St. Paul District

US Army Corps of Engineers®

Lake Eau Claire
CE-QUAL-W2

Model Submittal

Section 22 -Planning Assistance to States

Prepared for the

Wisconsin Department of Natural Resources

By the

St Paul District

United States Army Corps of Engineers

April 2009

TABLE OF CONTENTS

Abstract

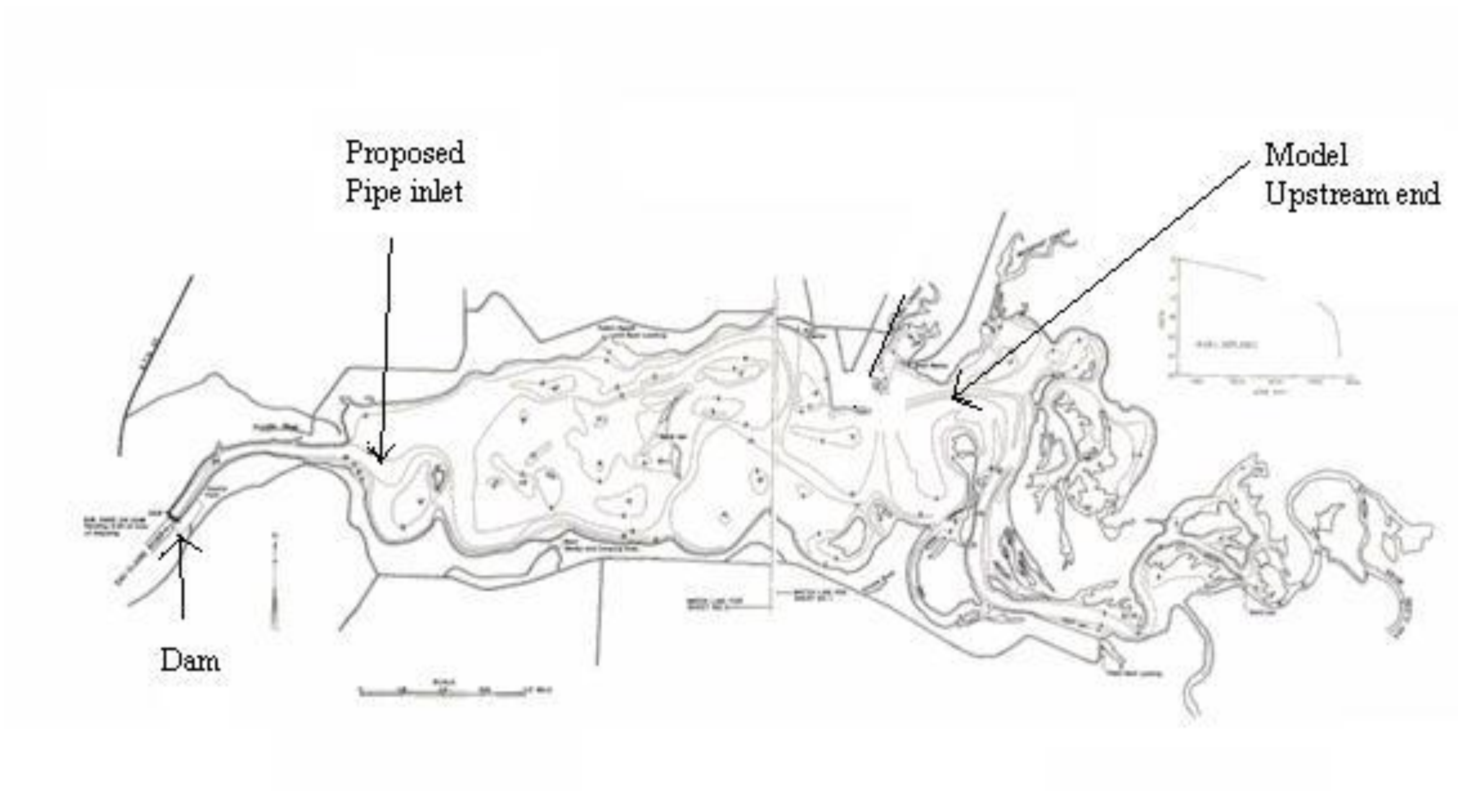
A CE-QUAL-W2 water quality model was developed for Lake Eau Claire to help predict the effectiveness of a proposed bottom withdrawal pipe on reducing internal phosphorus loading. In theory, this pipe-scenario would promote mixing throughout the summer and keep water overlaying the profundal sediments' oxic, which limits P flux into the water column. Predicted reductions of anoxic sediment surface area from the model runs varied with the rate of outflow from the pipe. In a 140-acre study area surrounding the withdrawal zone, the maximum "run of river" discharge pipe showed more than a 90 percent reduction from the existing modeled condition during 1998 and 2006 summer time periods. A fixed withdrawal pipe set at 70.8 cfs (2 cms) showed reductions around 87 percent for both summers. A fixed withdrawal pipe set at 35.4 cfs (1 cms) and a 35.4 cfs pipe with 2 intakes spaced 100 meters apart showed nearly the same reductions of about 63 percent and 48 percent for 1998 and 2006, respectively. Although the model predicts a reduction in anoxic build-up in the hypolimnion using a siphon, this study suggests that it is not a practical option for several reasons: the reduction appears to be localized to the pipe's inlet, periods of anoxia still existed under the maximum discharge scenario and conflicting evidence that suggests that P retention does not differ significantly between lakes with aeration/oxygenation and lakes with an anoxic hypolimnion.

Introduction

Lake Eau Claire (Eau Claire County, WI) is an eutrophic reservoir which exhibits strong stratification during the summer (James et al, 1998). For the deepest locations on Lake Eau Claire, dissolved oxygen (DO) concentrations near the sediment surface during stratification often become anoxic. Once anoxic, internal loading of P has been measured at the sediment surface at rates of 9.1 -17.5 mg $m^{-2}d^{-1}$ versus 0.5 - 2.1 $m^{-2}d^{-1}$ during oxic conditions (James, et al.1998). This change in P flux has also been shown in numerous studies in the lab (Einsele, 1936 and Mortimer, 1941) and in the field (e.g. Ashley, 1983 and Prepas and Burke, 1997) where P retention in the sediments increases if the overlaying water is oxic rather than anoxic. The purpose of this study is to predict using a CE-QUAL-W2 water quality model if a bottom release from the reservoir's dam using a siphon pipe (Figure 1) can prevent the lake from stratifying and becoming anoxic at the sediment surface.

In the model's current state, temperature and dissolved oxygen have been calibration to an acceptable degree for the summer months of 1998 and verified with 2006 summer conditions. In addition, 1998 phosphate and chlorophyll a have been calibrated to observed lake conditions. 2006 phosphate and chlorophyll a were included in the 2006 model, but in-lake conditions were not available for comparison. The funding for this two year study was made available from a Section 22 cost-sharing agreement between the Wisconsin Department of Natural Resources (WDNR) and the US Corps of Engineers, St. Paul District.

Figure 1. Lake Eau Claire map (taken from a 1960's Wisconsin Conservation Department Lake Survey Map)



Model description

CE-QUAL W2 version 3.5 is a two-dimensional (longitudinally/vertical), hydrodynamic and water quality model suitable for relatively long and narrow water bodies that exhibit vertical and longitudinal gradients. The original model was developed by Edinger and Buchak (1975) and was known as LARM (Laterally Averaged Reservoir Model). At its present version (3.5), the model has been shown to be successful in accurately modeling lakes, reservoirs, estuaries and rivers (Cole, 2002).

Model inputs

To run CE-QUAL W2 on Lake Eau Claire, several input data sets were needed. The available data supplied for the study were from the summer months of 1998 (James et al., 1988), 2004 and 2006. Due to the lack of water quality tributary data from 2004, the model was calibrated with 1998 data and verified with 2006 data. Inputs to the 1998 and 2006 models included: bathymetry data, meteorological data, time-varying tributary water quality data, tributary temperatures and flows, and dam releases.

Bathymetry:

The bathymetry file for the model was developed from a Wisconsin Conservation Department Lake Survey Map that was created from data collected in 1960. The reservoir body was divided longitudinally in the model into 59, 100 meter long segments oriented along the thalwag of the old river channel (Fig. 3). Vertically, the model is divided into 0.25 meter wide layers increasing from 9 layers at the upstream end to 30 layers at the dam (Fig. 4). To test the accuracy of the model's bathymetry, assuming the 1960's contour map of the lake is correct after four decades, a volume-depth comparison was made for the model and the observed data (Figure. 2). Figure 2 shows a close comparison of volume at the upper depths and at the bottom, which are critical for reproducing heat transport at the surface and at the sediments. The only noticeable difference is at around 4 meters where the model shows more volume than observed. Overall, the bathymetry in the model is suitable to represent the system adequately.

Figure 2 Volume-depth comparison between the model and observed data

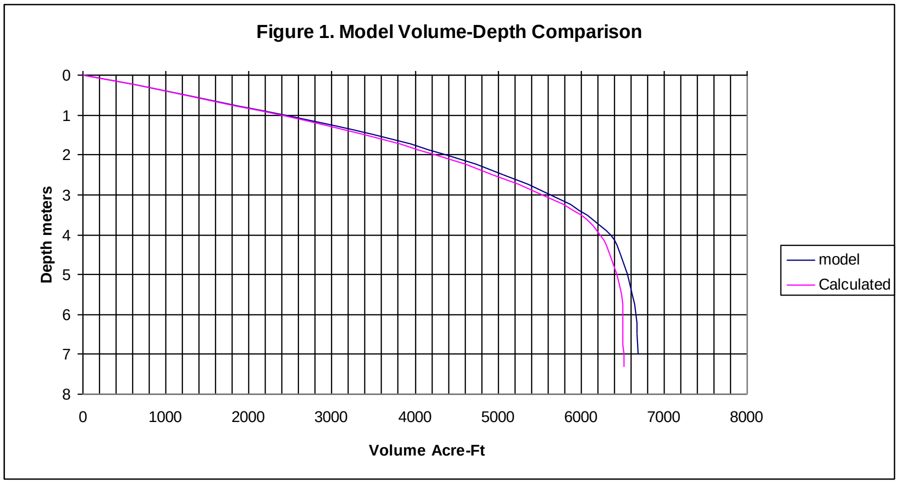


Figure 3. Water body segments

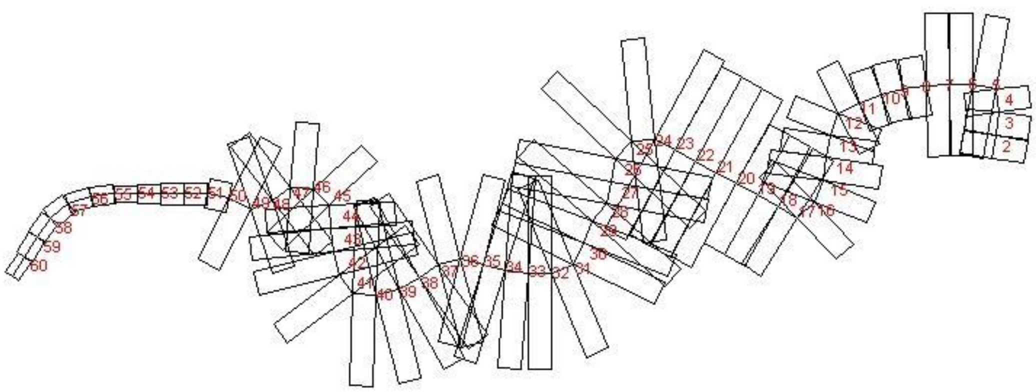
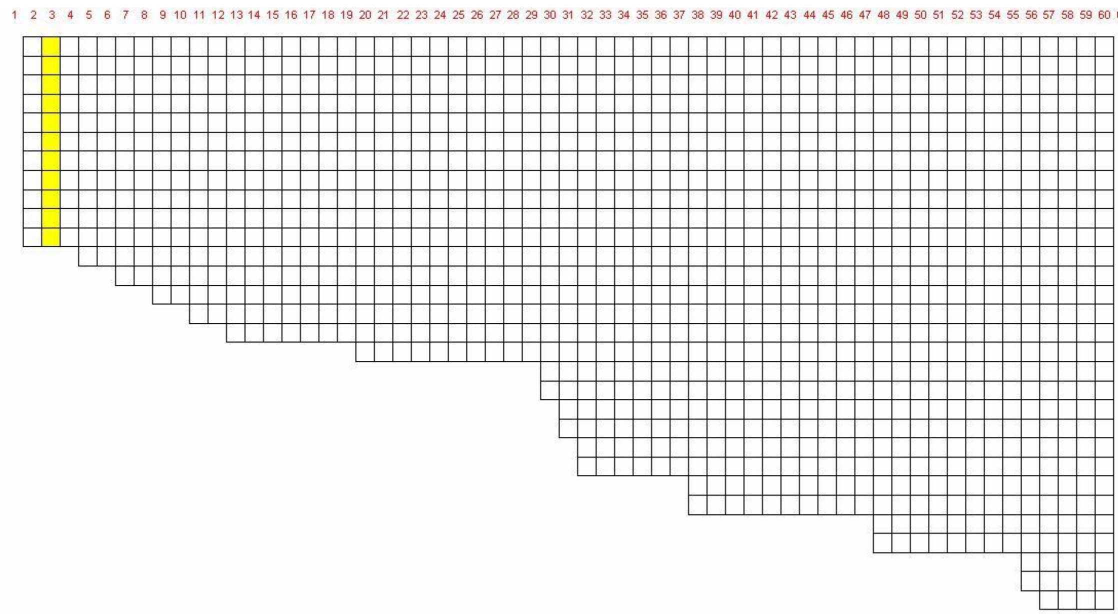


Figure 4 Side view of the Lake Eau Claire CE-Qual-W2 model



Meteorological Data:

The 1998 meteorological data were taken from the Eau Claire, WI Airport. The 2006 meteorological data were taken from a local weather gage near Augusta, WI. Types of meteorological data required for the model were air temperature, dew point, wind speed, wind direction, and cloud cover. As an added and more accurate method to measure surface heat exchange, 2006 incident short-wave solar radiation from the Augusta gage was also included in the model.

In-stream water temperatures and flows:

At the upper boundary of the model, flow measurements collected for a previous study (James, et al., 1998) on the Eau Claire River, Hay Creek and Muskrat Creek were used for the 1998 model. Unfortunately, the 1998 data set lacked observed stream temperatures. As an estimate for the 1998 temperature data, a relationship (Equation 1) between recorded 2006 air temperatures and observed 2006 tributary temperatures was developed and used with the 1998 air temperature data to create a reasonable time series of tributary temperature data. A comparison of the 2006 Eau Claire River temperatures and estimated temperatures using Equation 1 is shown in Figure 5.

Equation 1. 2006 air and stream temperature relationship

$$Est = ((A*B) + (C*D))/2$$

Est = Estimated instantaneous stream temperature
A= 1.2, Coefficient
B= Average Air Temp. (previous 3 days)
C= 0.9, Coefficient
D= Instantaneous Air Temp.

