2004 simulation were set equal to those in 1999, causing the spikes to occur in both years.

The calibration analyses indicated that chlorophyll a variations are dominated by the distributed flow boundary condition. This was apparent from both the 1999 and 2004 simulations.

The 2004 model simulated significantly smaller diel fluctuations of DO at LRKB because the growth of macrophytes is limited by nitrogen (and thus don't result in a major DO swing). This relatively low nitrogen level in the model is caused by the boundary condition representation. In the 2004 model, the DST boundary condition was set using monitoring data for several drains (which were assumed to represent the distributed flow water quality). This monitoring showed low nitrogen concentrations in the drains. Therefore the resulting in-stream nitrogen concentrations were relatively low (thereby limiting macrophyte growth). It is expected that if the distributed water quality boundary condition was set using the same approach used for the 1999 model (estimated based on LRKB data), the simulated nitrogen limiting condition might be alleviated.

3.3.2 Lost River at Harpold Dam (LRHD)

Similar to LRKB, the model results at LRHD follow the general observed trends reasonably well (Figures D_1999-2 and D_2004-2). No vertical stratification is apparent from either the model results or the observed data at this location either. For DO, the model simulated relatively high concentrations during winter, spring, and fall, and simulated relatively low values during summer. The diel fluctuation of DO and NH_4 is more prominent than in LRKB, suggesting a stronger biological impact on water quality. This conclusion is supported by the aquatic vegetation survey conducted in 2004, which shows that the macrophyte biomass at LRHD is about 6 times as high as that at LRKB. The model results show that the simulated peak macrophyte biomass at LRHD is about 7 times as high as that at the LRKB. The major factor affecting the spatial distribution of macrophytes is flow—the relatively high flow velocity at LRKB has limited the growth of macrophytes while the relatively stagnant conditions at Harpold Dam supports macrophyte growth.

The simulated spikes of NO_3 and PO_4 during March are due to boundary conditions at Malone Dam, where data show high concentrations of these two constituents in early March. As shown in Figure D_1999-2, the model under predicts NO_3 during summer 1999. This is because the distributed flow concentration was set equal to those at the LRKB, which has lower summer NO_3 concentrations than at LRHD. Since the distributed flow boundary condition dominates during the summer, the simulated NO_3 would directly reflect the relatively low NO_3 in the distributed flow boundary condition. Improved simulation might be achieved by using spatially variable distributed flow boundary conditions for upper and lower section of Waterbody #1, however sufficient data are not currently available. The same phenomena exist for the 2004 model.

3.3.3 Lost River at RM 27 (HPDS2)

Modeling results at RM 27 are presented in the Appendix, however no calibration discussion is presented because only one data point was available for comparison.

3.3.4 Lost River at Wilson Reservoir (LRWRC)

LRWRC is located inside Wilson Reservoir. The model results are compared with the observed data in Figures D_1999-3 and D_2004-4. The plots demonstrate that the model successfully reproduces the vertical stratification as well as the general seasonal trend for DO. The observed data show several very low DO concentrations during the end of 1999, however the model cannot reproduce this phenomenon since during winter the thermal stratification disappears. Hence the entire water column should be well mixed with oxygen replenished from the atmosphere. The very low DO in this period is likely caused by a highly site-specific feature that cannot be characterized and represented by the model, or it is caused by erroneous monitoring data. Another possible cause is that Wilson Reservoir reached a “quick inverse” stratification during the winter, when water at 4 °C remained at the bottom and colder water floated on top, forming a stratified condition. To develop a model that is capable of simulating this type of delicate thermal structure requires highly accurate bathymetric, flow, and atmospheric data. Such data are not available for the current modeling study.

As for the nutrients, the data show significant temporal fluctuation while the model simulates a relatively smooth transition. The large fluctuation of nutrient concentrations can most likely be attributed to sporadic loading to the system, which cannot be fully characterized in existing data sets. Therefore, it is not expected that the model can reproduce these highly time variable features of the system. The model does, however, represent the general trends seen in the data very well. Again, the simulated spikes of NO_3 and PO_4 during March are due to the boundary conditions at Malone Dam, where data show high concentration of these two constituents.

3.3.5 Lost River at Anderson Rose Dam (LRAR/ARDMUS)

The model results at LRAR/ARDMUS follow the general observed trends reasonably well (Figures D_1999-4 and D_2004-5). For DO, the model simulated relatively high concentrations during winter, spring, and fall, and simulated relatively low values during summer, with moderate vertical stratification and diurnal fluctuation. The model captures the chlorophyll a seasonal variability well. The simulation results for this portion of the Lost River system illustrate the influence of the Lost River Diversion Channel. For example, the peak in chlorophyll a that occurs during the summer of 1999 was primarily caused by loading from the Station 48 discharge. The simulated spikes of NH_4 during March for both 1999 and 2004 are due to the distributed flow boundary condition, where data show high NH_4 concentration during March

1999. Due to lack of data for 2004, boundary conditions during spring and winter of the 2004 simulation were set equal to those in 1999, causing the NH_4 spikes to occur in both years.

There is only one data point available at ARDMUS for comparison to model results, making it difficult to draw any definitive conclusions on the accuracy of the model simulations. In general, it is observed that the 1999 model performs better than the 2004 in predicting the low summer DO. The reason for the poor performance of the 2004 model is most likely the uncertainty in flow and concentration boundary conditions. Since 2004 was considered as a model corroboration run, no additional effort was made to adjust loading and parameters to improve the performance.

3.3.6 Lost River at East West Road (LREW)

The model results at LREW are compared with the observed data in Figures D_1999-5 and D_2004-6. For DO, the model simulated relatively high concentrations during winter, spring, and fall, as well as relatively low values during summer. The diel fluctuation of DO and NH_4 is very prominent, again suggesting very strong biological impact on water quality. The MaxDepth survey conducted in 2004 showed dense macrophyte vegetation in this area. The model reproduces the observed DO and NH_4 trends reasonably well. The 2004 model, however, was not able to predict the extremely high DO (16.0 mg/L) during June 2004. It was hypothesized that the system (i.e., the boundary conditions set in the model, which were based on limited 2004 monitoring data for inflows to the river) lacked sufficient nutrient loading to sustain extensive macrophyte growth. An alternative boundary condition loading scenario was run to test this theory, and it is described in the Diel Dissolved Oxygen Analysis section of the report. The alternative scenario demonstrated that the model responds to the increased nutrient load by predicting a wider range in DO fluctuation, and thus represents the dynamics of the system. Since 2004 was considered a model corroboration run, and since the boundaries were initially set based on observation data, no attempt was made to replace all boundary condition inputs for the system to improve the performance. It should also be noted that in the 1999 results, when the nutrient loading reached high levels during fall, the model was able to predict extremely high DO of over 20.0 mg/L. No vertical stratification is apparent from either the model results or monitoring data.

3.3.7 Lost River at Tule Lake (TLTO)

The model results for Tule Lake are compared with the observed data at the Tule Lake outlet (TLTO) in Figure D_1999-6. For DO, the model simulated the observed trends reasonably well. The simulated NH_4 and NO_3/NO_2 concentrations generally follow the observed data. However, simulated NH_4 is significantly lower than the observed concentrations, likely due to the representation of Tule Lake as a single segment. Using this representation, the entire load coming into the lake is instantaneously mixed throughout the entire lake, while in reality significant spatial gradients may exist. A direct consequence is that the response of nutrient concentrations to biological activity is significantly faster than response to external loading. Therefore, the NH_4 is quickly depleted by the algal growth but is more slowly replenished from external loading. In return, the depleted NH_4 limits biological activity in the lake. A better representation might be achieved using a higher resolution model. However, no attempt was made to further refine this model given time and data limitations.

3.3.8 P-Canal (PC)

The model results for P-Canal were compared to the observed data for 2004 (Figure D_2004-7). Since no distributed flow boundary condition was configured for P-Canal due to its relatively small drainage area, water quality in the canal is mainly controlled by the Tule Lake outflow conditions. For example, the lower predicted DO and NH_4 is inherited from the model uncertainty in Tule Lake. For better predictions, the processes between Tule Lake and P-Canal as well as the representation of Tule Lake itself would need to be improved.

3.3.9 Klamath Strait Drains at the State Line (KSDSR)

The model results for the Klamath Straits Drain at the state line were compared to the observed data at the same location (Figures D_1999-7 and D_2004-8). For DO, the model simulated relatively high values during the winter, spring, and fall, and represented the relatively low values during the summer. The model results show insignificant diel fluctuation of DO and NH_4. This is due to the very low chlorophyll a and macrophyte biomass resulting from the extremely unfavorable light conditions in the drain. The simulated NH_4 and NO_3/NO_2 results generally follow the observed data. However, significant disparities exist. Possible reasons for these disparities include:

- The observed data were collected in the Klamath Straits Drain, which is immediately downstream of Lower Klamath Lake. Water quality at this location is significantly impacted by the lake, which is represented very generally (as one segment) in the model.
- The DST boundary condition was set based on the DST of Tule Lake as well as the data at pumps E and F, and these show different trends from that of KSDSR.
- Uncertainty in flow balance.

Possible improvement may be achieved using spatially variable DST boundary conditions for different sections of this waterbody. No attempt was made to further refine these results given data limitations. The 2004 results indicate that the model captures trends reasonably well, except for PO_4, which is most likely caused by uncertainty in the boundary conditions.

3.3.10 Klamath Straits Drain at Pump E (KSDTR)

The model results for the Klamath Straits Drain at Pump E are compared with the observed data in Figure D_1999-8. The model reproduces the observed trends for DO, nutrient concentrations, and pH well. No vertical stratification is apparent from either the model results or monitoring data. The model results show insignificant diel fluctuation of DO and NH_4. This is due to the very low chlorophyll a and macrophyte biomass resulting from the extremely unfavorable light conditions in the drain. It should be noted that the model’s background light extinction coefficient was set to a high value (3.5/m) through the calibration process to account for the observed “dark water” (low light penetration) conditions.

3.3.11 Klamath Straits Drain at Pump F (KSDPSF)

The model results for the Klamath Straits Drain at Pump F are compared with the observed data in Figure D_1999-9. The model reproduces the observed trends for DO, nutrient concentrations, and pH well. No vertical stratification is apparent from either the model results or monitoring data. The model result shows insignificant diel fluctuation of DO and NH_4. This is due to the very low chlorophyll a and macrophyte biomass resulting from the extremely unfavorable light conditions in the KSD.

3.3.12 Klamath Straits Drain at Highway 97 (KSD97)

The model results for the Klamath Straits Drain at Highway 97 are compared with the observed data in Figure D_1999-10. The model once again reproduces the observed trends for DO, nutrient concentrations, and pH well. No vertical stratification is apparent from either the model results or monitoring data. The model results show insignificant diel fluctuation of DO and NH_4. Similar chlorophyll a and macrophyte biomass conditions exist as for previous sections of the drain.

3.3.13 Klamath Straits Drain at Railroad (KSDM)

The 2004 model results for the Klamath Straits Drain at railroad are compared to the observed data in Figure D_2004-9. The results indicate that the model generally predicts the observed condition well. Conditions are similar to previous sections of the Klamath Straits Drain.

3.3.14 Diel Dissolved Oxygen Analysis

Diel DO was measured at LROG, LRDR, LREW, and KSD97 from June 14 to June 17, 2004. The data reflect the most delicate dynamics in the waterbody including temperature, biological activities, and nutrient interactions, as well as benthic flux at specific times and locations. It is clear from monitoring data for the Lost River that the diel variation of in-stream water quality is significantly impacted by short-term patterns in local loadings (watershed return flows). Flow and loading to the river can be flashy and highly variable over short time periods (day-to-day or even hour-to-hour) rather than constant. A highly accurate reproduction of the observed diel DO data (as well as temperature and conductivity) requires accurate specification of all the major boundary conditions at sufficient spatial and temporal resolution. Unfortunately, no data representing such high resolution are currently available for any portion of the Lost River, or more importantly, to characterize the entire system.

As discussed previously, the model was configured for 2004 using data collected during two sampling events (one in June and one in July), each lasting for two consecutive days. Model predictions were compared to the raw DO data, as well as the temperature, pH, and conductivity data. These results are presented in Figures E_2004-1 through E_2004-4. The model simulates the general trends, however the magnitude of the DO swings is not closely matched at each location, particularly at LREW. This is a direct result of limitations with regard to setting the boundary conditions, as discussed in Section 3.3.6. It was hypothesized that the system lacked sufficient nutrient loading to sustain extensive macrophyte growth. Therefore, an alternative boundary condition loading scenario was run to test this theory for Waterbody #6 (which contains LREW).

In the original model run for 2004, the nutrient concentrations for the DST to Waterbody #6 were based on measured data at LREW. With the values being relatively low (between 0.05 and 0.3 mg/L for NH_4, 0.02 and 1.7 mg/L for NO_2/NO_3, and 0.1 and 0.4 mg/L for PO_4), macrophyte growth was limited (at least for the summer) and diel DO fluctuation was underpredicted. For the alternative loading scenario, NH_4, NO_2/NO_3, and PO_4 concentrations in the DST file were increased. No other changes were made. Concentrations were designated within a range of values identified in a recent monitoring study of conditions in the canals and drains surrounding Tule Lake (Danosky and Kaffka 2002). Although the monitoring locations are not in the same locations as the return flows contributing to Waterbody #6, it was assumed that conditions would be relatively comparable. The Danosky and Kaffka report summarized a data collection effort during 1999 for 18 surface water locations and 10 tile drain locations. Samples were collected at various locations every 10 days from April through October and one to two times a month for the rest of the year. Table 3-7 summarizes data from the report (which were used as bounds for the alternative loading scenario). Concentrations in Table 3-7 reflect the minimum, maximum, average, and standard deviation of samples across all locations for any given date.

Table 3-7. Alternative Loading Scenario Nutrient Concentrations (Danosky and Kaffka 2002)

	NO_2/NO_3 (mg/L)	NH_4 (mg/L)	PO_4 (mg/L)
Minimum	0.01	0.00	0.15
Maximum	14.37	16.23	1.94
Average	3.79	2.67	0.80
Standard Deviation	4.45	3.95	0.54

Results of the alternative loading scenario are presented in Figure E_2004-5. The figure includes comparisons of diel DO and pH data with modeling results. It is apparent from these plots that the increased nutrient loading (nitrogen, in particular) provides the macrophytes with the ability to sustain a larger biomass, thus resulting in a wider swing in DO levels. The scenario suggests that the model represents the physical, chemical, and biological attributes of the system reasonably well, and that it is important to provide accurate boundary loading conditions to match the observed diel DO data. A more detailed discussion is provided herein regarding the model's limitations with respect to diel simulation, as well as its capability of catching general trends:

- Mathematical models are constrained by the availability, quality, and resolution of input data. Built on very limited data, the Lost River model is not expected to be able to mimic the exact timing and location of all water quality conditions. The model is expected, however, to be able to represent general water quality trends in response to external loadings and internal dynamics of the system.
- While the Lost River watershed covers a large area and exhibits spatially-variable weather conditions, this model was built using only the data at the Klamath Falls weather station (the most complete dataset available). This station can represent the overall conditions in the watershed, however, it does not reflect site-specific conditions for each modeled Waterbody. This has large implications on the temperature and water quality simulation.
- The in-stream water quality at most locations in the Lost River system is primarily determined by characteristics of the local inflow. Therefore, the diel variation of in-stream water quality can be significantly impacted by time-variable patterns associated with local loadings. Flow and loading to the Lost River can vary significantly over a short time period. For example, the conductivity at LRARB has been observed to change by more than 300 uS/cm from one day to the next. This indicates that to accurately simulate the timing and magnitude of the diel fluctuation, or any short term variability of water quality in the river, accurate specification of boundary conditions at a similar resolution is necessary (i.e., spatially-variable loading at each segment on a daily or sub-daily timestep).
- Another factor impacting the model's capability of reproducing diel fluctuation in water quality is bathymetry information. Bathymetry is particularly important for the reservoirs, because an accurate representation of bathymetry determines the model's

capability of representing not only volume and flow but also the distribution of macrophytes. For example, if the bathymetry has a shallower bed area than in reality, the distribution of macrophytes and their impact on DO may be inaccurately simulated, and vice versa. Currently, there is no detailed bathymetry data for the reservoirs.

- The W2 model represents the river/reservoir system as a longitudinal-vertical 2-D system, where the water quality in each computational cell represents the average conditions in that cell. The observed data, however, represents highly localized conditions in an area immediately surrounding the monitoring device. While the model can predict the overall mass transport and balance on a large scale, it cannot necessarily mimic highly localized features.

3.3.15 Macrophyte Analysis

As discussed earlier in the report, an aquatic vegetation survey was conducted during July 2004. The lumped macrophyte biomass, in terms of dry weight per square meter, were reported at 10 locations along the Lost River system. To confirm the model's capability of matching the general spatial pattern of macrophyte distribution, the minimum and maximum values of the model-simulated average macrophyte biomass per square meter for July 2004 were plotted against the observed data in Figure E_2004-6. Note that the observed data are represented using the measured dry weight per square meter multiplied by the average trans-section coverage. The model performs reasonably well in reproducing the observed pattern for most locations. The model performs worst at the Lost River at Gift Road location, where the survey showed an extremely high density of macrophyte growth. One reason for this may be that there is a localized high nutrient loading which is not reflected in any of the monitoring data. Another reason is that the macrophytes may extract significant amounts of nutrients from the benthic mud to sustain such a high density of growth. Similarly, the model significantly underpredicts the macrophyte growth at LREW and P-Canal. This is most likely due to lack of sufficient nutrient boundary conditions. It is expected that the model performance for macrophyte simulation can be improved by: (1) configuring more macrophyte species to represent more detailed dynamics in terms of light competition, nutrient utilization, and response to flow conditions; (2) refining boundary conditions after further data collection; or (3) developing a comprehensive ecological model.

3.4 Model Sensitivity Analyses

Since a mathematical model is a simplified representation of the real world, its prediction is often subject to considerable uncertainty from a variety of sources. These sources include over-simplification of modeling assumptions and formulations, noise-distorted data, and model parameter values. It is important to gain a better understanding of a model's reliability by analyzing the uncertainty associated with a model. Sensitivity analysis is a prime method of measuring a model's uncertainty and reliability.

In this study, the sensitivity of the DO concentration was evaluated through a number of mechanisms. The first mechanism evaluated the impact of key parameters on DO at two locations (LRKB and LRHD). The analysis was performed by adjusting a single parameter at a time by 20% (higher and lower) and evaluating the DO response of the waterbody (in terms of DO change). The analysis was performed for the following parameters:

- Sediment oxygen demand (SOD)
- Phytoplankton growth rate
- CBOD decay rate
- Macrophyte growth rate

SOD is the total oxygen consumption incurred by the biochemical processes in the sediment layer. Generally, SOD is positively correlated to nutrient and organic loadings to a specific water body (Chapra, 1997). Figures F_1999-1 and F_1999-5 in Appendix F_1999 show that the DO concentration is mildly sensitive to a change in SOD. LRHD shows a greater response to SOD adjustment than LRKB.

The sensitivity of DO to phytoplankton growth rate is shown in Figures F_1999-2 and F_1999-6. DO concentrations are insensitive to the change in phytoplankton growth rate, meaning that phytoplankton plays a minor role in DO dynamics (for these locations).

The sensitivity of predicted DO concentration to CBOD decay rate is presented in Figures F_1999-3 and F_1999-7. As shown, the DO results are relatively insensitive to the change in decay rate, with a range of DO response within 0.2 mg/L. One reason for this insensitivity is due to the relatively low value of CBOD concentration in the river.

The DO is most sensitive to the macrophyte growth rate as shown in Figures F_1999-4 and F_1999-8. Results show that the DO concentrations react nonlinearly to macrophyte growth rate changes and both increase and decrease due to either an increase or decrease in rate. This exemplifies the complexity of nutrient and macrophyte interactions and its importance in DO dynamics.

The second sensitivity evaluation addressed the impact of phosphorus reductions versus nitrogen reductions on DO levels. This evaluation was performed by making two nutrient loading reduction simulations and comparing them to existing conditions. The only difference between the simulations was that the first simulation involved a reduction of phosphorus and nitrogen (approximately 90%) while the second involved a reduction of only nitrogen (also approximately 90%). The results of these simulations are presented for two locations (LRHD and LRWRC) for 1999 in Figures F_1999-9 and F_1999-10 and are labeled “Nitrogen and Phosphorus Reduction” and “Nitrogen Reduction Only,” respectively.

It’s apparent from the plots that both nutrient reduction simulations result in the same prediction. Thus, DO for the Lost River is more sensitive to nitrogen reduction than to phosphorus reduction. This observation is corroborated by the monitoring data, which show similar magnitudes of PO_4 and NH_4 concentrations in the water column. Macrophytes need about six times more nitrogen than phosphorus for growth, therefore, nitrogen tends to be a limiting factor once macrophytes grow to a certain level.

A third sensitivity evaluation addressed the potential impact of riparian shading on DO levels. This evaluation involved a comparison of DO levels under existing conditions to levels under an increased shade simulation. A 30% reduction of the solar radiation value was implemented for all Waterbodies except in Wilson, Tule, and Lower Klamath Lakes to grossly represent increased riparian shading. This 30% increase was assumed to represent the maximum possible shading for the system and is most applicable to relatively narrow, riverine portions and narrow impoundments (as opposed to wide lakes such as Wilson, Tule, and Lower Klamath). It should be noted that the increased shade simulation does not explicitly consider vegetation height/density, the path of the sun or impact of variable shading over the course of the day, orientation or geometry of the Waterbody (i.e., width of the river/impoundment), or topographic shading impacts. Results of the simulations are presented in Figures F_1999-11 through F_1999-19.

Increased riparian shading for the narrow Waterbodies resulted in noticeable changes to only a few areas. Specifically, minimum DO levels at Harpold Dam increased by as much as 1.0, while maximum DO levels decreased by as much as 2.0 mg/L. Minor increases in minimum values and decreases in maximum values were apparent at Anderson-Rose Dam and East-West Road. Most other locations showed little or no impact from increased shading.

4.0 TMDL SCENARIO

After calibrating and validating the model and conducting model sensitivity simulations, the model was applied to TMDL development using 1999 as the basis. The TMDL scenario involved making load reductions to external boundaries (including the upstream boundary at Malone Dam and all tributary and distributed flow inputs) in an upstream to downstream manner while ensuring that water quality criteria were met in all riverine sections. Load reductions (and incoming concentrations) were made for nitrogen and BOD, and these reductions varied throughout the system. Reductions were not made to phosphorus since sensitivity analyses and monitoring data indicated the DO levels were relatively insensitive to phosphorus reductions. DO criteria were not achieved in all the Oregon impoundments for this TMDL scenario based solely on nitrogen and BOD reductions. As such, an additional DO loading required to achieve DO criteria for Wilson and Anderson-Rose Reservoirs and the Klamath Straits Drain was identified subsequent to the nutrient and BOD loading reduction simulation.

The water quality criteria evaluated for compliance during the TMDL scenario are presented in Table 4-1. No margin of safety (MOS) was explicitly considered in the modeling. Multiple compliance points were evaluated throughout the system to ensure that water quality criteria were being met in critical locations. These stations, shown graphically in Figure 2-1, are as follows:

- Lost River at Gift Road (LRGR)
- Lost River at Keller Bridge (LRKB)
- Harpold Dam (LRHD)
- Lost River at Stevenson Park (LRSP)
- Lost River at Olene Gap (LROG)
- Wilson Dam (LRWRC)
- Lost River at Dehlinger Road (LRDR)
- Lost River at Hwy 39 n/w of Merrill (LR39)
- Anderson-Rose Dam (LRAR)
- Lost River at Stateline Road – OR/CA border (LRSR)
- Lost River at East-West Road (LREW)
- Tule Lake (TLTO)
- Lower Klamath Refuge/Lake (LKL)
- Klamath Straits Drain at Stateline Road – OR/CA border (KSDSR)
- Klamath Straits Drain at Township Road (KSDTR)
- Klamath Straits Drain at Hwy 97 (KSD97)
- Klamath Straits Drain at (KSDM)

Table 4-1. Water Quality Criteria Evaluated for Compliance During TMDL Scenario

Parameter	California	Oregon
Dissolved Oxygen	5.0 mg/L as an absolute minimum	4.0 mg/l as an absolute minimum 6.5 mg/l as a 30-day mean minimum 5.0 mg/l as a 7-day minimum mean
Ammonia	No objective	See Table 20, OAR 340-41-0965 (2)(p)(B)
chlorophyll-a	No objective	<0.015 mg/L
pH	7.0 - 9.0	6.5 - 9.0

The piece-wise simulation technique developed for this model enabled an efficient TMDL scenario analysis from upstream to downstream. Waterbody #1 was analyzed first, with reductions made to the boundary condition concentrations for BOD and nitrogen, as well as SOD. After several iterations and determining the external loading reduction required to achieve the water quality targets at Gift Road, Keller Bridge, and Harpold Dam (critical locations within Waterbody #1), the discharge at Harpold Dam was configured as the upstream boundary condition to Waterbody #2 and #3. A similar procedure was implemented to meet water quality criteria in this segment (at Stevenson Park and Olene Gap). This procedure was followed in an upstream to downstream manner until water quality criteria were achieved in all waterbodies (at all critical locations), with the exception of Wilson and Anderson-Rose Reservoirs and the Klamath Straits Drain. In general, the DO criteria were the most stringent criteria. Therefore, chlorophyll-a and ammonia criteria were achieved once DO criteria were met. Model simulation results at all compliance points are presented along with water quality criteria in Appendix G. The nitrogen and BOD load reductions required, by Waterbody, to achieve water quality criteria are presented in Table 4-2. It should be noted that pH and ammonia toxicity targets were slightly exceeded for the TMDL scenario in a number of locations due to model and boundary condition uncertainty. These exceptions to water quality criteria achievement are further described below.

Table 4-2. Nitrogen and BOD Load Reductions Required to Achieve Water Quality Criteria*

Waterbody #	Reduction %
1	50
2	50
3	50
4	50
5	50
6	50
7	49
8	49
9	49
10	49
11	49
12	49

* With the exception of Wilson and Anderson-Rose Reservoirs and the Klamath Straits Drain

DO criteria were nearly impossible to achieve in the hypolimnion of Wilson and Anderson-Rose Reservoirs or within the Klamath Straits Drain based solely on BOD, nitrogen, and SOD reductions. Therefore once the model had been run to achieve water quality criteria in all other waterbodies, the required DO loading to meet the DO criteria was calculated for Wilson and Anderson-Rose Reservoirs and the Klamath Straits Drain. This calculation was based on the most stringent DO criteria and average impoundment volumes.

Minimum modeled DO concentrations under the TMDL scenario for the minimum, 30-day, and 7-day Oregon DO criteria are presented in Table 4-3 at compliance points within Wilson and Anderson-Rose Reservoirs and the Klamath Straits Drain. The necessary DO concentration increase at each compliance point for each DO criteria is also presented, along with the DO criteria. The necessary DO increase is the difference between the DO criteria and the minimum modeled DO concentration, and it represents the greatest divergence from the DO criteria at any given time throughout the year.

Table 4-3. DO Concentrations in Impoundments Not Meeting All DO Criteria Based Solely on Load Reductions

Impoundment	Minimum Modeled DO (mg/L)			DO Criteria (mg/L)			Necessary DO Increase (mg/L)		
	Min	30-day	7-day	Min	30-day	7-day	Min	30-day	7-day
LRWRC	0.87	2.62	1.12	4.00	6.50	5.00	3.13	3.88	3.88
LRAR	2.15	6.02	3.42	4.00	6.50	5.00	1.85	0.48	1.58
KSDSR	5.2	5.75	5.36	4.00	6.50	5.00	N/A	0.75	N/A
KSDTR	4.56	5.73	4.93	4.00	6.50	5.00	N/A	0.77	0.07
KSD97	5.59	6.20	5.81	4.00	6.50	5.00	N/A	0.30	N/A
KSDM	5.56	6.17	5.79	4.00	6.50	5.00	N/A	0.33	N/A

The necessary DO increase was then converted to mass units to comply with ODEQ TMDL development requirements. This calculation was made for Wilson Reservoir, Anderson-Rose Reservoir, and three impounded regions of Klamath Straits Drain (Waterbody #10 – from KSDSR to KSDTR; Waterbody #11 – from KSDTR to KSD97; and Waterbody #12 – from KSD97 to KSDM). The necessary DO increase was multiplied by the average volume of the associated impoundment for the critical period (in terms of DO depression) from May through October to obtain a mass. Table 4-4 presents the required DO mass (in tons and kg) for each impoundment. It is recognized that DO changes over time and that the “static” or “instantaneous” mass presented reflects a worst case DO condition and an average volume during the critical season. It is assumed that the engineering solutions to improve the DO concentrations will further explore and evaluate the temporal variability of DO in identifying necessary DO inputs.

Table 4-4. DO Loading Requirements for Impoundments Not Meeting All DO Criteria Based Solely on Load Reductions

Location	Required DO Mass (kg)	Required DO Mass (tons)
Wilson Reservoir	16,929.71	16.93
Anderson-Rose Reservoir	496.96	0.50
Klamath Straits Drain – Waterbody #10	152.64	0.15
Klamath Straits Drain – Waterbody #11	70.89	0.07
Klamath Straits Drain – Waterbody #12	32.56	0.03

As noted above, a number of the water quality criteria were exceeded under the TMDL scenario due to model and boundary condition uncertainty. Ammonia toxicity model predictions were found to exceed limits in the spring at LRDR, LR39, LRAR, and LRSR. These high values can be attributed to the distributed boundary condition for NH4 between Wilson Dam and Anderson Rose Dam. Unfortunately, there was only one data point used to derive this boundary condition (and it was a high value-almost 1.6 mg/L, at Anderson Rose Dam). As such, the spring ammonia toxicity predictions for this stretch of river are not tremendously reliable. It should also be noted that based on a review of the monitoring data for this period, there were no apparent ammonia toxicity issues.

As with ammonia toxicity, pH exceeded criteria at a number of locations. The pH exceedances are largely attributed to background conditions (and in many cases are high throughout the year). pH was not found to be too sensitive to adjustments in nutrients, and thus was assumed not to be driven predominantly by biological processes. A few potential exceptions to this statement are at LR39, LRSR, and LREW during October. In these cases, the pH appears to be driven, at least partially, by biological activity. The predicted pH values during this period, however, are not entirely reliable due to modeling uncertainty. Specifically, insufficient alkalinity data and no TIC data were available to support boundary condition settings. It should also be noted that monitoring data for 1999 at these stations do not show pH exceedances.

Chlorophyll-a concentrations in Appendix G appear to exceed the criteria in a number of locations, however, these plots represent instantaneous levels. Oregon's chlorophyll-a criterion targets a 3-month average chlorophyll-a concentration, along with depth averaging in the photic zone. As such, the apparent exceedances at LRWRC and LRAR are actually below the 15 ug/L criterion when averaged over 90 days.

A number of important assumptions were made in the process of running the TMDL scenario:

- Nitrogen and BOD boundary conditions were reduced equally (within each waterbody).
- SOD was reduced by the same percentage as boundary condition reductions (e.g., a 20% boundary condition reduction would result in a 20% SOD reduction). This is based on the linear assumption, as described in Chapra 1997, and has been widely used in TMDL development when sediment diagenesis is not explicitly simulated. The SOD reduction ratio for all the downstream waterbodies was calculated based on the lumped loading from all tributaries, distributed loadings, as well as the contribution from upstream waterbodies. For example, the reduction of loading to Waterbody #1 also influences SOD reduction in Waterbody #2. The loading used to calculate the SOD reduction is on an annual basis, and ammonia, nitrite/nitrate, and CBOD were used as the corresponding

constituents. Since the loading reduction ratio of each of the constituents can be different, the average of the calculated reduction ratio for the constituents was used as the SOD reduction ratio.

- Boundary condition DO was kept at incoming levels (i.e., calibration conditions) when above water quality criteria; otherwise, it was set to Oregon's most stringent water quality criteria (6.5 mg/L – which is based on the Oregon 30-day average criteria for DO). This is based on the assumption that implementation in the watershed will enable DO levels for incoming water to achieve the water quality criteria. If the incoming water does not achieve the criteria, in-stream DO levels will violate the criteria at some locations (primarily where watershed return flow dominates).
- No change in temperature was made for boundary conditions from the calibrated model.
- The maximum algae concentration was forced to the 15 ug/L standard or lower (only when it was higher than the standard). This is based on the assumption that implementation in the watershed will reduce algae concentrations for the incoming water (based on corresponding nutrient reductions).

5.0 DISCUSSION

The Lost River is an extremely complex system consisting of different waterbodies with distinct physical, chemical, and biological features. In general, the riverine sections represent a system that moves relatively quickly, and they demonstrate a rapid response to external loading. The impounded sections represent a drastically different type of system - one that is relatively stagnant and shows a much slower response to external loading. A modified W2 modeling framework, specific to the Lost River, was developed to evaluate the temporal and spatial variability of loading and in-stream hydrodynamic and water quality conditions.

Although significant data limitations posed a challenge to model development and application, the approach implemented proved successful in deriving dominant boundary conditions and making relatively accurate in-stream hydrodynamic and water quality predictions. The modeling study suggests that macrophytes are the dominant factor controlling the diel DO and nutrient fluctuation, and specifically minimum DO levels. This is corroborated by the intensive aquatic vegetation survey conducted during the summer of 2004. Even though phytoplankton levels can be high in some riverine locations, it is primarily due to localized external contributions and has a less significant impact on internal dynamics and DO levels. In the impoundments, internal growth of phytoplankton generally plays a more significant role due to the stagnant environment, which is more favorable to algae growth.

The modeling also suggests many segments of the Lost River are limited more by nitrogen than by phosphorus, with respect to macrophyte development. This model-based observation is corroborated by the monitoring data, which show similar magnitudes of PO_4 and NH_4 concentrations in the water column. Macrophytes need about six times more nitrogen than phosphorus for growth, therefore, nitrogen tends to be a limiting factor once macrophytes grow to a certain level. This observation is also consistent with the Lost River aquatic vegetation survey conducted in 2004 by MaxDepth.

The current modeling framework utilizes the best available data for the Lost River and provides a sound technical basis for TMDL analysis and evaluation of water quality standards. Improvements to the framework can be grouped into two major categories: further data collection and model improvements. The most apparent data gaps are associated with defining the temporal and spatial variability of all inputs to and withdrawals from the Lost River and its impoundments. Characteristics data for Wilson Reservoir, Tule Lake, Lower Klamath Lake are also needed to improve the model.

Representing competition for nutrients and light between phytoplankton and macrophytes, as well as between different phytoplankton and macrophyte species, is seen as the most important model improvement to accurately predict primary productivity in the Lost River. In the current model, a single species of phytoplankton and macrophytes was used to represent the broader range of vegetation present. In reality, different species within each group may show significantly different biological behavior. For example, floating macroalgae, such as duckweed, could cover the water surface and shade the entire water column below. Even the modified version of W2 used for this application is not able to represent the impact of duckweed on phytoplankton and other macrophytes. Another issue not explicitly represented is the life cycle of macrophytes. Some macrophytes, such as duckweed, do not die during the winter. Instead, they transform into a dormant form and sink to the bottom of the water column until the next year. This is another feature that most existing water quality models, including W2, cannot represent. Accurately simulating the multi-year life cycles of macrophytes is important for enhancing the predictability of the model, especially when the long term effect of nutrient loading reductions are concerned.

6.0 REFERENCES

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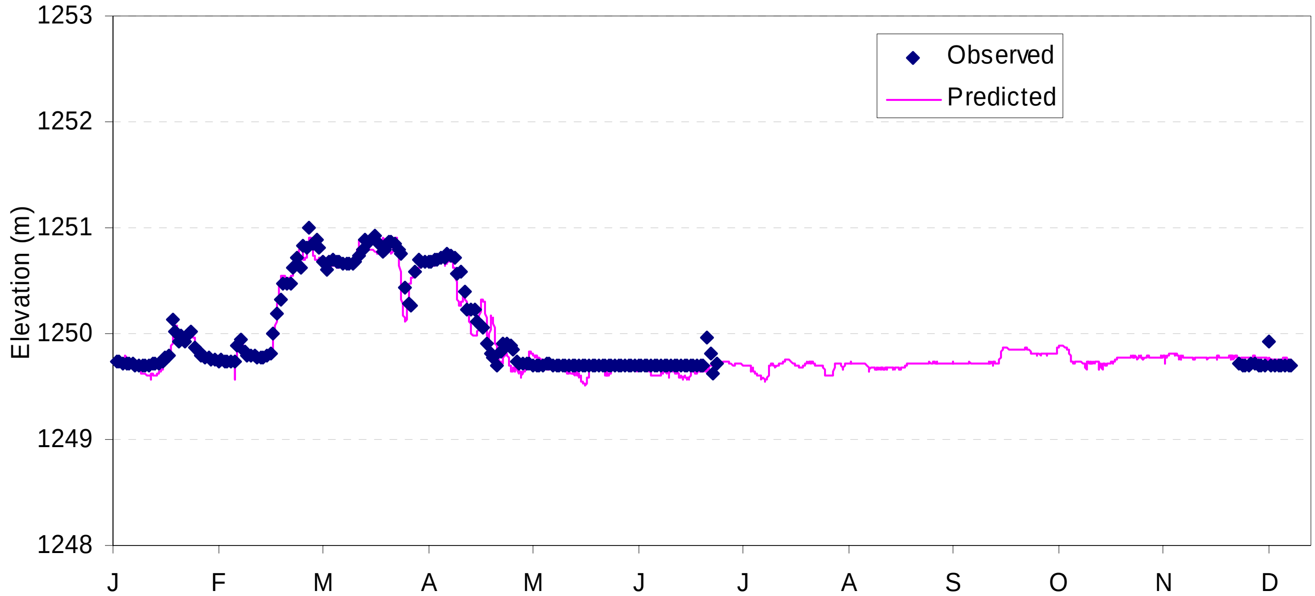
Appendix A_1999

Water Balance and Water Surface Elevation Calibration



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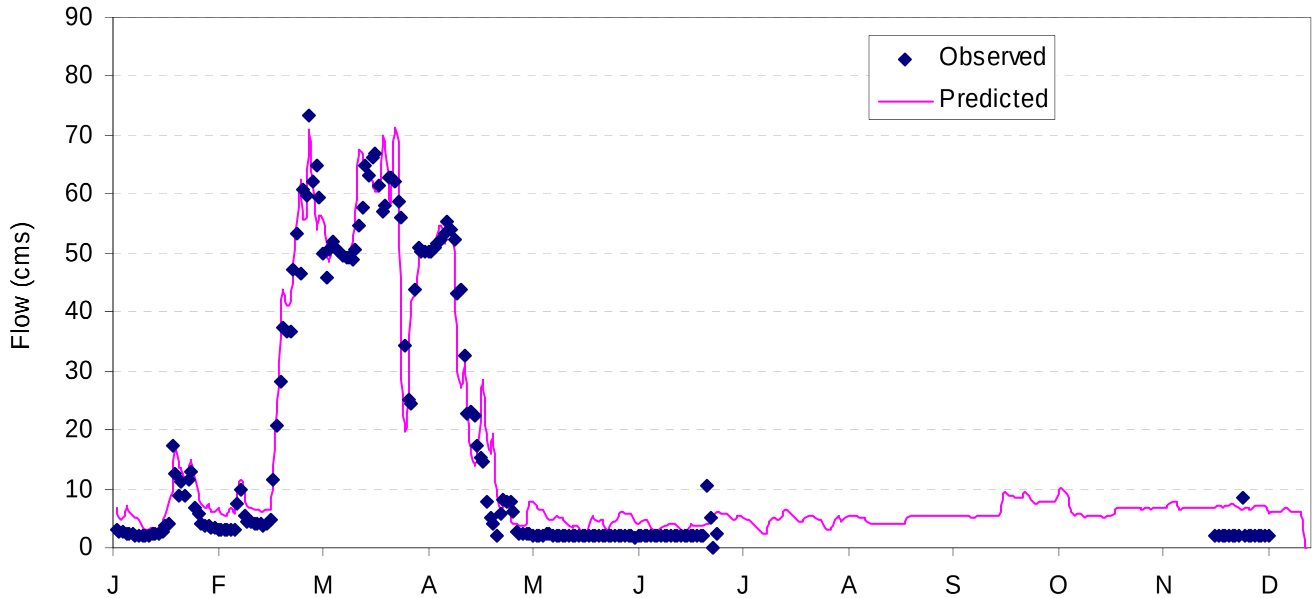

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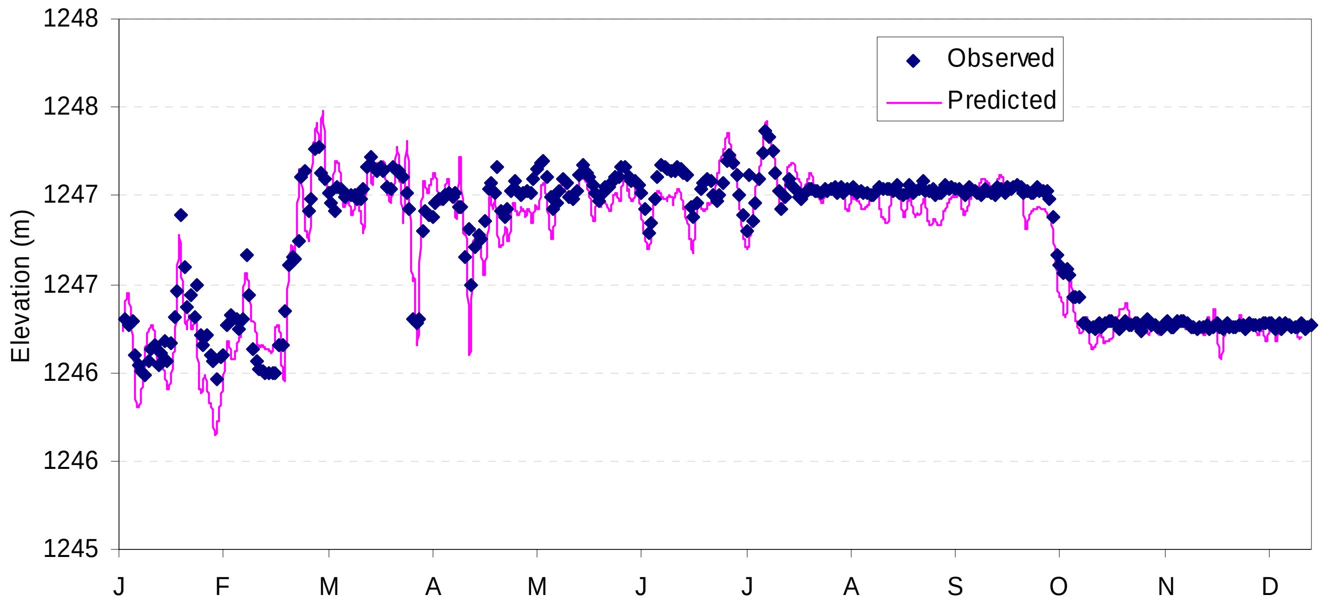

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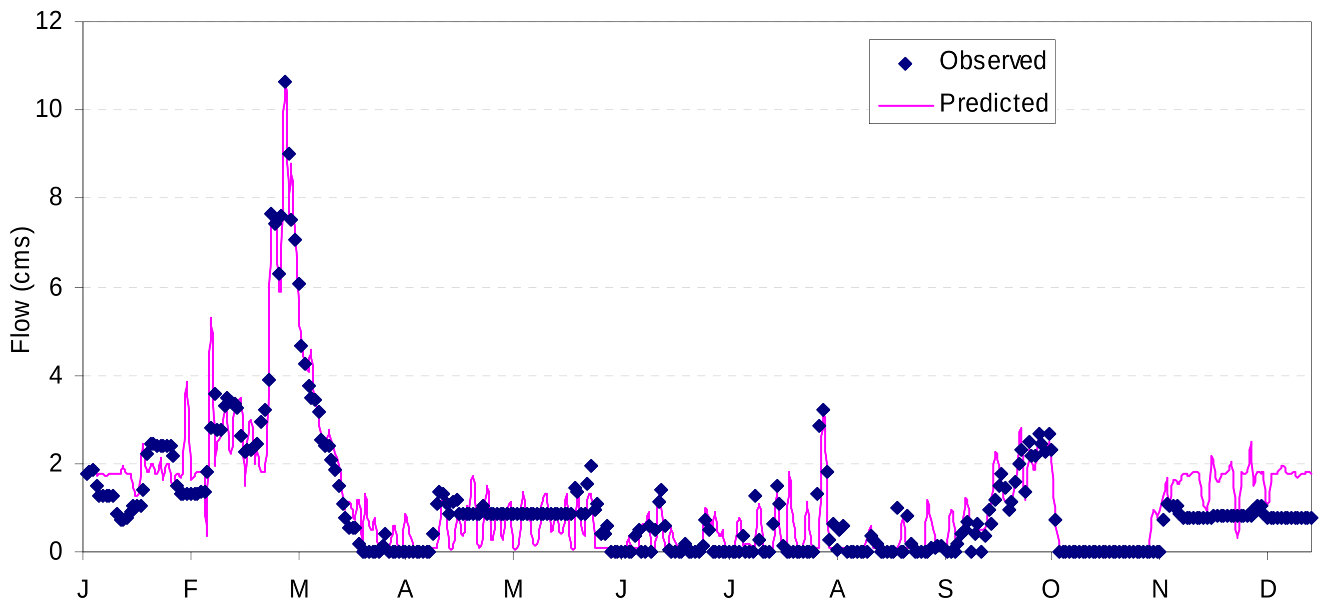
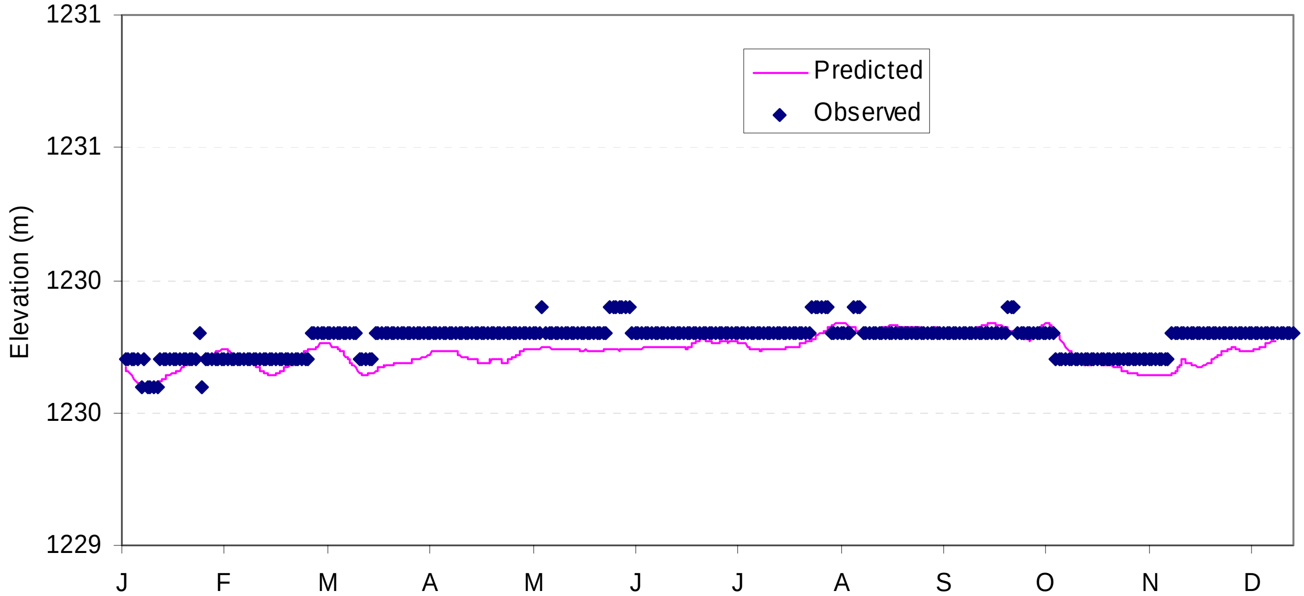
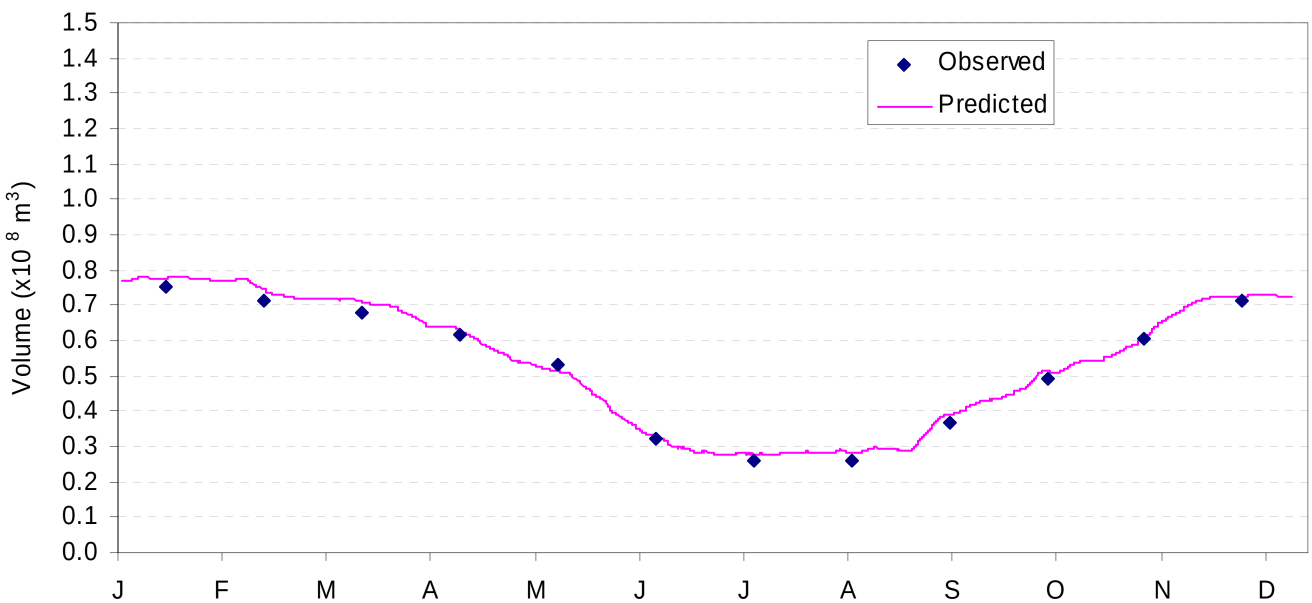


A_1999-4 Anderson Rose Spill (1999)



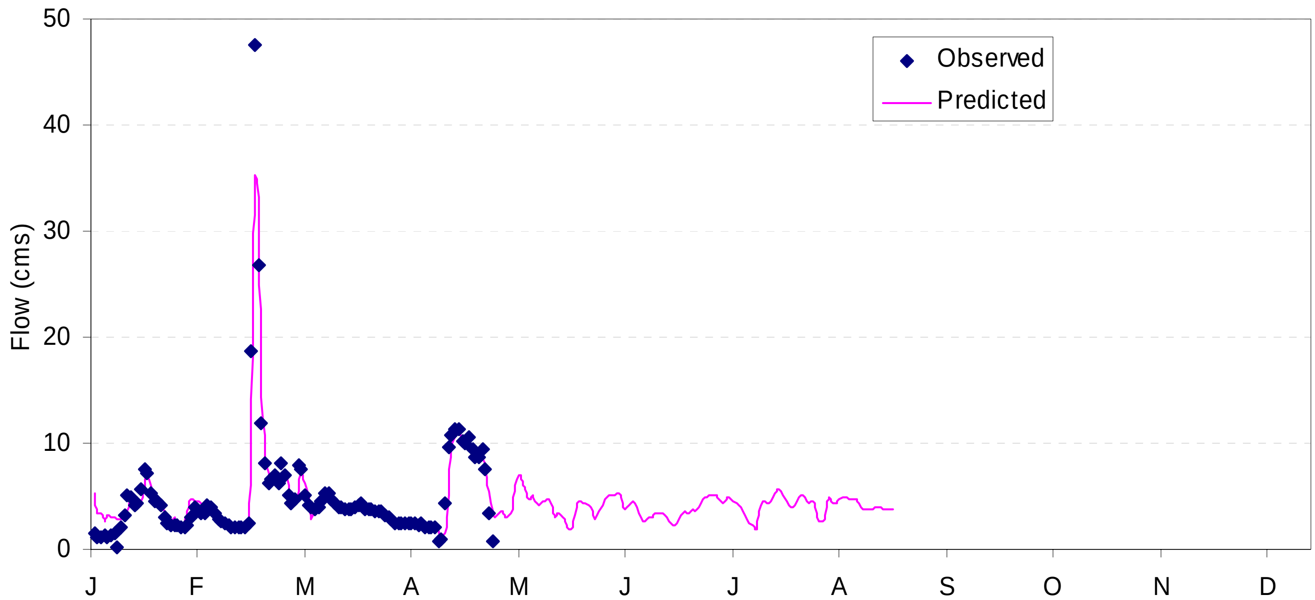
A_1999-5 Tule Lake Elevation (1999)



A_1999-6 Lower Klamath Lake Volume (1999)

Appendix A_2004

Water Balance and Water Surface Elevation Calibration



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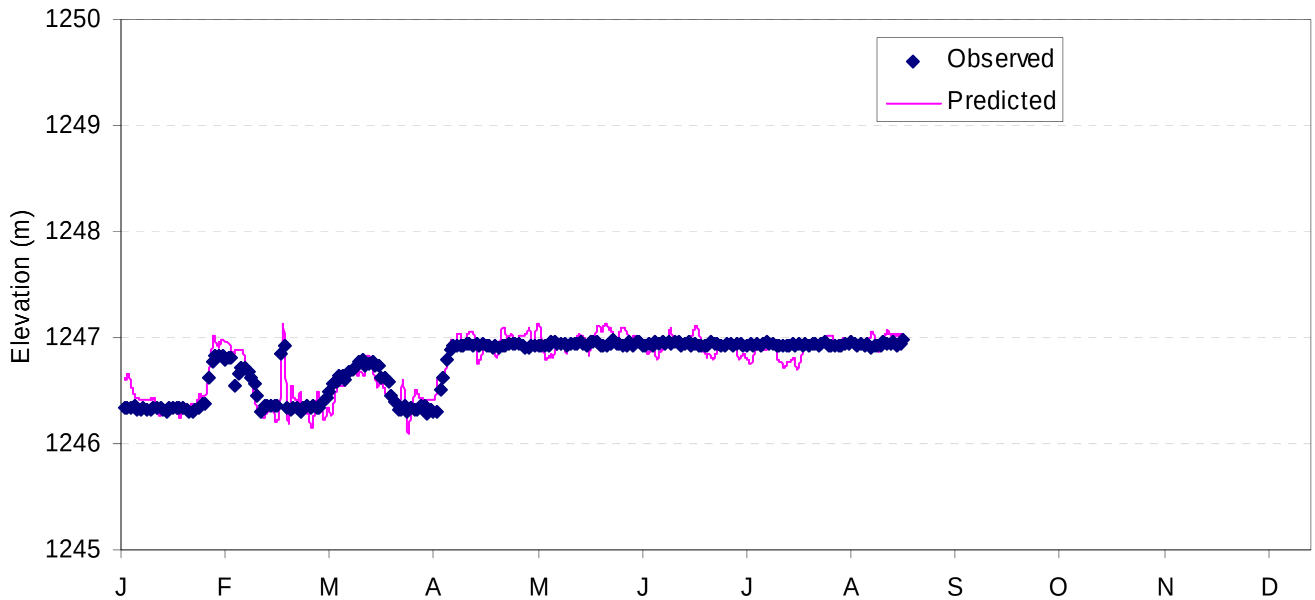

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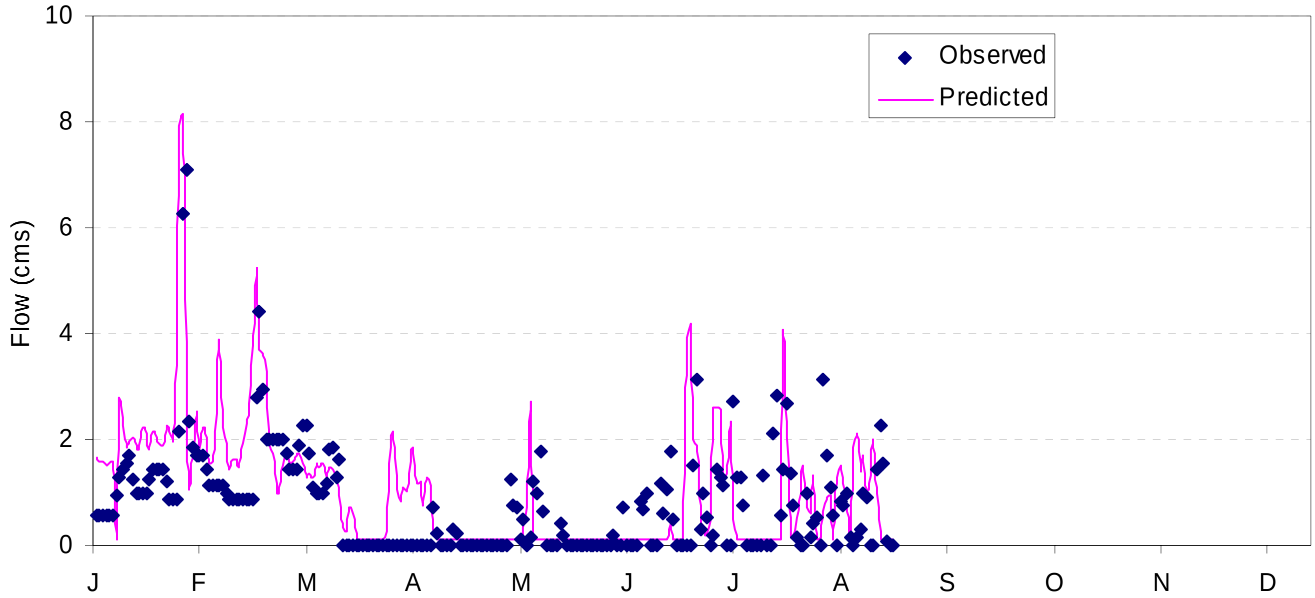
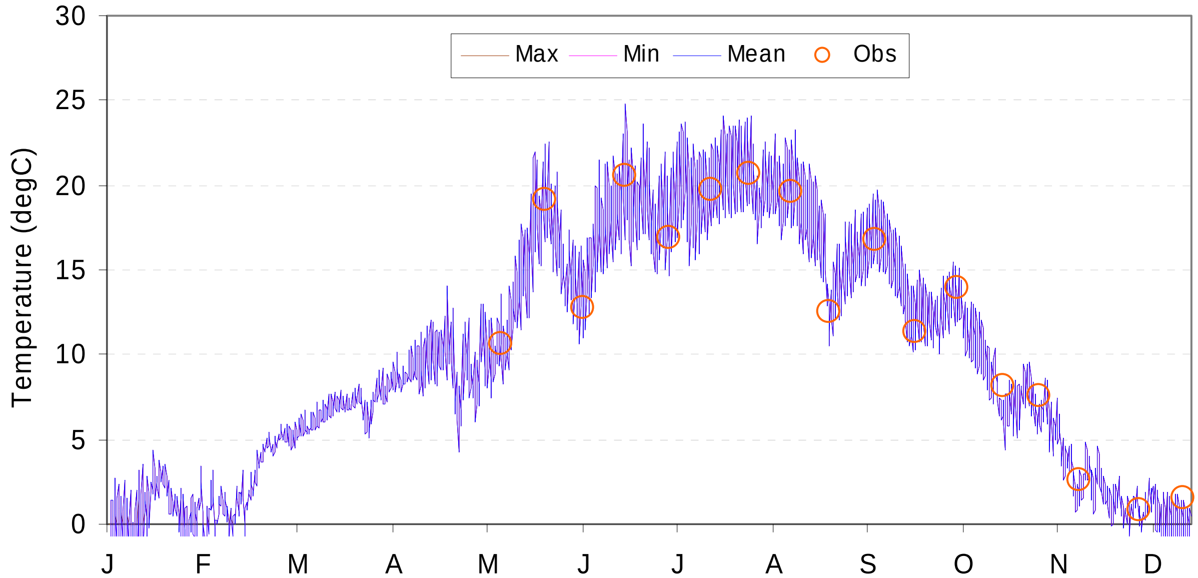


A_2004-3 Anderson Rose Spills (2004)

Appendix B_1999

Hydrodynamic Model Evaluation with Temperature Data



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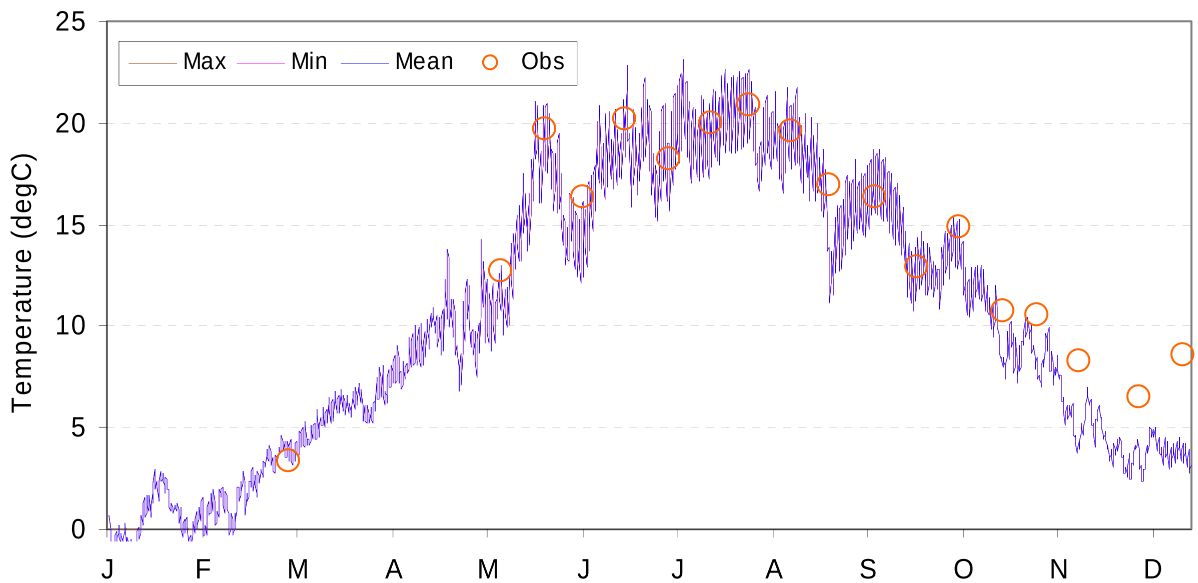

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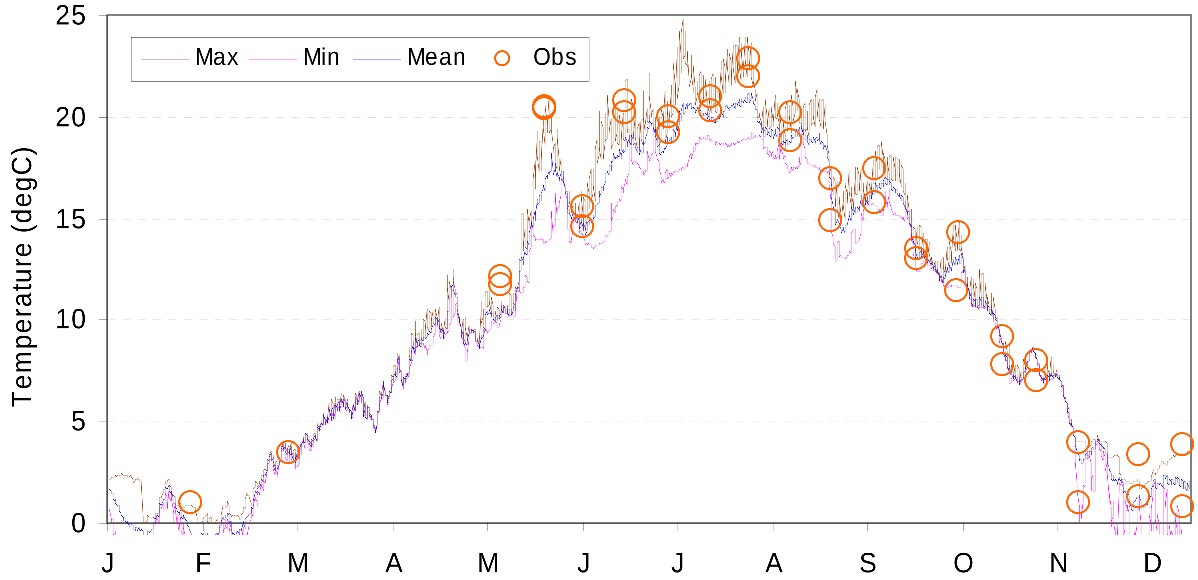

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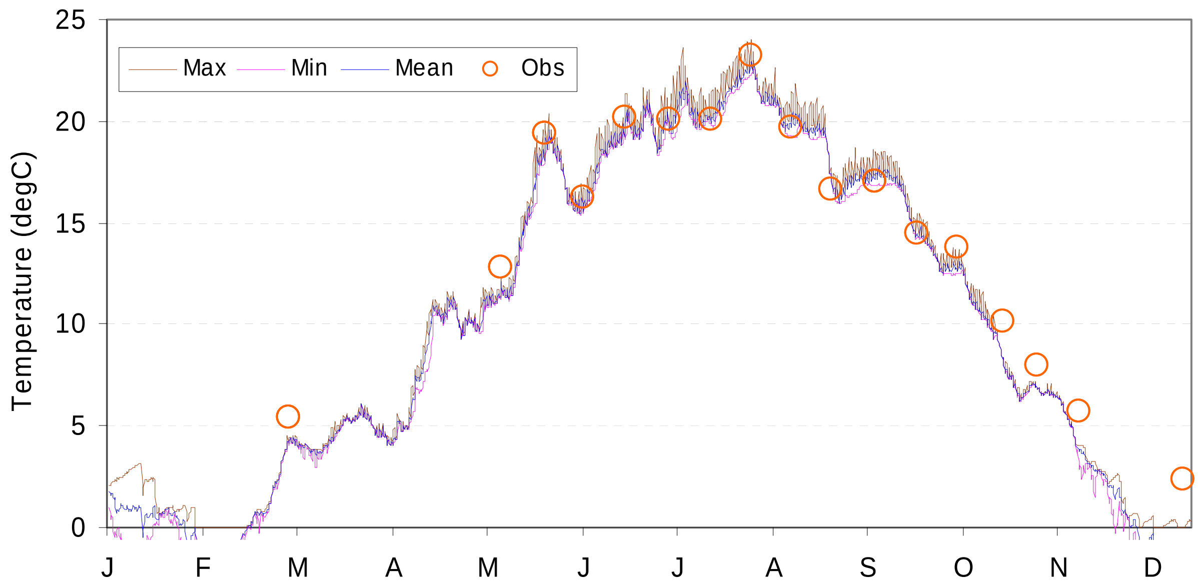

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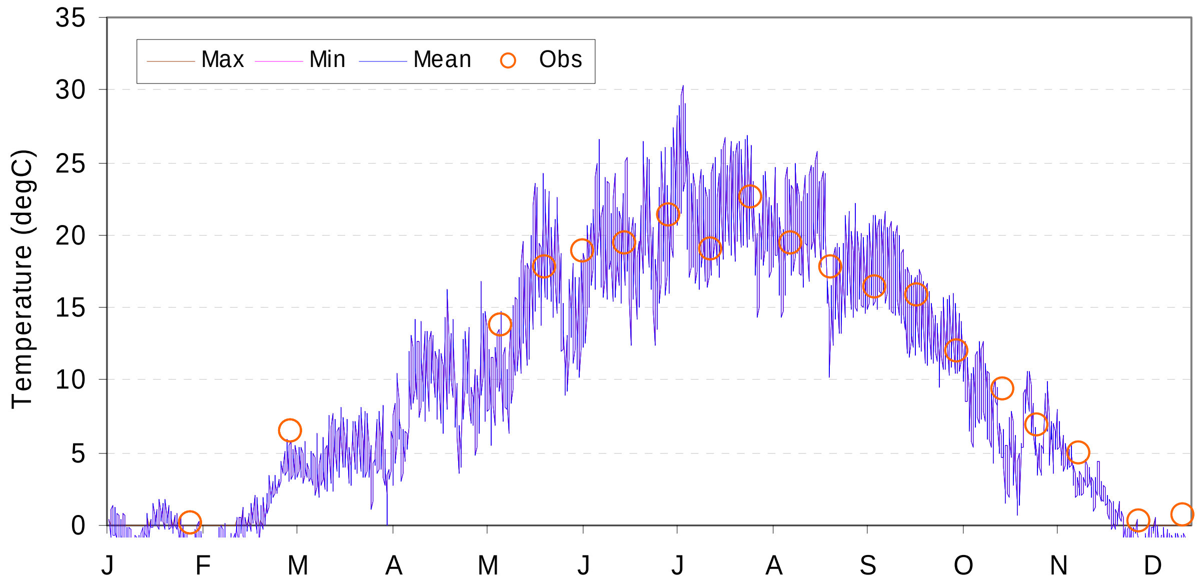
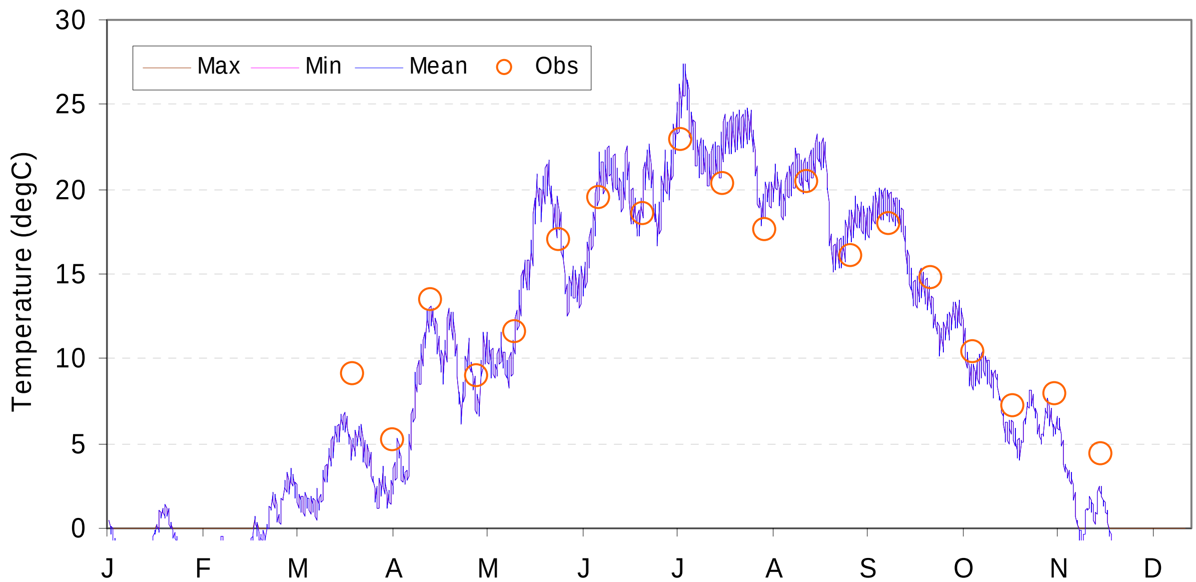
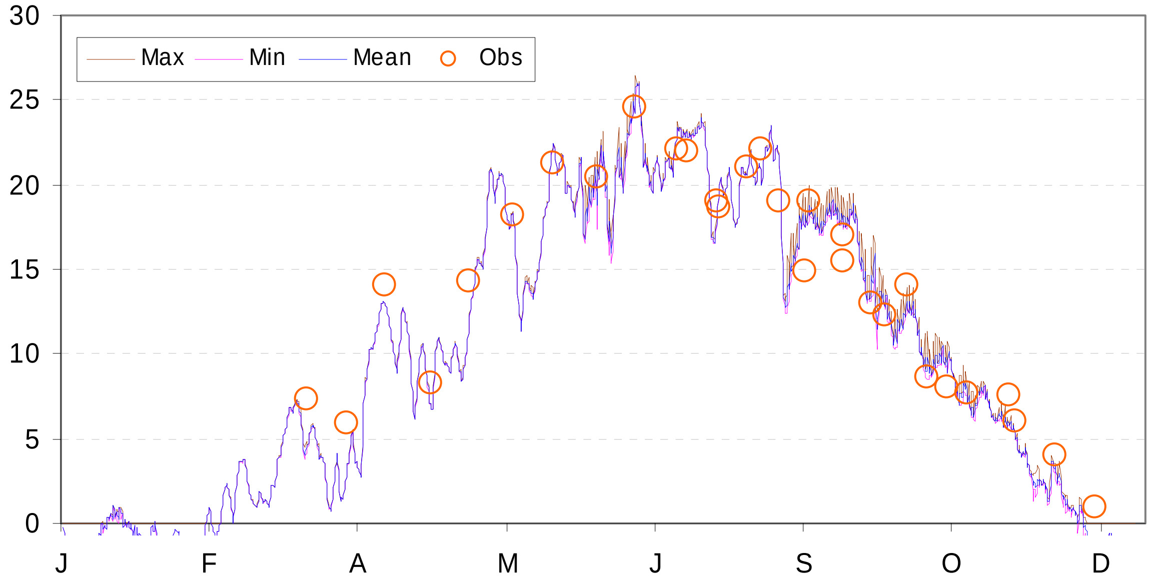


B_1999-5 Lost River at East West Road (LREW) - 1999

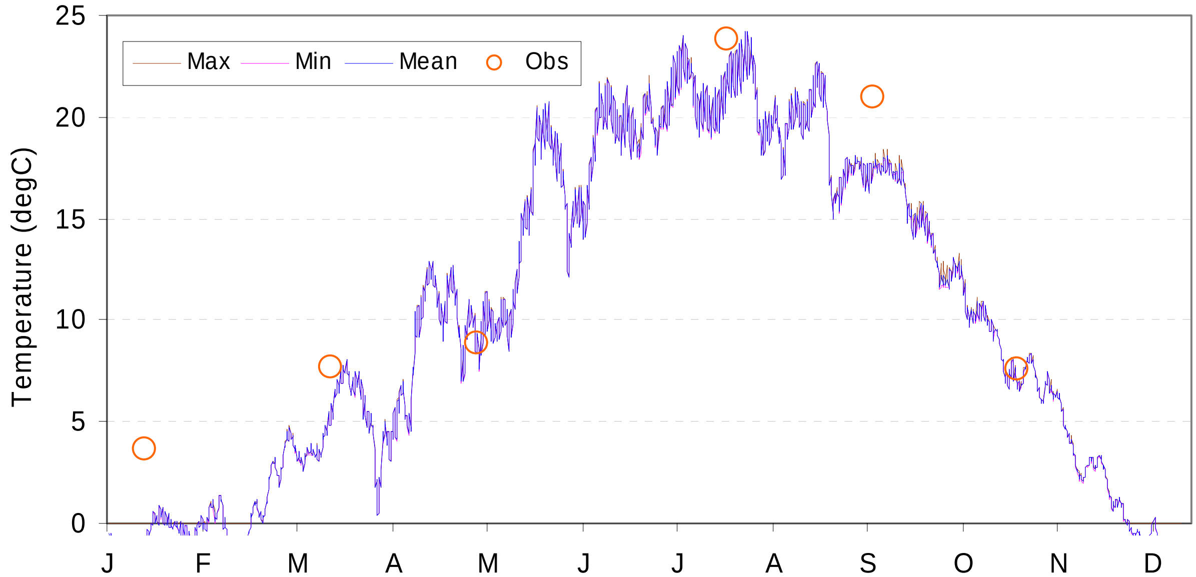


B_1999-6 Lost River at Tule Lake Tunnel Outlet (TLTO) – 1999



B_1999-7 Klamath Straits Drain at Stateline Road (KSDSR) – 1999

B_1999-8 Klamath Straits Drain at Township Road (pump E) (KSDTR) – 1999



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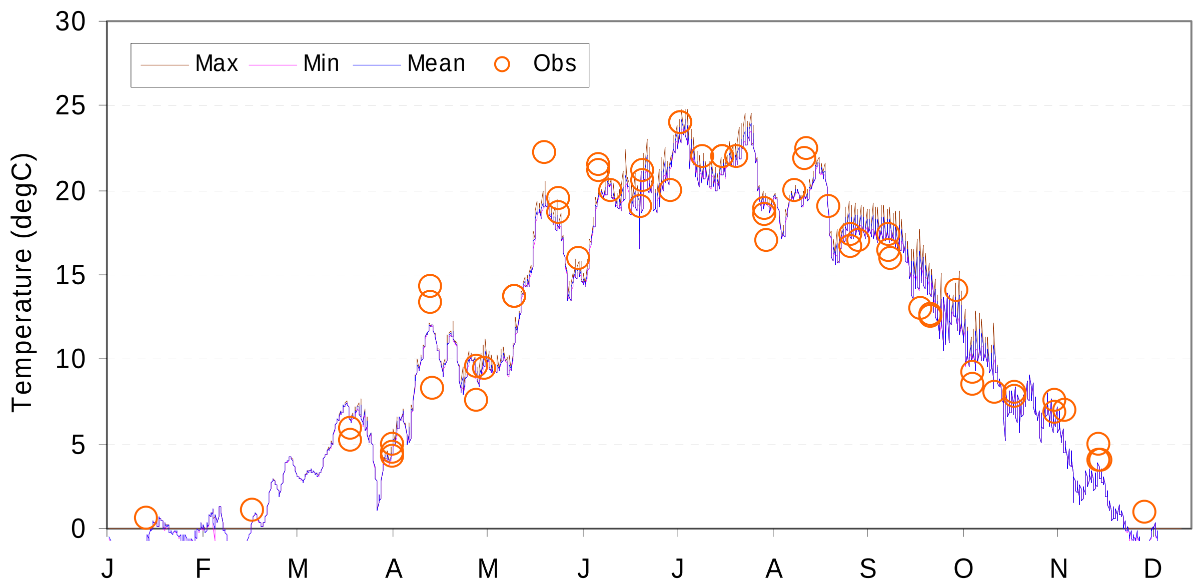
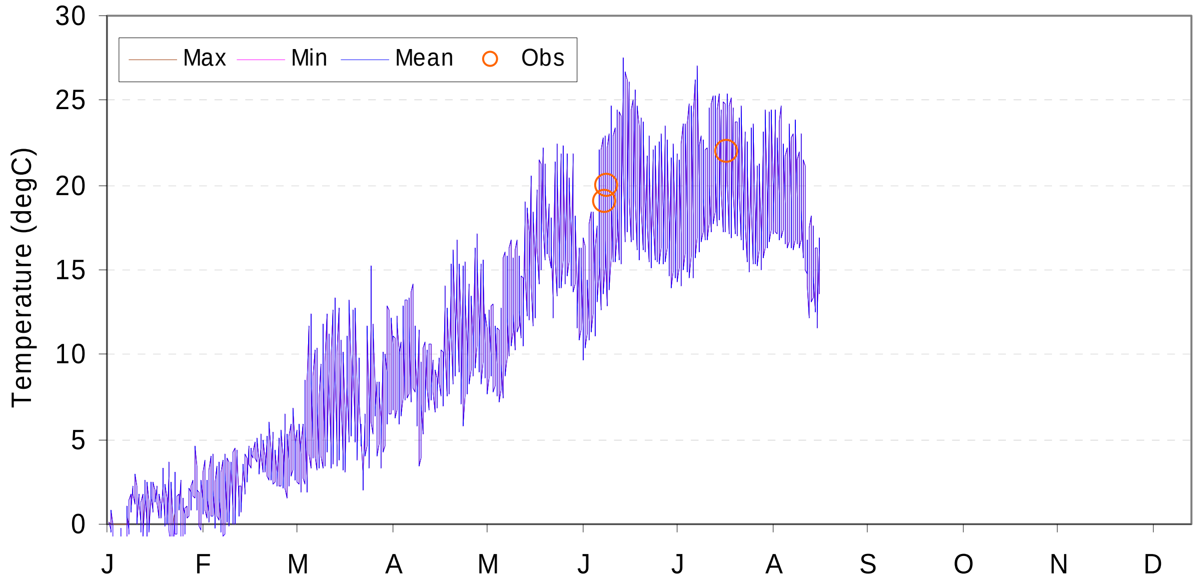


B_1999-10 Klamath Straits Drain at Highway 97 (KSD97) –1999

Appendix B_2004

Hydrodynamic Model Evaluation with Temperature Data



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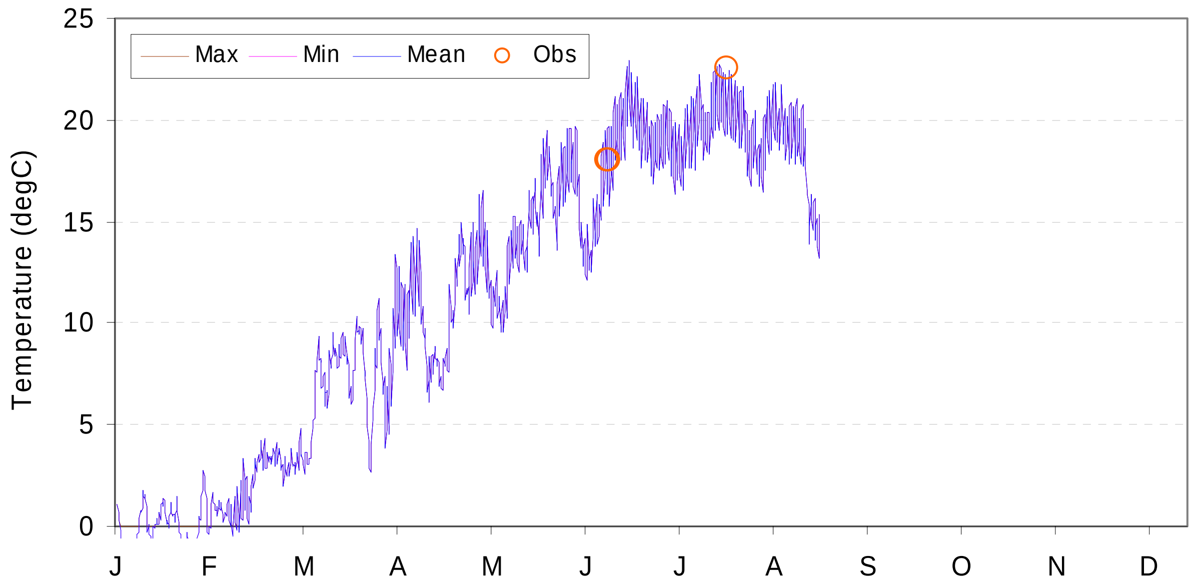

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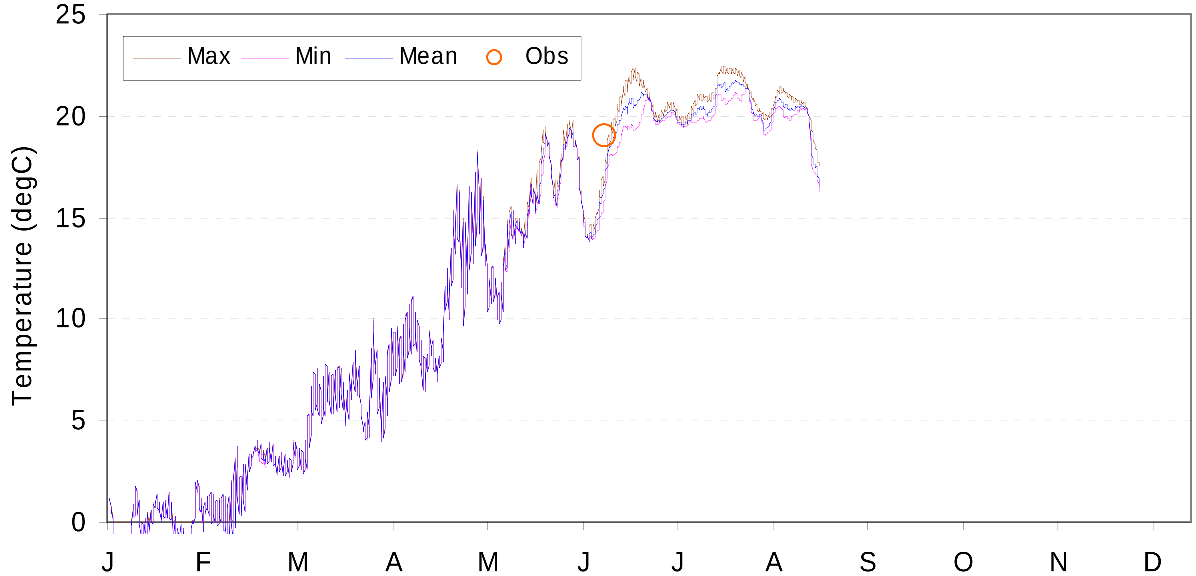
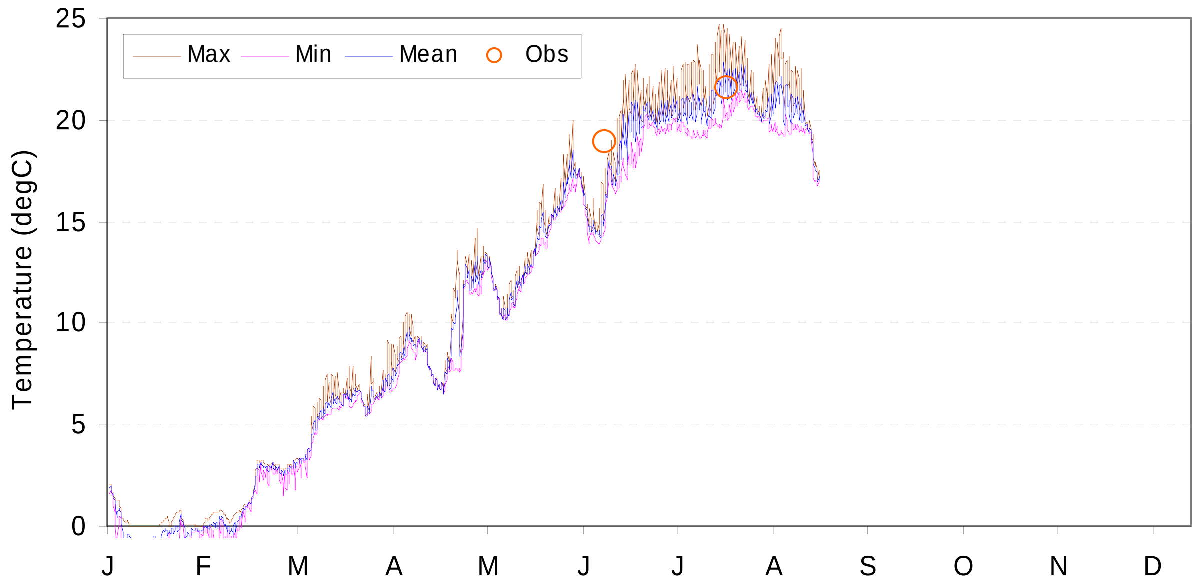


B_2004-3 Poe Valley Bridge at RM 27 (HPDS2) -2004



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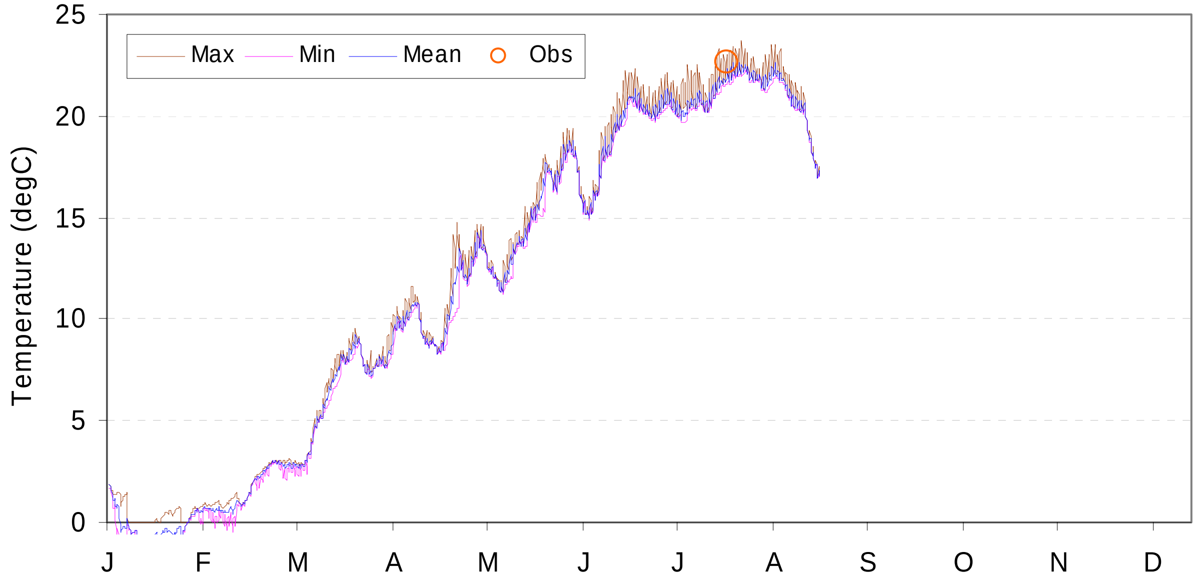
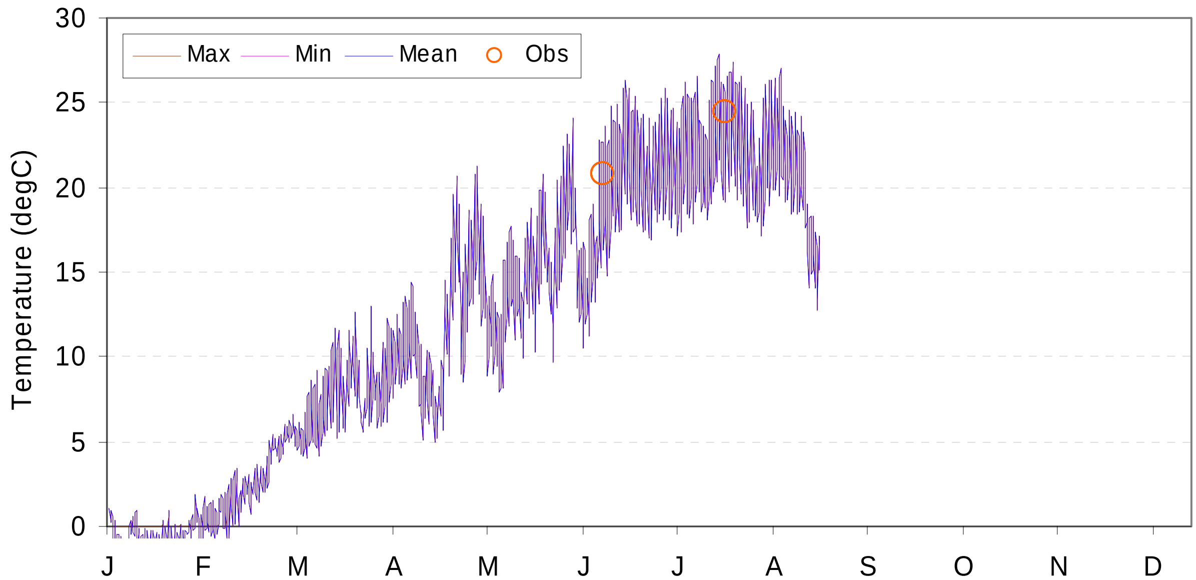


B_2004-5 Upstream of Anderson Rose Dam (ARDMUS) - 2004



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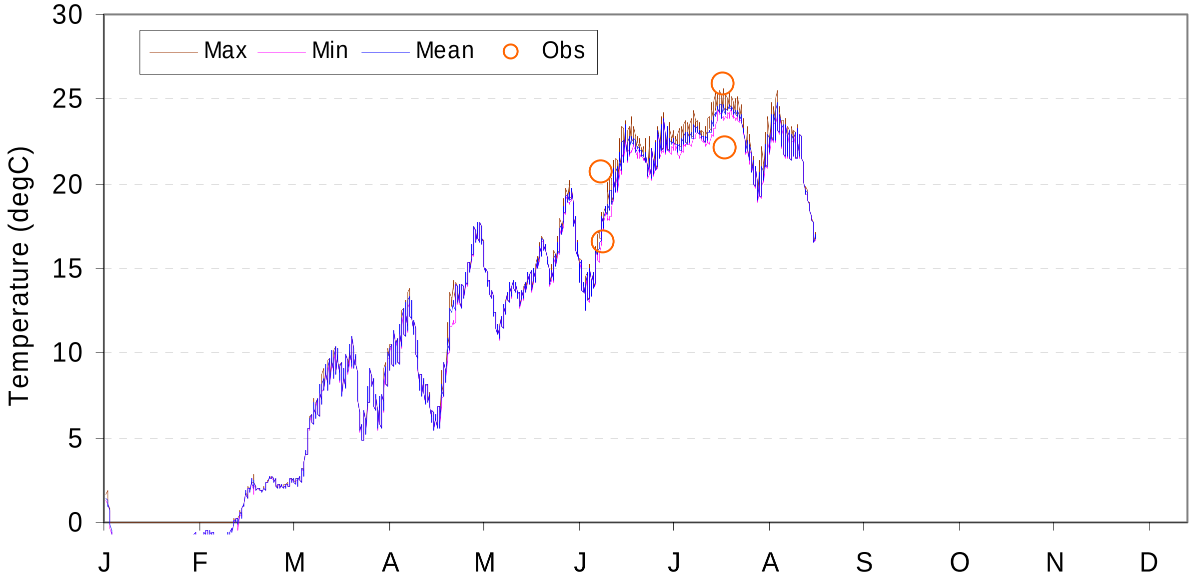

