APPENDIX O

Study of Salt Transport in the Lower Hillsborough River Using a Laterally Averaged Two-Dimensional Hydrodynamic Model

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Executive Summary

A laterally averaged model for estuary (LAMFE) was developed to simulate hydrodynamics and salinity transport in the Lower Hillsborough River. The model solves the differential equations for mass and momentum balances using the Finite Difference Method with a rectangular grid system (z-grid in the vertical direction). It was calibrated and verified with measured real-time data for a 12-month period from September 1981 to August 1982 and a 30-day period in June 1997. The verified model was then used to conduct a series of scenario runs to study the effects of upstream releases of fresh or near-fresh water on salinity distributions in the river under conditions of negligible rainfall. Model results of these scenario runs include:

(1) If the release of fresh water from the dam is small (5 cfs or less), the volume of fresh water (salinity less than 0.5 ppt) in the river will be too small for the model grid system to resolve.

(2) By increasing the freshwater release to 10 cfs, a small freshwater zone (540 m^3) can be maintained near the base of the dam. The size of the freshwater zone is affected by the Sulphur Springs flow entering to the river at about 2.2 miles downstream of the dam. For example, if the spring flow is 40 cfs or greater, the size of the freshwater zone is at least 150 meters in the longitudinal direction.

(3) With a release of water from the reservoir of 40 cfs or greater, a salinity zone with less than 1 ppt from the surface to the bottom can be maintained in the first 1000 meters downstream of the dam.

(4) Routing a portion of the flow from Sulphur Springs to the base of the dam could have a pronounced effect on salinity distributions in the river by reducing salinity below the dam. For example, routing 10 cfs of spring water to the base of the dam would create a zone of water below the dam with salinity values less than 4 ppt salinity. The size of this zone would be 82,700 m^3, with the lowest salinity values ranging between 2 and 3 ppt. Increasing the routed spring-flow to 15 cfs would result in some water less than 2 ppt occurring below the dam on all tides.

(5) Because the flow from Sulphur Springs has an average salinity of 1.2 ppt, routing a portion of spring water to the base of the dam would not create a freshwater zone (< 0.5 ppt) below the dam, unless flow released from the reservoir is at least 75% higher than the routed spring flow.

In additional to these scenario runs, the verified model was also used to study the salinity response time to the upstream freshwater releases. Four upstream freshwater release schedules were simulated over a 18-day period: (1) Q cfs in the first nine days and 0 cfs in the second nine days, (2) 0 cfs in the first nine days and Q cfs in the second nine days, (3) Q cfs in the first seven days, 0 cfs in Days 8 through 10, and Q cfs again in the rest eight days, and (4) Q cfs on Days 1, 3, 5, ..., and 17) and 0 cfs on Days 2, 4, 6, ..., and 18. Five Q values have been studied: 10, 20, 40, 60, and 100 cfs. Model results for the four release schedules with five different release rates lead to the following conclusions:

(1) Salinity in the river does not respond to an upstream freshwater release change immediately. There is a time lag between salinity and upstream freshwater release.

(2) Impact of freshwater release from the dam on salinity is less significant for the downstream portion of the river than for the upstream portion of the river. For example, while a release of 10 cfs freshwater from the reservoir can greatly change salinity at the 22nd Street station, it has only minor effect on salinity at the Columbus Drive station.

(3) The response time of salinity at the 22nd Street station depends on whether the upstream freshwater release increases or decreases. If the freshwater release is turned off, the response time for salinity at 22nd Street is about one week or longer. If the freshwater flow rate is increased from 0 cfs to Q cfs, the response time for salinity at 22nd Street depends on the magnitude of Q and is normally much smaller than that when the freshwater flow is suddenly turned off.

(4) Because of the difference in response times for increasing and decreasing flow rates, it is possible to allow two or three days of no release between two continuous releases with a period of at least one week without allowing salinity at 22nd Street to increase too much.

The model was also run for a continuous 274-day period to see how a 10 cfs minimum flow would affect the frequency distribution of salinity zone volumes under naturally occurring conditions of rainfall and resultant stormwater runoff below the dam. Two cases were studied during a period from the end of September 1981 to June 1982. In the first case, the 10 cfs minimum flow was released from the reservoir (with a salinity of 0.1 ppt). In the second case, a flow with a magnitude of $(10- Q_{dam})$cfs, where Q_{dam} is the discharge rate over the dam, was diverted from the Sulphur Springs and released at the base of the dam (with a salinity of 1.2 ppt). In both cases, the minimum flow was in effect only for days when flow over the dam(Q_{dam}) was less than 10 cfs. It was found that with a minimum flow of 10 cfs released from the reservoir, a salinity zone of < 4 ppt would always exist in the river and a freshwater zone would occur for at least 80 percent of the simulation period (274 days). With the option of flow diverted from Sulphur Springs to make a total of 10 cfs at the base of the dam, the increase in the freshwater and < 1 ppt volumes would be substantially less than that resulting from the release of 10 cfs of reservoir water. The frequency distributions for volumes of slightly higher salinity waters (<1.5 and < 4 ppt), however, were much more similar between the two scenarios.

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1. Introduction

The Lower Hillsborough River (Figure 1) is located in Tampa, west-central Florida. The river has a length of 10 miles and an average depth of about 2.9 meters (the deepest area is about 6.2 meters.) At the mean sea level, the average width is about 63 meters. The river starts at the Hillsborough dam, which releases fresh water to the river, and ends near Platt Street to meet the Hillsborough Bay. About 2.2 miles downstream from the dam, spring water from Sulphur Springs enters the river via a short spring run.

Hydrodynamics and salinity distributions in the river are controlled by (1) tide at Platt Street, (2) salinity distribution at Platt Street, (3) flow over the dam, (4) flow out of Sulphur Springs, and (5) stormwater runoff below the dam. The river is stratified most of the time due to the relative weak tide at Platt Street. The stratification is further enhanced by the lateral spring water input to the top layer of the river. Because of the narrowness, cross-sectional variations of salinity, surface elevation, and velocity are much smaller than those in the vertical direction and along the length of the river. Therefore, hydrodynamics and salinity transport in the river can be treated as two-dimensional problems, with one dimension in the vertical direction and the other dimension in the longitudinal direction starting from the dam.

As part of the procedure for establishing a minimum flow rate for the Lower Hillsborough River, a laterally averaged model for estuary (LAMFE) has been developed to simulate hydrodynamics and salinity transport in the river. The model solves the differential equations using the Finite Difference Method with a rectangular grid system (z-grid in the vertical direction). The model was calibrated and verified with a measured real-time data for a 12-month period from September 1981 to August 1982 and a 30-day period in June 1997. The verified model was used to conducted a series of scenario runs to study salinity transport processes in the river and effects of the upstream freshwater release on salinity distributions in the river. The simulation period for the scenario runs was a 18-day period during which only trace rainfall was received and the tide at the end of the period was a spring tide. Model results of these scenario runs are presented and discussed in this report.

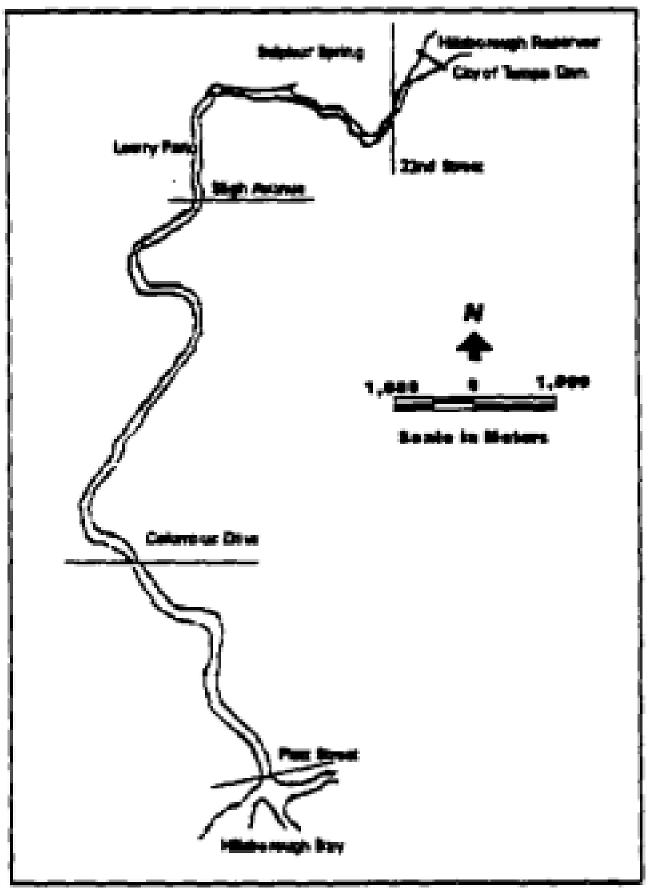

Figure 1 The Lower Hillsborough River of Tampa, Florida.

The model has also been used to study the salinity response time in the river to the upstream freshwater release. For the same 18-day period used for the scenario runs, four upstream freshwater release schedules were simulated: (1) Q cfs in the first 9 days and 0 cfs in the second 9 days, (2) 0 cfs in the first 9 days and Q cfs in the second 9 days, (3) Q cfs in the first 7 days, 0 cfs in Days 8 through 10, and Q cfs again in the rest 8 days, and (4) Q cfs on Days 1, 3, 5, ..., and 17 and 0 cfs on Days 2, 4, 6, ..., and 18. Five Q numbers have been studied. They were 10, 20, 40, 60, and 100 cfs.

To see how a 10 cfs minimum flow would affect the frequency distribution of salinity zone volumes under naturally occurring conditions of rainfall and resultant stormwater runoff below the dam, the model was run for a continuous 274-day period. Two cases were studied during a period from the end of September 1981 to June 1982. In the first case, the 10 cfs minimum flow was released from the reservoir (with a salinity of 0.1 ppt). In the second case, a flow with a magnitude of $(10- Q_{dam})$cfs, where Q_{dam} is the discharge rate over the dam, was diverted from the Sulphur Springs and released at the base of the dam (with a salinity of 1.2 ppt). In both cases, the minimum flow was in effect only for days when flow over the dam(Q_{dam}) was less than 10 cfs.

Model theory and development are described in Section 2 of this report. Measured data of surface elevation, salinity, rainfall, as well as discharges from the reservoir and the spring are presented in Section 3, which also shows how the model was calibrated and verified using measured in the Lower Hillsborough River. Section 4 presents forty-five scenario runs to study how various releasing options would affect salinity distributions in the river, while Section 5 studies the salinity response time in the river to changes in the upstream freshwater release. Section 6 presents model studies on how an assumed minimum flow of 10 cfs would affect frequency distributions of various salinity volumes. Conclusions of the current studies are summarized in Section 7.

2. Model Theory

The movement of water and the distribution of salt in an estuary like the Lower Hillsborough River can be described by a set of mathematical equations, which can be derived from the conservation of mass (water), momentum, and salt. In deriving these equations, it is assumed that water is a continuum and mean quantities on a time scale which is much larger than the turbulence time scale and much smaller than the time scale of phenomena (here, tidal motion) being considered. Effects of turbulent motion on the transport of mass and momentum are expressed by correlations of turbulent quantities, which are further assumed to be functions of mean quantities. Various models have been proposed to relate the correlations of turbulent quantities with mean quantities. Reviews of various turbulence closure models can be found in Chen (1994) and Nunes Vaz and Simpson (1994). This study uses the Sub-Grid Scale model to simulate horizontal transport of momentum and salt by turbulence. For vertical turbulent mixing, a turbulent kinetic energy (TKE) model (Sheng and Villaret, 1989; Chen, 1994) is used to calculate the vertical eddy viscosity and diffusivity.

2.1 Governing Equations

By integrating the general three-dimensional governing equations laterally, one can easily obtain the following equations of continuity, momentum, and salinity transport. These equations can also be derived by considering the balance of water, momentum, and salt in a small cubic with a dimension of $\Delta x \times \Delta y \times \Delta z$. Since the derivation is a straightforward mathematical exercise, details are omitted here.

Continuity Equation:

$$\frac{\partial ub}{\partial x} + \frac{\partial wb}{\partial z} = v \qquad (1)$$

where u and w are velocities in x- and z-directions, respectively, v is the velocity for lateral input (direct runoff, tributary, etc.), and b is the width of the estuary.

Equation for the free surface is

$$\left(h\frac{\partial b}{\partial h} + b \right)_f \frac{\partial h}{\partial t} = -\frac{\partial}{\partial x}\left(\int_{h_o}^{h} ub\,dz \right) + \int_{h_o}^{h} v\,dz + rb_f \qquad (2)$$

where t is time, h is the surface elevation, h_o is the bottom elevation, r is the rain intensity in cm/sec, and the subscript 'f' denotes the free surface

If Equation (2) is written just for the top layer, we have:

$$\left(\eta\frac{\partial b}{\partial h} + b \right)_f \frac{\partial \eta}{\partial t} = -\frac{\partial ub\eta}{\partial x} + (wb)_- + v\eta + rb_f \qquad (3)$$

where η is the thickness of the top layer, and the subscript '-' denotes the bottom of the top layer.

Momentum Equation:

$$\frac{\partial u}{\partial t}+u\frac{\partial u}{\partial x}+w\frac{\partial u}{\partial z}=-\frac{\tau_{wx}}{\rho b}-\frac{1}{\rho b}\frac{\partial pb}{\partial x}+\frac{1}{\rho b}\frac{\partial}{\partial x}\left(\rho bA_h\frac{\partial u}{\partial x}\right)+\frac{1}{\rho b}\frac{\partial}{\partial z}\left(\rho bA_v\frac{\partial u}{\partial z}\right) \tag{4}$$

where ρ is density, A_h and A_v are horizontal and vertical eddy viscosities, respectively, τ_{wx} is the wall shear stress, and p is pressure which depends on elevation z and salinity s:

$$p=g\int_z^{\eta}\rho(z,s)dz \tag{5}$$

The wall shear stress τ_{wx} is assumed to follow the quadratic law:

$$\tau_{wx}=\rho C_w u\sqrt{u^2+w^2}$$

where C_w is the friction coefficient for the wall.

The vertical eddy viscosity A_v is calculated by solving the turbulent kinetic energy equation from the velocity gradient, while the horizontal eddy viscosity A_h is calculated from the Sub-Grid Scale model (SGS) model and is controlled by cross-section length scale.

Boundary conditions specified in the z-direction are shear stresses. At the free surface, shear stress is induced by wind. At the bottom, it is assumed that turbulence is fully developed and a log--layer distribution of velocity can be used to calculate the bottom shear stress:

$$\tau_b=\rho\left[\frac{\kappa}{\ln(z_b/z_0)}\right]u_b|u_b|$$

where κ is the von Karman constant (0.41), u_b is the horizontal velocity at a level z_b near the bottom.

In the x-direction, boundary conditions are specified with either the free surface elevation or velocity. If surface elevation is specified, velocity at the boundary is calculated from Equation (4) with the assumption $\partial u/\partial x=0$

Salinity Equation:

$$b\frac{\partial s}{\partial t}+\frac{\partial ubs}{\partial x}+\frac{\partial wbs}{\partial z}=\frac{\partial}{\partial x}\left(bB_h\frac{\partial s}{\partial x}\right)+\frac{\partial}{\partial z}\left(bB_v\frac{\partial s}{\partial z}\right)+vs_0 \tag{6}$$

where s is salt concentration, B_h is the horizontal diffusivity, B_v is the vertical diffusivity, and s_0 represnets salt content in tributaries.

For the top layer, the above equation becomes

$$\frac{\partial\eta bs}{\partial t}+\frac{\partial ub\eta s}{\partial x}=\left(wbs+B_v b\frac{\partial s}{\partial z}\right)_-+\frac{\partial}{\partial x}\left(b\eta B_h\frac{\partial s}{\partial x}\right)+\eta vs_0+rb_f s_r \tag{7}$$

where s_r represents salinity in rainfall (0 for default).

Equation of State:

$$\rho = \frac{P-1}{\alpha - 0.698P} \tag{8}$$

where P and α are functions of temperature and salinity:

$$P = 5890 + 38T - 0.375T^2 + 3s$$

$$\alpha = 1779.5 + 11.25T - 0.0745T^2 - (3.8 + 0.01T)s$$

2.2 Difference Equations

Because of the complexity of the bathymetry and boundary conditions of the Lower Hillsborough River, a numerical method have to be employed to find solutions to the above equations. This study uses the finite difference method to solve the above equations numerically. A rectangular grid system with z-level (Figure 2) was used to derive the difference equations. Although a z-level model requires a lot of efforts of programming, it does have the advantages of reducing numerical diffusion and automatically taking care of the wetting-trying phenomena (Sheng et al., 1989; Casulli, 1990) of the river bank. Therefore, this study chose to use z-level, instead of σ-level, which has been widely used (e.g., Perrels and Karelse, 1981, Blumberg and Meller, 1987, Chen and Sheng, 1994).

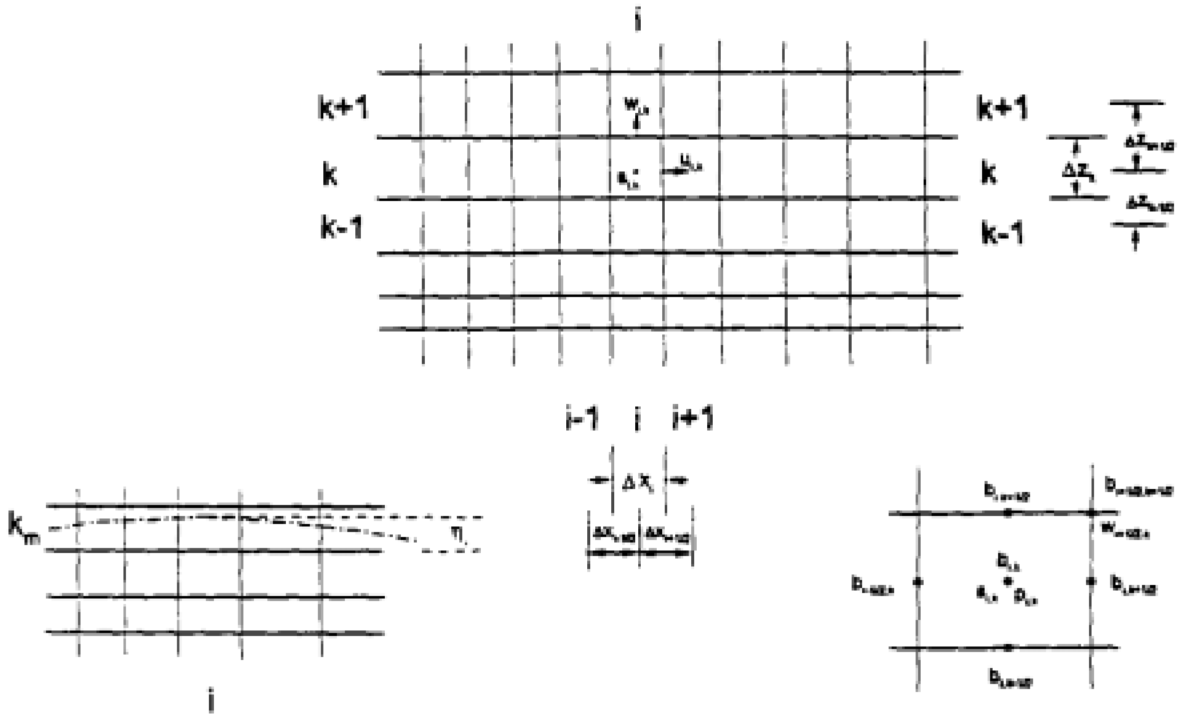

Figure 2 Rectangular, z-level grids for the laterally averaged 2-D model.

Continuity Equation:

$$\frac{w_{i,k}^{n+1} b_{i,k+1/2} - w_{i,k-1}^{n+1} b_{i,k-1/2}}{\Delta z_i} = v_{i,k}^{n+1/2} - \frac{1}{\Delta x_i}[u_{i,k}^n b_{i+1/2,k} - u_{i-1,k}^n b_{i-1/2,k}] \quad (9)$$

where Δx and Δz are grid sizes in x- and z-directions, n denotes the n-th time step, and the subscripts i and k are grid indexes in x- and z-directions, respectively.

For the top layer ($k=k_m^n$),

$$(\eta_i^n b_f' + b_f^n)\frac{\eta_i^{n+1} - \eta_i^n}{\Delta t} = -\frac{u_{i+1,k}^n b_{i+1/2,k}\eta_{i+1/2}^n - u_{i,k}^n b_{i-1/2,k}\eta_{i-1/2}^n}{\Delta x_i} + w_{i,k-1}^{n+1} b_{i,k-1/2} + v_{i,k}^{n+1/2}\eta_i^n + b_f^n r^{n+1/2} \quad (10)$$

where, b'^n_f is $\frac{\partial b}{\partial h}$ at the free surface at the n-th time step.

Momentum Equation:

$$\begin{aligned}
\frac{u_{i,k}^{n+1} - u_{i,k}^n}{\Delta t} = & -u_{i,k}^{n+1}\left(\alpha_i \frac{u_{i,k}^n - u_{i-1,k}^n}{\Delta x_{i-1/2}} + \beta_i \frac{u_{i+1,k}^n - u_{i,k}^n}{\Delta x_{i+1/2}}\right) + w_{i+1/2,k}^{n+1}(\theta u_z^{n+1} + (1-\theta)u_z^n \\
& + \frac{C_u u_{i,k}^{n+1}}{b_{i+1/2,k}}\sqrt{(u_{i,k}^n)^2 + (w_{i+1/2,k-1/2}^n)^2} - \frac{1}{\rho_{i+1/2,k}^{n+1} b_{i+1/2,k}} \frac{p_{i+1,k}^{n+1} b_{i+1,k} - p_{i,k}^{n+1} b_{i,k}}{\Delta x_{i+1/2}} \\
& + \frac{1}{\rho_{i+1/2,k}^{n+1} b_{i+1/2,k}} \frac{1}{\Delta x_{i+1/2}}\left(\rho_{i+1,k}^{n+1} b_{i+1,k} A_{x_{i+1,k}}^n \frac{u_{i+1,k}^n - u_{i,k}^n}{\Delta x_{i+1}} - \rho_{i,k}^{n+1} b_{i,k} A_{x_{i,k}}^n \frac{u_{i,k}^n - u_{i-1,k}^n}{\Delta x_i}\right) \\
& + \frac{1}{\rho_{i+1/2,k}^{n+1} b_{i+1/2,k}} \frac{1}{\Delta z_{k+1/2}}\left(\rho_{i+1/2,k+1/2}^{n+1} b_{i+1/2,k+1/2} A_{z_{i,k}}^n \frac{u_{i,k+1}^{n+1} - u_{i,k}^{n+1}}{\Delta z_{k+1/2}}\right. \\
& \left. - \rho_{i+1/2,k-1/2}^{n+1} b_{i+1/2,k-1/2} A_{z_{i,k-1}}^n \frac{u_{i,k}^{n+1} - u_{i,k-1}^{n+1}}{\Delta z_{k-1/2}}\right)
\end{aligned} \quad (11)$$

where θ varies between 0 (fully explicit) and 1 (fully implicit), and

$$\alpha_i = \frac{\Delta x_{i+1/2}}{\Delta x_{i-1/2} + \Delta x_{i+1/2}}$$

$$\beta_i = 1 - \alpha_i$$

$$u_z^n = \zeta_k \frac{u_{i,k}^n - u_{i,k-1}^n}{\Delta z_{k-1/2}} + \xi_k \frac{u_{i,k+1}^n - u_{i,k}^n}{\Delta z_{k+1/2}}$$

$$p_{i,k}^{n+1} = g\left(\rho_{i,k}^{n+1}\frac{\Delta z_k}{2} + \sum_{l=k+1}^{k_m^{n+1}-1} \rho_{i,l}^{n+1}\Delta z_l + \rho_{i,k_m^{n+1}}^{n+1}\eta_i^{n+1}\right)$$

whre k_m^{n+1} is the vertical grid index number of the free surface layer at the n+1-th time step, and

$$\zeta_k = \frac{\Delta z_{k+1/2}}{\Delta z_{k-1/2} + \Delta z_{k+1/2}}$$

$$\xi_k = 1 - \zeta_k$$

Salinity Equation:

$$
\begin{aligned}
b_{i,k}\frac{s_{i,k}^{n+1}-s_{i,k}^{n}}{\Delta t} = & -\frac{1}{\Delta x_i}(u_{i,k}^{n}b_{i+1/2,k}c_i - u_{i-1,k}^{n}b_{i-1/2,k}c_{i-1}) \\
& -\frac{1}{\Delta z_k}(w_{i,k}^{n}b_{i,k+1/2}c_k - w_{i,k-1}^{n}b_{i,k-1/2}c_{k-1}) - v_{i,k}^{n+1/2}s_{o_{i,k}}^{n+1/2} \\
& +\frac{1}{\Delta x_i}(B_{h_{i,k}}^{n}b_{i+1/2,k}\frac{s_{i+1,k}^{n}-s_{i,k}^{n}}{\Delta x_{i+1/2}} - B_{h_{i-1,k}}^{n}b_{i-1/2,k}\frac{s_{i,k}^{n}-s_{i-1,k}^{n}}{\Delta x_{i-1/2}}) \\
& +\frac{1}{\Delta z_k}(B_{v_{i,k}}^{n}b_{i,k+1/2}\frac{s_{i,k+1}^{n+1}-s_{i,k}^{n+1}}{\Delta z_{k+1/2}} - B_{v_{i,k-1}}^{n}b_{i,k-1/2}\frac{s_{i,k}^{n+1}-s_{i,k-1}^{n+1}}{\Delta z_{k-1/2}})
\end{aligned}
\tag{12}
$$

where

$$c_i = S(u_{i,k}^{n})s_{i,k}^{n} + S(-u_{i,k}^{n})s_{i+1,k}^{n}$$

$$c_k = S(w_{i,k}^{n})s_{i,k}^{n} + S(-w_{i,k}^{n})s_{i,k+1}^{n}$$

and $S = 0$ if the argument is less than 0, $S=1$ otherwise.

For the top layer ($k=k_m^n$),

$$
\begin{aligned}
\frac{\eta_i^{n+1}b_{i,k}^{n+1}s_{i,k}^{n+1}-\eta_i^{n}b_{i,k}^{n}s_{i,k}^{n}}{\Delta t} = & -\frac{1}{\Delta x_i}(u_{i,k}^{n}b_{i+1/2,k}\eta_{i+1/2}^{n+1}c_i - u_{i-1,k}^{n}b_{i-1/2,k}\eta_{i-1/2}^{n+1}c_{i-1}) \\
& + w_{i,k-1}^{n}b_{i,k-1/2}c_{k-1} - B_{v_{i,k-1}}^{n}b_{i,k-1/2}\frac{s_{i,k}^{n+1}-s_{i,k-1}^{n+1}}{\Delta z_{k-1/2}} \\
& +\frac{1}{\Delta x_i}(B_{h_{i,k}}^{n}b_{i+1/2,k}\frac{s_{i+1,k}^{n}-s_{i,k}^{n}}{\Delta x_{i+1/2}} - B_{h_{i-1,k}}^{n}b_{i-1/2,k}\frac{s_{i,k}^{n}-s_{i-1,k}^{n}}{\Delta x_{i-1/2}}) \\
& + \eta_i^{n+1/2}v_{i,k}^{n+1/2}s_{o_{i,k}}^{n+1/2} + r^{n+1/2}b_f^{n+1}s_r^{n+1,2}
\end{aligned}
\tag{13}
$$

2.3 Source Code

The source code of LAMFE is written in standard FORTRAN 77. It can run on PCs, UNIX workstations or mainframe computers. The program first solves the continuity equation to obtain surface elevations at the new time step, then it updates salinity distribution by solving the salinity equation. Finally, the momentum equation is solved to update the velocity field. In solving the difference equations for momentum and salinity, the Thomas Algorithm is used to inverse the matrix. A flow chart of the model is presented in Figure 3.

2.4 Model Validation

The model was first tested for mass/momentum conservation using an idealized open channel with constant width and a constant bottom slop. The model was then tested for mass conservation using the bathymetry of the Lower Hillsborough River. The model also was tested with a few analytical solutions for some idealized cases, including the steady-state open channel velocity distribution, the standing wave solution, an enclosed tank with constant wind shear stress applied at the surface, and a seiche oscillation in an enclosed tank.

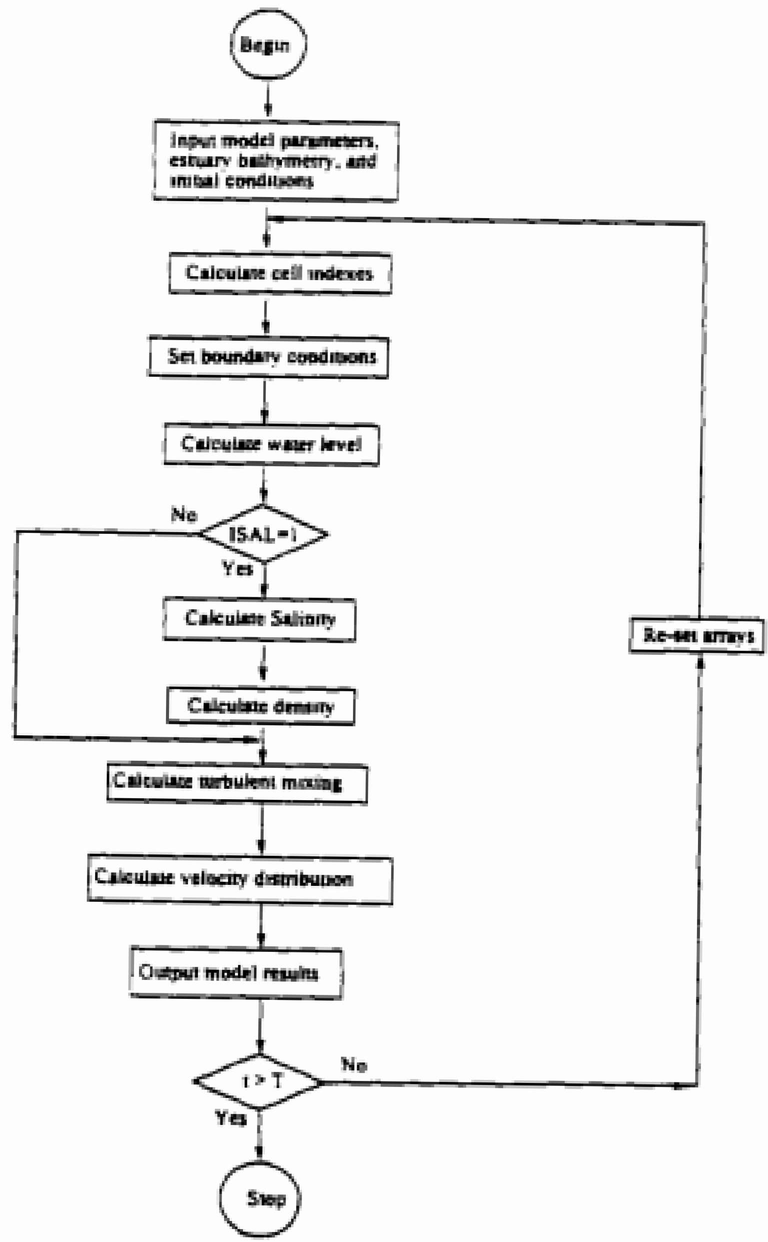

Figure 3 Flowchart of the model system LAMFE.

3. Model Calibration and Verification

To apply the model to the Lower Hillsborough River, a grid system shown in Figure 4 is used for the discretization of the river. Thirty-two grids ranging from 300 meters to 840 meters in length were used along the river and 16 vertical grids were used to resolve the depth. The smallest vertical grid size is 0.3 cm. In one particular scenario run, the first horizontal grid (the most upstream one with a horizontal grid size of 300 meters) was split into 3 grids (each with a horizontal grid size of 100 meters) and the total longitudinal grid number was thirty-four. Measured river bathymetry is input into the model by specifying the width of each grid.

Data needed to run the 2-D model include: (1) water surface elevations at the downstream boundary, (2) salinity profiles at the downstream boundary, (3) flow entering to the river from the upstream boundary, (4) salinity in the flow entering to the river from the upstream boundary, (5) flow in the tributary, (6) salinity in the tributary flow, and (7) hourly stormwater runoff to the river. Here, the upstream boundary is at the base of the dam and the downstream boundary is at Platt Street. Sulphur Springs flow was treated as a tributary. The effect of wind on the hydrodynamics in the river is negligible due to the narrowness and the meandering nature of the river. Thus, the model was run with a zero wind shear stress applied to the water surface.

3.1 Measured Field Data

Real-time stage data with a 15-minute interval were collected by the USGS at the Platt Street, Sligh Avenue, and the 22nd Street stations (Figure 1) for the period from September 1981 to September 1982. For the same time frame, hourly mid-depth salinity were also measured by the USGS at Platt Street, Columbus Avenue, Sligh Avenue, and the 22nd Street. Because Platt Street is the downstream boundary of the river, measured data at this station were used as boundary conditions in the simulation, while field data at other stations were used to calibrate and verify the model. Measured water elevation data for the period September 1981 through September 1982 are presented in Figures A-1 through A-7, while measured salinity for the same period are shown in Figures A-8 through A-14.

The USGS has also reports of spring flow from Sulphur Springs and daily discharge data from the dam. Daily flows from Sulphur Springs and from the dam for the period September 1981 through September 1982 are shown in Figures A-15 through A-21 (middle and bottom graphs).

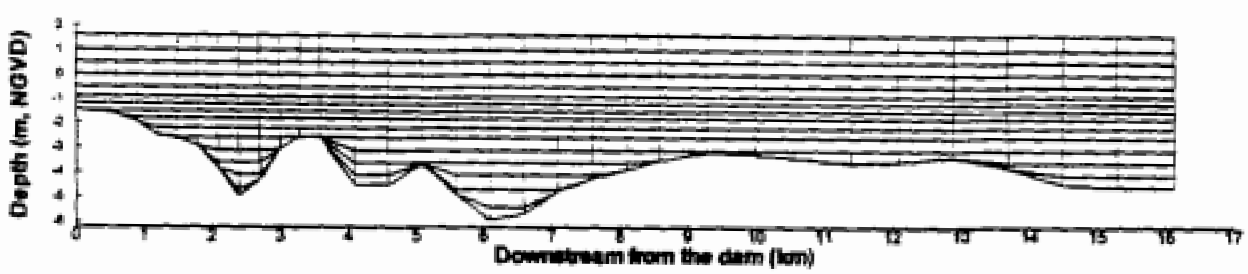

Figure 4 Grid system for the Lower Hillsborough River.

Discharges at the dam were used as the boundary condition for the upstream, while the spring discharge was input to the model as a tributary which flows laterally to the top layer of the water column (to those vertical grids which are either totally or partially above the bottom elevation of the spring run at the same longitudinal location as that of the spring).

Another freshwater input to the river is the stormwater runoff from the watershed below the dam. In order to account for the effect of runoff on salinity in the river during a rainfall event, rainfall data were used in the model to calculate runoffs, which are also treated as tributaries entering to the surface layer of the river laterally. The sheet flows from the two banks of the river are assumed to be uniformly distributed along individual longitudinal top-layer grids. The magnitude of the sheet flow to each top-layer grid was calculated as follows:

$$q_i = \frac{1}{\Delta x_i} \sum_{j=1}^{M} Q_j l_{ij} \tag{13}$$

where i is a grid number counter for the longitudinal grids, j is the a sub-basin number counter, M is the total number of the sub-basins, q_i is the sheet flow entering to the top-layer of the i-th grid in the longitudinal direction, Q_j is the flow of runoff from the j-th sub-basin, l_{ij} is the length of the intersection between the water surface of the i-th grid and the j-th sub-basin, and Δx_i is the grid size of the i-th grid in the longitudinal direction.

The flow of runoff from the j-th sub-basin, Q_j, is calculated from the area of the sub-basin, the rainfall intensity, a runoff coefficient for the sub-basin, and a unit hydrograph for the Lower Hillsborough River basin. The runoff coefficients for each sub-basins and the unit hydrograph were obtain from a previous study done by the HSW Engineering (1992).

Daily rainfall data collected by the SWFWMD near Lowry Park are available since January 1982. Measured hourly rainfall data at the Tampa International Airport (TIA) were used to estimate hourly rainfall from the daily rainfall data at the Lowry Park (LP) rainfall station. The assumption used for the estimation of hourly rainfall is that the daily rainfall at the Lowry Park station is distributed within 24 hours in the same way as that at the TIA, except for the magnitude. This can be expressed in the following form:

$$r^i_{LP} = r^i_{TIA} \frac{R_{LP}}{R_{TIA}} \qquad i = 1, 2, \ldots, 24 \tag{14}$$

where r^i_{LP} is estimated hourly rainfall during the i-th hour at the Lowry Park station, r^i_{TIA} is measured hourly rainfall at the TIA, and R_{TIA} and R_{LP} are measured daily rainfalls at the LP and TIA stations, respectively. For the period before 1982, hourly rainfall data measured at the TIP was used because no rainfall data was collected at the Lowry Park station. Rainfall data used for the period from September 1981 to September 1982 are presented in Figures A-15 through A-21(top graphs). While Figure A-15 and A-16 show hourly rainfall measured at the TIA, Figure A-17 through A-21 present estimated hourly rainfall data at the Lowry Park station using the above equation.

In addition to the above data (from September 1981 to September 1982), this study also collected salinity and stage data at the Platt Street, Sulphur Springs, and the 22nd Street stations through the USGS. The measurement period was January 1997 through July 1997. Measured surface levels are presented in Figures A-22 through A-24. Figures A-25 through A-27 are measured salinity.

Some physical characteristics of the river can easily be seen from these measured discharge, rainfall, salinity and surface elevation data:

(1) Tide is the driving force for the river. Surface elevations measured at all three stations show very significant tidal variations.

(2) From Platt Street to Sligh Avenue, tidal data only show minor damping and time lag, indicating small friction of the river bottom for this river reach. From Sligh Avenue to the 22nd Street, some small damping and time lag in tidal data can be seen. Nevertheless, they are not significant, because the distance is short.

(3) Salinity in the river also show strong tidal signals, especially from Sligh Avenue downstream. This means salinity downstream of Sligh Avenue is heavily influenced by tide. For the region near the dam, salinity varies with tide more significantly when the discharge rate from the dam is small than when the discharge rate is large. In the latter case, the discharge from the dam pushes salt water further downstream and keeps water near the dam fresh. In fact, if discharge rate from the dam is increased to about 1000 cfs or above, fresh water can even reach Platt Street.

(4) Rainfall runoff can heavily affect salinity distributions in the river. Because the drainage basin for the Lower Hillsborough River is a well-developed urban area (City of Tampa), time of concentration for the runoff is very short and is in the order of less than a few hours, and average runoff coefficient can be as high as 0.6 (HSW, 1992). As an example, let's consider a storm event with a rainfall of 1 inch per hour, the direct runoff would be on the order of 1000 cfs for 3 to 4 hours. As mentioned above, an input of 1000 cfs fresh water would dramatically decrease the salt content in the river.

(5) While discharge from the dam can vary from 0 cfs to thousands of cfs, discharge out of the spring has just little variation. Recent data show that discharge from the spring change between low 20's and high 60's, with an average of 31 cfs.

3.2 Model Calibration and Verification Using Field Data

A numerical model should be calibrated and verified before it is used for management purposes. Calibration means to tune the model parameters to obtain a best agreement between model results and field data. It can also mean a modification of the model, so that the model can better represent the real world. However, a calibrated model is not automatically a predictive tool which can be used for management, because the predictive ability of the model has not been proved if the model is just calibrated.

In order to prove that the model is a suitable predictive tool, verifications of the model using data collected in other periods of time (not those used for calibration) should be conducted. During the process of verification, calibrated model parameters should not be tuned. Only a satisfactory agreement between model results and field data is reached in verification can we say that the model can be used as a predictive model. The following describes how the model developed in this study was calibrated and verified.

Before applying the model to the real nature, field data which will be used by the model (as boundary and/or initial conditions) should be analyzed to see if data are usable or not. Generally, it is very seldom for one to get a perfect set of data. More often, one will see a lot of bad data and missing data in the data set. It is very important to have a good data set, especially for those data which will be used as boundary conditions. It is obvious that if measured tide and salinity at the mouth of the river were problematic, simulated surface elevation and salinity in the river would not be any better. Based upon these considerations and the quality of measured data which should be read by the model as boundary conditions (data at Platt Street and at the dam, as well as spring flow and rainfall), this study chose two time periods for model calibration and verification: a 12-month period from September 1, 1981 to August 31, 1982 and a 30-day period in June 1997. In the 12-month period, because data were missing for 15 days (September 22 - October 6, 1981) at Platt Street, the model was not run continuously for 12 months. Instead, the 12-month period was divided into two smaller periods: September 1 - 21, 1981 and October 7, 1981 through August 31, 1982.

As mentioned before, salinity and surface elevation data measured at the Platt Street station were used as boundary conditions at the downstream end of the river. Because salinity is stratified at Platt Street most of the time and was measured only at the mid-depth for the 1981 and 1982 data, measured data can not be directly used in the simulation, because the model requires real-time vertical salinity profiles to represent the stratification. This study developed a pre-process program to estimate salinity profiles at Platt Street from the mid-depth salinity data based on the assumption that the stratification at Platt Street is solely a function of the total fresh water release from the dam and the spring in the previous day. Using salinity profile data collected during the WAR study in 1991 through 1993, this relationship between stratification at Platt Street and fresh water release can be obtained.

For the upstream boundary, a uniform velocity distribution was assumed and can be calculated from the discharge data and the instantaneous cross-section area. A small salinity value (0.1 ppt) was assumed in the water released from the dam, as historical data show that the water upstream of the dam has low mineral content. The Sulphur Springs flow was uniformly distributed only to the top portion of the corresponding water column (-2.0 feet, NGVD, and above), because the bottom of the spring run is about -2.0 feet, NGVD. Recent data show that the spring has salinity values that vary around 1.2 ppt. Thus, a constant salinity of 1.2 ppt was assumed in the spring flow.

Rainfall data measured at the Lowry Park station and the TIA were used to estimate runoff below the dam. Equation (14) was used to estimate hourly rainfall from the daily rain data measured at Lowry Park. It is assumed that rains were uniformly distributed over the entire drainage basin.

By incorporating a previous study conducted by HSW Engineering, Inc.(1992), the drainage basin was divided into 17 sub-basins (Figure 5) to account for the variations of runoff characteristics among sub-basins. Hourly runoff from each individual sub-basin was calculated from the sub-basin area, rainfall and its runoff coefficient. The hourly runoff was then distributed within 16 hours. The temporal distribution of the runoff in the 16 hours was calculated using the unit hydrograph method, which can be estimated from the HSW study in 1992. The final fresh water input to the river from a individual sub-basin during a simulation time step was add to its corresponding river portion in accordance with Equation (13) in the model.

Arbitrary initial conditions for salinity and velocity fields were selected in the simulation. The initial conditions for flow die out after about 48 hours of simulation, while the initial conditions for salinity need about a week to become insignificant. This means that the spin-up period of a model run is about a week. One should not be surprised by the disagreement of model results with data for the spin-up period of a model run when the effect of assumed initial conditions are still significant.

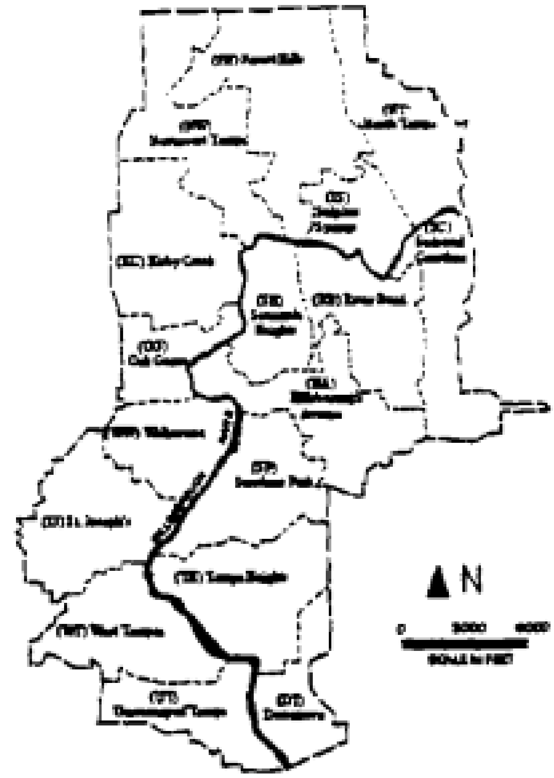

Figure 5 Drainage basin of the Lower Hillsborough River and its 17 sub-basins.

Simulated time series of surface elevations and salinity at Columbus Drive, Sligh Avenue, and the 22nd Street stations were compared to the data measured by the USGS. Figures B-1 through B-6 show comparisons between simulated and measured surface elevations at Sligh Avenue and the 22nd Street station for the simulation periods of September 1 through 21, 1981, and October 7, 1981 through August 31, 1982. Figures B-7 through B-12 show comparisons of simulated salinity with data at the 22nd Street, Sligh Avenue, and Columbus Drive stations for these two simulation periods. Comparisons of simulated and measured salinity for the 30-day period in June 1997 are shown in Figure B-13.

It can be seen from the comparisons that the model works very well. Although bad/missing data can be noticed in these field data, they do not affect the good agreement between model results and data. The comparison of surface elevation shows that simulated surface elevations are almost the same as the measured data (Figures B-1 through B-6). Although not as good as the comparison between simulated and measured surface elevations, the agreement between simulated salinity and measured data is reasonablely good. Because the quality of simulated surface elevation and salinity in the river is more or less dependent on the quality of the boundary conditions for these parameters, a successful simulation of hydrodynamics and salinity transport in the river is dependent on the quality of measured surface elevation and salinity at the Platt Street station. It was fortunate the data were temporally most complete at Platt St., with fewer periods of missing data compared to the Columbus Drive, Sligh Avenue, or 22[nd] St. stations. The availability of accurate data at the Platt St. stations allows for good model results at the Columbus, Sligh, and 22[nd] St. stations, during periods when salinity data were unavailable at those sites

One important thing this study found out is that the effect of rainfall on salinity distributions can not be neglected and runoff below the dam must be considered in the model. From the rainfall data, it can be seen that a storm event occurred on June 12th, followed by a few storm events on June 16th and 17th (Figure A-19). As a result, the data show a significant increase in water levels and a steady decrease in salinity at all measurement stations (Figures A-5 and A-12). These changes were due to local runoff as no water was released from the reservoir during this period and spring flow showed little variation. To examine the effect of local runoff on salinity, a model run was conducted that did not include any runoff from the basin below the dam. Model results of this run are shown in Figure 6. It can be seen from this figure that without considering runoff effect, the simulated salinity time series at the 22nd Street and Columbus Drive do not represent the real condition. The slight steady decrease in simulated salinity time series is due to the steady decrease of salinity boundary condition at Platt Street (measured data). Model experiments show that only when the runoff below the dam was included could a good agreement between data and simulated salinity be reached (Figure 7).

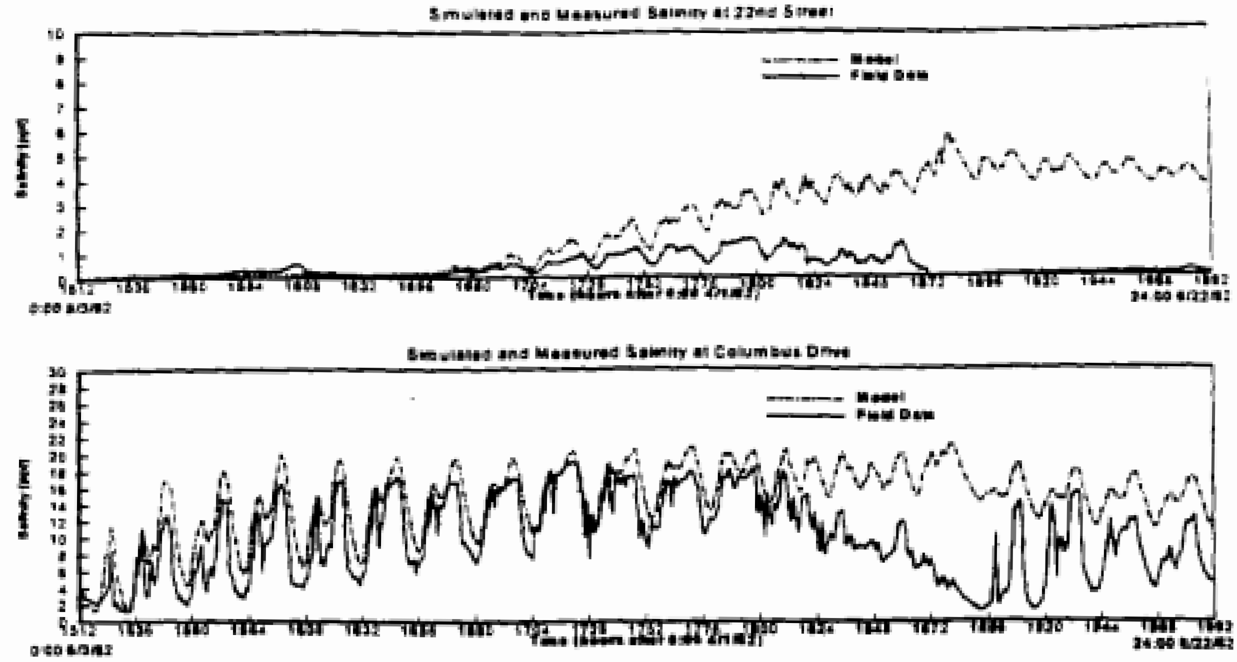

Figure 6 Comparisons of measured salinity and simulated salinity without runoff effects.

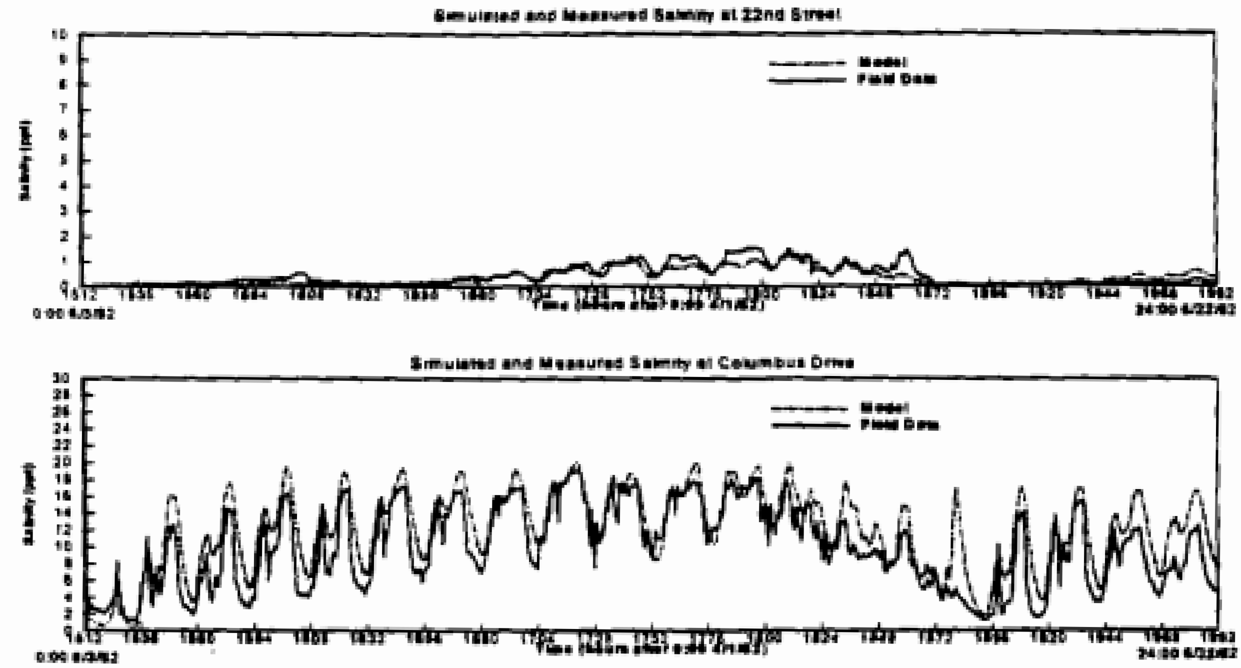

Figure 7 Comparisons of measured salinity and simulated salinity with runoff effects.

4. Scenario Runs

After the model was calibrated and verified, it was used to study different freshwater release scenarios. The purpose of the scenario runs is to study how the release of fresh water from the dam would affect salinity distributions in the river. A total of 45 scenario runs were made based on variations of spring flow and reservoir flow over the dam. The possibility of routing a portion of spring water to the base of the dam was also considered.

All 45 runs used the same model parameters determined in the model calibration process. Again, measured surface elevations and salinity at Platt Street were used as boundary conditions. The time period in which field data were used as boundary conditions was a 18-day period in 1982 (from May 11 through May 28). The reason for using this time period is that very little rainfall was received during this time span and the tide around May 28 was the spring tide period. In order to further isolate the effect of fresh water release on salinity distributions in the river, runoff caused by rains was turned off in the scenario test runs (runoff was actually very small during these 18 days). Therefore, if no freshwater flow were released from the reservoir, the condition in the river would represent a worst case scenario.

Considering the fact that measured salinity in spring flows had an average of 1.2 ppt during the last couple of years, spring flow was set to have a constant salinity value of 1.2 ppt in these scenario runs. Instead of using measured Sulphur Springs flow data collected during the period from May 11 through May 28, 1982, a constant spring flow of 31 cfs was used in the scenario runs. The number 31 cfs has been the average flow out of the Sulphur Springs in recent years.

The final results for each run include velocity/salinity fields and water volumes for various salinity zones during the last 48 hours of simulation with a 30-minute interval. Figure C-1 shows the salinity and velocity distributions at high and low tides as well as at the mean tide level for one of the scenario runs, while Figure C-2 through C-46 present salinity distributions for the 45 scenarios. Average water volumes during the last two days of the simulation period for various salinity ranges for each scenario run are presented in Table 1.

Based on model results of these scenario runs, the following conclusions can be drawn:

(1) If the release of fresh water from the dam is small (5 cfs or less), the volume of fresh water (salinity less than 0.5 ppt) in the river will be too small for the model grid system to resolve.

(2) By increasing the freshwater release to 10 cfs, a small freshwater zone (540 m^3) can be maintained near the base of the dam. The size of the freshwater zone is affected by the Sulphur Springs flow entering to the river at about 2.2 miles downstream of the dam. For example, if the spring flow is 40 cfs or greater, the size of the freshwater zone is at least 150 meters in the longitudinal direction.

(3) With a release of water from the reservoir of 40 cfs or greater, a salinity zone with less than 1 ppt from the surface to the bottom can be maintained in the first 1000 meters downstream

of the dam.

(4) Routing a portion of the flow from Sulphur Springs to the base of the dam could have a pronounced effect on salinity distributions in the river by reducing salinity below the dam. For example, routing 10 cfs of spring water to the base of the dam would create a zone of water below the dam with salinity values less than 4 ppt salinity. The size of this zone would be 82,700 m^3, with the lowest salinity values ranging between 2 and 3 ppt. Increasing the routed spring-flow to 15 cfs would result in some water less than 2 ppt occurring below the dam on all tides.

(5) Because the flow from Sulphur Springs has an average salinity of 1.2 ppt, routing a portion of spring water to the base of the dam would not create a freshwater zone (< 0.5 ppt) below the dam, unless flow released from the reservoir is at least 75% higher than the routed spring flow.

It should be pointed out that Table 1 was calculated from the model results using a grid system with a longitudinal resolution of 300 meters or longer, except for Scenario 23a. This means that any salinity zone which is smaller than 150 meters (the salinity point is at the center of the grid) in the longitudinal direction would not be recognized by the model . For a low freshwater release rate, there might be a smaller freshwater zone (salinity < 0.5 ppt) near the base of the dam. However, the model could overlook this freshwater zone if it is smaller than 150 meters in the longitudinal direction. One example is Scenario 23 with a release rate of 10 cfs from the reservoir and a constant Sulphur Springs discharge of 31 cfs. Intuitively, one would think that there must be a small freshwater zone near the base of the dam because 10 cfs would make some difference. However, the model results shown in Table 1 indicate that no freshwater zone exists in the river for this scenario. The reason for this obvious discrepancy is that the model did not use a grid system which is small enough for the region near the dam to be resolved. In order to improve the model resolution for low flows, a new grid system was created by splitting the first grid, which has a length of 300 meters, into three equal grids, each with a length of 100 meters. The model was re-run for Scenario No. 23 using the new grid system with a grid size of 100 meters in the longitudinal direction near the base of the dam. Model results show that the model was able to detect a freshwater zone near the base of the dam, which had a two-day average volume of over 500 cubic meters (Scenario 23a).

Run No.	River Flow	Spring Flow at Dam	Spring Flow	Salinity Range (ppt)									
				0 - 0.5	<1	<1.5	< 4	< 5	1 - 10	5 - 11	4 - 11	11 - 18	10 - 20
	(cfs)	(cfs)	(cfs)										
1	0	0	20	0.0	0.0	0.0	0.0	0.1	315.1	381.6	381.7	1010.4	1696.4
2	10	0	20	0.0	0.8	13.0	116.4	168.6	455.6	347.3	399.4	1127.6	1663.4
3	20	0	20	28.7	48.3	73.7	212.9	272.0	519.0	374.5	433.7	1152.3	1615.5
4	40	0	20	112.5	155.3	199.3	374.1	430.4	651.9	484.7	540.9	1063.6	1466.1
5	80	0	20	262.0	337.5	384.9	588.9	678.9	858.6	636.0	726.0	835.4	1165.1
6	100	0	20	319.1	400.8	460.5	710.1	812.9	950.5	656.6	759.3	736.1	1036.6
7	0	0	40	0.0	0.0	0.0	58.5	204.9	533.0	404.2	550.5	1153.9	1633.0
8	10	0	40	3.8	30.2	50.8	254.8	327.5	618.9	418.3	491.0	1134.9	1572.8
9	20	0	40	51.6	95.0	142.9	348.2	408.6	675.8	472.1	532.4	1076.4	1493.4
10	40	0	40	154.3	217.4	283.7	461.6	525.7	779.5	584.4	648.5	956.9	1324.9
11	80	0	40	265.7	377.2	440.6	690.7	794.9	960.2	660.4	764.6	745.3	1048.9
12	100	0	40	307.0	447.9	514.7	809.0	920.7	1029.3	663.5	775.2	661.8	928.6
13	0	10	10	0.0	0.0	0.0	31.3	58.0	323.7	325.2	351.9	1002.1	1685.1
14	5	10	10	0.0	0.0	3.4	80.1	122.6	399.2	331.9	374.3	1086.3	1674.6
15	10	10	10	0.0	13.2	33.2	132.7	177.7	442.5	337.2	382.3	1127.5	1664.1
16	15	10	10	0.0	37.2	58.2	176.1	228.1	474.3	350.9	402.9	1149.2	1639.7
17	0	20	20	0.0	0.0	25.8	173.2	233.6	533.0	375.0	435.4	1153.1	1632.9
18	5	20	20	0.0	15.6	54.3	224.4	289.2	572.9	386.4	451.3	1154.5	1609.0
19	10	20	20	0.0	46.9	91.4	269.6	335.2	601.1	409.0	474.7	1137.3	1574.8
20	15	20	20	0.0	79.2	126.1	313.1	374.5	632.0	442.4	503.8	1106.6	1534.9
21	0	0	31	0.0	0.0	0.0	6.6	47.5	446.9	460.6	501.4	1129.3	1669.0
22	5	0	31	0.0	0.0	0.0	136.6	200.8	506.2	372.2	436.5	1149.2	1645.1
23	10	0	31	0.0	14.7	32.3	192.6	253.9	546.8	386.4	447.4	1154.1	1619.8
23a	10	0	31	0.54	14.0	30.4	190.4	251.7	544.7	385.6	446.9	1153.0	1618.7
24	15	0	31	20.3	42.4	67.7	240.2	309.5	577.6	398.5	468.7	1143.1	1587.9
25	20	0	31	41.9	73.4	107.5	289.2	357.1	606.1	419.8	487.8	1123.0	1550.8
26	30	0	31	86.4	130.6	177.9	367.7	425.4	669.0	483.5	541.1	1067.9	1472.7
27	40	0	31	134.1	186.0	245.6	424.2	482.1	727.2	546.3	604.1	1005.0	1386.9
28	60	0	31	220.5	293.3	340.5	527.7	606.0	818.7	618.2	696.6	889.4	1227.9
29	80	0	31	264.0	358.3	416.2	644.2	743.3	921.3	651.6	750.7	784.4	1096.2
30	100	0	31	318.7	425.3	491.9	762.3	868.8	1000.5	686.2	772.8	694.6	972.1
31	0	10	21	0.0	0.0	0.0	82.7	153.9	447.5	353.7	424.9	1128.1	1667.7
32	5	10	21	0.0	0.0	22.2	154.9	209.5	503.4	361.1	415.6	1149.5	1645.1
33	10	10	21	0.0	29.5	50.6	202.0	261.2	530.8	377.8	437.0	1154.6	1620.8
34	15	10	21	1.3	51.4	86.0	247.0	312.6	567.7	395.9	461.5	1142.5	1588.5
35	20	10	21	35.2	81.7	120.0	293.6	357.3	597.1	418.7	482.4	1125.4	1552.4
36	0	15	16	0.0	0.0	0.0	106.6	161.1	447.3	346.3	400.8	1126.5	1666.9
37	5	15	16	0.0	1.4	32.8	161.7	214.5	503.3	357.3	410.1	1149.6	1645.0
38	10	15	16	0.0	34.0	59.8	206.3	265.2	525.4	373.0	432.0	1154.7	1622.4
39	15	15	16	0.0	55.1	94.0	250.5	314.5	564.1	394.3	458.3	1144.0	1590.2
40	20	15	16	0.2	85.9	125.0	295.3	357.4	593.2	418.6	480.7	1125.9	1552.2
41	0	31	0	0.0	0.0	34.5	135.6	176.9	447.7	330.9	372.2	1128.1	1666.8
42	0	41	0	0.0	0.0	62.6	199.1	257.4	542.6	359.8	418.1	1156.0	1628.8
43	0	10	31	0.0	0.0	0.0	169.4	233.9	545.0	386.2	450.7	1153.0	1626.7
44	0	10	41	0.0	0.0	11.4	245.6	320.3	641.4	416.5	491.3	1140.8	1578.9
45	0	20	31	0.0	0.0	39.5	249.7	321.1	640.8	414.2	485.6	1143.1	1579.8

Table 1 Two-day average water volumes (1000 m^3) for various salinity ranges for the 45 scenarios.