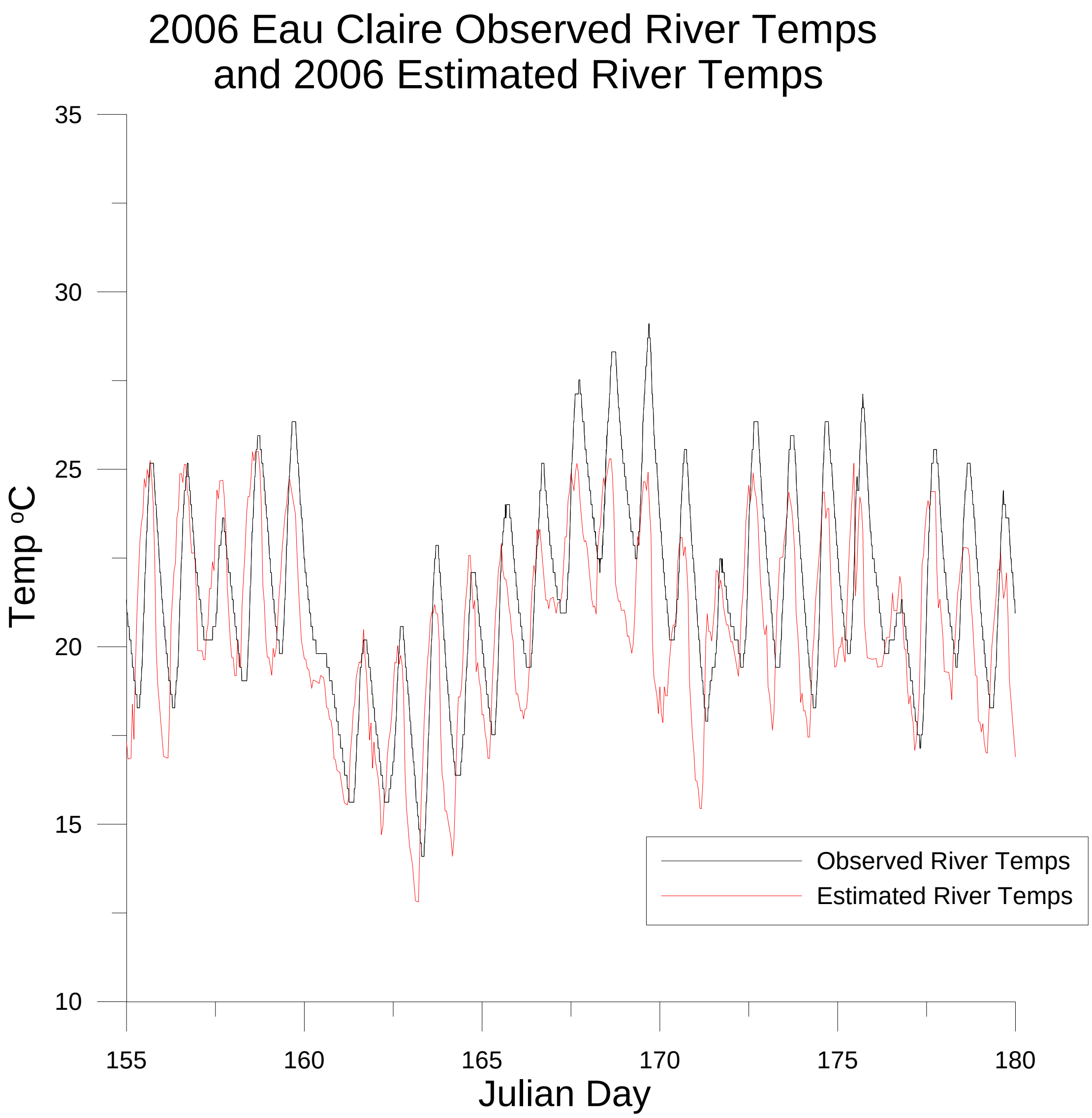
The 2006 inflows for the model were calculated from 2006 lake elevations and discharges. The calculated inflows were then partitioned into the flows attributable to the reservoir's three surface water inputs (Eau Claire River, Hay Creek and Muskrat Creek) by using the 1998 observed percentage of each tributary's contribution to the reservoir. The 2006 temperatures for the tributaries were measured for the summer months with a thermistor placed above each confluence of the three tributaries and the reservoir.

Lake Eau Claire pool elevations and gate settings for 1998 and 2006 were obtained from the Eau Claire Dam.

In-stream water quality:

All of the water quality data used as inputs to the 1998 model were taken from the 1998 study (James, et al.,1998). Parameters used for the water quality input files includes: inorganic suspended sediment (ISS), phosphate, ammonium, nitrate, POM, CBOD, algae, DO and inorganic carbon. To use the data, several assumptions were made. ISS was not measured directly and values between 10 and 50 mg/L were used based on a positive correlation with flow. Phosphate was assumed to be equal to the collected SRP measurements and missing values were generated based on the changes in TP. POM was assumed to be in the labile fraction. CBOD was not measured and was assumed to be a constant 1.4 mg/L. Algae was not measured in the tributaries and was assumed to be a constant 0.1 mg/L. DO was not measured in the tributaries, but in-lake measurements at the furthest upstream station was used as a guide. Lastly, inorganic carbon was not measured and was assumed to be a constant 0.45 mg/L.

Figure 5 Observed Eau Claire River Temperatures and estimated River Temperatures using Equation 1.



2006 water quality inputs to the model were identical to the 1998 inputs except for fluctuations in concentration of ISS, phosphate and POM that seem to correlate somewhat with flow. In these cases professional judgment was used. Table 1 summarizes the inputs to the 1998 and 2006 model.

Table 1. 1998 and 2006 Model Input Parameters

Parameter	**Source**	**Frequency**	**Comments**
Bathymetry	Wisconsin Conservation Department Lake Survey Map Circa 1960	n/a	Sufficient for general shape of reservoir, but years of sedimentation may be a source of error in the model.
Dam Gate Settings and Lake Elevations	Lake Eau Claire Dam Records	Daily	Adequate for reproducing the model's hydrodynamics
Met Data	1998 - Eau Claire Airport 2006 - Augusta, WI	Hourly	The Eau Claire Airport is too far away (~ 30 miles) to accurately describe lake conditions for isolated storm events. The model may not be capturing some mixing events.
Tributary Flows	1998 - James, et al. 2006 – calculated from elevation and discharge	Daily	In step with Lake Eau Claire's water surface elevations and discharges.
Tributary Temps	1998 - Estimated from 1998 air temperatures. 2006 – Collected with themistors	Hourly	Observed data would greatly improve model confidence near the reservoir's upstream end, but sensitivity runs with inflow temperatures ranging +/- 2 ^{o}C, showed only small changes near the dam.
Tributary Water Quality	1998 - report James, et.al. 2006 - estimated	Daily	Seston, POM, TP and TN data were daily. Unfortunately, data for SRP and NH3 were sporadic. Good WQ data is critical for modeling water quality.

Model Scenarios

To predict the range of effects of operating a siphon pipe in Lake Eau Claire, four scenarios shown in Table 2 were run for both the 1998 and 2006 summer months.

Table 2 Scenarios run for 1998 and 2006

Scenario	**Flow Rate**	**Intake location**	**Intake depth** meters below normal pool
“run of river”	Regulated	Segment 47	5.5
35.4 cfs (1 cms)	Constant	Segment 47	5.5
70.8 cfs (2 cms)	Constant	Segment 47	5.5
35.4 cfs - 2 intakes (17.7 cfs each)	Constant	Segment 46 and 47	5.5

The “run of river” scenario was regulated to discharge all outflow from the reservoir during the simulation runs while keeping the pool level as close as possible to the dam’s spillway elevation. Figures 6 and 7 show the regulated pipe discharges for 1998 and 2006, respectively.

Figure 6

1998 "run of river" pipe withdrawal -Segment 47

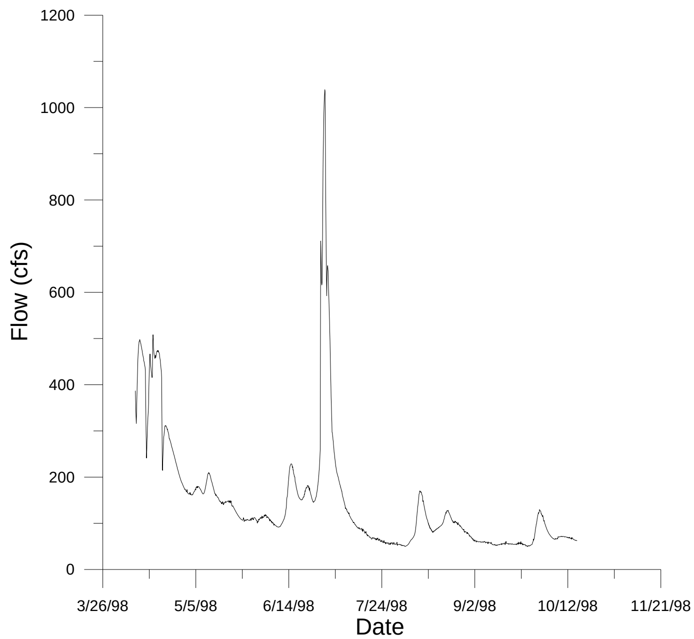
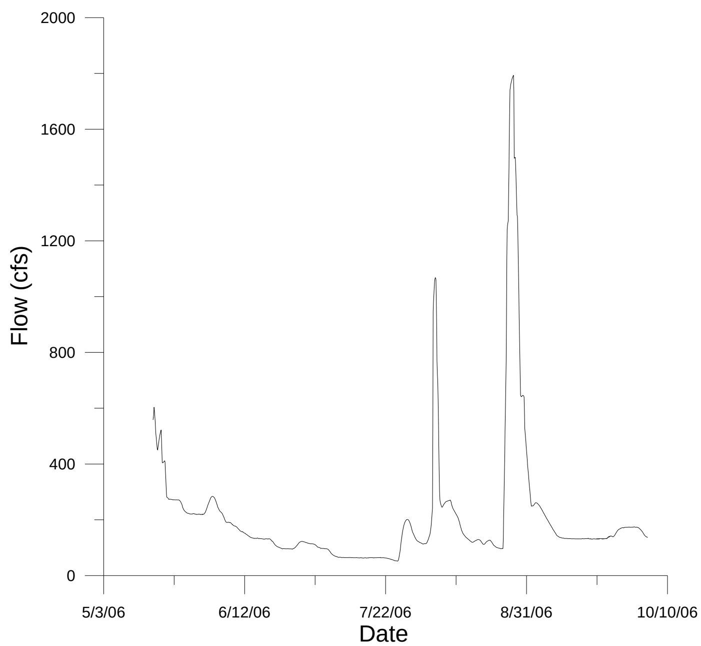


Figure 7

2006 "run of river" pipe withdrawal -Segment 47



Model Calibration

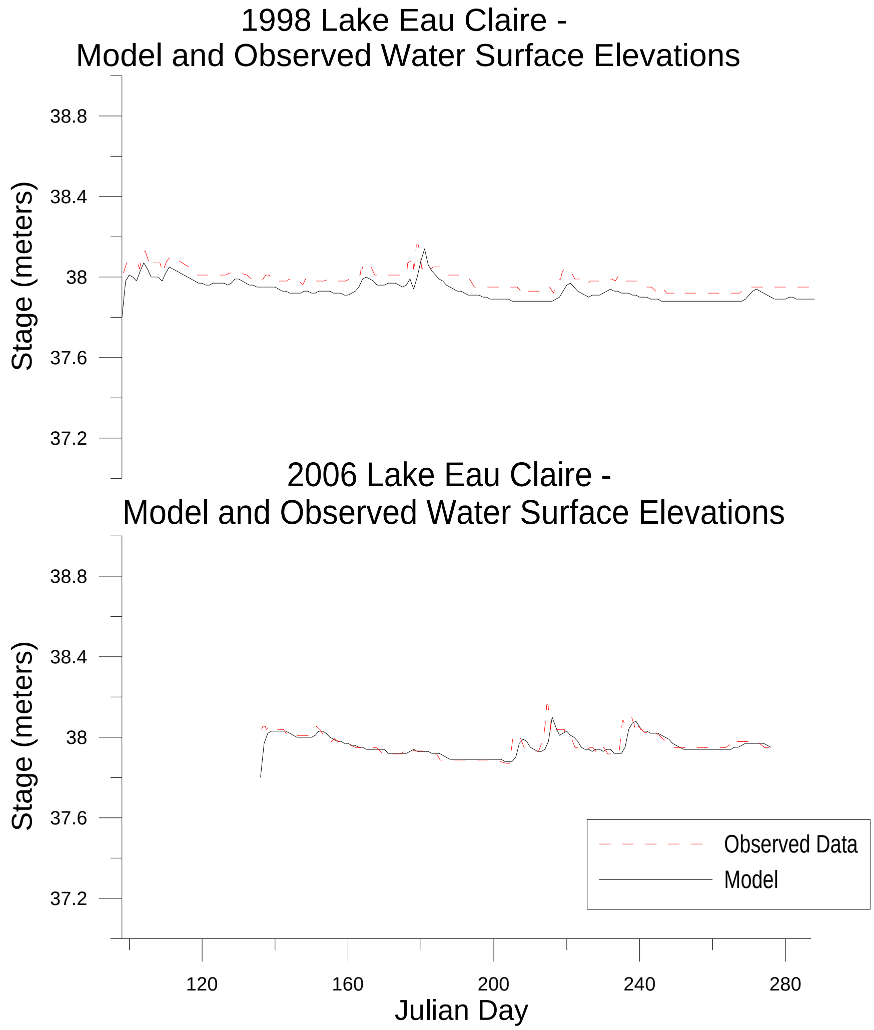
Field data from 1998 were used to calibrate the model's temperature and water quality parameters at site 1 (James, et al. 1998). 2006 field data were used to verify temperature and DO recorded at "new" site 1, located closer to the channel that leads up to the dam.

Calibration Parameters:

Hydrodynamics

Using the default hydrodynamic parameters in the model, the 1998 and 2006 runs produced close comparisons with observed elevation fluctuations of the water surface (Fig 8). This is a good test to make sure the bathymetry and the hydrodynamic parameters are close to reality and would allow further calibration for water quality.

Figure 8



Temperature calibration in CE-QUAL W2 version 3.5 is limited by the accuracy of the input data and the model calculations. Under ideal conditions, few parameters need to be adjusted after input data is taken from the field. Assuming the bathymetry data, meteorological data, shading data, bottom roughness, flow and water temperature data, and parameters that control solar radiation attenuation are correct; the model should come close to predicting observed data without changing the model's default settings (Cole, 2002). In this study the only parameters that were adjusted were the shading parameter, the wind sheltering coefficient (WSC) and the fraction of solar radiation reflected by the sediments back into the water column (TSEDF). Table 3 lists the calibrated values used for calibrating for temperature. Plots showing the 1998 calibration, the 2006 verification and the effects of a regulated pipe withdrawal for temperature are shown in Figures 9 and 10.

Table 3 Calibrated values for the Lake Eau Claire CE-QUAL-W2 thermal model

Coefficient	Value
WSC	0.9
TSEDF	0.0
Shading	1.0

Dissolved oxygen (DO), phosphate and chlorophyll a calibration needed a little more tweaking of parameter values to achieve acceptable results. Initially, DO was going to be calibrated using only two parameters: a constant sediment oxygen demand (SOD) value to control the DO concentration near the sediments and a constant CBOD value to control the DO concentrations in the water column. In Lake Eau Claire, however, it was obvious that algae growth in the summer also impacted DO levels through photosynthesis, respirations and excretion. To grow algae in the model, nutrients were added to the system and parameters affecting algae growth and nutrient cycling were turn on in the model. Parameters that were adjusted to calibrate the growth of algae are summarized in Table 4. Figures 11-16 show the 1998 calibration of water quality, 2006 verification of DO and predicted effects of the regulated pipe scenario.

Table 4 1998 and 2006 Model WQ parameters

Parameter	default	Value used	Comments
AG –algal growth rate *1/day*	2.0	1.1	A slower growth rate was needed for the timing of algal blooms
(AHSP) Algal half-saturation P $g\ m^{-3}$	0.005	0.003	Growth rate was decreasing too fast with default setting.
(AT1) Lower Temperature for max. algal growth ^oC	20	15	Algal blooms were observed at colder water temperatures than default.
(PO4R) Sediment Release Rate $g\ m^{-2}\ s^{-1}$	none	0.005	Critical for matching anoxic internal loading of phosphate.
Zero Order SOD $g\ O_2\ m^{-2}\ day^{-1}$	none	1.0	Critical for reducing DO at the sediments.
CBOD5 decay rate at *20C, 1/day*	none	0.25	Critical for reducing DO in the water column.