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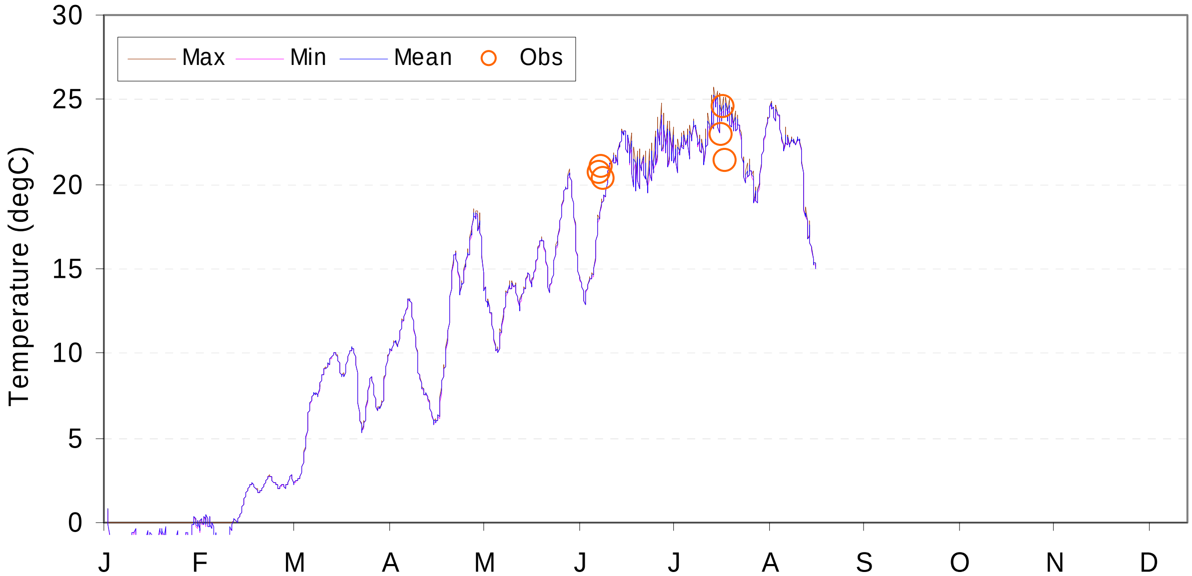
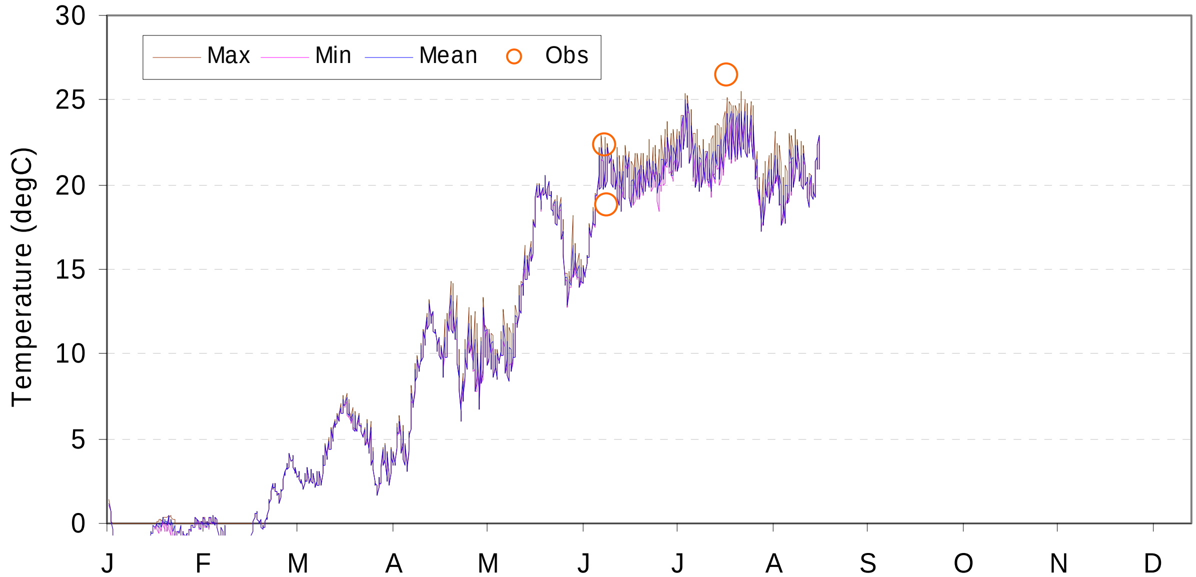


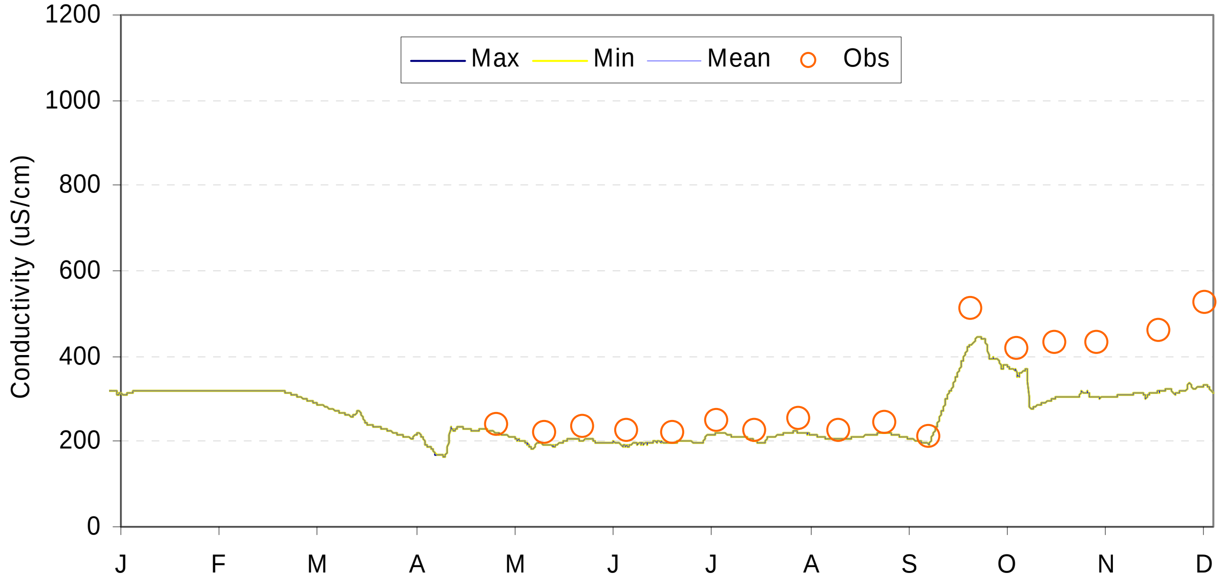
B_2004-8 Klamath Straits Drain at Stateline Road (KSDSR) – 2004



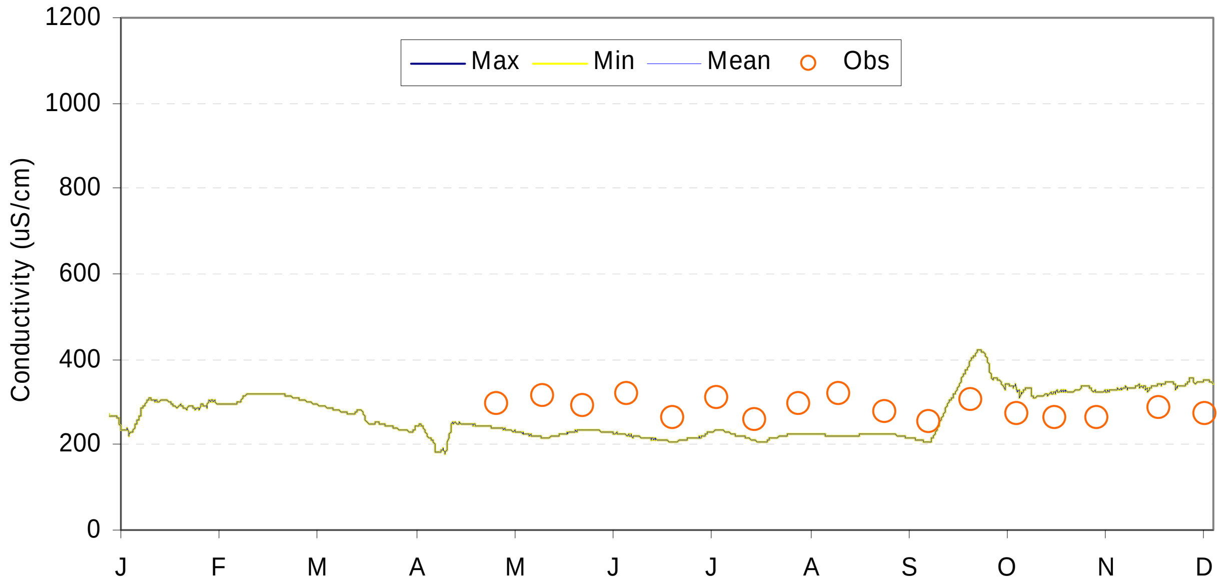
B_2004-9 Klamath Straits Drain at Railroad (KSDM) – 2004

Appendix C_1999

Further Hydrodynamic Model Evaluation with Conductivity Data



C_1999-1 Lost River at Keller Bridge (LRKB) –1999



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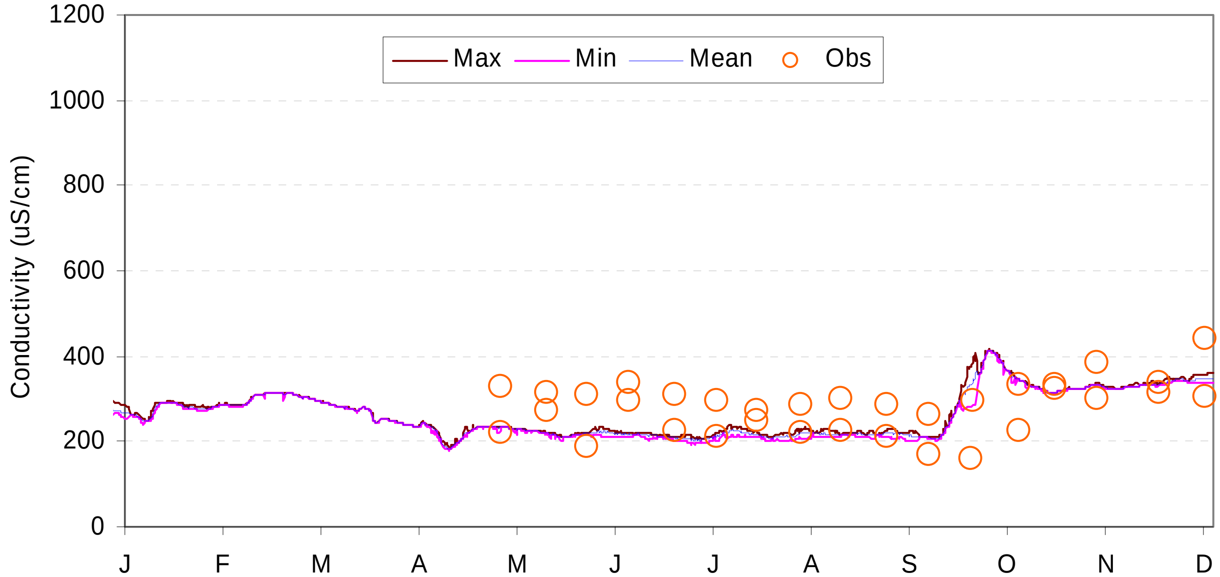

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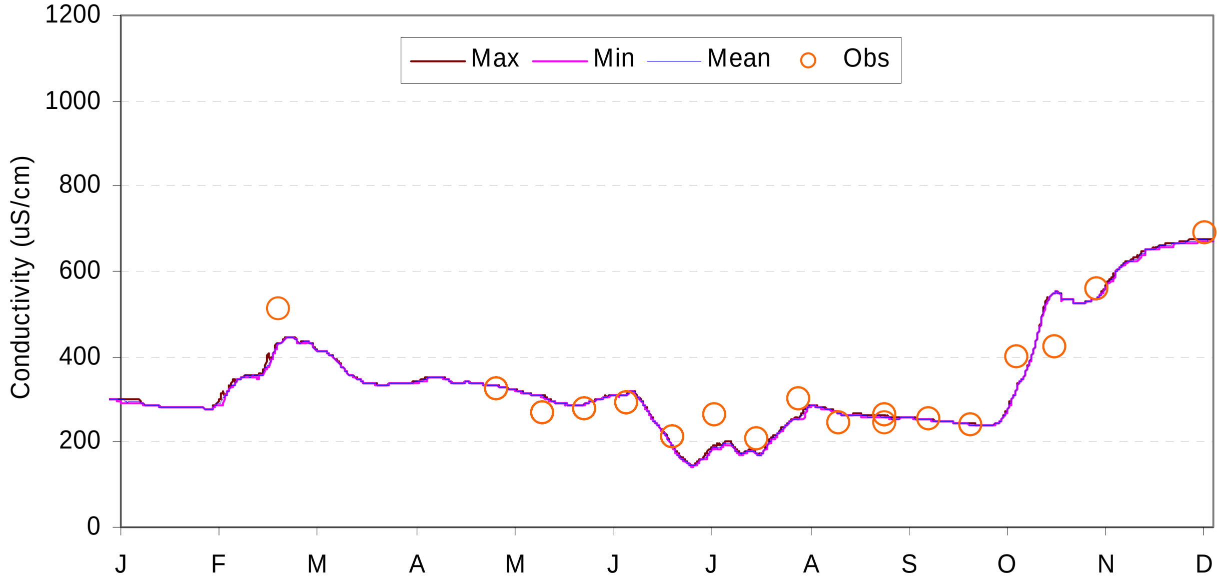
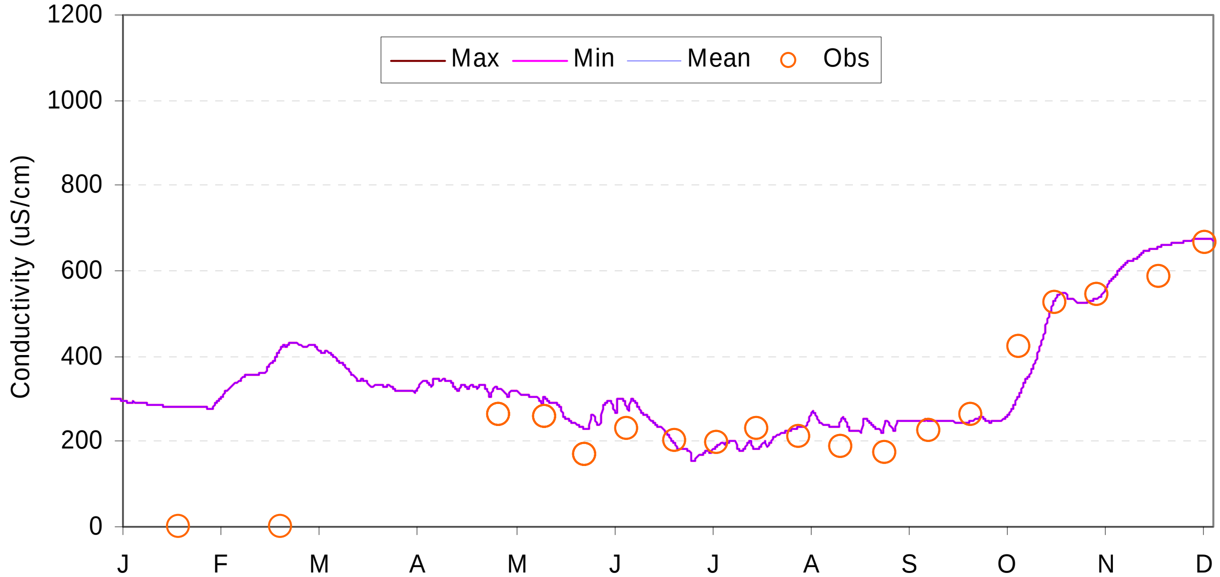


C_1999-4 Lost River at Anderson Rose Dam (LRAR) – 1999



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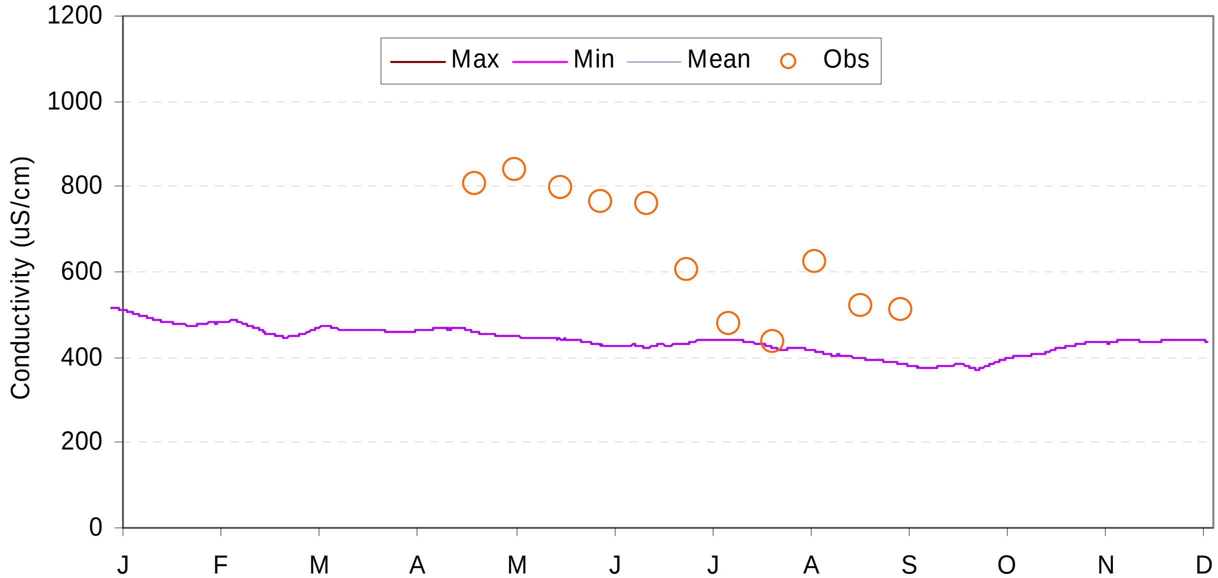

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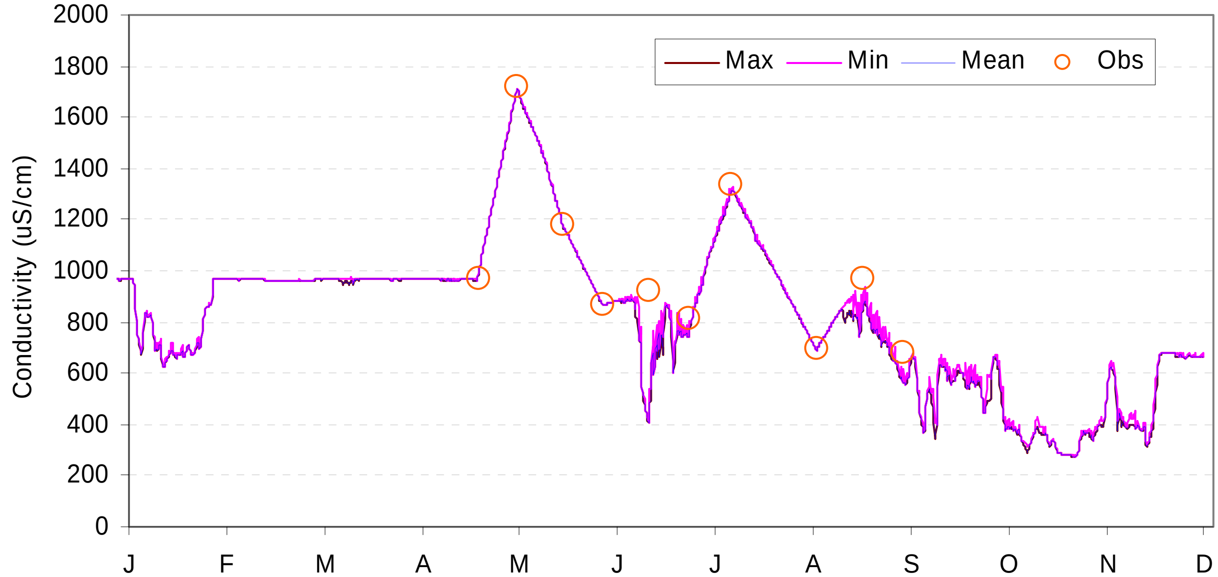
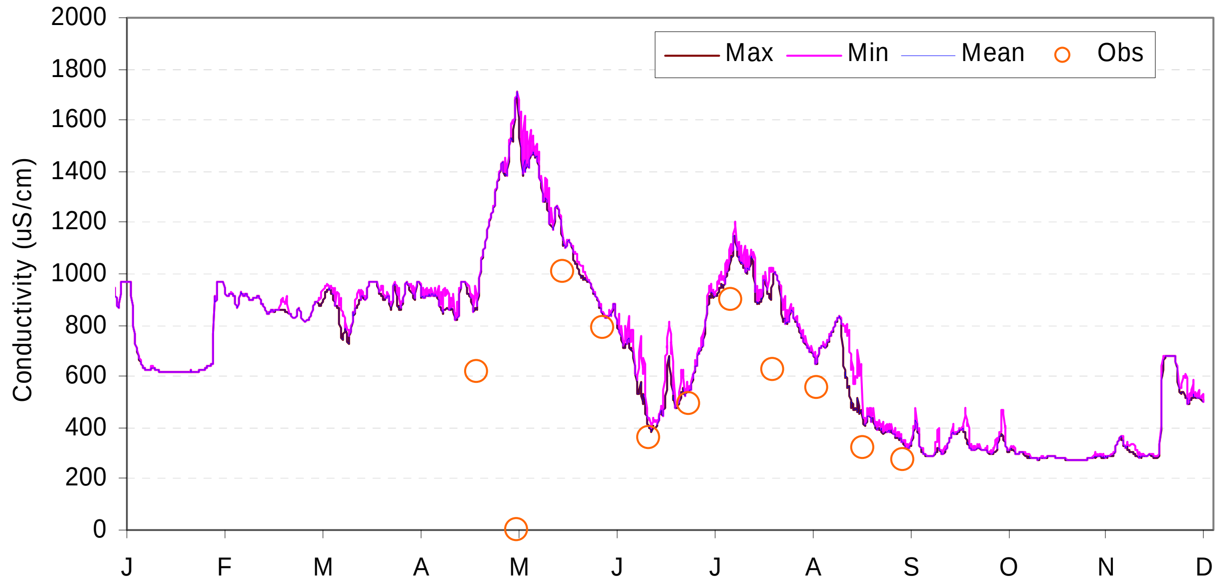
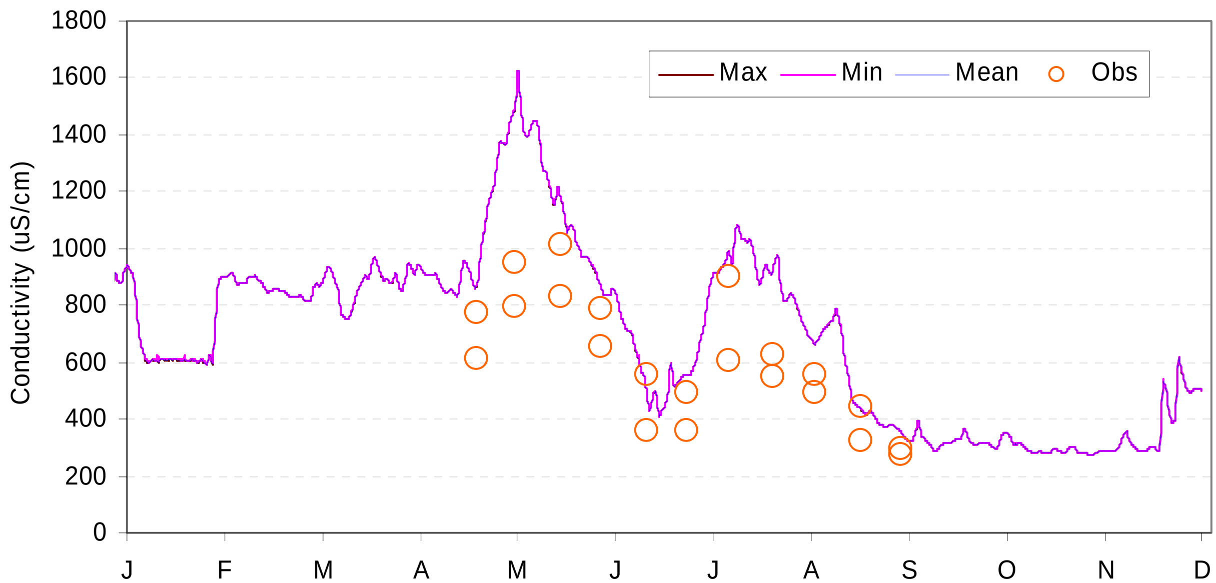


C_1999-7 Klamath Straits Drain at Stateline Road (KSDSR) – 1999



C_1999-8 Klamath Straits Drain at Township Road (pump E) (KSDTR) - 1999

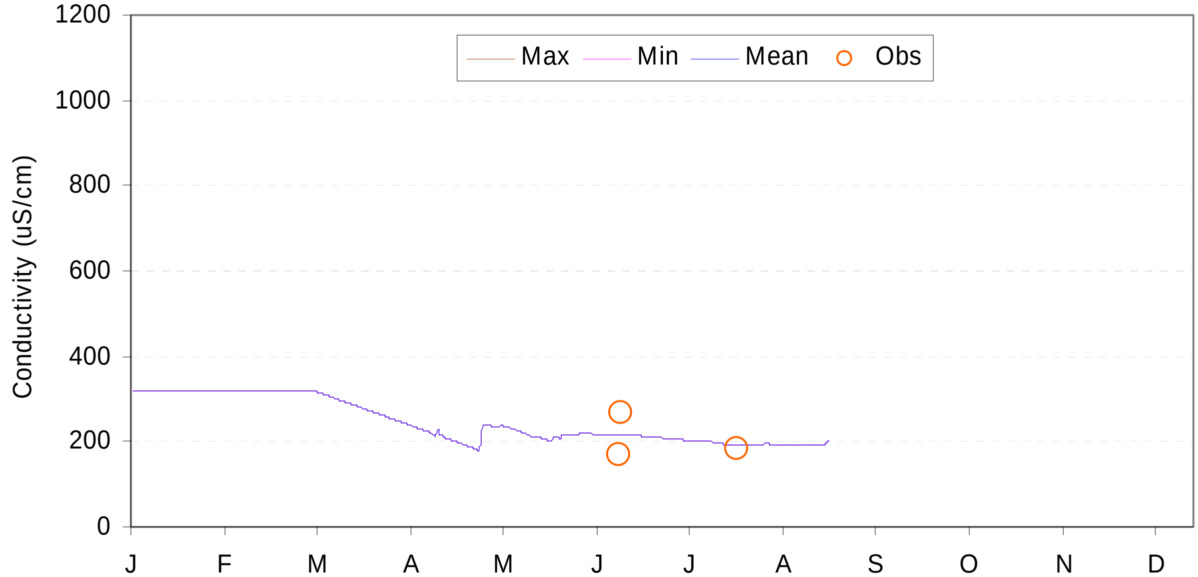
C_1999-9 Klamath Straits Drain at Pump Station F (KSDPSF) - 1999



C_1999-10 Klamath Straits Drain at Highway 97 (KSD97) - 1999

Appendix C_2004

Further Hydrodynamic Model Evaluation with Conductivity Data



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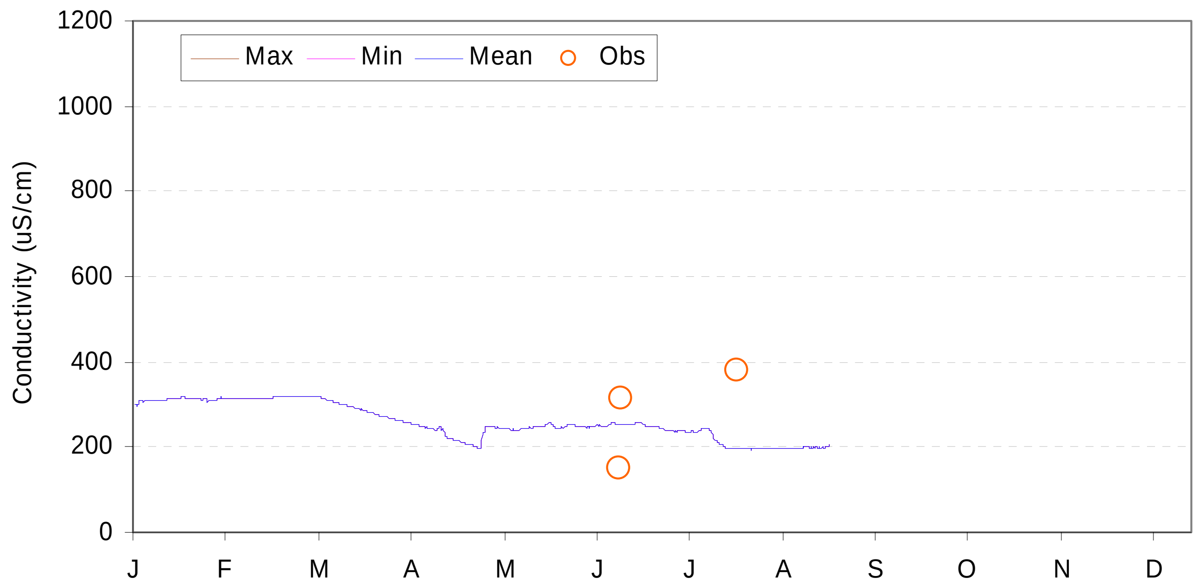

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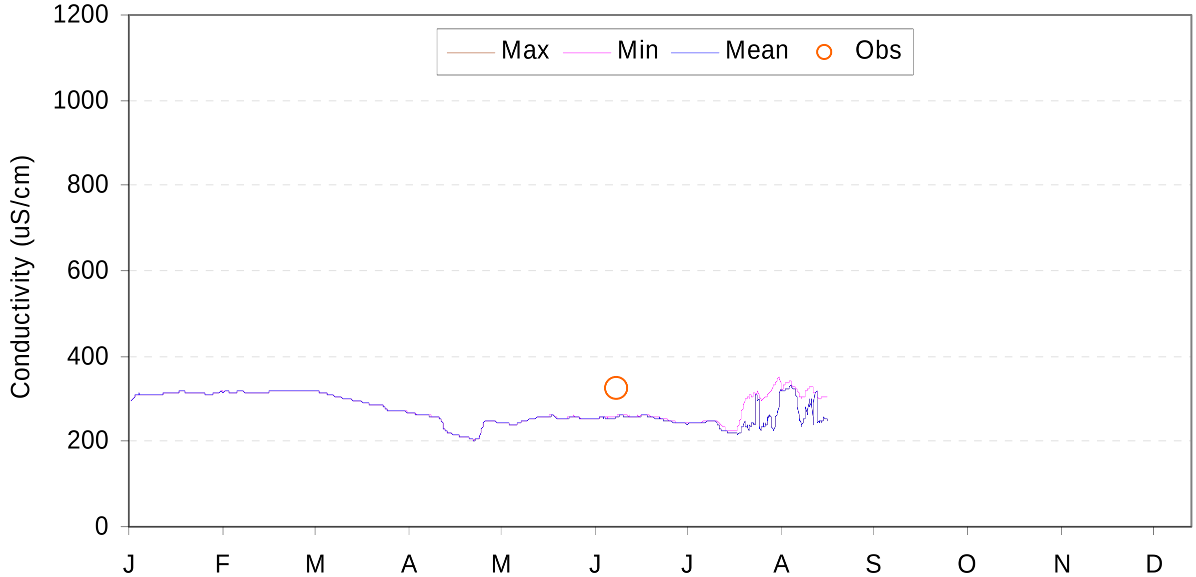
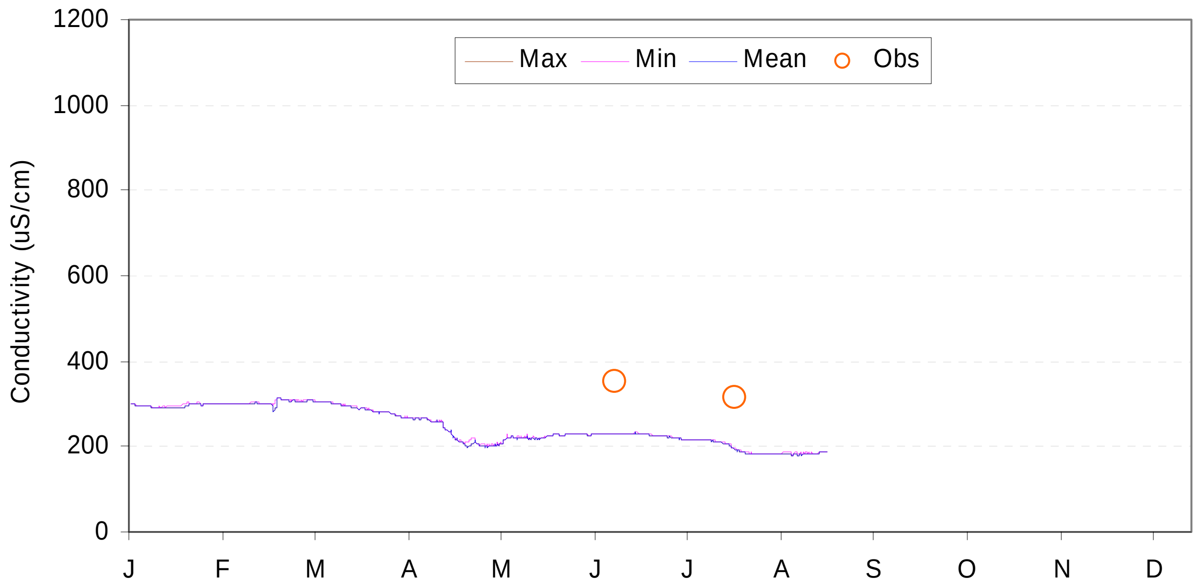


C_2004-3 Poe Valley Bridge at RM 27(HPDS2) 2004



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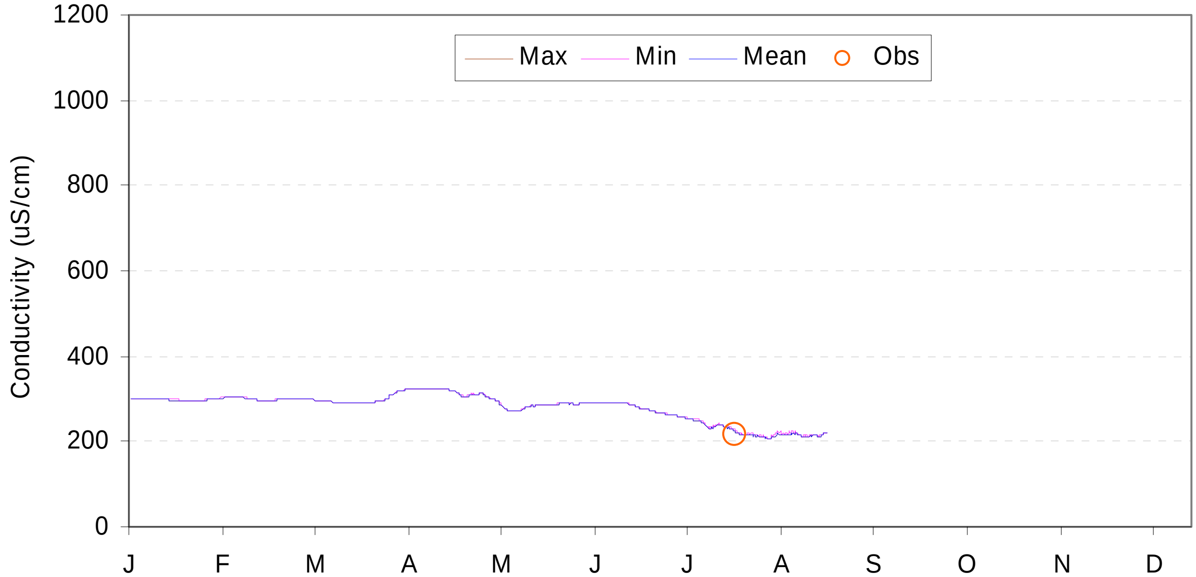

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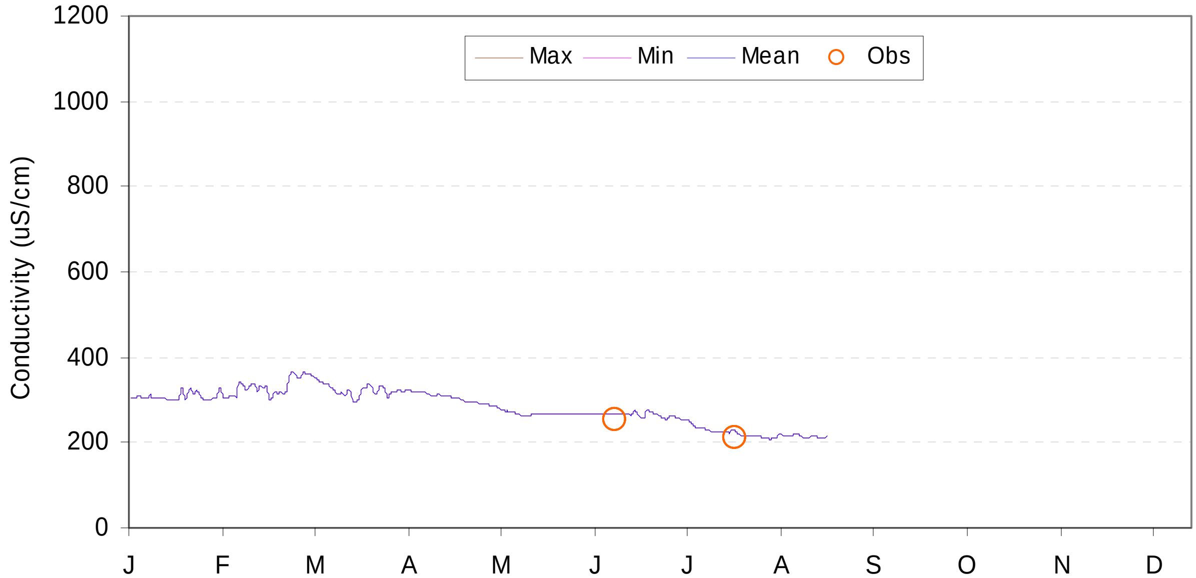
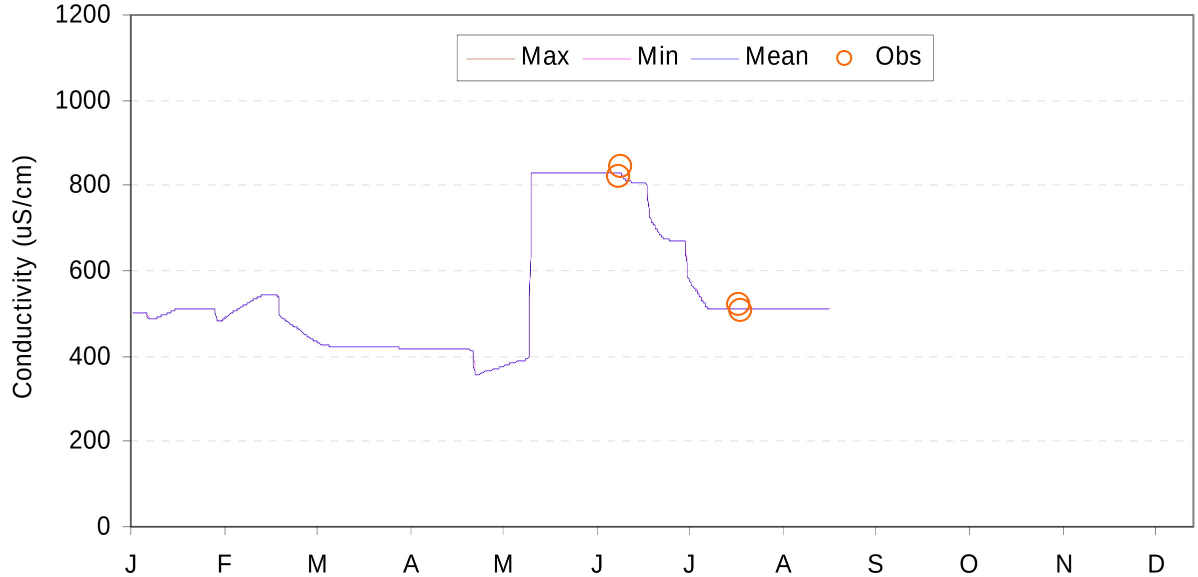
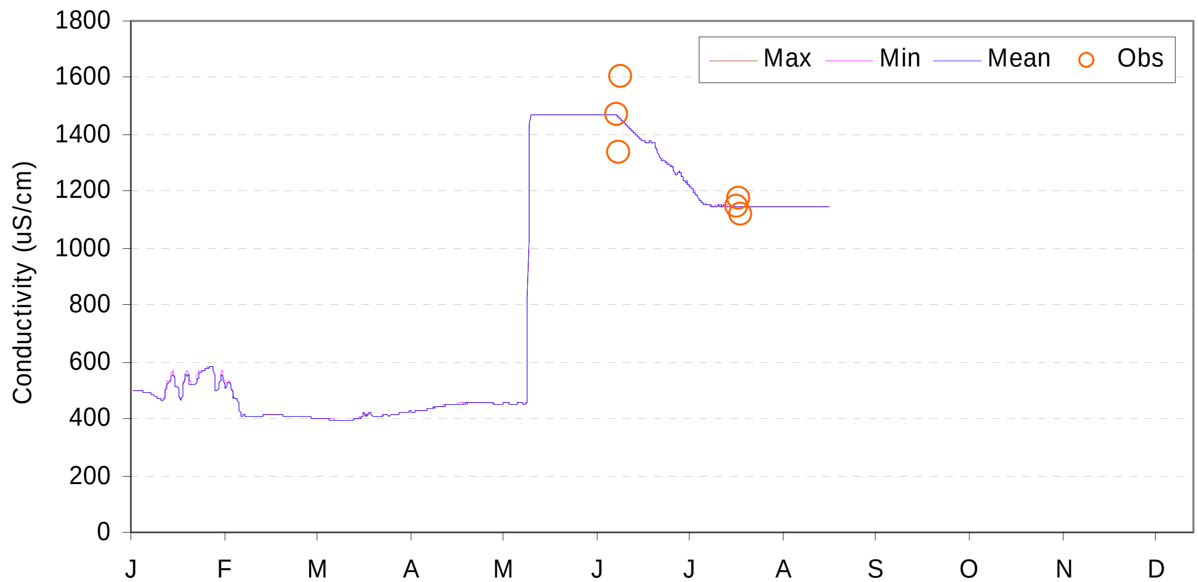


C_2004-6 Lost River at East West Road (LREW) – 2004



C_2004-7 P-Canal (PC) – 2004

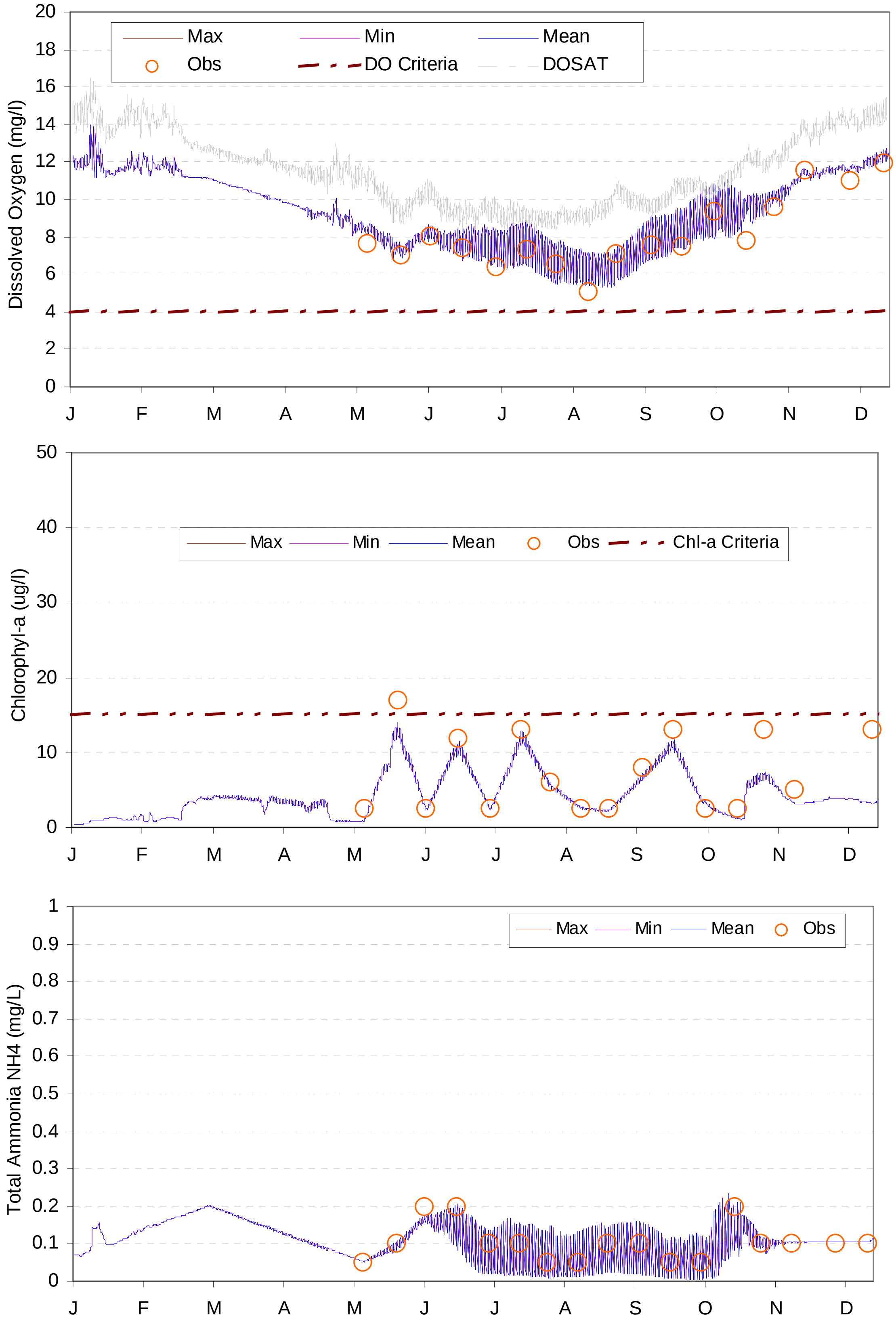


C_2004-8 Klamath Straits Drain at Stateline Road (KSDSR) – 2004

C_2004-9 Klamath Straits Drain at Railroad (KSDM) – 2004

Appendix D_1999

Water Quality Calibration Results



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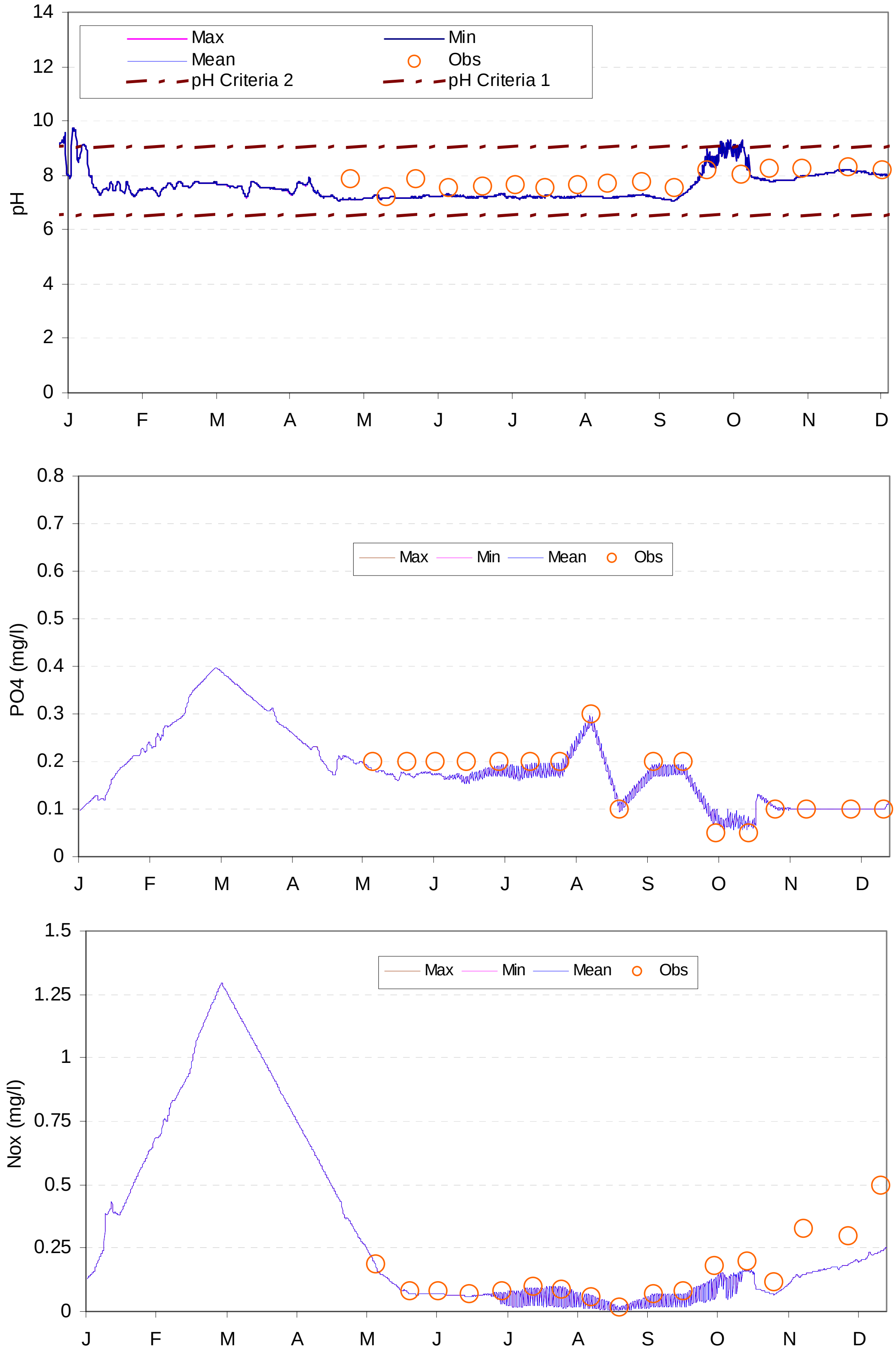

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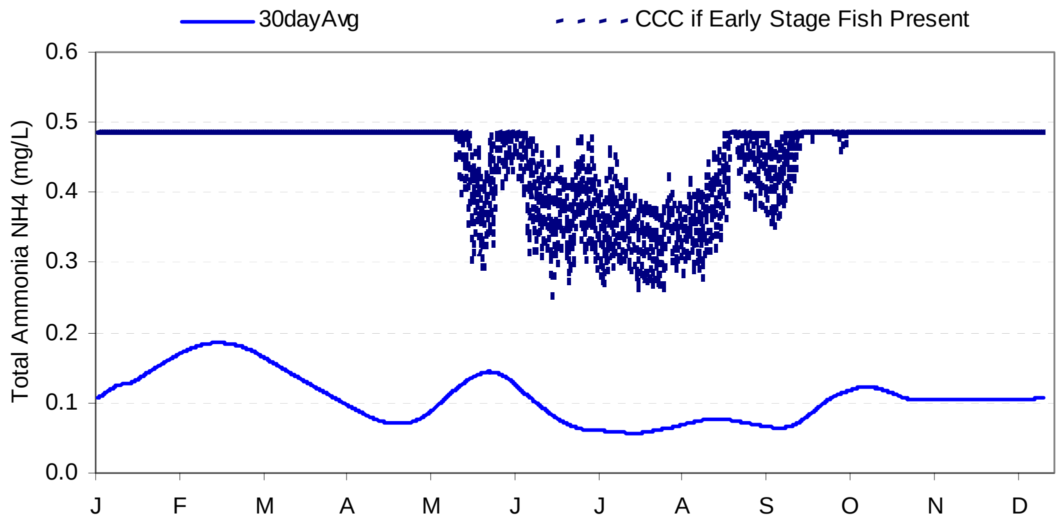

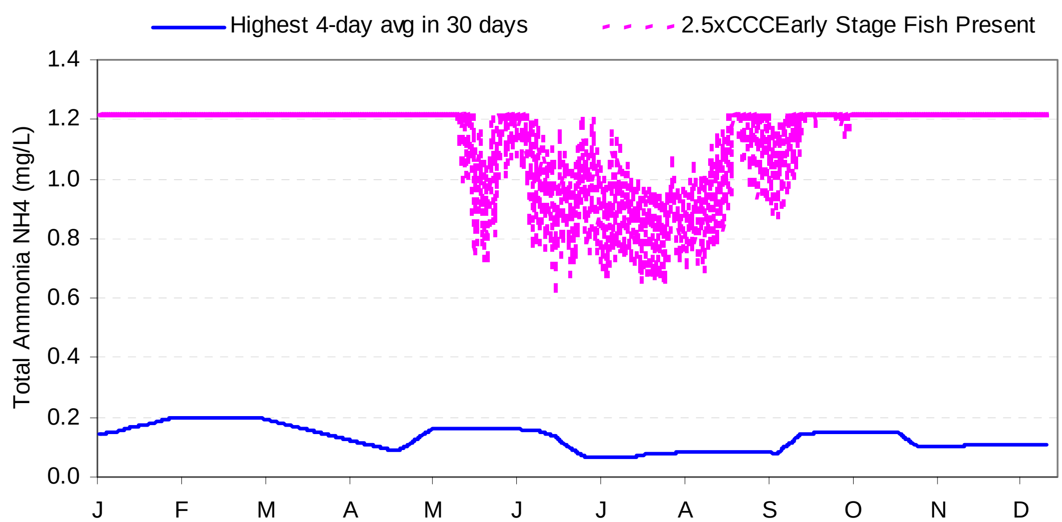

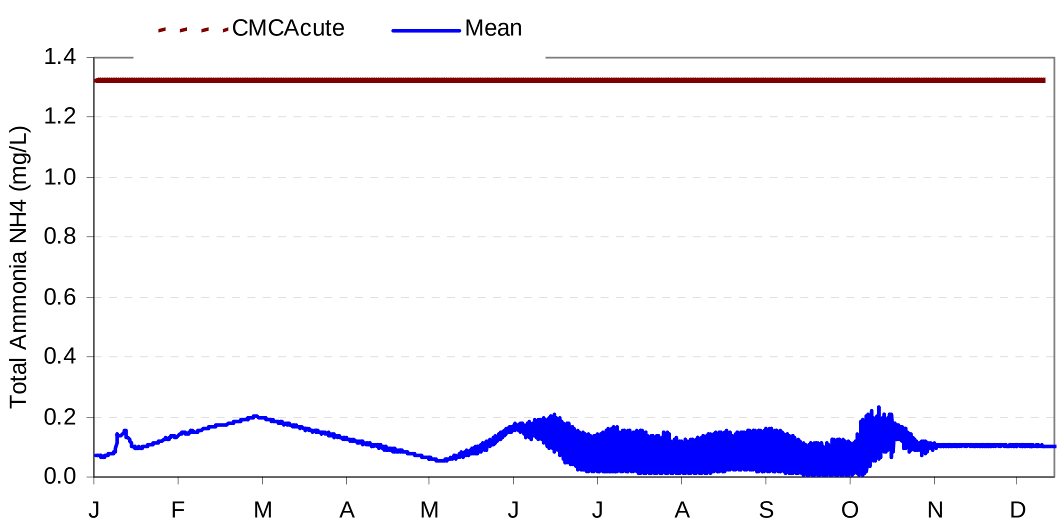

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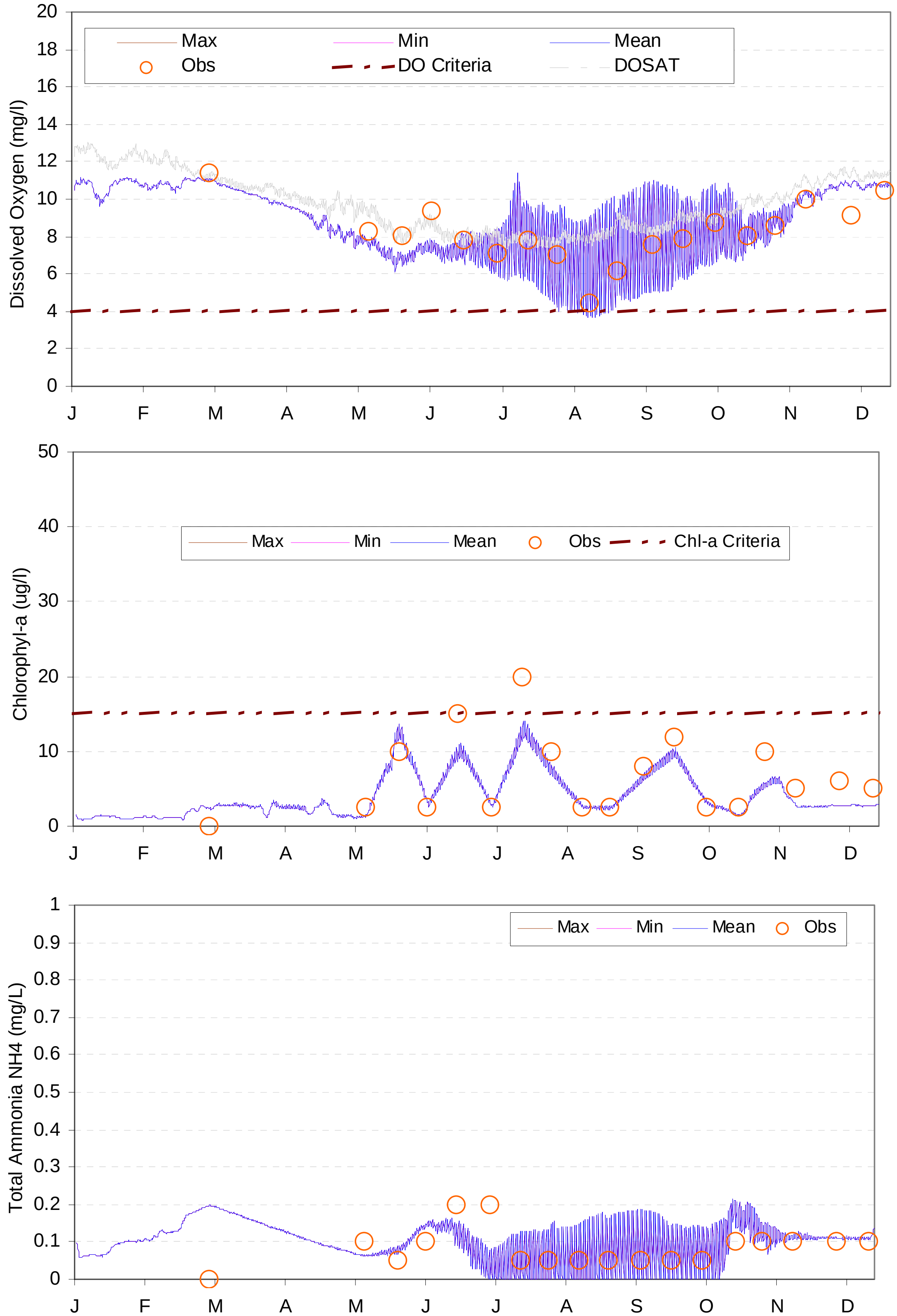
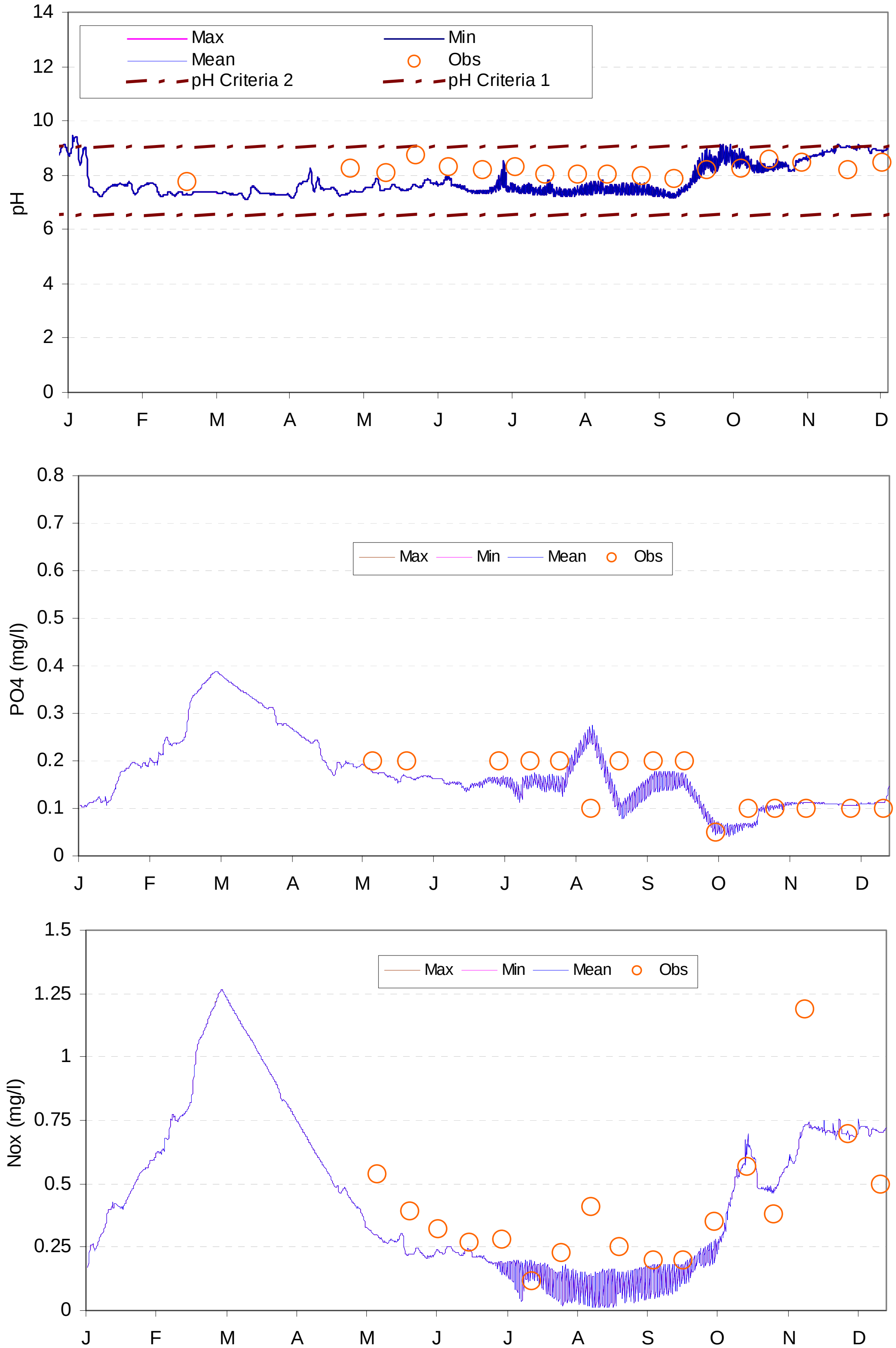


D_1999-2 Lost River at Harpold Dam (LRHD) -1999



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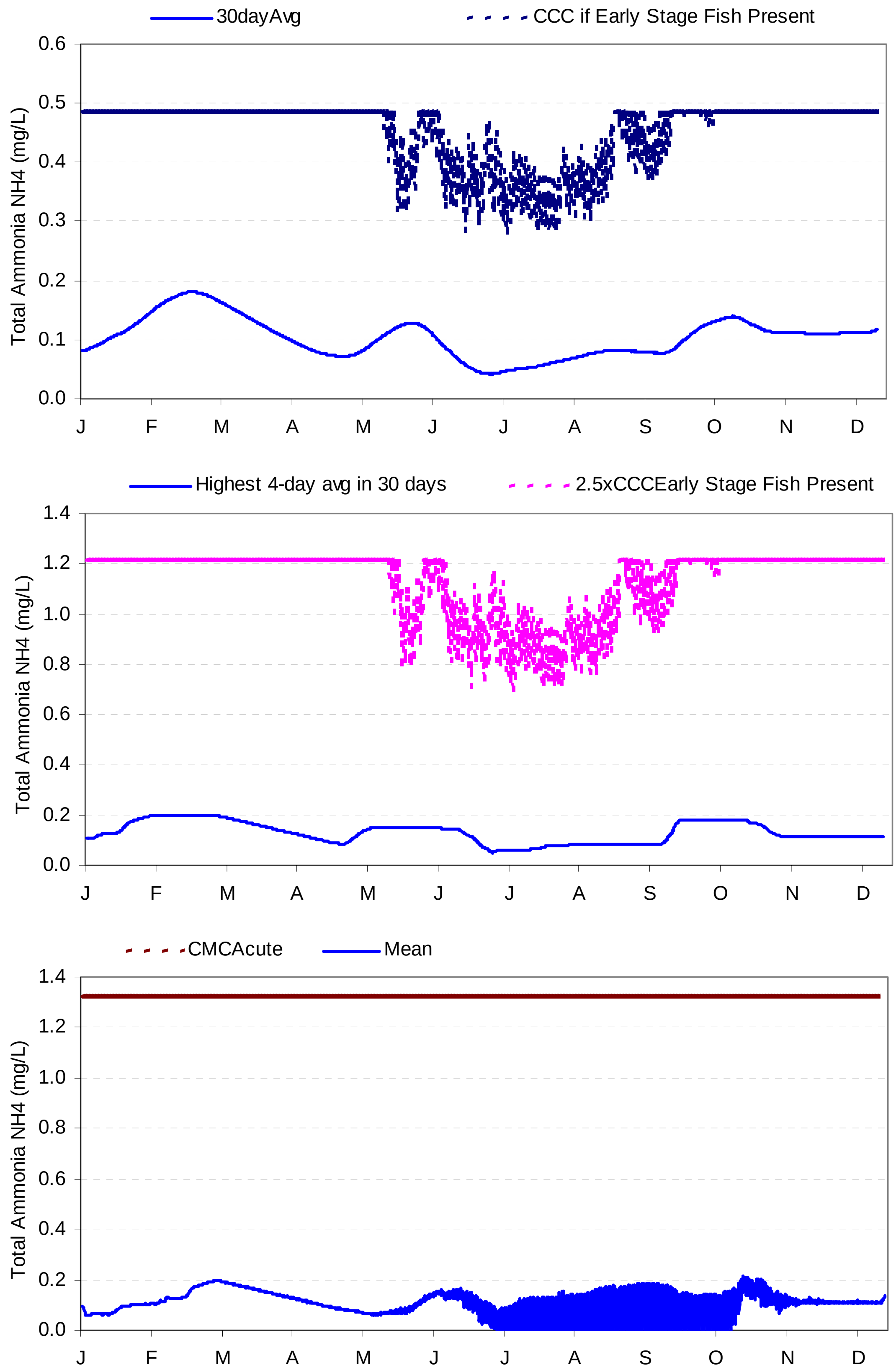

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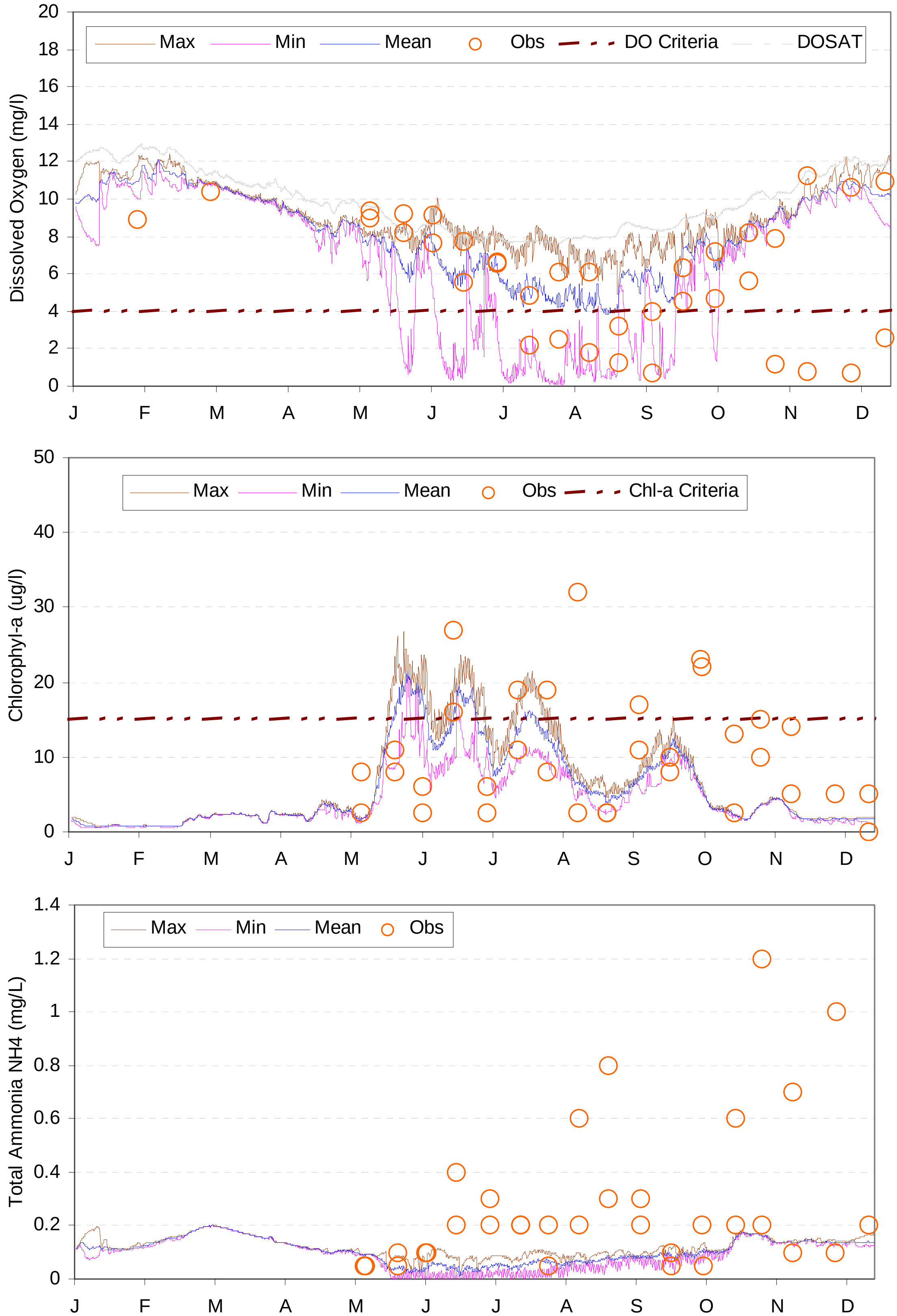
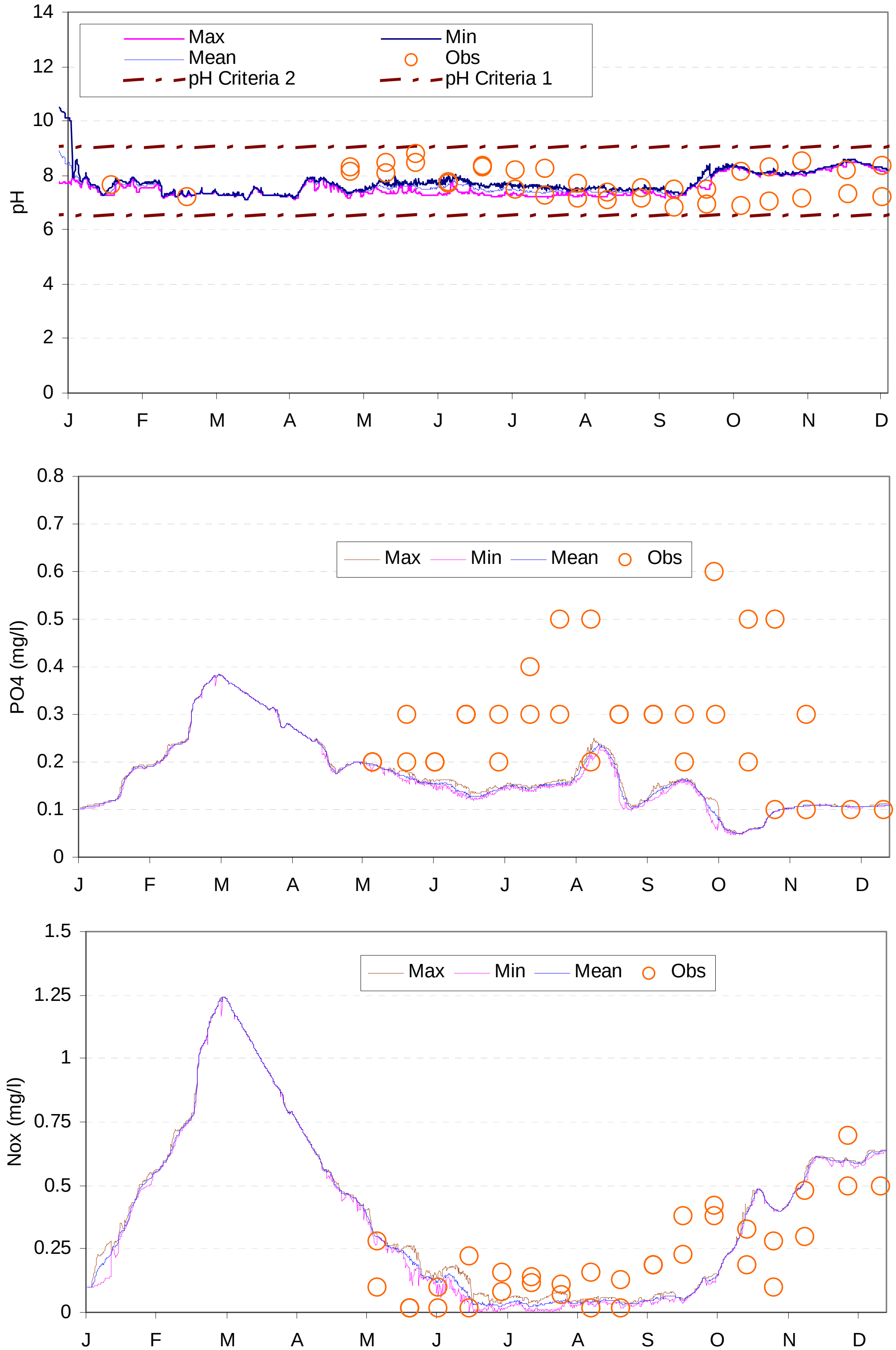


D_1999-3 Lost River at Crystal Springs (LRWRC) -1999



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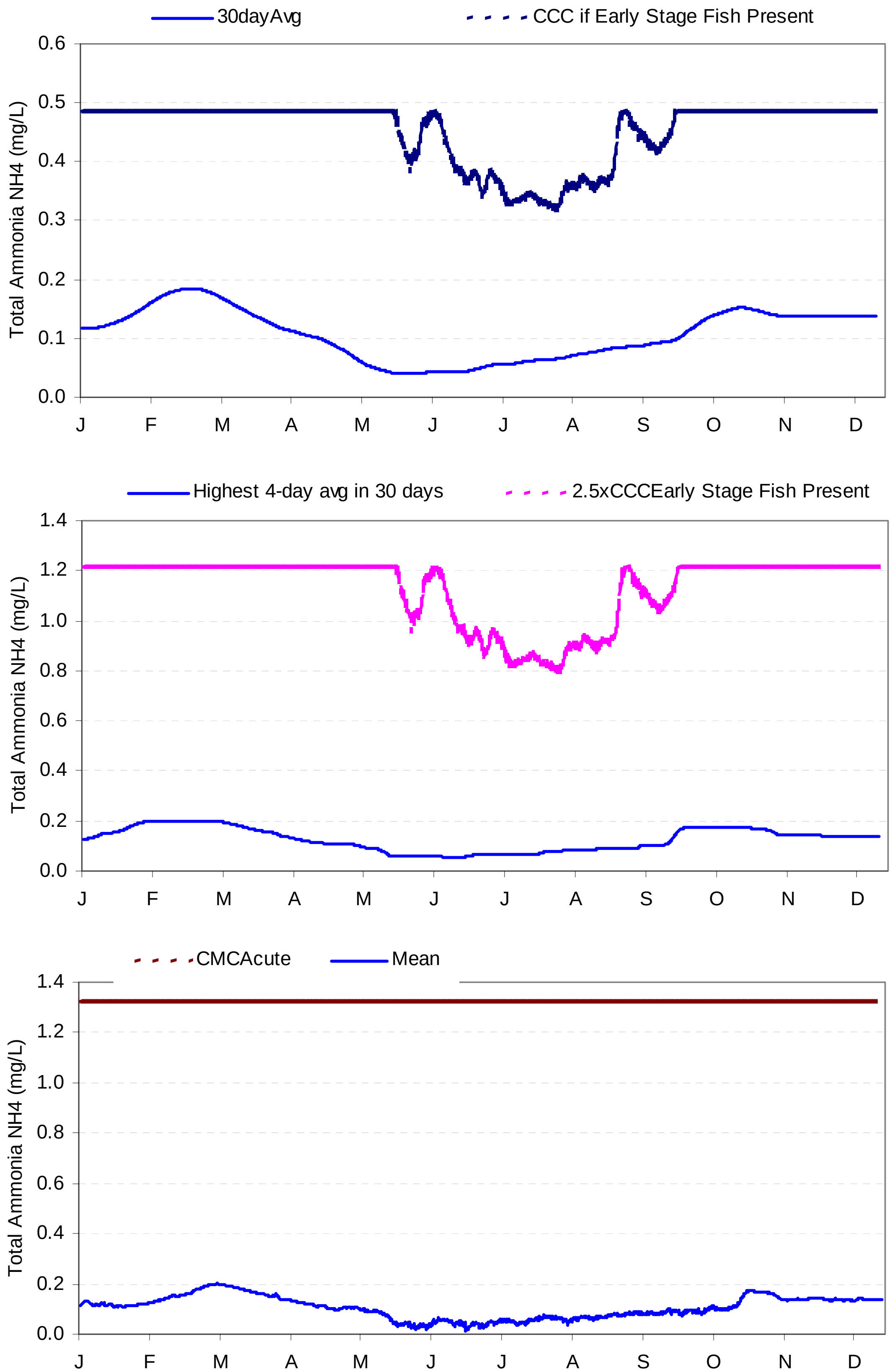

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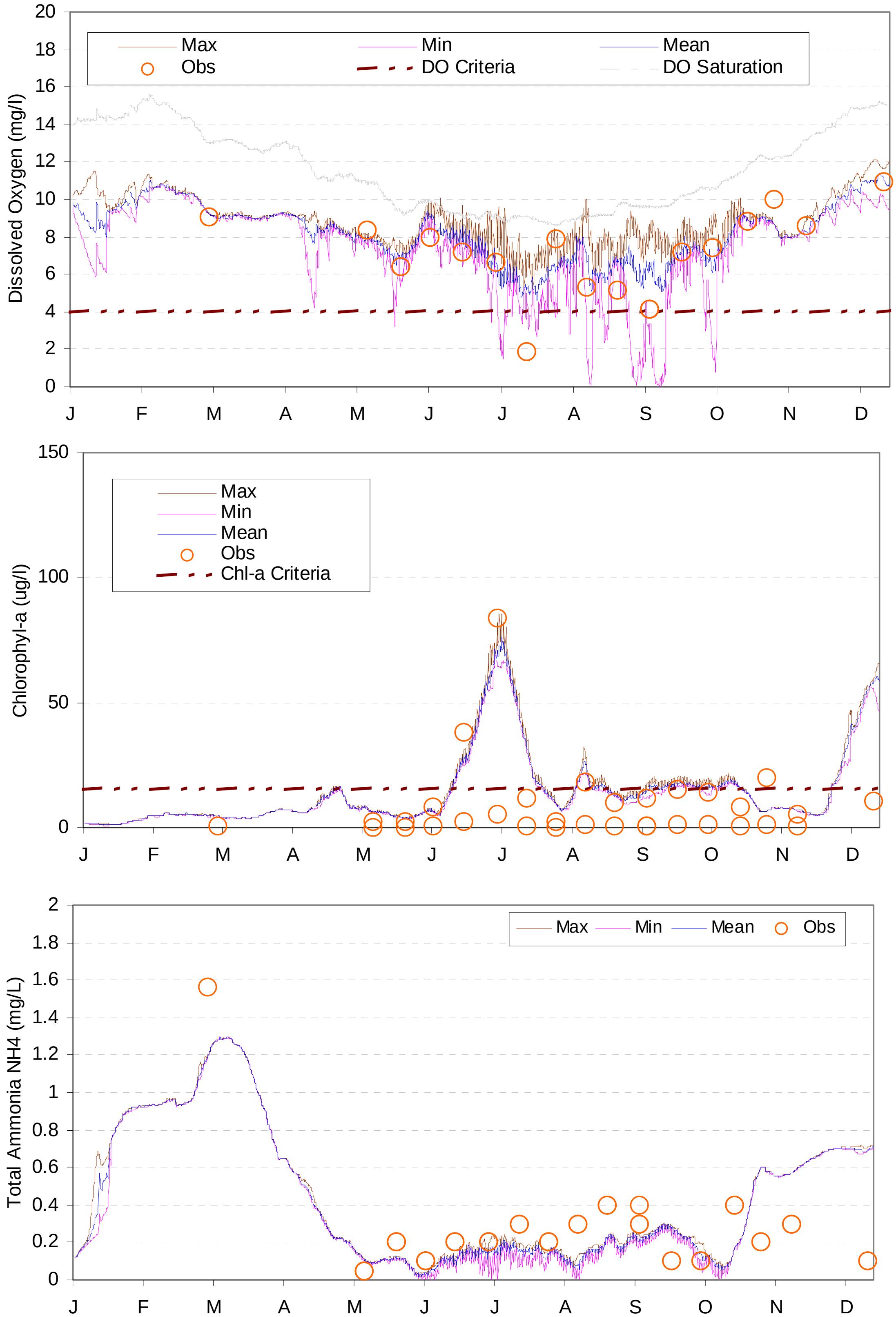

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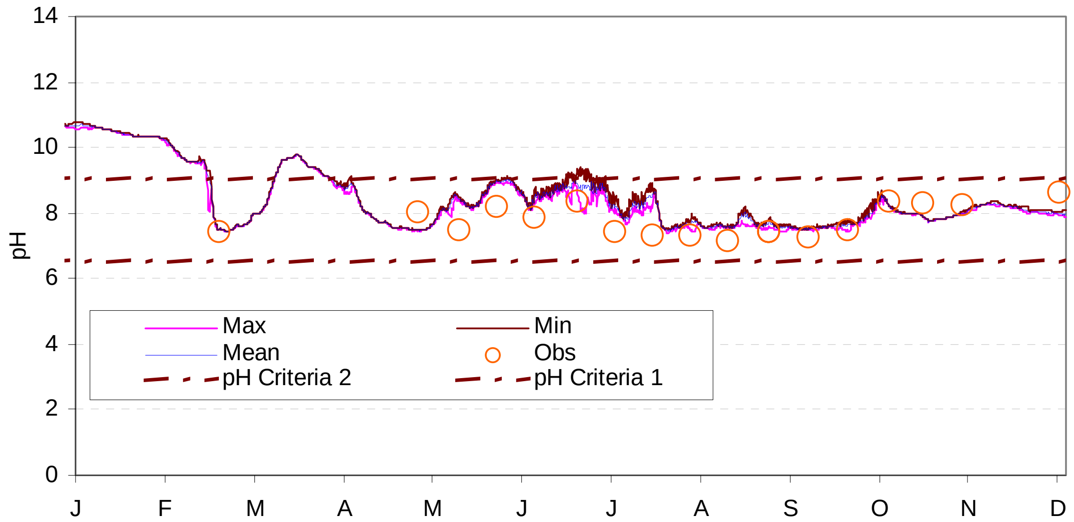

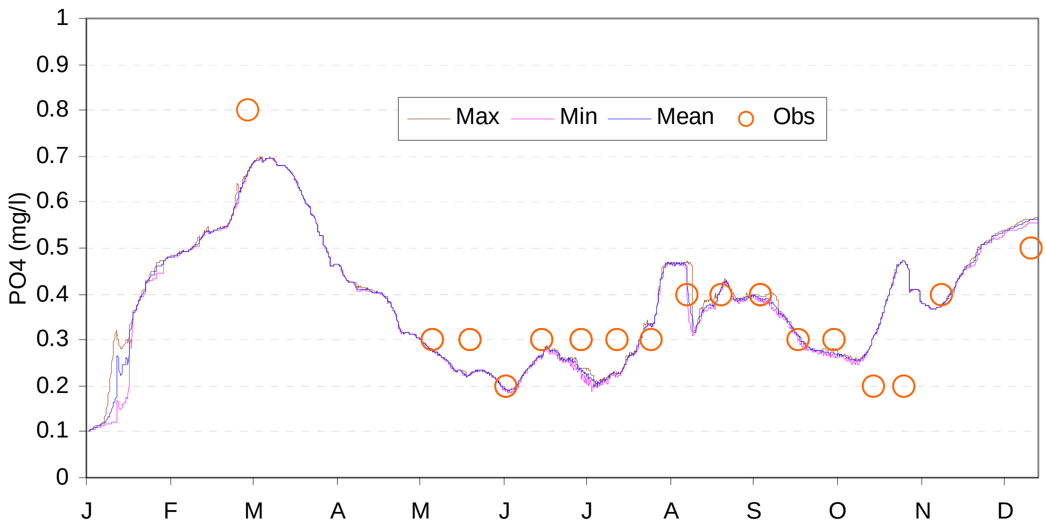

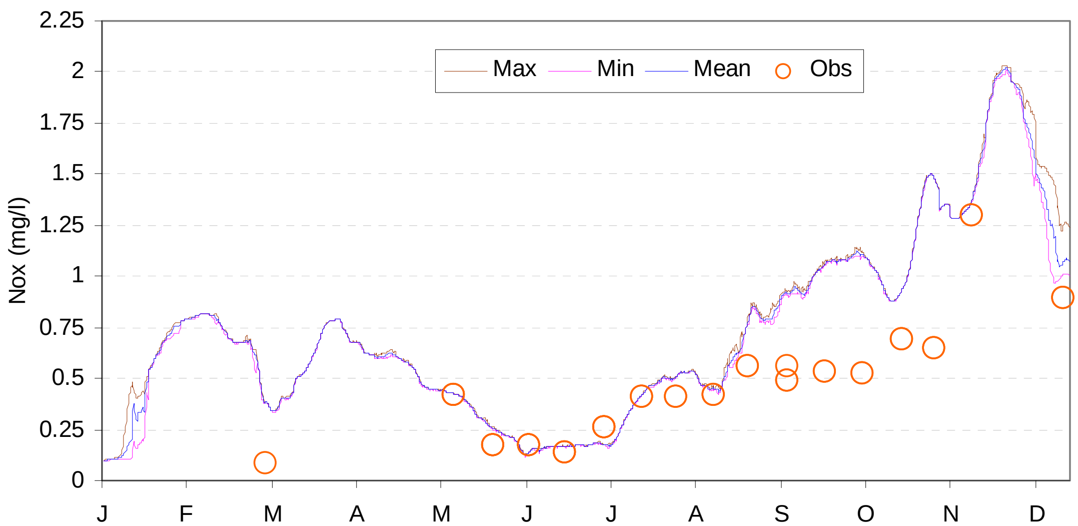

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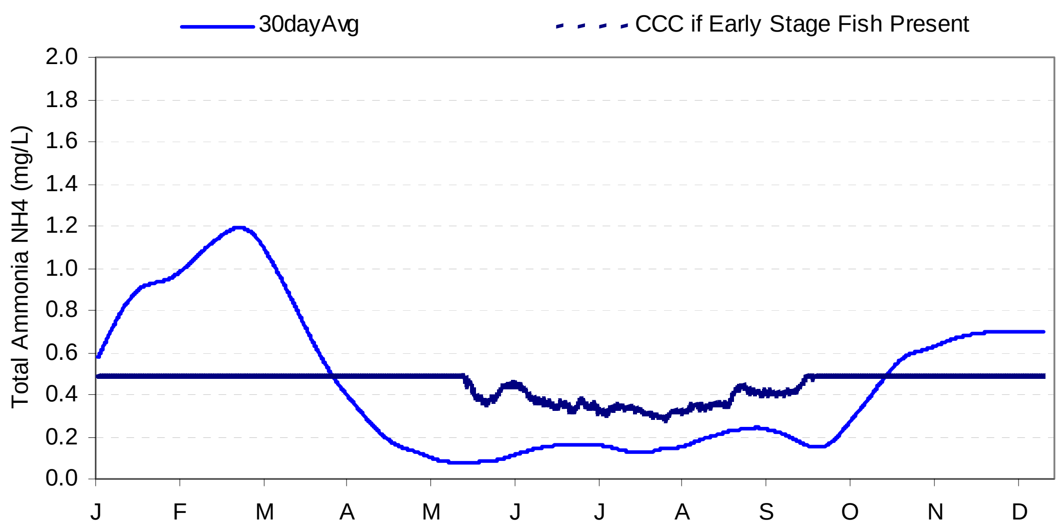