5. Salinity Response to the Change of the Upstream Freshwater Release Rate

In the above discussions, it has been mentioned that model results during the first couple of days would normally not have good agreement with measured data because a spin-up period is needed for the initial conditions to become insignificant. This implies that the reaction time of salinity to changes of tide, upstream freshwater discharge, etc. is in the order of couple of days. Consideration of the time lag between salinity and upstream freshwater release is important in seeking the relationship between salinity in the river and the upstream freshwater release rate. For example, a low salinity at the 22nd station may be unexplainable with a low same-day flow released from the dam, but may be explained by high flows during preceding days.

This section studies the response time of salinity in the Lower Hillsborough River to the change of the upstream freshwater release rate. In the following, the salinity response time was first analyzed mathematically for two idealized cases: a pure advective transport case and a pure diffusive transport case. Then, the LAMFE model was used to study salinity responses to the upstream freshwater release changes for the Lower Hillsborough River.

5.1 Quantitative Analyses

Before conducting numerical simulations of salinity response to the changes in upstream freshwater discharge using the LAMFE model, let us have some quantitative considerations. First, let us consider salinity transport in an open channel with a steady, uniform flow of Q cfs. Before time = 0, the flow entering the channel had a constant salinity of S_0. From time = 0 on, salinity in the flow entering to the upstream of the channel suddenly reduced to 0 ppt. Intuitively, once salinity in the incoming water is reduced to 0 ppt, a freshwater front would be formed and move in the downstream direction with a speed of Q/A, where A is the cross-section area of the river. If the vertical transport is negligible, salinity transport in the channel can be approximated with a one-dimensional advective transport equation as follows

$$\frac{\partial s}{\partial t} + u\frac{\partial s}{\partial x} = 0 \tag{15}$$

where s is salinity, t is time, u is velocity, and x is the x-coordinate whose direction is from the upstream to the downstream. The initial condition is that $s = S_0$ everywhere at $t = 0$. The velocity, $u = Q/A$, is a constant. The above equation has the following solution:

$$s = s_0\varphi(x - ut) \tag{16}$$

where $\varphi(\eta) = \begin{cases} 0 & \eta < 0 \\ 1 & \eta \geq 0 \end{cases}$

This solution shows that the freshwater front moves from the upstream side to the downstream side without changing its shape with a speed of u. At a distance $x = a$ from the upstream boundary, salinity would have a sudden decrease from S_0 to zero at $t = a/u$. In other words, salinity at $x = a$ does not response to the change of the upstream discharge until $t \geq a/u$. Thus, the time lag at $x = a$ would be a/u.

This time lag at $x = a$ can also be sought by a dimensional analysis of Equation (15). Let $x = x^*a$, $t = t^*T$, and $s = s^*s_0$, Equation (15) becomes

$$\frac{\partial s^*}{\partial t^*} + \frac{uT}{a}\frac{\partial s^*}{\partial x^*} = 0 \tag{17}$$

Because x^*, t^*, and s^* are non-dimensional, the quantity uT/a would be in the order of unity

$$\frac{uT}{a} = O(1)$$

This means that $T \sim a/u$.

Now, let us consider a pure diffusive transport case. For the same open channel, assume that the upstream is a dead end and water in the channel has a zero velocity. The initial condition for salinity is that $s = 0$ for $x < L$ and $s = S_0$ for $x > L$. For this case, salinity transport is mainly diffusive transport. Assuming that vertical transport is negligible and the horizontal diffusivity is a constant, the following one-dimensional equation can be obtained:

$$\frac{\partial s}{\partial t} = D\frac{\partial^2 s}{\partial x^2} \tag{18}$$

where D is the horizontal diffusivity along the x-axis. The initially condition for salinity can be expressed as

$$s = s_0\varphi(x - L)$$

Equation (18) has the following solution:

$$s = \frac{s_0}{2}[1 - erf(\frac{L - x}{\sqrt{4Dt}})]$$

where $erf(\eta) = \int_0^\eta e^{\lambda^2}d\lambda$ is the error function. As $t \to \infty$, $s \to s_0/2$. Therefore the ambient salinity is $s_0/2$. Let us define the threshold of salinity response as 50% of the ambient salinity at $x = a$. In other words, after a time lag T, salinity at $x = a$ will be 50% of the ambient value or higher. We get

$$erf(\frac{L - a}{\sqrt{4DT}}) = 0.5$$

This leads to $T \approx (L - a)^2/D$, which means that the time lag for salinity response at $x = a$ is proportional to the square of the distance from the downstream boundary and inversely proportional to the diffusivity.

This relationship can also be sought by a dimensional analysis of Equation (18). Let $x = x^*(L-a)$, $t = t^*T$, and $s = s^*s_0$, Equation (18) becomes

$$\frac{\partial s^*}{\partial t^*} = \frac{TD}{(L - a)^2}\frac{\partial^2 s^*}{\partial x^{*2}} \tag{19}$$

The quantity $TD/(L-a)^2$ has to be of the order of unity, $O(1)$. This also leads to $T \sim (L-a)^2/D$.

The above discussions are for idealized cases. In reality, longitudinal salinity transport in the Lower Hillsborough River consists of both advection and diffusion/mixing. Salinity response time at a certain location (e.g., 22nd Street) would be functions of both u and D, which vary with time and location. Other factors such as bathymetry, wind, tide, stratification, vertical mixing, etc. would also affect salinity response time. Nevertheless, when the freshwater release from the reservoir is high, salinity in the upstream portion (especially upstream of the Sulphur Springs) of the river is primarily controlled by the advective transport and the salinity response time can be estimated by a/u. For example, if no freshwater is released from the dam for over a week, salinity near the dam would be around 5 - 6 ppt. As freshwater is released from the reservoir, the salty water will be pushed toward downstream. Within a short course from the base of the dam, the salt wedge will move toward downstream at a speed approximately Q/A. The average cross-section area from the dam to 22nd Street is about 200 square feet for an average tide. If Q is 40 cfs, then the speed of the salt wedge movement would be 6.1 cm/sec or less within the distance from the dam to 22nd Street, which is about 1000 meters downstream of the dam. A rough estimate is that it takes the freshwater front about 5 hours to reach 22nd Street. As the salt wedge moves further downstream, its speed will become smaller and smaller. Eventually, the salt wedge will stay at a quasi-steady location. On the other hand, if the freshwater release is suddenly reduced to zero, then the longitudinal salinity transport in the upstream portion of the river would be primarily controlled by longitudinal mixing/diffusion. Let us assume that a salt wedge is located about 3 kilometers below the dam when there is a freshwater release from the dam. If the release is suddenly reduced to zero, then the wedge will migrate to upstream. If we assume that D is in the order of 10 m^2/s, then about 5 days later salinity at a cross-section 1000 meters downstream of the dam would reach about 50% of its ambient value.

5.2 Salinity Response to Various Release Schedules

The two-dimensional model was used to study the salinity response in the river to the freshwater release from the upstream reservoir. The model was run for the same 18-day period as that in the scenario runs. Measured surface elevations and salinity at Platt Street were used as boundary conditions. The time period in which field data were used as boundary conditions was the same as that for the scenario runs. Again, runoff caused by rains were turned off in the model simulations. Same as in the scenario runs, a constant flow of 31 cfs was assumed for Sulphur Springs flow with a constant salinity of 1.2 ppt.

Various release schedules were studied using the two-dimensional hydrodynamic model LAMFE. For five upstream freshwater release rates (10, 20, 40, 60, and 100 cfs), the model was run to study the following release schedules:

1. Fresh water is released in the first 9 days, but not in the second 9 days,
2. Fresh water is released in the second 9 days, but not in the first 9 days,
3. Fresh water is release in the first 7 days, then turned off (0 cfs) on Days 8 through 10, and then released again from Day 11 to Day 18, and
4. Freshwater release is turned on and off every other day with a doubled rate of the above four cases.

Table 2 illustrates the above four cases for the freshwater release rate of 10 cfs. Note that the release rate in Case 4 is actually twice the rate of the rate in Cases 1, 2, and 3.

Model results of the four release schedules for different release rates are presented in Figures D-1 through D-20, which also show model results of a baseline run with 0 cfs release. For comparison, model results of continuous releases of 10, 20, 40, 60, 100 cfs are also plotted in the correspondent figures.

Case No. \ Day(s)	1, 3, 5, 7	2, 4, 6	8	9	10	11, 13, 15, 17	12, 14, 16, 18
1	10.0	10.0	10.0	10.0	0.0	0.0	0.0
2	0.0	0.0	0.0	0.0	10.0	10.0	10.0
3	10.0	10.0	0.0	0.0	0.0	10.0	10.0
4	20.0	0.0	0.0	20.0	0.0	20.0	0.0

Table 2 Four upstream freshwater release schedules for the freshwater release rate of 10 cfs.

Figures D-1 through D-20 clearly confirm the quantitative analyses presented above. There is indeed a response time lag between salinity and upstream freshwater release. The response time lag is generally longer for a decreasing upstream releasing rate than that for a increasing release rate. When freshwater flow increases from 0 cfs to a certain rate of Q, the response time lag is dependant on the magnitude of Q. A larger Q results in a shorter time lag because larger freshwater release will cause larger downstream velocity and thus pushes the salt wedge toward downstream quicker.

From Figure D-1 through D-20, it can also be concluded that the freshwater release from the reservoir has a less effect on downstream salinity than on upstream salinity for a flow rate ranging from 0 cfs to 100 cfs. This is understandable because the downstream salinity is mainly controlled by the downstream tide and salinity. If the release is very higher, however, it can greatly reduce downstream salinity. For example, with a release rate of 1000 cfs, freshwater can reach the downstream boundary.

Model results for the fourth release schedule indicate that releasing fresh water at a doubled rate of $2Q$ every other day has almost the same effect on salinity as releasing it at a constant rate of Q every day. This can be explained by the time lag of salinity response to the upstream freshwater discharge. Because the salinity response time is about a week and the frequency of upstream freshwater release is 0.5 1/day, the relatively quicker variation of the upstream freshwater discharge is filtered out by the river system. Therefore, salinity at a cross-section of the river (let us say at 22nd Street) is, to a great extent, a function of the average upstream freshwater flow during the preceding week or so.

6. Case Studies for a Minimum Flow of 10 cfs

Model results presented in Table 1 can be useful for the evaluation of minimum flows for the Lower Hillsborough River. Depending on the ecological target to be set for the river, a water volume for a certain range of salinity can be predicted for the river. Then, a minimum flow can be determined from Table 1 based on the established water volume target. However, the 18 days used in creating Table 1 actually represent a worst case scenario, in which rainfall was turned off and the tide was spring tide at the end of the 18-day period. In order to see how a minimum flow would improve salinity in the river, especially the upstream reaches, it was worthwhile to re-run the two-dimensional model for the 12-month period from September 1981 through August 1982 with an assumed minimum flow.

As mentioned in Section 3, a 10 cfs freshwater release from the dam would create a small freshwater zone (<0.5 ppt) near the base of the dam. Although the two-day average water volume for this freshwater zone is just about 540 cubic meters, and can not be detected by the model with a grid size of 300 meters in the longitudinal direction, it is detectable if the grid size near the dam is reduced to 100 meters. Therefore, 10 cfs of freshwater flow from the reservoir does make some differences as long as a freshwater zone is concerned. It would be very interesting to see what kind of differences a 10 cfs minimum flow would make to the frequency distribution of water volumes for various salinity ranges if measured data during the 12-month period from September 1981 to August 1982 are used to run the model. The minimum flow of 10 cfs may be maintained by either releasing reservoir water or diverting Sulphur Springs flow. For the former case, we have

$$Q_1 = \mathrm{Max}\,(Q_{dam},\ 10) \tag{20}$$

where Q_{dam} is measured flow (in cfs) released from the reservoir and Q_1 is the flow (in cfs) entering to the first grid in the model.

For the latter case, we have

$$\begin{aligned} Q_1 &= Q_{dam} + \Delta Q_{ss} \\ Q_2 &= Q_{ss} - \Delta Q_{ss} \\ \Delta Q_{ss} &= \mathrm{Max}(0,\ 10 - Q_{dam}) \end{aligned} \tag{21}$$

where Q_{ss} is measured flow (in cfs) from the Sulphur Springs, ΔQ_{ss} is the flow (in cfs) diverted from the Sulphur Springs (ΔQ_{ss} = 10 - Q_{dam} if Q_{dam} is less than 10 cfs, otherwise ΔQ_{ss} = 0 cfs) to the base of the dam, and Q_2 is the remaining spring flow (in cfs) entering to the river after ΔQ_{ss} is diverted.

In Equation (21), flow from the reservoir has a salinity of 0.1 ppt, while flow out of the Sulphur Springs has a salinity of 1.2 ppt. Consequently, Q_1 in Equation (20) has a salinity of 0.1 ppt, while salinity in Q_1 of Equation (21) is $(0.1\ Q_{dam} + 1.2\ \Delta Q_{ss})/(Q_{dam} + \Delta Q_{ss})$.

Equations (20) and (21) were unnecessary for the months of September 1981 and July and August 1982 because the flow from the reservoir in these months was very high (> 300 cfs). In fact, due to the high flow, the 22nd Street station was consistently fresh during these three months. Since a 10 cfs minimum flow would not be in effect during this period, this study chose to just run the model for a period from the end of September 1981 through June 1982, instead of running it for the entire 12 months.

Model results for the two cases were compared with those for the 0 cfs minimum flow case, which was the real case which used flow data collected at the dam in 1981 and 1982. Frequency analyses were conducted for the two 10 cfs minimum flow cases and the real case with a minimum flow of 0 cfs. The model was modified to output hourly water volumes for various salinity ranges in the river. Daily averaged water volumes for each salinity range were then calculated and used for the frequency analysis. Because the model needs about a week to spin-up, model results during the first seven days were not included in the analysis. The total number of days available for the analysis was 274 days, of which 135 days had less than 10 cfs released from the reservoir. Frequency analysis was done separately for the entire 274 days and for the subset of the 135 days which had less than 10 cfs flow released from the reservoir in the historic record.

For the zero cfs minimum flow case, model results presented in the Section 3 (Model Calibration and Verification) can be directly used for the frequency analysis. For the two 10 cfs minimum flow cases, the model was run with the same input files as the 0 cfs minimum flow case, except that the daily flow rates from the reservoir and the spring were adjusted according to either Equation (20) or Equation (21).

Results of these analyses are presented in Tables 3 and 4 in terms of cumulative frequency functions of daily average salinity zone volumes. Each table has three parts: the top one shows results for the 0 cfs minimum flow case, while the middle one is for the case of releasing10 cfs minimum flow from the reservoir. Results for routing ΔQ_{ss} Sulphur Springs flow to the base of the dam when the freshwater release rate was less than 10 cfs are shown at the bottom of the two tables. Cumulative frequency functions in Table 3 were calculated from the entire 274 days of daily average water volumes, while those in Table 4 are the cumulative frequency functions calculated from the results of the 135 days with less than 10 cfs discharge from the reservoir.

It can be seen from Table 3 that with a minimum flow of 0 cfs (real case), the daily average freshwater volume (<0.5 ppt) in the river was 45,700 m^3 or less for 40 percent of the 274 days. For at least 30 percent of the 274 days, a freshwater zone did not exist in the river. There was no guarantee that a salinity zone with less than 4 ppt would always exist, although the river had a salinity zone of less than 4 ppt with a water volume of 30,270 m^3 or larger 90 percent of the time. The less than 1 ppt and less than 1.5 ppt salinity ranges did not occur in the river for at least 30 and 20 percent of the 274 days, respectively.

The above salinity condition could be significantly improved if a minimum flow of 10 cfs were released from the reservoir. As can be seen in the middle portion of Table 3, a salinity zone with less than 4 ppt would always exist in the river and have a minimum volume of 35,420m^3. The freshwater zone (< 0.5 ppt) would occur in the river with a minimum volume of 2,130m^3 for at least 80 percent of the 274 days. Water volumes for the salinity ranges of < 1 ppt and < 1.5 ppt also improved. The < 1 ppt and < 1.5 ppt water volumes were at least 8,570m^3 and 23,690m^3, respectively, for at least 90% of the 274 days.

With spring flow routed to the base of the dam to guarantee a minimum flow of 10 cfs, the improvement of salinity range in the river would not be as significant as that of releasing 10 cfs reservoir water. The bottom portion of Table 3 shows that a salinity range of less than 4 ppt would not be guaranteed 100% of the time. The salinity range of less than 1.5 ppt had just a minor improvement. Because the Sulphur Springs flow has an average salinity of 1.2 ppt, the frequencies for freshwater and the less than 1 ppt salinity zones show slight decrease compared to the zero cfs minimum flow case.

Results of the frequency analyses for the 135 days of less than 10 cfs released from the reservoir are similar to those for the entire 274 days. As can be seen from Table 4, the river did not have a freshwater zone (< 0.5 ppt) of any size in over 70 percent of days of these 135 days for the zero minimum flow case. It did not even have a zone with a salinity range less than 4 ppt for at least 10 percent of the 135 days. Releasing a minimum of 10 cfs of flow from the reservoir would make a significant difference. For example, the less than 4 ppt zone would be guaranteed all the time, and a freshwater pool would occur for at least 40 percent of 135 days with a size of 1,680m^3 or larger. Over 90 percent of the 135 days, the river would have a less than 1 ppt water volume of 1010m^3 or larger. The < 1.5 ppt salinity range would have a volume of 18,140 m^3 or larger for at least 90 percent of the low flow days (< 10 cfs).

Figure 8 shows the comparisons of simulated salinity values in November 1981 at the 22nd Street, Sligh Avenue, and Columbus Drive stations for 0 cfs minimum flow, 10 cfs minimum flow released from the reservoir, and 10 cfs minimum flow guaranteed by routing a portion of Sulphur Springs flow to the base of the dam. As can be seen from this figure, a minimum flow of 10 cfs will make a difference to salinity at the 22nd Street station, no matter whether it is from the reservoir or from the Sulphur Springs. A 10 cfs minimum flow from the reservoir would improve salinity condition at the 22nd Strret station more significantly than routing a portion of spring flow. The minimum flow of 10 cfs has a much greater effect on salinity at 22nd Street than at Sligh Avenue. It barely has any effect on salinity at Columbus Drive.

Salinity / Percent	< 0.5	< 1	< 1.5	< 4	4 - 11
No Minimum Flow					
100	2604.96	2677.40	2707.85	2789.80	1220.93
90	1208.24	1454.70	1571.71	1883.36	819.53
80	857.58	1095.72	1245.36	1636.36	711.11
70	601.16	828.66	965.49	1357.80	639.16
60	371.24	583.56	683.19	1080.35	594.40
50	204.47	319.62	398.10	660.96	560.38
40	45.70	107.22	190.45	407.47	525.24
30	0.00	0.00	5.36	251.86	459.18
20	0.00	0.00	0.00	87.06	385.84
10	0.00	0.00	0.00	30.27	280.31
0	0.00	0.00	0.00	0.00	74.04
10 cfs Minimum Flow From the Reservoir					
100	2605.61	2677.43	2707.13	2789.83	1174.13
90	1239.28	1454.45	1577.15	1882.11	817.82
80	873.41	1114.55	1245.15	1636.76	712.95
70	601.91	828.43	969.63	1358.56	645.90
60	410.64	588.89	695.24	1097.56	599.78
50	209.66	343.18	413.62	688.88	562.67
40	95.70	163.49	242.82	454.59	510.40
30	27.13	54.27	104.19	335.97	448.35
20	2.13	25.30	43.71	249.99	398.78
10	0.00	6.57	23.69	183.68	306.43
0	0.00	0.00	0.00	35.42	74.04
10 cfs Minimum Flow Guaranteed by Sulphur Springs Flow					
100	2583.69	2662.28	2694.22	2780.31	1223.09
90	1208.36	1456.23	1574.24	1879.41	816.89
80	878.96	1105.82	1249.04	1646.96	705.61
70	600.01	820.07	957.47	1363.89	632.77
60	372.78	586.34	697.04	1083.88	570.15
50	7.79	322.81	407.48	661.20	509.97
40	0.00	38.97	208.29	408.87	461.09
30	0.00	0.00	87.08	275.46	413.67
20	0.00	0.00	46.61	191.70	381.71
10	0.00	0.00	29.20	147.00	279.58
0	0.00	0.00	0.00	0.00	74.04

Table 3 Cumulative frequency functions of daily average water volume (in $1000 m^3$) for various salinity ranges in the Lower Hillsborough River with 0 cfs minimum flow (MF), 10 cfs MF from the reservoir, and 10 cfs MF guaranteed by Sulphur Springs flow (sample size:274 days).

Percent \ Salinity	< 0.5	< 1	< 1.5	< 4	4 - 11
No Minimum Flow					
100	1135.15	1567.90	1801.29	2480.09	1130.64
90	145.18	244.10	353.74	656.94	849.10
80	40.42	107.22	190.45	416.94	769.32
70	0.00	8.35	38.39	338.02	630.79
60	0.00	0.00	4.78	242.50	594.24
50	0.00	0.00	0.24	190.60	565.02
40	0.00	0.00	0.00	76.40	550.00
30	0.00	0.00	0.00	44.72	525.24
20	0.00	0.00	0.00	29.15	491.23
10	0.00	0.00	0.00	0.00	383.47
0	0.00	0.00	0.00	0.00	145.28
10 cfs Minimum Flow From the Reservoir					
100	1252.17	1654.49	1876.03	2518.25	1124.34
90	162.06	282.92	387.36	712.34	850.67
80	94.78	170.91	245.88	486.16	768.24
70	38.01	96.14	169.61	389.33	646.16
60	26.86	50.41	101.96	334.48	599.28
50	15.92	39.39	74.90	306.74	567.48
40	1.68	24.21	42.89	249.17	548.63
30	0.00	11.99	30.59	220.36	494.90
20	0.00	8.43	23.11	181.99	451.27
10	0.00	1.01	18.14	112.45	425.17
0	0.00	0.00	0.00	35.42	287.53
10 cfs Minimum Flow Guaranteed by Sulphur Springs Flow					
100	1062.33	1564.92	1802.81	2466.64	1130.94
90	0.98	234.38	350.09	657.93	842.66
80	0.00	30.60	208.29	420.99	769.79
70	0.00	0.00	127.70	337.65	613.36
60	0.00	0.00	84.86	270.61	548.73
50	0.00	0.00	64.35	237.98	502.46
40	0.00	0.00	46.36	190.22	473.64
30	0.00	0.00	40.17	169.89	426.51
20	0.00	0.00	28.53	146.12	392.33
10	0.00	0.00	0.00	4.79	375.91
0	0.00	0.00	0.00	0.00	159.55

Table 4 Cumulative frequency functions of daily average water volume (in 1000m^3) for various salinity ranges in the river with 0 cfs minimum flow (MF), 10 cfs MF from the reservoir, and 10 cfs MF guaranteed by Sulphur Springs flow (sample size:size:135 days of < 10 cfs reservoir flow).

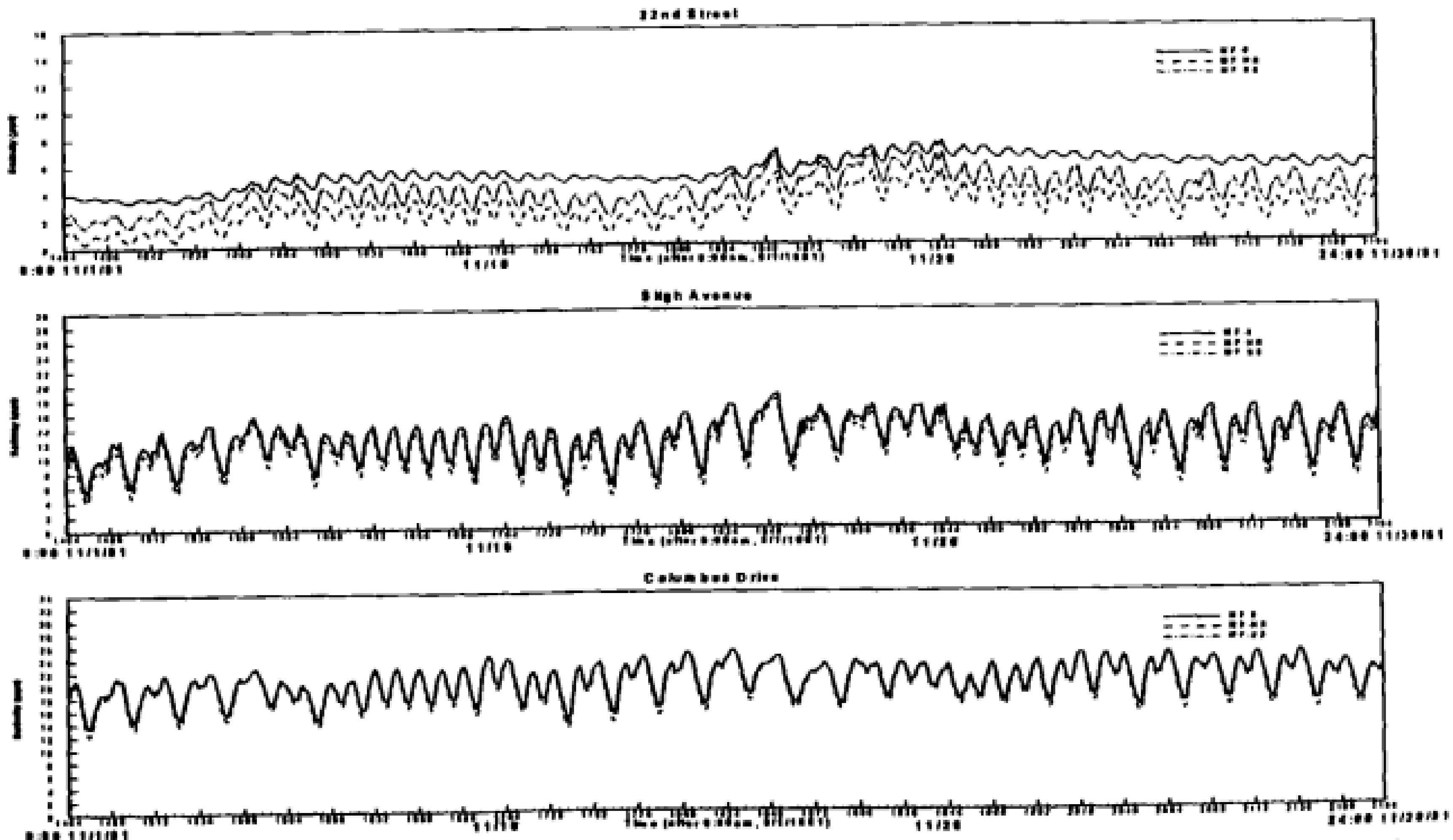

Figure 8 Comparisons of simulated salinity values in November 1981 at the 22[nd] Street, Sligh Avenue, and Columbus Drive stations for 0 cfs minimum flow(solid lines), 10 cfs minimum flow released from the reservoir (dashed lines), and 10 cfs minimum flow guaranteed by Sulphur Springs flow (dash-dotted lines)

7. Conclusions

The two-dimensional hydrodynamic model for the Lower Hillsborough River was verified using measured data of water surface elevation and salinity during a 12-month period during 1981 and 1982 and a 30-day period during June 1997. The verified model was used to conduct 45 scenario runs. The following conclusions can be drawn from these scenario runs:

(1) If the release of fresh water from the dam is small (5 cfs or less), the volume of fresh water (salinity less than 0.5 ppt) in the river will be too small for the model grid system to resolve.

(2) By increasing the freshwater release to 10 cfs, a small freshwater zone (540 m^3) can be maintained near the base of the dam. The size of the freshwater zone is affected by the Sulphur Springs flow entering to the river at about 2.2 miles downstream of the dam. For example, if the spring flow is 40 cfs or greater, the size of the freshwater zone is at least 150 meters in the longitudinal direction.

(3) With a release of water from the reservoir of 40 cfs or greater, a salinity zone with less than 1 ppt from the surface to the bottom can be maintained in the first 1000 meters downstream of the dam.

(4) Routing a portion of the flow from Sulphur Springs to the base of the dam could have a pronounced effect on salinity distributions in the river by reducing salinity below the dam. For example, routing 10 cfs of spring water to the base of the dam would create a zone of water below the dam with salinity values less than 4 ppt salinity. The size of this zone would be 82,700 m^3, with the lowest salinity values ranging between 2 and 3 ppt. Increasing the routed spring-flow to 15 cfs would result in some water less than 2 ppt occurring below the dam on all tides.

(5) Because the flow from Sulphur Springs has an average salinity of 1.2 ppt, routing a portion of spring water to the base of the dam would not create a freshwater zone (< 0.5 ppt) below the dam, unless flow released from the reservoir is at least 75% higher than the routed spring flow.

Salinity in the river does not follow the change of the upstream freshwater release immediately. There is a salinity response time lag which can be a week or longer. Quantitative analyses of the salinity response time were given and confirmed by numerical studies using the two-dimensional model LAMFE. Four upstream release schedules with five different release rates were simulated to see how salinity in the river responses to various release schedules for each release rate. Conclusions of these model studies include:

(1) For the release rate ranging from10 cfs to100 cfs, the salinity time lag is significant only in the upstream portion of the river. For the downstream portion of the river,

although a salinity time lag still exists, it is not very significant because the effect of an upstream freshwater release on salinity becomes weaker and weaker toward the downstream with a rate less than 100 cfs.

(2) The response time of salinity at the 22nd Street station depends on whether the upstream freshwater release increases or decreases. If the release is increased from 0 cfs to Q cfs, the response time decreases as Q increases. For example, if $Q = 10$ cfs, it takes salinity at the 22nd Street about two days to reach the ambient condition. If $Q = 40$ cfs, it takes salinity at the 22nd Street less than 24 hours to reach the ambient condition. On the other hand, if the freshwater release rate is decreased from Q cfs to 0 cfs, the response time will be much longer. Usually, it takes salinity at the 22nd Street station about one week to reach its ambient condition.

(3) Because of the difference in response times for increasing and decreasing flow rates, it is possible to allow 0 cfs freshwater release to occur for two or three days between two long-term release event without letting salinity at the 22nd Street station have a significant increase.

(4) Releasing freshwater from the dam every other day with a doubled flow rate ($2Q$ cfs) does not make a lot of differences from releasing freshwater every day with the rate Q cfs to salinity at the 22nd Street station. This is because salinity responses to the change of the upstream release slowly and the relatively quicker change in releasing fresh water at the upstream boundary is filtered out by the river system. Because nothing can be gained from this kind of release schedule, it is not recommended to release freshwater from the dam every other day with a doubled flow rate ($2Q$ cfs).

A minimum flow of 10 cfs released from the reservoir can significantly improved salinity condition in the upstream portion of the river. A salinity zone with less than 4 ppt would always exist in the river and have a minimum volume of 35,420 m^3. The freshwater zone (< 0.5 ppt) would occur in the river with a minimum volume of 2,130 m^3 for at least 80 percent of the simulation period (274 days).

With the option that routing a portion of the Sulphur Springs flow to the base of the dam to make up a minimum flow of 10 cfs, however, the freshwater and less than 1 ppt volumes in the river would be substantially less than that resulting from the release of 10 cfs of reservoir water. The salinity range of less than 4 ppt would not be guaranteed 100% of the time. Because the Sulphur Springs flow has an average salinity of 1.2 ppt, the frequencies of freshwater and the less than 1 ppt salinity zones show slight decreases compared to the zero cfs minimum flow case.

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Appendix A. Measured Data in the Lower Hillsborough River

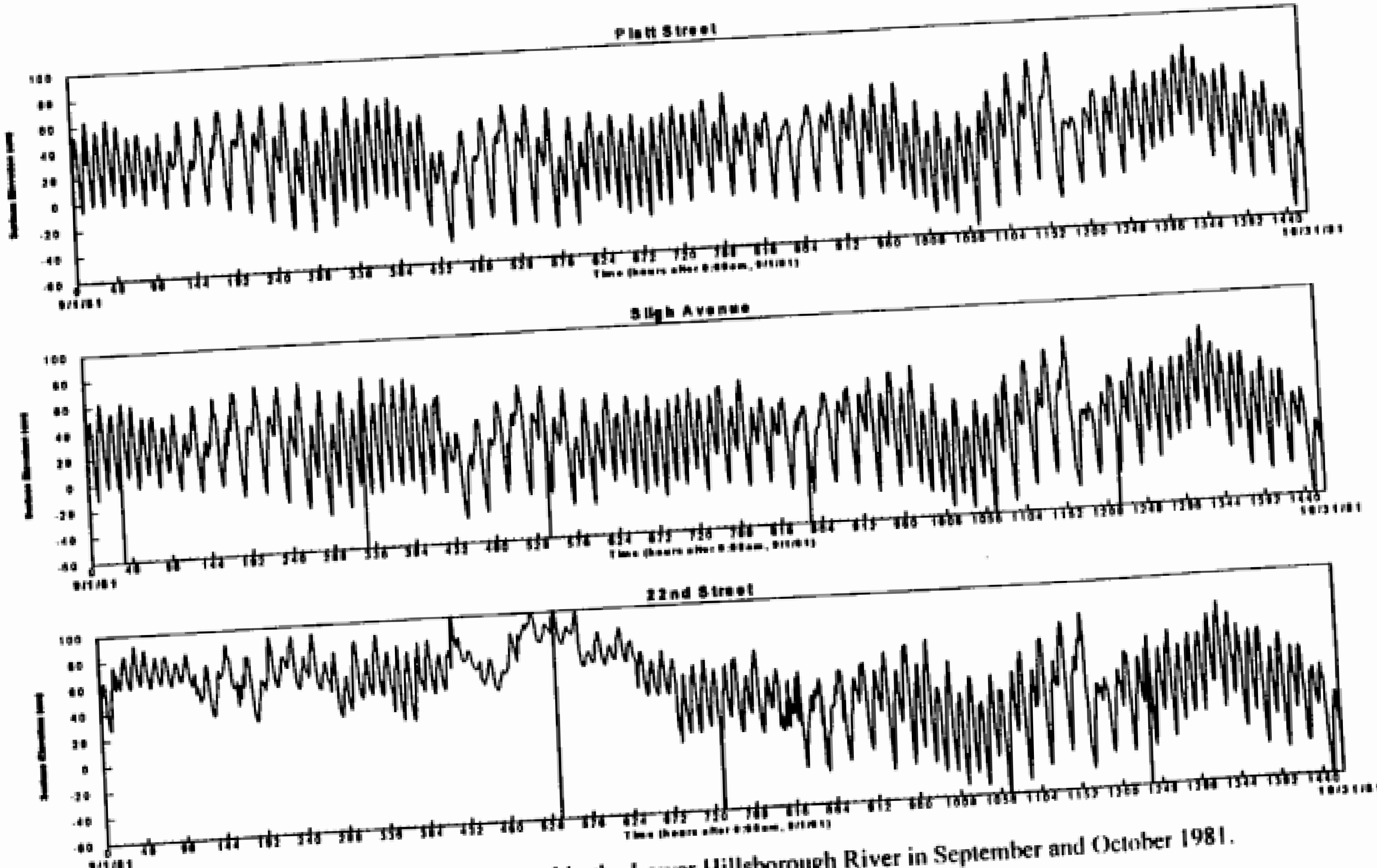


Figure A-1 Real-time water elevation data measured in the Lower Hillsborough River in September and October 1981.

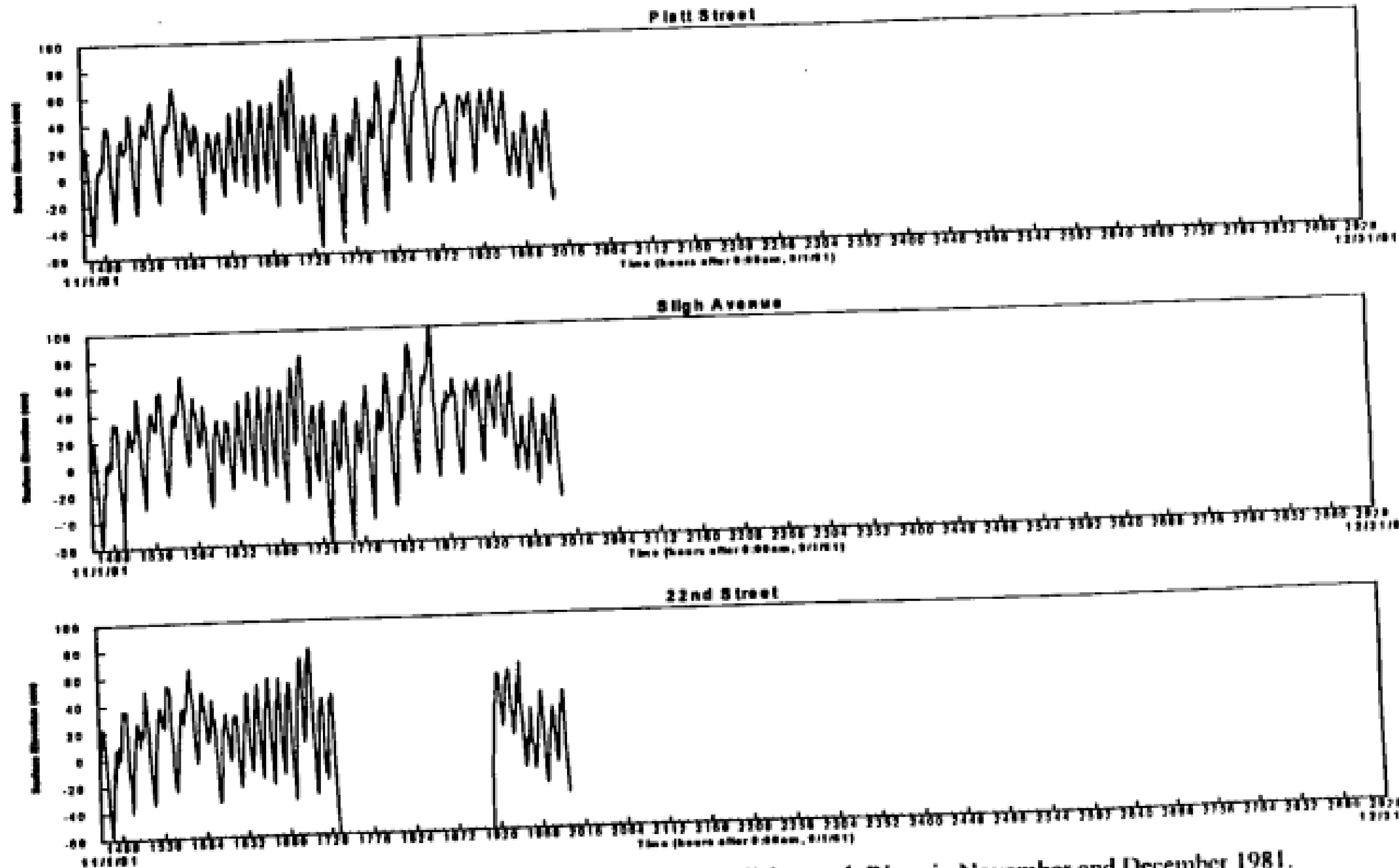


Figure A-2 Real-time water elevation data measured in the Lower Hillsborough River in November and December 1981.

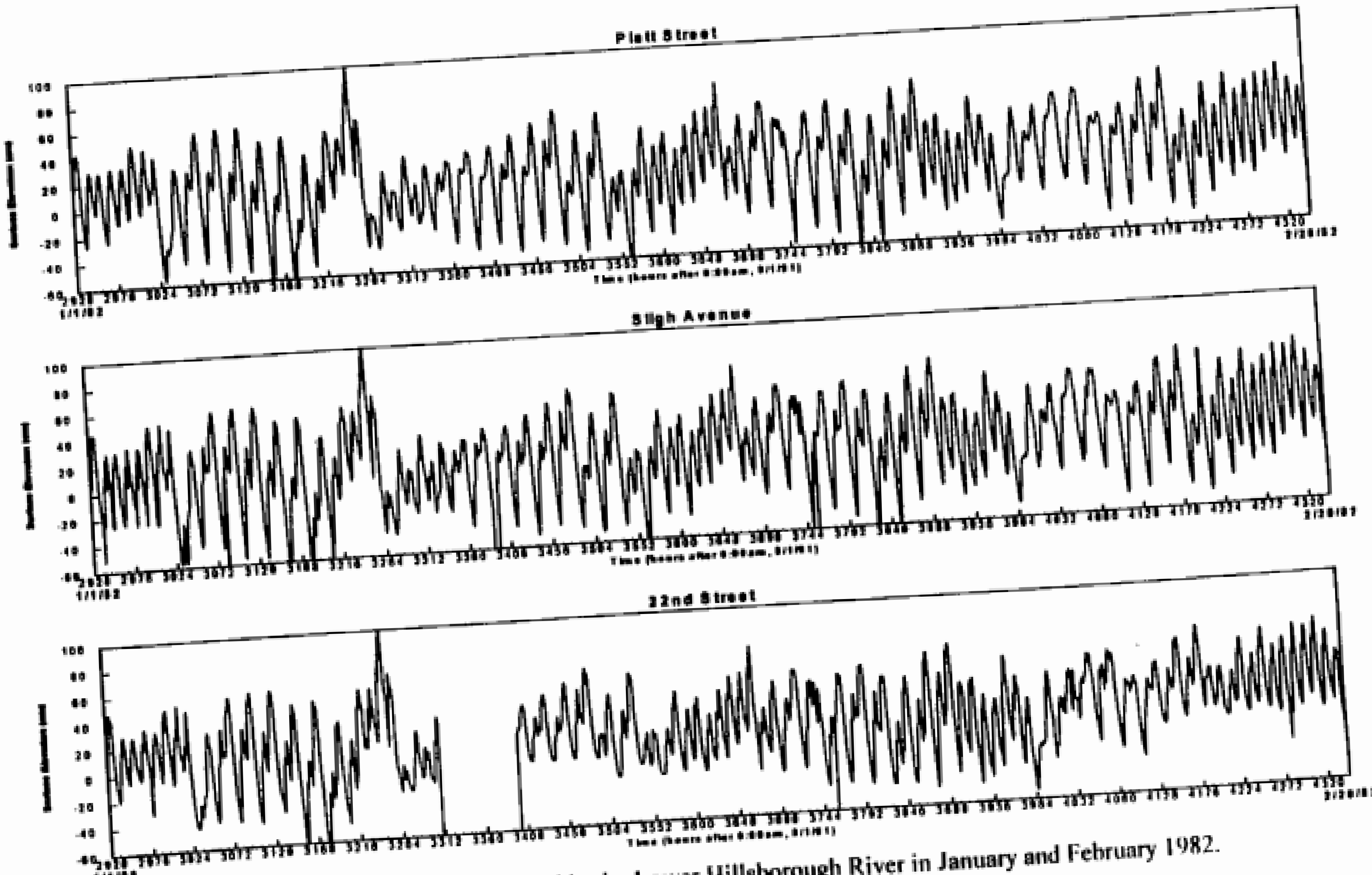


Figure A-3 Real-time water elevation data measured in the Lower Hillsborough River in January and February 1982.

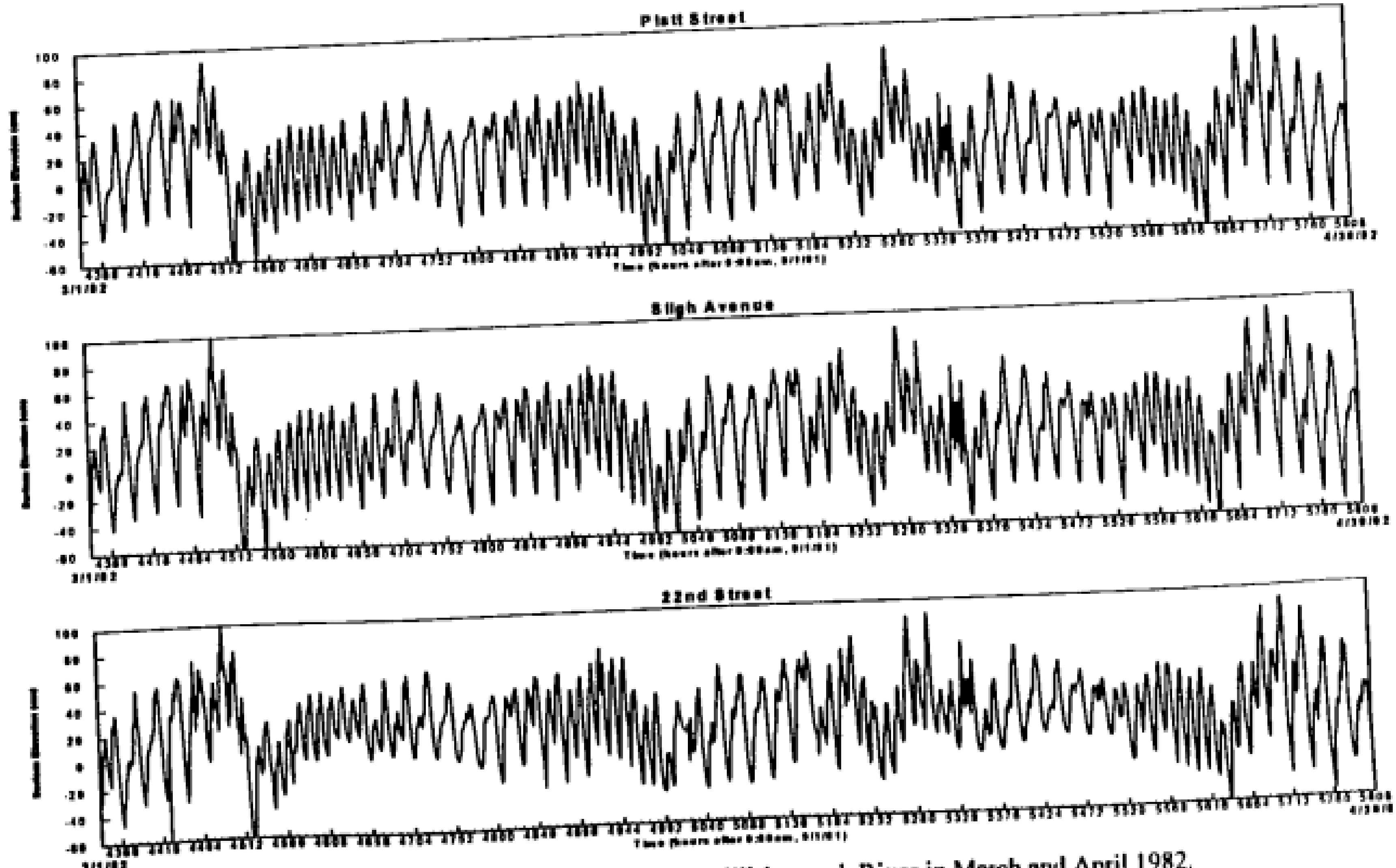


Figure A-4 Real-time water elevation data measured in the Lower Hillsborough River in March and April 1982.

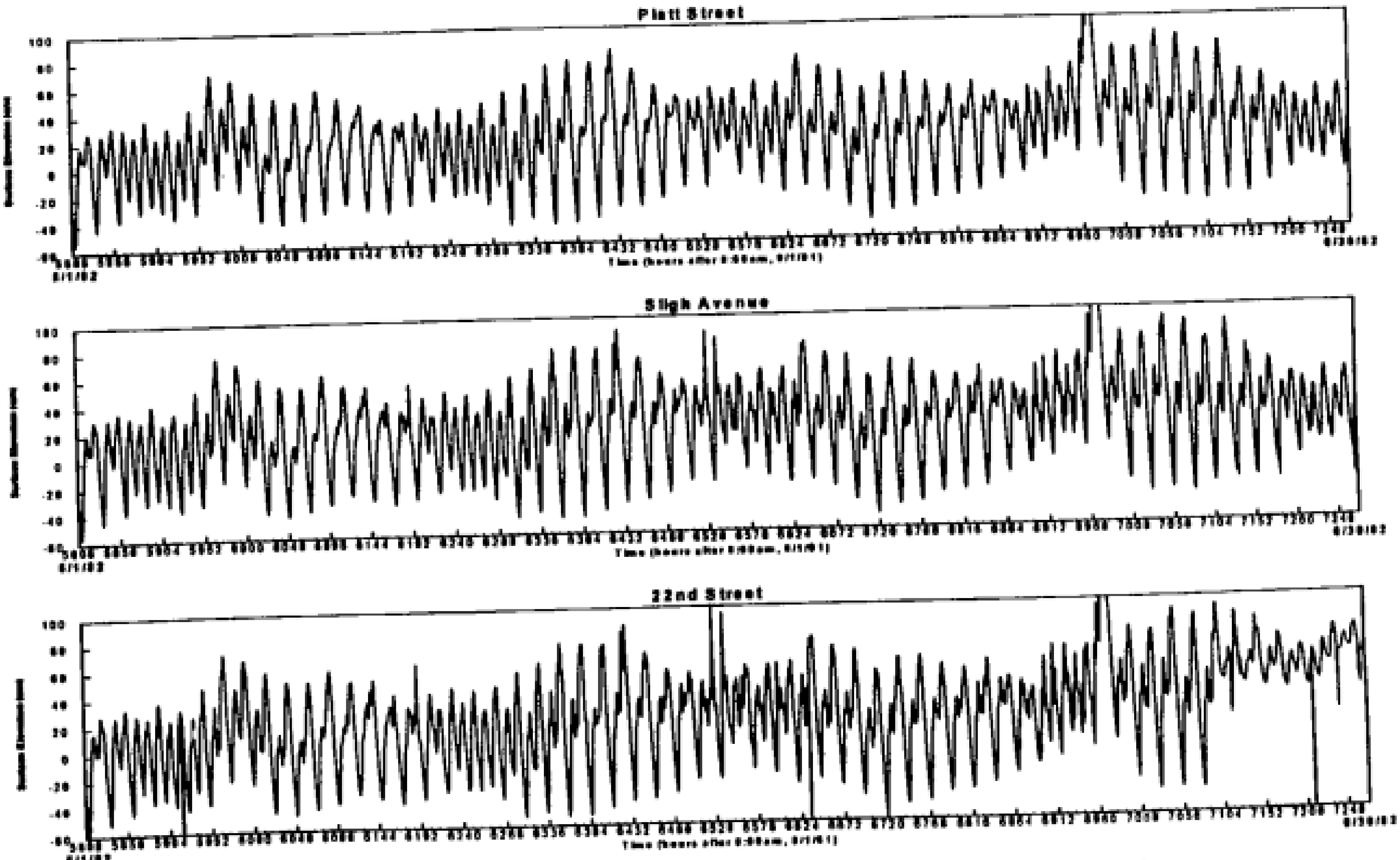


Figure A-5 Real-time water elevation data measured in the Lower Hillsborough River in May and June 1982.

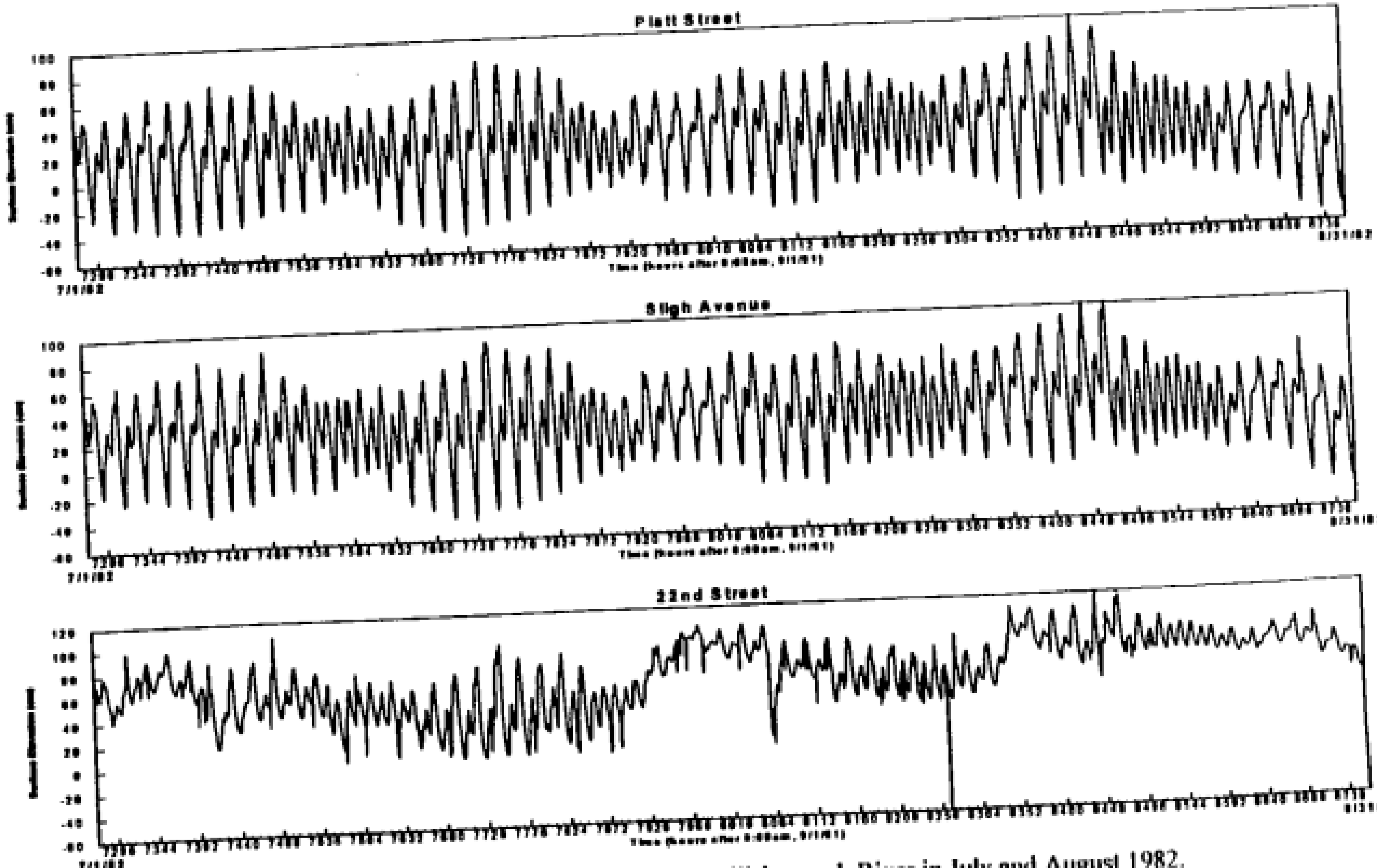


Figure A-6 Real-time water elevation data measured in the Lower Hillsborough River in July and August 1982.

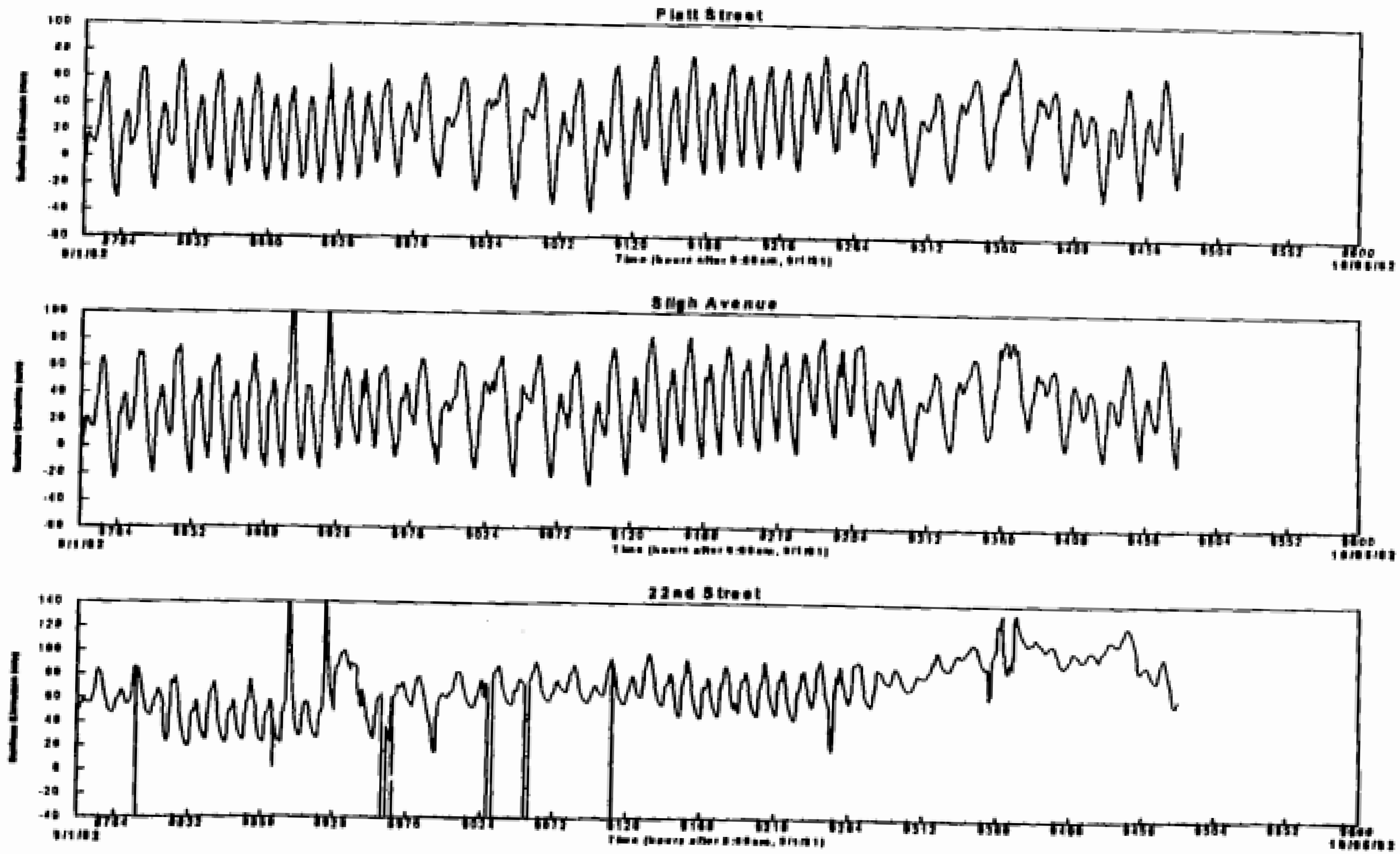


Figure A-7 Real-time water elevation data measured in the *Lower Hillsborough River* in September 1982.