Figure 9

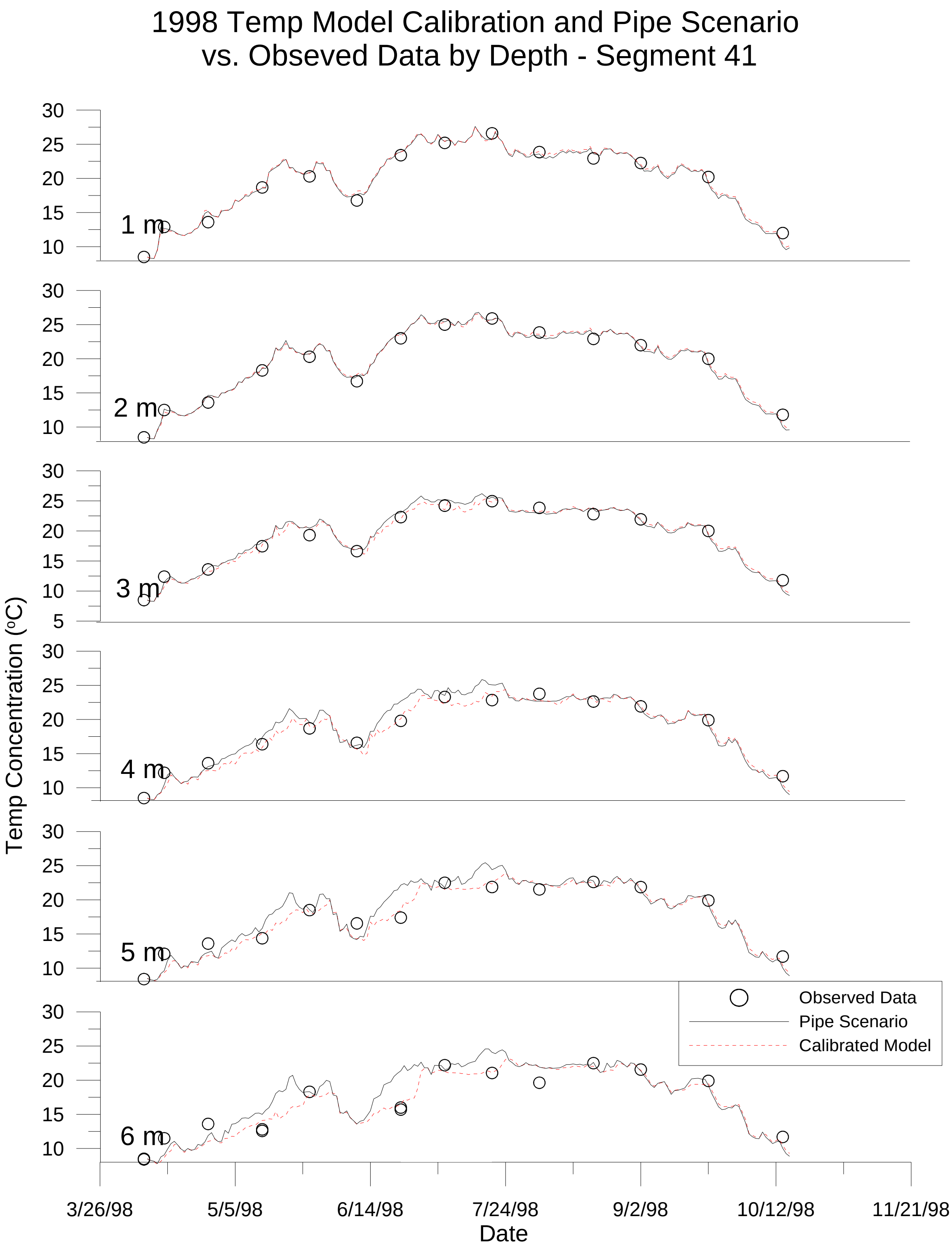
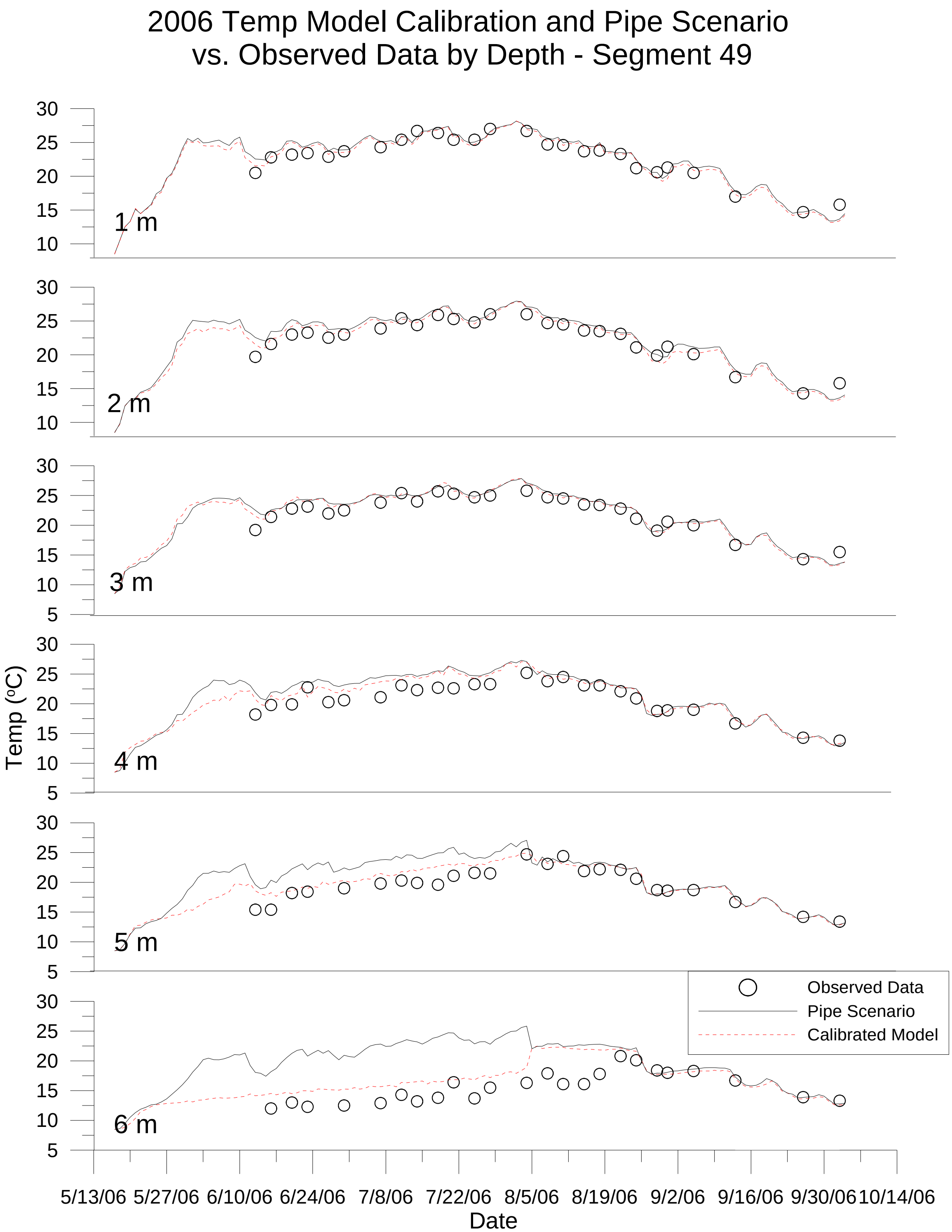

1998 Temp Model Calibration and Pipe Scenario
vs. Obseved Data by Depth - Segment 41
1 m
2 m
3 m
4 m
5 m
6 m
Temp Concentration (ºC)
Date
3/26/98
5/5/98
6/14/98
7/24/98
9/2/98
10/12/98
11/21/98
Observed Data
Pipe Scenario
Calibrated Model

Figure 10



2006 Temp Model Calibration and Pipe Scenario
vs. Observed Data by Depth - Segment 49
Temp (ºC)
1 m
2 m
3 m
4 m
5 m
6 m
30
25
20
15
10
5
Observed Data
Pipe Scenario
Calibrated Model
5/13/06
5/27/06
6/10/06
6/24/06
7/8/06
7/22/06
8/5/06
8/19/06
9/2/06
9/16/06
9/30/06
10/14/06
Date

Figure 11

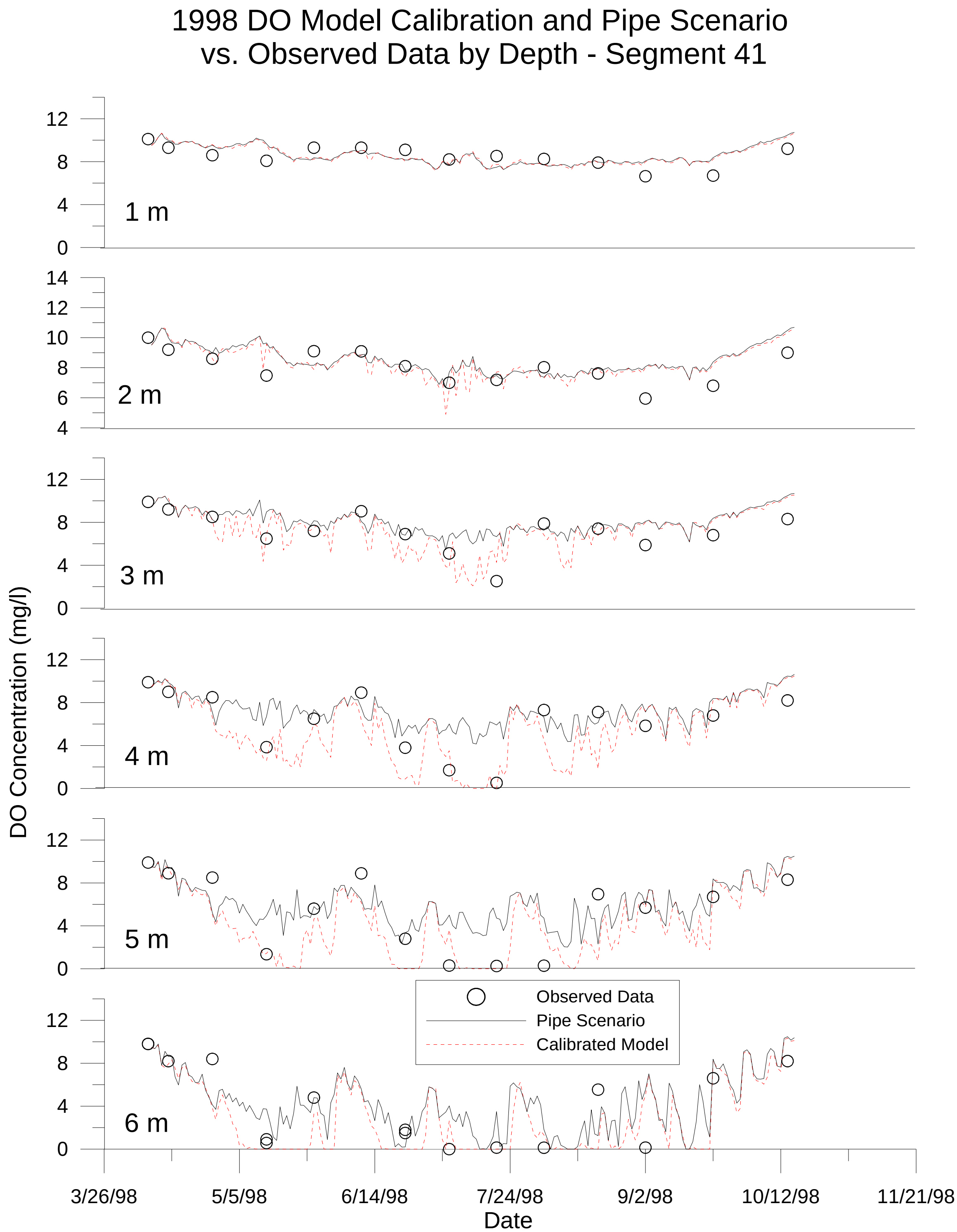

1998 DO Model Calibration and Pipe Scenario
vs. Observed Data by Depth - Segment 41
DO Concentration (mg/l)
1 m
2 m
3 m
4 m
5 m
6 m
0
4
8
12
14
10
6
Observed Data
Pipe Scenario
Calibrated Model
3/26/98
5/5/98
6/14/98
7/24/98
9/2/98
10/12/98
11/21/98
Date

Figure 12

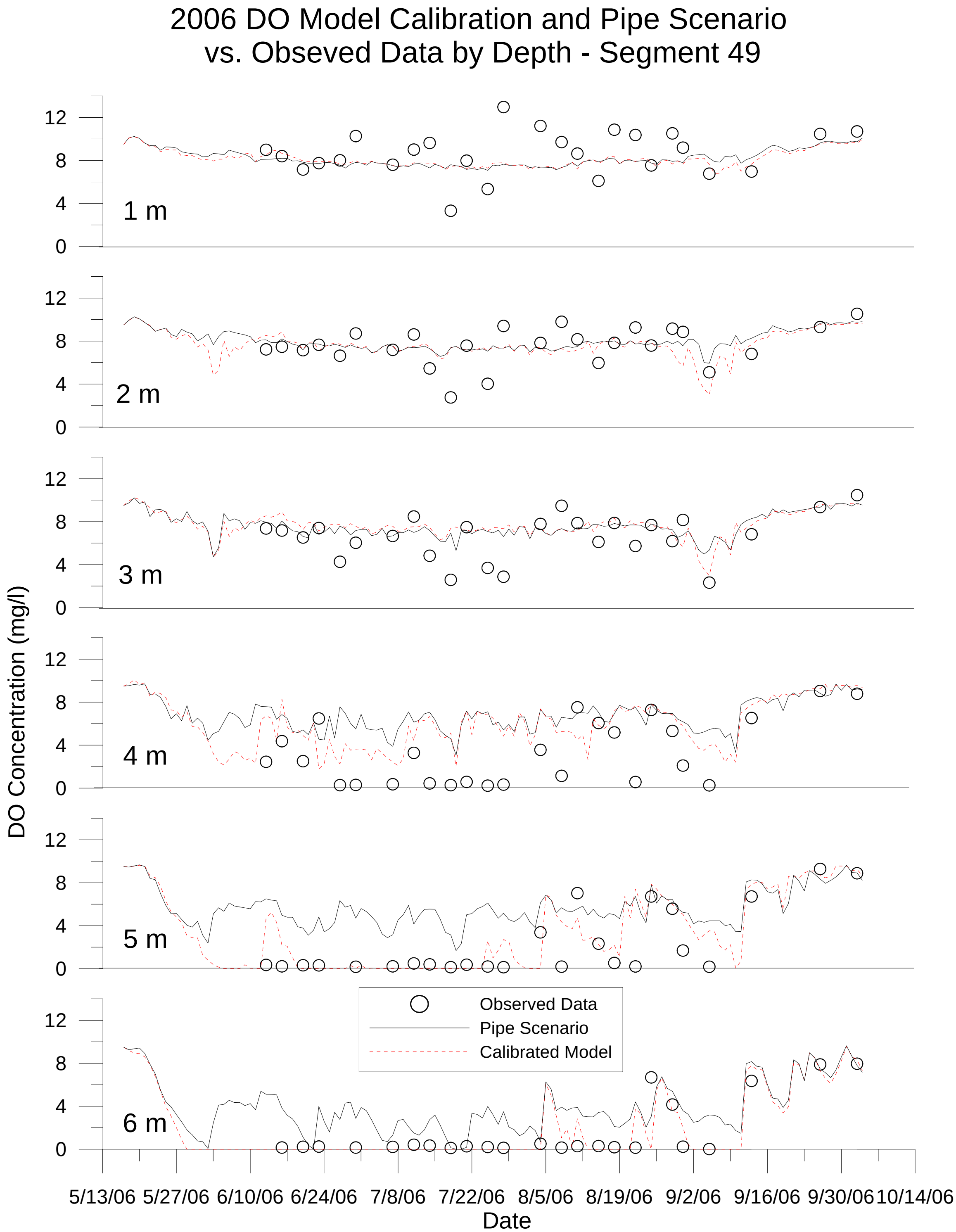

2006 DO Model Calibration and Pipe Scenario
vs. Obseved Data by Depth - Segment 49
1 m
2 m
3 m
4 m
5 m
6 m
0
4
8
12
DO Concentration (mg/l)
Observed Data
Pipe Scenario
Calibrated Model
5/13/06
5/27/06
6/10/06
6/24/06
7/8/06
7/22/06
8/5/06
8/19/06
9/2/06
9/16/06
9/30/06
10/14/06
Date