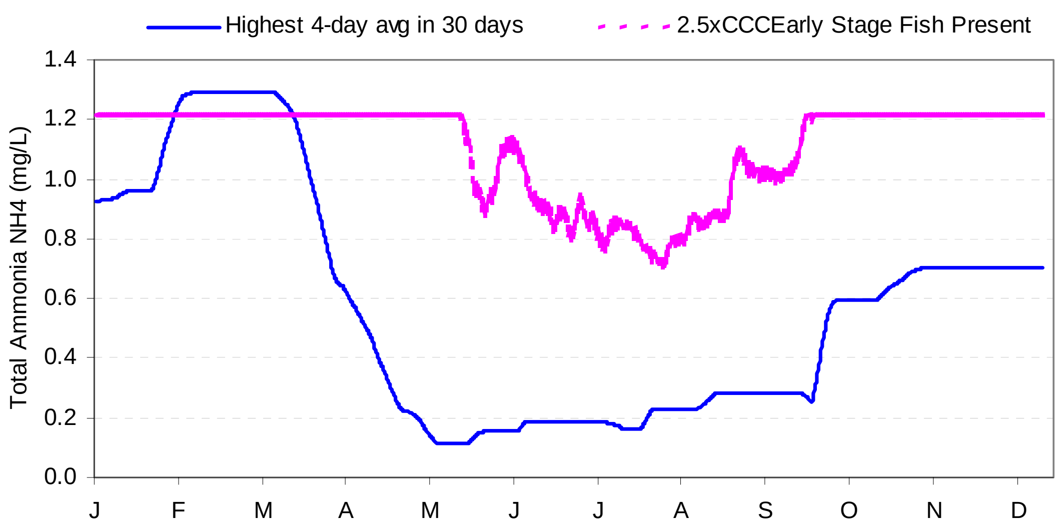

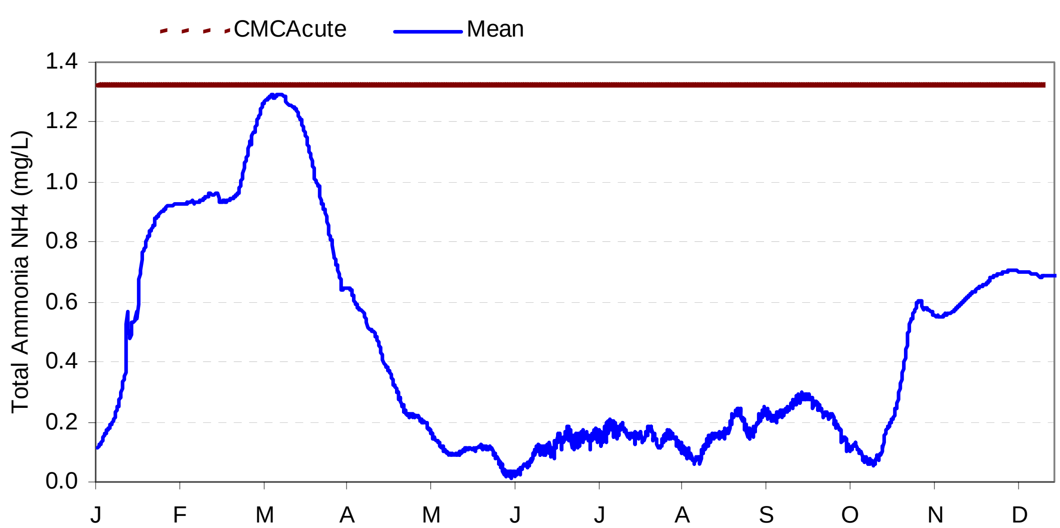

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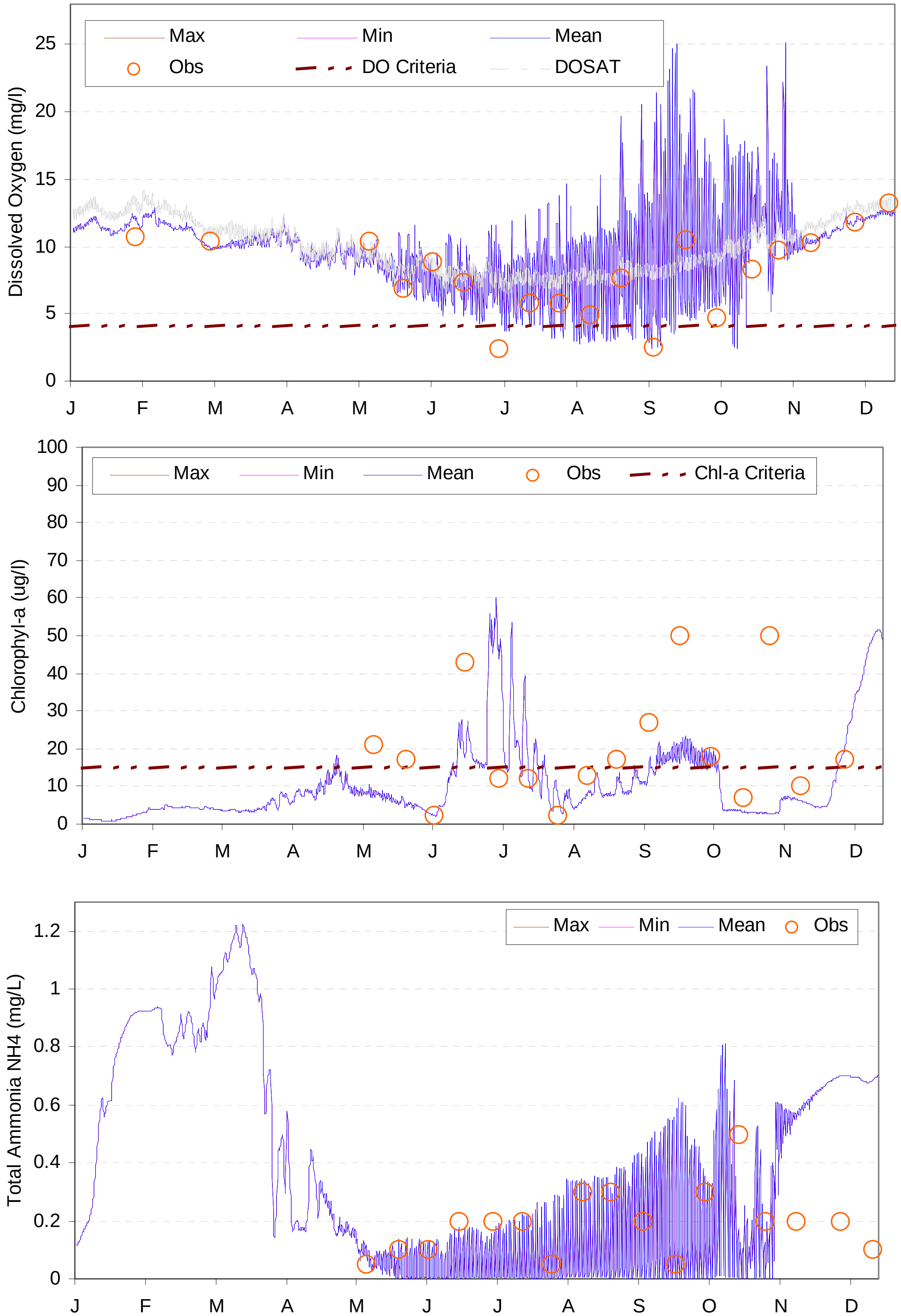
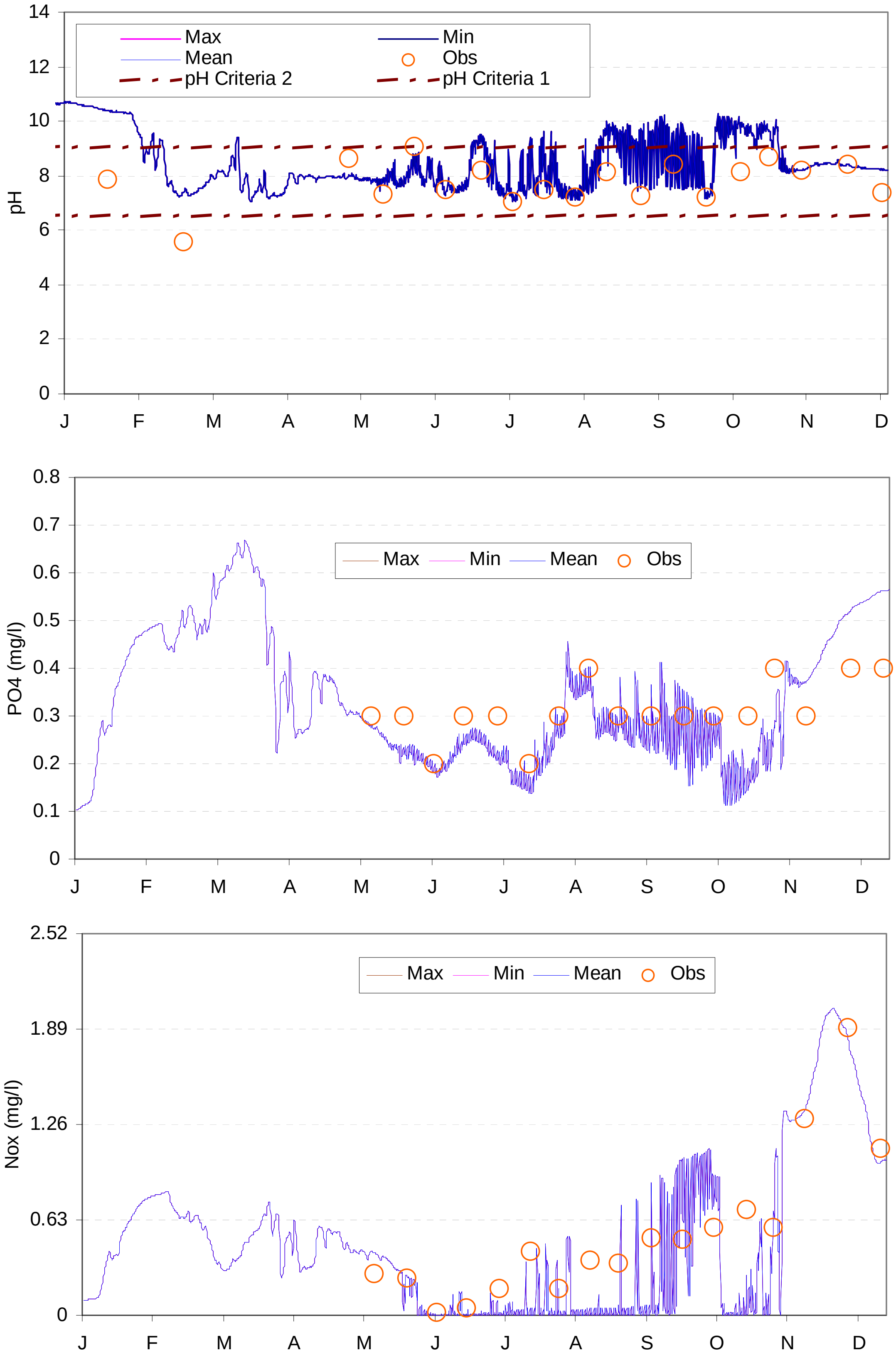


D_1999-5 Lost River at East West Road (LREW) - 1999



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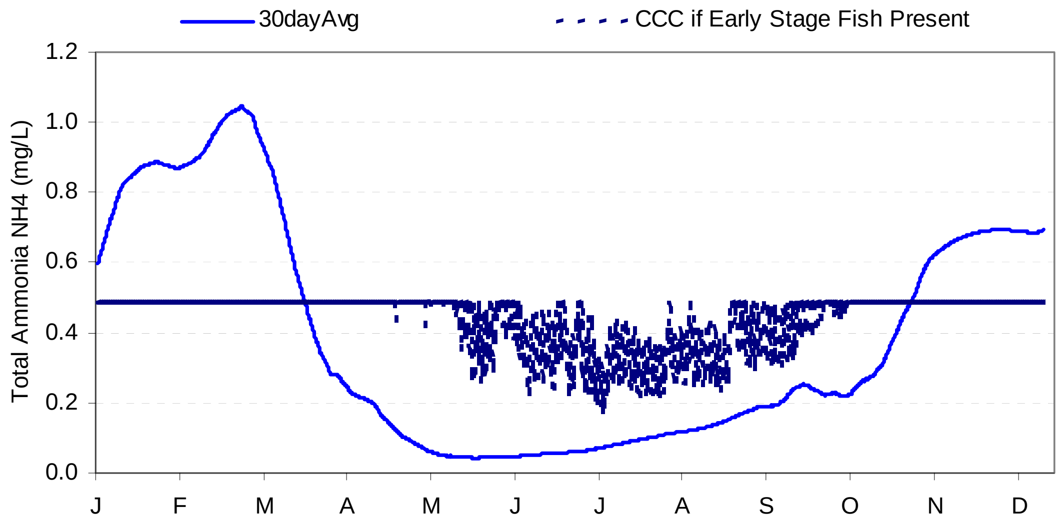

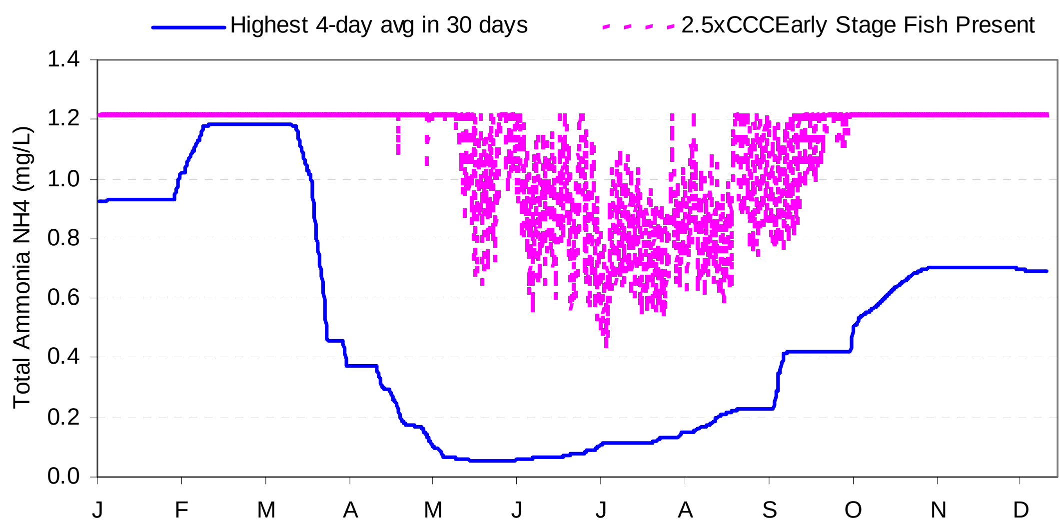

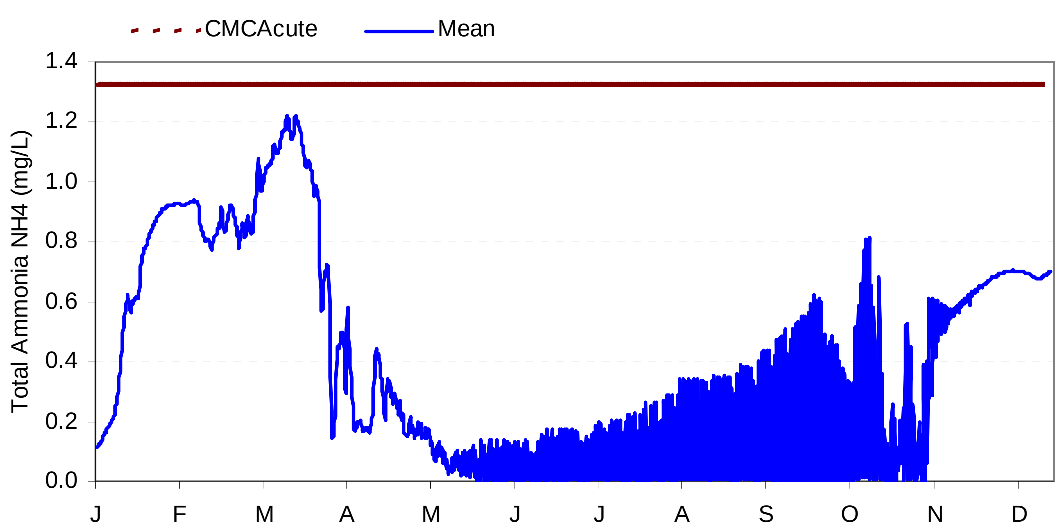

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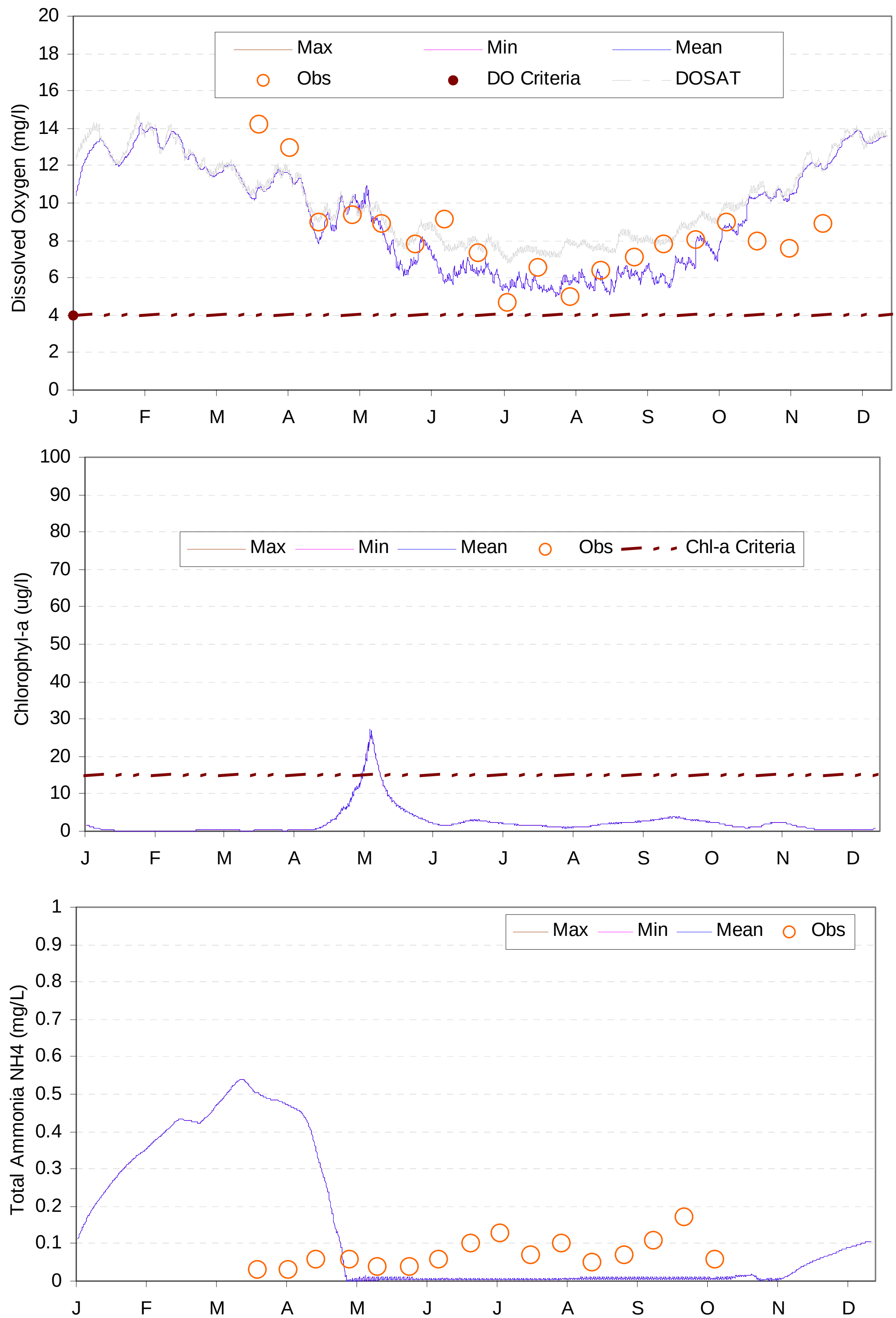
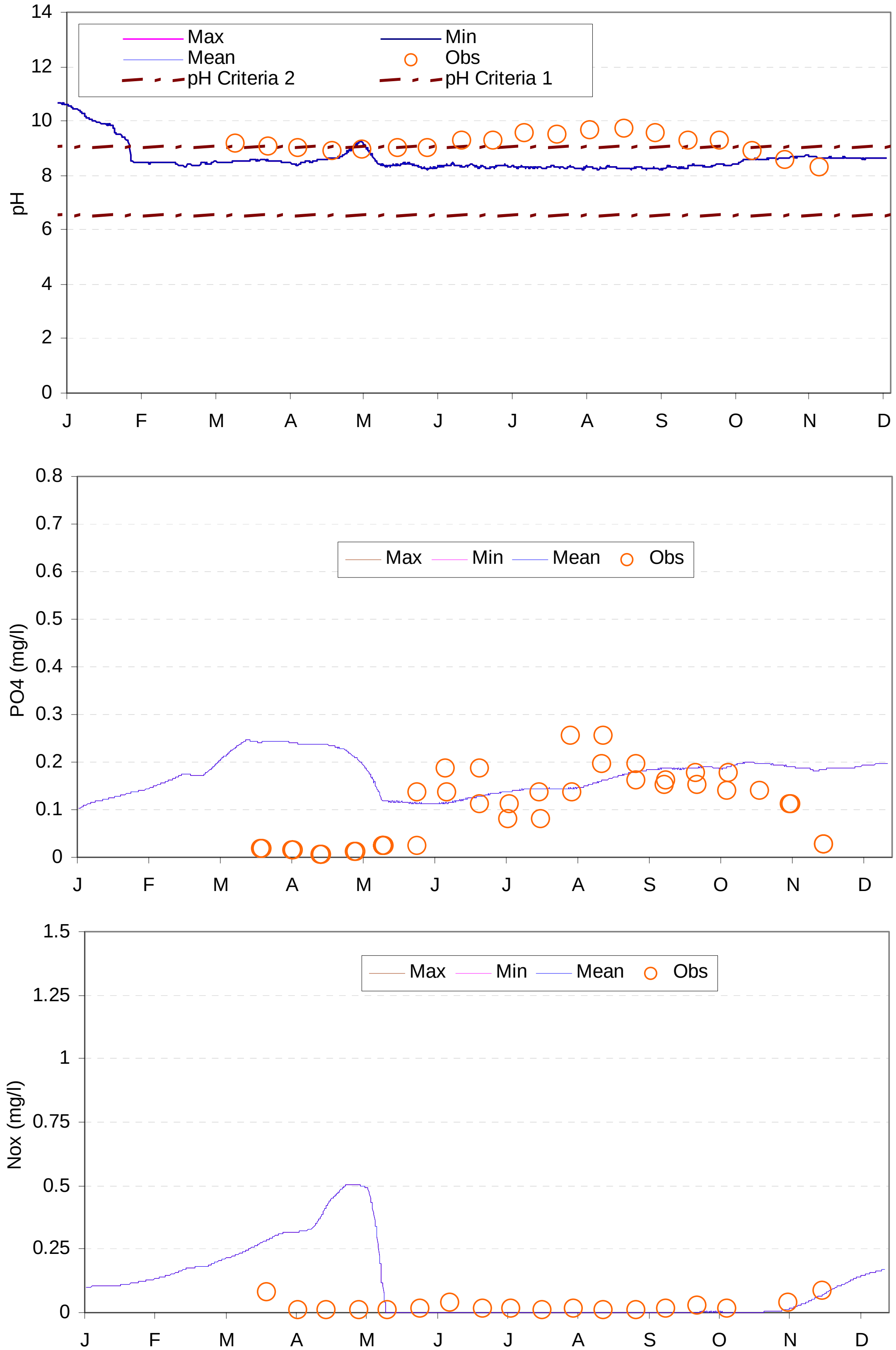


D_1999-6 Lost River at Tule Lake Tunnel Outlet (TLTO) –1999



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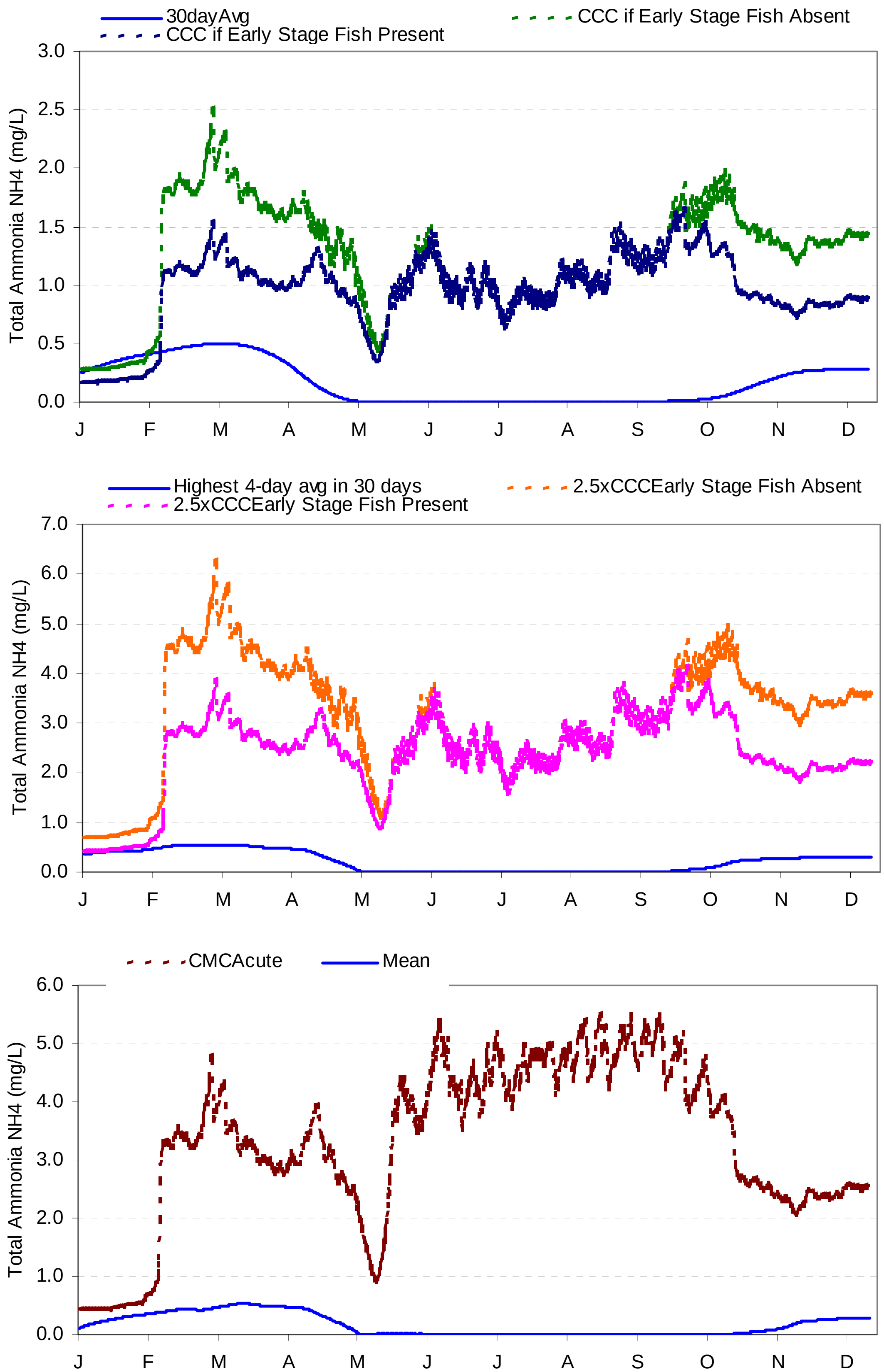

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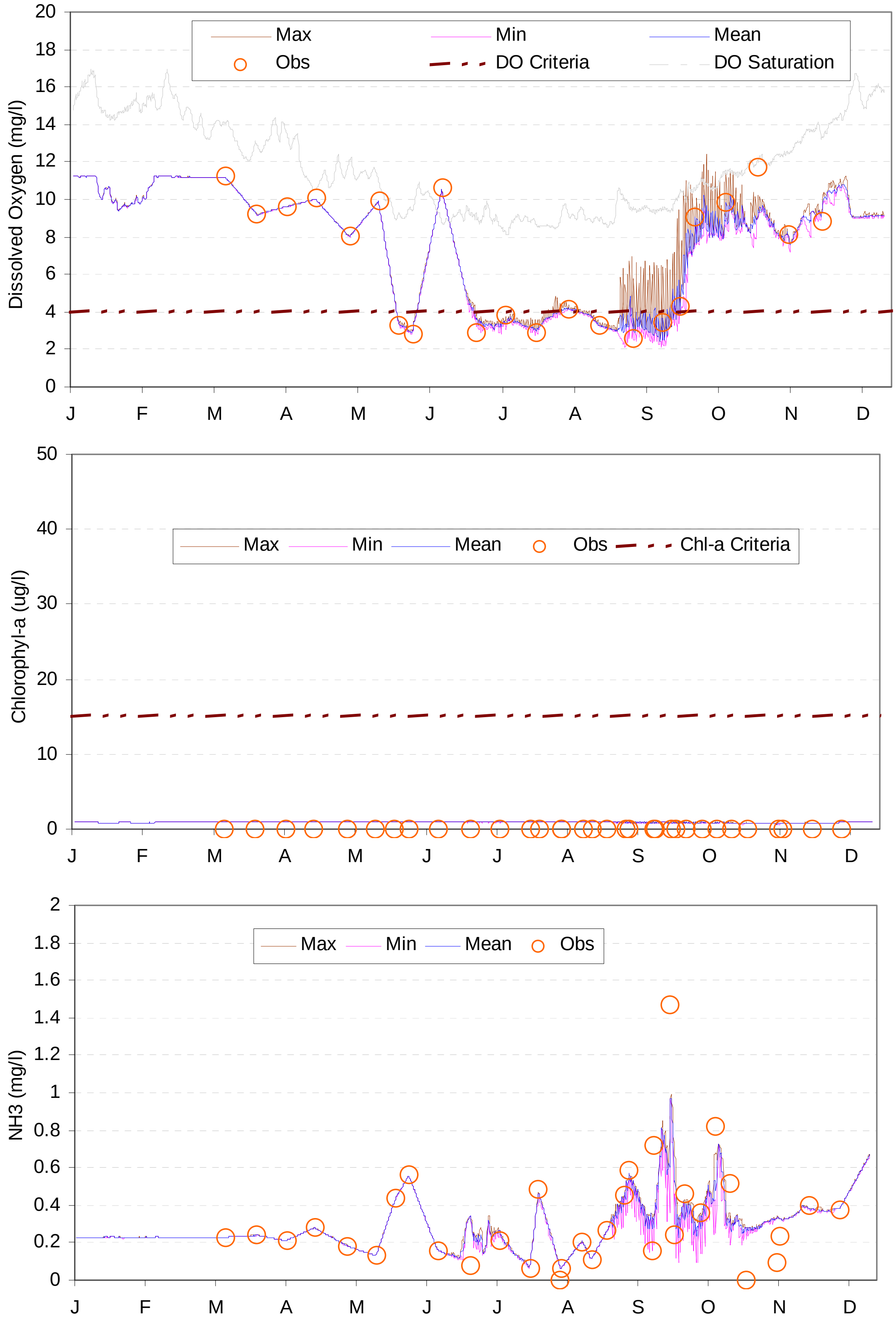
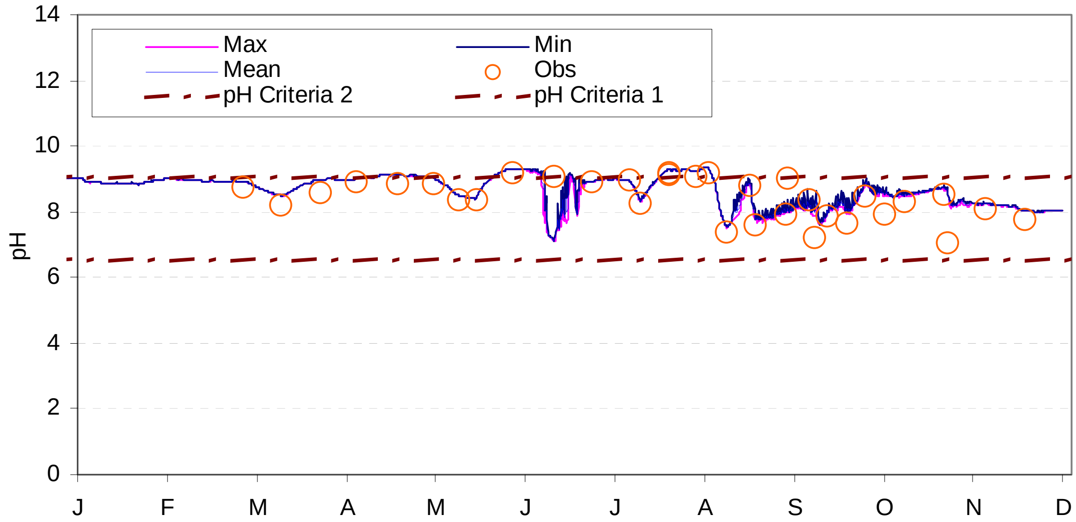
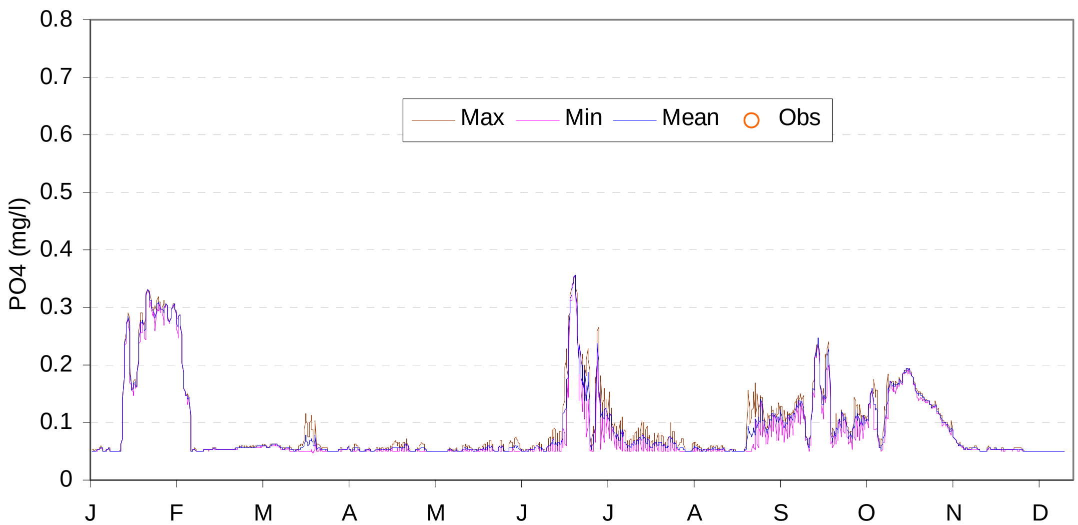
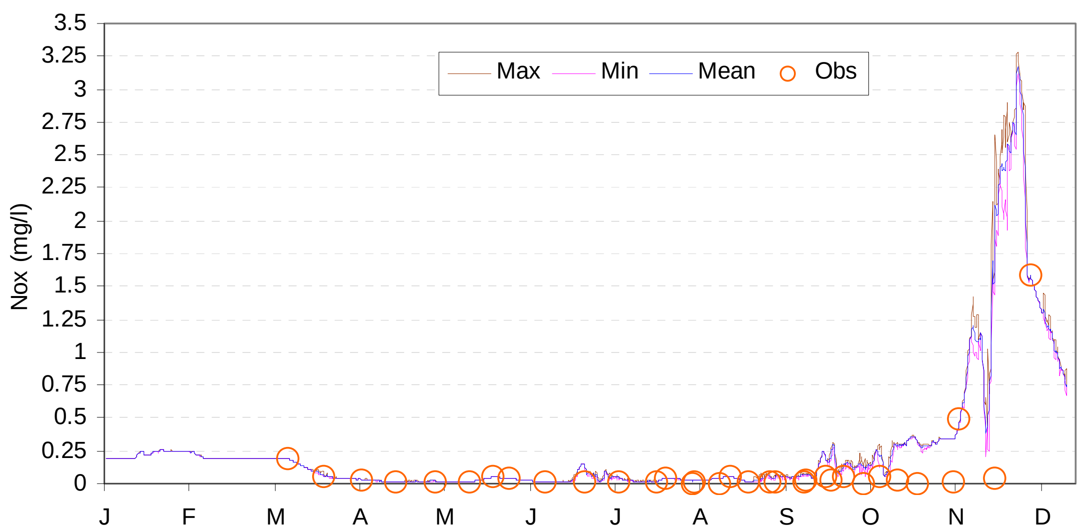


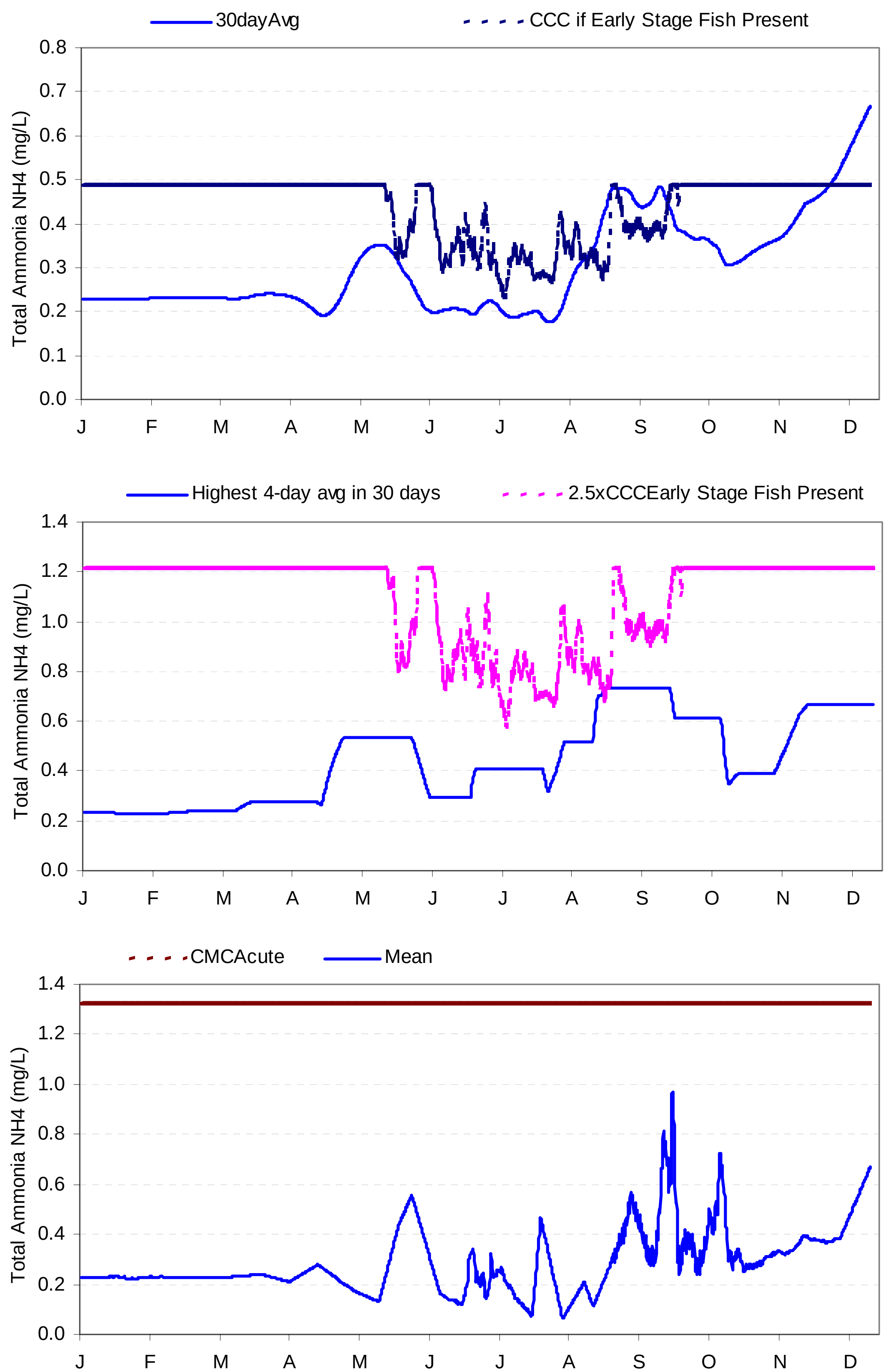
D_1999-7 Klamath Straits Drain at Stateline Road (KSDSR) –1999







D_1999-7 Klamath Straits Drain at Stateline Road (KSDSR) –1999 continued



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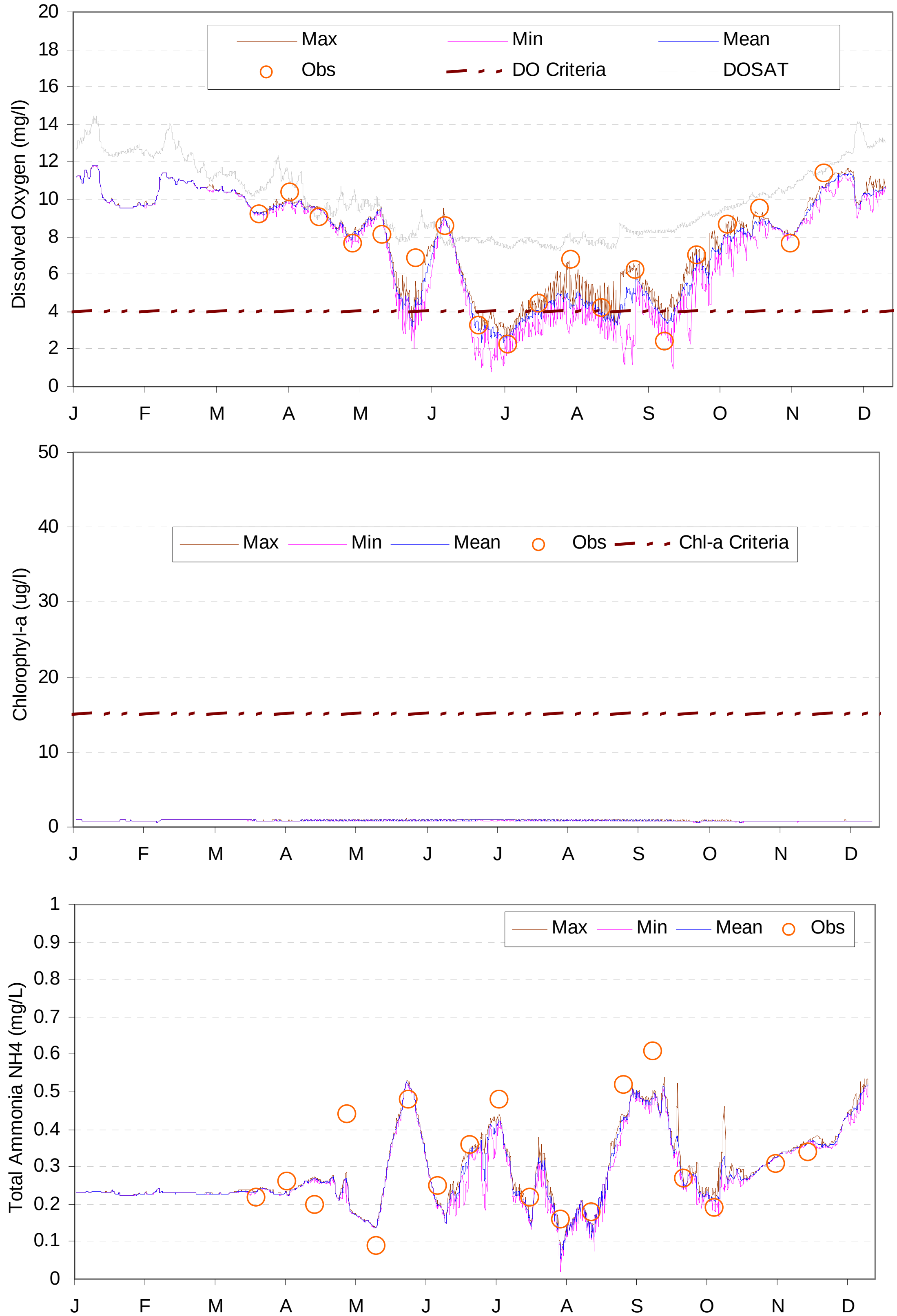
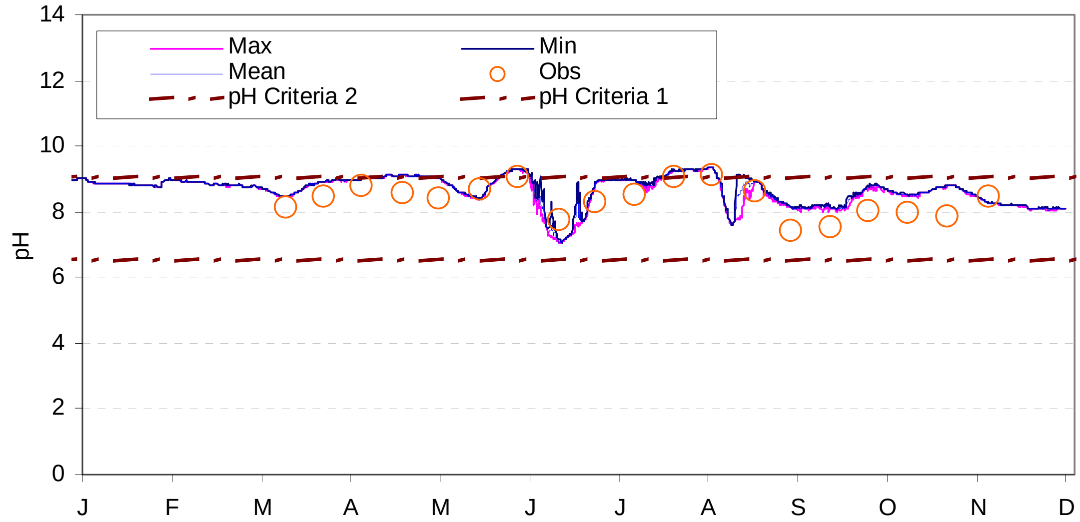
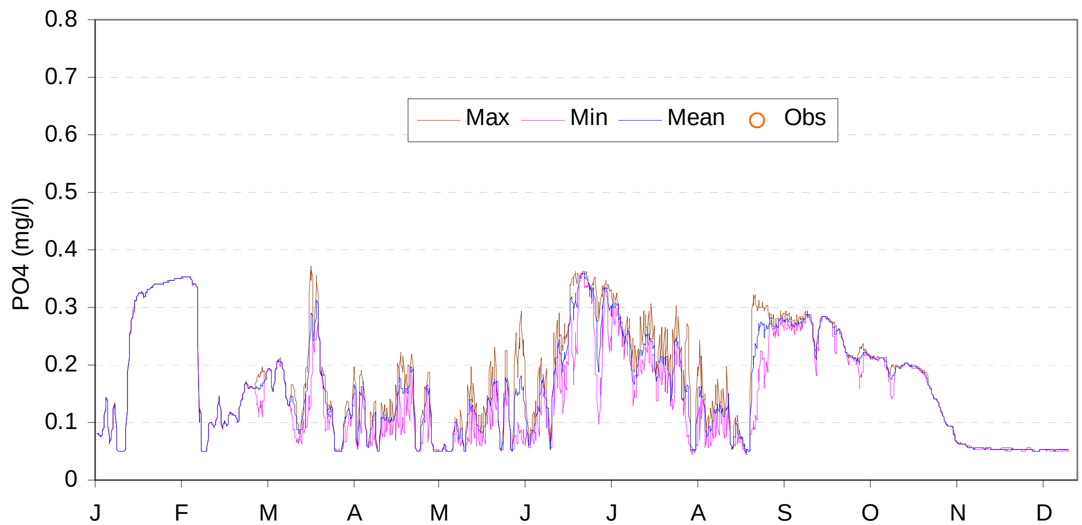
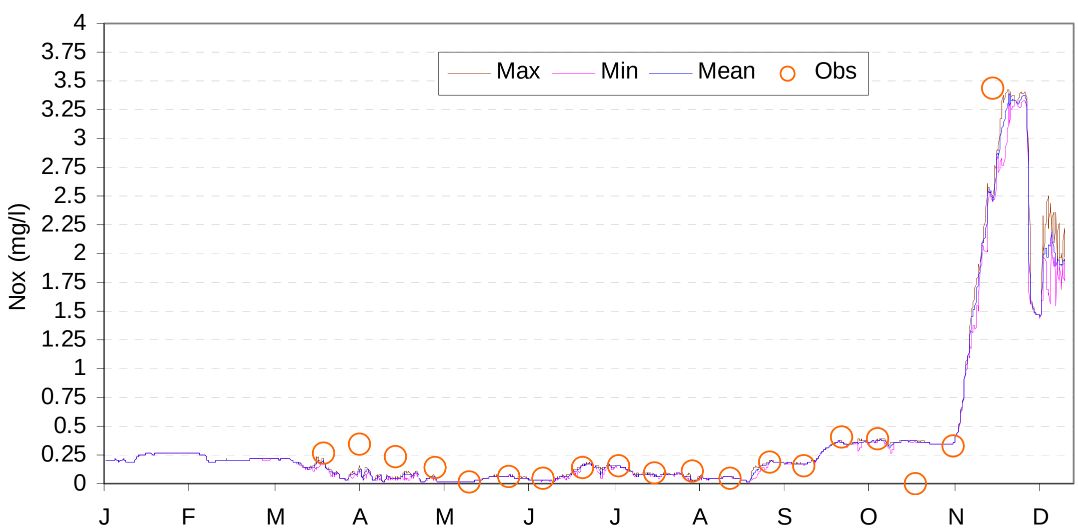


D_1999-8 Klamath Straits Drain at Township Road (pump E) (KSDTR) –1999







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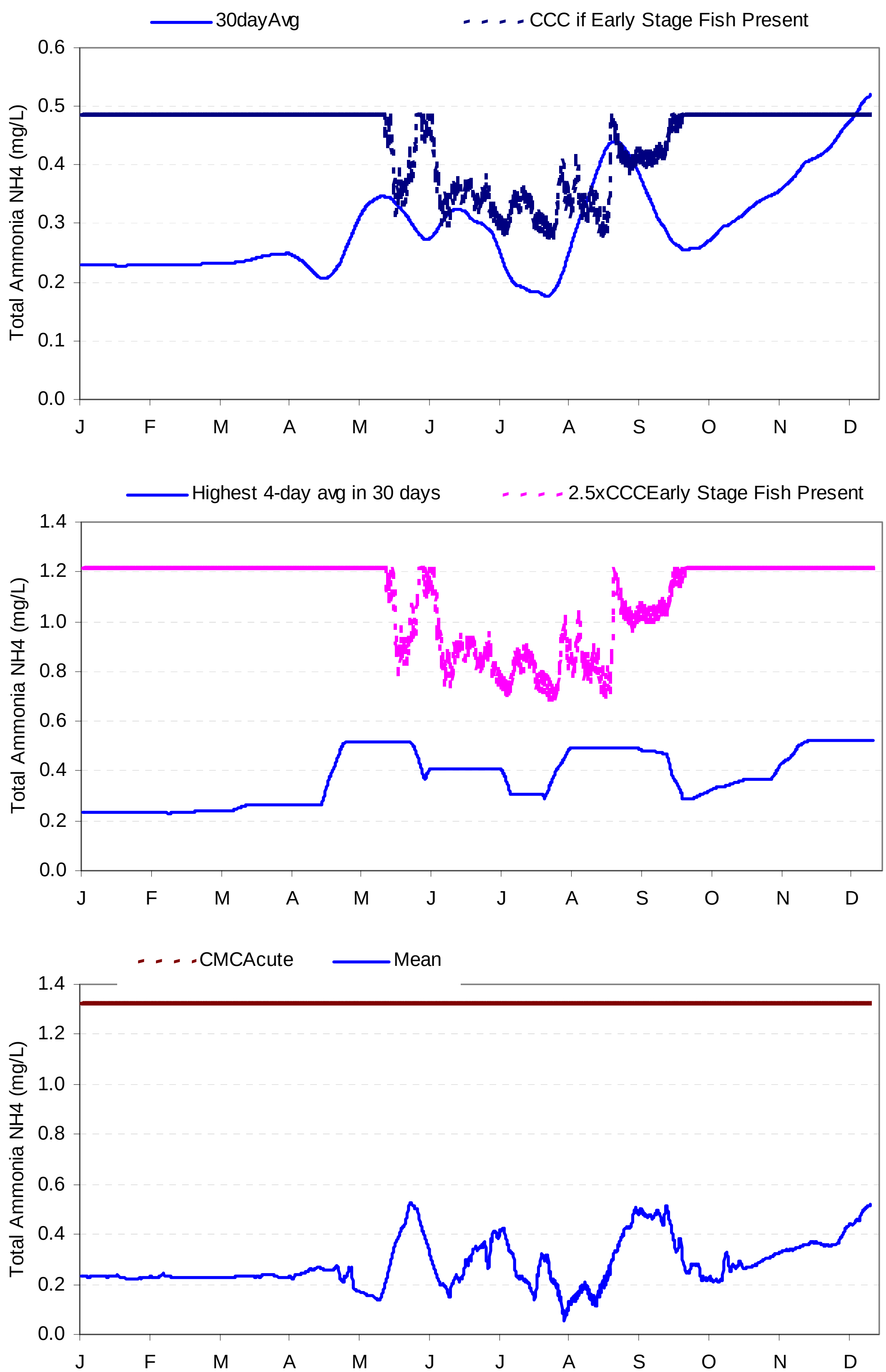

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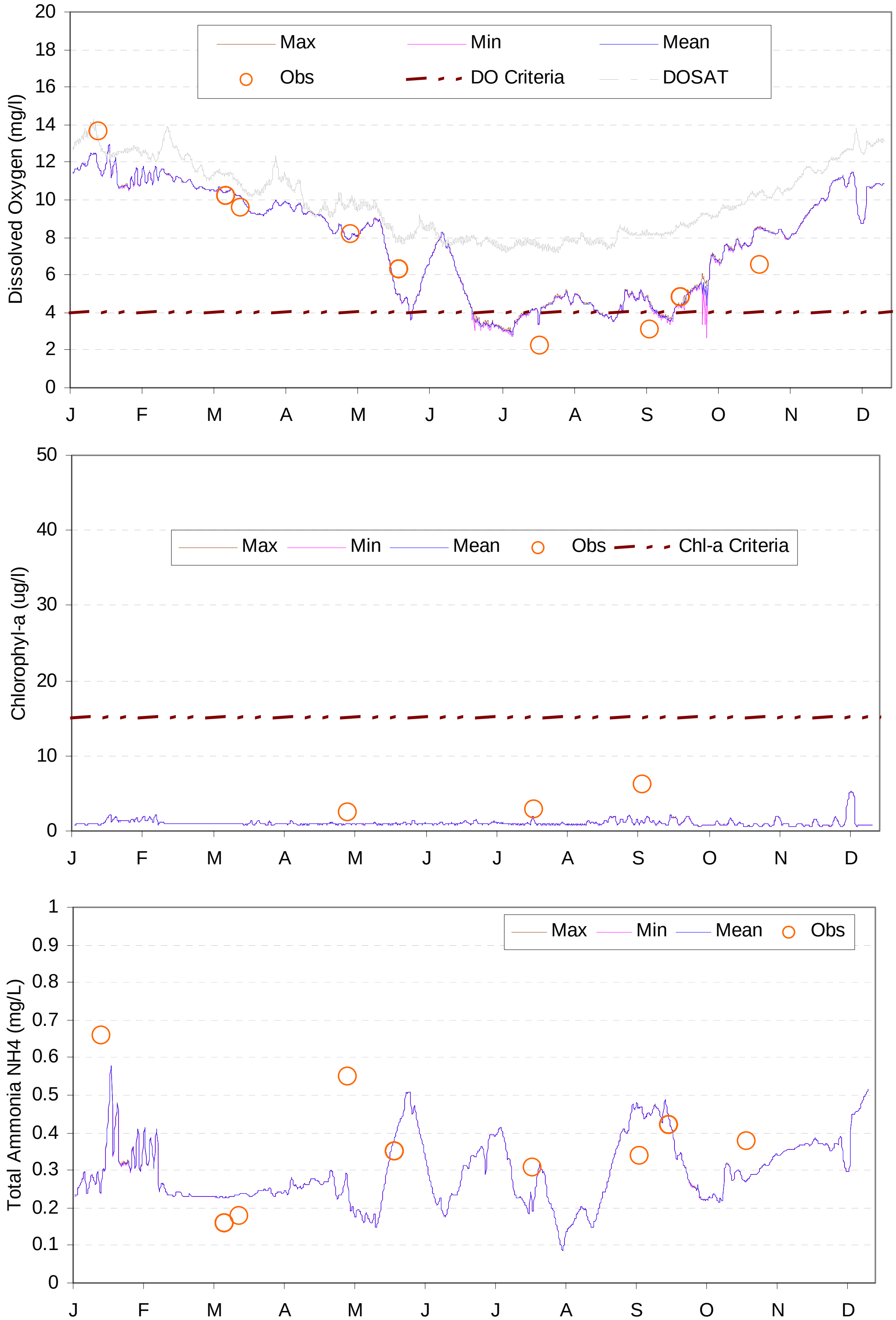
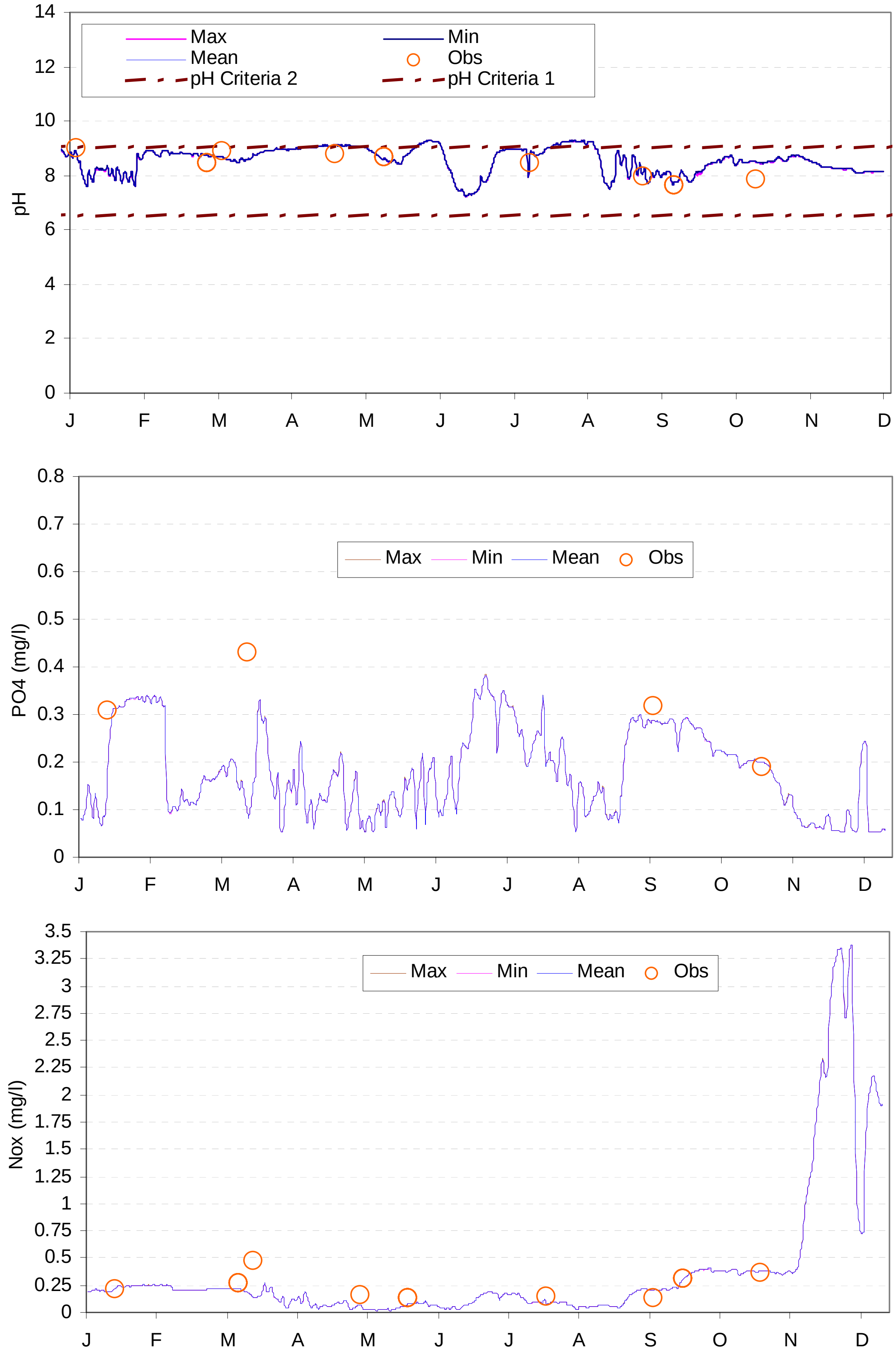


D_1999-9 Klamath Straits Drain at Pump Station F (KSDPSF) –1999



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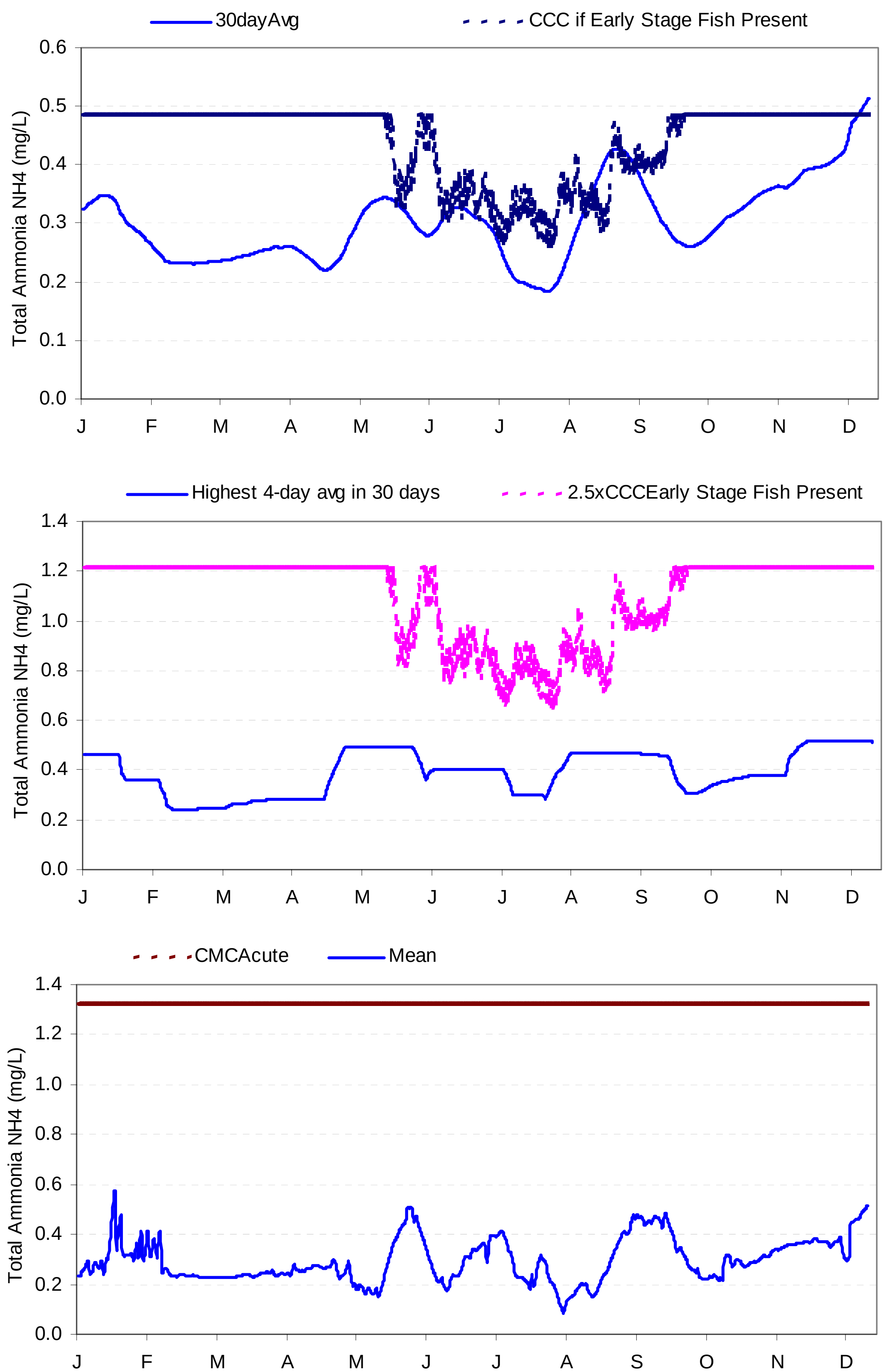

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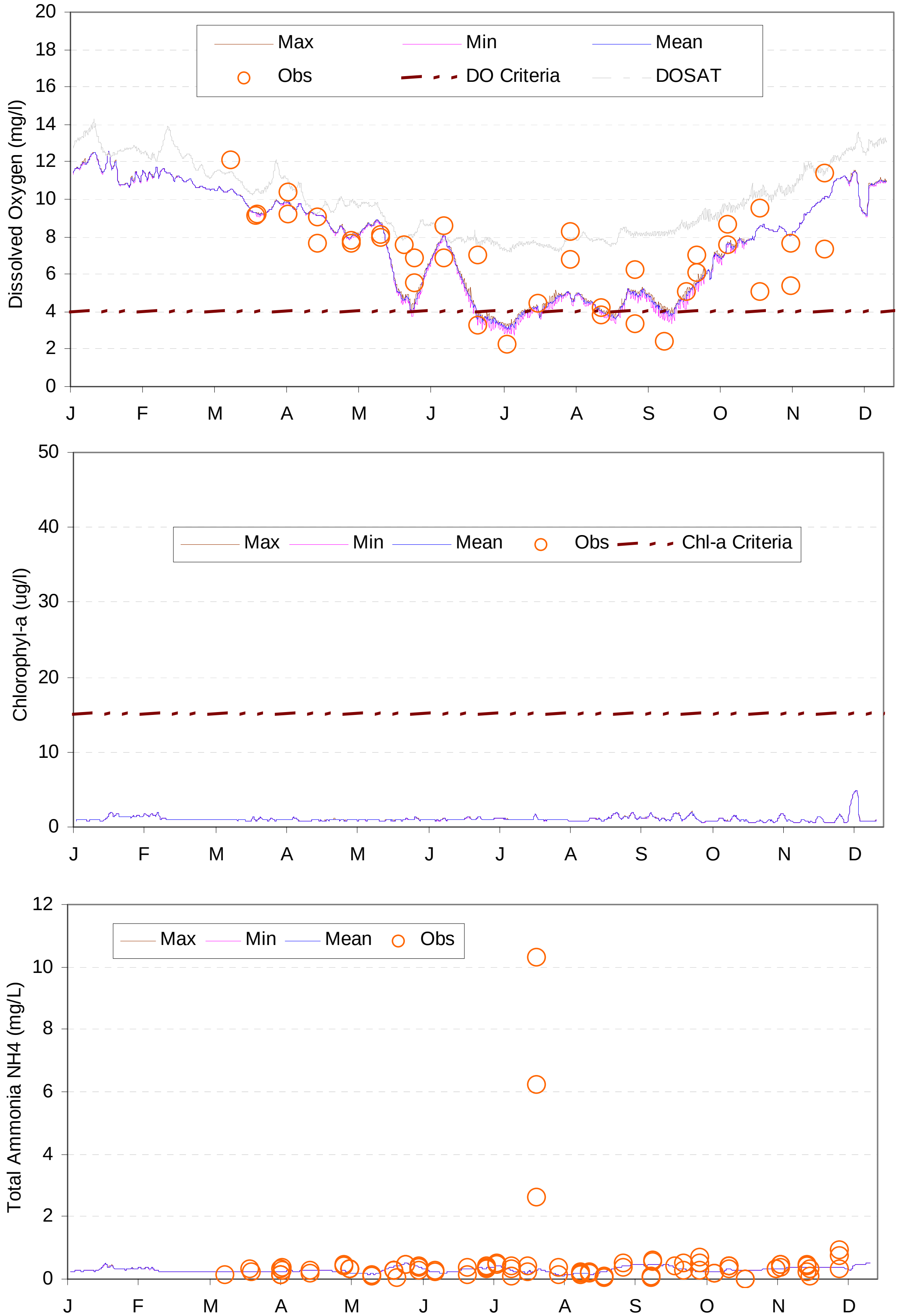
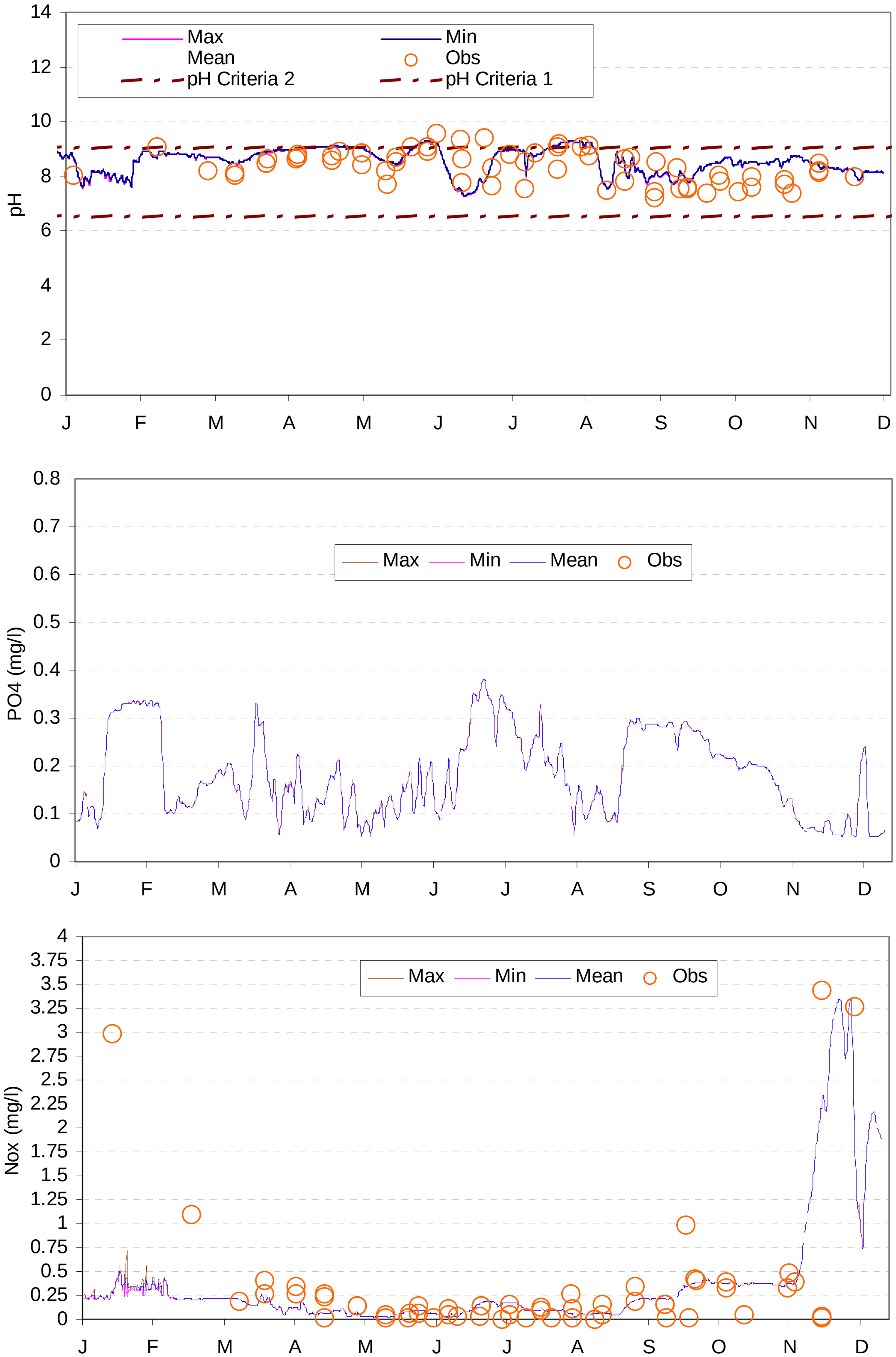


D_1999-10 Klamath Straits Drain at Highway 97 (KSD97) –1999



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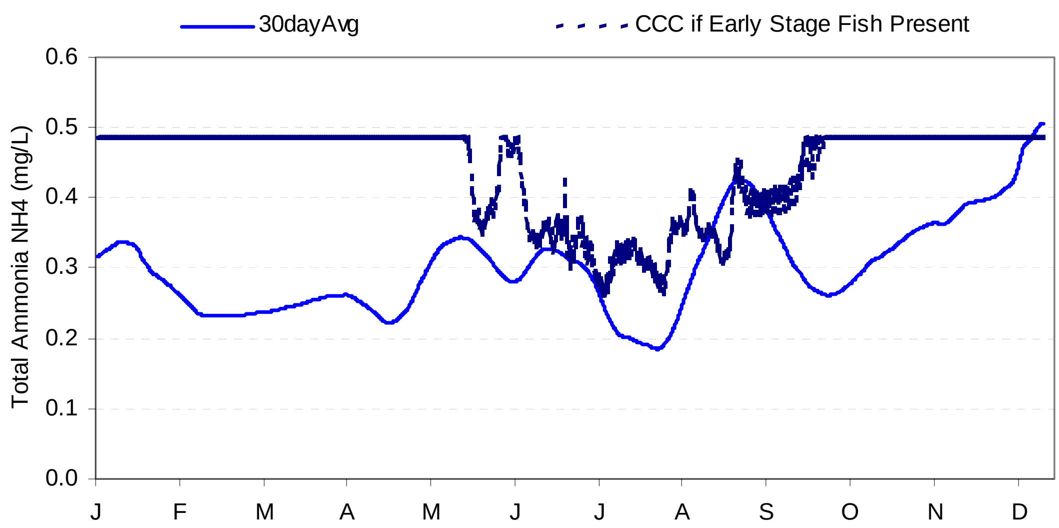

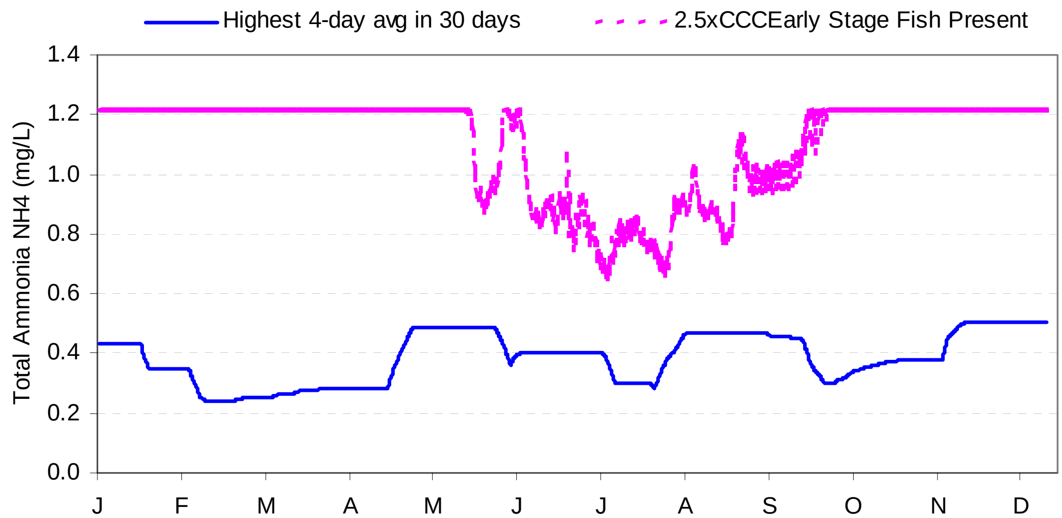

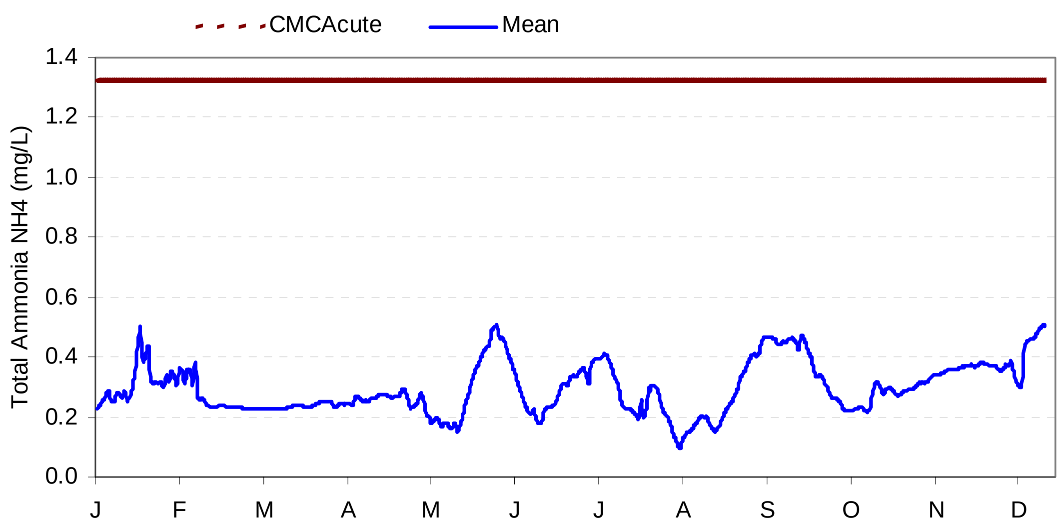

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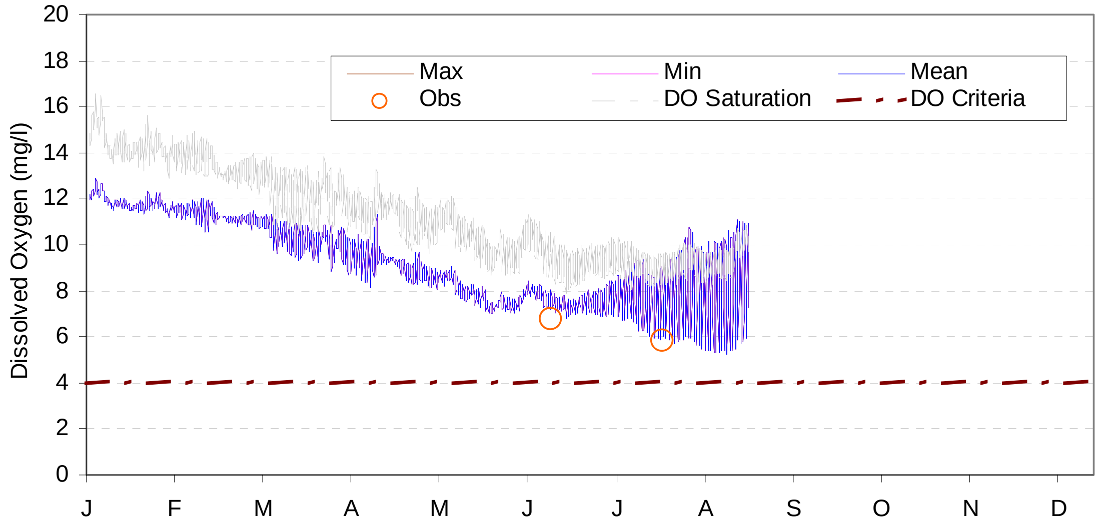
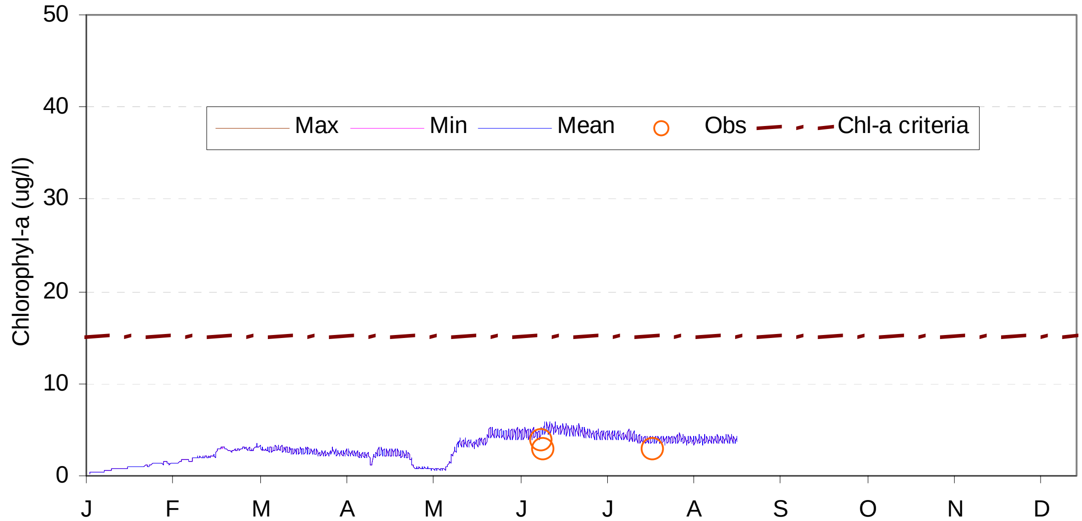
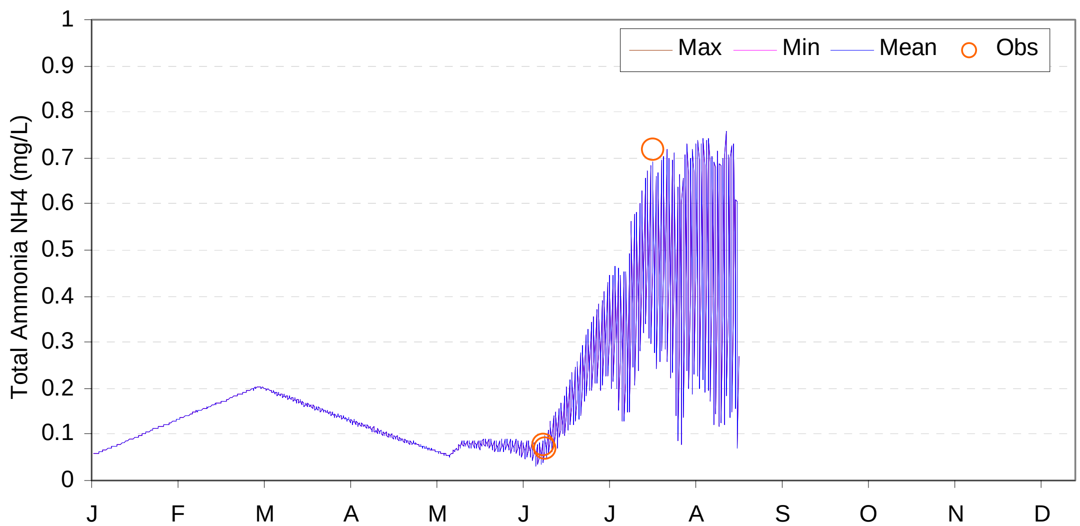
Appendix D_2004

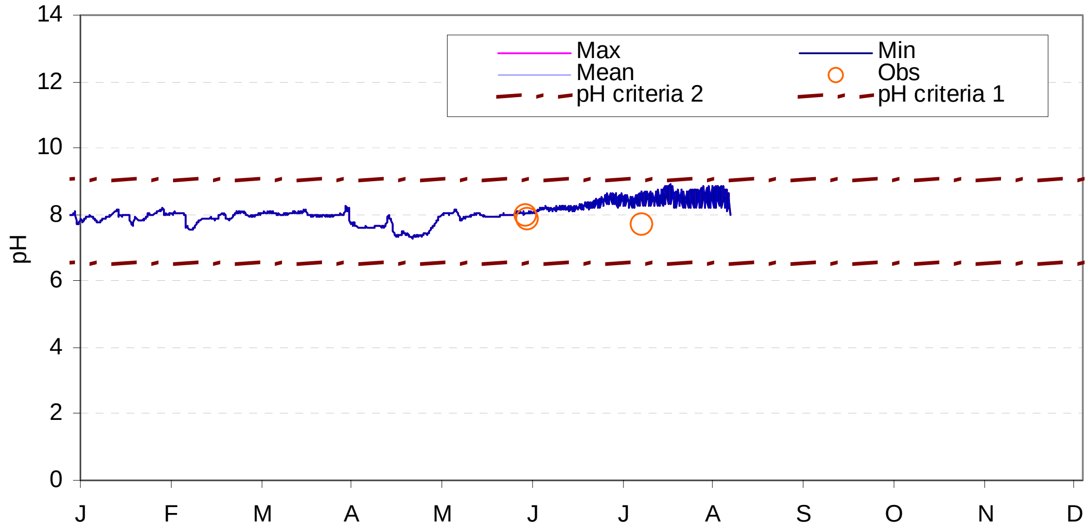
Water Quality Calibration Results

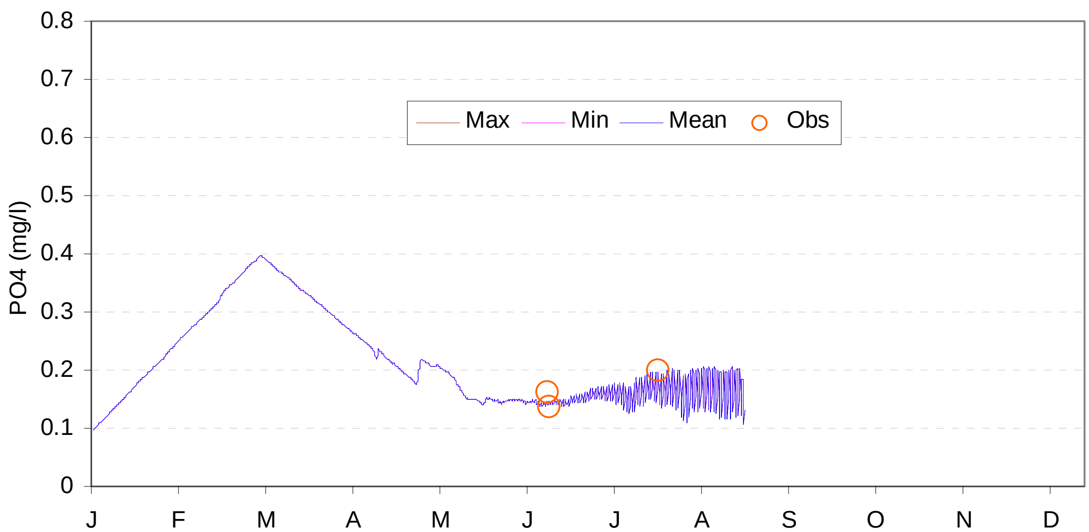


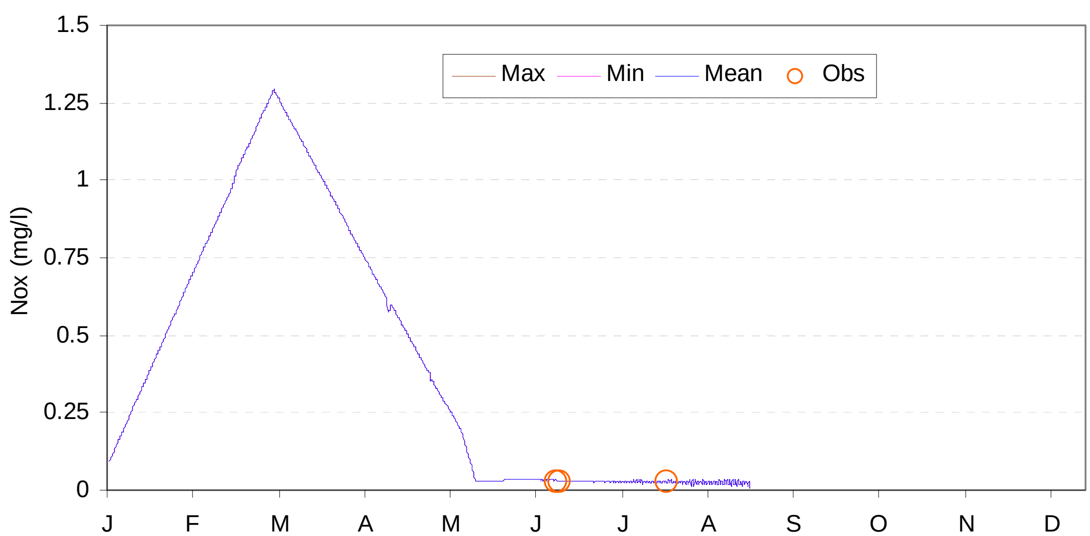




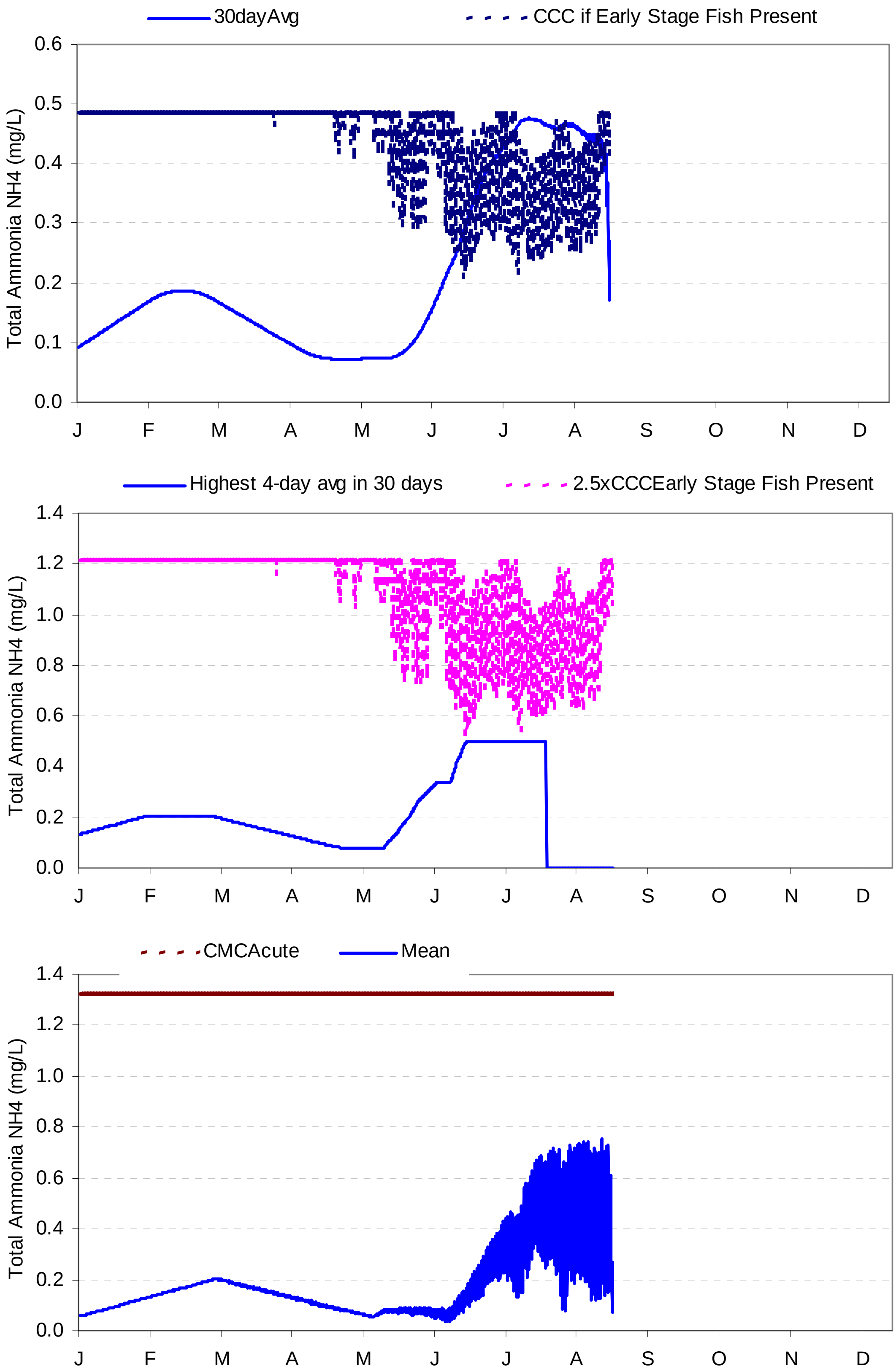
D_2004-1 Lost River at Keller Bridge (LRKB) –2004



