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OREGON DEPARTMENT OF ENVIRONMENTAL QUALITY

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WATER QUALITY MODEL
OF THE KLAMATH RIVER
BETWEEN LINK RIVER AND KENO DAM

PREPARED BY

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DEPARTMENT OF ENVIRONMENTAL QUALITY
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1. INTRODUCTION

The Oregon Department of Environmental Quality (DEQ) has determined that the Klamath River between Upper Klamath Lake near Klamath and Keno Dam is water quality limited. This designation requires the DEQ to conduct a study to collect data on pollutant loading and water quality effects and to determine waste load allocations for point and non-point pollutant sources. The data collection, pollutant loading estimates and water quality effect studies are used to determine appropriate Total Maximum Daily Loads (TMDLs). This report was prepared for the DEQ by CH2M HILL and Dr. Scott Wells and details the development of a water quality model to estimate water quality effects and possible pollutant load reduction or control alternatives.

The remainder of this Section details the study reach and other physical conditions such as climate and river hydrology. Section 2 discusses the selection of a water quality model that would adequately address the water quality issues associated with the Klamath such as high nutrient loading, algae growth and high temperatures. The Corps of Engineer's CE-QUAL-W2 model was selected by DEQ for use in the study. The details of the theory and operation of the selected water quality model is summarized in Section 3. In Section 4 the model set-up and sources of data are discussed. Section 5 contains details of the boundary conditions used in the model and the development of loading from the various point and non-point sources modeled. Section 6 contains details of the model calibration and verification for two distinct periods (1990 and 1992).

1.1 SCOPE OF THIS STUDY

The scope of the study is to develop a water quality model of the reach of the Klamath River between the Link River and Keno Dam. The model will be initially used by DEQ in determining appropriate point source loading rates to the Klamath River in the study reach and in determining point source load allocations. The determination of point source load allocations is the first step in determining comprehensive load allocations for point and non-point source loading in the overall setting of TMDLs for the reach.

1.2 STUDY REACH

The Klamath River, shown in Figure 1-?, is located in the southwest corner of Oregon and Northwest California. The river originates at the mouth of the Link River and flows Southwest through Oregon and California discharging to the Pacific Ocean near ____ California. This study is limited to a reach between river mile 253 and river mile 233.5.

This reach is generally a slow moving, variable depth water body representing at times a stratified reservoir rather than a free flowing river. The normal water surface elevation is generally flat and in the range of 4083 to 4086 ft (USBR datum). Water depths range from about 9 ft to about 20 ft and channel widths from about 300 ft to about 2600 ft. The study reach contains two systems; Lake Ewauna (a very wide water body with deep "holes" from RM. 253 to RM. 251) and Keno Dam Reservoir (a more-narrow system from RM. 235 to RM. 233.5).

1.2.1 Profile

In the early 1970's the Pacific Power and Light Company (PP&L) dredged the channel from the city of Keno at RM. 235 to just downstream of Lake Ewauna near RM. 248.5. Typical channel depths prior to dredging were 10 ft below the water surface. The purpose of this dredging was to improve conveyance capacity between Lake Ewauna and Keno Dam. Figure 1-? shows the profile of the reach after the dredging.

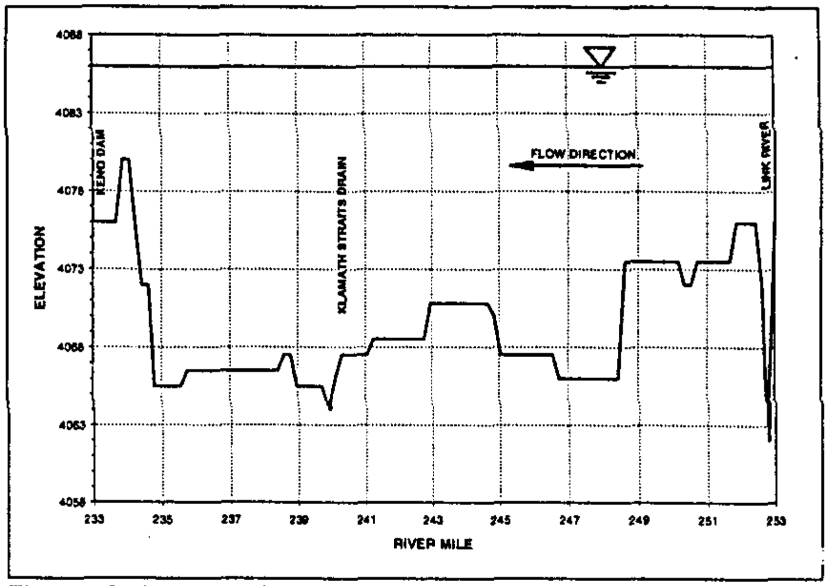

Figure 1-?. Study Reach Longitudinal Profile
Source: PP&L, FEMA, CH2M HILL

1.2.2 Inflows and Withdrawals

The study reach water balance is affected by discharge from Upper Klamath Lake and withdrawals from the following major irrigation canals; "A" Canal, Lost River, North Canal, and Ady Canal. The "A" Canal withdrawal point is upstream of the Link River gage. Return irrigation flows occur at a pump station on the Klamath Strait Drain and from various discharge points on the northern banks. The Lost River can also discharge to the Klamath River during high flow conditions in the far eastern portions of the irrigation district.

Irrigation withdrawals consume a significant fraction of the total inflow in the summer period. Figure 1-__is a plot of average monthly inflows and discharges for the study reach. This plot shows that average discharge at Keno Dam during the months of June through September are significantly less than inflows from Link River.

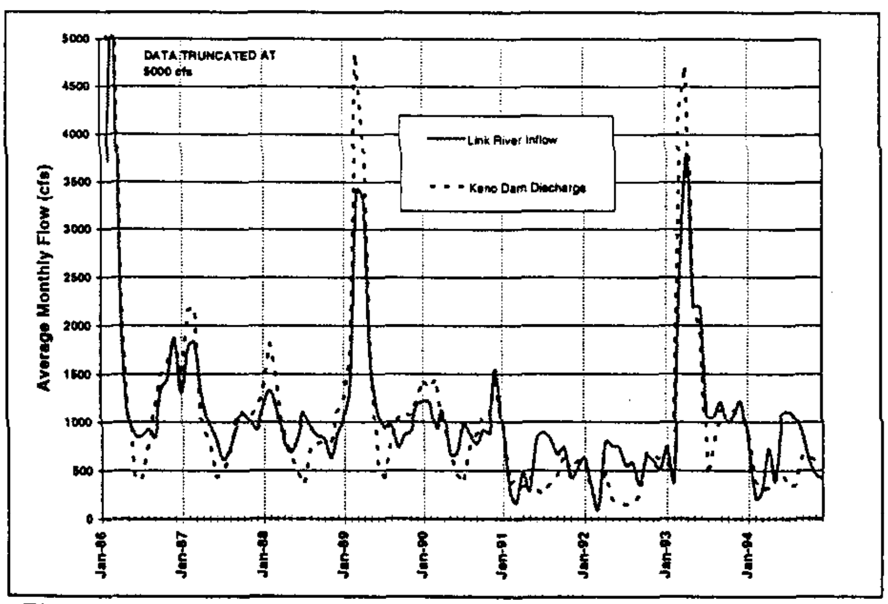

Figure 1-?. Study Reach Inflow and Discharge

Source: USBR

1.2.3 Detention Time

Detention time is the average time a drop of water remains in the study reach and is often an important indicator of possible water quality conditions. Water quality will generally decrease as detention time increases due to greater time for pollutants to have an effect such as in depressing oxygen or in allowing sufficient time for algae to grow. Table 1-1 shows estimated detention times for the summer periods of 1990 to 1994. This period was one of the driest periods of record.

Table 1-?. Detention Time

YEAR	Average Summer Flow (cfs)	Average Detention Time (days)
1990	617	14
1991	344	40
1992	183	60
1993	1086	7
1994	453	18

Period: June 1 - September 30

1.3 CLIMATE

Weather conditions in the Klamath Falls area are representative of the high desert of eastern Oregon. Summers are generally warm with average July temperatures of 68 °F (20 °C) with average highs of 85 °F (29 °C). June through September precipitation averages 2.21 inches. Winter temperatures are cool with average January temperatures of 30 °F (-1 °C) with average lows of 20 °F (-7 °C). Precipitation between October and March averages 9.71 inches. Average annual precipitation is 13.5 inches. Mean, maximum, and minimum monthly temperatures and average monthly precipitation data are given in Table 1-?.

Table 1-?. Climate Summary for Klamath Falls, Oregon

Month	Temperature (°F)			Precipitation (inches)
	Average	Minimum	Maximum	
January	29.8	20.4	39.2	1.81
February	35.1	24.9	45.2	1.28
March	39.2	27.8	50.6	1.35
April	44.8	30.8	58.3	.75
May	52.9	38.2	67.6	.86
June	61.1	45.6	76.5	.69
July	67.9	50.9	84.9	.35
August	66.8	49.7	83.8	.62
September	59.4	42.8	75.9	.55
October	49.4	34.6	64.1	1.07
November	37.5	27.6	47.4	1.97
December	30.5	21.7	39.2	2.23
Annual	47.9	34.6	61.1	13.5

Source: Climatological Data for Oregon Agricultural Regions; OSU Special Report No. 912, May, 1993, pages 17-20. Klamath Falls Station.

1.4 WATER QUALITY ISSUES

In general, the water quality problems of the study reach are associated with low dissolved oxygen (DO) and algal blooms.

Based on the monitoring data available, it appears that low DO concentrations occur in the study reach under three conditions. The first occurs because of diurnal variations in DO, likely caused by biological processes. DO is highest in the early evening and lowest in the early morning. The second condition appears to be event-based, where DO decreased for a few days and then increases again. This is likely the result of decomposing plant material such as algae. The third condition is a result of high sediment oxygen demand (SOD).

Table 1- is a summary of exceedances of the proposed OAR standard for dissolved oxygen. Approximately 70% of the samples represented in the table were collected using a continuous monitor at the Highway 66 bridge near Keno.

Table 1-?. Exceedances of Proposed OAR Dissolved Oxygen Standard since 1/1/90

Month	N	% < 5 mg/l	Minimum	Maximum	Begin Date	End Date
January	1422	0	5.7	11.8	1/1/93	1/24/95
February	961	0	6.0	17.7	2/26/92	2/28/94
March	1443	6	1.8	18.2	3/18/92	3/29/94
April	1627	9	3.4	17.7	4/17/90	4/19/94
May	446	2	3.3	13.3	5/23/91	5/20/94
June	1747	7	2.1	15.5	6/11/90	6/22/94
July	1363	53	0.0	17.7	7/31/90	7/19/94
August	3509	40	0.0	22.0	8/1/90	8/20/94
September	2438	54	0.0	19.9	9/24/90	9/30/94
October	1731	28	0.1	14.7	10/2/92	10/31/94
November	1001	0	5.5	12.5	11/20/91	11/15/94
December	1237	0	6.9	11.6	12/1/92	12/25/93

Source: Storet, USBR, DEQ. N = Number of samples

The table shows that the majority of the water quality violations occur during July through October. This table was produced by combining water quality data from a variety of sources into a single database and querying the database to produce the results presented. Data was obtained from the DEQ, the US Environmental Protection Agency (EPA) (principally from STORET), and the USBR. This database can be used in the future by DEQ to continue the management of data and for additional assessment of the Klamath's water quality. The database can also be used to assess water quality standard changes and other compliance issues.

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2. Model Selection

The model selection process attempted to balance the needs of DEQ to produce a tool for determining waste load allocations and the time constraints and availability of appropriate data to build the model. In general, as a model becomes more complex, the costs of developing the input data needed and of model operation increase dramatically while the benefits level off from an initial rapid increase. The goal was to provide the greatest benefit for the least cost.

2.1 MODEL REQUIREMENTS

In general, the water quality model used should be the simplest model possible that can simulate relevant physical and chemical phenomena. Often model selection is driven by availability of data; complex models require large data sets for adequate model calibration and verification but can deliver a wide array of analysis options and parameter interests. Simpler models may provide reasonable results for common water quality parameters that can convey the health of a water body (such as temperature and dissolved oxygen) with much lower effort and with fewer data requirements. Some key considerations for model selection for the Klamath River include:

I. Site Specific Considerations:
   A. Physical conditions, such as flow velocity, reservoir operations, stratification
   B. Chemistry and key parameters of concern; such as temperature, dissolved oxygen, nitrogen cycle, algae

II. Management Objectives:
   A. Required accuracy
   B. General model purpose for initial application and future applications

III. Project Resources
   A. Data availability
   B. Staffing resources and familiarity with models
   C. Time constraints

For the Klamath River the water quality model should be able to simulate water quality for the following parameters and chemistry and adequately simulate the hydraulics if the river-reservoir system of the reach.

- temperature
- dissolved oxygen
- $CBOD_5$
- nitrate, ammonia
- chlorophyll-*a*
- sediment oxygen demand
- total phosphorus, and orthophosphorus

2.2 AVAILABLE MODELS

There are many models that will meet most of the considerations given above. Table 2 provides a summary of capabilities and features of various models used for analysis of water quality problems in rivers, lakes and estuaries. The information provided in these tables is primarily qualitative and sufficient to determine whether a model may be suitable for a particular application but is not inclusive of all models currently available.

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2.2.1 Model Features

Table 2 summarizes the basic features of the models. the time scales are dynamic (D), quasi-dynamic (Q), and steady (SS). Spatial dimensions are 1 (x), 2 (xy, xz, or xx for link-node networks), or 3 (xyz or B, for box models). Hydrodynamics are either input by the user (I) or simulated (S). Solution techniques are analytical (A), finite difference (FD) or finite element (FE). Finally, models are implemented on mainframes (M) or personal computers (PC).

Table 2. Basic Model Features

MODEL	TIME SCALE	SPATIAL DIMENSION	HYDRODYNAMICS	SOLUTION TECH.	COMPUTER
SEM	SS	x	I	A	--
WQAM	SS	x	I	A	--
HAR03	SS	B	I	FD	M
FEDBAK03	SS	B	I	FD	M
QUAL2E	SS	x	I	FD	M, PC
AUTOQUAL/QA	Q	x	I	FD	M, PC
WASP5:					
Stand Alone	Q	B	I	FD	M, PC
with DYNHYD4	D	xx	S	FD	M, PC
DEM	D	xx	S	FD	M
EXPLOR-1	D	xx	S	FD	M
MIT-DNM	D	x	S	FD	M
Chen	D	xy	S	FE	M
FETRA	D	xy	I	FE	M
CE-QUAL-W2	D	xz	S	FD	M, PC
TABS-2	D	xy	S	FE	M
WIFM-SAL	D	xy	S	FE	M
FCSTM-H	D	xy	S	FE	M
EHSM3D	D	xyz	S	FD	M

D - dynamic Q - quasi-dynamic (tidal-averaged) SS - steady state	x - 1 dimensional xy-3 dimensional, longitudinal-lateral xz-2-dimensional, longitudinal-vertical xyz-3-dimensional B-compartment or box 3D xx-link node branching 2D	I- hydrodynamics input S-hydrodynamics simulated	A-analytical solution FD-finite difference solution FE-finite element solution	M-mainframe computers PC-personal computers

2.2.2 Water Quality Problems

Table 3 summarizes the water quality problems that may be directly addressed by the models. The numbers in the table and following test refer the modeling technique used to simulate the physical parameter or process. All models address salinity and bacteria either explicitly or by specifying appropriate boundaries, loads, and first order decay constants for another state variable.

Sediment may be modeled using calibrated deposition and scour velocities (1), or by using functional relationships with shear stress and shear strength to predict these velocities (2). Dissolved oxygen may be modeled along with total BOD (1), with CBOD, NBOD, and prescribed sediment oxygen demand (SOD) and net photosynthetic production (2), or with CBOD nitrification, SOD and simulated nutrients and phytoplankton (3).

Nutrient enrichment and eutrophication may be simulated using total phytoplankton biomass (1), multiple phytoplankton classes (2), or multiple phytoplanton and zooplankton classes (3).

Organic chemicals may be modeled with calibrated decay rates and partition coefficients, with predicted transformation rates and partition coefficients, or with predicted rates and coefficients for the original chemical plus reaction products. *Metals* may be modeled as dissolved and particulate fractions with calibrated partition coefficients(1), or as multiple species predicted with a thermodynamic data base and process models (2).

Table 3
Water Quality Problems Addressed

MODEL	SALINITY BACTERIA	SEDIMENT	DO	EUTRO-PHICATION	ORG. CHEM.	METALS
SEM	X		2			
WQAM	X	1	2		1	
HAR03	X		2			
FEDBAK03	X		2			
QUAL2	X		3	1		
AUTOQUAL/OA	X		2			
WASP5:						
EUTRO4	X		3	1		
TOXI4	X	1			1,2,3	1
DEM	X		3	1		
EXPLOR-1	X		3	3		
MIT-DNM	X		3	1		
Chen	X		3	1		
FETRA	X	2				1
CE-QUAL-W2	X	1	3	1		
TABS-2	X	2				
WIFM-SAL	X					
FCSTM-H	X	2				
EHSM3D	X	2				

2.3 SHORT-LISTED MODELS

The following provides a summary of models short-listed based on discussions with DEQ staff and literature review.

2.3.1 QUAL2E

QUAL2E is a steady state one-dimensional model designed for simulating conventional pollutants in streams and well-mixed lakes. It has been applied to tidal rivers with minor adaptations to the hydraulic geometry and dispersion functions. Water quality variables simulated include conservation substances, temperature, bacteria, BOD, DO, ammonia, nitrite, nitrate, and organic nitrogen, phosphate and organic phosphorus, and algae. QUAL2E is widely used for stream waste load allocations and discharge permit determinations in the United States and other countries. It has a 15-year history of application and is a proven, effective analysis tool. QUAL2E Version 3 incorporates several uncertainty analysis techniques useful in risk management. This model can be obtained from the Center for Exposure Assessment Modeling, Athens, Georgia.

2.3.2 WASP5

WASP5 is a general, multi-dimensional model that utilizes compartment modeling techniques (DiToro et al, 1981; Ambrose et al. 1987). Operated in either the quasi-dynamic or steady state mode, the use must supply initial segment volumes, network flow fields, and inflow time functions. The user also must calibrate dispersion coefficients between compartments. Depending on the process model with which it is linked, WASP5 has the capability of simulating a range of conventional and toxic pollutants. Problems that have been studied using WASP5 include BOD, DO dynamics, nutrients and eutrophication, bacterial contamination, and toxic chemical movement (DiToro, 1981). WASP5, along with the associated programs TOXI4, EUTRO4, and DYNHYD4, can be obtained from the Center for Exposure Assessment Modeling, Athens, Georgia.

2.3.3 TOXI4

TOXI4 is a version of WASP5 that is designed to simulate organic chemicals and heavy metals (Ambrose et al. 1987). TOXI4 was created by adapting the kinetic structure of EXAMS-II to the transport framework of WASP5 and adding sediment balance algorithms. It can simulate up to three chemicals and three sediment classes. In addition to segment volumes, flows, and dispersive exchanges, the user must supply sediment deposition and scour rates, bed sediment velocity, water column/sediment exchange coefficients, and sediment/pore water exchange coefficients.

In TOXI4 the total transformation rate of an organic chemical is based on the simple addition of the rate constants for individual photolysis, hydrolysis, biolysis, and oxidation reactions. These rate constants may either be specified by the user or calculated internally from second order rate constants and such environmental conditions as light intensity, pH, bacteria, oxidants, depth, velocity, and wind speed. Internal transport and export of organic chemicals occur via advective and dispersive movement of dissolved, sediment-sorbed, and biosorbed materials, and by volatilization losses at the air-water interface. Internal transport and export of heavy metals occur via advective and dispersive movement of dissolved, sediment-sorbed, and biosorbed materials. Sorption of both organic chemicals and heavy metals on sediments and biomass is calculated assuming local equilibrium using a constant partition coefficient and spatially varying environmental organic carbon fractions. TOXI4 has the capability of simulating up to two daughter products of organic chemical transformations. Exchange between the water column and the bed can occur by settling or re-suspension of particulates, diffusion of dissolved pollutants between the water column and pore water, direct adsorption/desorption between the water column and bed, and percolation or infiltration. Within the bed, a pollutant can move vertically by diffusion, turnover, percolation and burial, and horizontally with bed load transport.

2.3.4 EUTRO4

EUTRO4 is a version of WASP5 that is designed to simulate conventional pollutants. EUTRO4 combines a kinetic structure adapted from the Potomac Eutrophication Model and the WASP transport structure. EUTRO4 predicts DO, carbonaceous BOD, phytoplankton carbon and chlorophyll a, ammonia, nitrate, organic nitrogen, organic phosphorus, and orthophosphate in the water column and, if specified, the underlying bed. In addition to segment volumes, flows, and dispersive exchanges, the use must supply deposition and re-suspension velocities for organic solids, inorganic solids, and phytoplankton. the fraction of each water quality variable associated with these solids also must be given. Rate constants and half-saturation coefficients for the various biochemical transformation reactions must be specified by the user. Finally, the time and/or space variable environmental forcing functions, such as light intensity, light extinction, wind speed, cloud cover, temperature, and benthic fluxes must be input.

2.3.5 WIFM-SAL

WIFM-SAL is a two dimensional depth-averaged (x-y) finite difference model that generates time-varying water surface elevations, velocities, and constituent fields over a space staggered grid (Schmalz, 1985). This model was developed by the U.S. Army Engineers, Waterways Experiment Station. Units of measure are expressed in the English system (slug-ft-second). Results computed on a global grid may be employed as boundary conditions on more spatially limited refined grid concentrated around the area of interest. in addition, the user may select either of two distinct transport schemes, Scheme 1 is a flux-corrected transport scheme capable of resolving sharp front without oscillation. Scheme 2 is a full, three time level scheme directly

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compatible with the three time level hydrodynamics. The telescoping grid capability in conjunction with the user selected constituent transport scheme is a powerful concept in practical transport problem solving

2.3.6 CE-QUAL-W2

CE-QUAL-W2 is a dynamic 2-d (x-z) model developed for stratified water bodies (Env. and Hyd. Laboratories 1986). This is a Corps of Engineers modification of the Laterally Averaged Reservoir Model (Edinger and Buchak 1983, Buchak and Edinger, 1984a, 1984b). CE-QUAL-W2 consists of directly coupled hydrodynamic and water quality transport models. Hydrodynamic computations are influenced by variable water density caused by temperature, salinity, and dissolved and suspended solids. Developed for reservoirs and narrow, stratified estuaries, CE-QUAL-W2 can handle a branched and/or looped system with flow and/or head boundary conditions. With two dimensions depicted, point and non-point loading can be spatially distributed. Relative to other 2-d models, CE-QUAL-W2 is efficient and cost effective to use.