Figure 13

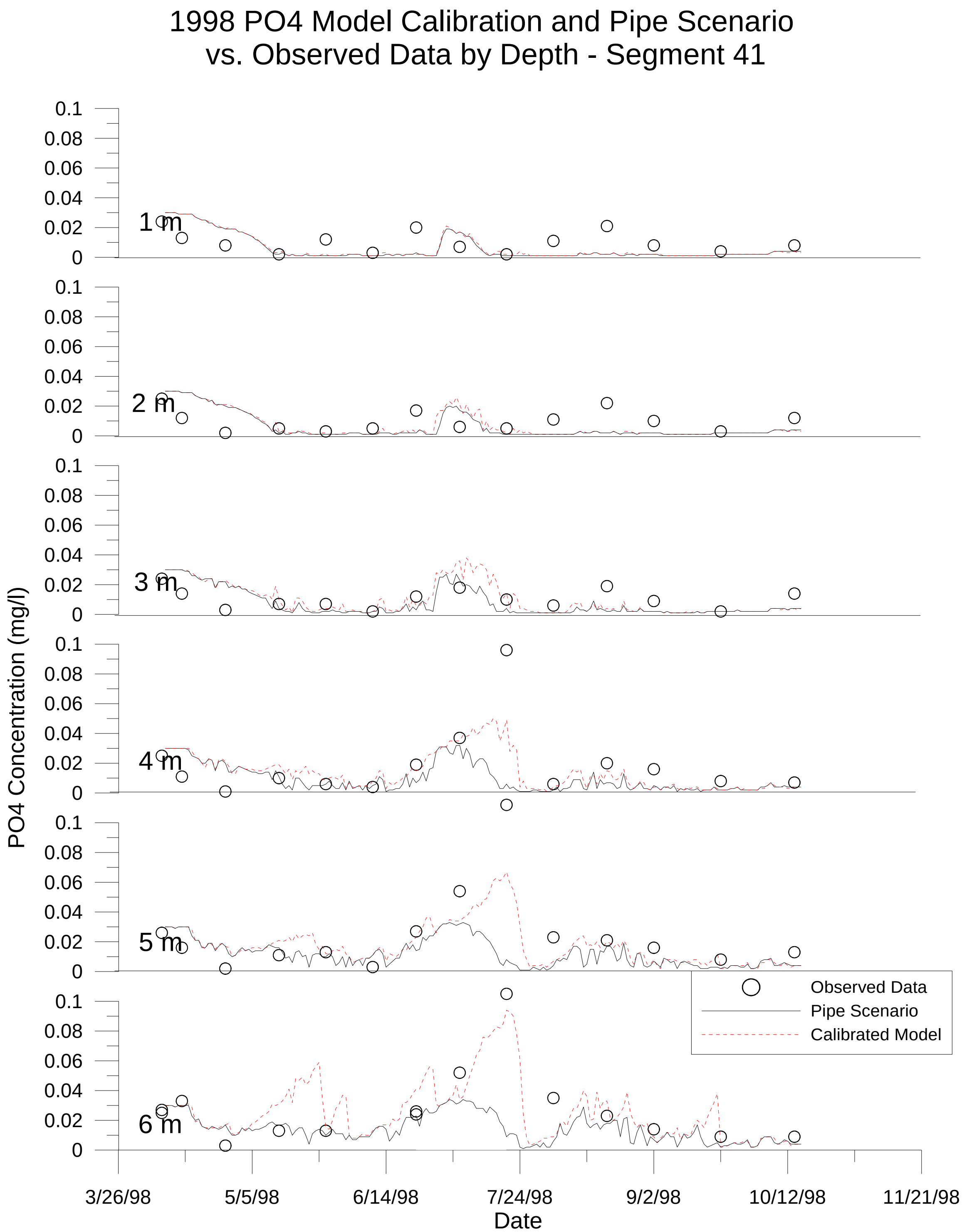

1998 PO4 Model Calibration and Pipe Scenario
vs. Observed Data by Depth - Segment 41
PO4 Concentration (mg/l)
0.1
0.08
0.06
0.04
0.02
0
1 m
2 m
3 m
4 m
5 m
6 m
Observed Data
Pipe Scenario
Calibrated Model
3/26/98
5/5/98
6/14/98
7/24/98
9/2/98
10/12/98
11/21/98
Date

Figure 14

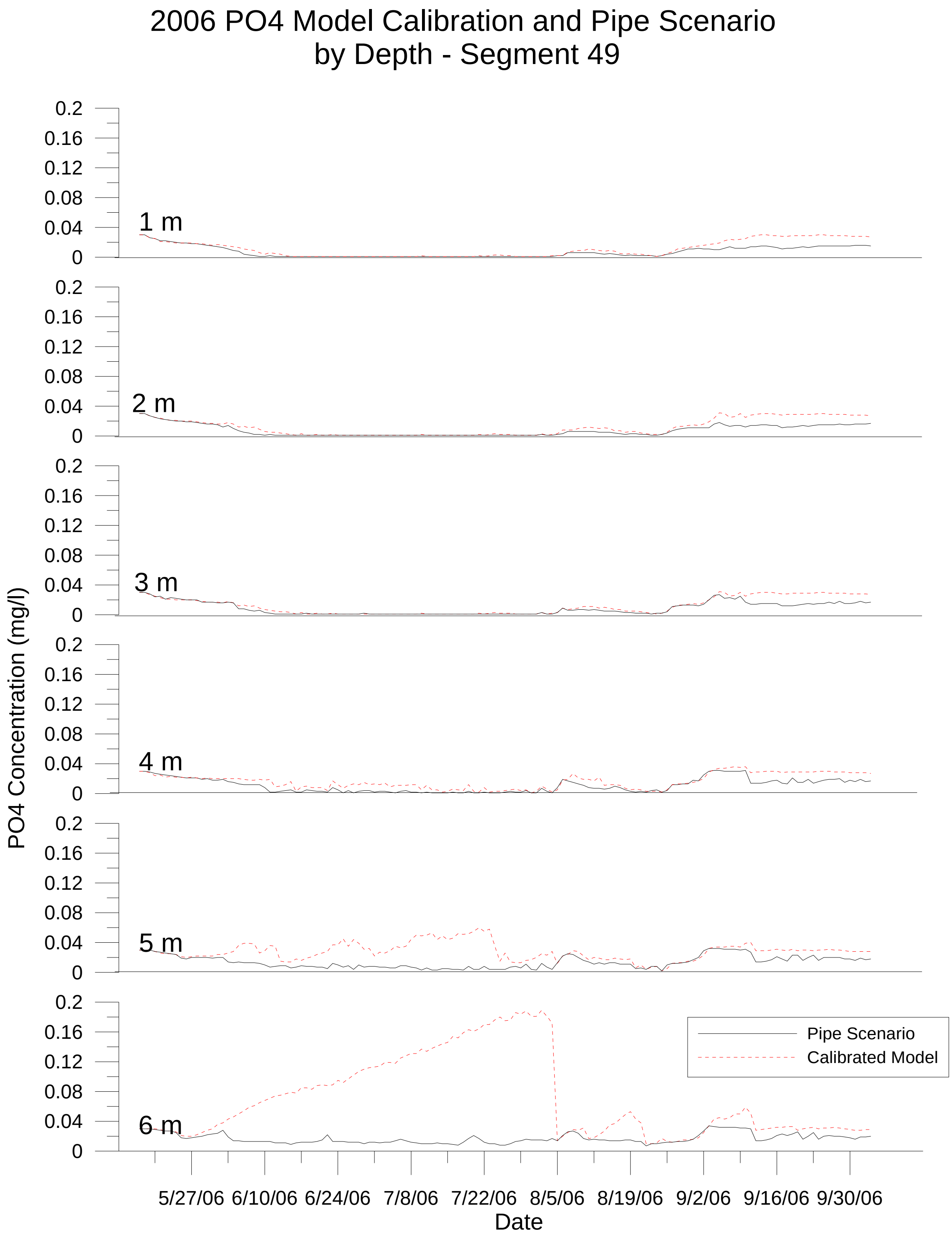

2006 PO4 Model Calibration and Pipe Scenario
by Depth - Segment 49
PO4 Concentration (mg/l)
0.2
0.16
0.12
0.08
0.04
0
1 m
2 m
3 m
4 m
5 m
6 m
Pipe Scenario
Calibrated Model
5/27/06
6/10/06
6/24/06
7/8/06
7/22/06
8/5/06
8/19/06
9/2/06
9/16/06
9/30/06
Date

Figure 15

1998 CHL a Model Calibration and Pipe Scenario
vs. Observed Data by Depth - Segment 41

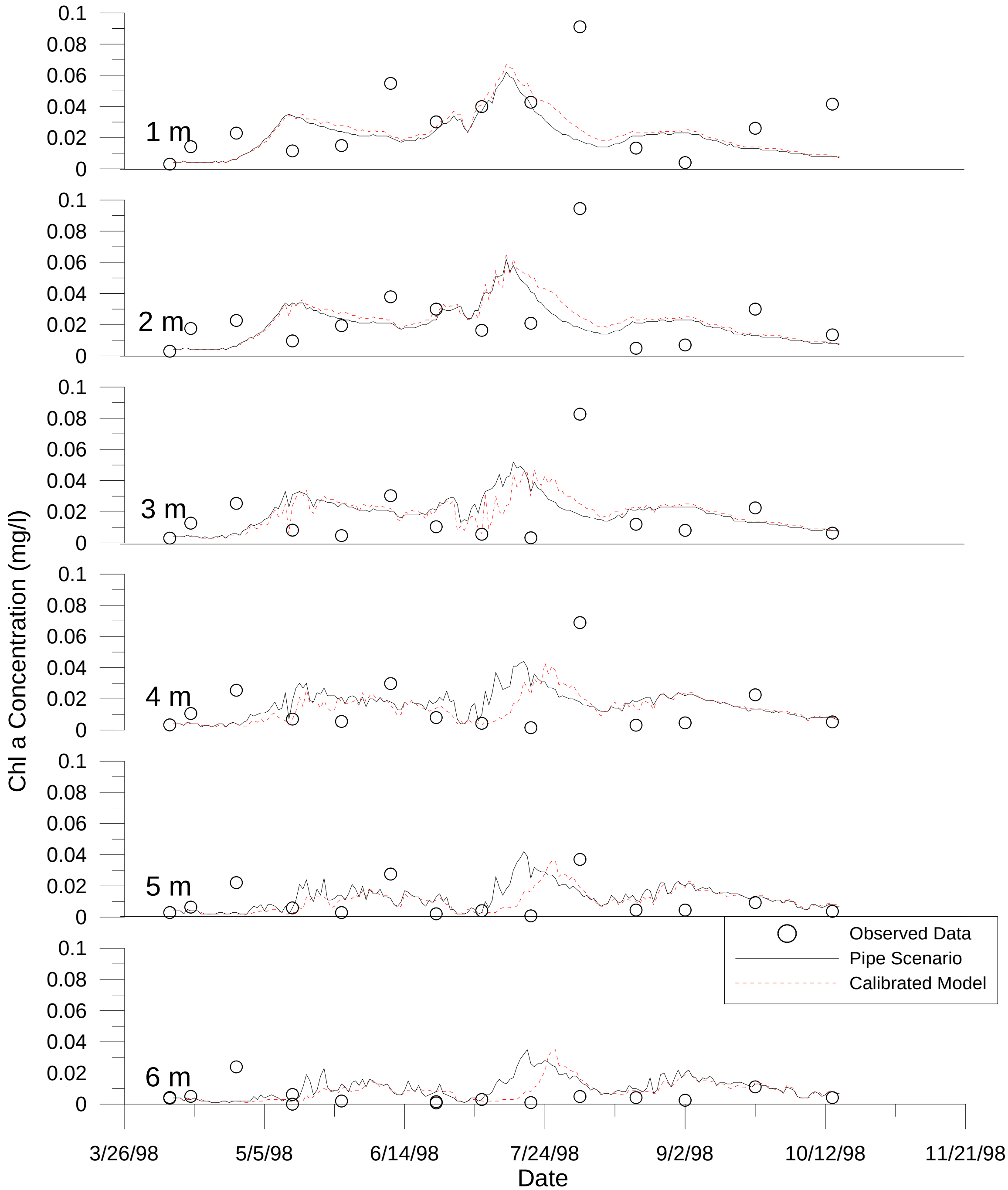


Figure 16

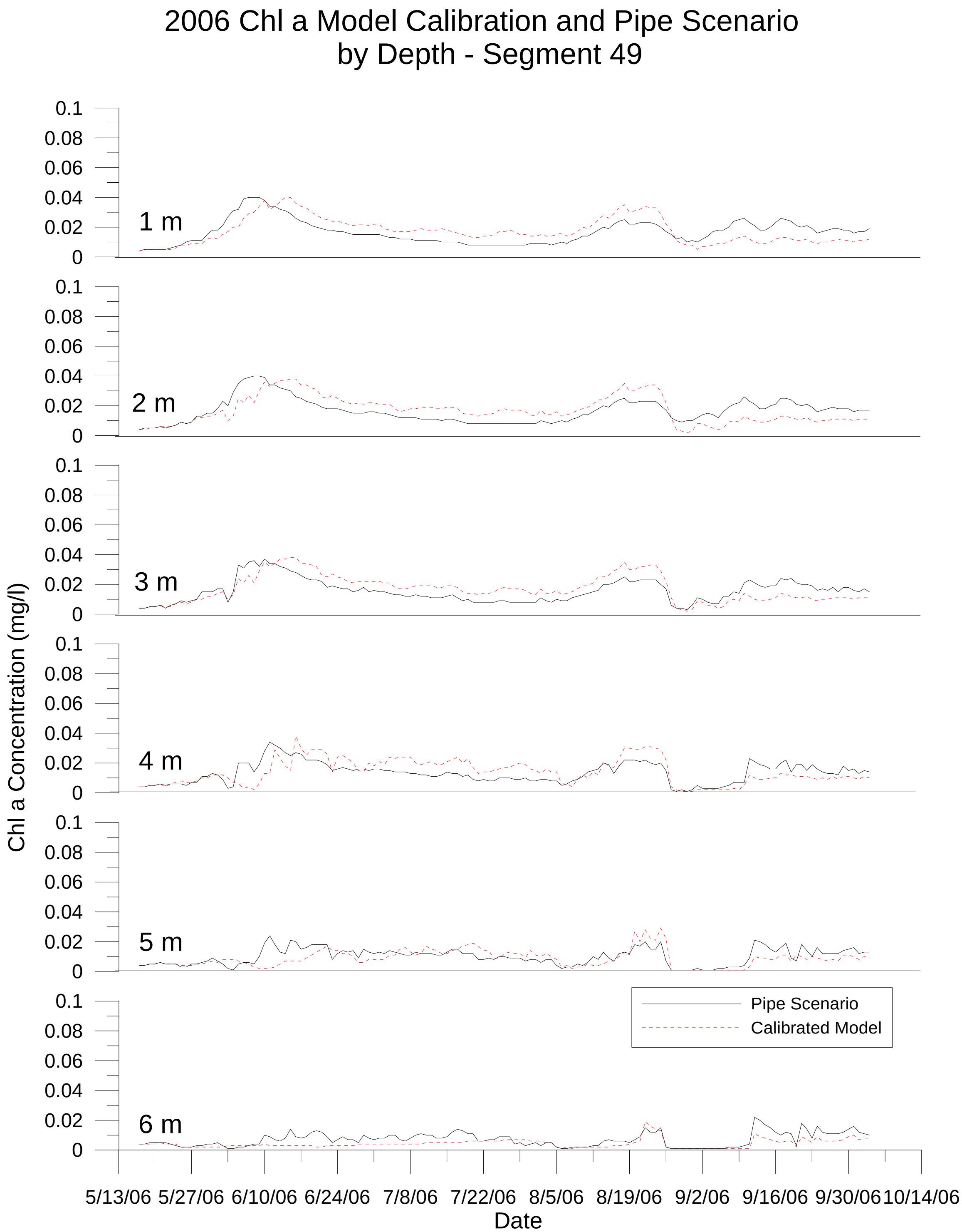

2006 Chl a Model Calibration and Pipe Scenario
by Depth - Segment 49
Chl a Concentration (mg/l)
0.1
0.08
0.06
0.04
0.02
0
1 m
2 m
3 m
4 m
5 m
6 m
Pipe Scenario
Calibrated Model
5/13/06
5/27/06
6/10/06
6/24/06
7/8/06
7/22/06
8/5/06
8/19/06
9/2/06
9/16/06
9/30/06
10/14/06
Date

