HYDRAULIC AND WATER QUALITY MODELING OF OPENING SMITH AND BYBEE LAKES TO THE LOWER COLUMBIA SLOUGH

by

Scott A. Wells
Professor

Technical Report EWR-6-95

Research sponsored by
Metro,
Solid Waste Department

Portland State University
1995

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ENVIRONMENTAL AND WATER RESOURCES ENGINEERING
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Acknowledgments

The project managers at METRO, Joanna Karl and Jim Morgan, were instrumental in obtaining necessary data for the modeling effort and guiding the modeling effort. Dennis O'Neal in the Solid Waste Department also contributed to the success of this modeling study. Their assistance is gratefully acknowledged.

A series of reports have been written on Columbia Slough at Portland State University. A listing of some of these reports are shown below:

Report Number	Date	Title	Author(s)	Research Sponsor
EWR-1-92	2/92	Assessment of Management Alternatives for Water Quality Improvement in the Columbia Slough System, Vol. 1 & Vol. 2	Wells, S.	City of Portland
EWR-2-92	3/92	Lower Columbia Slough System Field Data Summaries - August 1990 through June 1991	Wells, S.	City of Portland
EWR-3-92	3/92	User's Manual for the Columbia Slough Model Using CE-QUAL-W2	Wells, S.	City of Portland
EWR-4-92	3/92	Storm Runoff and CSO Simulation in the Lower Columbia Slough	Laliberte, D.	City of Portland
EWR-5-92	3/92	Bybee and Smith Lake Discharge Models	Laliberte, D.	City of Portland
EWR-6-92	5/92	St. John's Landfill and Columbia Slough System Water Quality Database	Collins, D. and Wells, S.	METRO
EWR-8-92	8/92	Analysis of Management Alternatives for Improving Water Quality in North Slough Adjacent to the St. John's Landfill	Wells, S.	METRO
EWR-5-93	10/93	Predicting Seepage of Leachate from the St. Johns Landfill to Ground and Surface Water Systems	Schock, Kevin A. (Thesis advisor: S. Wells)	METRO
EWR-2-94	4/94	Upper and Lower Columbia Slough Water Level Test: September 1 through October 29, 1993	Wells, Scott A. Berger, Chris	City of Portland Bureau of Env. Services
EWR-1 -95	4/95	Analysis of Impacts of Flow Augmentation from Smith and Bybee Lakes on North Slough Dissolved Oxygen Conditions	Wells, S.	METRO
EWR-2- 95	4/95	Hydraulic and Water Quality Modeling of the Upper and Lower Columbia Slough: Model Calibration, verification, and Management Alternatives Report for 1992-1995	Wells, S. and Berger, C.	City of Portland
EWR- 3- 95	4/95	Upper and Lower Columbia Slough Water Level Test and Winter Sampling Analysis: June 1994-March 1995	Wells, S. and Berger, C.	City of Portland
EWR- 7-95	4/95	Modeling the Hydraulcs of the Discharge Structure at the end of North Slough	Boyko, M. and Wells, S.	METRO

1. INTRODUCTION

The Lower Columbia Slough is about 9 miles and from 50 ft to 200 ft wide water body in the Portland metropolitan area. The Lower Columbia Slough, as shown in Figure 1, is connected to the Willamette River where it experiences a tidal fluctuation of between 1 to 3 ft resulting in peak inflows of up to 1000-2000 cfs and peak outflows (but of longer duration) of up to 1000 cfs. Inflows to the Lower Columbia Slough include combined-sewer-overflows (CSOs), storm water (from storm water pipes and from pump stations on the Northern edge of the Lower Slough), water from Smith and Bybee Lakes and from the Upper Columbia Slough.

The Upper Columbia Slough is maintained to provide irrigation water to agricultural and commercial users. At MCDD1, gravity pipes and pumps allow water from the Upper Slough to enter the Lower Slough. In the summer, the water entering the Upper Slough and discharged to the Lower Slough is primarily nutrient-rich groundwater.

The Lower Columbia Slough often exceeds Oregon Department of Environmental Quality goals of 15 μg/l of chlorophyll a. Water quality data in HDR (1994) show that often the pH exceeds 8.5, chlorophyll a exceeds 15 μg/l, and dissolved oxygen is super-saturated, except in the North Slough. Wells and Berger (1994) showed that a major cause of the high algae growth in the Lower Columbia Slough was primarily from discharges of nutrient and algal rich water from the Upper Slough. N also was in excess because of groundwater N concentrations coming into the Upper Slough of 6 mg/l NO_3-N. Wells (1995) showed that dissolved oxygen levels in the North Slough were often below 50% saturation and that it was related to a lack of mixing of water in the North Slough.

The North Slough was open to Bybee Lake prior to the construction of a water control structure at the east end of North Slough (ENS) in 1983. This structure was built to reduce the probability of avian botulism by keeping water from ponding into stagnant pools during low water periods. METRO and other agencies have recently looked into opening up the Lakes again to the North Slough.

In order to evaluate the impacts of opening up the Lakes to North Slough, a modeling study of the Lakes was performed in this report assessing the hydraulics in the Lakes and the impact on the lakes of CSOs, the Willamette River, and leachate from the St. John's Landfill during low-water and high-water conditions.

The present modeling study was an enlargement of a model study of the Lower Columbia Slough initially described in Wells (1992a). Calibration of the Lower Slough model was performed and management alternatives simulated in Wells and Berger (1994) and more recently by Wells and Berger (1995).

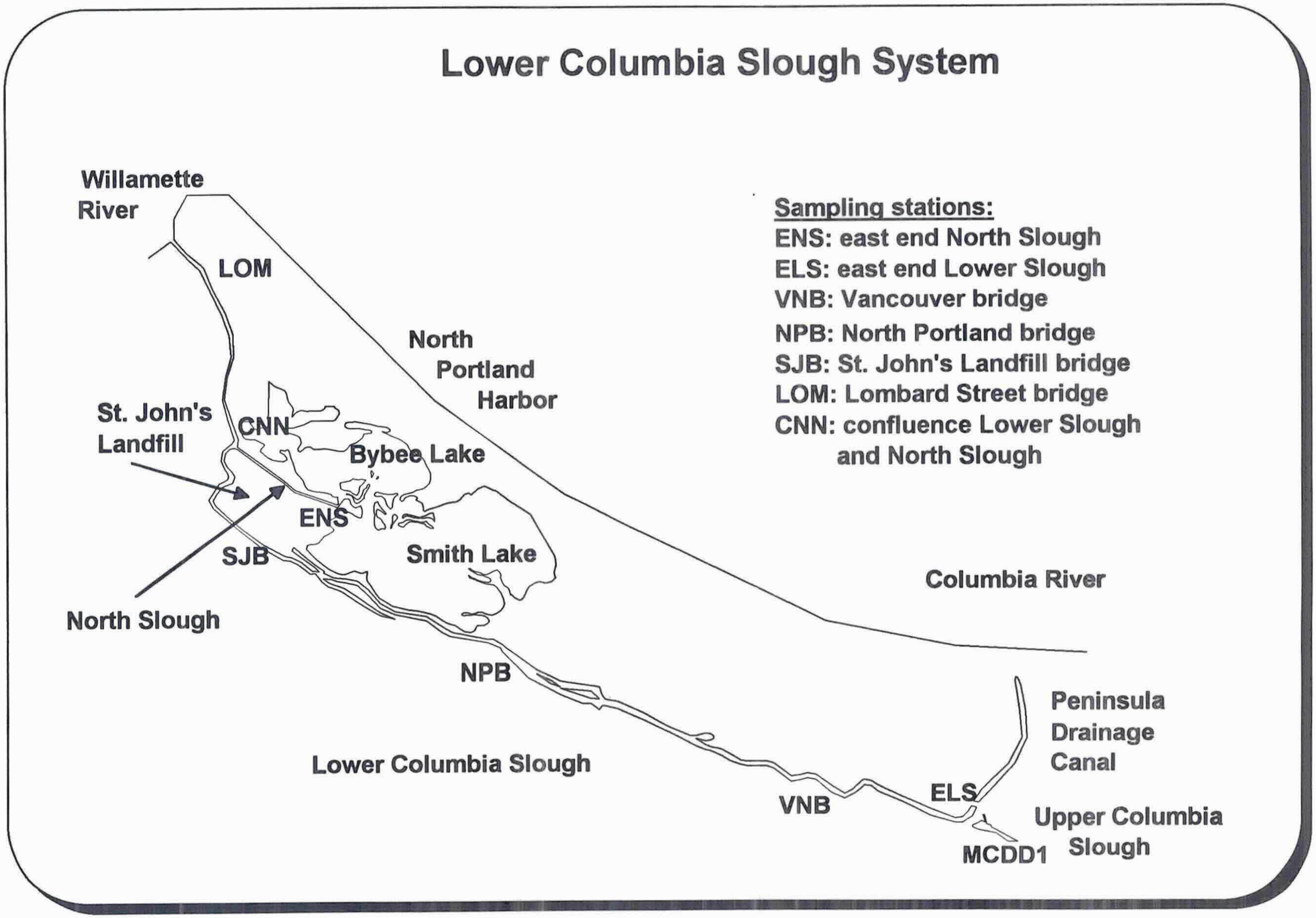

Figure 1. The Lower Columbia Slough.

2. EXISTING LOWER SLOUGH MODEL DESCRIPTION

The water quality and hydrodynamic model used for the Lower Columbia Slough was an adaptation of the Corps of Engineers' model CE-QUAL-W2 (Corps of Engineers, 1986, 1990; Cole and Buchak, 1994). Detailed descriptions of the model theory, model boundary conditions, and the rationale for using this two-dimensional (longitudinal and vertical) model were described in Wells (1992a). Figure 2 shows the layout of the 100 longitudinal cells and the 2 branches for the Lower Columbia Slough model. Table 1 shows the vertical cell layout for the Lower Slough model and Table 2 shows physical model characteristics.

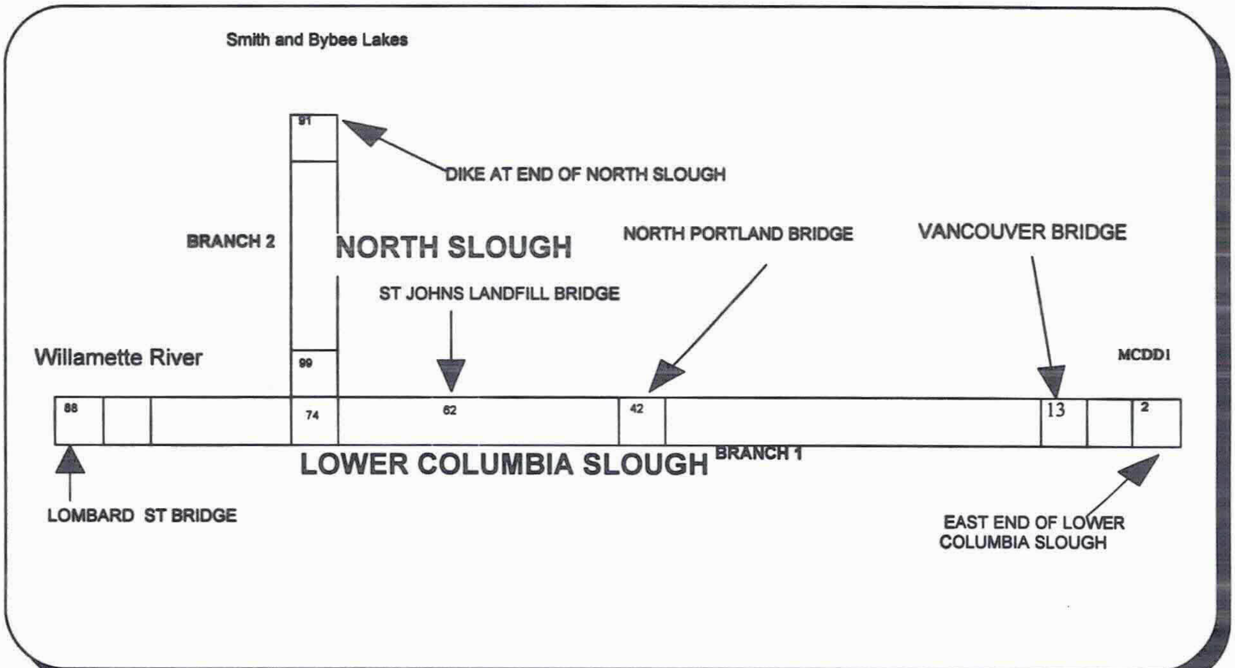

Figure 2. Longitudinal cell and branch layout for the Lower Columbia Slough model described in Wells (1992a).

The Lower Slough is dominated by flows from tidal fluctuations of the Willamette River and inflows from MCDD1, CSOs, and storm water. CSO and storm water inflows to the Lower Slough have been modeled by LaLiberte (1992), Juza (1993), OTAK (1993), and Woodward-Clyde (1993). These storm water and CSO loadings were simulated for 1990, 1991, and 1992, but were not simulated for 1993 and 1994.

Because the storm water and CSO loadings were simulated during the 1990 and 1991 periods and because tidal height data for 1990 and 1991 were typical of tidal data obtained between 1990 and 1995, the model simulation periods chosen for this study were during the summer of 1990 (low-water, summer rain events) and the winter/spring of 1991 (high-water, numerous rain events). A summary of storm water and CSO characteristics for these time periods were shown in Wells (1992a).

Table 1. Vertical cell layout for Lower Columbia Slough model.

Vertical cell number	Elevation of top of cell in ft MSL	Elevation of top of cell in m MSL
1	20 (inactive)	6.1 (inactive)
2	18	5.49
3	16	4.88
4	14	4.27
5	12	3.66
6	10	3.05
7	8	2.44
8	6	1.83
9	5	1.53
10	4	1.22
11	3	0.92
12	2	0.61
13	1	0.31
14	0	0
15	-1	-0.31
16	-2	-0.61
17	-3 (inactive)	-0.92 (inactive)

Table 2. Model characteristics of the Lower Columbia Slough model.

Model	**Longitudinal cells, IMP**	**Vertical cells, KMP**	**Number of branches, NBP**	**Longitudinal cell spacing, dx, m**	**Vertical cell spacing, dz, m**
Lower Columbia Slough	100	17	5	153 (500 ft)	0.31-0.61 (1-2 ft)

3. ADDITION OF SMITH AND BYBEE LAKES TO LOWER SLOUGH MODEL

The bathymetry of the Smith and Bybee Lakes have been defined by data taken by Fishman et al (1986) and were evaluated in Wells (1992a). Historical photographs were obtained from Jim Morgan at METRO to evaluate more carefully the channel morphology and to update the bathymetric maps.

Channel centerlines were developed for the Lakes based on these aerial photographs. Along these centerlines additional points with an elevation of 4 ft MSL were added to the original soundings data. A new bathymetric map was then produced as shown in Figure 3.

Based on the geometry of the deep channels, the lake was divided into 4 sections or segments and cross-sections were taken every 500 ft along the main flow line or channel as shown in Figures 4 through 7. From these slices of the topographic map, cell widths as a function of elevation were input to the CE-QUAL-W2 model. A detailed cell-by-cell breakdown of this geometry is shown in Appendix A.

A new longitudinal cell layout was constructed with the CE-QUAL-W2 model including the 4 Lake segments as shown in Figure 8. The new model has 152 model cells of about 500 ft in length and 5 model branches. Branch 1 is the Lower Columbia Slough; Branch 2 is North Slough connected to Smith Lake (including the main channel into Smith Lake); Branch 3 is the southern arm of Smith Lake; Branch 4 is the main arm of Bybee Lake; and Branch 5 is the northern arm of Bybee Lake. An alternative layout is to connect the end of North Slough with Bybee Lake arm, rather than directly to the narrow channel separating Smith and Bybee Lake. The effect of connecting model branches in this way is shown in Section 6.1.

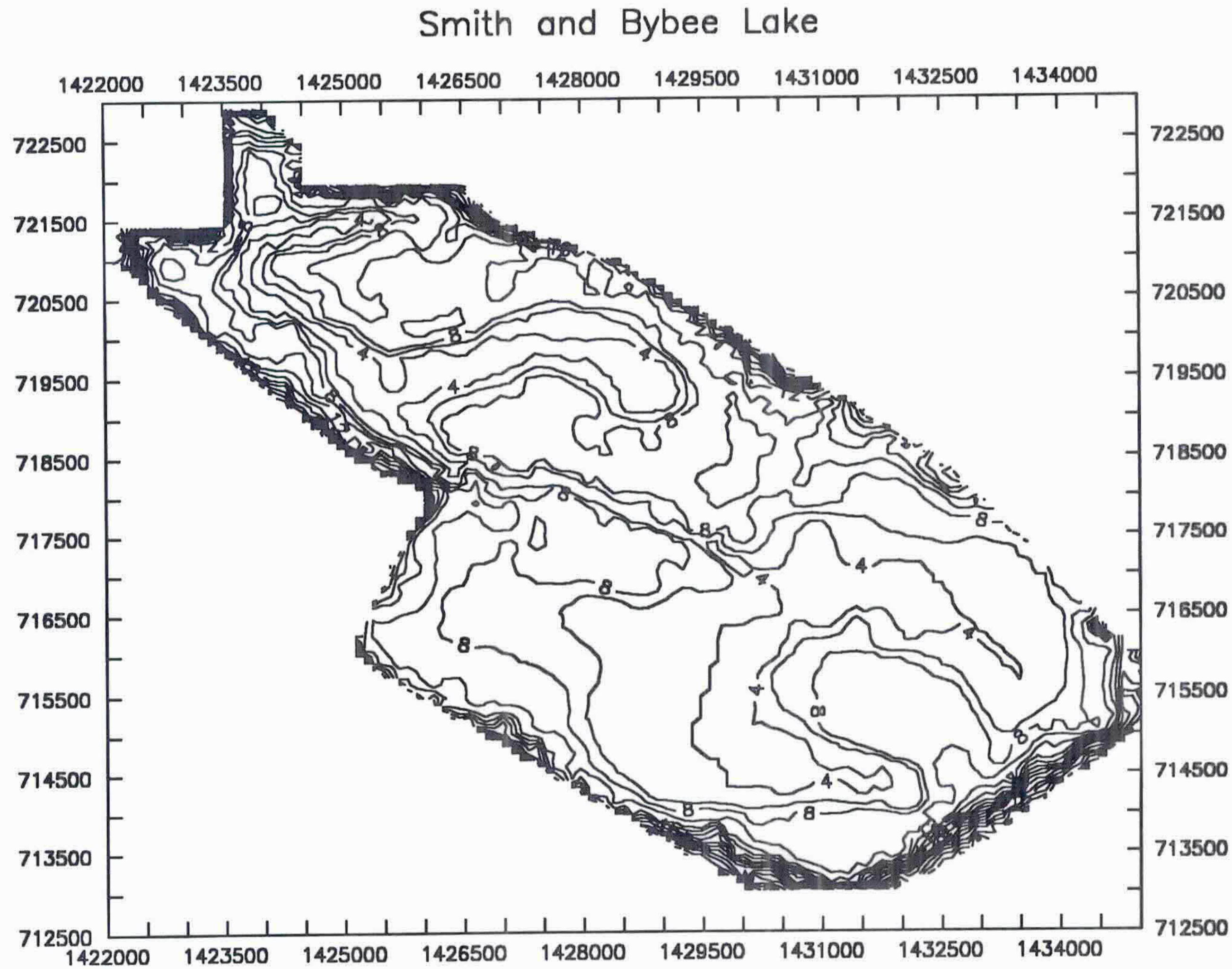

Figure 3. Bathymetric map of Smith and Bybee Lakes (distances are in ft).

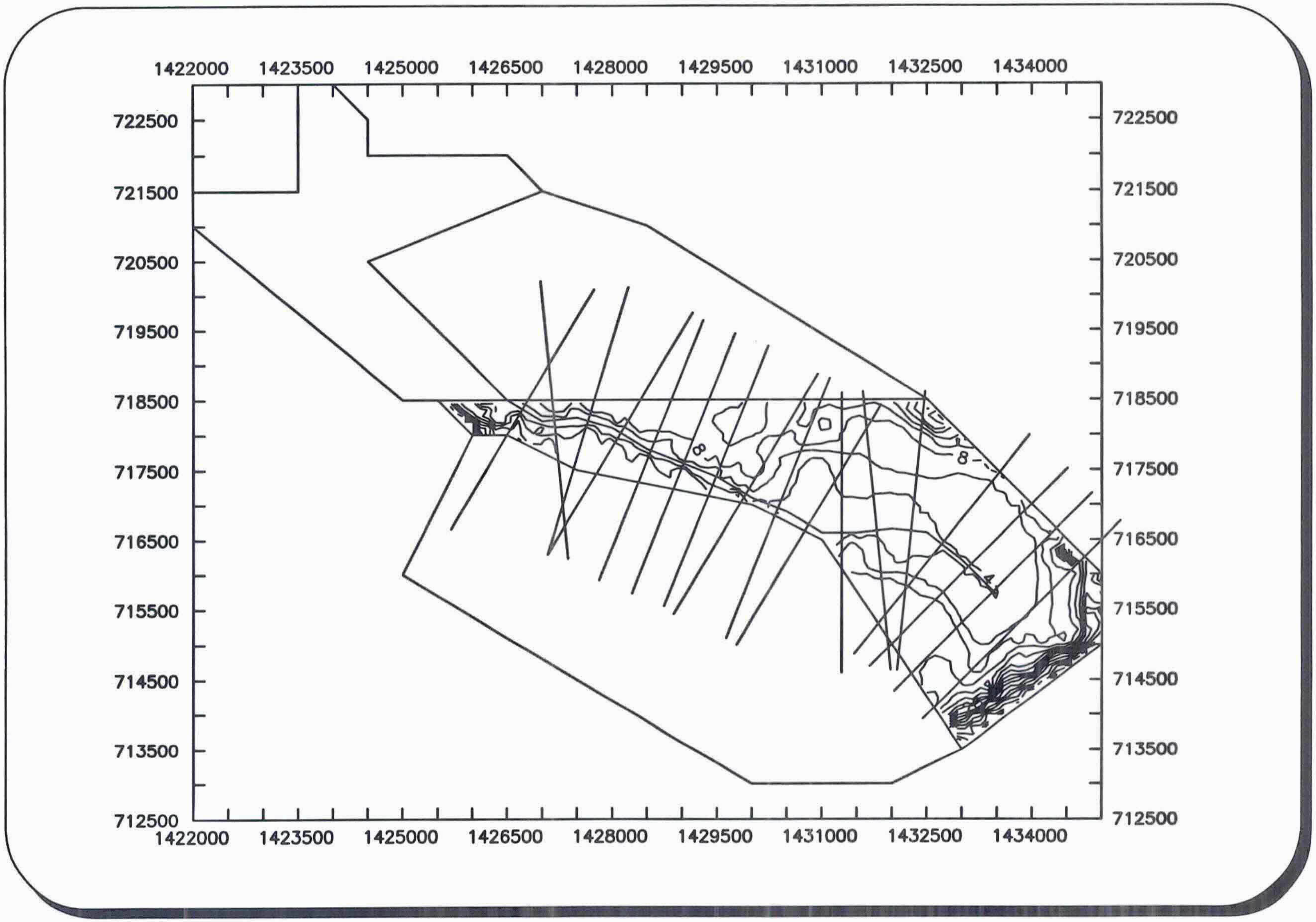

Figure 4. Segment 1 of Smith and Bybee Lakes with cross-sectional slices used for model cell geometry.