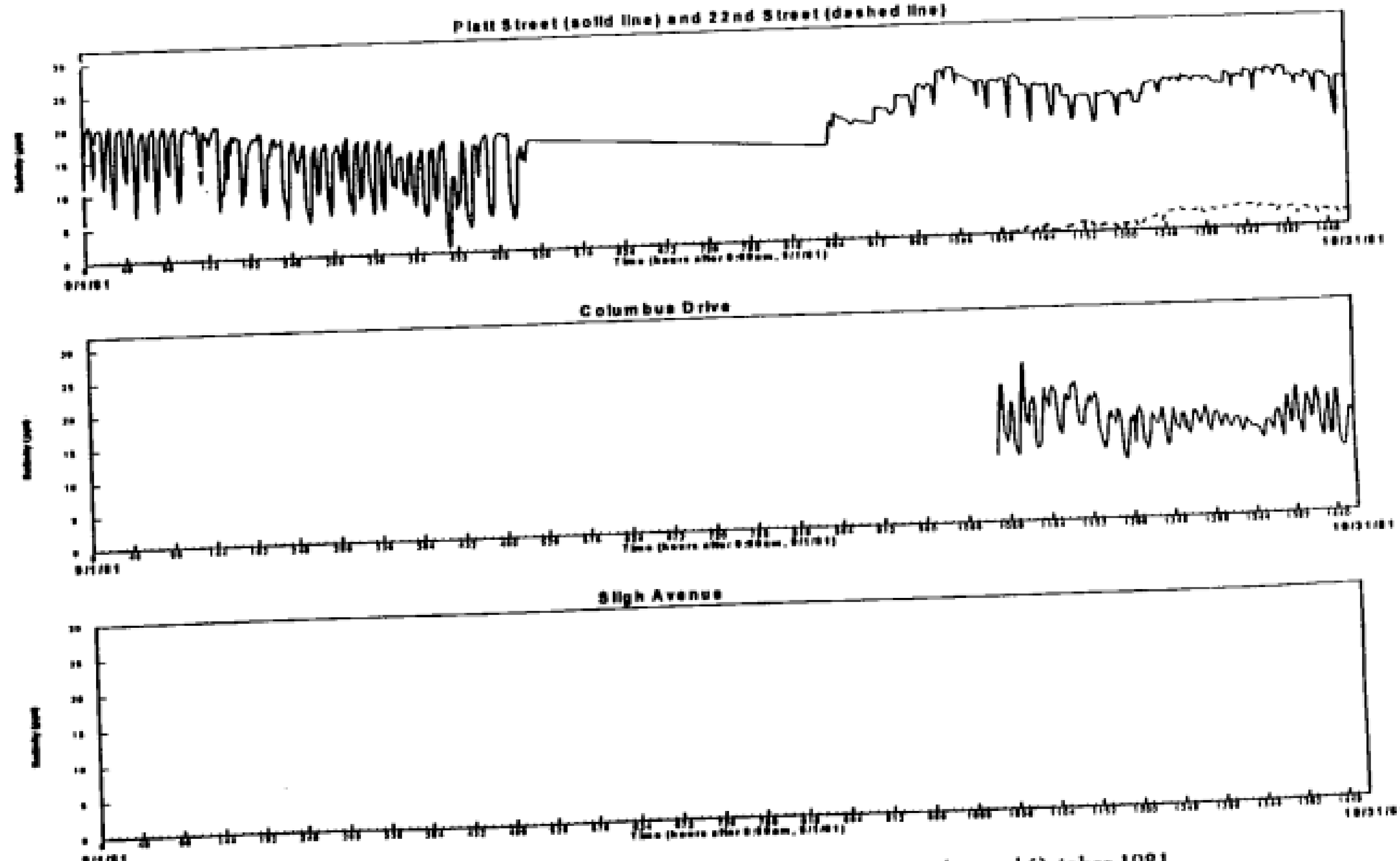


Figure A-8 Real-time salinity data measured in the Lower Hillsborough River in September and October 1981.

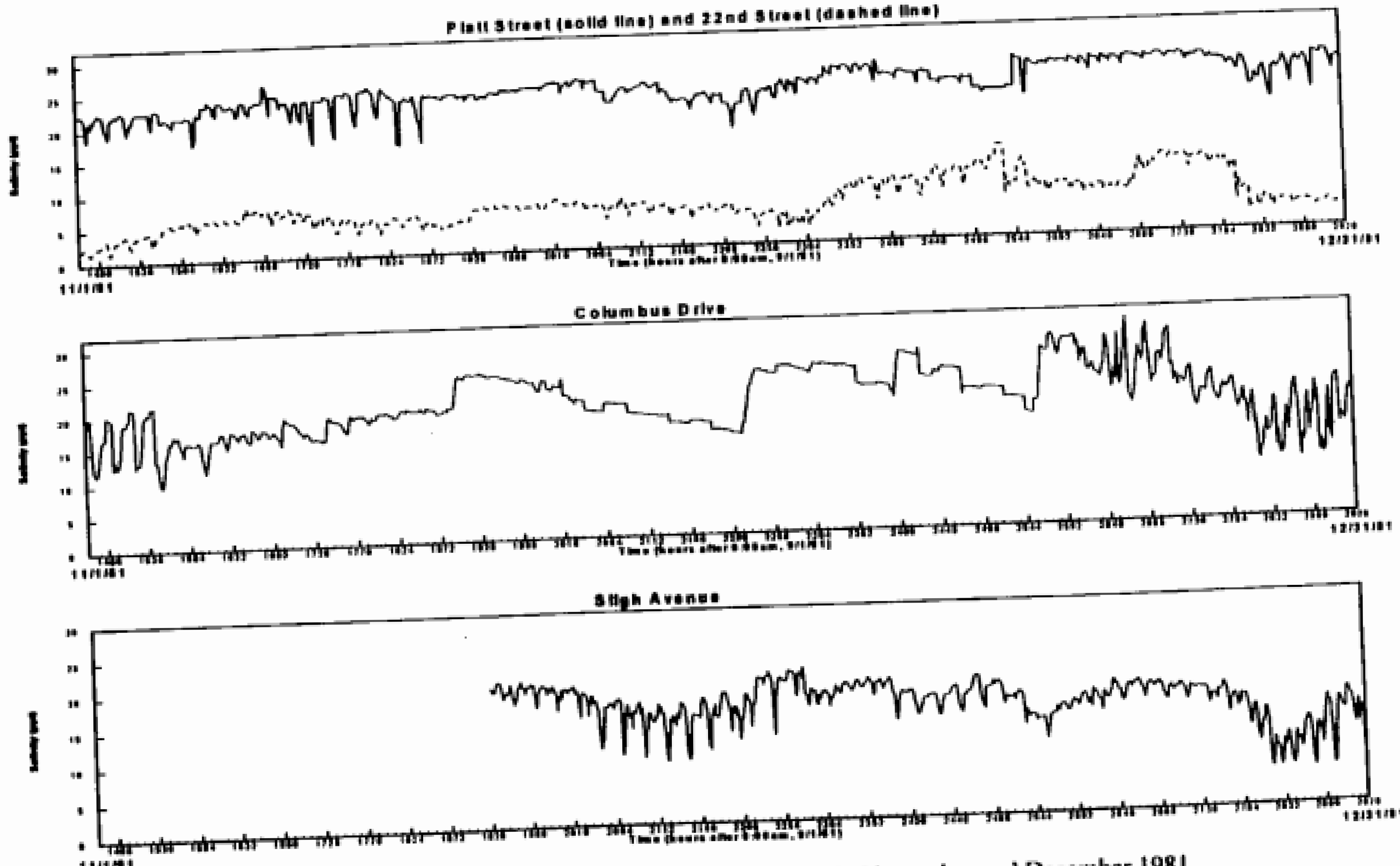


Figure A-9 Real-time salinity data measured in the Lower Hillsborough River in November and December 1981.

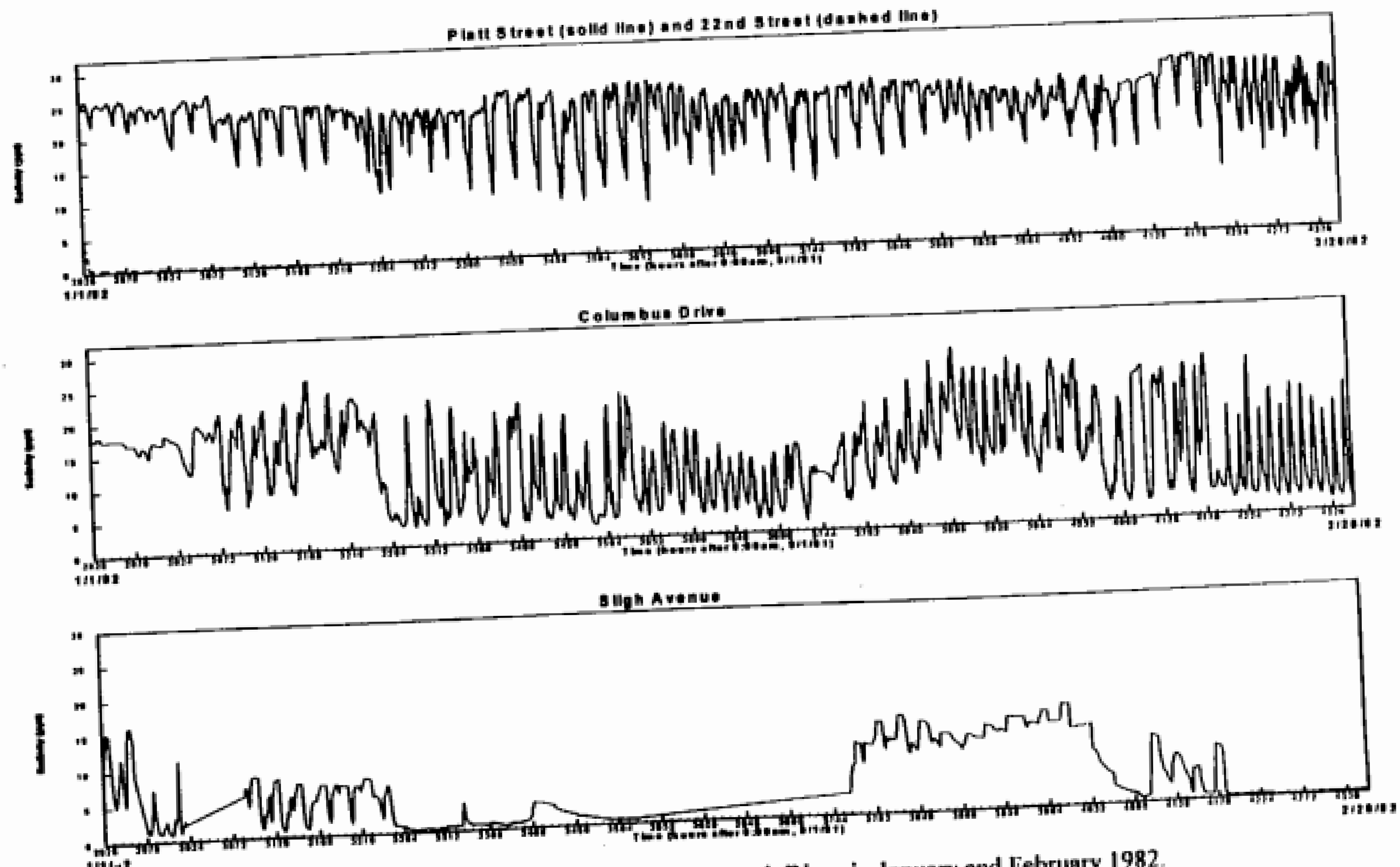


Figure A-10 Real-time salinity data measured in the Lower Hillsborough River in January and February 1982.

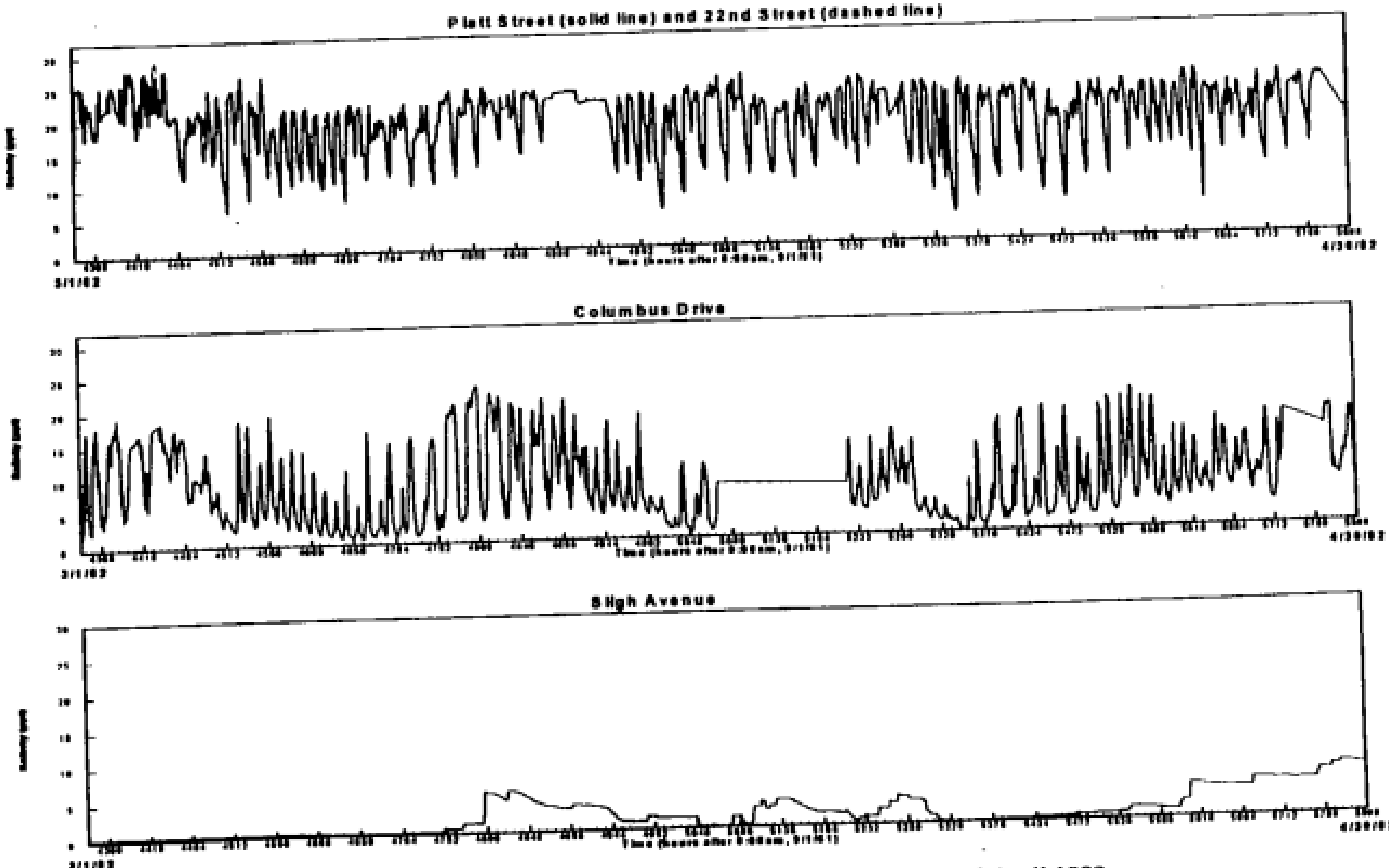


Figure A-11 Real-time salinity data measured in the Lower Hillsborough River in March and April 1982.

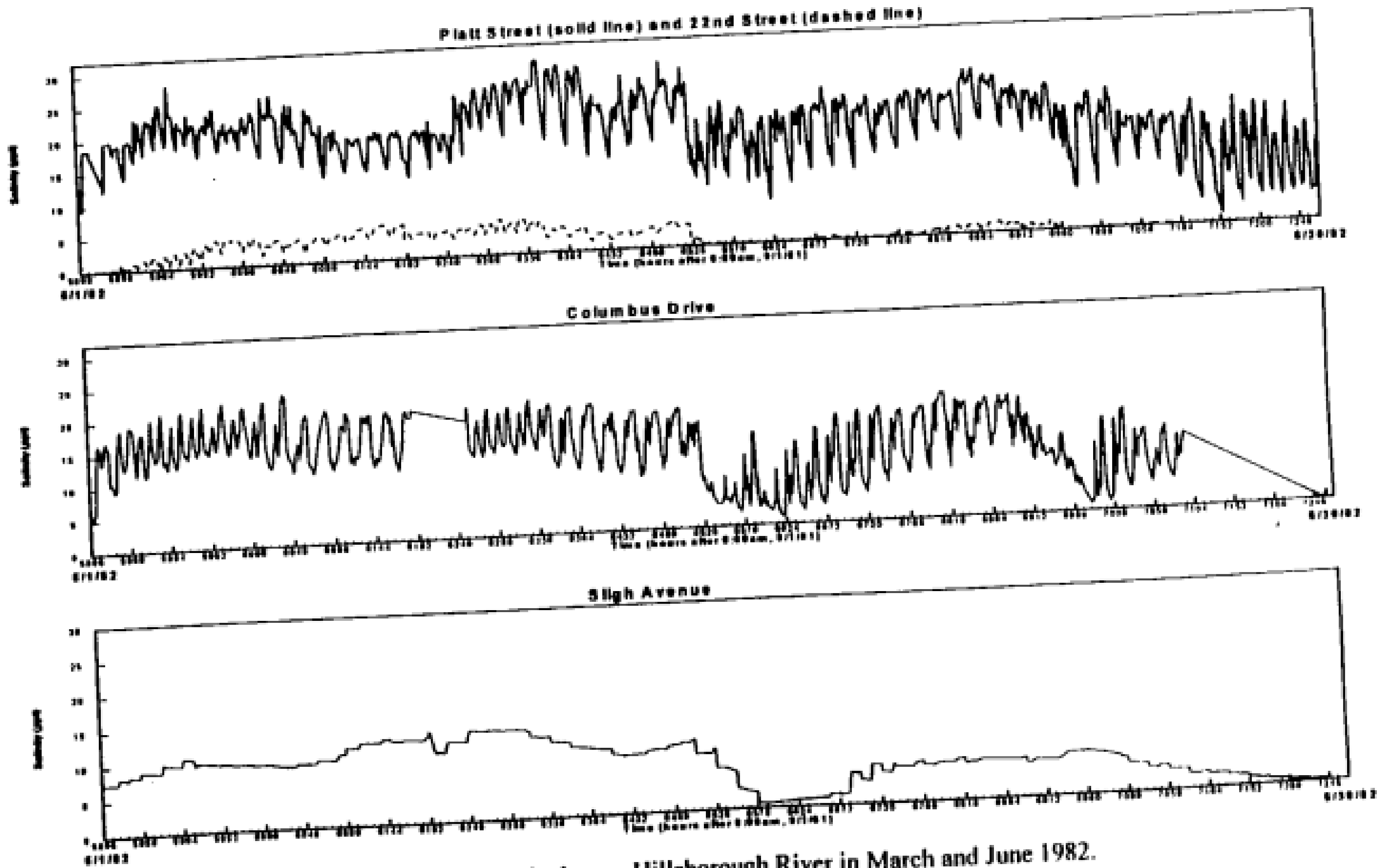


Figure A-12 Real-time salinity data measured in the Lower Hillsborough River in March and June 1982.

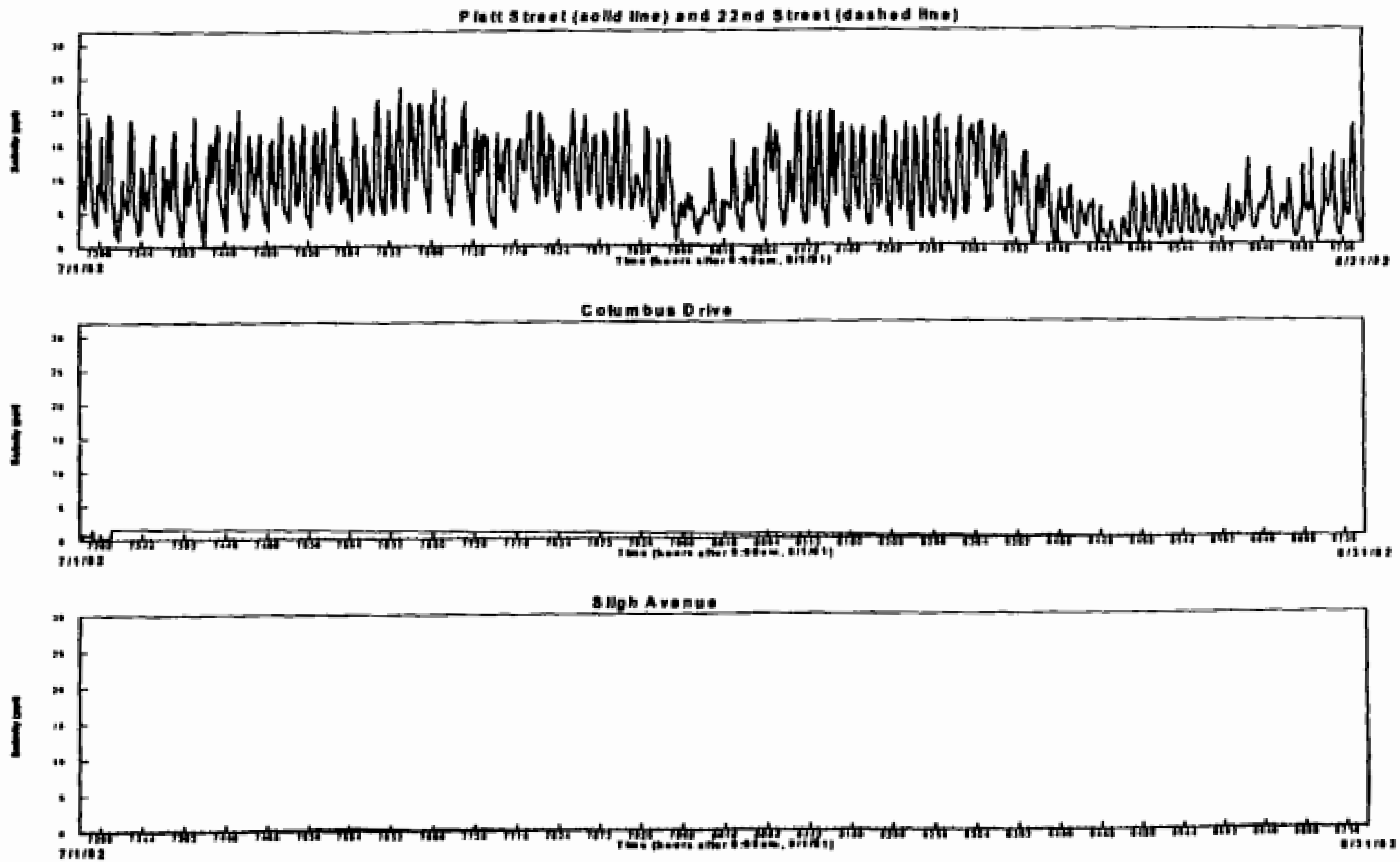


Figure A-13 Real-time salinity data measured in the Lower Hillsborough River in July and August 1982.

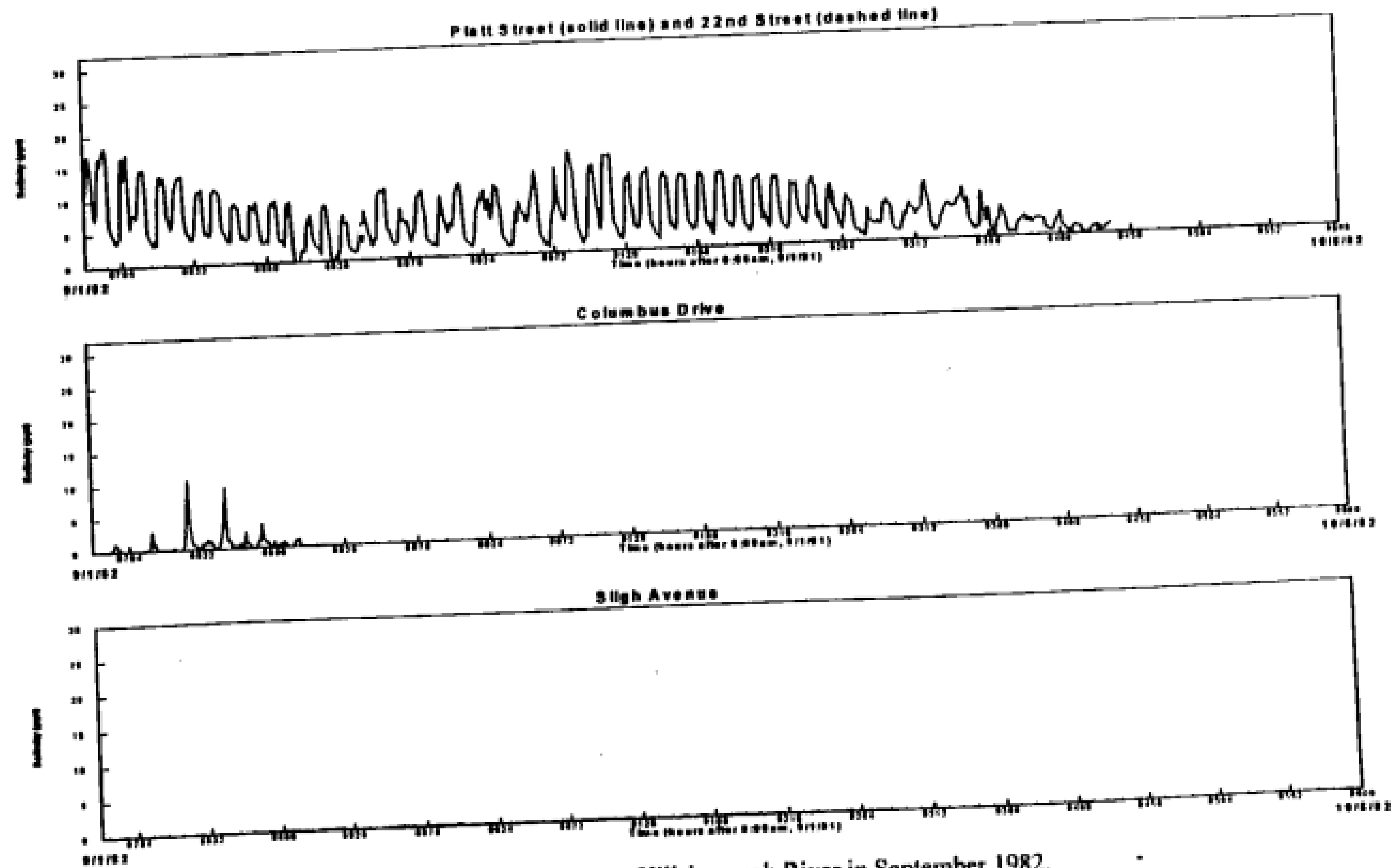


Figure A-14 Real-time salinity data measured in the Lower Hillsborough River in September 1982.

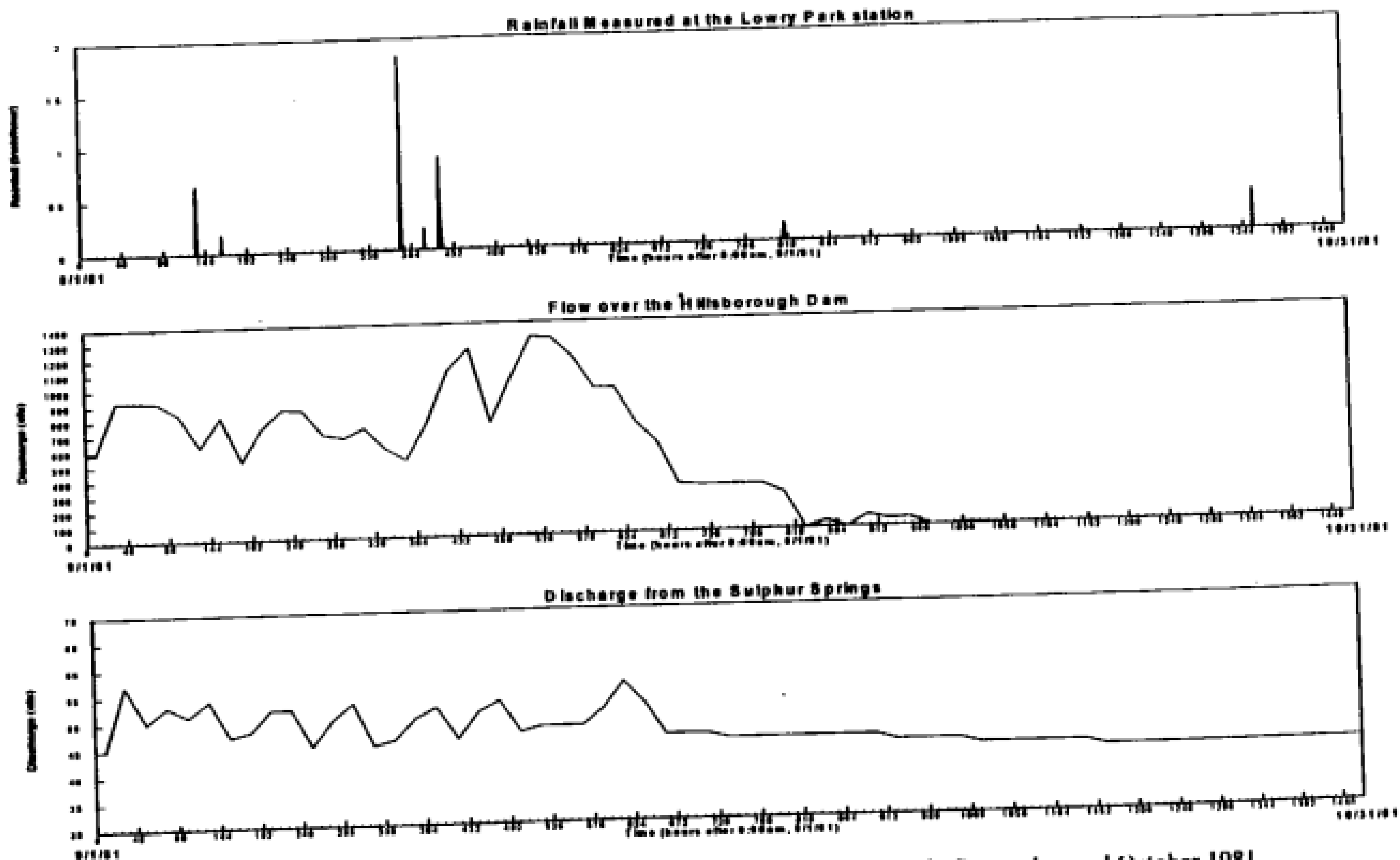


Figure A-15 Hourly rainfall and discharges over the dam and from the Sulphur Springs in September and October 1981.

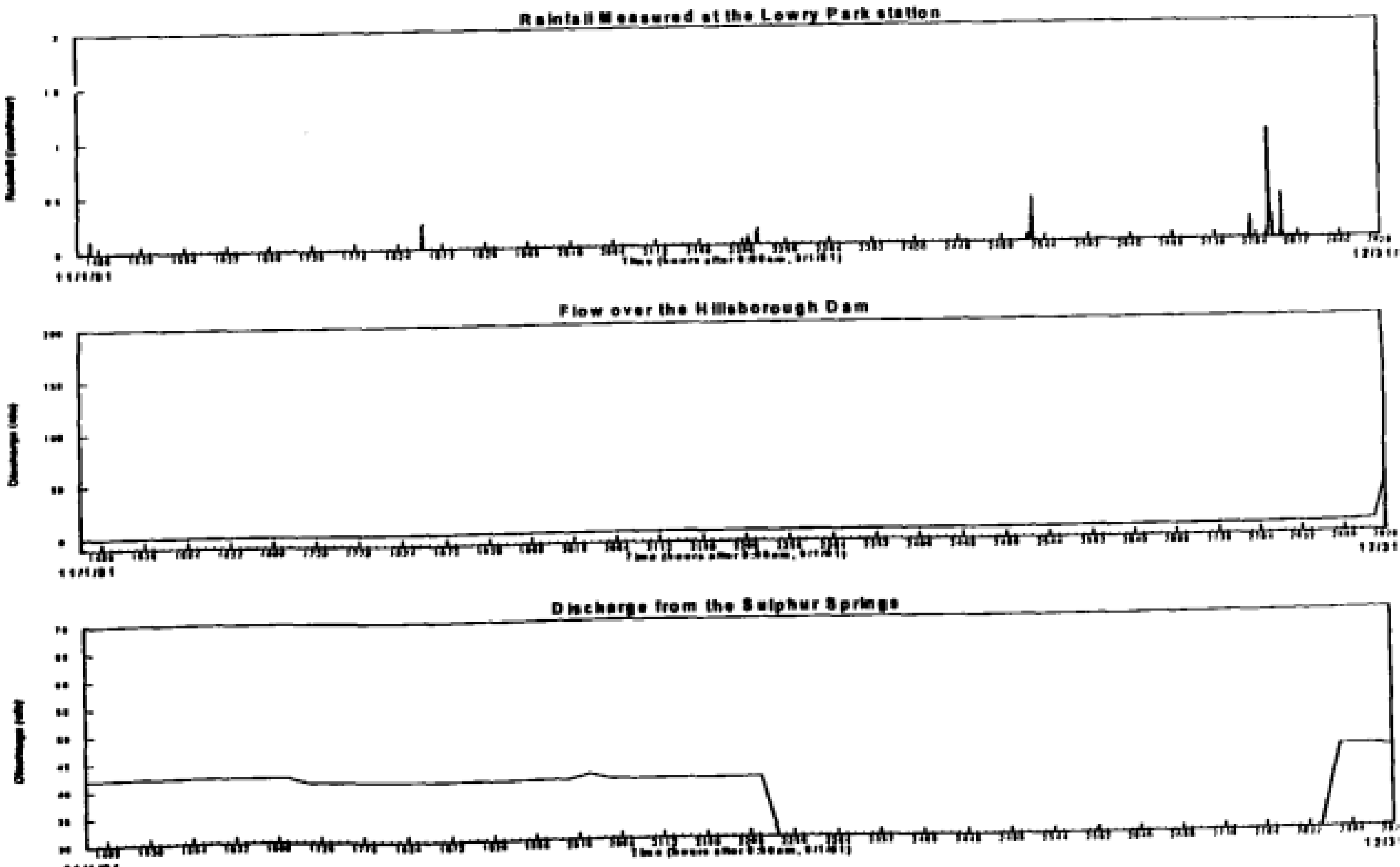


Figure A-16 Hourly rainfall and discharges over the dam and from the Sulphur Springs in November and December 1981.

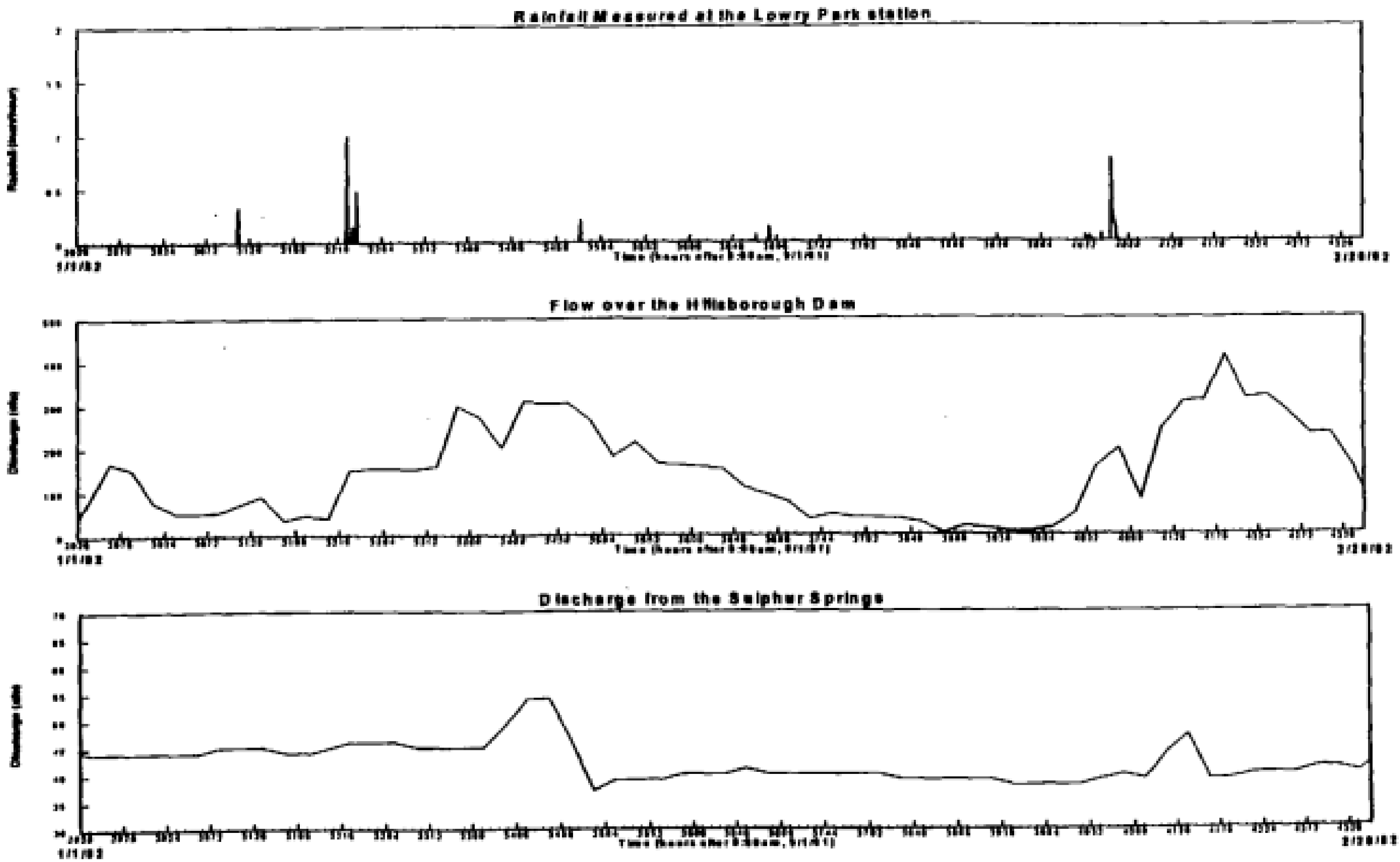


Figure A-17 Hourly rainfall and discharges over the dam and from the Sulphur Springs in January and February 1982.

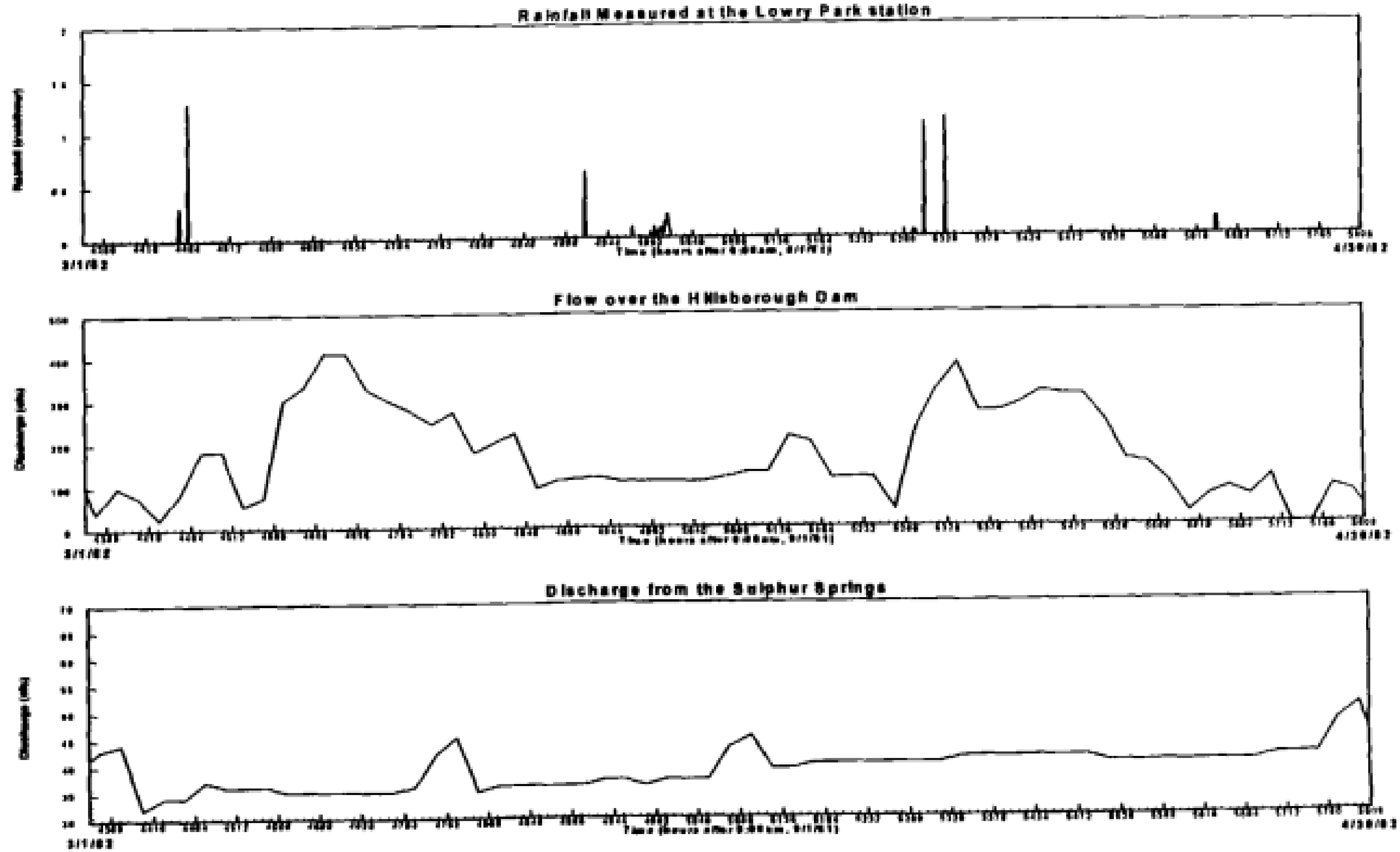


Figure A-18 Hourly rainfall and discharges over the dam and from the Sulphur Springs in March and April 1982.

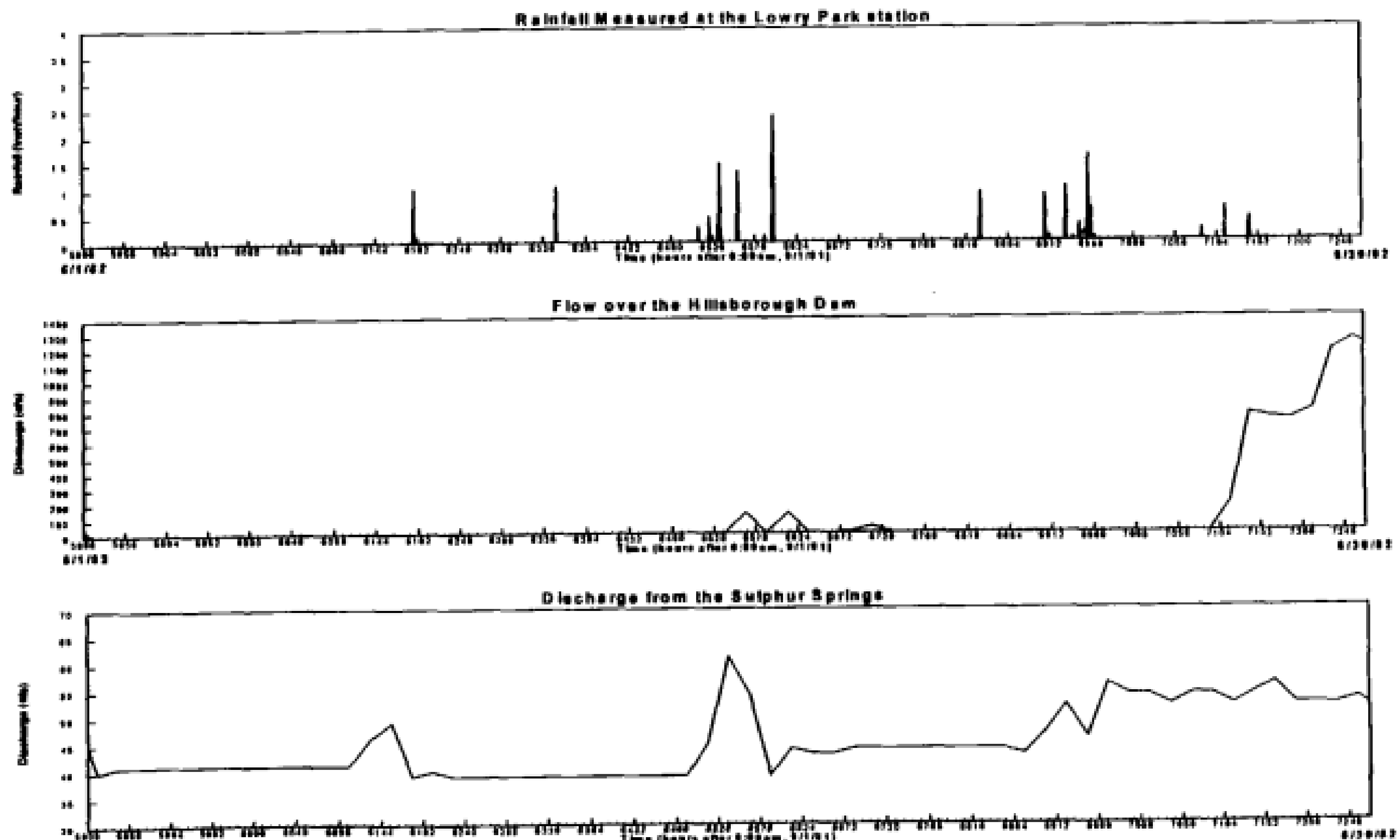


Figure A-19 Hourly rainfall and discharges over the dam and from the Sulphur Springs in May and June 1982.

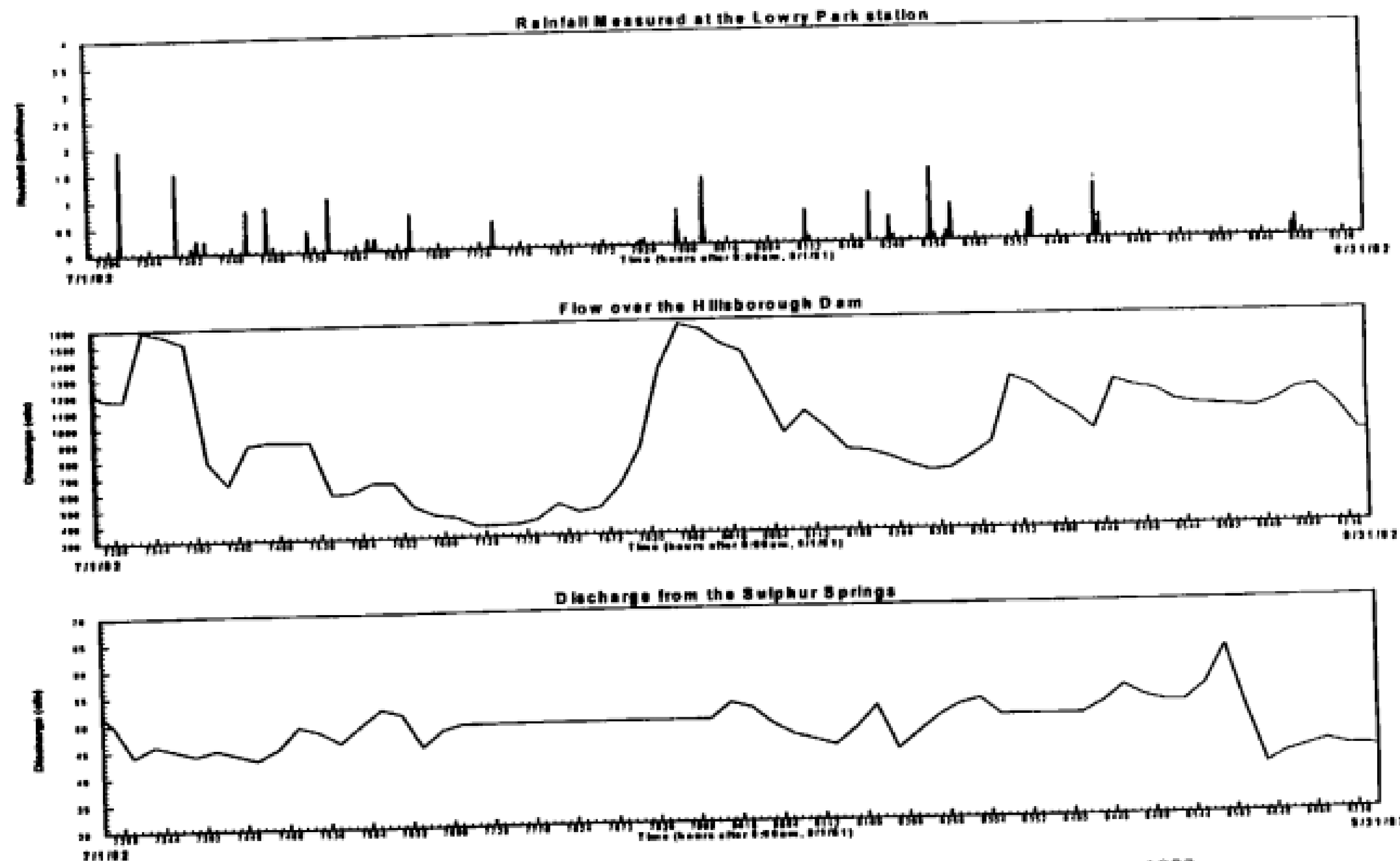


Figure A-20 Hourly rainfall and discharges over the dam and from the Sulphur Springs in July and August 1982.

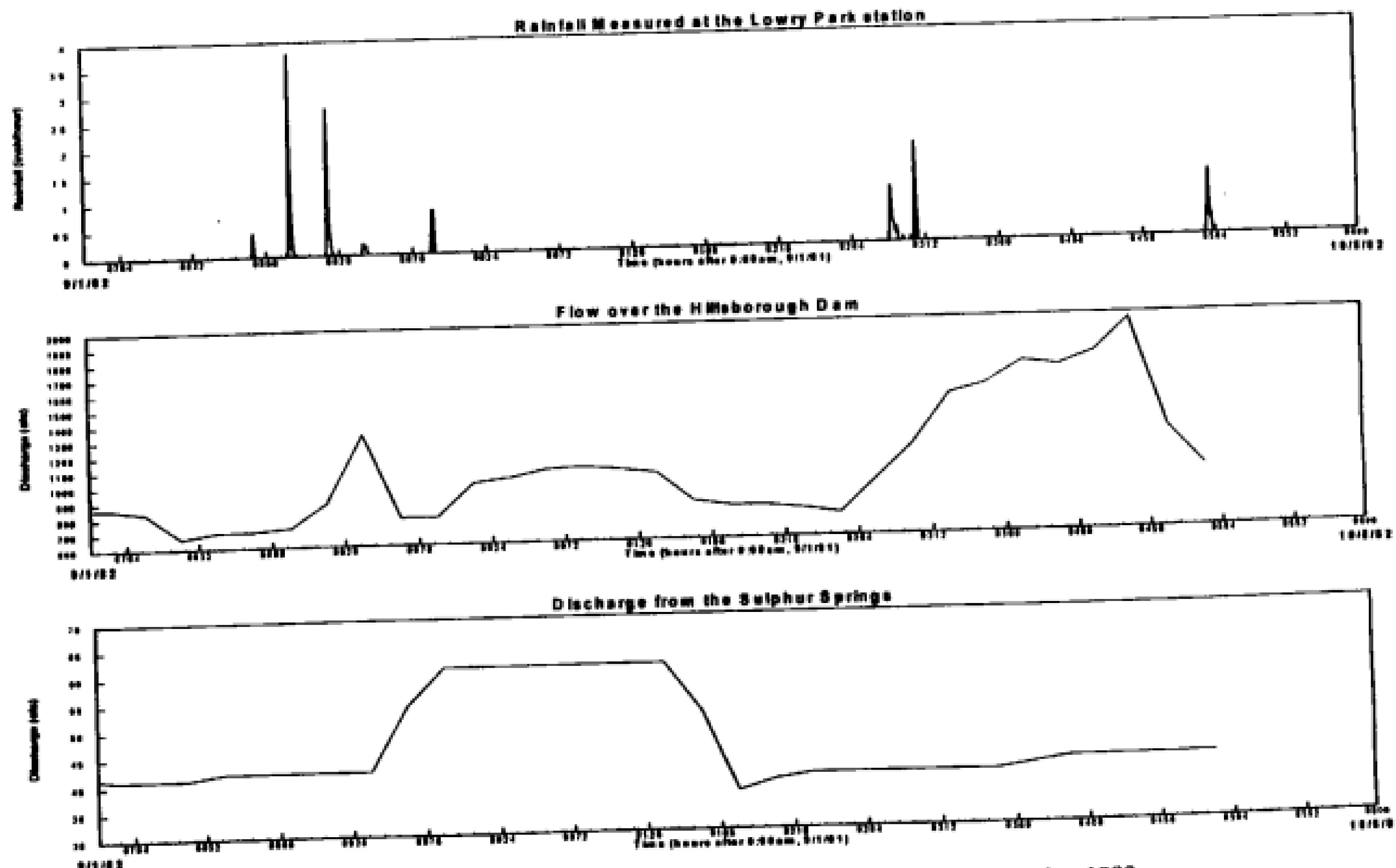
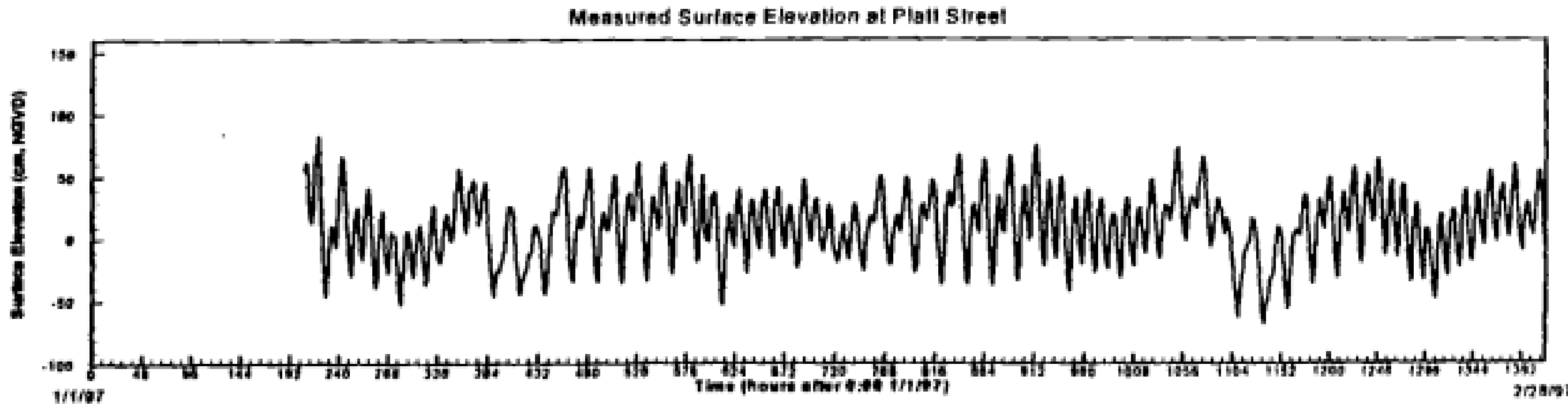


Figure A-21 Hourly rainfall and discharges over the dam and from the Sulphur Springs in September 1982.



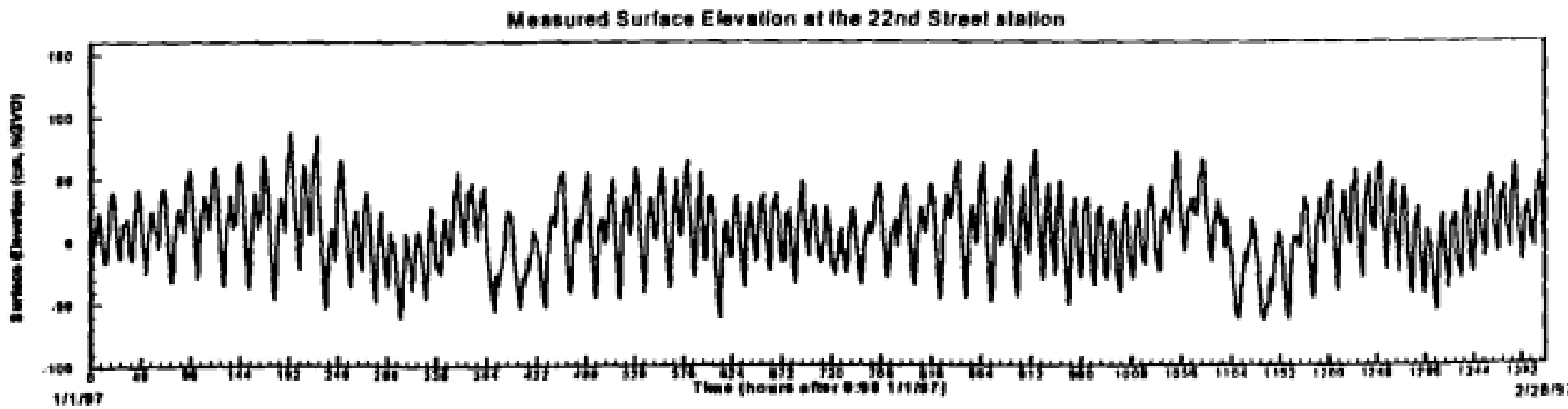


Figure A-22 Real-time water elevation data measured in the Lower Hillsborough River in January and February 1997.

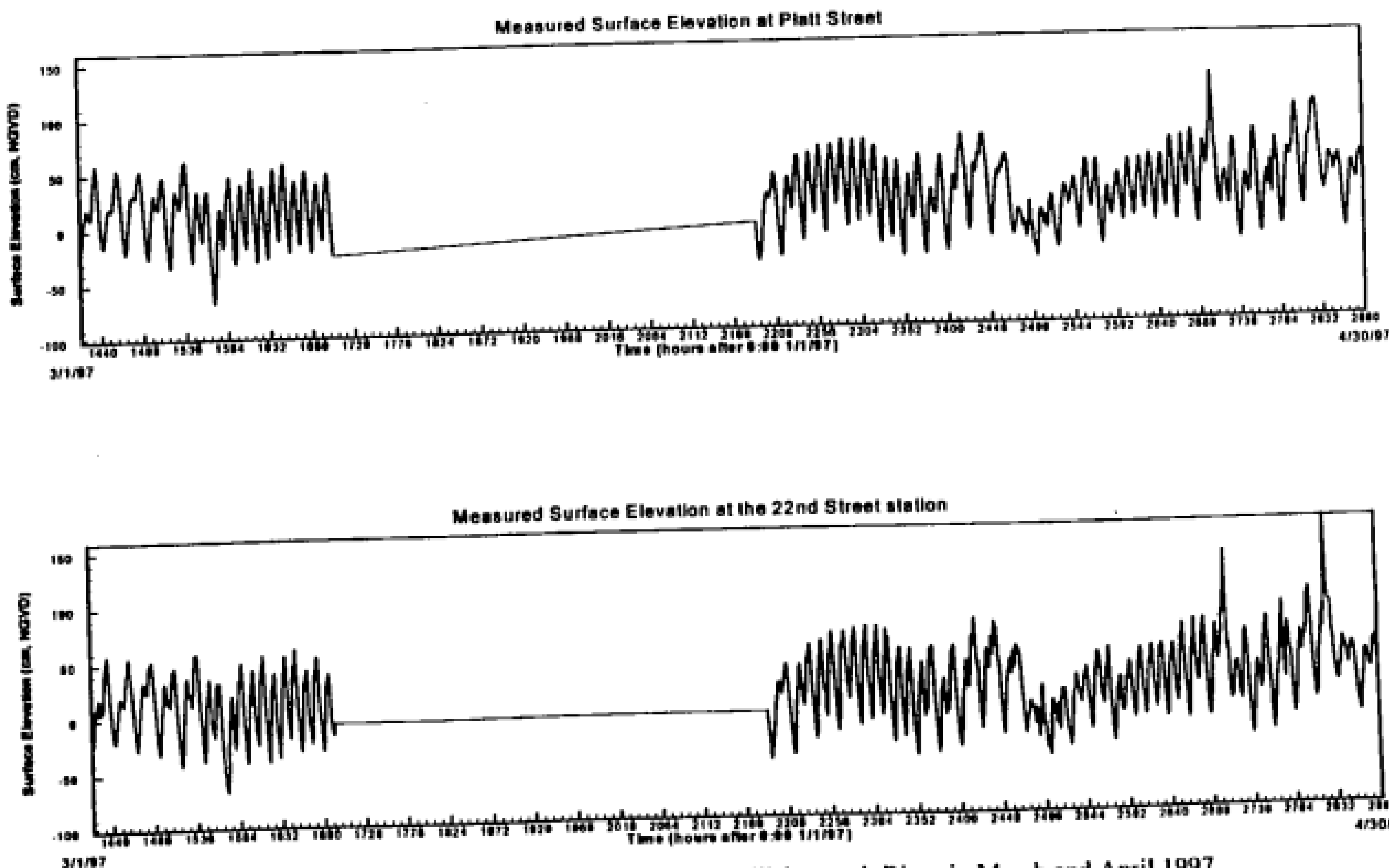


Figure A-23 Real-time water elevation data measured in the Lower Hillsborough River in March and April 1997.