In addition to temperature, CE-QUAL-W2 simulates as many as 20 other water quality variables. Primary physical processes included are surface heat transfer, short-wave and long-wave radiation and penetration, convective mixing, wind and flow induced mixing, entrainment of ambient water by pumped-storage inflows, inflow density stratification as impacted by temperature and dissolved and suspended solids. Major chemical and biological processes in CE-QUAL-W2 include: the effects of DO of atmospheric exchange, photosynthesis, respiration, organic matter decomposition, nitrification, and chemical oxidation of reduced substances; uptake, excretion, and regeneration of phosphorus and nitrogen and nitrification-denitrification under aerobic and anaerobic conditions; carbon cycling and alkalinity-pH-CO_2 interactions; trophic relationships for total phytoplankton; accumulation and decomposition of detritus and organic sediment; and coliform bacteria mortality.

2.4 MODEL SELECTED

The analysis of eutrophication and algae production, in addition to normal physical processes of temperature and dissolved oxygen demand, and physical constraints, primarily stratification of temperature and dissolved oxygen, results in the selection of a comprehensive analysis model in two dimensions. Review of available data suggested sufficient coverage for model calibration and verification. The familiarity of DEQ staff with the CE-QUAL-W2 model through work on the Columbia Slough and other projects and the fully-two dimensional modeling of the flow regime resulted in a decision to use CE-QUAL-W2 to model the Klamath River.

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3. Model Description

This section is a summary of sections of the Corps of Engineers CE-QUAL-W2 Users Manual and describes key aspects of the model that pertain to the Klamath River System modeled.

3.1 MODEL OVERVIEW

The simulation model used in this study is a modified version of CE-QUAL-W2 developed by the Corps of Engineers with modifications made by Portland State University. The model is a two-dimensional, laterally averaged, dynamic model of hydrodynamics and water quality. The model predicts water surface elevations, velocities, and temperatures. The model is able to predict the following water quality parameters: conservative tracer, inorganic suspended solids, coliform bacteria, total dissolved solids, dissolved organic matter, algae, sediment, orthophosphate, ammonia, nitrate, dissolved oxygen, total inorganic carbon, alkalinity, pH, and carbonate species.

3.2 GOVERNING EQUATIONS

CE-QUAL-W2 uses the laterally averaged equations of fluid motion derived from the three dimensional equations (Edinger and Buchak, 1975). They consist of six equations and six unknowns. The equations are:

3.2.1 Horizontal Momentum

$$\frac{\partial UB}{\partial t} + \frac{\partial UUB}{\partial x} + \frac{\partial WUB}{\partial z} = -\frac{1}{\rho}\frac{\partial BP}{\partial x} + \frac{\partial\left(BA_x\frac{\partial U}{\partial x}\right)}{\partial x} + \frac{\partial B\tau_x}{\partial z} \qquad (1)$$

where

- U = longitudinal, laterally averaged velocity, $m\ sec^{-1}$
- B = waterbody width, m
- t = time, sec
- x = longitudinal Cartesian coordinate: x is along the centerline at the water surface, positive to the right (there is no y component as the model is laterally averaged)
- z = vertical Cartesian coordinate; z is positive downward
- W = vertical, laterally averaged velocity, $m\ sec^{-1}$
- ρ = density, $kg\ m^{-3}$
- P = pressure, $N\ m^{-2}$
- A_x = longitudinal momentum dispersion coefficient, $m^2\ sec^{-1}$
- τ_x = shear stress per unit mass resulting from the vertical gradient of the horizontal velocity, U, $m^2\ sec^{-2}$

The first on the left-hand side (LHS) term represents the time rate of change of horizontal momentum, and the second and third terms are the horizontal and vertical advection of momentum. The first term on the right-hand side (RHS) of equation (1) is the force imposed by the horizontal pressure gradient. The second term on the RHS is the horizontal dispersion of momentum, and the third term is the force due to shear stress.

3.2.2 Constituent Transport

The time and space dependent balance is given by equation 2.

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$$\frac{\partial B\Phi}{\partial t} + \frac{\partial UB\Phi}{\partial x} + \frac{\partial WB\Phi}{\partial z} - \frac{\partial\left(BD_x\frac{\partial\Phi}{\partial x}\right)}{\partial x} - \frac{\partial\left(BD_z\frac{\partial\Phi}{\partial z}\right)}{\partial z} = q\Phi B + S\Phi B \qquad (2)$$

where

Φ = laterally averaged constituent concentration, $g\ m^{-3}$
D_x = longitudinal temperature and constituent dispersion coefficient, $m^2\ sec^{-1}$
D_z = vertical temperature and constituent dispersion coefficient, $m^2\ sec^{-1}$
q_Φ = lateral inflow or outflow mass flow rate of constituent per unit volume, $g\ m^{-3}\ sec^{-1}$
S_Φ = kinetics source/sink term for constituent concentrations, $g\ m^{-3}\ sec^{-1}$

Each constituent has a balance as in equation (2) with specific source and sink terms. The first term is equation (2) represents the time rate of change of constituent concentration and the second and third terms are the horizontal and vertical advection of constituents. The fourth and fifth terms are the horizontal and vertical diffusion of constituents. The first term on the RHS is the lateral inflow/outflow of constituents, and the second term represents kinetic source/sink rates for constituents.

3.2.3 Free Water Surface Elevation

$$\frac{\partial B_\eta \eta}{\partial t} = \frac{\partial}{\partial x}\int_\eta^h UBdz - \int_\eta^h qBdz \qquad (3)$$

where

B_η = time and spatially varying surface width, m
η = free water surface location, m
h = total depth, m
q = lateral boundary inflow or outflow, $m^{-3}\ sec^{-1}$

3.2.4 Hydrostatic Pressure

$$\frac{\partial P}{\partial z} = \rho g \qquad (4)$$

where

g = acceleration due to gravity, $m\ sec^{-2}$

3.2.5 Continuity

$$\frac{\partial UB}{\partial x} + \frac{\partial WB}{\partial z} = qB \qquad (5)$$

3.2.6 Equation of State

$$\rho = f(T_W, \Phi_{TDS}, \Phi_{SS}) \qquad (6)$$

where

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$f(T_W, \Phi_{TDS}, \Phi_{SS}) =$ density function dependent upon temperature, total dissolved solids or salinity, and suspended solids

These six equations result in six unknown:

1. free water surface elevation, η
2. pressure, P
3. horizontal laterally averaged velocity, U
4. vertical laterally averaged velocity, W
5. constituent concentration, Φ
6. density, ρ

Lateral averaging eliminates the lateral momentum balance, lateral velocity, and Coriolis acceleration. The solution of the six equations for the six unknowns forms the basic structure of CE-QUAL-W2.

3.3 MODEL LIMITATIONS

The governing equations are laterally averaged. Lateral averaging assumes lateral variations in velocities, temperatures, and constituents are negligible. This assumptions may be inappropriate for large waterbodies exhibiting significant lateral variations in water quality.

Other limitations of the current version of the model include:

a. One algal compartment. The model includes only one algal compartment and thus does not presently model algal succession.

b. No zooplankton. The model does not explicitly include zooplankton and their effects on algae or recycling of nutrients. For the Klamath system, if dominated by blue-greens, zooplankton do not prefer blue-green algae and hence, may not be an important loss of blue-green algae to the system.

c. No macrophytes. The model does not explicitly reproduce the effects of macrophytes on hydraulics and water quality.

d. Predictive sediment oxygen demand model is not yet reliable for long-term, multi-year predictions of the sediment compartment. Calibration of the sediment oxygen demand on a year-by-year basis and recognizing that the link between the water column dynamics (i.e., sedimentation of particulate organics) and the sediment decay of those organics is still being developed.

Additional algal compartments and zooplankton can be added to the formulation as more field data become available in order to extend the applicability of the model to this system.

3.4 DESCRIPTION of Water Quality Cycles

The User's Manual discusses the water quality cycles in detail. Table ? below itemizes the principle source sink terms for each of the modeled water quality parameters.

Table ?. Source/sink terms for water quality parameters modeled in CE-QUAL-W2.

Water Quality Constituent	Internal Source Modeled (other than transport and inflow/outflow)	Internal Sink Modeled (other than transport and inflow/outflow)
Tracer	none	none
Suspended solids (inorganic)	none	sedimentation
Coliform bacteria	none	first order decay

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Table ?. Source/sink terms for water quality parameters modeled in CE-QUAL-W2.		
Water Quality Constituent	Internal Source Modeled (other than transport and inflow/outflow)	Internal Sink Modeled (other than transport and inflow/outflow)
Total dissolved solids	none	none
Labile dissolved organic matter ($BOD_{ultimate}$)	algae mortality/excretion	decomposition
Refractory dissolved organic matter	decomposition of labile dissolved organic matter	decomposition
Algae	algae growth	algae respiration, death, and sedimentation
Detritus	algae mortality	sedimentation, decomposition
Ortho-Phosphorus	algae respiration, decomposition of labile dissolved organic matter, refractory dissolved organic matter, detritus, and sediment	algae growth, adsorption onto suspended solids
Ammonia	sediment decomposition, nitrate reduction, algae respiration	algae growth, nitrification, adsorption onto suspended solids, decomposition of labile dissolved organic matter, refractory dissolved organic matter, and detritus
Nitrate+Nitrite	nitrification	nitrate reduction, algae growth
Dissolved Oxygen	surface exchange, algae growth	surface exchange, algae respiration, nitrification, decomposition of sediment, detritus, labile dissolved organic matter, and refractory dissolved organic matter
Sediment	algae settling, detritus settling	decomposition
Inorganic Carbon	decomposition of labile dissolved organic matter, refractory dissolved organic matter, detritus, and sediment, surface exchange, algae respiration	surface exchange, algae growth
Alkalinity	none*	none*
pH	none*	none*
Carbon dioxide	none*	none*
Bicarbonate	none*	none*
Carbonate	none*	none*
* alkalinity, pH, and the carbonate species are all treated conservatively, but are based on carbonate chemistry equilibrium and inorganic dissolved carbon		

3.5 *ENVIRONMENTAL PERFORMANCE CRITERIA*

Time and volume weighted environmental performance criteria were developed to evaluate the water quality performance between different model simulations. This attempt to create an environmental performance criterion was first discussed in Wells and Berger (1993). The development here is an extension and improvement on that work.

Conceptually, these performance criteria provide the user with an evaluation technique to compare conventional water quality predictions between model simulations using different management strategies. These criteria determine what average fraction of the system volume is in violation of a water quality goal or standard over the entire simulation period. For example, the dissolved oxygen criteria is a statistic which shows how much of the volume of the water body over the simulation period was less than 6.0 mg/l. A histogram statistic shows what percentage of the dissolved oxygen was between 6.0 and 5.8, 5.8 and 5.6, etc. The average of the "violation" for the entire simulation period is also calculated. Table ? shows the conventional water quality parameters violation criteria for each parameter.

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Table ?. Violation Limits And Histogram Intervals For Volume Weighted Environmental Performance Criteria.

Parameter	"Violation" limit	Histogram interval (20 histogram divisions)
Dissolved oxygen	6.0 mg/l	0.4 mg/l
pH - upper	8.5	0.4
pH - lower	6.5	0.4
coliform bacteria	200 col/100 ml	2 (multiplicative factor)
algae	15 ug/l chlorophyll a	10 ug/l
velocity	0.0 m/s	0.01 m/s

Average concentration of the violation was determined from

$$C_{volume} = \frac{\sum_{i=1}^{nt}\sum_{j=1}^{nc}(C_{ij}Vol_{ij}\Delta t_i)}{\sum_{i=1}^{nt}\sum_{j=1}^{nc}(Vol_{ij}\Delta t_i)}$$

where nt: number of model time steps for the model simulation period
nc: number of violations of concentration above or below the "violation" limit
C_{ij}: concentration at time level i and cell j in "violation" of "violation" limit
Vol_{ij} : volume of cell j at time level i where water quality standard is in violation
Δt_i: model time step at time level i

The average volume in violation for the entire system was determined from

$$Volume_{fraction} = \frac{\sum_{i=1}^{nt}\sum_{j=1}^{nc}(Vol_{ij}\Delta t_i)}{\sum_{i=1}^{nt}(\sum_{k=1}^{n}Vol_{ik})\Delta t_i}$$

where n: number of model cells at time level i
k: index for cell number
Vol_{ik}: volume of cell k at time level i
Δt_i: model time step at time level i

The volume fraction equation is also used to compute the volume fraction histogram where the average volume in violation for a specific range of the parameter (for example, from a pH between 8.5 and 8.7).

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4. Model Bathymetry

This section discusses the physical representation of the study reach.

4.1 SOURCES OF DATA

Existing bathymetric data were obtained from the sources described below. These data were supplemented by depths measured using a boat equipped with a depth finder.

4.1.1 Federal Emergency Management Agency

FEMA flood boundary and floodway maps were used to determine channel width from the mouth of link river (RM 253) to the Highway 97 bridge (RM 249).

4.1.2 City of Klamath Falls

Cross sections from a mixing zone study for the City of Klamath Falls WWTP were used to determine depths in Lake Ewauna. The cross sections taken in July 1991 show a deep channel near the west side of the lake that transitions to a broad flat shallow area on the east side of the lake. These data were supplemented by field depths taken using a boat with depth finder.

4.1.5 Oregon Department of Environmental Quality

Depths recorded on water quality field data forms were used to determine channel depth from RM 251 to 249. This data was supplemented by field depths taken using a boat with depth finder.

4.1.1 Pacific Power and Light

PP&L dredged the center of the channel from below the Highway 97 bridge (RM 248.5) to the Highway 66 bridge at Keno (RM 235) during the early 1970's. Prior to the dredging the channel, PP&L had 126 lateral cross sections taken from the highway 97 bridge (RM 249) to the Highway 66 bridge at Keno (RM 235) and 10 cross sections taken between the Highway 66 bridge and RM 234.

PP&L provided a series of aerial photographs showing RM 249 to RM 235 with a grid referenced to the northeast corner of the Highway 66 bridge. The air photos showed the location of the cross sections taken in this section of the reach and depths before and after dredging.

The cross sections from RM 235 to RM 234.2 in the undredged section were provided on graph paper with elevation and distance downstream of the Highway 66 bridge.

PP&L also provided a cross section of the Keno Dam.

4.1.4 United States Geological Survey

The Keno 7.5 minute topographical map was used to determine the channel width from the Highway 66 bridge (RM 235) and Keno Dam (RM 233).

4.2 DATA REDUCTION

The data were digitized and input into a surface plotting and analysis program to create a bathymetric map. This map is included as Appendix ?. The map was created using the same grid reference as the PP&L cross sections. Figure 4-? shows the water surface area and volume of the study reach as a function of depth based on the bathymetric map.

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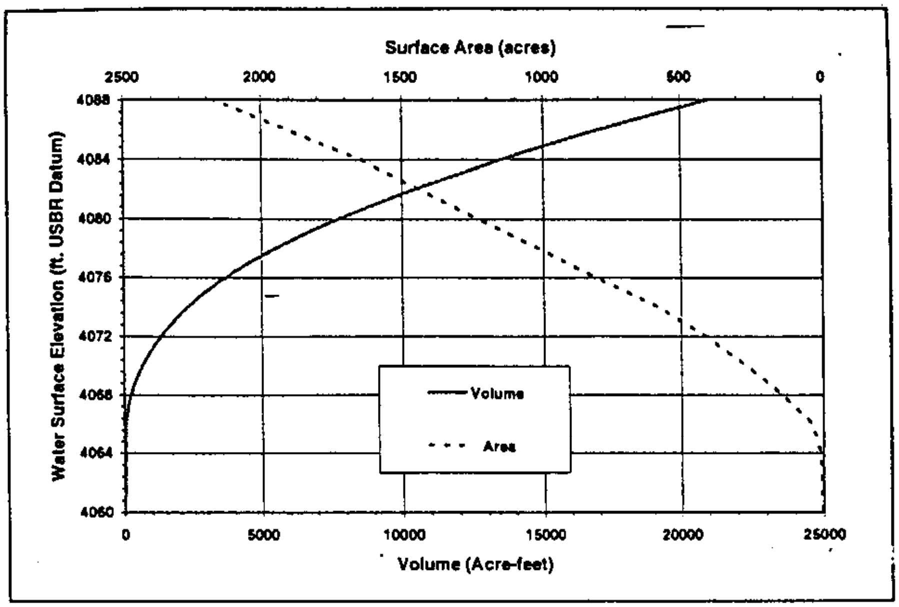
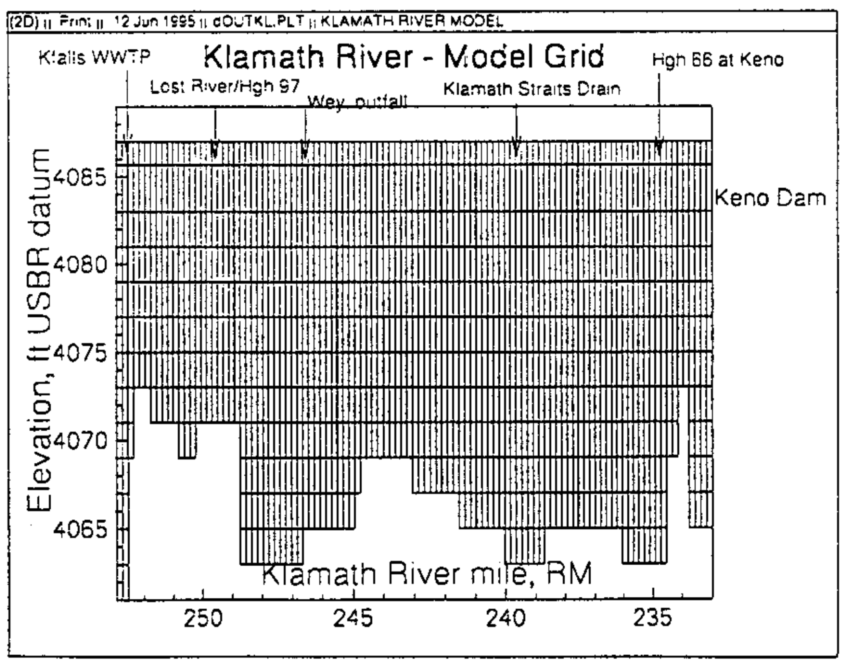


Figure 4-? Study Reach Area-Volume Curve

4.3 MODEL REPRESENTATION

The surface plotting and analysis program was used to determine the width at two foot vertical increments every 1000 longitudinal feet. The model represents the river as cells measuring two feet high, one thousand feet long, and varying in width.

The model grid is shown in Figure 4-?.



5. Boundary Condition Data

This section describes the tributaries, withdrawals, meteorlogical conditions, and other boundary condtions that influence the study reach.

5.1 WATER QUANTITY DATA

Flow data were obtained from the USBR and the four major four major dischargers to the study reach; Weyerhauser, City of Klamath Falls, South Suburban, and Columbia Plywood. Table 5-? provides an overview of all the point and non-point sources coming into or being withdrawn from the Klamath system. A more detailed description of each of these sources is presented in section 5.?

Table 5-?. Summary of point and non-point sources to the study reach

Point and Non-point source/sink to/from Klamath River	River Mile	1990 Average Flow (cfs)	1992 Averge Flow (cfs)	Comment
Link River	253	827	556	Upstream inflow
Kfalls WTP	252.6	4.77	4.42	point source
South Suburban WTP	251.6	2.35	2.28	point source
Lost River Diversion Inflow	249.7	127	21	
Lost River Diversion Withdrawal	249.7	317	304	
Columbia Plywood				flows are based on permitted discharge -- no flow meter installed
Weyerhaesuer Domestic Waste	246.4	0.28	0.12	point source
Weyerhaesuer Plant	246.4	2.14	1.77	point source
North Canal Withdrawal	244.3	65	41	
Ady Canal Withdrawal	241.2	150	61	
Klamath Straits Drain	239.8	141	12.8	flow measured at pump station
Private irrigators				
Groundwater inflow/outflow				unknown loss or gain to system, includes irrigation return flows
Storm water inflows				Stormwater drainage to the system assuming a runoff coefficient of 0.5
Keno Dam				Downstream Boundary

5.2 WATER QUALITY DATA

Water quality data were obtained from DEQ, EPA (Storet), USBR, Klamath Tribes. Effluent water quality data were provided by the four dischargers. These data were input into a converted to a uniform format using database management software.

Synoptic water quality surveys have be done on the study reach and tributaries since 1959. These data are stored in the EPA Storet database. Continuous monitors measuring pH, DO, and temperature have been maintained since 1990 by the USBR. DEQ installed continuous monitors during portions of the summer months during 1990 and 1991. The Klamath Tribes have conducted water quality surveys in the Upper Klamath Lake for several years.

The following tables summarize the water quality of water bodies and dischargers tributary to the study reach during the two summers modeled.

Table 5-?? Typical Concentration of Inputs to Klamath River for 6/1/90 - 10/1/90

Parameter	Units	Klamath Straits Drain	Lost River Diversion	Link River	South Suburban	Weyerhaeuser Plant	Weyerhaeuser STP	Klamath Falls STP
Alk_fld	mg/l	143-196	*	48-59	*	*	*	*
Alk_lab	mg/l	140-185	52-131	50-55	*	*	*	*
BODU	mg/l	*	2.5-2.5	19.6-45.7	35.6-134.7	5.9-48.3	1.8-38.1	2.5-55.9
Chl_a	ug/l	2.7-27.0	0.1-10.0	0.1-205.3	*	*	*	*
Cond	umhos	192-794	121-293	10-340	*	*	*	*
DO	mg/l	0.00-11.69	2.10-9.70	0.47-13.93	0.30-7.30	*	*	1.00-4.70
Fecal	#/100 ml	*	*	*	0-395	*	31-170	1-860
NH3_4-N	mg/l	0.1-1.16	0.09-0.24	0.03-0.17	*	*	*	*
NO2_3-N	mg/l	0.1-0.47	0.07-0.16	0-0.05	*	*	*	*
OP_dis	mg/l	0.176-0.344	0.1-0.23	0.005-0.081	*	*	*	*
pH		6.8-9.5	7.4-9	6.87-10.23	7.5-8.4	7.4-9.1	6.9-9.8	7-7.5
TS	mg/l	410-680	110-240	130-180	*	*	*	*
TSS	mg/l	8-80	1-13	2-31	9-82	4-46	1.3-80	1-19

* no data available

Table 5-?? Typical Concentration of Inputs to Klamath River for 6/1/92 - 10/1/92

Parameter	Units	Klamath Straits Drain	Lost River Diversion	Link River	South Suburban	Weyerhaeuser Plant	Weyerhaeuser STP	Klamath Falls STP
Alk_fld	mg/l	155	*	58	*	*	*	*
Alk_lab	mg/l	138	*	47	*	*	*	*
BODU	mg/l	23.9	*	26.7	20.3-134.7	10.2-61.0	17.8-61.0	5.1-142.3
Chl_a	ug/l	84.0-130.0	*	49.3-460.8	*	*	*	*
Cond	umhos	233-822	*	0-800	*	*	*	*
DO	mg/l	0.00-19.95	*	3.72-13.36	0.50-7.50	*	*	1.20-8.00
Fecal	#/100 ml	17	*	2	5-380	*	2-240	1-145
NH3_4-N	mg/l	0.53-0.53	*	0.005-0.06	*	*	*	*
NO2_3-N	mg/l	0.06-0.06	*	0.005-0.065	*	*	*	*
OP_dis	mg/l	*	*	0.01-0.063	*	*	*	*
pH		7.25-9.47	*	0.97-10.4	7.4-8.5	7.3-8.8	7.4-9.1	6.8-7.9
TS	mg/l	380	*	160	*	*		*
TSS	mg/l	26	*	29	16-70	3-48	7-34	1-34

* no data available

5.3 DESCRIPTION OF TRIBUTARIES AND WITHDRAWALS

The following discussion charaterizes the water quality and quantity data available for major tributaries, withdrawals and permitted dischargers.