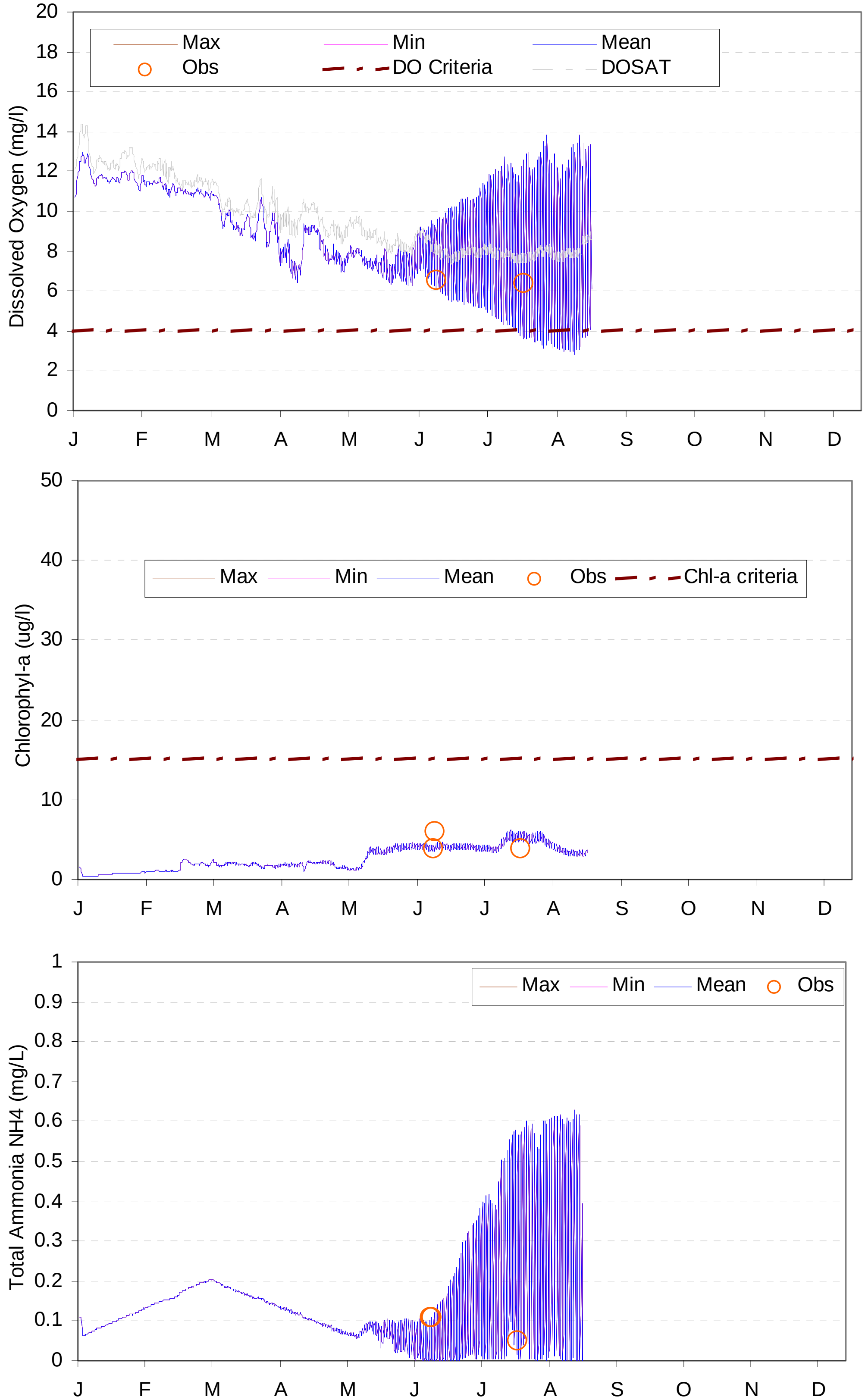




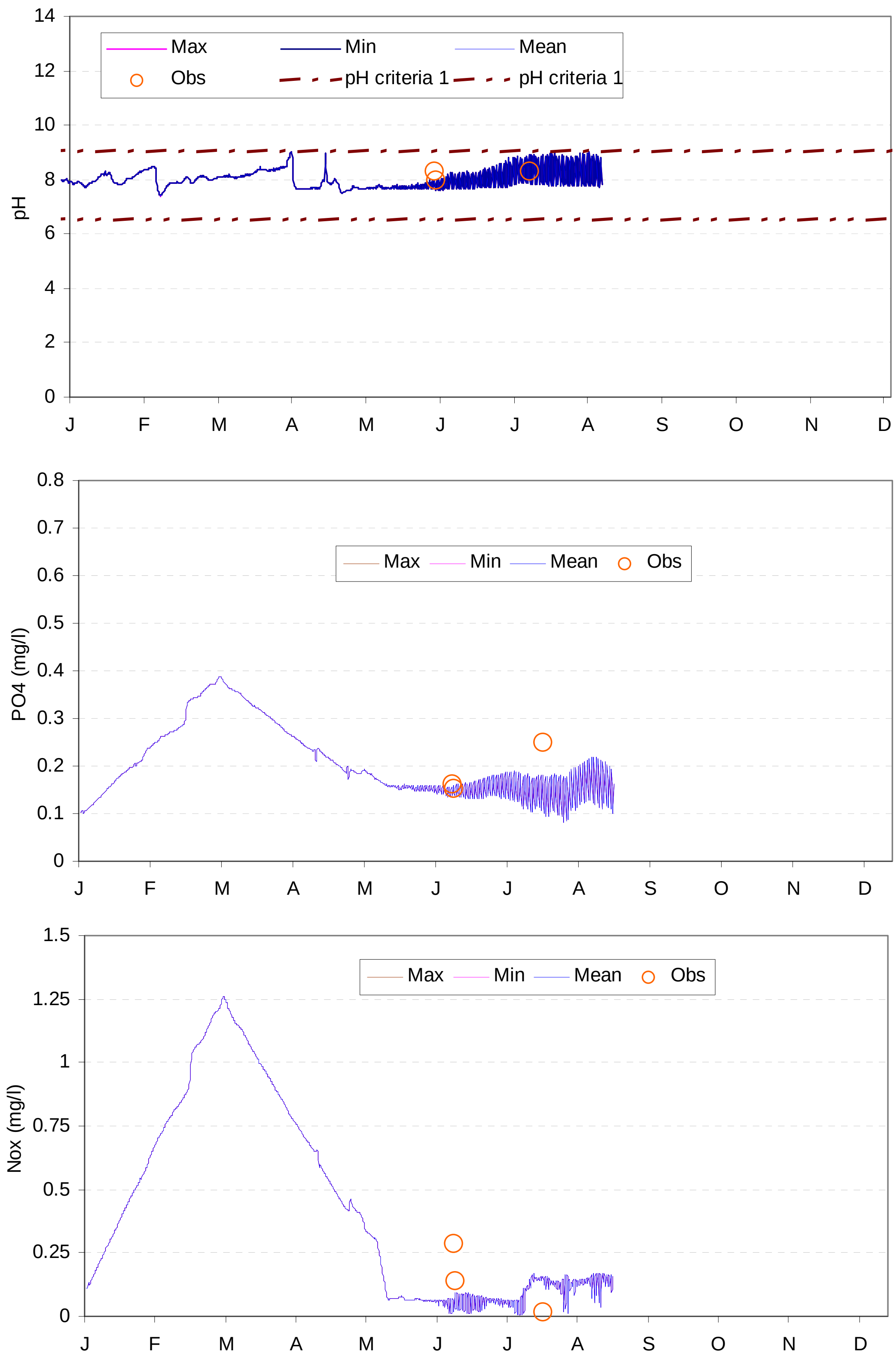
D_2004-1 Lost River at Keller Bridge (LRKB) – 2004 continued



D_2004-1 Lost River at Keller Bridge (LRKB) – 2004 continued



D_2004-2 Lost River at Harpold Dam (LRHD) – 2004



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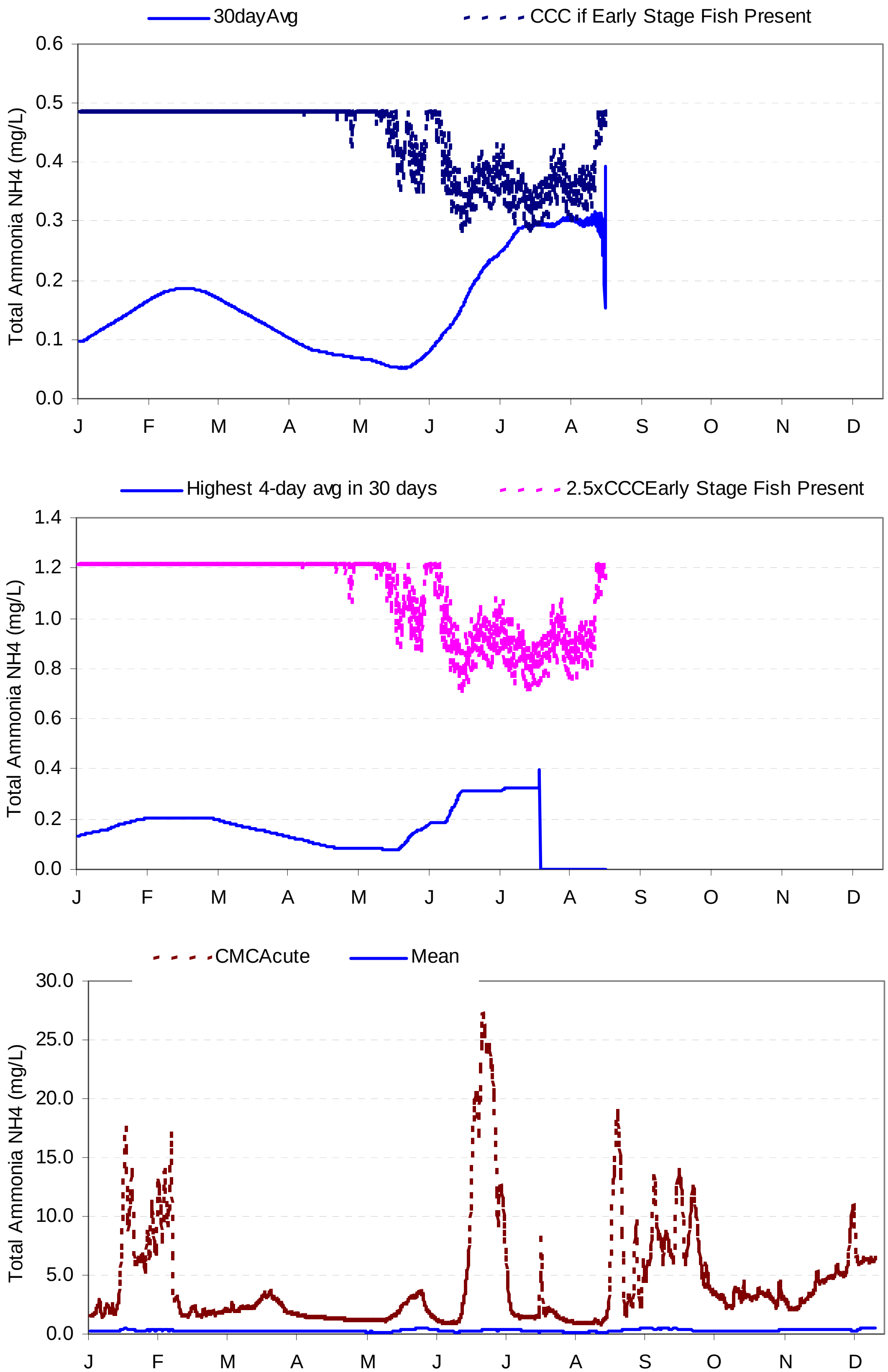

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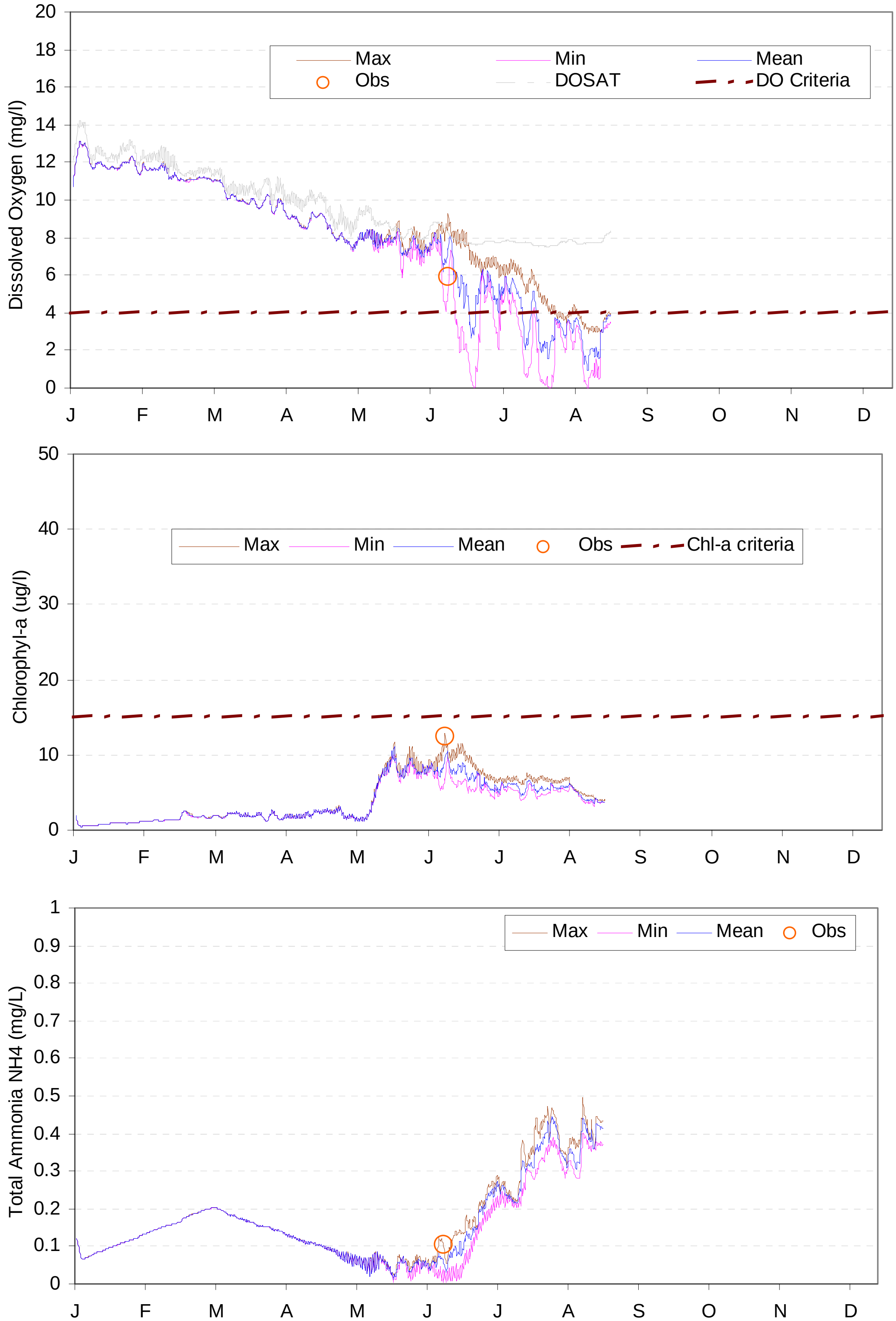
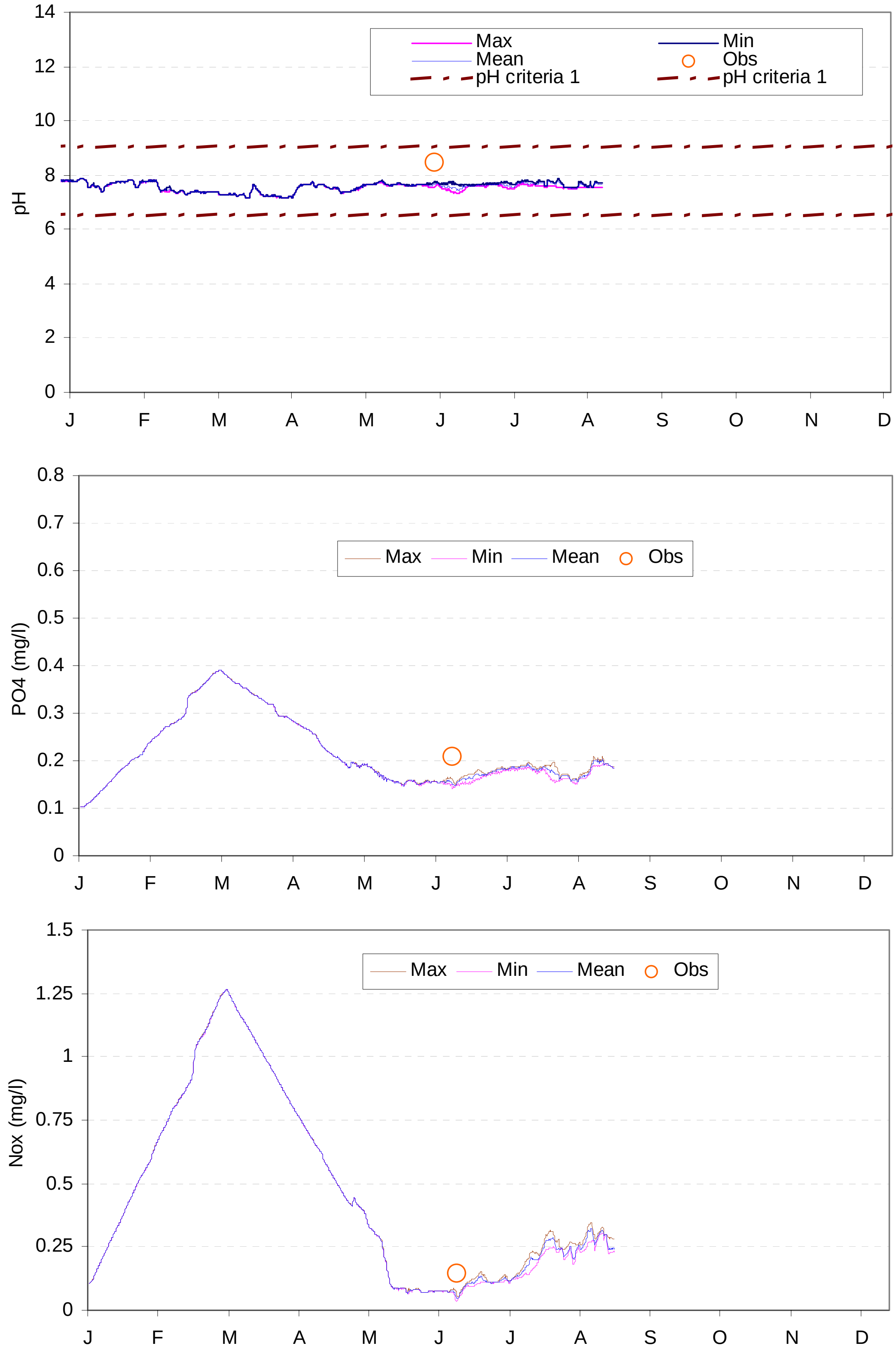


D_2004-3 Poe Valley Bridge at RM 27 (HPDS2) 2004



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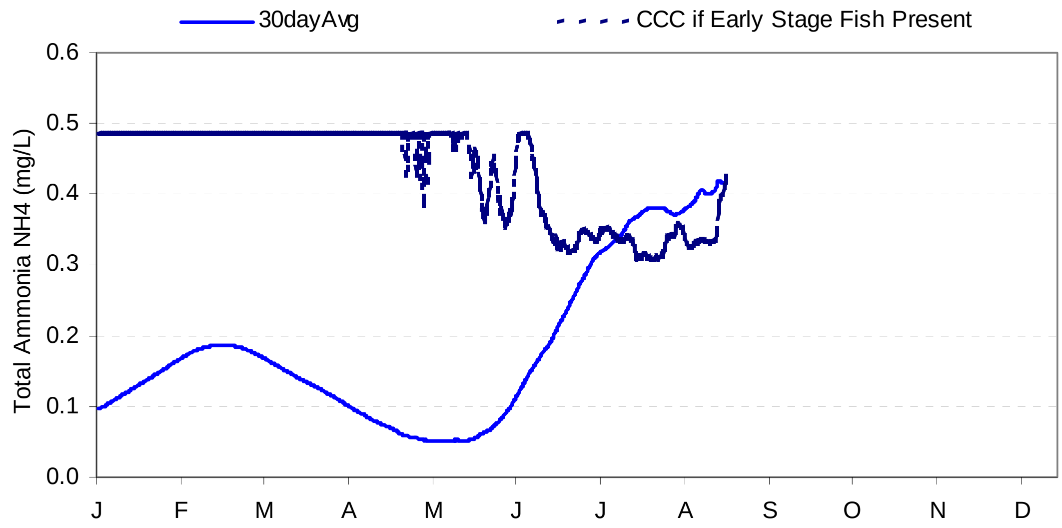
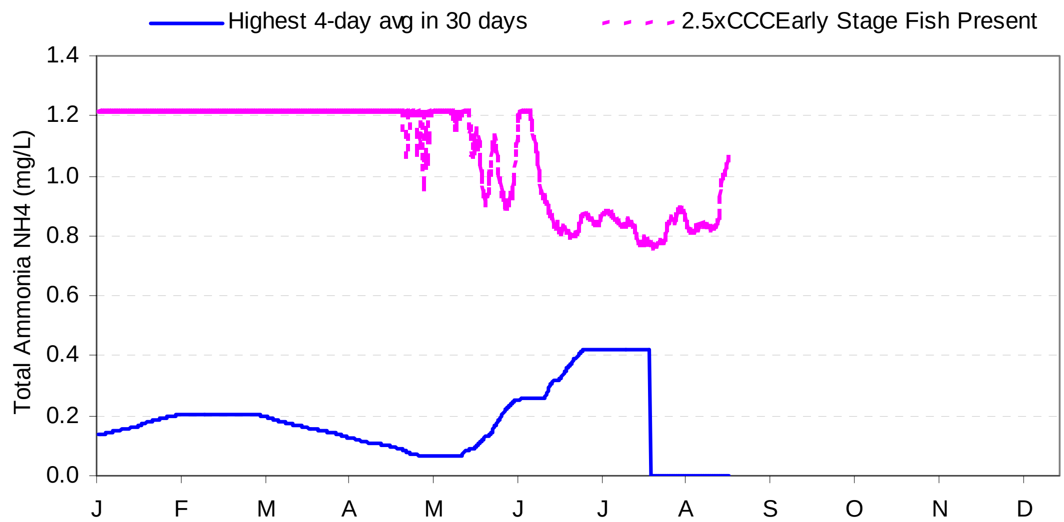
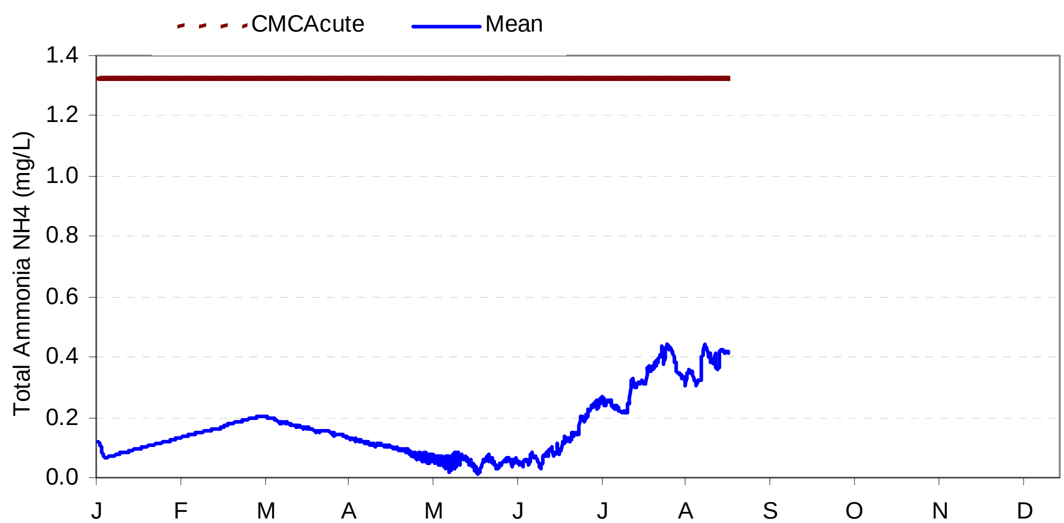
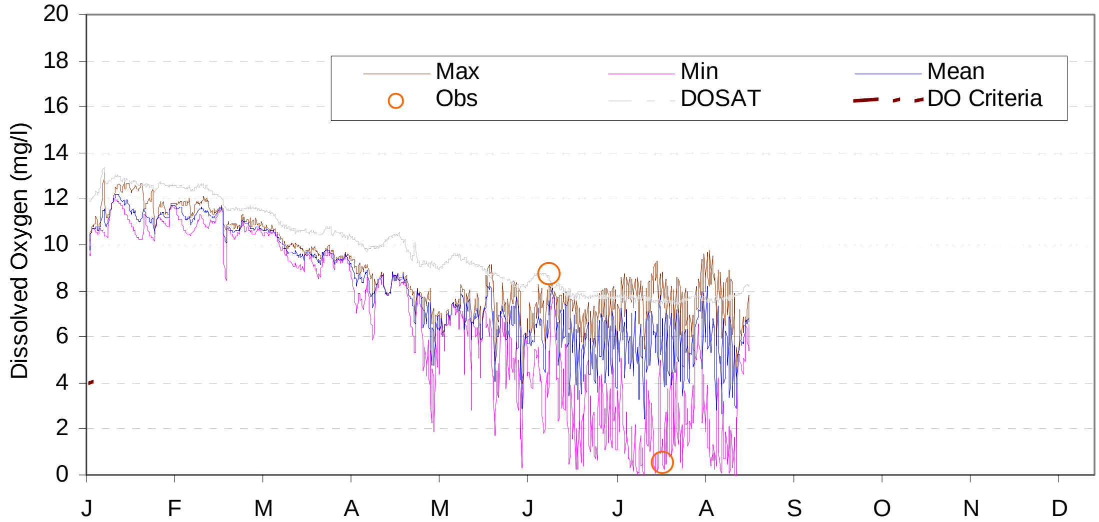
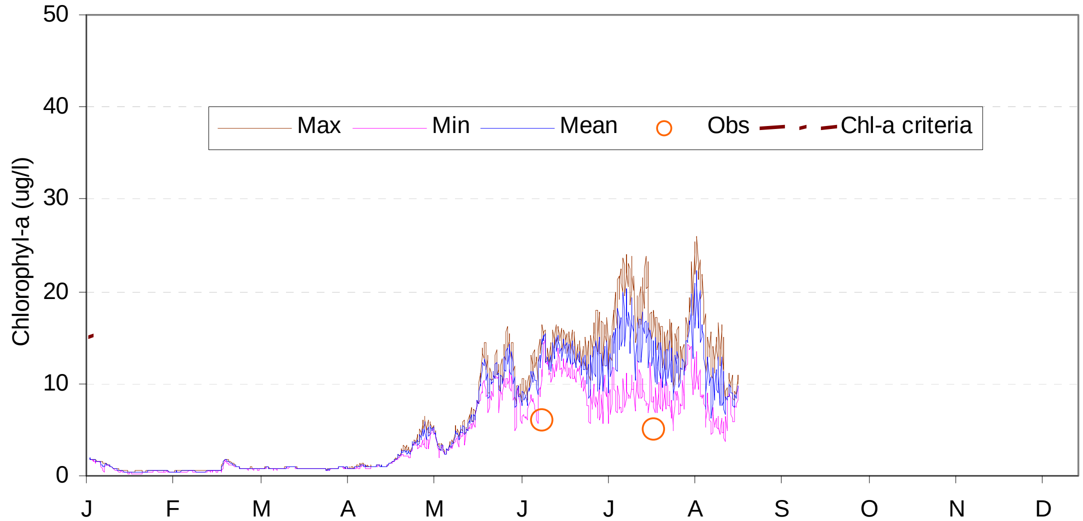


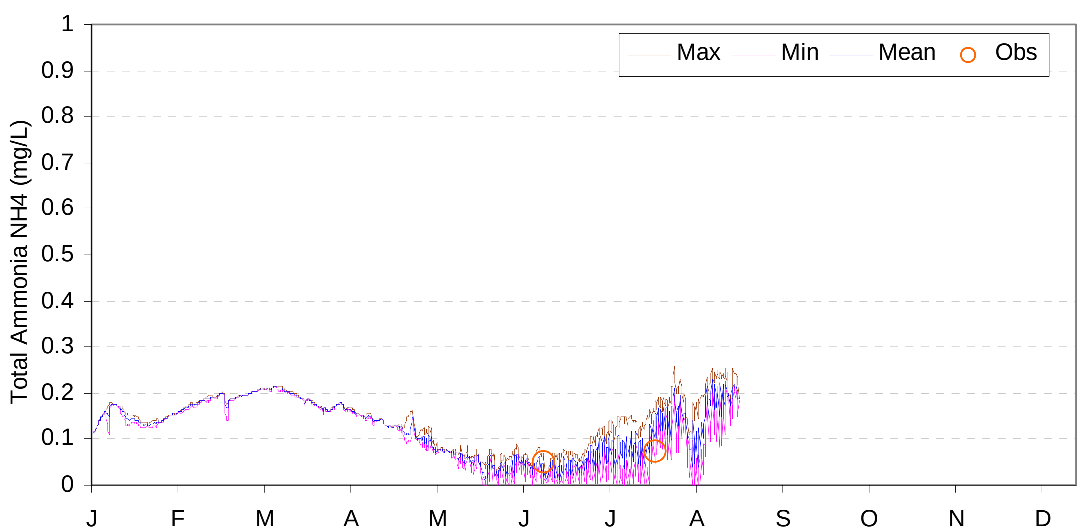




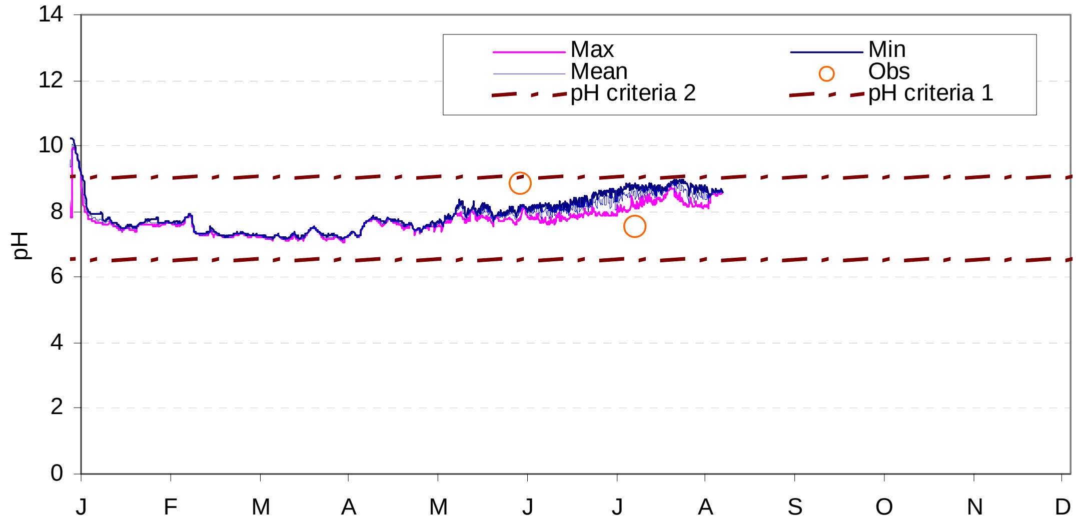
D_2004-3 Poe Valley Bridge at RM 27 (HPDS2) 2004 continued

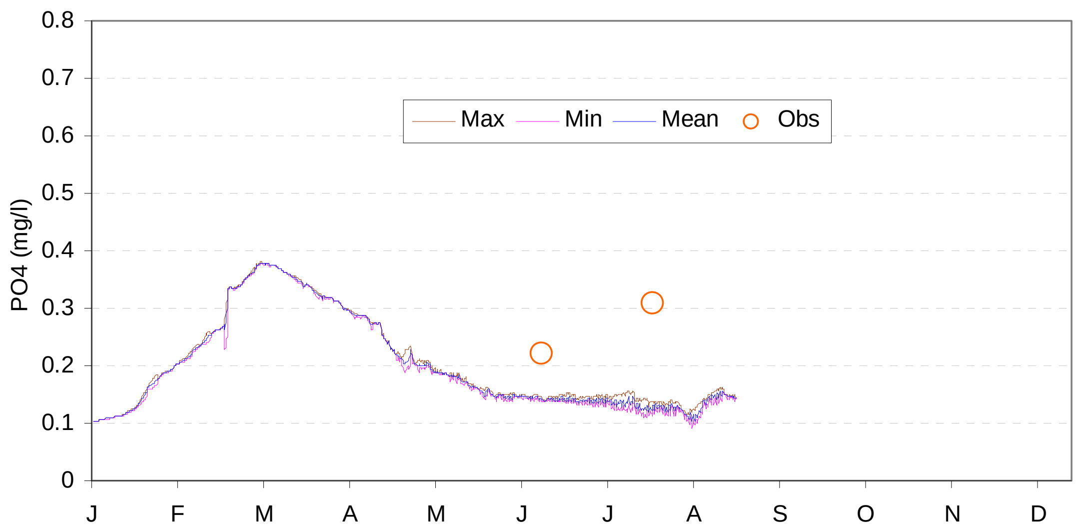


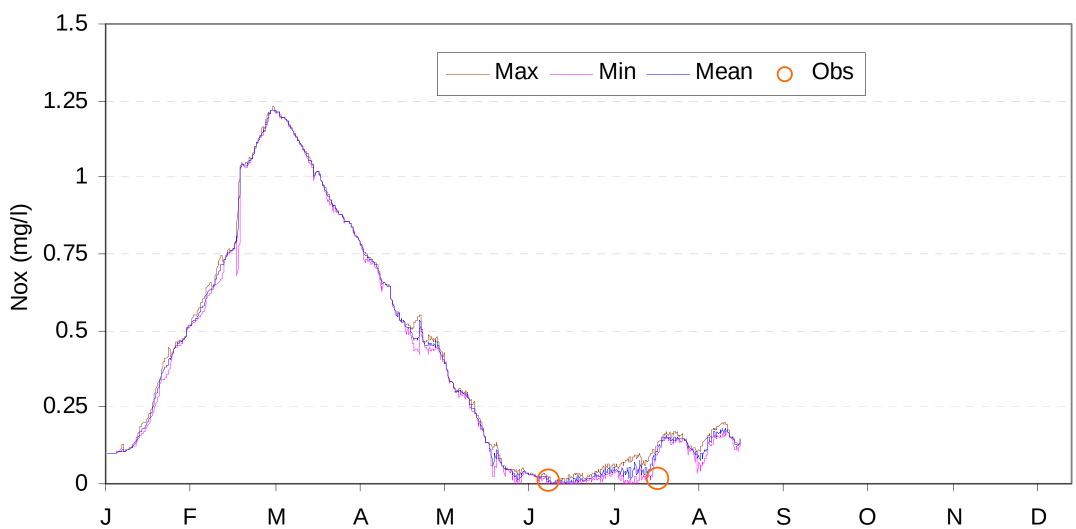




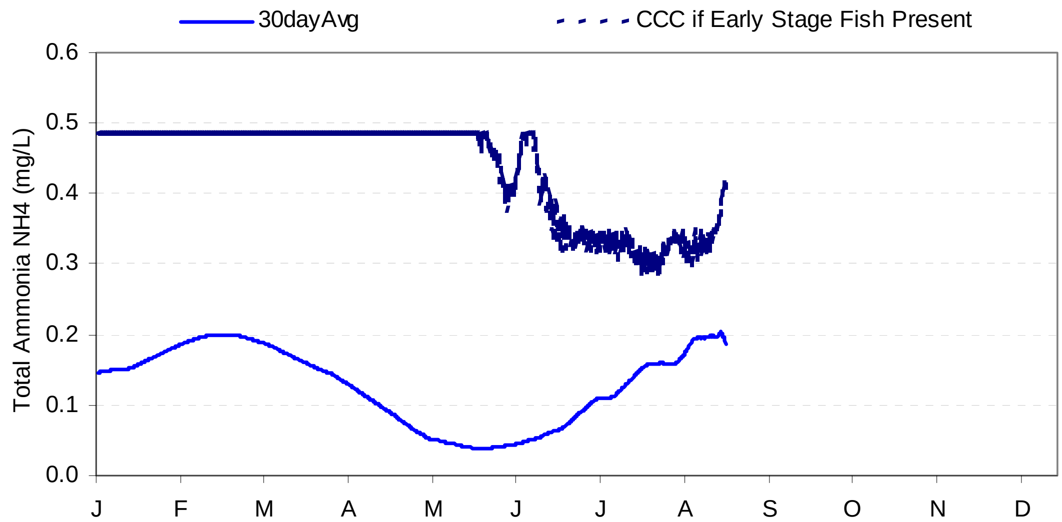
D_2004-4 Lost River at Crystal Springs (WDUS/LRWRC) –2004

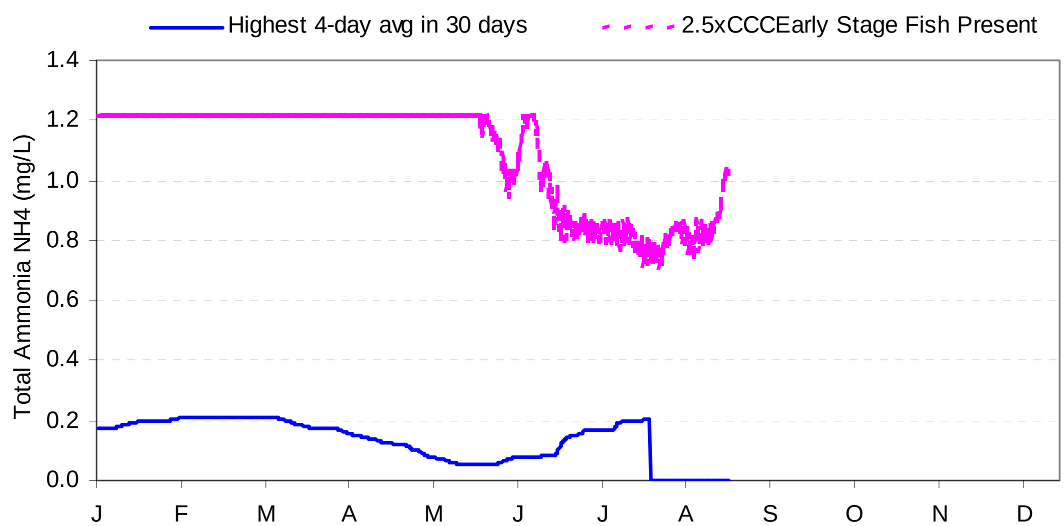


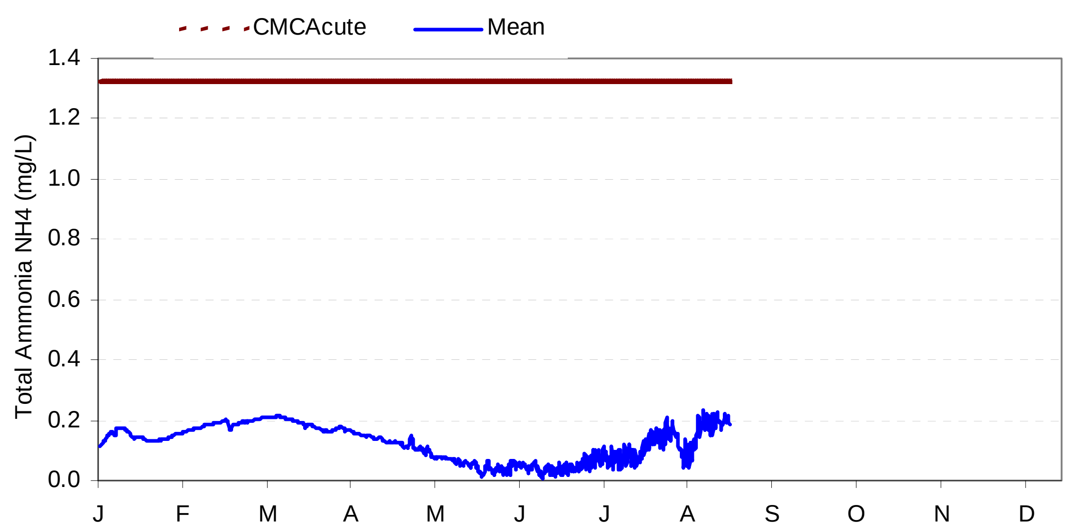




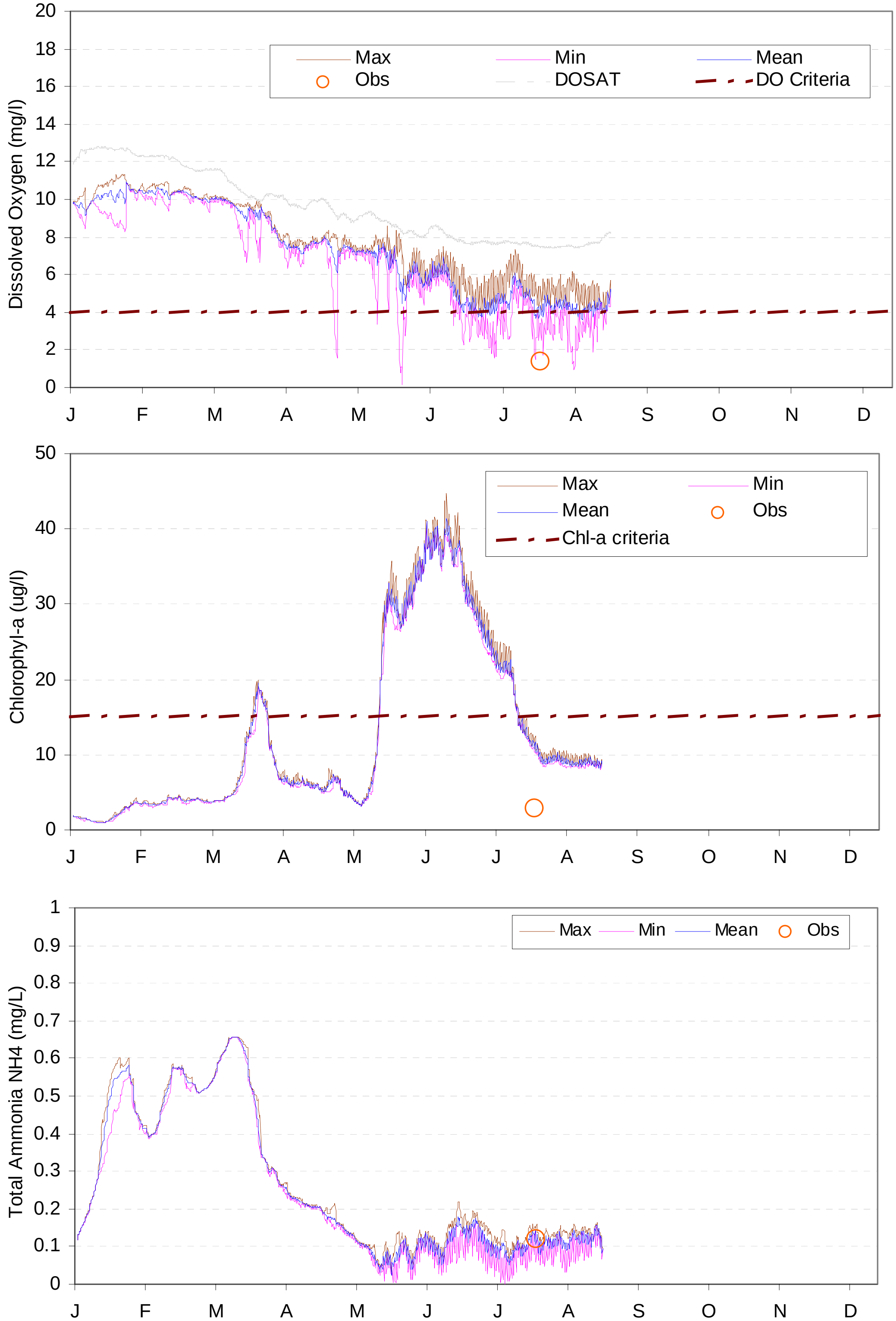
D_2004-4 Lost River at Crystal Springs (WDUS/LRWRC) –2004 continued



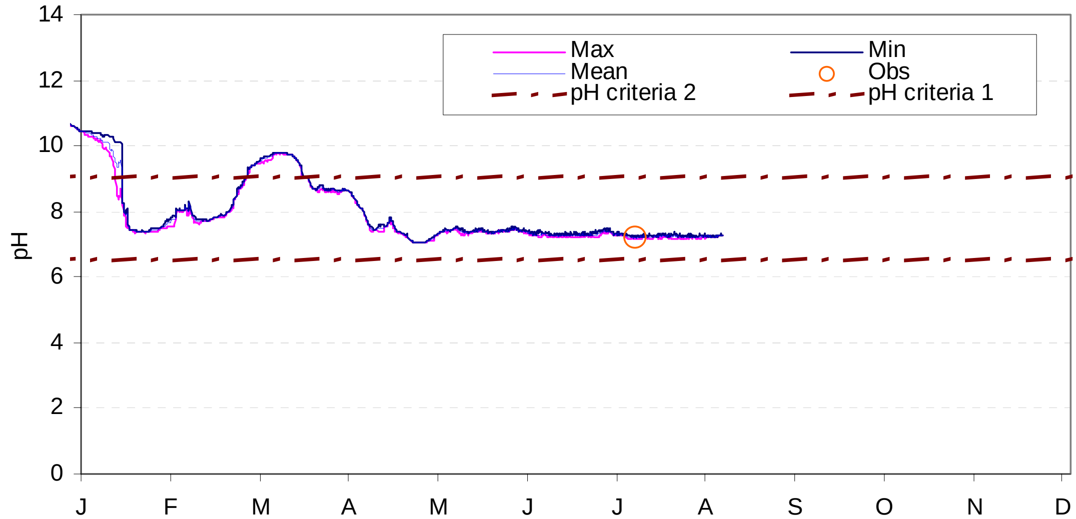


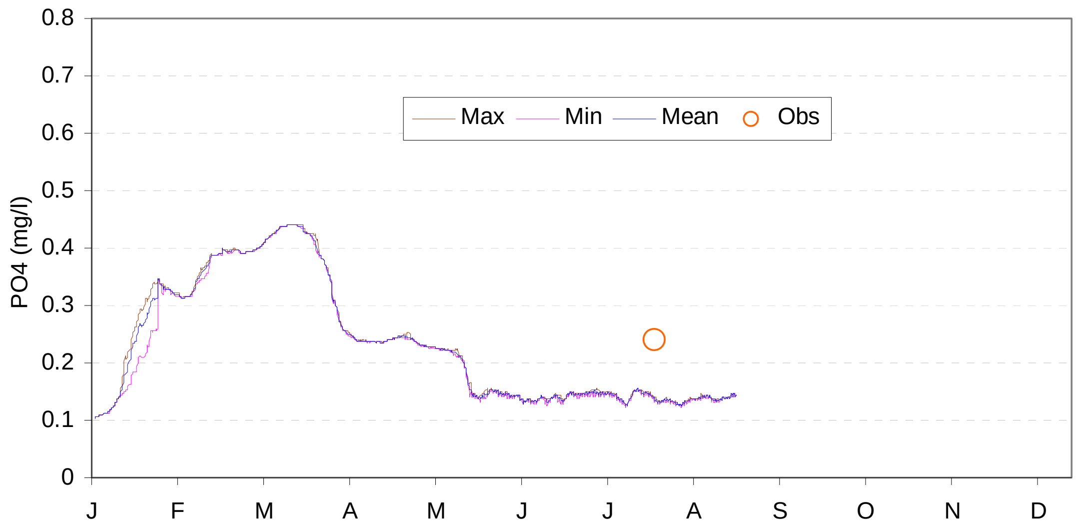


D_2004-4 Lost River at Crystal Springs (WDUS/LRWRC) –2004 continued

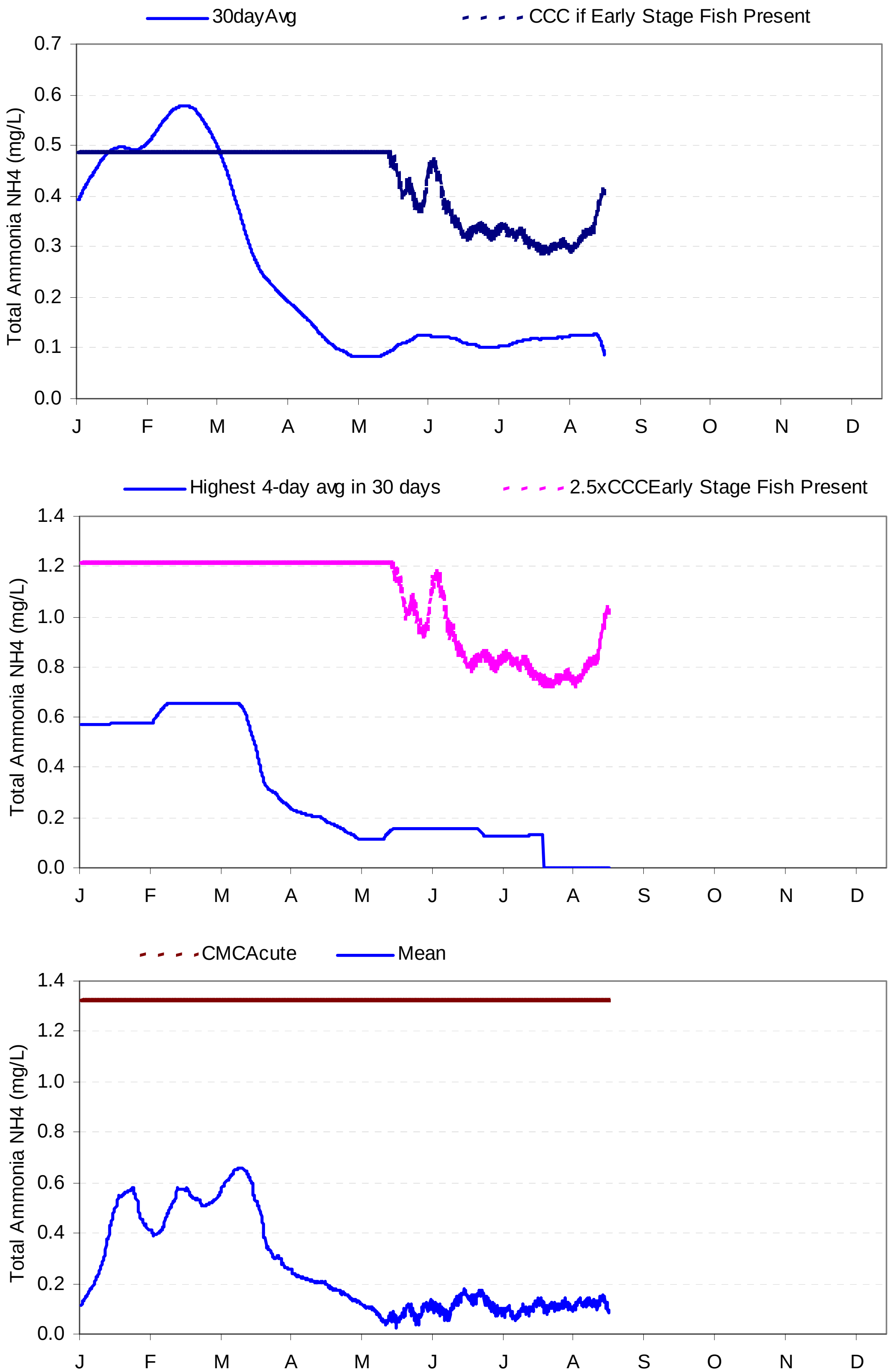


D_2004-5 Upstream of Anderson Rose Dam (ARDMUS) –2004

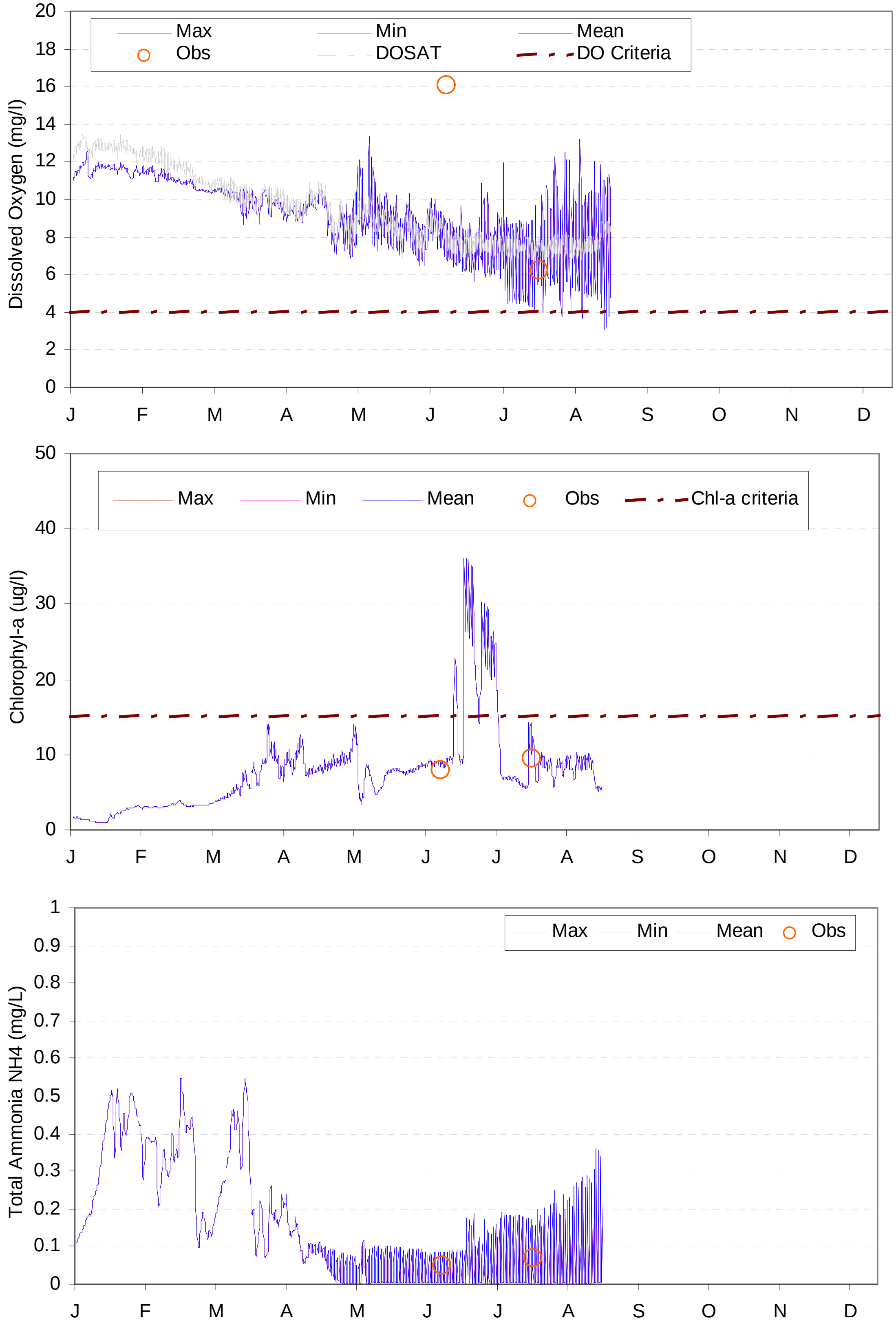




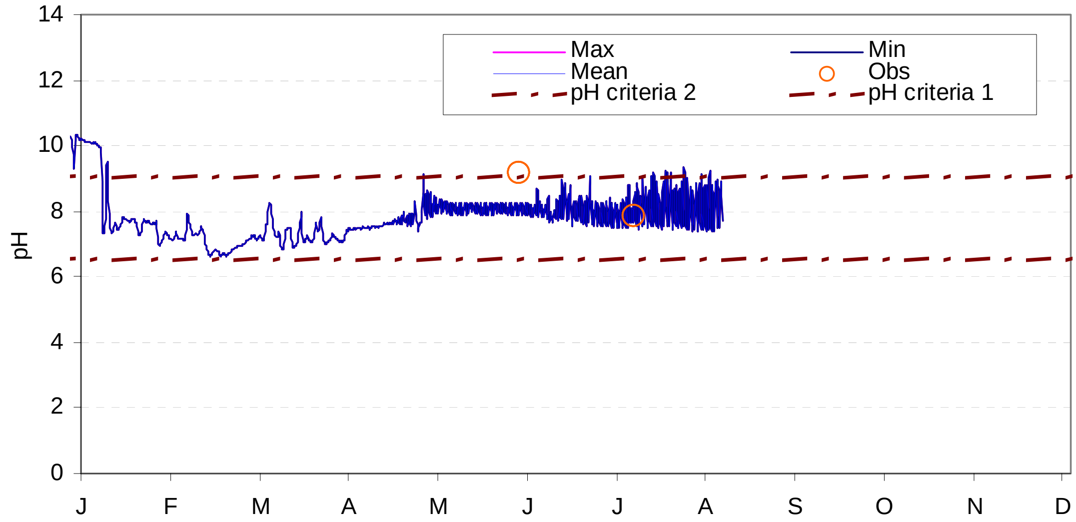
D_2004-5 Upstream of Anderson Rose Dam (ARDMUS) – 2004 continued

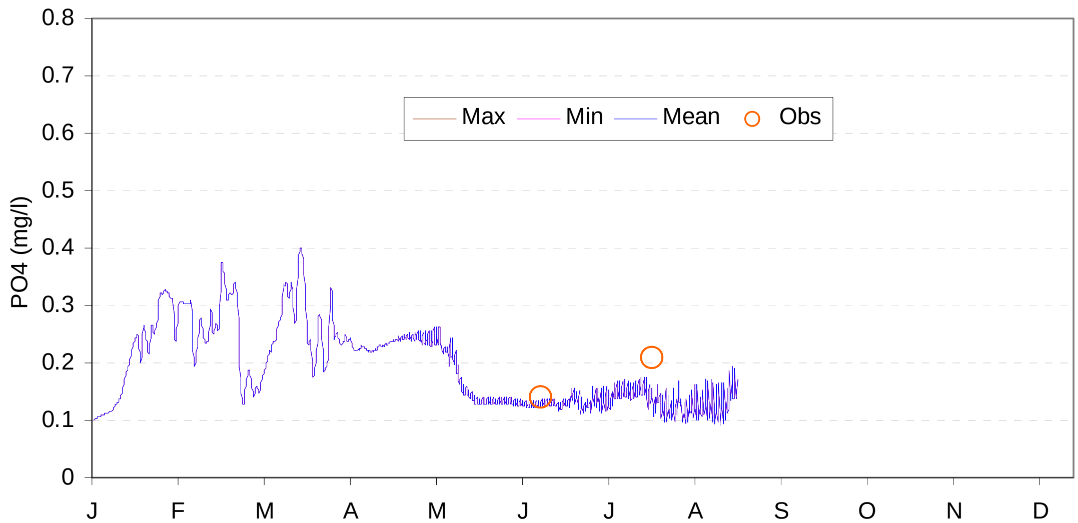


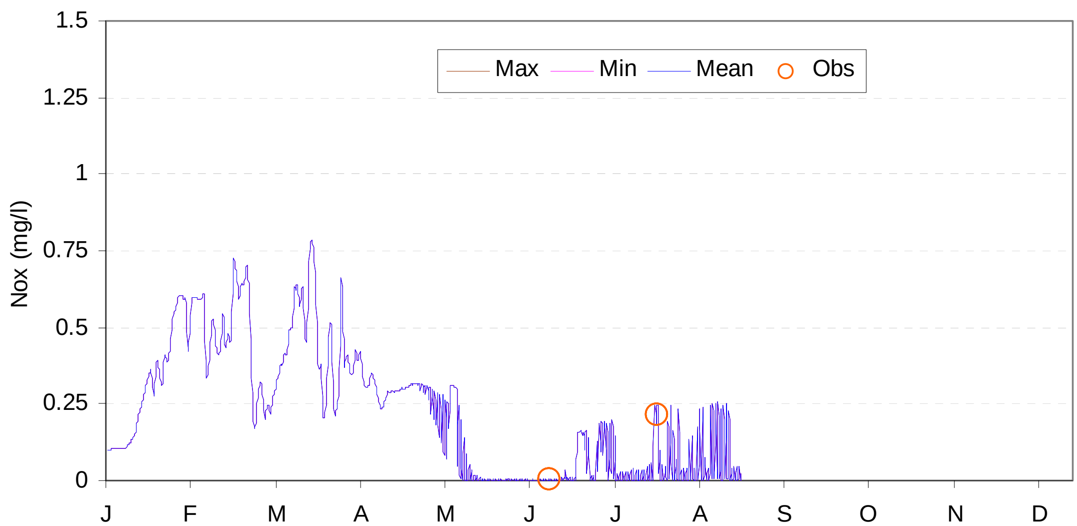
D_2004-5 Upstream of Anderson Rose Dam (ARDMUS) – 2004 continued



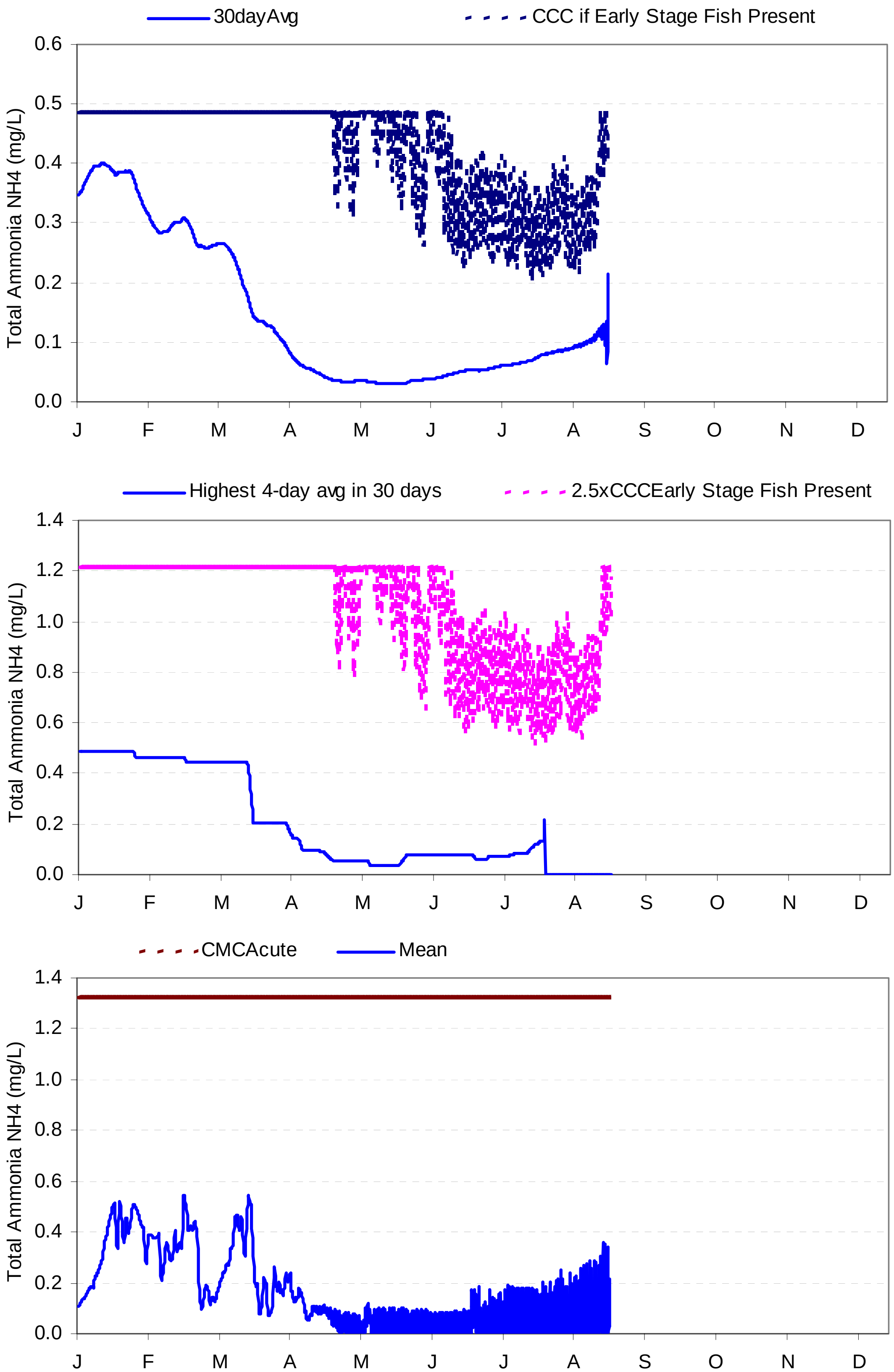
D_2004-6 Lost River at East West Road (LREW) – 2004



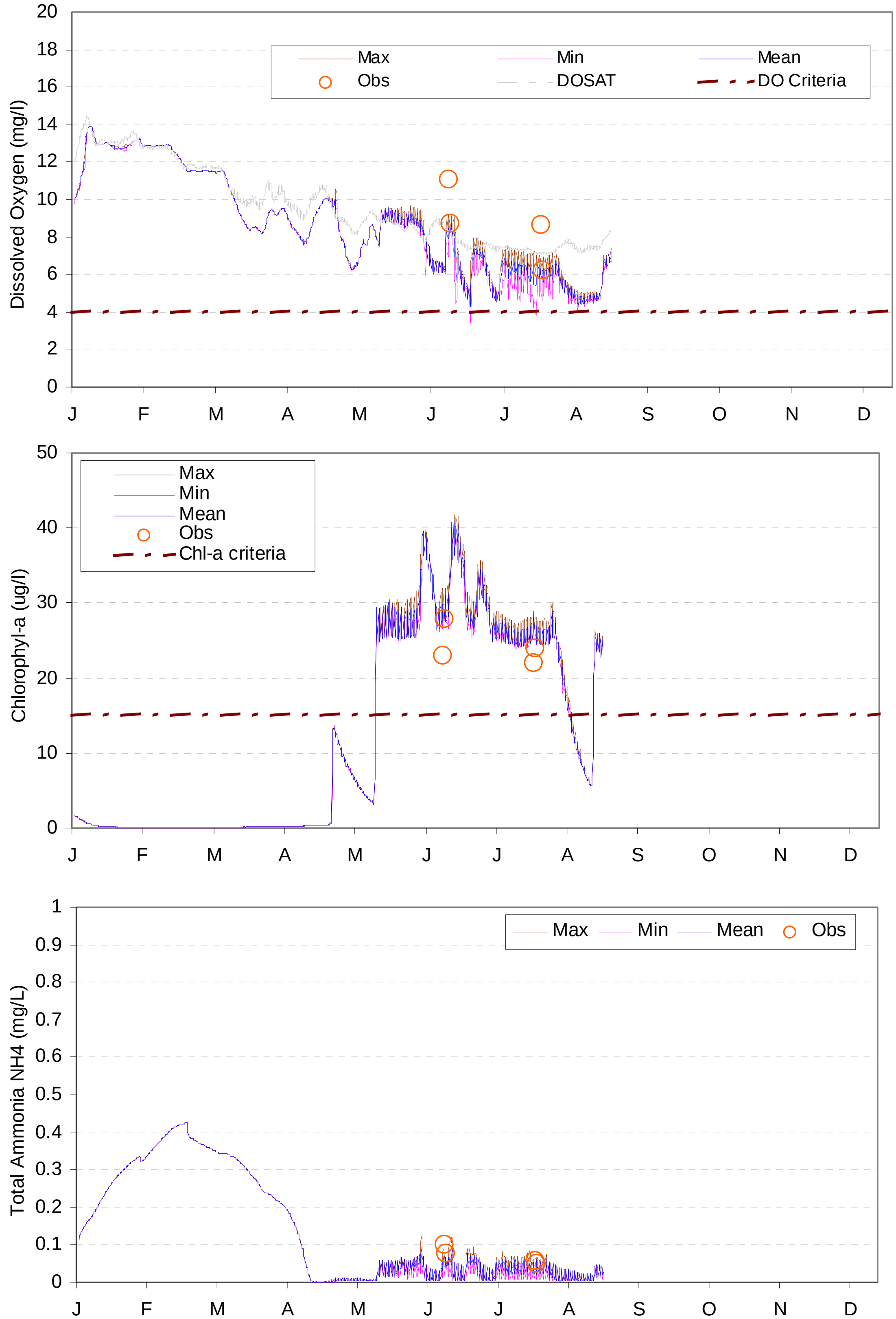




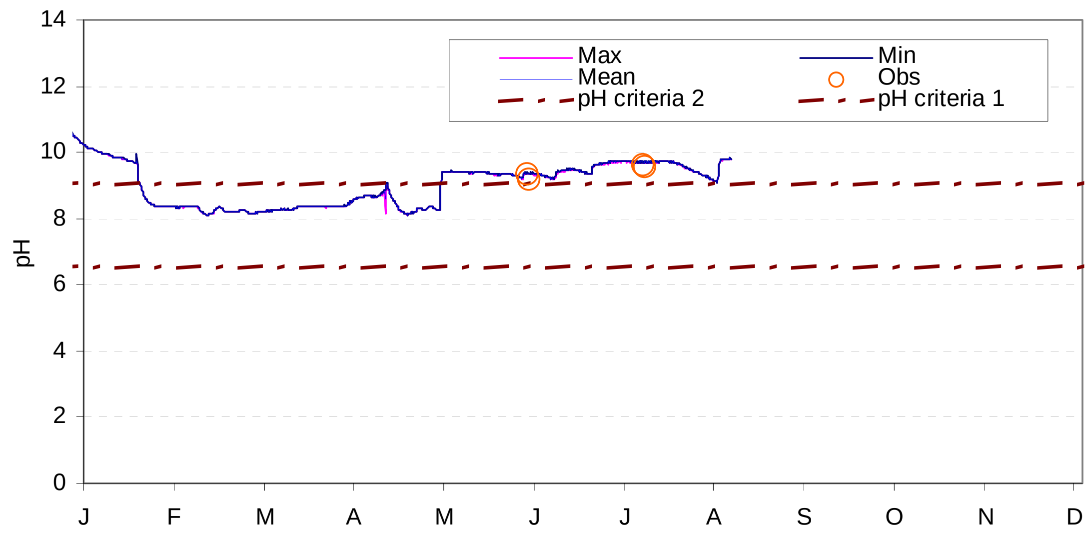
D_2004-6 Lost River at East West Road (LREW) – 2004 continued

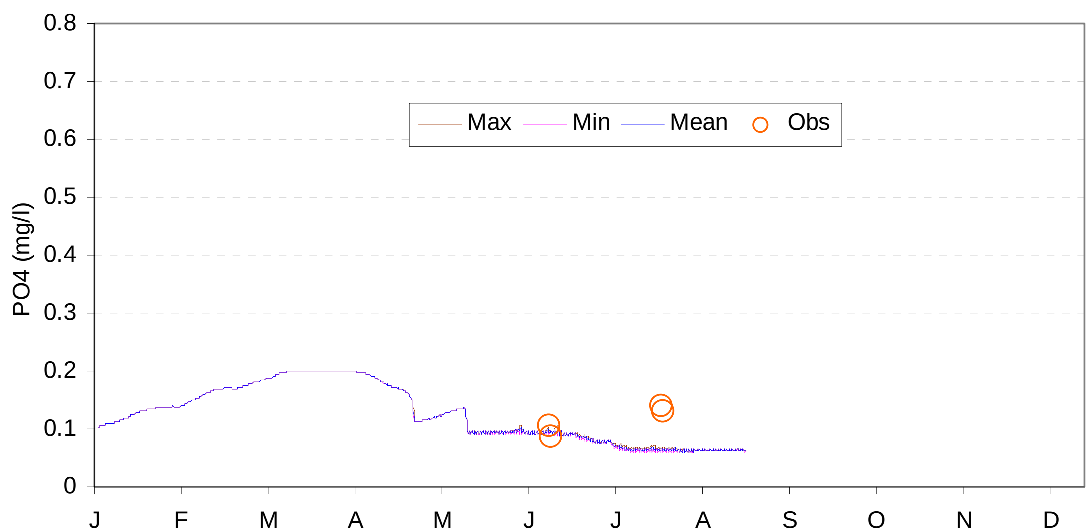


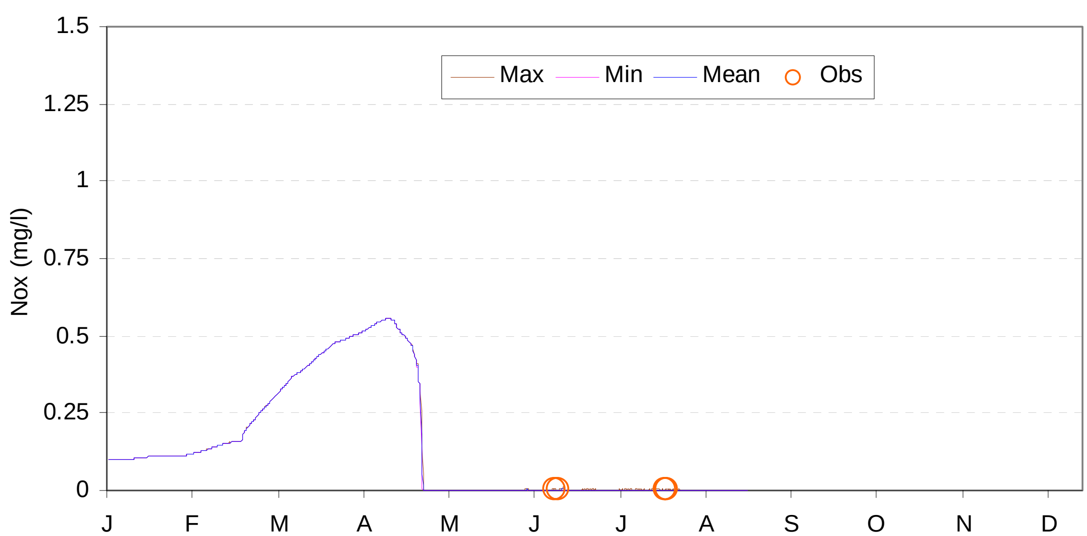
D_2004-6 Lost River at East West Road (LREW) – 2004 continued



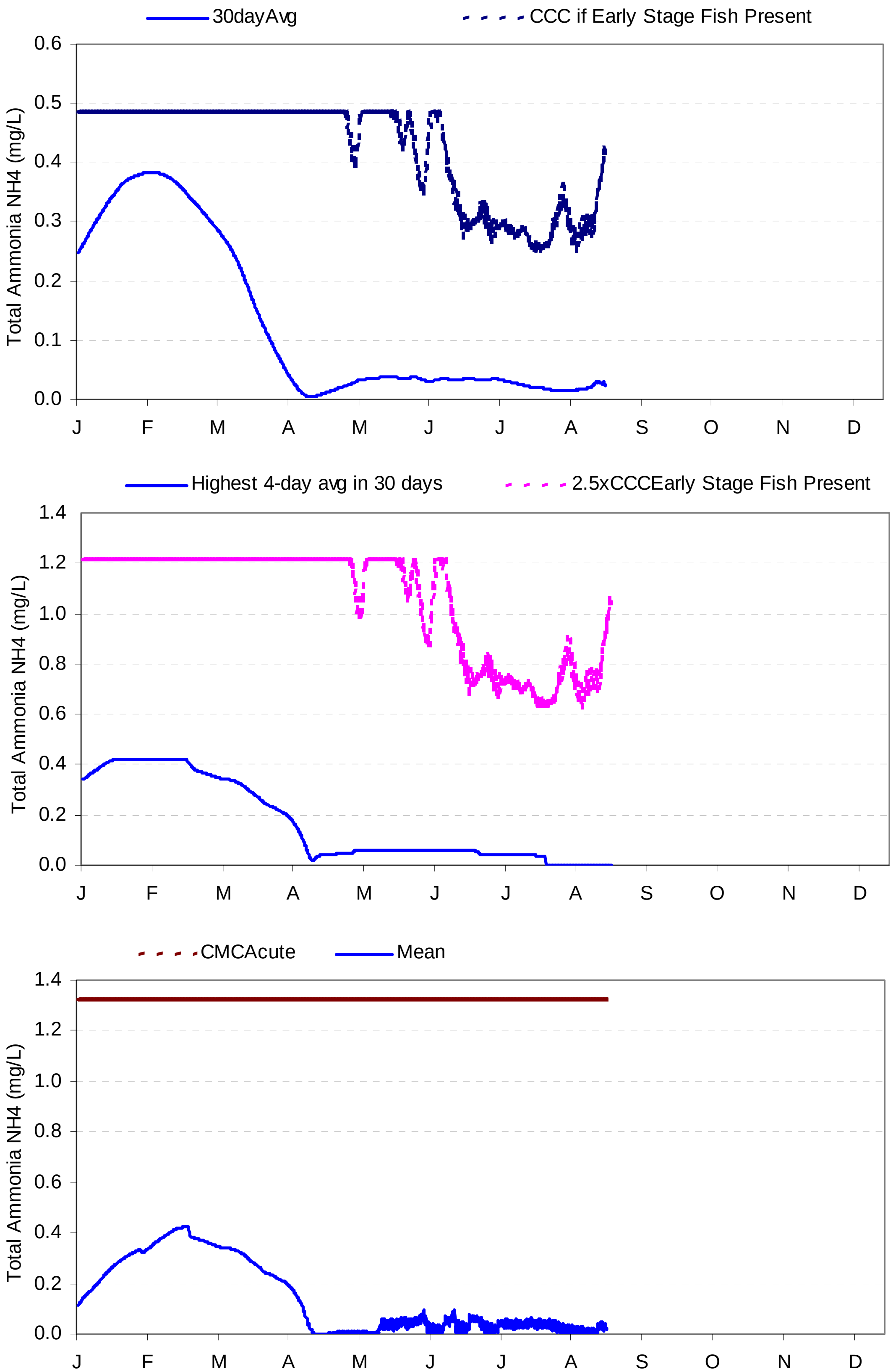
D_2004-7 P-Canal (PC) – 2004



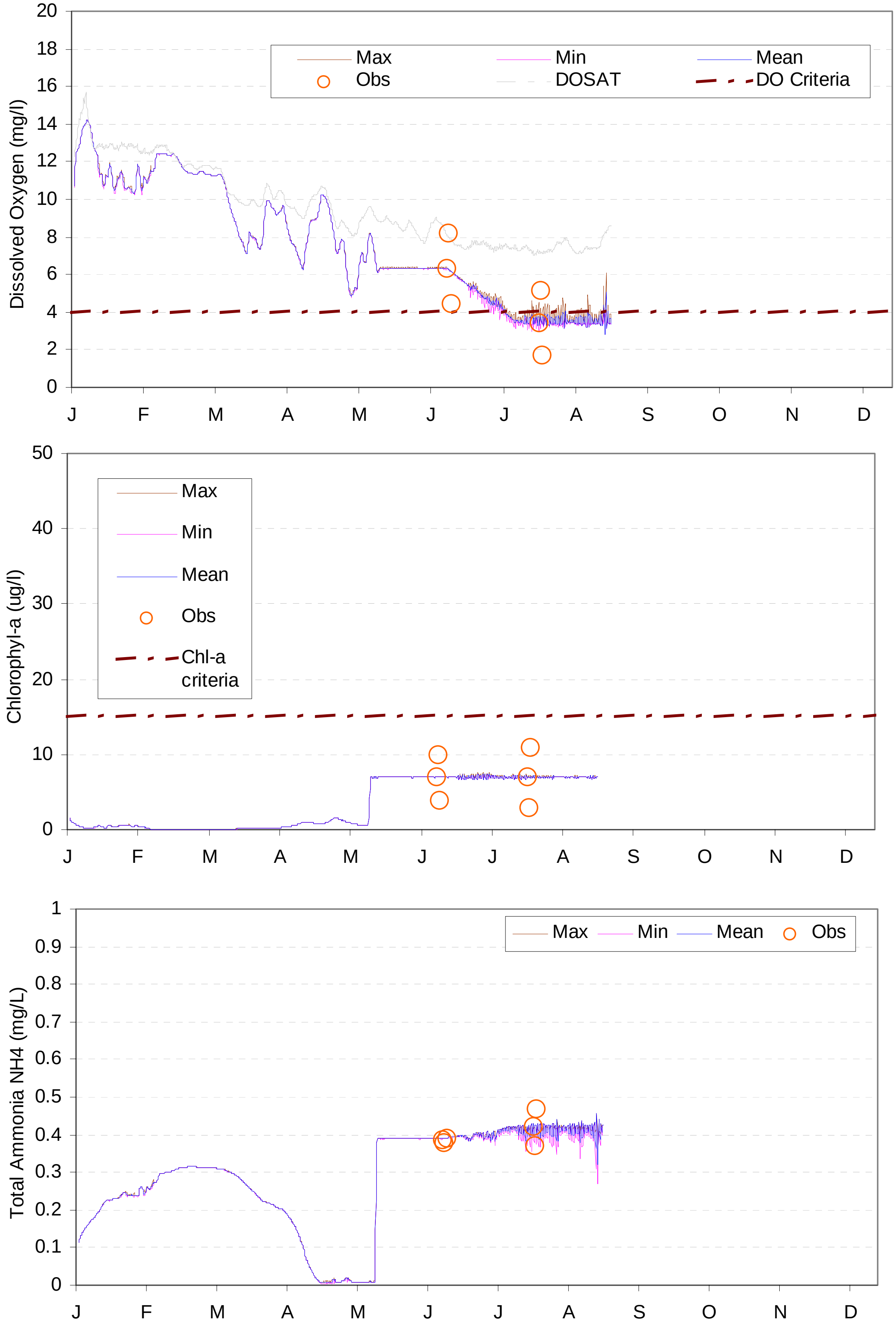




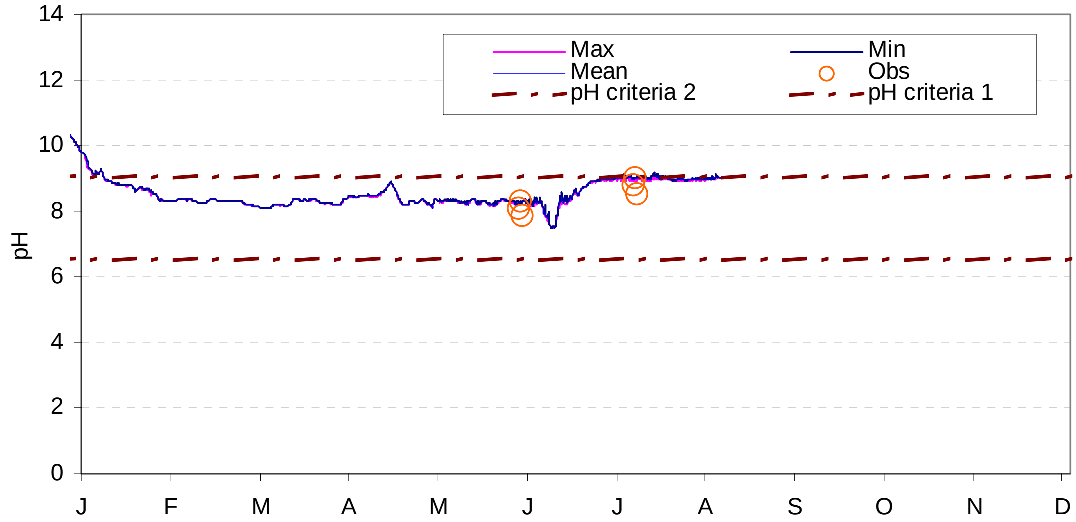
D_2004-7 P-Canal (PC) – 2004 continued

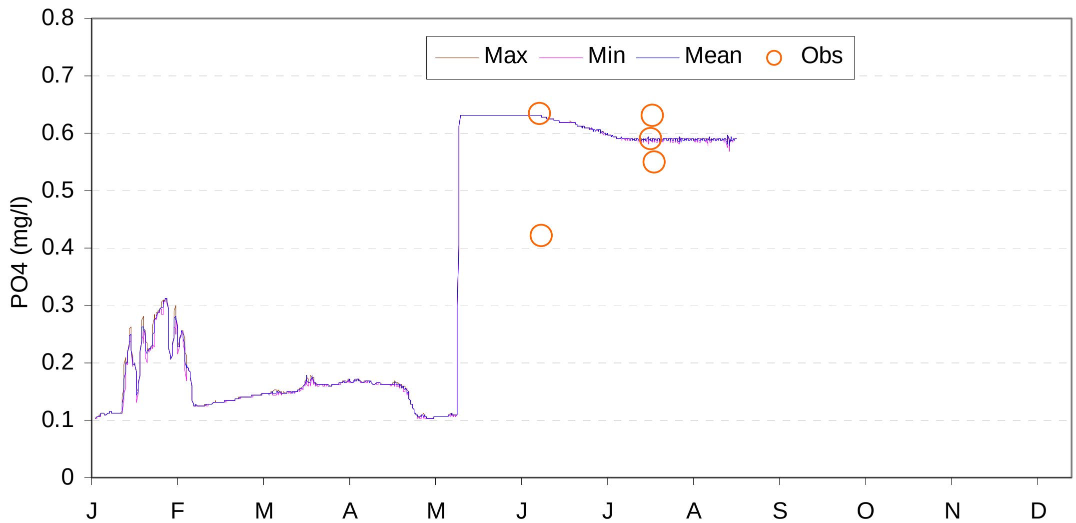


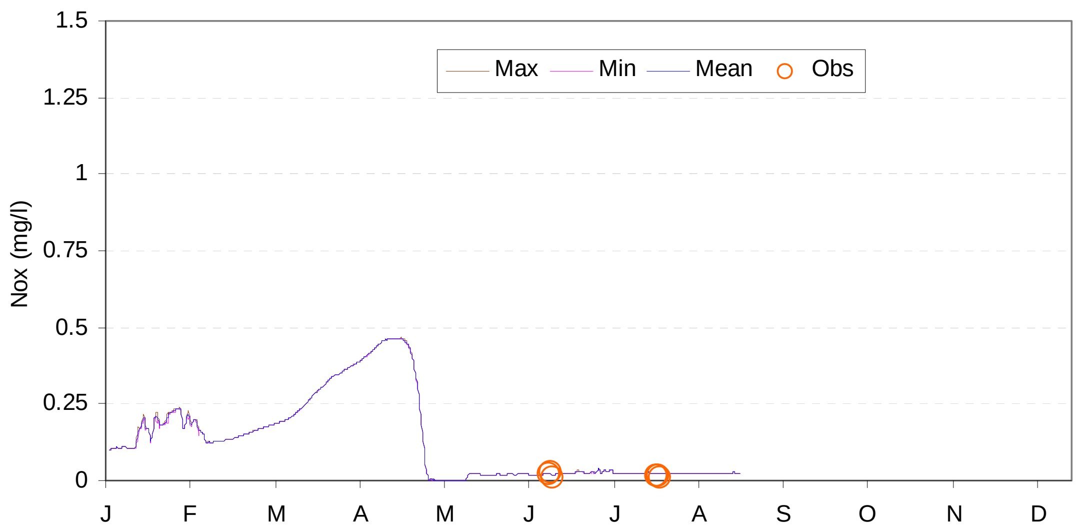
D_2004-7 P-Canal (PC) – 2004 continued



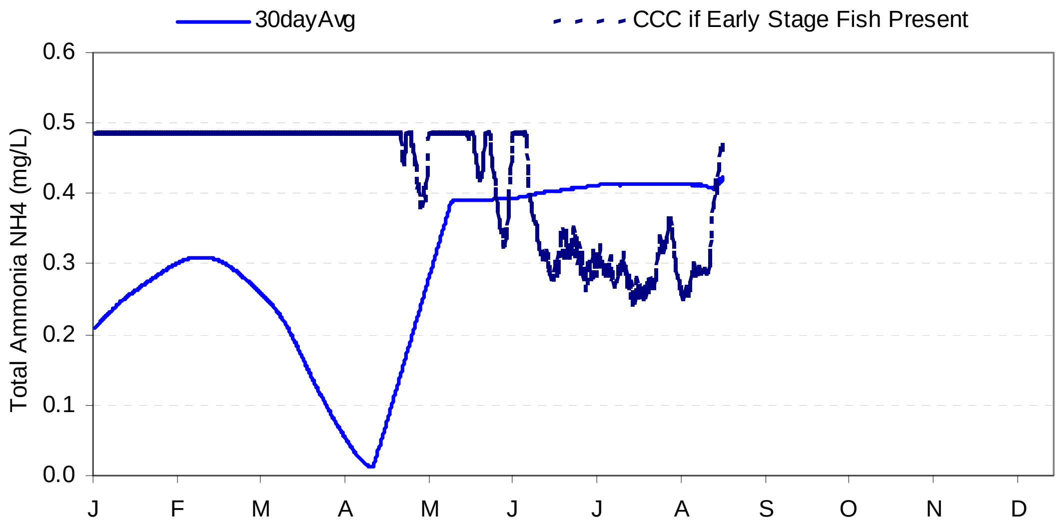
D_2004-8 Klamath Straits Drain at Stateline Road (KSDSR) – 2004

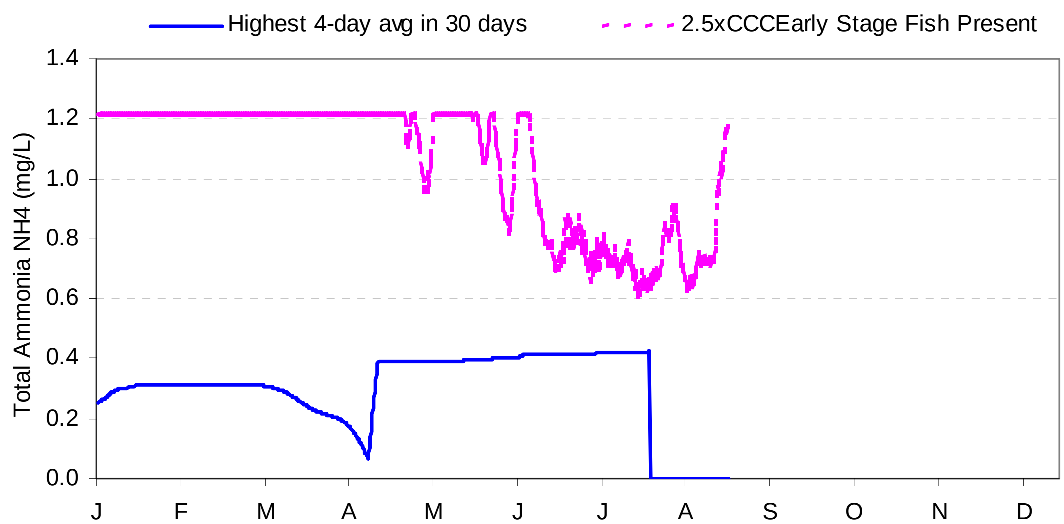


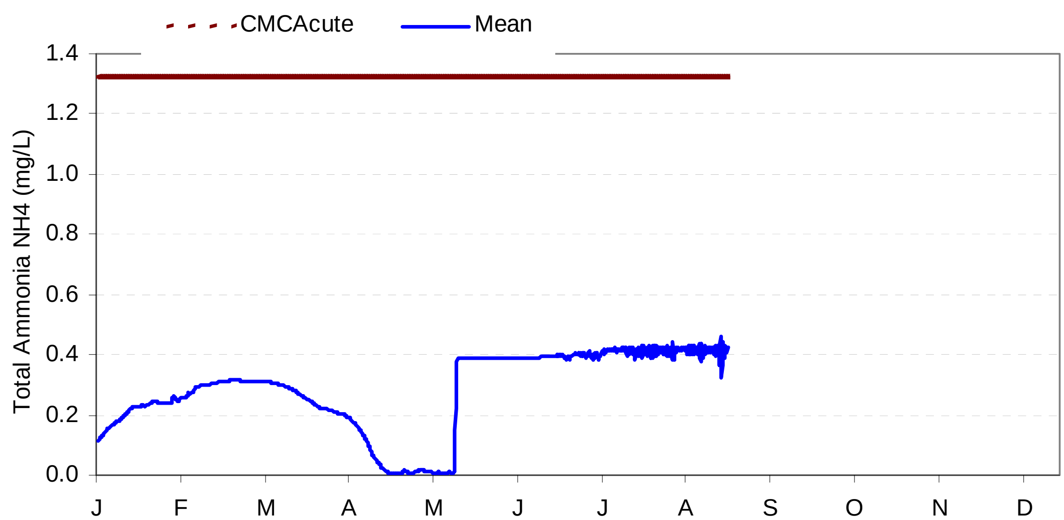




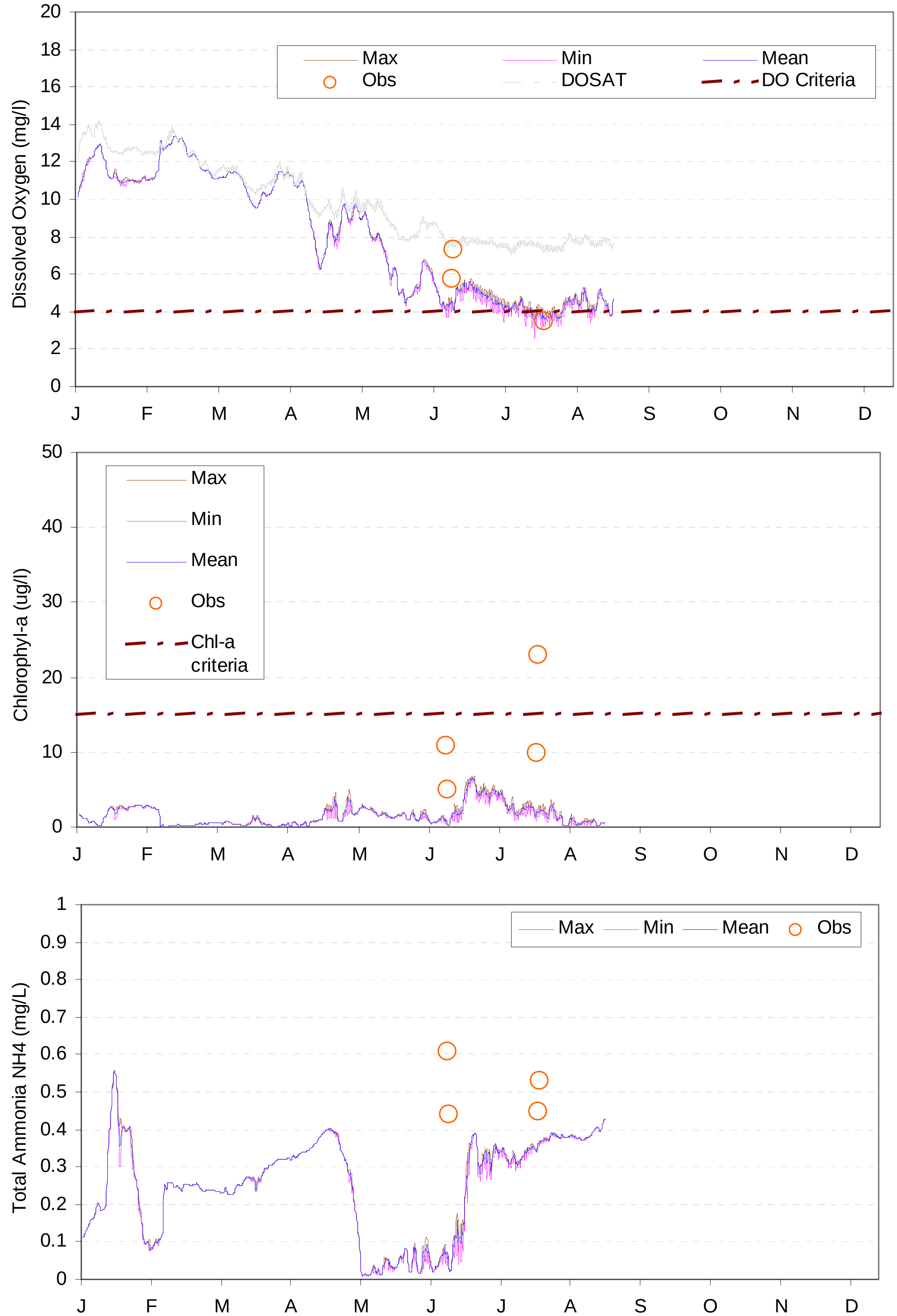
D_2004-8 Klamath Straits Drain at Stateline Road (KSDSR) – 2004 continued