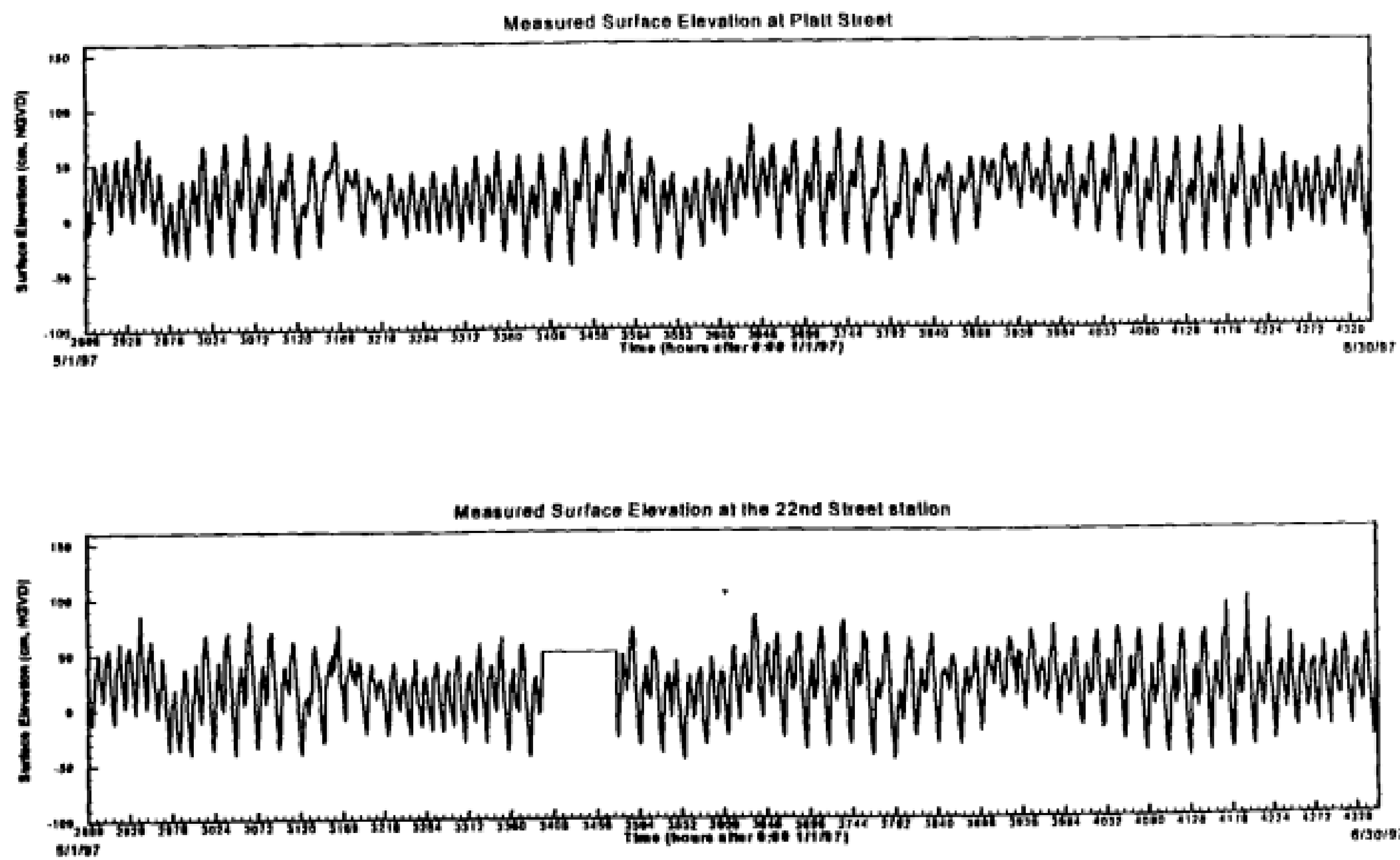


Figure A-24 Real-time water elevation data measured in the Lower Hillsborough River in May and June 1997.

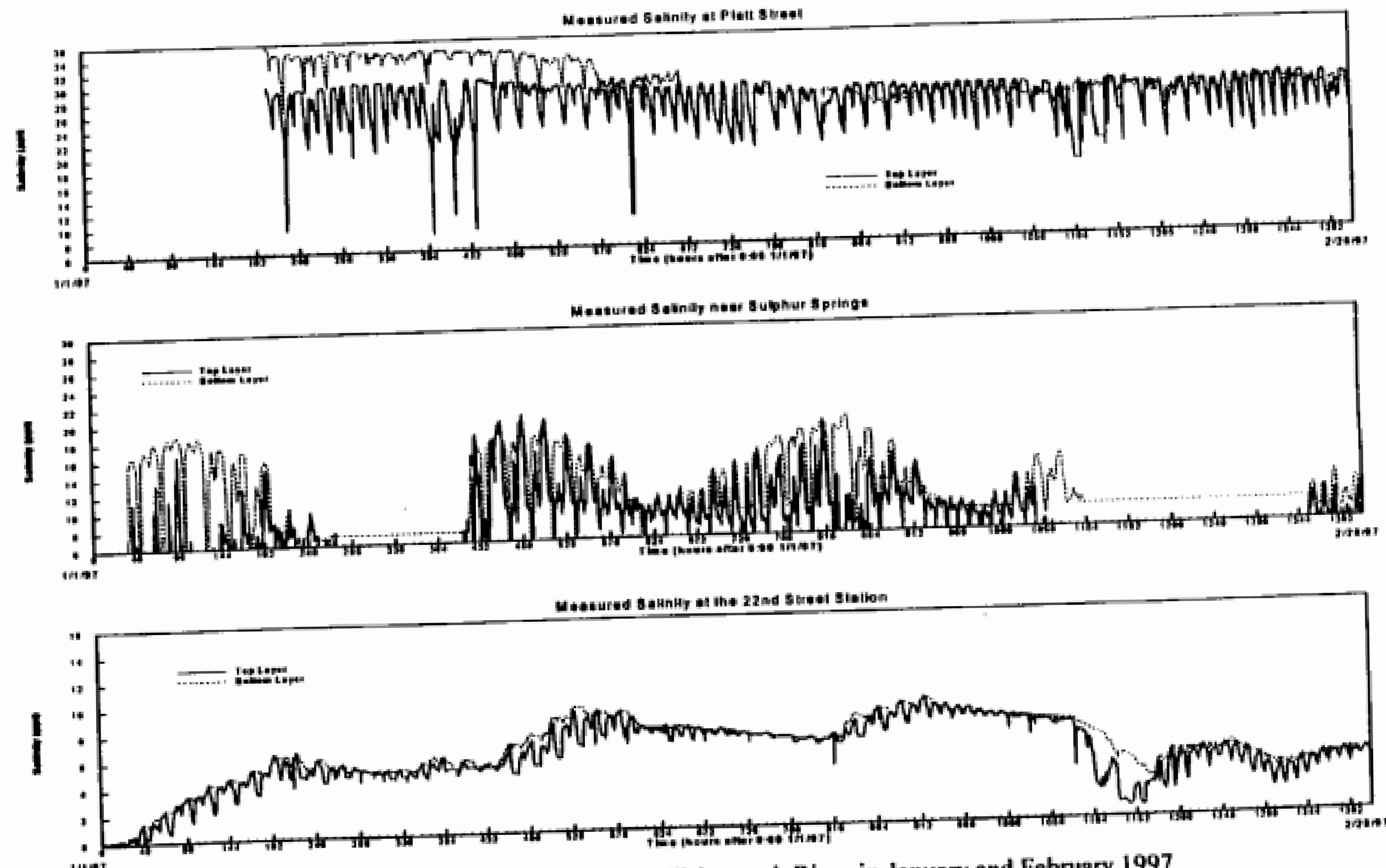


Figure A-25 Real-time salinity data measured in the Lower Hillsborough River in January and February 1997.

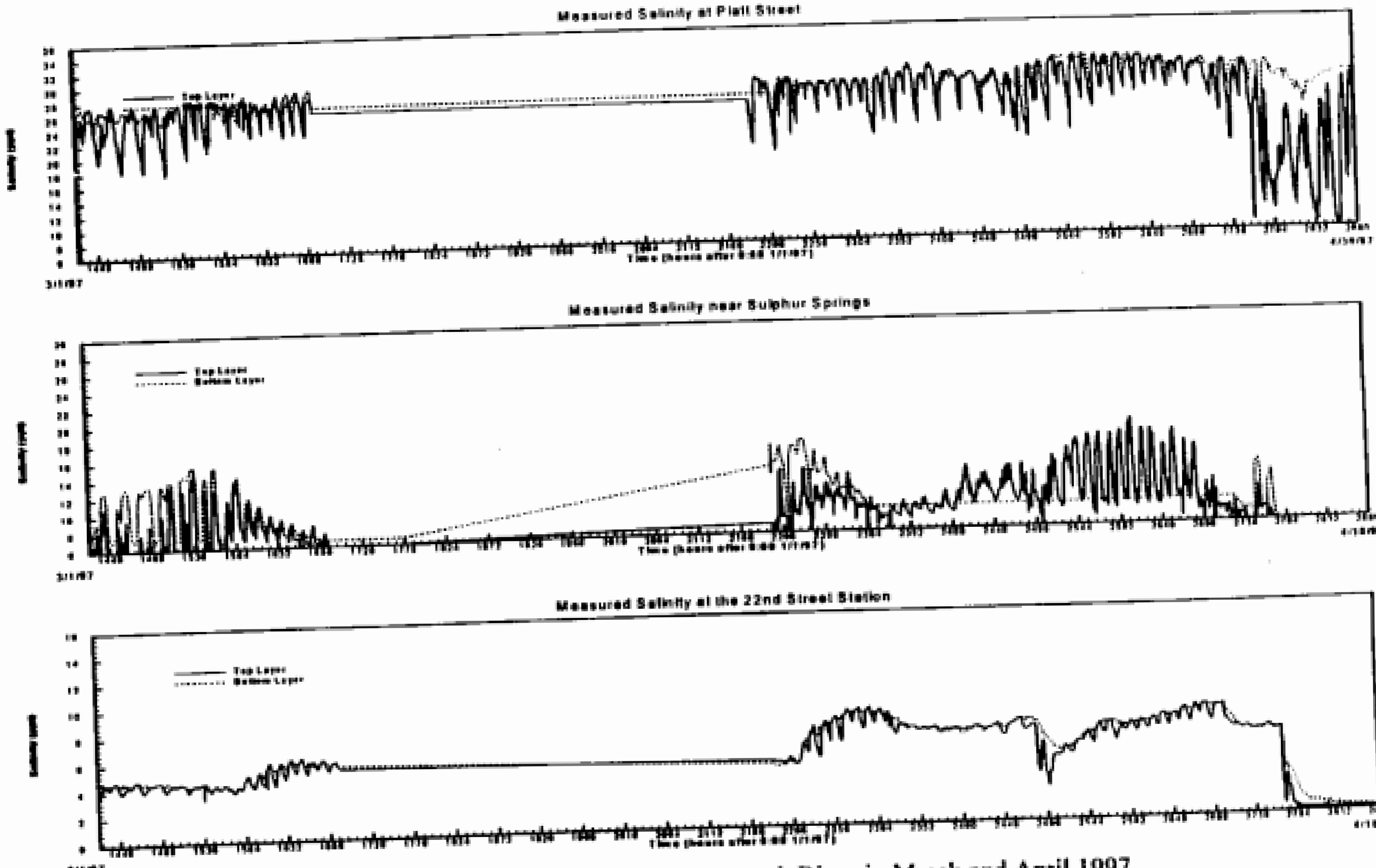


Figure A-26 Real-time salinity data measured in the Lower Hillsborough River in March and April 1997.

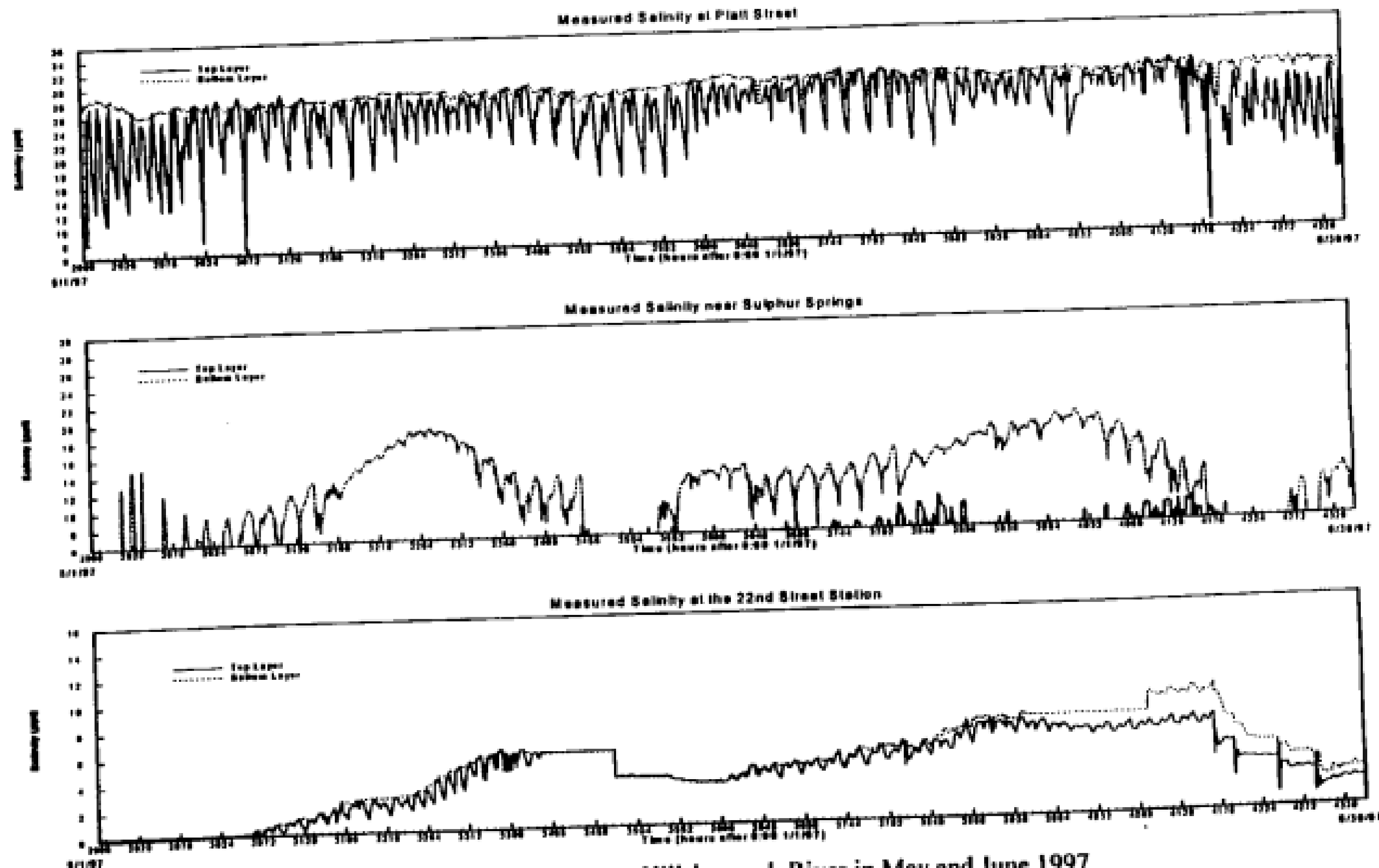


Figure A-27 Real-time salinity data measured in the Lower Hillsborough River in May and June 1997.

Appendix B. Comparisons of Model Results with Measured Data

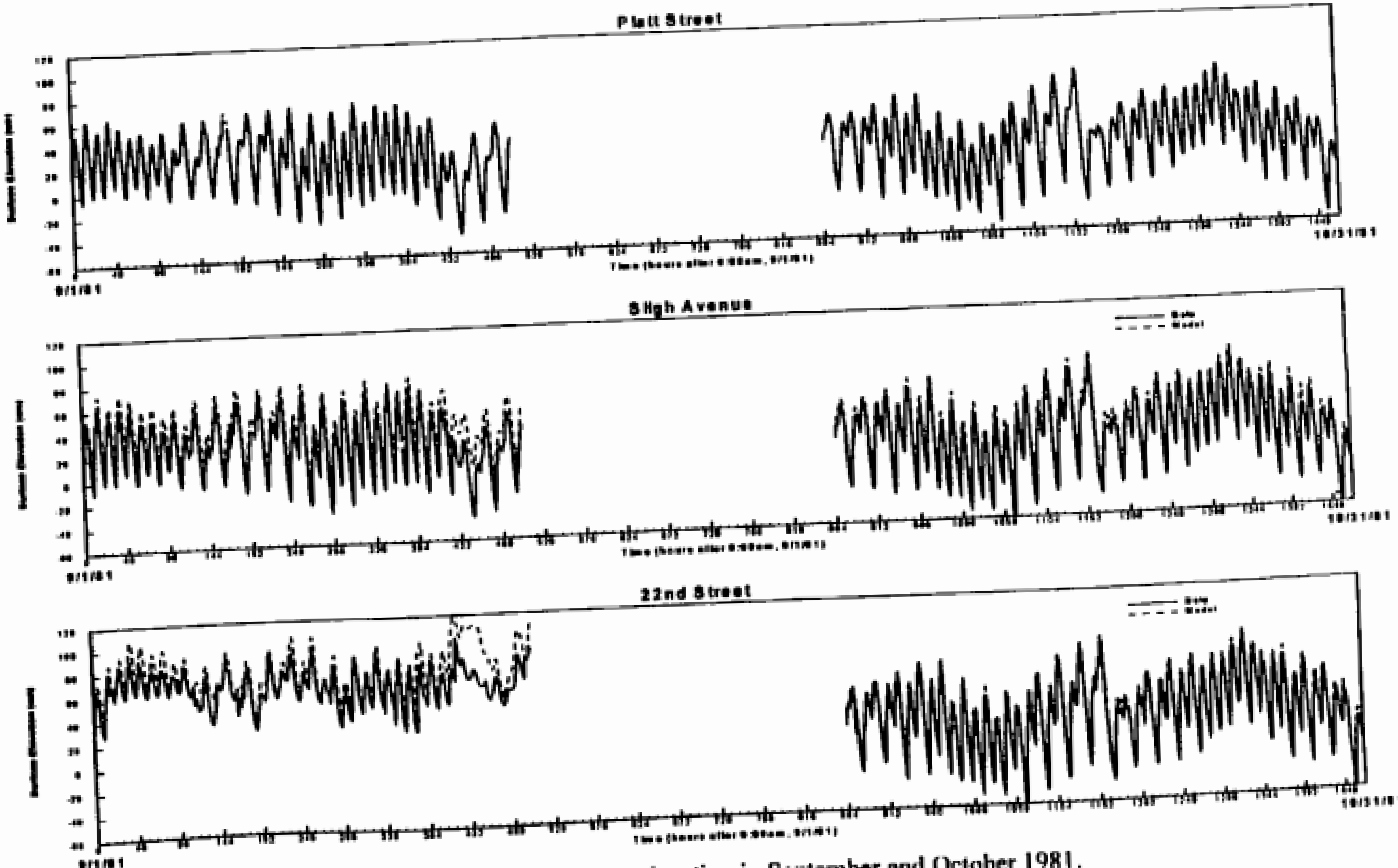


Figure B-1 Comparison of simulated and measured surface elevation in September and October 1981.

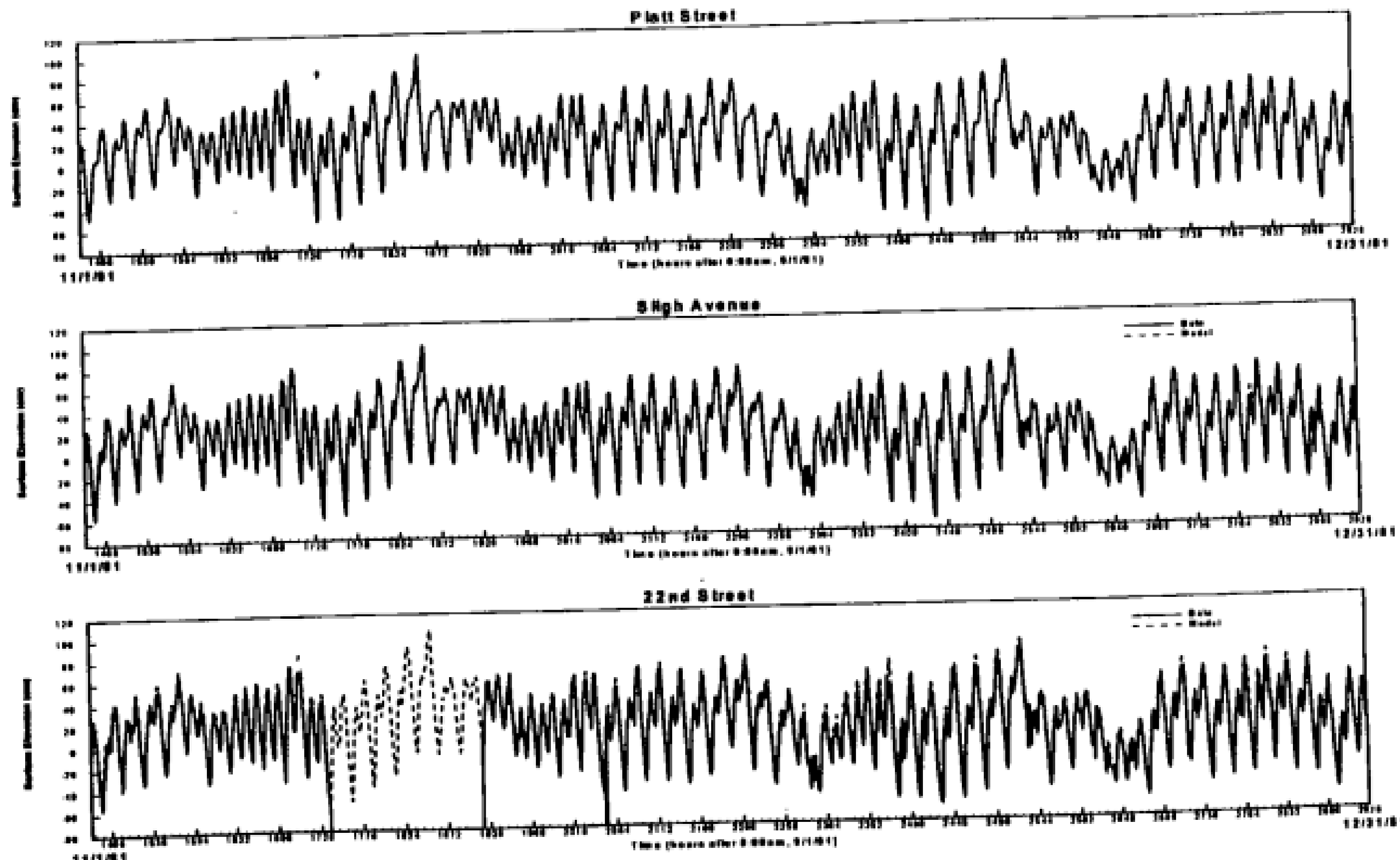


Figure B-2 Comparison of simulated and measured surface elevation in November and December 1981.

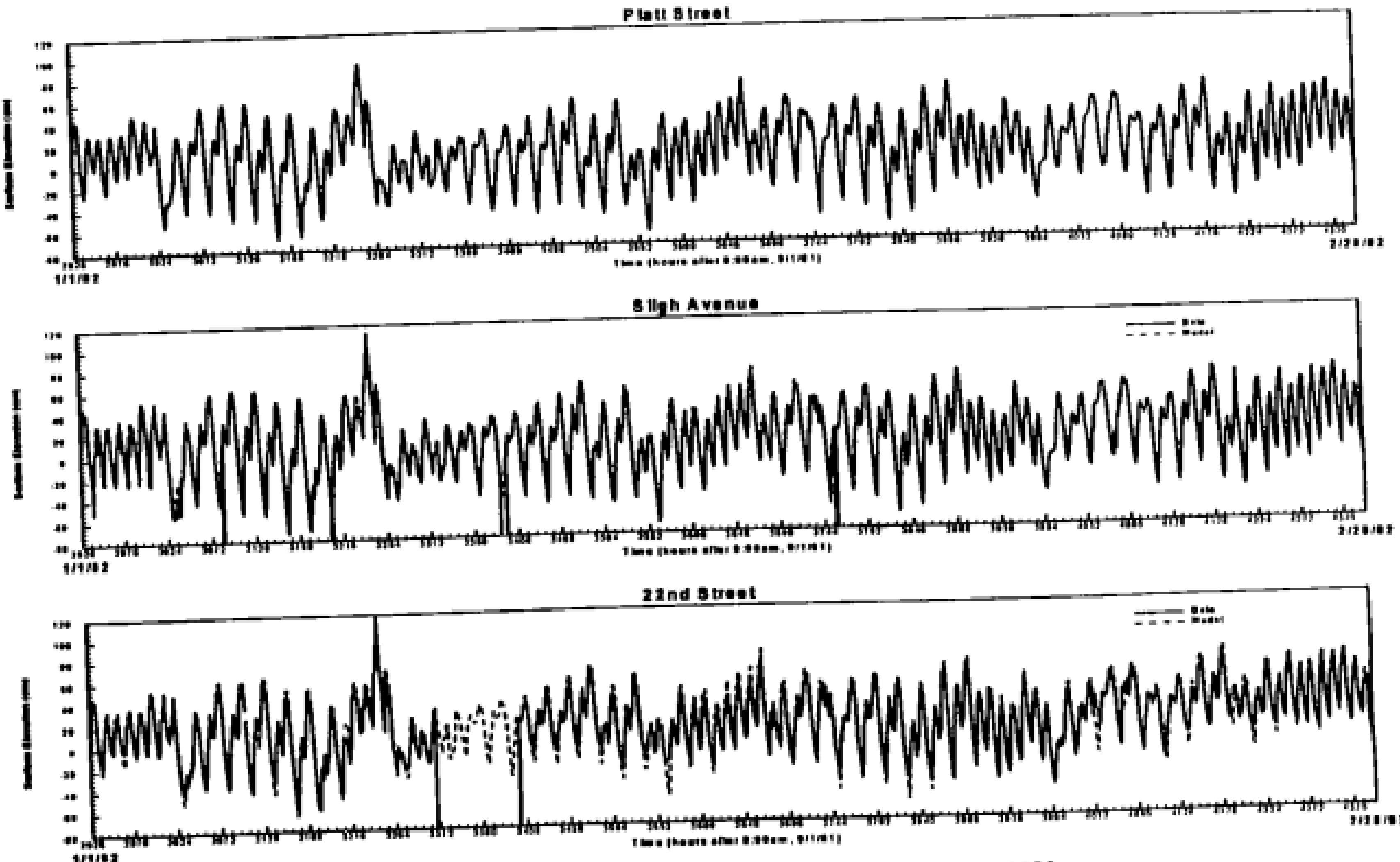


Figure B-3 Comparison of simulated and measured surface elevation in January and February 1982.

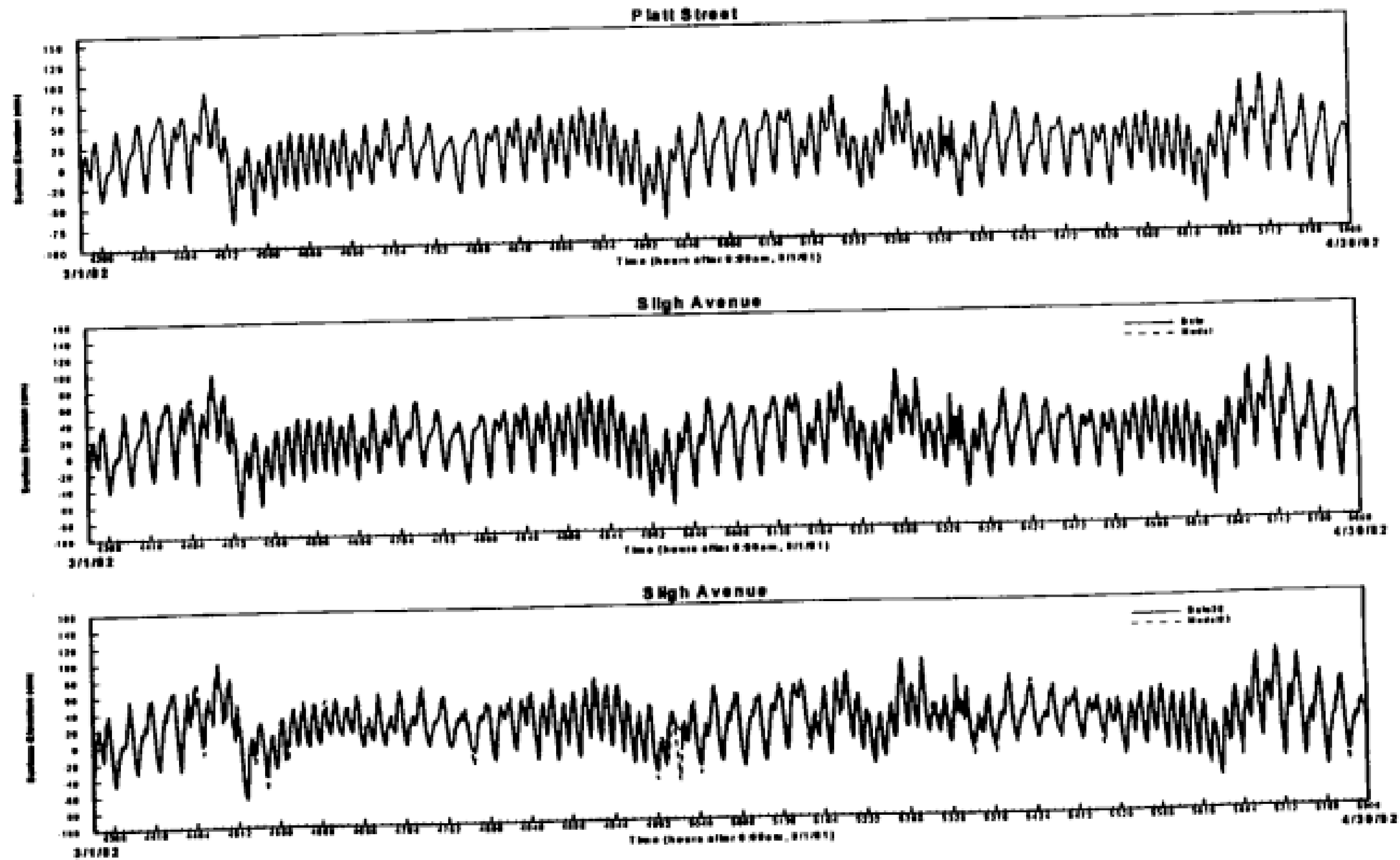


Figure B-4 Comparison of simulated and measured surface elevation in March and April 1982.

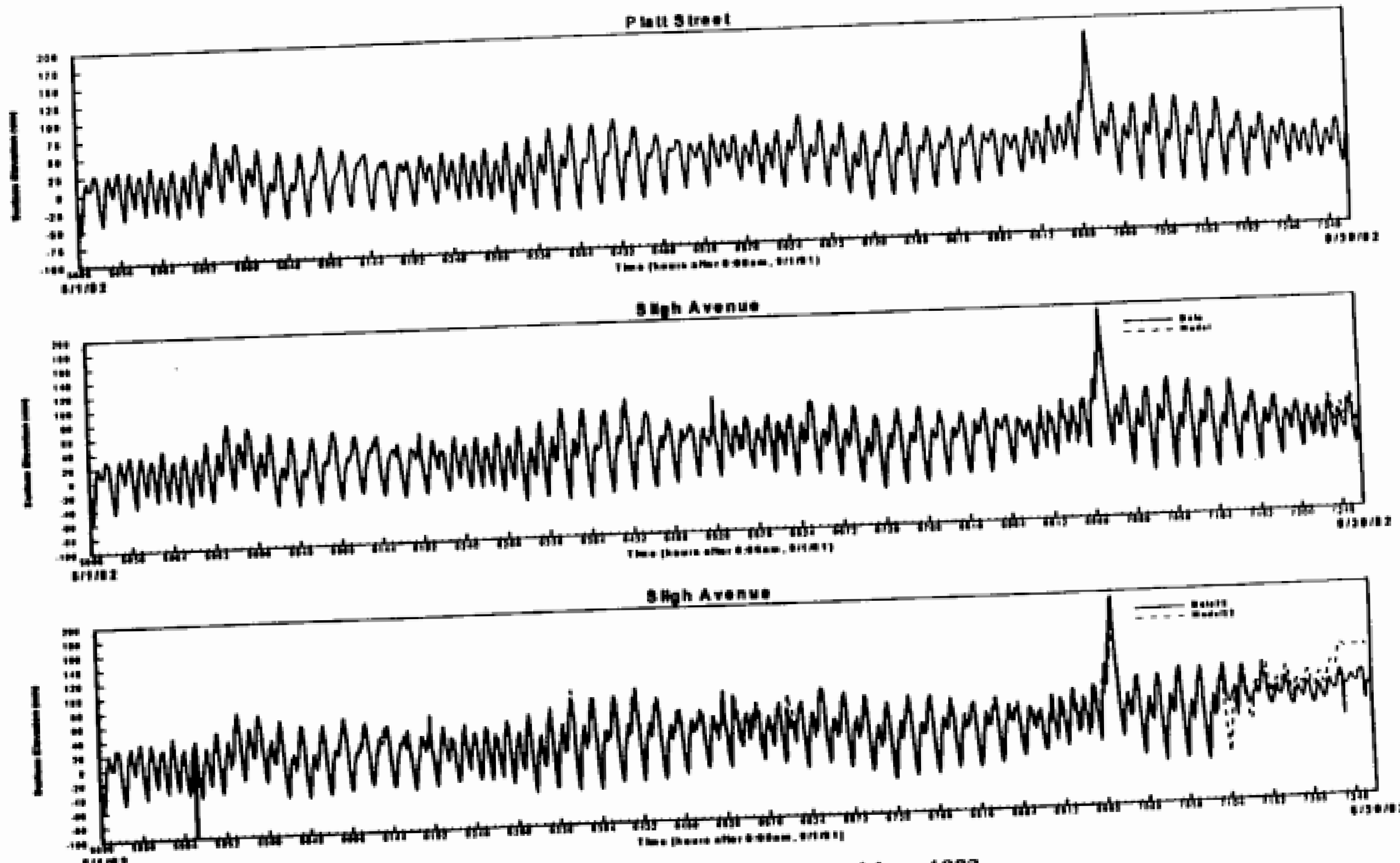


Figure B-5 Comparison of simulated and measured surface elevation in May and June 1982.

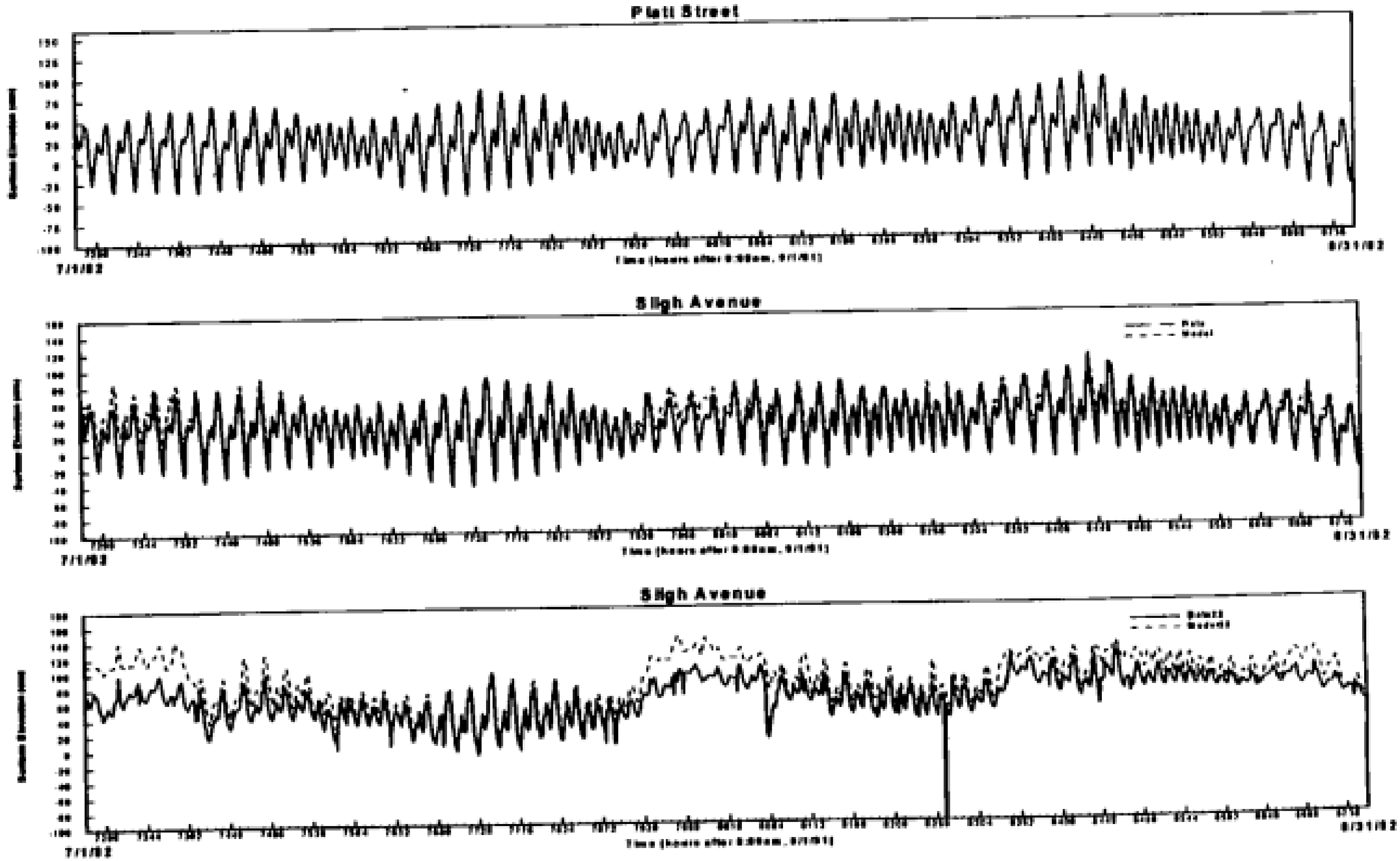


Figure B-6 Comparison of simulated and measured surface elevation in July and August 1982.

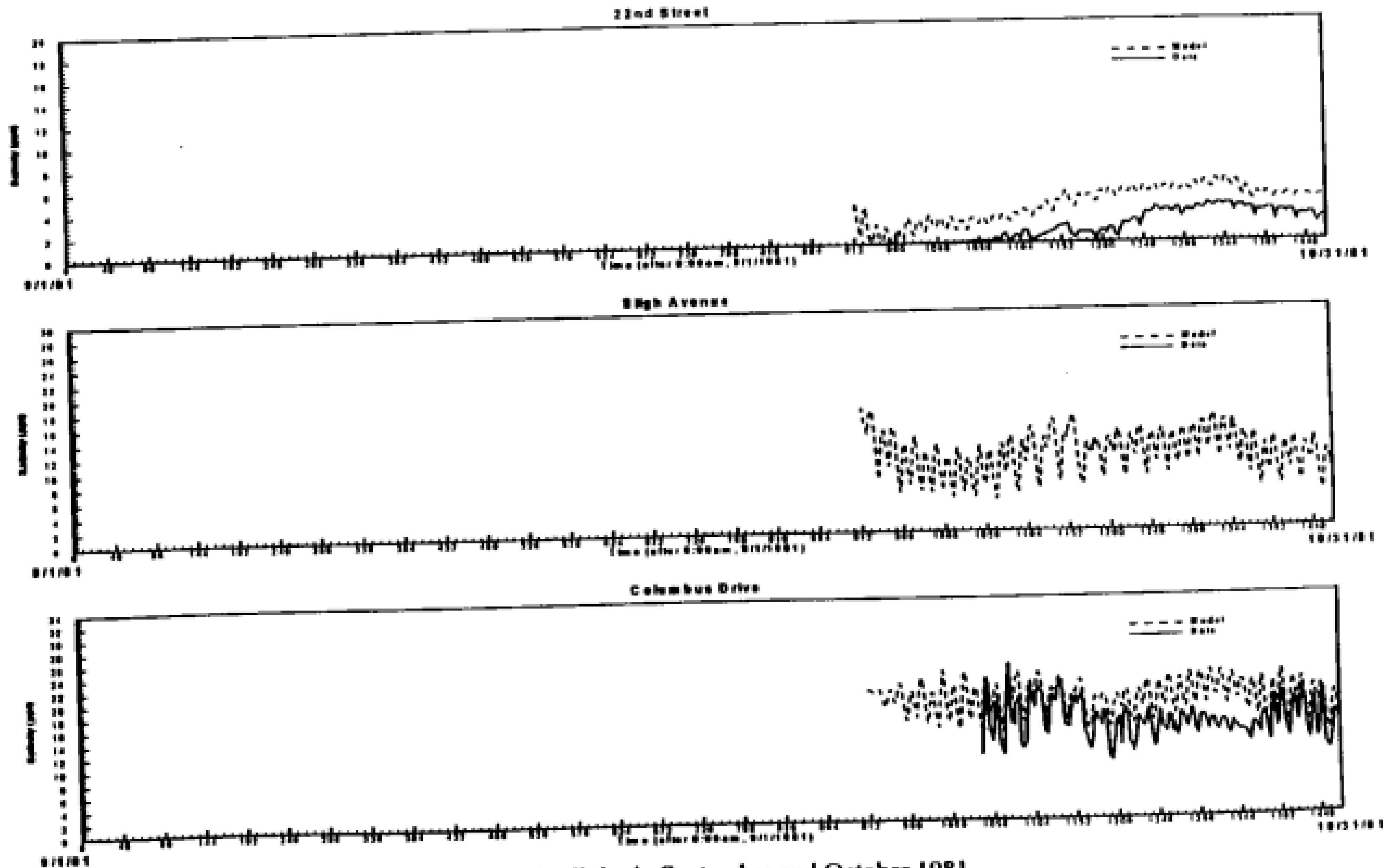


Figure B-7 Comparison of simulated and measured salinity in September and October 1981.

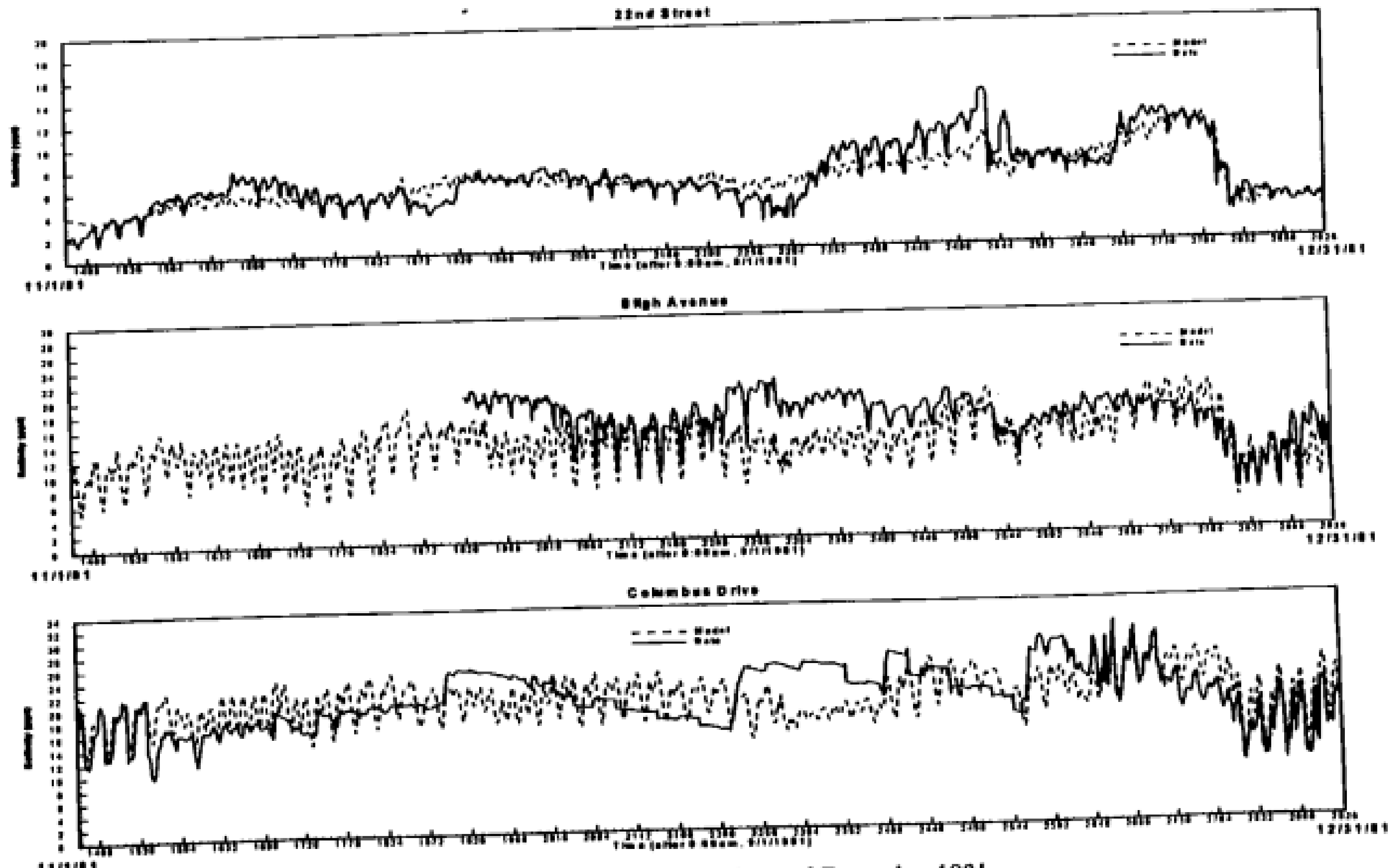


Figure B-8 Comparison of simulated and measured salinity in November and December 1981.

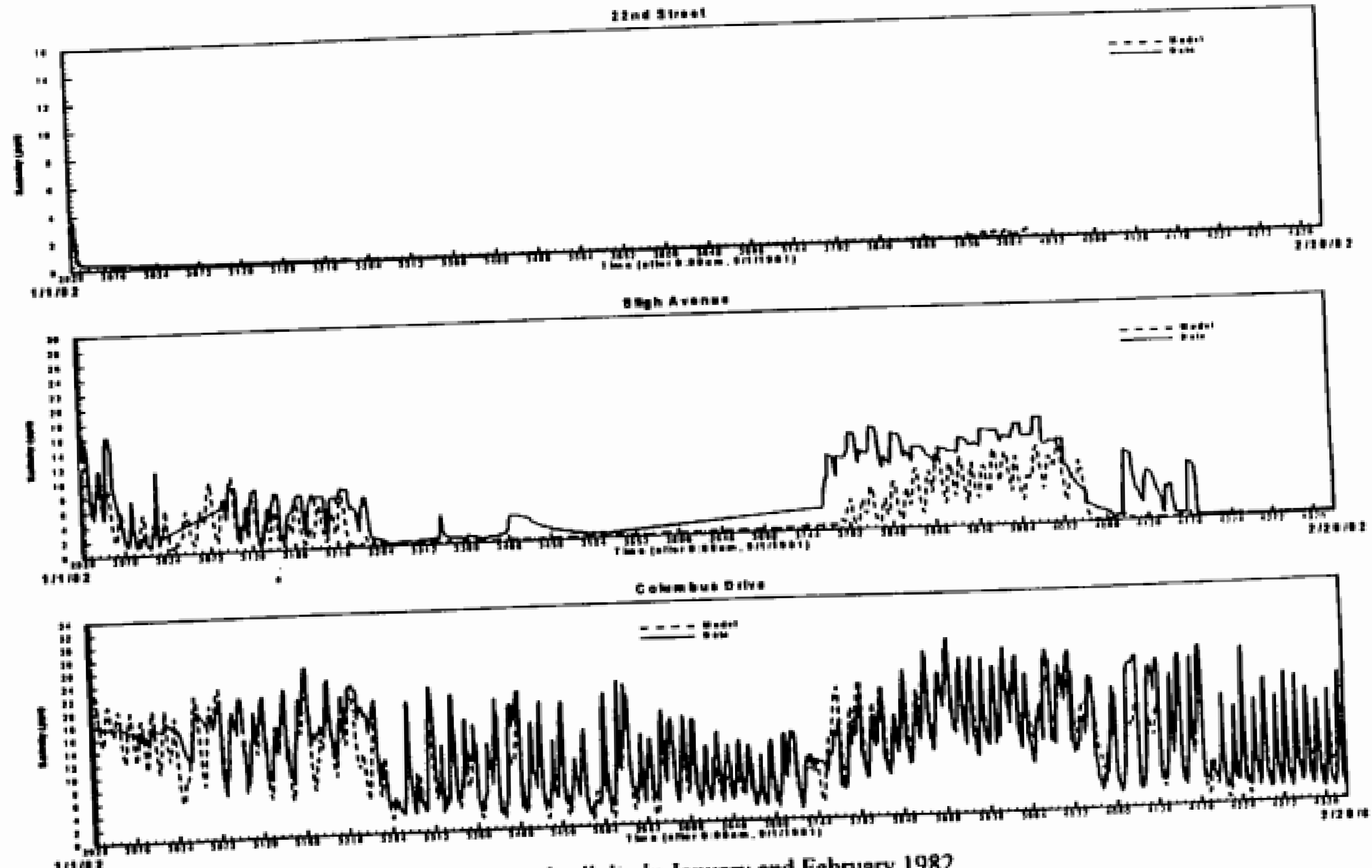


Figure B-9 Comparison of simulated and measured salinity in January and February 1982.

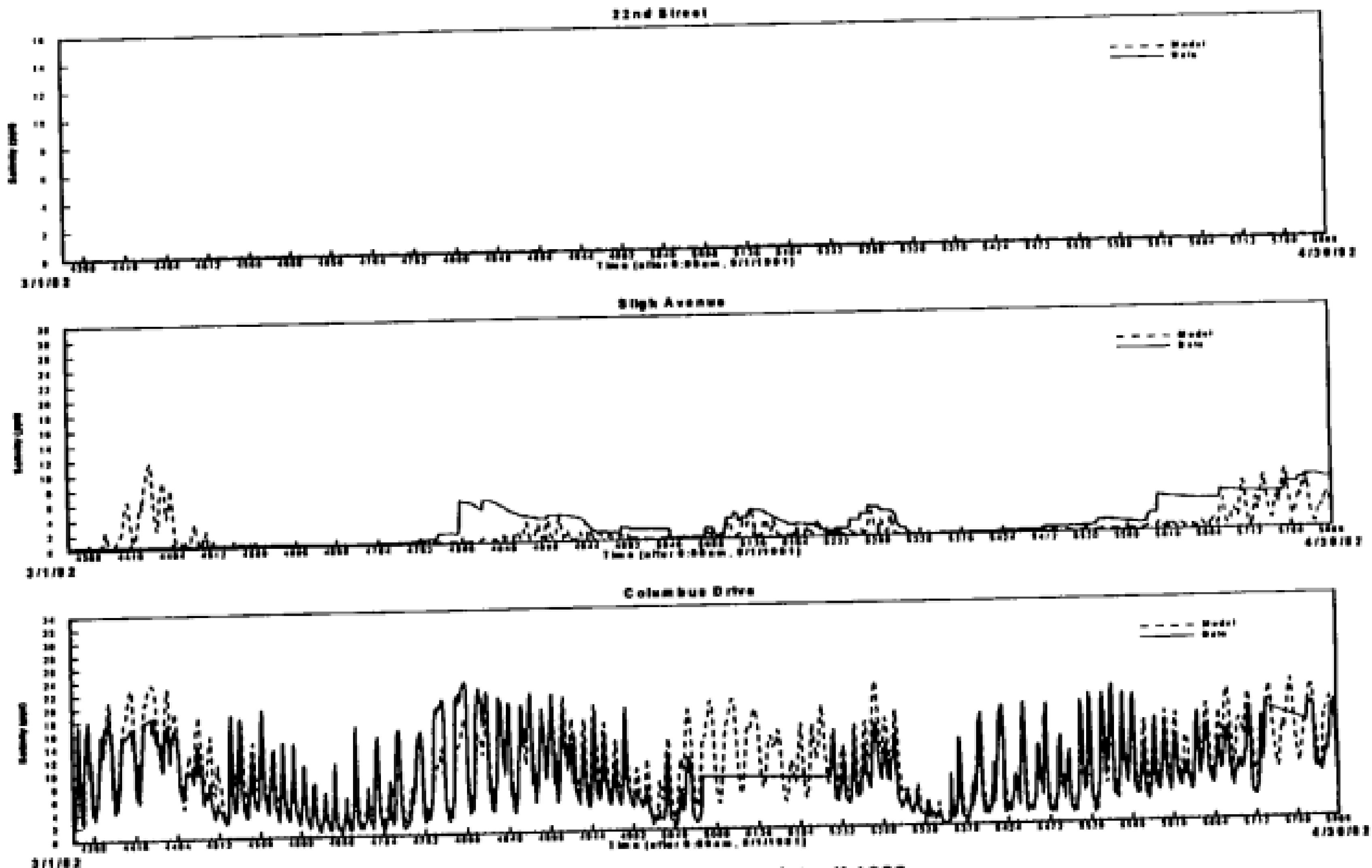


Figure B-10 Comparison of simulated and measured salinity in March and April 1982.

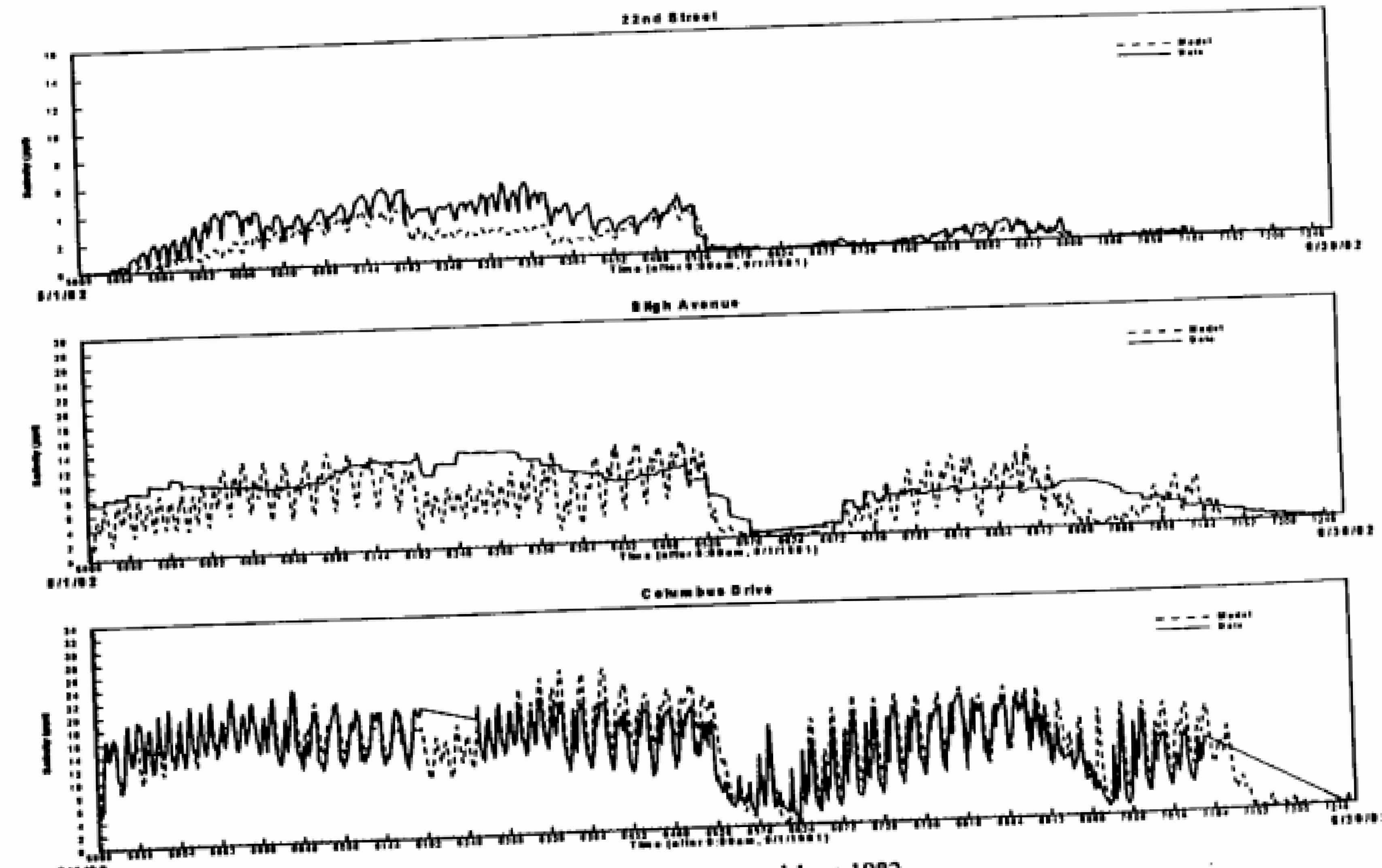


Figure B-11 Comparison of simulated and measured salinity in May and June 1982.