5.1.1 Link River

The majority of the water enters the study reach from Upper Klamath Lake via the Link River. The Link River Dam at the extreme southern end of Upper Klamath Lake controls the flow into the Link River. Average daily flow data for the Link River was obtained from USBR. Flow data for the simulation periods are presented in figure 5-?.

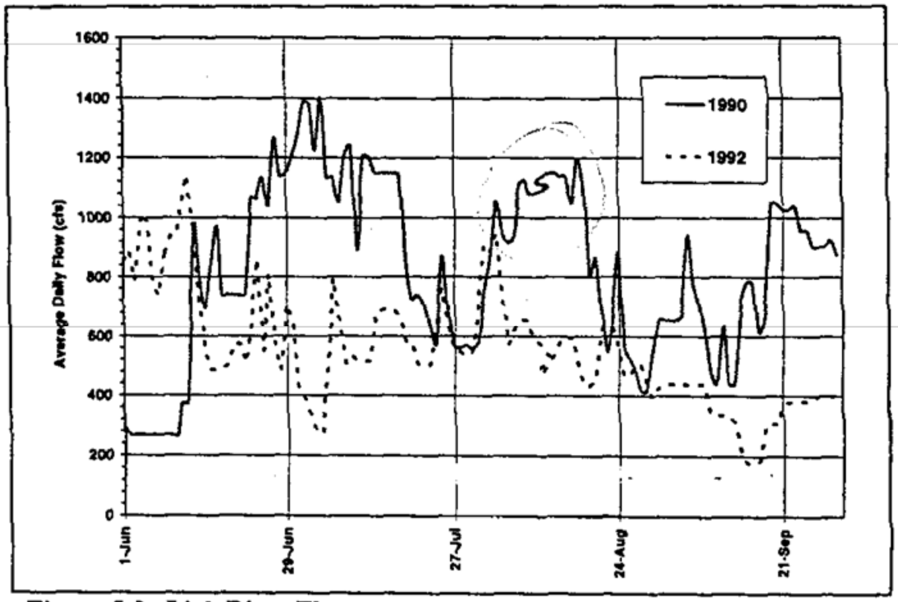


Figure 5-?. Link River Flows

The physical upstream boundary of the model is Lake Ewauna at the point where the mouth of the link river enters the lake. Assuming the water in Link River has an average velocity of one foot-per-second throughout its two mile reach, then the travel time from Upper Klamath Lake is 3.2 hours. Based on the low residence time, it was assumed that the quality of the water flowing from Link River is identical to the quality of the water entering the Link River from Upper Klamath Lake.

A continuous Hydrolab installed by USBR at the entrance of A-Canal about 2000 feet upstream of the Link River Dam. The A-Canal Hydrolab provided Temperature, pH, and Dissolved Oxygen data.

The Klamath Tribes provided nutrirent and algae data collected at Pelecan Marina and Freemont Bridge. These data were collected at once per month during 1990 and every two weeks during 1992.

Fecal coliform, nutrient, and alkalinity data from the Link River were obtained from EPA Storet database.

5.1.2 Keno Dam

Keno Dam, is the downstream boundary of the study reach. The dam has six top-discharge radial gates. The discharge point is 4 to 5 feet below the water surface. The sill elevation is at 4070 feet. Keno dam is operated to maintain a water surface elevation of 4086 ± 0.5 feet. River stage is recorded by PP&L at Weed Bridge and Keno Dam. Figure 5-? is a plot of dam releases during the simulation periods.

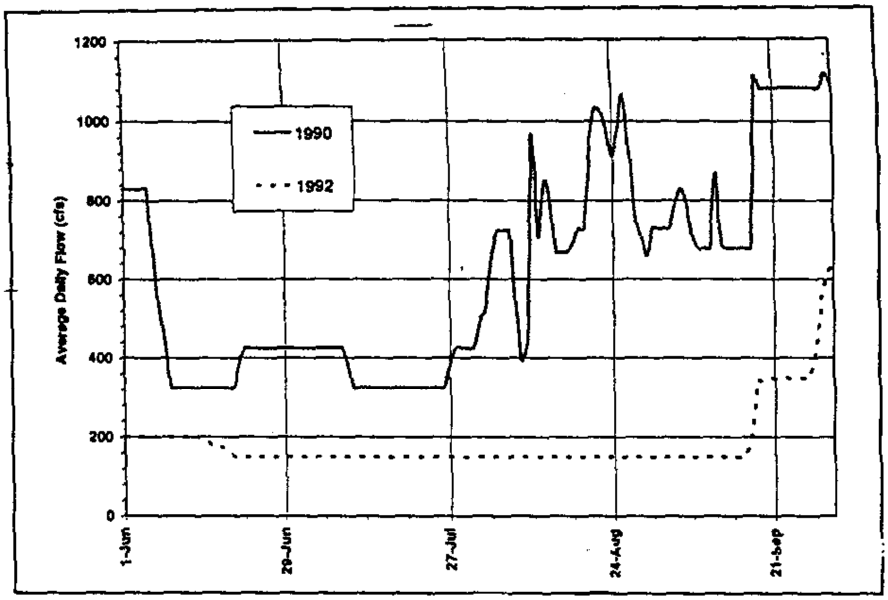


Figure 5-?. Keno Dam Releases

5.1.3 Lost River Diversion

The lost river diversion is a two-way canal that connects the Lost River to the Kamath River. No direct flow measurement is made on the lost river. The USBR does record daily average flow at significant input and withdrawal points to the Diversion. The net contribution to the Klamath River may be determined by the following:

+	Lost River flows into diversion channel
+	spills over Lost River Dam
-	Miller Hill pumping
-	Station 48 pumping
=	inflow to (+) withdrawal from (-) Klamath River

Figure 5-? presents the results of this calculation during the simulation periods. The Lost River Diversion acted as a withdrawal for most the 1992 simulation period.

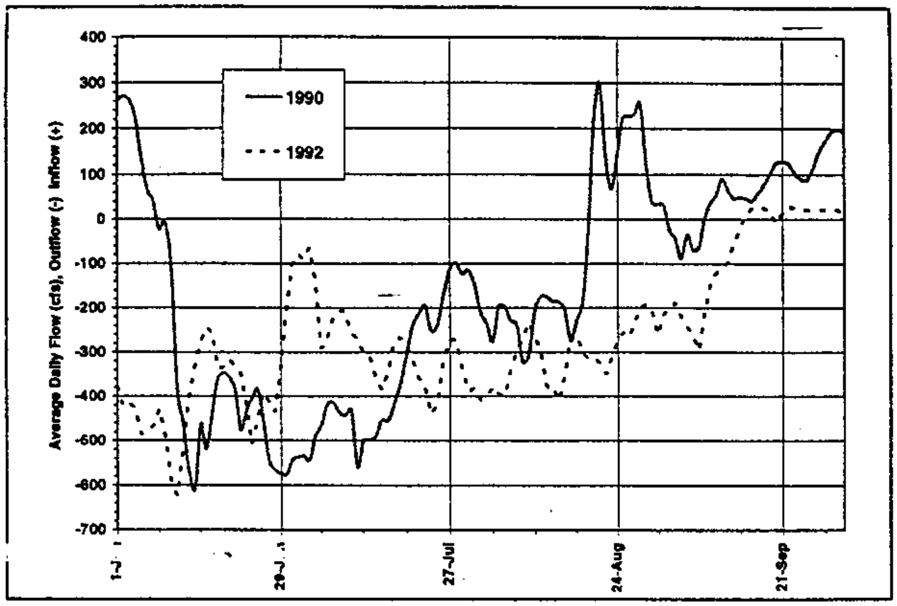


Figure 5-?. Lost River Diversion Inflow and Outflow

Water quality data were not available for the Lost River Diversion during the summer of 1992. Lost River Diversion model input was based on Klamath Straits Drain data for 1992 simulations.

5.1.4 Klamath Straits Drain

The Klamath Straits Drain receives runoff from the Lower Klamath Wildlife Refuge. The Straits Drain is physically separated from the Klamath River by a dike. USBR pump station F pumps water from the KSD into the Klamath River. Pump station flow records were used to determine inflows for the model. Figure 5-? shows flows for the simulation period. Note that the pumpstation reached its 8.5 m^3/s (300 cfs) limit during the first week of June in 1990.

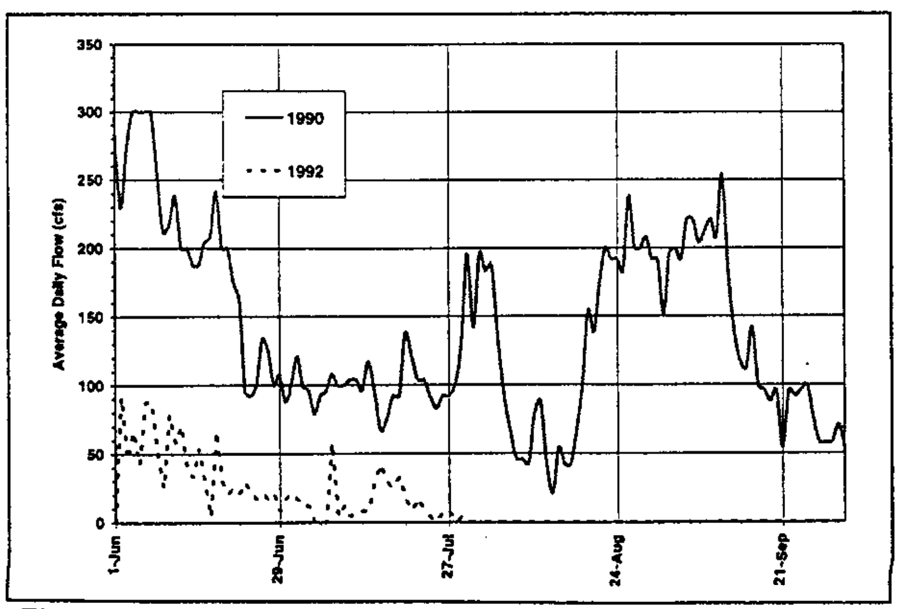


Figure 5-?. Klamath Straits Drain Inflows

The USBR maintains a continuous hydrolab near pump station F. This hydrolab was the source for pH, DO, and temperature inputs. DEQ has a storet station near pumpstation F (402440) which provided nutrient, alkalinity, chlorophyll-a, TS, and TSS data.

5.1.5 Klamath Falls STP

Klamath Falls STP handles waste from the City of Klamath Falls. The plant has both primary and secondary treatment. Effluent flow, pH, TSS, and DO data were recorded most days. Fecal Coliform counts were taken weekly. BOD was recorded about twice a week. Effluent nutrient samples were taken from 1991 through 1994. Plant personal indicated a low confidence in nutrient data taken prior to 1994 because a HACH kit was used. Nutrient data for the summer months of 1994 were averaged and used as model input. Alkalinity was assumed to be 50 mg/l based on data from Upper Klamath Lake. While plant processes could affect alkalinity, it was background levels were assumed since no data was available.

5.1.6 South Suburban STP

The South Suburban facilities received waste from areas not serve by the Klamath Falls STP. The facilities consist mainly of aerated lagoons. Effluent flow, pH, TSS, Temperature and DO data were recorded most days. Fecal Coliform counts were taken weekly. BOD was recorded about twice a week. No nutrient data was available so the averages determined for the Klamath Falls facility were used. Alkalinity was assumed to be 50 mg/l based on Upper Klamath Lake data because no other data were available.

5.1.7 Weyerhaeuser Plant

The Weyerhaeuser Klamath Falls mill produces particle board, hard board and plywood. Lumber operations were discontinued in 1992. Effluent is primarily non-contact cooling water. Other sources include boiler blowdown, condensate and washdown of plant floors. Plywood conditioning water is drained once or twice per year. (Telephone Conversation with Ted Devore)

Weyerhaeuser provided daily effluent flow rates, typically about 1 MGD. BOD, TSS, pH, and temperature were provided for most days. Alkalinity was assumed to be 53 as in the other point sources. Nutrients were assumed to be ___.

5.1.8 Weyerhauser STP

The Weyerhaeuser sewage treatment plant typically flows less that 0.2 MGD. In addition to daily flow rates, pH, BOD, TSS, Temperature, and Fecal Coliform were provided at intervals ranging from once per month to nearly every day.

5.1.9 Columbia Plywood

Columbia Plywood does not have a flow monitor or an ongoing sampling program. A flow rate of 26,000 gallons per day was assumed based on the maximum amount listed on their premit application. The Weyerhaeuser plant effluent concentrations were used for Columbia Plywood. Their NPDES permit application shows a the following concentrations: NO2-NO3 of 0.24 mg/l, total N of 7.68 mg/l, and total P of 0.27 mg/l. Model assumptions were made based on these data.

5.1.10 Groundwater, and Stormwater Inflows

Contributing drainage basins were deliniated on USGS quad maps. Storm water runoff was estimated using Q=CIA. This runoff was input to the model at the 11 points shown in Table 5-?.

Table 5-?. Stormwater Inflow Areas			
Stormwater Tributary #	Area (acres)	Approximate River Mile	Model Cell Number
1	2737	248.2	27
2	6090	246.3	37
3	3050	245.1	43
4	508	242.7	56
5	508	241.0	65
6	508	240.0	70
7	3000	239.5	73
8	508	239.1	75
9	508	238.1	80
10	508	237.2	85
11	3000	235.5	94

The model focused on summer conditions when little rainfall occurs (about three inches on average between May and September). Therefore this approximation is believed to be reasonable. The rainfall intensity and the runoff coefficient were used as model calibration factors for agreement between the model and field data water levels in the Klamath system. These are discussed in the "Model calibration" section.

5.3 METEORLOGICAL DATA

The nearest meterologic station with continuous records for air temperature, dew point temperature, wind speed, wind direction, and cloud cover is the Klamath Falls Airport. Hourly observations for 1990 through 1994 were obtained from the National Climatic Data Center in Ashville S.C. A program was created using the TAWK text processing language to convert the NCDC data into a format acceptable to the model.

5.4 SEDIMENT OXYGEN DEMAND

DEQ performed SOD measurements during the summer of 1994 at three sites. Two of the three tests failed due to . A successful SOD measurement of 19.12 g/m^2-day was obtained at storet site 404283 in Lake Ewauna. This is an extremly high consumption of oxygen. For example an SOD measurement in the immediate vicinity of a municipal sewage outfall might be as high as 10g/m2-day. (thomann and mueller 1987). A discussion of the model values for SOD is shown in the "Model Calibration" section. SOD was a calibration tool for model-data agreement.

Surface Withdrawals

Two surface withdrawal points are located between Lost River Diversion and Keno Dam. North Canal is located at river mile 244.3. Ady Canal is located at river mile 241.2.

6. COMPARISON OF MODEL PREDICTIONS AND FIELD DATA

The process of developing a model involves several calibration, adjustment, verification, adjustment cycles until the model results are as close to field data as possible. Once the model is calibrated and verified, it can be used to predict the response of the water body to different inputs. This section presents the results of the model calibration and verification,

6.1 1990 CALIBRATION YEAR

Field data for 1990 included continuous hydrolab data taken at many stations throughout the Klamath system, as well as point measurements of various water quality parameters. Table 6-shows a comparison of the errors of model predictions and field data taken at various stations throughout the Klamath system for temperature and water quality variables. These error statistics will be discussed below for each water quality parameter.

Table 6-1. Mean and RMS errors for model predictions and field data for 1990.

Cell #	Statistic	Temp (degrees C)	chlorophyll-a (ug/l)	dissolved oxygen (mg/l)	pH	PO_4 (mg/l N)	NO_3 (mg/l N)	NH_4 (mg/l N)	coliform (col/100ml)
6	Mean	-0.0432	3.258	-0.4862	-0.9609	0.0153	0.0008347	-0.07125	
6	RMS	1.434	3.6	2.477	1.112	0.03239	0.0246	0.115	
6	N	262	10	263	262	14	14	14	
9	Mean	-0.1732		0.5449	-0.237	-0.081	-0.1336	0.04974	-232.3
9	RMS	0.1732		0.5471	0.237	0.081	0.1776	0.09034	232.3
9	N	1		2	1	2	3	3	1
11	Mean	0.3913	5.9	0.08451	-0.798	-0.00298	-0.003	-0.1346	
11	RMS	0.929	6.8	2.555	1.12	0.0558	0.086	0.1924	
11	N	15	10	16	15	15	15	15	
13	Mean	0.8703	7.86	-0.422	-0.08	-0.0122	-0.047	-0.085	
13	RMS	1.474	8.12	2.171	0.412	0.0158	0.053	0.097	
13	N	242	2	239	133	2	3	3	
14	Mean	0.6614	9.401	1.969	-0.1517	-0.04593	-0.03536	-0.3176	
14	RMS	1.179	10.09	2.332	0.9441	0.05471	0.07115	0.3524	
14	N	5	4	5	5	5	5	5	
17	Mean	-0.00265	10.84	-1.192	-0.8305	-0.0446	-0.0796	-0.1372	
17	RMS	1.081	10.98	3.482	1.137	0.0464	0.089	0.2098	
17	N	258	8	258	258	11	11	11	
22	Mean	0.368	10.7	1.43	-0.8433	-0.021	-0.0323	-0.202	
22	RMS	1.035	11.36	3.394	1.042	0.045	0.09085	0.264	
22	N	294	9	209	294	12	13	13	
30	Mean	-1.11	1.85	-0.1663	-0.5011	0.01891	0.0571	-0.6444	
30	RMS	1.559	2.47	0.664	0.5601	0.04075	0.06846	0.6574	
30	N	8	4	8	8	8	8	8	
40	Mean	-0.107	8.34	-0.038	-0.0635	0.0145	0.0163	-0.451	
40	RMS	1.904	9.4	2.747	0.617	0.0249	0.0517	0.55	
40	N	12	7	13	12	12	15	15	
50	Mean	2.006	7.91	1.335	1.025	0.0232	0.0187	-0.3648	
50	RMS	2.517	9.458	3.079	1.169	0.0408	0.0475	0.4674	
50	N	106	11	106	105	16	16	16	
60	Mean	0.2472	8.099	-1.86	0.03432	0.0347	-0.01307	-0.04288	

Table 6-1. Mean and RMS errors for model predictions and field data for 1990.

Cell #	Statistic	Temp (degrees C)	chlorophyll-a (ug/l)	dissolved oxygen (mg/l)	pH	PO_4 (mg/l N)	NO_3 (mg/l N)	NH_4 (mg/l N)	coliform (col/100ml)
60	RMS	0.4948	9.956	1.884	0.1155	0.07793	0.01332	0.04318	
60	N	3	3	3	3	3	3	3	
63	Mean	0.04833	11.9	-1.266	-0.5343	-0.0092	-0.0378	-0.402	
63	RMS	1.645	13.27	4.197	0.8662	0.0772	0.084	0.515	
63	N	114	10	114	114	18	17	17	
68	Mean	-0.04344	13.89	2.692	0.4441	-0.04316	-0.03988	-0.4925	-599
68	RMS	2.1	15	4.09	0.6518	0.0893	0.0847	0.5878	599
68	N	18	11	18	18	18	17	17	1
74	Mean	-0.533	7.99	-1.977	-0.8514	-0.03275	-0.0535	-0.4048	
74	RMS	1.712	9.28	5.466	1.067	0.0644	0.0782	0.5176	
74	N	116	12	116	116	19	21	21	
80	Mean	1.642	13.85	5.209	0.3371	-0.04268	-0.03353	-0.7141	
80	RMS	2.249	14.04	5.445	0.5357	0.04621	0.03761	0.7428	
80	N	10	5	10	10	10	10	10	
99	Mean	0.766	20.4	-0.146	-0.00727	0.0135	0.007378	-0.3746	
99	RMS	1.712	21.04	4.388	0.489	0.078	0.04486	0.4999	
99	N	487	4	479	487	9	56	56	

6.1.1 1990 Temperature Calibration

Figures ? through ? show model predictions of temperature at the water surface compared to continuous field data at model cell numbers 6 (RM 252.3), 17 (RM 250.1), 22 (RM 249.4), 50 (RM 244.1), 74 (RM 239.3), and 99 (RM 234.2). These figures show that in general the model reproduces the field data trends. For some stations, e.g. cell 6 and 50, the vertical placement of the hydrolab may have been below the active surface layer for heating and cooling, since these data did not agree with model predictions at the surface. This was particularly important since strong stratification existed in the system (see 1992 temperature comparisons).