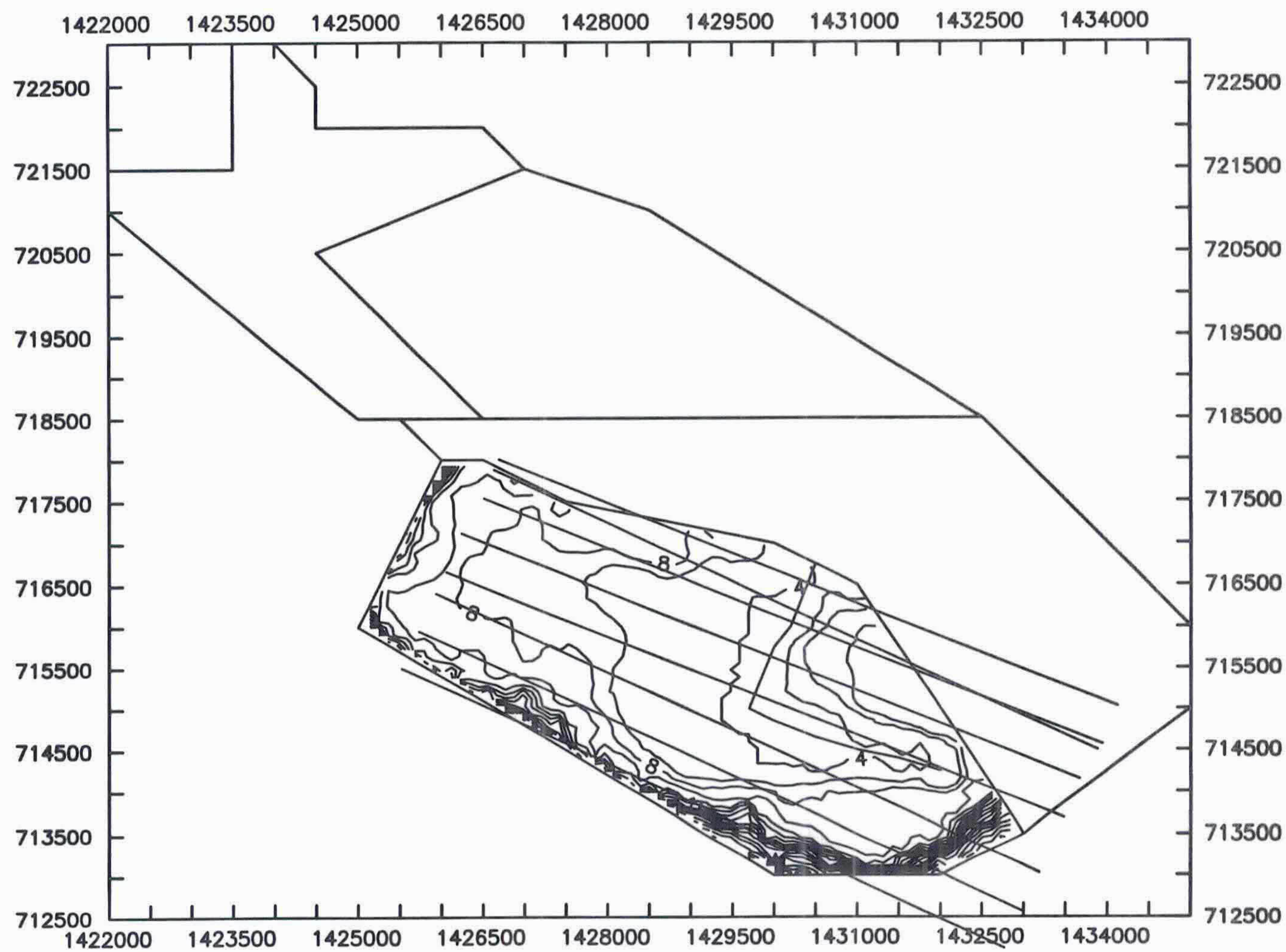

Figure 5. Segment 2 of Smith and Bybee Lakes with cross-sectional slices used for model cell geometry.

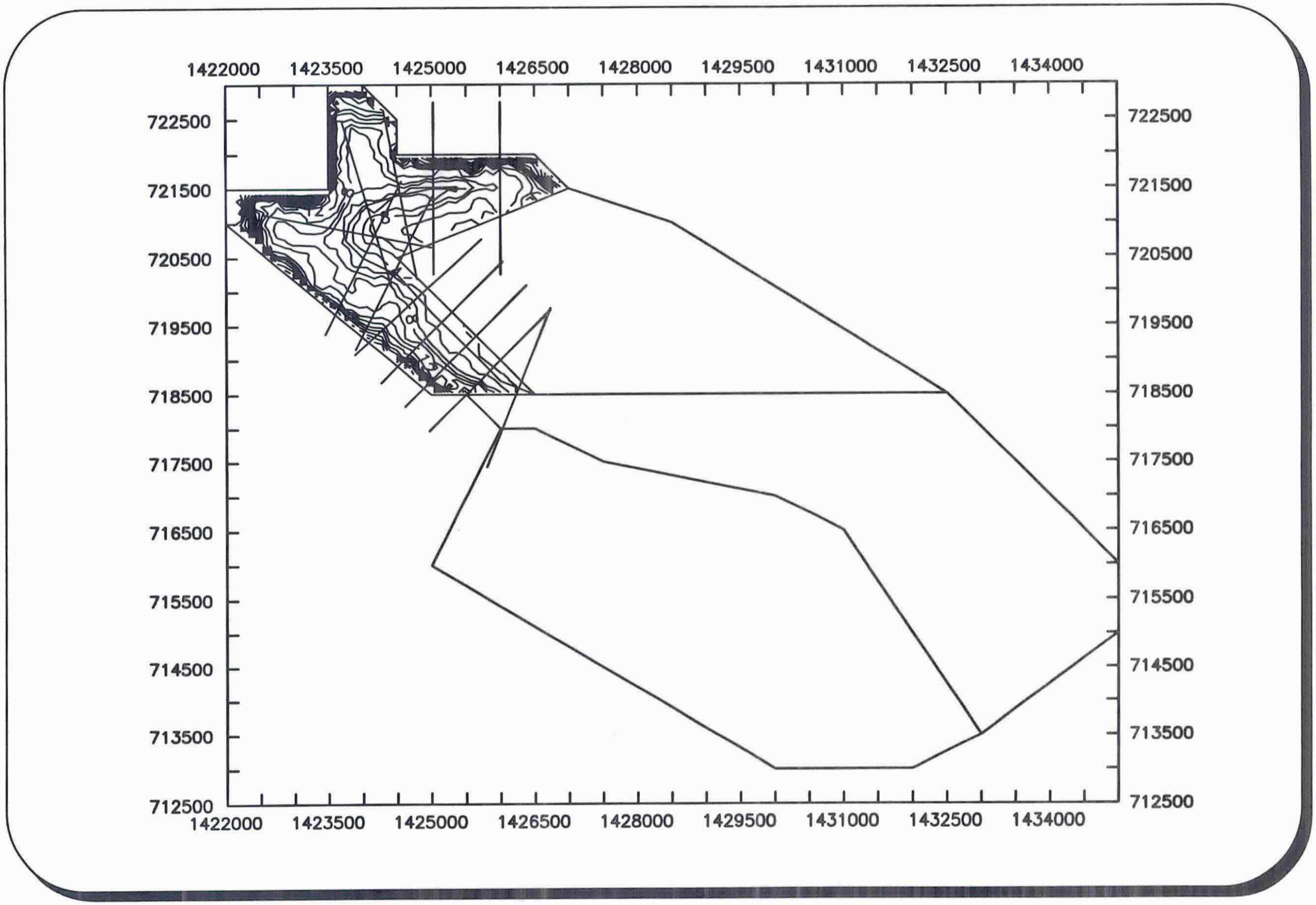

Figure 6. Segment 3 of Smith and Bybee Lakes with cross-sectional slices used for model cell geometry.

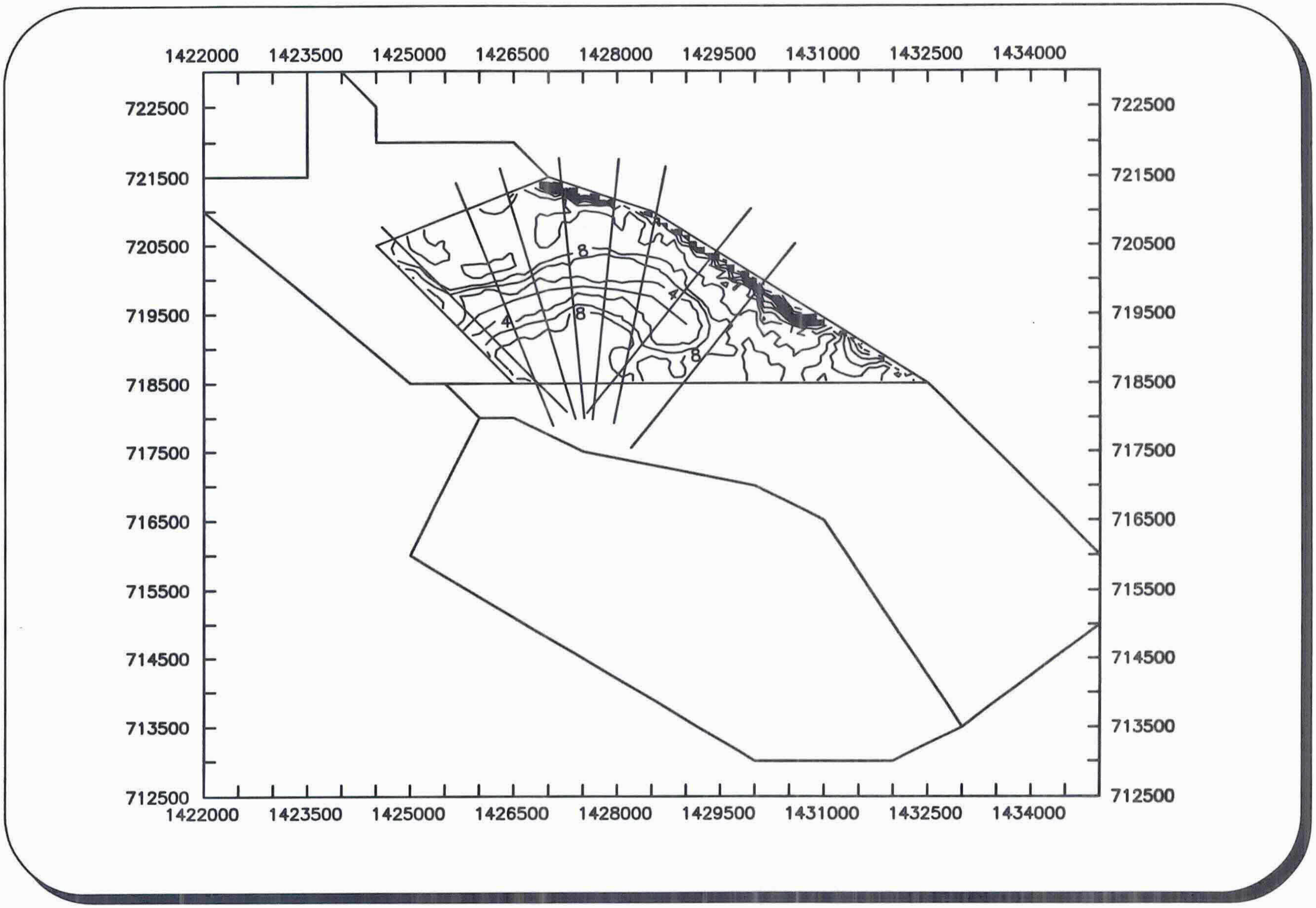

Figure 7. Segment 4 of Smith and Bybee Lakes with cross-sectional slices used for model cell geometry.

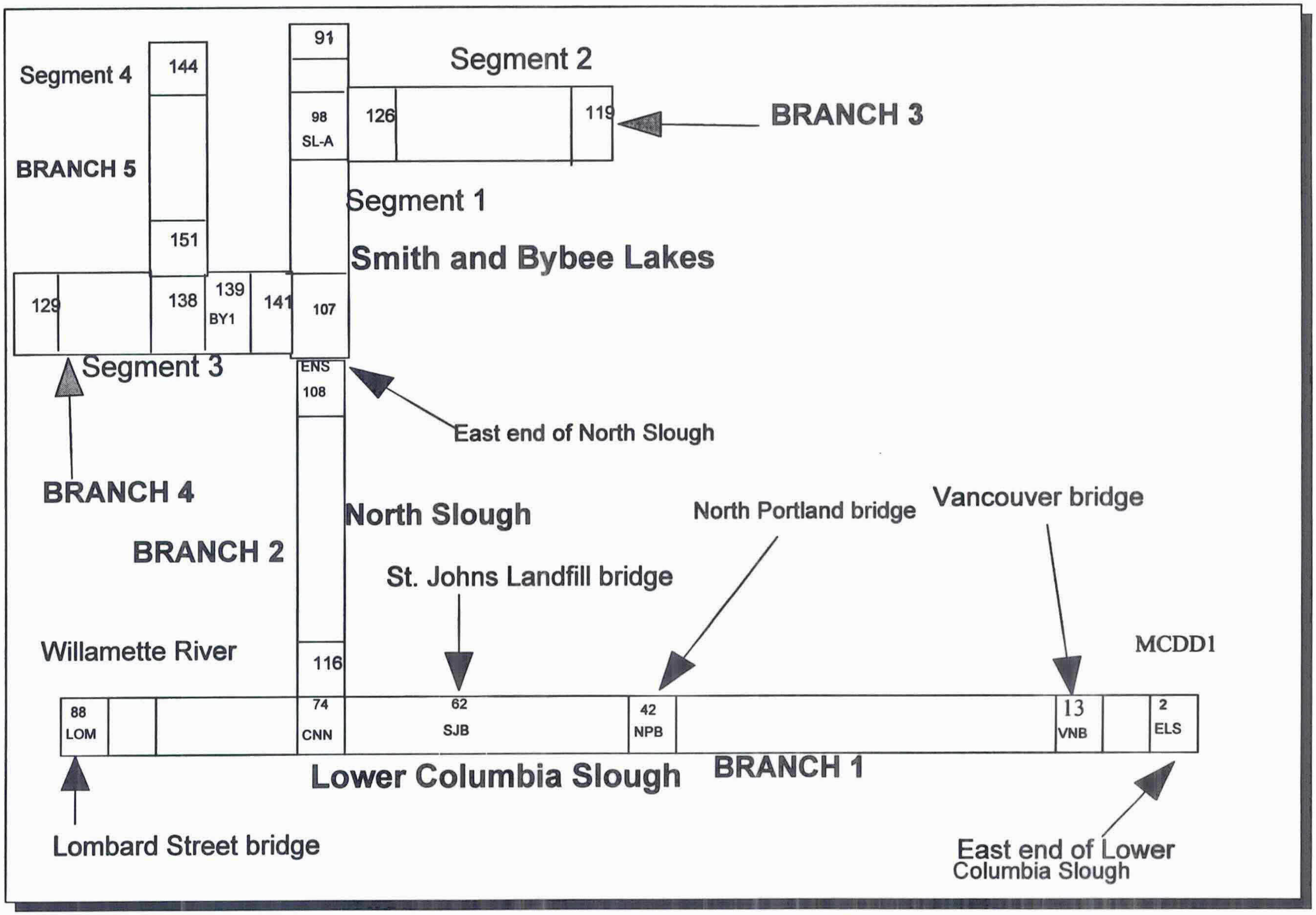

Figure 8. Model cell layout for the Lower Columbia Slough model with Smith and Bybee Lakes.

4. MODEL SIMULATIONS

In order to evaluate the impact of CSOs, Willamette River, and landfill leachate on Smith and Bybee Lakes, model simulations were performed evaluating the transport of a conservative tracer from each source independently under low-water and high-water conditions. The time period 8/8/90 through 9/11/90 was chosen as the low-water period and 2/8/91 through 4/2/91 was chosen as the high-water period. Table 3 summarizes the simulation numbers for each of the simulations. (Note that in Section 6 additional model simulations are presented evaluating the sensitivity of the model to variation in branch layout and Manning's friction factor.)

Table 3. Summary of model simulations during low-water and high-water conditions.

Run number	Time period of simulation	Description
1	8/8/90-9/11/90	Low water, 4 storm events, CSO tracer conc 100 mg/l, WRR* tracer 0 mg/l, landfill tracer 0 mg/l
2	2/8/91-4/2/91	High water, 15 storm events, CSO tracer conc 100 mg/l, WRR* tracer 0 mg/l, landfill tracer 0 mg/l
3	8/8/90-9/11/90	Low water, 4 storm events, WRR* tracer conc 100 mg/l, CSO tracer 0 mg/l, landfill tracer 0 mg/l
4	2/8/91-4/2/91	High water, 15 storm events, WRR* tracer conc 100 mg/l, CSO tracer 0 mg/l, landfill tracer 0 mg/l
5	8/8/90-9/11/90	Low water, 4 storm events, Landfill leachate tracer 463 mg/l**, CSO tracer 0 mg/l, WRR* tracer 0 mg/l
6	2/8/91-4/2/91	High water, 15 storm events, Landfill leachate tracer 463 mg/l**, CSO tracer 0 mg/l, WRR* tracer 0 mg/l

* WRR=Willamette River outside mouth of Columbia Slough

** The value of 100 mg/l of tracer in the CSOs and Willamette River was arbitrary, but the 463 mg/l in the landfill leachate was measured concentration of Cl^- in landfill seeps (unless noted, the background concentrations of tracer were set equal to 0 for each run)

4.1 Common Model Characteristics for All Simulations

The water quality model simulated the water levels, velocities, and the following water quality variables: dissolved oxygen, temperature, algae, nutrient dynamics, pH, alkalinity, coliform bacteria, suspended solids (inorganic and organic), soluble BOD, and a conservative tracer. The CSO and storm flows and water quality were determined by model simulation and this modeling effort was discussed in LaLiberte (1992) and Wells (1992a). For the boundary conditions with the Willamette River and the Upper Columbia Slough inflow, field data were used for water quality concentrations and temperature.

Recent information was provided by METRO (1995) on the landfill leachate loading. The landfill leachate was distributed along all the North Slough cells (9 model cells) and those cells of the Columbia Slough adjoining the landfill (14 model cells). The subsurface flow rate into the Columbia Slough cells was set at 0.070 cfs/14 or 0.005 cfs for each cell. The subsurface flow rate into the North Slough was set at 0.024 cfs/9 or 0.0027 cfs for each cell. The water quality concentrations of the leachate were estimated as those coming from landfill seeps (Metro, 1995): soluble PO_4-P of 0.39 mg/l, NH_4-N of 286 mg/l, soluble ultimate BOD of 122 mg/l (estimated from a BOD_5 of 48 mg/l). Other concentration data were estimated from historical data taken in the landfill wells: NO_3-N of 0.07 mg/l, dissolved oxygen of 3 mg/l, alkalinity of 500 mg/l as $CaCO_3$, and pH of 7.1.

Sediment oxygen demands were lowered in North Slough from those chosen by Wells (1992a) from 5 g/m^2/day to 1.0 g/m^2/day because the earlier model simulations did not account for the landfill leachate. Wells (1995) shows that this leachate theoretical oxygen demand is over 1400 mg/l.

4.2 Low-Water Characteristics 8/8/90-9/11/90

During this period, water levels ranged from a low of about 2.5 ft MSL to a high of almost 8.5 ft MSL. Figure 9 shows the water level variation during this period at Lombard Street bridge (the downstream model boundary condition). During this summer period, there were also 4 storm events which are itemized in Table 4.

4.3 High-Water Characteristics 2/8/91-4/2/91

During the high-water period, water levels ranged from a low of about 6 ft MSL to a high of almost 11.5 ft MSL. Figure 10 shows the water level variation during this period at Lombard Street bridge (the downstream model boundary condition). During this summer period, there were also 15 storm events which are itemized in Table 5.

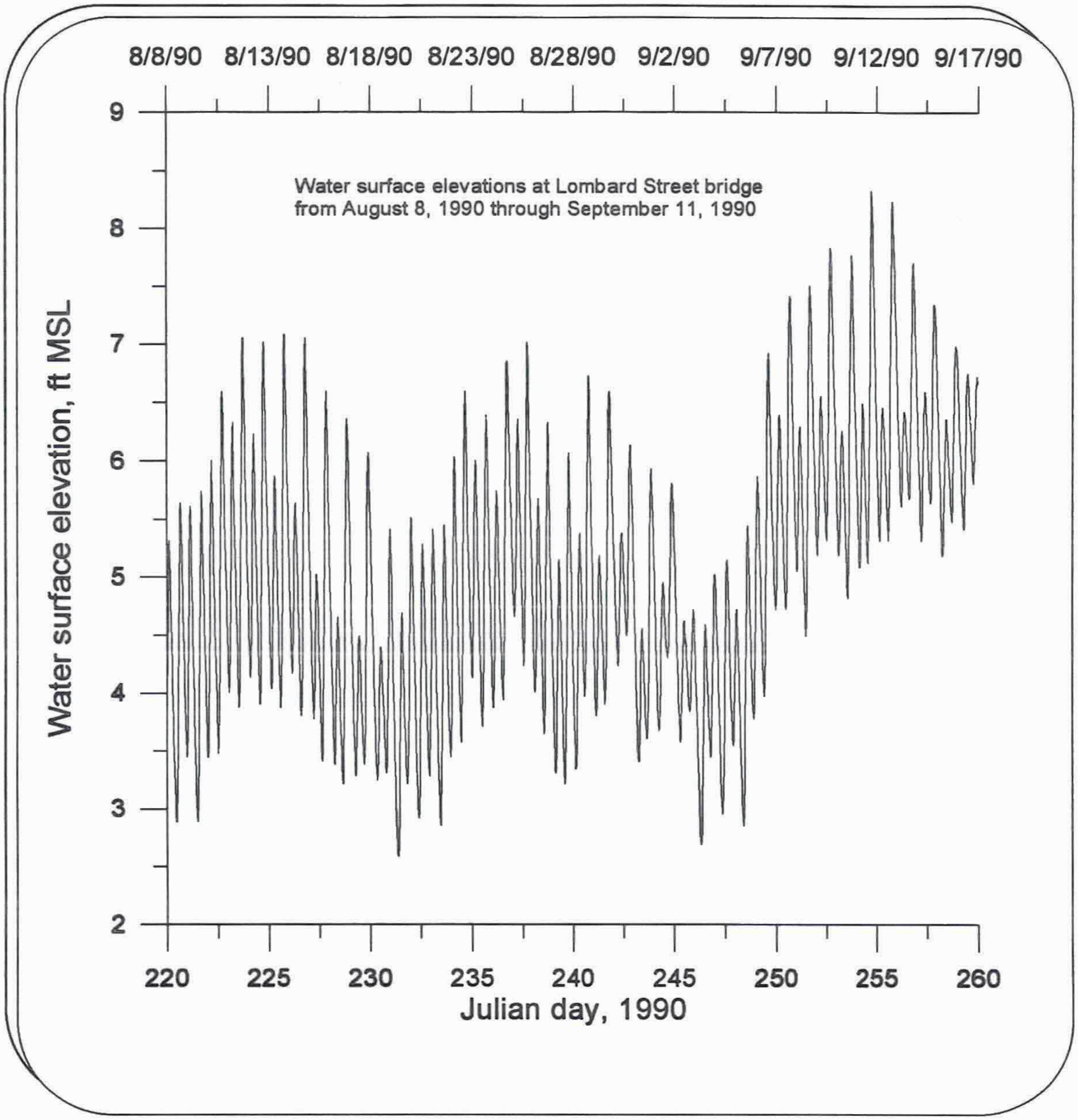

Figure 9. Water levels during low-water simulation period 8/8/90 through 9/11/90 at Lombard Street bridge.