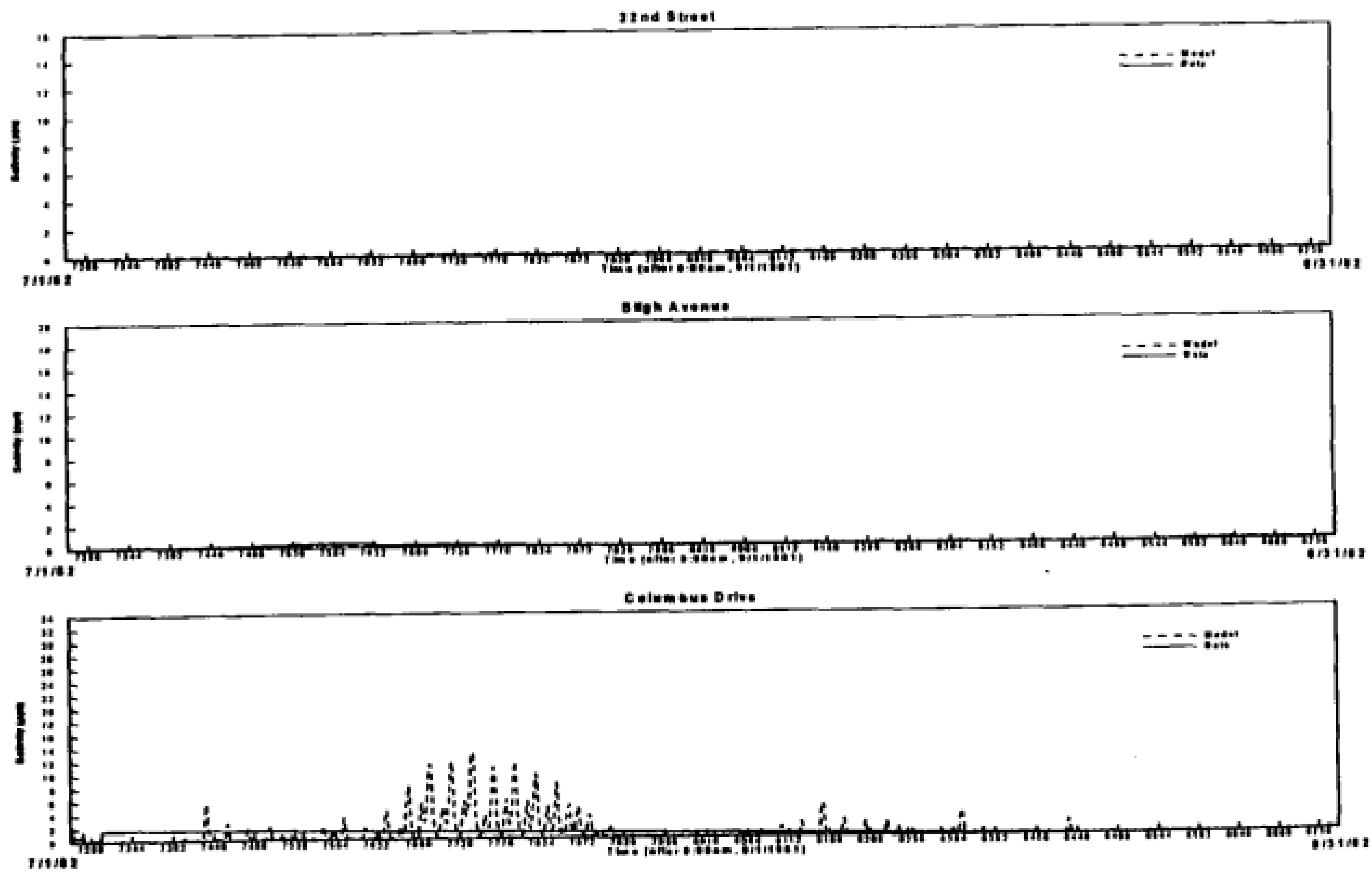


Figure B-12 Comparison of simulated and measured salinity in July and August 1982.

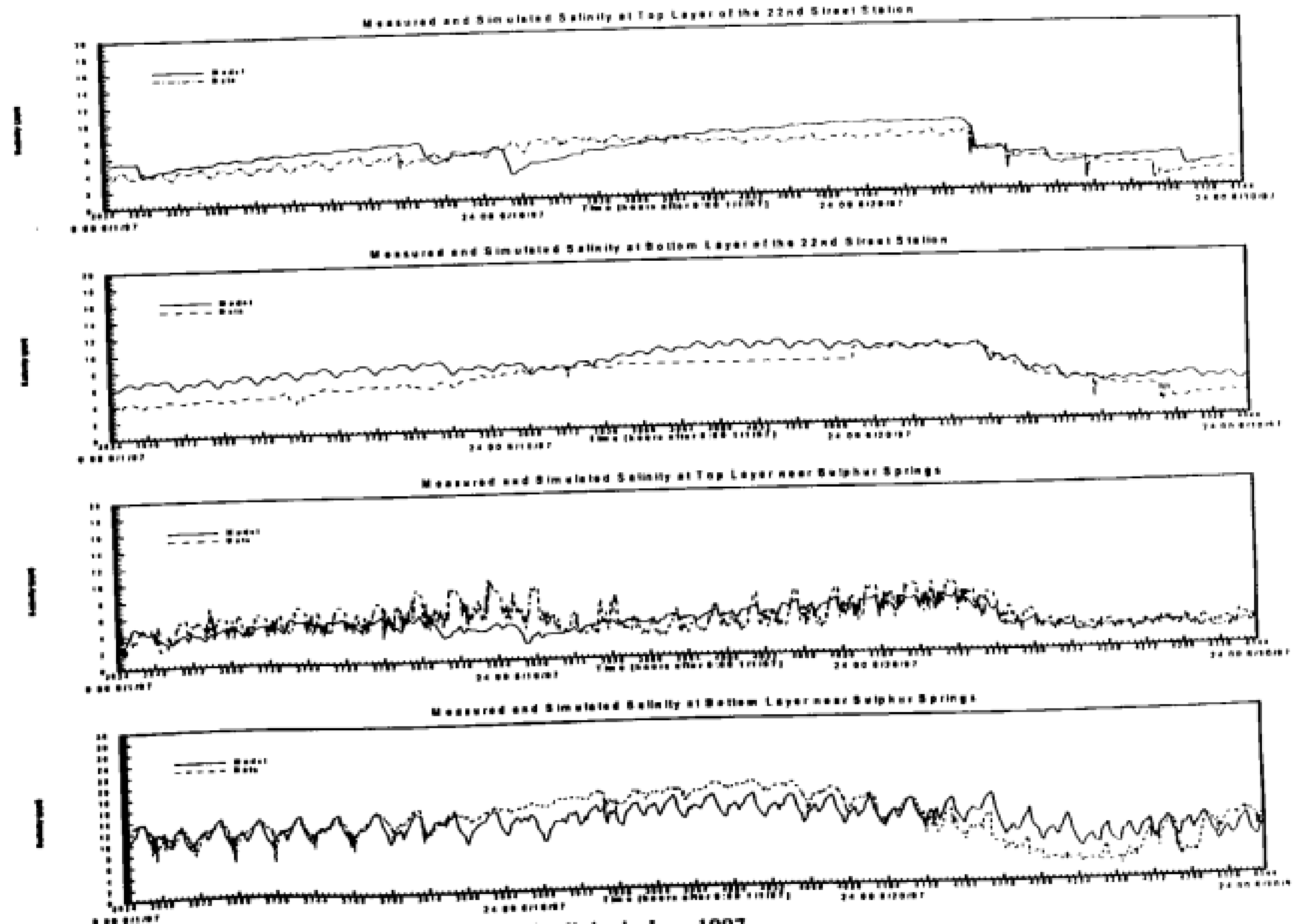


Figure B-13 Comparison of simulated and measured salinity in June 1997.

Appendix C New Model Results of the Scenario Runs --- Simulated Velocity and Salinity Distributions in the Lower Hillsborough River

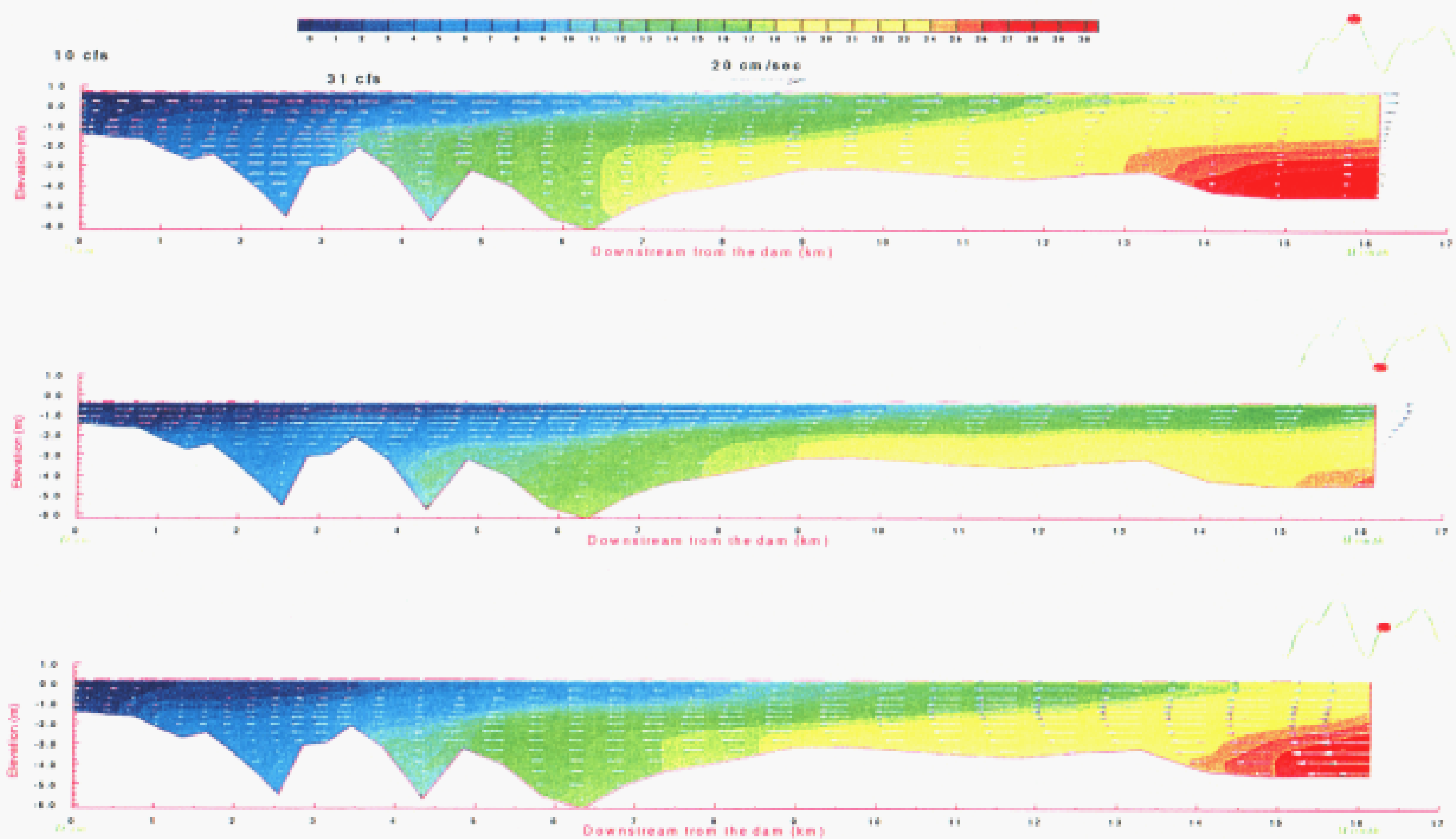


Figure C-1 Simulated velocity and salinity distributions at three tidal levels for one of the scenario runs.

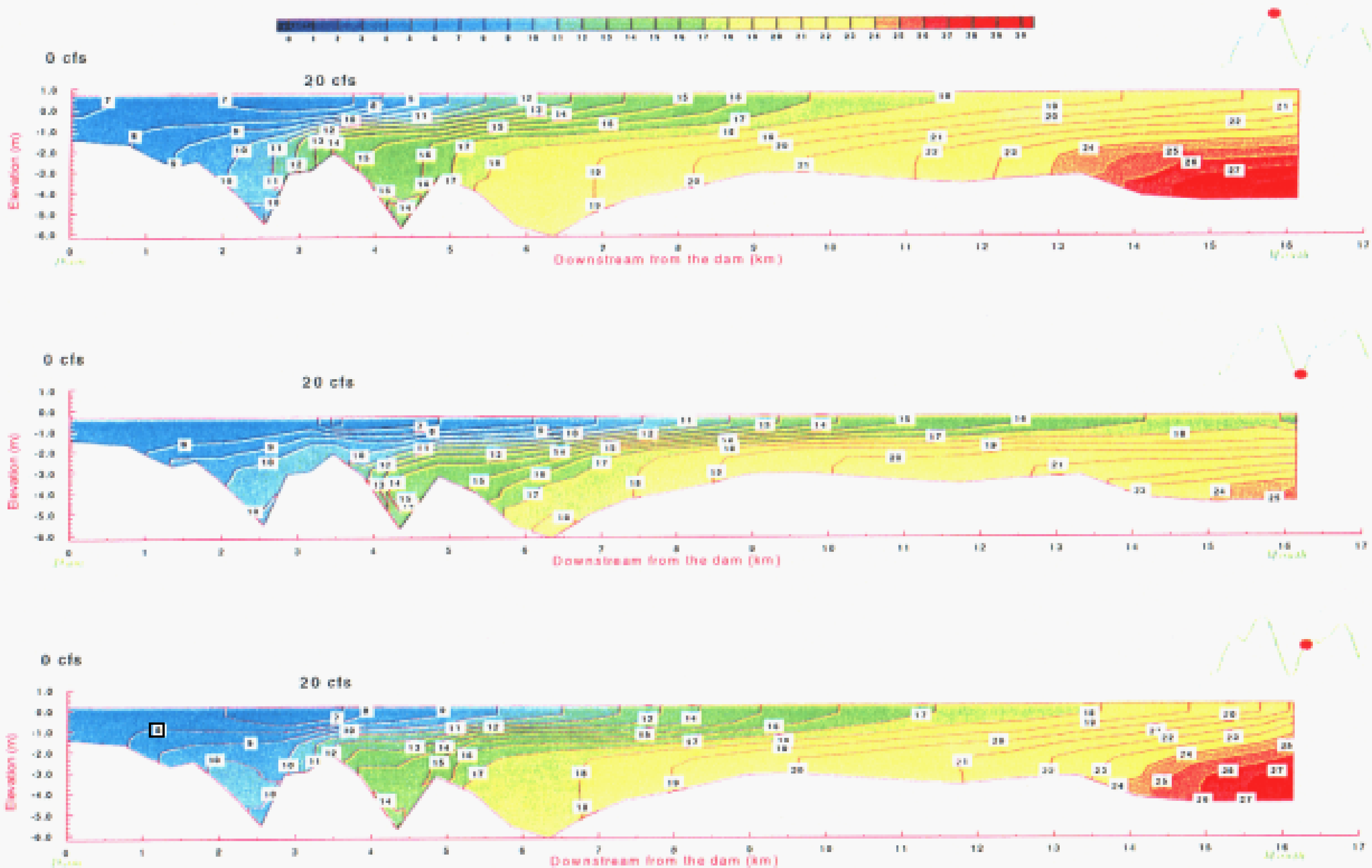


Figure C-2 Simulated salinity distributions for Case 1: 0 cfs released from the reservoir and 20 cfs spring flow.

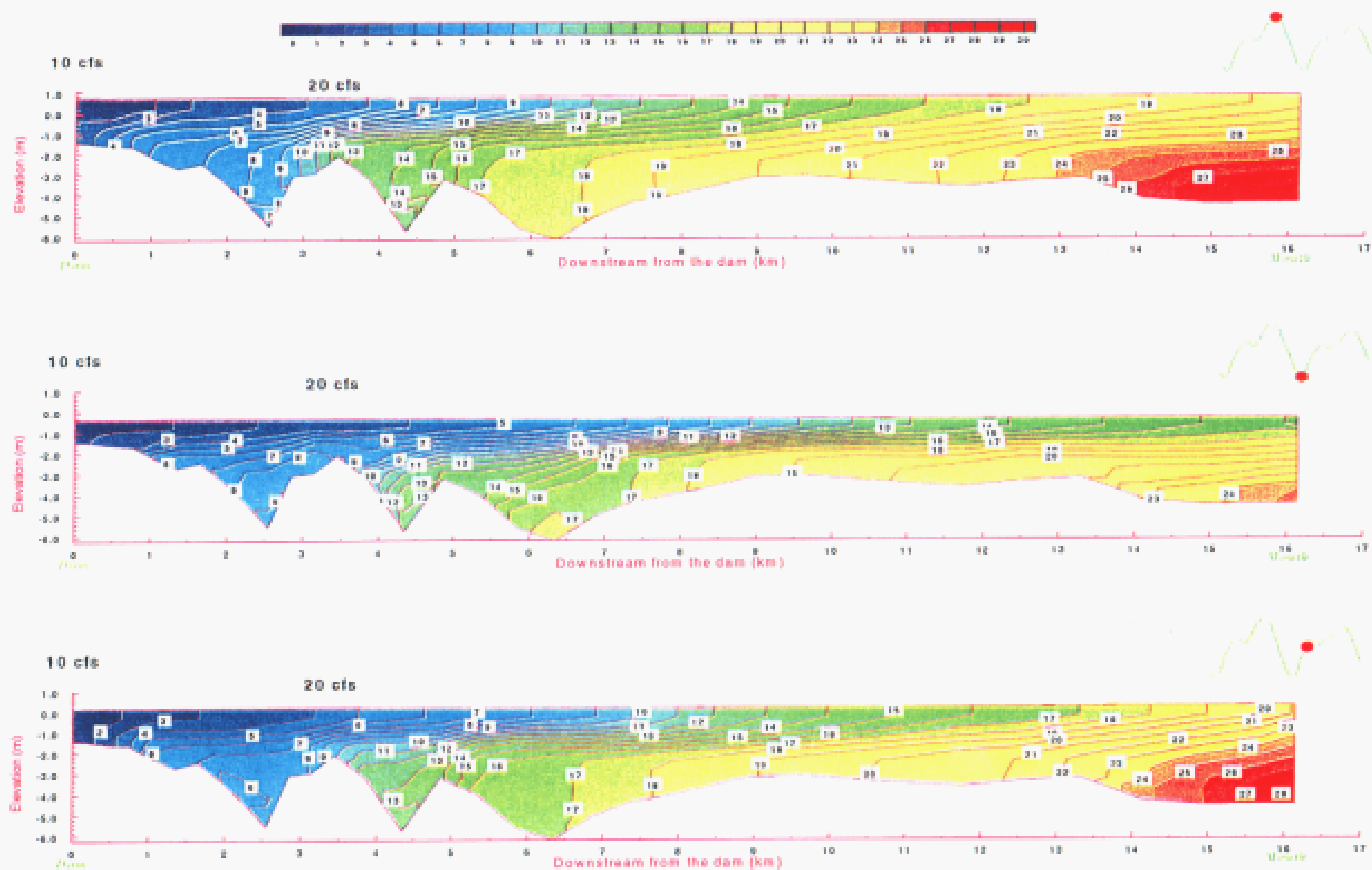


Figure C-3 Simulated salinity distributions for Case 2: 10 cfs released from the reservoir and 20 cfs spring flow.

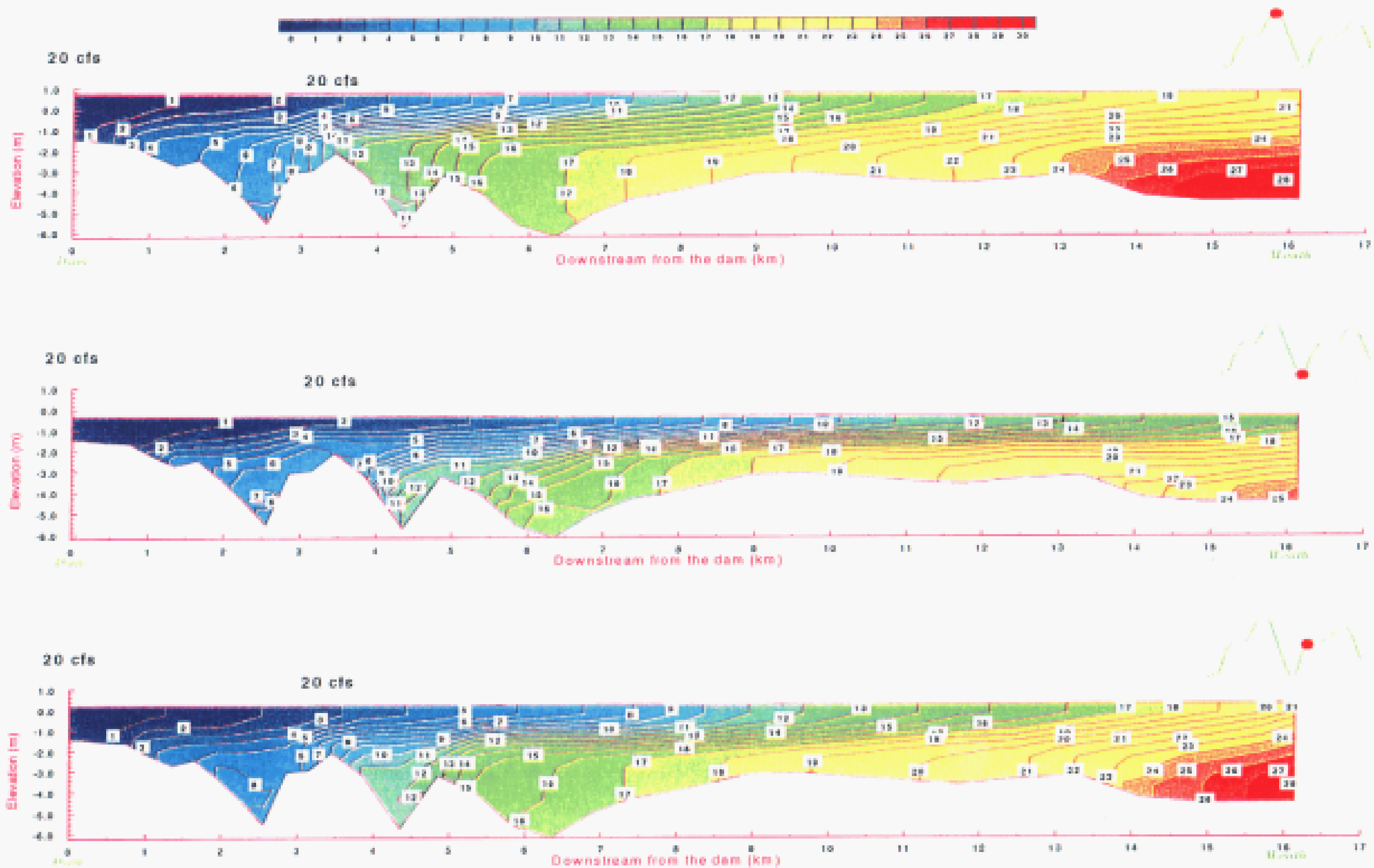


Figure C-4 Simulated salinity distributions for Case 3: 20 cfs released from the reservoir and 20 cfs spring flow.

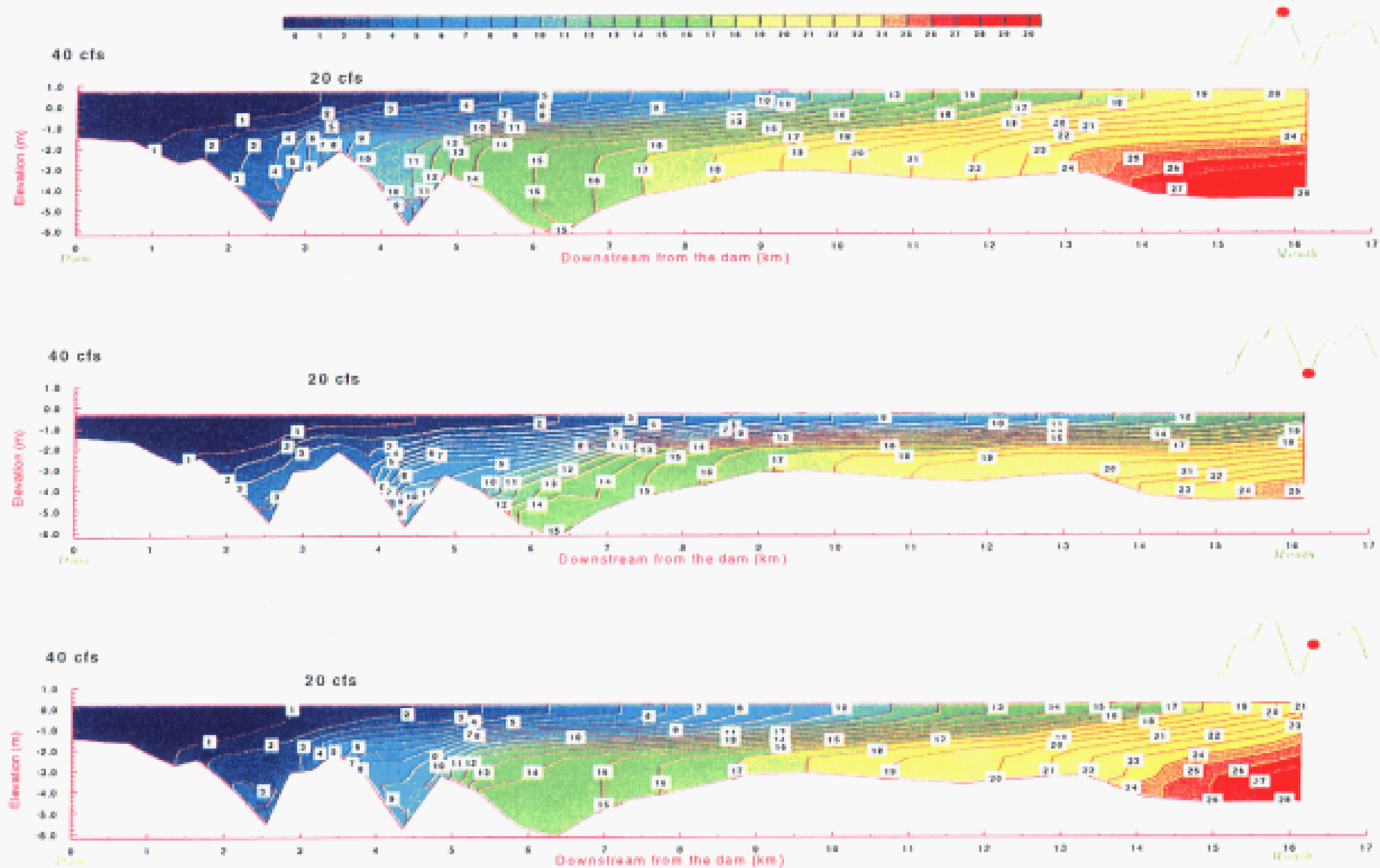


Figure C-5 Simulated salinity distributions for Case 4: 40 cfs released from the reservoir and 20 cfs spring flow.

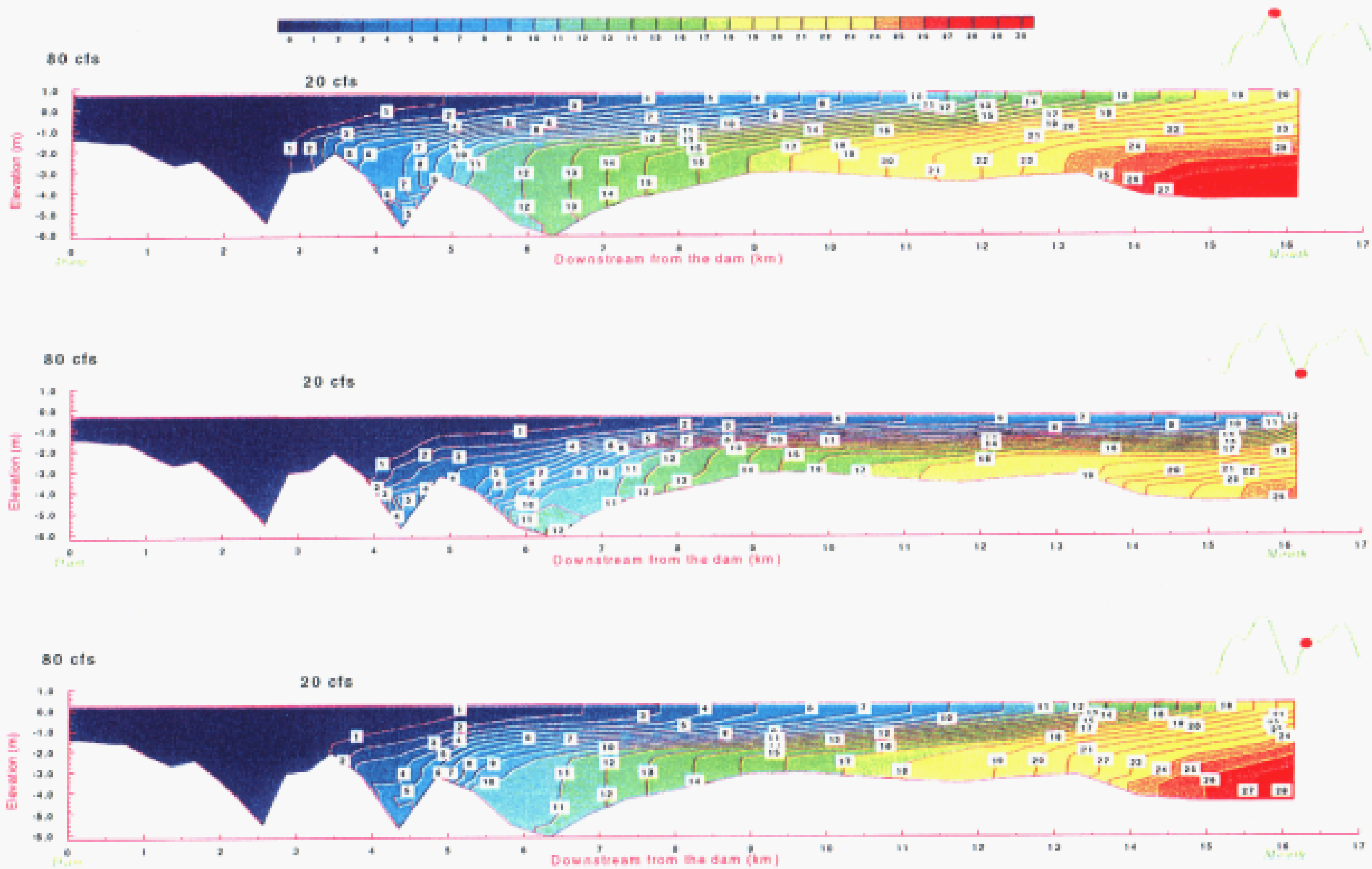


Figure C-6 Simulated salinity distributions for Case 5: 80 cfs released from the reservoir and 20 cfs spring flow.

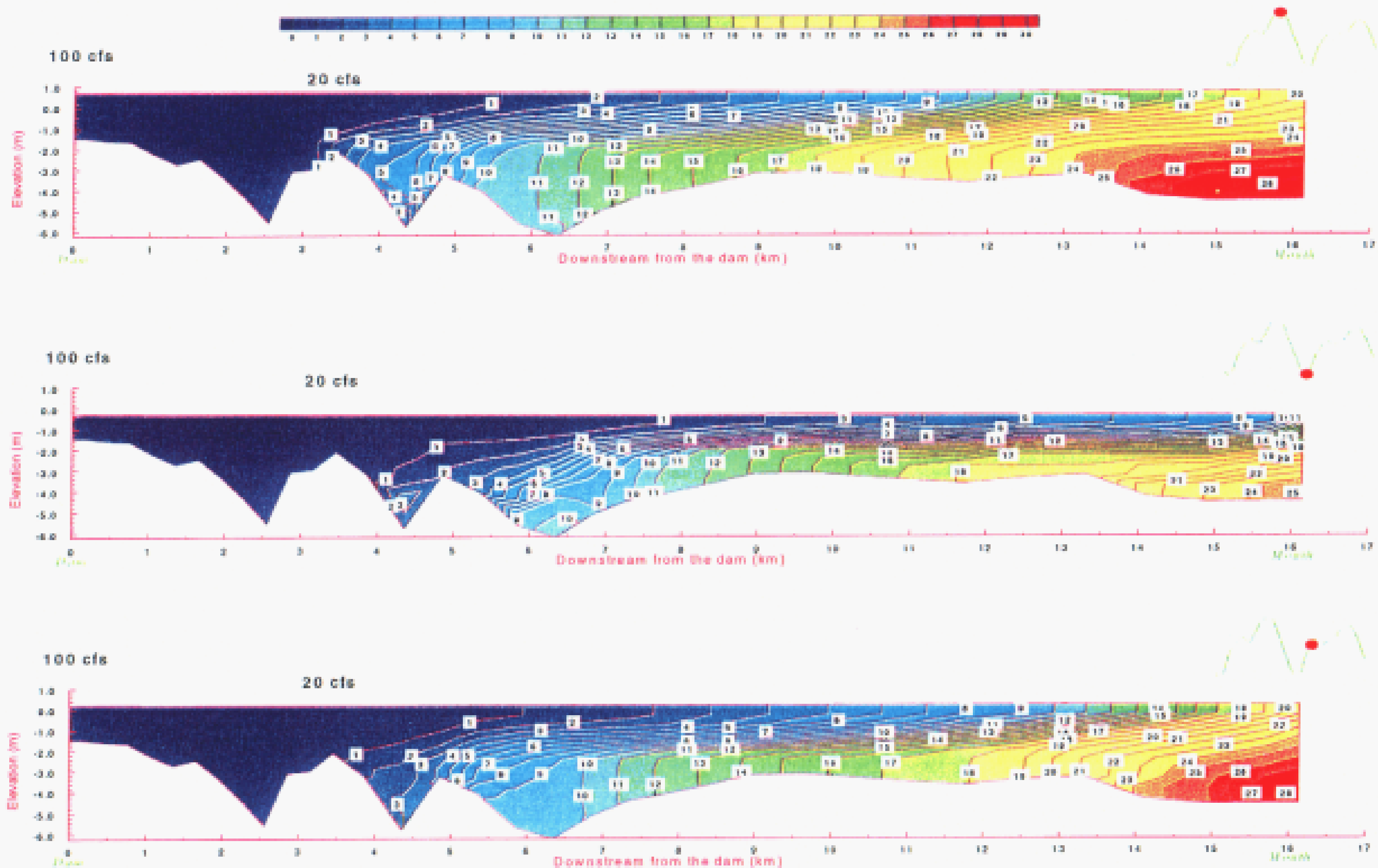


Figure C-7 Simulated salinity distributions for Case 6: 100 cfs released from the reservoir and 20 cfs spring flow.

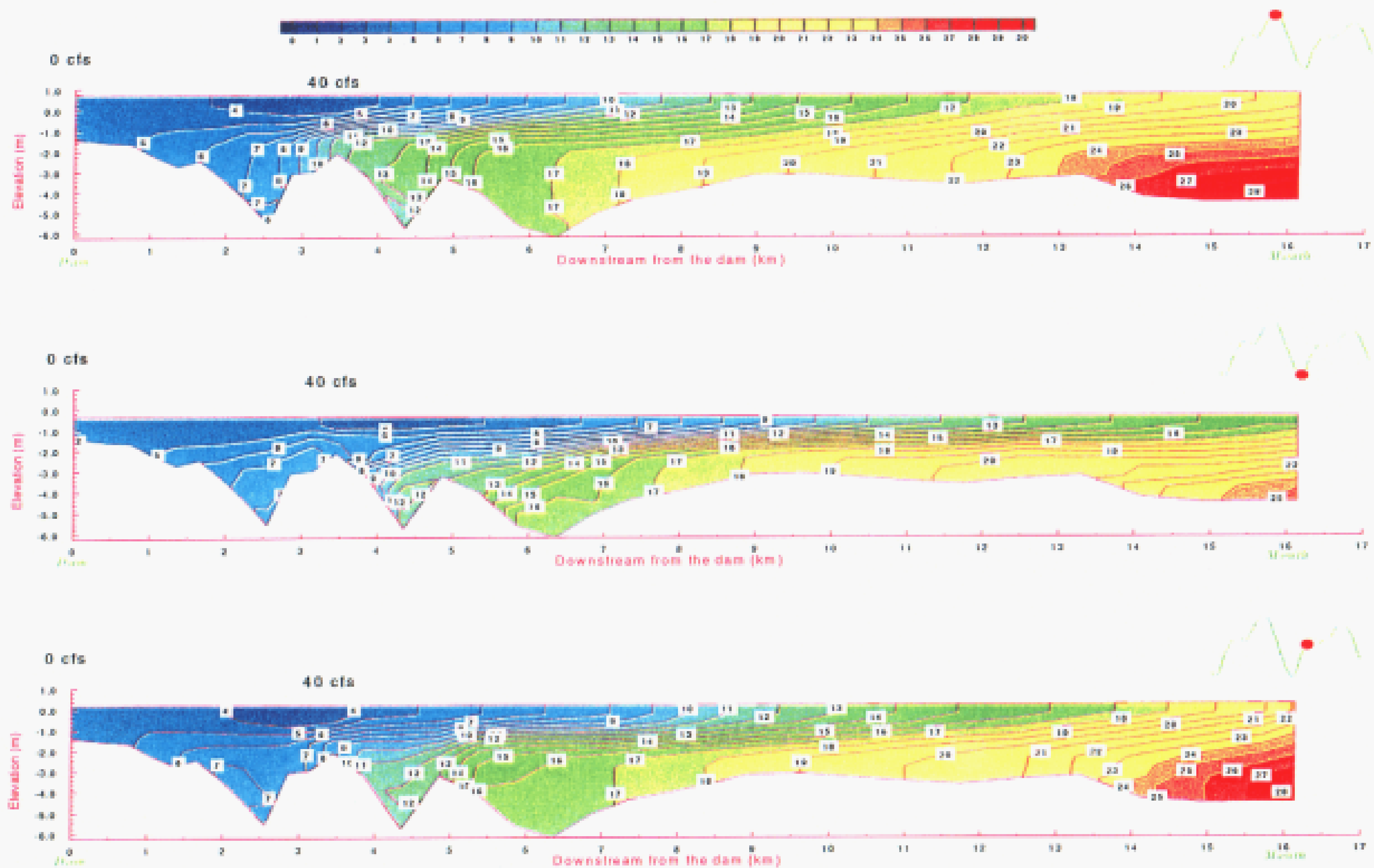


Figure C-8 Simulated salinity distributions for Case 7: 0 cfs released from the reservoir and 40 cfs spring flow.

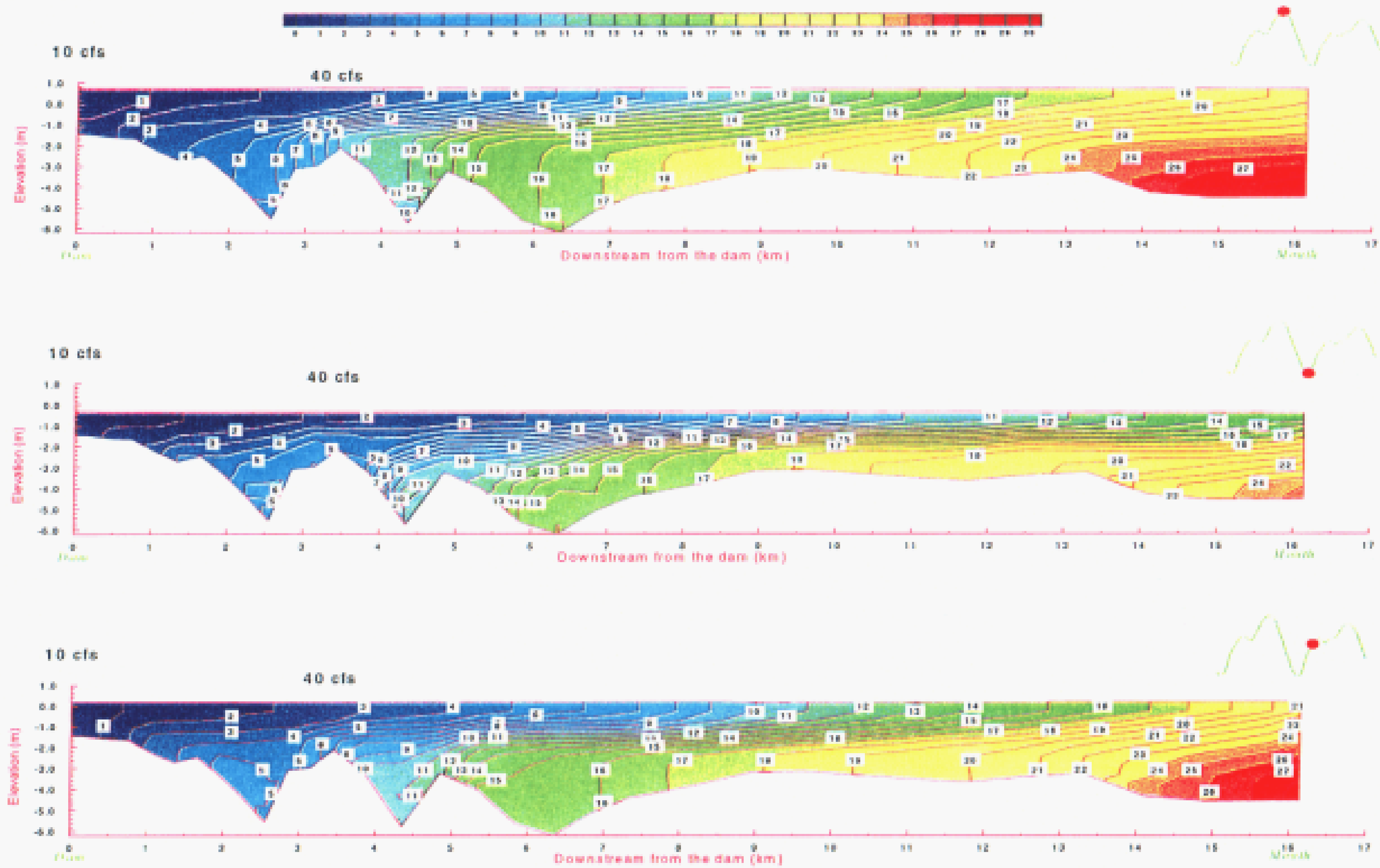


Figure C-9 Simulated salinity distributions for Case 8: 10 cfs released from the reservoir and 40 cfs spring flow.

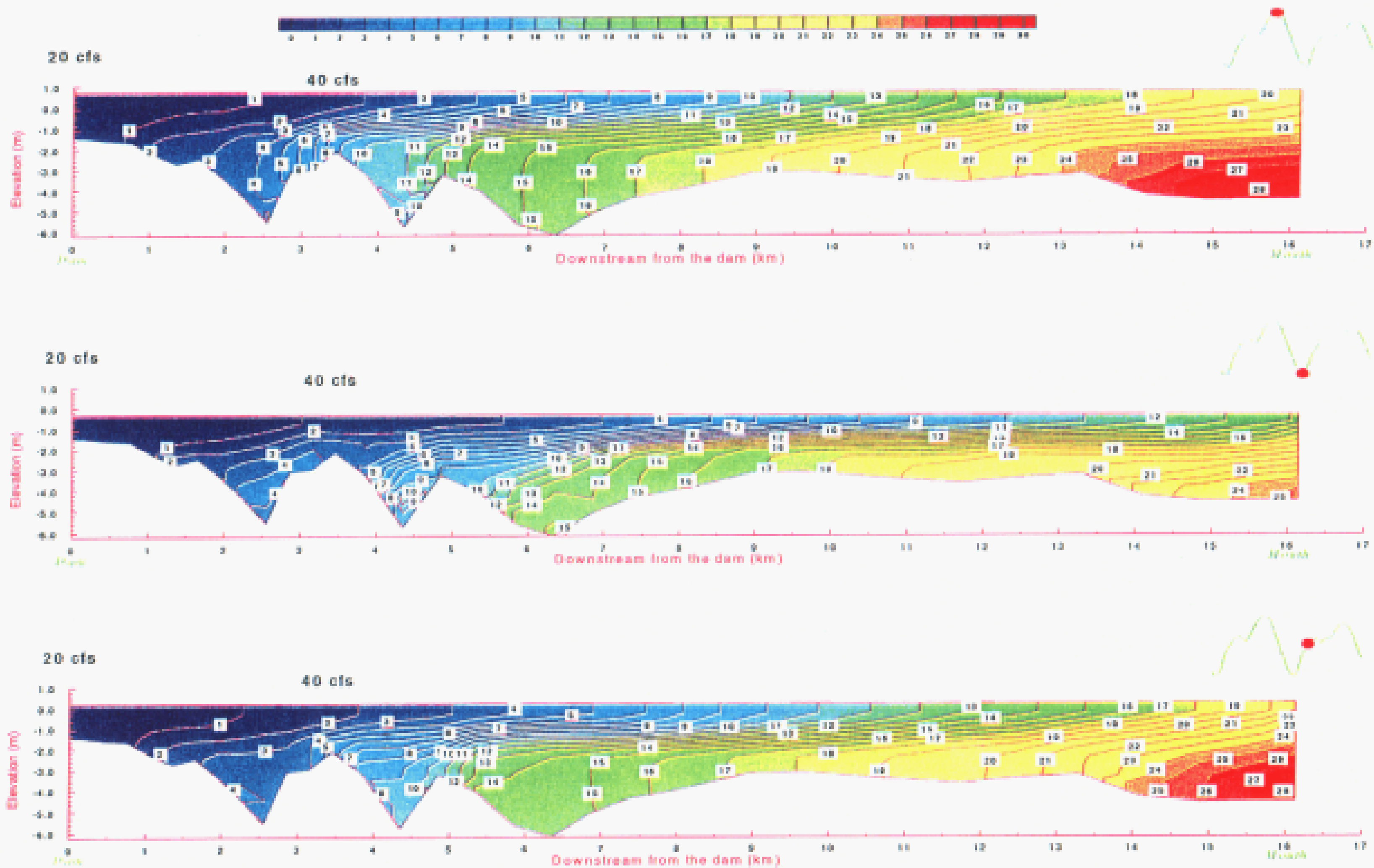


Figure C-10 Simulated salinity distributions for Case 9: 20 cfs released from the reservoir and 40 cfs spring flow.

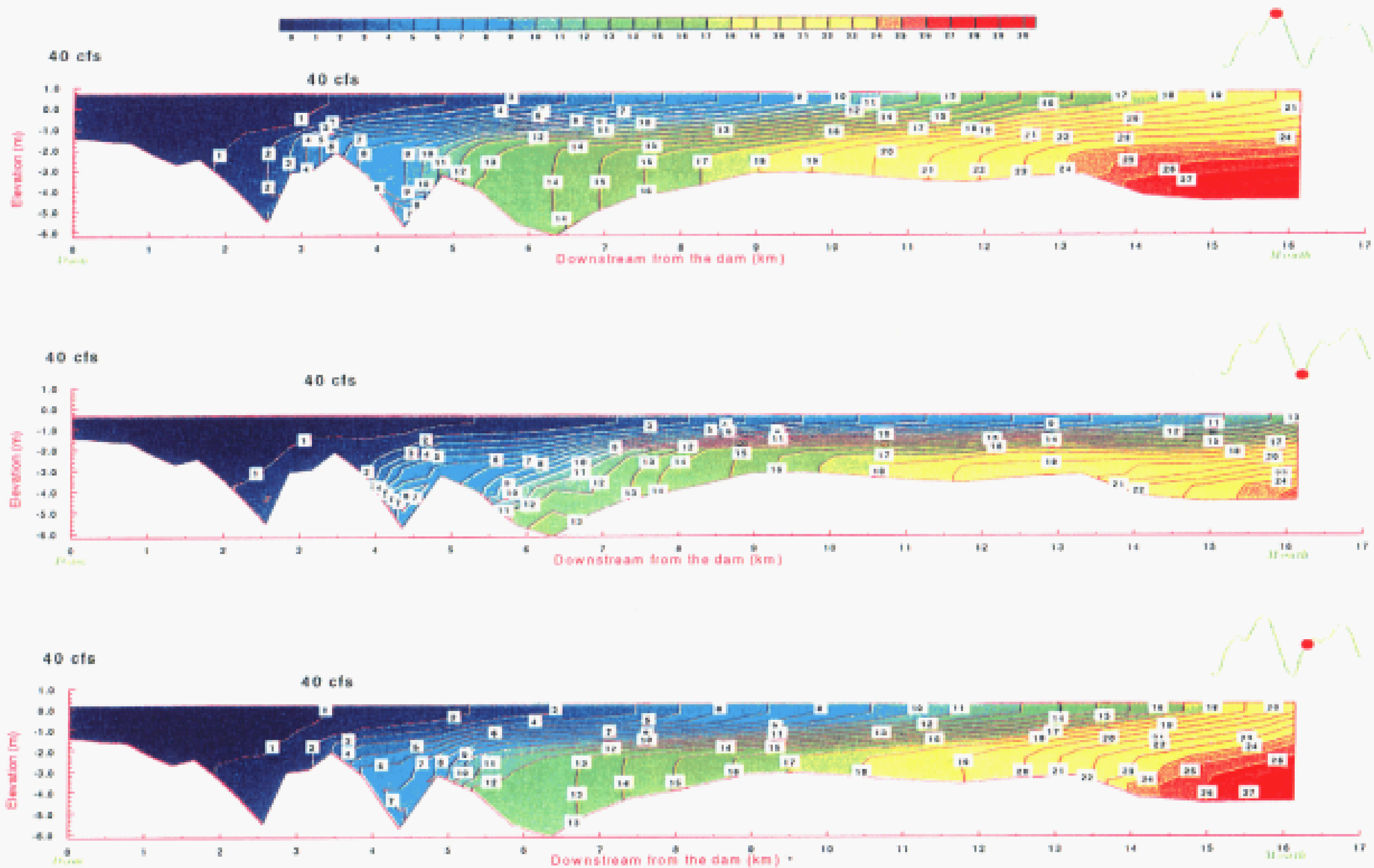


Figure C-11 Simulated salinity distributions for Case 10: 40 cfs released from the reservoir and 40 cfs spring flow.

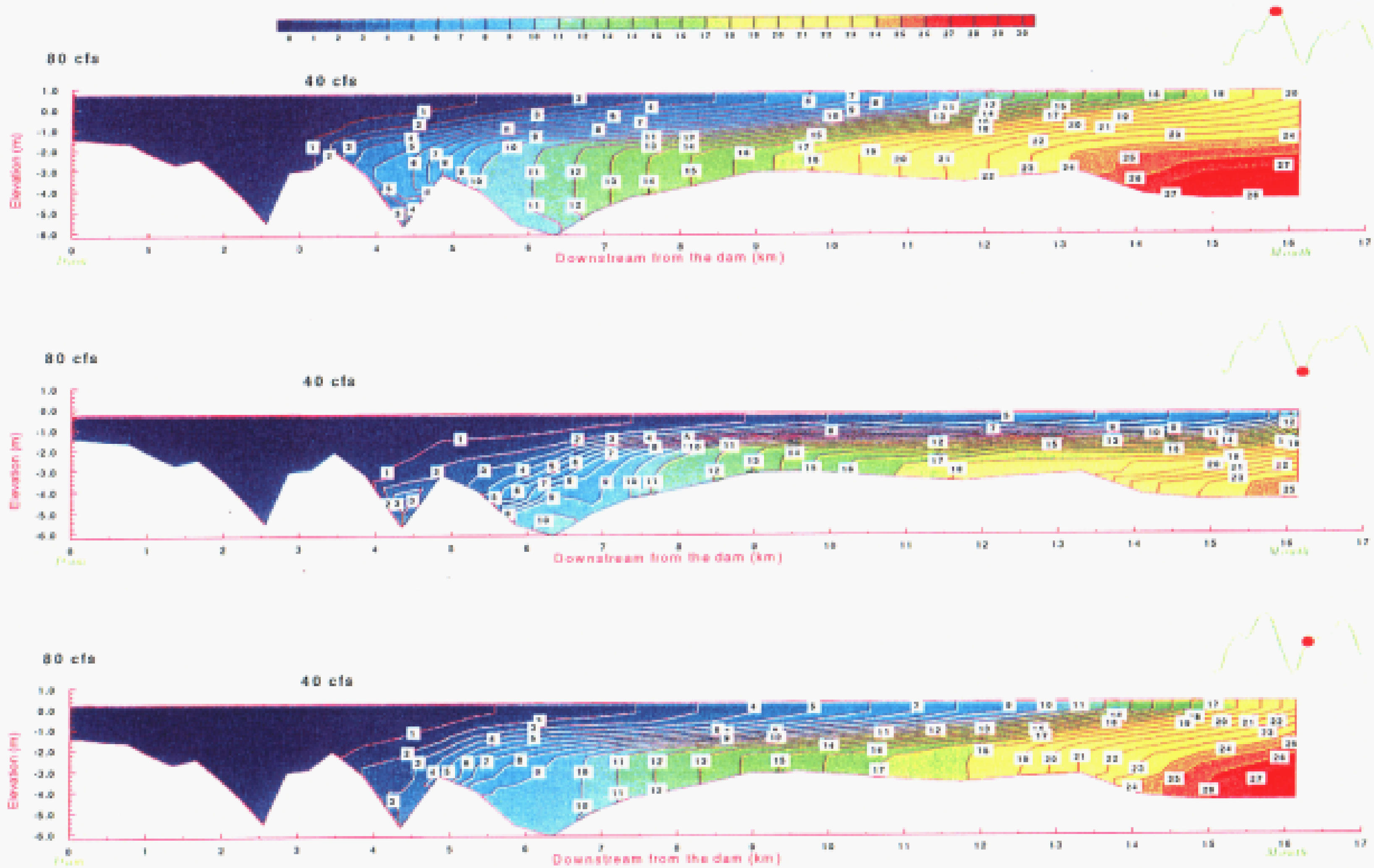


Figure C-12 Simulated salinity distributions for Case 11: 80 cfs released from the reservoir and 40 cfs spring flow.

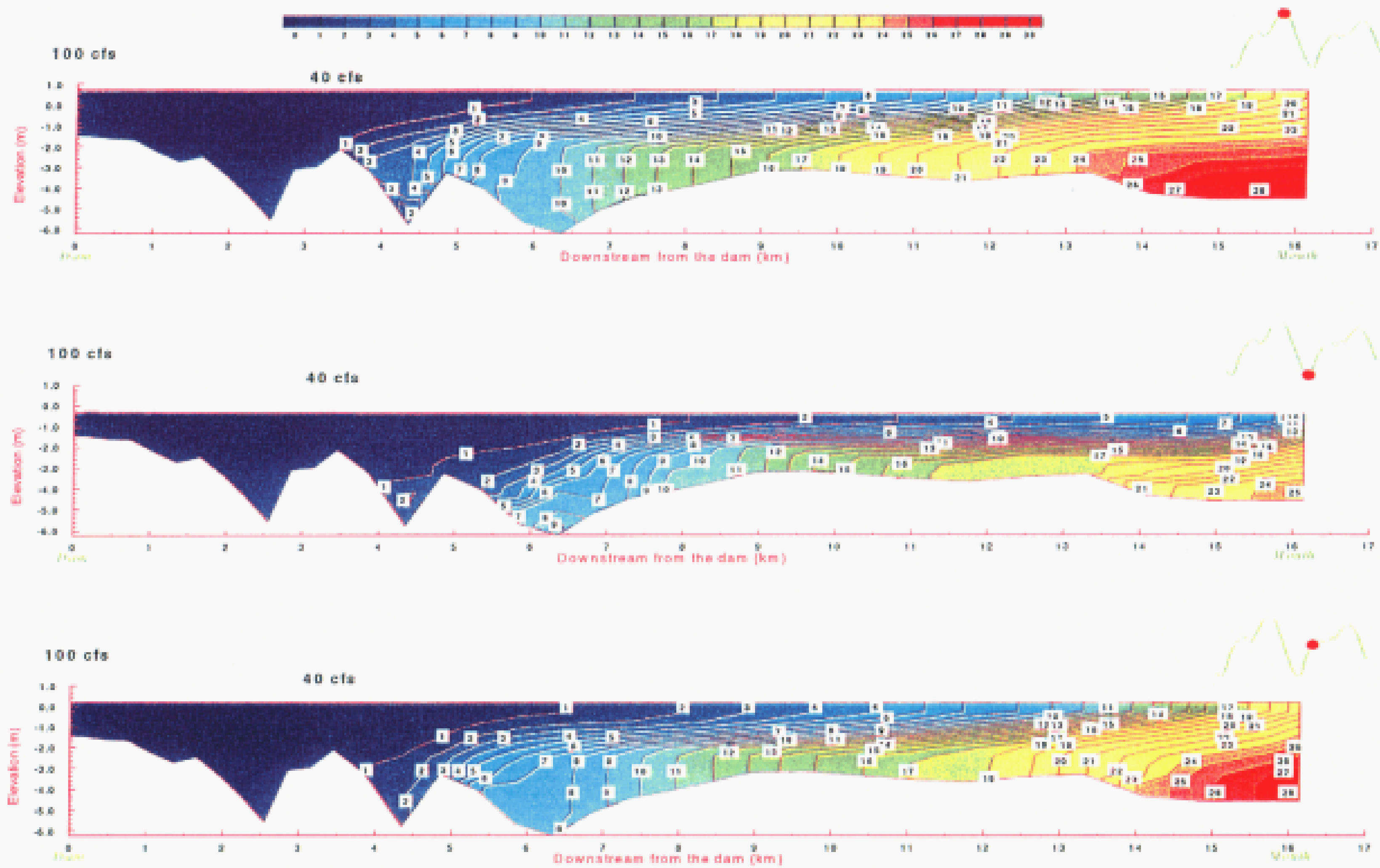


Figure C-13 Simulated salinity distributions for Case 12: 100 cfs released from the reservoir and 40 cfs spring flow.