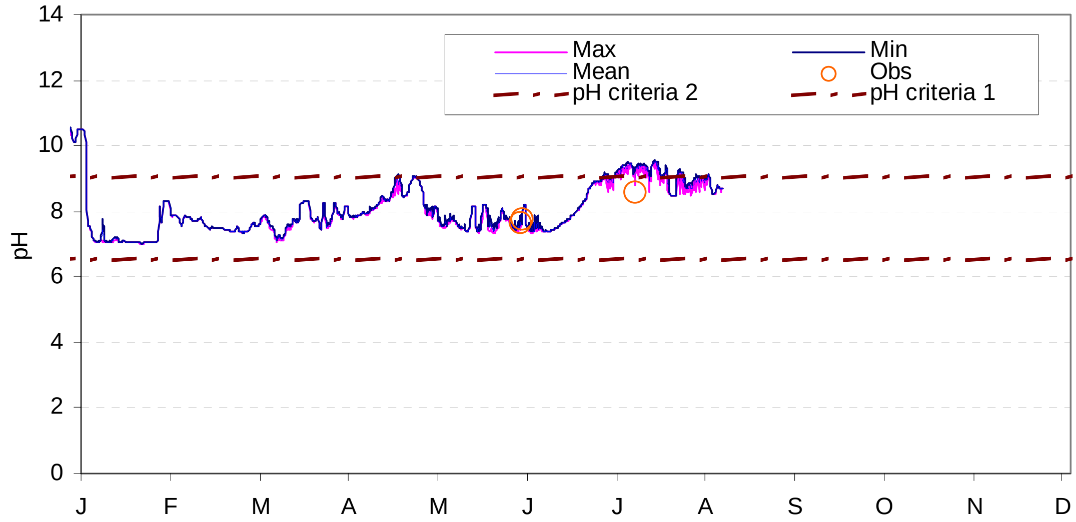


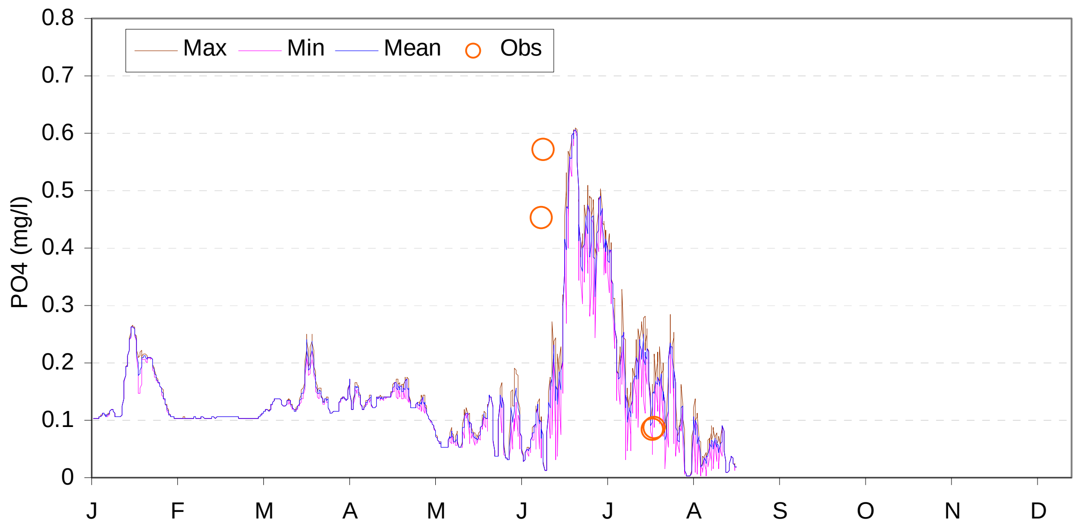


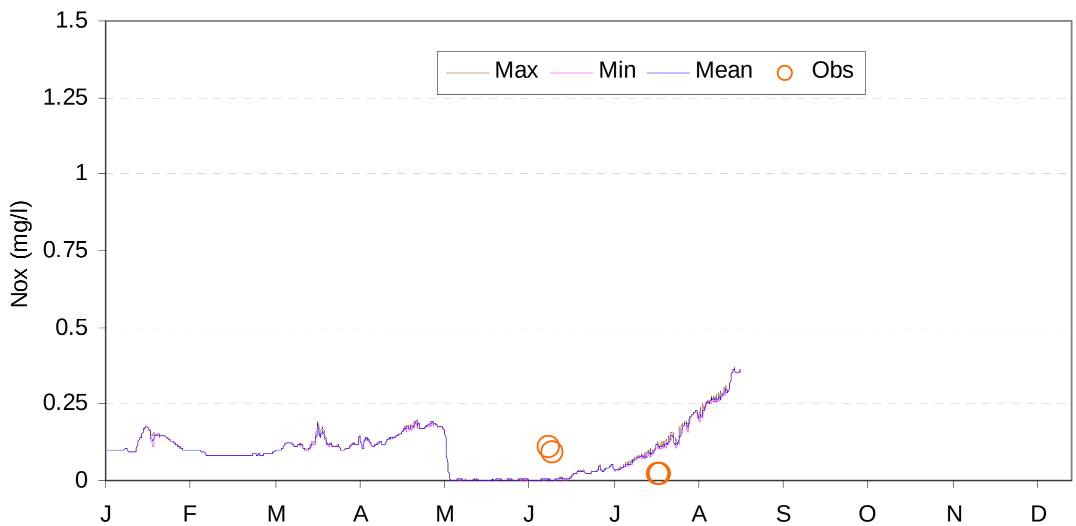
D_2004-8 Klamath Straits Drain at Stateline Road (KSDSR) – 2004 continued



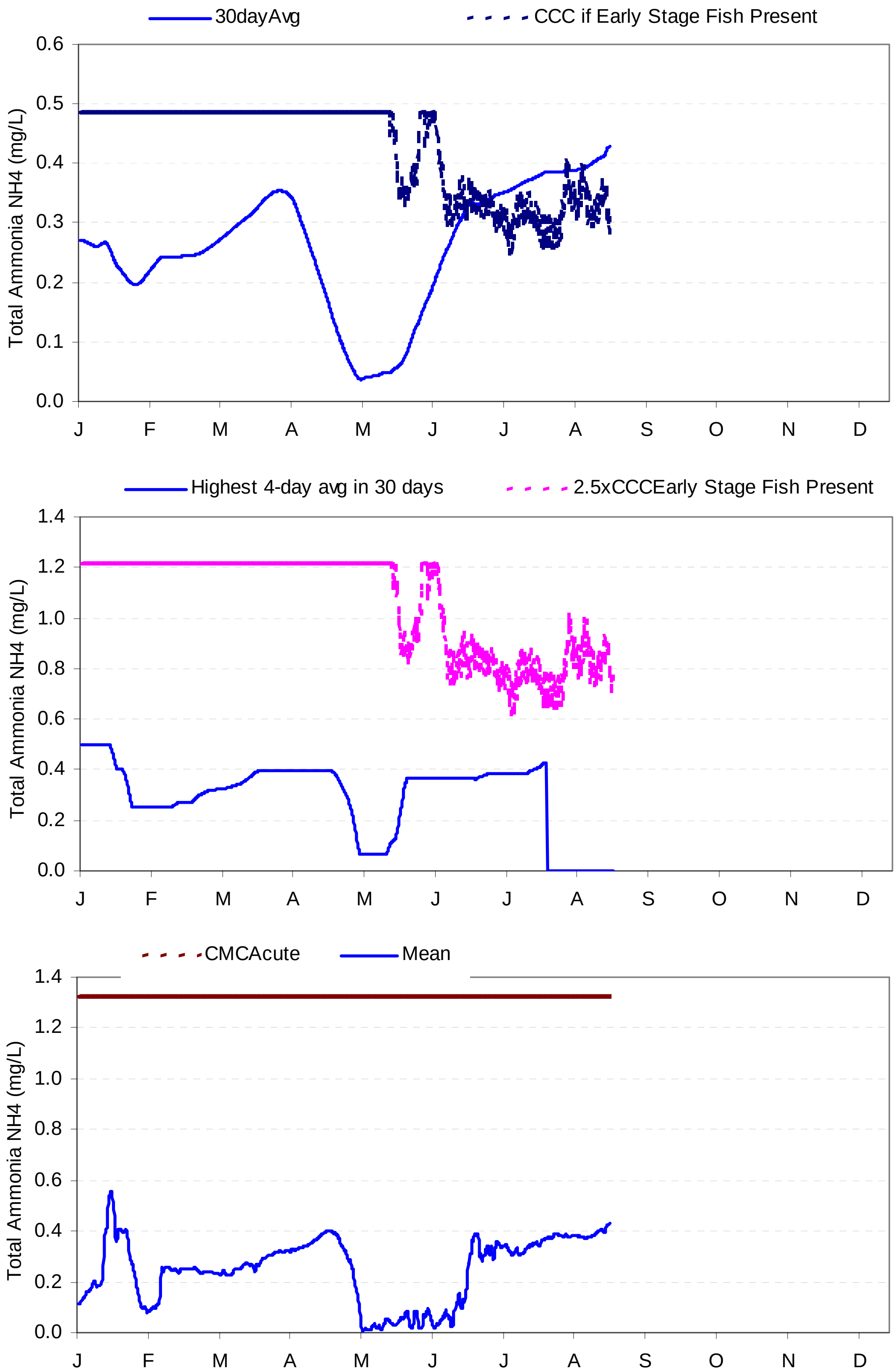
D_2004-9 Klamath Straits Drain at Railroad (KSDM) – 2004







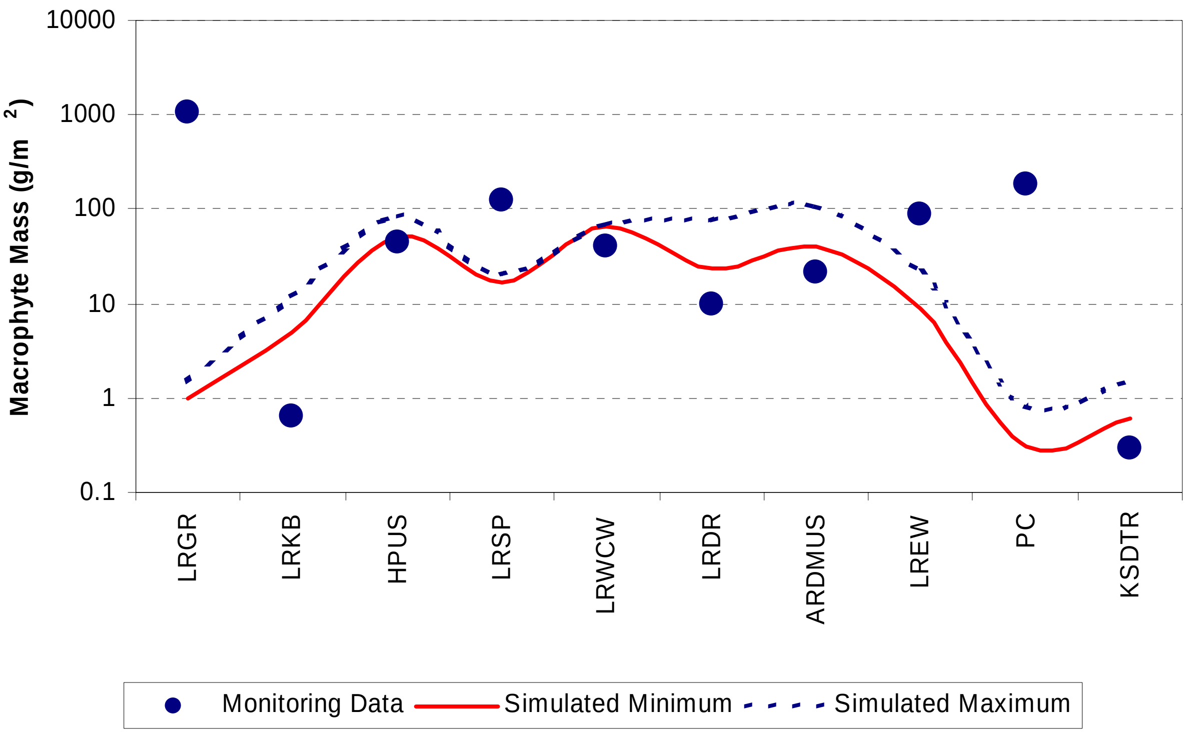
D_2004-9 Klamath Straits Drain at Railroad (KSDM) – 2004 continued



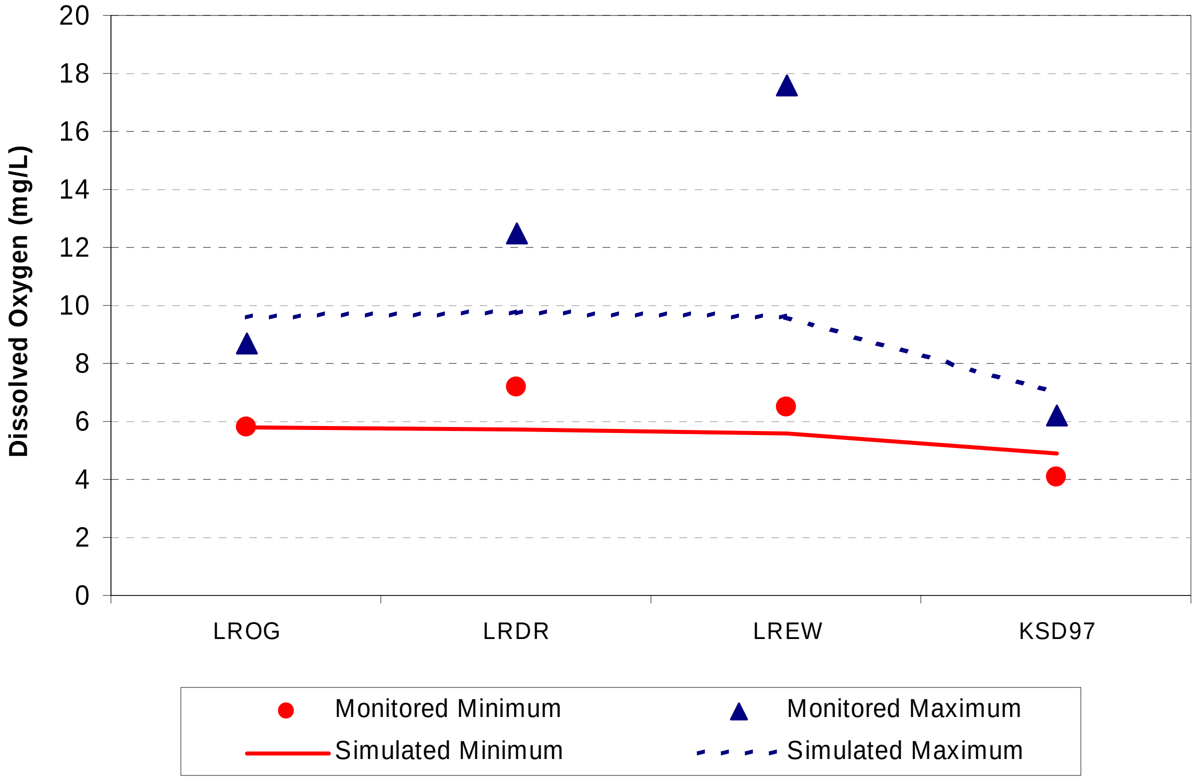
D_2004-9 Klamath Straits Drain at Railroad (KSDM) – 2004 continued

Appendix E_2004

Evaluation of Macrophyte Mass and Diel DO Comparison



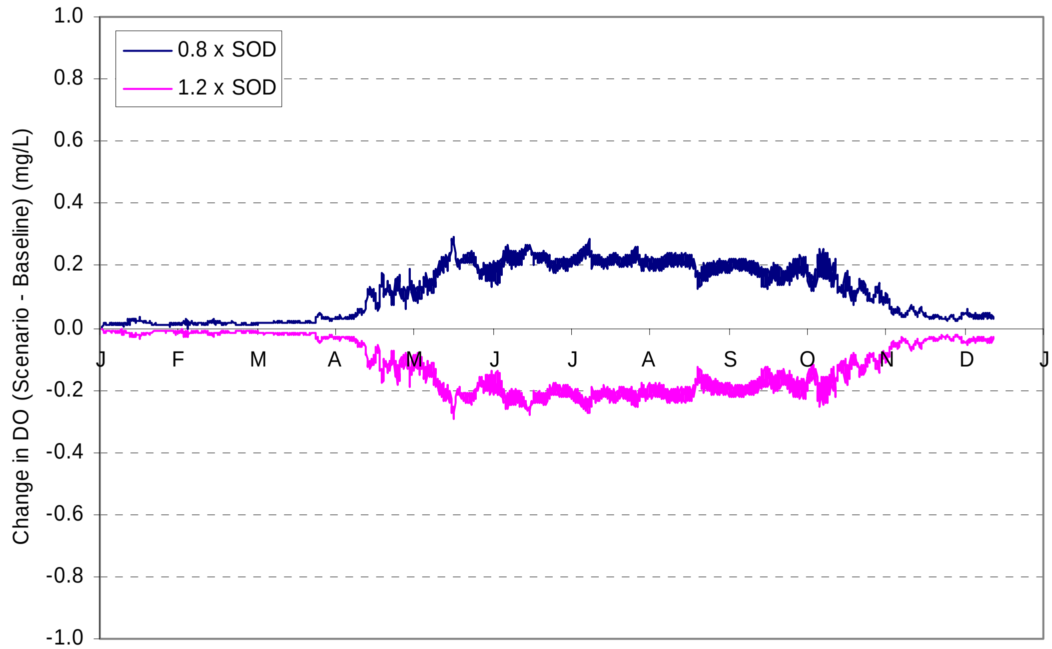
E_2004-1 Comparison of macrophyte mass (g/m^2) along the Lost River



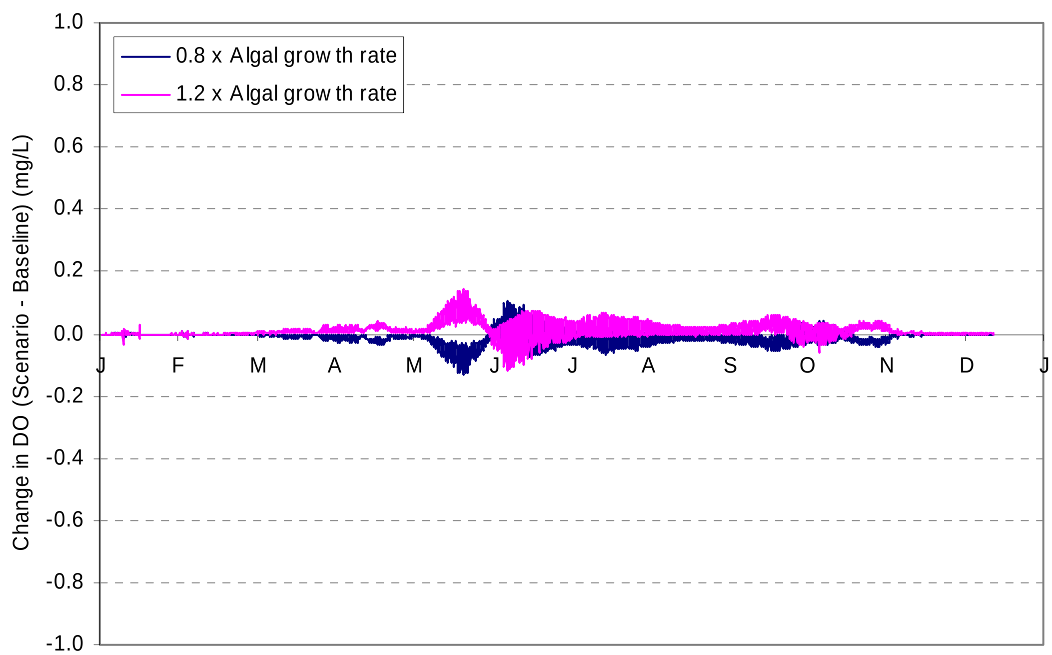
E_2004-1 Comparison of diel DO along the Lost River

Appendix F_1999

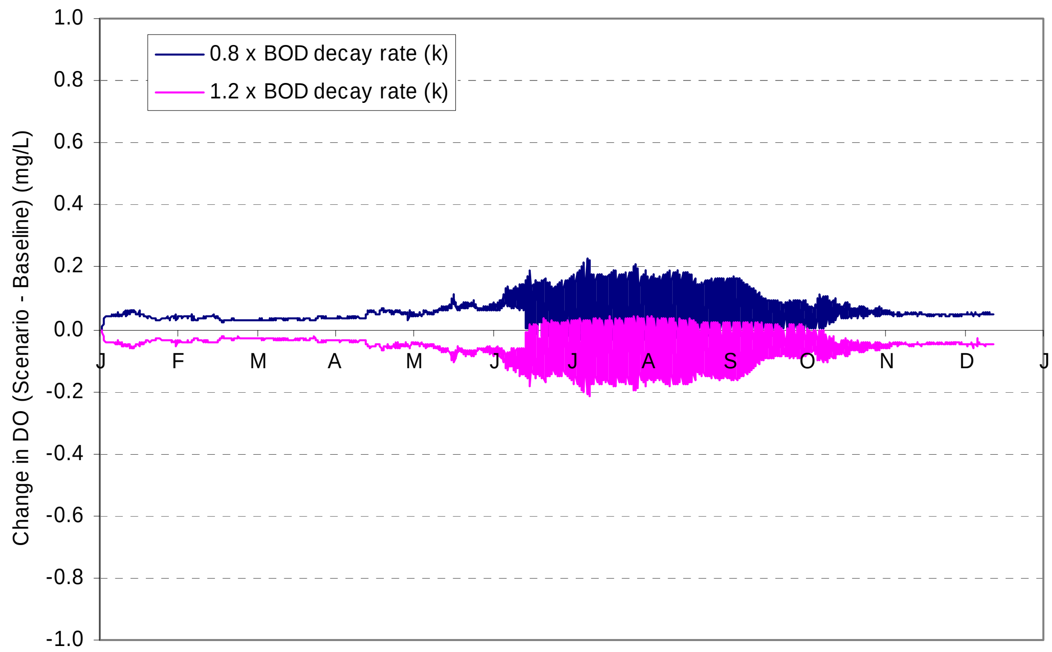
Sensitivity Analysis



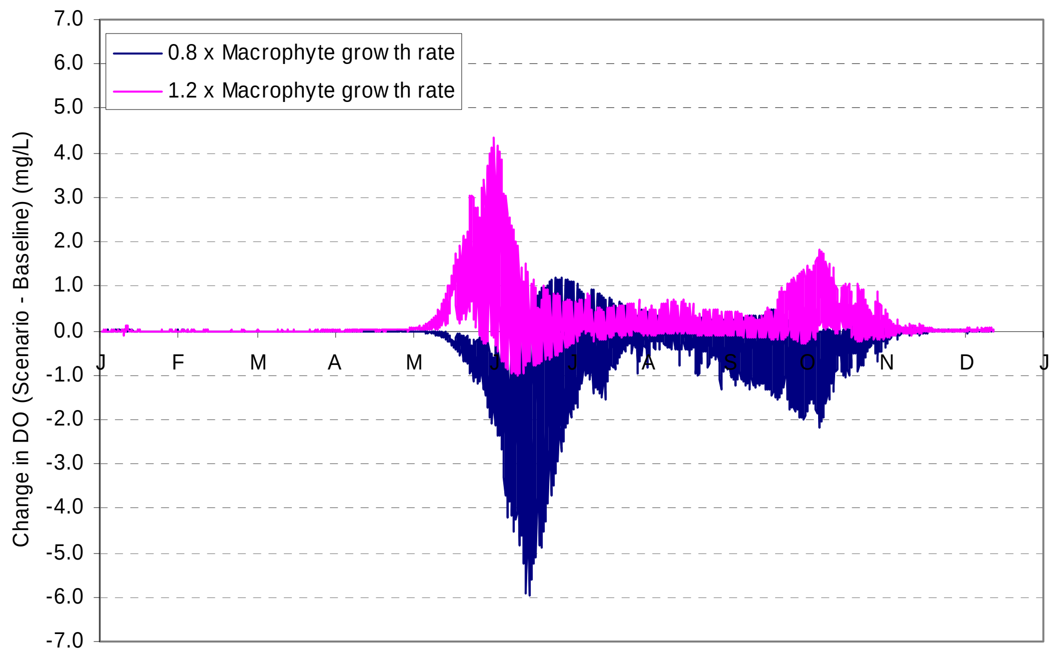
F_1999-1 SOD sensitivity simulation at Lost River at Harpold Dam (LRHD)



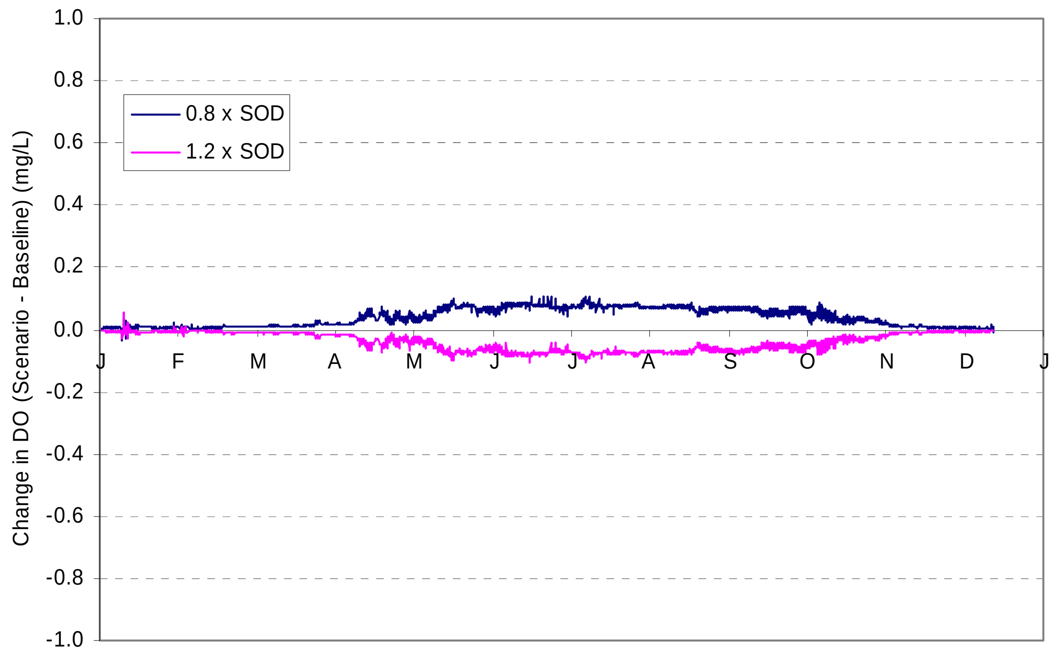
F_1999-2 Algal growth rate sensitivity simulation - Lost River at Harpold Dam (LRHD)



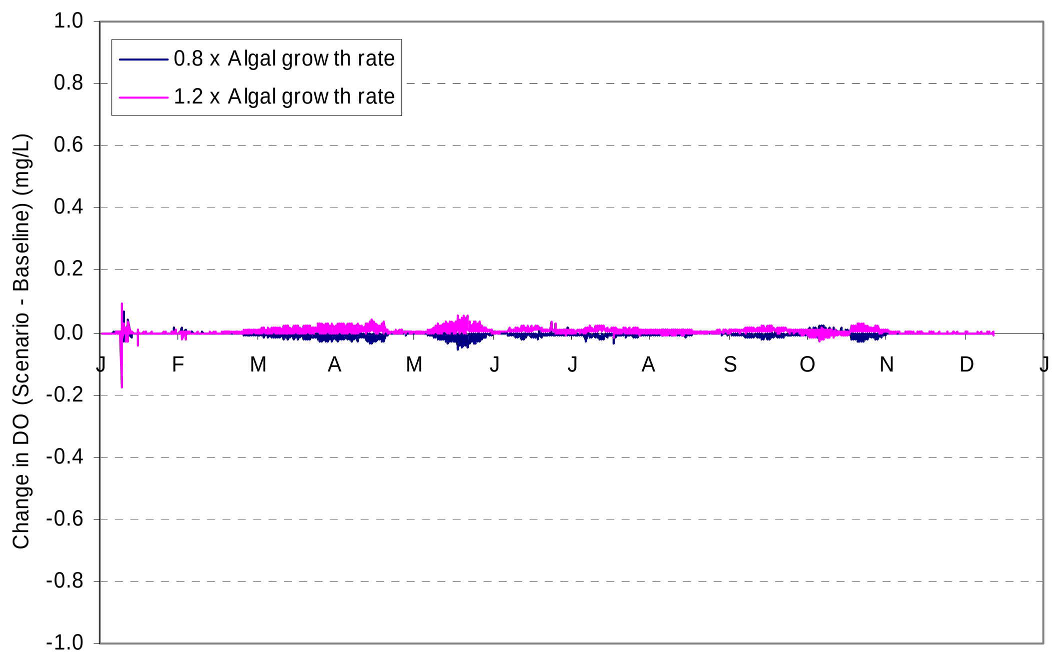
F_1999-3 BOD decay rate sensitivity simulation - Lost River at Harpold Dam (LRHD)



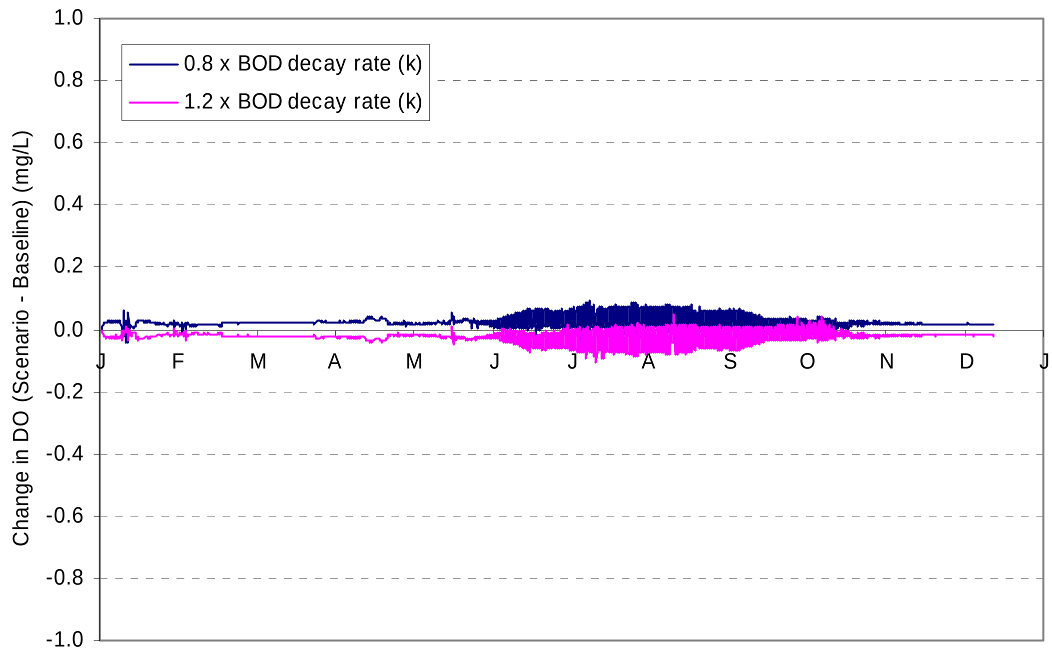
F_1999-4 Macrophyte growth rate sensitivity simulation - Lost River at Harpold Dam (LRHD)



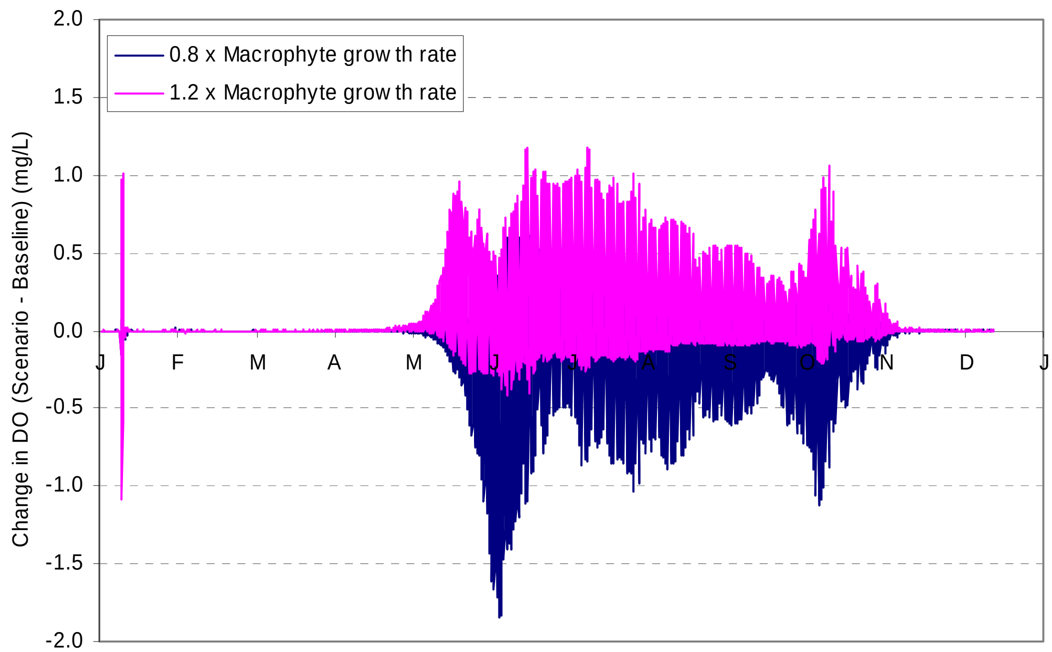
F_1999-5 SOD sensitivity simulation - Lost River at Keller Bridge (LRKB)



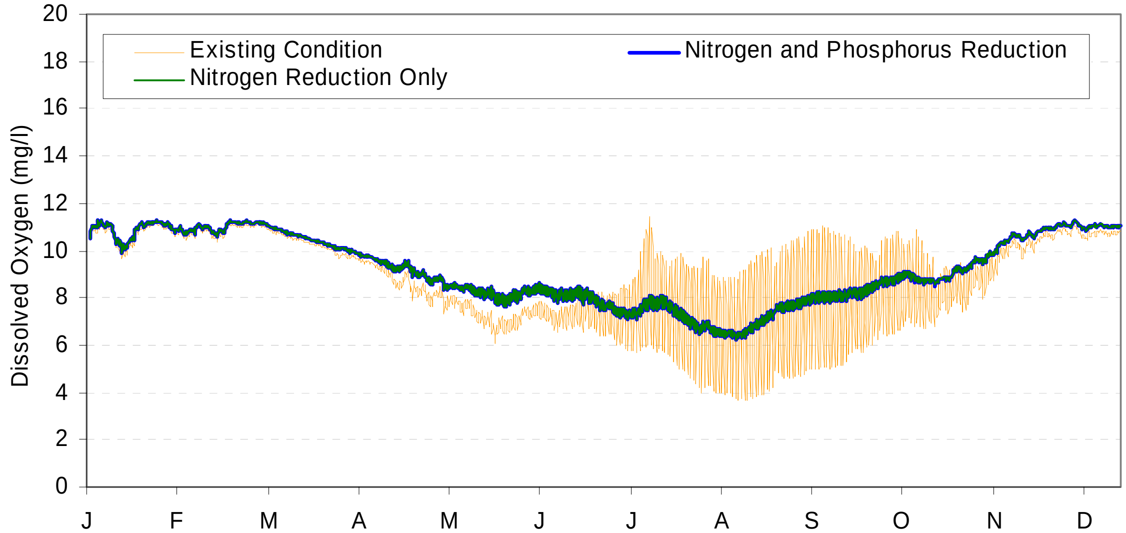
F_1999-6 Algal growth rate sensitivity simulation - Lost River at Keller Bridge (LRKB)



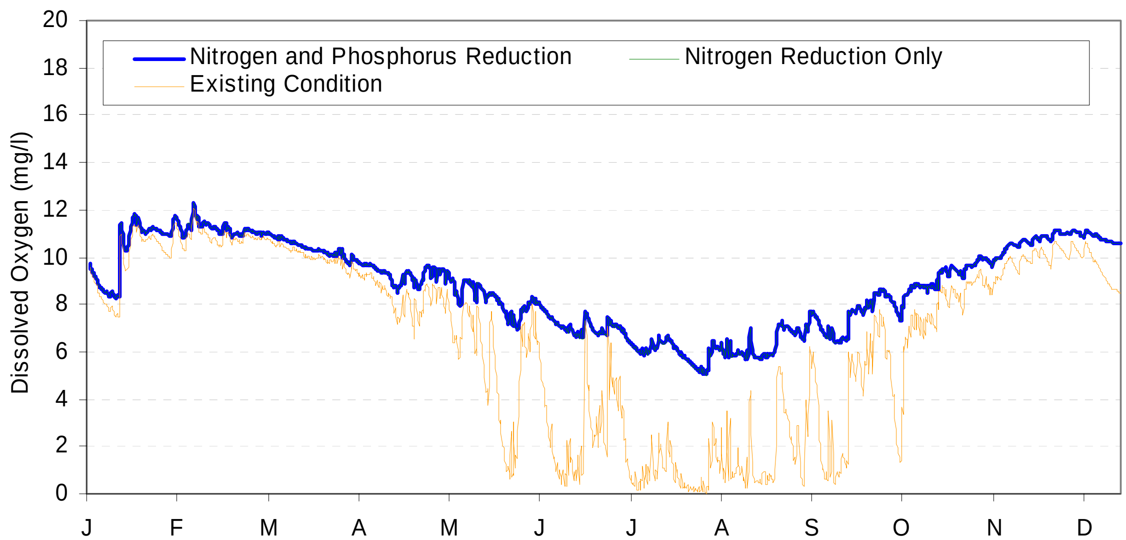
F_1999-7 BOD decay rate sensitivity simulation - Lost River at Keller Bridge (LRKB)



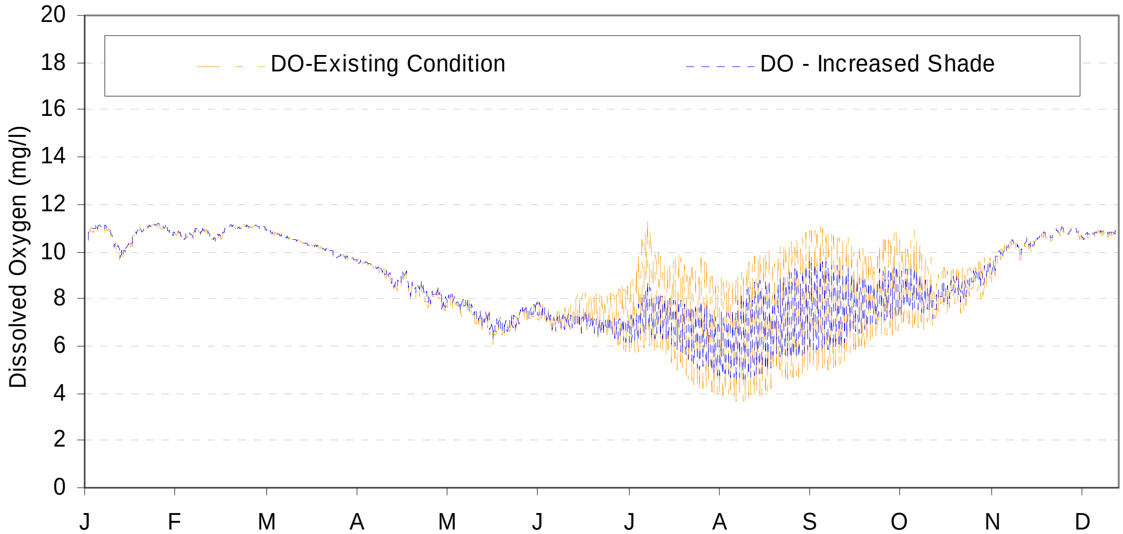
F_1999-8 Macrophyte growth rate sensitivity simulation - Lost River at Keller Bridge (LRKB)



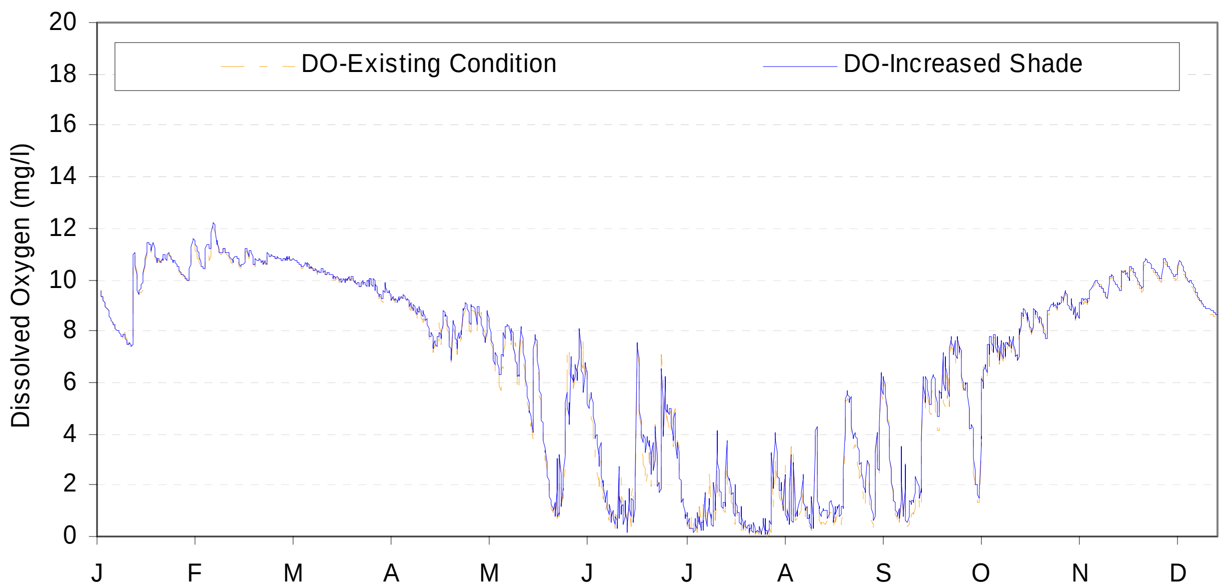
F_1999-9 Nutrient load reduction simulation – Lost River at Harpold Dam (LRHD)



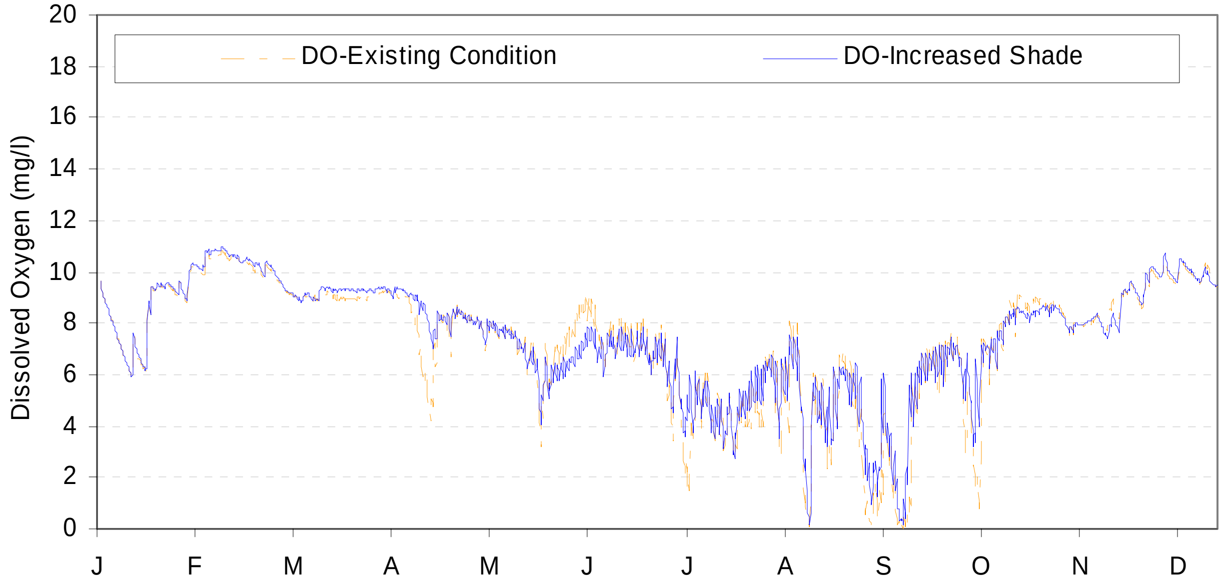
F_1999-10 Nutrient load reduction simulation – Lost River at Crystal Springs (LRWRC)



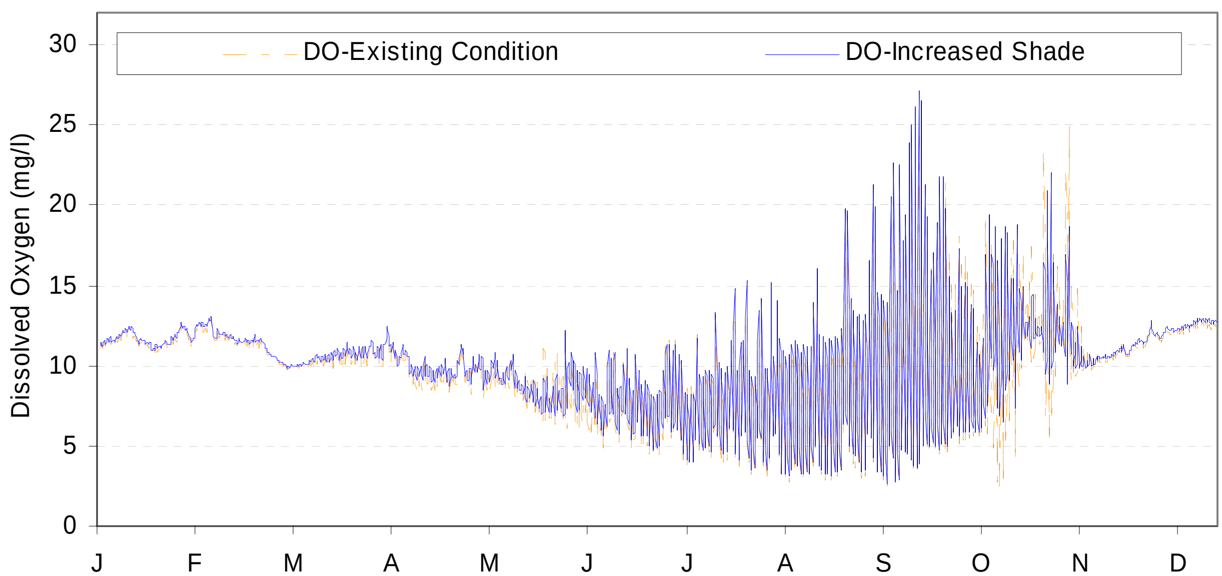
F_1999-11 Increased shade simulation - Lost River at Harpold Dam (LRHD)



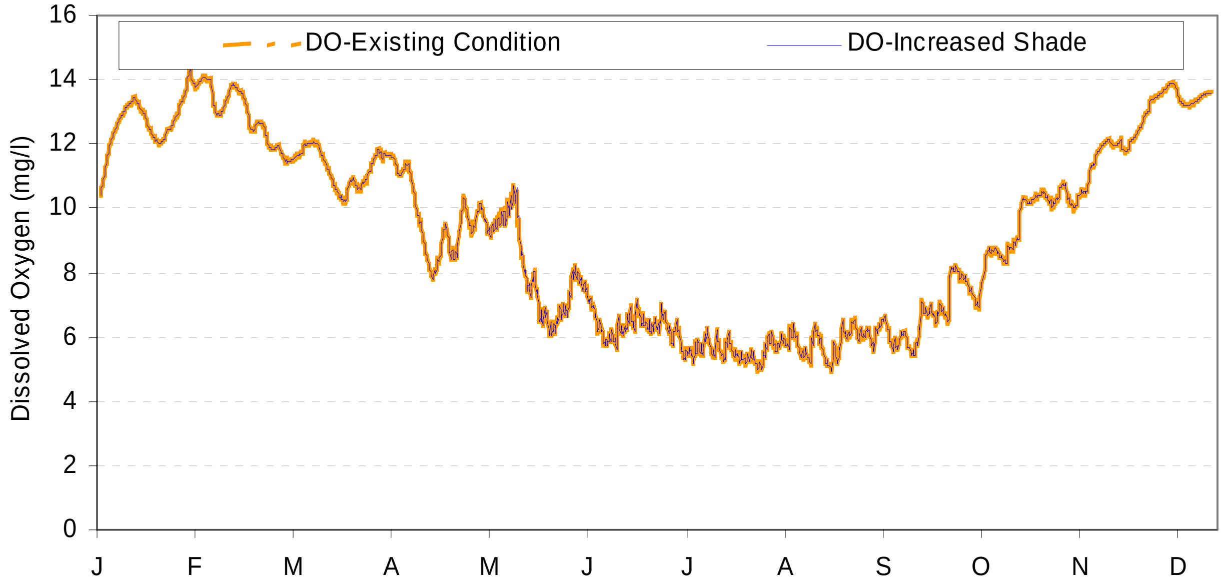
F_1999-12 Increased shade simulation - Lost River at Crystal Springs (LRWRC)



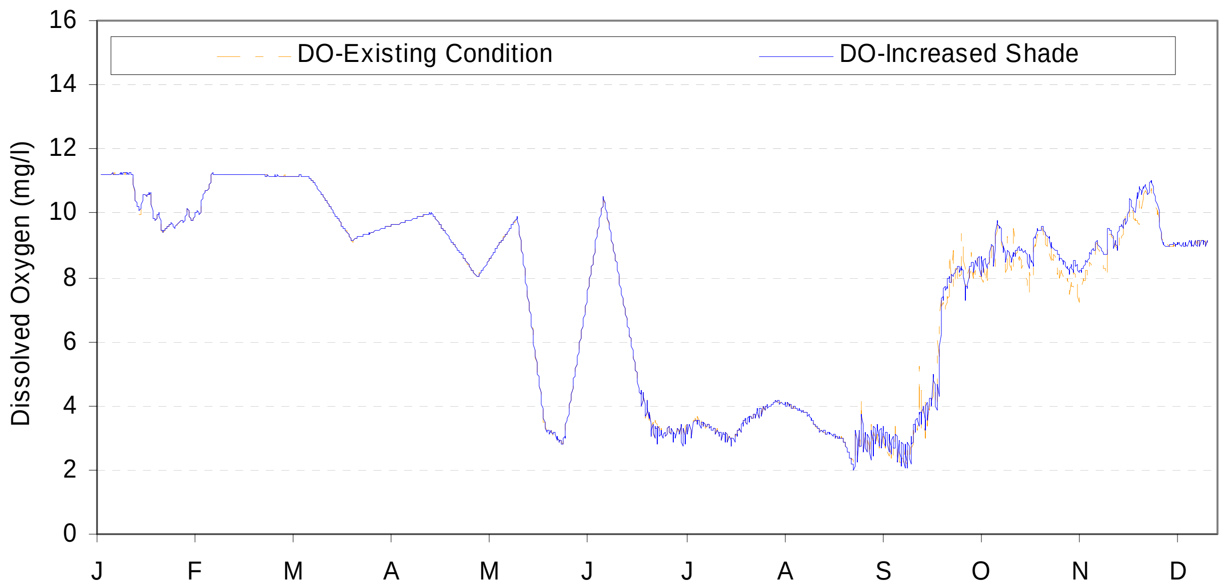
F_1999-13 Increased shade simulation - Anderson-Rose Dam (LRAR)



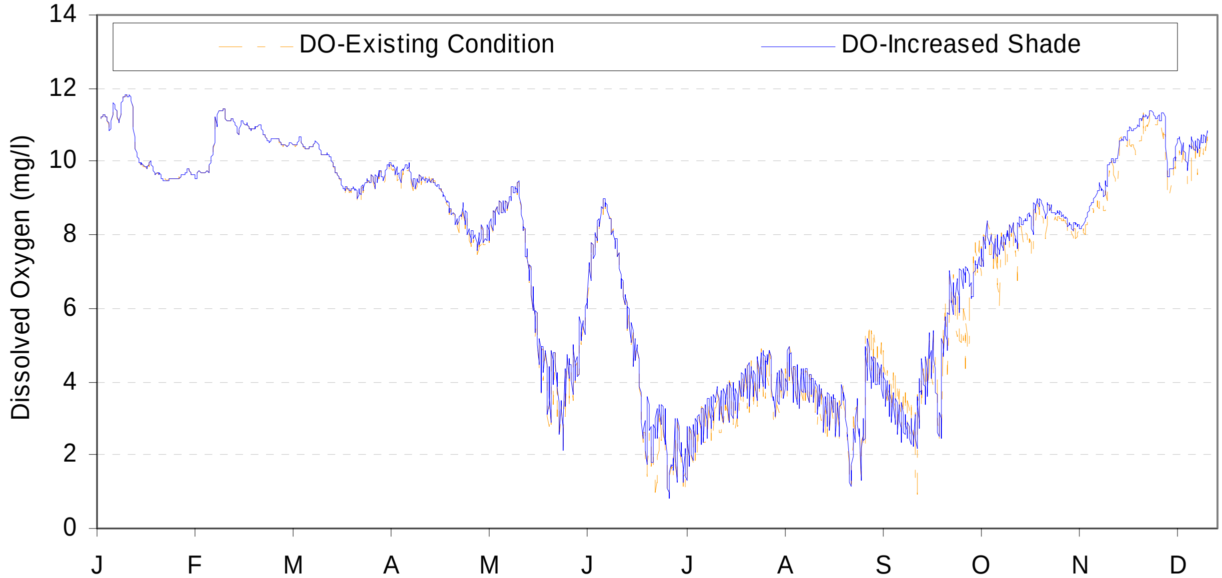
F_1999-14 Increased shade simulation - Lost River at East-West Road (LREW)



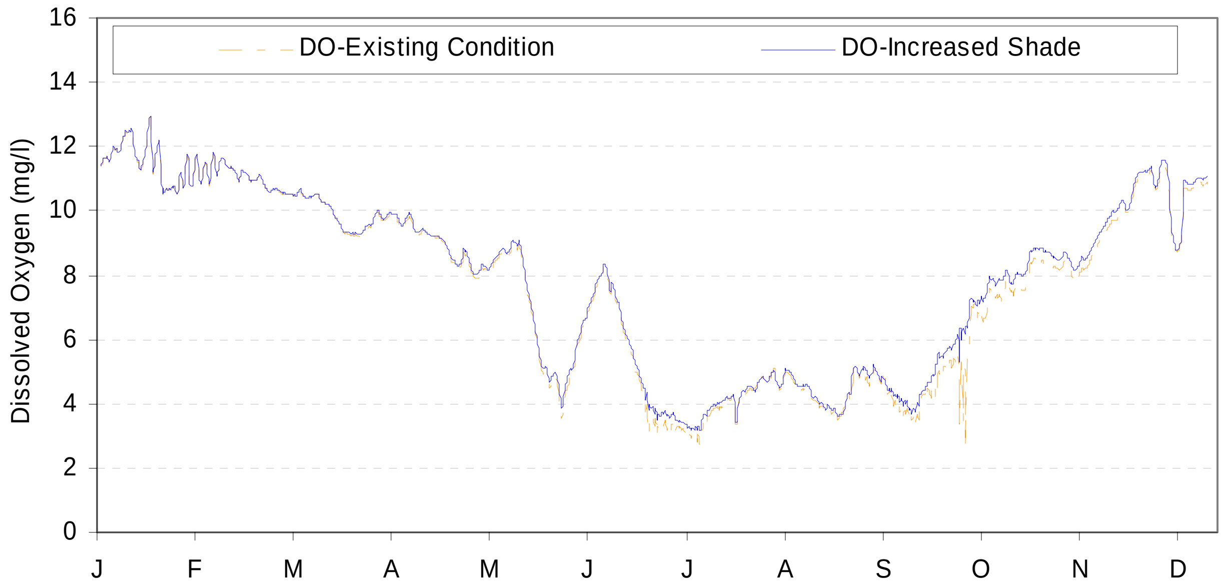
F_1999-15 Increased shade simulation – Tule Lake (TLTO)



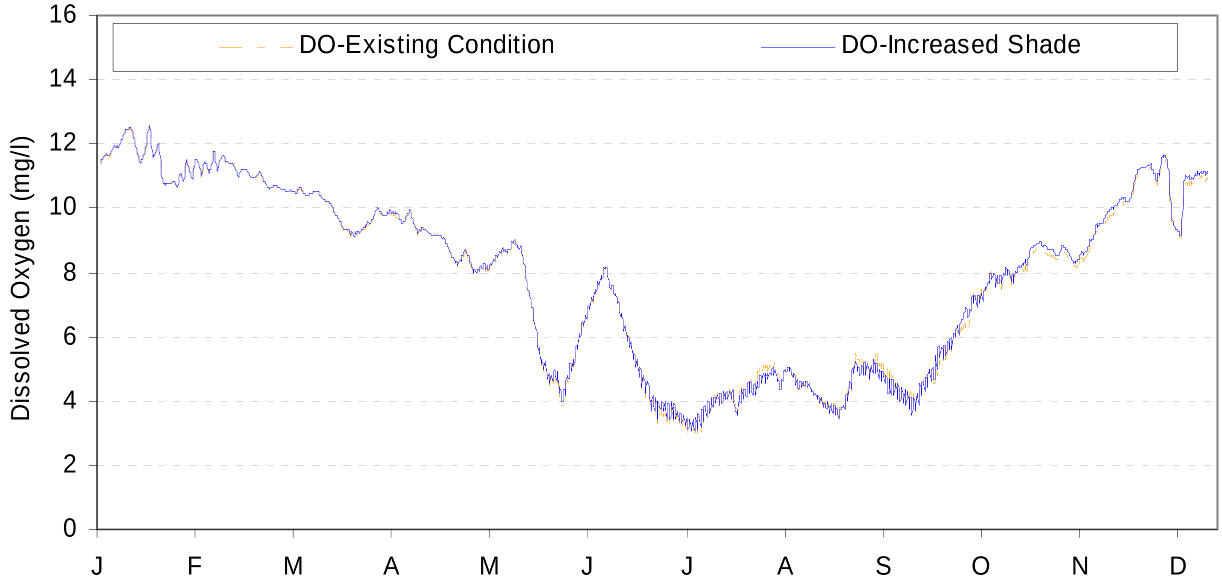
F_1999-16 Increased shade simulation - Klamath Straits Drain at Stateline Road (KSDSR)



F_1999-17 Increased shade simulation - Klamath Straits Drain at Township Road (KSDTR)



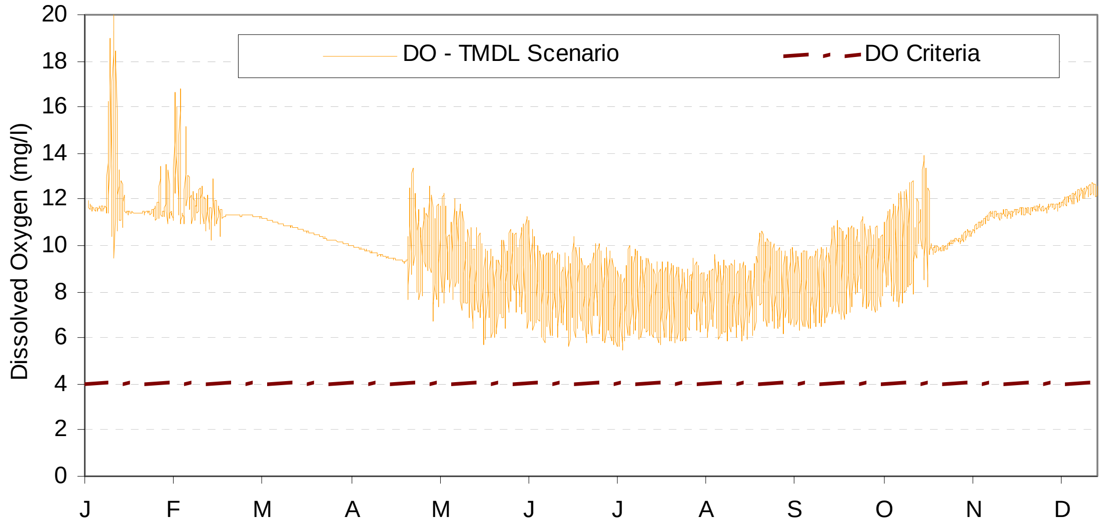
F_1999-18 Increased shade simulation - Klamath Straits Drain at Pump Station F (KSDPSF)



F_1999-19 Increased shade simulation - Klamath Straits Drain at Hwy 97 (KSD97)

Appendix G

TMDL Scenario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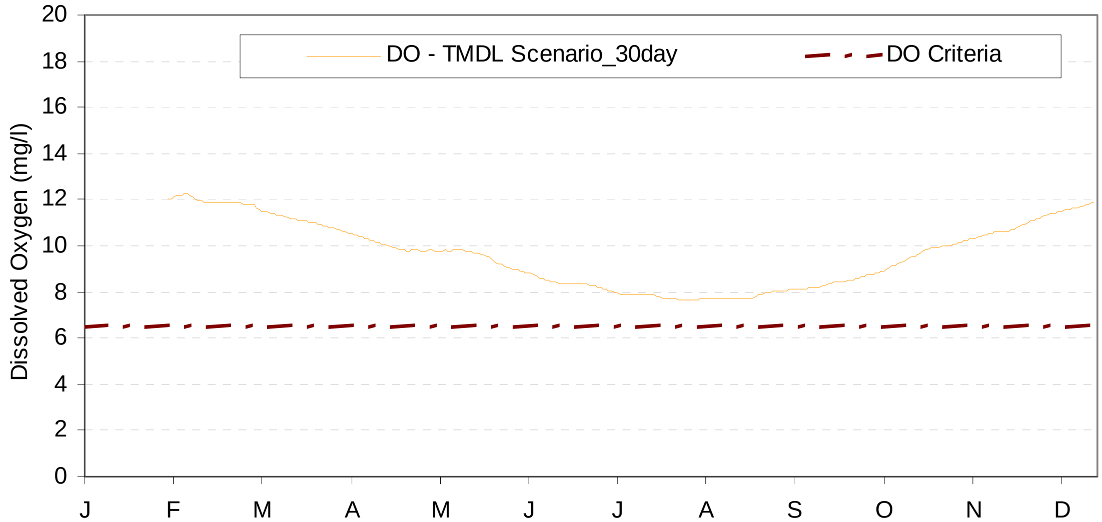
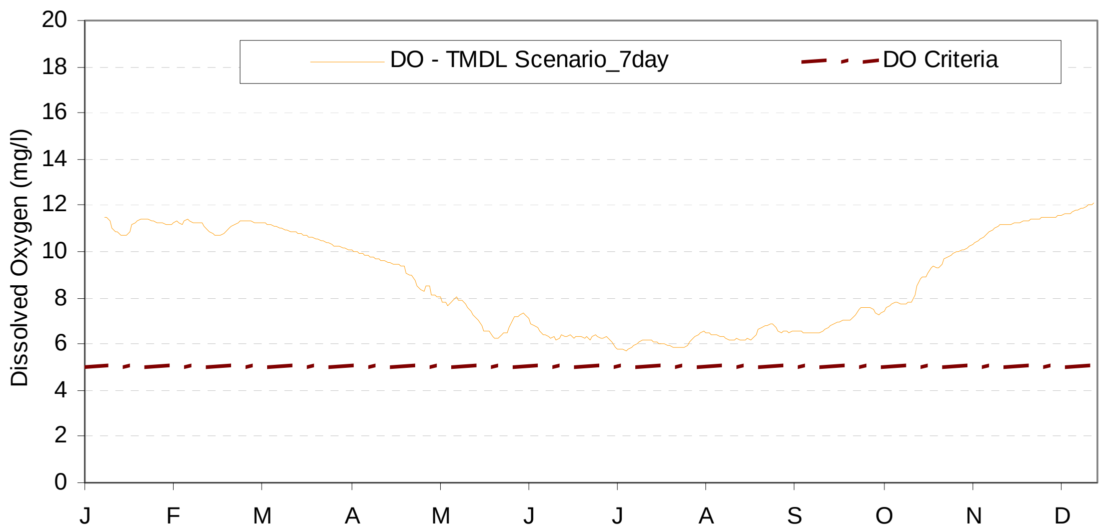
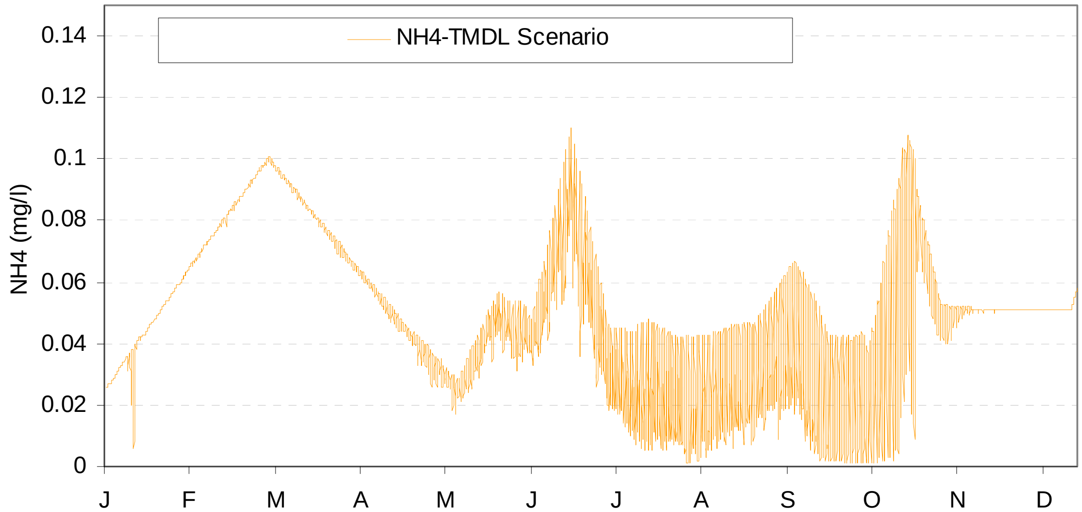
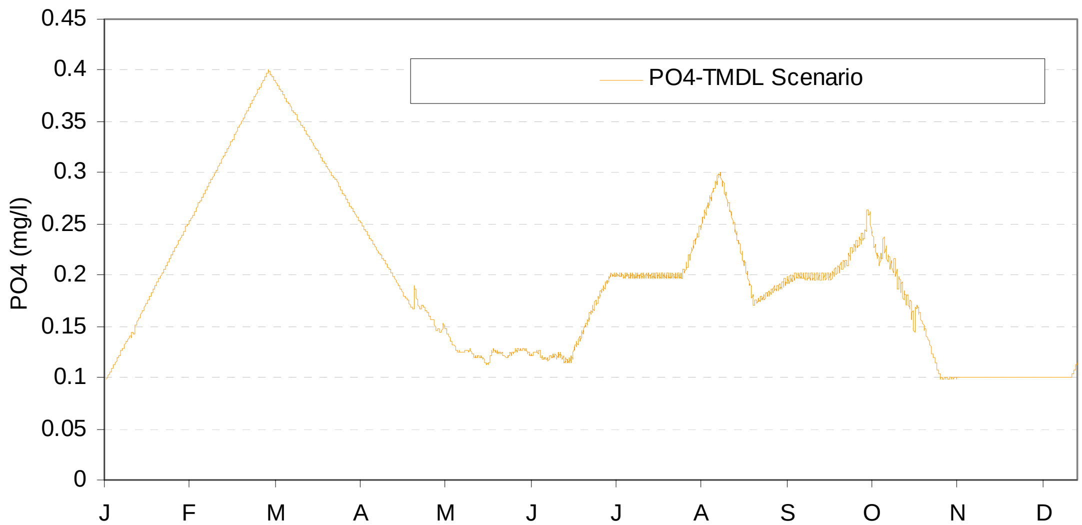
DO Criteria
Dissolved Oxygen (mg/l)
20
18
16
14
12
10
8
6
4
2
0
J
F
M
A
M
J
J
A
S
O
N
D

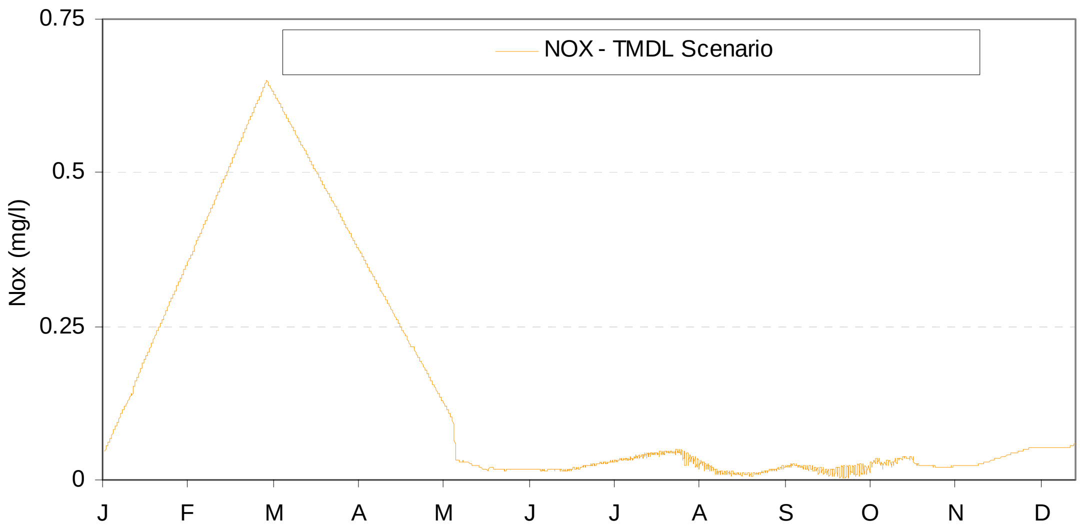

DO - TMDL Scenario_30day
DO Criteria
Dissolved Oxygen (mg/l)
20
18
16
14
12
10
8
6
4
2
0
J
F
M
A
M
J
J
A
S
O
N
D


DO - TMDL Scenario_7day
DO Criteria
Dissolved Oxygen (mg/l)
20
18
16
14
12
10
8
6
4
2
0
J
F
M
A
M
J
J
A
S
O
N
D

LRGR







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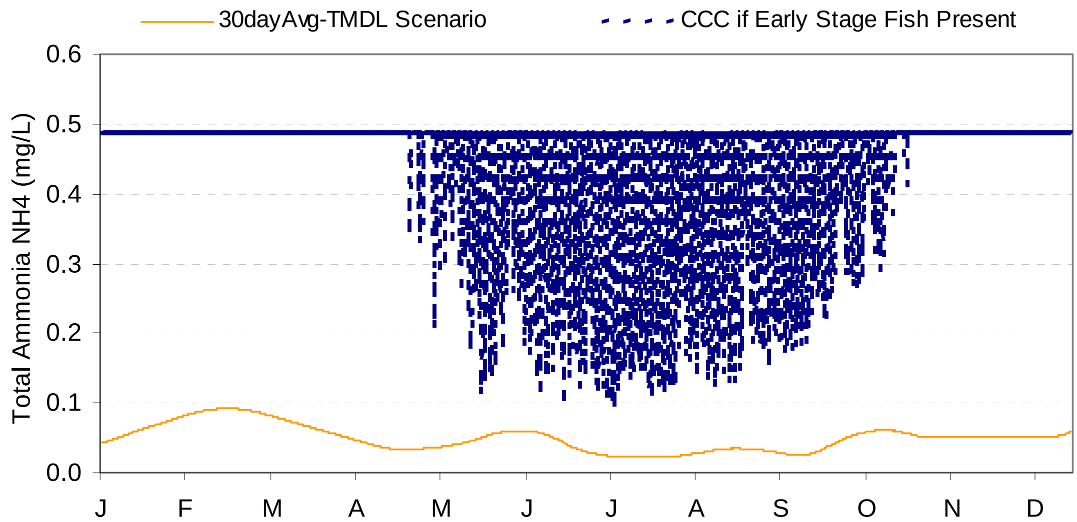
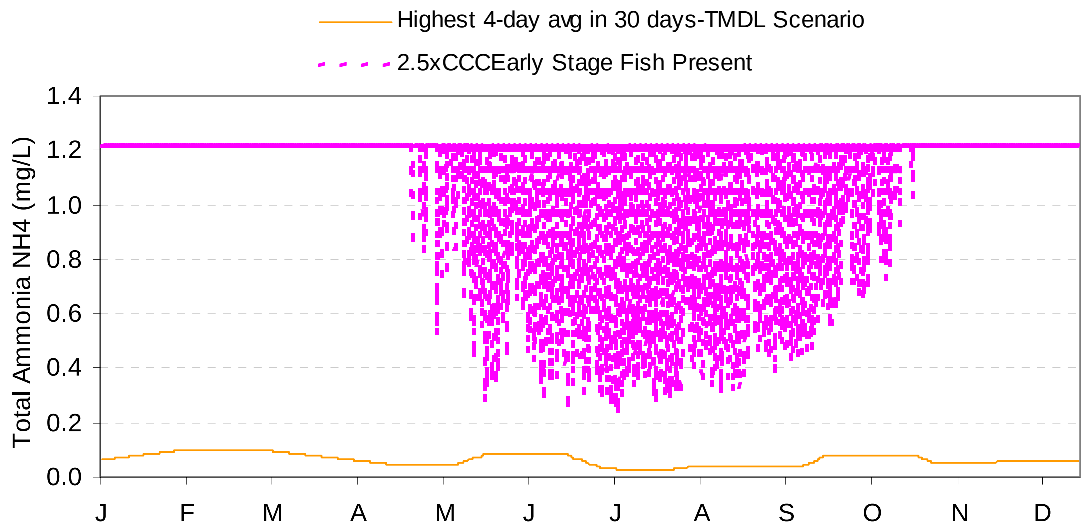
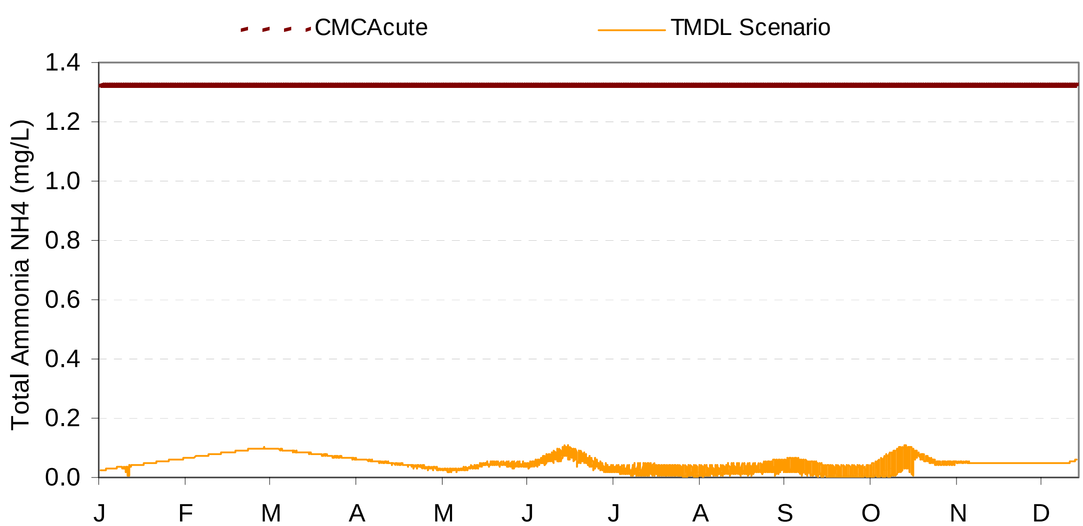
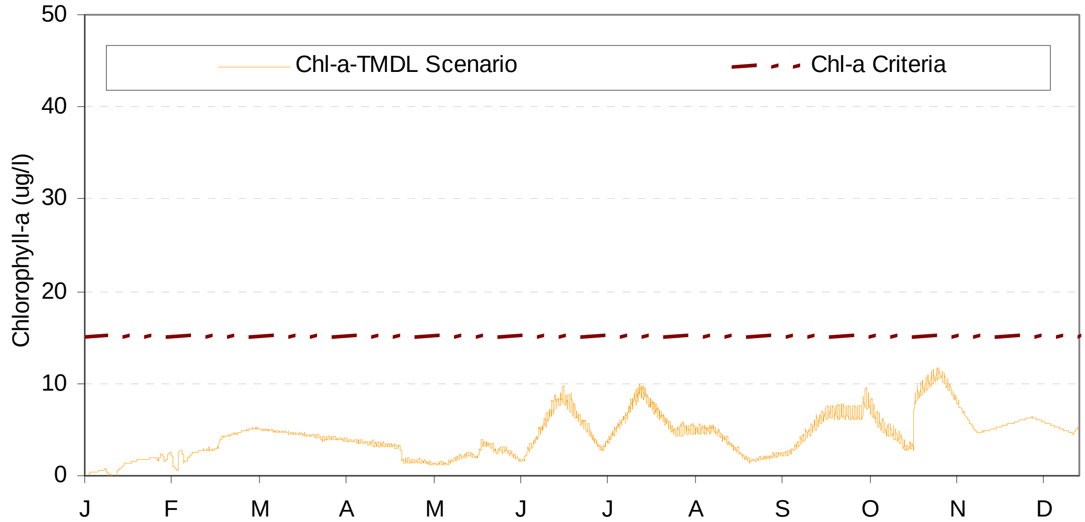
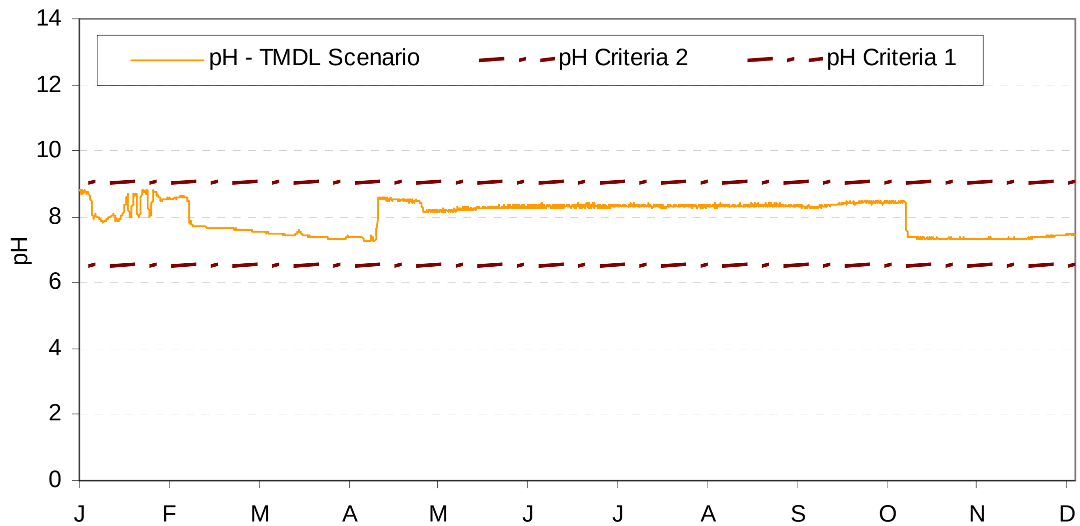






LRGR continued





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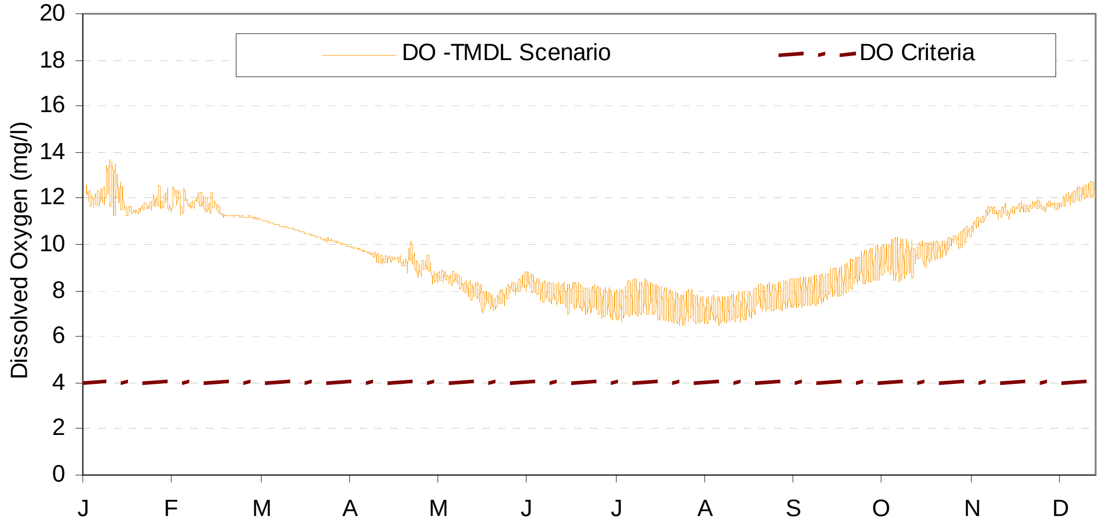
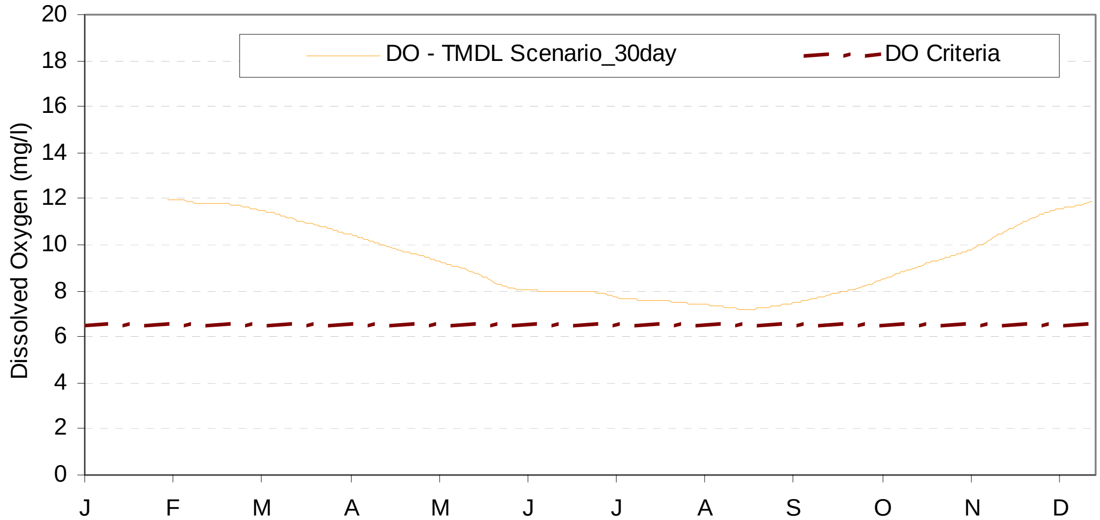
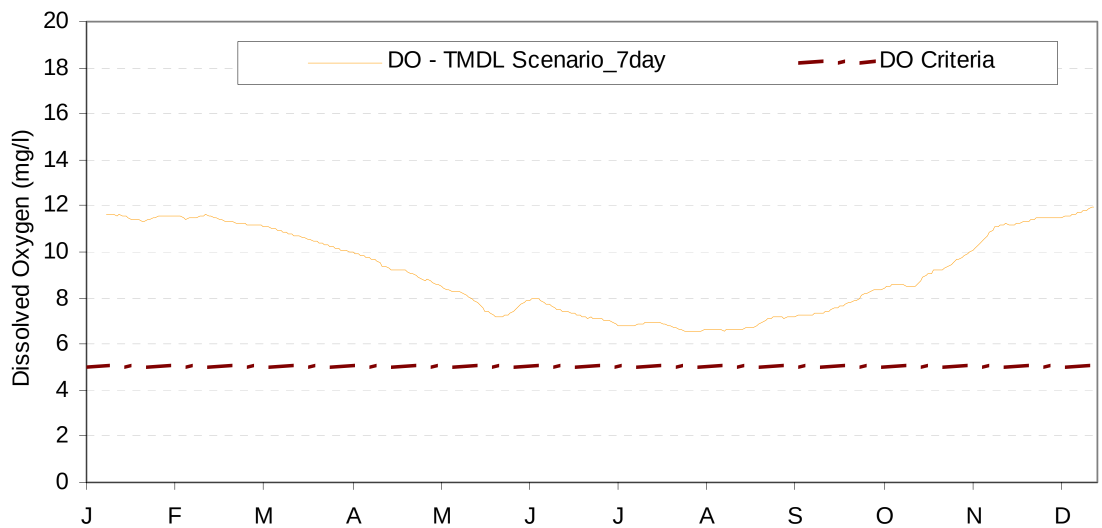
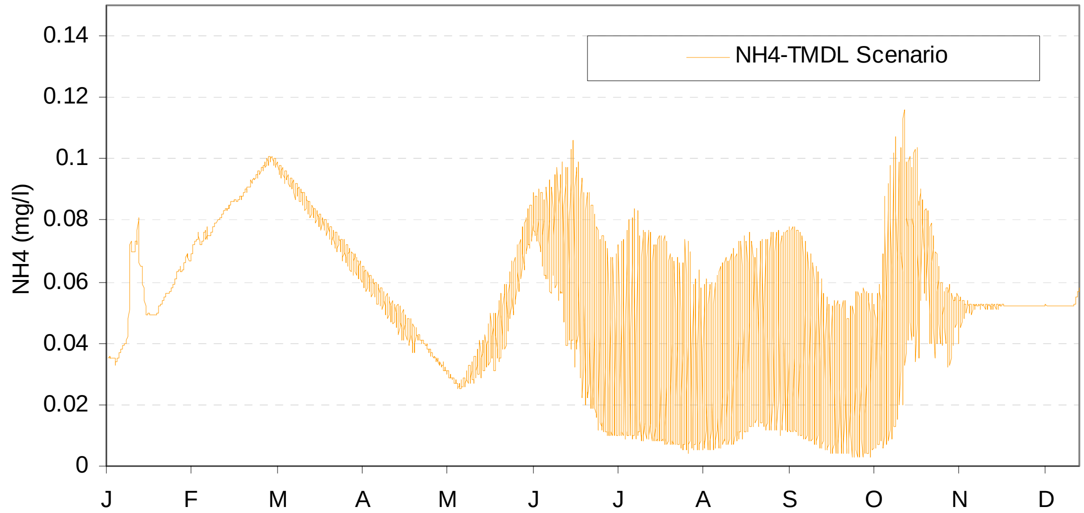
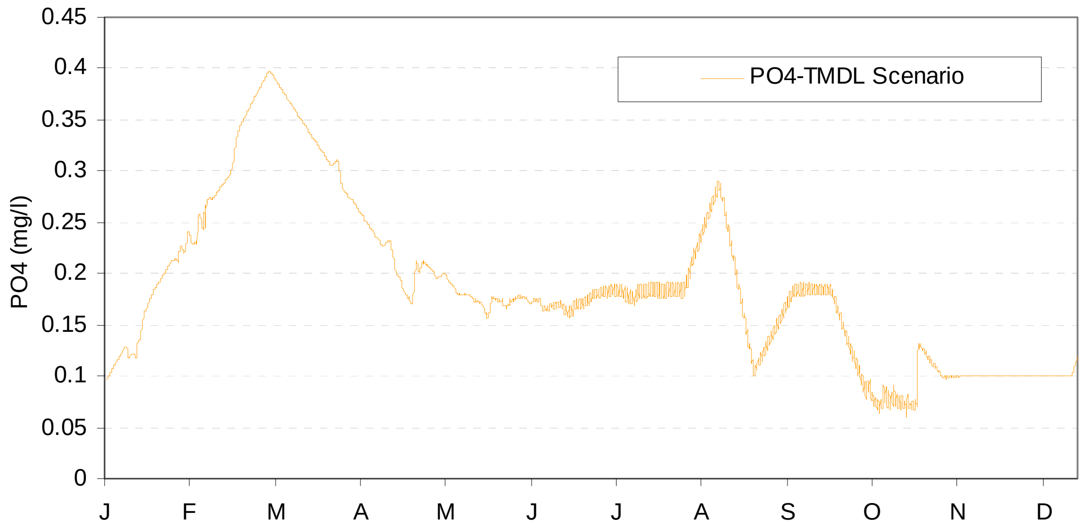

DO -TMDL Scenario
DO Criteria
Dissolved Oxygen (mg/l)
0
2
4
6
8
10
12
14
16
18
20
J
F
M
A
M
J
J
A
S
O
N
D

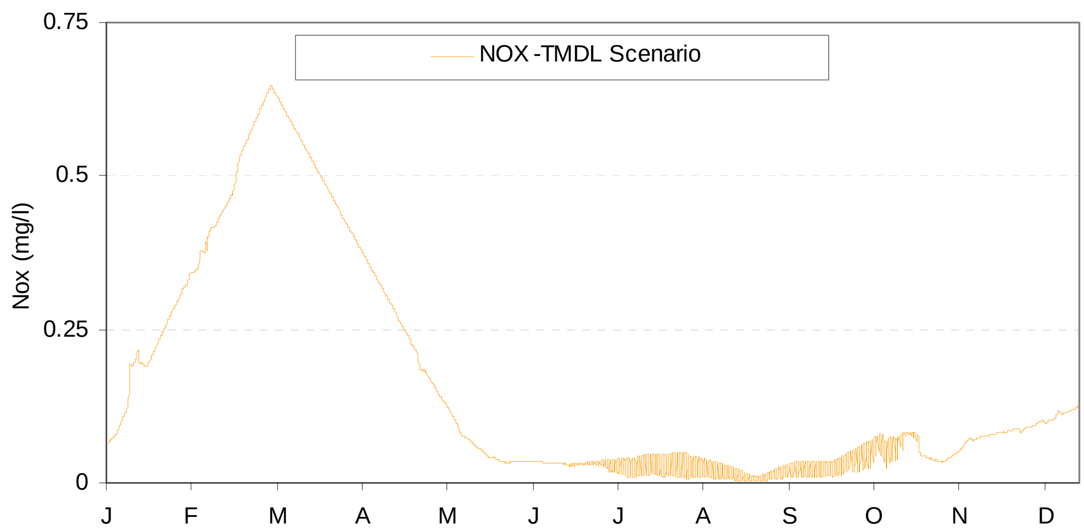

DO - TMDL Scenario_30day
DO Criteria
Dissolved Oxygen (mg/l)
0
2
4
6
8
10
12
14
16
18
20
J
F
M
A
M
J
J
A
S
O
N
D


DO - TMDL Scenario_7day
DO Criteria
Dissolved Oxygen (mg/l)
0
2
4
6
8
10
12
14
16
18
20
J
F
M
A
M
J
J
A
S
O
N
D