Table 4. Storm events during summer low-water simulation: 8/8/90-9/11/90.

Date	Julian day	Hour	Inches of rain	Duration, hours
August 17	229	14	0.2	2
August 21	233	9	0.21	11
August 24	236	18	0.12	2
August 29	241	10	0.42	11

Table 5. Storm events during high water late winter/early spring period: 2/8/91-4/1/91.

Date	Julian day	Hour	Inches of rain	Duration, hours
Feb 11	42	10	0.1	3
Feb 11	42	18	0.24	6
Feb 12	43	9	0.52	25
Feb 15	46	18	0.14	4
Feb 18	49	9	0.09	5
Feb 19	50	24	1.21	12
March 1	60	17	0.7	27
March 3	62	4	0.91	12
March 4	63	5	0.54	10
March 6	65	4	0.08	2
March 9	68	14	0.2	6
March 11	70	13	0.16	7
March 18	77	9	0.16	5
March 21	80	5	0.68	15
March 22	81	19	0.17	4
March 23	82	19	0.71	10

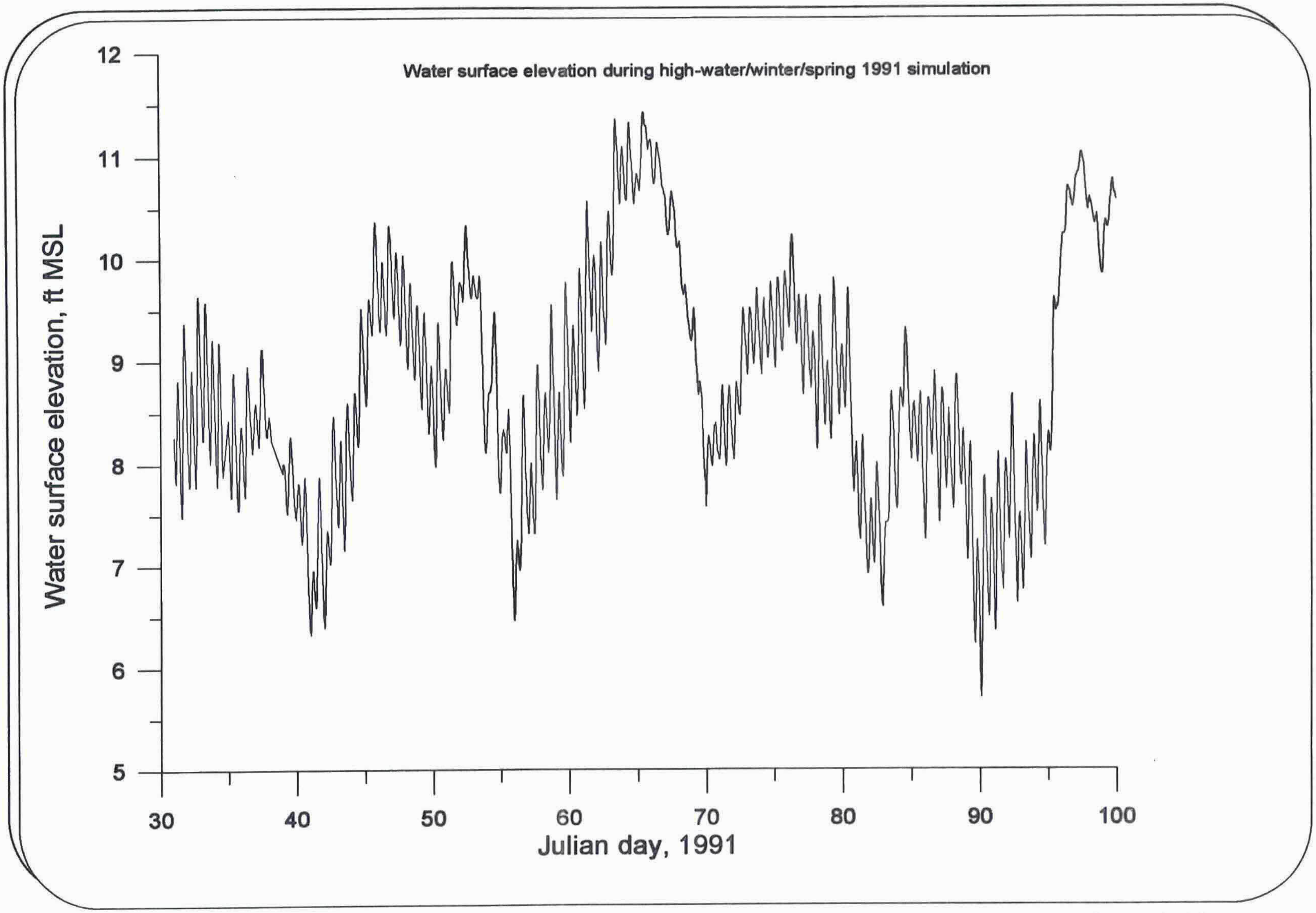

Figure 10. Water level variation during high-water period from 2/8/91 through 4/2/91 at Lombard Street bridge.

5. MODEL SIMULATION RESULTS

5.1 Water Level Variation in Smith and Bybee Lakes

In a U.S. Geological Survey report (1983), the observation was made that Bybee Lake responded to tidal forcing but Smith Lake did not during low-water conditions before the water level control structure was built. The restricted amplitude in Smith Lake was a result of a constricted flow channel between Bybee and Smith Lake. Since there were no data to calibrate the water level variation in these lakes, a Manning's friction factor was chosen that was typical of the Lower Columbia Slough system for the Lakes of between 0.02 and 0.03. The channel friction factor was chosen to be 0.035, slightly greater than the rest of the system. Section 6.2 explores the sensitivity of the model results to variability of the Manning's friction factor.

5.1.1 Low-water period

A summary of the average and standard deviation of the water levels, and the average, standard deviation, and root-mean-squared (RMS) values of flow rate are shown in Table 6 for various locations in the Lower Slough system. The water level variation can be related to the standard deviation of the water level (an approximate average variation using + or - 1 standard deviation about the mean). For Smith Lake the variation (standard deviation) in water level was 0.11 ft less than in Bybee Lake. This implies that Bybee Lake variation in tidal elevation is muted on average about an inch or two. This does not reflect periods when this difference is much greater as shown below. For example, Figures 11 through 13 show the water level variation at LOM, ENS, SL-A, and BY1 during the periods Julian day 220-230 (8/8/90-8/18/90), 230-240 (8/18/90-8/27/90), and 240-250 (8/27/90-9/7/90), respectively.

These figures show that Bybee Lake tracks similar to the east end of North Slough and that Smith lake lags behind considerably. The tidal amplitude in Smith Lake often is 1 ft less over a tidal period. and the phase lag between Bybee and Smith Lake can be up to 0.2 days on high high-water events.

Flow rate variation at different control points is also shown in Figure 14 during the low-water period.

Table 6. Water level and flow statistics over the entire low-water simulation period.

PARAMETER	Mean*	Std Dev	RMS-Q
Water level			
ELS (cell 2) water level, ft MSL	5.131	0.698	
VNB (cell 13) water level, ft MSL	5.118	0.706	
Cell 24 water level, ft MSL	5.110	0.708	
NPB (cell 43) water level, ft MSL	5.075	0.730	
SJB (cell 63) water level, ft MSL	4.966	0.854	
CNN (cell 74) water level, ft MSL	4.925	0.881	
LOM (cell 88) water level, ft MSL	4.823	1.109	
ENS (cell 108) water level, ft MSL	4.925	0.786	
SL-A (cell 98) water level, ft MSL	4.904	0.664	
BY1 (cell 139) water level, ft MSL	4.942	0.778	
Flow rate			
Entr to Col Sl (cell 88) flow rate, cfs	56.45	737.25	651.88
Entr to North Sl (cell 116) flow rate, cfs	-8.32	162.82	144.28
Entr to Bybee Lk (cell 141) flow rate, cfs	7.90	180.72	161.75
Entr to S/B Lks (cell 108) flow rate, cfs	-11.60	253.46	225.33

RMS: root-mean-squared value

* Note that the model time step and sample for calculating the mean was every 50 model time steps (about 30 minutes), negative mean flow is upstream flow (into Columbia Slough), positive mean flow is downstream (out of Columbia Slough).

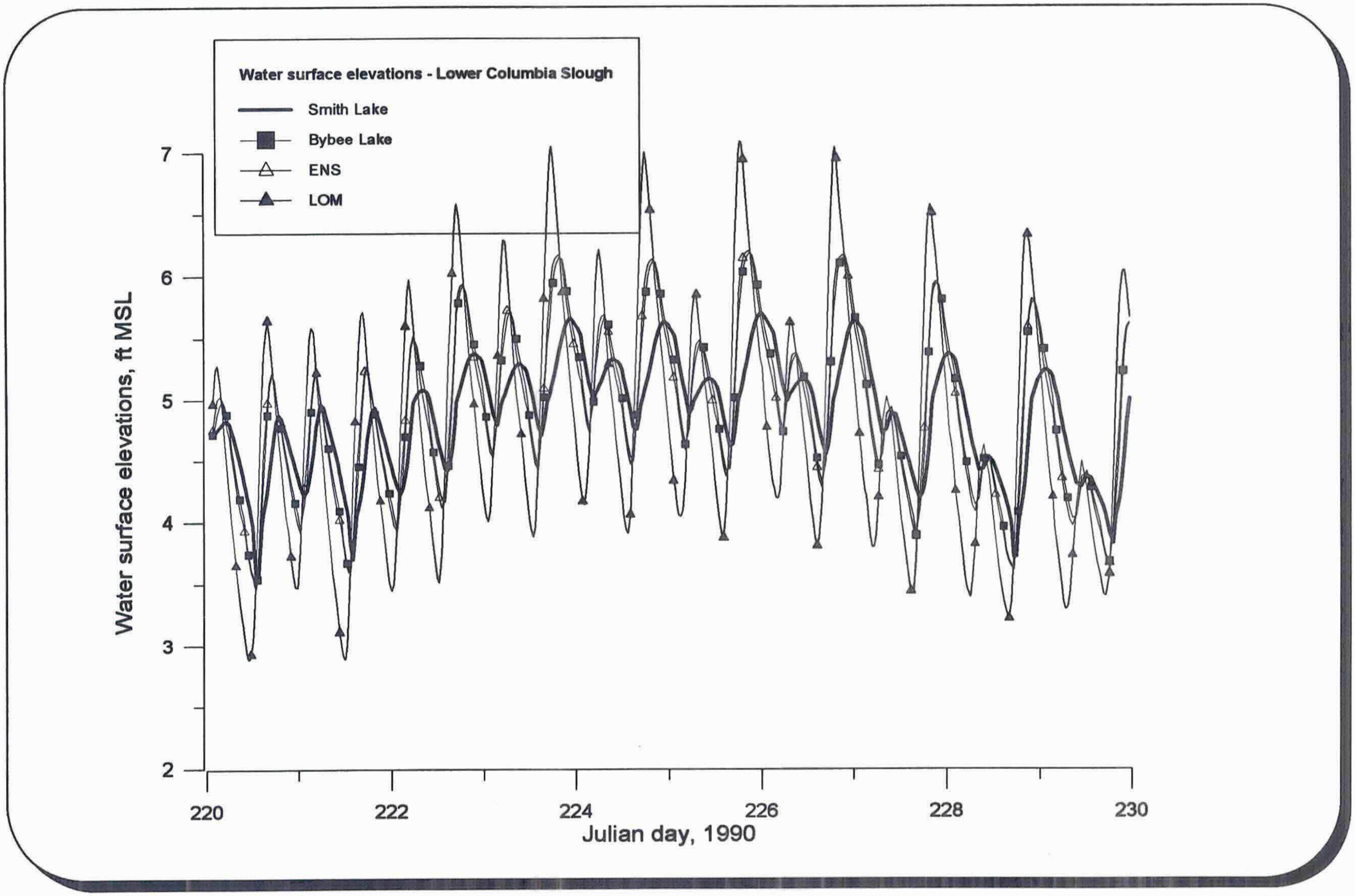

Figure 11. Water level variation in Smith Lake, Bybee Lake, East end of North Slough (ENS), and at Lombard Street bridge (LOM) during Julian day 220-230.

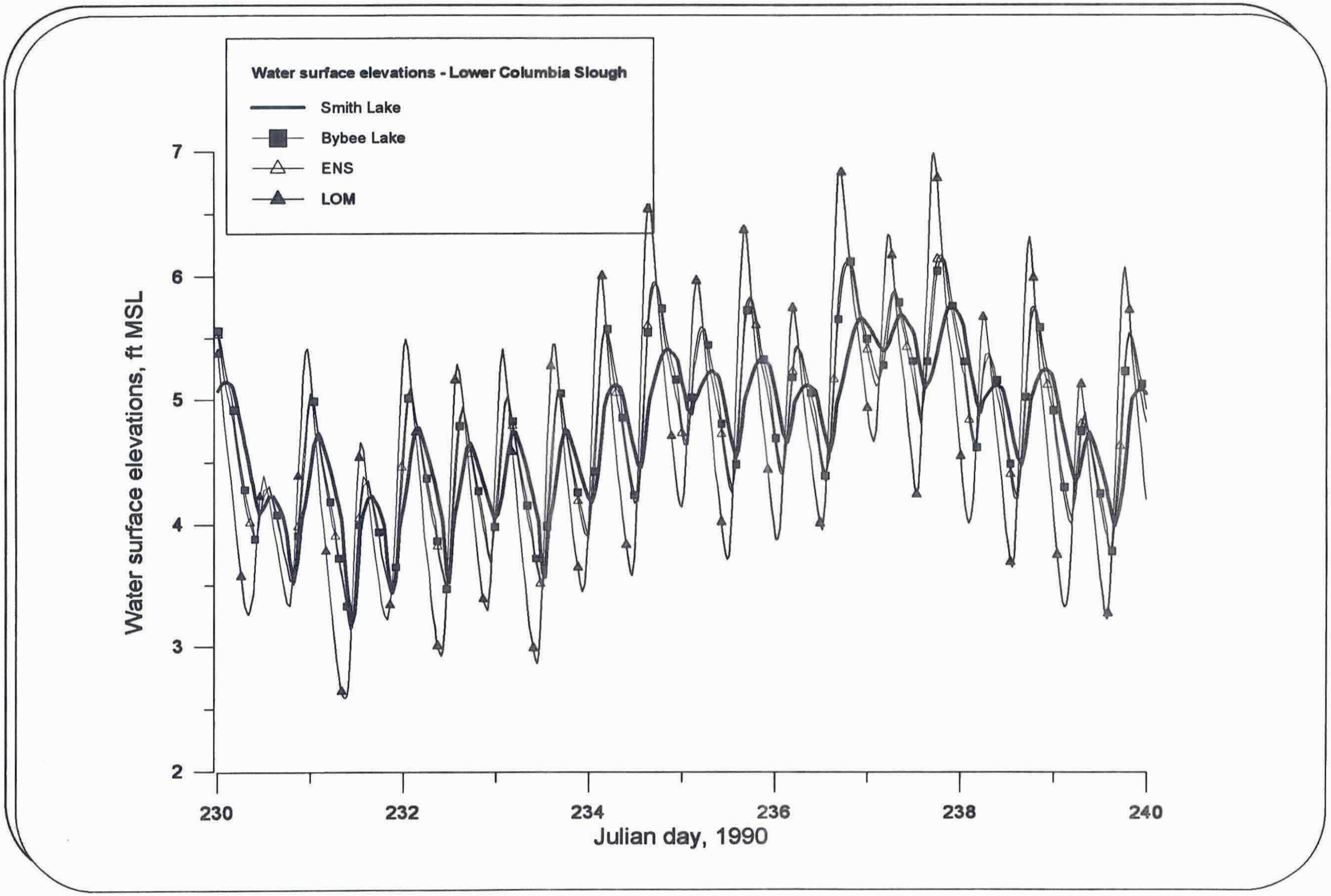

Figure 12. Water level variation in Smith Lake, Bybee Lake, East end of North Slough (ENS), and at Lombard Street bridge (LOM) during Julian day 230-240.

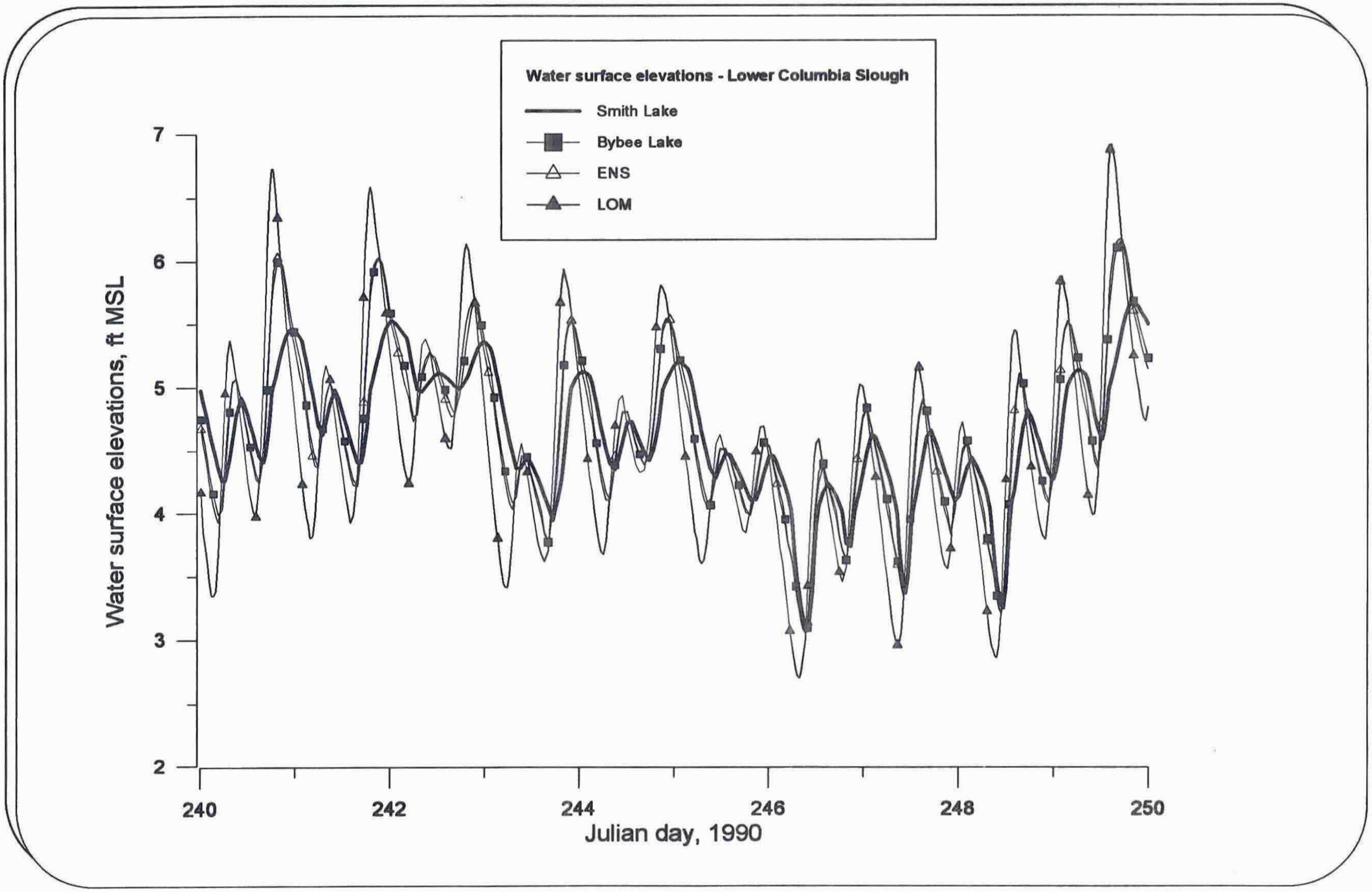

Figure 13. Water level variation in Smith Lake, Bybee Lake, East end of North Slough (ENS), and at Lombard Street bridge (LOM) during Julian day 240-250.

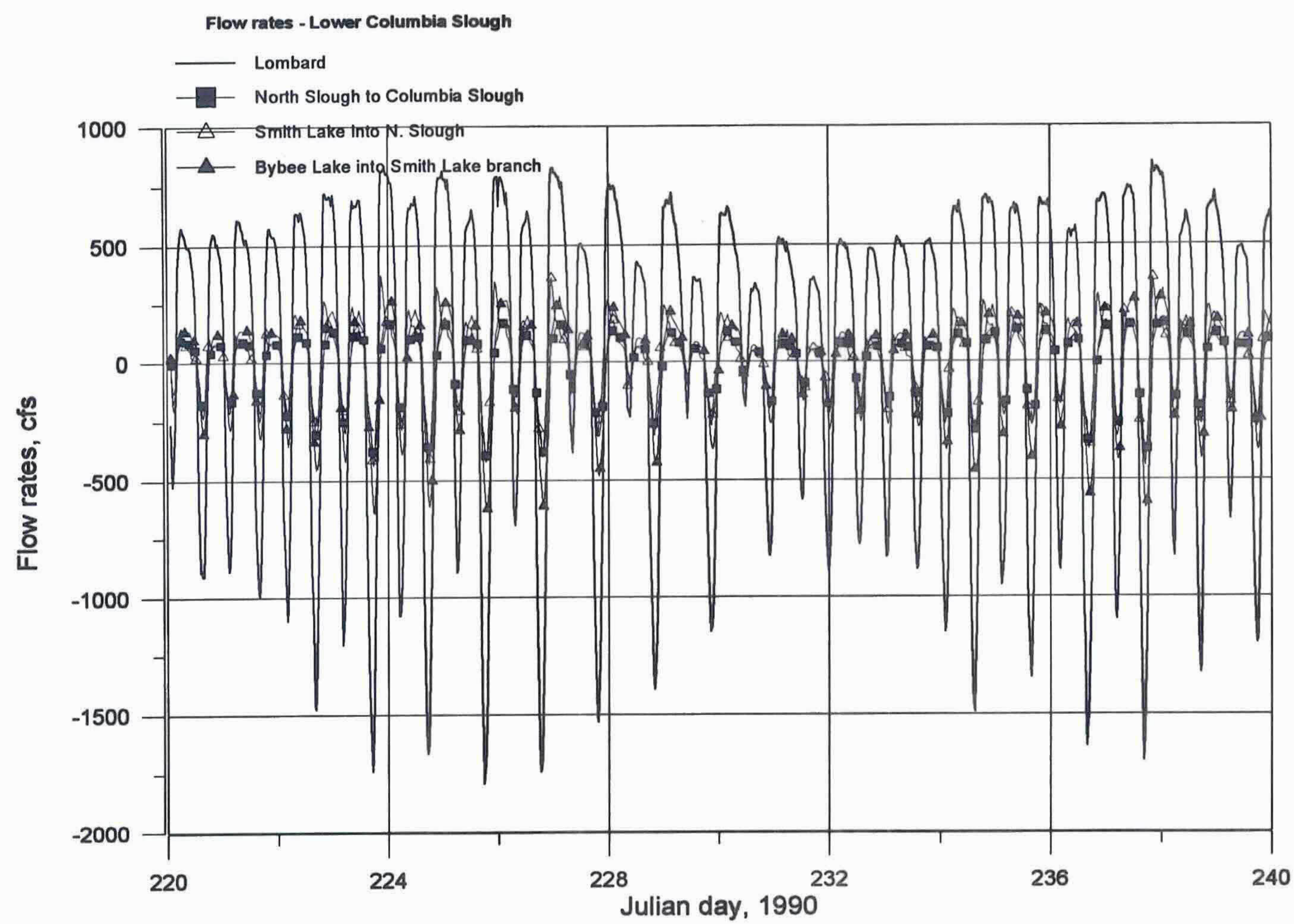

Figure 14. Flow rate variation at noted control points during Julian day 220-240 (8/8/90-8/28/90) during the low-water period (note that negative flow is flow into the Columbia Slough and positive flow is flow out of the Columbia Slough).