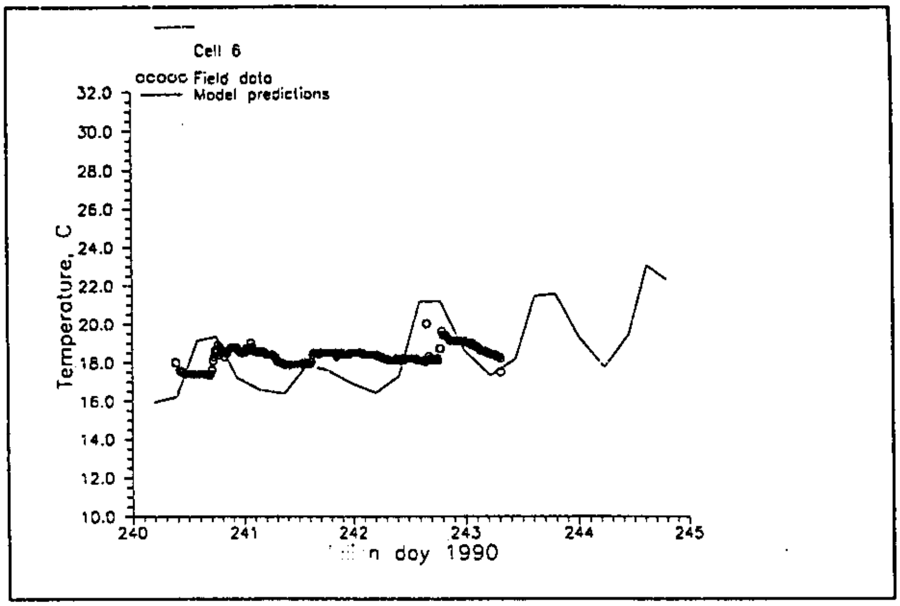


Figure 6-?. Temperature Calibration. Cell 6 8/28-9/2/90

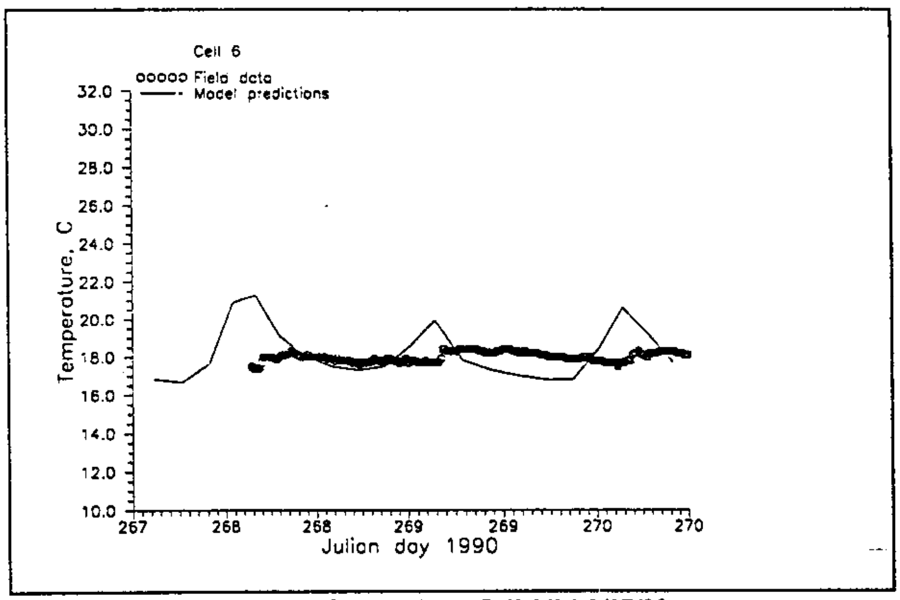


Figure 6-?. Temperature Calibration. Cell 9/24-9/27/90

DRAFT

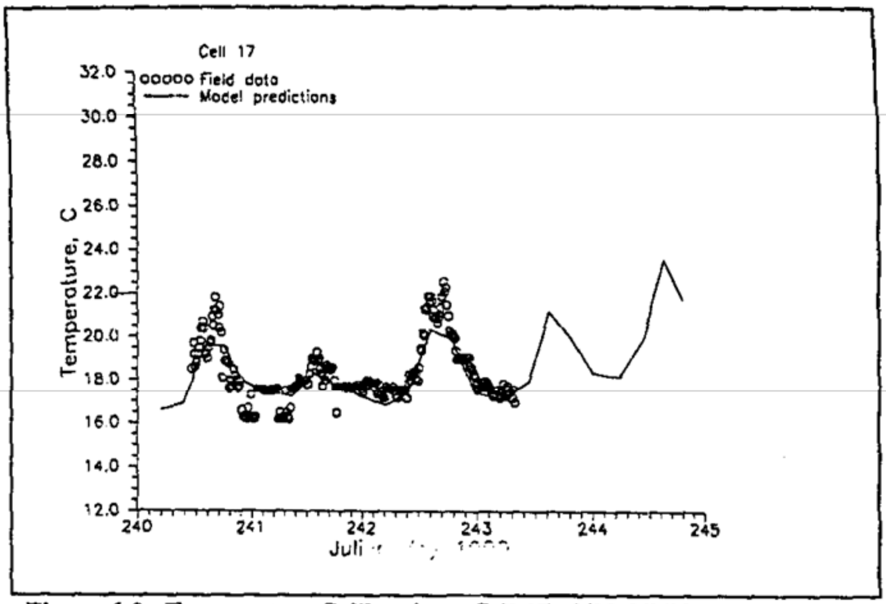


Figure 6-?. Temperature Calibration. Cell 17. 8/28-9/2/90

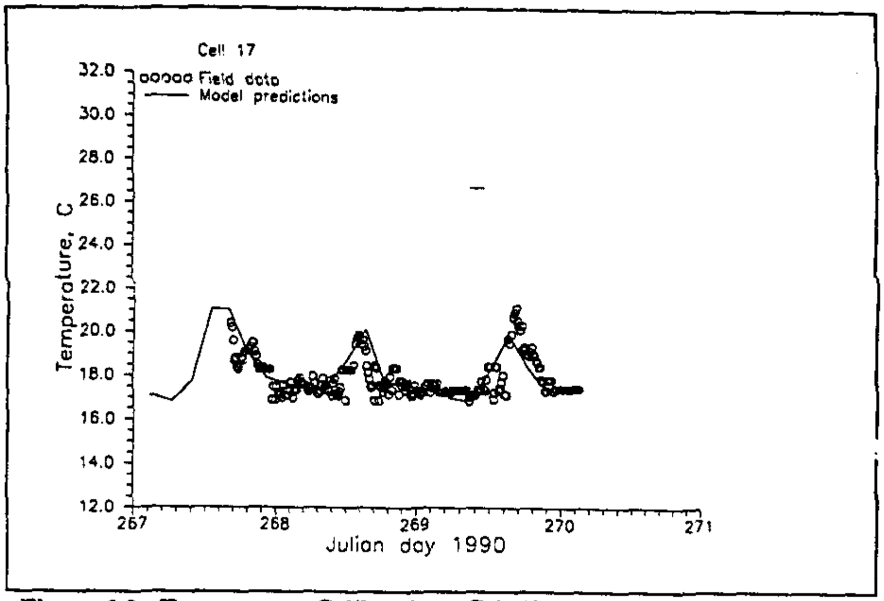


Figure 6-?. Temperature Calibration. Cell 17. 9/24-9/28/90

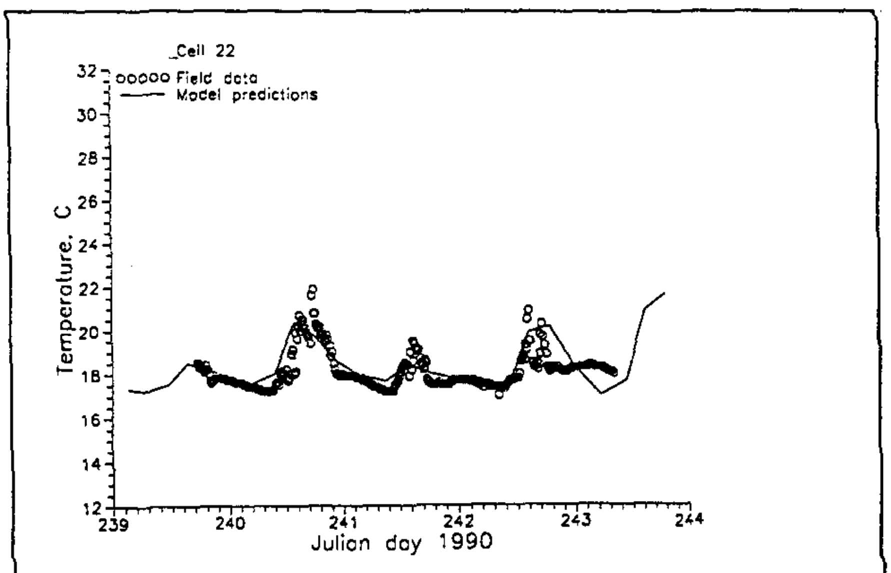


Figure 6-?. Temperature Calibration. Cell 22. 8/27-9/1/90

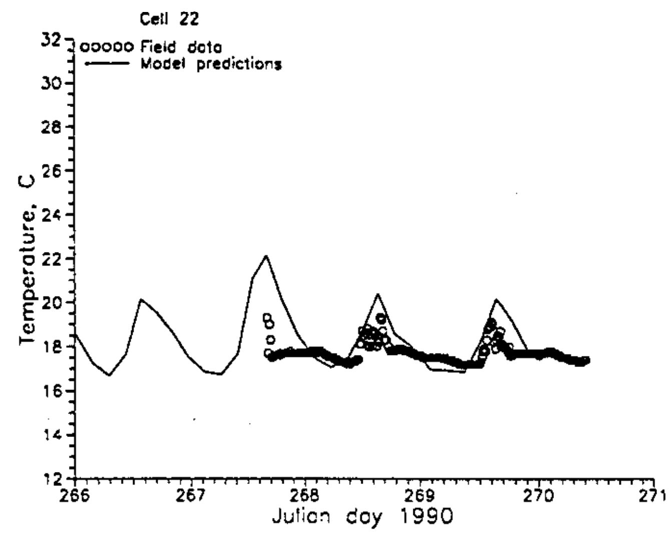


Figure 6-?. Temperature Calibration. Cell 22. 9/23-9/28/90

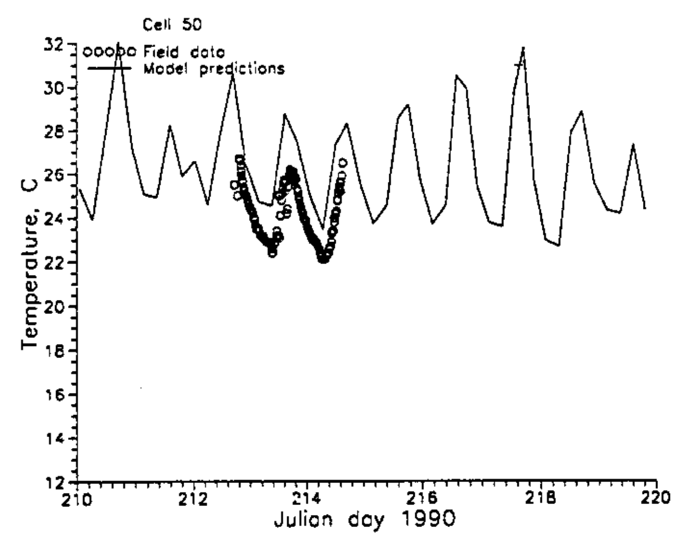


Figure 6-?. Temperature Calibration. Cell 50. 7/29-8/8/90

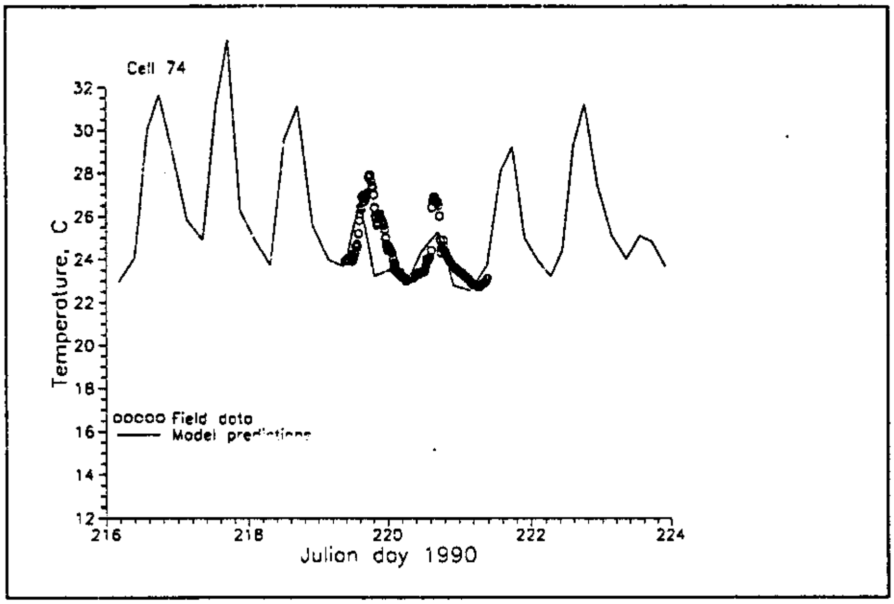


Figure 6-?. Temperature Calibration. Cell 74. 8/4-8/12/90

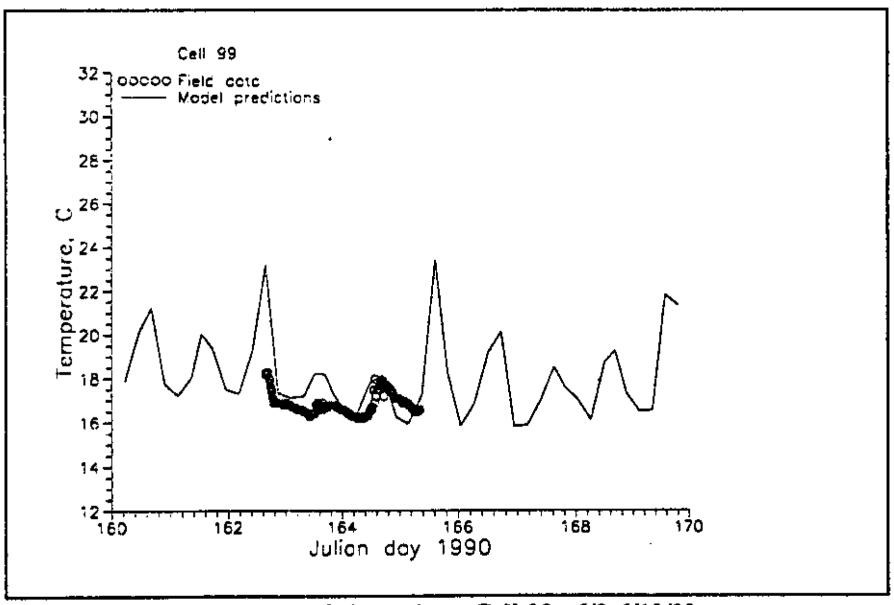


Figure 6-?. Temperature Calibration. Cell 99. 6/9-6/19/90

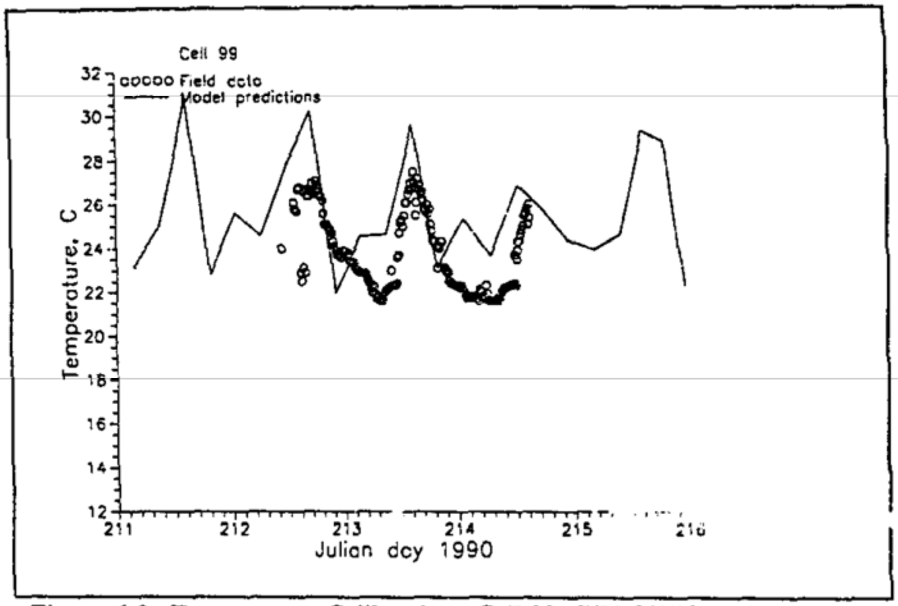


Figure 6-?. Temperature Calibration. Cell 99. 7/30-8/4/90

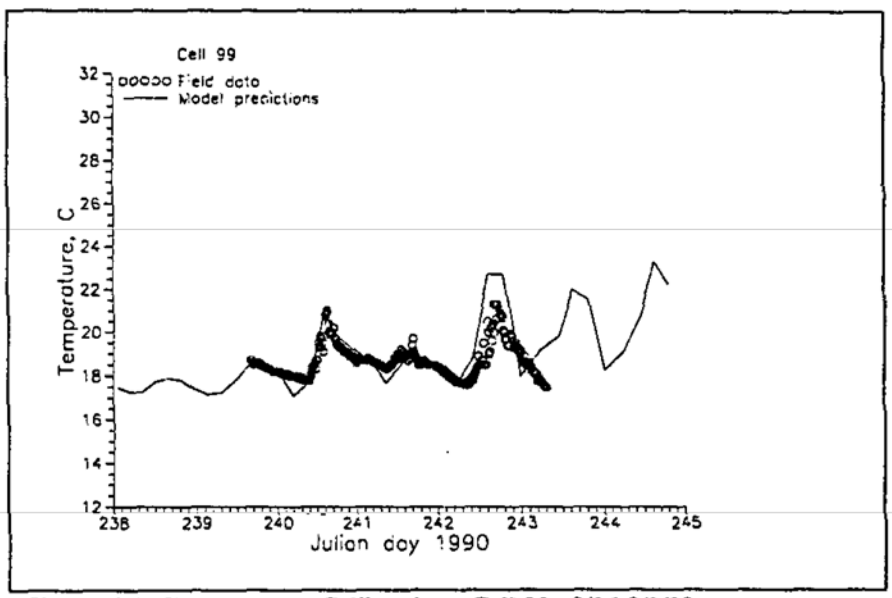


Figure 6-?. Temperature Calibration. Cell 99. 8/26-9/2/90

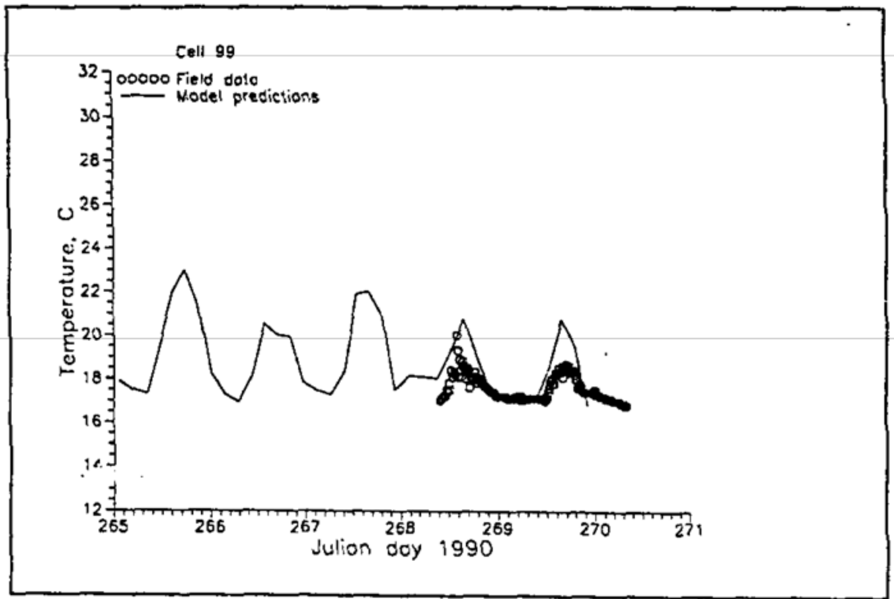


Figure 6-?. Temperature Calibration. Cell 99. 9/22-9/28/90

6.1.2 1990 Dissolved Oxygen Calibration

Figures ? through ? show model predictions of dissolved oxygen at the water surface compared to continuous hydrolab field data at model cell numbers 6 (RM 252.3), 17 (RM 250.1), 22 (RM 249.4), 50 (RM 244.1), 74 (RM 239.3), and 99 (RM 234.2). These figures show that the model predictions often reproduce the field data trends. Again, the vertical placement of the hydrolabs could have dramatically affected the model-data comparisons. Dissolved oxygen modeling is a summation of many factors which are difficult to model, i.e., dissolved oxygen in the system is based on proper modeling of (i) algae growth, (ii) oxygen surface transfer, (iii) sediment oxygen demand, (iv) BOD decay from point sources of BOD, and (v) nitrification kinetics. Further refinements in the model could account for different algal species dominant in different parts of the reservoir. For example, compare Figure ? and Figure ? at Cells 17 and 99 during the same time period (JD 267-270). At cell 17, diurnal dissolved oxygen variation in the model and data was about 8 mg/l, whereas the field data at Cell 99 showed only about 1 mg/l. Assuming nutrients are in excess (as field data suggest), this difference could be explained by (i) vertical placement of the hydrolab was not in the surface layer, or (ii) different algal species (with different growth rates, etc.) are in evidence at different locations in the system. The latter is a reasonable hypothesis since the inflow from Klamath Straits Drain significantly impacts the lower section of the Klamath River. Also, algae growth parameters were selected for blue-greens, which are known to be dominant in the Upper Klamath Lake. Model adjustments in the future could include addition of other algal types to model this progression of algae and better predict dissolved oxygen concentrations.