Figure 17

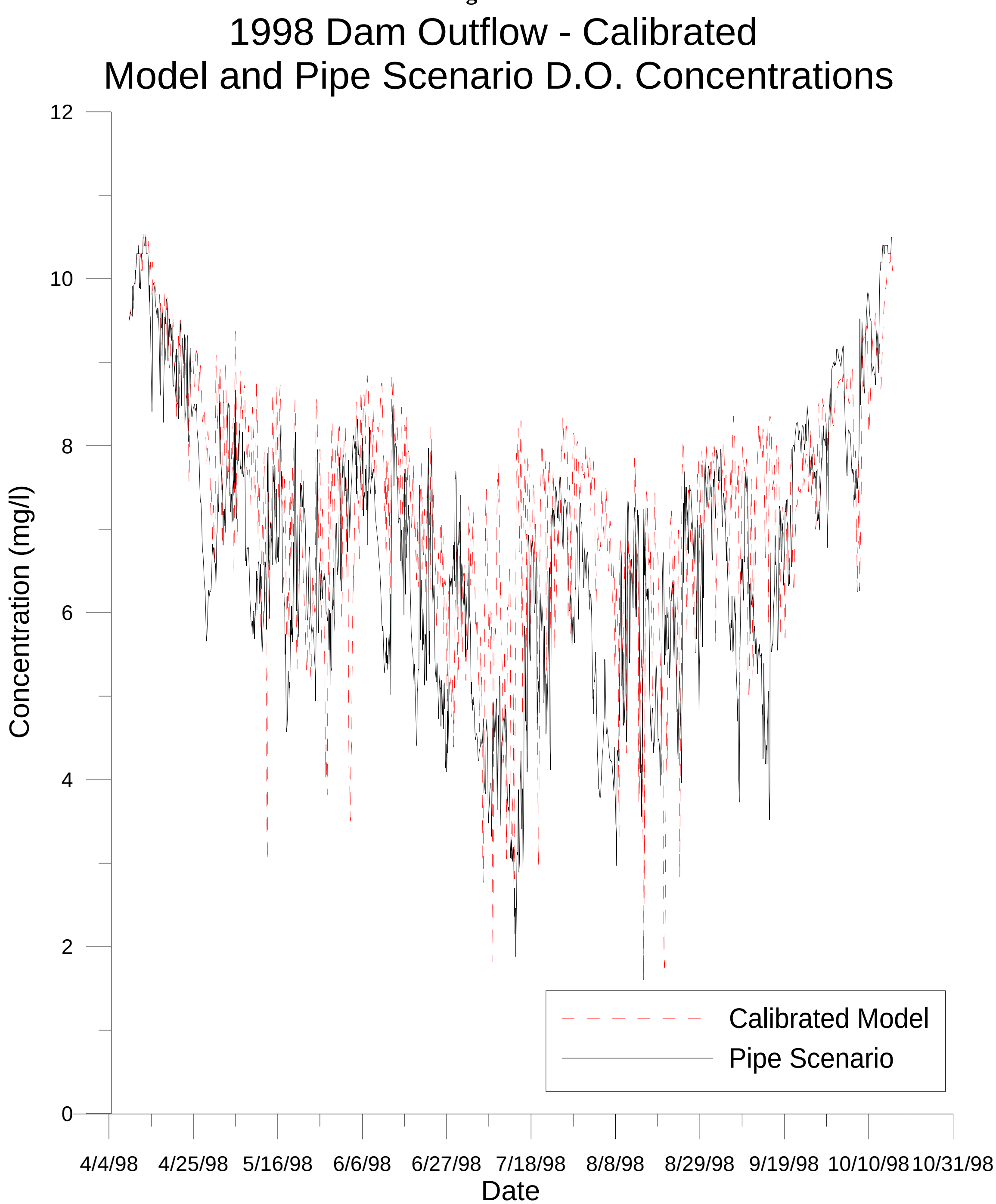
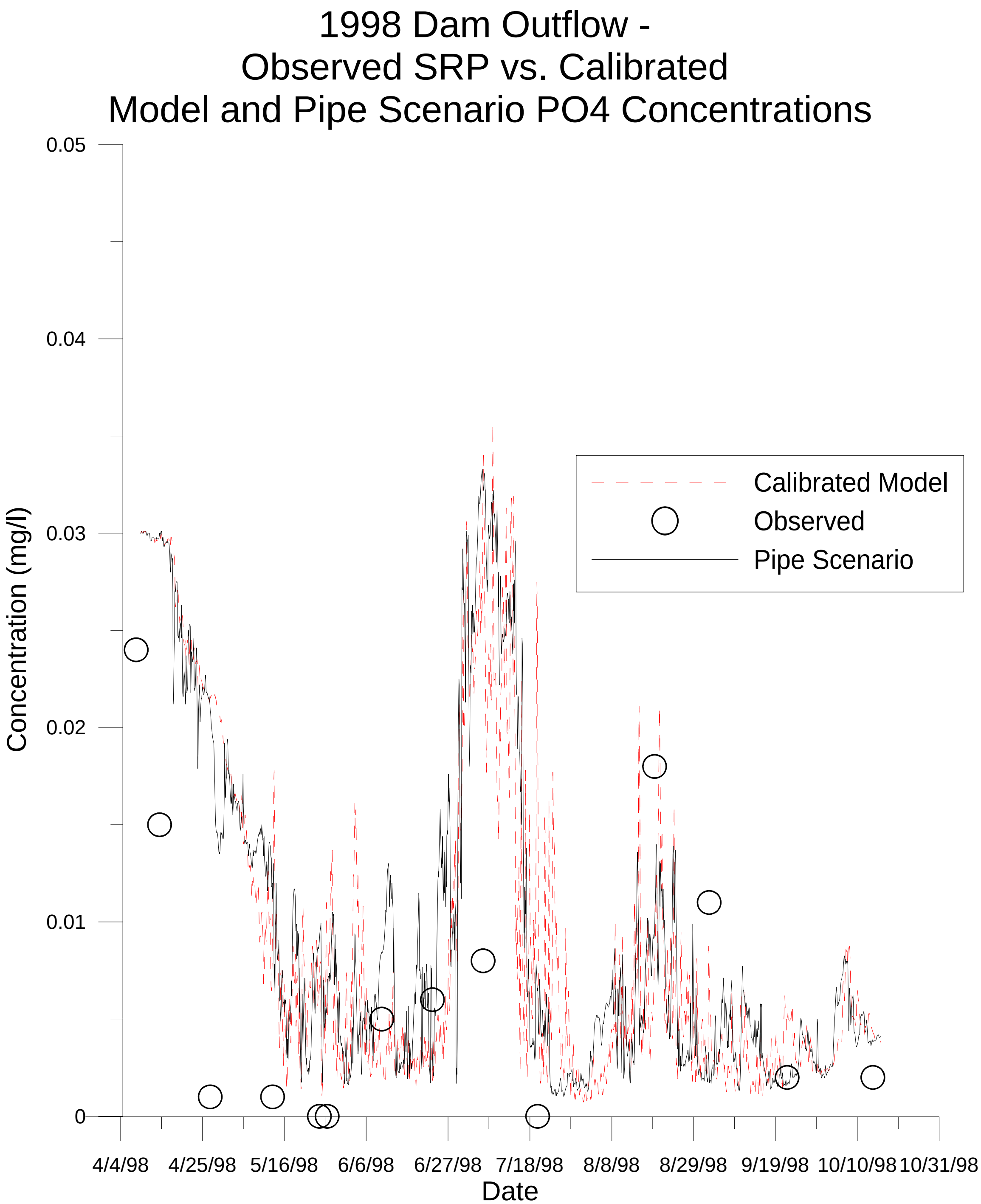

1998 Dam Outflow - Calibrated
Model and Pipe Scenario D.O. Concentrations
Concentration (mg/l)
0
2
4
6
8
10
12
Date
4/4/98
4/25/98
5/16/98
6/6/98
6/27/98
7/18/98
8/8/98
8/29/98
9/19/98
10/10/98
10/31/98
Calibrated Model
Pipe Scenario

Figure 18


1998 Dam Outflow -
Observed SRP vs. Calibrated
Model and Pipe Scenario PO4 Concentrations
Concentration (mg/l)
0.05
0.04
0.03
0.02
0.01
0
Calibrated Model
Observed
Pipe Scenario
4/4/98
4/25/98
5/16/98
6/6/98
6/27/98
7/18/98
8/8/98
8/29/98
9/19/98
10/10/98
10/31/98
Date

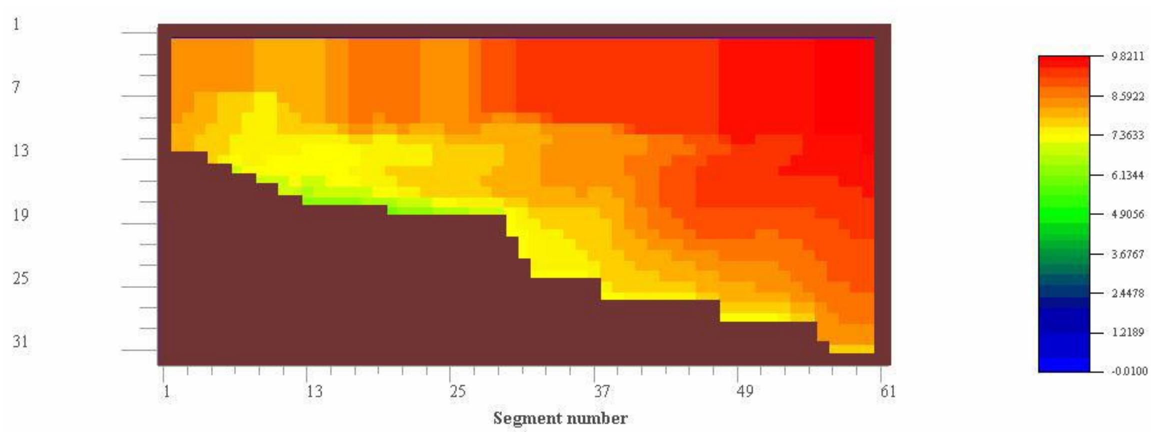
Scenario Results and Discussion

To evaluate the predicted water quality effects of withdrawing bottom water from outside the channel compared to the existing regulation of the dam, four pipe scenarios were examined through a few different analytical methods. The first way was to visually compare several sets of DO plots from the regulated "run of river" scenario for the 2006 model. In each set, the first plot demonstrates the levels of DO in the reservoir by depth under the normal operation procedures. The second plot shows the DO levels for the reservoir at the same moment in time under a regulated "run of river" pipe withdrawal. In the regulated pipe withdrawal scenario, the model was set up to discharge the same flow as would have been discharging from the dam at an intake placed at segment 47 and zero discharge would be exiting from the gates and spillway. The predicted results of this scenario demonstrated a clear distinction between the DO levels of the normal operations. Specifically, the DO near the intake of the pipe was significantly higher at most times and the depth of the hypolimnion was depressed. Unclear, however, in the figures is to what extent internal loading was reduced. Because the pipe effect seems to have only a localized destratification effect, internal loading was probably taking place at some distance from the intake. To try to quantify the effect of the pipe in terms of internal loading, figures 17 and 18 shows PO4 by depth at segment 41 for 1998 and segment 49 for 2006. These results indicate that PO4 levels 600 meters from the pipe intake for 1998 and 200 meters from the intake in 2006 are markedly reduced, especially at lower depths. Another clue to the effect of the pipe scenario on internal loadings of phosphate is seen in Figures 19 and 20 that show chlorophyll a levels. In these figures indirect evidence of a lower sediment release of phosphorus could be concluded if the algae in the photic zone was phosphorus limited and a decrease of algal growth was predicted. In this case, the algae is assumed to be phosphorus limited, even with external sources turned on, but little or no algal growth reduction is seen. This lack of reduced algal production in the lake under the pipe scenario can be explained two ways. First, the reduction of phosphate release from the sediments seen in Figure 17 and Figure 18 is such a localized phenomenon that the reduced nutrient entrainment to the surface is insignificant to algal growth. Or secondly, the model is not accurately describing vertical flux and diffusion of phosphorus to the surface. Intuitively, it appears that the latter is most likely the case and further evaluation of the scenarios using phosphorus and algae comparisons would be problematic.

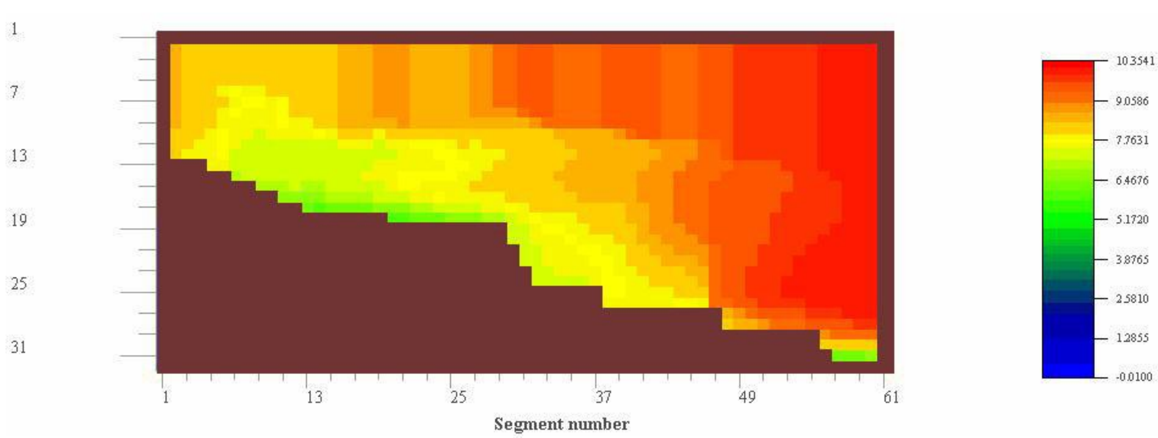
Lastly, a more practical method to determine the effects of the siphon pipe is to compare the reductions of anoxic sediment surface areas, defined for this study as the area of the lake bottom with overlying water below 1 mg/L dissolved oxygen. In figures 19 and 20, results from the1998 and 2006 scenario runs were analyzed to show the number of days and the corresponding acres of anoxic sediment within the 140 acre study area (Figure 21). A prediction of acre-days was then calculated for each scenario by integrating the area under the curves (Table 5). Not surprisingly, the model predicts that as pipe flow increases, the longevity and areal extent of anoxic sediment is reduced. In combination with existing data for phosphorus release rates from Lake Eau Claire sediments (James, et al. 1998), acre-days can also estimate anoxic internal loading of phosphorus for the study area.

In summary, the model's use of a siphon pipe does show water being drawn down from the reservoir's surface to its sediments, especially during the maximum "run of river" scenario. However, the draw down effect was seen as localized and there were still periodic stratifications during the summer months that would allow anoxic P flux from the sediments. Without a more complete mixing that kept a larger sediment area oxic throughout the summer, combined with recent studies that question whether DO or P concentrations control P sedimentation (Moosmann, L, 2006), this study believes that other alternatives should be explored to prevent anoxic build-up in the reservoir.