5.1.2 High-water period

A summary of the average and standard deviation of the water levels, and the average, standard deviation, and root-mean-squared (RMS) values of flow rate are shown in Table 7 for various locations in the Lower Slough system. For Smith Lake the variation (standard deviation) in water level was 0.01 ft less than in Bybee Lake. This implies that there was little difference in tidal dynamics between stations BY1 and SL-A during high-water conditions. During high-water conditions, the narrow channel did not constrict the flow between Bybee Lake and Smith Lake making the amplitude of the variation almost the same. For example, Figure 16 shows the water level variation at LOM, ENS, SL-A, and BY1 during the period Julian day 44-52 (2/13/91-2/21/91).

These figures show that Bybee Lake, Smith Lake, and the east end of North Slough all track similarly for high-water periods, but that Smith lake begins to show a phase lag and an amplitude reduction as the water level gets lower.

Flow rate variation at different control points is also shown in Figure 17 during the high-water period.

Table 7. Water level and flow statistics over the entire high-water simulation period.

PARAMETER	Mean*	Std Dev	RMS-Q*
Water level			
ELS (cell 2) water level, ft MSL	8.880	0.99	
VNB (cell 13) water level, ft MSL	8.872	0.990	
Cell 24 water level, ft MSL	8.863	0.991	
NPB (cell 43) water level, ft MSL	8.846	0.994	
SJB (cell 63) water level, ft MSL	8.818	1.002	
CNN (cell 74) water level, ft MSL	8.790	0.989	
LOM (cell 88) water level, ft MSL	8.755	1.059	
ENS (cell 108) water level, ft MSL	8.776	0.927	
SL-A (cell 98) water level, ft MSL	8.815	0.903	
BY1 (cell 139) water level, ft MSL	8.803	0.914	
Flow rate			
Entr to Col Sl (cell 88) flow rate, cfs	205.8	1132.8	984
Entr to North Sl (cell 116) flow rate, cfs	0.06	505.77	424.73
Entr to Bybee Lk (cell 141) flow rate, cfs	2.78	292.27	252.48
Entr to S/B Lks (cell 108) flow rate, cfs	0.80	821.87	690.46

* Note that the model time step and sample for calculating the mean was every 50 model time steps (about 30 minutes), negative mean flow is upstream flow (into Columbia Slough), positive mean flow is downstream (out of Columbia Slough).

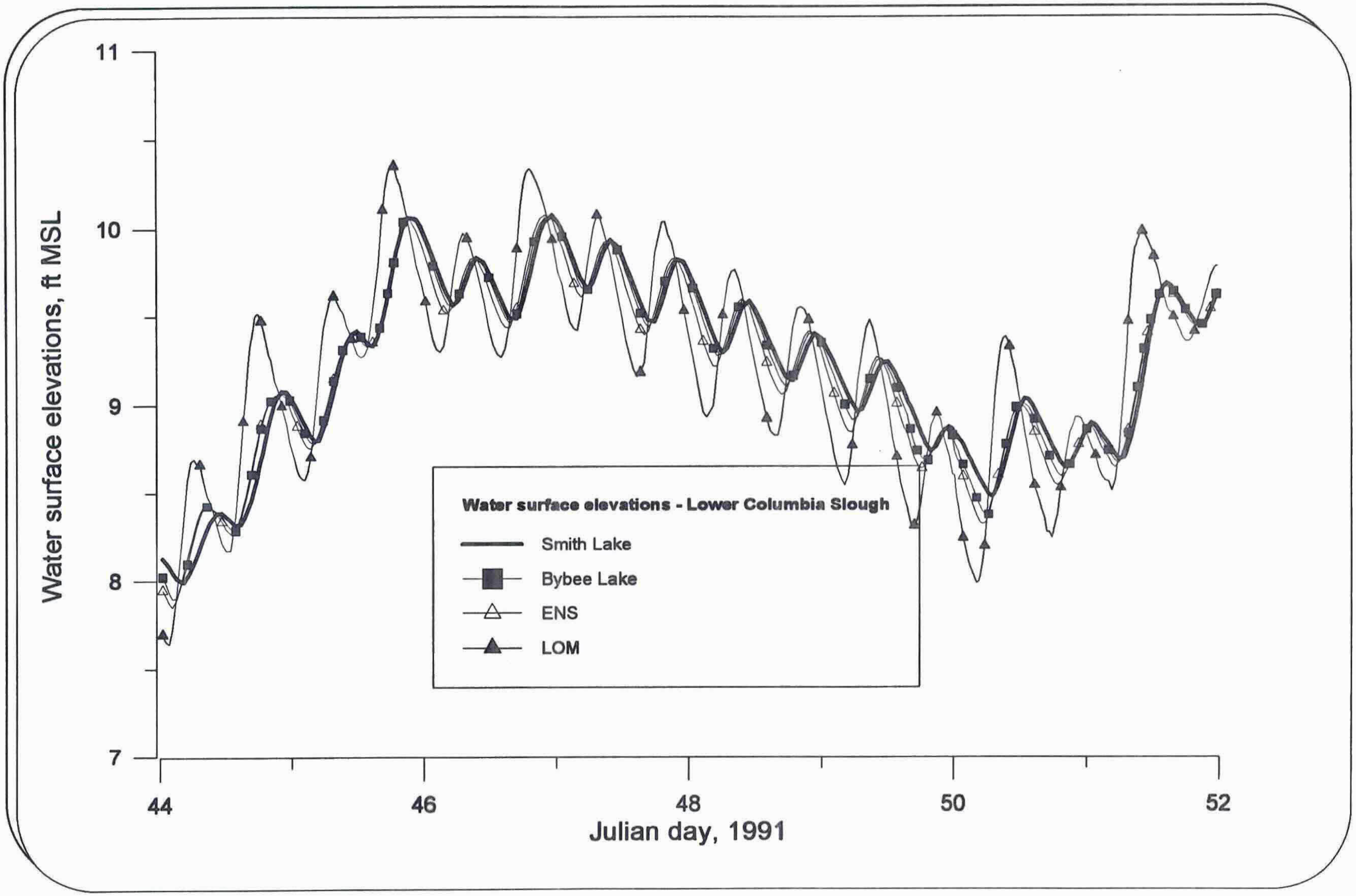

Figure 15. Water level variation in Smith Lake, Bybee Lake, East end of North Slough (ENS), and at Lombard Street bridge (LOM) during Julian day 44-52 (2/13/91-2/21/91).

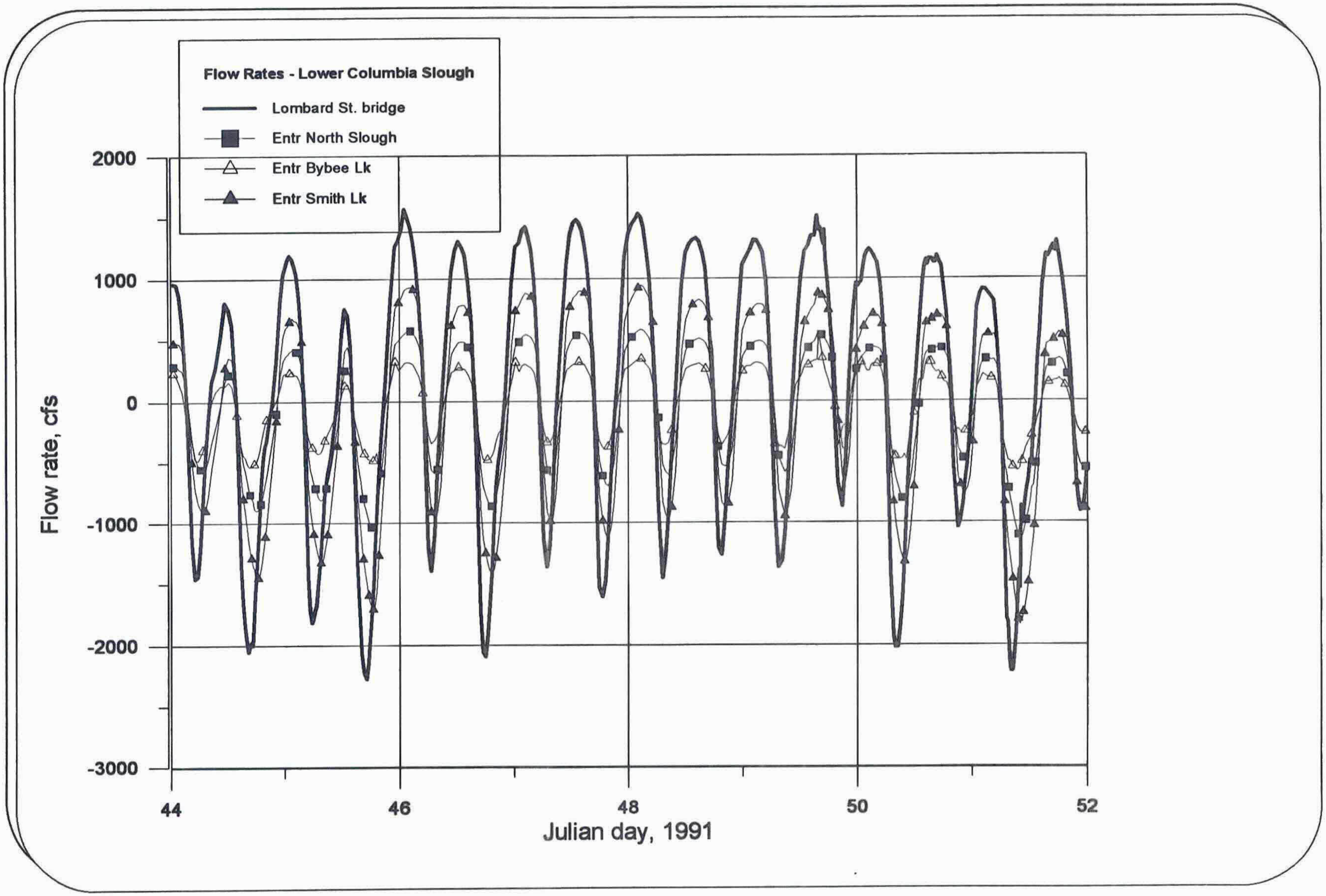

Figure 16. Flow rate variation at noted control points during Julian day 44-52 (2/13/91-2/21/91) during the high-water period (note that negative flow is flow into the Columbia Slough and positive flow is flow out of the Columbia Slough).

5.2 Dilution of Tracer

The average impact of combined sewer overflows (CSOs), the Willamette River, and landfill leachate are summarized in Table 8 which shows both the average dilution and the minimum dilution in Smith Lake and Bybee Lake for each of the model simulations. Dilution is defined as C_o/C if there is no background concentration of material, where C_o is the initial tracer concentration coming from each source (see Table 3) , and C is the model predicted concentration at the given sampling location.

Table 8. Average and minimum dilutions in Smith and Bybee Lake during each of the model simulations.

Run number	Time period of simulation	Average dilution* at SL-A	Average dilution* at BY1	Minimum dilution at SL-A	Minimum dilution at BY1	Description
1	8/8/90-9/11/90	578	416	40	20	Low water, 4 storm events, CSO tracer conc=100 mg/l
2	2/8/91-4/2/91	335	255	45	30	High water, 15 storm events, CSO tracer conc=100 mg/l
3	8/8/90-9/11/90	2.1	2.8	1	1	Low water, 4 storm events, Willamette River tracer conc=100 mg/l
4	2/8/91-4/2/91	1.4	1.4	1	1	High water, 15 storm events, Willamette River tracer conc=100 mg/l
5	8/8/90-9/11/90	5,091	3,607	1,800	1,000	Low water, 4 storm events, Landfill leachate tracer=463 mg/l
6	2/8/91-4/2/91	9,267	7,937	3,000	2,500	High water, 15 storm events, Landfill leachate tracer = 463 mg/l

* The average calculated dilution for each run did not factor in cases where there was no tracer (i.e., infinite dilution). This was accomplished by evaluating averages after the first couple days of the simulation. For the CSO events in the summer, because of there being no CSO events during the latter period of the summer simulation, averages were made only between JD 230 (8/18/90) and JD 240 (8/28/90). See accompanying Figures 17-22.

This table shows that the Willamette River often reaches Smith Lake and Bybee Lake undiluted during both high-water and low-water events, that CSOs will be diluted at a minimum over the simulation period only by 20-40 times in the Lakes (note that dilutions on the order of 1000 -10,000 would be required to reduce bacteria concentrations after a CSO event to meet the Department of Environmental Quality standards of 200 col/100 ml since inflow bacteria concentrations are often of order 100,000 col/100 ml or more), and that opening up the lakes to North Slough reduces landfill leachate problems because of high dilution on the order of 1000.

These dilution results are merely estimates as determined by the conditions surrounding the rain events, hydraulics, and tidal conditions of 1990 and 1991. These results should be used with caution if extrapolating to other conditions or time periods.

5.2.1 Dilution of Combined Sewer Overflows (CSOs)

Figures 17 and 18 show how the dilution in Smith and Bybee Lakes varied over time for low-water and high-water periods, respectively. Also shown on these graphs is the dilution at Vancouver bridge (VNB), near the major CSO on the Lower Columbia Slough, the 13th Street CSO.

5.2.2 Dilution of Willamette River

Figures 19 and 20 show how the dilution in Smith and Bybee Lakes varied over time for low-water and high-water periods, respectively.

5.2.2 Dilution of Landfill Leachate

Figures 21 and 22 show how the dilution in Smith and Bybee Lakes varied over time for low-water and high-water periods, respectively.

5.3 Water Quality Impacts

The purpose of this study was not intended to evaluate water quality impacts explicitly, but to quantify dilution of a conservative tracer. But several conclusions can be drawn from looking at several important water quality variables. For example, as shown in Wells (1992a), opening up Smith and Bybee Lakes did solve the problems with dissolved oxygen in North Slough. To assist in this evaluation, Tables 9 and 10 summarize averages and standard deviations of the water quality variables for low-water and high-water simulation periods, respectively, at several locations throughout the Lower Columbia Slough system.

The impact of the dilution and decay of bacteria after storm water and CSO loadings in the low-water, summer and high-water winter/spring periods is shown in Figures 23 and 24, respectively. These figures show that bacteria standards (200 col/100 ml water quality goal) will be violated in the Lakes as a result of bacteria loading from CSOs until they are removed. The station at Vancouver bridge was plotted on these graphs to show the timing of CSOs, especially the largest one at NE 13th. Note that the WRR bacteria levels were based on field data and were usually on the order of 90 col/100 ml. Excursions above the DEQ standard of 200 col/100 ml could be due to inflows from the Willamette River even after CSOs have been removed from the Lower Slough.

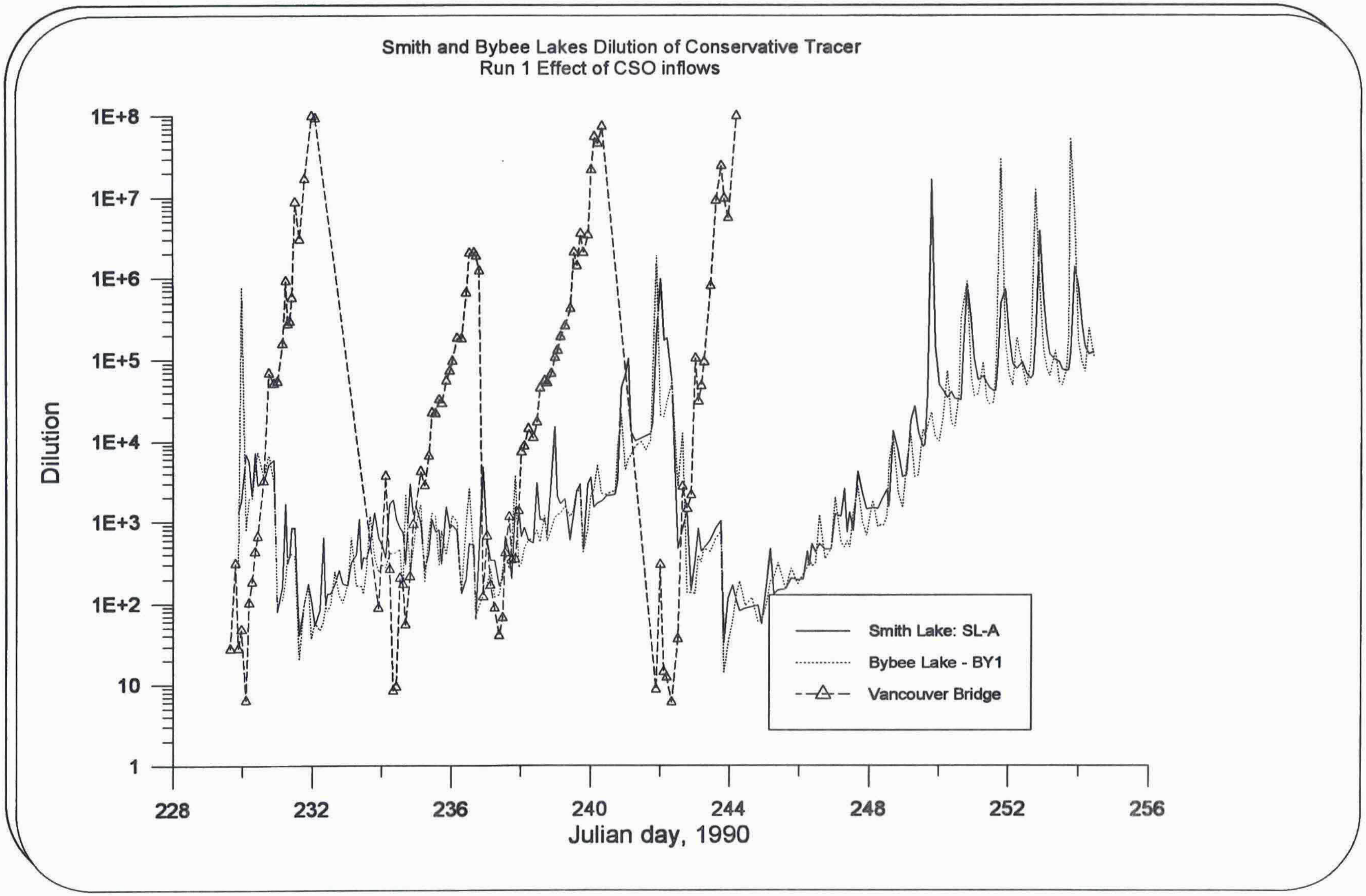

Figure 17. Predicted dilution as a function of time during the low-water period for Run 1 at Smith and Bybee lakes and at Vancouver bridge.

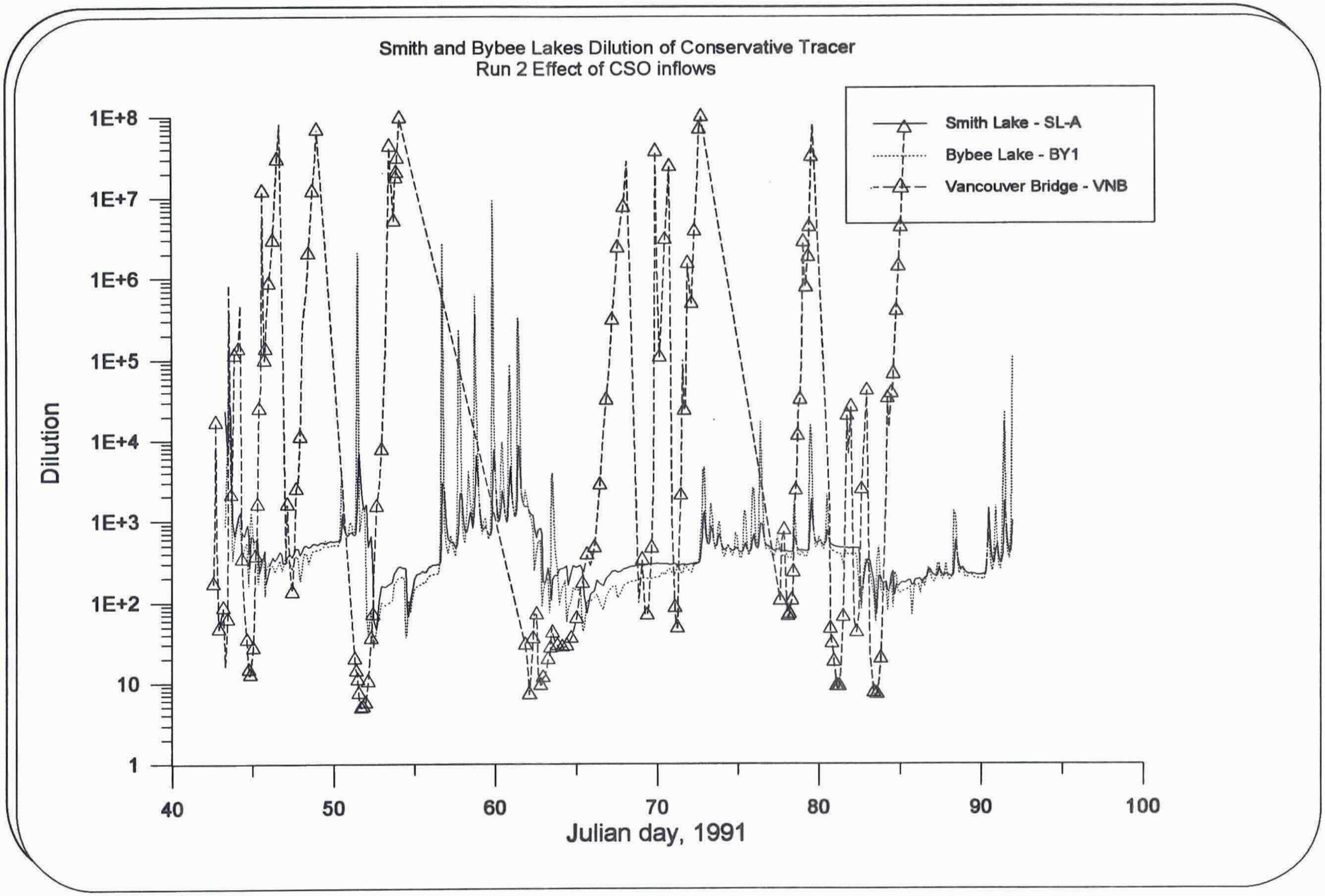

Figure 18. Predicted dilution as a function of time during the high-water period for Run 2 at Smith and Bybee lakes and at Vancouver bridge.