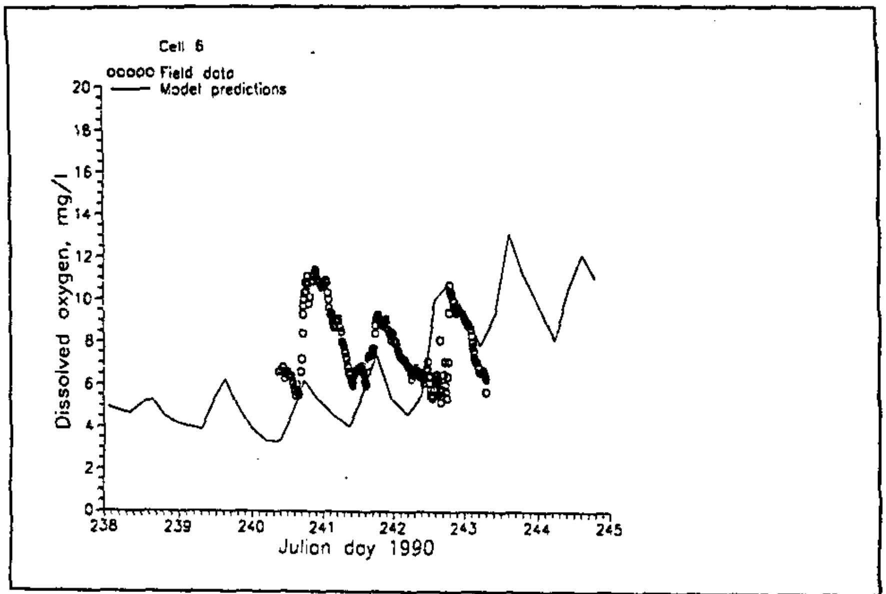


Figure 6-?. Dissolved Oxygen Calibration. Cell 6 238-245

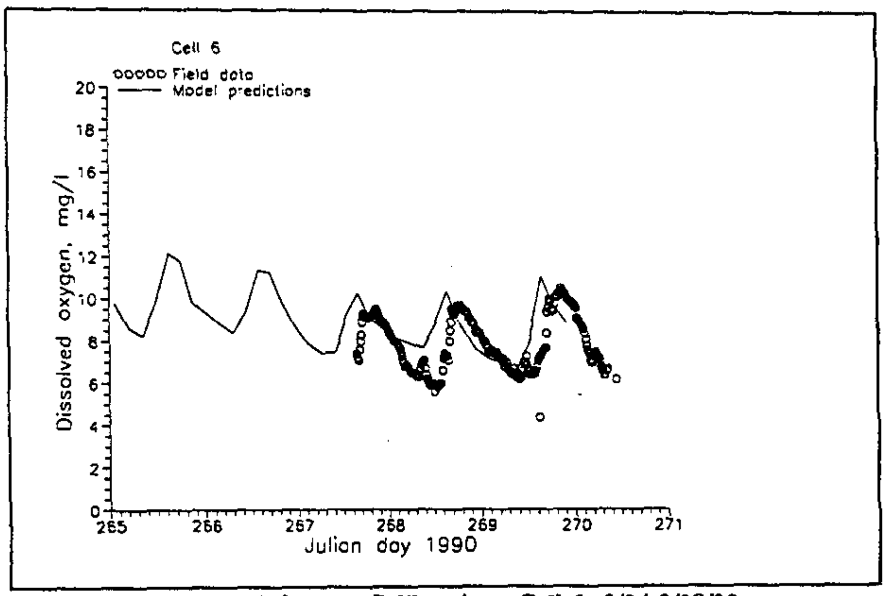


Figure 6-?. Dissolved Oxygen Calibration. Cell 6, 9/24-9/28/90

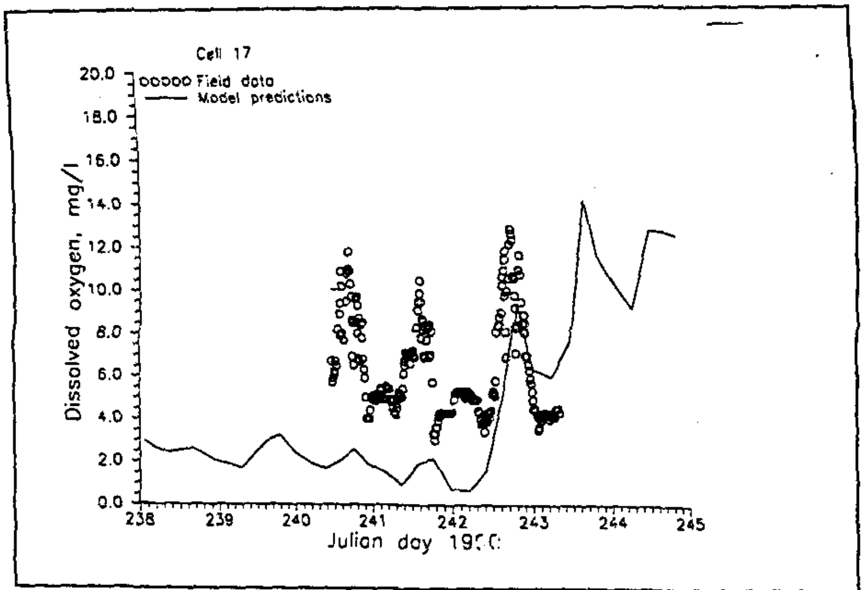


Figure 6-?. Dissolved Oxygen Calibration. Cell 17, 8/28-9/1/90

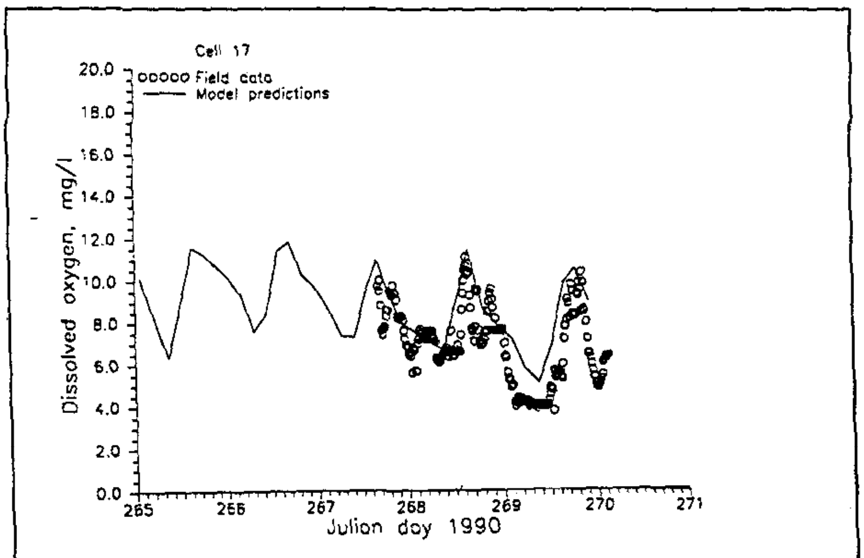


Figure 6-?. Dissolved Oxygen at Cell 17, 9/24-9/27/90

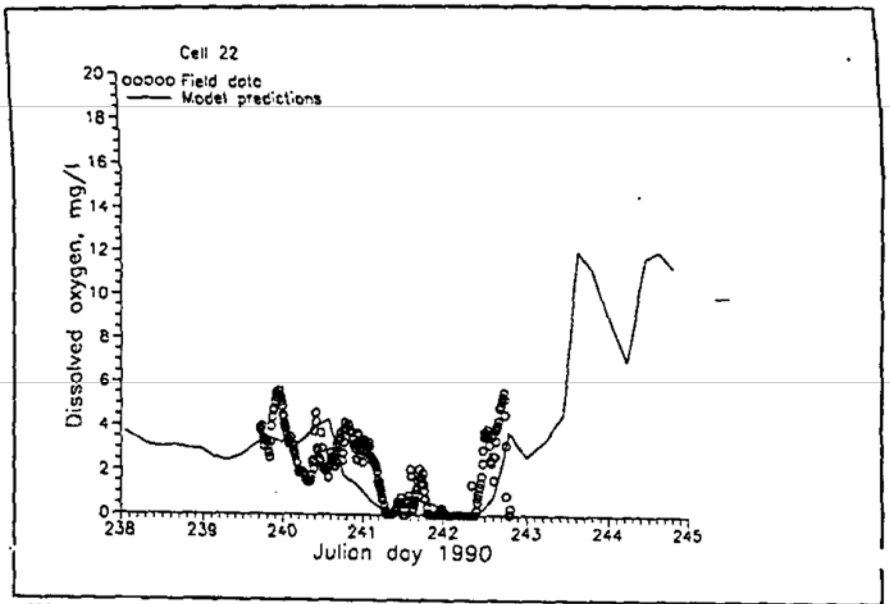


Figure 6-?. Dissolved Oxygen at Cell 22. 8/27-8/31/90 Field Data

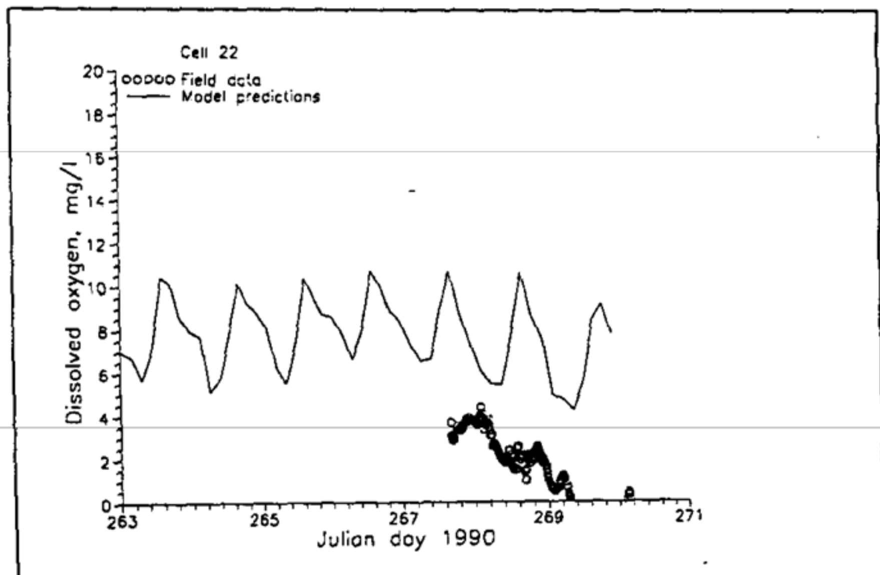


Figure 6-?. Dissolved Oxygen at Cell 22. 9/24-9/27/90 Field Data

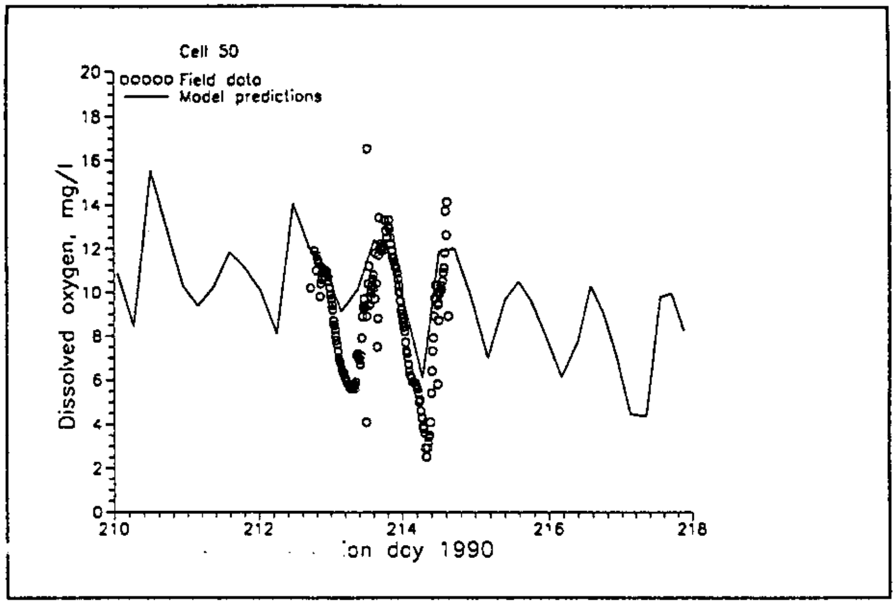


Figure 6-?. Dissolved Oxygen at Cell 50. 8/1-8/3/90 Field Data

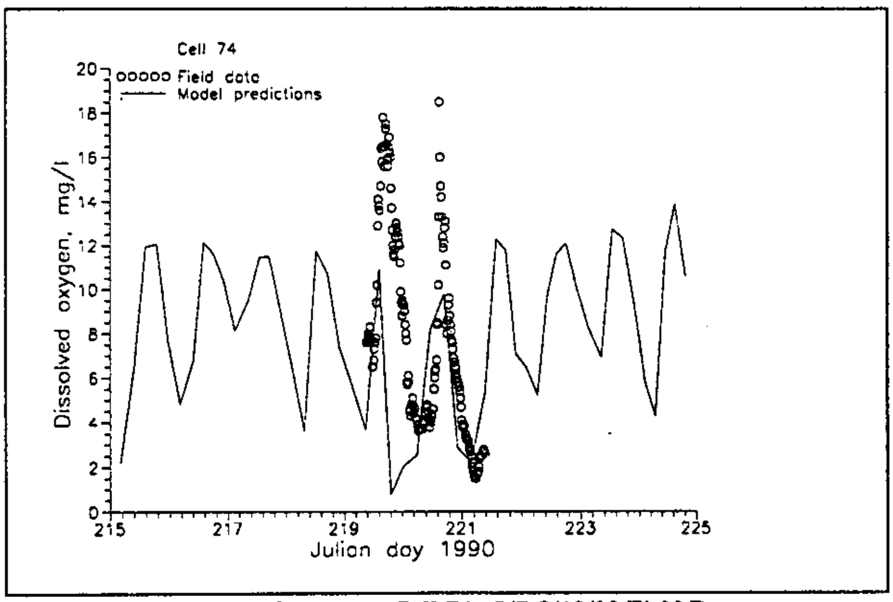


Figure 6-?. Dissolved Oxygen at Cell 74. 8/7-8/10/90 Field Data

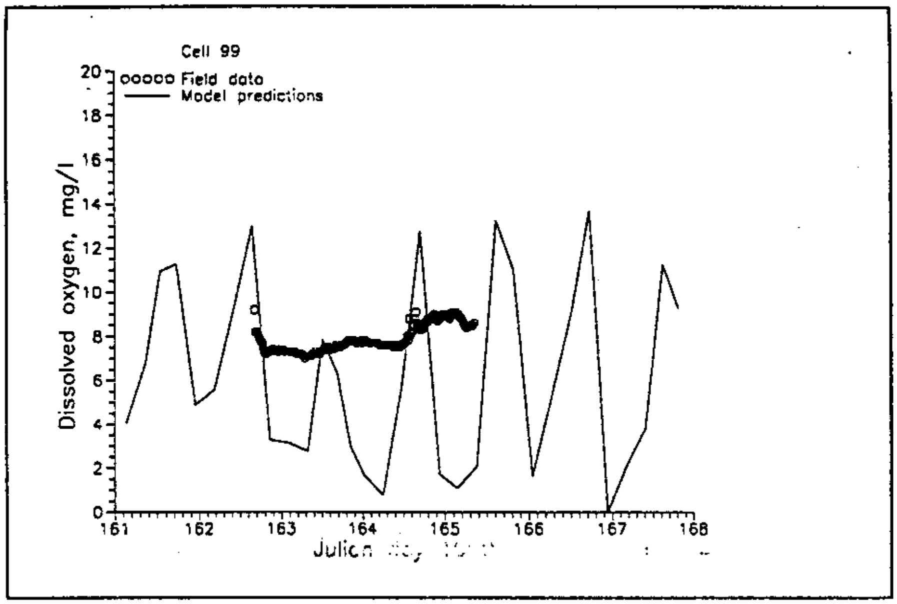


Figure 6-?. Dissolved Oxygen at Cell 99. 6/11-6/15/90 Field Data

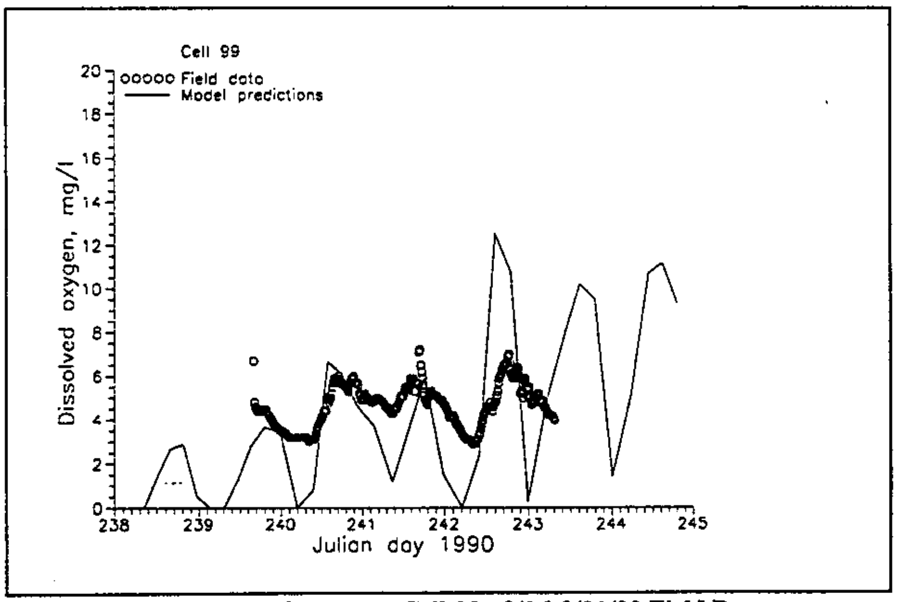


Figure 6-?. Dissolved Oxygen at Cell 99. 8/26-8/31/90 Field Data

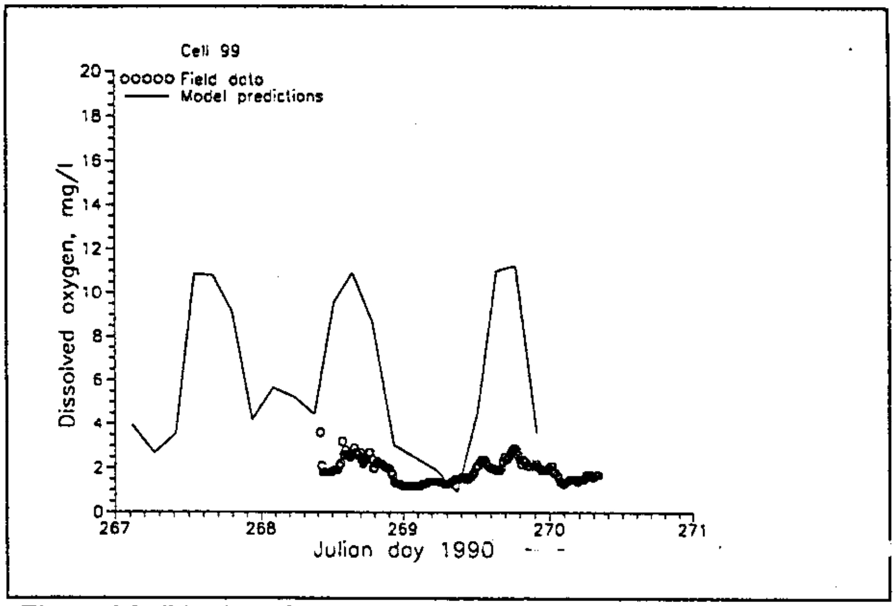


Figure 6-?. Dissolved Oxygen at Cell 99. 9/25-9/27/90 Field Data

6.1.3 1990 pH Calibration

Figures ? through ? show time series of model predictions of pH to field data taken at many different stations in the system. These comparisons are based on measurements and model predictions of the surface layer. As shown in Table ?, the mean errors for model predictions of pH are both positive and negative at different model stations, and typical RMS errors range from about 0.4 to 1. Again the vertical placement of the hydrolab probe and any accumulation of biofouling on the probes would affect the pH results dramatically.

pH Plots to be added

6.2 1992 CALIBRATION YEAR

Field data for the 1992 year were taken primarily as continuous point hydrolab measurements and synoptic hydrolab profiles. Very few nutrient and algae field data were taken. In contrast to the 1990 calibration year where only surface data available to be compared to model predictions, during 1992 vertical profiles of pH, temperature, and dissolved oxygen were available to compare with model predictions. Unfortunately, limited input field data were available for boundary conditions.

Table 6-2 shows model-data-errors during the 1992 period for near-surface comparisons.

Table 6-2. Mean and RMS errors for model predictions and field data for 1992.

Cell #	Statistic	Temp (degrees C)	chlorophyll-a (ug/l)	dissolved oxygen (mg/l)	pH	PO_4 (mg/l N)	NO_3 (mg/l N)	NH_4 (mg/l N)	coliform (col/100ml)
9	mean error	-1.021	0	-2.96	-0.968	0	0	0	0
9	rms error	1.303	0	3.572	1.066	0	0	0	0
9	N	4	0	4	4	0	0	0	0
14	mean error	-1.061	0	-3.772	-1.063	0	0	0	0
14	rms error	1.242	0	4.995	1.277	0	0	0	0
14	N	4	0	4	4	0	0	0	0
22	mean error	-0.7635	0	0.606	-0.4432	0	0	0	0
22	rms error	1.051	0	3.508	0.8087	0	0	0	0
22	N	4	0	4	4	0	0	0	0
29	mean error	4.91E-03	0	6.21E-02	-0.7367	0	0	0	0
29	rms error	0.5309	0	1.59	0.9442	0	0	0	0
29	N	4	0	4	4	0	0	0	0
36	mean error	-0.3867	0	-1.844	-0.865	0	0	0	0
36	rms error	0.7118	0	2.752	1.031	0	0	0	0
36	N	4	0	4	4	0	0	0	0
45	mean error	-0.3533	0	0.2084	-0.8187	0	0	0	0
45	rms error	0.7149	0	1.724	0.8732	0	0	0	0
45	N	4	0	4	4	0	0	0	0
52	mean error	-1.125	0	-2.498	-1.307	0	0	0	0
52	rms error	1.19	0	2.968	1.323	0	0	0	0
52	N	4	0	4	4	0	0	0	0
64	mean error	-1.296	0	-1.144	-1.428	0	0	0	0
64	rms error	1.31	0	2.375	1.429	0	0	0	0
64	N	3	0	3	3	0	0	0	0
72	mean error	-3.262	0	-7.664	-2.075	0	0	0	0
72	rms error	3.302	0	7.669	2.078	0	0	0	0
72	N	2	0	2	2	0	0	0	0
89	mean error	-0.5685	0	-1.205	-0.8083	0	0	0	0
89	rms error	1.385	0	3.98	1.055	0	0	0	0
89	N	4	0	4	4	0	0	0	0
99	mean error	-8.75E-02	-30.36	1.48	-0.432	-2.59E-02	-7.50E-03	-5.90E-02	-48
99	rms error	1.246	30.36	4.1	0.9664	2.59E-02	7.50E-03	5.90E-02	48
99	N	949	1	949	679	1	1	1	1

NOTE: I need to get the figures referred to below in a format that I can read into word. -- Dave Collins

6.2.1 Temperature

Comparison of point measurements of temperature at the near-surface as a function of model cell number is shown in Figures ? and ?. In general, model predictions follow field data very well. This is evident also with the continuous data at Cell 99 near Keno in Figure ?.

6.2.2 Dissolved Oxygen

Figures ? and ? show a comparison of model predictions of surface layer dissolved oxygen concentrations and field data. The only continuous data were recorded at Cell 99 at Keno shown in Figure ?.

6.2.3 pH

Figures ? and ? show a comparison of model predictions of surface layer pH and field data. The only continuous data were recorded at Cell 99 at Keno shown in Figure ?.

6.2.4 Ammonia

Figures ? through ? show time series of model predictions of total ammonia to field data taken at many different stations in the system. These comparisons are based on measurements and model predictions of the surface layer. As shown in Table ?, the mean errors for model predictions of ammonia are usually negative, implying that the model under predicts the value of ammonia. This could be easily changed by adjusting the release rate of ammonia under anoxic conditions upward. But because all the nutrient concentrations are also dependent on algae dynamics, it was thought best to adjust this after adding another algal system to the model.

The model predictions and field data show that the ammonia concentrations tend to increase as one moves down from Lake Ewauna to Keno Dam. This may indicate accumulation from sediment nutrient release, or it may be a result of high ammonia in return waters from irrigators and Klamath Straits Drain.

6.2.5 Nitrate

Figures ? through ? show time series of model predictions of nitrate and nitrite to field data taken at many different sampling stations in the system. Measurements and model predictions are surface layer comparisons. In general model predictions track field measurements very well.