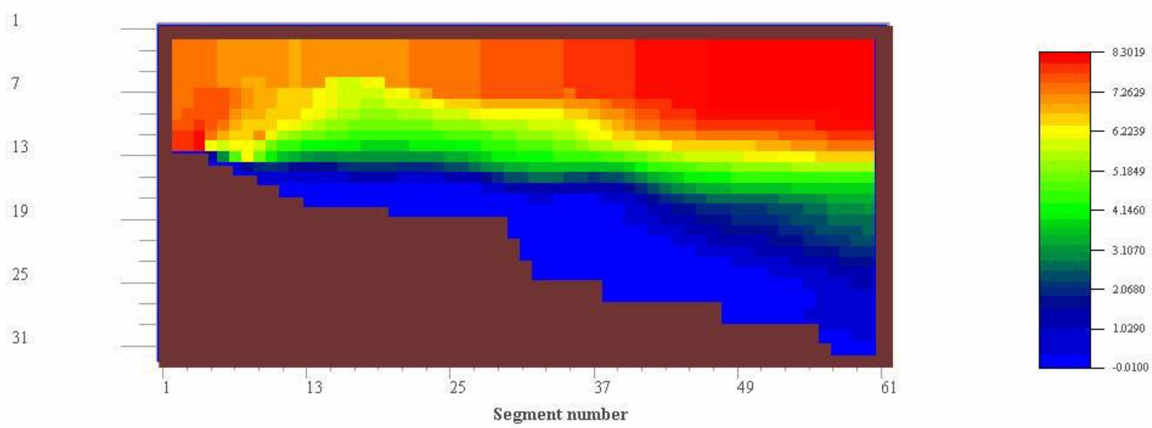
21 May 2006 – DO Calibrated Withdrawal



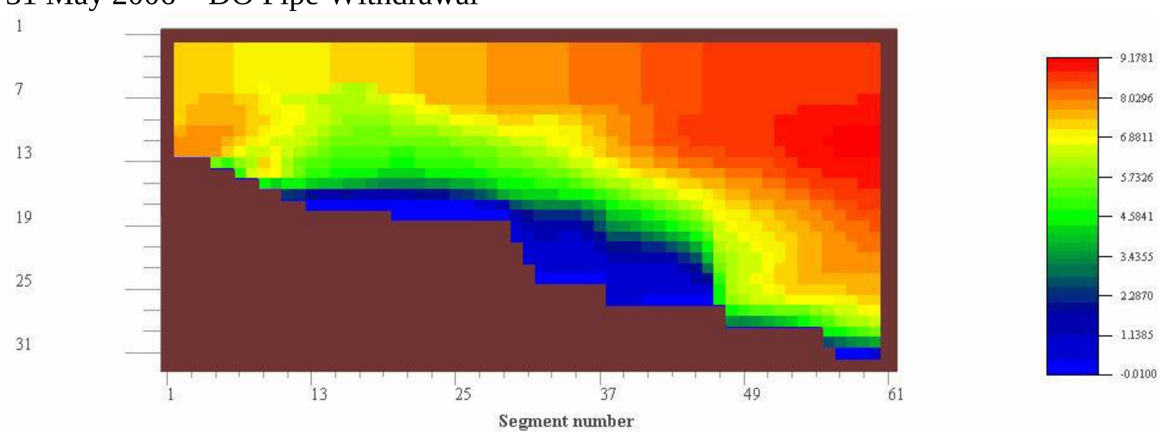
21 May 2006 – DO Pipe Withdrawal



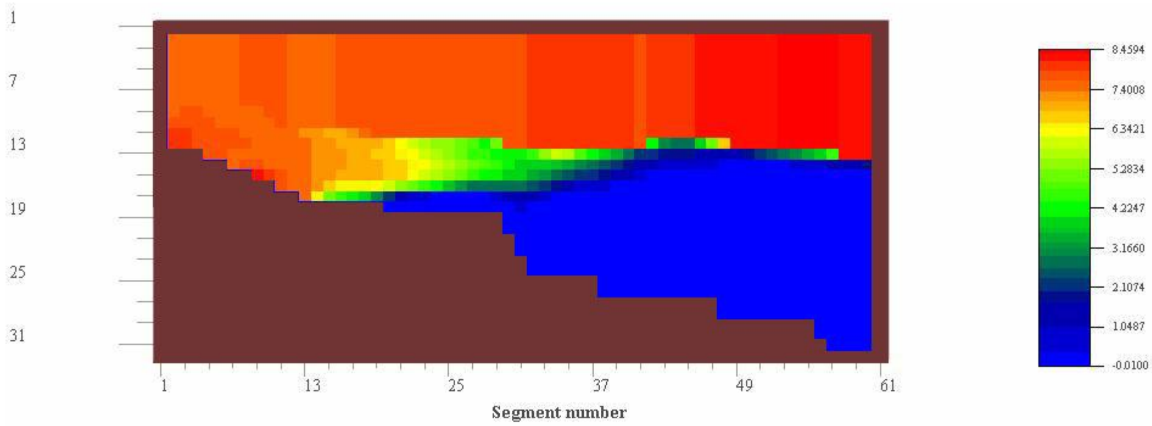
31 May 2006 – DO Calibrated Withdrawal



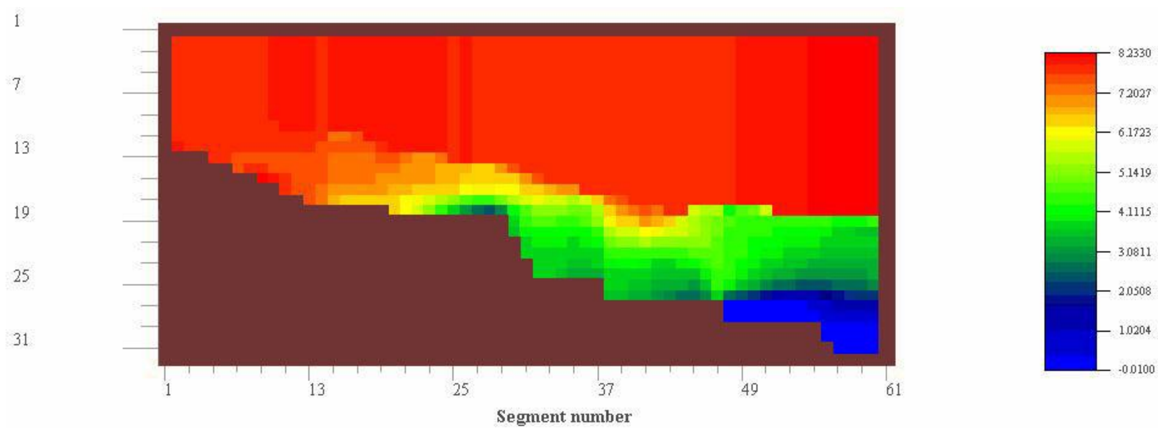
31 May 2006 – DO Pipe Withdrawal



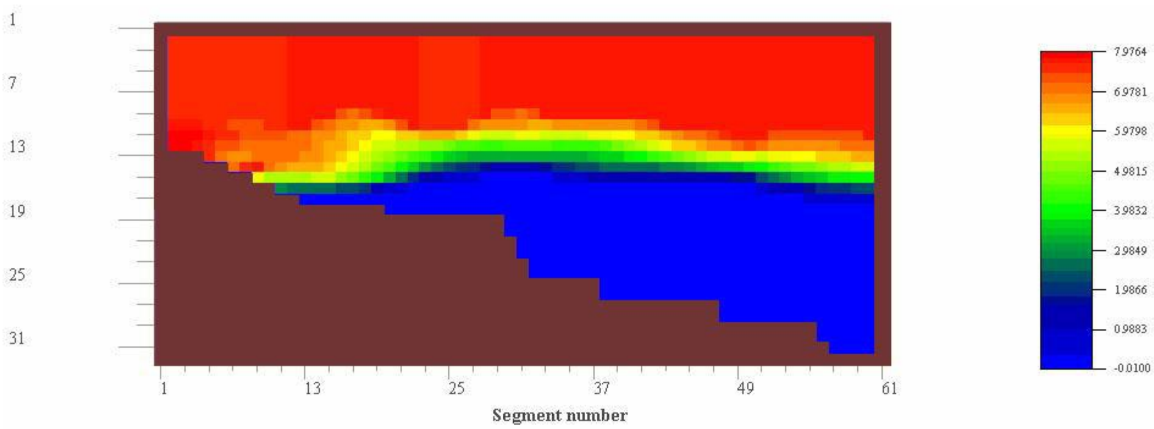
10 Jun 2006 – DO Calibrated Withdrawal



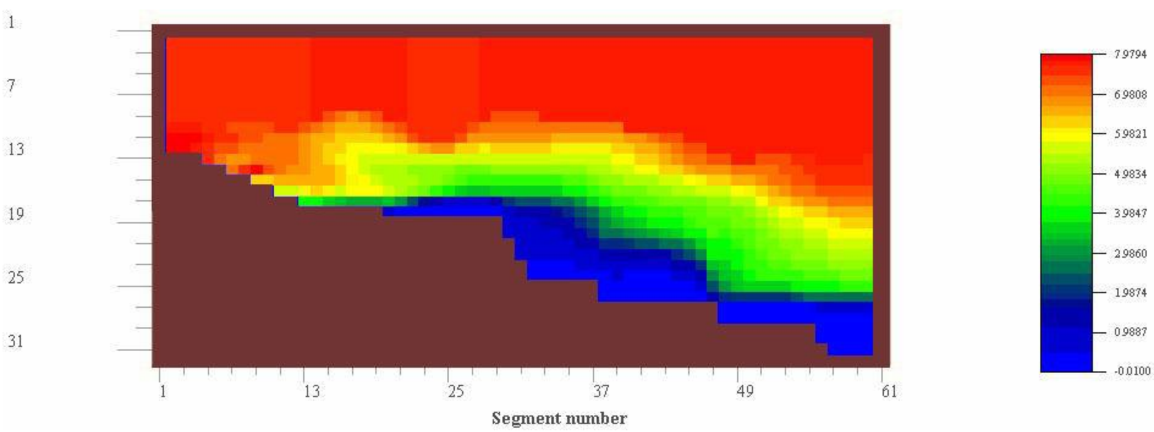
10 Jun 2006 – DO Pipe Withdrawal



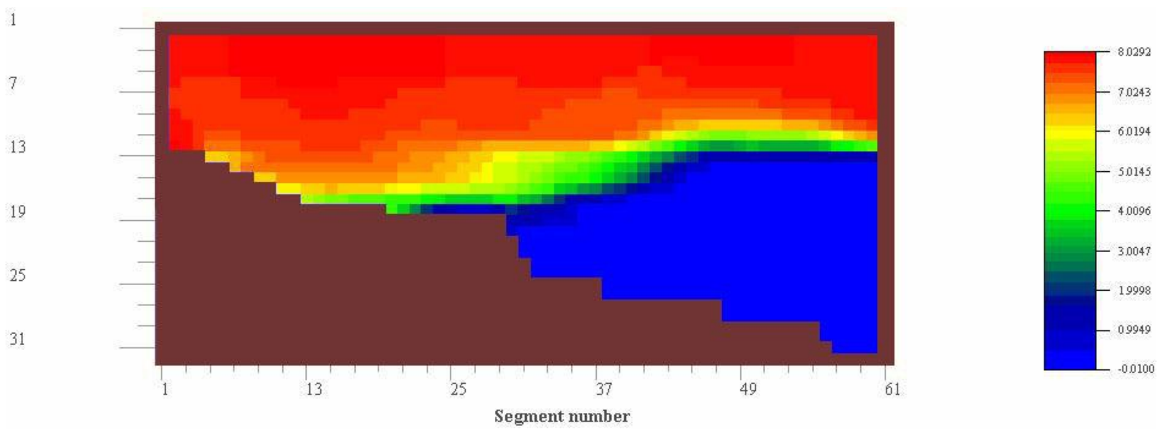
20 Jun 2006 – DO Calibrated Withdrawal



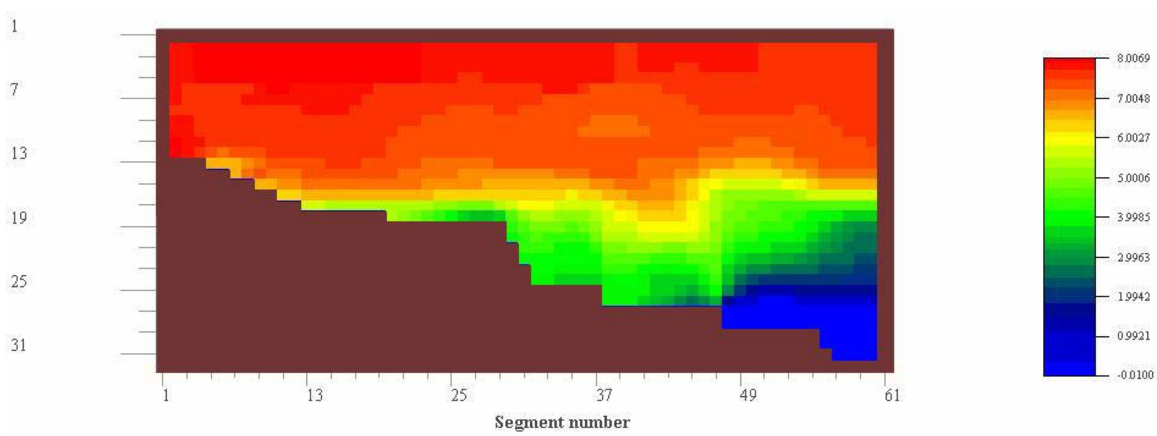
20 Jun 2006 – DO Pipe Withdrawal



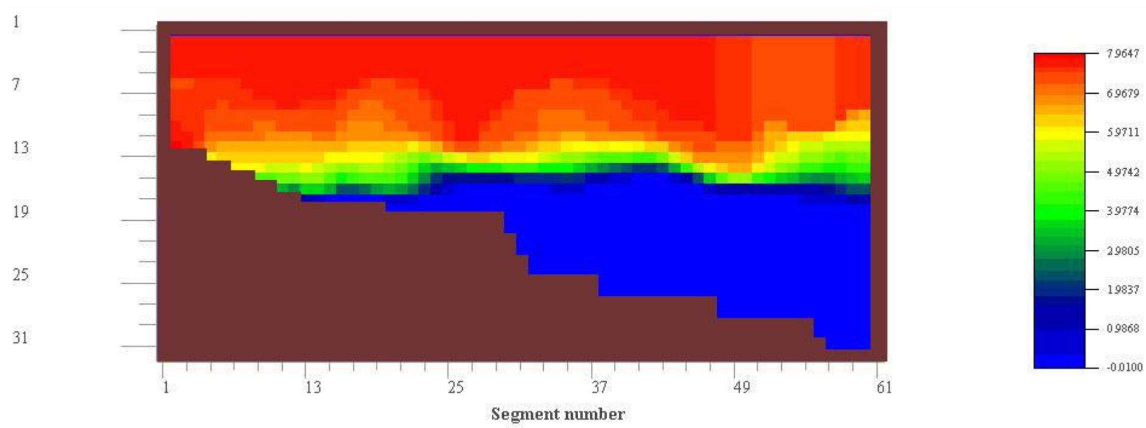
30 Jun 2006 – DO Calibrated Withdrawal



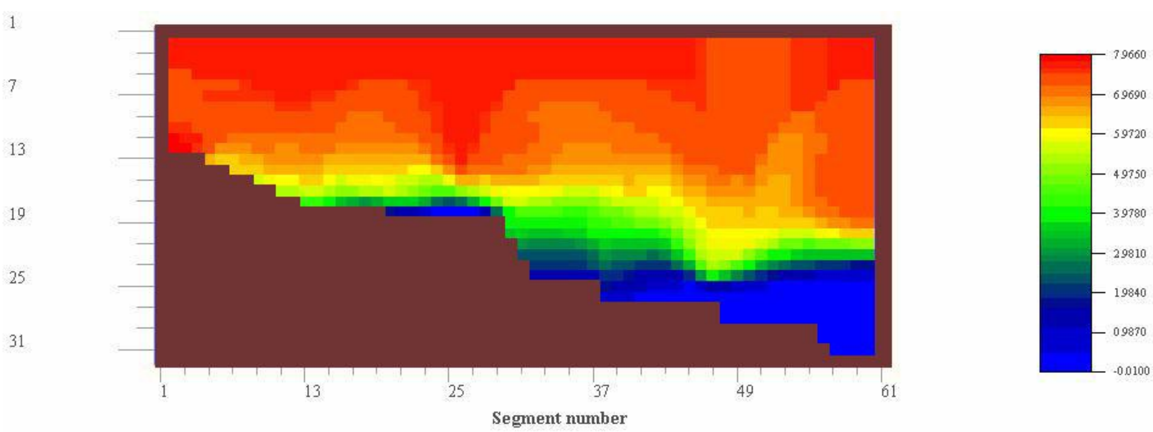
30 Jun 2006 – DO Pipe Withdrawal



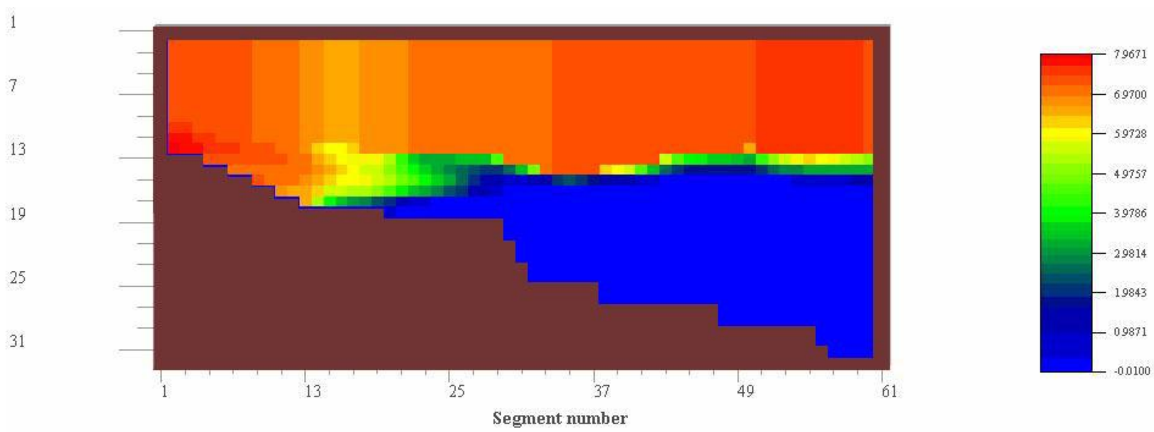
10 Jul 2006 – DO Calibrated Withdrawal



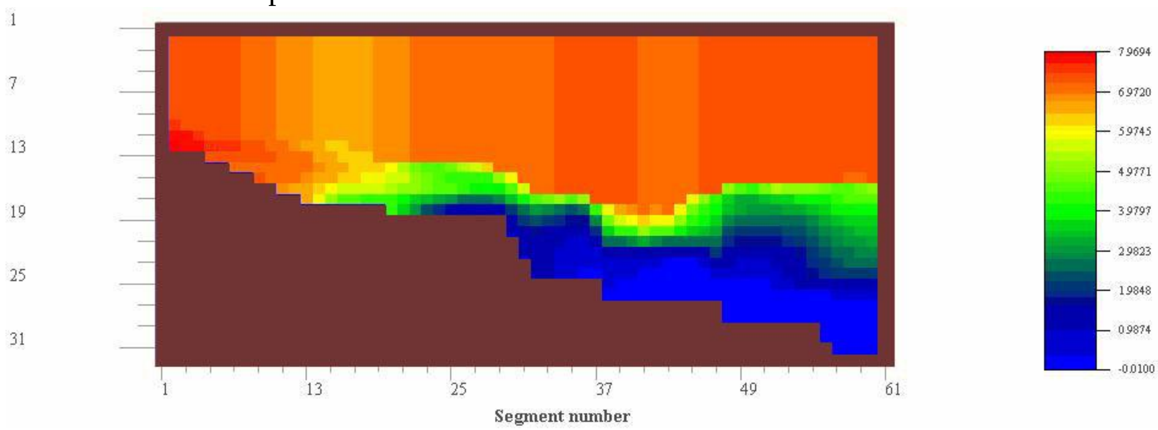
10 Jul 2006 – DO Pipe Withdrawal



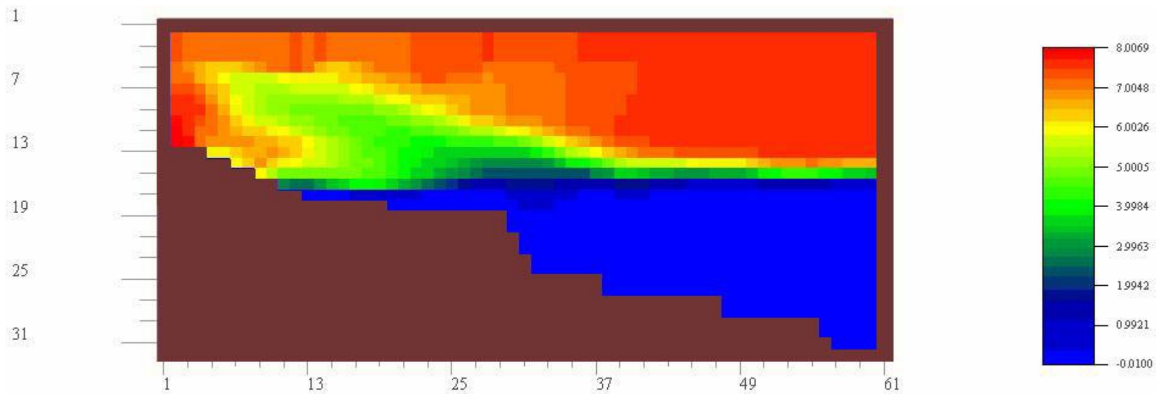
20 Jul 2006 – DO Calibrated Withdrawal



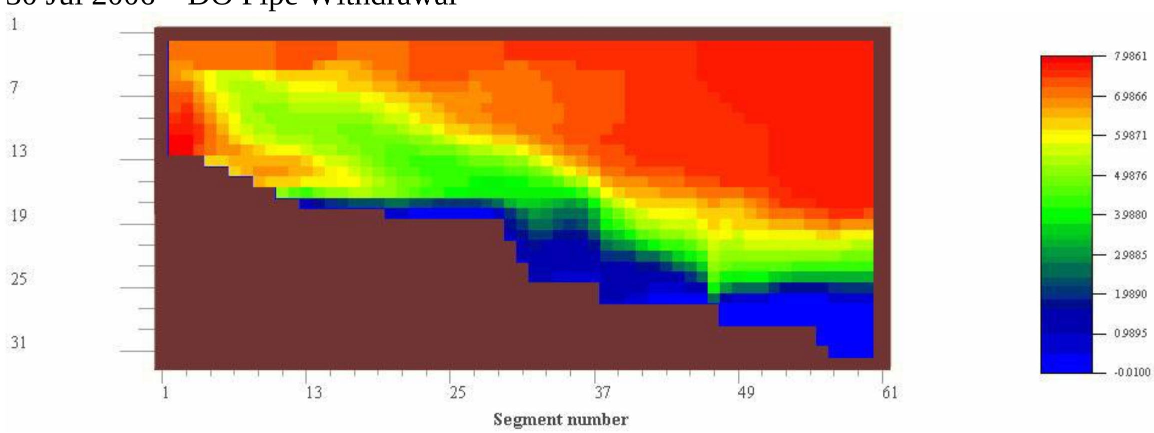
20 Jul 2006 – DO Pipe Withdrawal



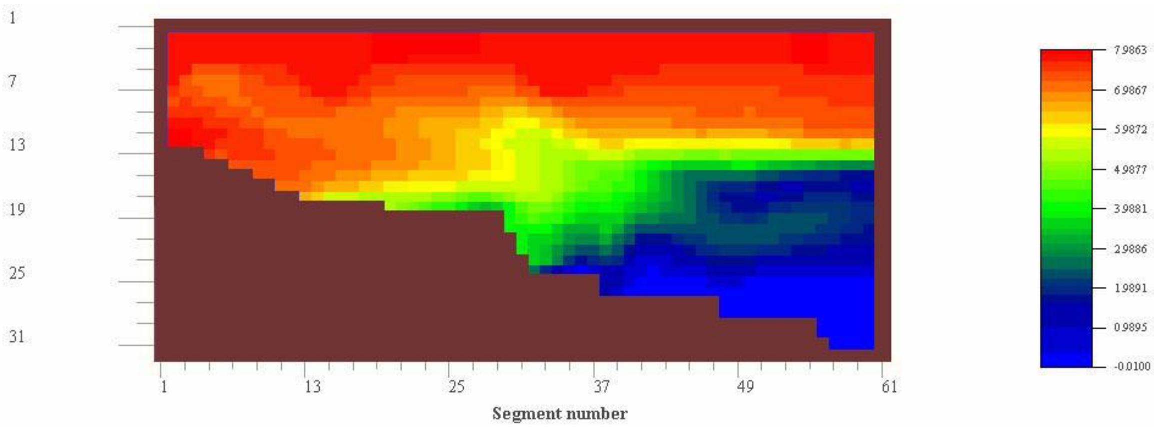
30 Jul 2006 – DO Calibrated Withdrawal



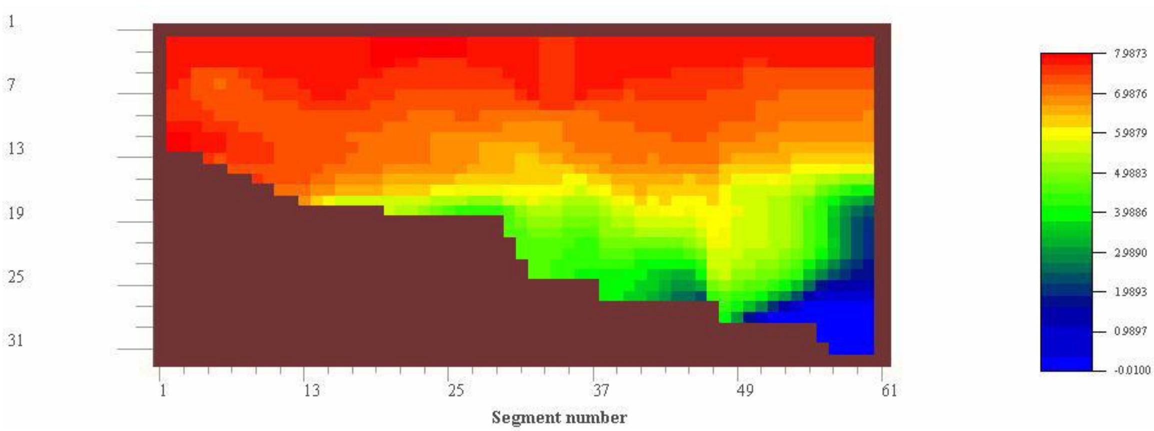
30 Jul 2006 – DO Pipe Withdrawal



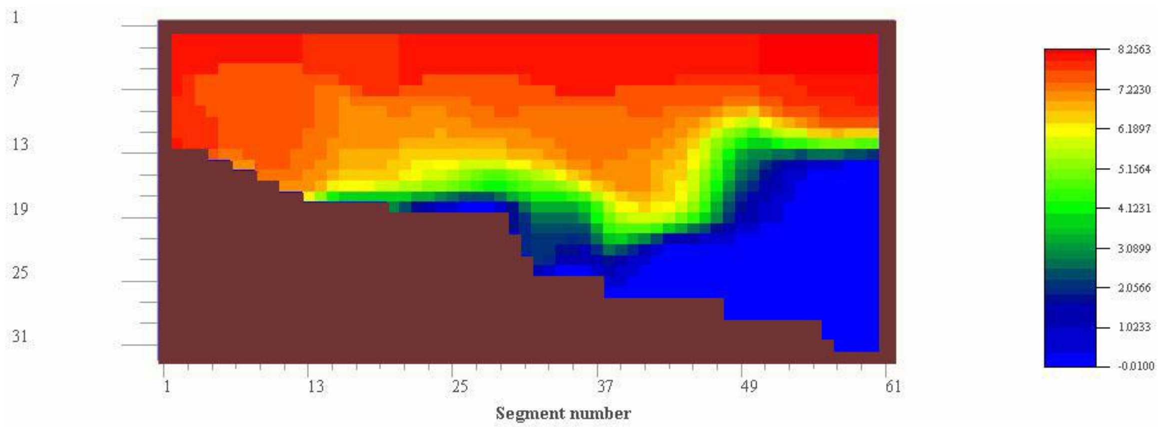
9 Aug 2006 – DO Calibrated Withdrawal



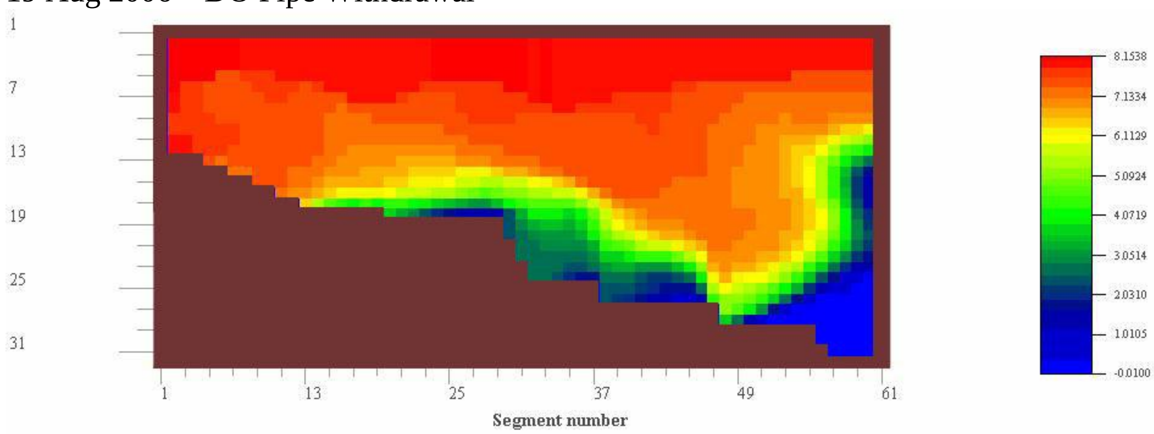
9 Aug 2006 – DO Pipe Withdrawal



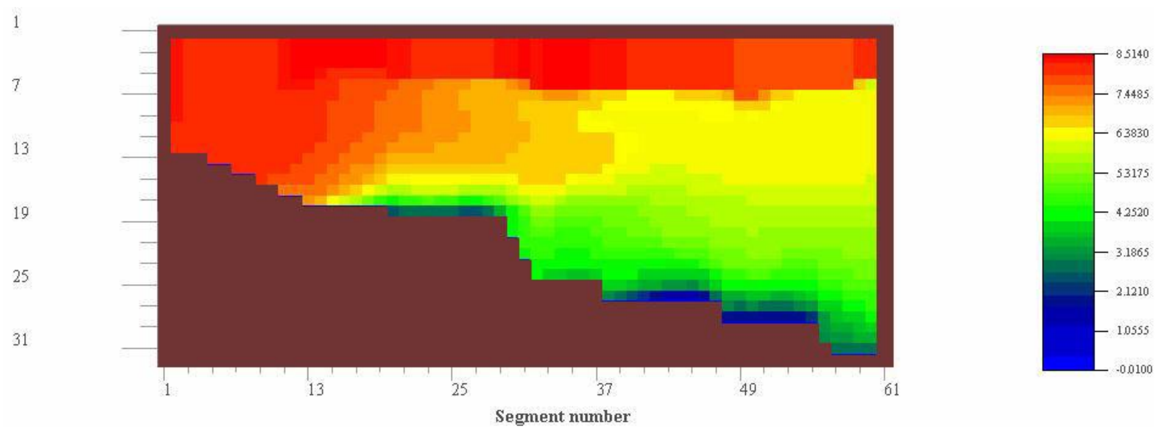
19 Aug 2006– DO Calibrated Withdrawal



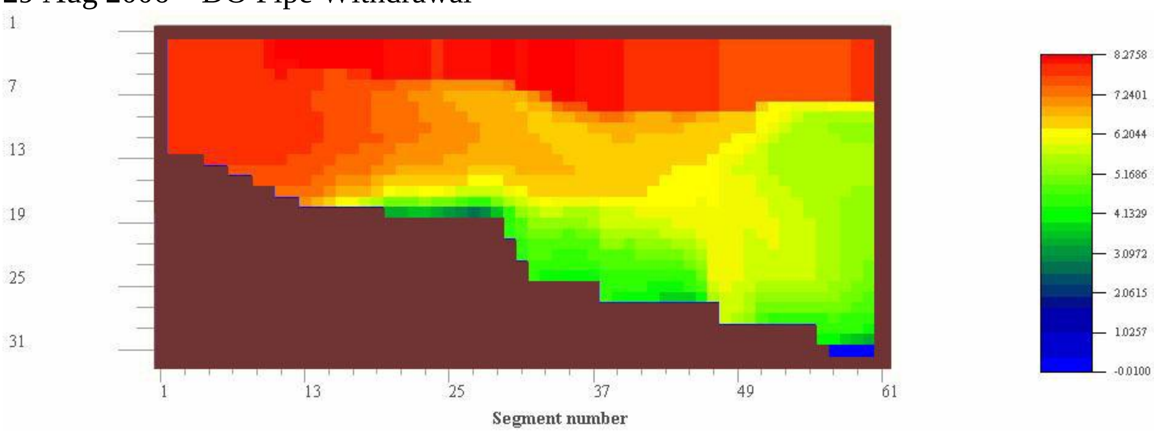
19 Aug 2006 – DO Pipe Withdrawal



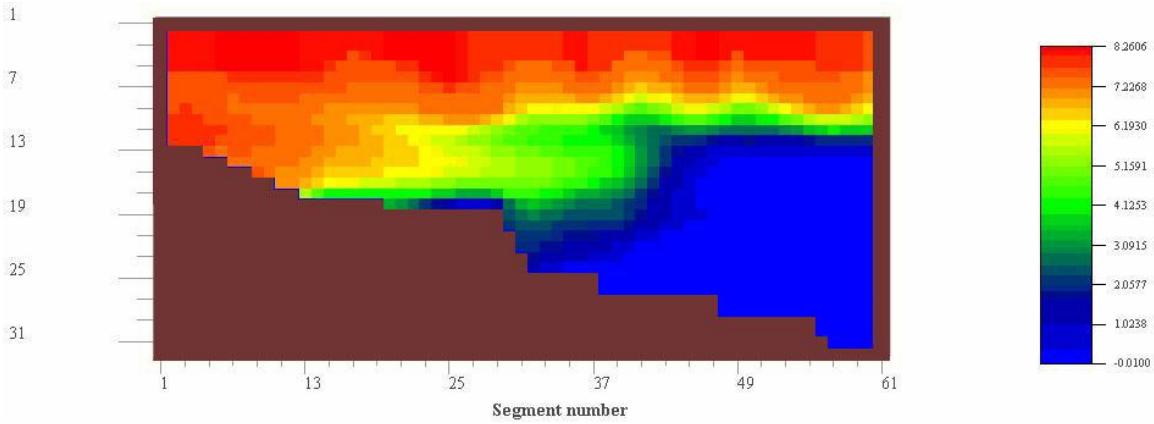
29 Aug 2006 – DO Calibrated Withdrawal



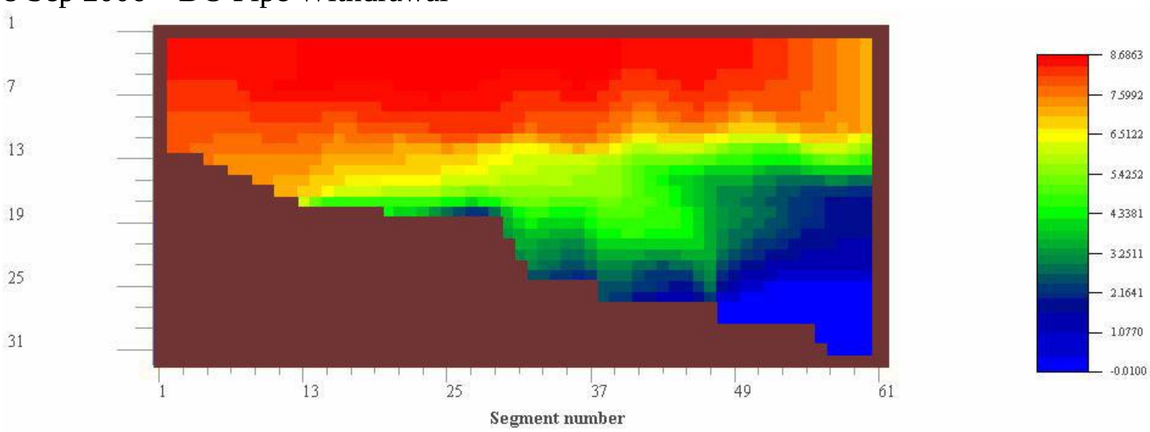
29 Aug 2006 – DO Pipe Withdrawal