LRKB







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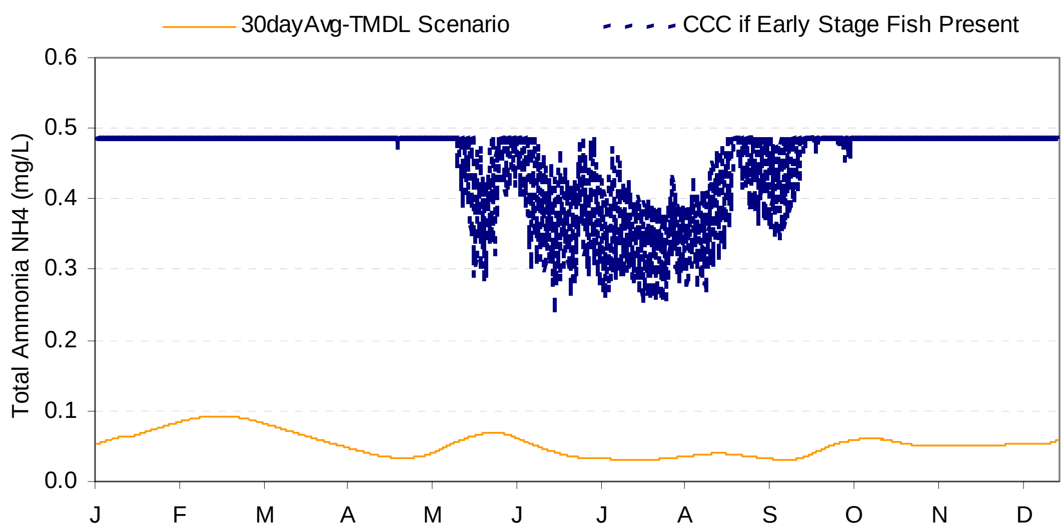

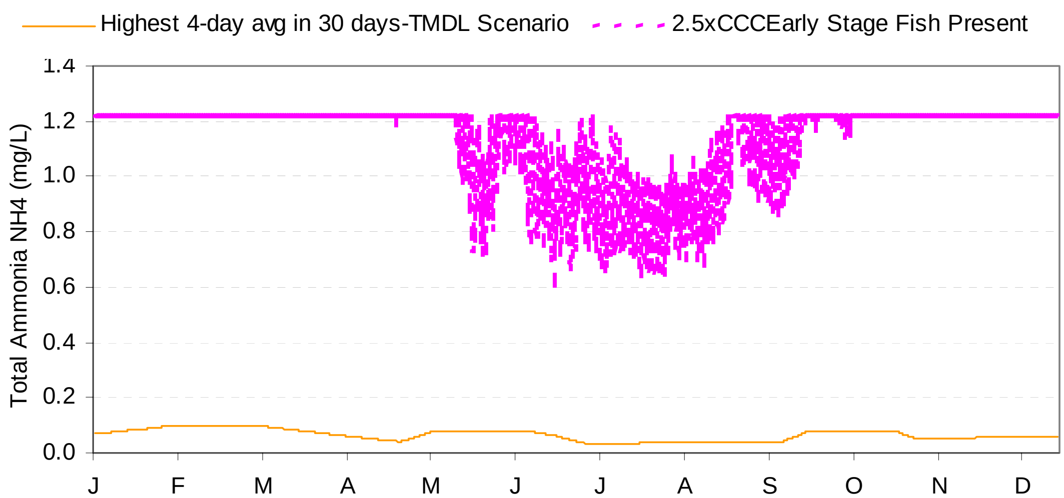

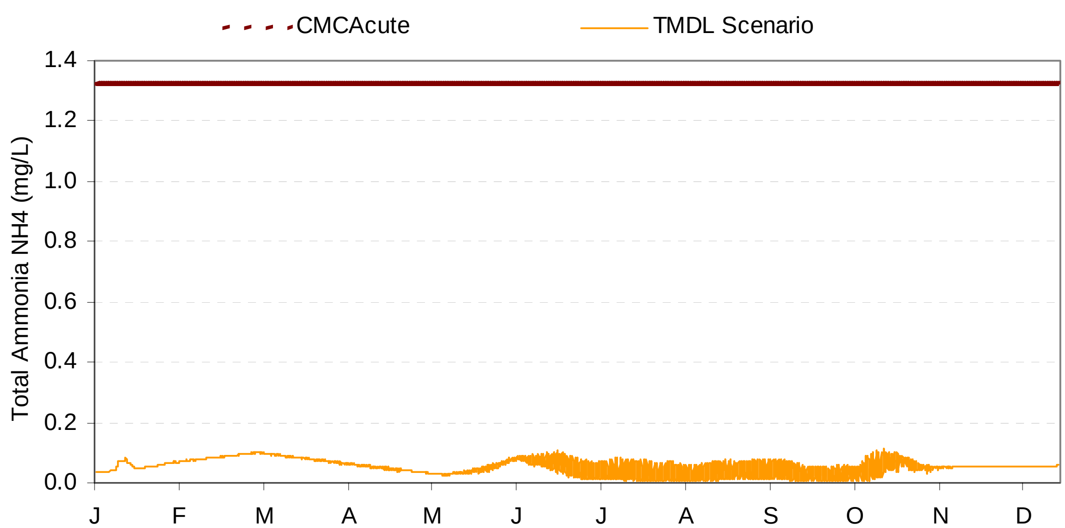

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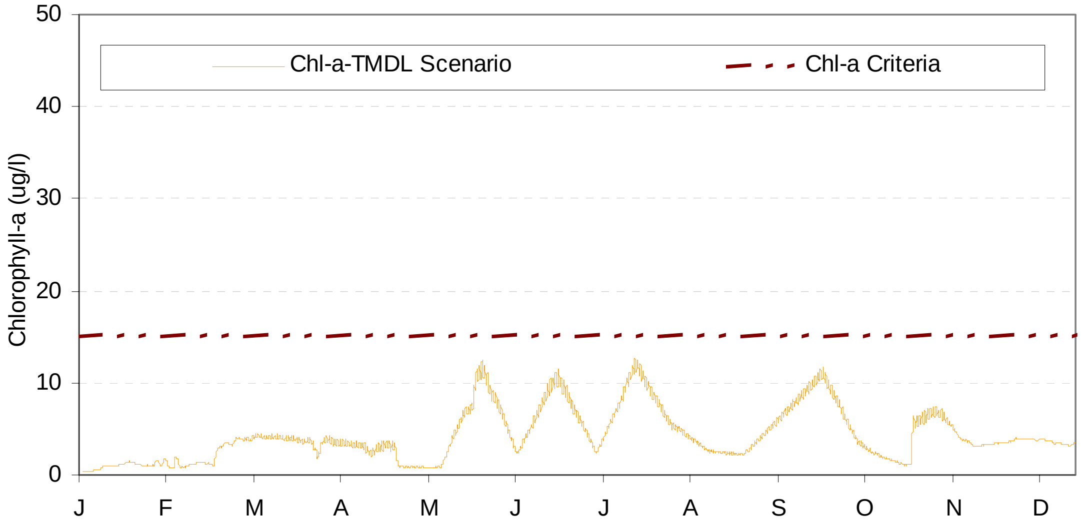

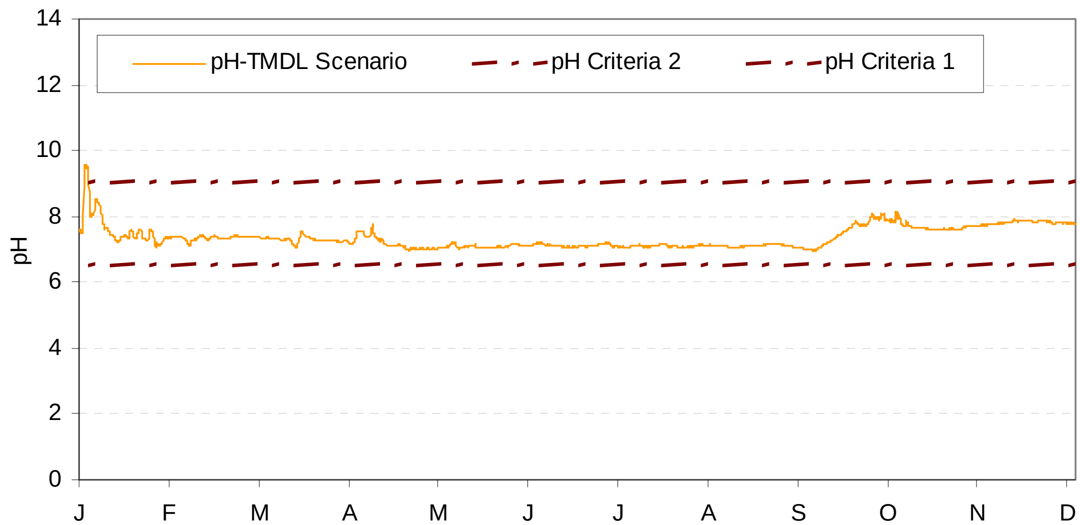

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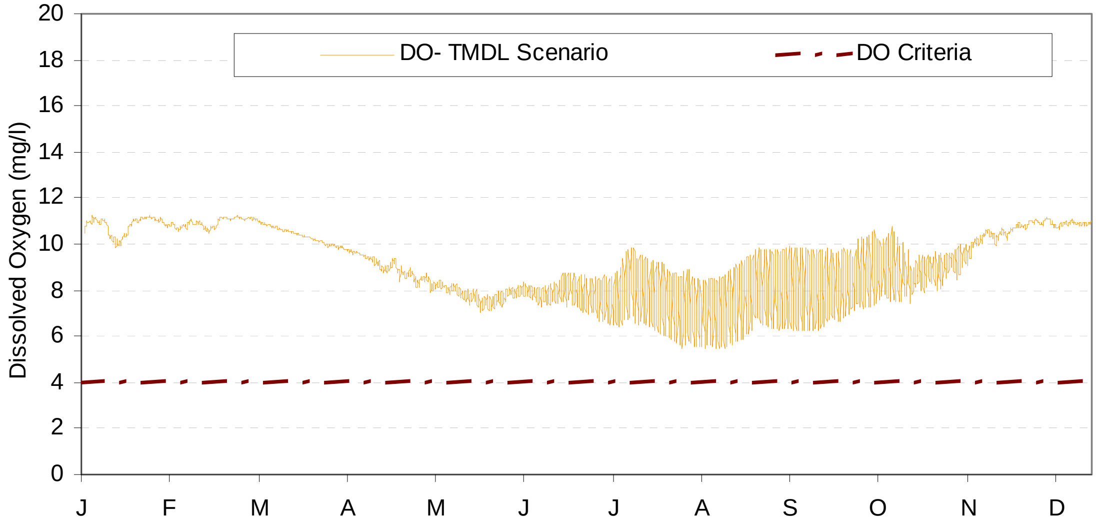
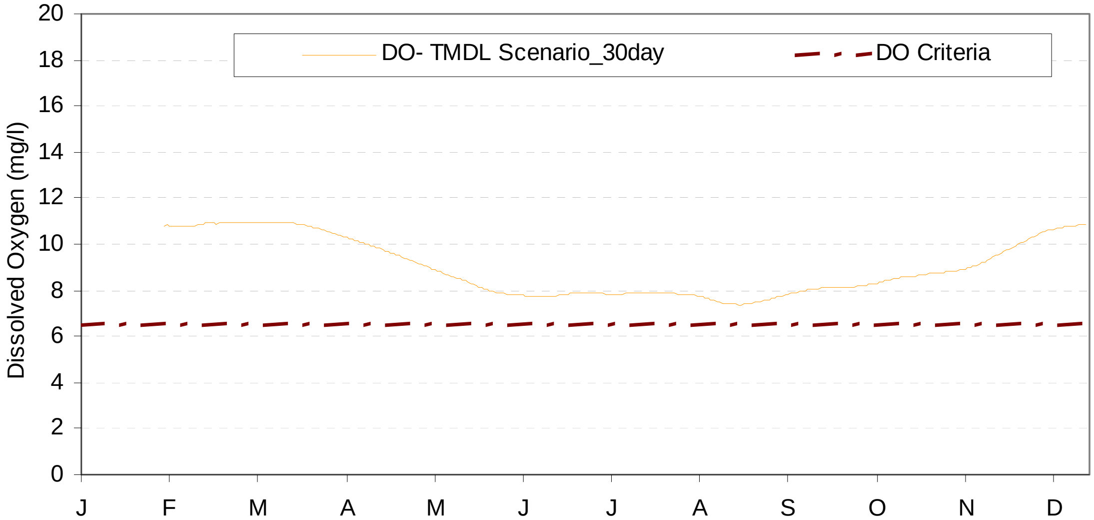
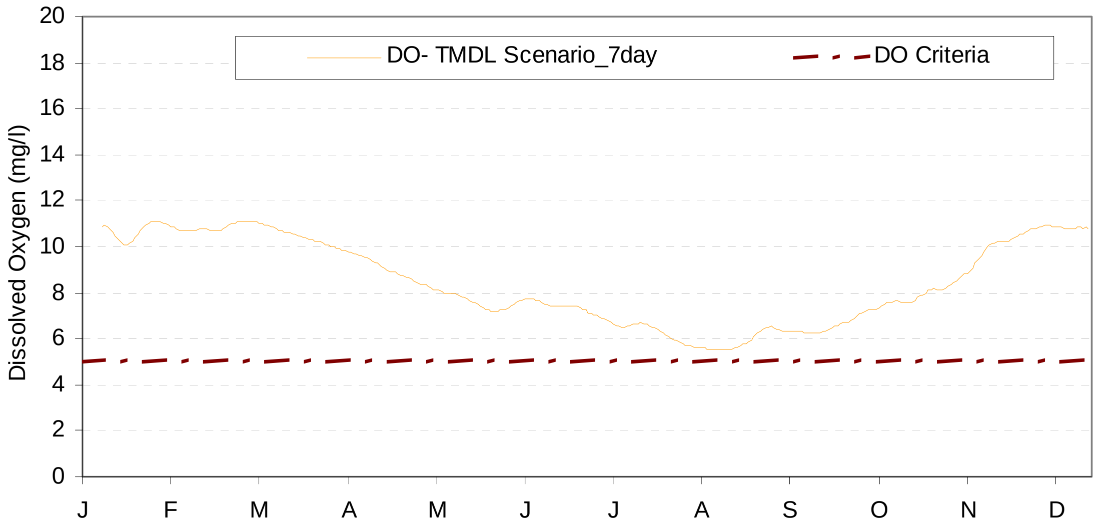
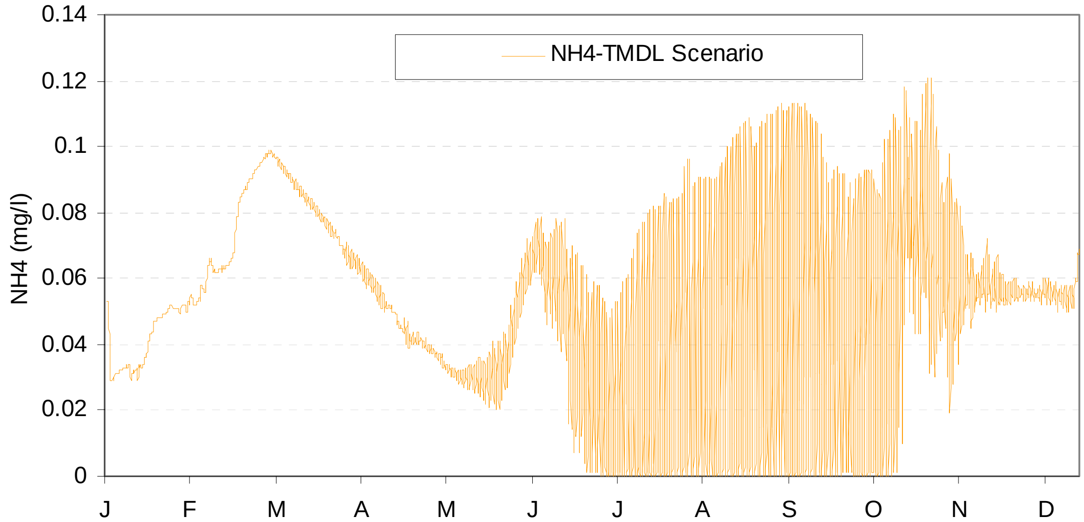
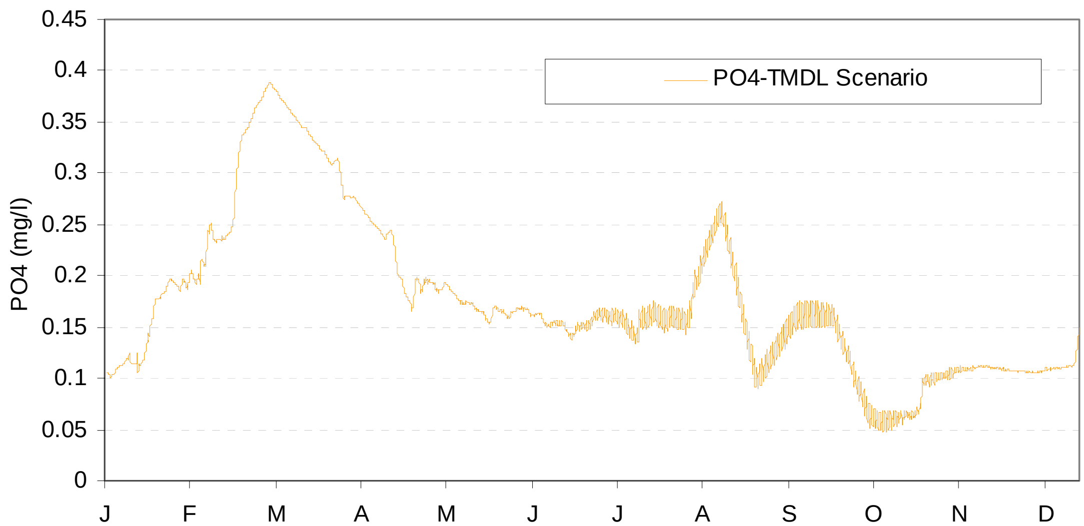

DO- TMDL Scenario
DO Criteria
Dissolved Oxygen (mg/l)
0
2
4
6
8
10
12
14
16
18
20
J
F
M
A
M
J
J
A
S
O
N
D

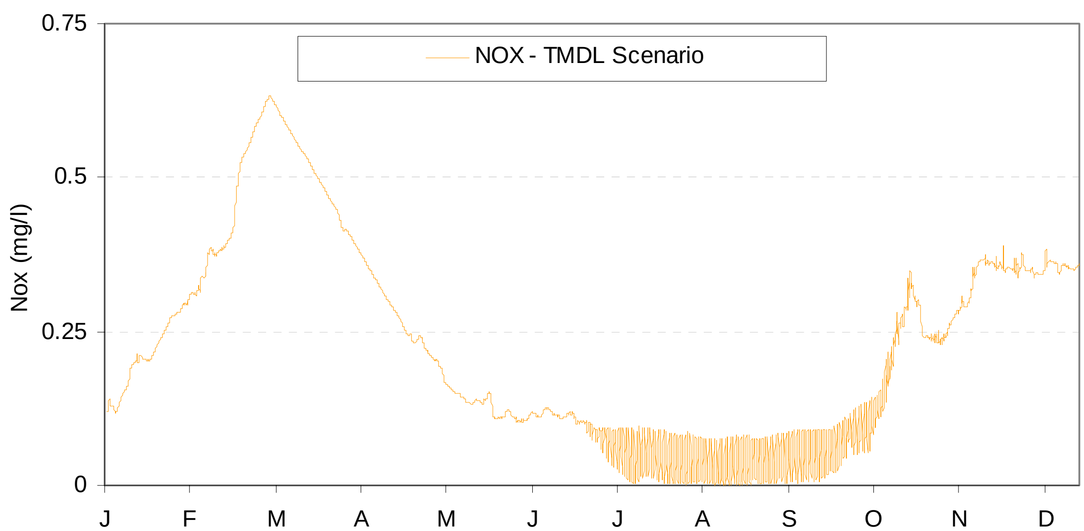

DO- TMDL Scenario_30day
DO Criteria
Dissolved Oxygen (mg/l)
0
2
4
6
8
10
12
14
16
18
20
J
F
M
A
M
J
J
A
S
O
N
D


DO- TMDL Scenario_7day
DO Criteria
Dissolved Oxygen (mg/l)
0
2
4
6
8
10
12
14
16
18
20
J
F
M
A
M
J
J
A
S
O
N
D

LRHD







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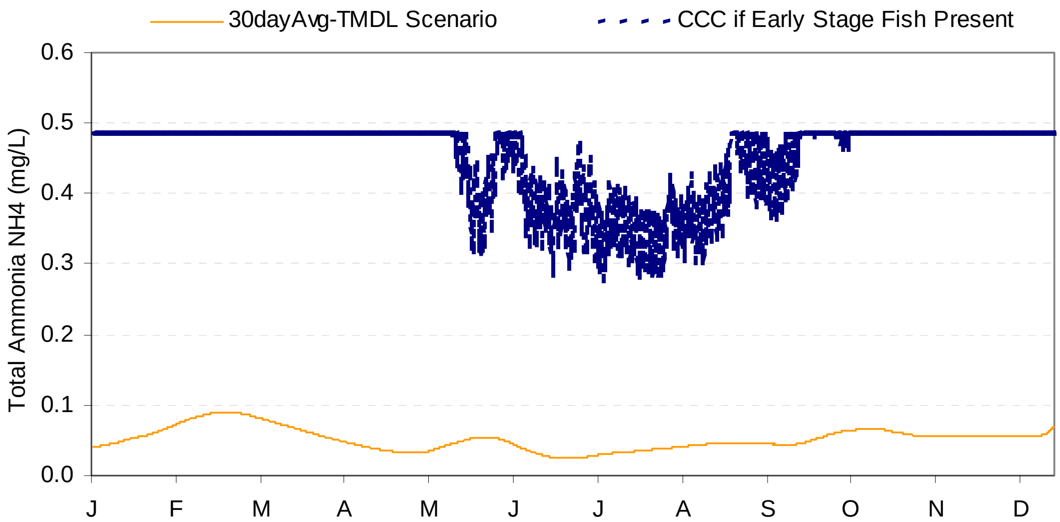

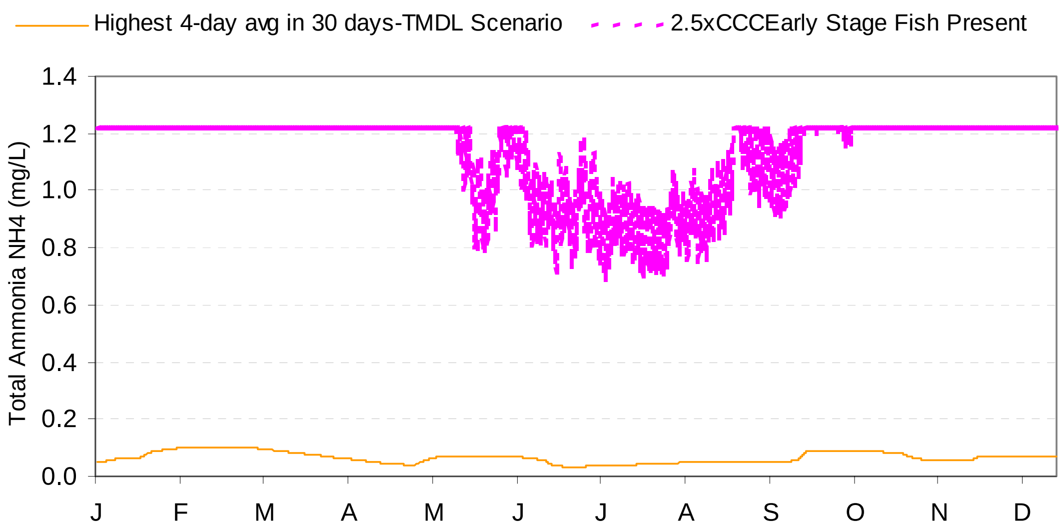

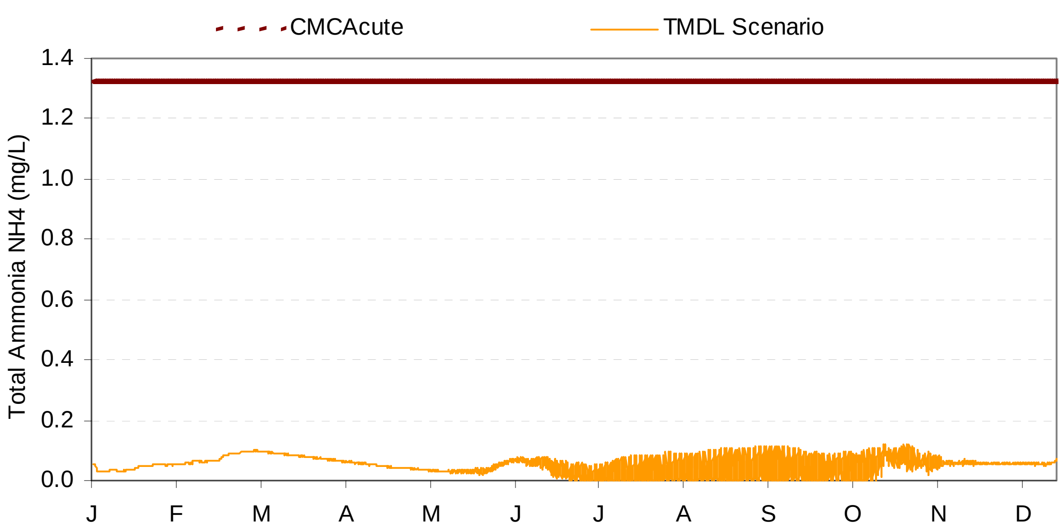

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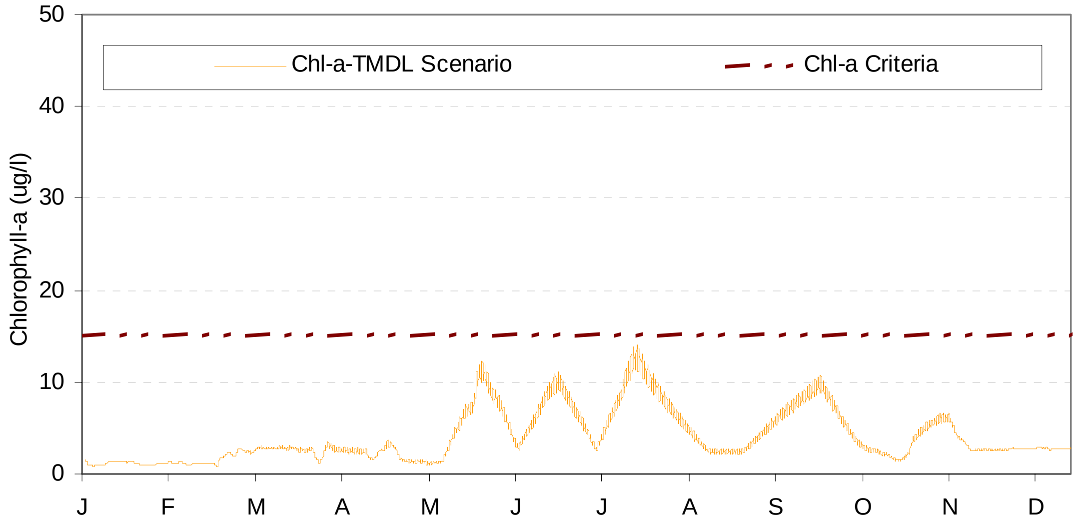
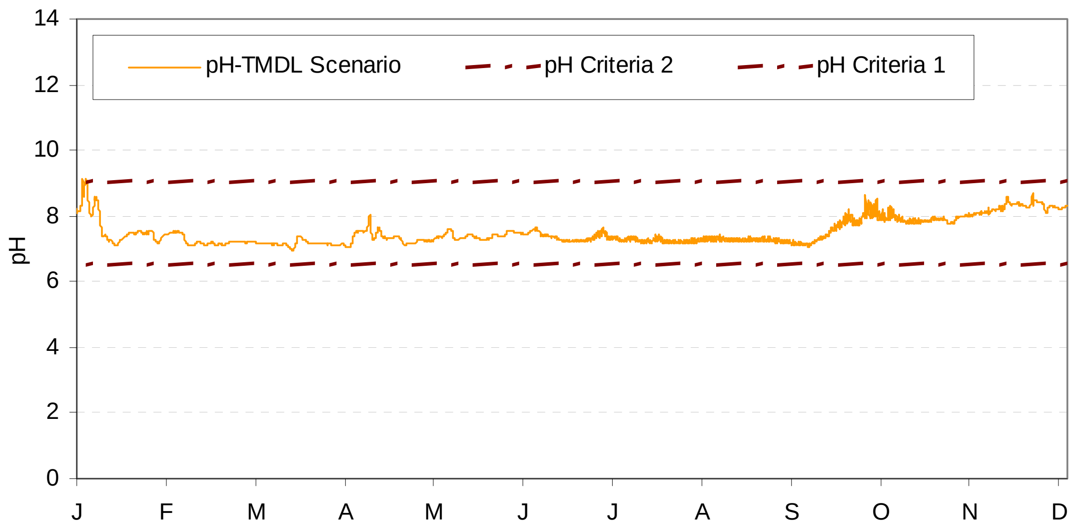
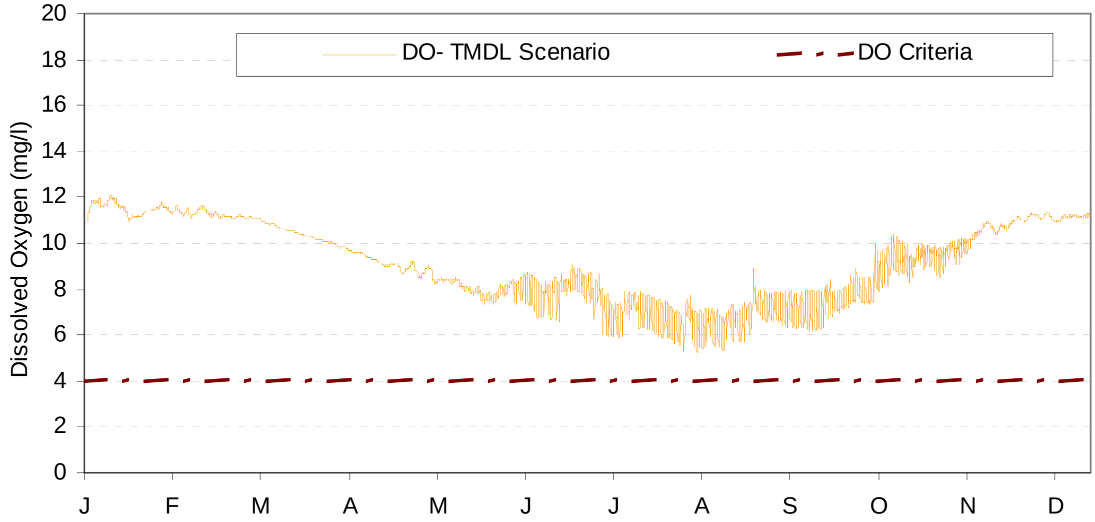
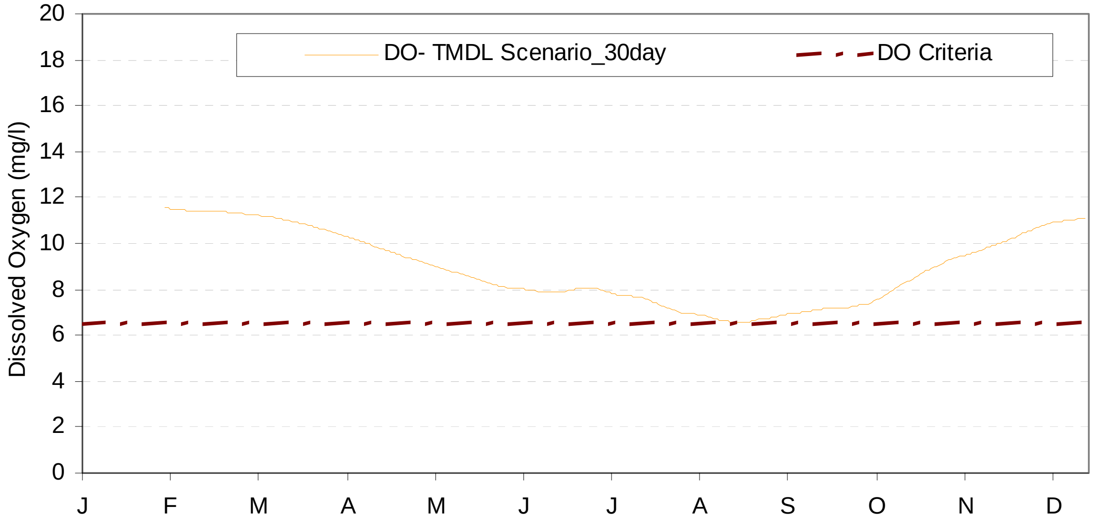
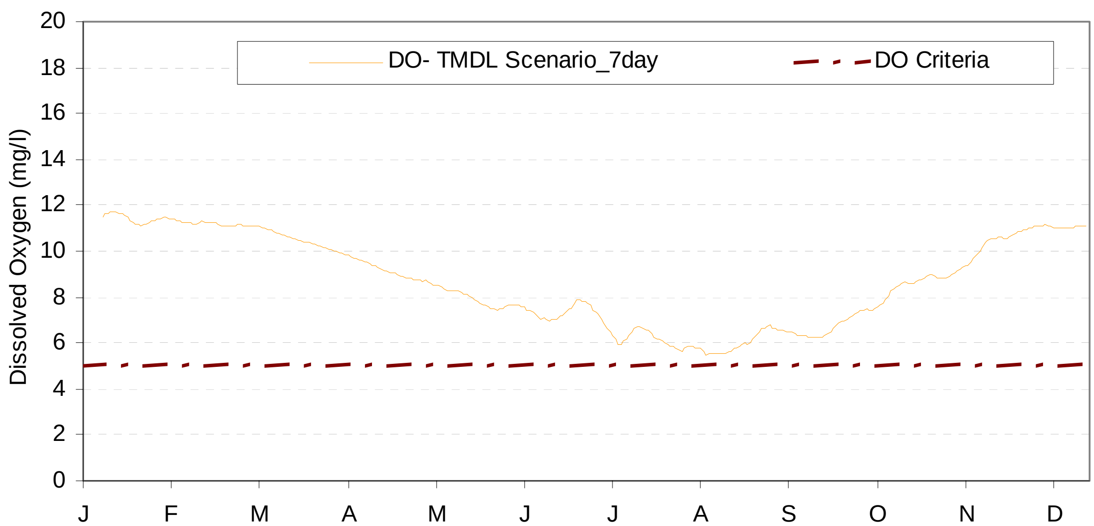




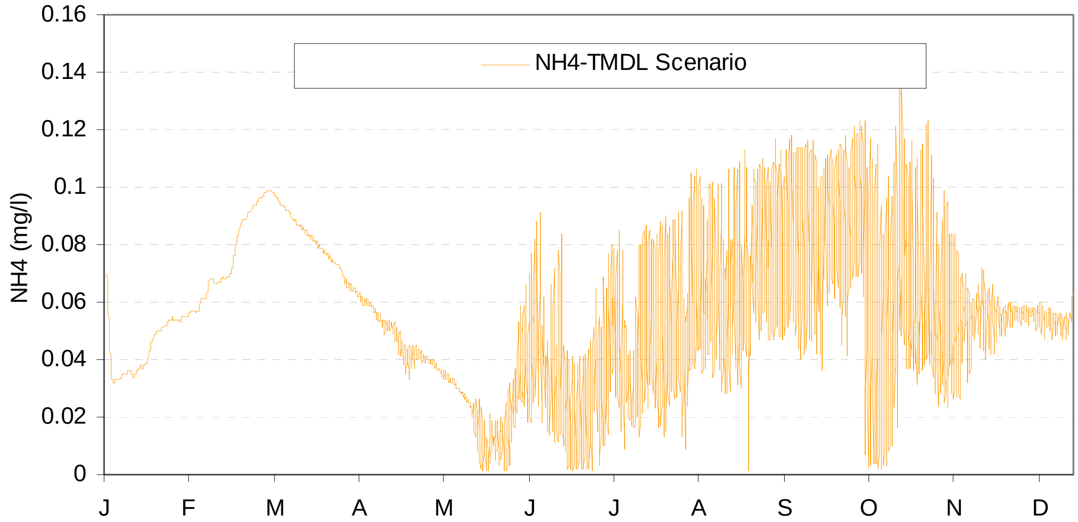
LRHD continued

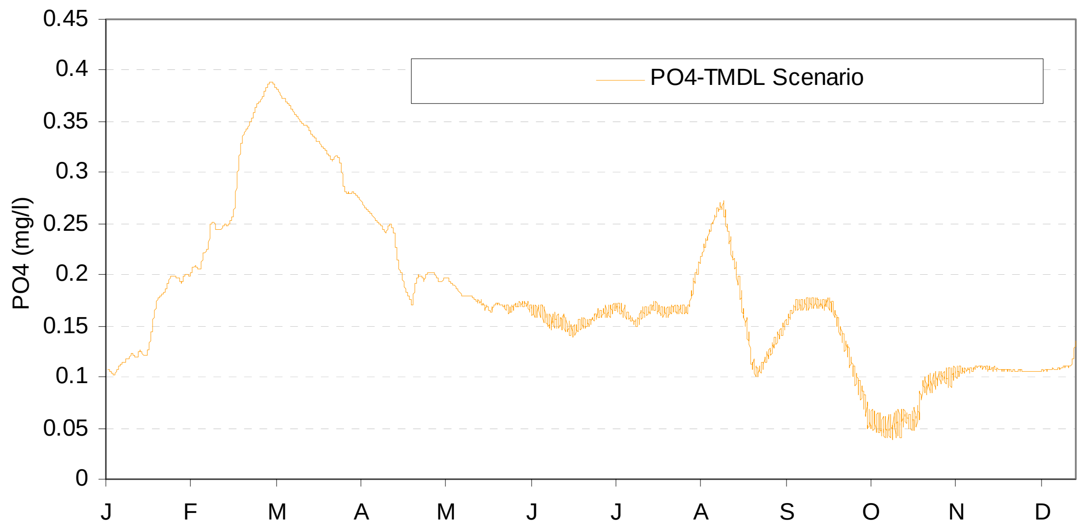

DO- TMDL Scenario
DO Criteria
Dissolved Oxygen (mg/l)
20
18
16
14
12
10
8
6
4
2
0
J F M A M J J A S O N D

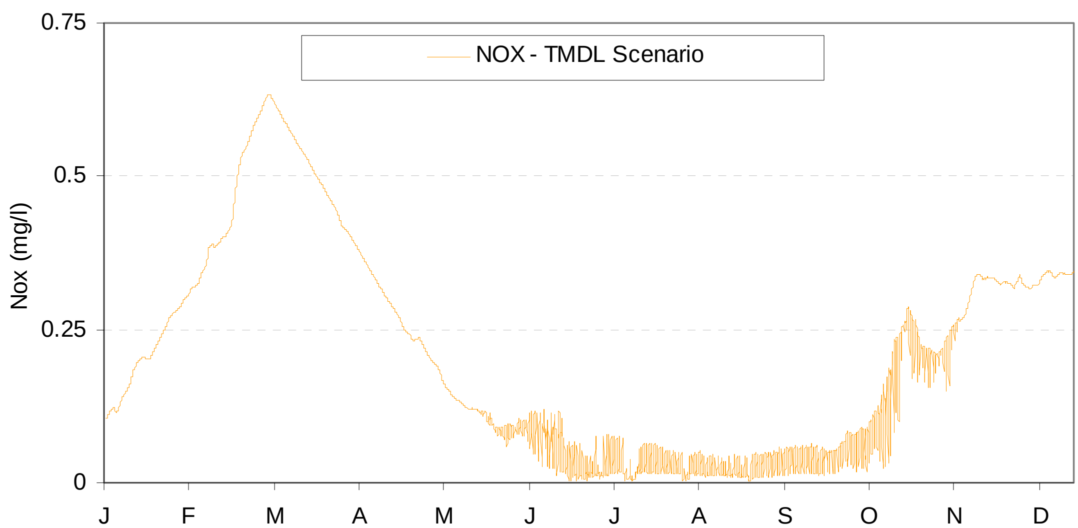

DO- TMDL Scenario_30day
DO Criteria
Dissolved Oxygen (mg/l)
20
18
16
14
12
10
8
6
4
2
0
J F M A M J J A S O N D


DO- TMDL Scenario_7day
DO Criteria
Dissolved Oxygen (mg/l)
20
18
16
14
12
10
8
6
4
2
0
J F M A M J J A S O N D

LRSP







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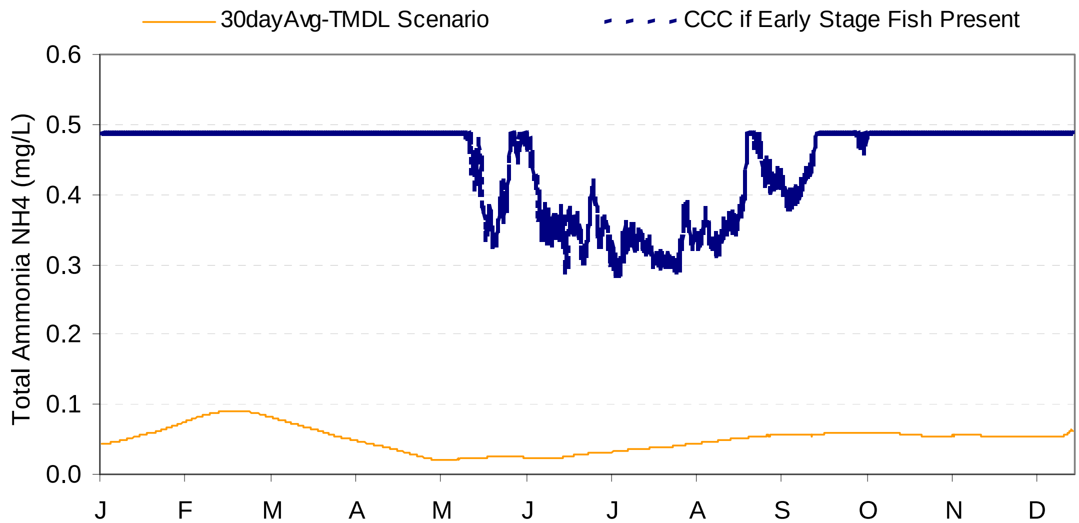

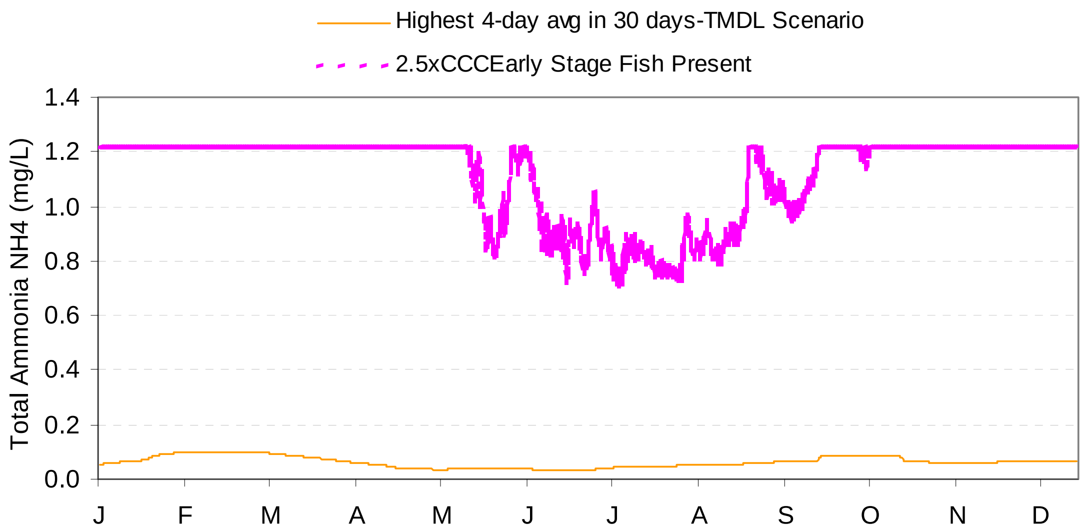

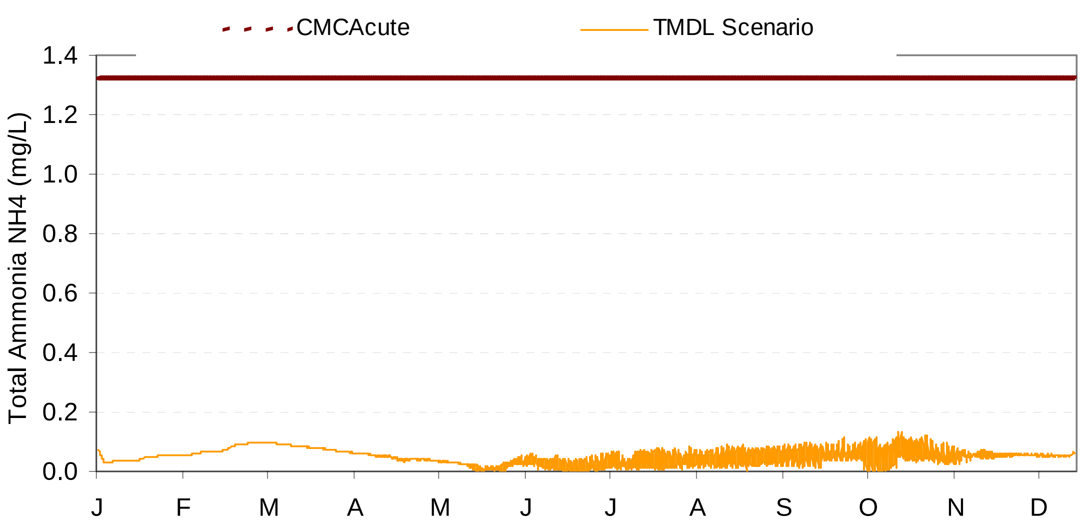

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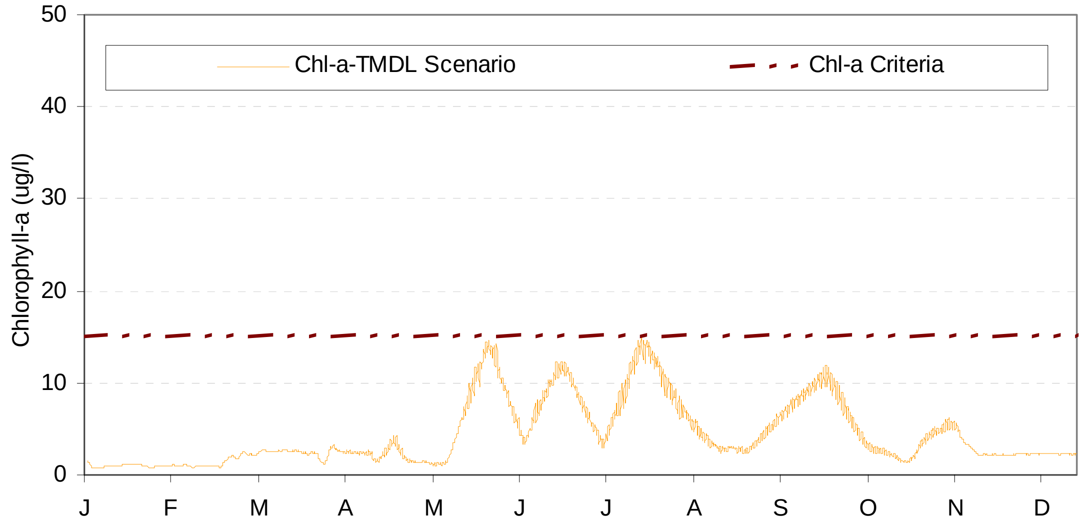

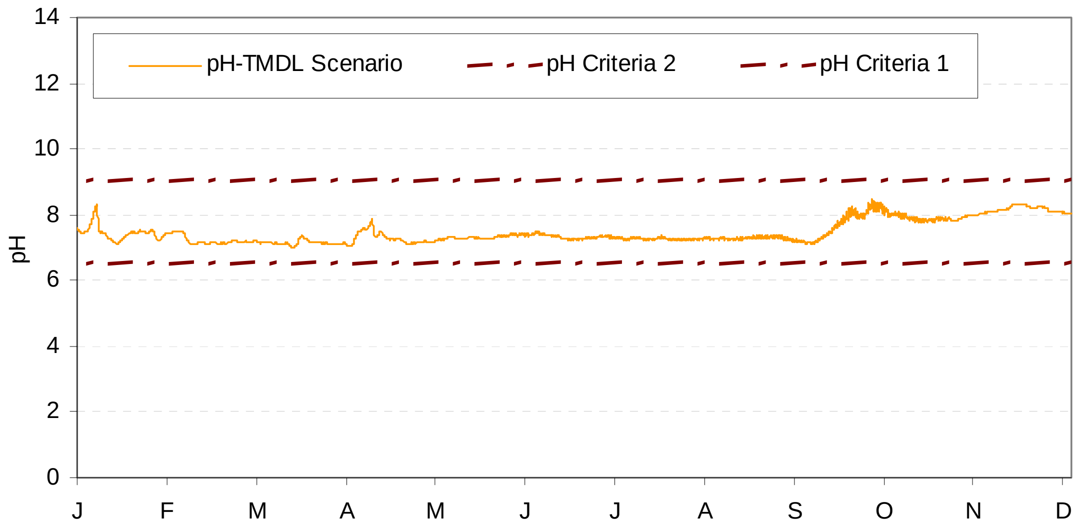

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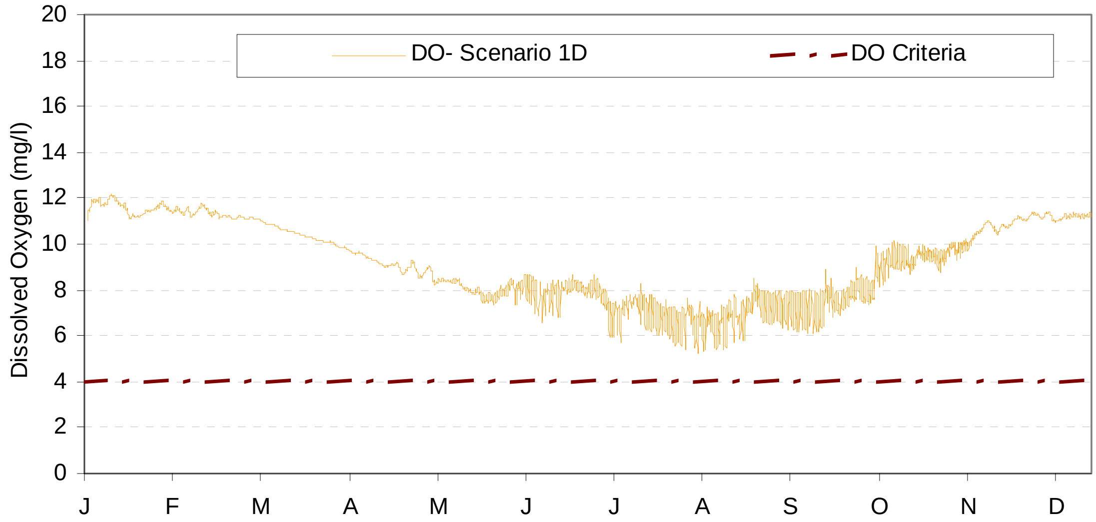
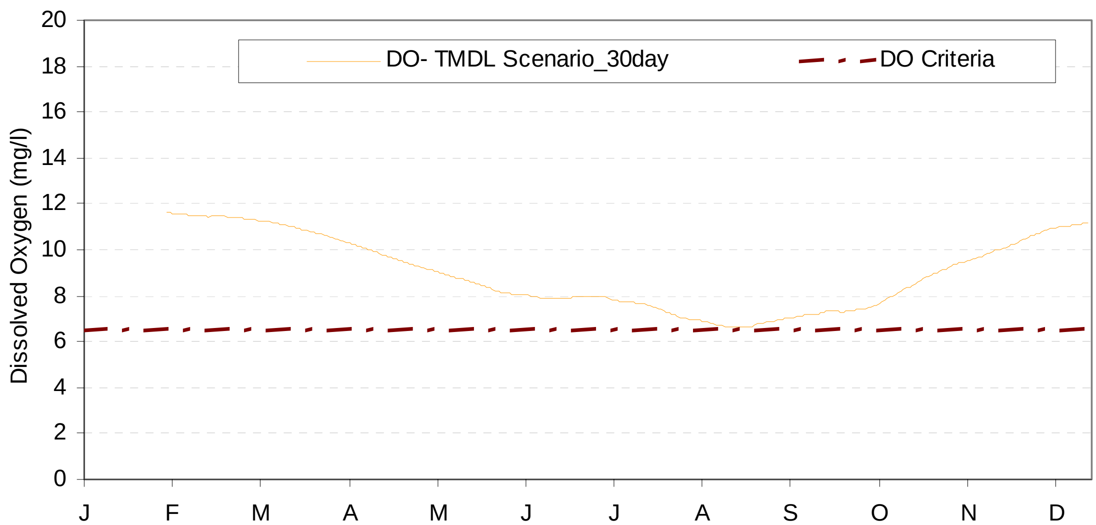
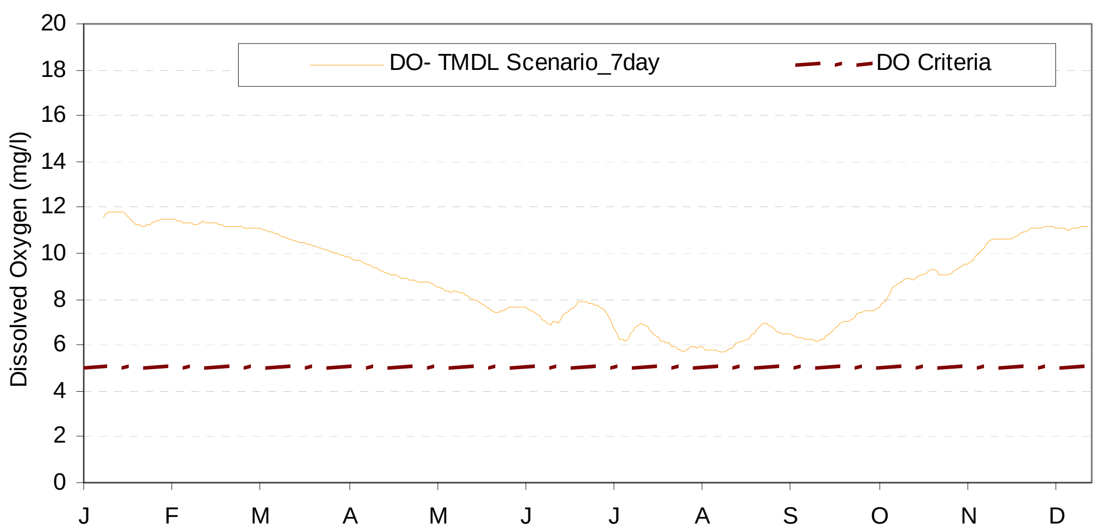
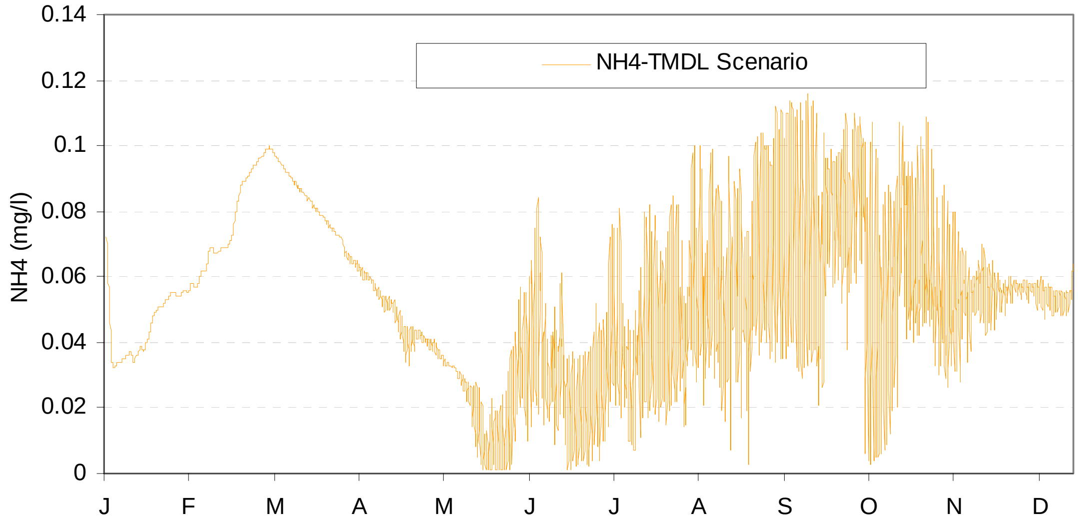
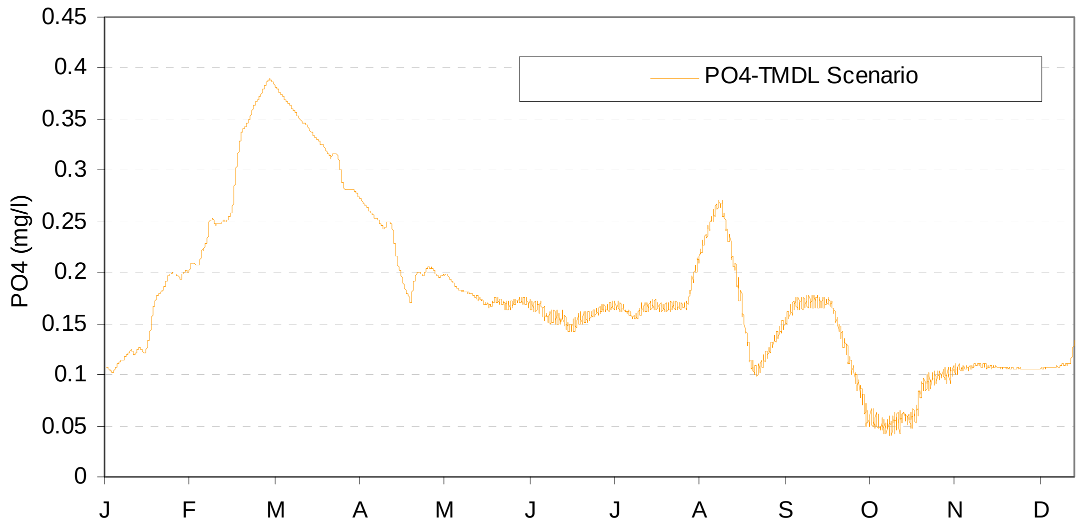

DO- Scenario 1D
DO Criteria
Dissolved Oxygen (mg/l)
20
18
16
14
12
10
8
6
4
2
0
J F M A M J J A S O N D

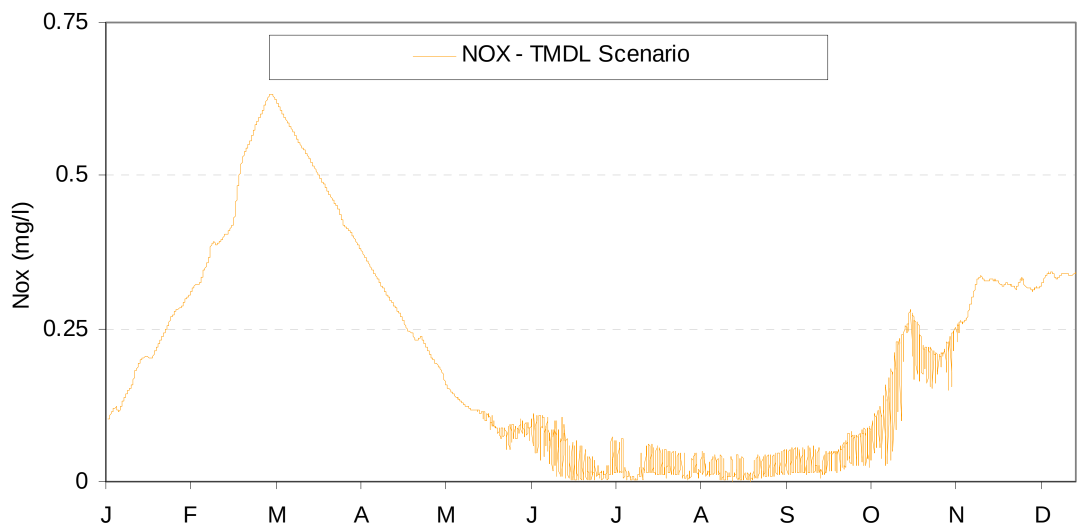

DO- TMDL Scenario_30day
DO Criteria
Dissolved Oxygen (mg/l)
20
18
16
14
12
10
8
6
4
2
0
J F M A M J J A S O N D


DO- TMDL Scenario_7day
DO Criteria
Dissolved Oxygen (mg/l)
20
18
16
14
12
10
8
6
4
2
0
J F M A M J J A S O N D

LROG







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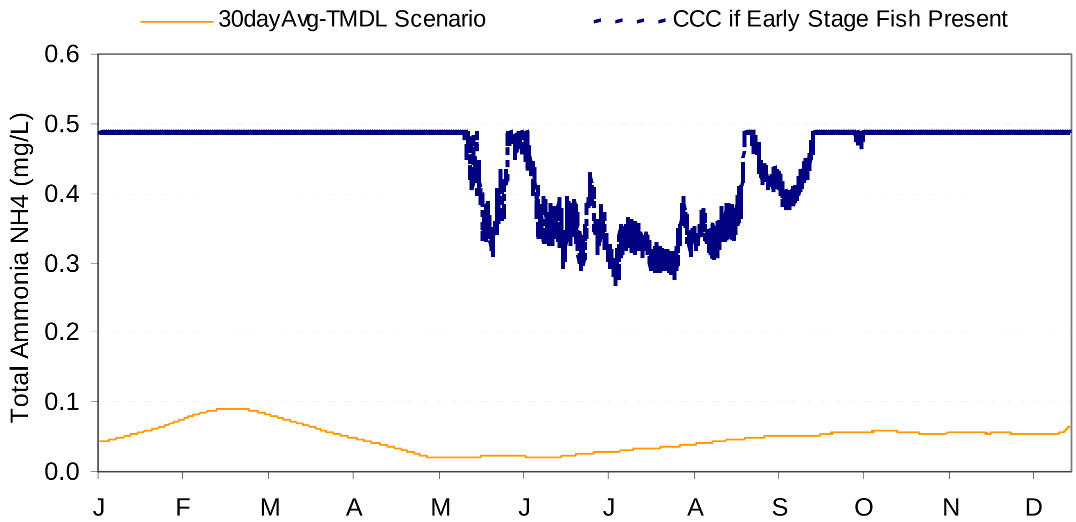

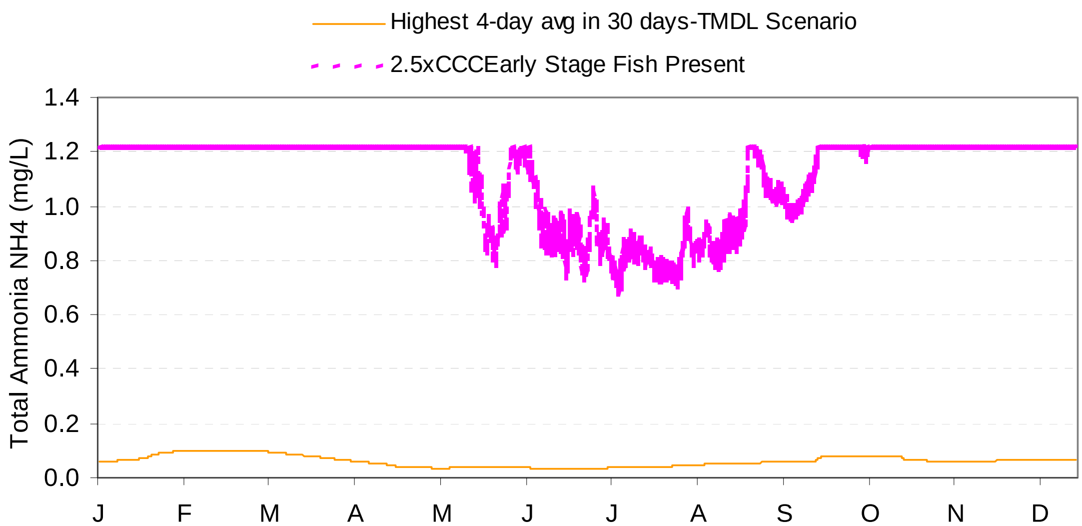

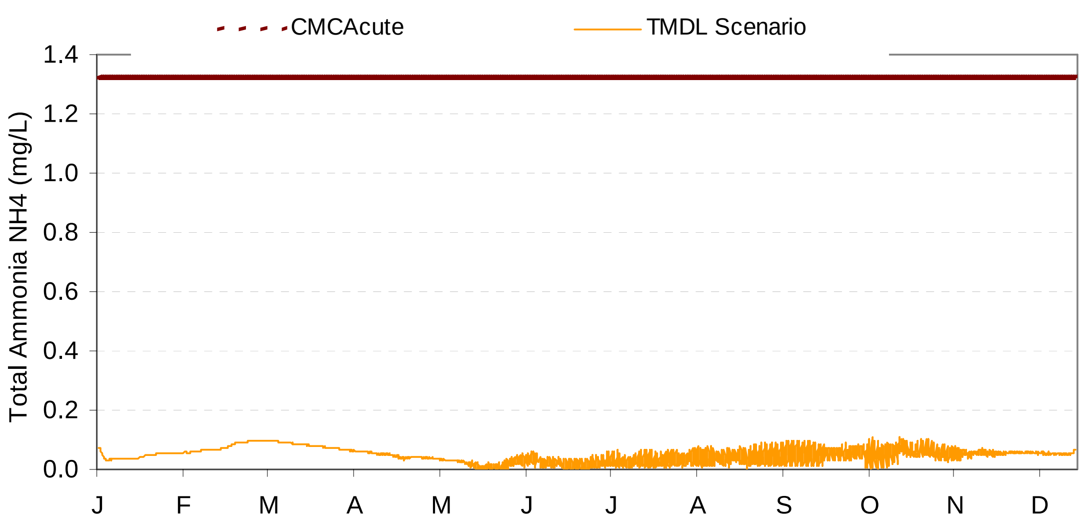

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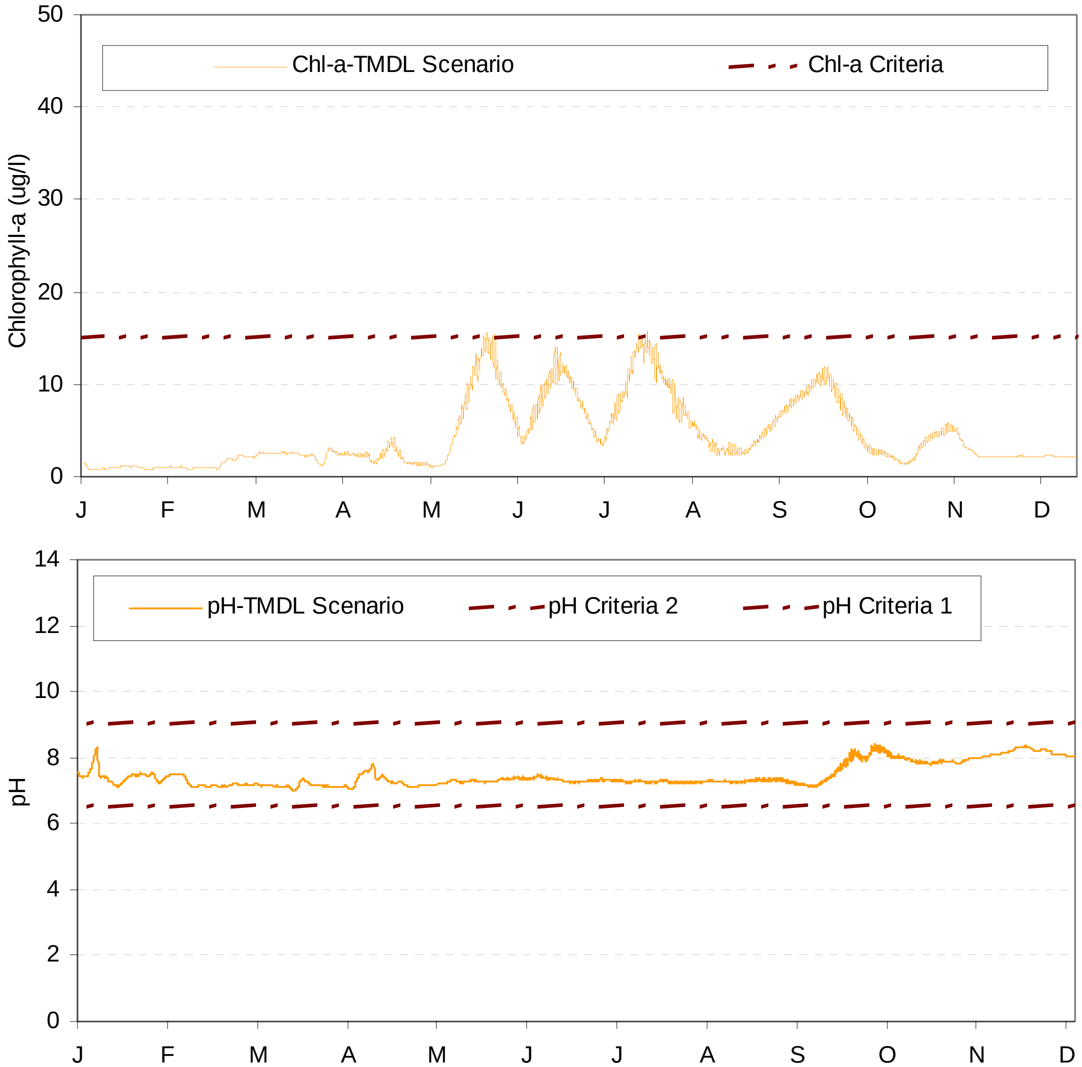
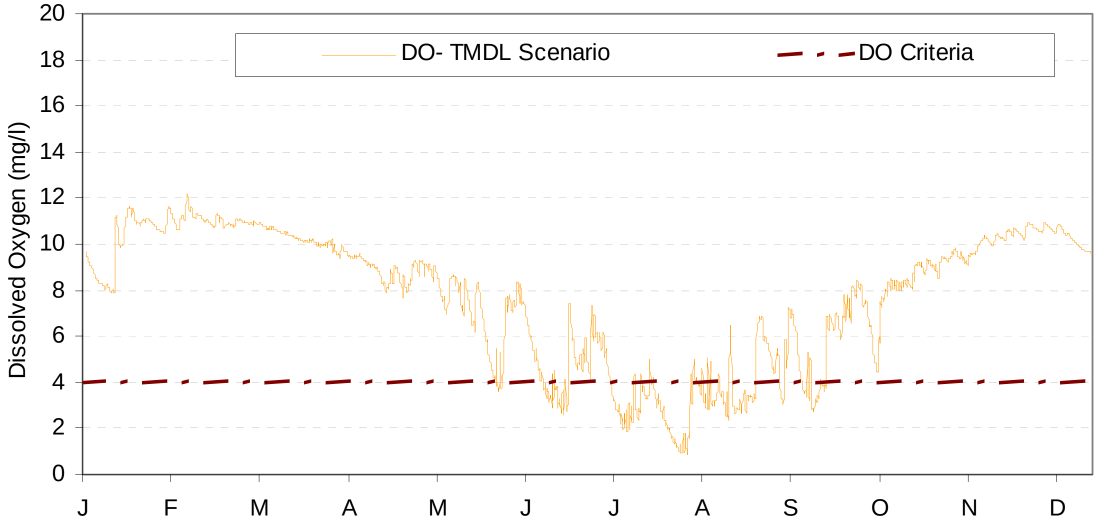
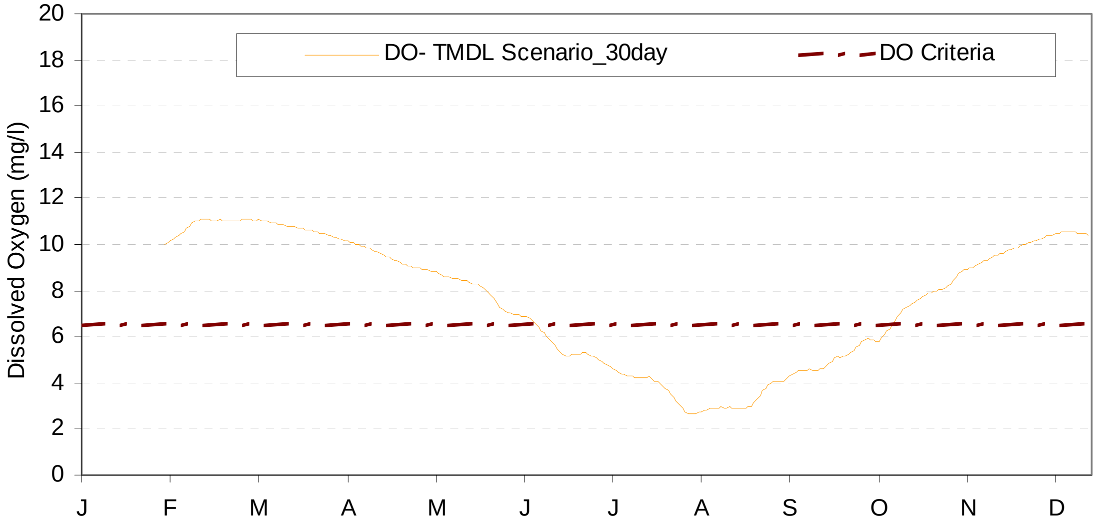


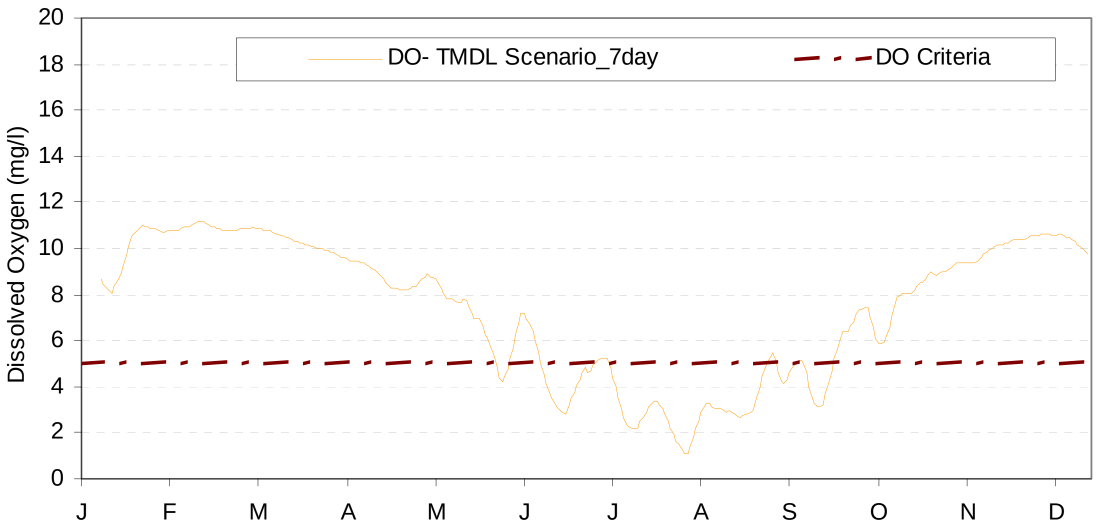
LROG continued



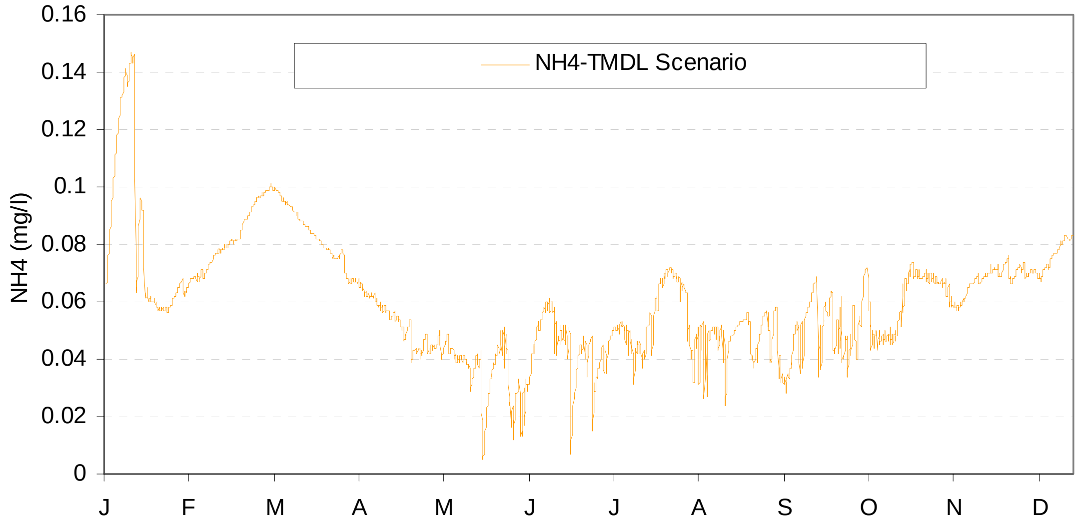
DO- TMDL Scenario
DO Criteria
Dissolved Oxygen (mg/l)
20
18
16
14
12
10
8
6
4
2
0
J
F
M
A
M
J
J
A
S
O
N
D

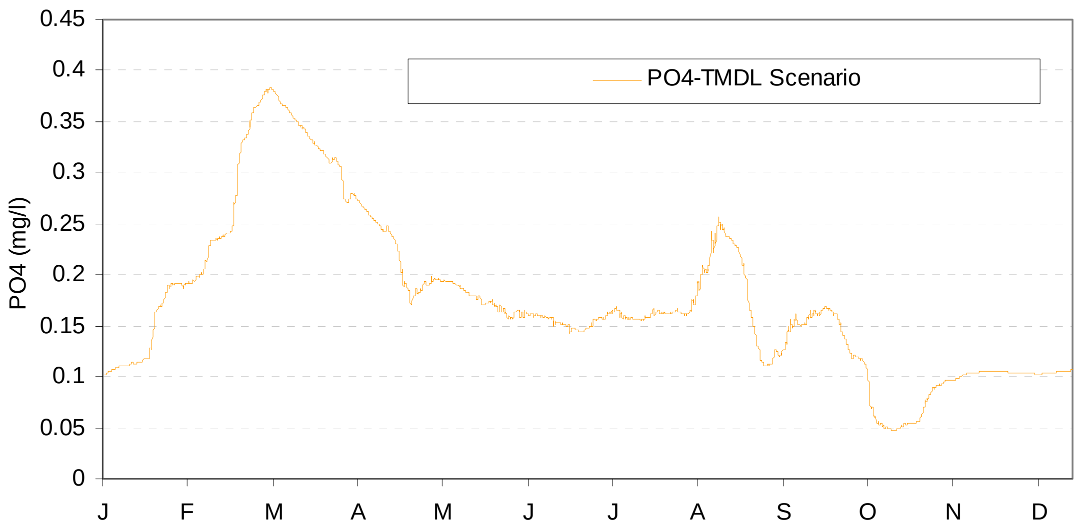


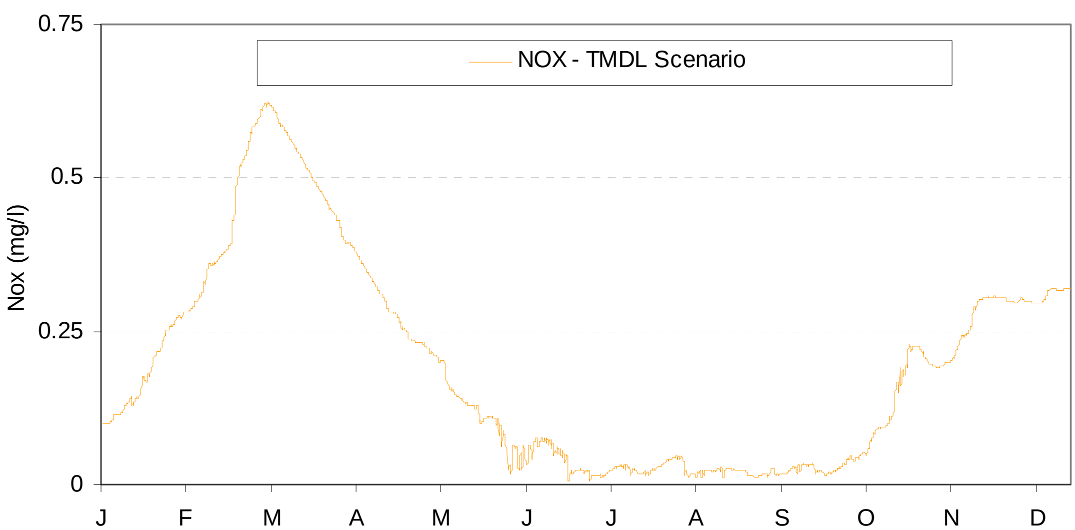
DO- TMDL Scenario_30day
DO Criteria
Dissolved Oxygen (mg/l)
20
18
16
14
12
10
8
6
4
2
0
J
F
M
A
M
J
J
A
S
O
N
D



DO- TMDL Scenario_7day
DO Criteria
Dissolved Oxygen (mg/l)
20
18
16
14
12
10
8
6
4
2
0
J
F
M
A
M
J
J
A
S
O
N
D







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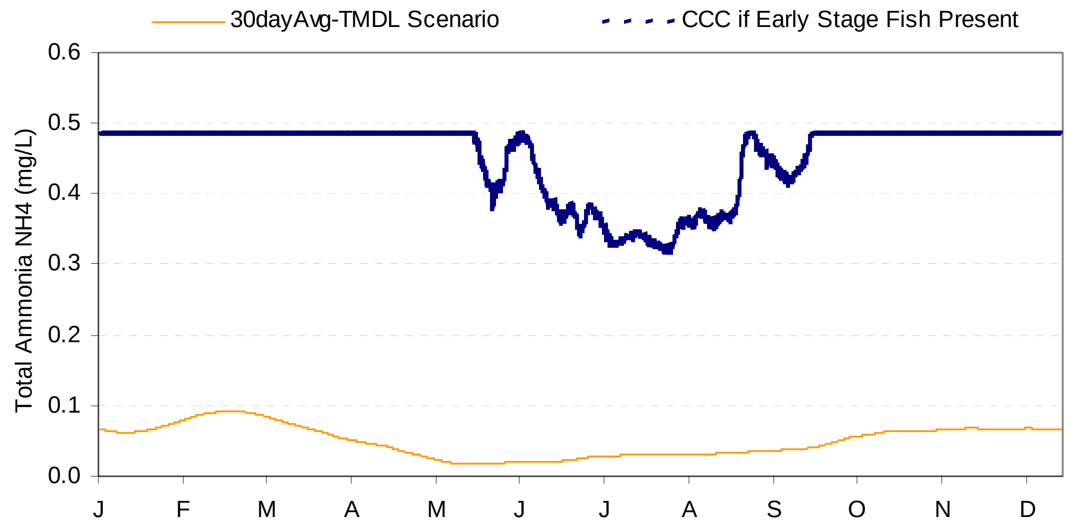
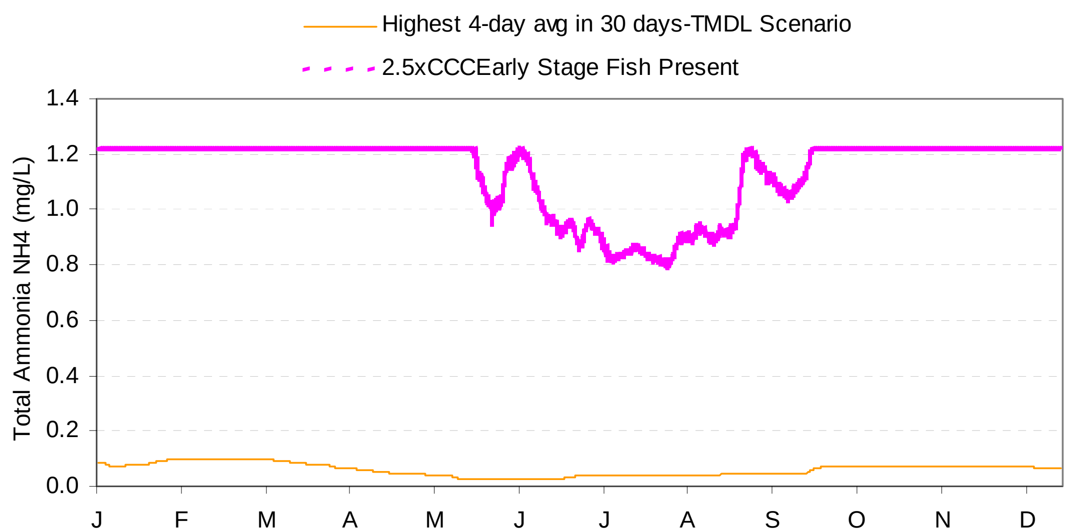
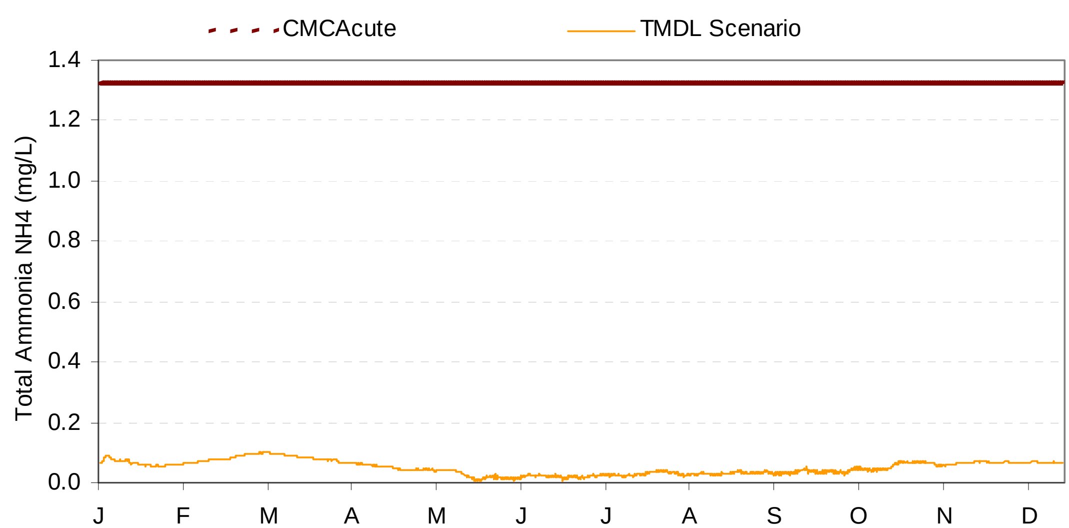
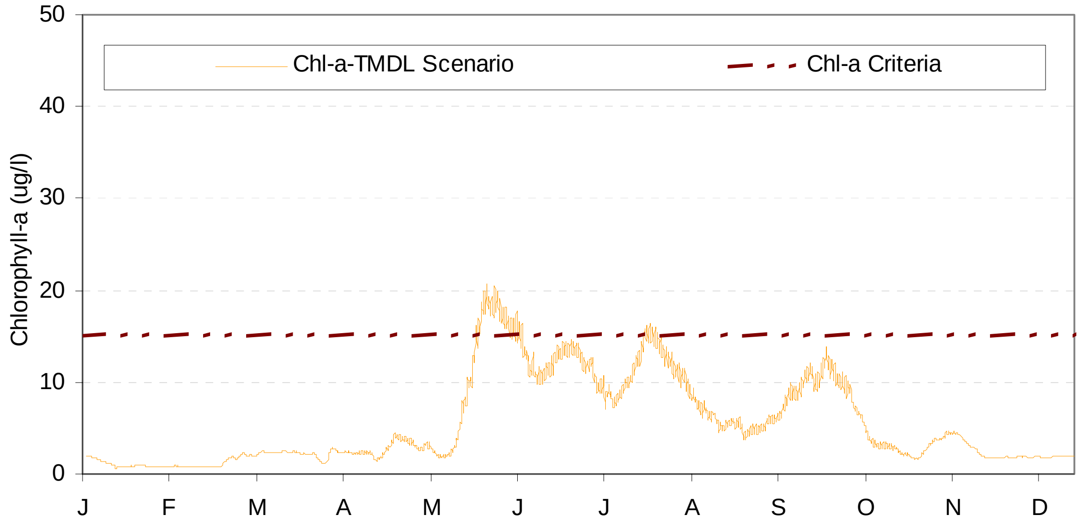
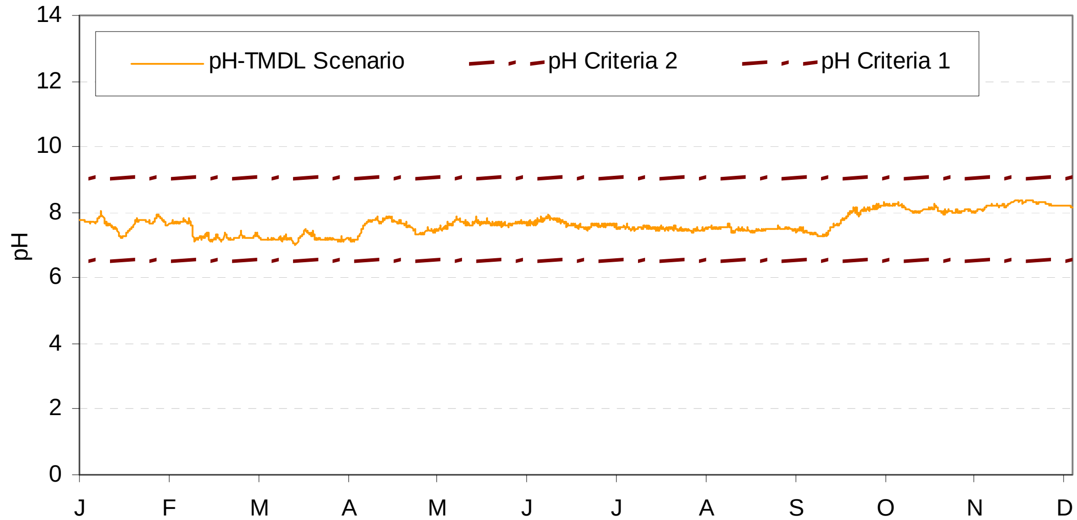




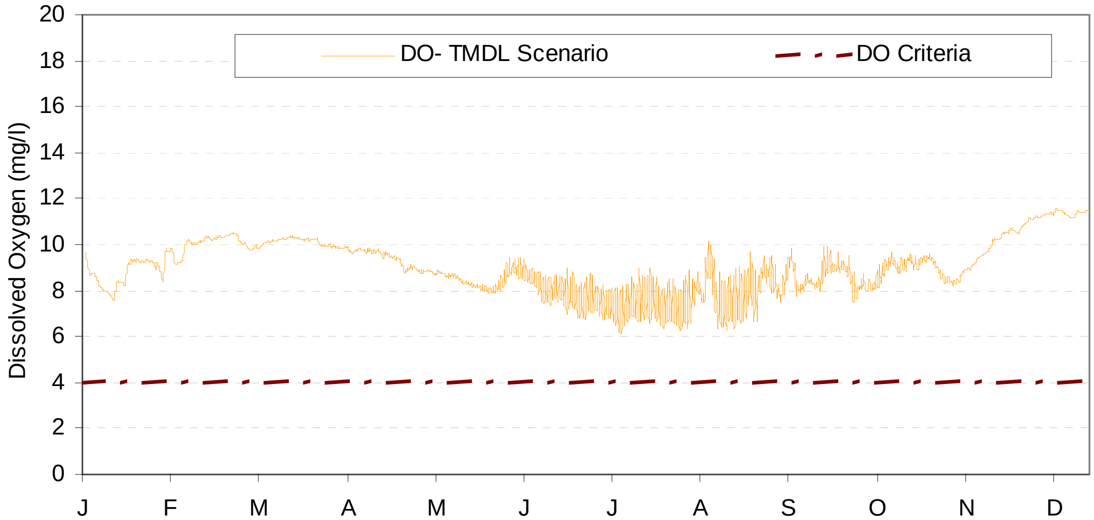


LRWRC continued

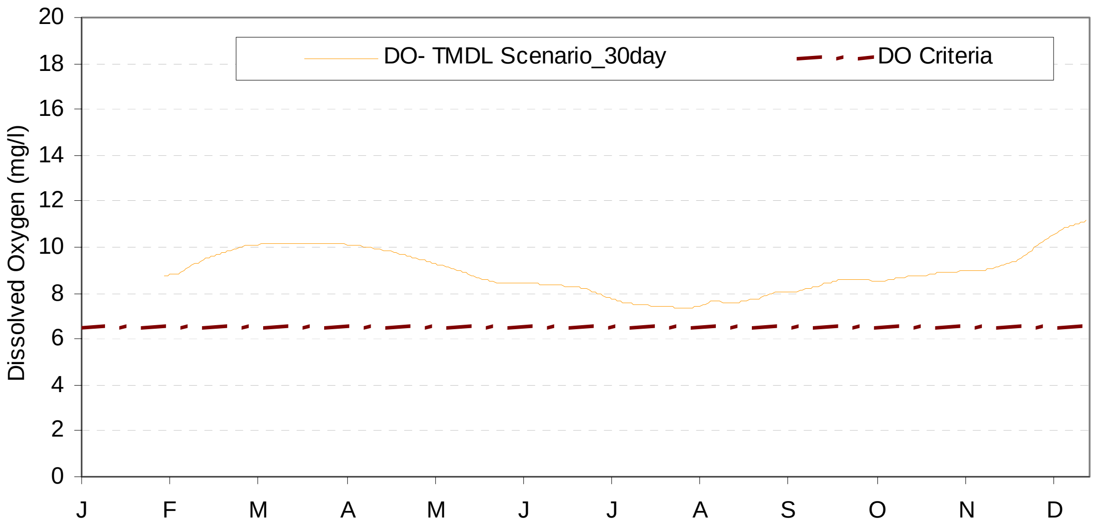




LRWRC continued



DO- TMDL Scenario
DO Criteria
Dissolved Oxygen (mg/l)
20
18
16
14
12
10
8
6
4
2
0
J
F
M
A
M
J
J
A
S
O
N
D