7. Model Alternatives Analysis

This section describes the alternative loading scenarios modeled. Model simu...ns were performed evaluating the impact of the point sources, the Klamath Straits Drain, and the Upper Klamath Lake inflow on in-stream water quality. Table summarizes the model simulations made evaluating model alternatives. These alternatives are changes from the base case 1990 and 1992 simulations presented in Section 6. Environmental performance criteria described in section 3 are used as a basis for determining the effects of different management strategies.

7.1 LOADING SCENARIOS

7.1.1 Point Source Removal - ALT#1

This purpose of this alternative was to investigate the maximum benefit that could be achieved by improving the water quality of the waste stream from the four major dischargers to the study reach. These dischargers are Klamath Falls Sewage Treatment Plant, South Suburban Treatment Facilities, Columbia Plywood, and Weyerhauser.

All point sources were set equal to zero flow in the model simulatation. The simulation was run for both years.

7.1.2 Improve Klamath Straits Drain Water Quality - ALT#2

The Klamath Straits Drain has a higher loading that most if not all the point sources. This simulation investigated the potential benifits of improving Klamath Straits Drain water quatlity.

This alternative assumed a 90 % reduction of BOD and nutrients (PO_4-P, NH_4-N, and NO_3-N) nd no dissolved oxygen concentration below 8 mg/l for the Klamath Straits Drain.

7.1.3 Improve Upper Klamath Lake Water Quality - ALT#3

The majority of inflow to the study reach is from Upper Klamath Lake via the Link River.

This alternative assumed an optimistic 50 % reduction of BOD and nutrients (PO_4-P, NH_4-N, and NO_3-N) and no dissolved oxygen concentration below 8 mg/l for the Upper Klamath Lake inflow.

7.2 MASS LOADING AND MODEL RESULTS

Appendix A shows mass loading for each source.
Appendix B shows selected environmental performance criteria.

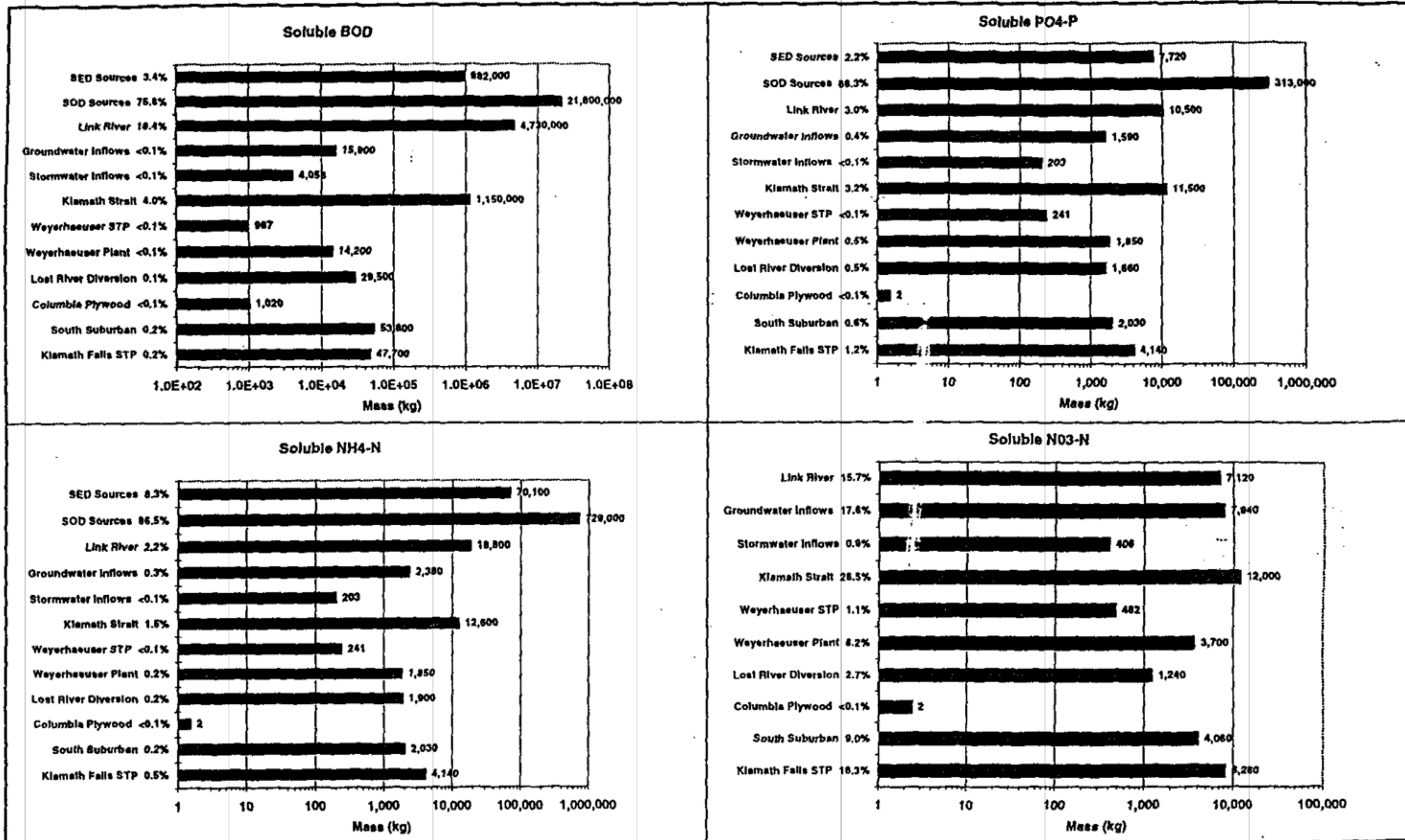


Figure ??. Mass Loading. 1990 Base Case.

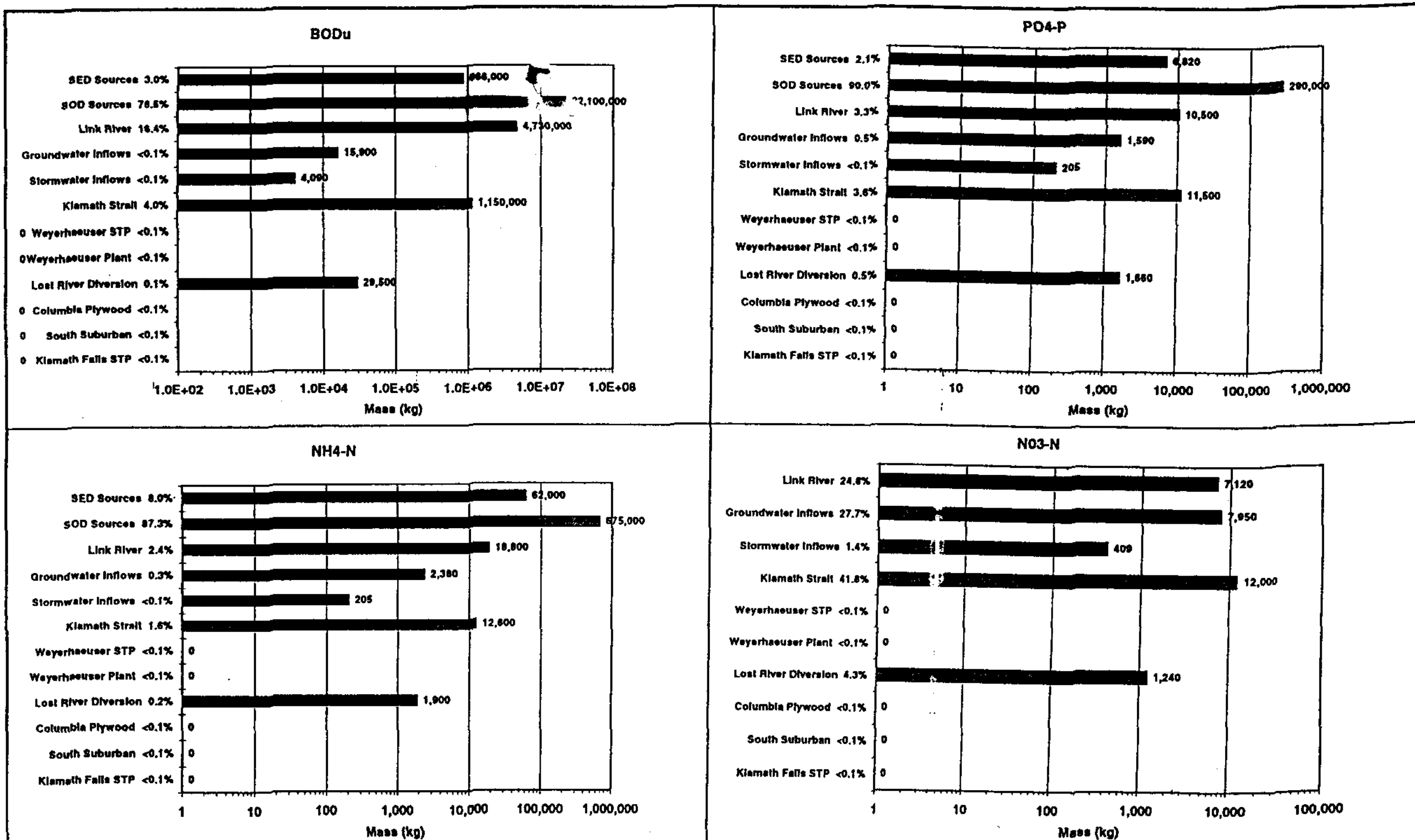


Figure ??. Mass Loading. 1990 Alternative 1.

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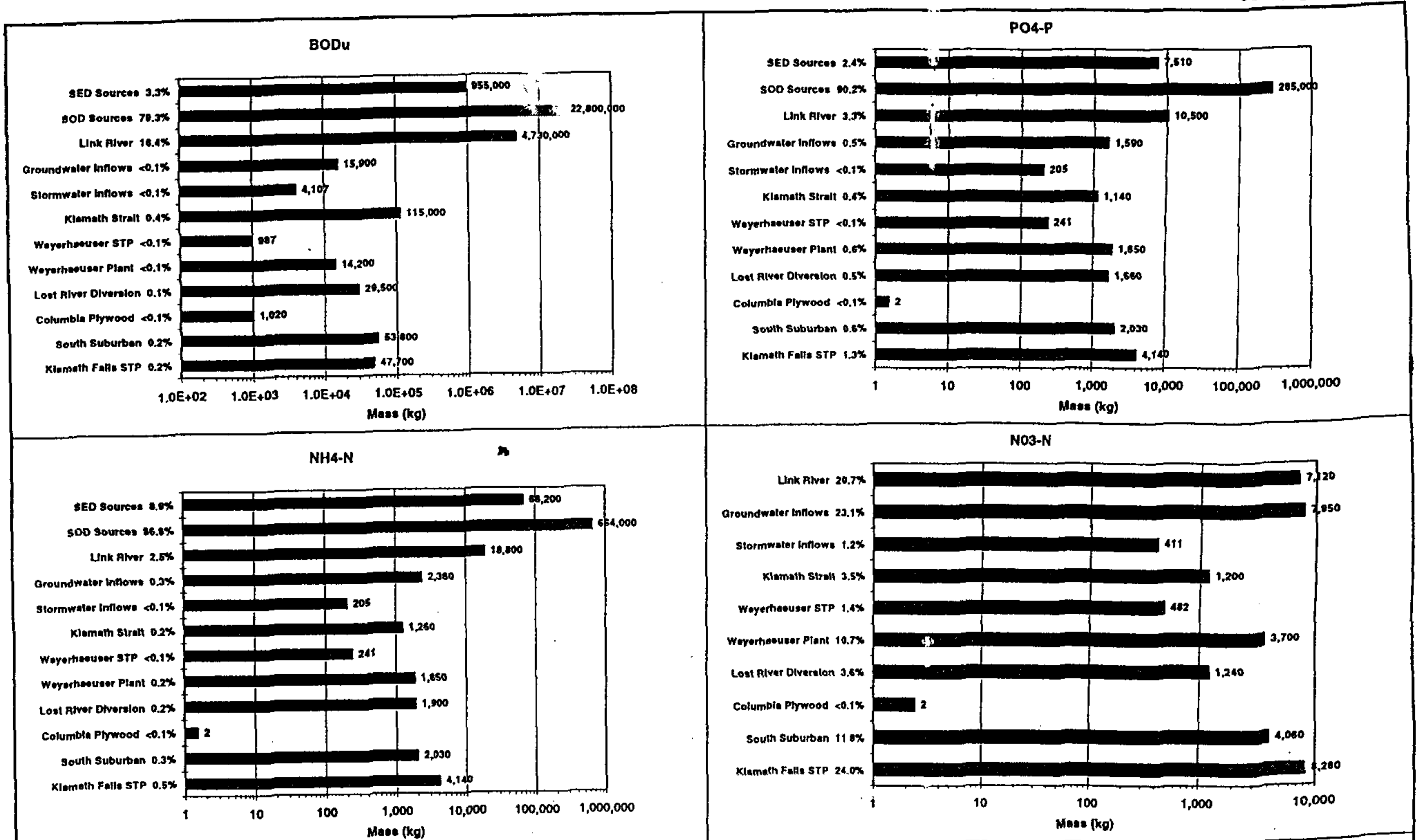

Figure ??. Mass Loading. 1990 Alternative 2.

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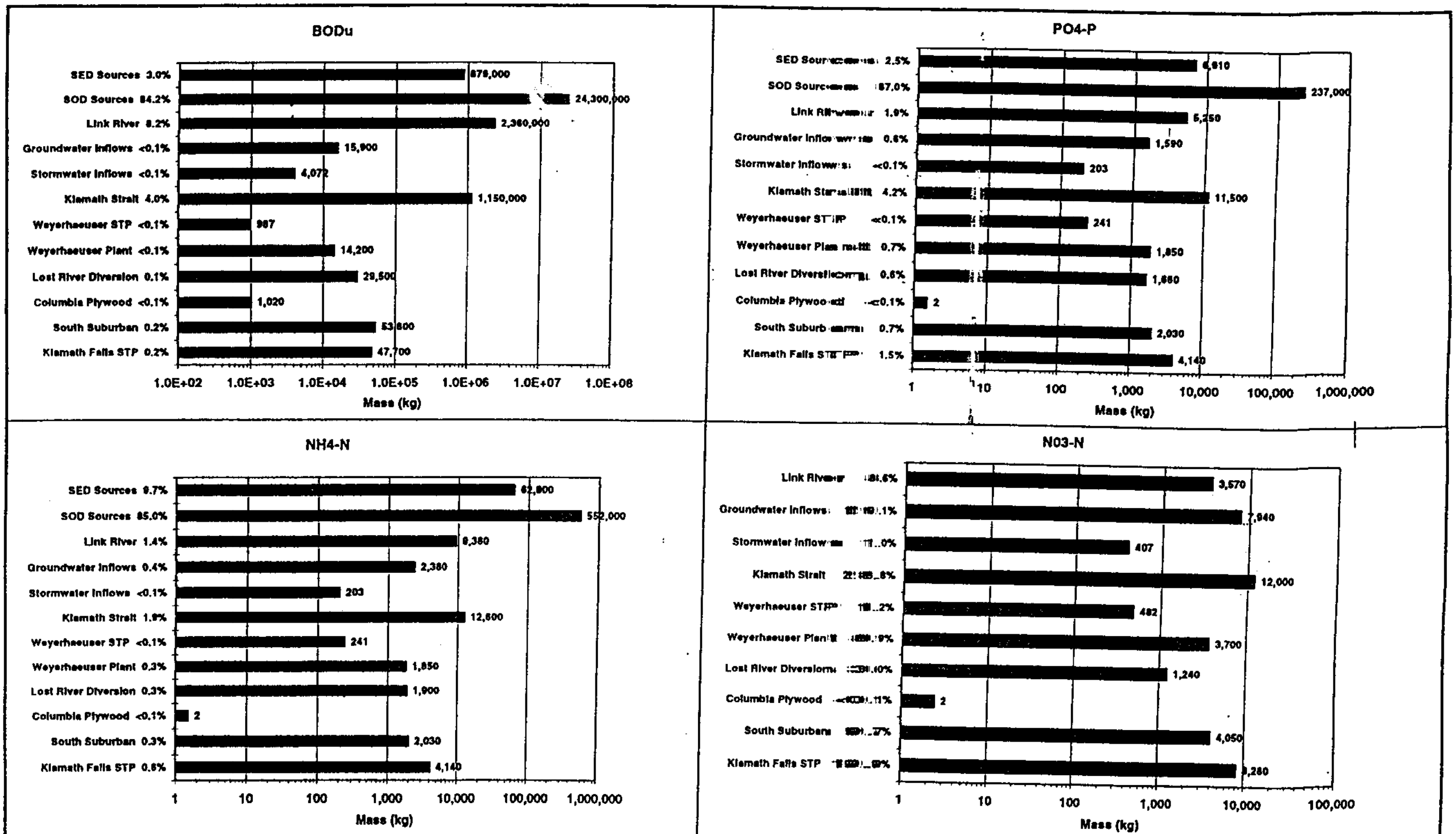

Figure ??. Mass Loading. 1990 Alternative 3.

DRAFT

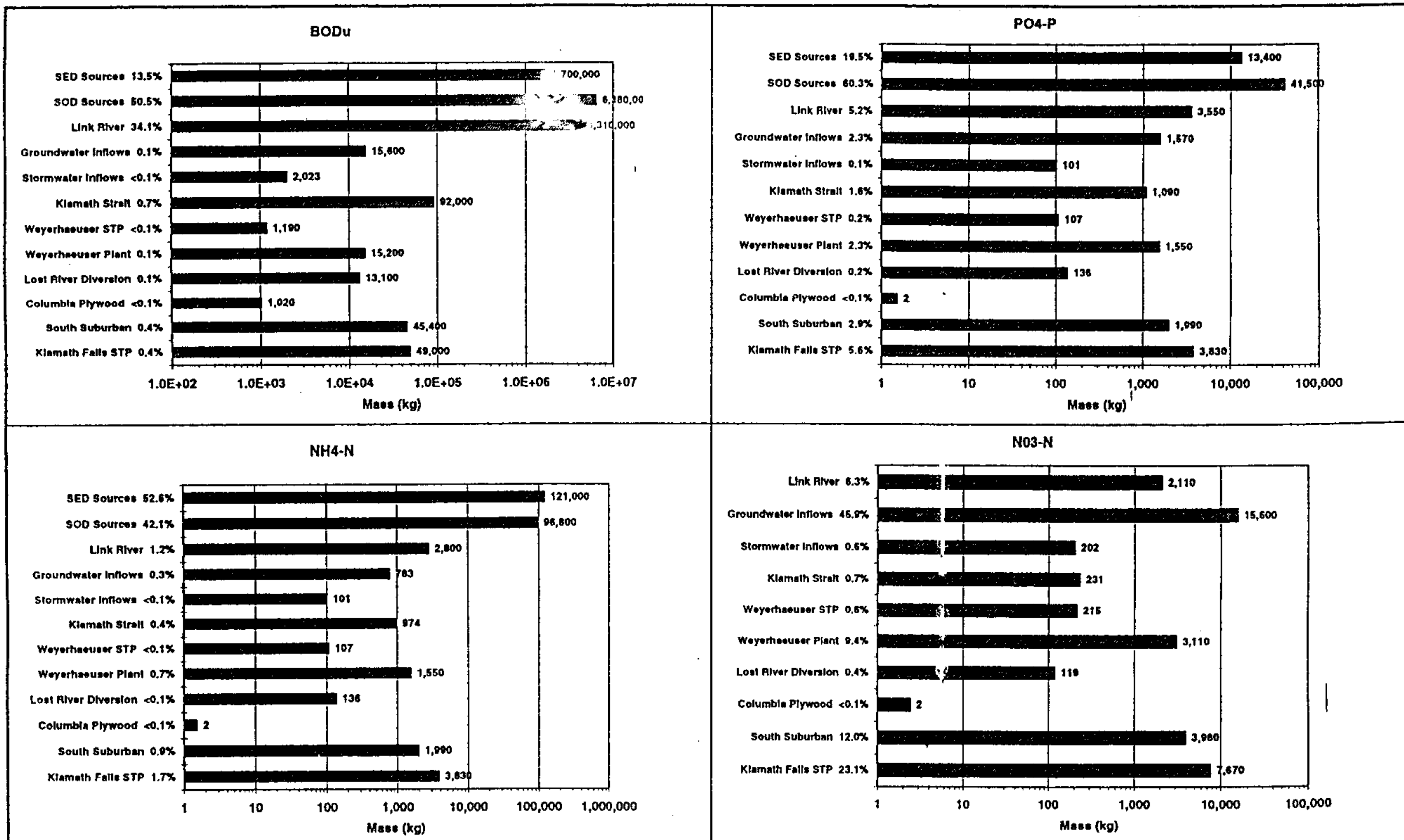

Figure ??. Mass Loading. 1992 Base Case.

DRAFT

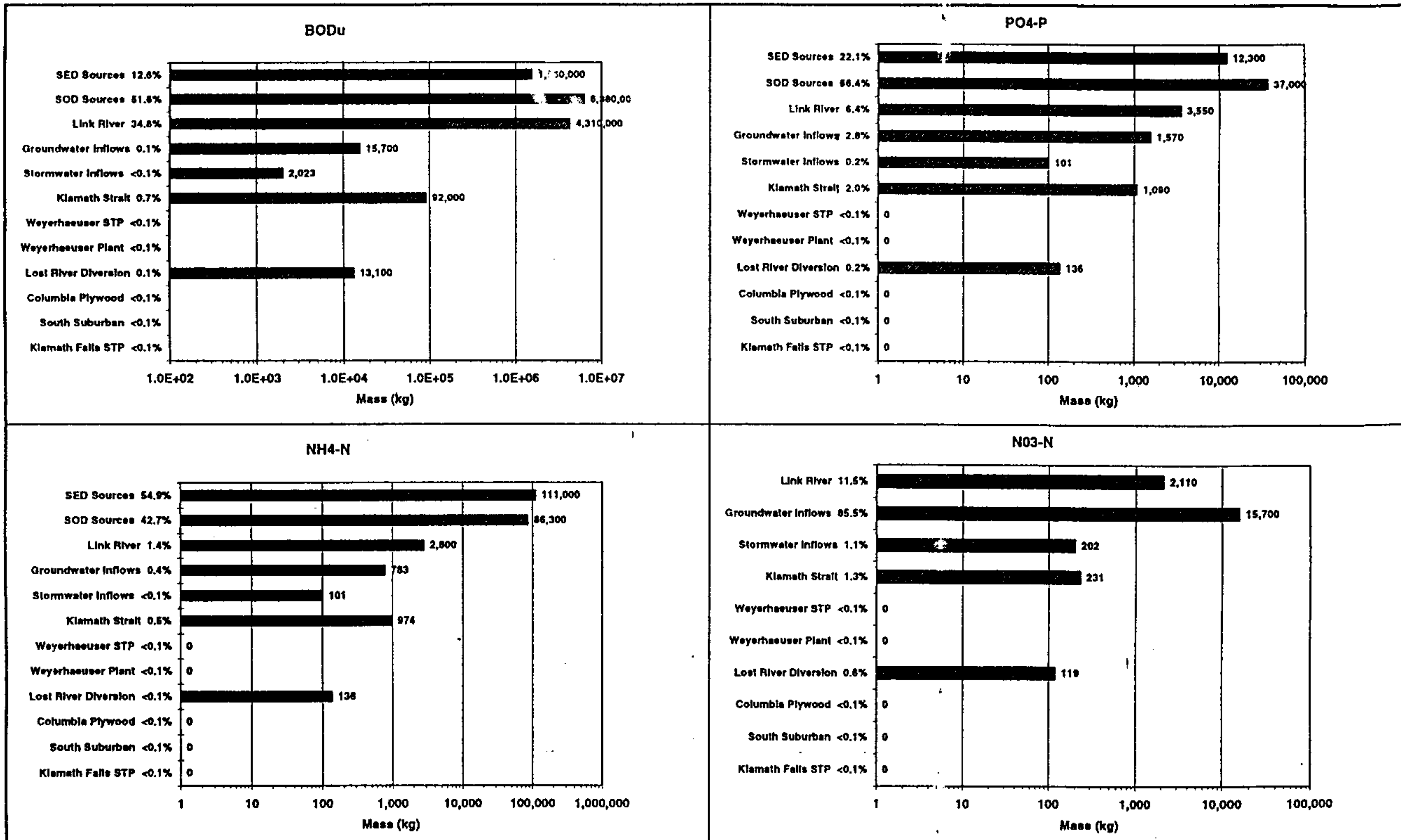

Figure ??. Mass Loading. 1992 Alternative 1.