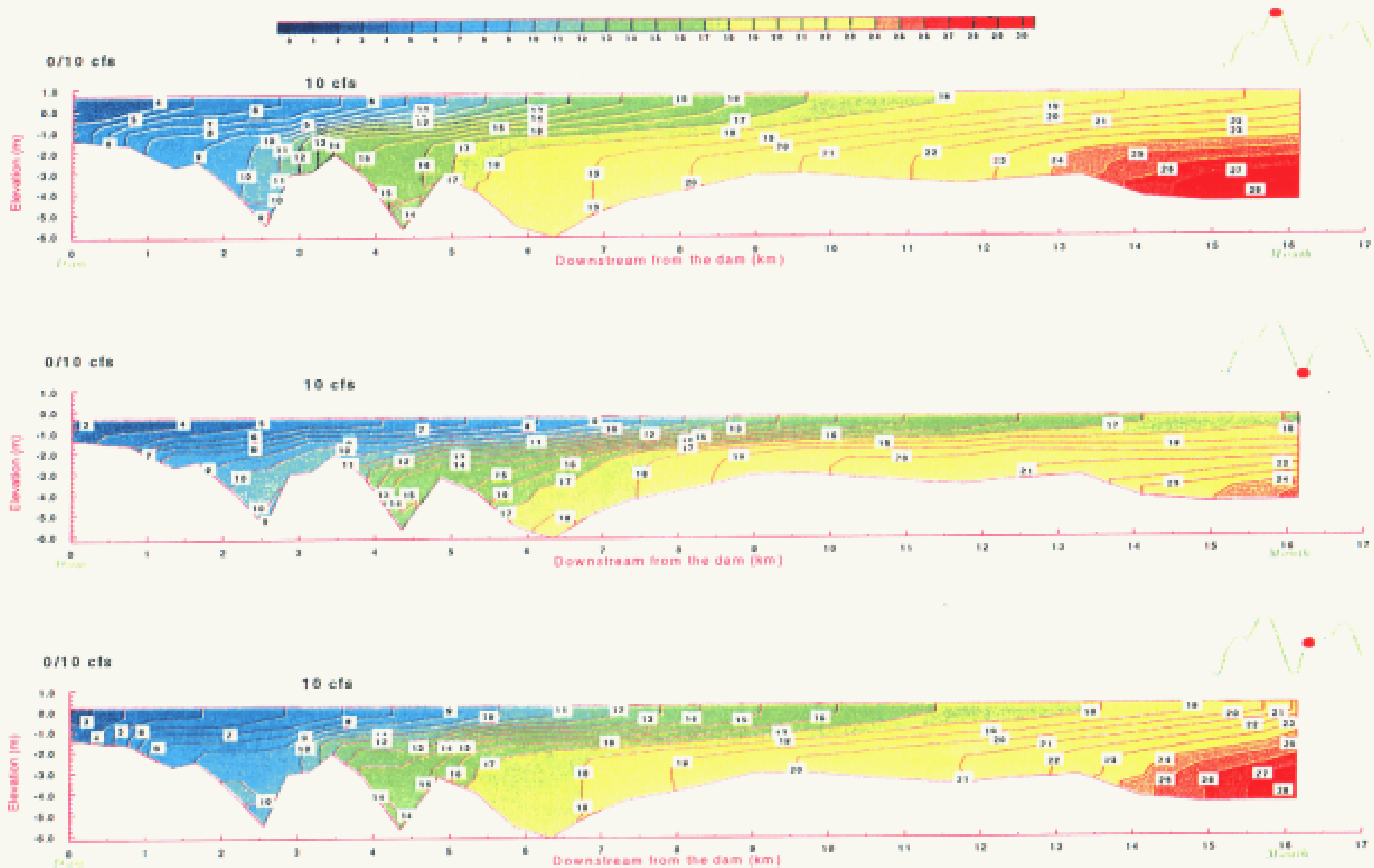


Figure C-14 Simulated salinity distributions for Case 13: 0 cfs released from the reservoir, 10 cfs spring flow routed to the dam, and 10 cfs spring flow remained

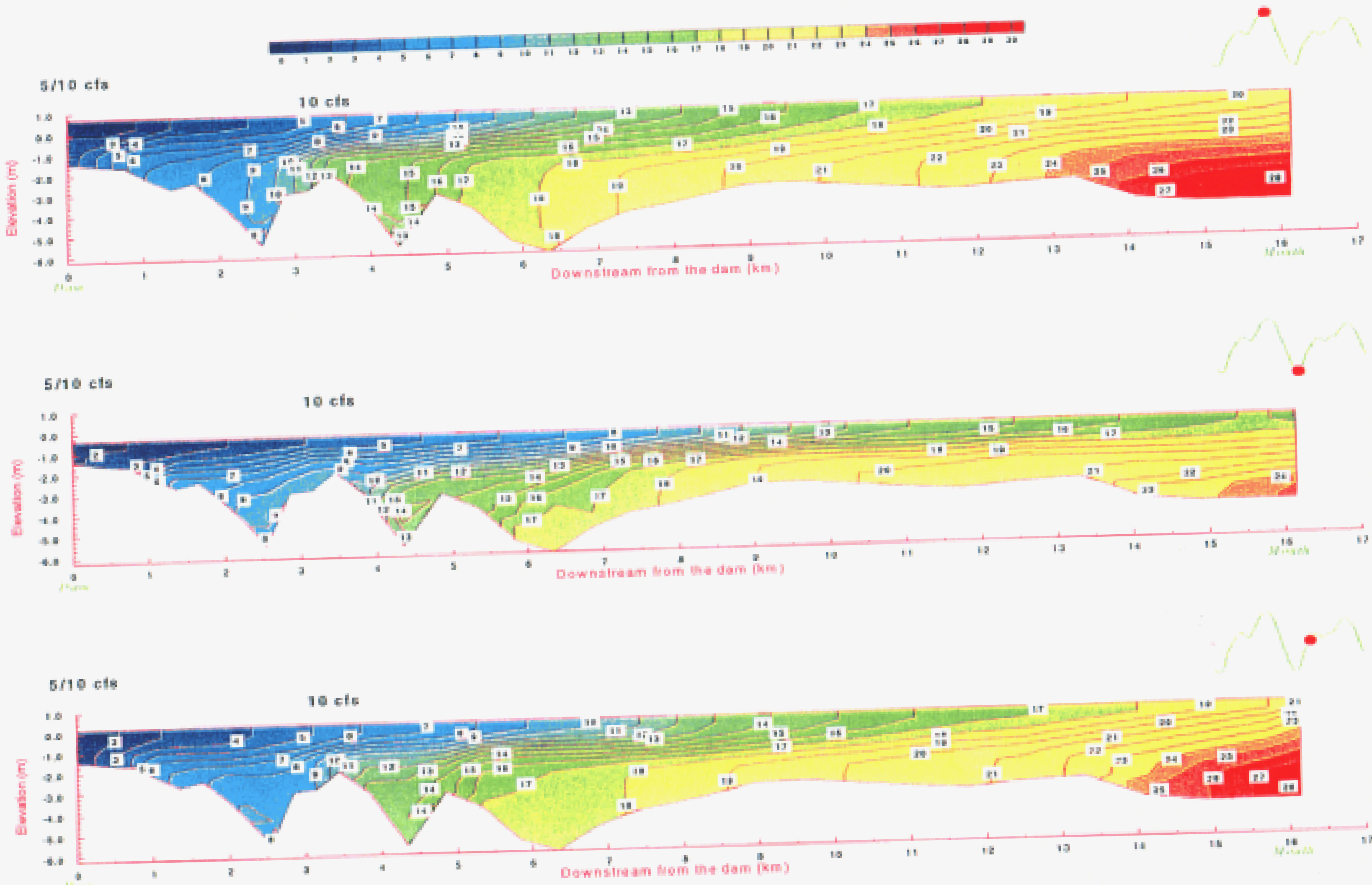


Figure C-15 Simulated salinity distributions for Case 14: 5 cfs released from the reservoir, 10 cfs spring flow routed to the dam, and 10 cfs spring flow remained

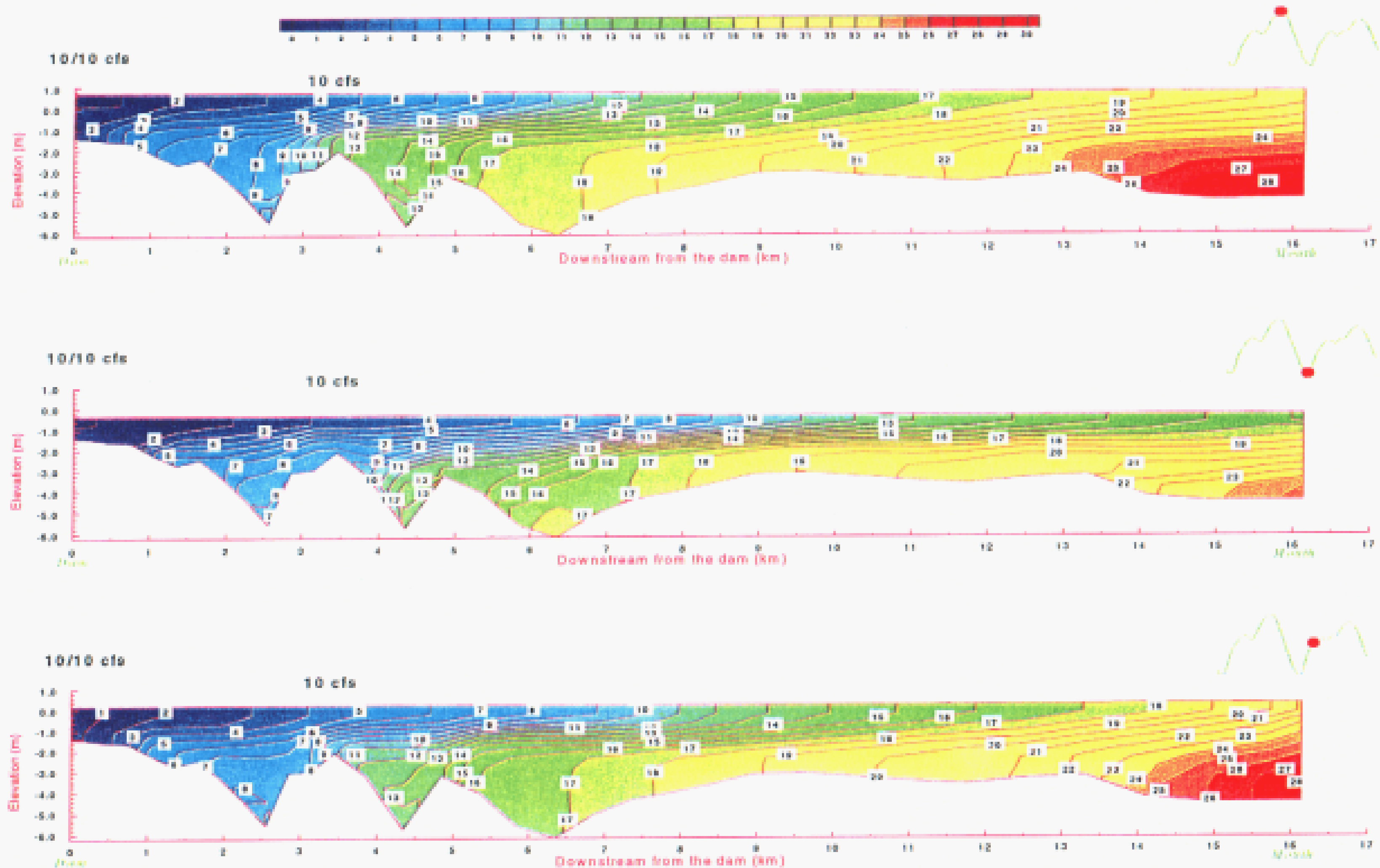


Figure C-16 Simulated salinity distributions for Case 15: 10 cfs released from the reservoir, 10 cfs spring flow routed to the dam, and 10 cfs spring flow remained

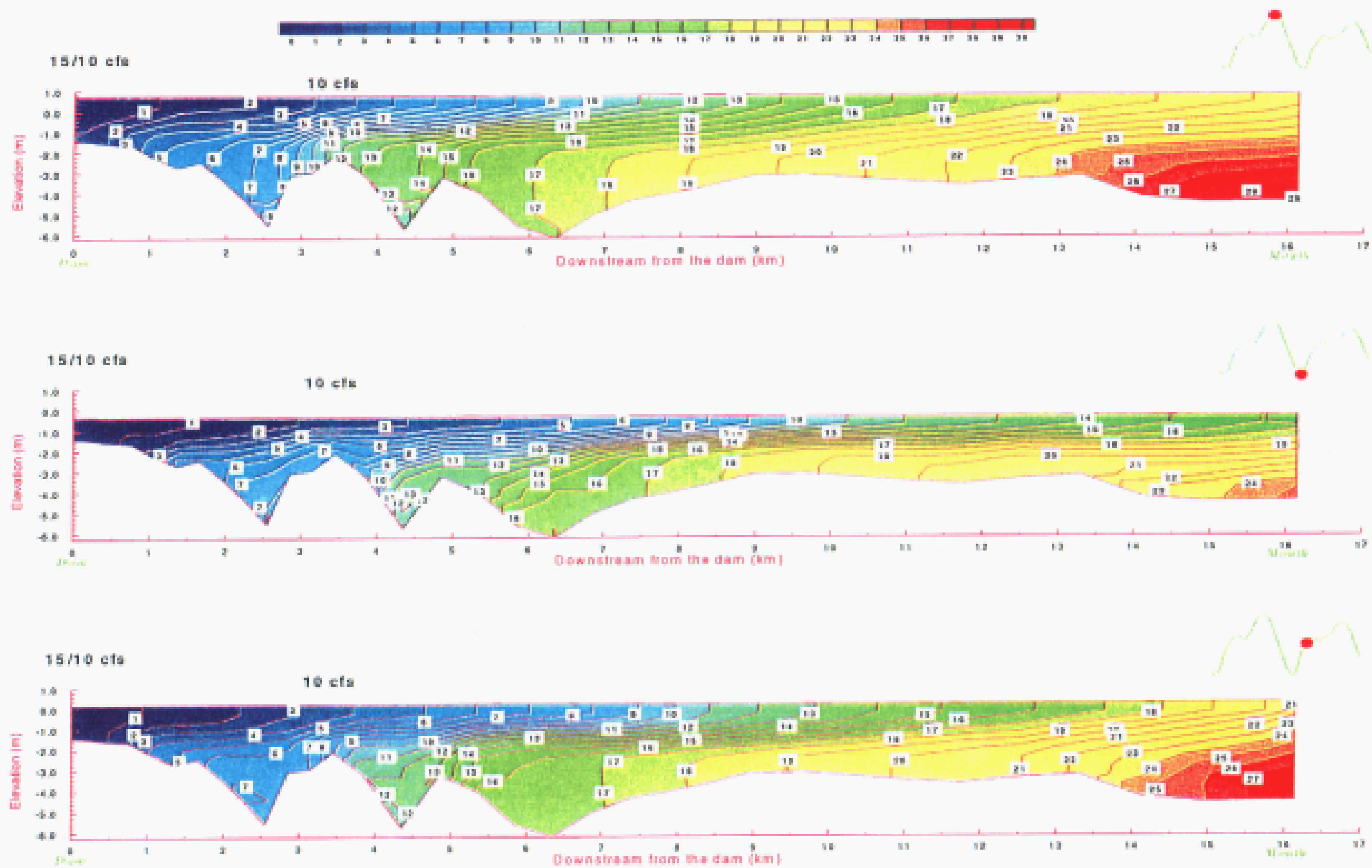


Figure C-17 Simulated salinity distributions for Case 16: 15 cfs released from the reservoir, 10 cfs spring flow routed to the dam, and 10 cfs spring flow remained

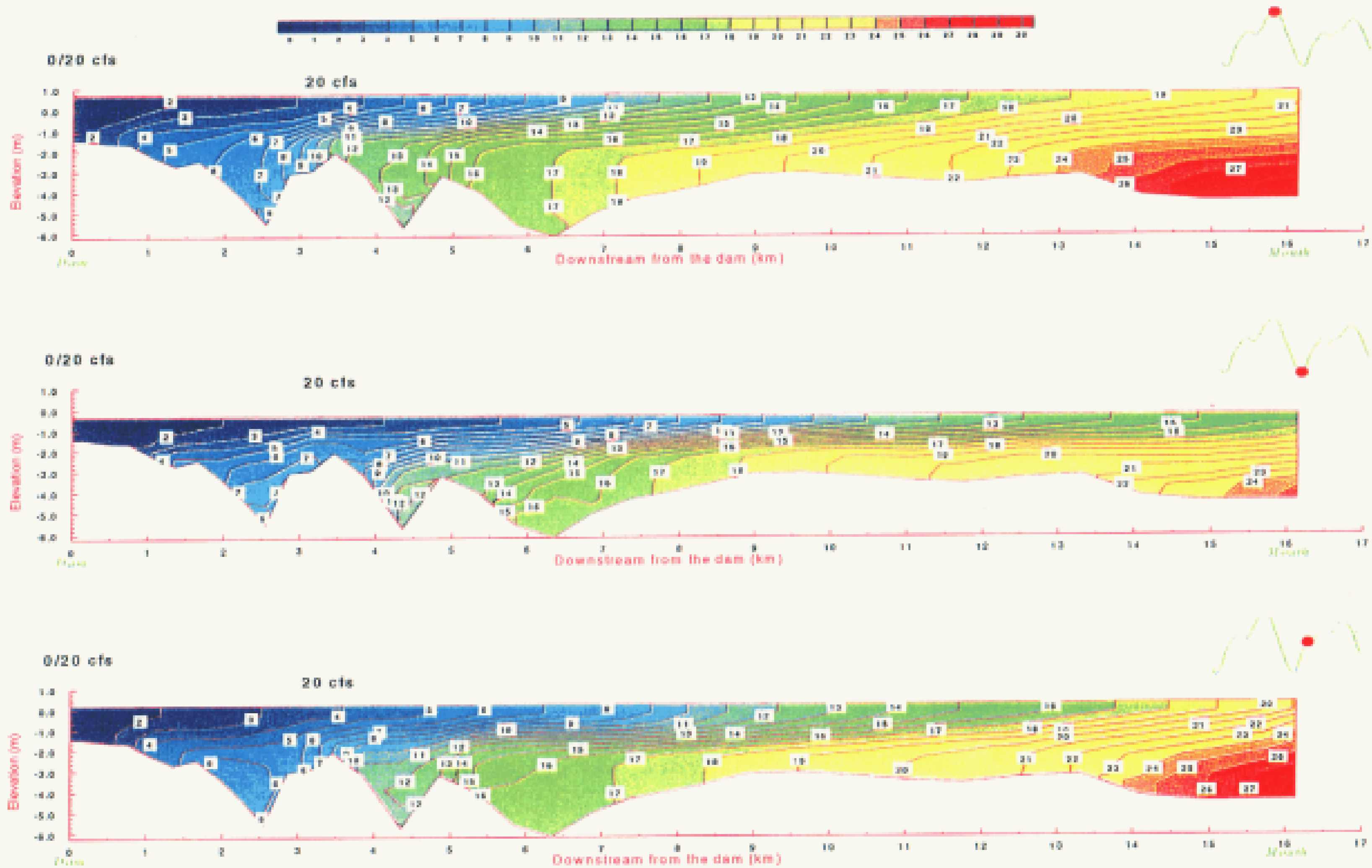


Figure C-18 Simulated salinity distributions for Case 17: 0 cfs released from the reservoir, 20 cfs spring flow routed to the dam, and 20 cfs spring remained.

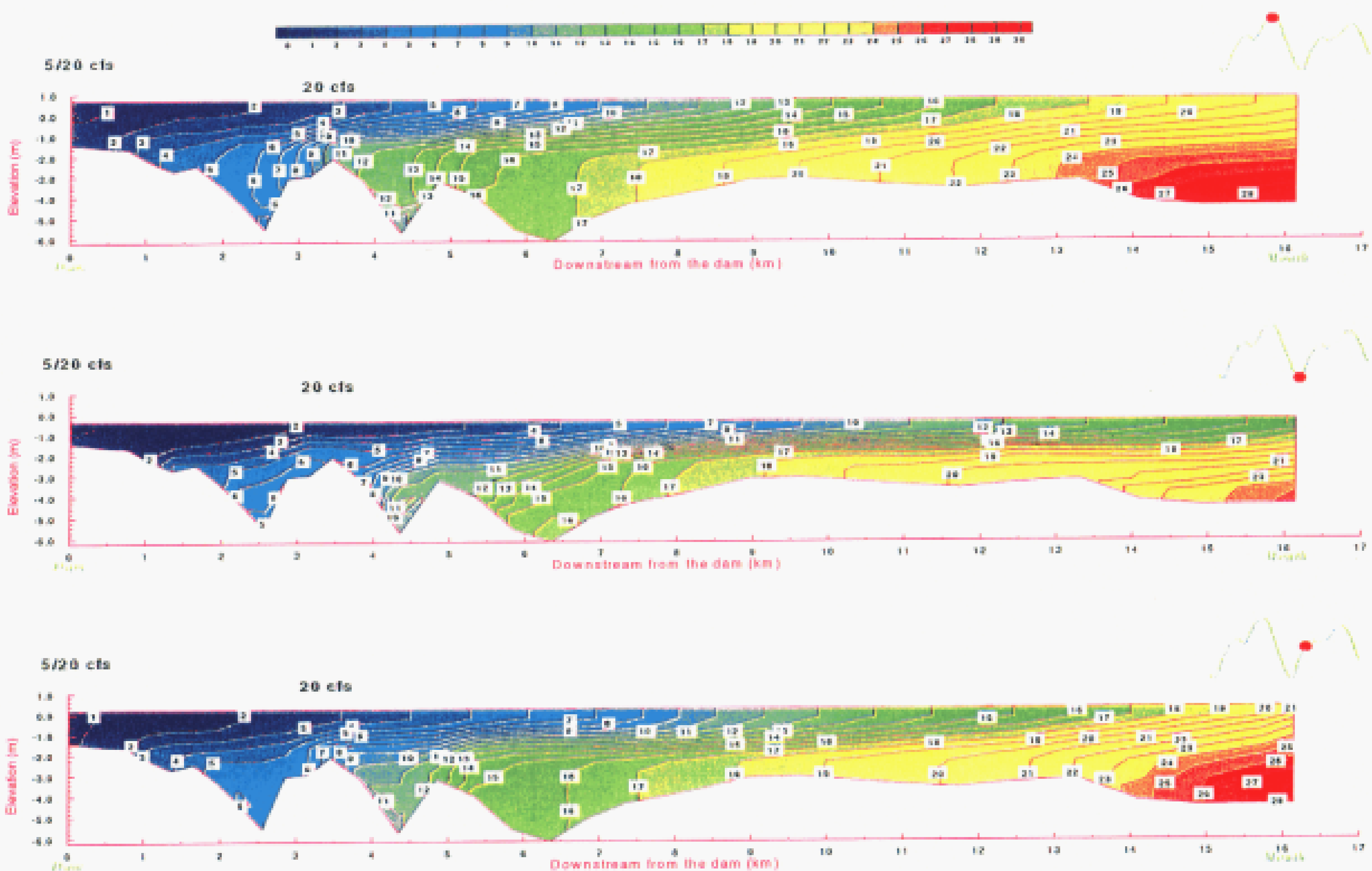


Figure C-19 Simulated salinity distributions for Case 18: 5 cfs released from the reservoir, 20 cfs spring flow routed to the dam, and 20 cfs spring remained.

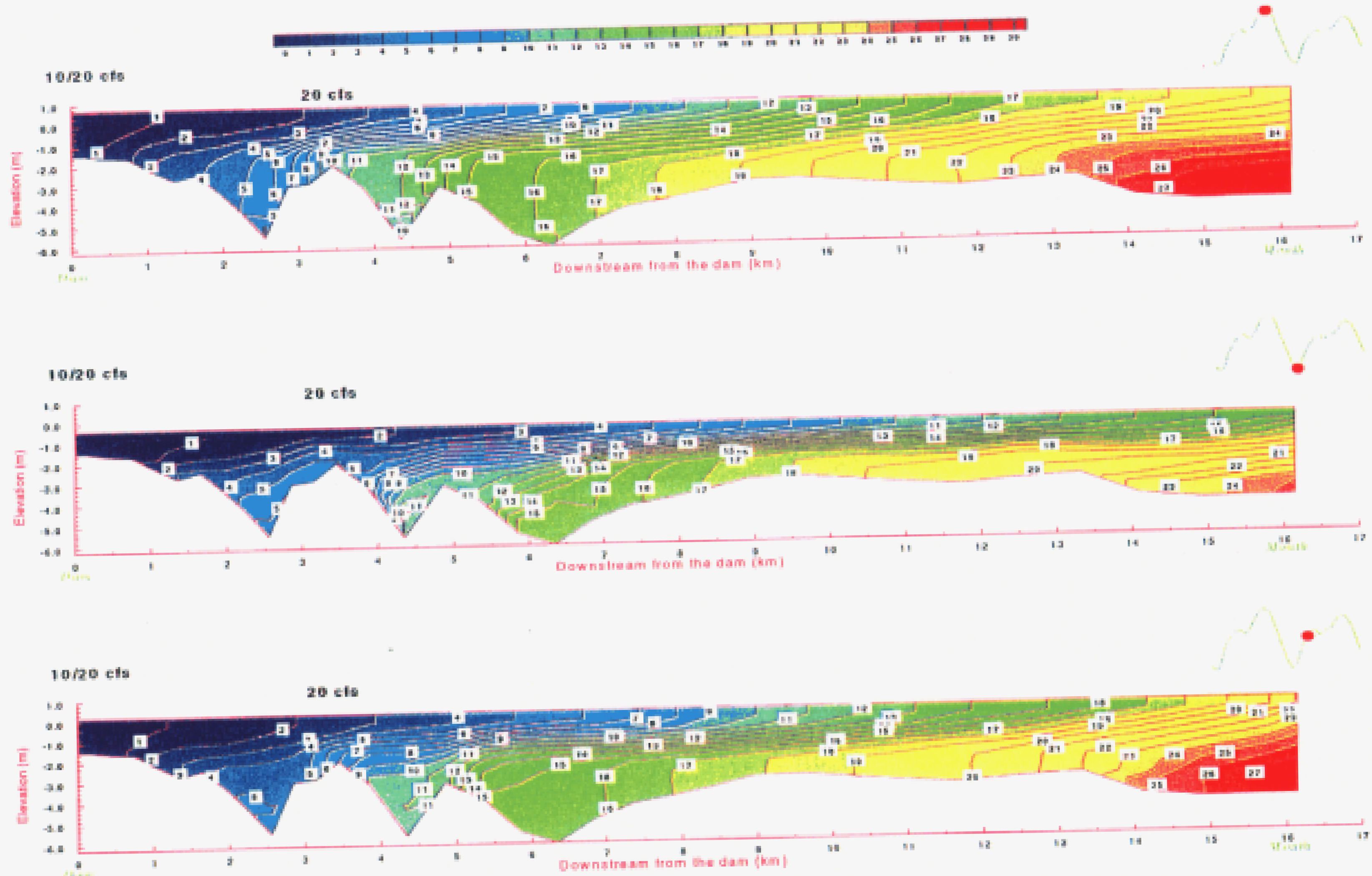


Figure C-20 Simulated salinity distributions for Case 19: 10 cfs released from the reservoir, 20 cfs spring flow routed to the dam, and 20 cfs spring remained.

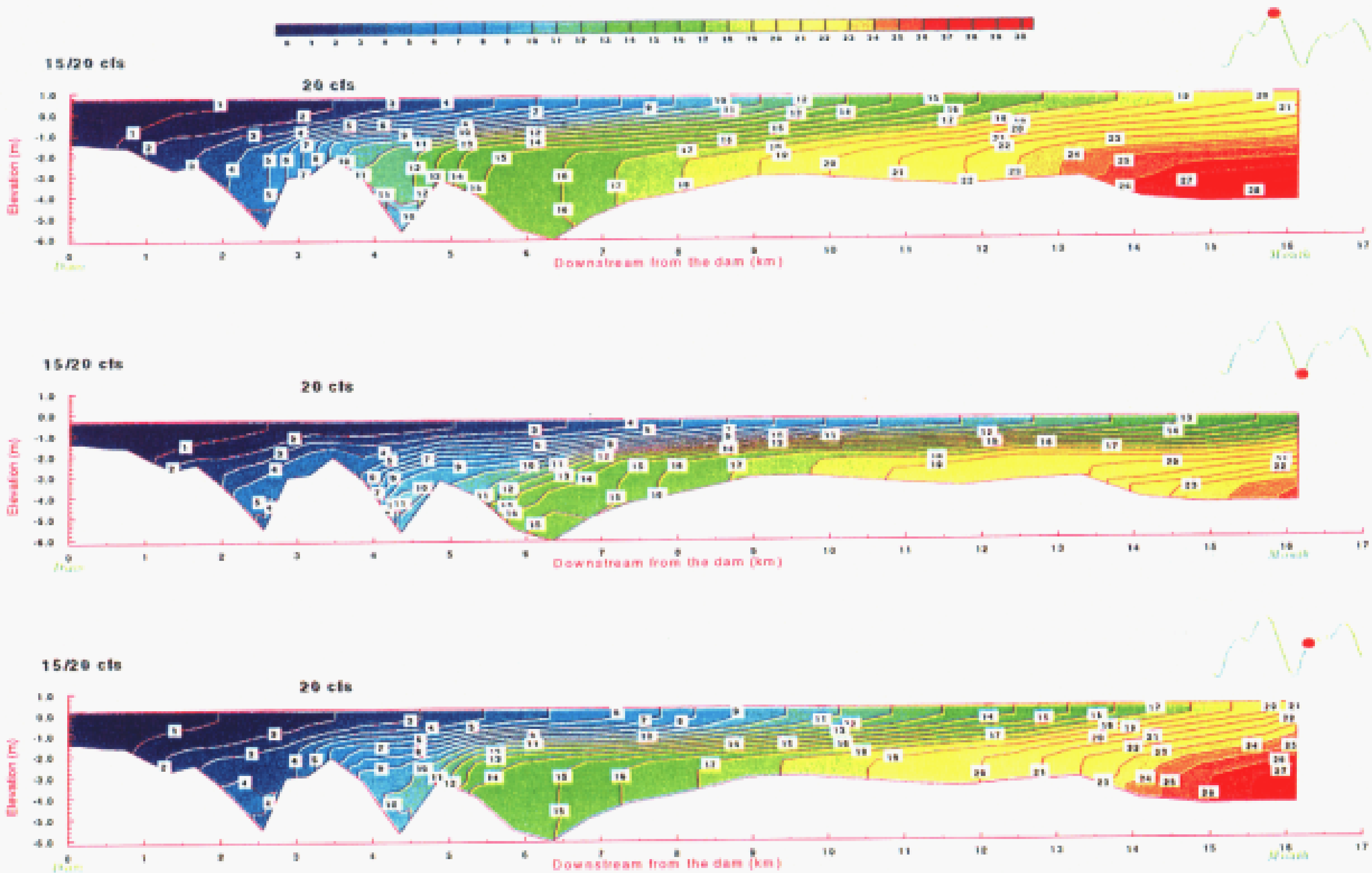


Figure C-21 Simulated salinity distributions for Case 20: 15 cfs released from the reservoir, 20 cfs spring flow routed to the dam, and 20 cfs spring remained.

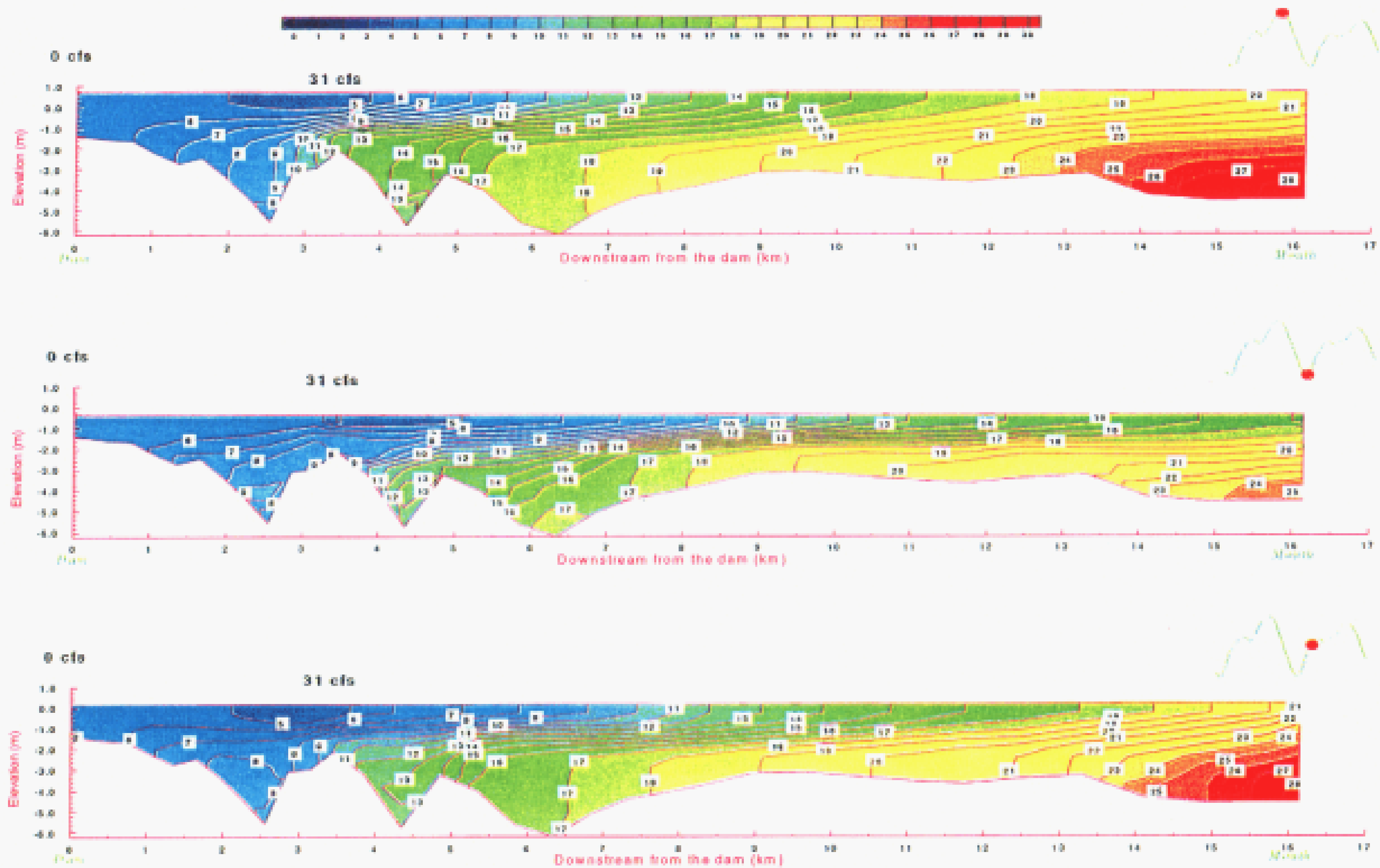


Figure C-22 Simulated salinity distributions for Case 21: 0 cfs released from the reservoir and 31 cfs spring flow.

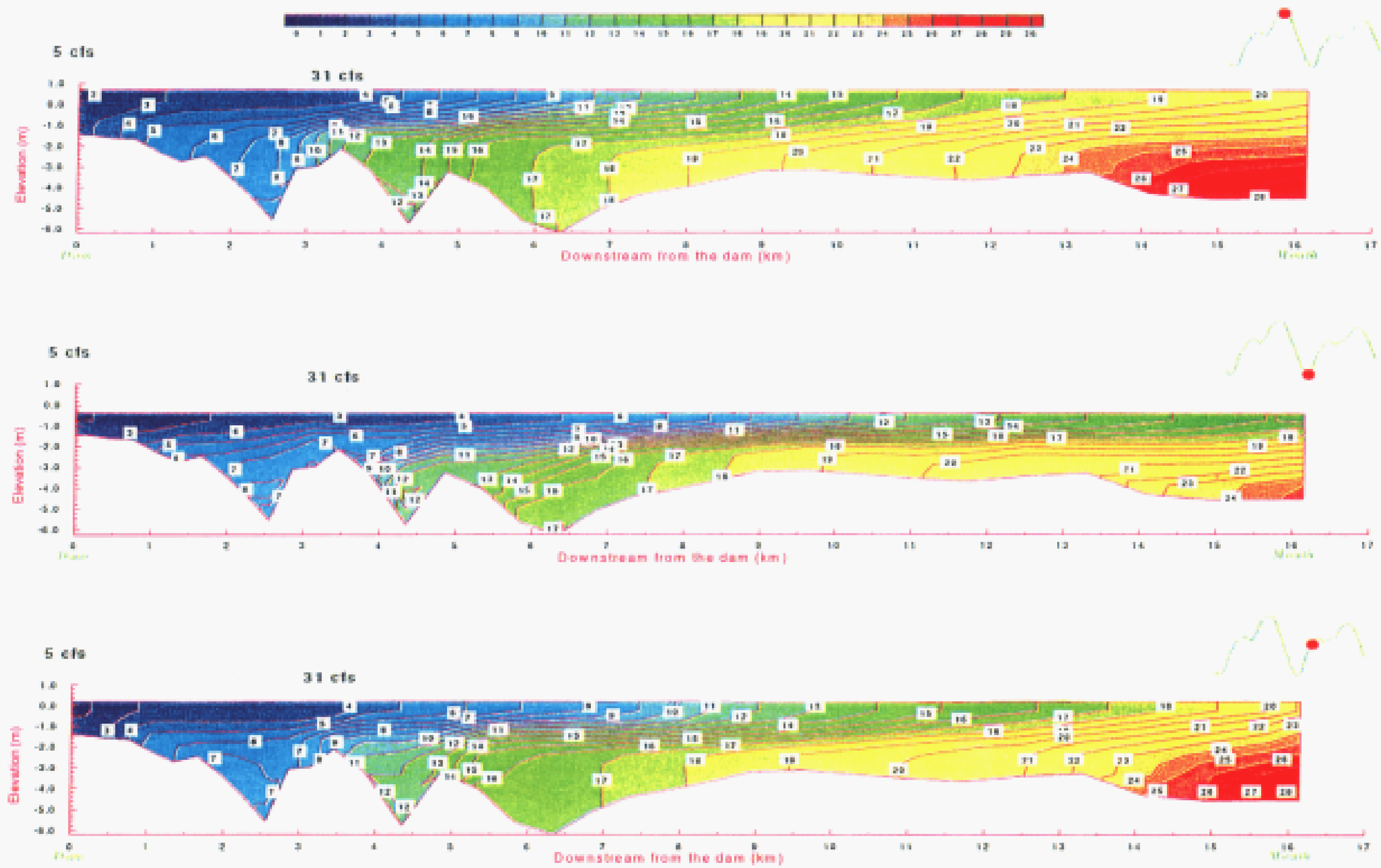


Figure C-23 *Simulated salinity distributions for Case 22: 5 cfs released from the reservoir and 31 cfs spring flow.*

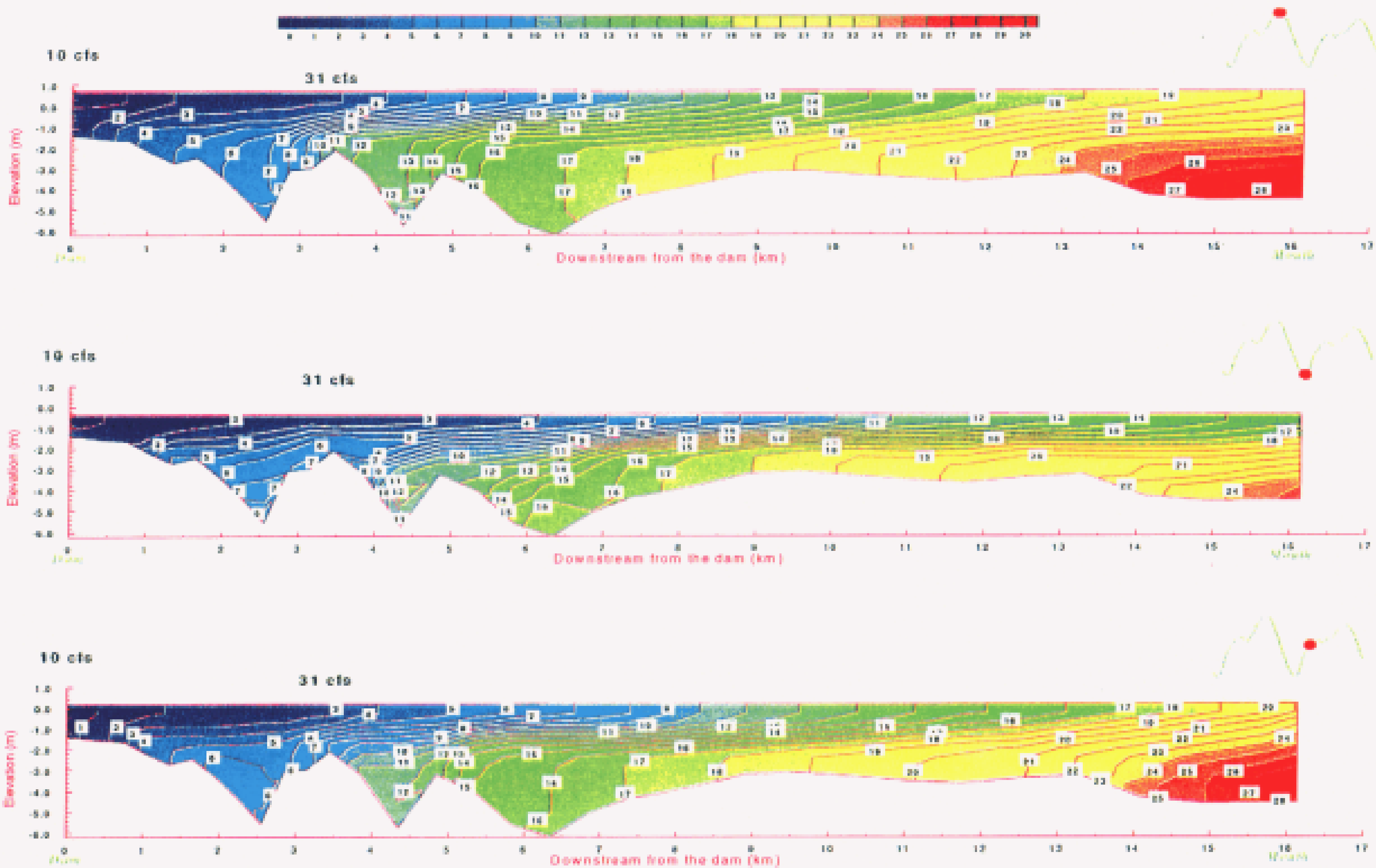


Figure C-24 Simulated salinity distributions for Case 23: 10 cfs released from the reservoir and 31 cfs spring flow.

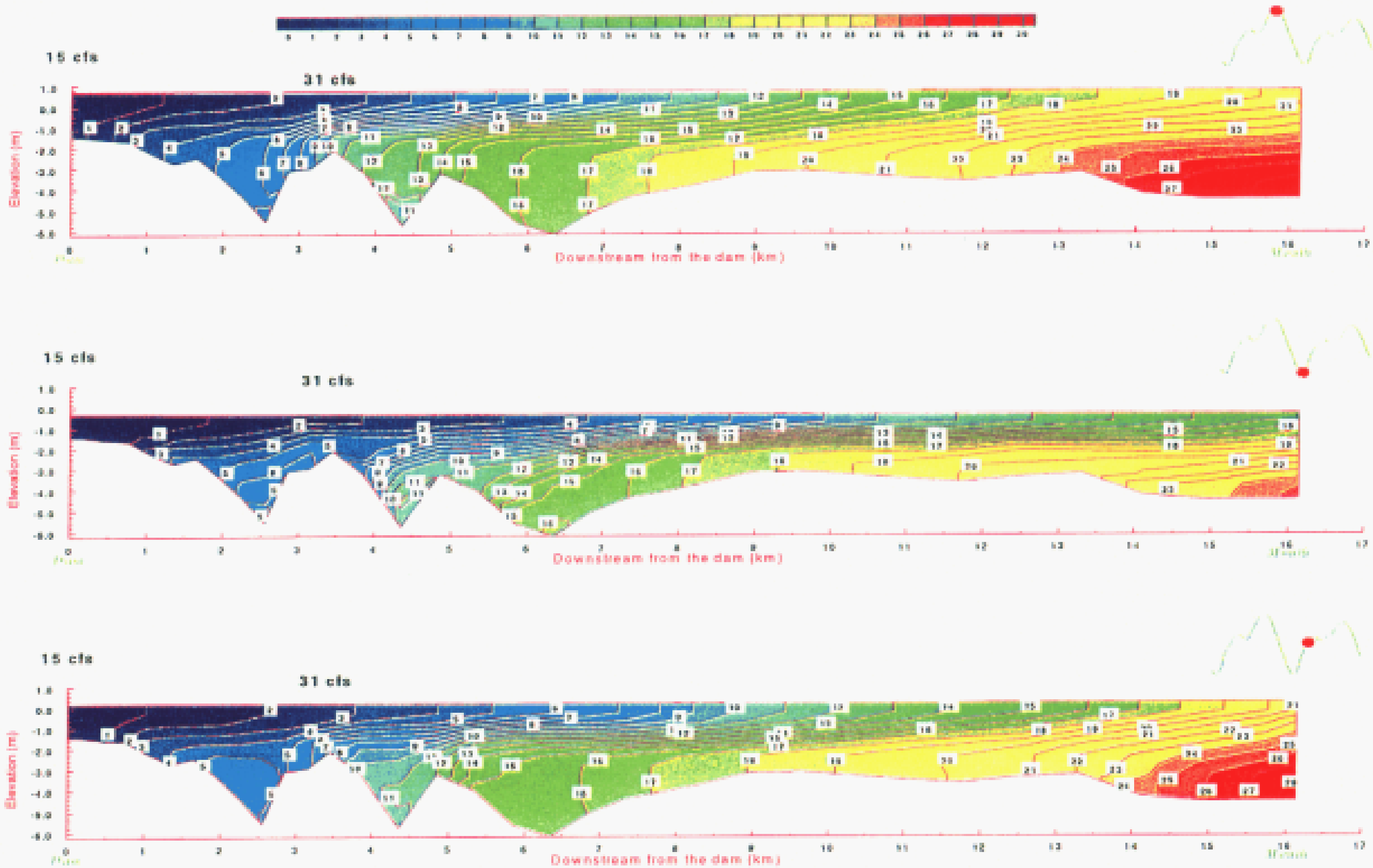


Figure C-25 Simulated salinity distributions for Case 24: 15 cfs released from the reservoir and 31 cfs spring flow.

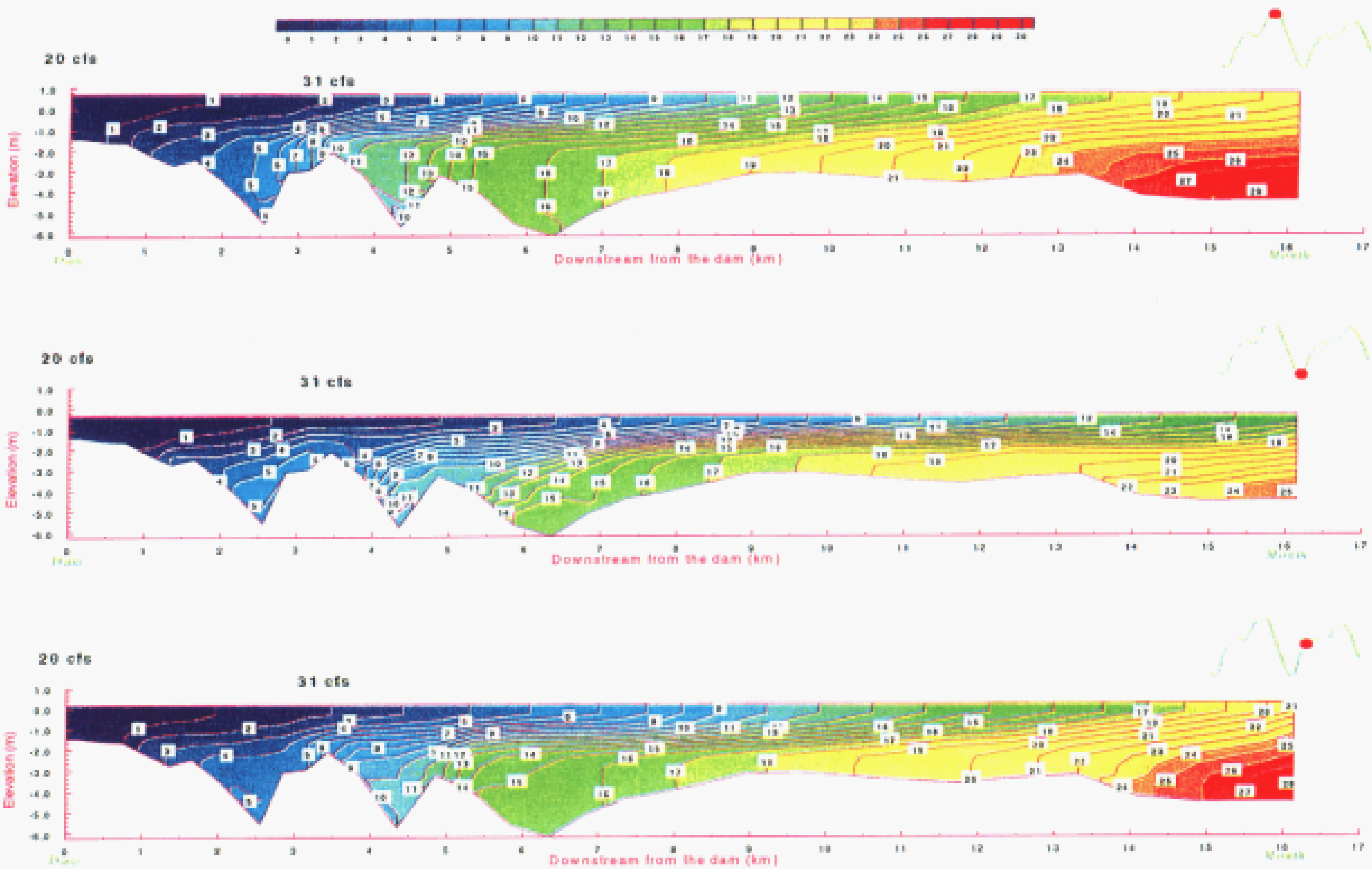


Figure C-26 Simulated salinity distributions for Case 25: 20 cfs released from the reservoir and 31 cfs spring flow.

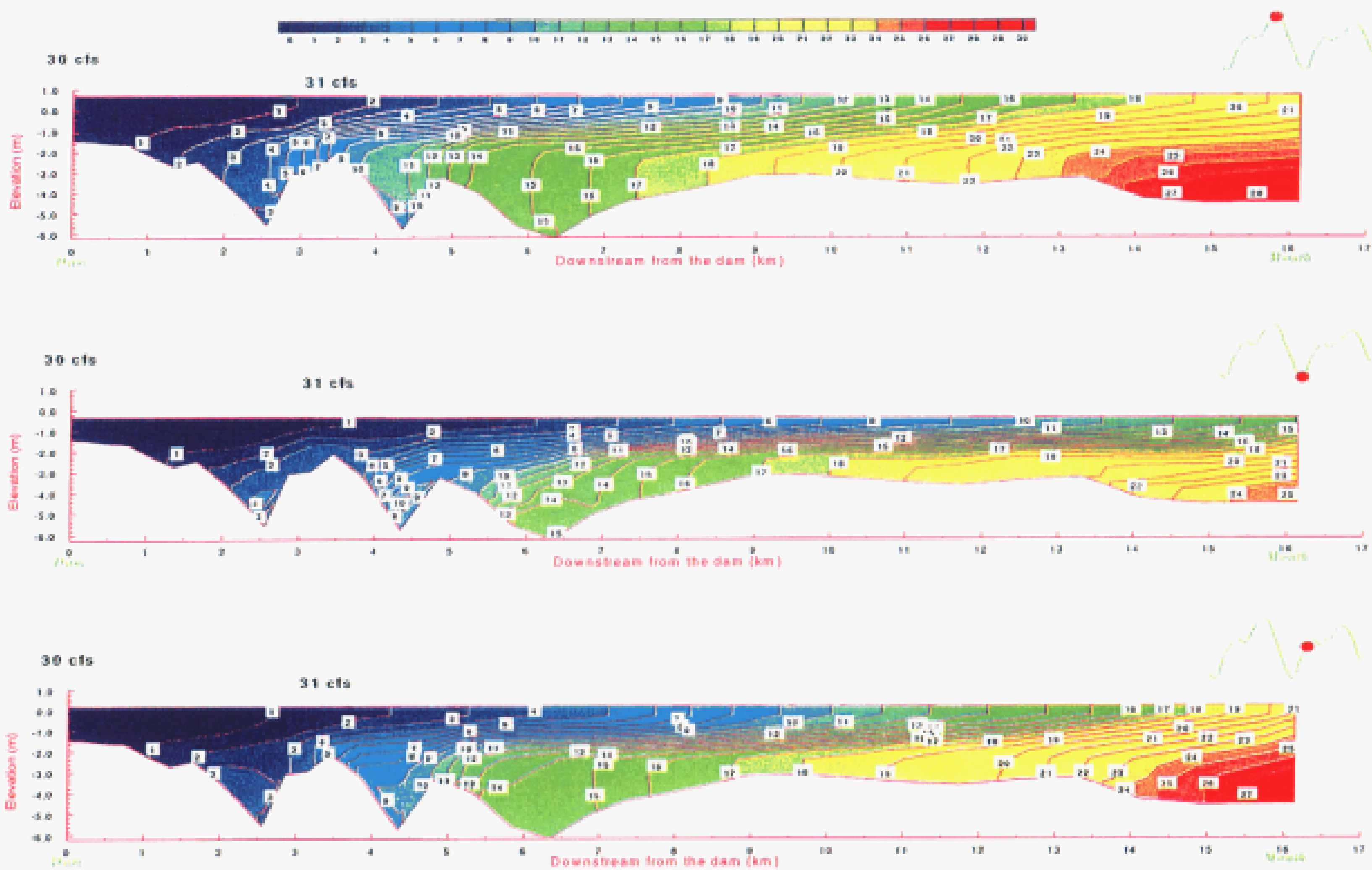


Figure C-27 Simulated salinity distributions for Case 26: 30 cfs released from the reservoir and 31 cfs spring flow.

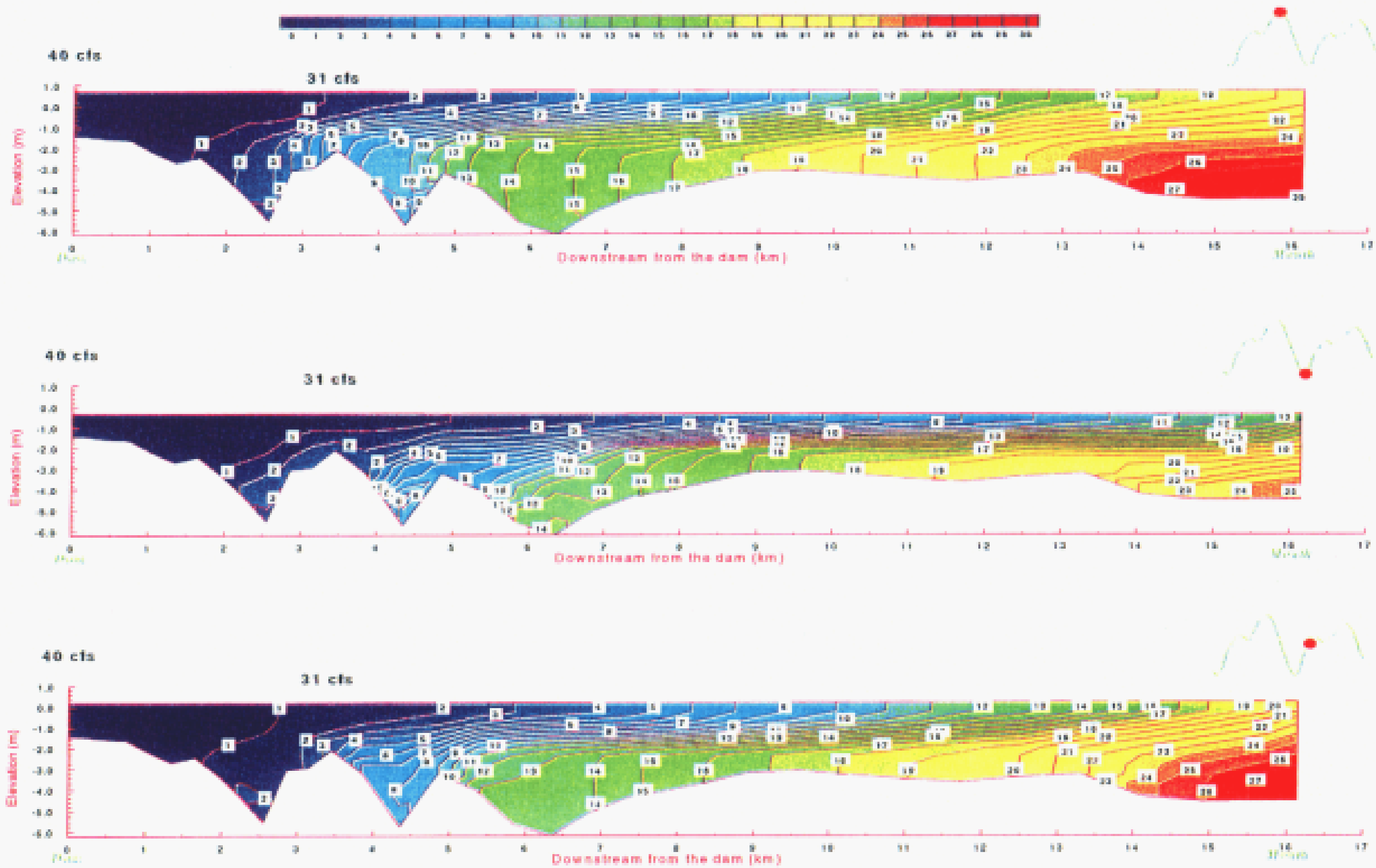


Figure C-28 Simulated salinity distributions for Case 27: 40 cfs released from the reservoir and 31 cfs spring flow.

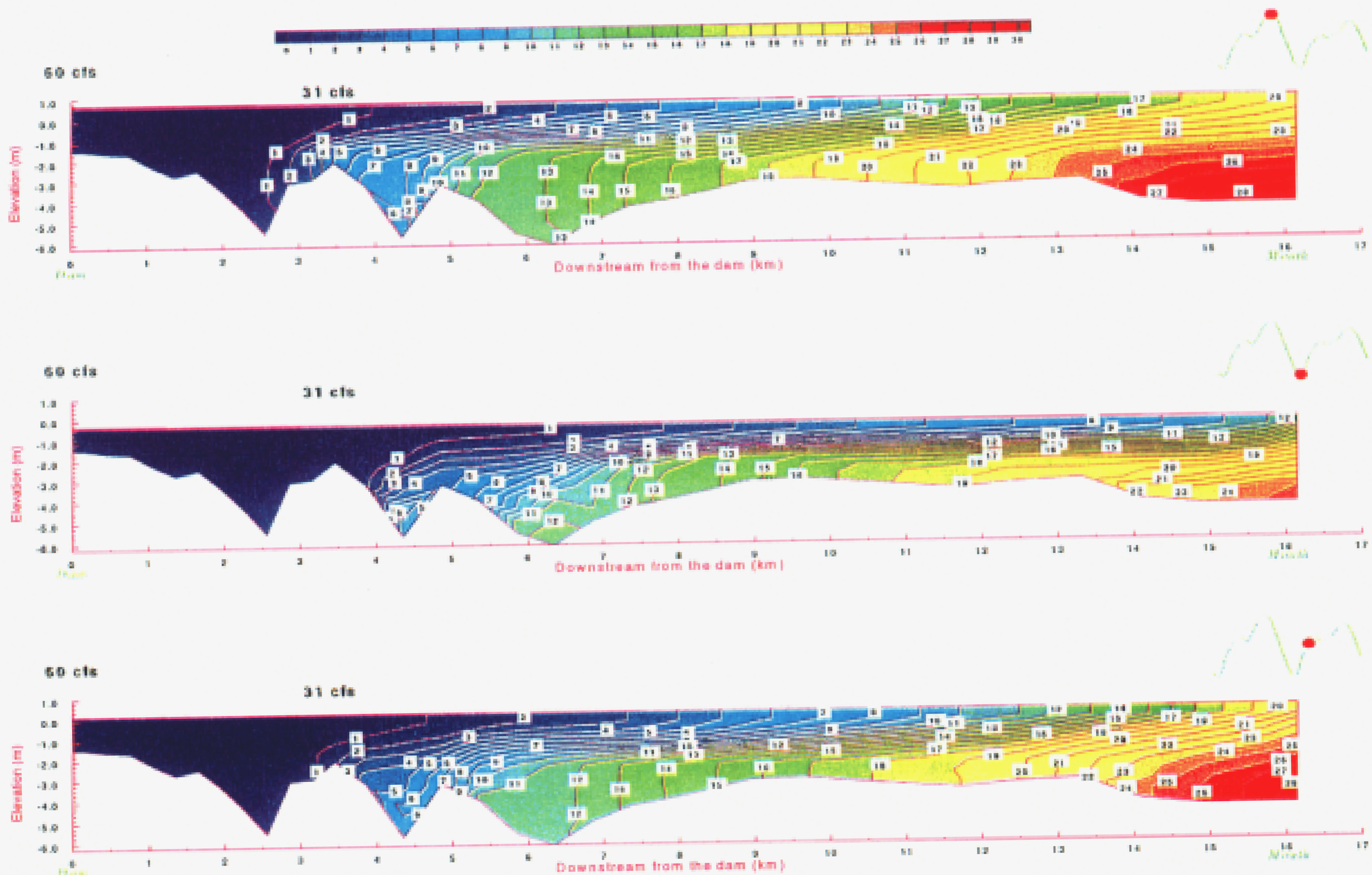


Figure C-29 Simulated salinity distributions for Case 28: 60 cfs released from the reservoir and 31 cfs spring flow.