DO- TMDL Scenario_30day
DO Criteria
Dissolved Oxygen (mg/l)
20
18
16
14
12
10
8
6
4
2
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J
F
M
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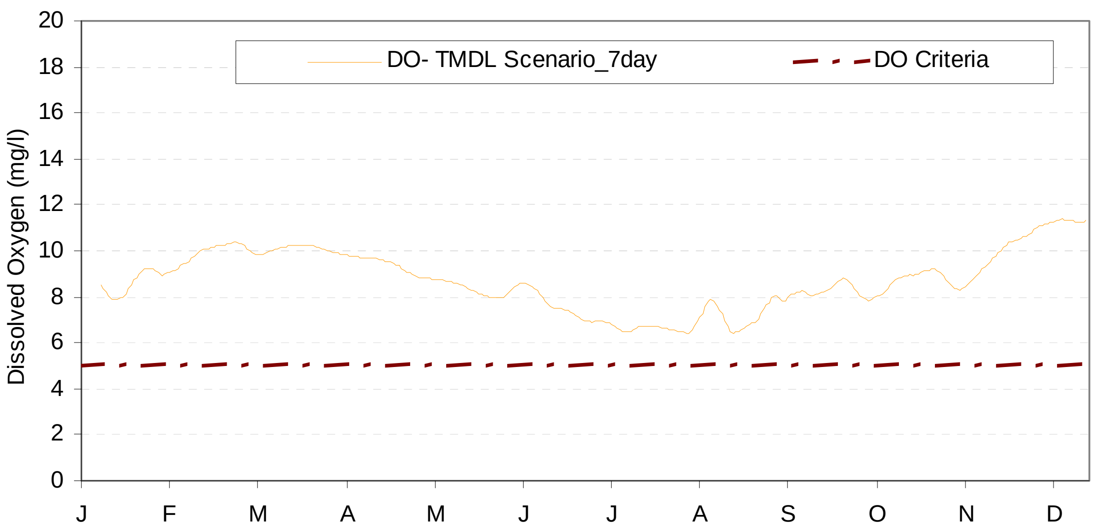
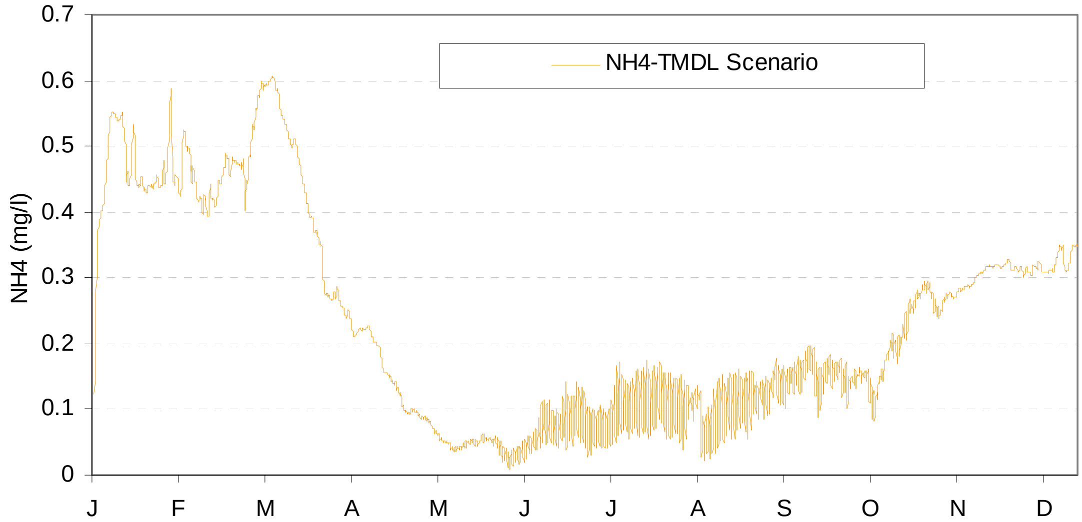
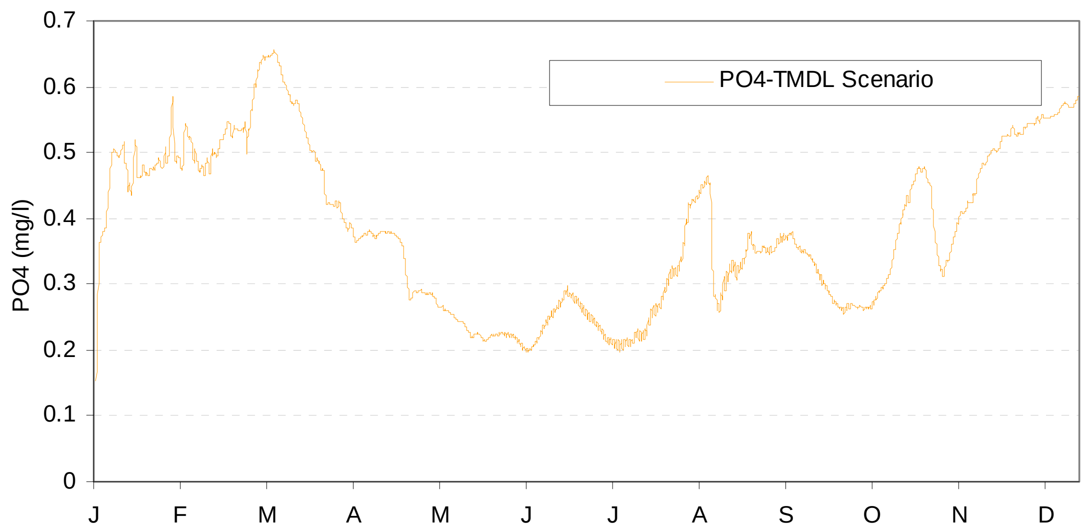
M
J
J
A
S
O
N
D

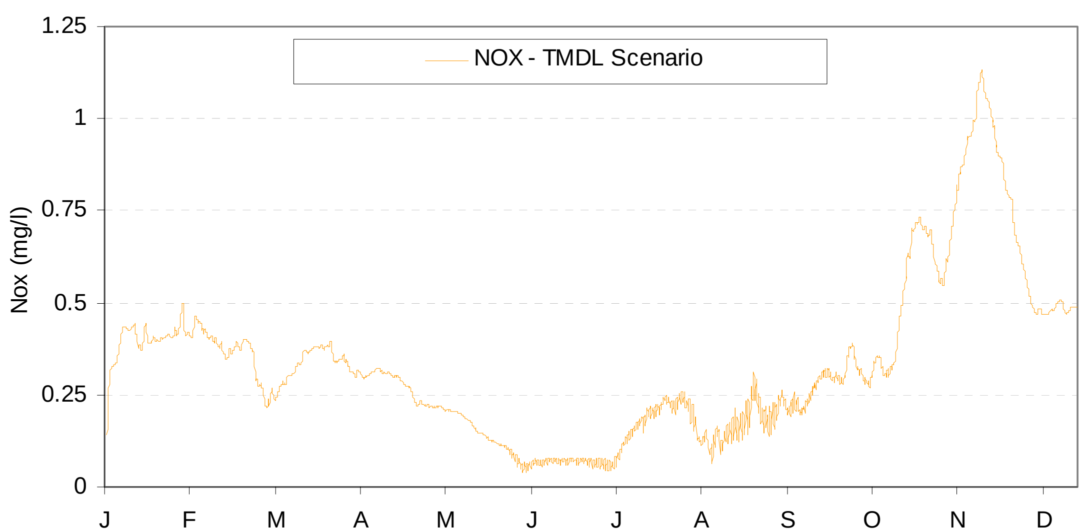


DO- TMDL Scenario_7day
DO Criteria
Dissolved Oxygen (mg/l)
20
18
16
14
12
10
8
6
4
2
0
J
F
M
A
M
J
J
A
S
O
N
D

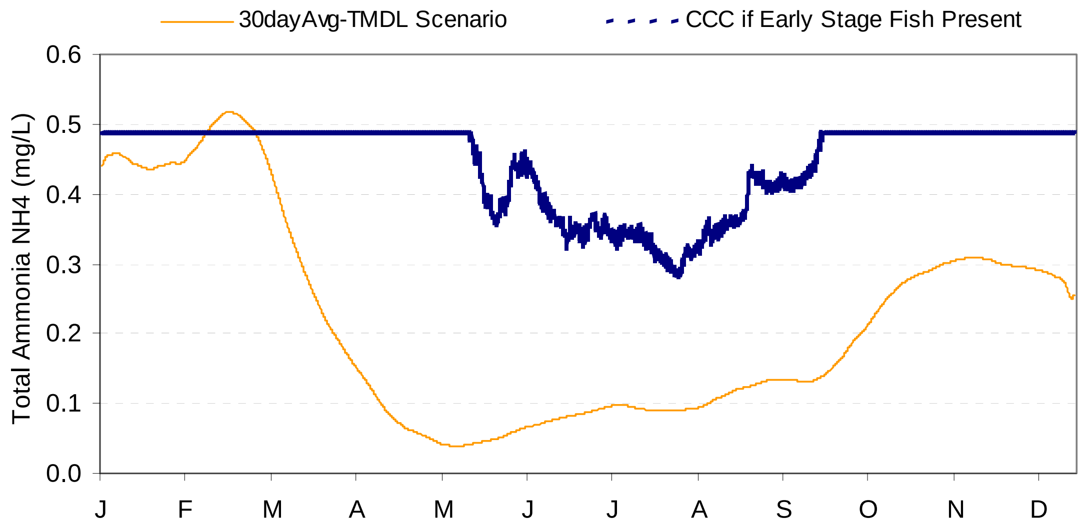
LRDR

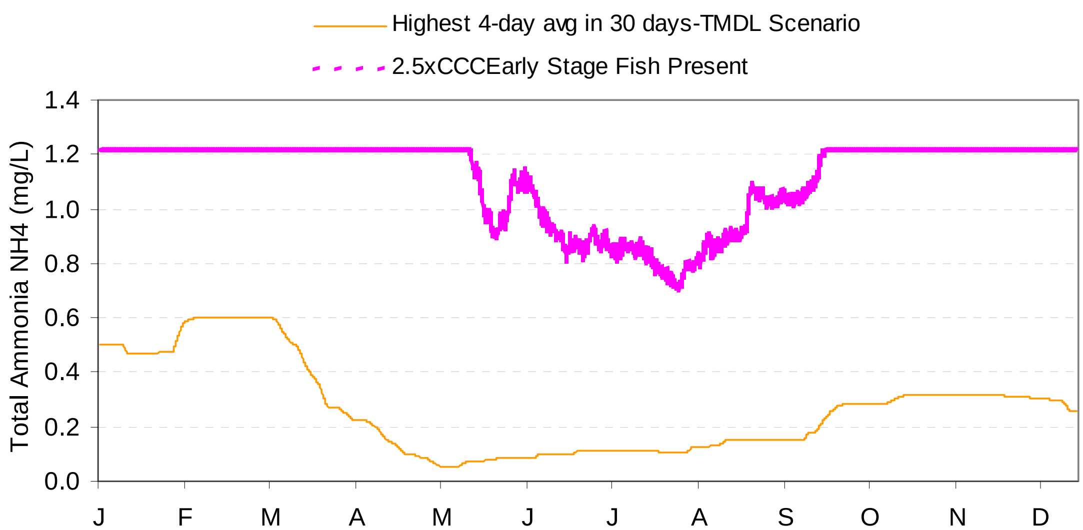


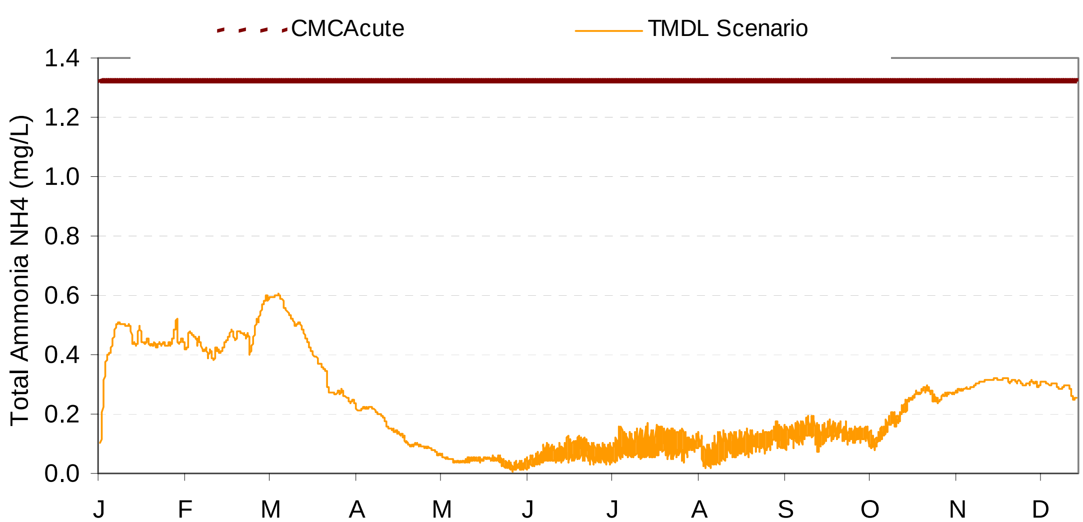




LRDR continued







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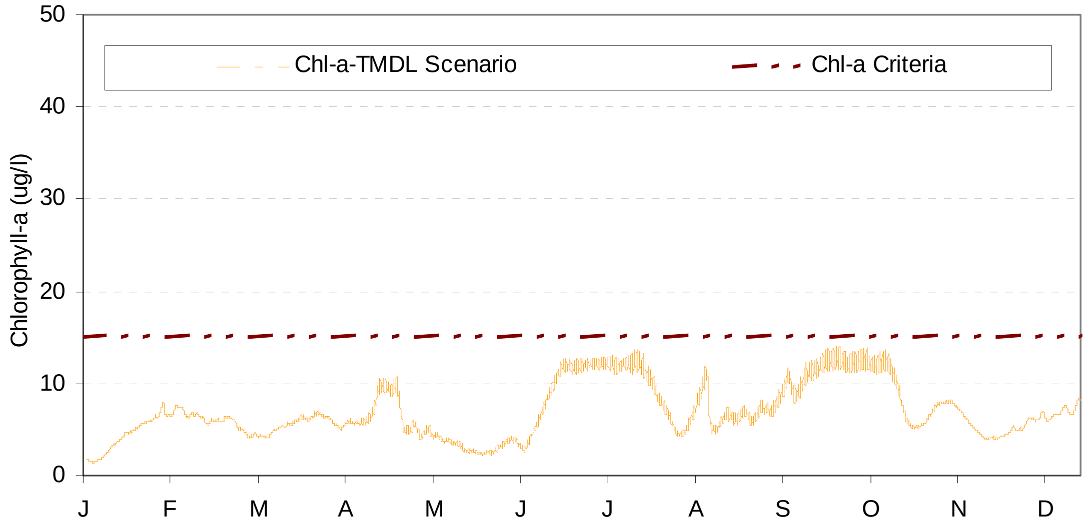
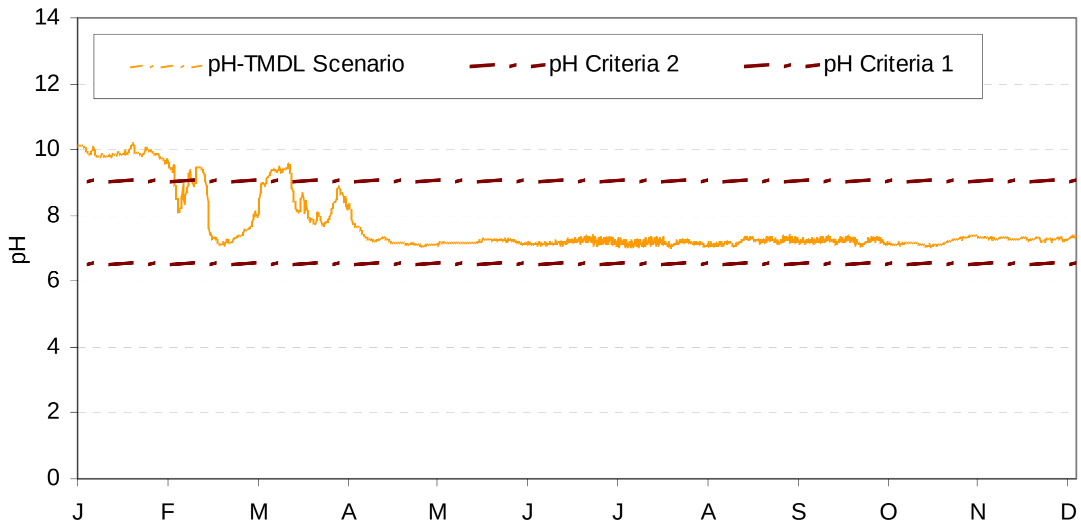
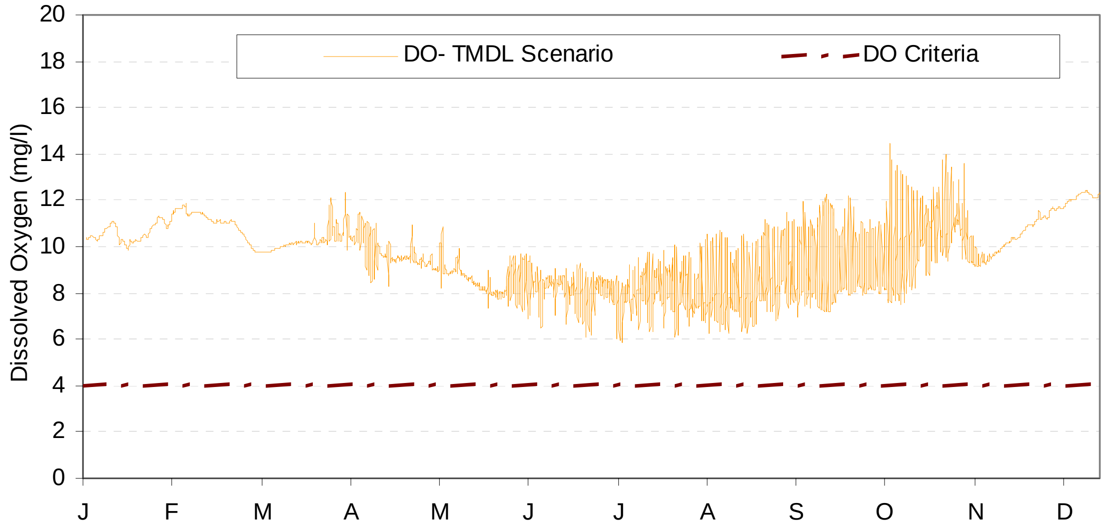




LRDR continued


DO- TMDL Scenario
DO Criteria
Dissolved Oxygen (mg/l)
20
18
16
14
12
10
8
6
4
2
0
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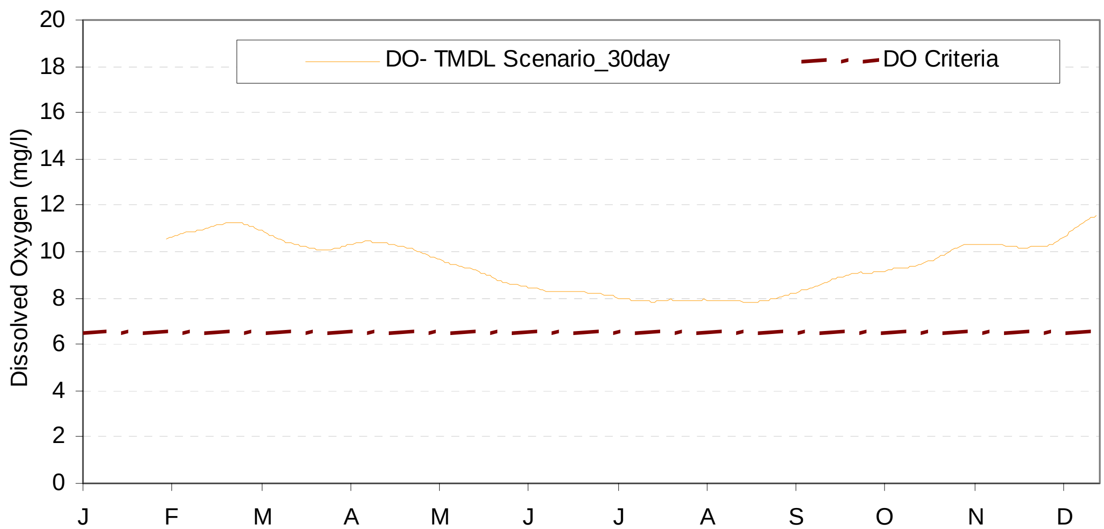
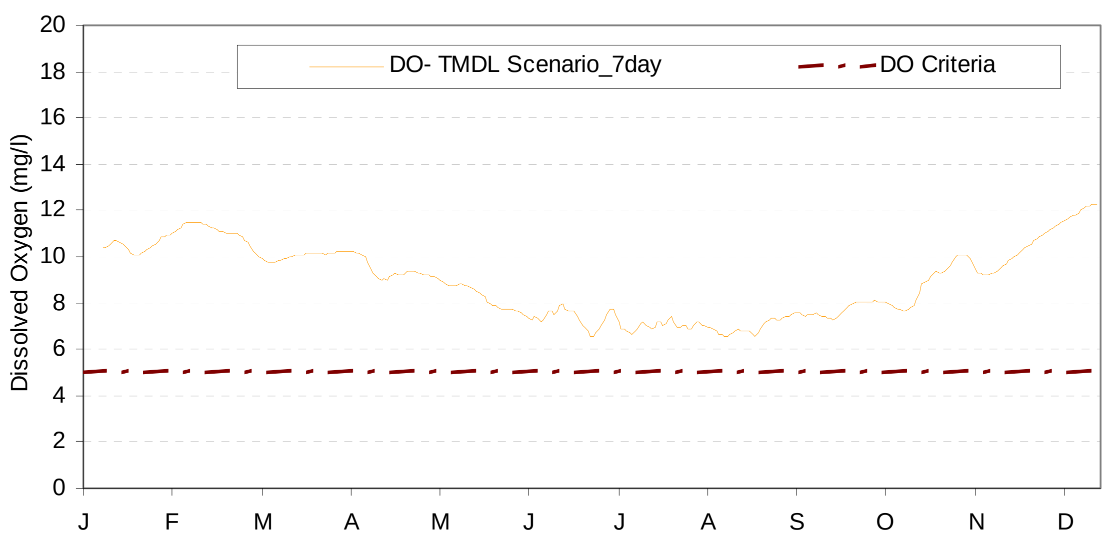
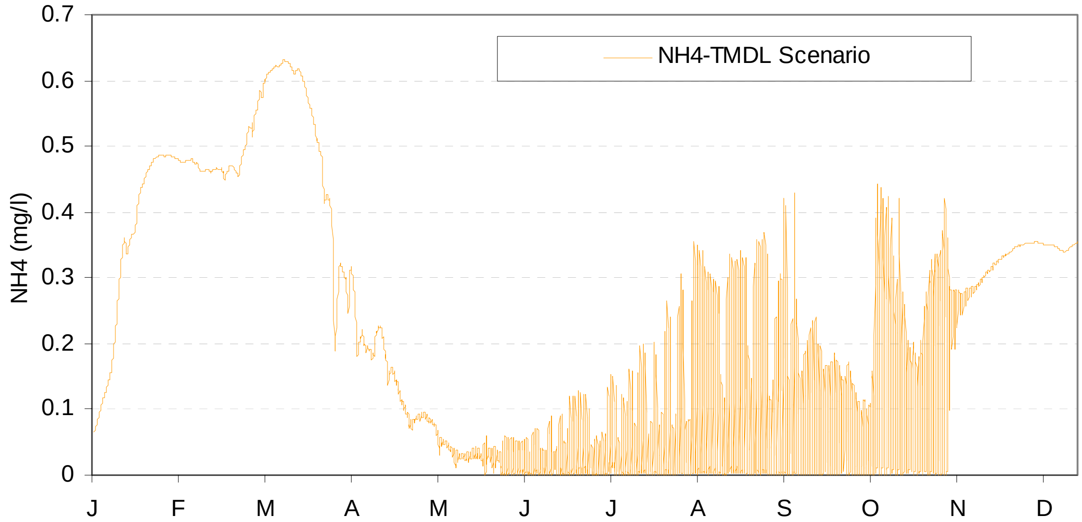
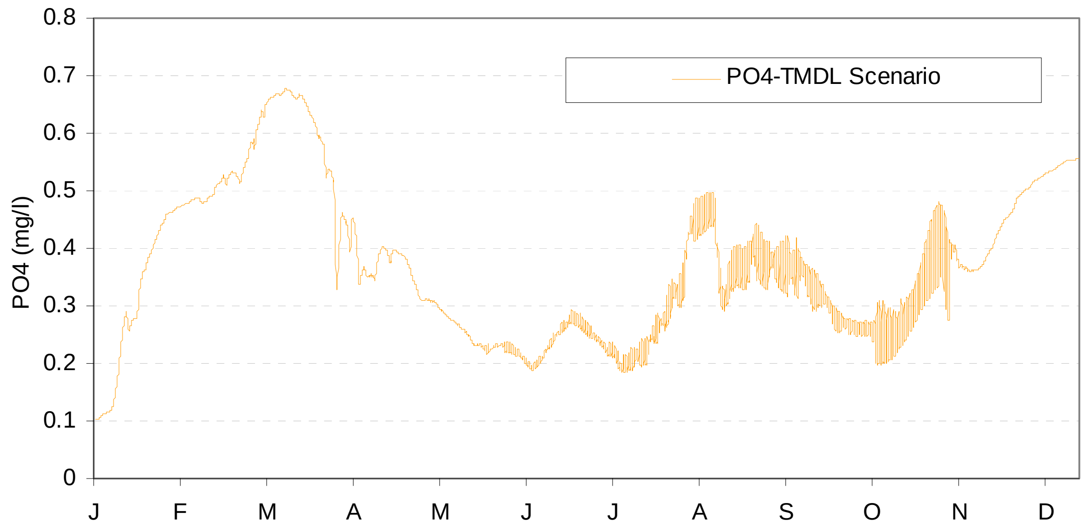
F
M
A
M
J
J
A
S
O
N
D

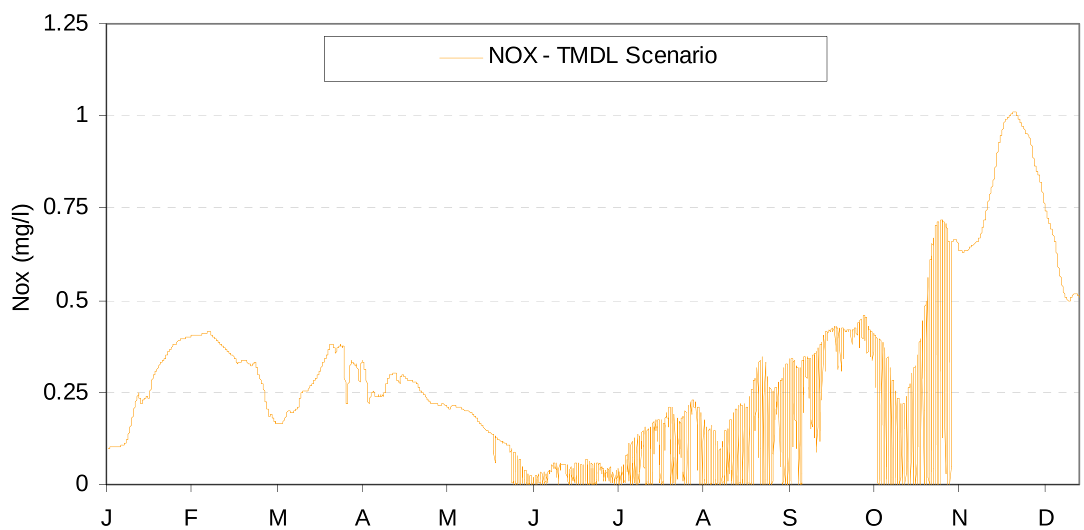

DO- TMDL Scenario_30day
DO Criteria
Dissolved Oxygen (mg/l)
20
18
16
14
12
10
8
6
4
2
0
J
F
M
A
M
J
J
A
S
O
N
D


DO- TMDL Scenario_7day
DO Criteria
Dissolved Oxygen (mg/l)
20
18
16
14
12
10
8
6
4
2
0
J
F
M
A
M
J
J
A
S
O
N
D

LR39







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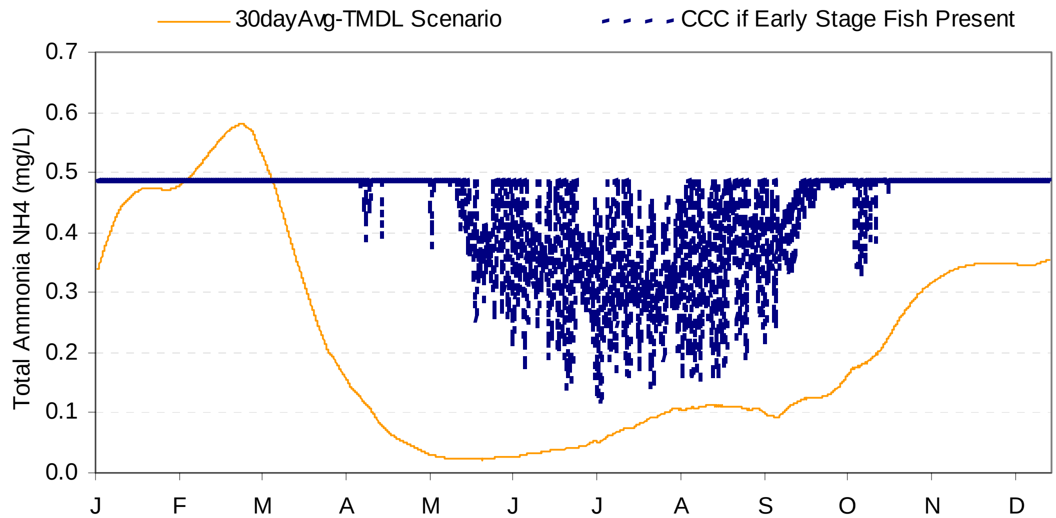

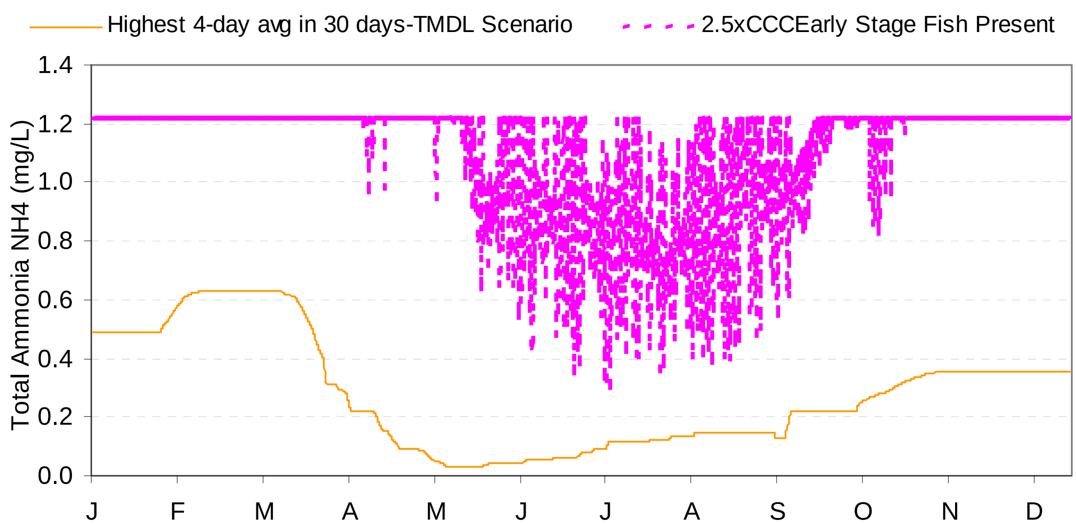

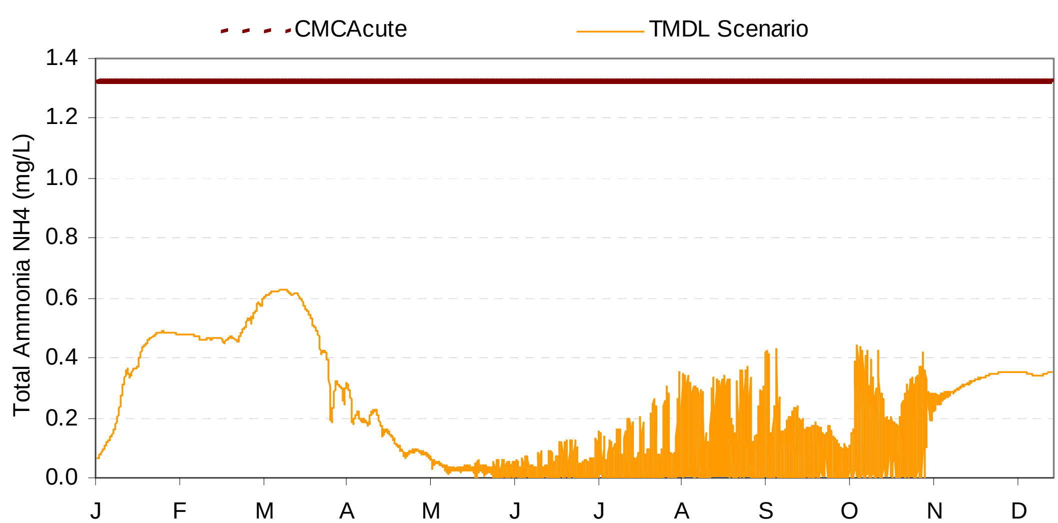

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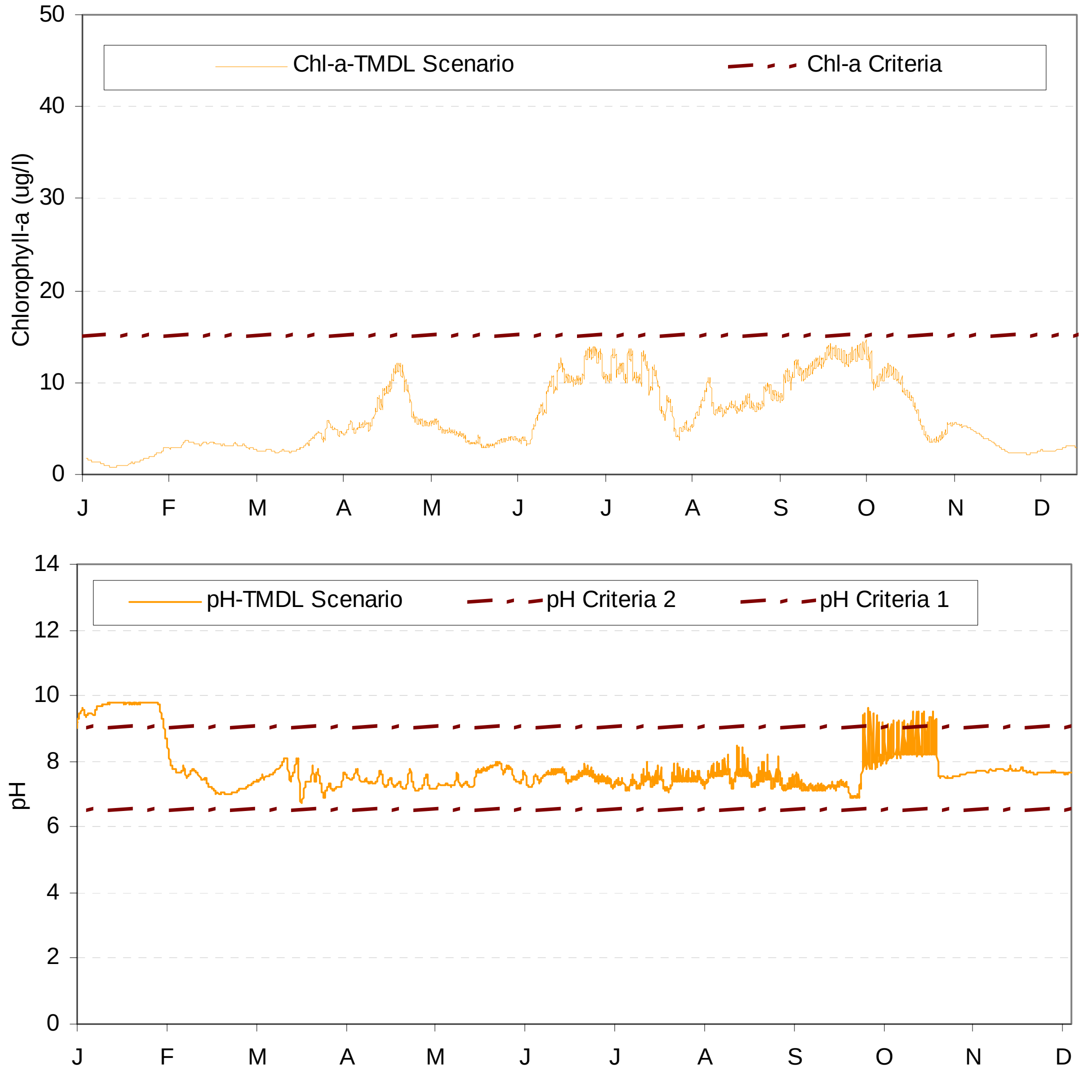

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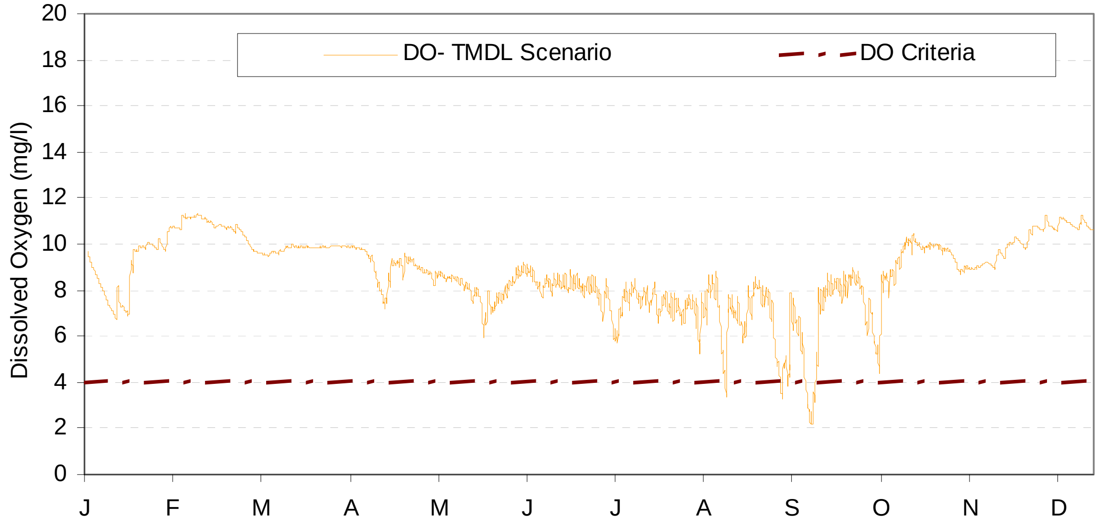
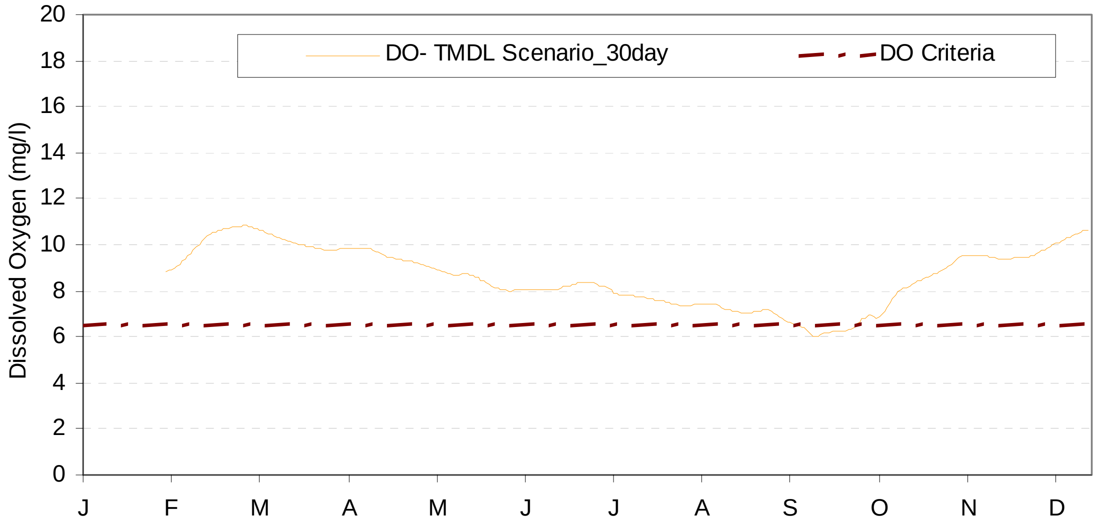
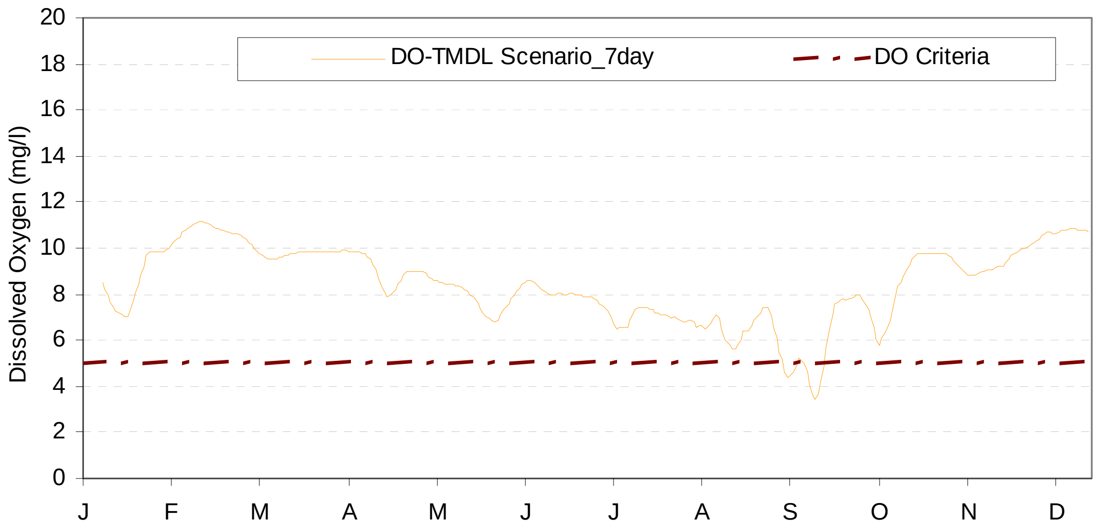
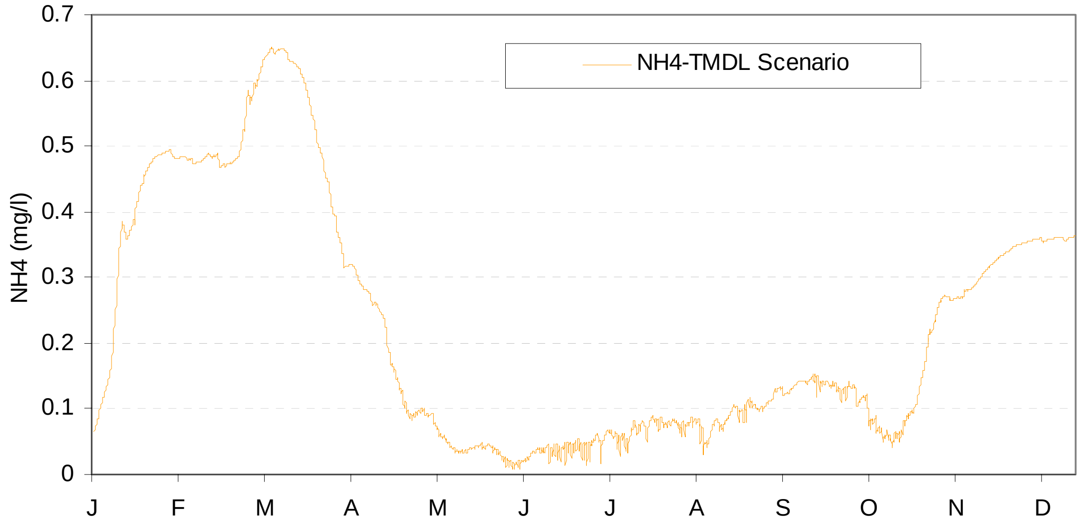
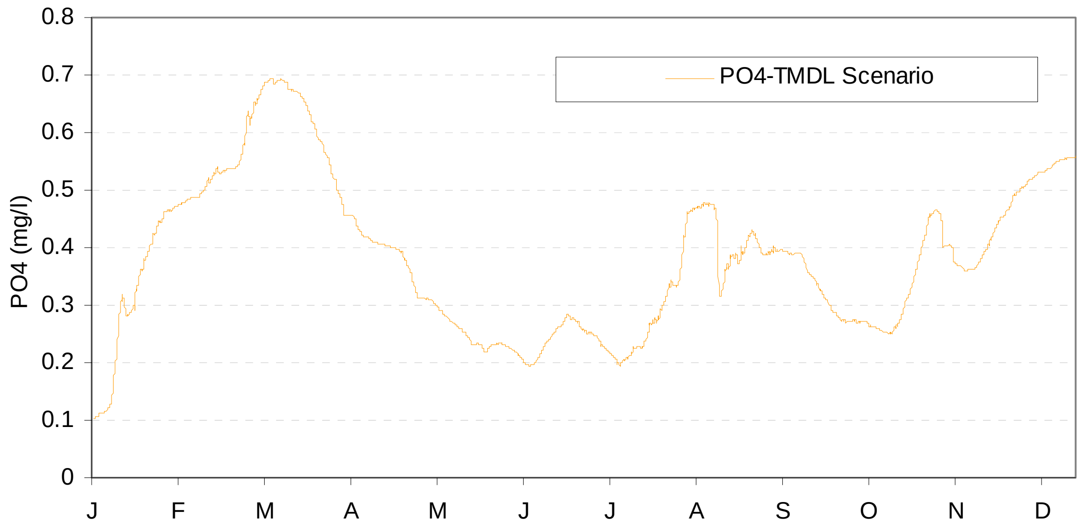

DO- TMDL Scenario
DO Criteria
Dissolved Oxygen (mg/l)
0
2
4
6
8
10
12
14
16
18
20
J
F
M
A
M
J
J
A
S
O
N
D

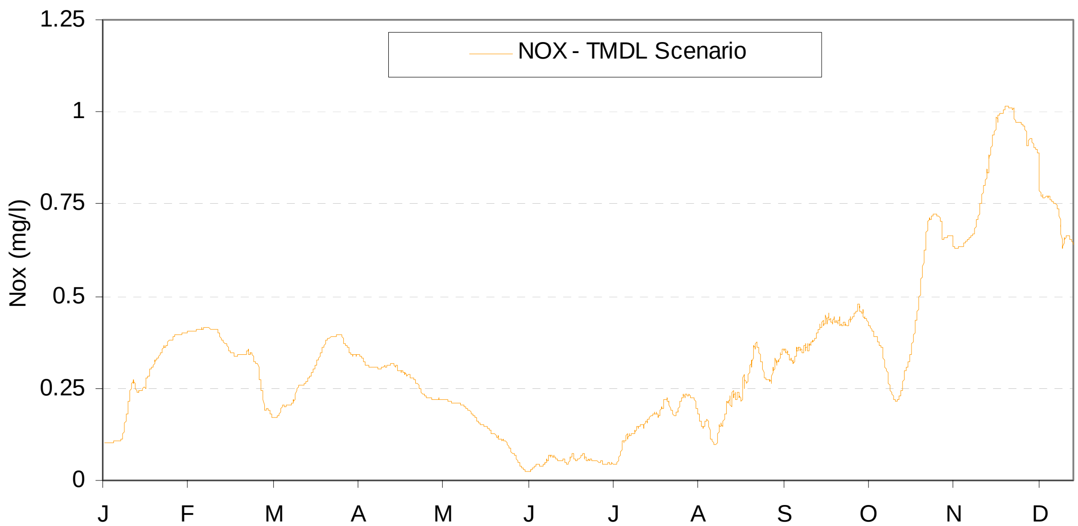

DO- TMDL Scenario_30day
DO Criteria
Dissolved Oxygen (mg/l)
0
2
4
6
8
10
12
14
16
18
20
J
F
M
A
M
J
J
A
S
O
N
D


DO-TMDL Scenario_7day
DO Criteria
Dissolved Oxygen (mg/l)
0
2
4
6
8
10
12
14
16
18
20
J
F
M
A
M
J
J
A
S
O
N
D

LRAR







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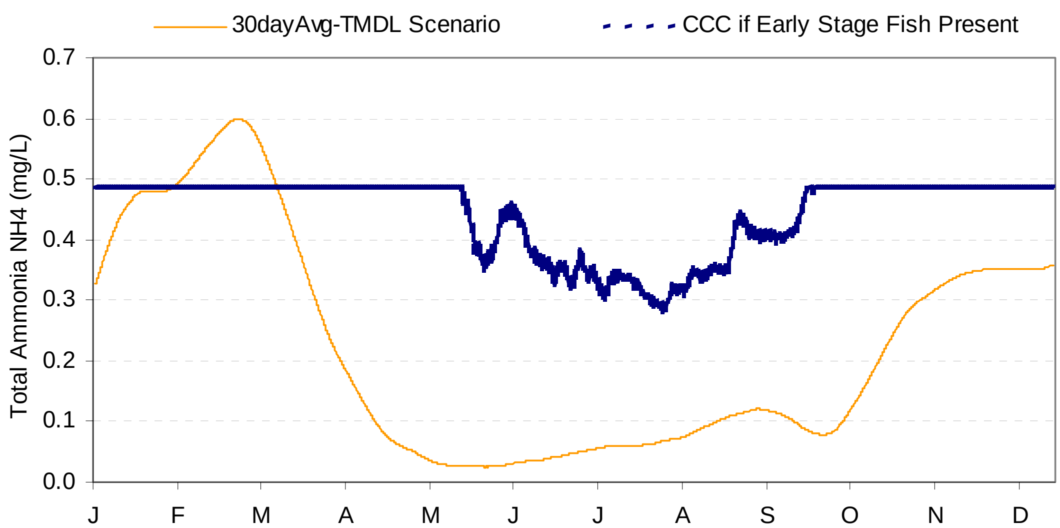

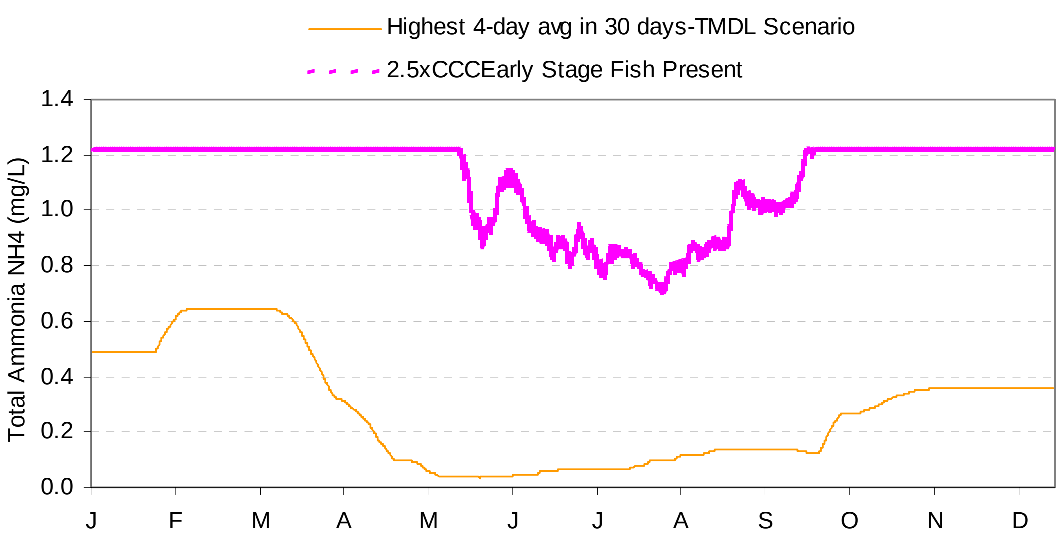

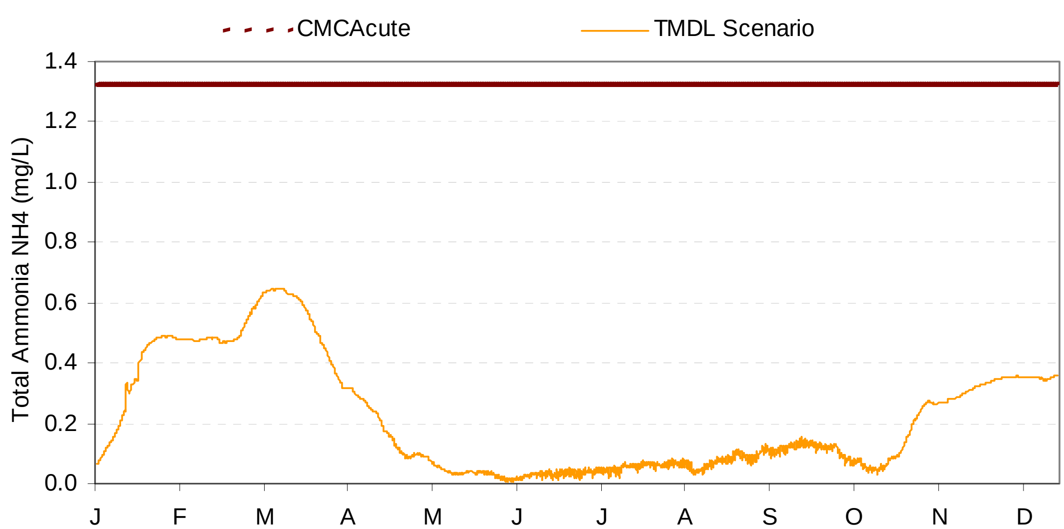

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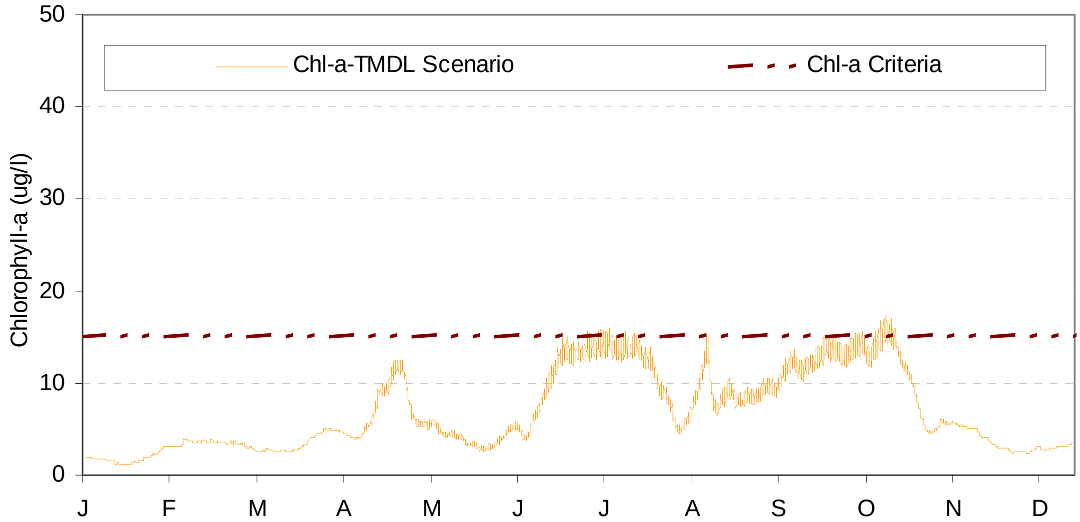
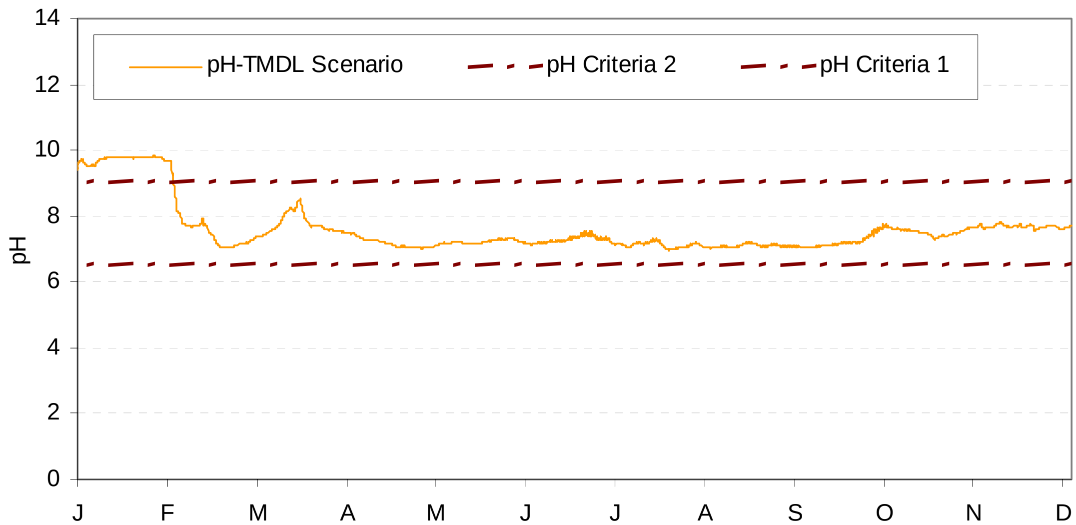
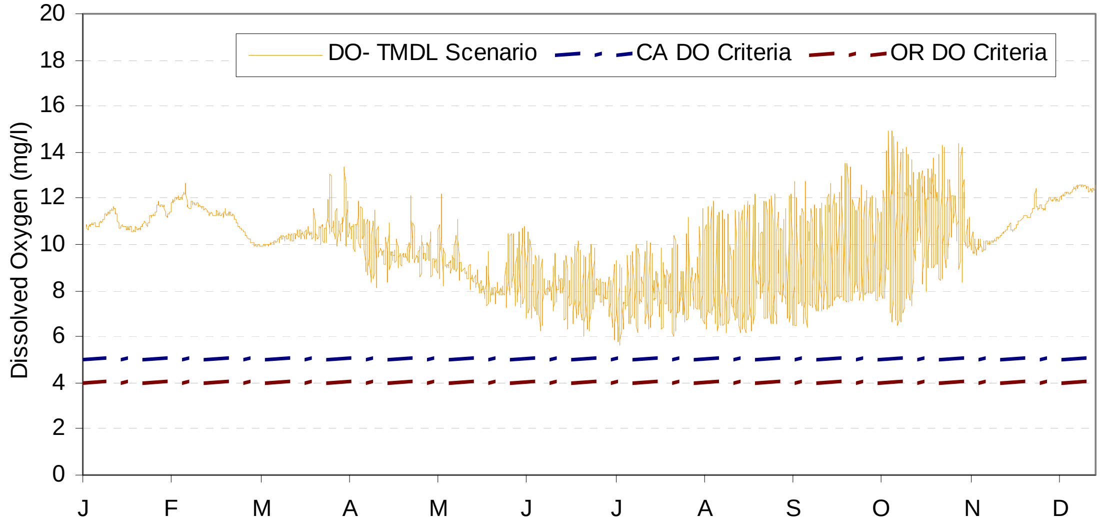




LRAR continued


DO- TMDL Scenario
CA DO Criteria
OR DO Criteria
Dissolved Oxygen (mg/l)
20
18
16
14
12
10
8
6
4
2
0
J
F
M
A
M
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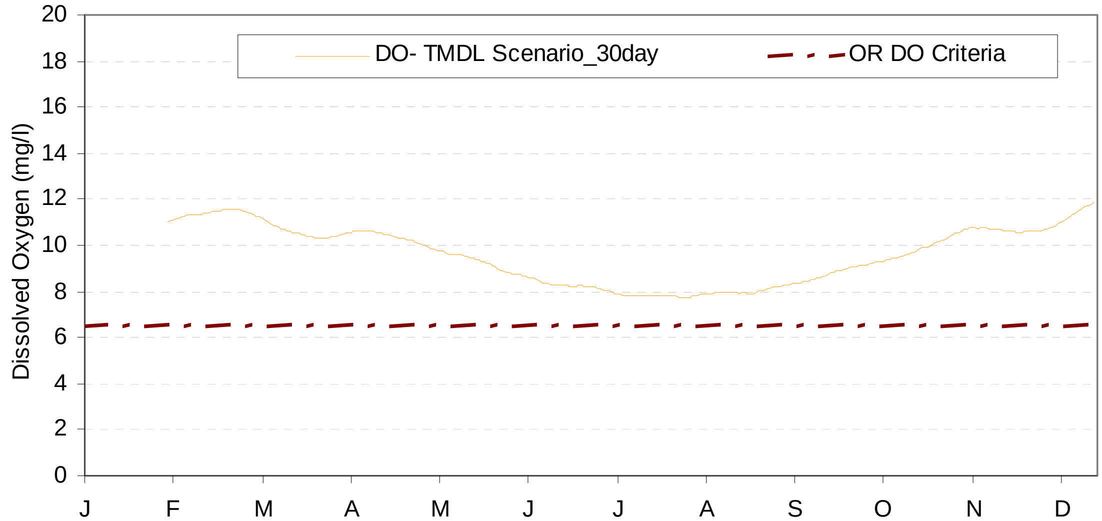
J
A
S
O
N
D


DO- TMDL Scenario_30day
OR DO Criteria
Dissolved Oxygen (mg/l)
20
18
16
14
12
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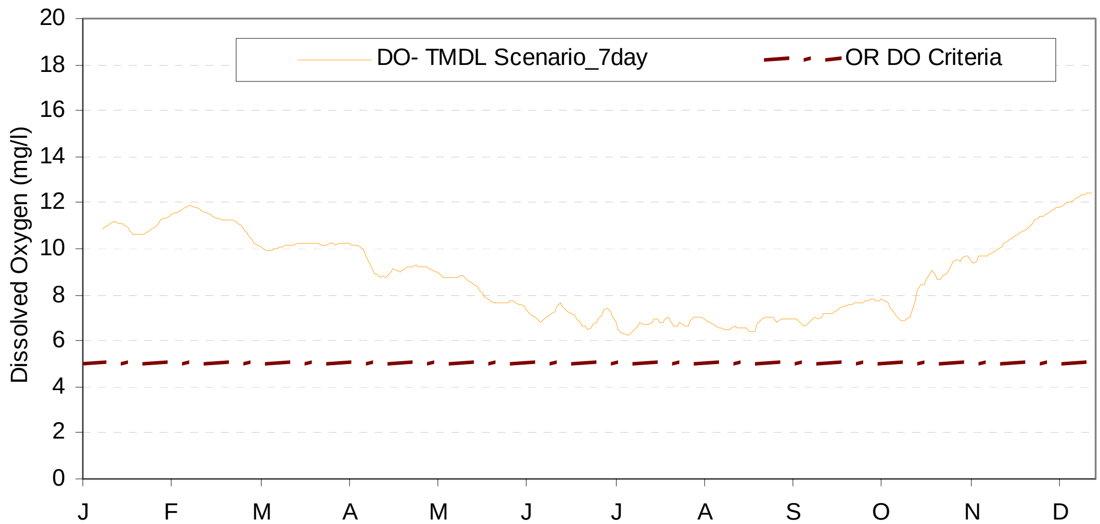
6
4
2
0
J
F
M
A
M
J
J
A
S
O
N
D


DO- TMDL Scenario_7day
OR DO Criteria
Dissolved Oxygen (mg/l)
20
18
16
14
12
10
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4
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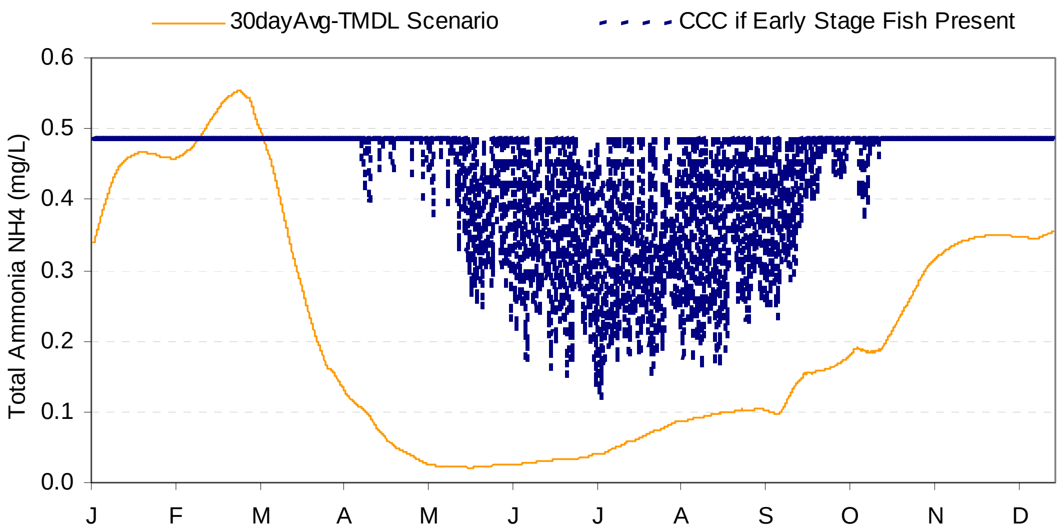
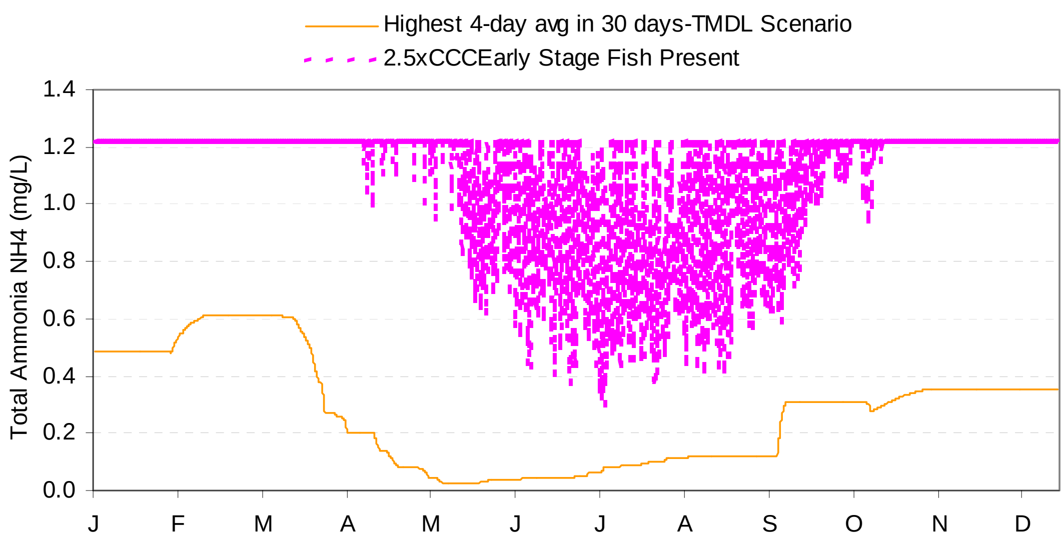
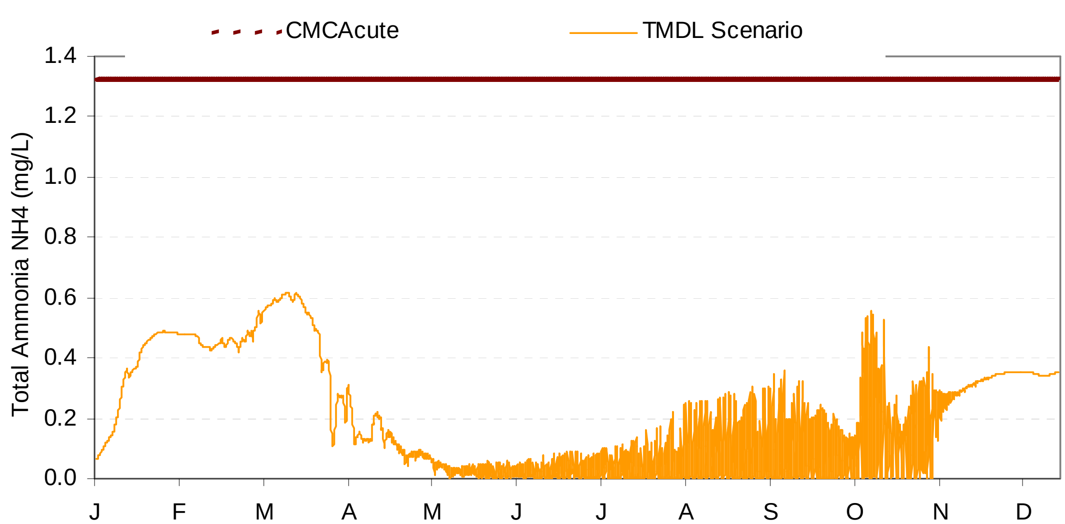
0
J
F
M
A
M
J
J
A
S
O
N
D

LRSR

LRSR continued







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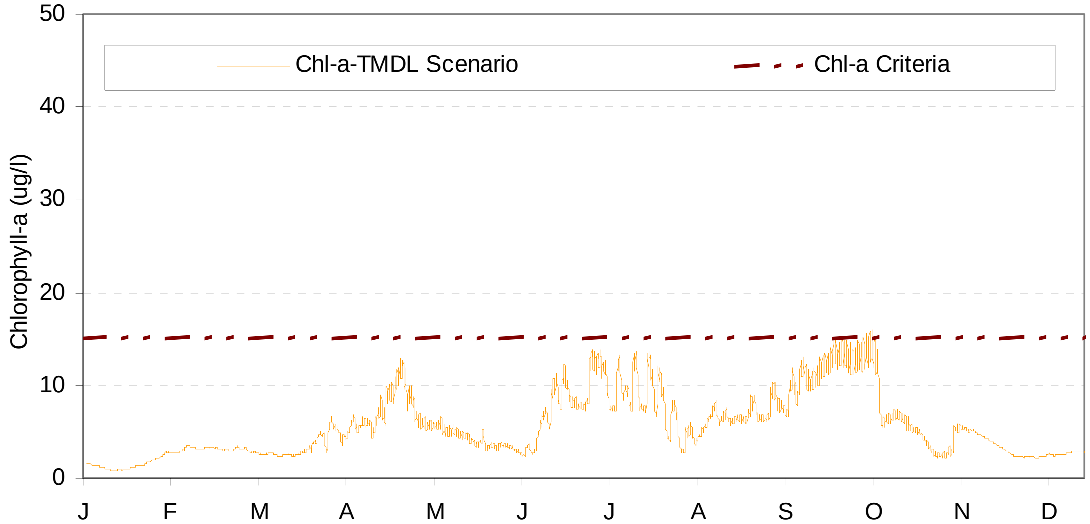

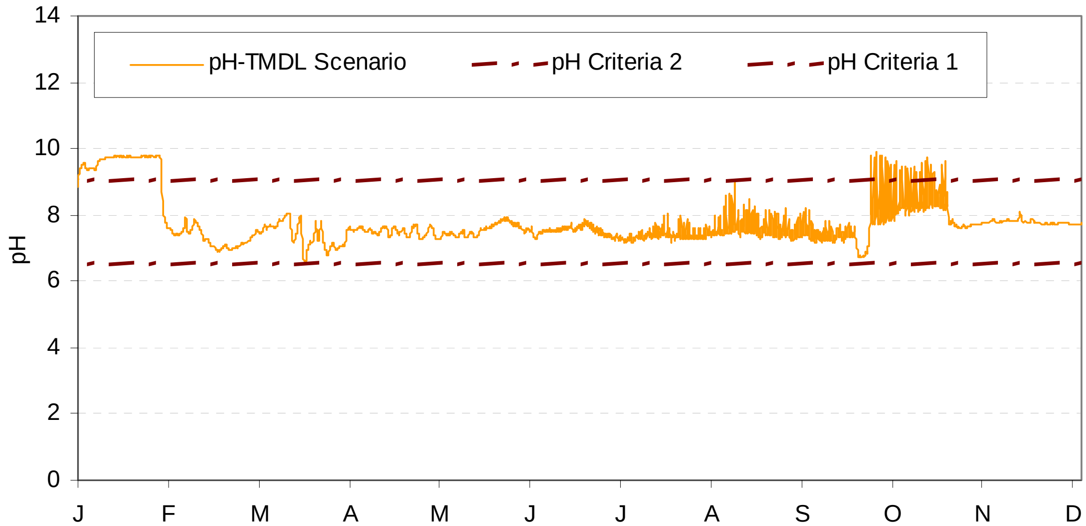

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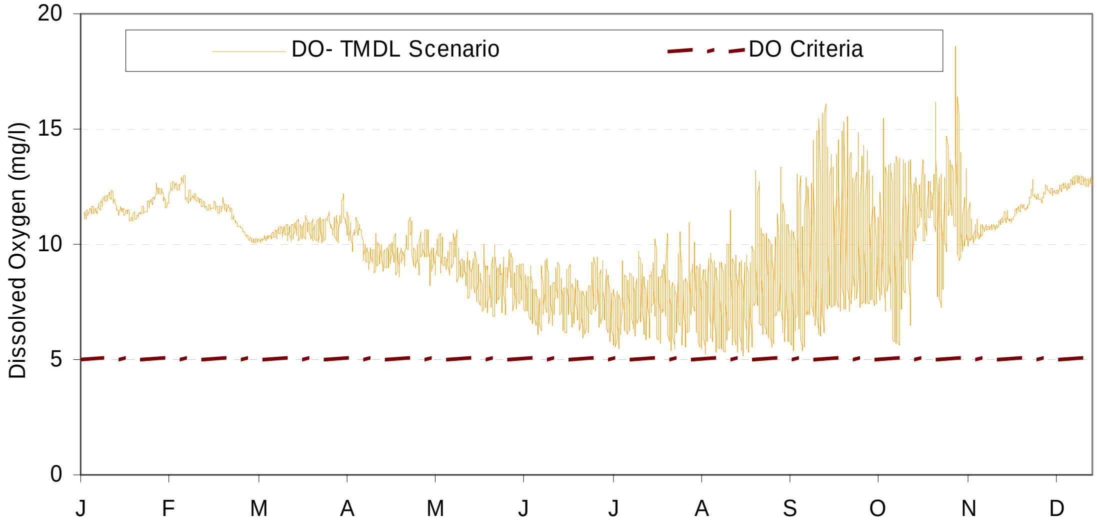
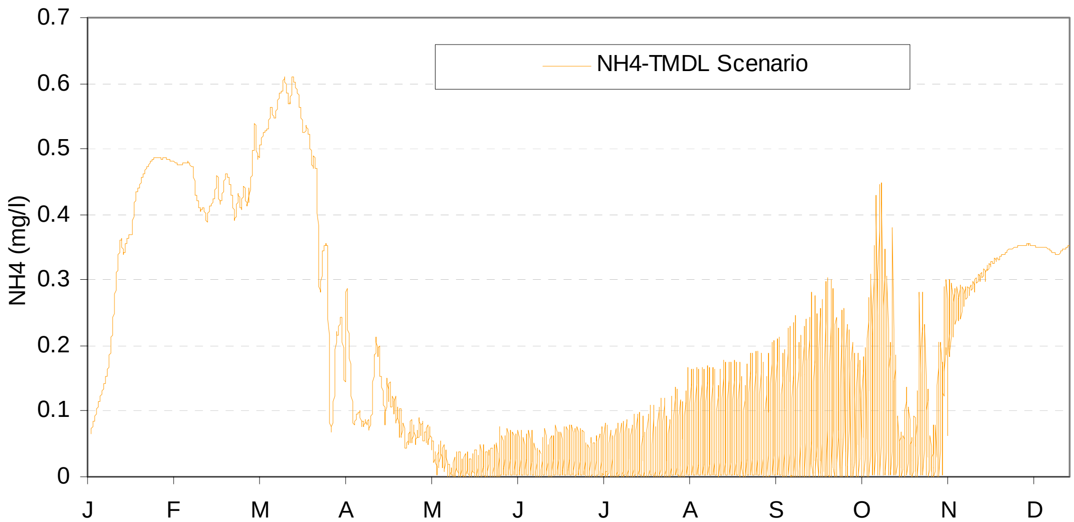
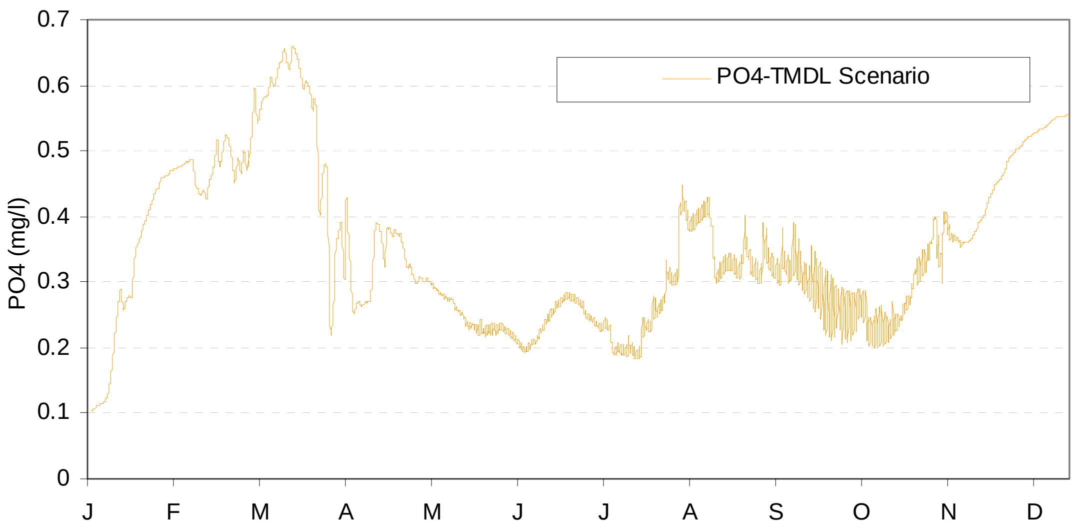
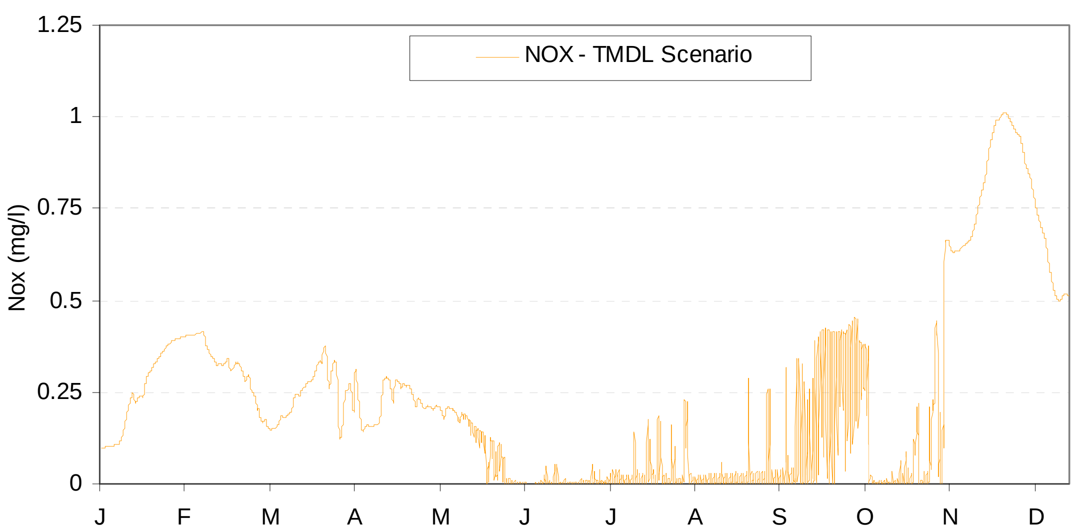


20
15
10
5
0
Dissolved Oxygen (mg/l)
DO- TMDL Scenario
DO Criteria
J
F
M
A
M
J
J
A
S
O
N
D

LREW







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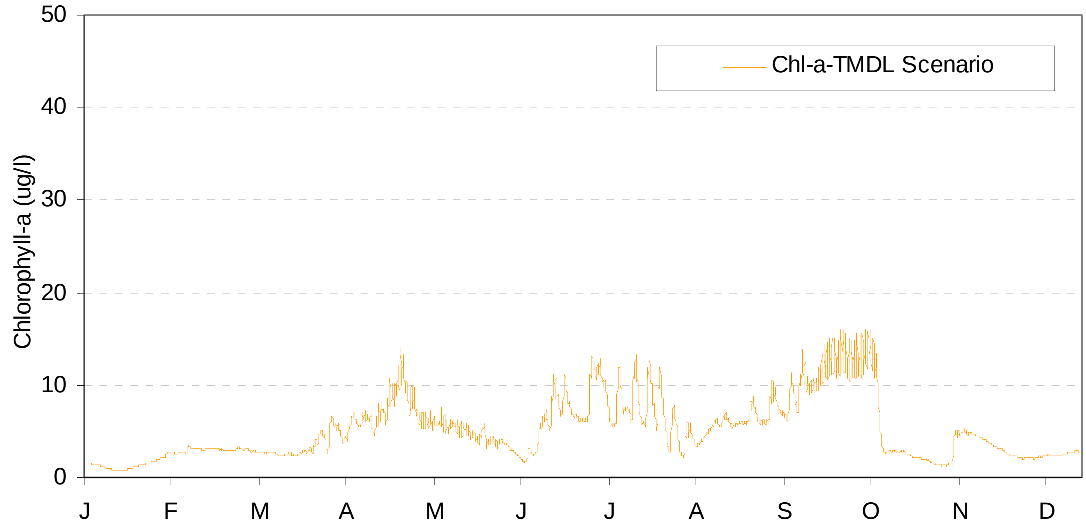
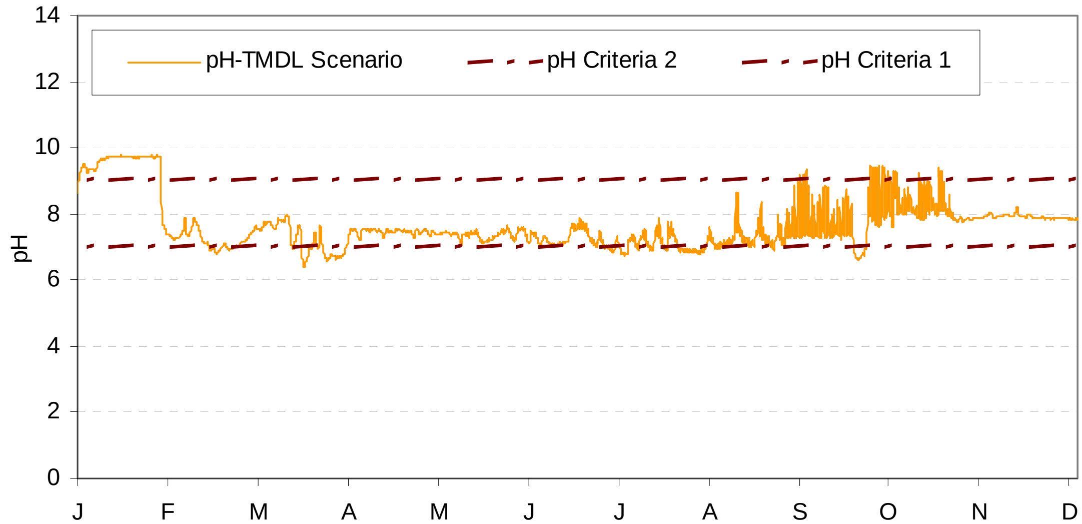
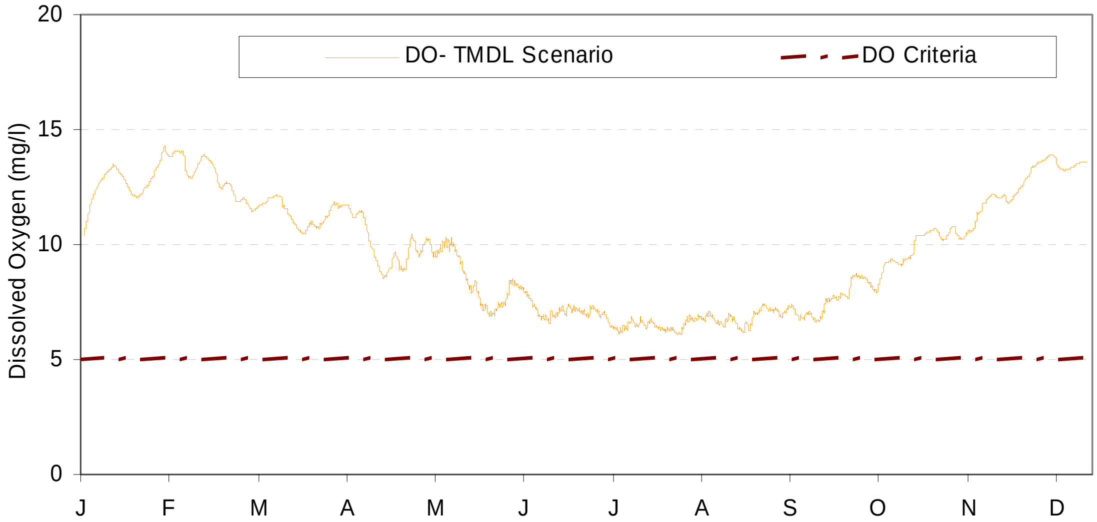
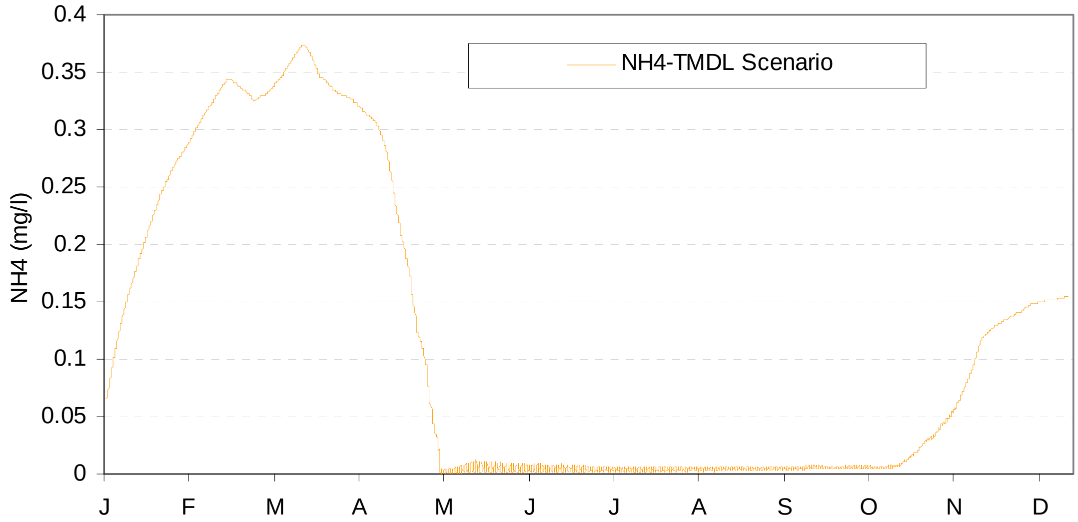


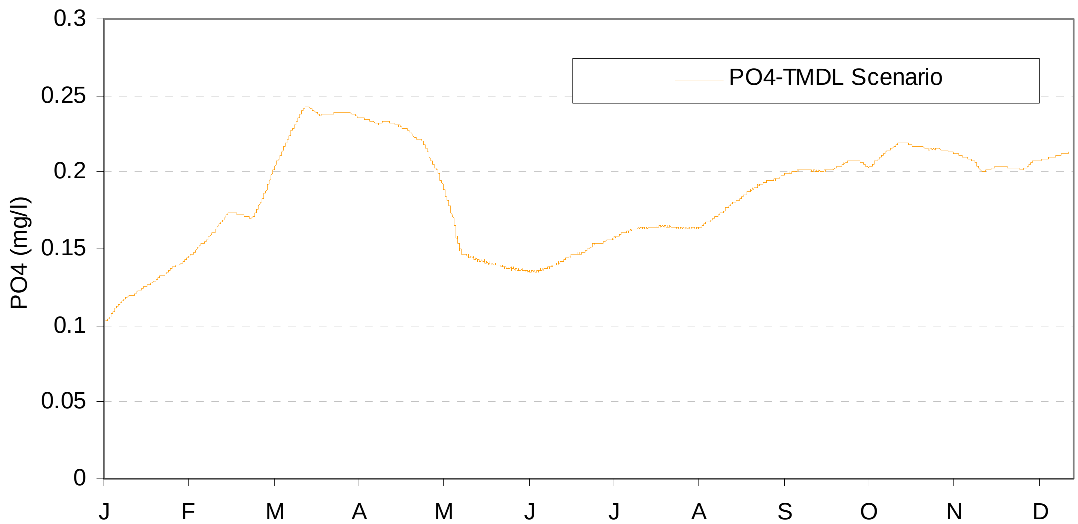


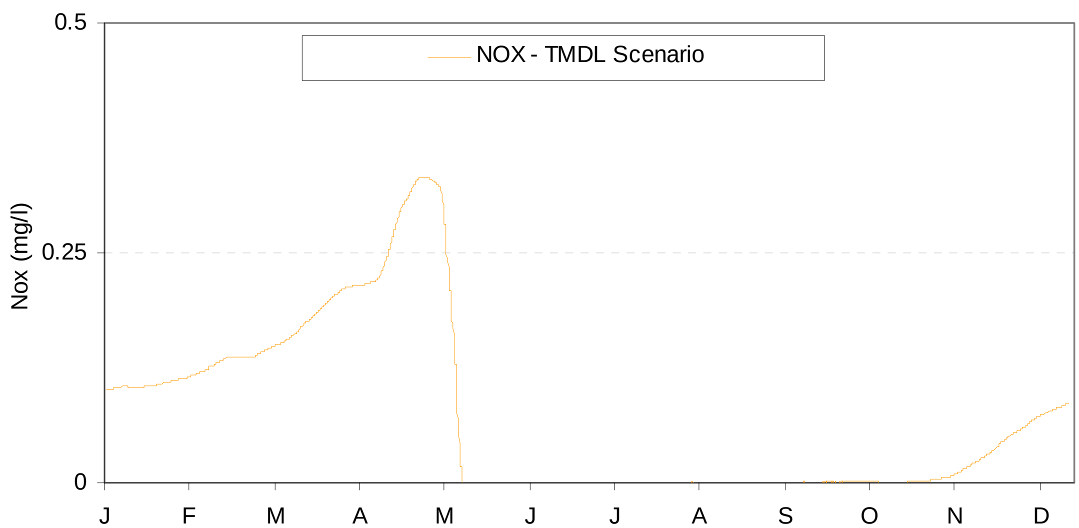
LREW continued


20
15
10
5
0
Dissolved Oxygen (mg/l)
DO- TMDL Scenario
DO Criteria
J
F
M
A
M
J
J
A
S
O
N
D