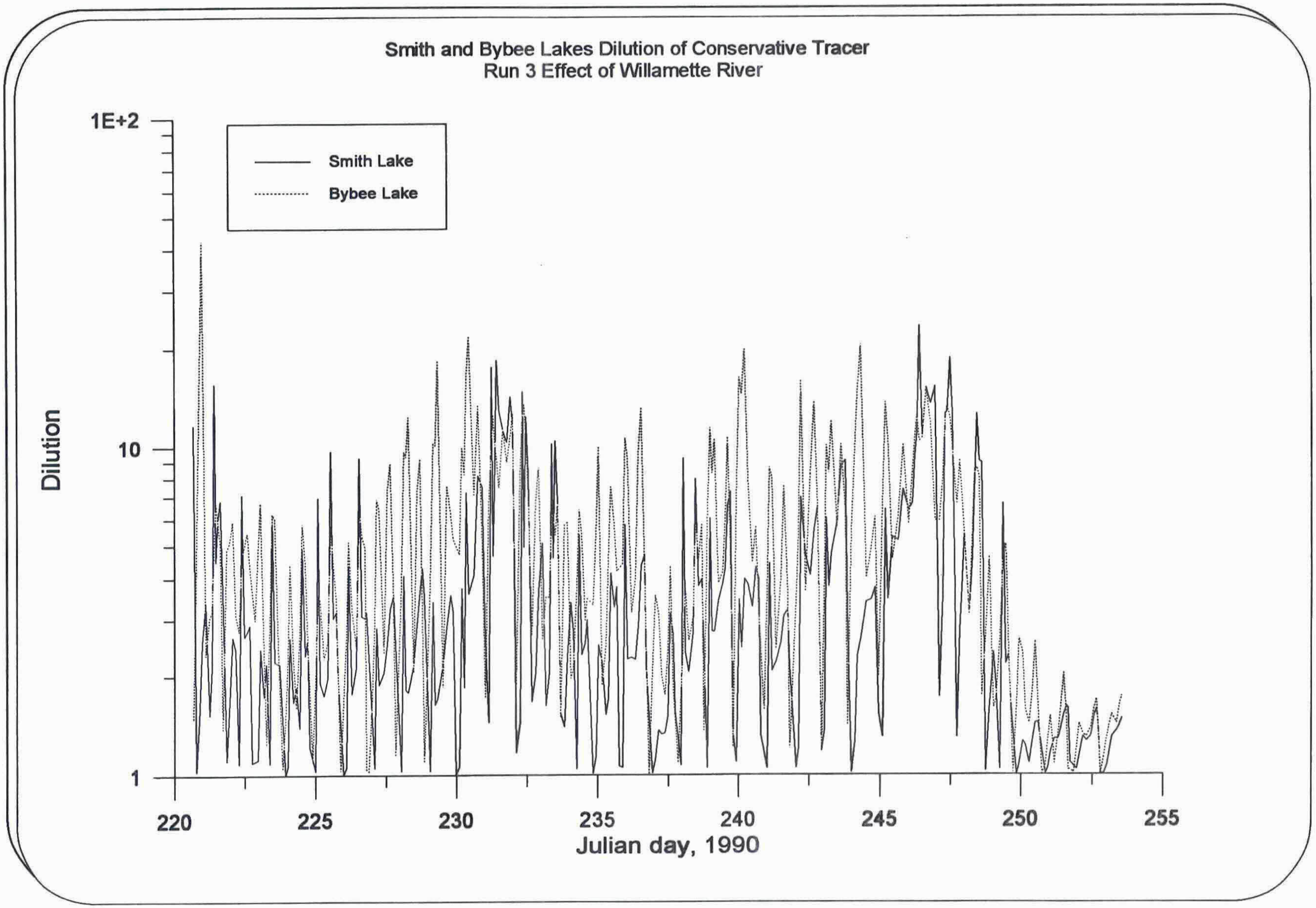

Figure 19. Predicted dilution as a function of time during the low-water period for Run 3 at Smith and Bybee lakes.

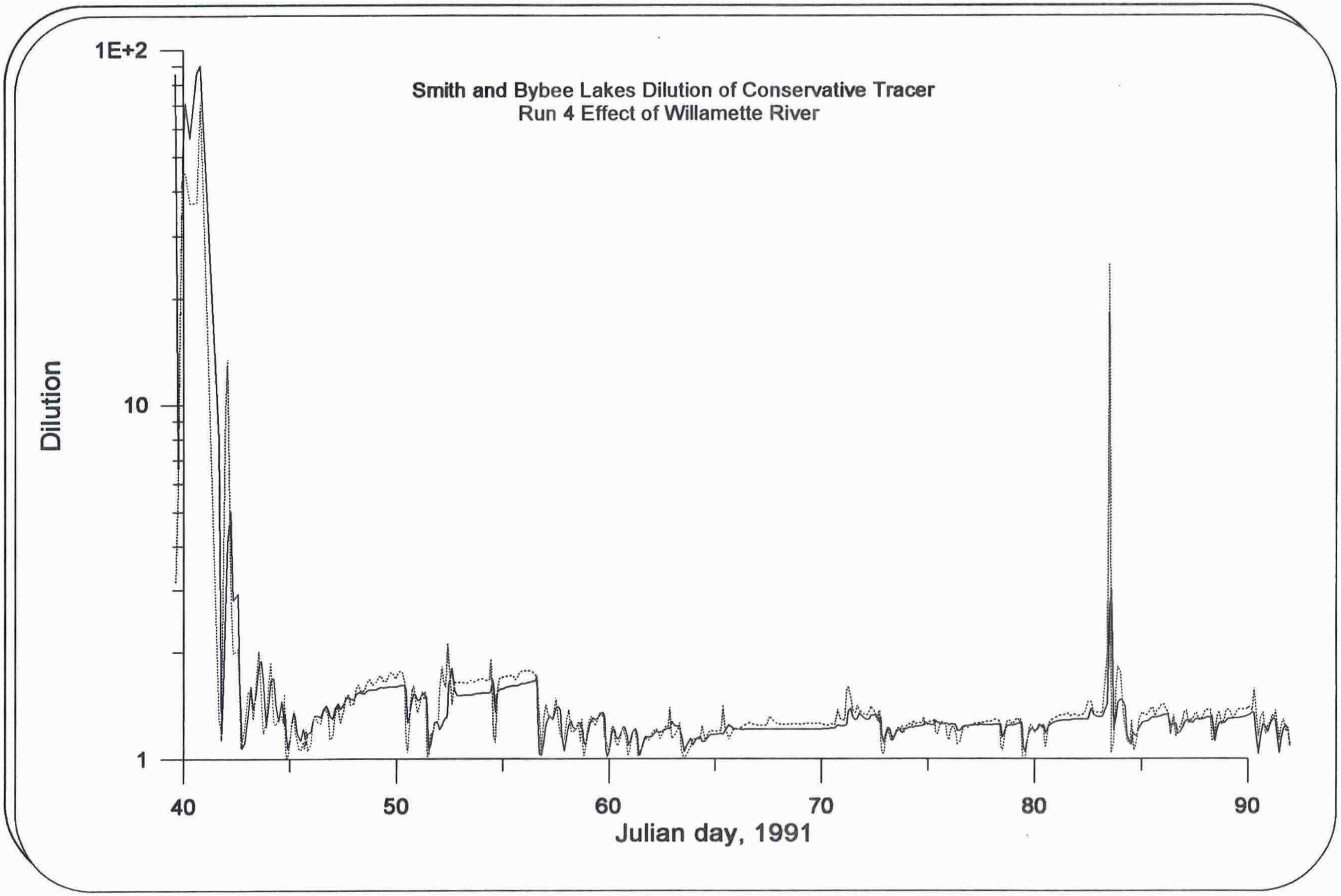

Figure 20. Predicted dilution as a function of time during the high-water period for Run 4 at Smith and Bybee lakes.

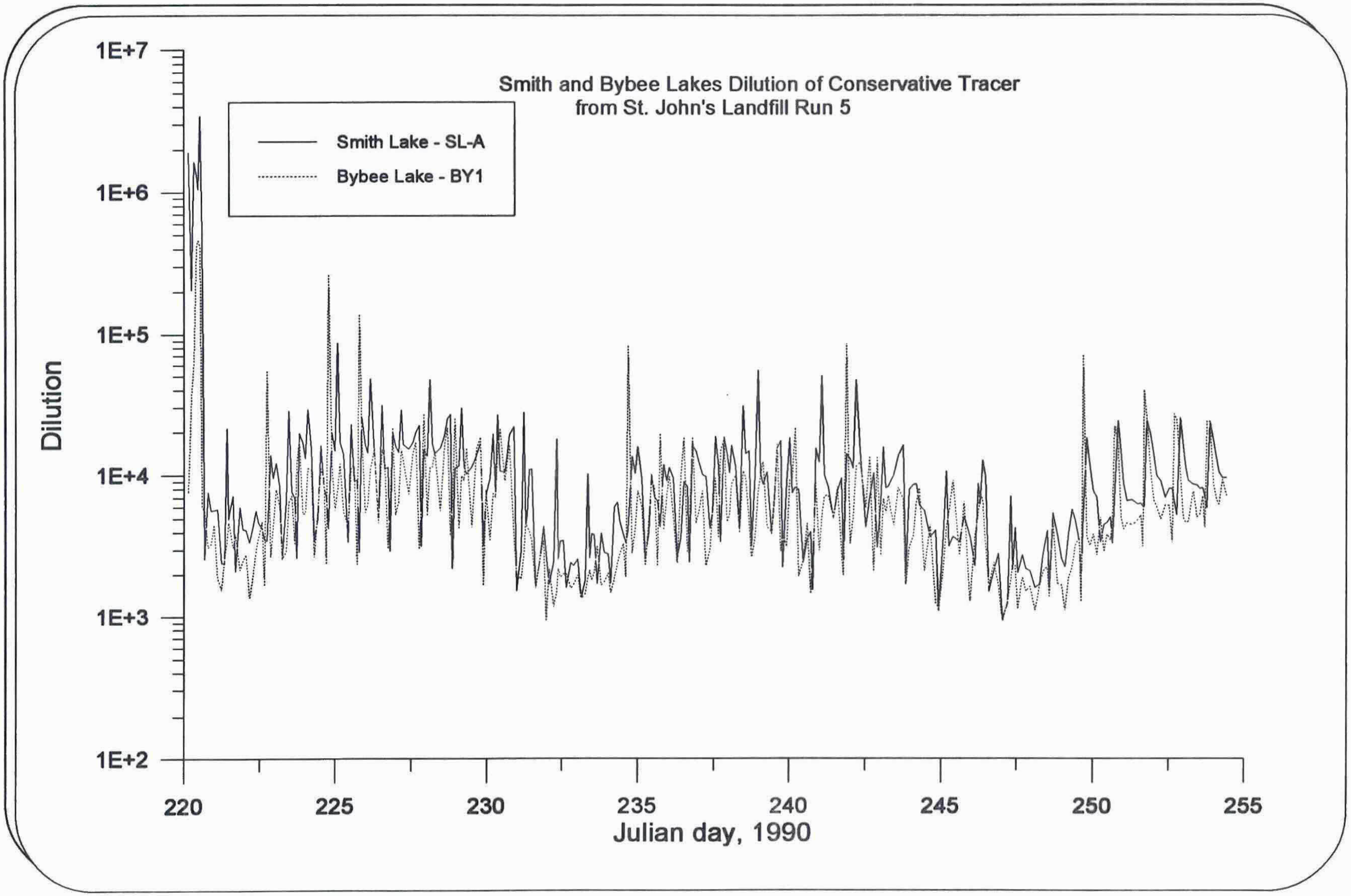

Figure 21. Predicted dilution as a function of time during the low-water period for Run 5 at Smith and Bybee lakes.

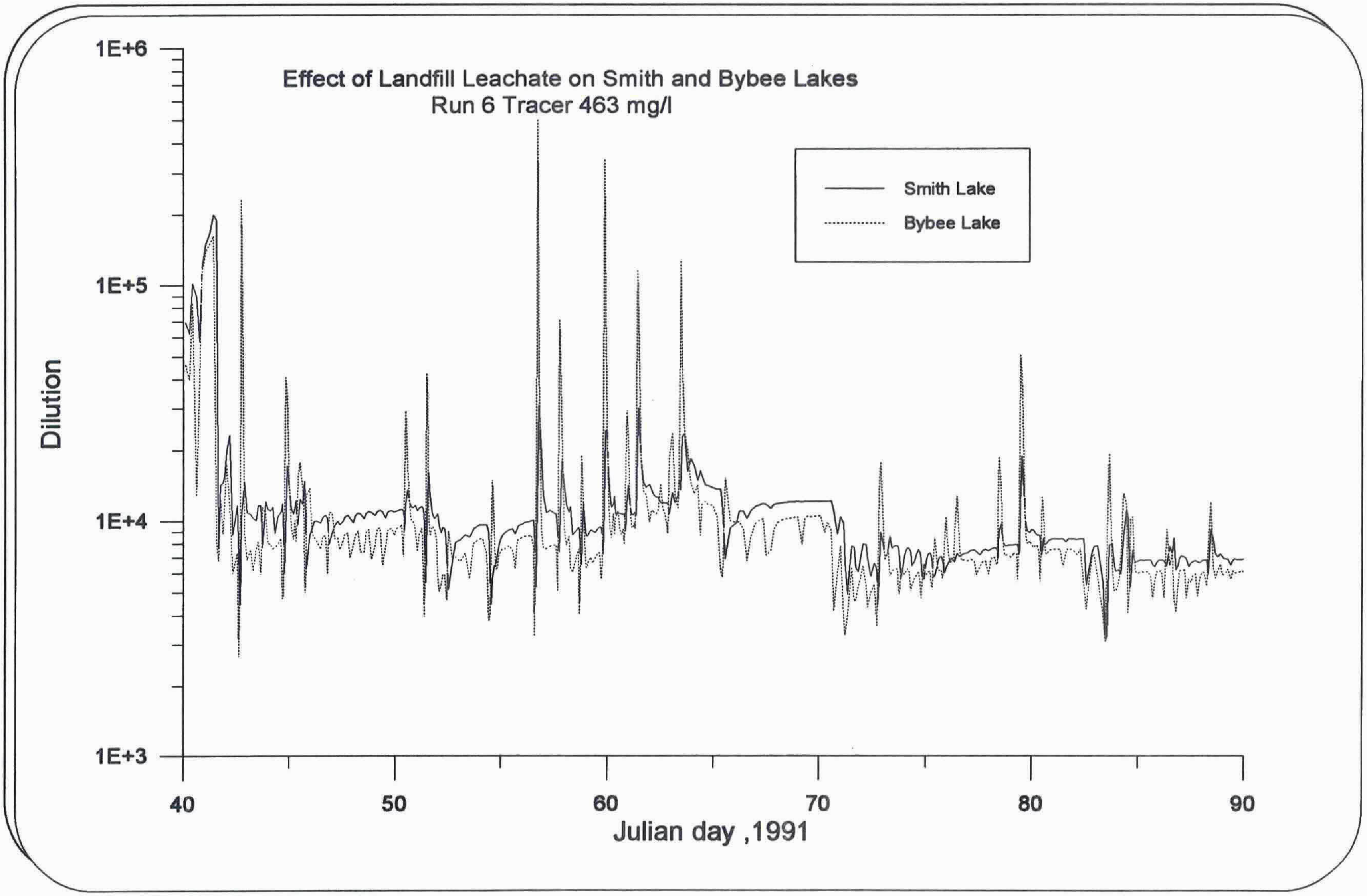

Figure 22. Predicted dilution as a function of time during the high-water period for Run 6 at Smith and Bybee lakes.

Table 9. Low-water water quality means (-M) and standard deviations (-SD) at noted stations for Runs 1, 3, and 5.

Parameter	ELS-M	ELS-SD	VNB-M	VNB-SD	NPB-M	NPB-SD	SJB-M	SJB-SD	CNN-M	CNN-SD	ENS-M	ENS-SD	LOM-M	LOM-SD	SLA-M	SLA-SD	BY1-M	BY1-SD
temp, C	19.29	1.105	20.24	2.170	22.07	2.4043	21.712	1.872	20.87	1.464	20.57	2.703	20.96	1.119	21.143	3.295	20.03	3.417
velocity, m/s	0.065	0.021	0.0392	0.031	0.037	0.12	0.064	0.214	0.051	0.252	0.008	0.223	0.049	0.205	-0.007	0.052	0.008	0.081
tracer, mg/l	2.4E-10	2.82E-09	0.362	1.49	0.566	1.36	0.623	1.29	0.396	0.893	0.463	0.899	0.206	0.540	0.173	0.31	0.24	0.528
inorg SS, mg/l	8.909	1.045	3.365	1.542	0.522	1.1448	0.91	1.1628	1.690	1.21	2.261	2.1658	2.526	1.1648	0.6169	0.695	0.540	0.821
coliform, col/100ml	24.75	60.37	535.72	2129.9	310.97	737.71	288.72	752.98	162.82	363.35	127.84	184.76	114.95	223.36	38.916	43.382	44.92	81.339
soluble BOD, mg/l	2.72	0.866	2.769	1.05	2.68	0.987	3.85	1.84	5.58	1.74	11.4	4.27	6.72	1.4322	4.35	1.95	4.40	1.46
chlorophyll a, ug/l	14.59	1.66	22.12	6.305	50.62	15.49	46.69	21.14	25.02	17.38	35.98	22.62	13.76	14.68	12.80	8.564	17.657	10.996
detritus, mg/l	0.0001	7.9E-05	0.008	0.050	0.043	0.095	0.047	0.090	0.035	0.075	0.103	0.129	0.02	0.060	0.027	0.036	0.073	0.0691
diss PO4-P, mg/l	0.075	0.0085	0.066	0.0080	0.0530	0.0104	0.040	0.016	0.023	0.0134	0.03	0.018	0.02	0.011	0.011	0.01	0.015	0.0103
NH4-N, mg/l	0.238	0.0254	0.223	0.0221	0.2284	0.0509	0.283	0.059	0.283	0.059	0.485	0.150	0.252	0.056	0.170	0.062	0.189	0.069
NO3-N, mg/l	3.54	0.380	3.50	0.273	3.11	0.619	2.37	0.967	1.377	0.684	1.806	0.834	0.99	0.540	0.648	0.302	0.73	0.442
Dissolved Oxygen, mg/l	9.97	1.10	10.4	0.782	12.1	1.50	11.0	2.08	8.75	1.39	15.49	4.33	8.02	1.10	5.83	1.675	6.81	1.46
% O_2 saturation	108		115		139		125		98		172		90		66		75	
pH	7.57	0.428	7.95	0.28	8.63	0.49	8.40	0.60	7.95	0.49	7.71	0.38	7.68	0.36	7.56	0.56	7.78	0.32

Table 10. High-water water quality means (-M) and standard deviations (-SD) at noted stations and standard deviations for Runs 2, 4, and 6.

Parameter	ELS-M	ELS-SD	VNB-M	VNB-SD	NPB-M	NPB-SD	SJB-M	SJB-SD	CNN-M	CNN-SD	ENS-M	ENS-SD	LOM-M	LOM-SD	SLA-M	SLA-SD	BY1-M	BY1-SD
temp, C	11.01	0.817	10.175	1.211	8.375	1.98	7.81	2.12	7.93	1.80	7.79	1.92	8.45	1.2	6.93	2.162	7.24	2.113
velocity, m/s	0.051	0.012	0.047	0.017	0.05	0.063	0.072	0.116	0.05	0.23	-0.01	0.368	0.049	0.203	-0.001	0.027	-0.0002	0.037
tracer, mg/l	0.0013	0.013	0.97	3.05	1.60	2.46	1.85	2.50	0.83	1.16	0.410	0.743	0.51	0.95	0.29	0.233	0.392	0.414
inorg SS, mg/l	9.24	0.93	5.81	1.786	1.679	2.537	0.894	1.341	1.59	1.23	1.76	1.85	2.45	1.28	0.42	0.64	0.767	1.016
coliform, col/100ml	51.3	83.1	1290.6	3869	1119	1990	943.6	1562	376.8	744.6	172.9	516.8	242.6	467.1	58.3	105.3	102.1	230.4
soluble BOD, mg/l	3.27	1.11	3.517	1.512	3.64	1.37	3.88	1.38	5.99	1.10	7.98	3.31	6.74	1.18	5.99	0.67	6.15	0.82
chlorophyll a, ug/l	6.85	4.33	7.84	4.97	11.22	6.06	12.28	6.28	7.89	5.36	9.07	9.273	5.29	5.41	10.25	4.57	9.53	5.59
detritus, mg/l	7.62E-05	0.02	0.0045	0.04	0.019	0.076	0.022	0.08	0.018	0.066	0.029	0.108	0.011	0.039	0.023	0.072	0.023	0.072
diss PO4-P, mg/l	0.078	0.005	0.076	0.006	0.074	0.01	0.070	0.015	0.035	0.015	0.029	0.023	0.025	0.014	0.023	0.012	0.025	0.012
NH4-N, mg/l	0.247	0.005	0.2404	0.019	0.232	0.042	0.255	0.049	0.247	0.036	0.265	0.111	0.228	0.031	0.194	0.033	0.206	0.036
NO3-N, mg/l	3.69	0.071	3.62	0.218	3.43	0.45	3.22	0.66	1.59	0.56	1.24	0.68	1.22	0.57	0.93	0.18	1.024	0.246
Dissolved Oxygen, mg/l	10.73	1.88	10.59	1.79	10.43	1.54	9.92	1.39	10.03	0.84	12.47	4.98	10.08	0.801	10.28	0.62	10.227	0.678
% O_2 saturation	97		94		89		83		85		105		86		85		85	
pH	7.70	0.012	7.74	0.11	7.78	0.20	7.66	0.18	7.63	0.154	9.39	3.64	7.59	0.113	7.71	0.16	7.69	0.17

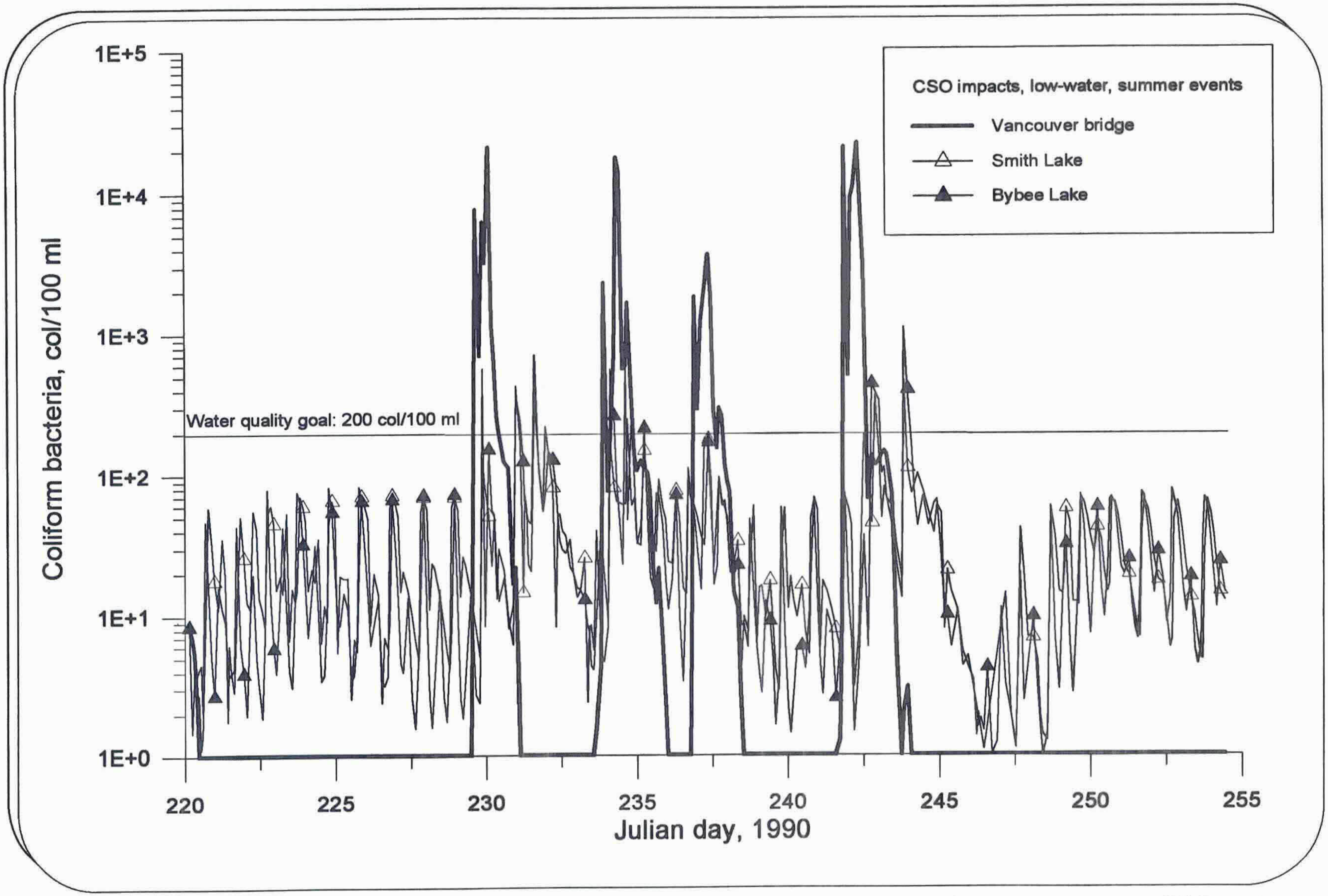

Figure 23. Coliform bacteria at Vancouver bridge, Smith Lake, and Bybee Lake during low-water summer CSO and storm water events.