DRAFT

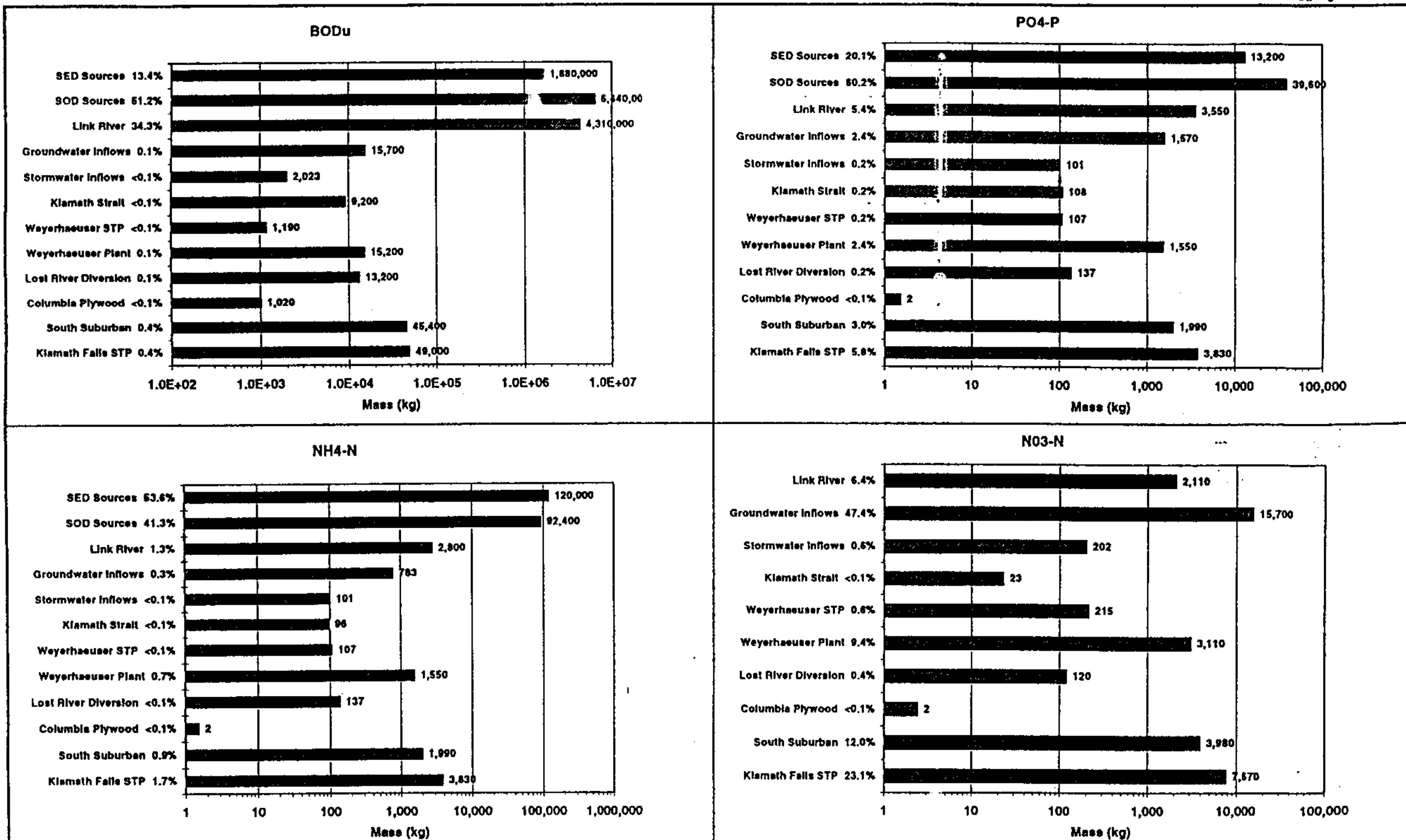

Figure ??. Mass Loading. 1992 Alternative 2.

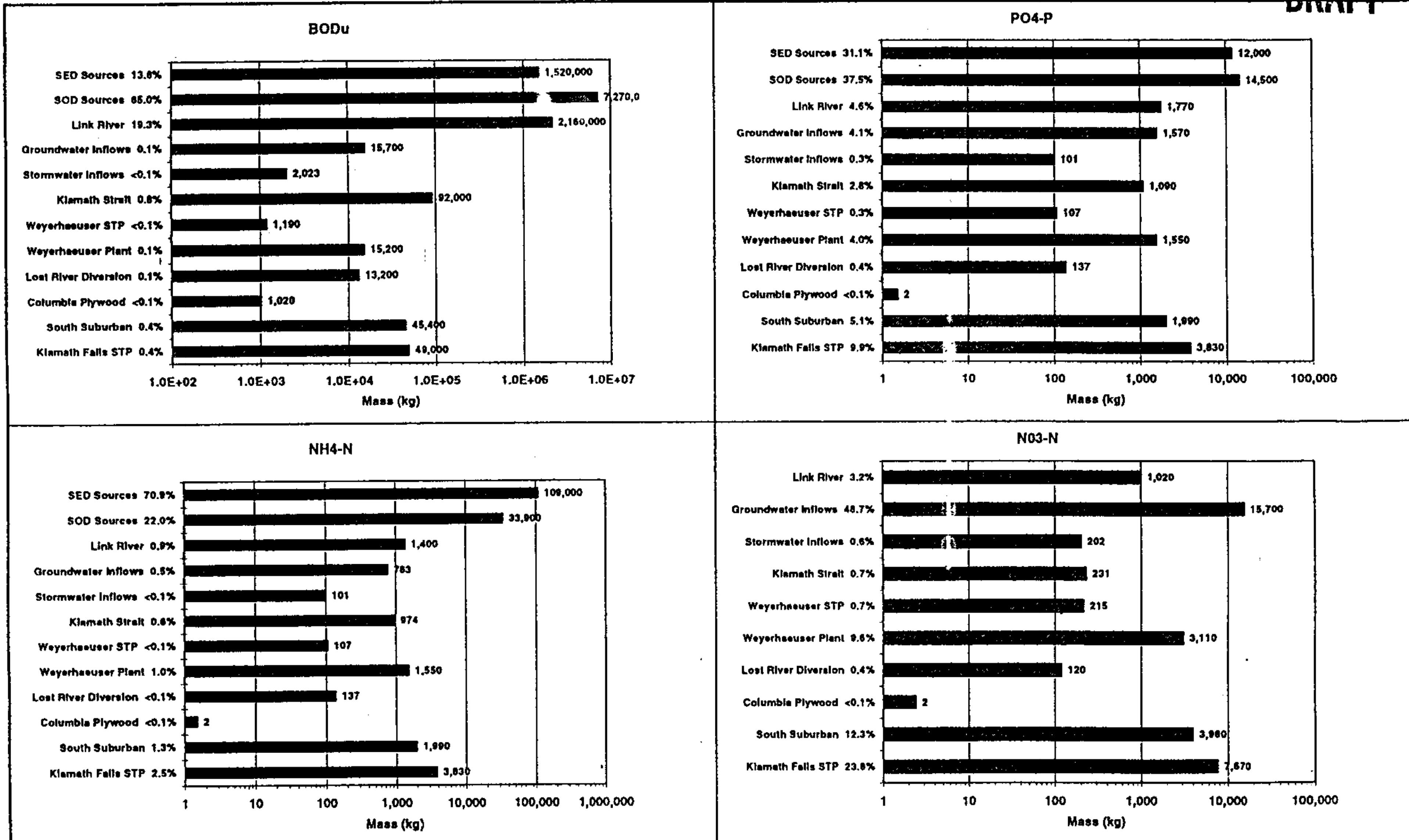

Figure ??. Mass Loading. 1992 Alternative 3.

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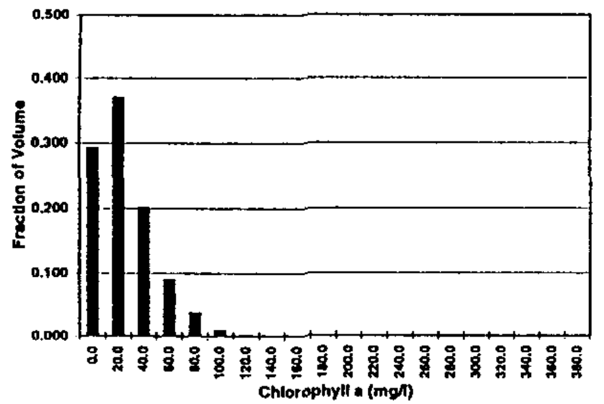
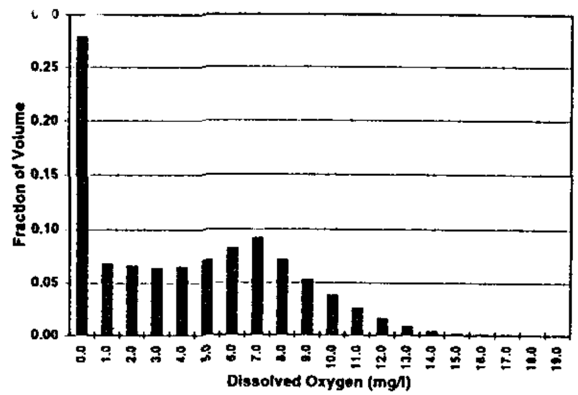
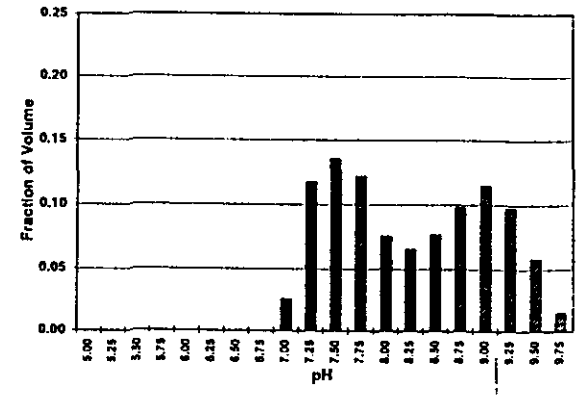
Chlorophyll a: Goal < 15 ug/l chlorophyll a
Total fraction in violation: 0.810
Weighted mean: 34.3 ug/l



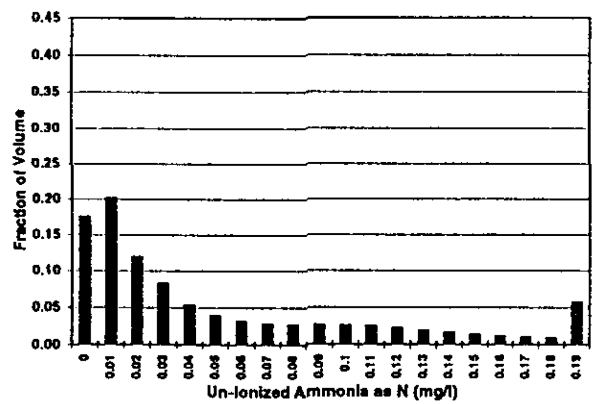
Dissolved Oxygen: Goal > 6 mg/l
Total fraction in violation: 0.476
Weighted mean: 4.60 mg/l



pH: 6.5 < Goal < 9.0
Total fraction in violation: 0.285
Weighted mean: 8.39



Un-ionized Ammonia: Goal varies w/ pH, temp
Total fraction in violation: 0.488
Weighted mean: 0.059 mg/l



Ammonia:

Weighted mean: 0.512 mg/l

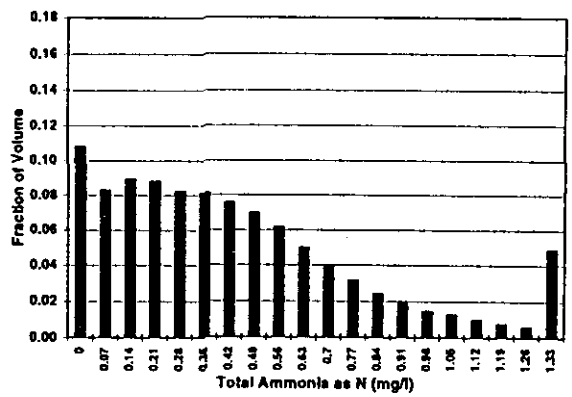


Figure ??: Environmental performance histogram of predictions of violations of water quality guidelines. 1990 model base case.

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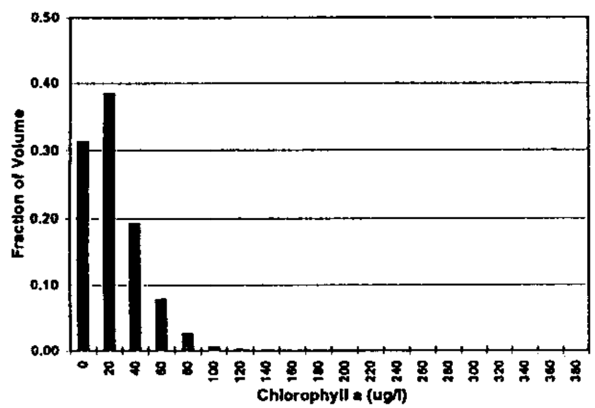
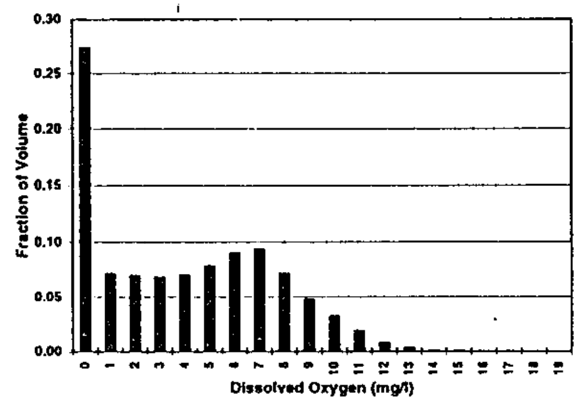
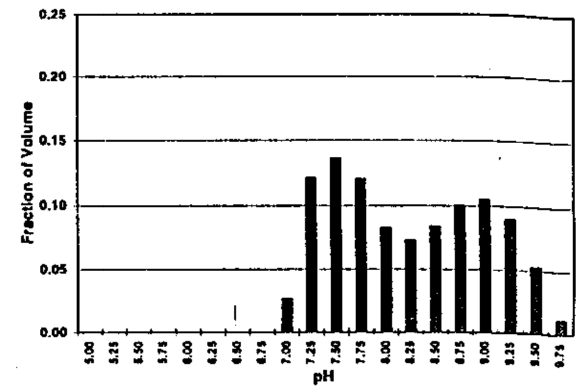
Chlorophyll a: Goal < 15 ug/l chlorophyll a
Total fraction in violation: 0.797
Weighted mean: 32.3 ug/l



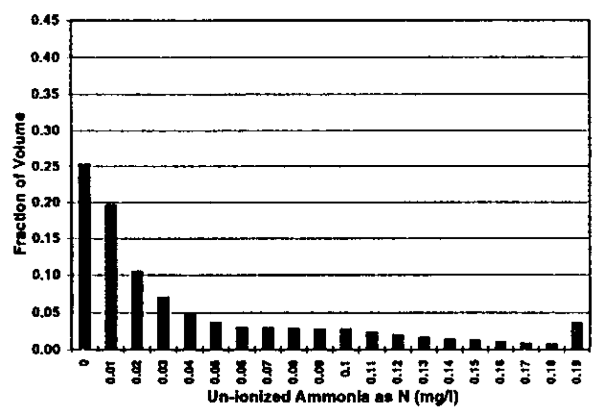
Dissolved Oxygen: Goal > 6 mg/l
Total fraction in violation: 0.482
Weighted mean: 4.41 mg/l



pH: 6.5 < Goal < 9.0
Total fraction in violation: 0.258
Weighted mean: 8.36



Un-ionized Ammonia: Goal varies w/ pH, temp
Total fraction in violation: 0.427
Weighted mean: 0.051 mg/l



Ammonia:

Weighted mean: 0.455 mg/l

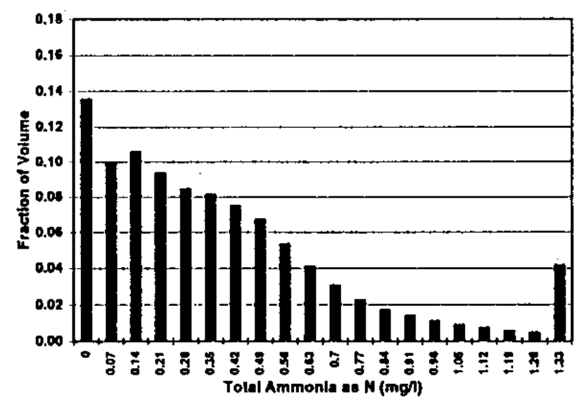
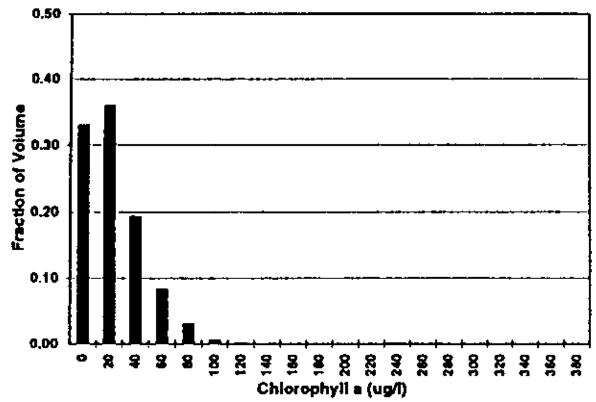


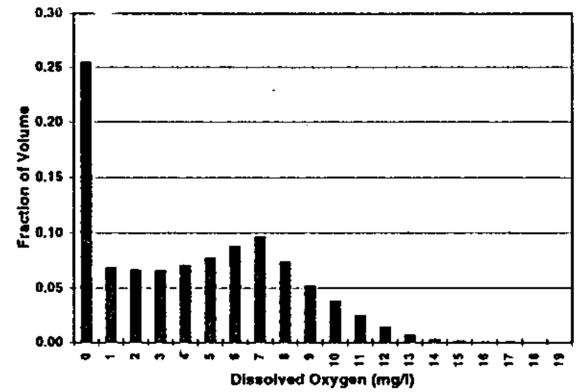
Figure ??: Environmental performance histogram of predictions of violations of water quality gu delines. 1990 Alternative 1.

DRAFT

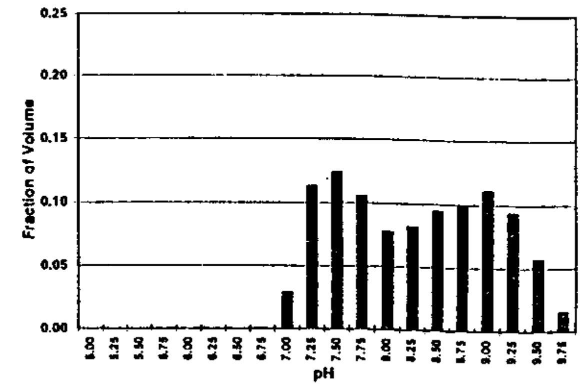
Chlorophyll a: Goal < 15 ug/l chlorophyll a
Total fraction in violation: 0.783
Weighted mean: 32.4 ug/l



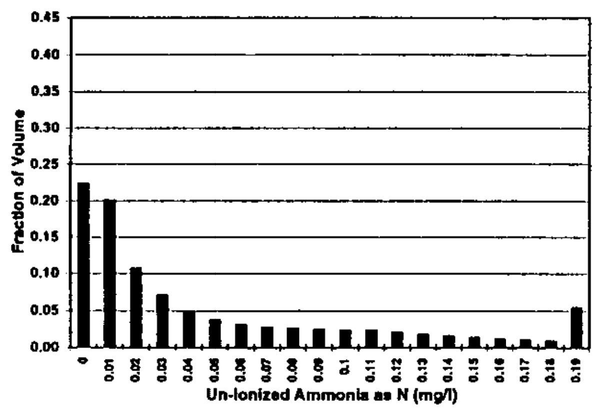
Dissolved Oxygen: Goal > 6 mg/l
Total fraction in violation: 0.455
Weighted mean: 4.71 mg/l



pH: 6.5 < Goal < 9.0
Total fraction in violation: 0.276
Weighted mean: 8.4



Un-ionized Ammonia: Goal varies w/ pH, temp
Total fraction in violation: 0.450
Weighted mean: 0.057 mg/l



Ammonia:

Weighted mean: 0.469 mg/l

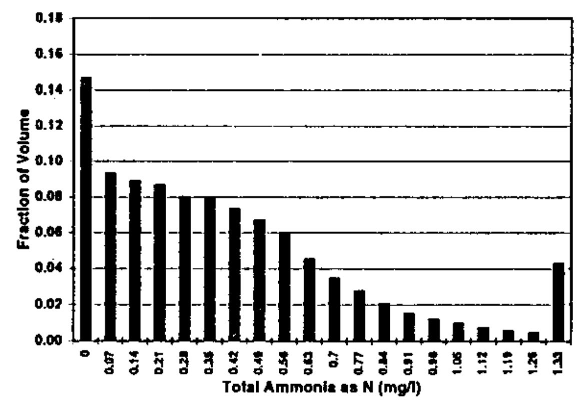
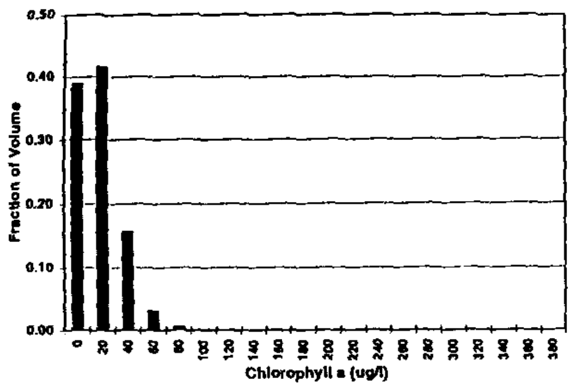


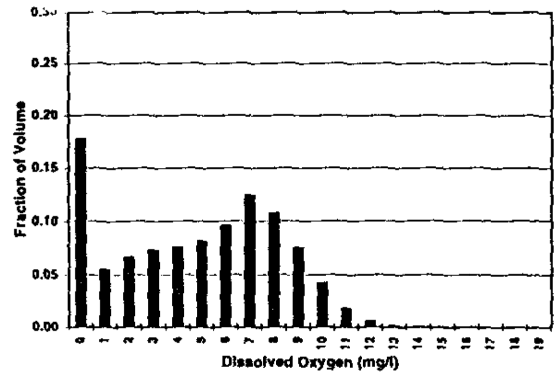
Figure ??: Environmental performance histogram of predictions of violations of water quality guidelines. 1990 Alternative 2.