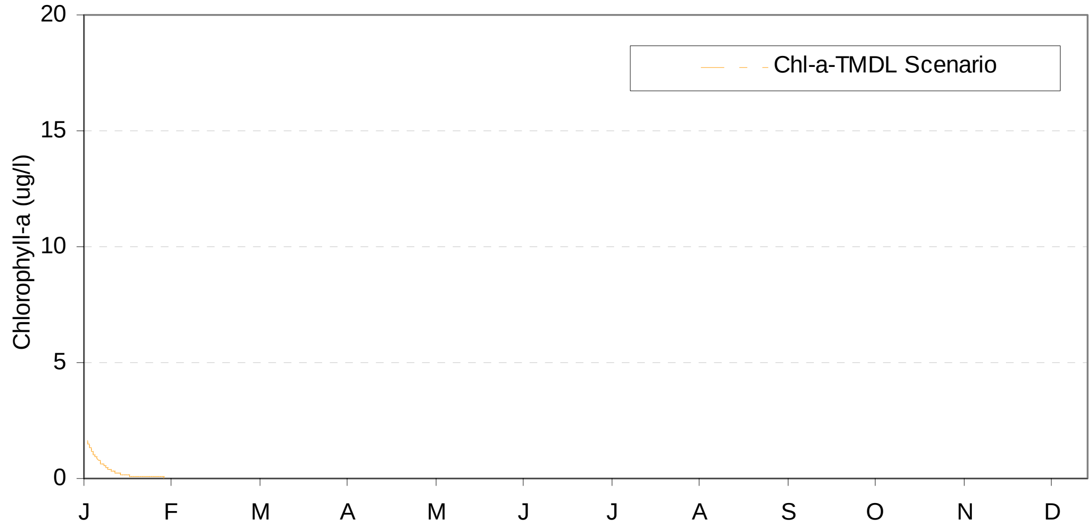
TLTO

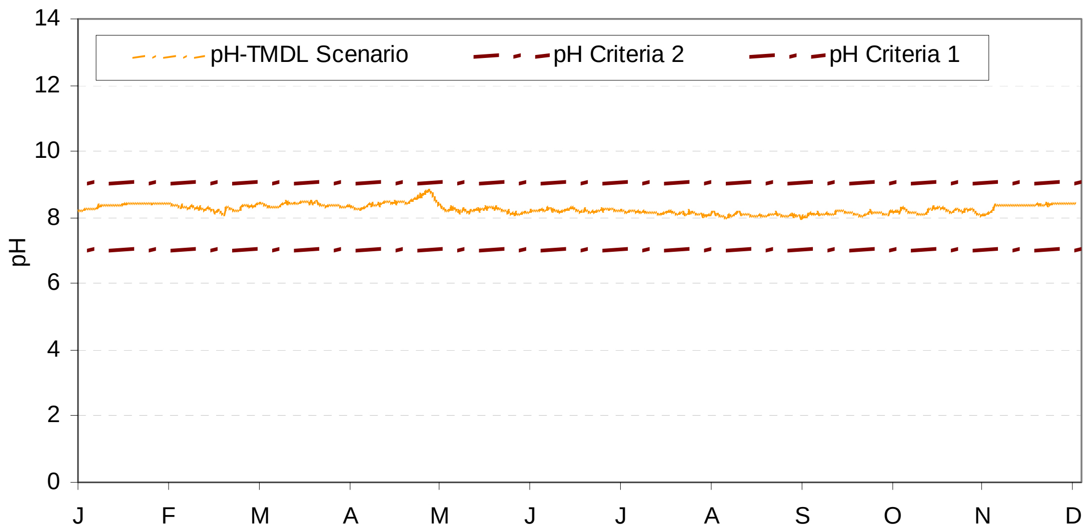




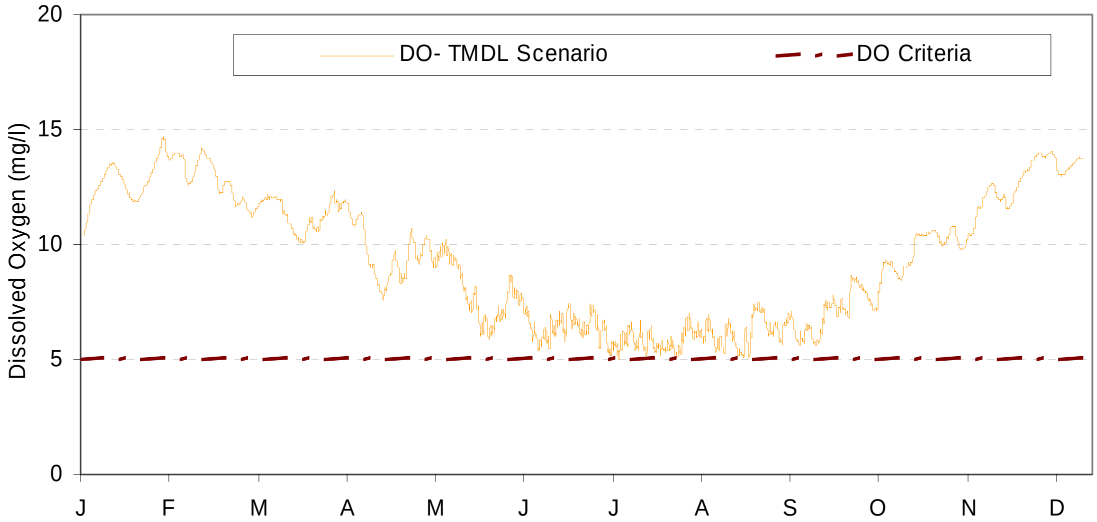


TLTO continued



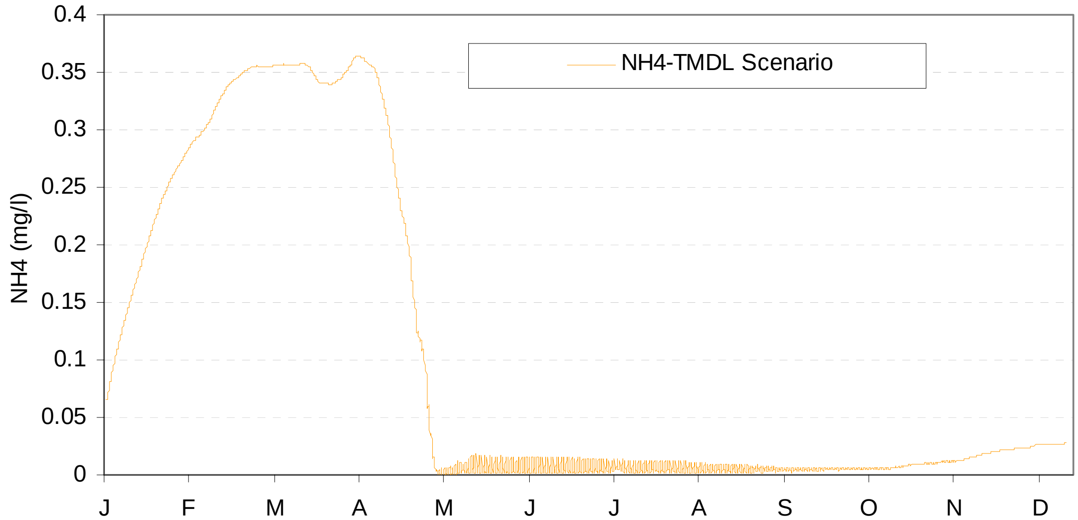


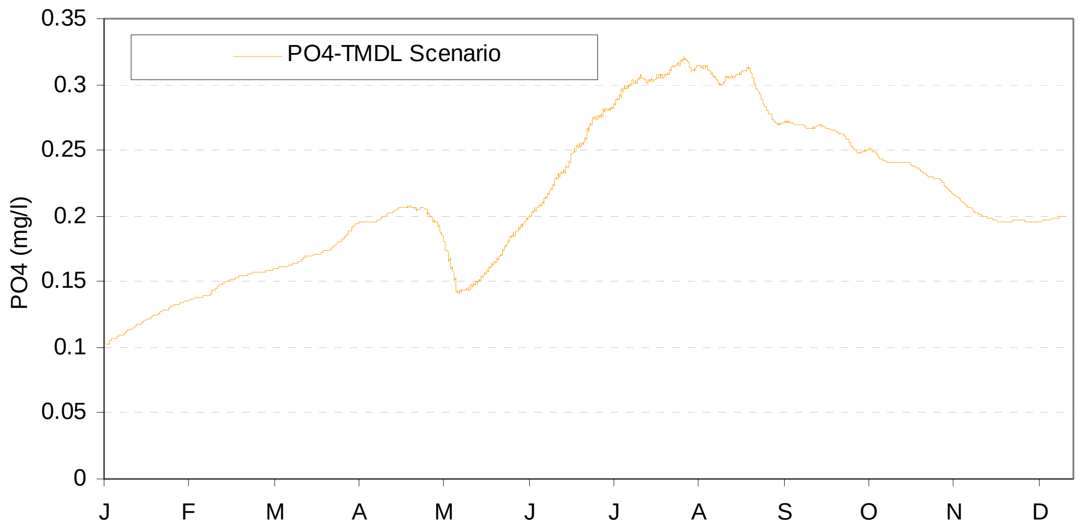
TLTO continued

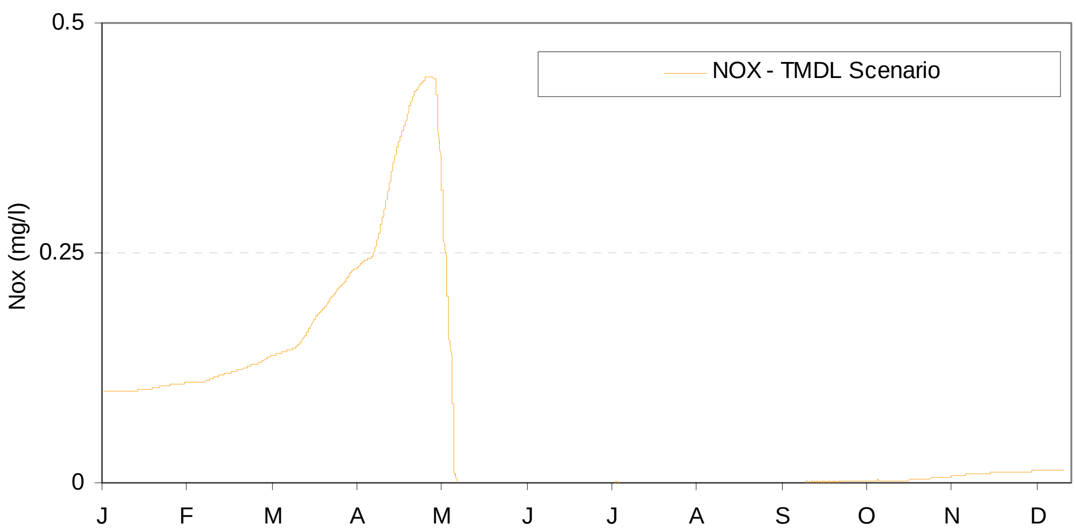


20
15
10
5
0
Dissolved Oxygen (mg/l)
DO- TMDL Scenario
DO Criteria
J
F
M
A
M
J
J
A
S
O
N
D

LKL







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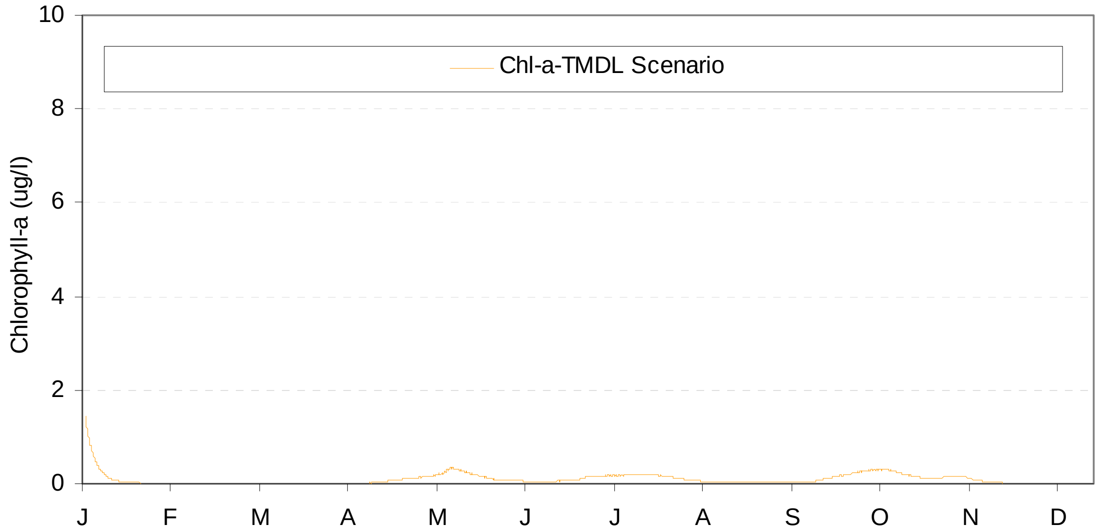
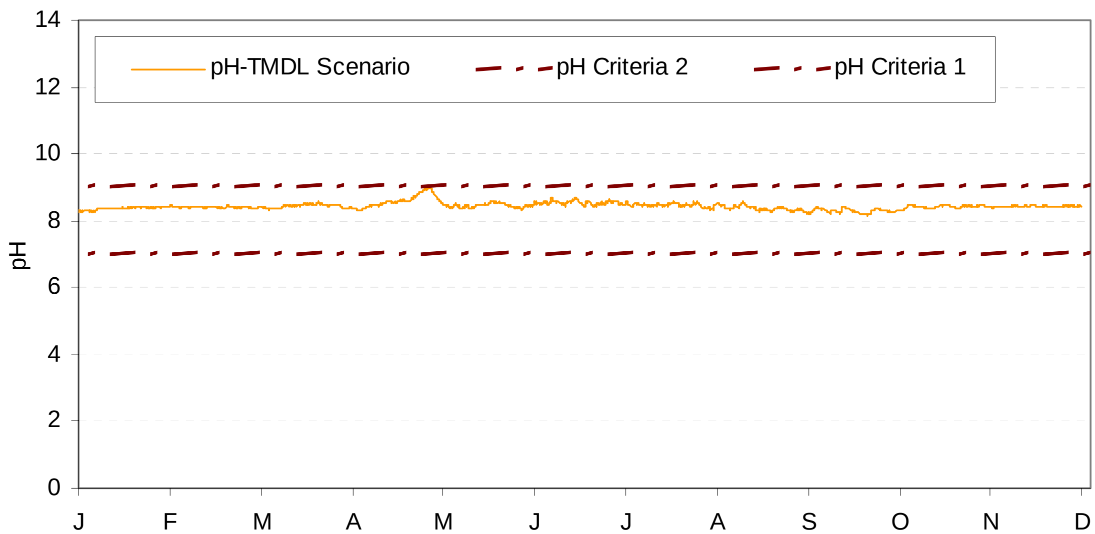
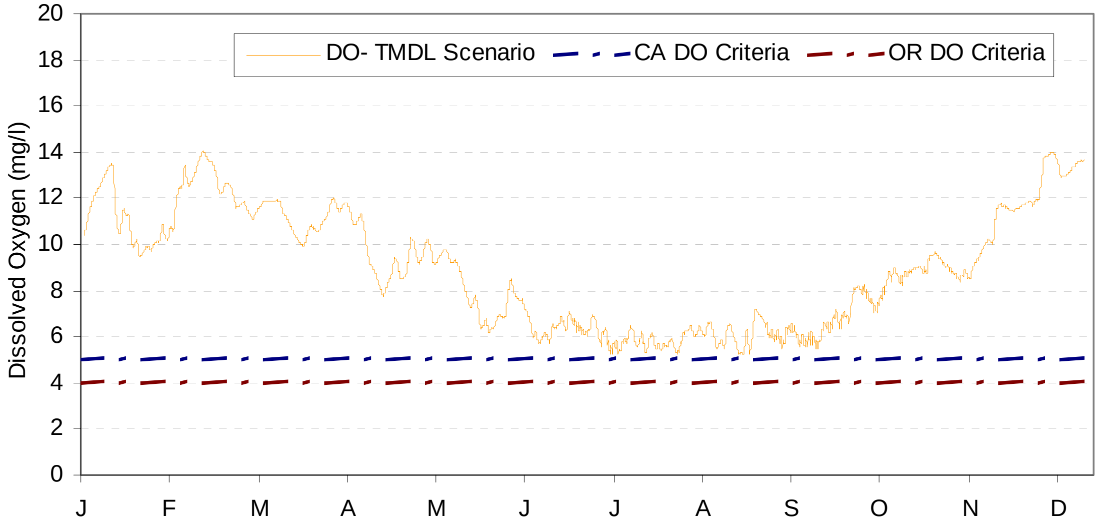
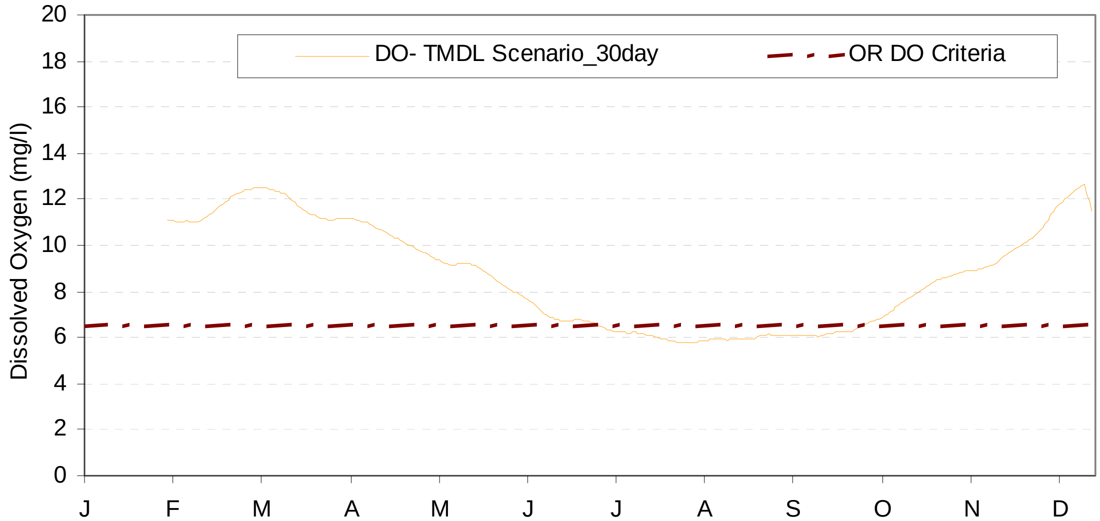
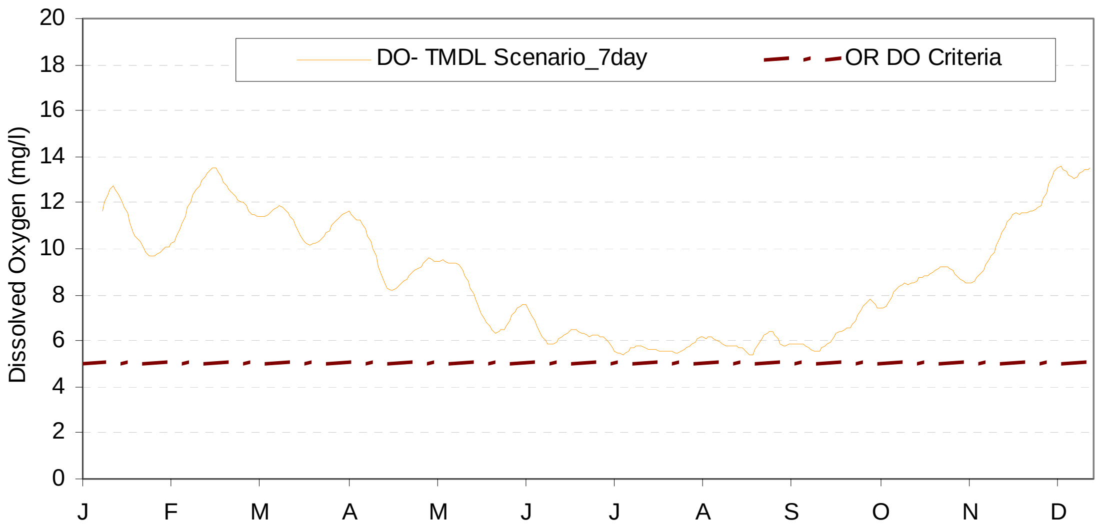




LKL continued


DO- TMDL Scenario
CA DO Criteria
OR DO Criteria
Dissolved Oxygen (mg/l)
0
2
4
6
8
10
12
14
16
18
20
J
F
M
A
M
J
J
A
S
O
N
D


DO- TMDL Scenario_30day
OR DO Criteria
Dissolved Oxygen (mg/l)
0
2
4
6
8
10
12
14
16
18
20
J
F
M
A
M
J
J
A
S
O
N
D


DO- TMDL Scenario_7day
OR DO Criteria
Dissolved Oxygen (mg/l)
0
2
4
6
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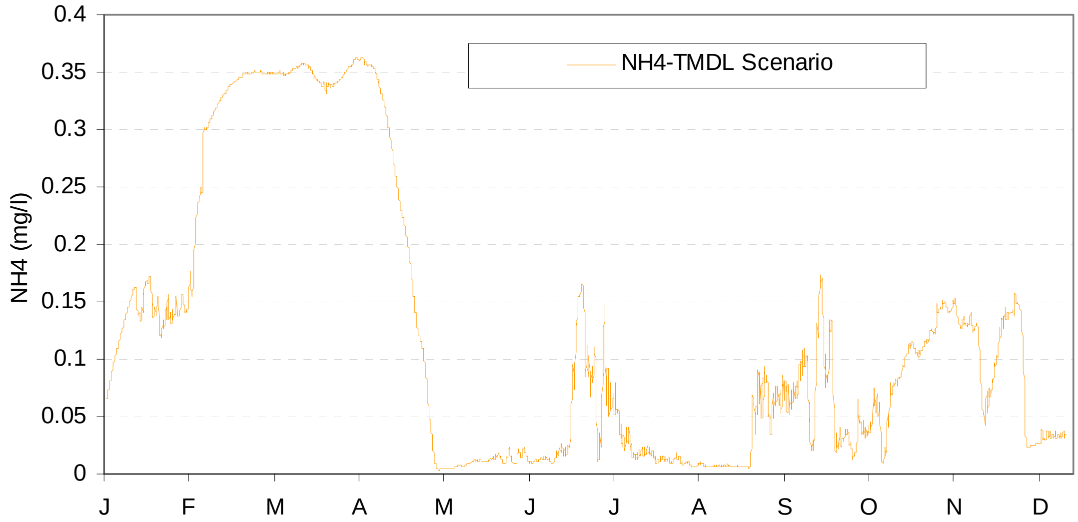
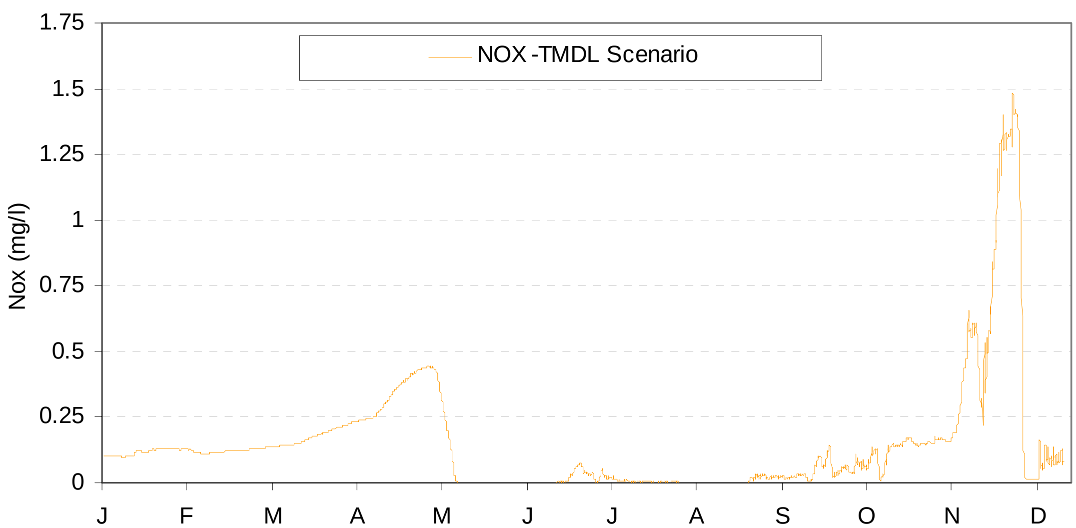
F
M
A
M
J
J
A
S
O
N
D

KSDSR





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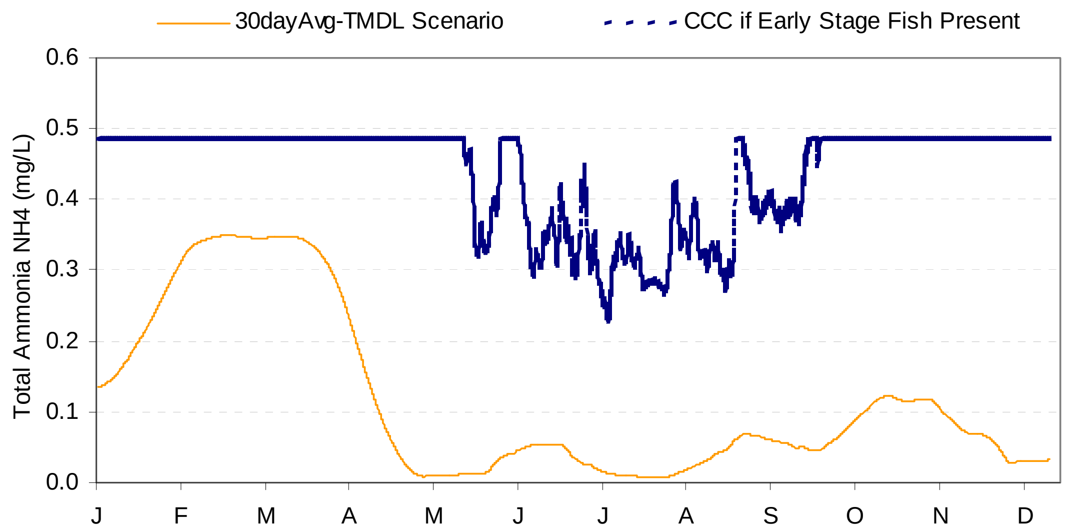

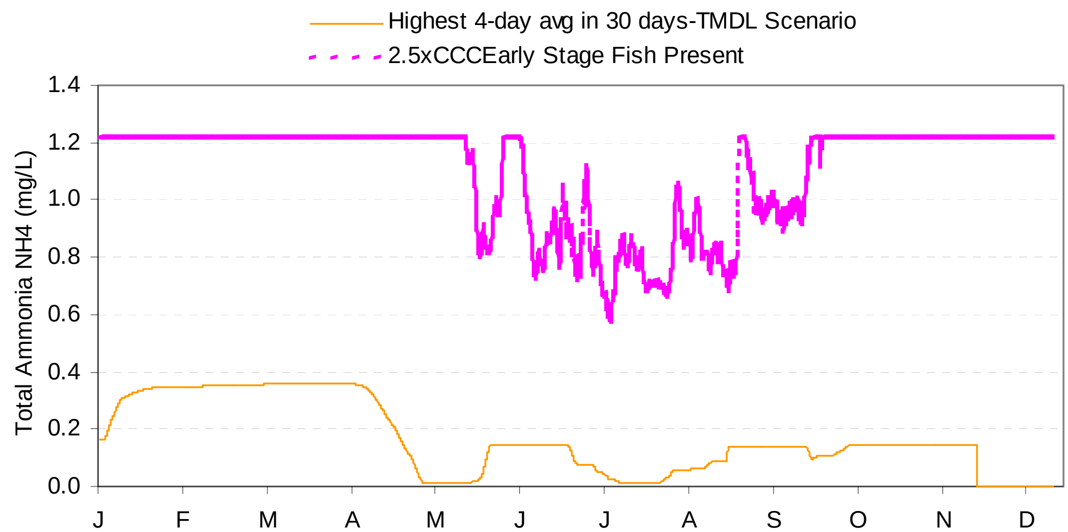

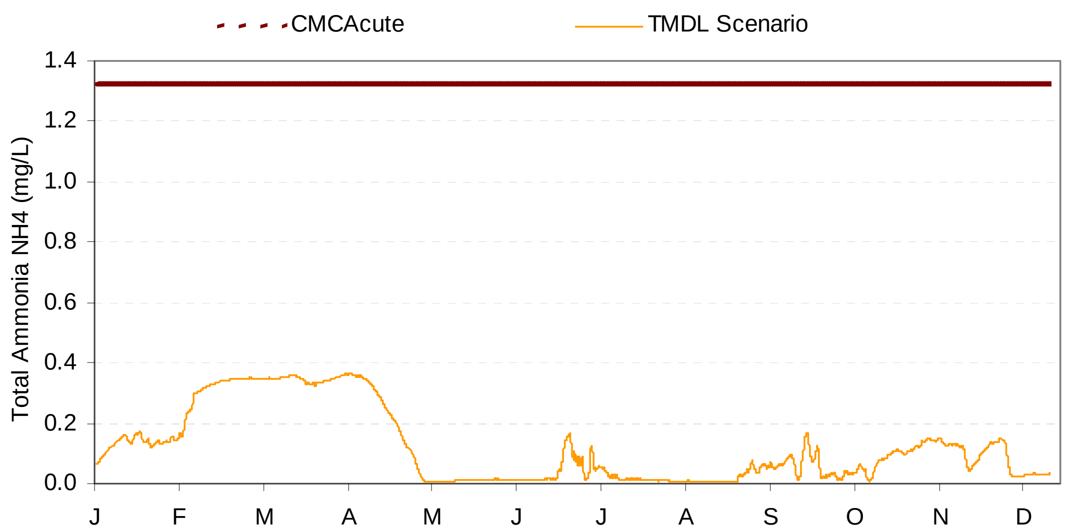

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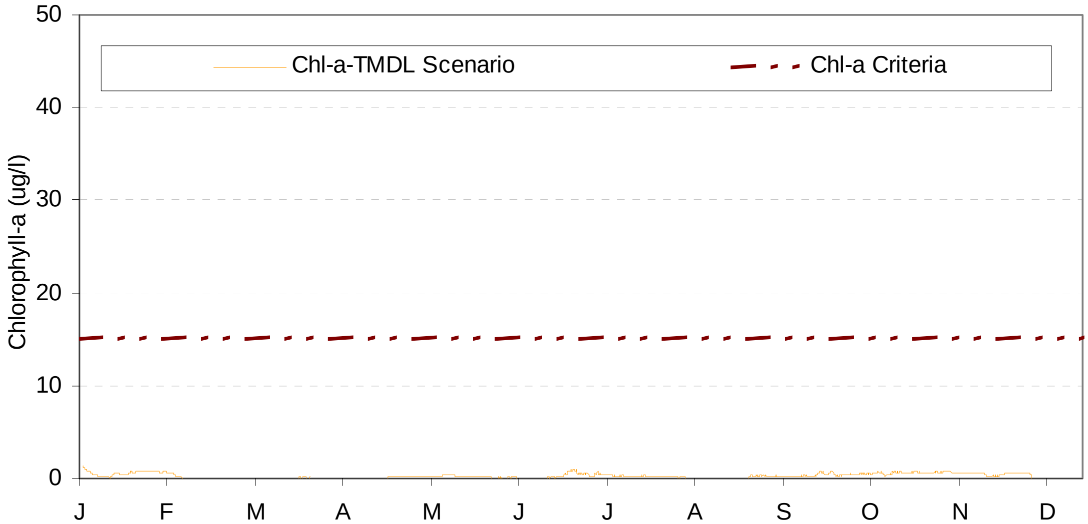

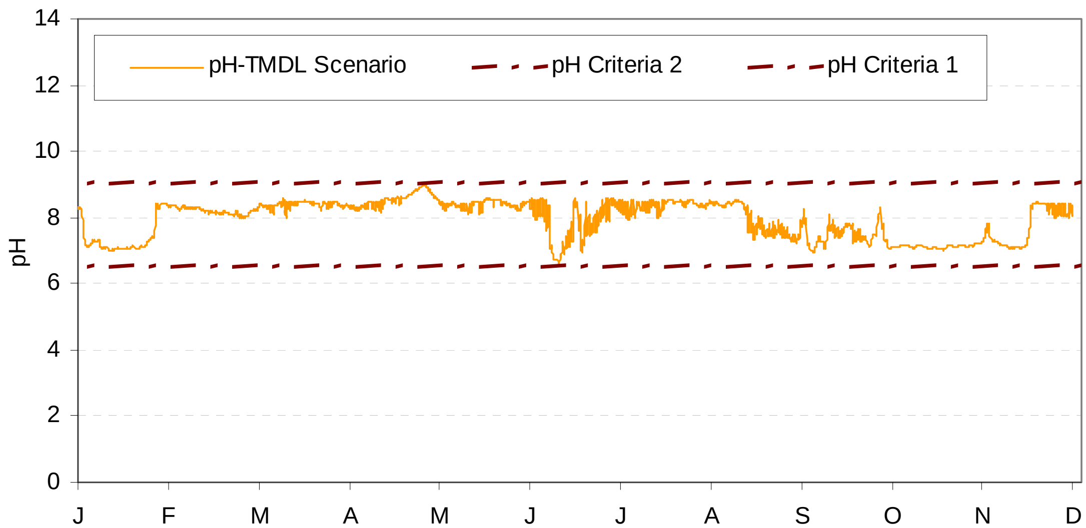

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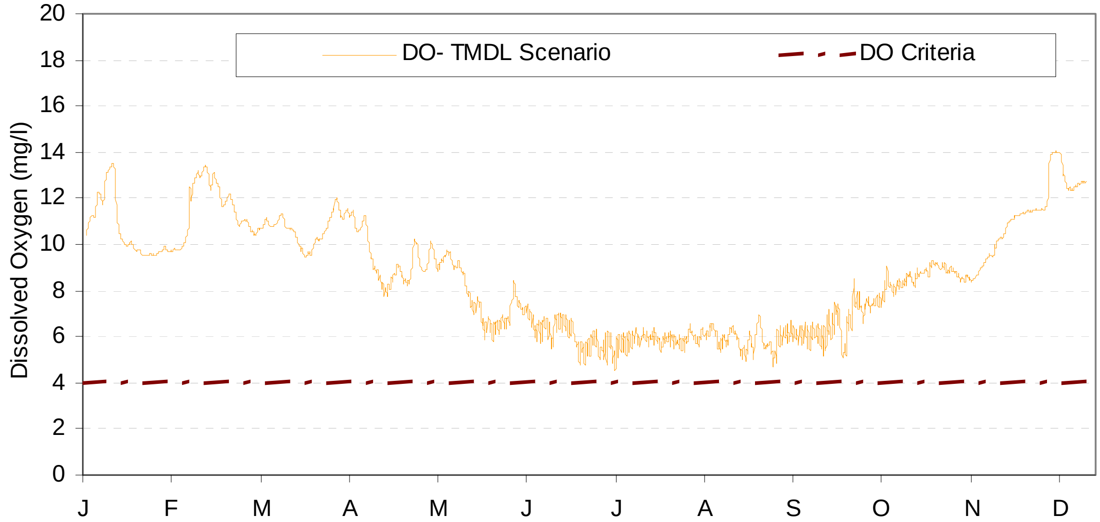

DO- TMDL Scenario
DO Criteria
Dissolved Oxygen (mg/l)
20
18
16
14
12
10
8
6
4
2
0
J
F
M
A
M
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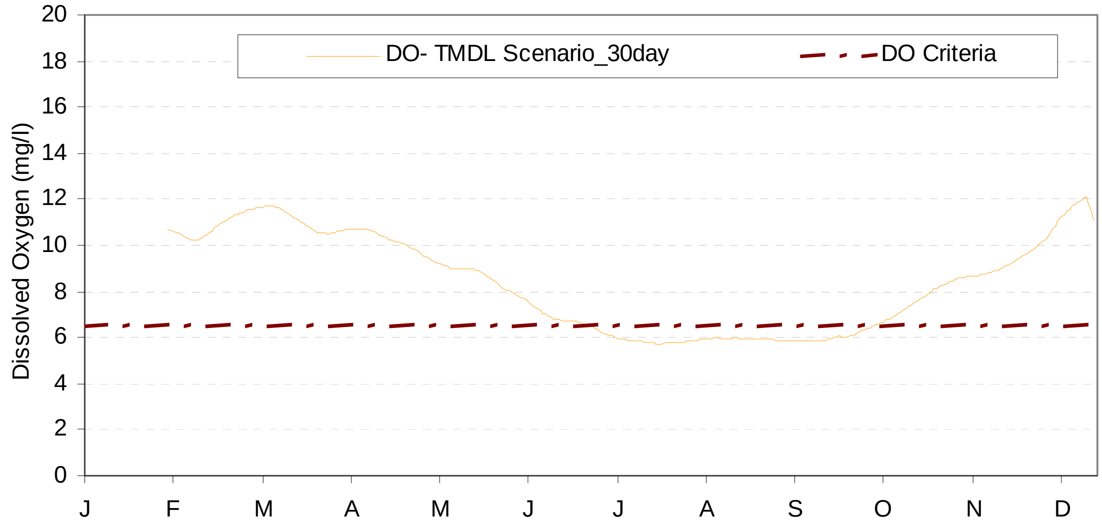
J
A
S
O
N
D



DO- TMDL Scenario_30day
DO Criteria
Dissolved Oxygen (mg/l)
20
18
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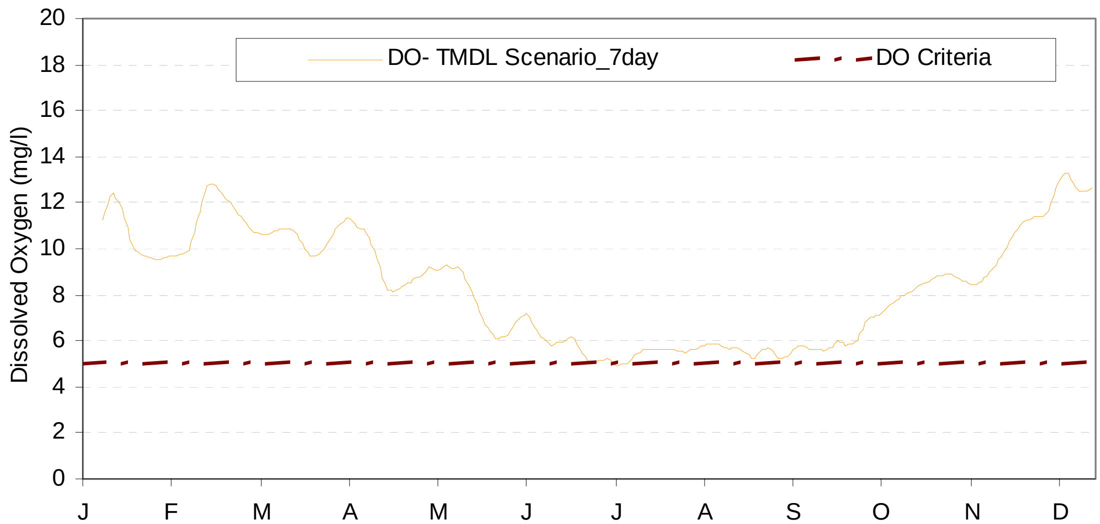
6
4
2
0
J
F
M
A
M
J
J
A
S
O
N
D



DO- TMDL Scenario_7day
DO Criteria
Dissolved Oxygen (mg/l)
20
18
16
14
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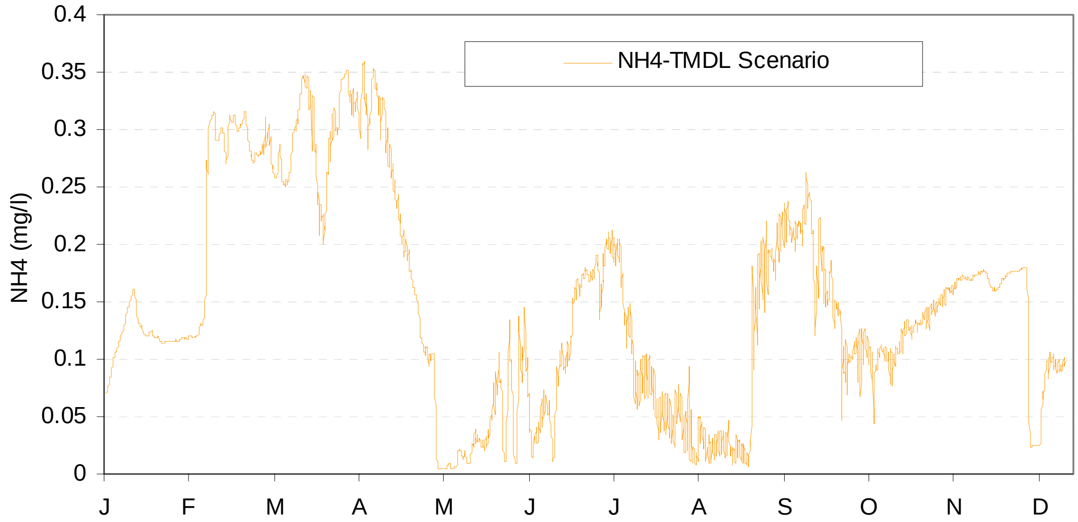
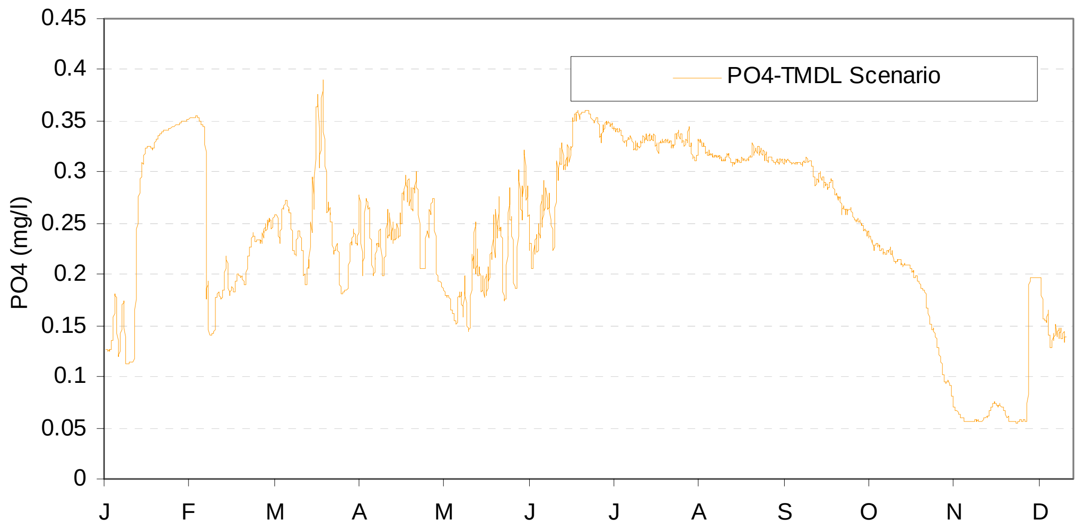
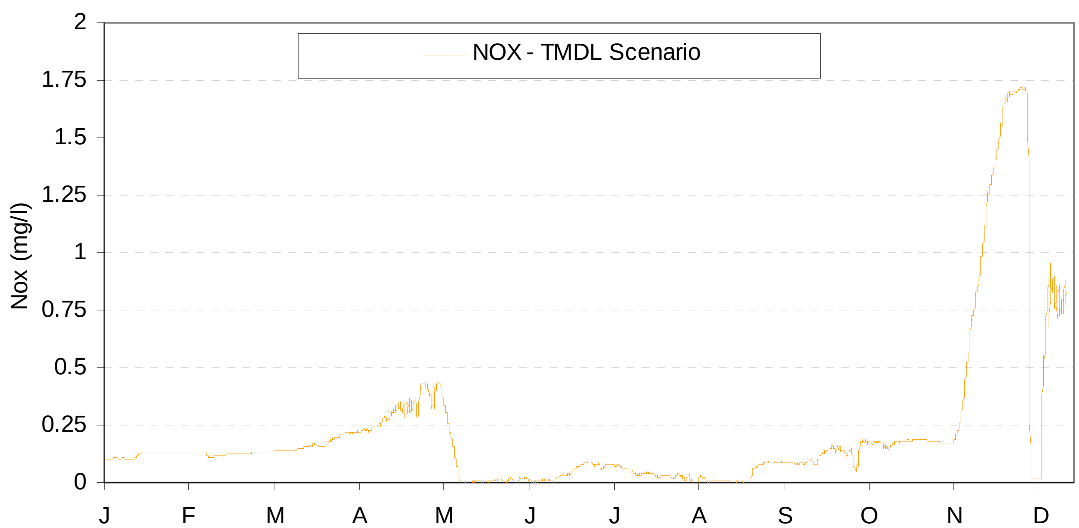
2
0
J
F
M
A
M
J
J
A
S
O
N
D

KSDTR







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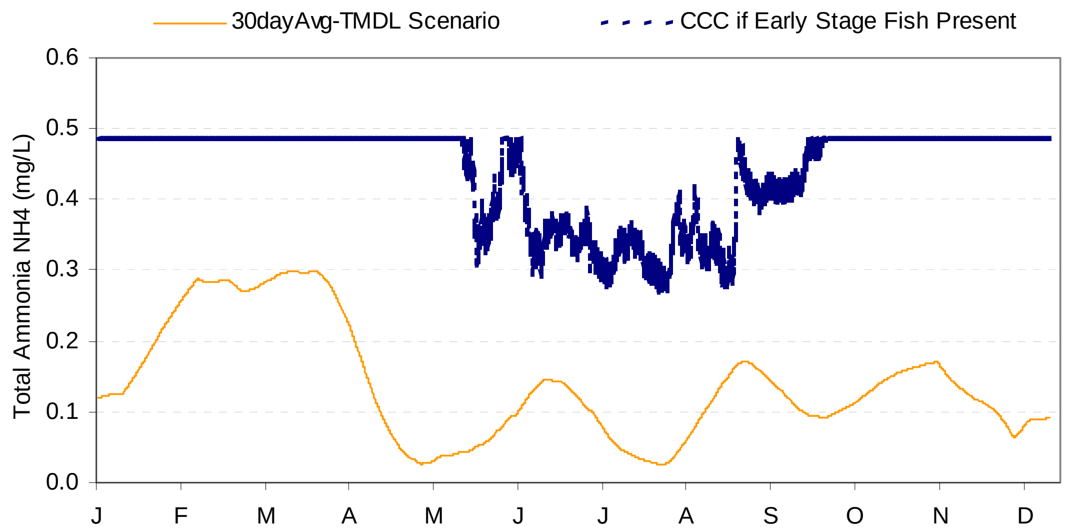

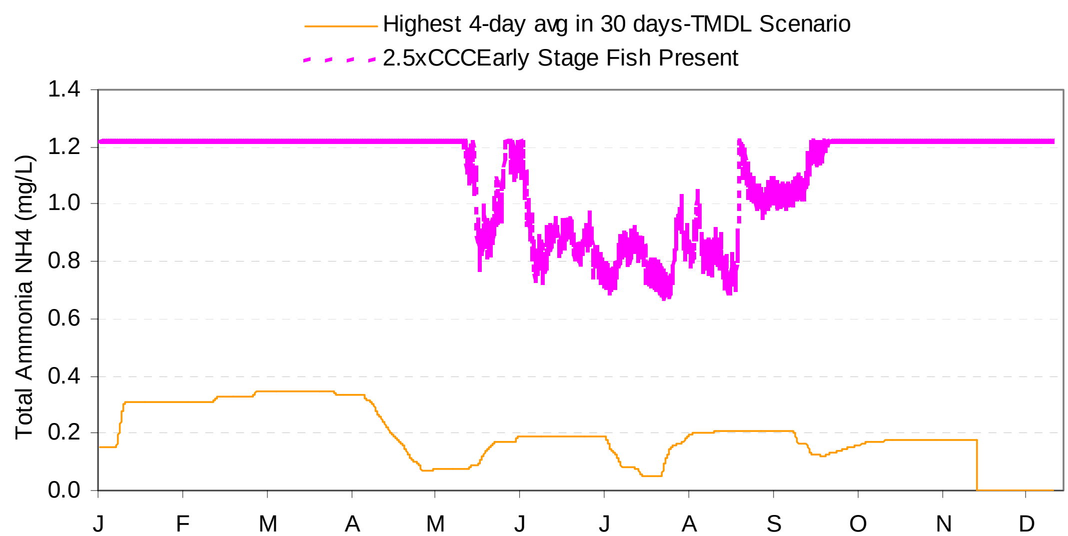

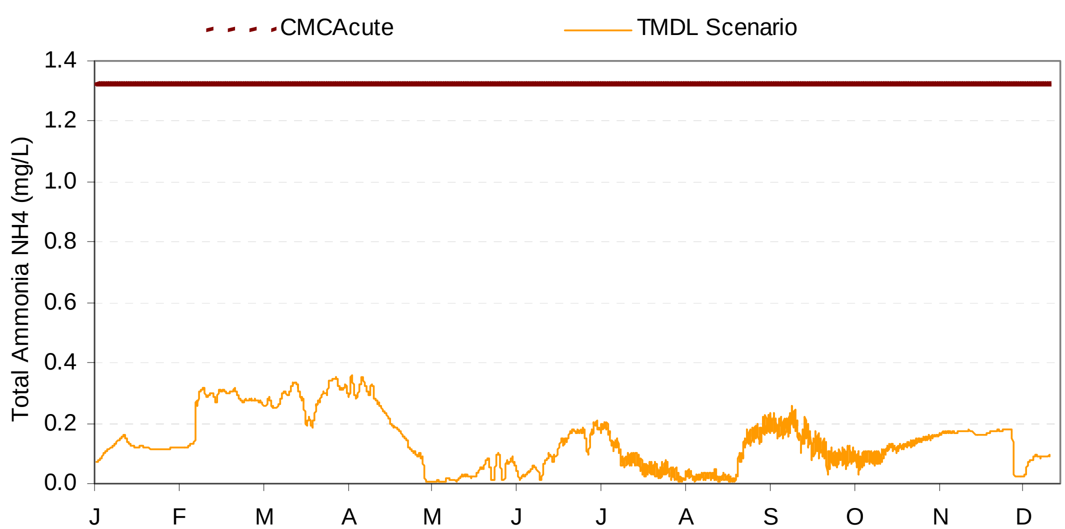

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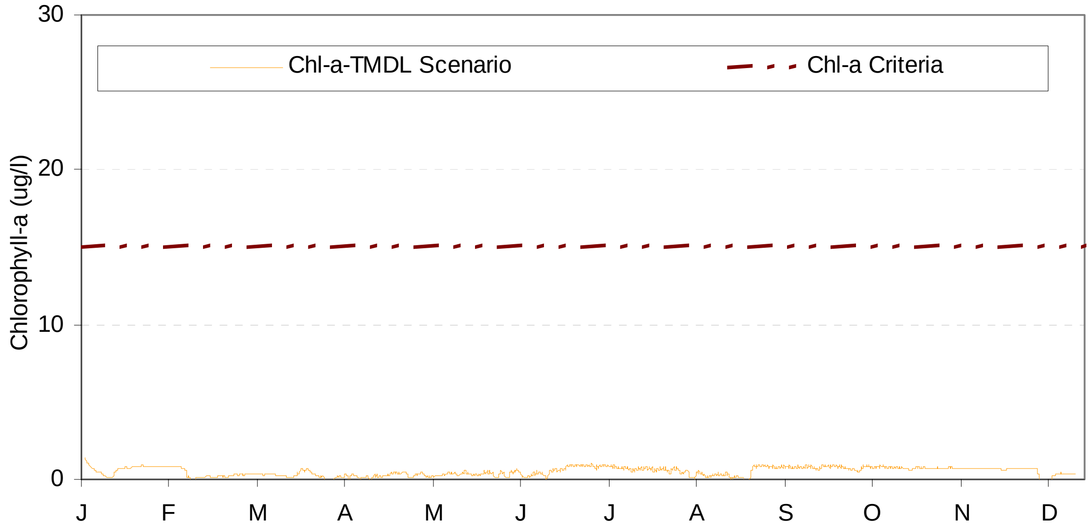

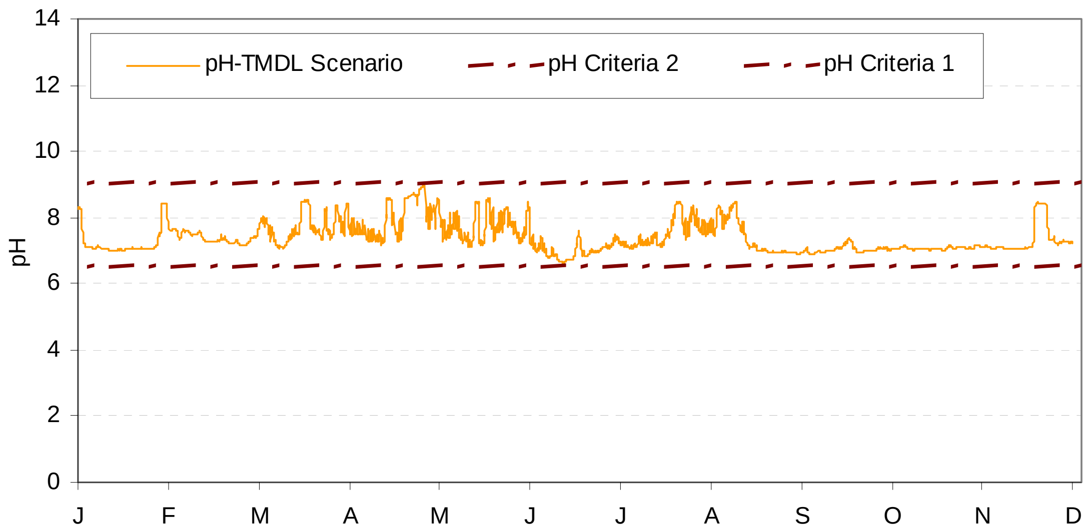

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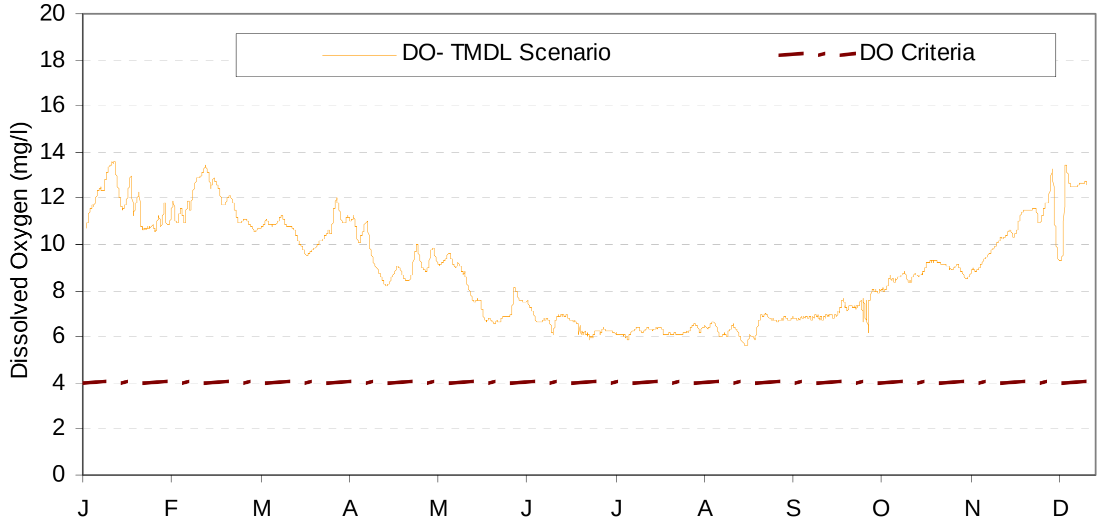
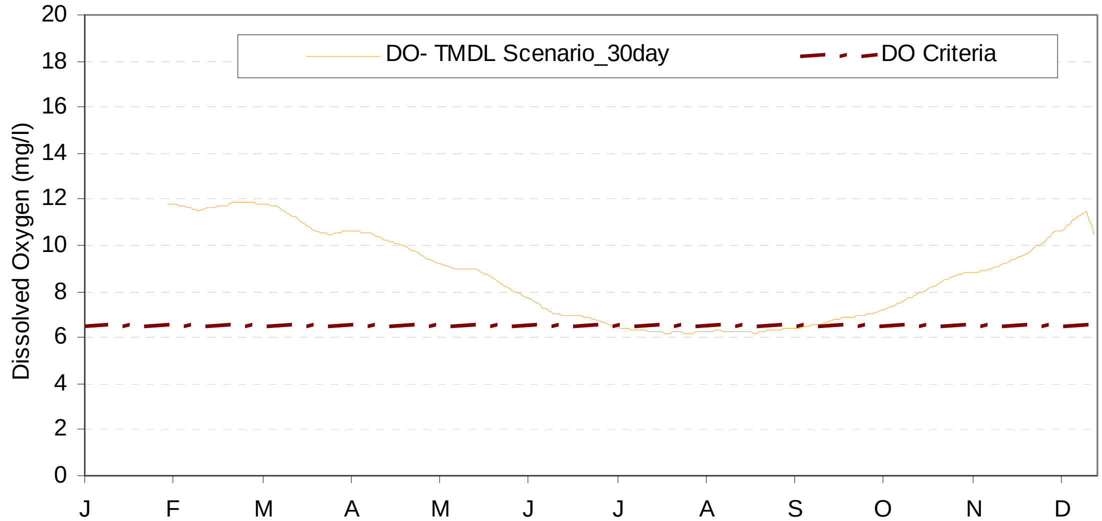
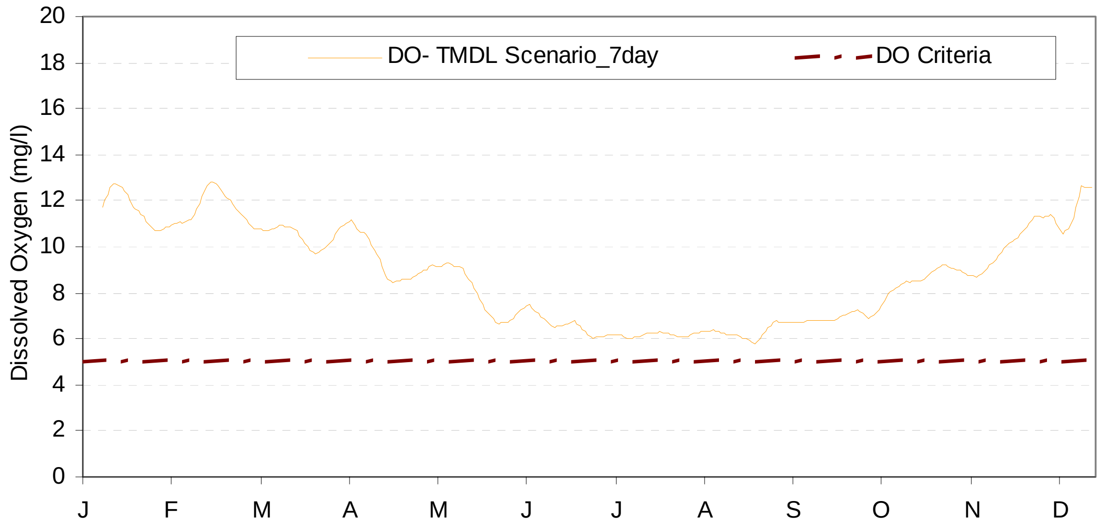


DO- TMDL Scenario
DO Criteria
Dissolved Oxygen (mg/l)
20
18
16
14
12
10
8
6
4
2
0
J
F
M
A
M
J
J
A
S
O
N
D

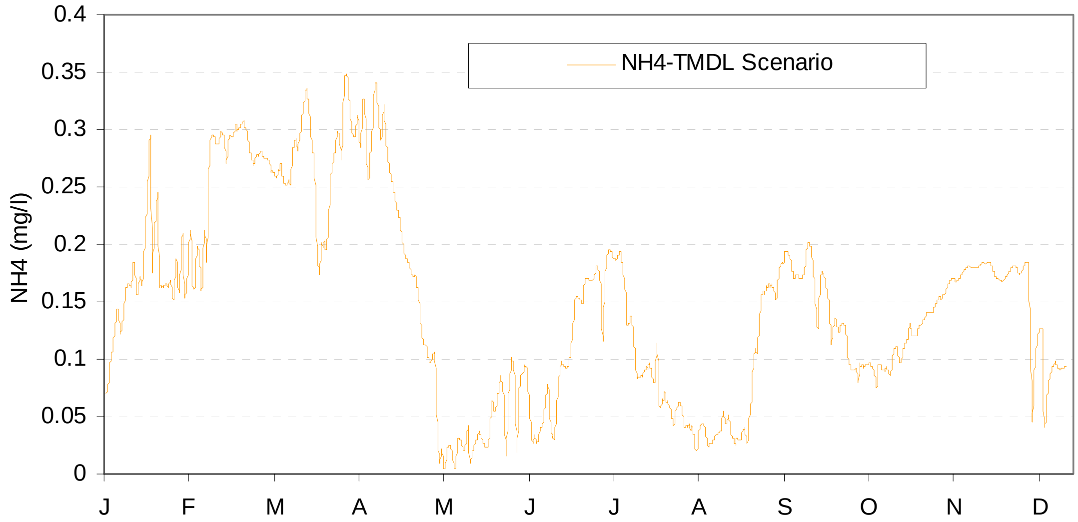


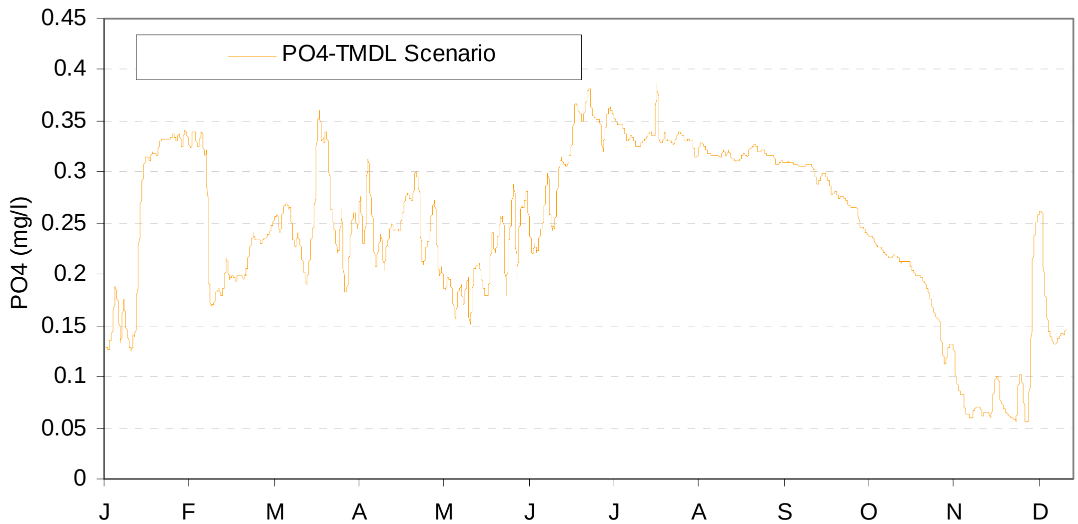
DO- TMDL Scenario_30day
DO Criteria
Dissolved Oxygen (mg/l)
20
18
16
14
12
10
8
6
4
2
0
J
F
M
A
M
J
J
A
S
O
N
D

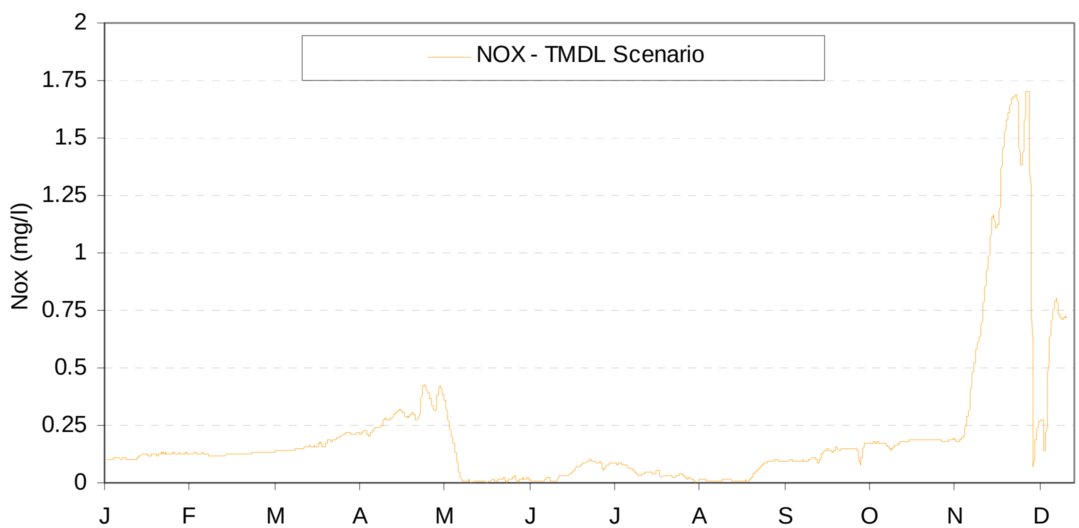


DO- TMDL Scenario_7day
DO Criteria
Dissolved Oxygen (mg/l)
20
18
16
14
12
10
8
6
4
2
0
J
F
M
A
M
J
J
A
S
O
N
D

KSD97







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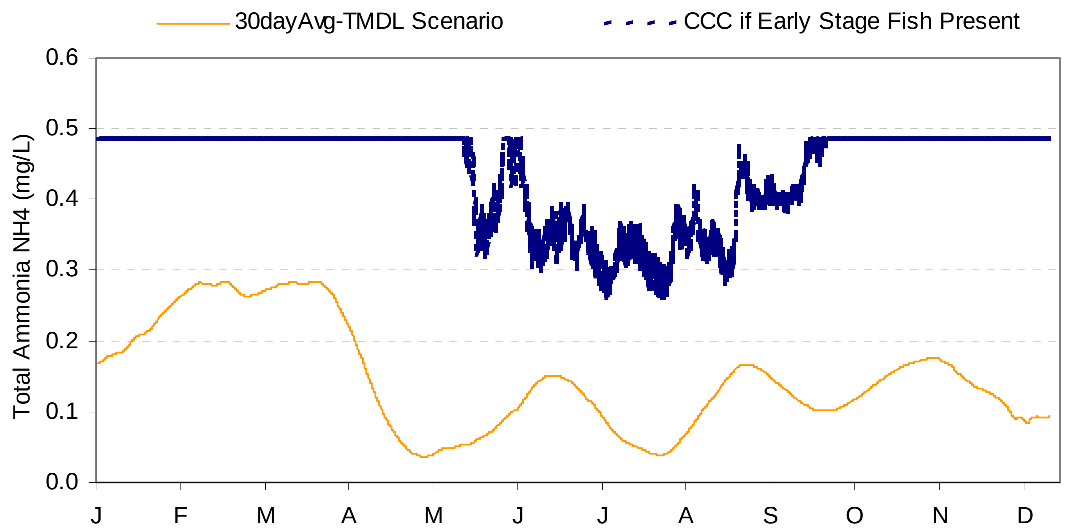

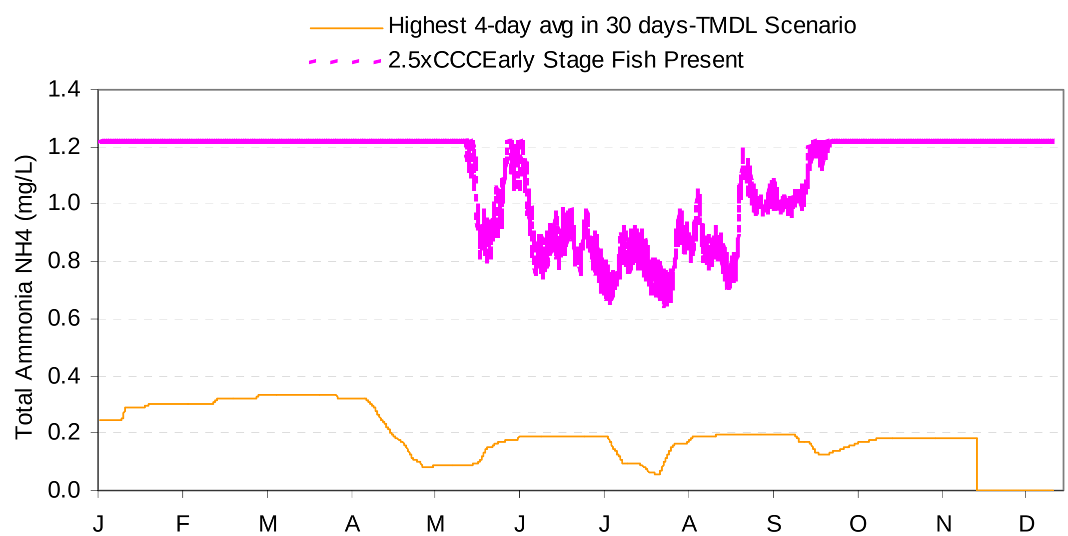

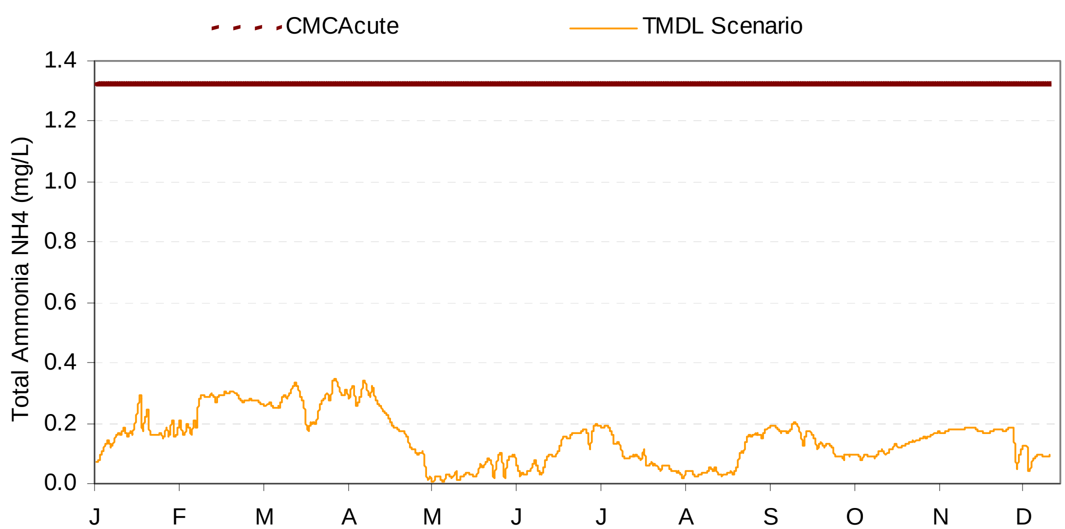

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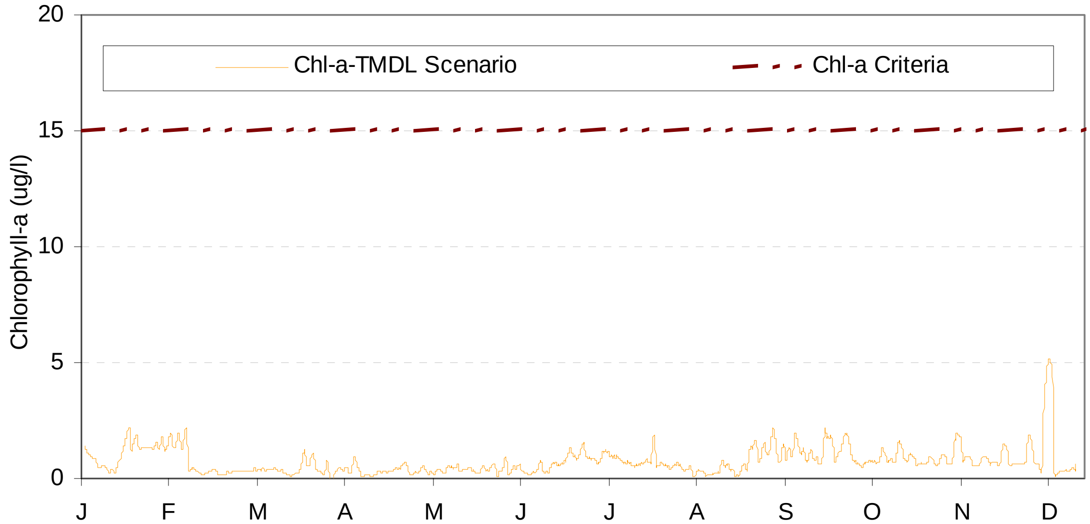

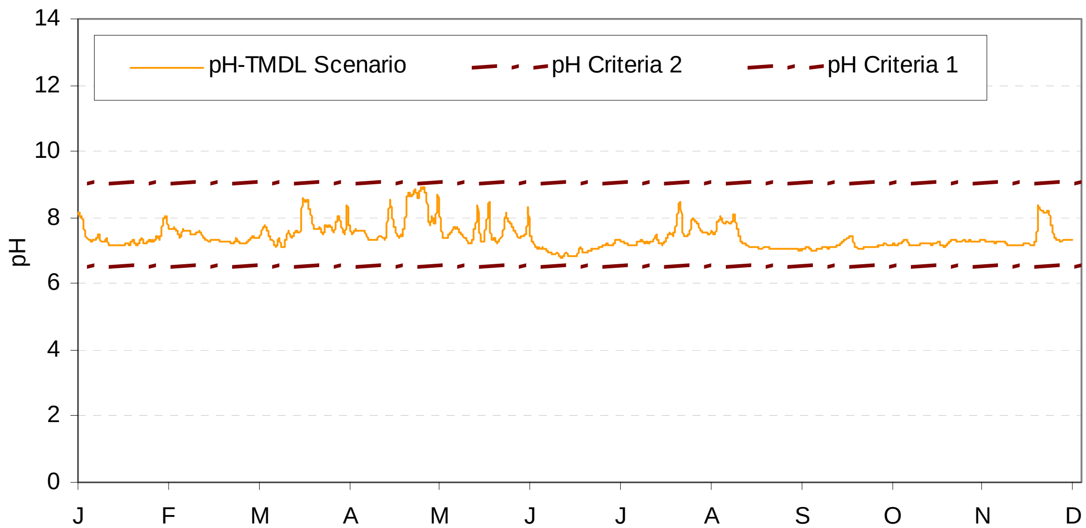

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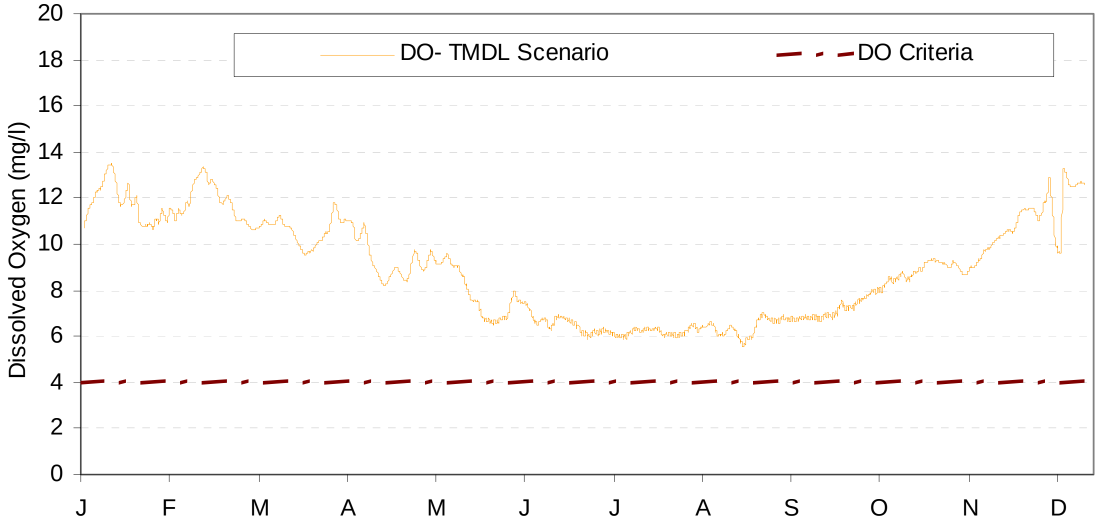
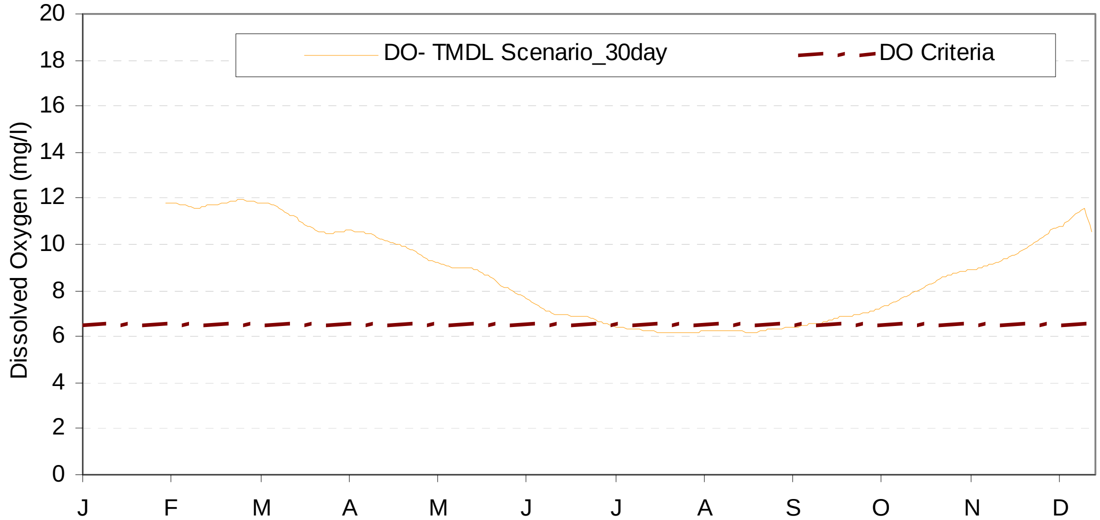
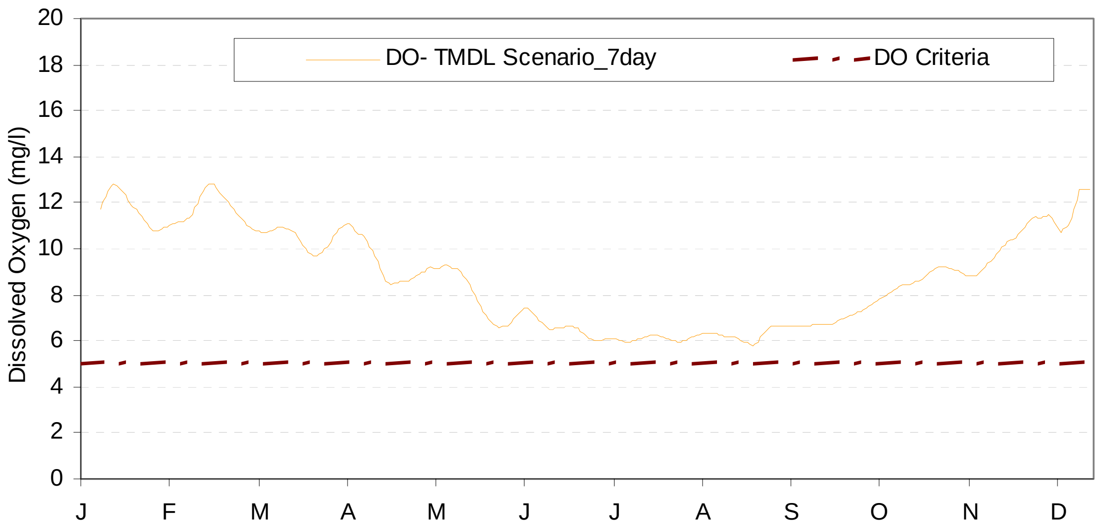


DO- TMDL Scenario
DO Criteria
Dissolved Oxygen (mg/l)
20
18
16
14
12
10
8
6
4
2
0
J
F
M
A
M
J
J
A
S
O
N
D

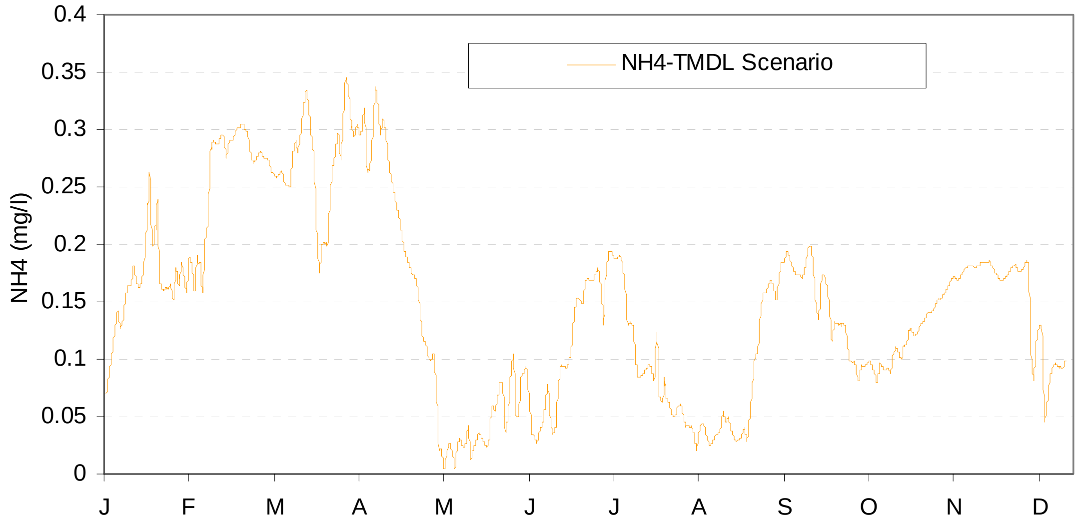


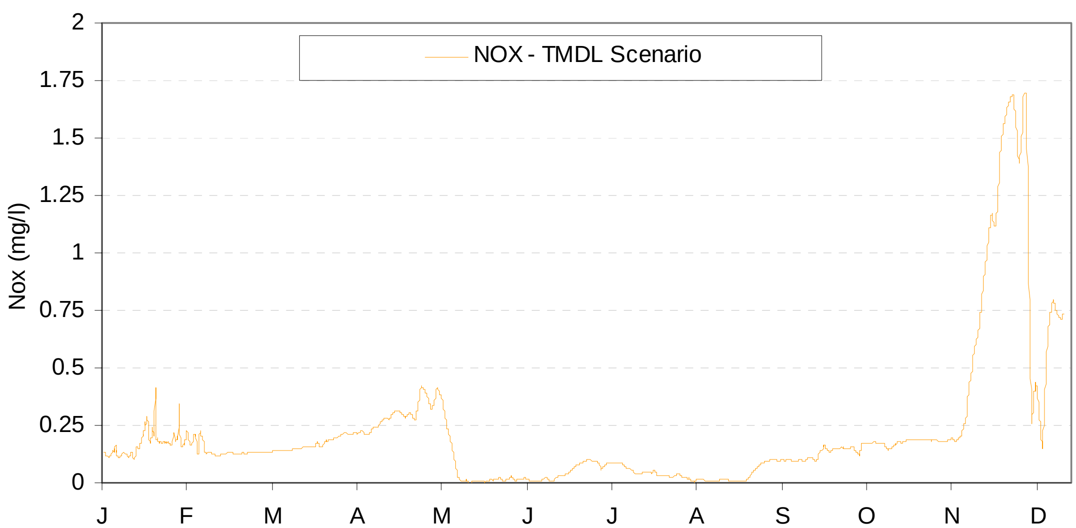
DO- TMDL Scenario_30day
DO Criteria
Dissolved Oxygen (mg/l)
20
18
16
14
12
10
8
6
4
2
0
J
F
M
A
M
J
J
A
S
O
N
D



DO- TMDL Scenario_7day
DO Criteria
Dissolved Oxygen (mg/l)
20
18
16
14
12
10
8
6
4
2
0
J
F
M
A
M
J
J
A
S
O
N
D

KSDM





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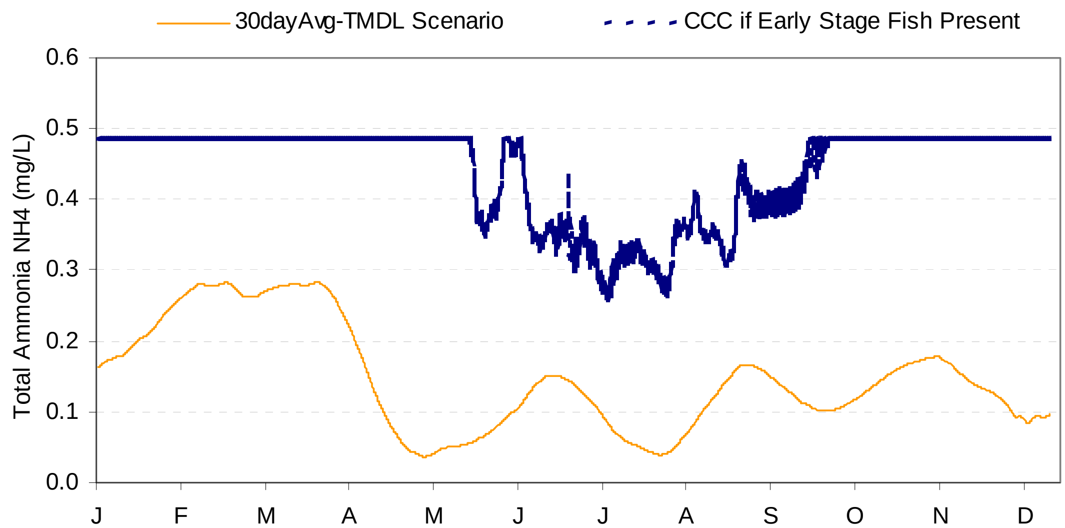
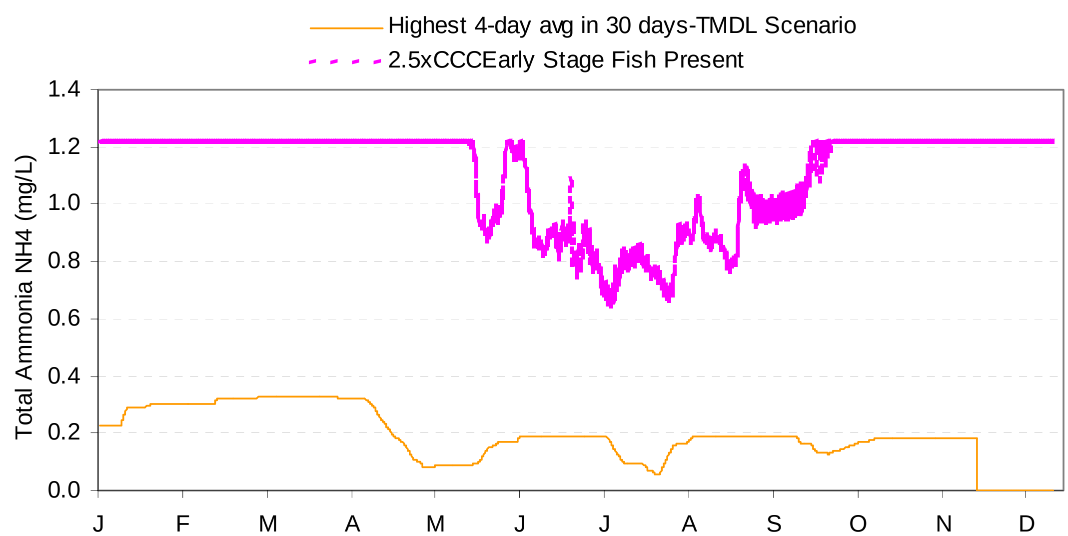
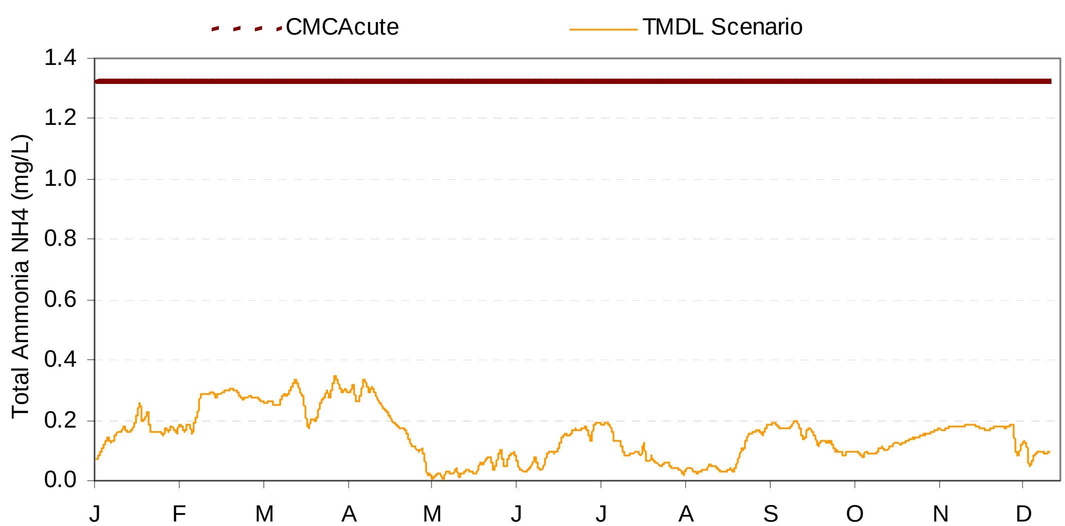
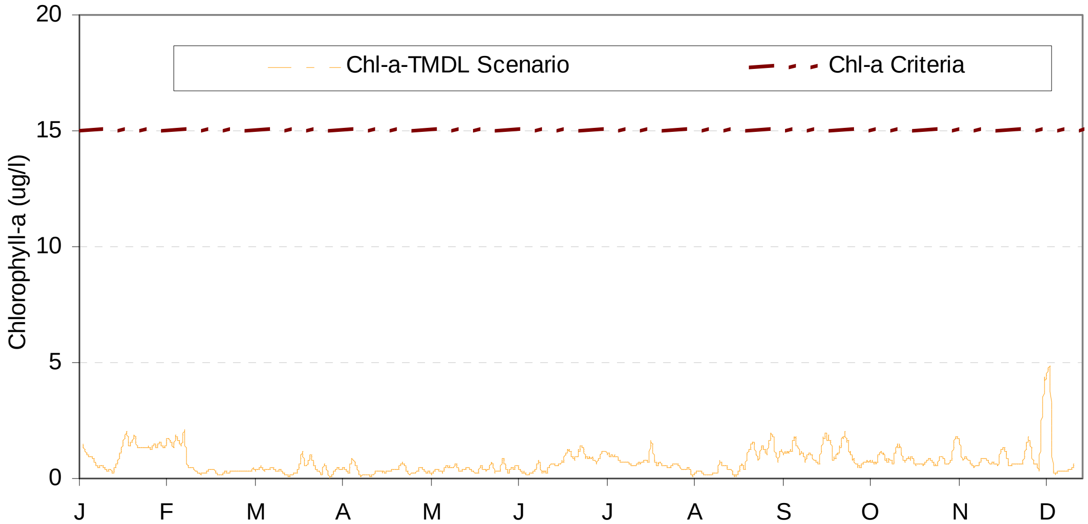
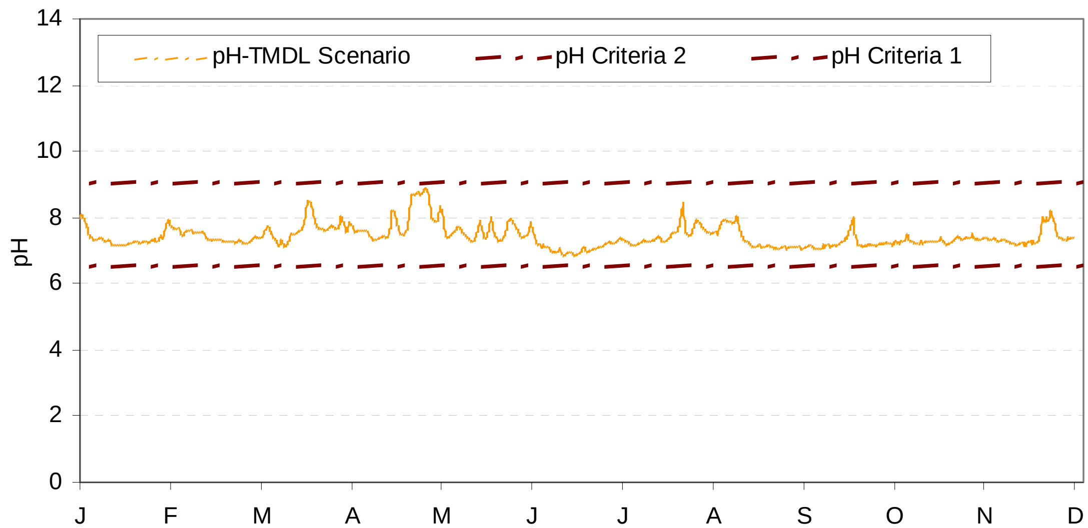






KSDM continued





KSDM continued