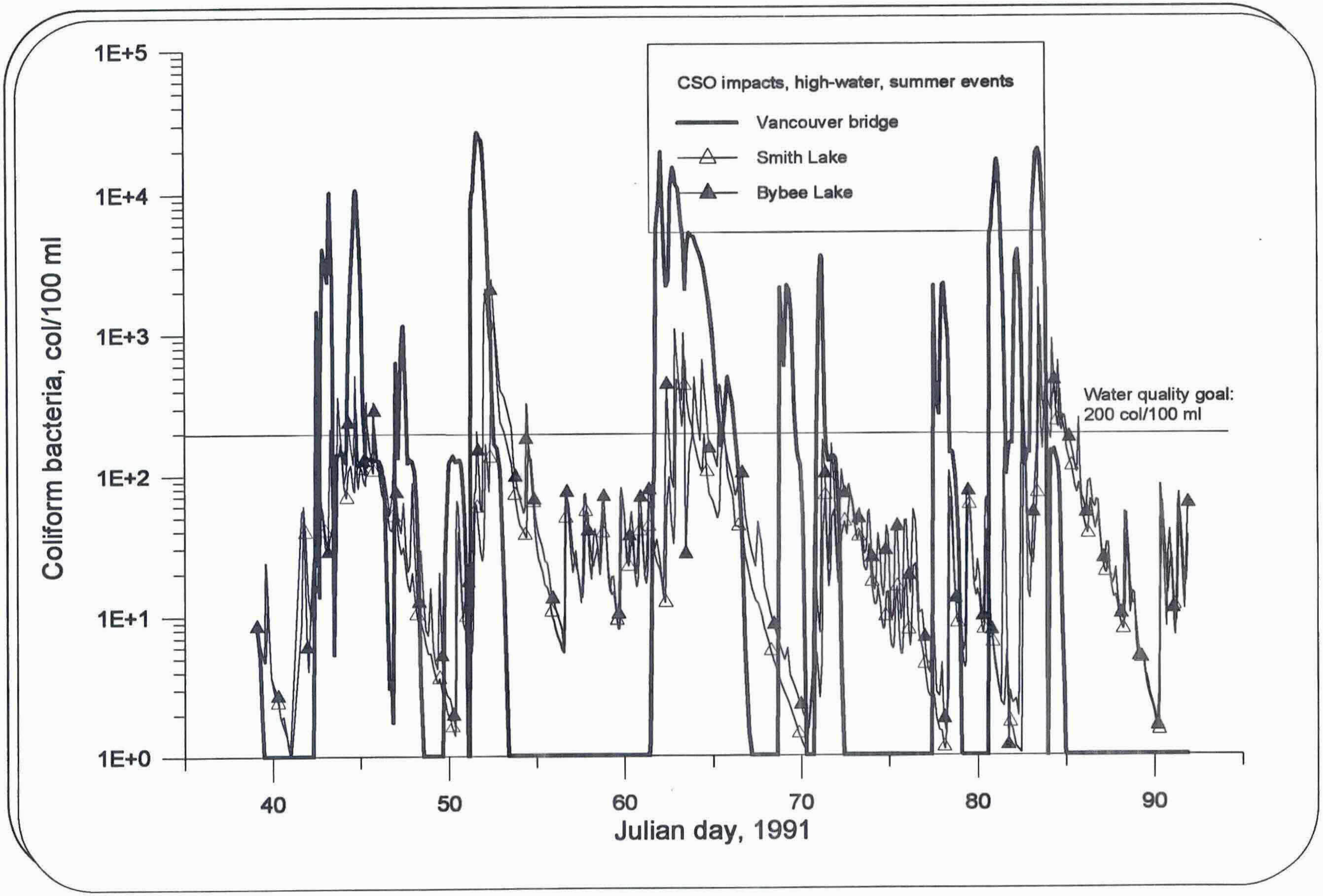

Figure 24. Coliform bacteria at Vancouver bridge, Smith Lake, and Bybee Lake during high-water winter/spring CSO and storm water events.

6. MODEL SENSITIVITY ANALYSIS

6.1 Variation of Model Branch Layout

In the model development presented in Section 3, the narrow channel between Smith Lake and Bybee Lake was connected directly to the end of the North Slough. Hence, longitudinal momentum would be transferred between this channel and North Slough. In order to test whether this model configuration affected the model results presented in Section 5, the narrow channel to Smith Lake was not connected directly to the North Slough branch. In this new configuration, longitudinal momentum would be transferred from North Slough to the curving channel going toward Bybee Lake. The new model layout is shown in Figure 25. Table 11 shows a correspondency between the cell number layout for the old and new branch layout. Model simulations were made with the new model layout for both high-water and low-water conditions.

Table 11. Cell number correspondency between model simulations varying branch layout.

Location	Cell number for simulations presented in Sections 3-5	Cell number for variation in branch layout
East end of North Slough	108	104
West end of North Slough	116	112
Adjacent cell to east end of North Slough in Bybee Lake	107	103
Upstream end of principal Bybee branch (termed branch #3 in Section 3)	129	91
Downstream end of principal Bybee branch (termed branch #3 in Section 3)	141	103
Upstream end of secondary Bybee branch (termed branch #4 in Section 3)	144	144
Downstream end of secondary Bybee branch (termed branch #4 in Section 3)	151	151
Upstream end of principal Smith branch (termed branch #1 in Section 3)	91	115
Downstream end of principal Smith branch (termed branch #1 in Section 3)	107	131
Upstream end of secondary Smith branch (termed branch #2 in Section 3)	119	134
Downstream end of secondary Smith branch (termed branch #2 in Section 3)	126	141

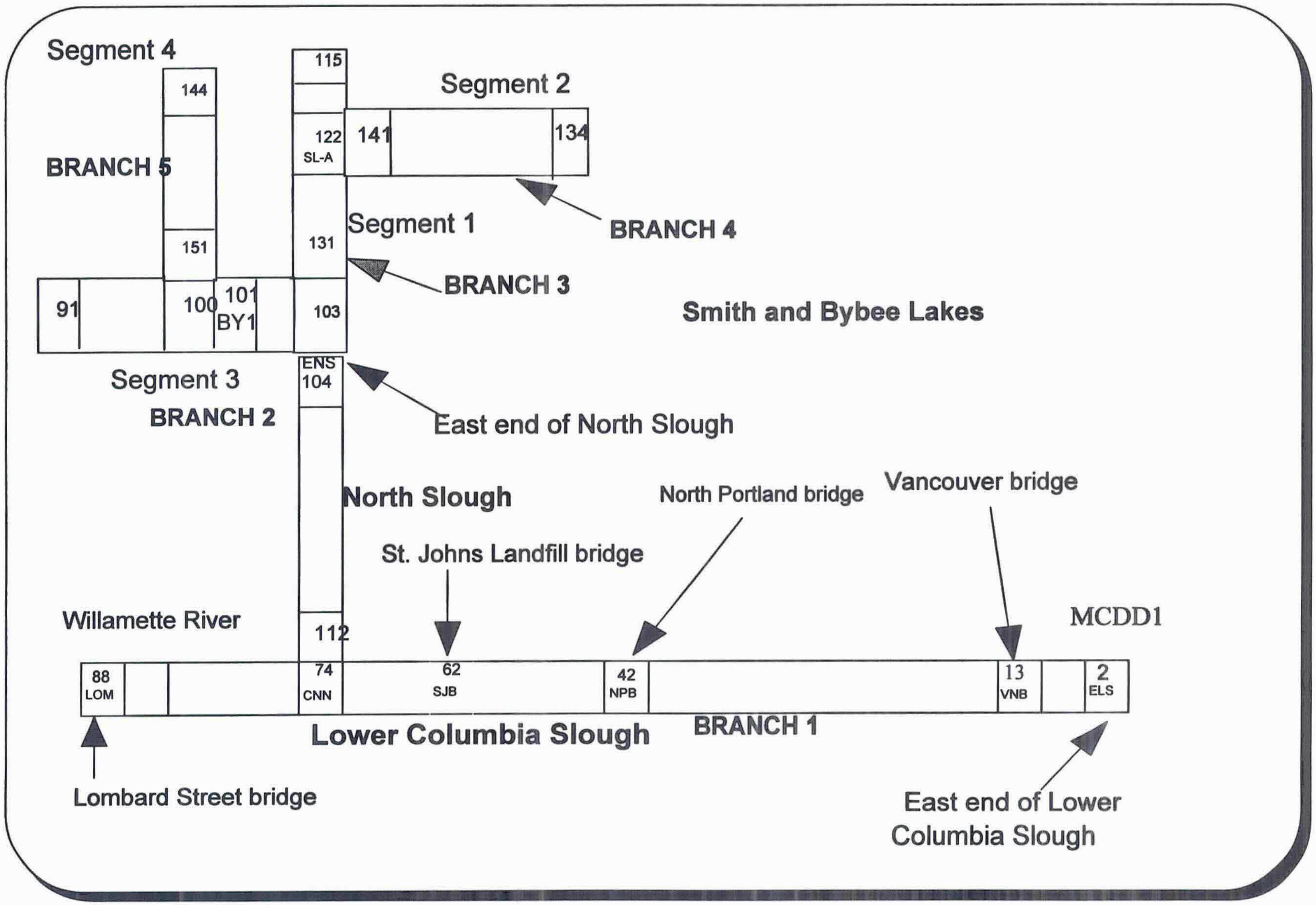

Figure 25. New branch layout with North Slough attached to Bybee Lake.

6.1.1 Summer, low-water conditions

Table 12 shows a comparison of mean water level and rms flow rates from the old and new branch layout for summer, low-water conditions. For low-water conditions, mean water level predictions comparing the old and new branch layouts (comparing Table 12 and Table 6) were within 0.07% at BY1 (standard deviation of 1.9%) and 0.15% at SL-A (standard deviation of 1.9%) indicating that the mean water level prediction was not very sensitive to branch layout. RMS flow rates predicted at model control points varied up to only 2.9% between the old and new branch layout. Figure 26 shows a comparison of predicted water levels between the old and new branch layout at Bybee Lake and Smith Lake.

Water level variation was larger in Bybee Lake and was smaller in Smith Lake with the new branch layout. This occurred with the new branch layout because more energy was transmitted from the east end of North Slough to Bybee Lake, and less was transmitted through the channel to Smith Lake. As shown in Figure 26, this only affected high-water conditions on an incoming tide in Bybee Lake. But actual differences in water level were small between the two model simulations.

Table 12. Comparison of water level and flow statistics between existing branch layout and the new branch layout for low-water simulation period.

	Existing model branch layout			New model branch layout		
	Mean	Std Dev	RMS-Q	Mean	Std Dev	RMS-Q
Water level						
ELS (cell 2) water level, ft MSL	5.1306	0.69763		5.1339	0.70301	
VNB (cell 13) water level, ft MSL	5.118	0.70546		5.1212	0.71093	
Cell 24 water level, ft MSL	5.1097	0.70749		5.1129	0.71297	
NPB (cell 43) water level, ft MSL	5.075	0.72997		5.0781	0.7349	
SJB (cell 63) water level, ft MSL	4.9656	0.85389		4.9674	0.8576	
CNN (cell 74) water level, ft MSL	4.9245	0.88077		4.9256	0.88497	
LOM (cell 88) water level, ft MSL	4.8231	1.1086		4.8228	1.1075	
ENS water level, ft MSL	4.9254	0.78605		4.9318	0.79845	
SL-A water level, ft MSL	4.9039	0.66354		4.8967	0.65093	
BY1 water level, ft MSL	4.9416	0.77789		4.945	0.79298	
Flow rate						
Entr to Col Sl (cell 88) flow rate, cfs	56.446	737.25	651.88	59.675	740.21	657.48
Entr to North Slough flow rate, cfs	-8.3159	162.82	144.28	-6.5656	159.23	140.99
Entr to S/B Lks flow rate, cfs	-11.604	253.46	225.33	-9.1927	246.78	218.68

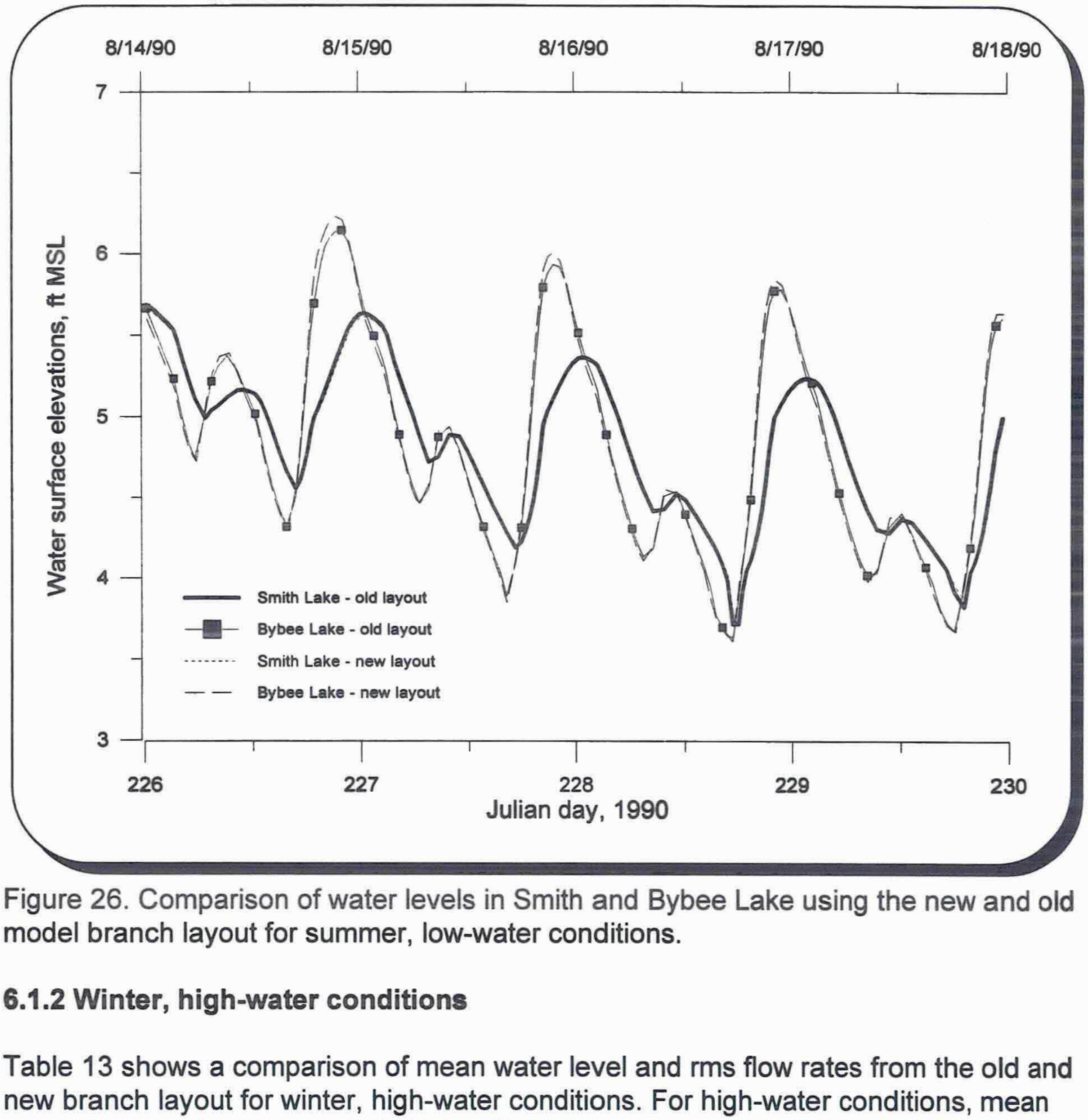

Figure 26. Comparison of water levels in Smith and Bybee Lake using the new and old model branch layout for summer, low-water conditions.

6.1.2 Winter, high-water conditions

Table 13 shows a comparison of mean water level and rms flow rates from the old and new branch layout for winter, high-water conditions. For high-water conditions, mean water level predictions were within 0.07% at BY1 (standard deviation of 1.8%) and 0.09% at SL-A (standard deviation of 0.9%) between the old and new branch layouts. RMS flow rates predicted at model control points varied up to only 1.6%. Figure 27 shows a comparison of predicted water levels between the old and new branch layout at Bybee Lake and Smith Lake for high-water conditions.

Again water level variation in Bybee Lake was greater (comparing the standard deviation of water levels between Table 13 and 7) with new branch layout because more energy was transmitted from the east end of North Slough to Bybee Lake. As shown in Figure 27, both high-water and low-water conditions were affected in Bybee Lake. But actual differences were still small between the two model simulations.

Table 13. Comparison of water level and flow statistics between existing branch layout and the new branch layout for high-water simulation period.

	Existing model branch layout			New model branch layout		
	Mean	Std Dev	RMS-Q	Mean	Std Dev	RMS-Q
Water level						
ELS (cell 2) water level, ft MSL	8.8799	0.98773		8.8789	0.99206	
VNB (cell 13) water level, ft MSL	8.8715	0.98965		8.8705	0.99399	
Cell 24 water level, ft MSL	8.8633	0.99091		8.8622	0.9953	
NPB (cell 43) water level, ft MSL	8.8464	0.99403		8.8453	0.99849	
SJB (cell 63) water level, ft MSL	8.8178	1.0026		8.8166	1.0072	
CNN (cell 74) water level, ft MSL	8.7903	0.98883		8.7893	0.99389	
LOM (cell 88) water level, ft MSL	8.7548	1.0589		8.7543	1.0624	
ENS water level, ft MSL	8.7756	0.9268		8.7821	0.93086	
SL-A water level, ft MSL	8.8154	0.90326		8.8079	0.91111	
BY1 water level, ft MSL	8.8034	0.91406		8.8095	0.93062	
Flow rate						
Entr to Col SI (cell 88) flow rate, cfs	205.78	1132.8	984	205.79	1132.3	981.65
Entr to North SI flow rate, cfs	0.056164	505.77	424.73	0.07458	497.51	418.05
Entr to S/B Lks flow rate, cfs	0.80306	821.87	690.46	-1.0834	808.21	679.25

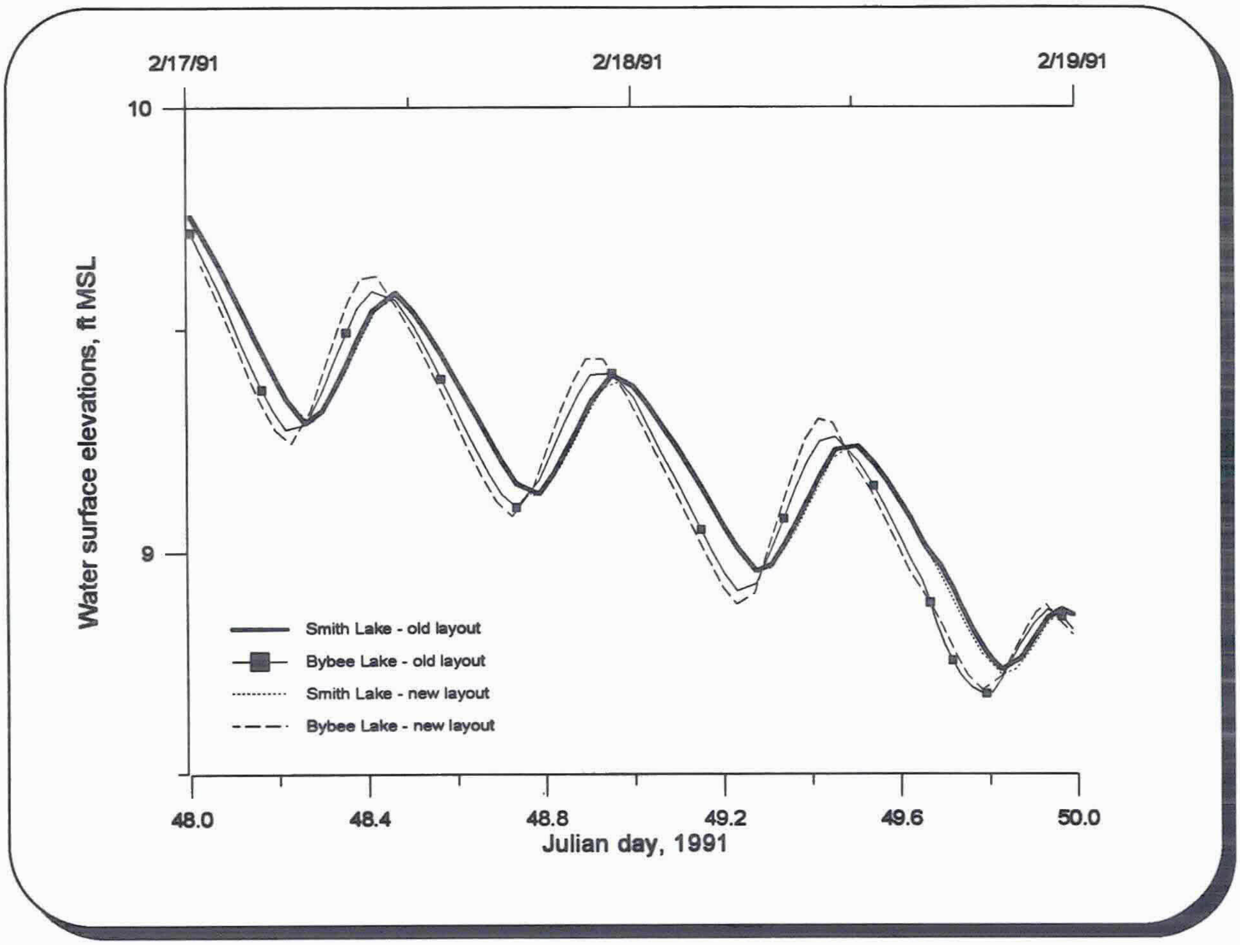

Figure 27. Comparison of water levels in Smith and Bybee Lake using the new and old model branch layout for winter, high-water conditions.