DRAFT

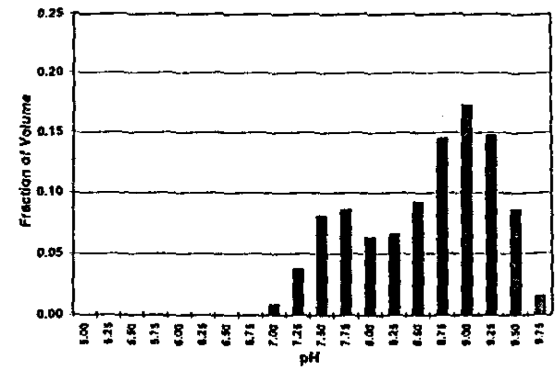
Chlorophyll a: Goal < 15 ug/l chlorophyll a
Total fraction in violation: 0.752
Weighted mean: 26.6 ug/l



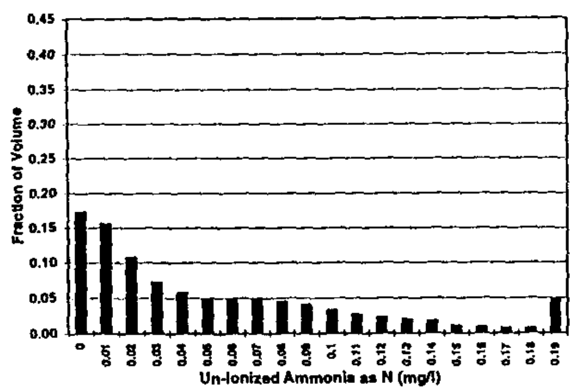
Dissolved Oxygen: Goal > 6 mg/l
Total fraction in violation: 0.372
Weighted mean: 5.26 mg/l



pH: 6.5 < Goal < 9.0
Total fraction in violation: 0.422
Weighted mean: 8.71



Un-ionized Ammonia: Goal varies w/ pH, temp
Total fraction in violation: 0.521
Weighted mean: 0.063 mg/l



Ammonia:

Weighted mean: 0.345 mg/l

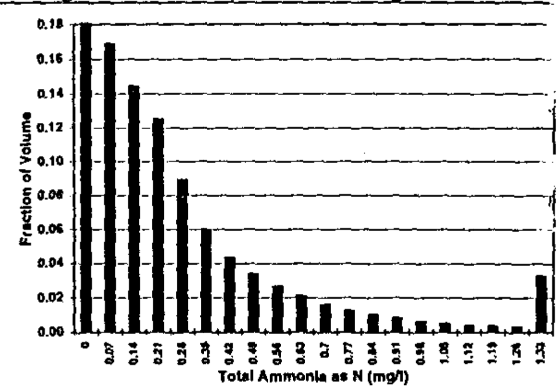
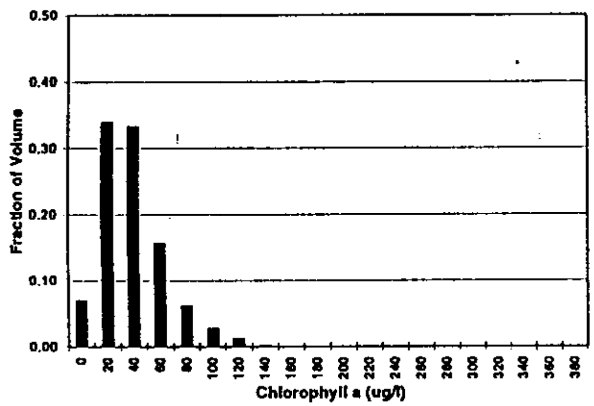


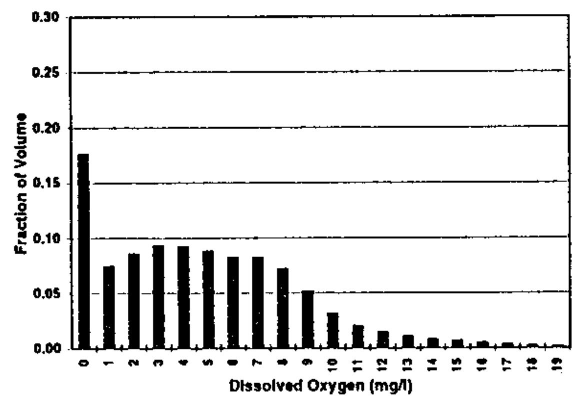
Figure ??: Environmental performance histogram of predictions of violations of water quality guidelines. 1990 Alternative 3.

DRAFT

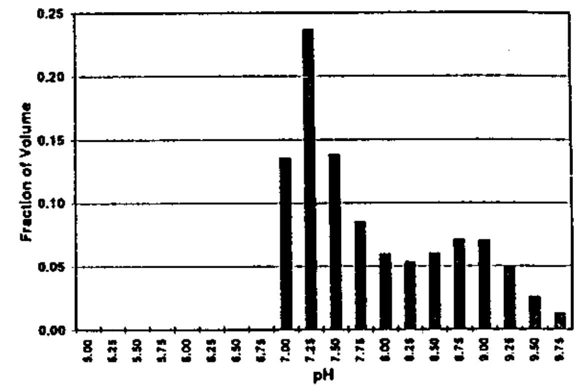
Chlorophyll a: Goal < 15 ug/l chlorophyll a
Total fraction in violation: 0.972
Weighted mean: 48.9 ug/l



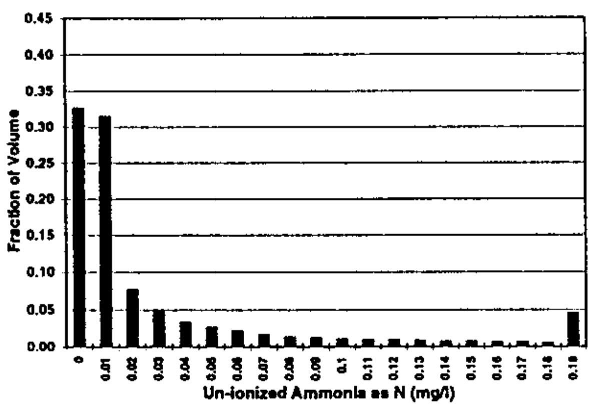
Dissolved Oxygen: Goal > 6 mg/l
Total fraction in violation: 0.429
Weighted mean: 5.13 mg/l



pH: 6.5 < Goal < 9.0
Total fraction in violation: 0.163
Weighted mean: 8.00



Un-ionized Ammonia: Goal varies w/ pH, temp
Total fraction in violation: 0.313
Weighted mean: 0.040 mg/l



Ammonia:

Weighted mean: 0.538 mg/l

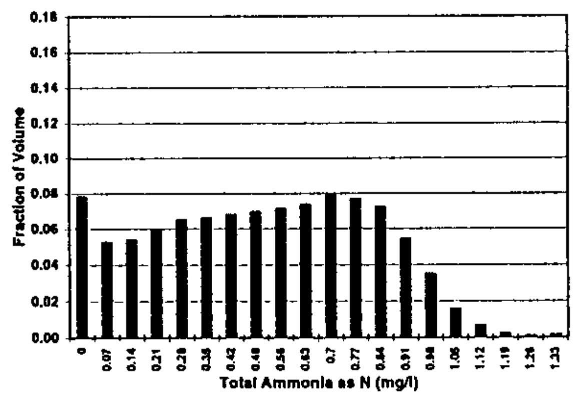
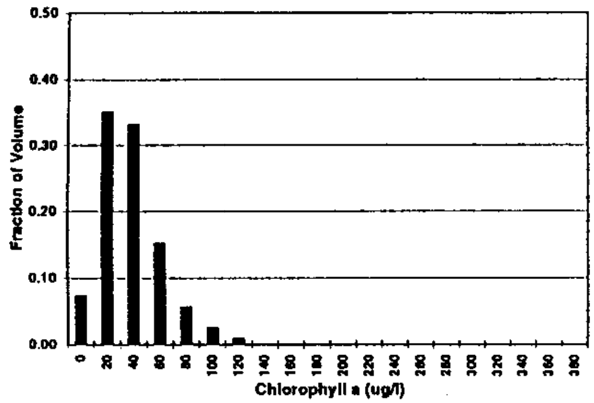


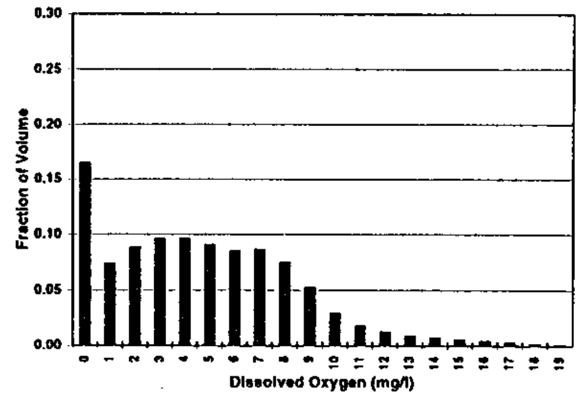
Figure ??: Environmental performance histogram of predictions of violations of water quality guidelines. 1992 Base Case.

DRAFT

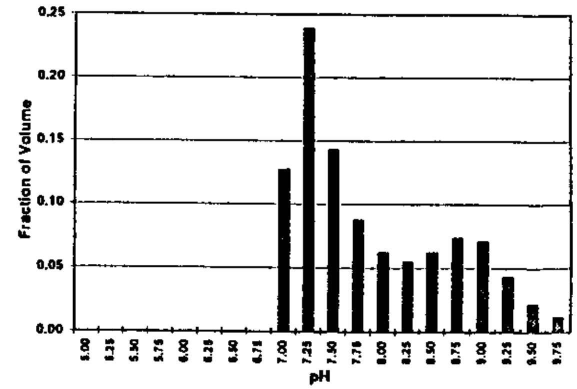
Chlorophyll a: Goal < 15 ug/l chlorophyll a
Total fraction in violation: 0.970
Weighted mean: 47.9 ug/l



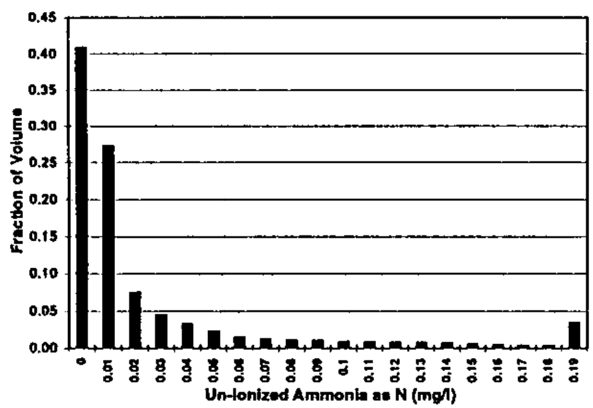
Dissolved Oxygen: Goal > 6 mg/l
Total fraction in violation: 0.423
Weighted mean: 5.12 mg/l



pH: 6.5 < Goal < 9.0
Total fraction in violation: 0.154
Weighted mean: 8.00



Un-ionized Ammonia: Goal varies w/ pH, temp
Total fraction in violation: 0.244
Weighted mean: 0.035 mg/l



Ammonia:

Weighted mean: 0.478 mg/l

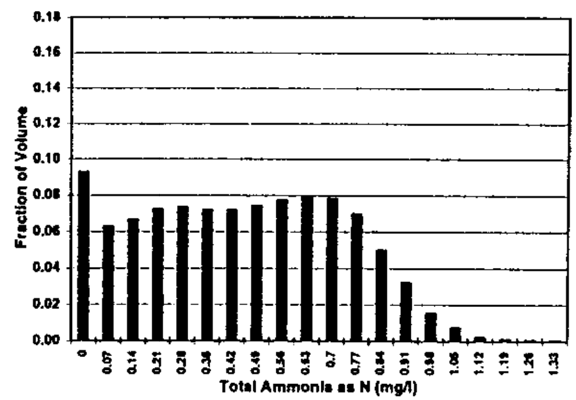
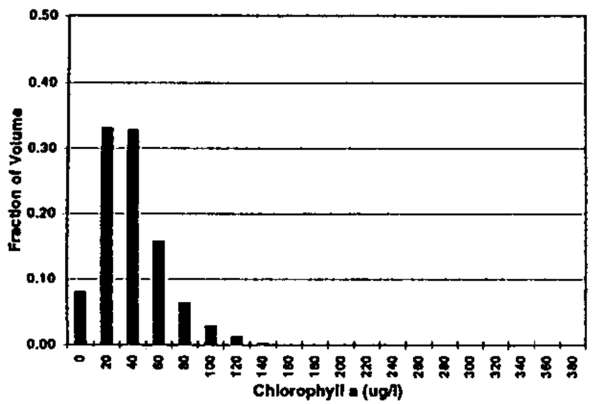


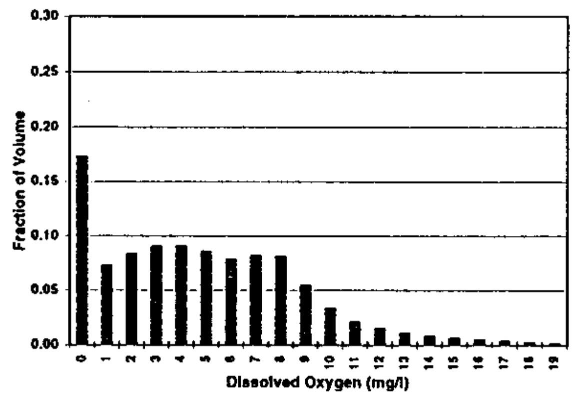
Figure ??: Environmental performance histogram of predictions of violations of water quality guidelines. 1992 Alternative 1.

DRAFT

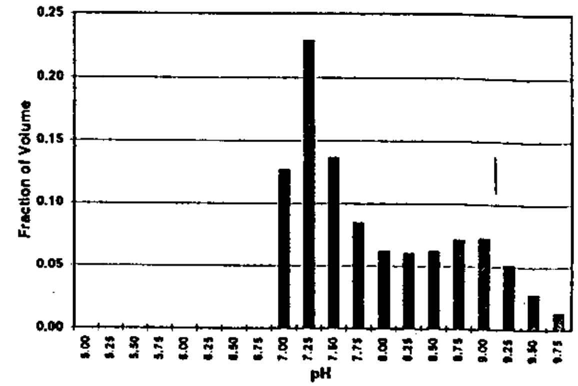
Chlorophyll a: Goal < 15 ug/l chlorophyll a
Total fraction in violation: 0.969
Weighted mean: 48.9 ug/l



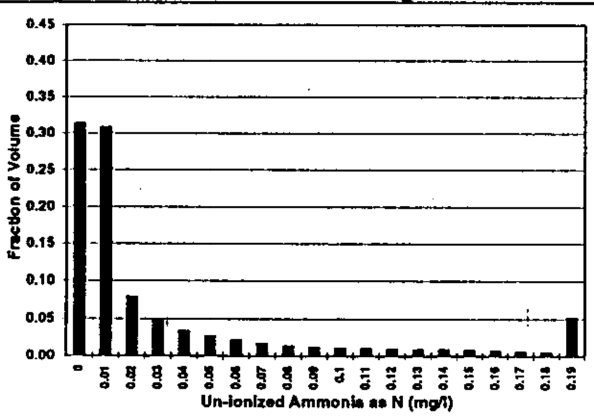
Dissolved Oxygen: Goal > 6 mg/l
Total fraction in violation: 0.420
Weighted mean: 5.24 mg/l



pH: 6.5 < Goal < 9.0
Total fraction in violation: 0.170
Weighted mean: 8.03



Un-ionized Ammonia: Goal varies w/ pH, temp
Total fraction in violation: 0.337
Weighted mean: 0.043 mg/l



Ammonia:

Weighted mean: 0.54 mg/l

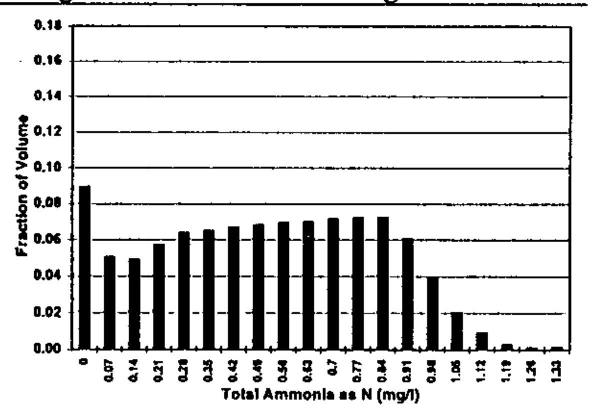
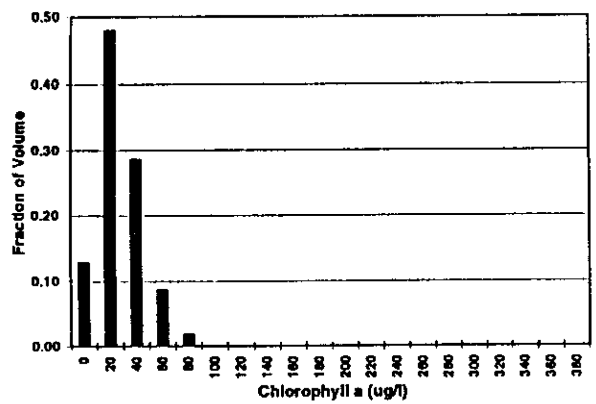


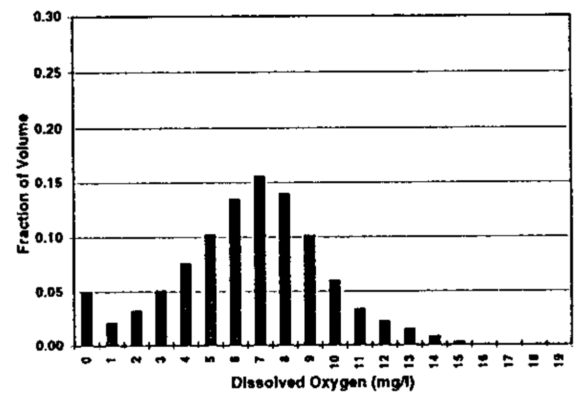
Figure ??: Environmental performance histogram of predictions of violations of water quality guidelines. 1992 Alternative 2.

DRAFT

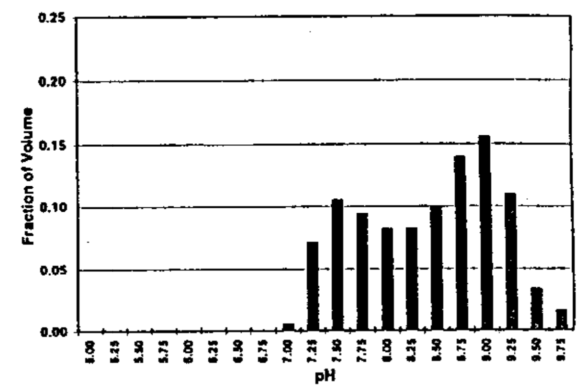
Chlorophyll a: Goal < 15 ug/l chlorophyll a
Total fraction in violation: 0.945
Weighted mean: 37.8 ug/l



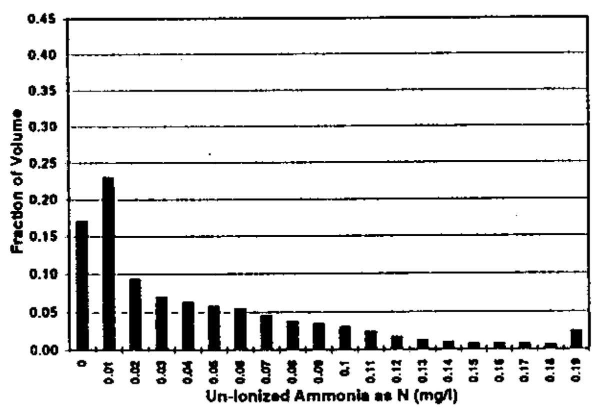
Dissolved Oxygen: Goal > 6 mg/l
Total fraction in violation: 0.153
Weighted mean: 7.00 mg/l



pH: 6.5 < Goal < 9.0
Total fraction in violation: 0.324
Weighted mean: 8.53



Un-ionized Ammonia: Goal varies w/ pH, temp
Total fraction in violation: 0.453
Weighted mean: 0.050 mg/l



Ammonia:

Weighted mean: 0.298 mg/l

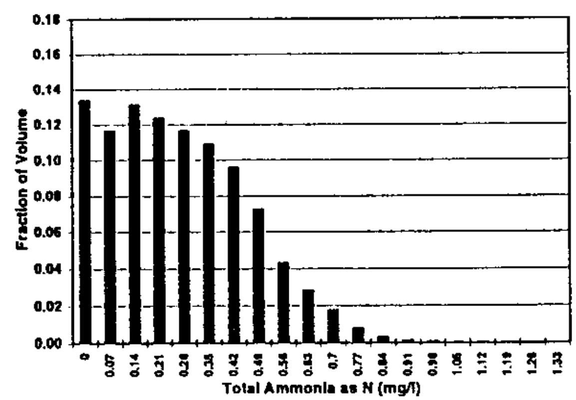


Figure ??: Environmental performance histogram of predictions of violations of water quality guidelines. 1992 Alternative 3.