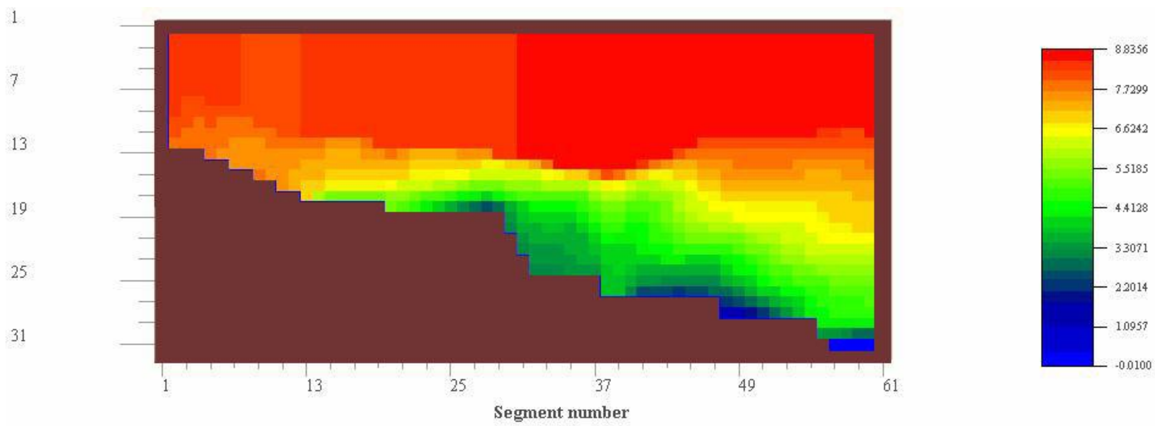
8 Sep 2006 – DO Calibrated Withdrawal



8 Sep 2006 – DO Pipe Withdrawal



18 Sep 2006 – DO Calibrated Withdrawal



18 Sep 2006 – DO Pipe Withdrawal

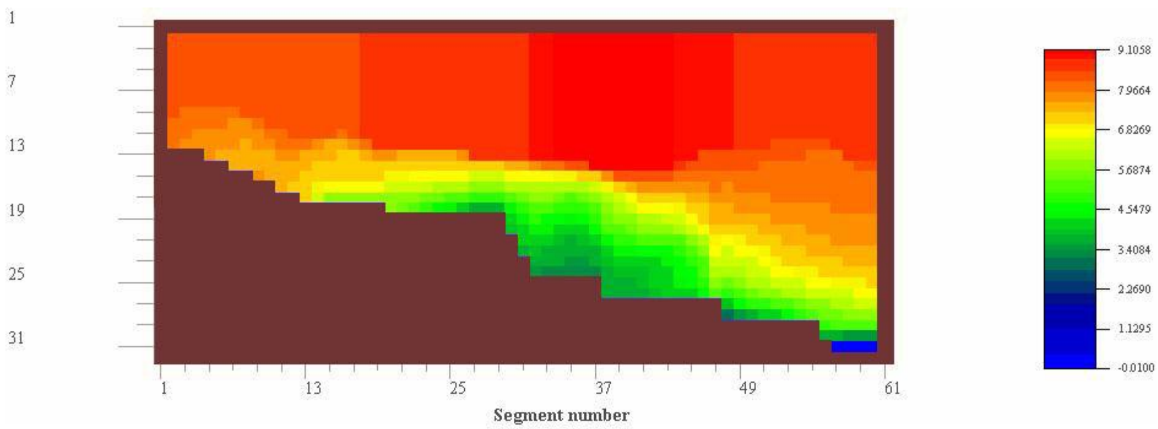


Figure 19

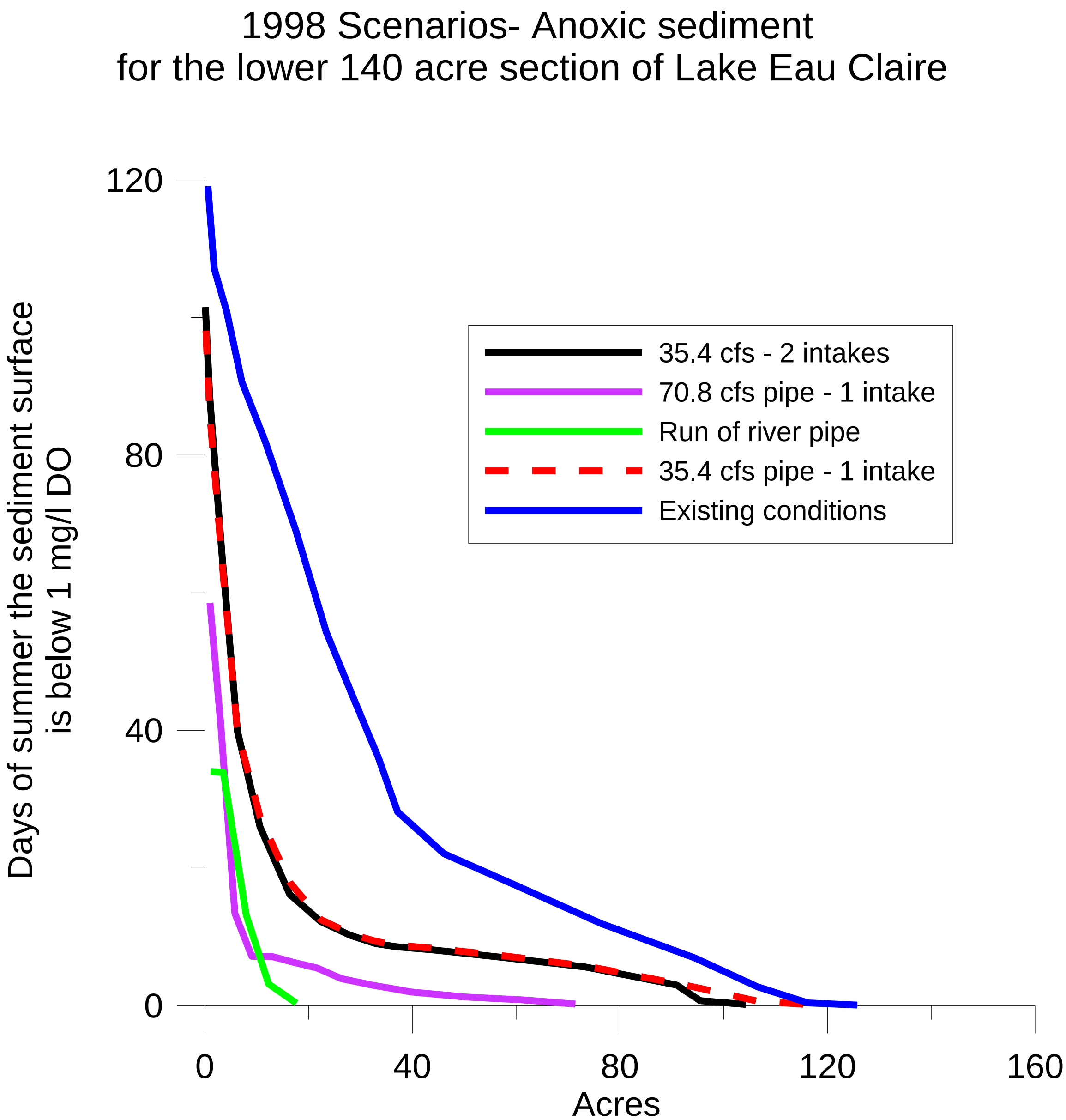

1998 Scenarios- Anoxic sediment
for the lower 140 acre section of Lake Eau Claire
Days of summer the sediment surface
is below 1 mg/l DO
120
80
40
0
0
40
80
120
160
Acres
35.4 cfs - 2 intakes
70.8 cfs pipe - 1 intake
Run of river pipe
35.4 cfs pipe - 1 intake
Existing conditions

Figure 20

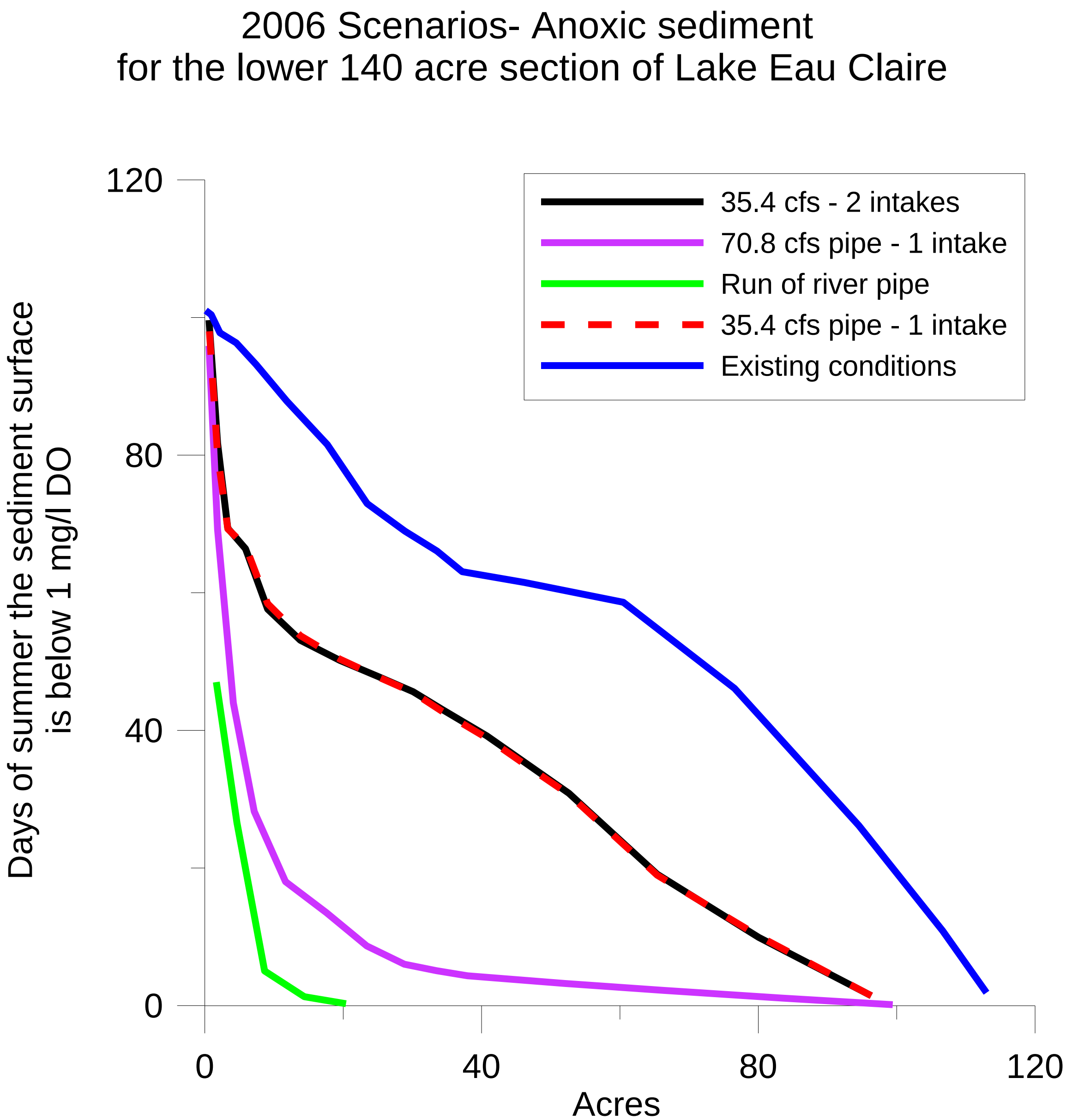

2006 Scenarios- Anoxic sediment
for the lower 140 acre section of Lake Eau Claire
Days of summer the sediment surface
is below 1 mg/l DO
120
80
40
0
0
40
80
120
Acres
35.4 cfs - 2 intakes
70.8 cfs pipe - 1 intake
Run of river pipe
35.4 cfs pipe - 1 intake
Existing conditions

Figure 21 Map of the 140 acre study area.

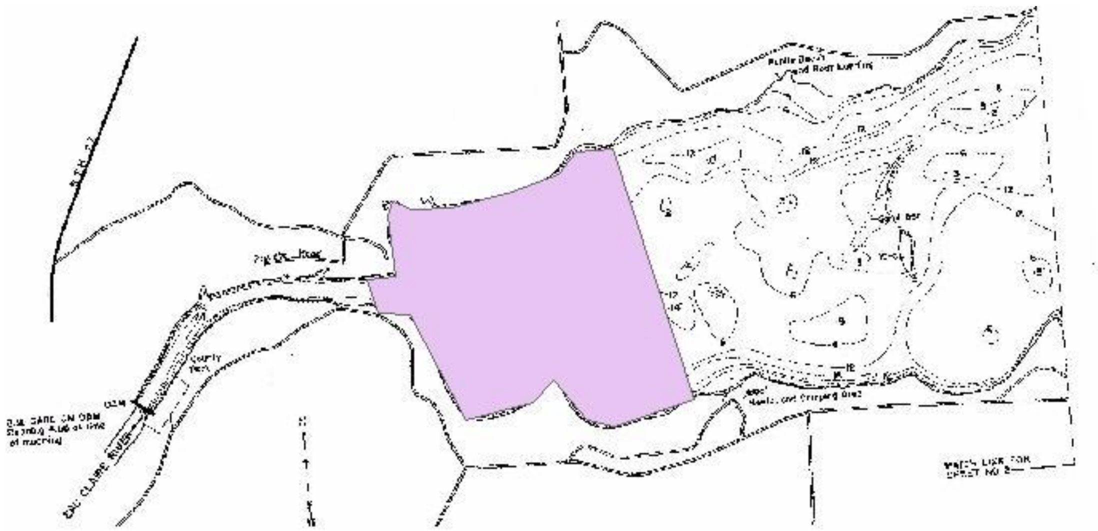


Table 5 Acre-days of anoxic sediment in the study area for each scenario

Scenarios	1998 Acre-days (Apr 18-Oct 15)	1998 % reduction from Existing Condition	2006 Acre-days (May 16-Oct 3)	2006 % reduction from Existing Condition
35.4 cfs pipe – 2 intakes	1267	63.3	3180	48.4
70.8 cfs pipe – 1 intake	417	87.9	848	86.2
Run of river pipe	251	92.7	223	96.4
35.4 cfs pipe – 1 intake	1315	62.0	3180	48.4
Existing Conditions	3457	-	6163	-

References

Ashley, K. L. (1983) Hypolimnetic aeration of a naturally eutrophic lake: Physical and chemical effects. Can. J. Fish. Aquat. Sci.40: 1343–1359.

Cole, T. M. and E. M. Buchak. (1995). CE-QUAL-W2: a two-dimensional, laterally averaged, hydrodynamic and water quality model, version 2.0 Instruction Report EL-95- U.S. Army Corps of Engineers, Waterways Experiment Station, Vicksburg. 59 p.