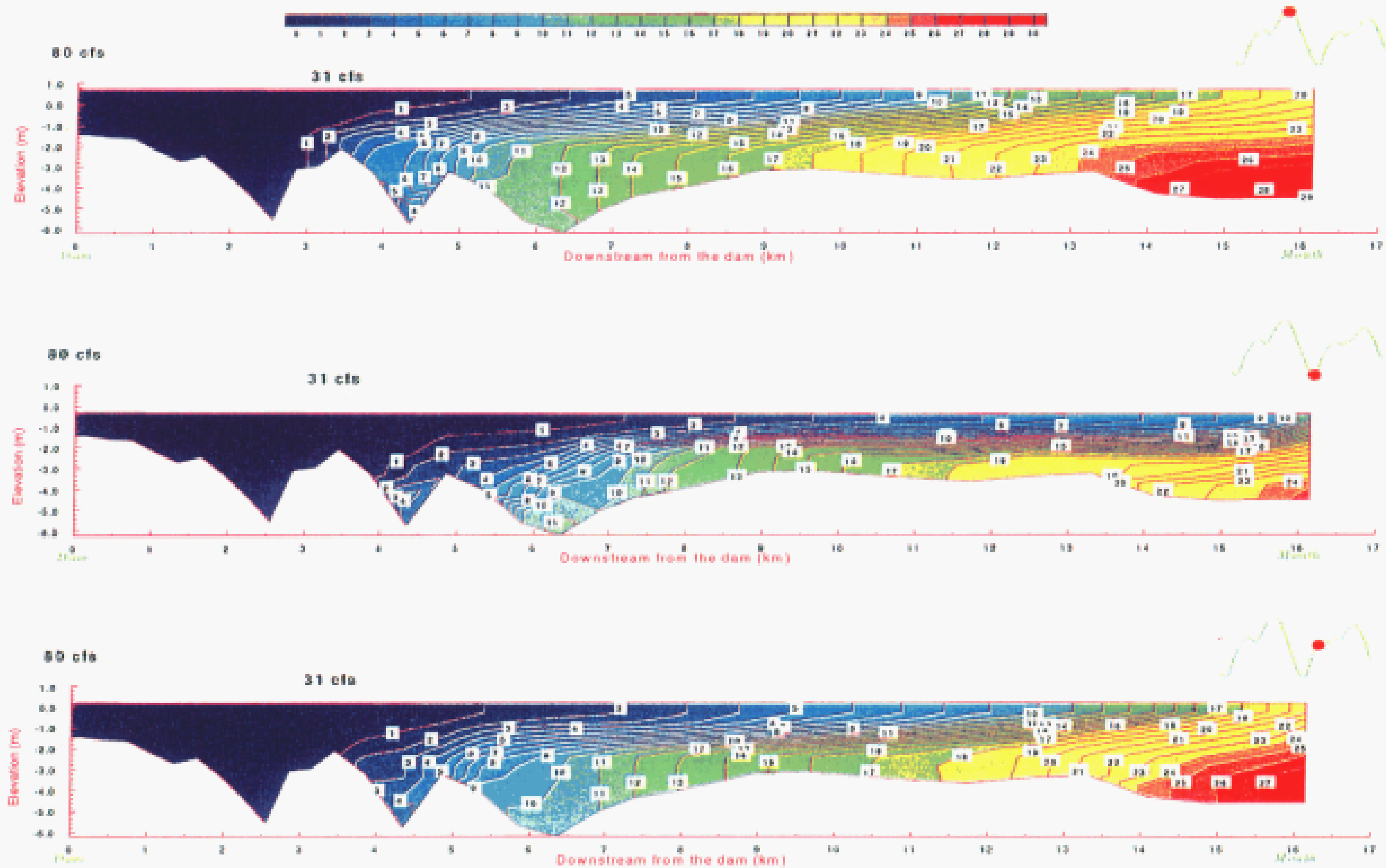


Figure C-30 Simulated salinity distributions for Case 29: 80 cfs released from the reservoir and 31 cfs spring flow.

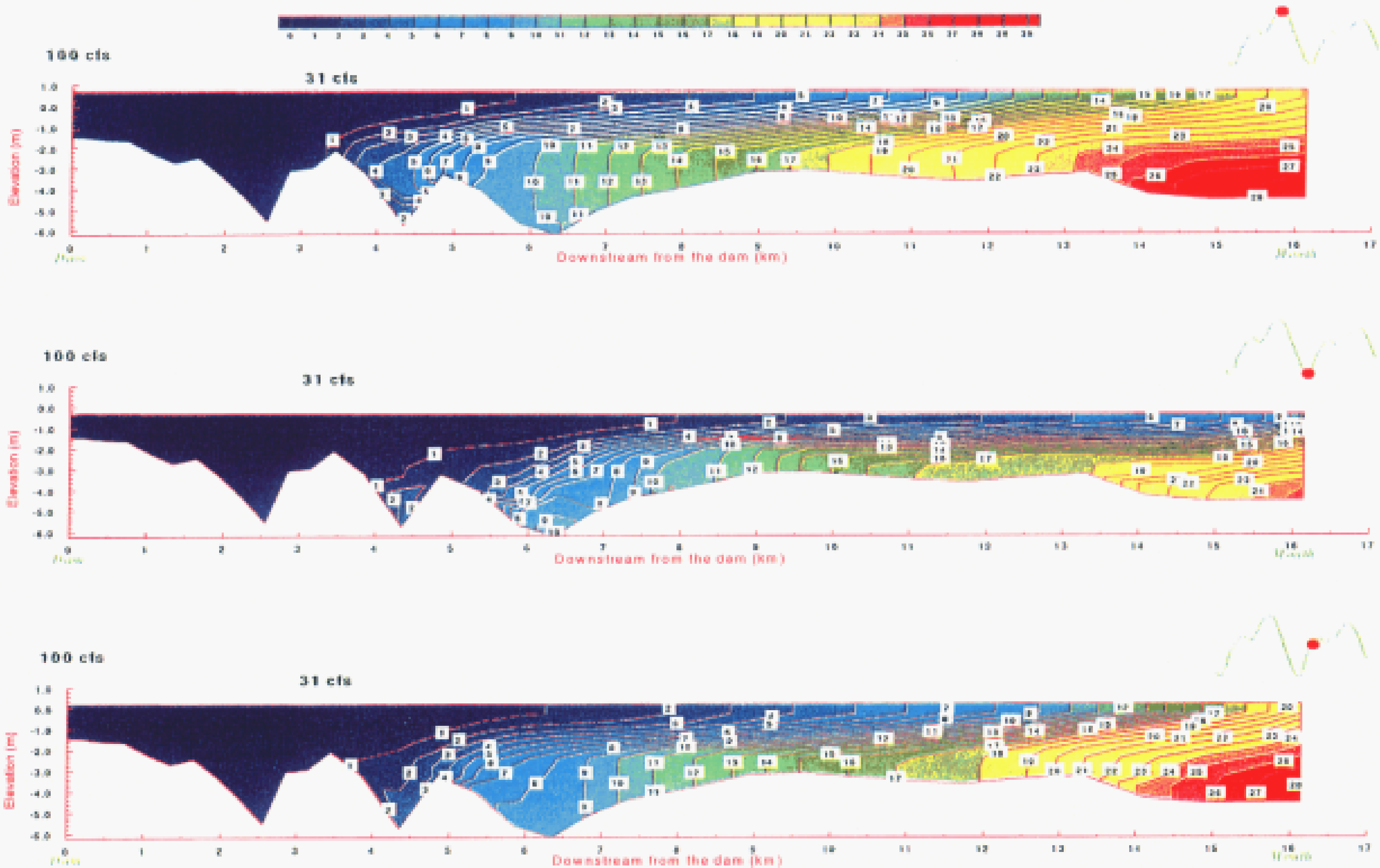


Figure C-31 Simulated salinity distributions for Case 30: 100 cfs released from the reservoir and 31 cfs spring flow.

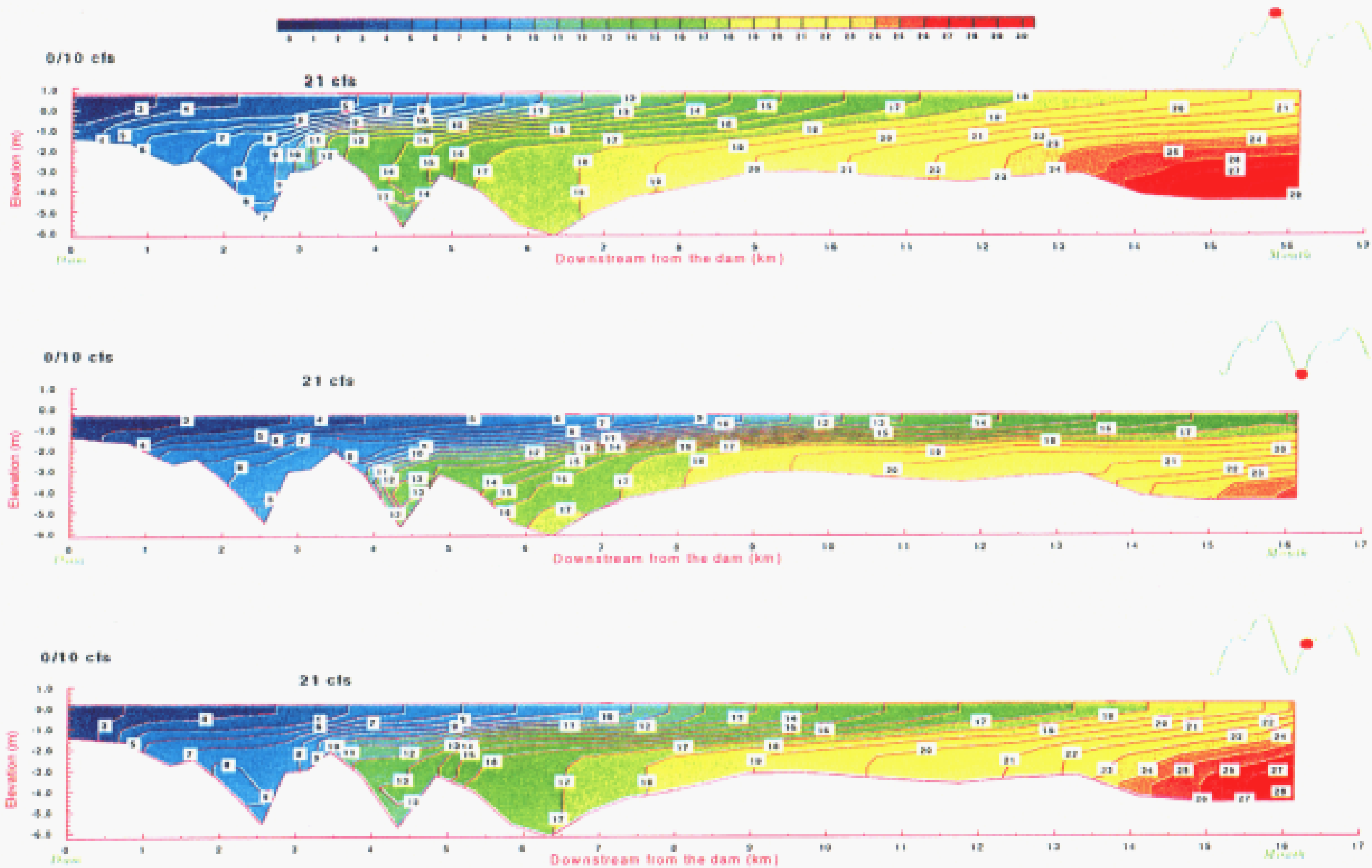


Figure C-32 Simulated salinity distributions for Case 31: 0 cfs released from the reservoir, 10 cfs spring flow routed to the dam, and 21 cfs spring flow re0mained.

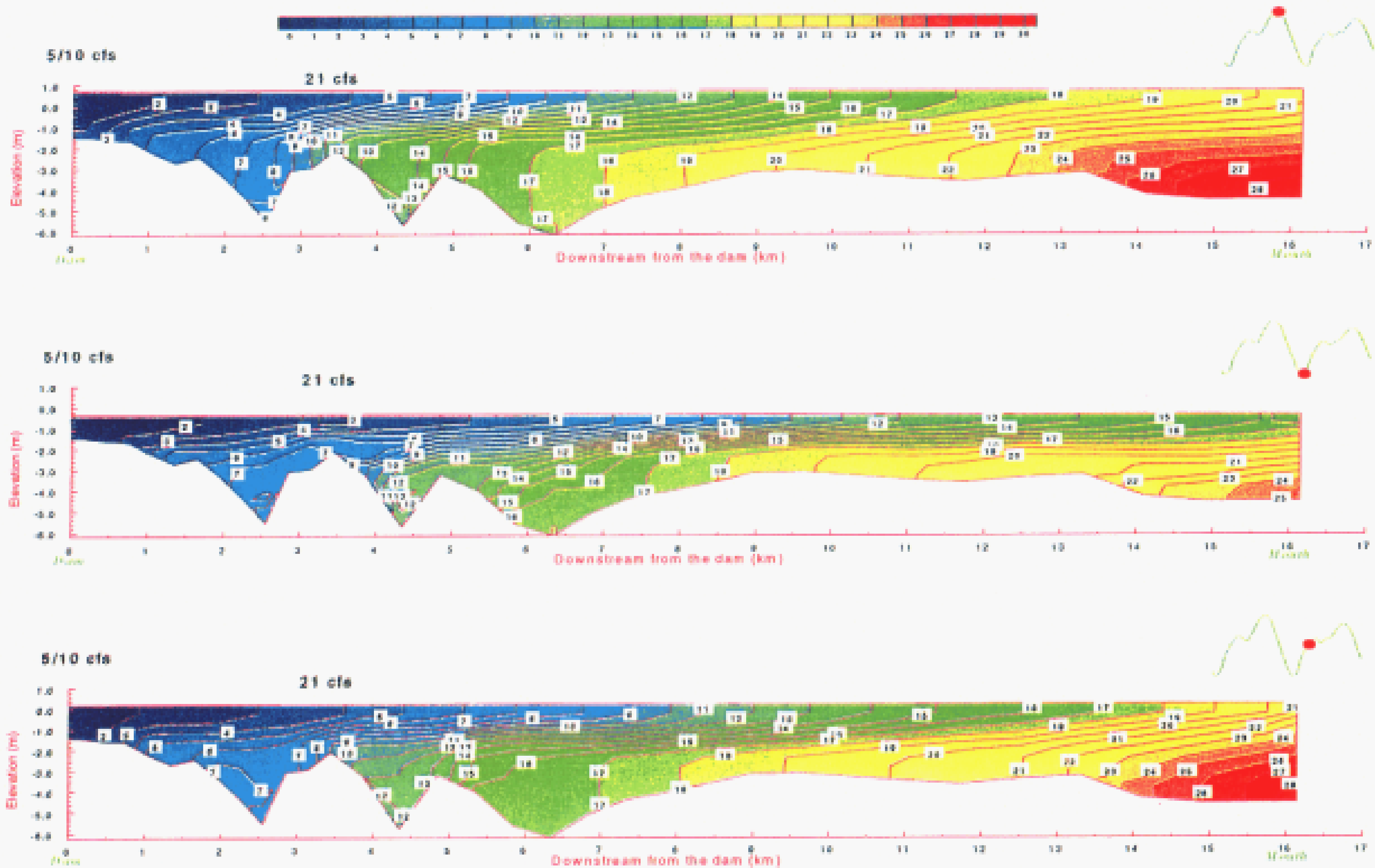


Figure C-33 Simulated salinity distributions for Case 32: 5 cfs released from the reservoir, 10 cfs spring flow routed to the dam, and 21 cfs spring flow remained.

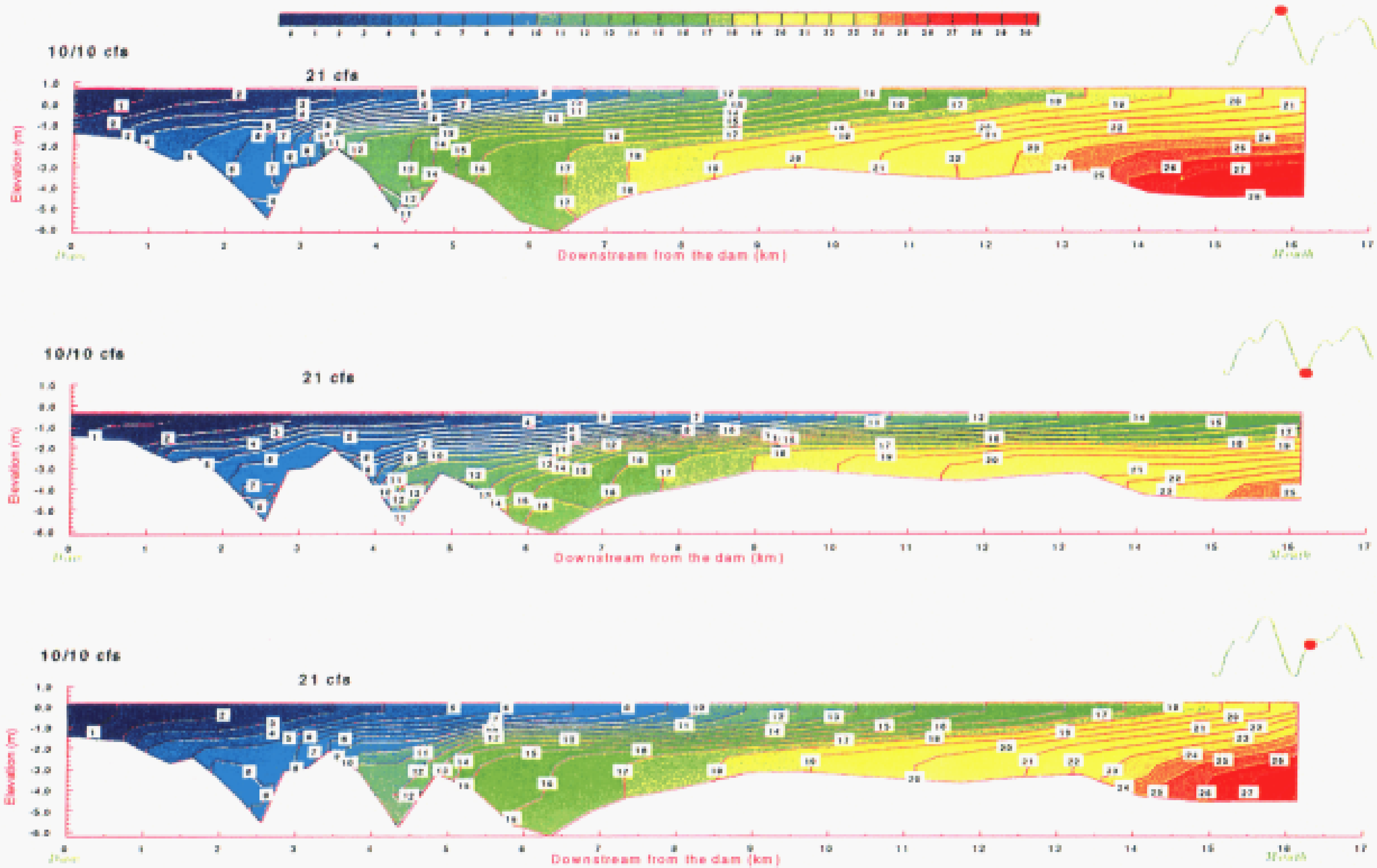


Figure C-34 Simulated salinity distributions for Case 33: 10 cfs released from the reservoir, 10 cfs spring flow routed to the dam, and 21 cfs spring flow remained.

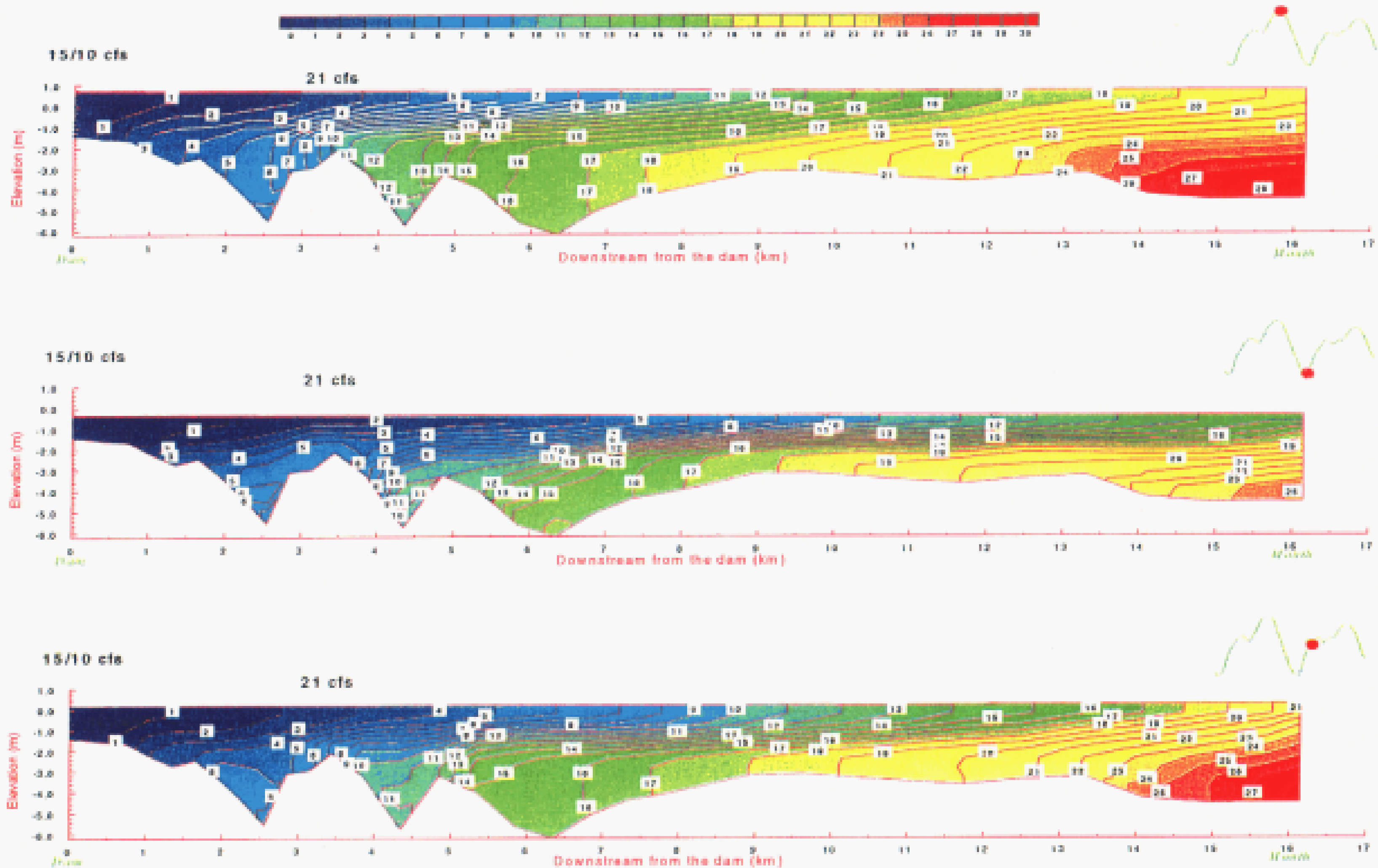


Figure C-35 Simulated salinity distributions for Case 34: 15 cfs released from the reservoir, 10 cfs spring flow routed to the dam, and 21 cfs spring flow remained.

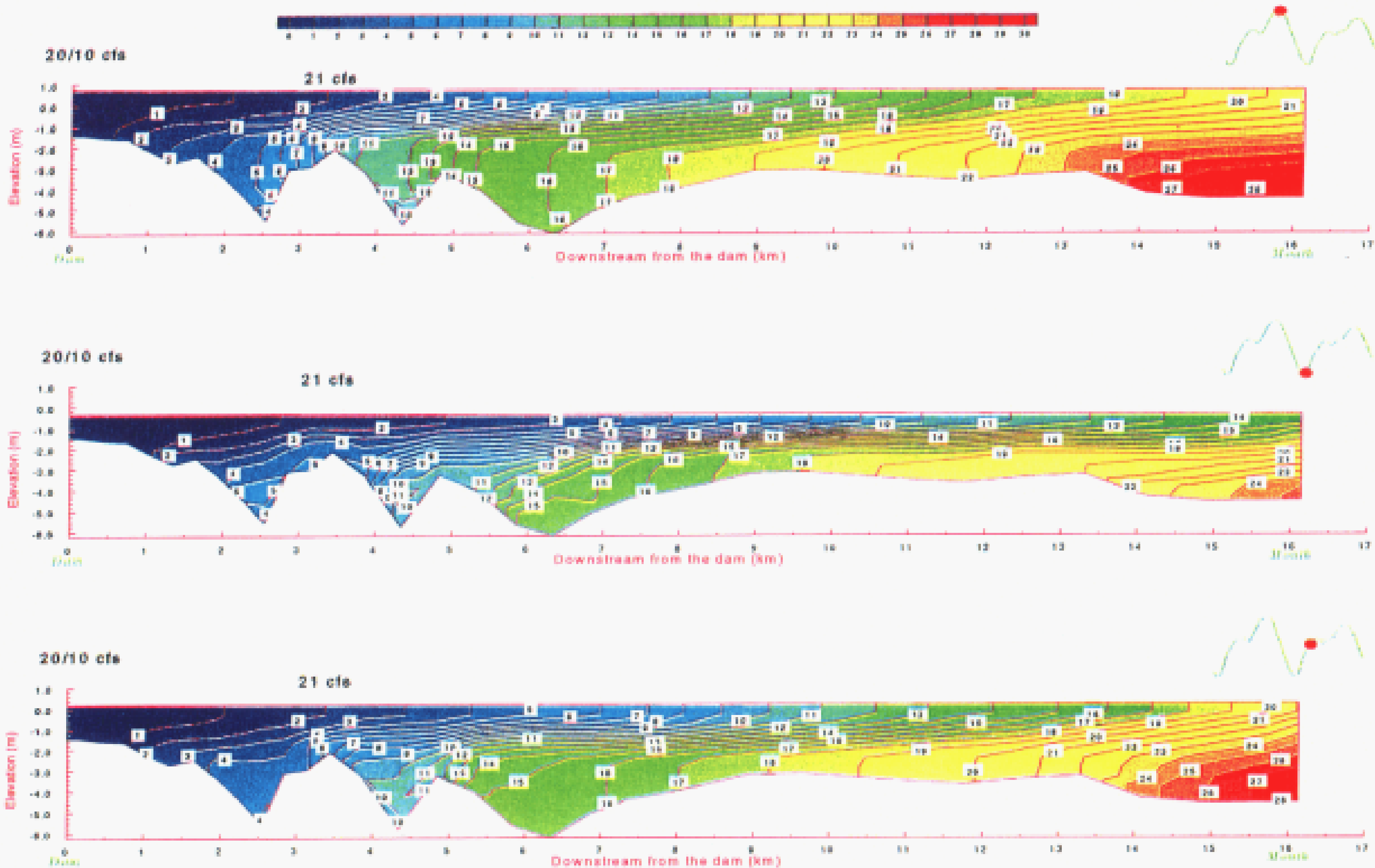


Figure C-36 Simulated salinity distributions for Case 35: 20 cfs released from the reservoir, 10 cfs spring flow routed to the dam, and 21 cfs spring flow remained.

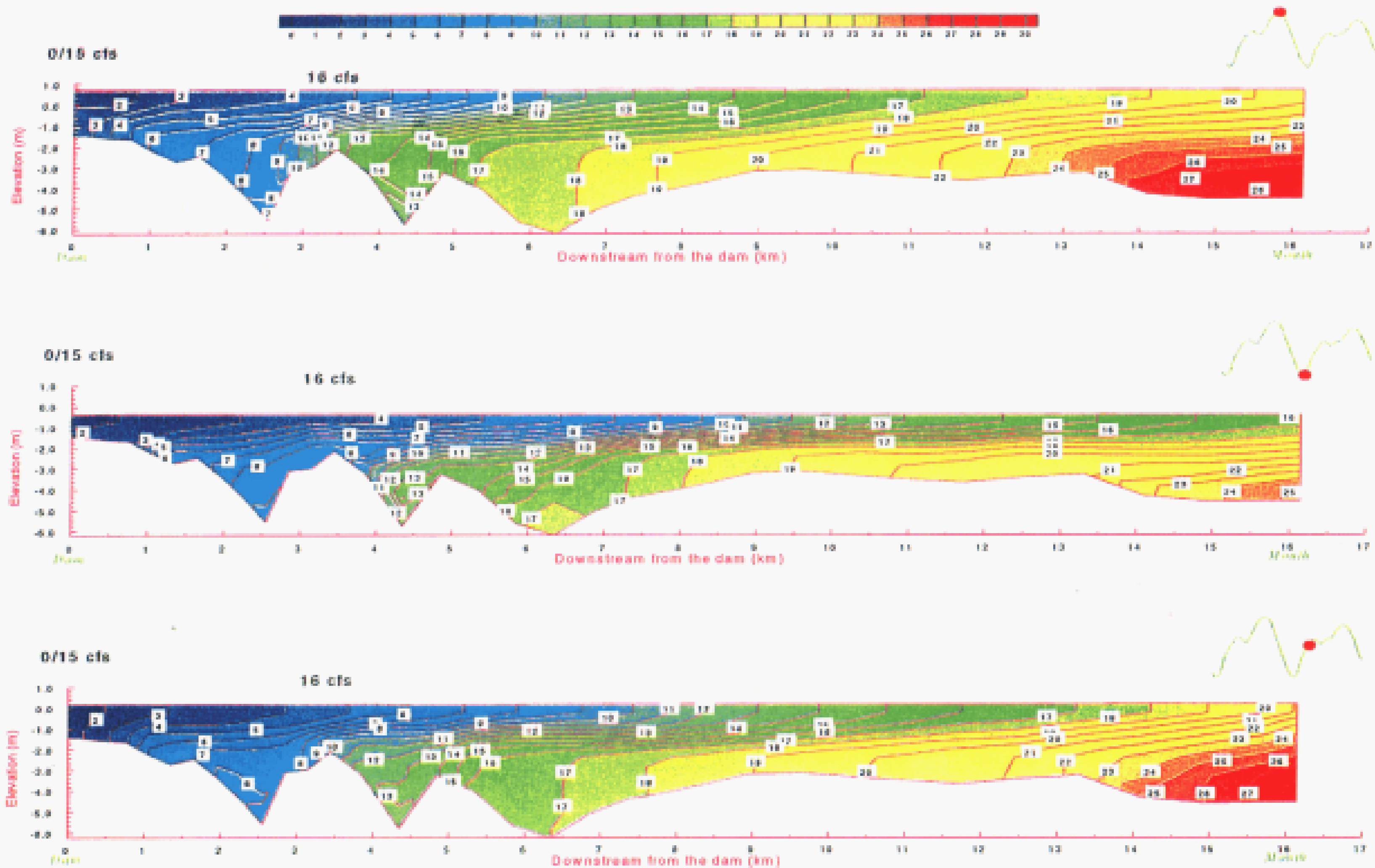


Figure C-37 Simulated salinity distributions for Case 36: 0 cfs released from the reservoir, 15 cfs spring flow routed to the dam, and 16 cfs spring flow remained.

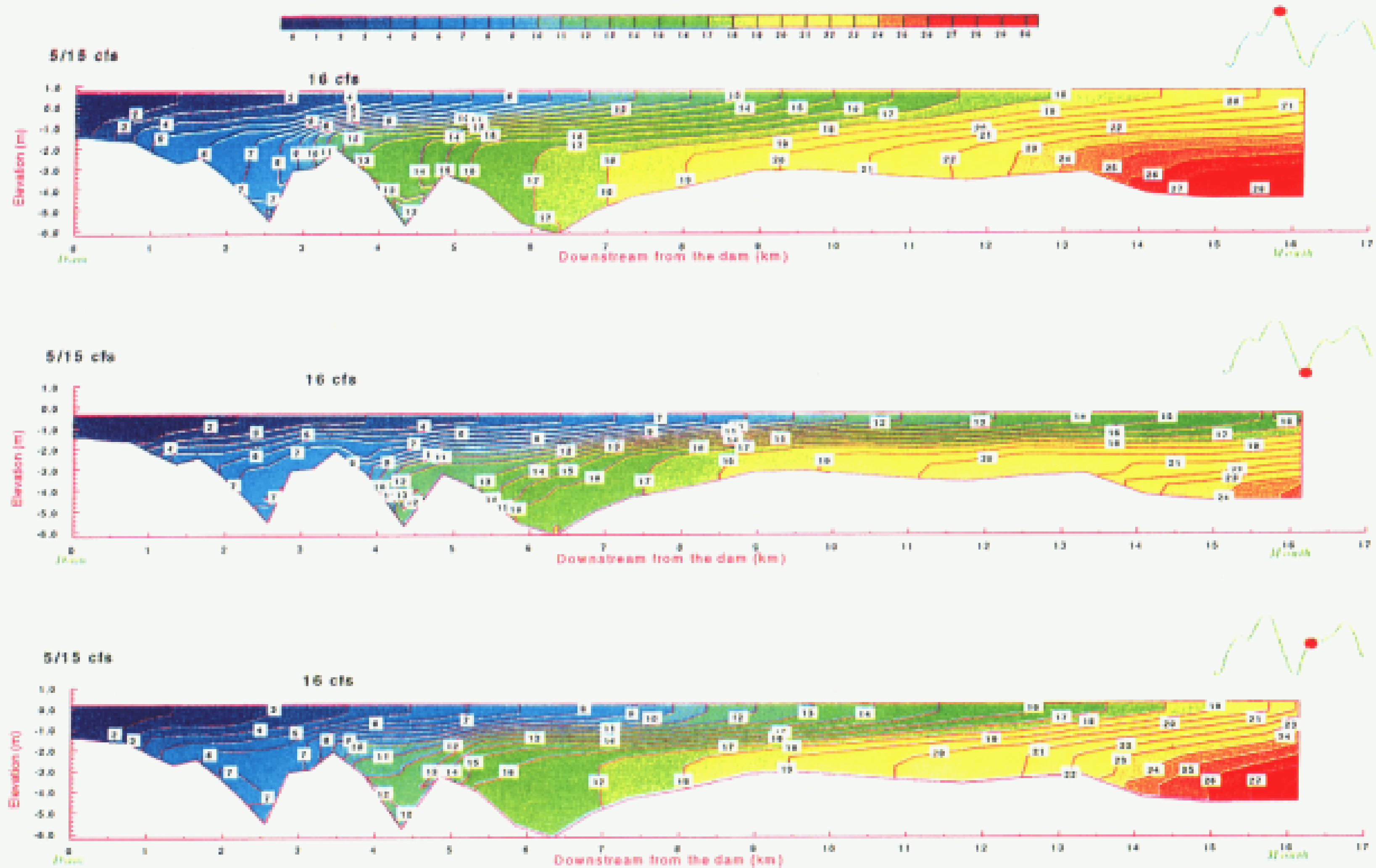


Figure C-38 Simulated salinity distributions for Case 37: 5 cfs released from the reservoir, 15 cfs spring flow routed to the dam, and 16 cfs spring flow remained.

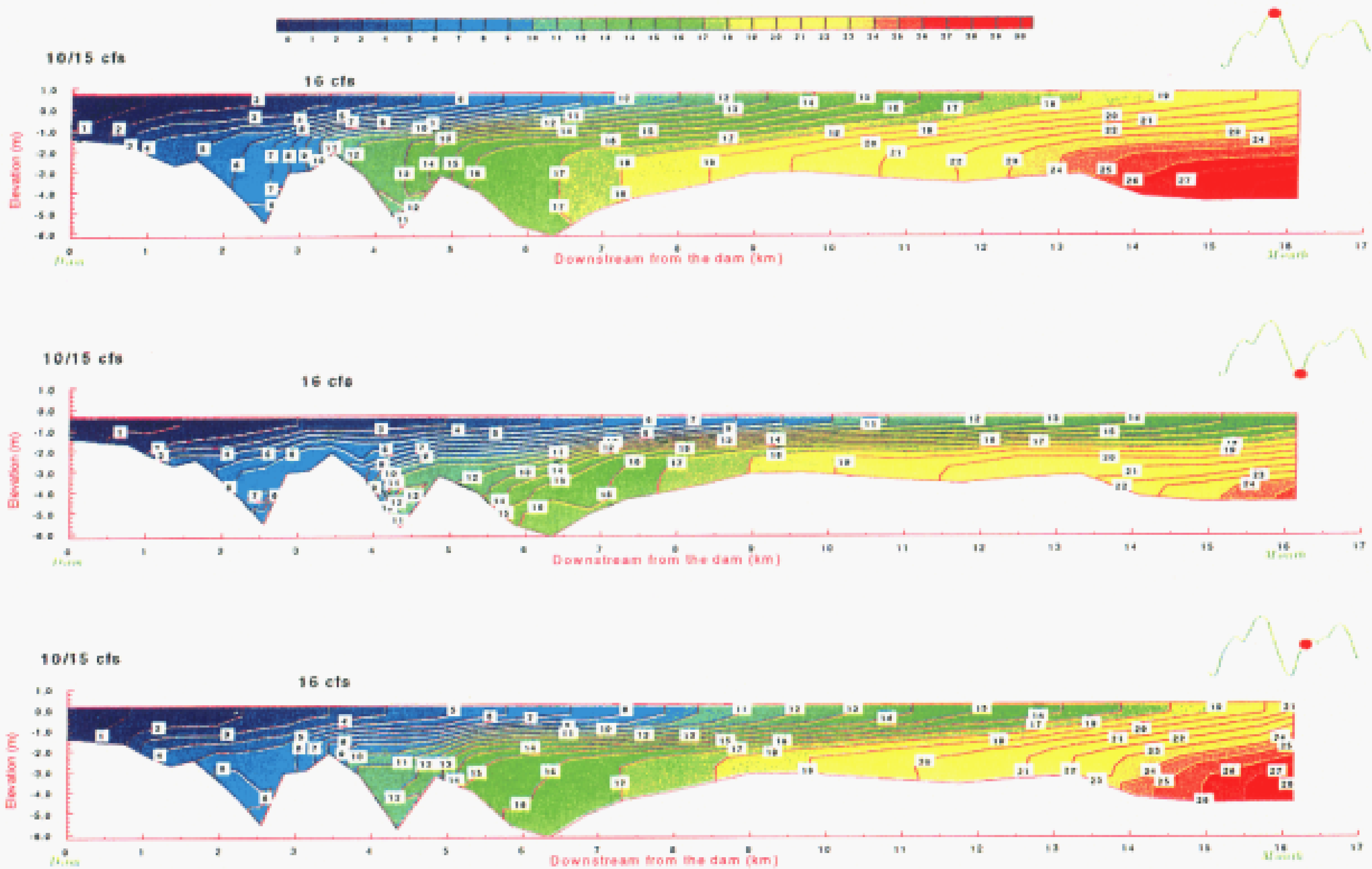


Figure C-39 Simulated salinity distributions for Case 38: 10 cfs released from the reservoir, 15 cfs spring flow routed to the dam, and 16 cfs spring flow remained.

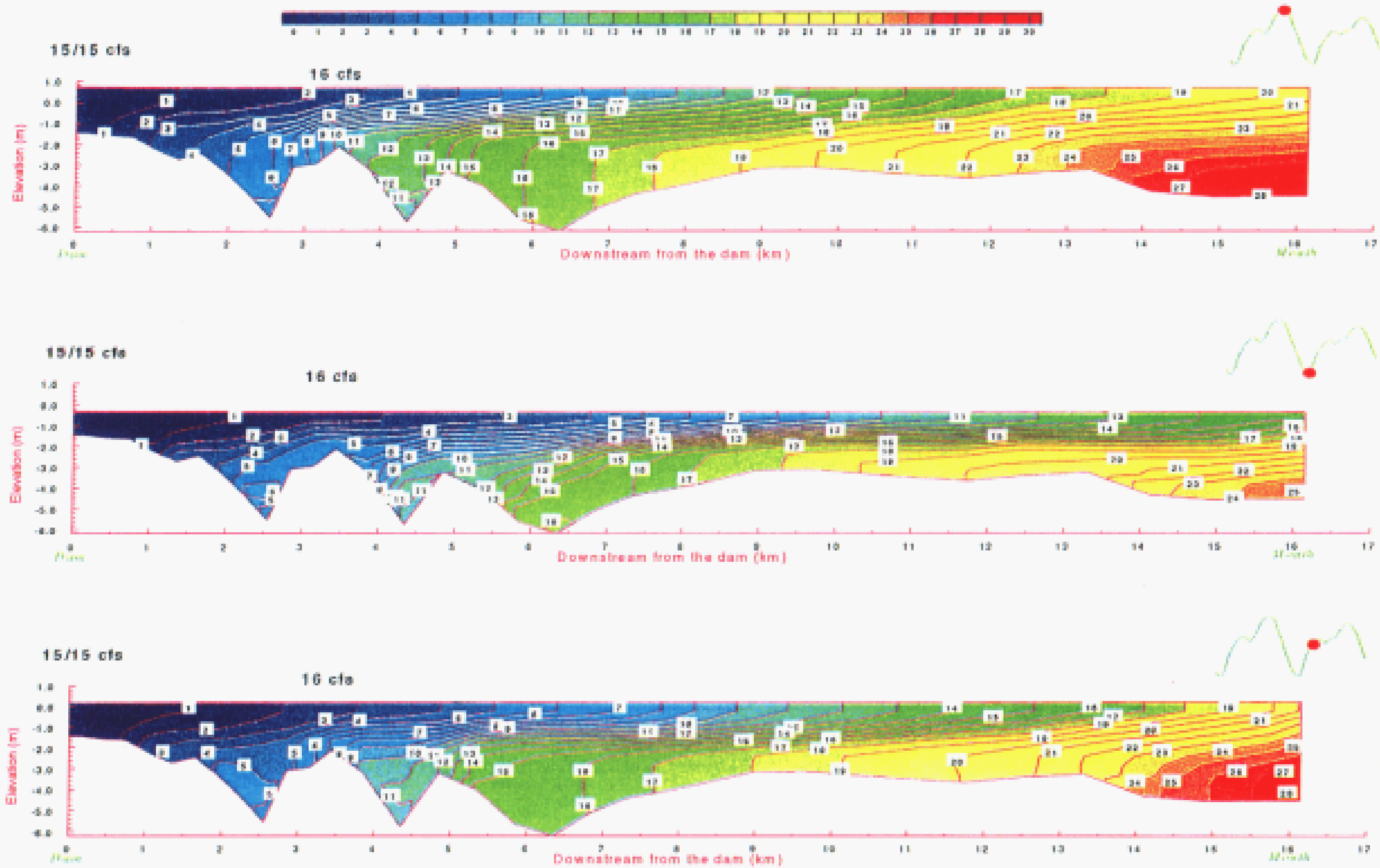


Figure C-40 Simulated salinity distributions for Case 39: 15 cfs released from the reservoir, 15 cfs spring flow routed to the dam, and 16 cfs spring flow remained.

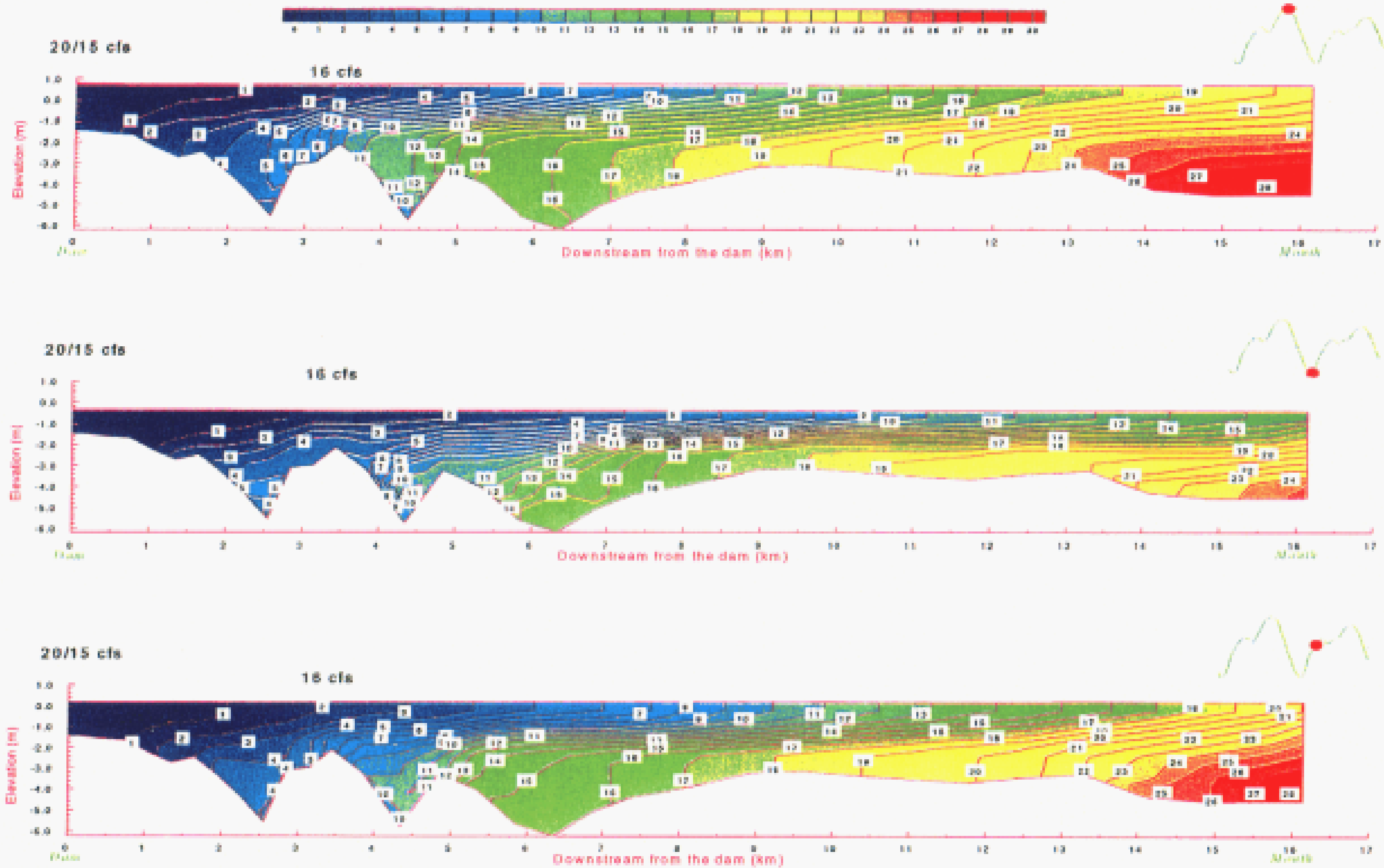


Figure C-41 Simulated salinity distributions for Case 40: 20 cfs released from the reservoir, 15 cfs spring flow routed to the dam, and 16 cfs spring flow remained.

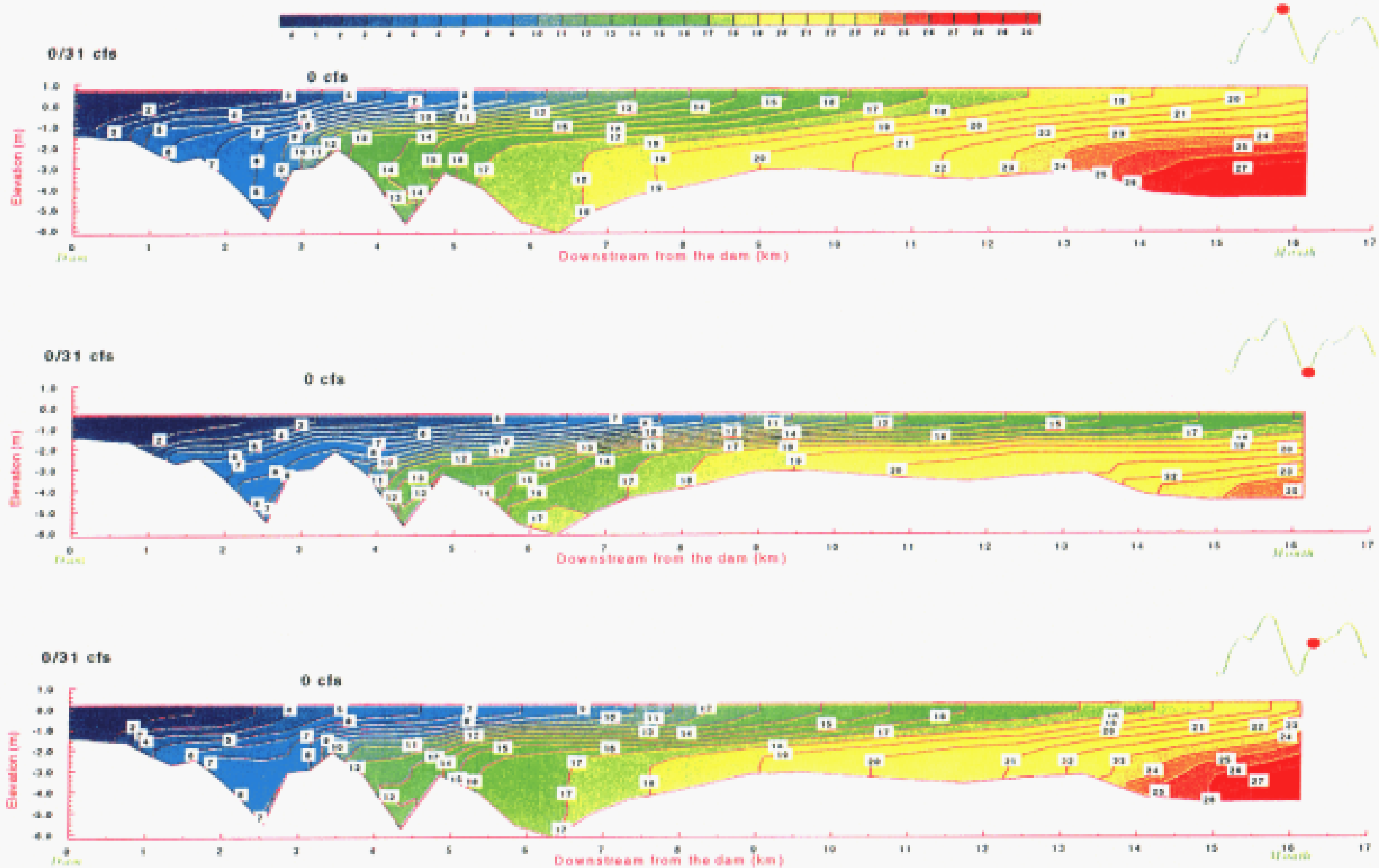


Figure C-42 Simulated salinity distributions for Case 41: 0 cfs released from the reservoir, 31 cfs spring flow routed to the dam, and 0 cfs spring flow remained.

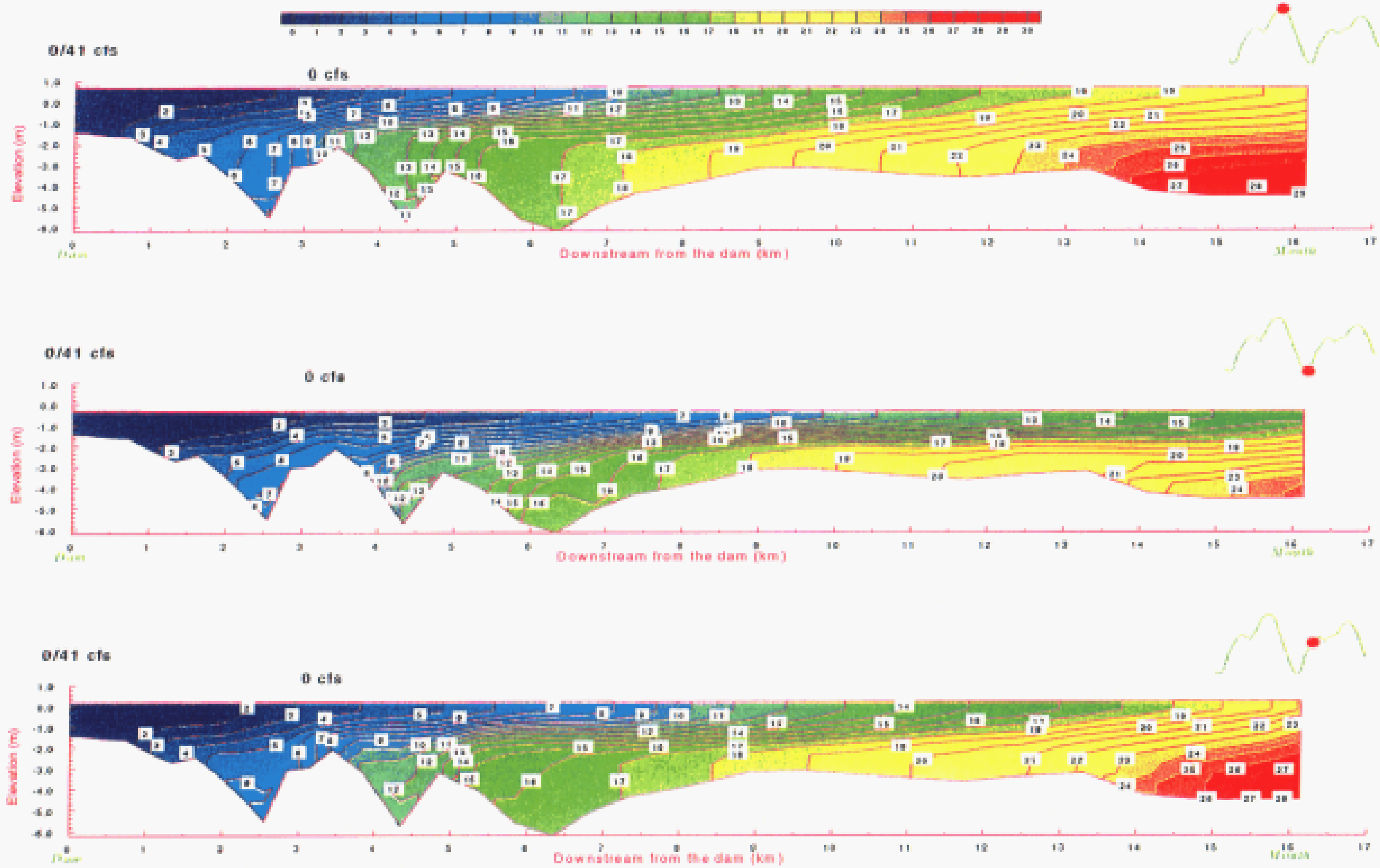


Figure C-43 Simulated salinity distributions for Case 42: 0 cfs released from the reservoir, 41 cfs spring flow routed to the dam, and 0 cfs spring flow remained.

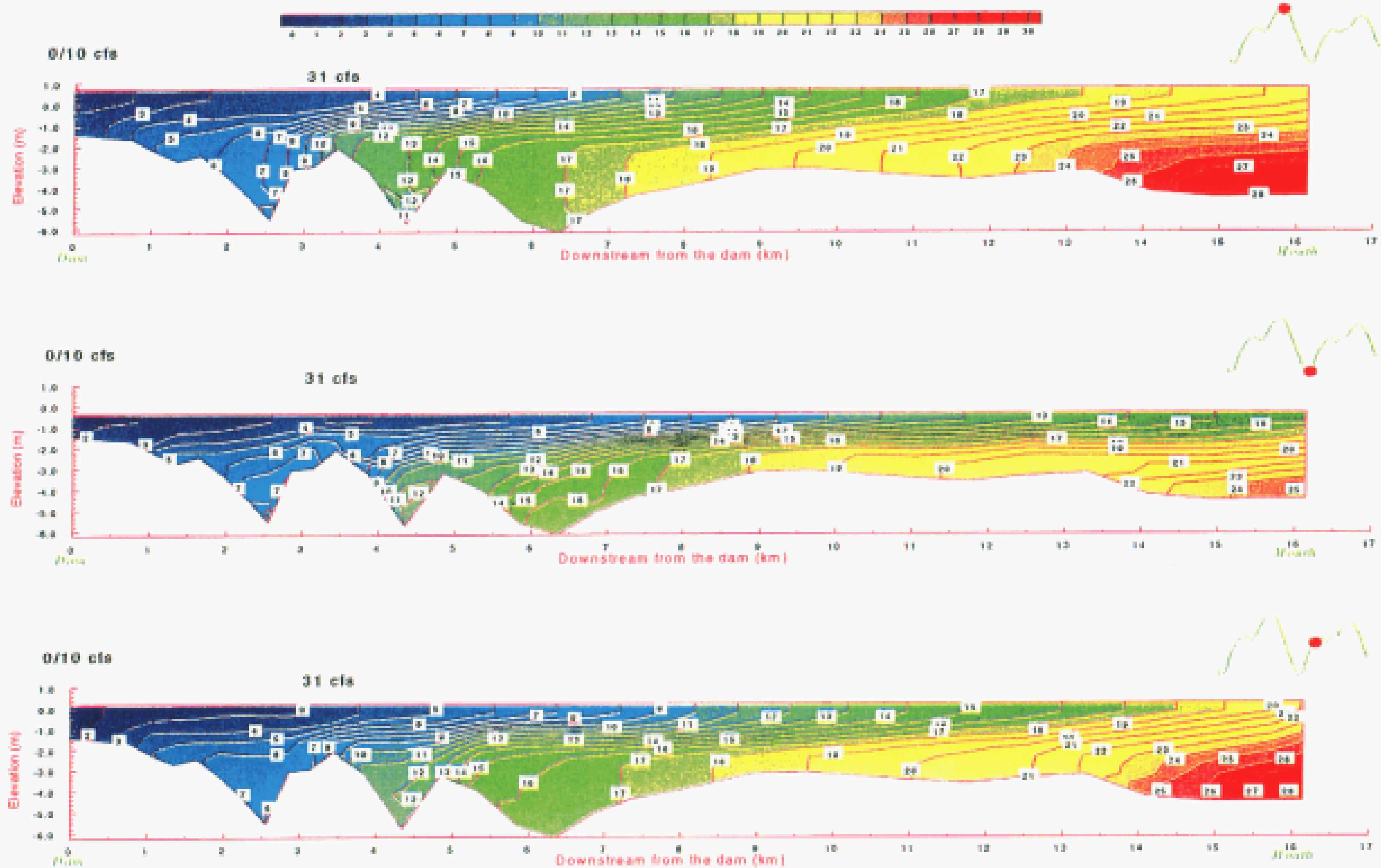


Figure C-44 Simulated salinity distributions for Case 43: 0 cfs released from the reservoir, 10 cfs spring flow routed to the dam, and 31 cfs spring flow remained.

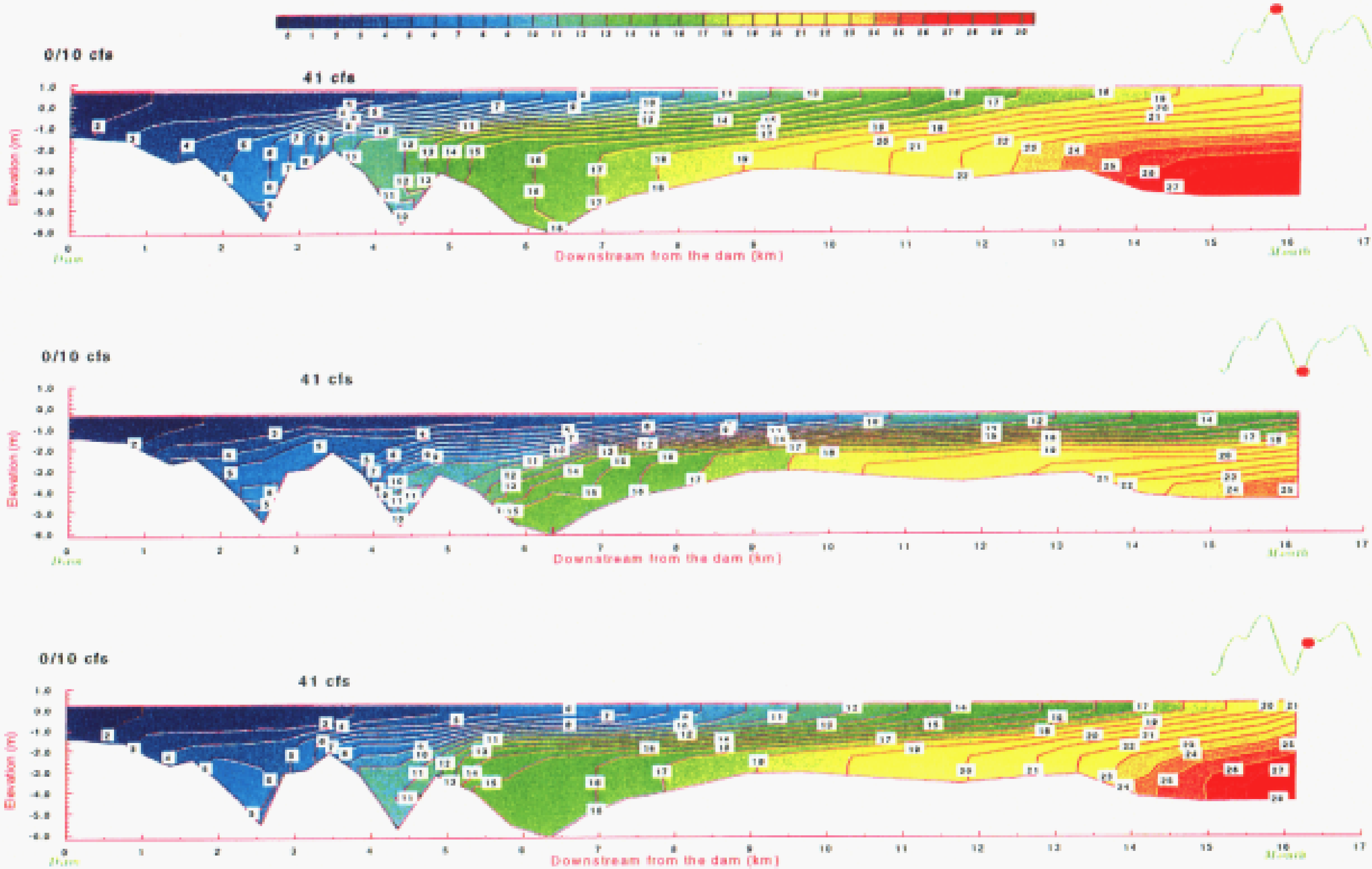


Figure C-45 Simulated salinity distributions for Case 44: 0 cfs released from the reservoir, 10 cfs spring flow routed to the dam, and 41 cfs spring flow remained.