6.2 Variation of Manning's Friction Factor

The friction factors chosen for Smith and Bybee lake were 0.030 everywhere except along the narrow channel separating Smith Lake from Bybee Lake where a value of 0.035 was used (indicating more friction). The sensitivity of this choice of friction factors was evaluated in this section. Typical values of Manning's friction factors used throughout the Lower Slough system ranged from 0.02 to 0.03 for the model calibration work shown in Wells (1992a). The slightly higher values in the Lakes were assumed to be reflective of slightly higher friction characteristics because of aquatic plants.

Simulations were made using friction factors of 0.02 everywhere in the Lake system for both high-water and low-water conditions.

6.2.1 Summer, low-water conditions

Table 14 shows a comparison of mean water level and rms flow rates from the existing and new friction factors for summer, low-water conditions. Variation of the friction factor from 0.03-0.035 to 0.02 increased the inflows and outflows from the Smith and Bybee Lake system by about 17%. Because of the lowering the friction factors, the system was more "slippery" and more water could move in and out during a tidal cycle. Figure 28 shows a comparison of water levels during the low-water period in Smith and Bybee Lake. Mean water levels were about the same, but water levels in Smith Lake increased and those in Bybee Lake decreased since water was not as restricted from flowing through the narrow channel between Smith and Bybee Lake. Variability of water levels in Bybee Lake were about the same between simulations, but Smith Lake had an increased variability in water levels (as indicated by the standard deviation of the water level at SL-A increasing from 0.66 ft to 0.71 ft).

Table 14. Comparison of water level and flow statistics between existing (n between 0.03 and 0.035) and new (n=0.02) friction factors in Smith and Bybee Lake for low-water conditions.

	Existing Manning's friction factors in Smith/Bybee Lake (n=0.03-0.035)			New Manning's friction factors in Smith/Bybee Lake (n=0.02)		
	Mean	Std Dev	RMS-Q	Mean	Std Dev	RMS-Q
Water level						
ELS (cell 2) water level, ft MSL	5.1306	0.69763		5.1292	0.69493	
VNB (cell 13) water level, ft MSL	5.118	0.70546		5.1167	0.70285	
Cell 24 water level, ft MSL	5.1097	0.70749		5.1086	0.70489	
NPB (cell 43) water level, ft MSL	5.075	0.72997		5.0746	0.72711	
SJB (cell 63) water level, ft MSL	4.9656	0.85389		4.9712	0.84588	
CNN (cell 74) water level, ft MSL	4.9245	0.88077		4.9297	0.86676	
LOM (cell 88) water level, ft MSL	4.8231	1.1086		4.8233	1.1136	
ENS water level, ft MSL	4.9254	0.78605		4.9202	0.76794	
SL-A water level, ft MSL	4.9039	0.66354		4.908	0.70711	
BY1 water level, ft MSL	4.9416	0.77789		4.9386	0.77067	
Flow rate						
Entr to Col Sl (cell 88) flow rate, cfs	56.446	737.25	651.88	52.079	759.83	669.85
Entr to North Slough flow rate, cfs	-8.3159	162.82	144.28	-10.6	190.48	168.45
Entr to S/B Lks flow rate, cfs	-11.604	253.46	225.33	-14.88	299.19	265.23

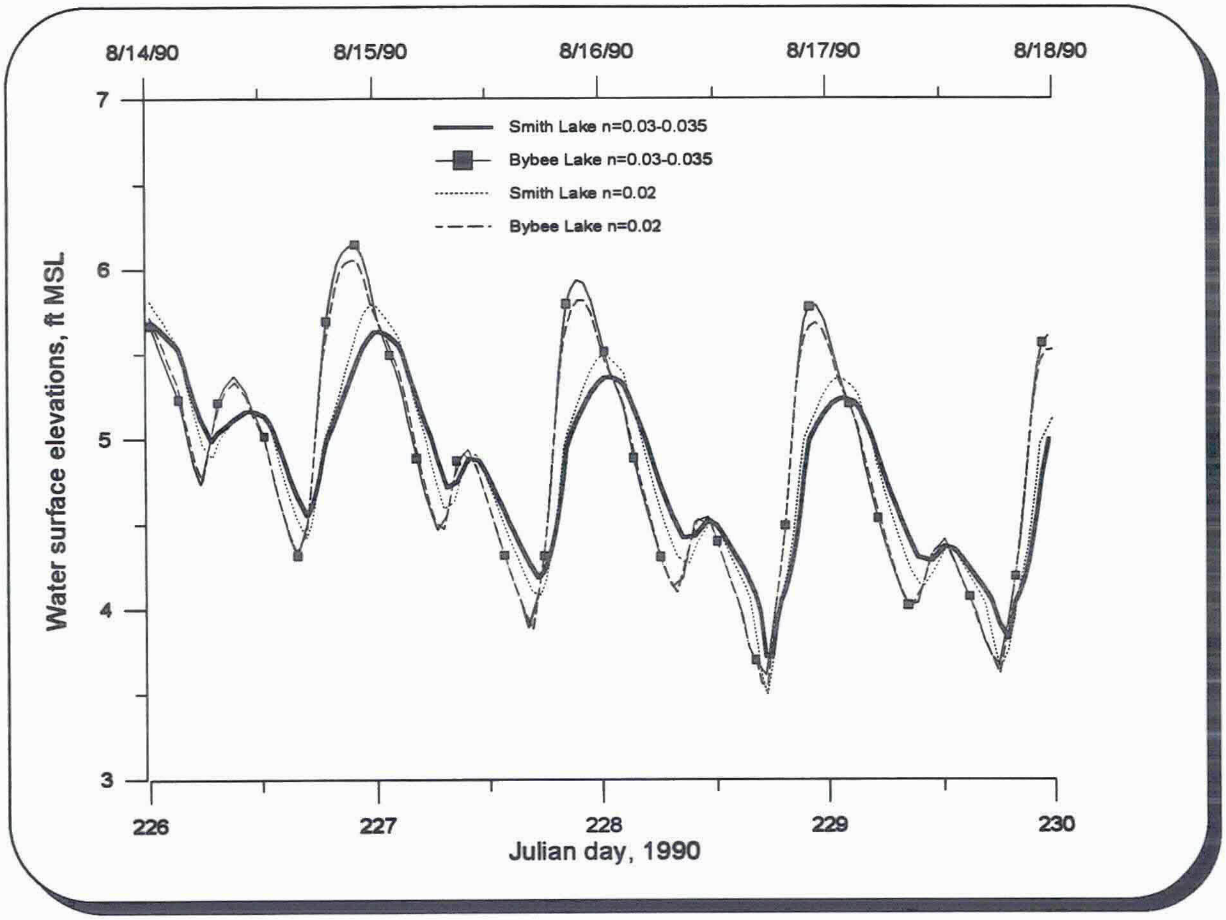

Figure 28. Comparison of water levels in Smith and Bybee Lake using the new and old Manning's friction factors for summer, low-water conditions.

6.2.2 Winter, high-water conditions

Table 15 shows a comparison of mean water level and rms flow rates from the existing and new friction factors for winter, high-water conditions. Variation of the friction factor from 0.03-0.035 to 0.02 increased the inflows and outflows from the Smith and Bybee Lake system by about 11%. Figure 29 shows a comparison of water levels during the high-water period in Smith and Bybee Lake. Mean water levels were the same between simulations, but peak values were somewhat different (by about an inch). Variability of water levels in Bybee Lake and Smith Lake were increased using the lower friction values. For example, the standard deviation of the water level at SL-A increased from 0.90 ft to 0.96 ft and at BY-1 from 0.91 ft to 0.95 ft.

Table 15. Comparison of water level and flow statistics between existing (n between 0.03 and 0.035) and new (n=0.02) friction factors in Smith and Bybee Lake for high-water conditions.

	Existing Manning's friction factors in Smith/Bybee Lake (n=0.03-0.035)			New Manning's friction factors in Smith/Bybee Lake (n=0.02)		
	Mean	Std Dev	RMS-Q	Mean	Std Dev	RMS-Q
Water level						
ELS (cell 2) water level, ft MSL	8.8799	0.98773		8.8858	1.0179	
VNB (cell 13) water level, ft MSL	8.8715	0.98965		8.8775	1.0199	
Cell 24 water level, ft MSL	8.8633	0.99091		8.8694	1.0213	
NPB (cell 43) water level, ft MSL	8.8464	0.99403		8.8528	1.0247	
SJB (cell 63) water level, ft MSL	8.8178	1.0026		8.8249	1.0335	
CNN (cell 74) water level, ft MSL	8.7903	0.98883		8.7954	1.0266	
LOM (cell 88) water level, ft MSL	8.7548	1.0589		8.7549	1.0967	
ENS water level, ft MSL	8.7756	0.9268		8.7698	0.9653	
SL-A water level, ft MSL	8.8154	0.90326		8.8166	0.95451	
BY1 water level, ft MSL	8.8034	0.91406		8.8035	0.95301	
Flow rate						
Entr to Col Sl (cell 88) flow rate, cfs	205.78	1132.8	984	204.29	1206.6	1048.4
Entr to North Sl flow rate, cfs	0.056164	505.77	424.73	0.01	608.91	473.92
Entr to S/B Lks flow rate, cfs	0.80306	821.87	690.46	-0.37101	904.82	769.95

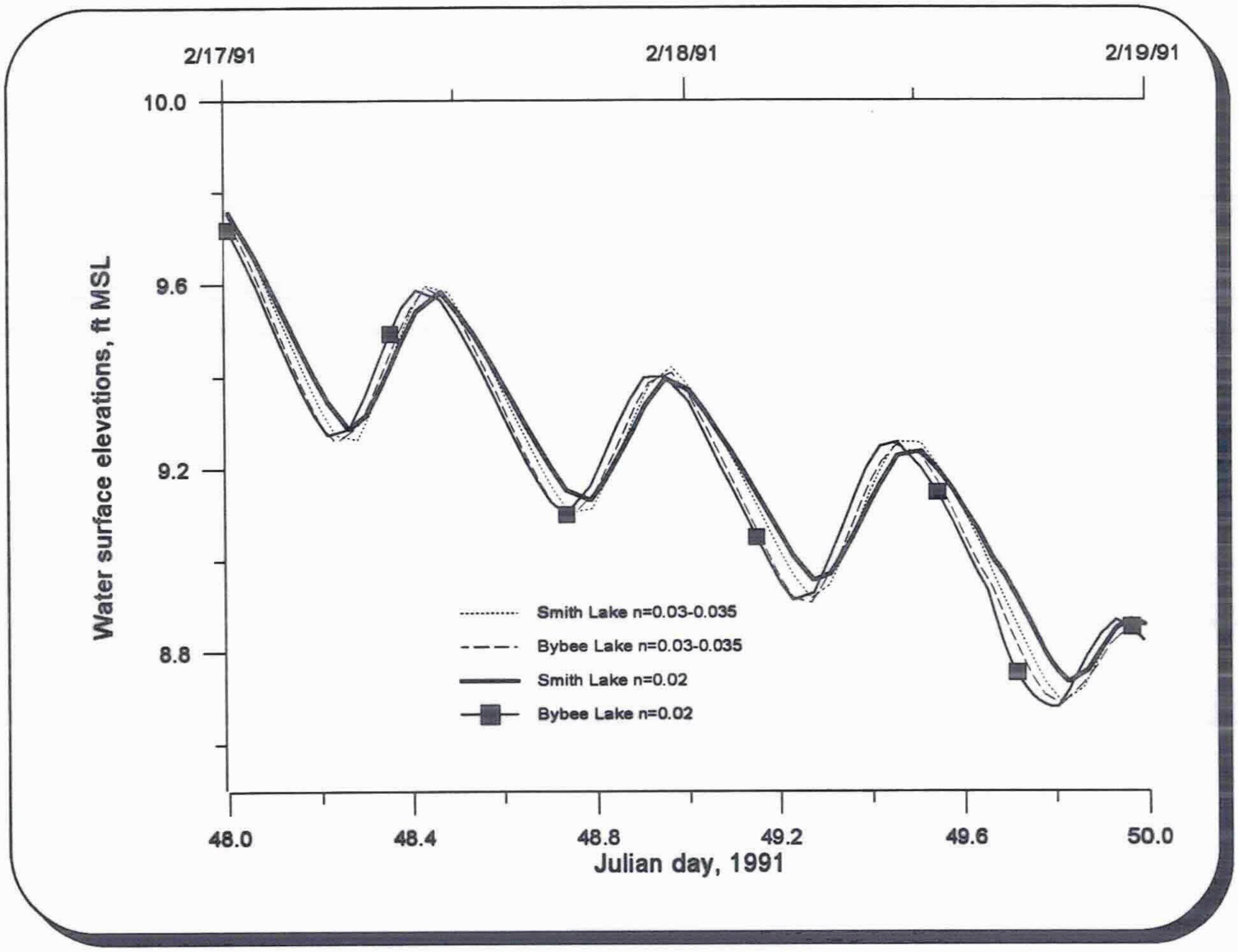

Figure 29. Comparison of water levels in Smith and Bybee Lake using the new and old Manning's friction factors for winter, low-water conditions.

7. SUMMARY AND CONCLUSIONS

A model of Smith and Bybee Lakes was used with a model of the Lower Columbia Slough to evaluate the impacts of opening up the Lakes to the North Slough. The impacts of the Willamette River, CSOs, and St. John's Landfill leachate were evaluated looking at conservative tracer transport from each source and evaluating the dilution in Smith Lake and Bybee Lake.

Conclusions from the modeling study include:

(i) During low-water conditions, Smith Lake does not respond as readily to tidal fluctuations as Bybee Lake. Tidal amplitude in Smith Lake was reduced by up to 1 ft and water level phase shift up to 0.2 days compared to Bybee Lake water level fluctuation. During high-water conditions, Smith Lake and Bybee Lake responded similarly to the water level variation in the Willamette River.

(ii) With North Slough open to the Lakes, dissolved oxygen problems in North Slough were not apparent. Even though the model showed reduced dissolved oxygen in the Lakes (see Table 9) during low-water summer conditions, this may be a result of the assumed value of sediment oxygen demand for the Lakes, the impacts of landfill leachate with a high BOD, and/or sedimentation of algae and subsequent decay in the Lakes. Further analysis is required to determine the cause of this lowered dissolved oxygen in Smith and Bybee Lakes.

(iii) CSOs in the summer and winter would cause water quality violations in Smith and Bybee Lake until they are removed from the Lower Slough.

(iv) Dilution of landfill leachate is of the order of 1000 times in Smith and Bybee Lakes.

(v) Almost undiluted Willamette River water will reach both Smith and Bybee Lakes with the lakes open to North Slough.

A sensitivity analysis was performed varying the branch geometry and the friction factors in the system. Adjustment of the branch layout and decreasing the Manning's friction factor did not significantly alter conclusions reached with the existing model layout. Of more significance to successful modeling of the system would be the model bathymetry.

Suggestions for further analysis include:

(i) using the new landfill leachate loading determined by METRO (1995) to compare the impacts on North Slough with the existing conditions to compare with the Lakes open to North Slough

(ii) investigate the lowered dissolved oxygen in Smith and Bybee Lakes during low-water summer conditions

(iii) perform a bathymetric study of the Lake system to re-define the bathymetry used in the modeling study

(iv) when the dike at the end of North Slough is removed, monitor water levels in the Lakes so that the friction factors can be determined by model-data calibration of water levels

(v) when the dike at the end of North Slough is removed, measure the flow rate at the end of North Slough using a continuous monitor and use these data to further verify the model predictions of flow into and out from the Lake system.

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9. APPENDIX A - SMITH AND BYBEE LAKE MODEL BATHYMETRY

Lakes Bathymetry

The bathymetry of Smith and Bybee Lake was evaluated using the program SURFER. From this program, surface area and volume as a function of elevation were determined for each branch and for the overall system. Table A1 shows the area and volume of Smith and Bybee Lake as a function of elevation for the overall system and for each segment detailed in Figures 4 through 7. Figure A1 and A2 show the volume and area as functions of elevation for each segment.

Model Bathymetry

Tables A2 through A5 show the model geometry (cell widths in m) as a function of cell number (longitudinal and vertical) for segments 1, 2, 3, and 4, respectively. Table A6 shows the model volume as a function of vertical cell number for each segment in Smith and Bybee Lakes. Figures A3 through A6 show a comparison of the SURFER generated and model generated (taking the slices of the SURFER graphs and resolving into vertical and longitudinal averages) volumes.

Table A1. Area and Volume of Smith and Bybee Lake as a function of elevation.

	Smith and Bybee Lake		Segment 1 - Smith Lk		Segment 2- Smith Lk		Segment 3 - Bybee Lk		Segment 4 - Bybee Lk	
Elevation ft MSL	Volume ft^3	Area ft^2	Volume ft^3	Area ft^2	Volume ft^3	Area ft^2	Volume ft^3	Area ft^2	Volume ft^3	Area ft^2
11	2.02E+08	5.19E+07	6.49E+07	1.66E+07	7.81E+07	1.85E+07	2.31E+07	6.60E+06	3.72E+07	1.18E+07
10	1.53E+08	4.72E+07	4.94E+07	1.55E+07	6.04E+07	1.74E+07	1.72E+07	5.50E+06	2.64E+07	1.02E+07
9	1.11E+08	3.72E+07	3.61E+07	1.22E+07	4.45E+07	1.47E+07	1.26E+07	4.24E+06	1.82E+07	6.96E+06
8	7.76E+07	2.89E+07	2.52E+07	1.01E+07	3.14E+07	1.18E+07	8.88E+06	3.54E+06	1.26E+07	4.68E+06
7	5.16E+07	2.36E+07	1.62E+07	8.25E+06	2.10E+07	9.42E+06	5.82E+06	2.78E+06	8.55E+06	3.77E+06
6	3.00E+07	1.95E+07	8.87E+06	6.66E+06	1.24E+07	7.75E+06	3.41E+06	2.33E+06	5.17E+06	3.20E+06
5	1.24E+07	1.47E+07	3.12E+06	4.20E+06	5.40E+06	6.33E+06	1.45E+06	1.78E+06	2.32E+06	2.58E+06
4	8.27E+05	6.64E+06	2.38E+05	1.89E+06	2.52E+05	2.28E+06	1.10E+05	9.24E+05	2.12E+05	1.59E+06
3	0	0	0	0	0	0	0	0	0	0
2	0	0	0	0	0	0	0	0	0	0
1	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0
-1	0	0	0	0	0	0	0	0	0	0
-2	0	0	0	0	0	0	0	0	0	0

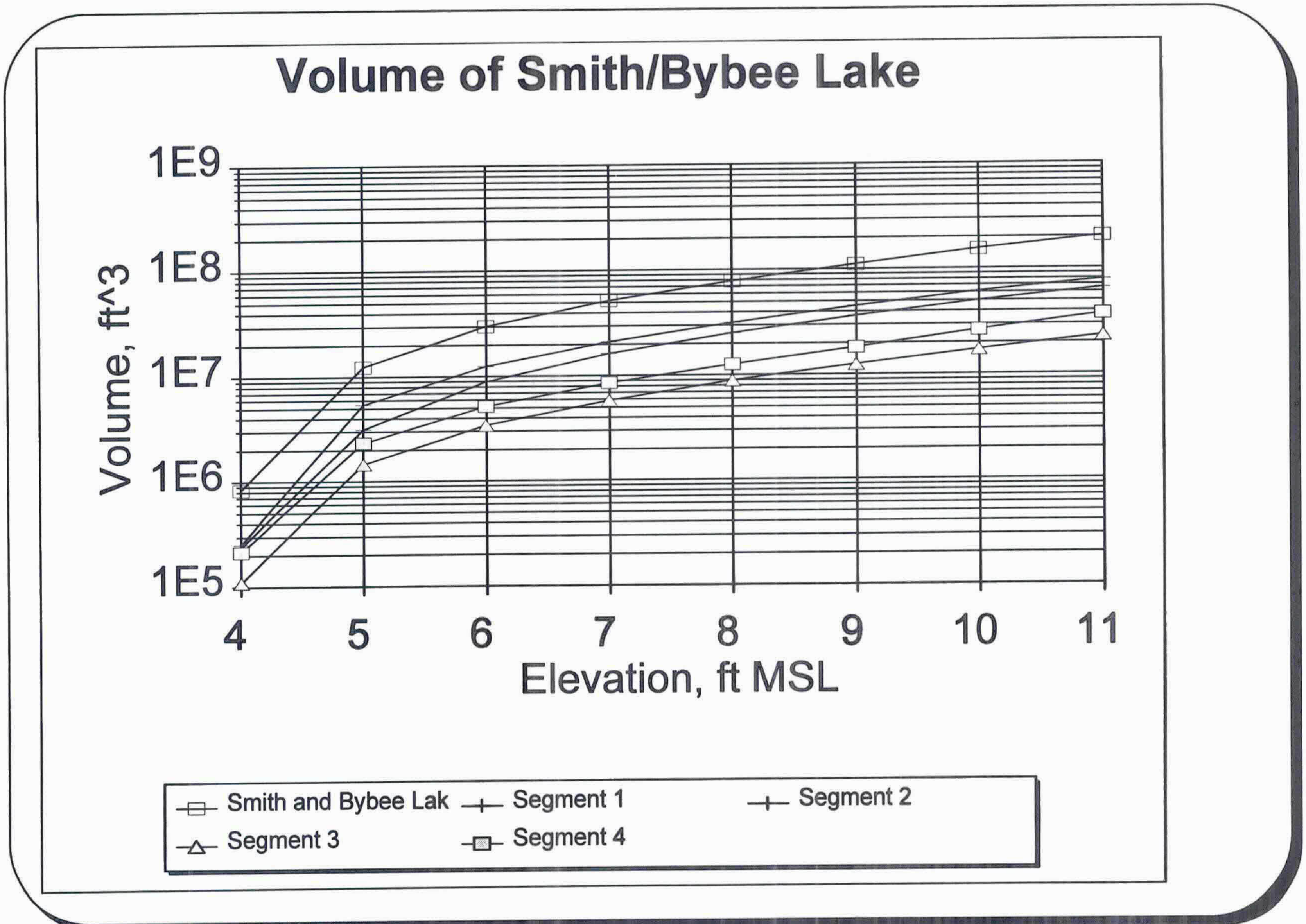

Figure A1. Volume of Smith and Bybee Lake as a function of elevation.