Cole, T M. and S A. Wells (2002) A Two-Dimensional, Laterally Averaged, Hydrodynamic and Water Quality Model, Version 3.1. User Manual. U.S. Army Corps of Engineers Instruction Report EL-02-1.

Edinger, J. E. and E. M. Buchak, (1975). A Hydrodynamic, Two Dimensional Reservoir Model: The Computational Basis, Prepared for US Army Engineer Division, Ohio River, Cincinnati, Ohio.

Einsele, W. (1936) U¨ ber die Beziehung des Eisenkreislaufs zum Phosphorkreislauf in eutrophen Seen. Arch. Hydrobiol. 29:664–686.

James, F. W., J.W.Barko, and H. L. Eakin (1998) Limnological Analysis of Lake Eau Claire, Wisconsin U.S. Army Corps of Engineers, Waterways Experiment Station, Vicksburg.

Mortimer, C. H. (1941) The exchange of dissolved substances between mud and water in lakes. J. Ecology 29: 280–329.

Moosmann, L., Gachter, R., Muller, B., and A. Wuest (2006) Is phosphorus retention in autochthonous lake sediments controlled by oxygen or phosphorus? Limnol. Oceanogr., 51(1, part 2), 763-771

Prepas, E. E., and J. M. Burke. (1997) Effect of hypolimnetic oxygenation on water quality in Amisk Lake, Alberta, a deep, eutrophic lake with high internal phosphorus loading rates. Can. J. Fish. Aquat. Sci. 54: 2111–2120.

Acknowledgments

The Army Corps of Engineers would like to acknowledge the many individuals from the Lake Eau Claire Association, Beaver Creek Reserve Citizen Science Center, Wildlands School, Eau Claire County Land Conservation Division and the Wisconsin Department of Natural Resources whose assistance made this project possible. The many individuals from these groups assisted by collecting lake data, mapping the lake, providing technical review and financial assistance.