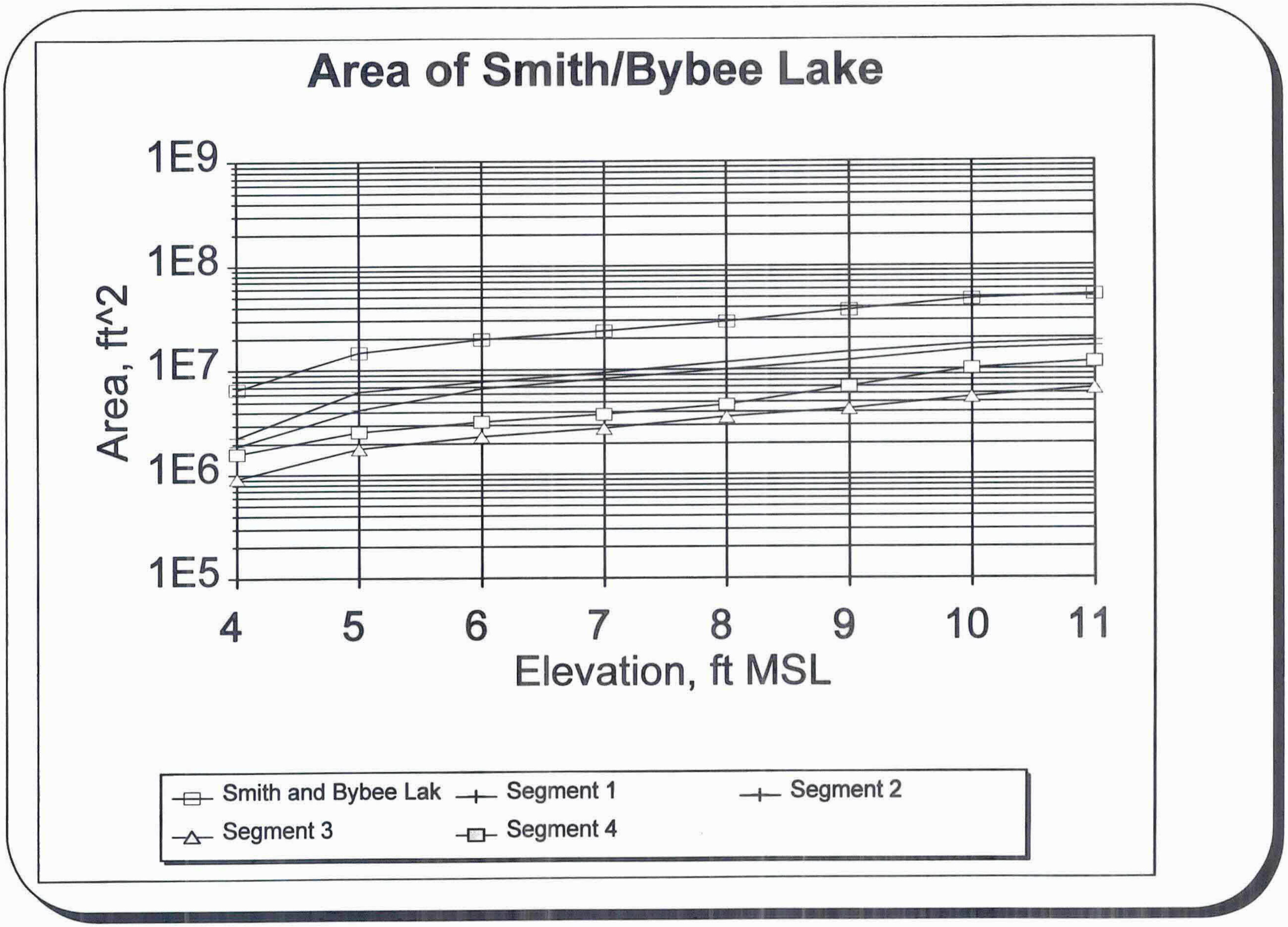

Figure A2. Area of Smith and Bybee Lakes as a function of elevation.

Table A2. Cell widths in m for each cell of Smith and Bybee Lake segment 1.

KT	Elevation of top of cell, ft MSL	90	91	92	93	94	95	96	97	98	99	100	101	102	103	104	105	106	107
		BR1																	
1	20	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2	18	0	894	869.6	813.1	800	1031.6	942.5	645.2	725.9	488.7	488.6	405.2	349.5	319.1	316.2	255.8	219.1	130.3
3	16	0	892.8	869.2	812	798.7	1000.7	941.4	644.1	693.2	488	487.7	404.4	348.2	318.3	314.8	254.5	217.9	129
4	14	0	889.9	868.7	810.8	797.4	977.6	940.2	642.9	660.4	487.3	486.7	403.6	347	317.4	313.4	253.3	216.7	127.6
5	12	0	785.3	868.3	809.6	796.1	957.9	939	641.8	627.7	486.6	485.8	317.5	345.7	316.6	312	252.1	215.5	114.9
6	10	0	588.8	733	678.8	704.9	700	700	590.7	575.3	402.6	306.1	186.4	239.9	216.5	212.6	162.8	157	62.5
7	8	0	272.6	522.7	509.9	525	525	525	489.1	451.8	304.2	91.4	108.5	78.8	85.7	88.2	59.8	73.4	15.3
8	6	0	25.3	250	275	275	290	275	241	241	150	41.2	39	14.9	27.3	43.4	36.1	35.3	15
9	5	0	0	100	100	120	200	250	240	240	163	13.2	11	10	10	12.1	13.4	11.4	10.8
10	4	0	0	13.5	14.6	39	40	40	40	40	29.5	11	10	10	8	8	8	8	8
11	3	0	0	0	0	0	0	0	0	10	10	10	5	5	5	5	5	5	5
12	2	0	0	0	0	0	0	0	0	5	5	5	5	5	5	5	5	5	5
13	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
14	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
15	-1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
16	-2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
17	-3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Table A3. Cell widths in m for each cell of Smith and Bybee Lake segment 2.

	Elevation of top	118	119	120	121	122	123	124	125	126	127
KT	of cell ft MSL	BR2									
1	20	0	0	0	0	0	0	0	0	0	0
2	18	0	1310.5	613.8	1988.5	2112	2128.5	1916.3	1682.9	829.6	0
3	16	0	1301.4	462.9	1970.6	2098.4	2125.4	1906.6	1674.7	819.6	0
4	14	0	1292.2	241.7	1951.1	2083.2	2122.3	1896.8	1666.4	809.6	0
5	12	0	1283.1	170	1652.2	2062.1	2102	1887	1658.2	799.6	0
6	10	0	983.7	150	998	1587	2042.3	1663.3	1253.8	753.2	0
7	8	0	275	140	550.9	1025.8	1662	1170.9	702.3	350	0
8	6	0	250	100	250	355	860	375	350	300	0
9	5	0	240	100	240	350	859	374	350	290	0
10	4	0	20	20	20	50	70	70	70	34.2	0
11	3	0	0	0	0	0	0	10	10	10	0
12	2	0	0	0	0	0	0	5	5	5	0
13	1	0	0	0	0	0	0	0	0	0	0
14	0	0	0	0	0	0	0	0	0	0	0
15	-1	0	0	0	0	0	0	0	0	0	0
16	-2	0	0	0	0	0	0	0	0	0	0
17	-3	0	0	0	0	0	0	0	0	0	0

Table A4. Cell widths in m for each cell of Smith and Bybee Lake segment 3.

KT	Elevation of top of cell in ft MSL	128	129	130	131	132	133	134	135	136	137	138	139	140	141	142
		BR3														
1	20	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2	18	0	239.5	355.6	355.6	614.2	1050.1	722.9	2674.4	797.8	264	266.5	268.7	212.3	63.2	0
3	16	0	223.8	343.1	343.1	601.3	888.3	700.6	2055.2	691.3	248.9	244.7	260.1	197.3	57.7	0
4	14	0	209.6	330.5	330.5	497.5	726.6	678.2	1435.9	580.4	225.6	216.2	250	173.6	52.3	0
5	12	0	195.5	255.9	255.9	315.1	561.7	655.8	806.6	450	184.2	191.8	211.6	150.2	46.8	0
6	10	0	94.3	160.1	160.1	190.5	400	400	374.4	270.7	131.8	171.3	168.8	134.8	41.3	0
7	8	0	0	100	100	110	190	188.1	200.6	126.5	89	152.2	147.8	120.5	35.9	0
8	6	0	0	50	60	65	65	75	92	60	55	75	70	50	31.7	0
9	5	0	0	50	57	39.8	57.8	71.3	91	29.8	30.4	74	69	50	30	0
10	4	0	0	10	10	10	10	15	20	12.8	14.7	20	20	20	15	0
11	3	0	0	0	0	0	0	0	0	0	0	10	10	10	10	0
12	2	0	0	0	0	0	0	0	0	0	0	5	5	5	5	0
13	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
14	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
15	-1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
16	-2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
17	-3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Table A5. Cell widths in m for each cell of Smith and Bybee Lake segment 4.

KT	Elevation of top of cell ft MSL	143 BR4	144	145	146	147	148	149	150	151	152
1	20	0	0	0	0	0	0	0	0	0	0
2	18	0	519.8	723.4	749.2	803.1	859.4	850.2	811.6	859.4	0
3	16	0	502.8	712.2	738.4	792.8	849.7	845.3	803.4	854.1	0
4	14	0	479.6	699.8	723.8	777.1	839	840.3	795.2	848.8	0
5	12	0	420.3	647.1	668.2	748.3	769.5	825.1	654.1	843.5	0
6	10	0	385	545.7	491	513.9	484.3	542.4	393.9	613.2	0
7	8	0	84.2	350	320	270.3	223.4	240.5	237.8	330.4	0
8	6	0	0	230	175	143	151	155	160	170	0
9	5	0	0	228.6	174.2	142	150	154	157.8	168.3	0
10	4	0	0	35	35	30	30	35	35	35	0
11	3	0	0	0	0	0	0	10	10	10	0
12	2	0	0	0	0	0	0	5	5	5	0
13	1	0	0	0	0	0	0	0	0	0	0
14	0	0	0	0	0	0	0	0	0	0	0
15	-1	0	0	0	0	0	0	0	0	0	0
16	-2	0	0	0	0	0	0	0	0	0	0
17	-3	0	0	0	0	0	0	0	0	0	0

Table A6. Model volume as a function of cell layer for each segment of Smith and Bybee Lake.

Elevation of top of cell ft MSL	Segment 1 ft3	Segment 2 ft3	Segment 3 ft3	Segment 4 ft3
20				
18	1.747E+08	2.242E+08	9.891E+07	1.042E+08
16	1.429E+08	1.830E+08	7.305E+07	8.397E+07
14	1.114E+08	1.424E+08	5.055E+07	6.396E+07
12	8.008E+07	1.028E+08	3.183E+07	4.426E+07
10	4.966E+07	6.472E+07	1.779E+07	2.597E+07
8	2.597E+07	3.378E+07	8.934E+06	1.294E+07
6	1.047E+07	1.450E+07	3.814E+06	6.197E+06
5	3.006E+06	5.179E+06	1.358E+06	2.313E+06
4	5.374E+05	5.810E+05	2.912E+05	3.855E+05
3	2.133E+05	9.842E+04	1.312E+05	9.842E+04
2	1.312E+05	4.921E+04	6.562E+04	4.921E+04
1	0.000E+00	0.000E+00	0.000E+00	0.000E+00
0				

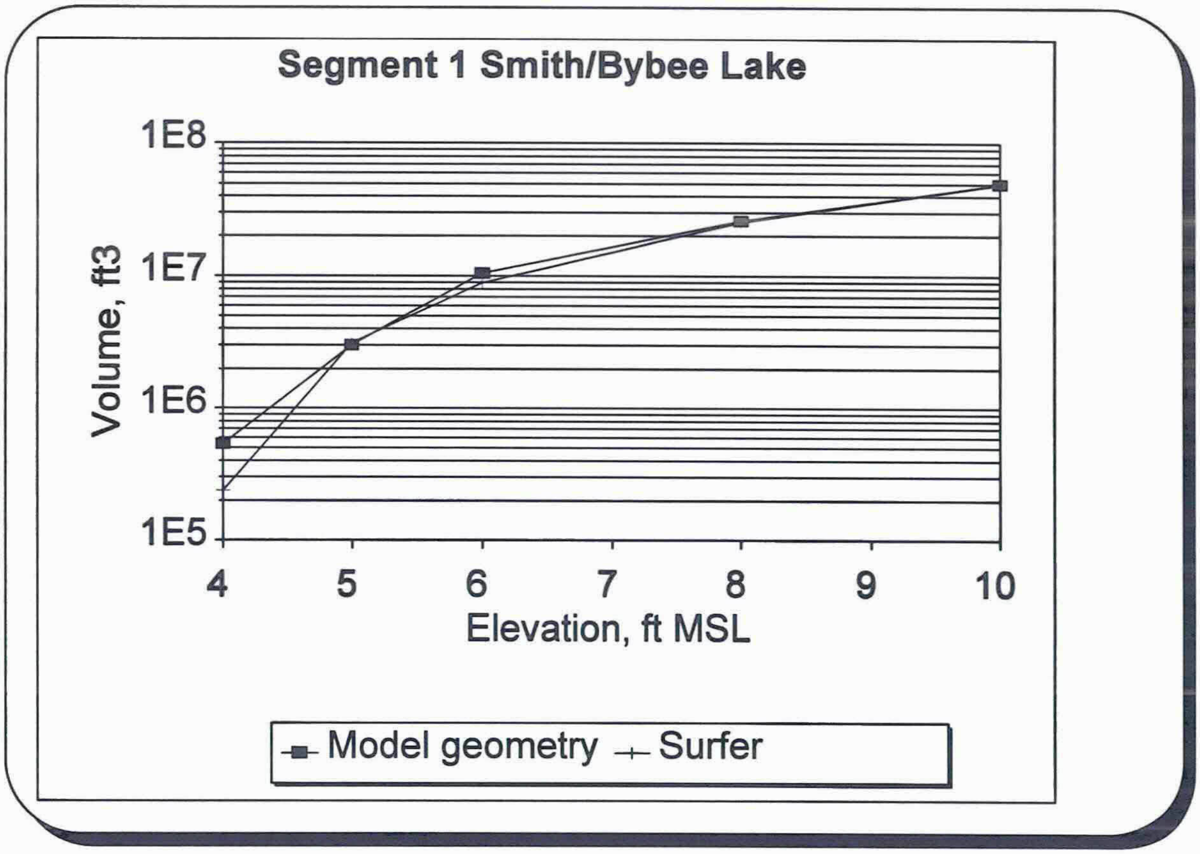

Figure A3. Comparison of model geometry volume compared to SURFER volume as a function of elevation for Segment 1.

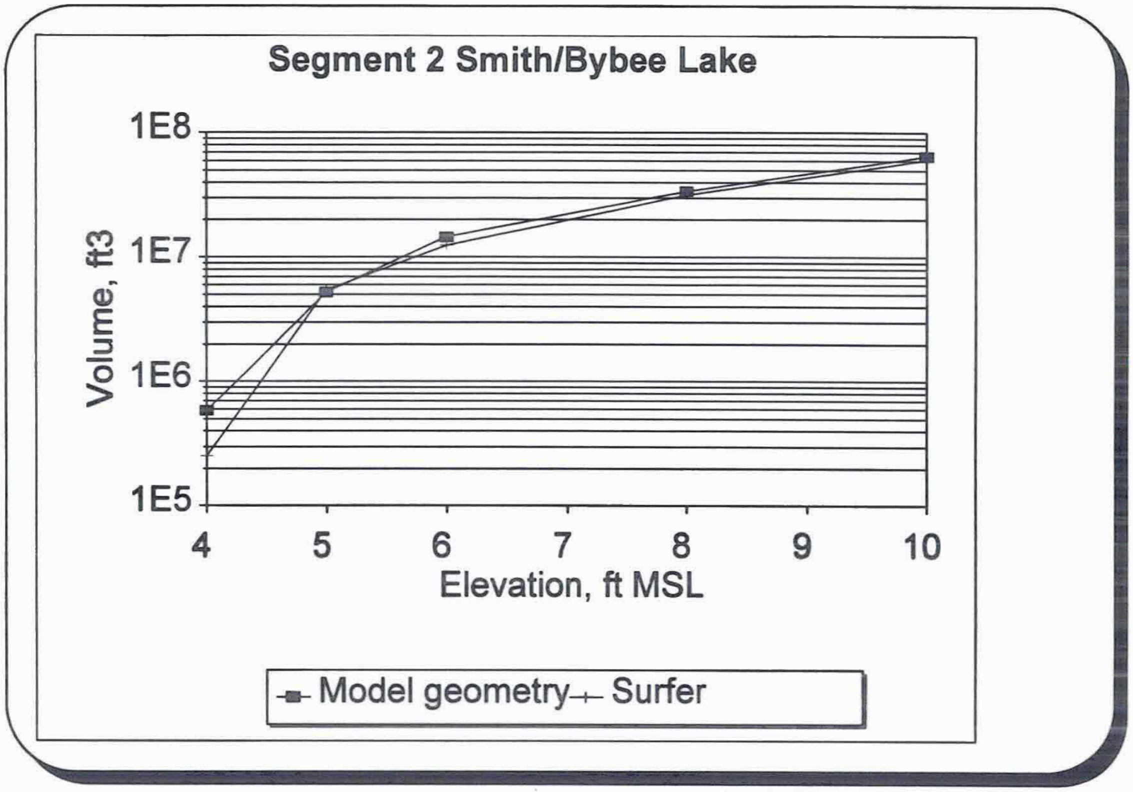

Figure A4. Comparison of model geometry volume compared to SURFER volume as a function of elevation for Segment 2.

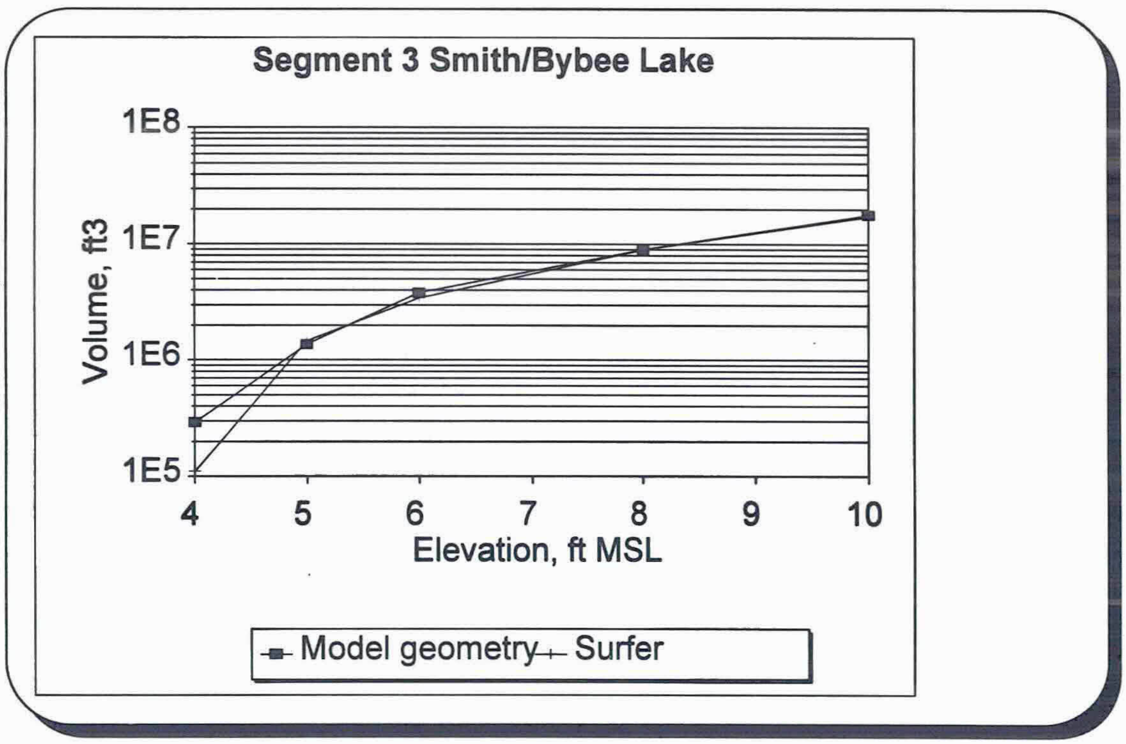

Figure A5. Comparison of model geometry volume compared to SURFER volume as a function of elevation for Segment 3

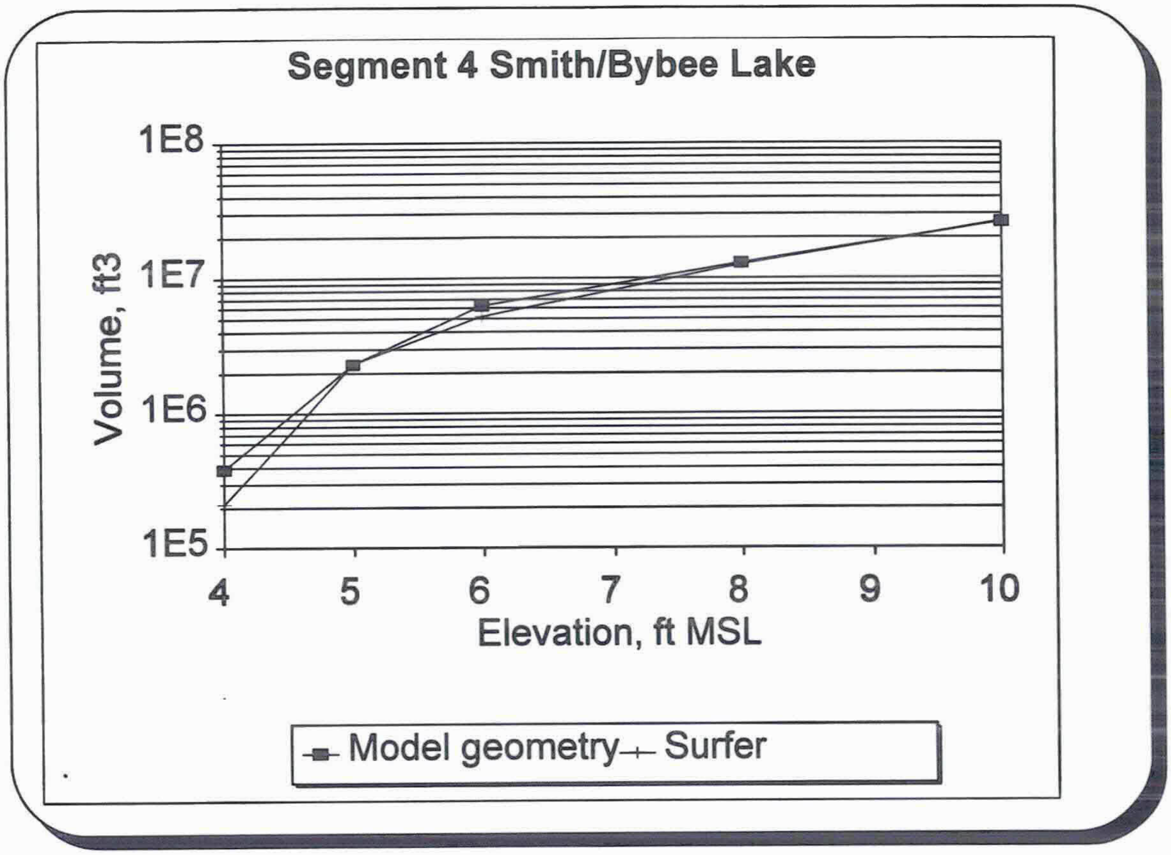

Figure A6. Comparison of model geometry volume compared to SURFER volume as a function of elevation for Segment 4.