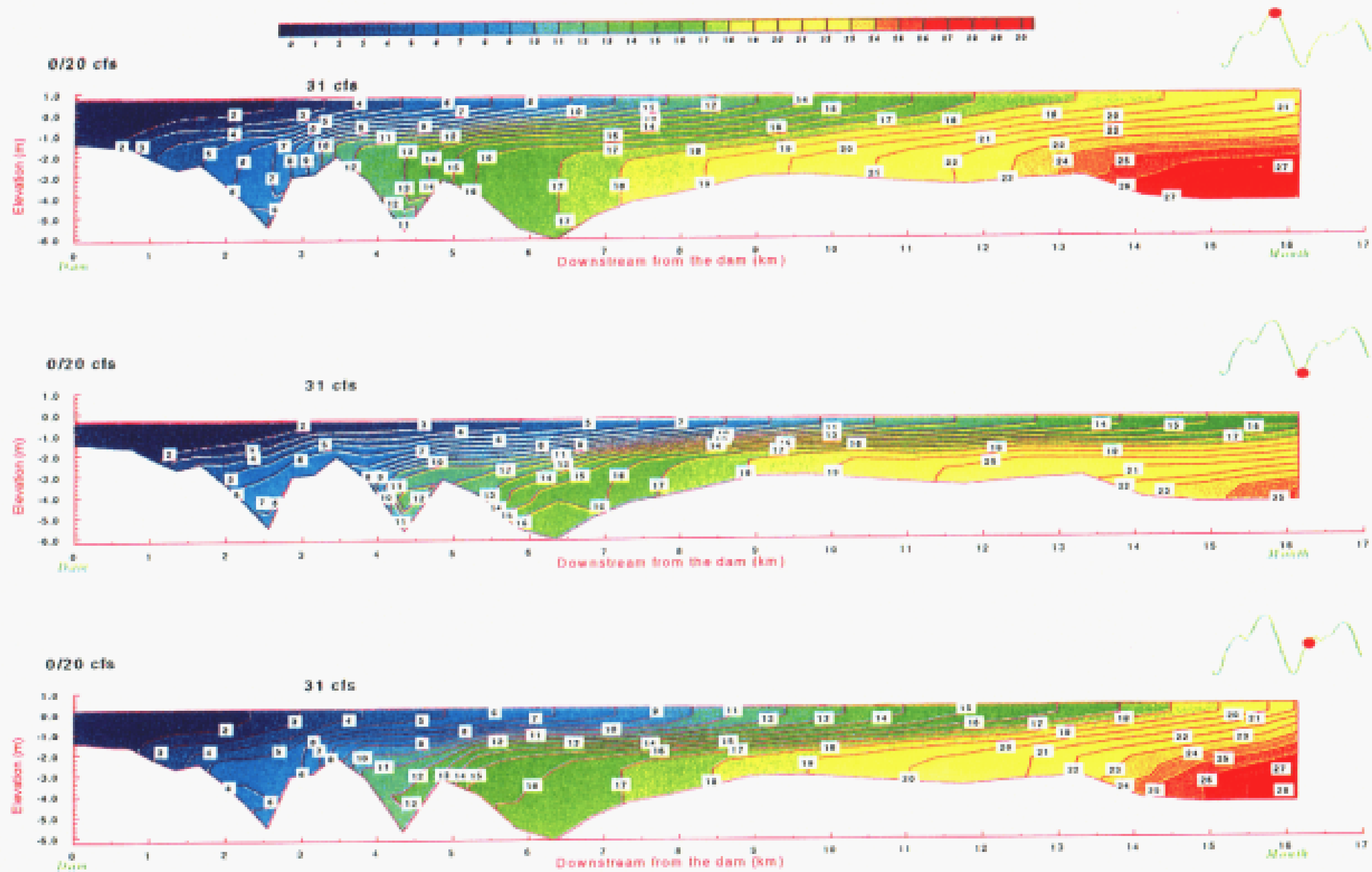


Figure C-46 Simulated salinity distributions for Case 45: 0 cfs released from the reservoir, 20 cfs spring flow routed to the dam, and 31 cfs spring flow remained.

Appendix D. Model Results of Salinity Response to Various Upstream Freshwater Release Schedules

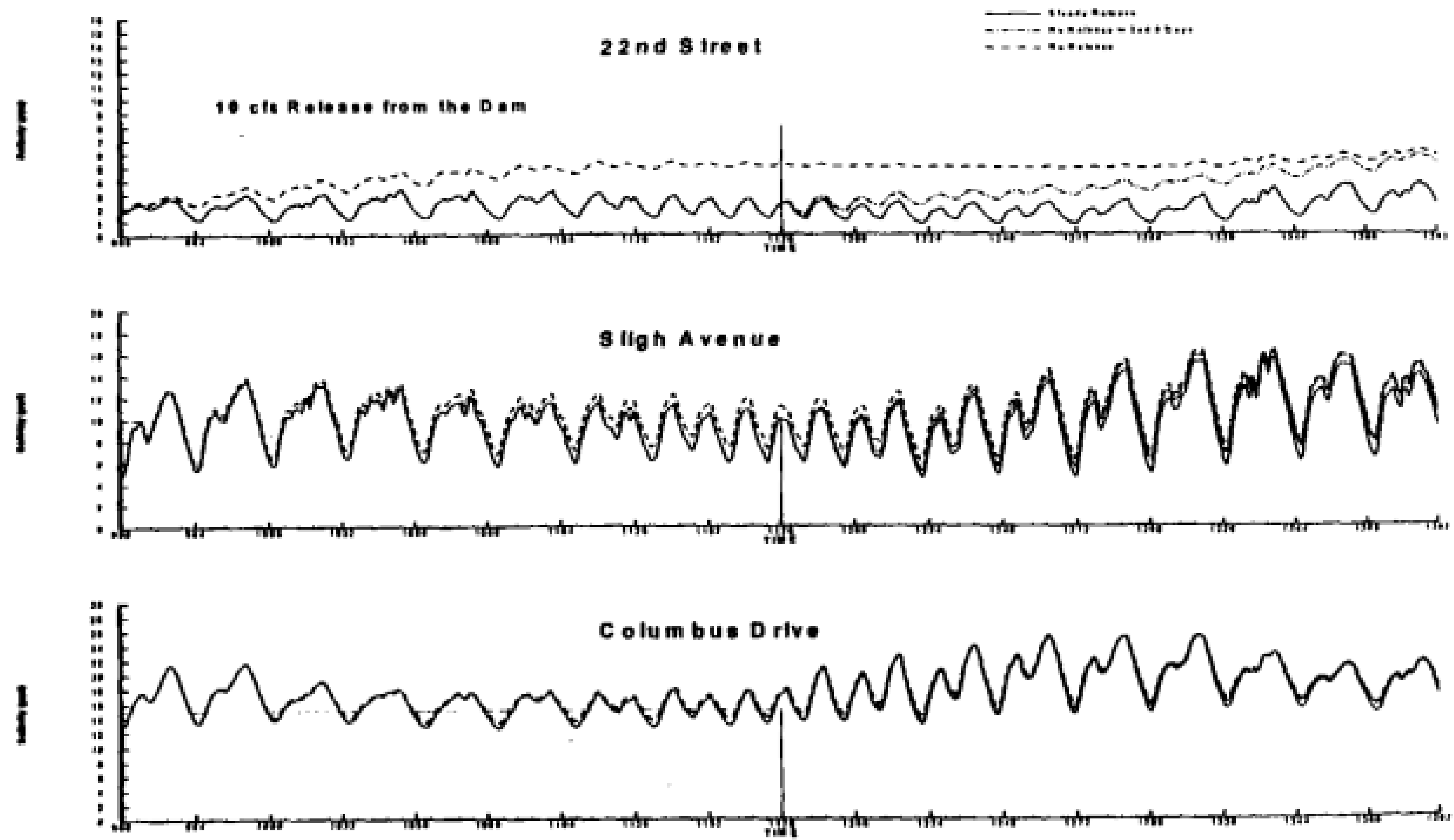


Figure D-1 Comparisons of simulated salinity for Schedule 1a (10 cfs in the first 9 days and 0 cfs in the second 9 days) to those of continuous releases of 10 cfs and 0 cfs.

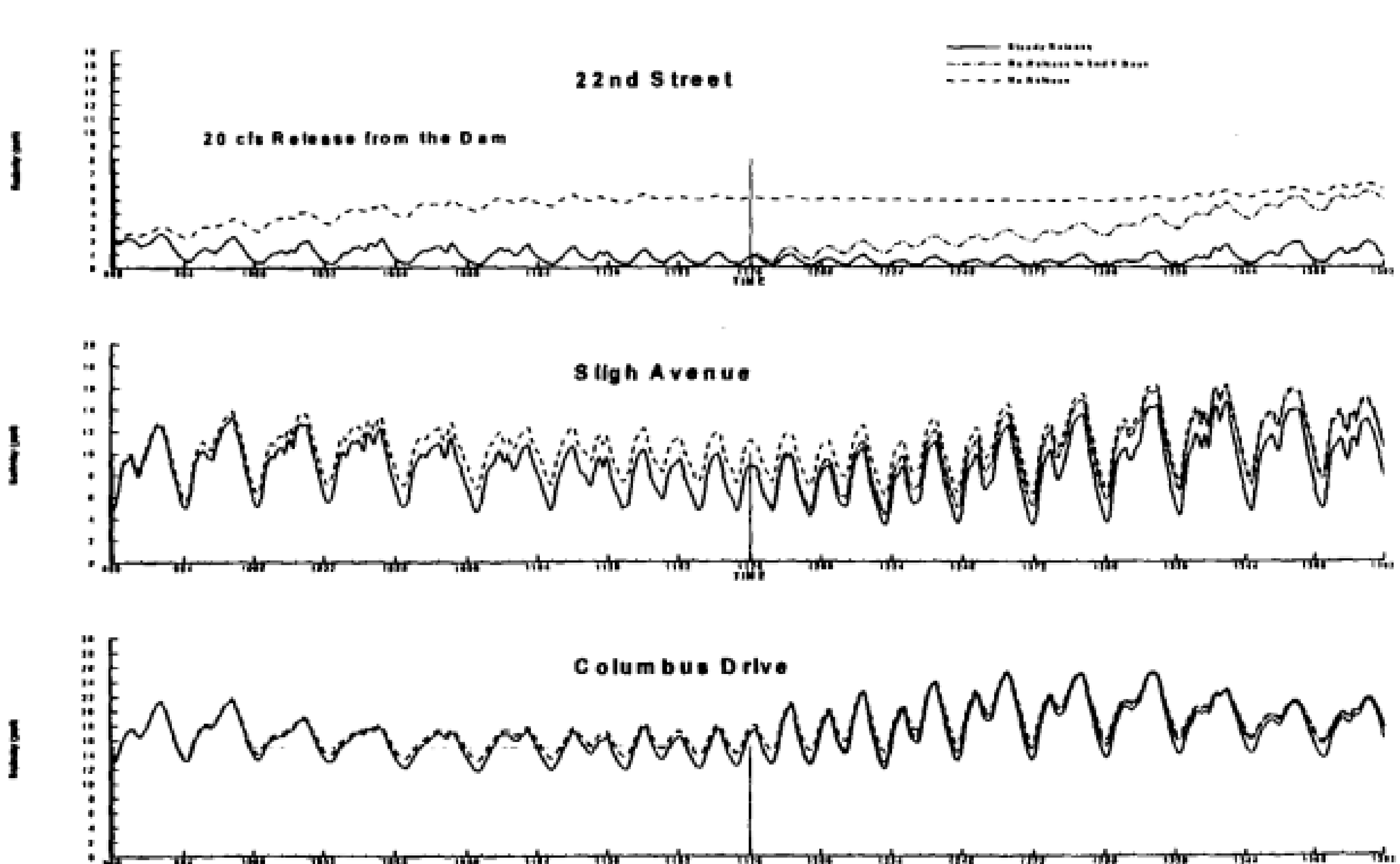


Figure D-2 Comparisons of simulated salinity for Schedule 1b (20 cfs in the first 9 days and 0 cfs in the second 9 days) to those of continuous releases of 20 cfs and 0 cfs.

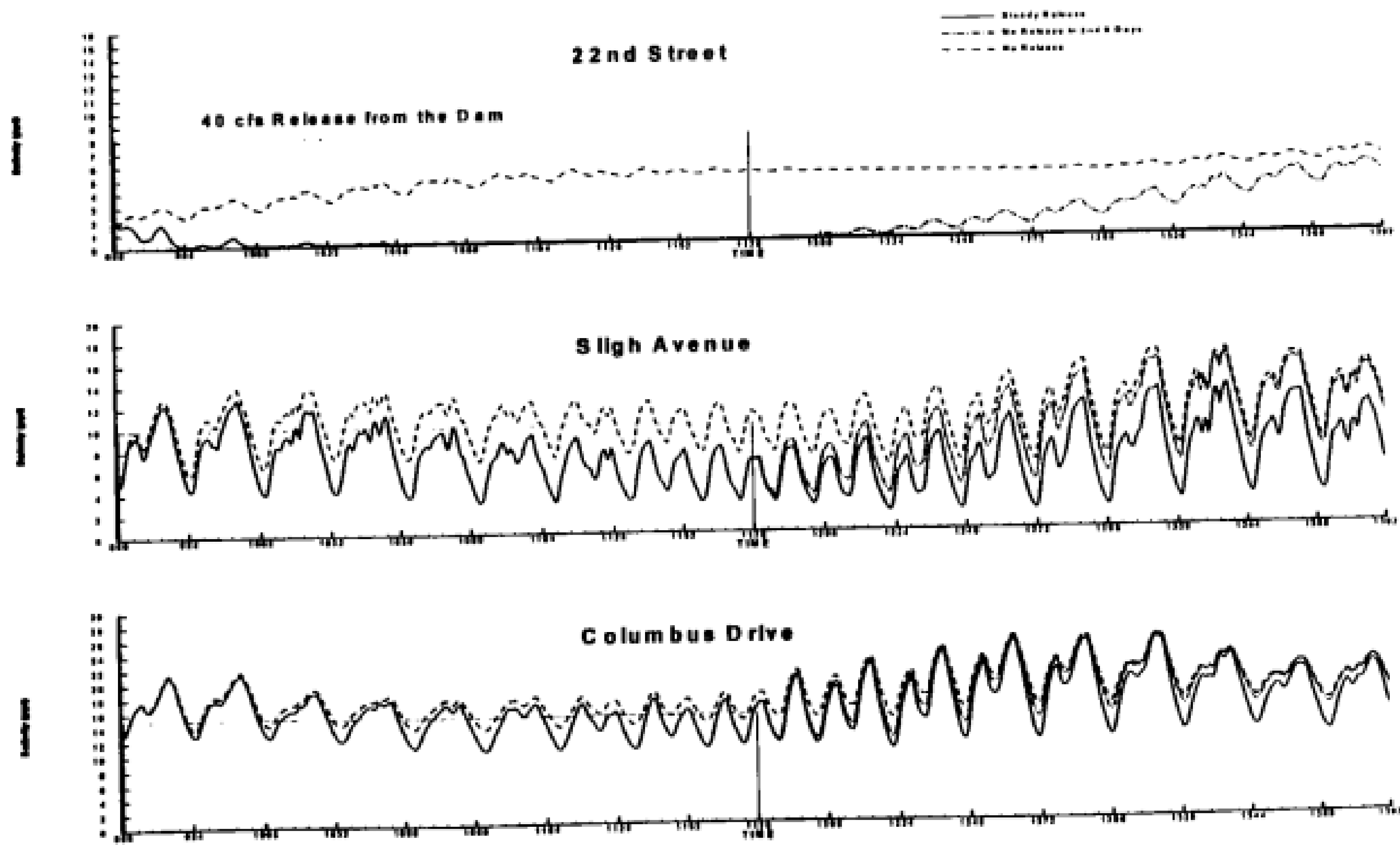


Figure D-3 Comparisons of simulated salinity for Schedule 1c (40 cfs in the first 9 days and 0 cfs in the second 9 days) to those of continuous releases of 40 cfs and 0 cfs.

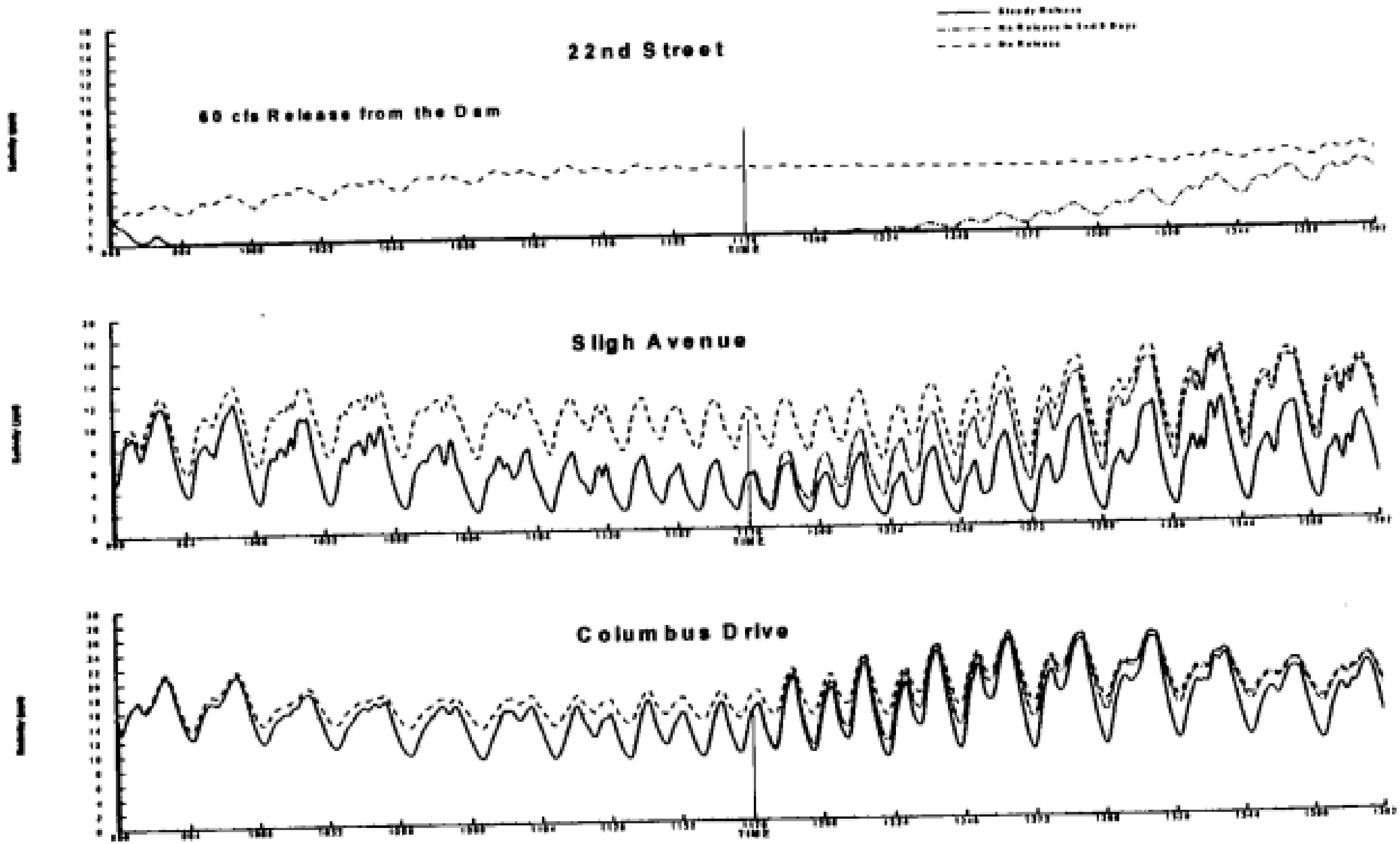


Figure D-4 Comparisons of simulated salinity for Schedule 1d (60 cfs in the first 9 days and 0 cfs in the second 9 days) to those of continuous releases of 60 cfs and 0 cfs.

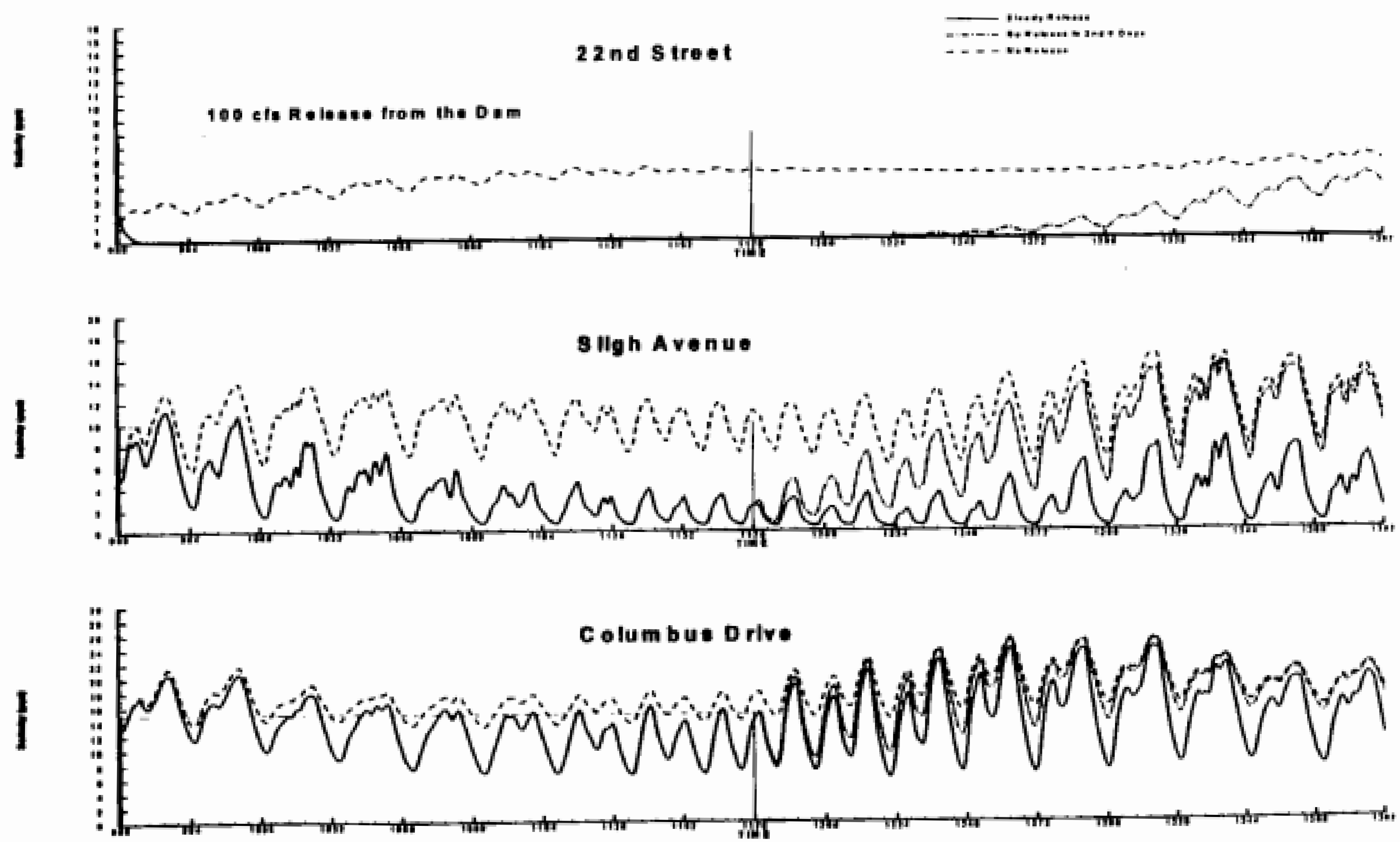


Figure D-5 Comparisons of simulated salinity for Schedule 1e (100 cfs in the first 9 days and 0 cfs in the second 9 days) to those of continuous releases of 100 cfs and 0 cfs.

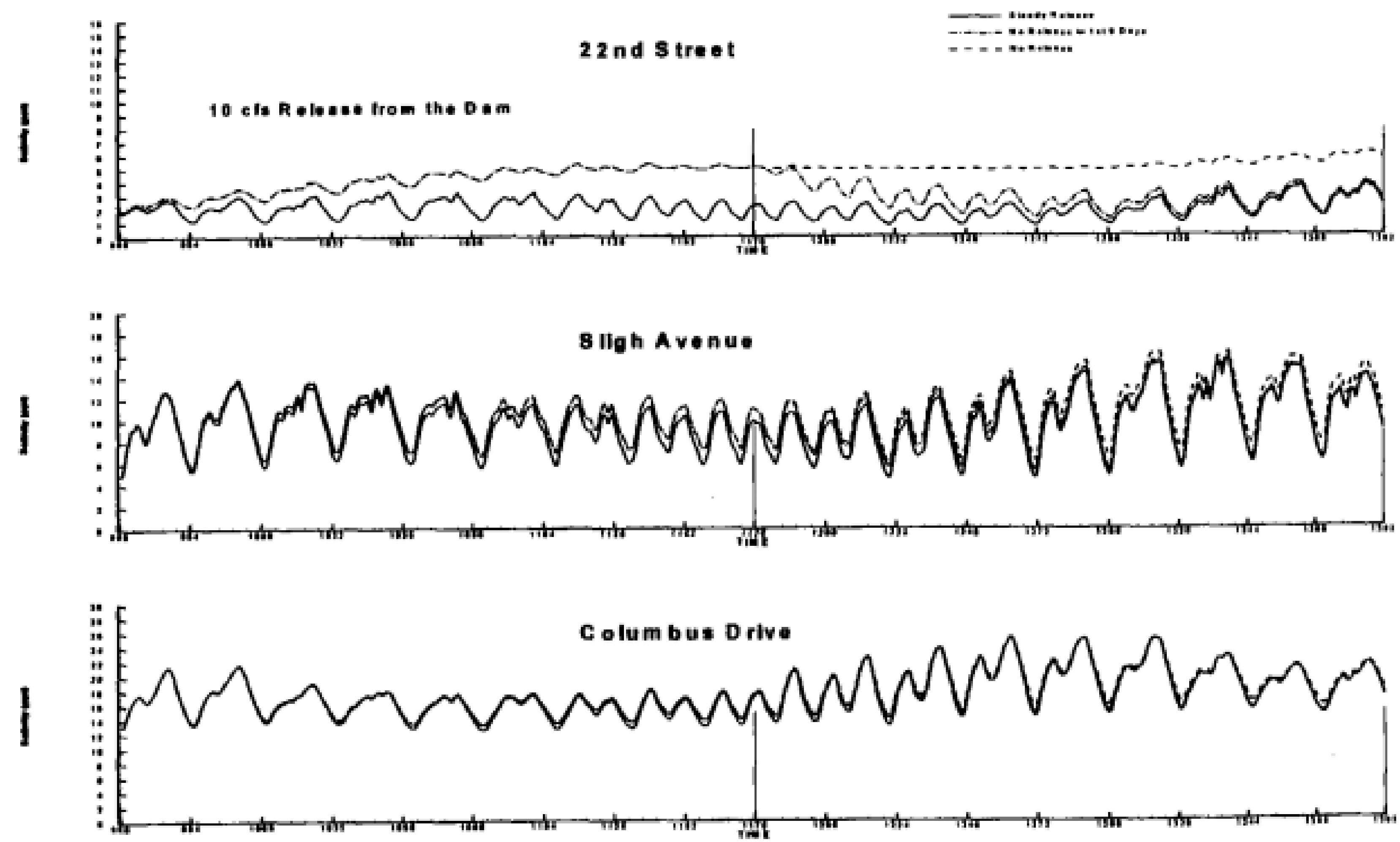


Figure D-6 Comparisons of simulated salinity for Schedule 2a (0 cfs in the first 9 days and 10 cfs in the second 9 days) to those of continuous releases of 10 cfs and 0 cfs.

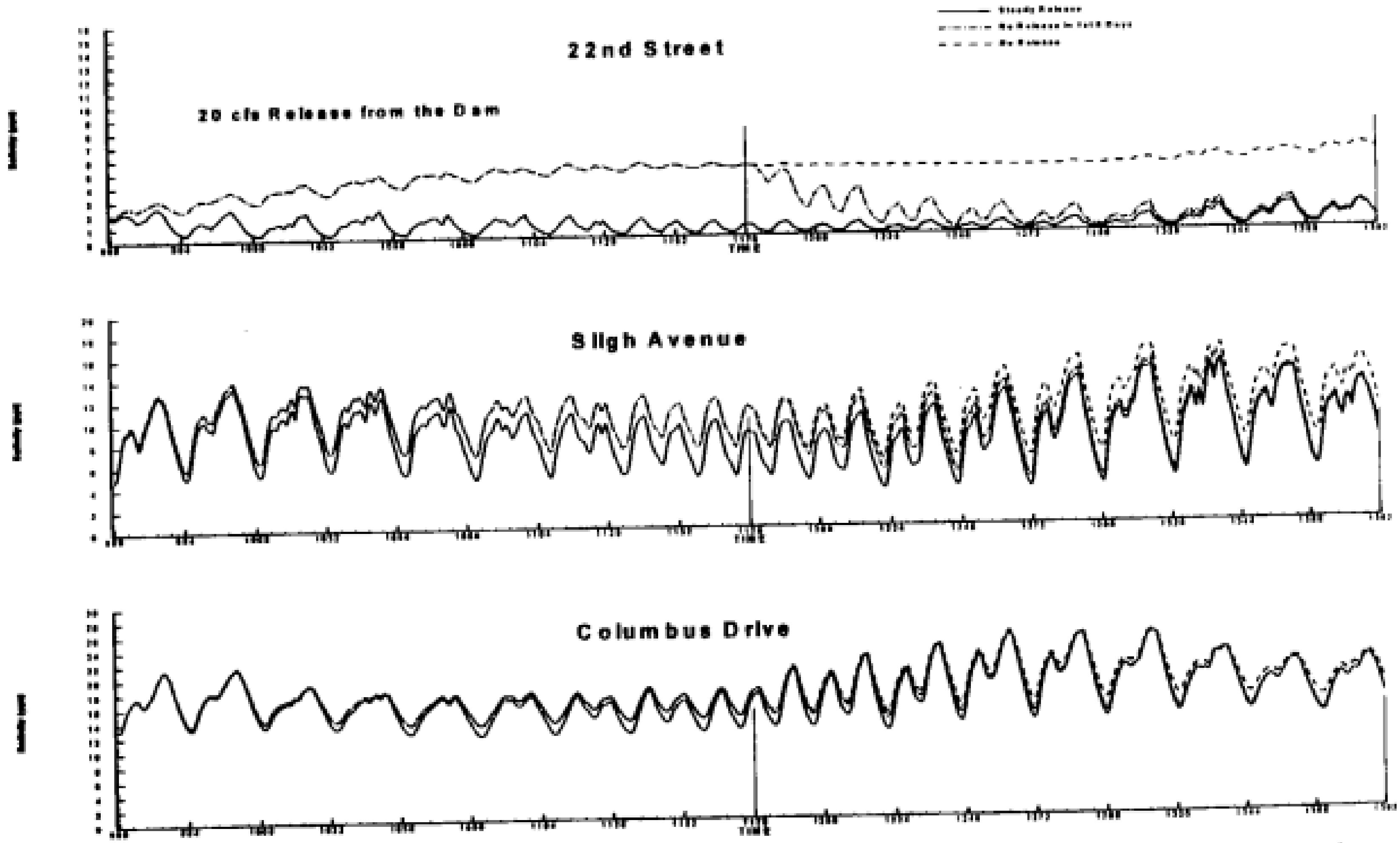


Figure D-7 Comparisons of simulated salinity for Schedule 2b (0 cfs in the first 9 days and 20 cfs in the second 9 days) to those of continuous releases of 20 cfs and 0 cfs.

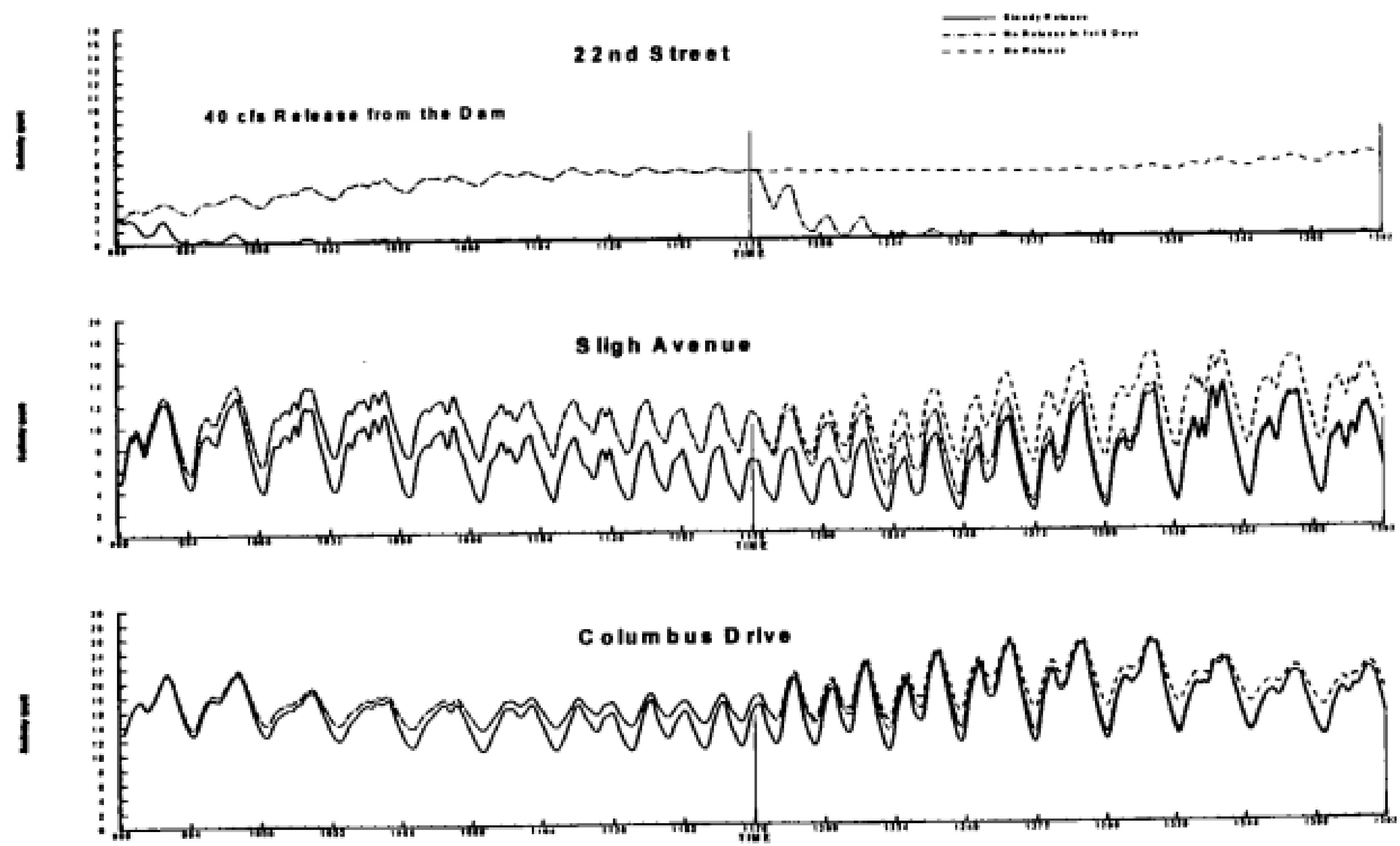


Figure D-8 Comparisons of simulated salinity for Schedule 2c (0 cfs in the first 9 days and 40 cfs in the second 9 days) to those of continuous releases of 40 cfs and 0 cfs.

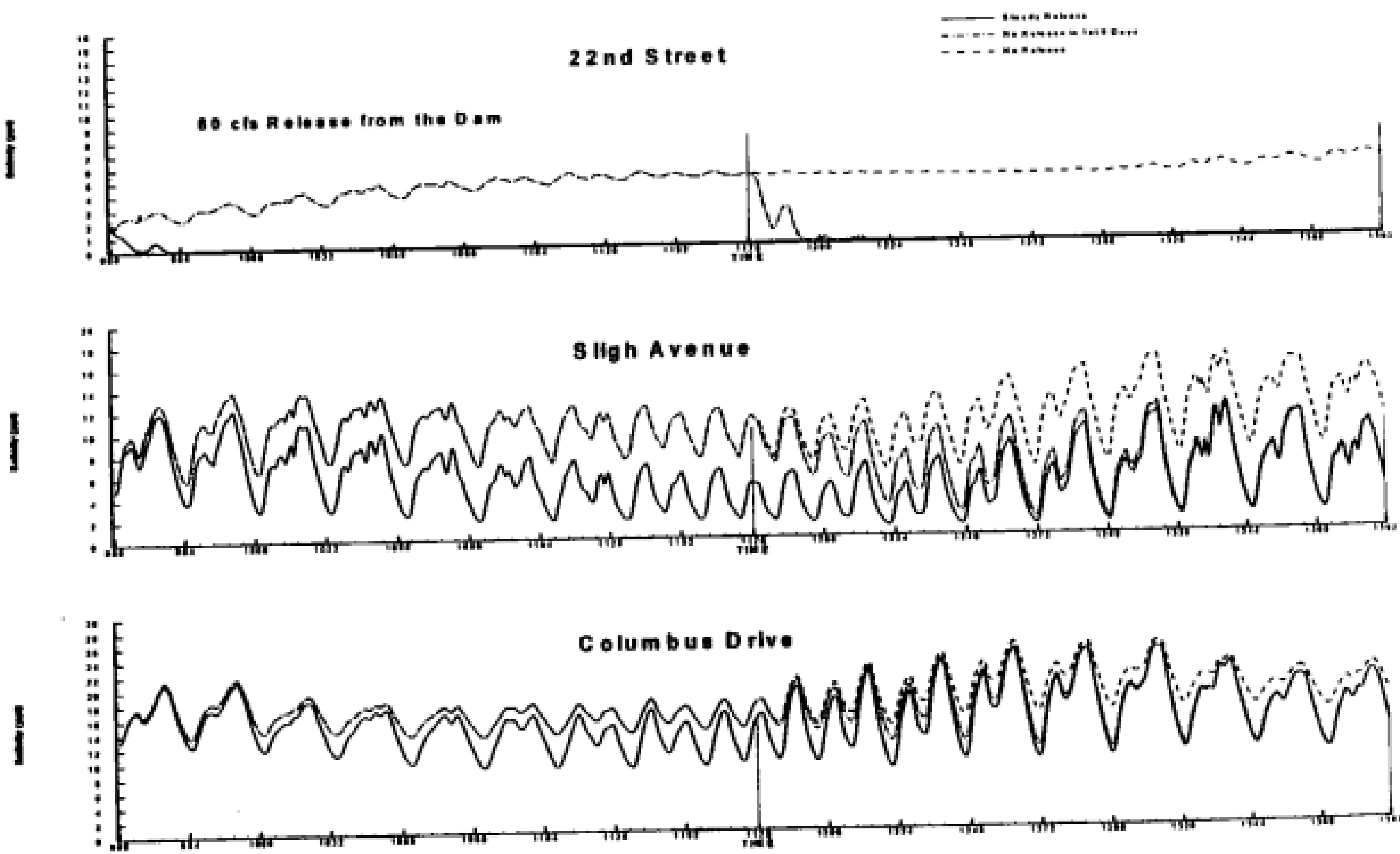


Figure D-9 Comparisons of simulated salinity for Schedule 2d (0 cfs in the first 9 days and 60 cfs in the second 9 days) to those of continuous releases of 60 cfs and 0 cfs.

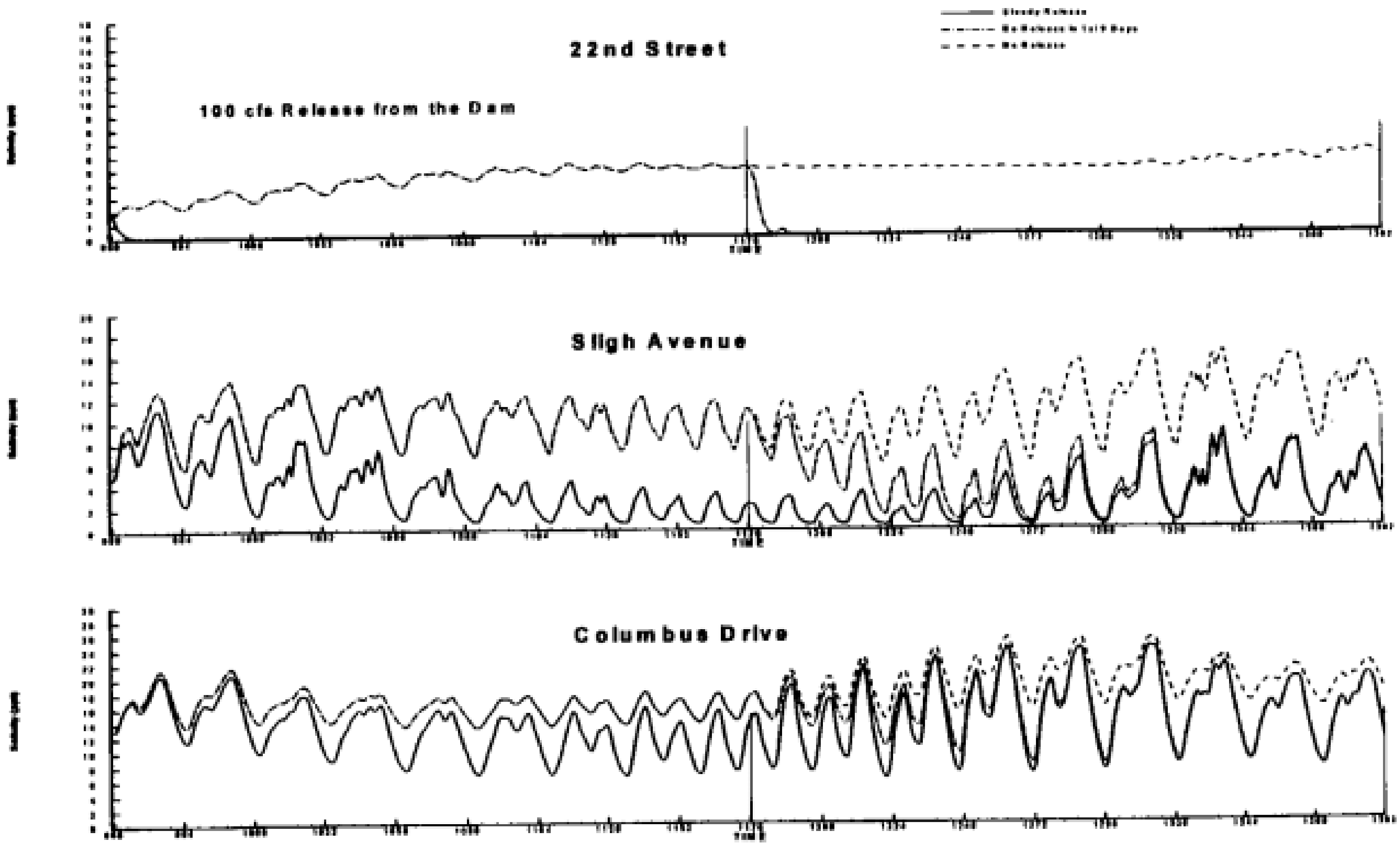


Figure D-10 Comparisons of simulated salinity for Schedule 2e (0 cfs in the first 9 days and 100 cfs in the second 9 days) to those of continuous releases of 100 cfs and 0 cfs.

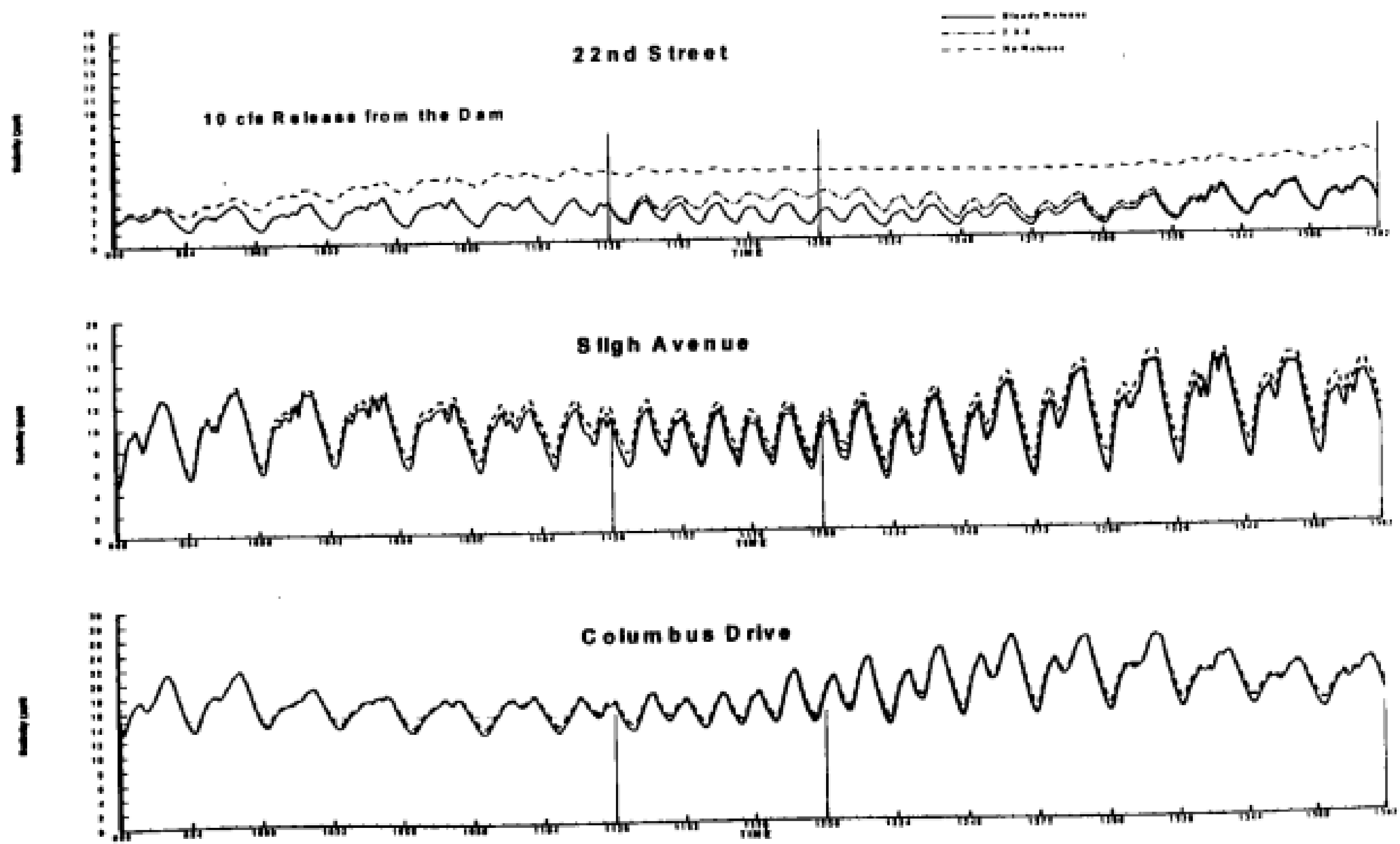


Figure D-11 Comparisons of simulated salinity for Schedule 3a (10 cfs in the first seven days, 0 cfs in Days 8 through 9, and 10 cfs for Days 10 through 18) to those of continuous releases of 10 cfs and 0 cfs.

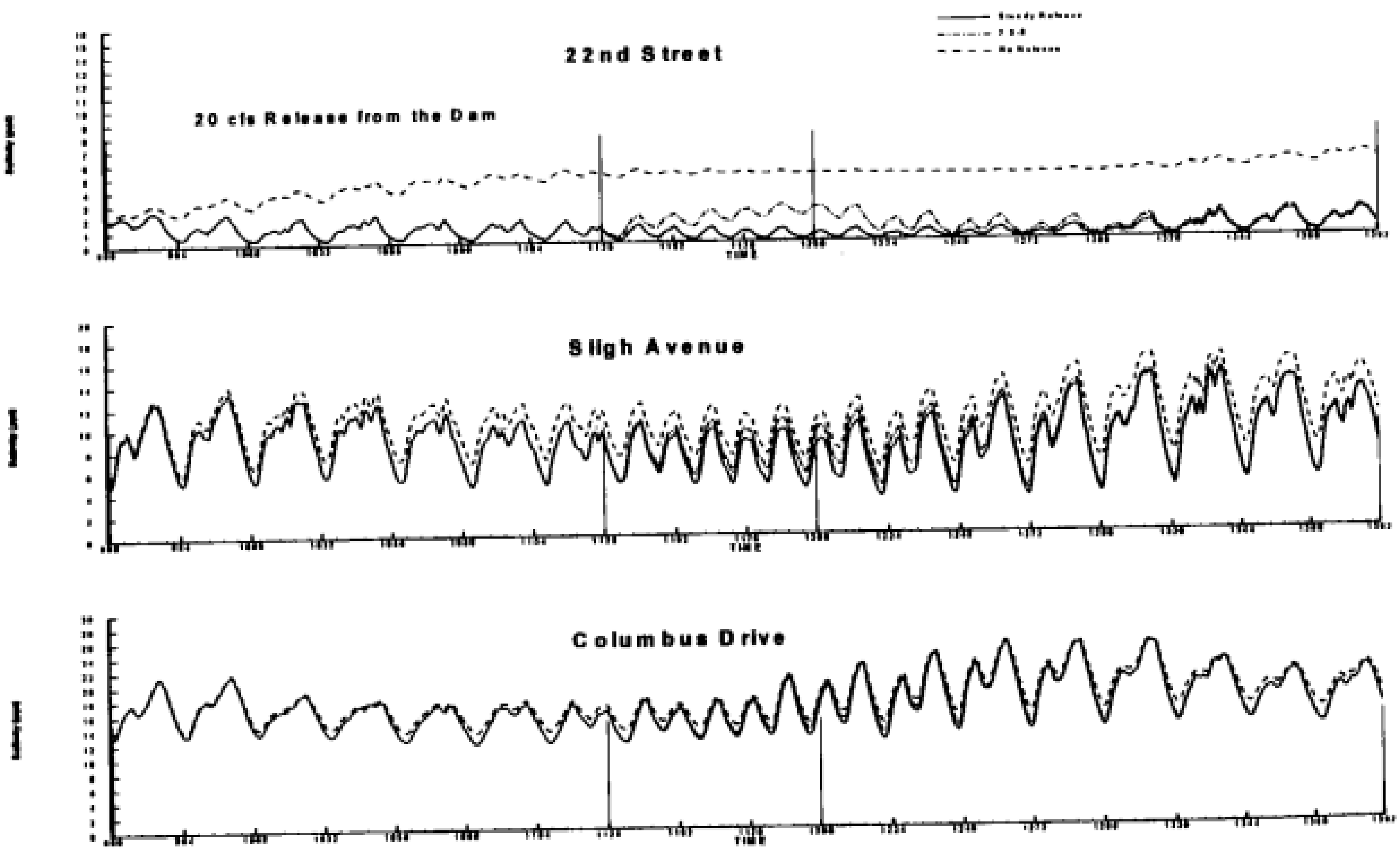


Figure D-12 Comparisons of simulated salinity for Schedule 3b (20 cfs in the first seven days, 0 cfs in Days 8 through 9, and 20 cfs for Days 10 through 18) to those of continuous releases of 20 cfs and 0 cfs.

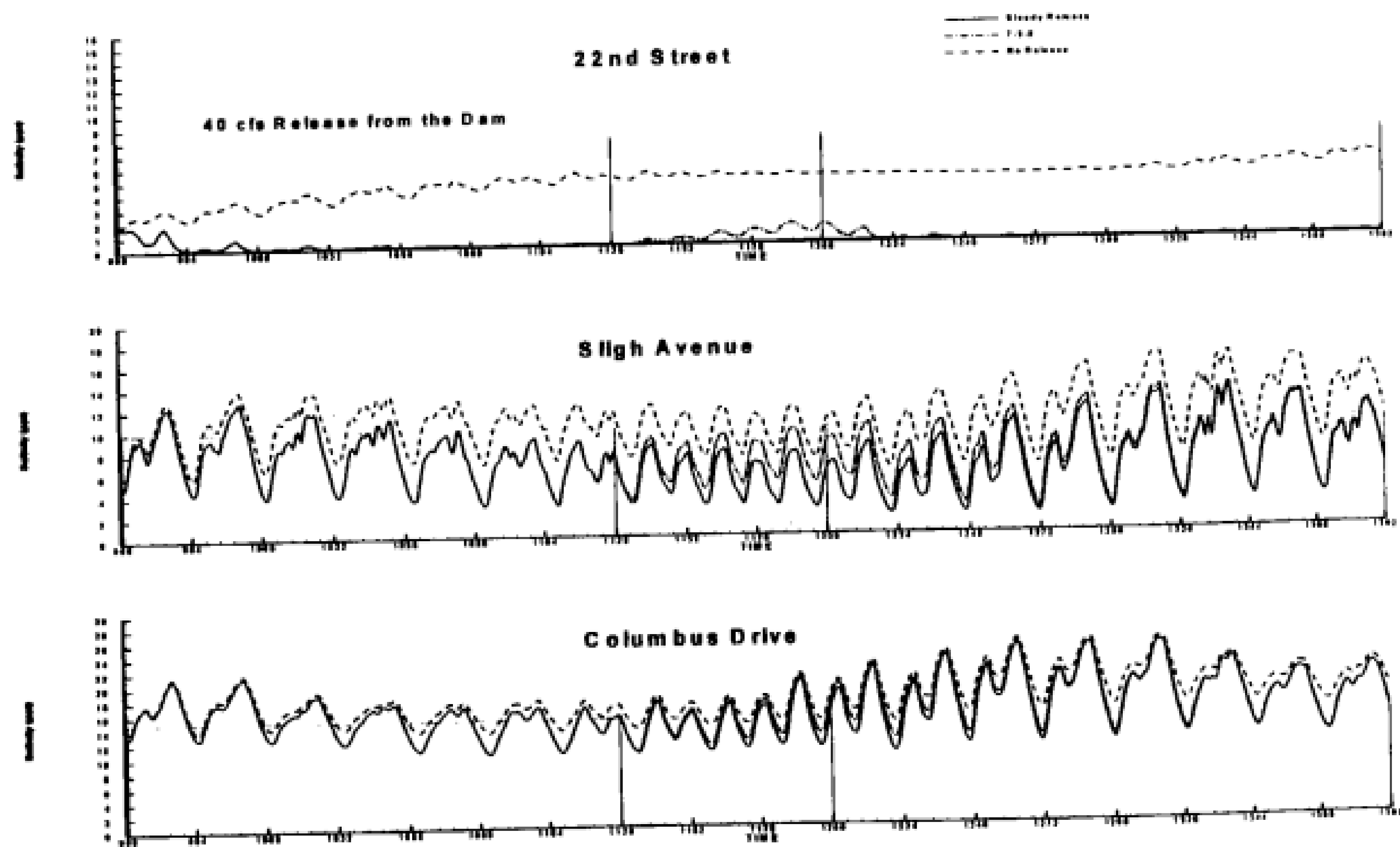


Figure D-13 Comparisons of simulated salinity for Schedule 3c (40 cfs in the first seven days, 0 cfs in Days 8 through 9, and 40 cfs for Days 10 through 18) to those of continuous releases of 40 cfs and 0 cfs.

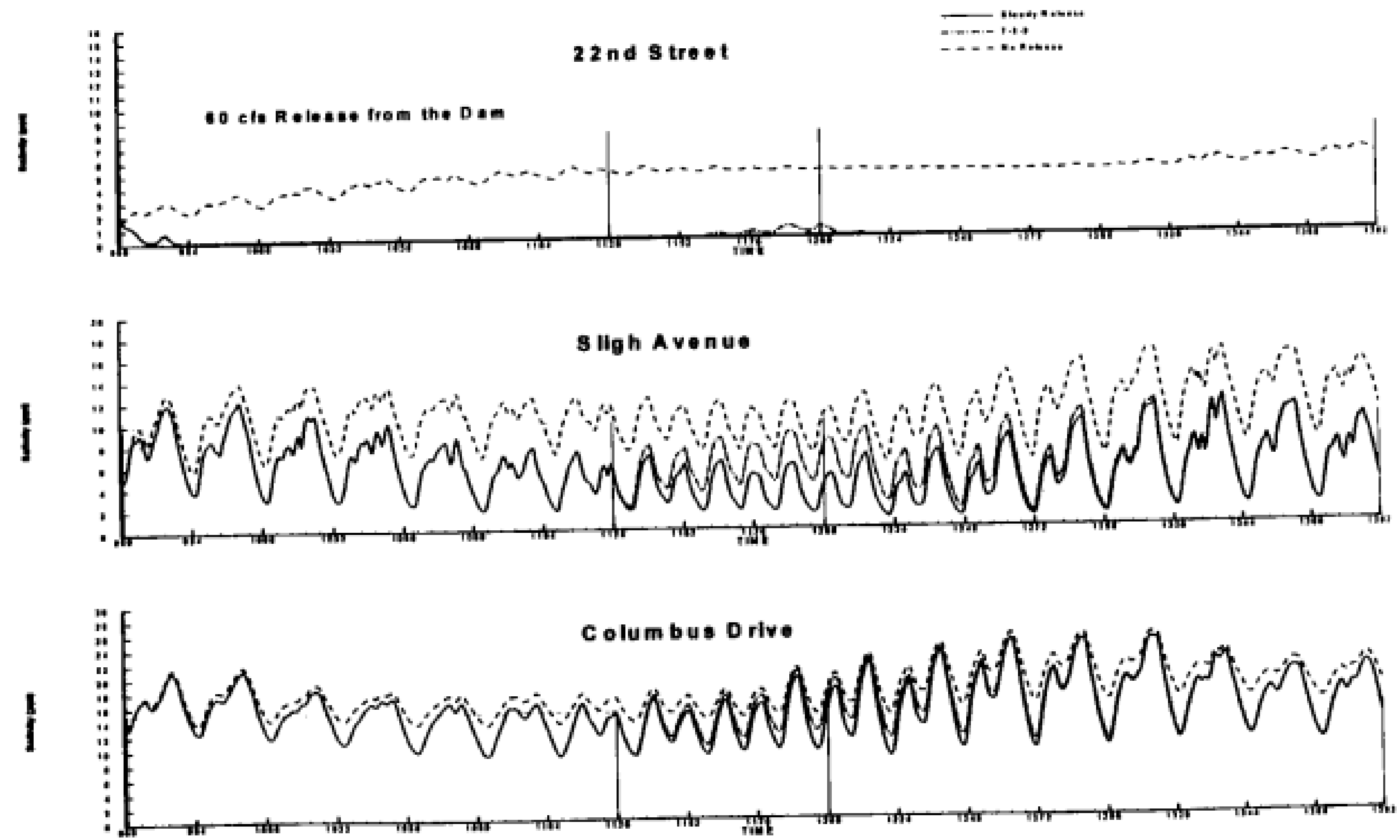


Figure D-14 Comparisons of simulated salinity for Schedule 3d (60 cfs in the first seven days, 0 cfs in Days 8 through 9, and 60 cfs for Days 10 through 18) to those of continuous releases of 60 cfs and 0 cfs.

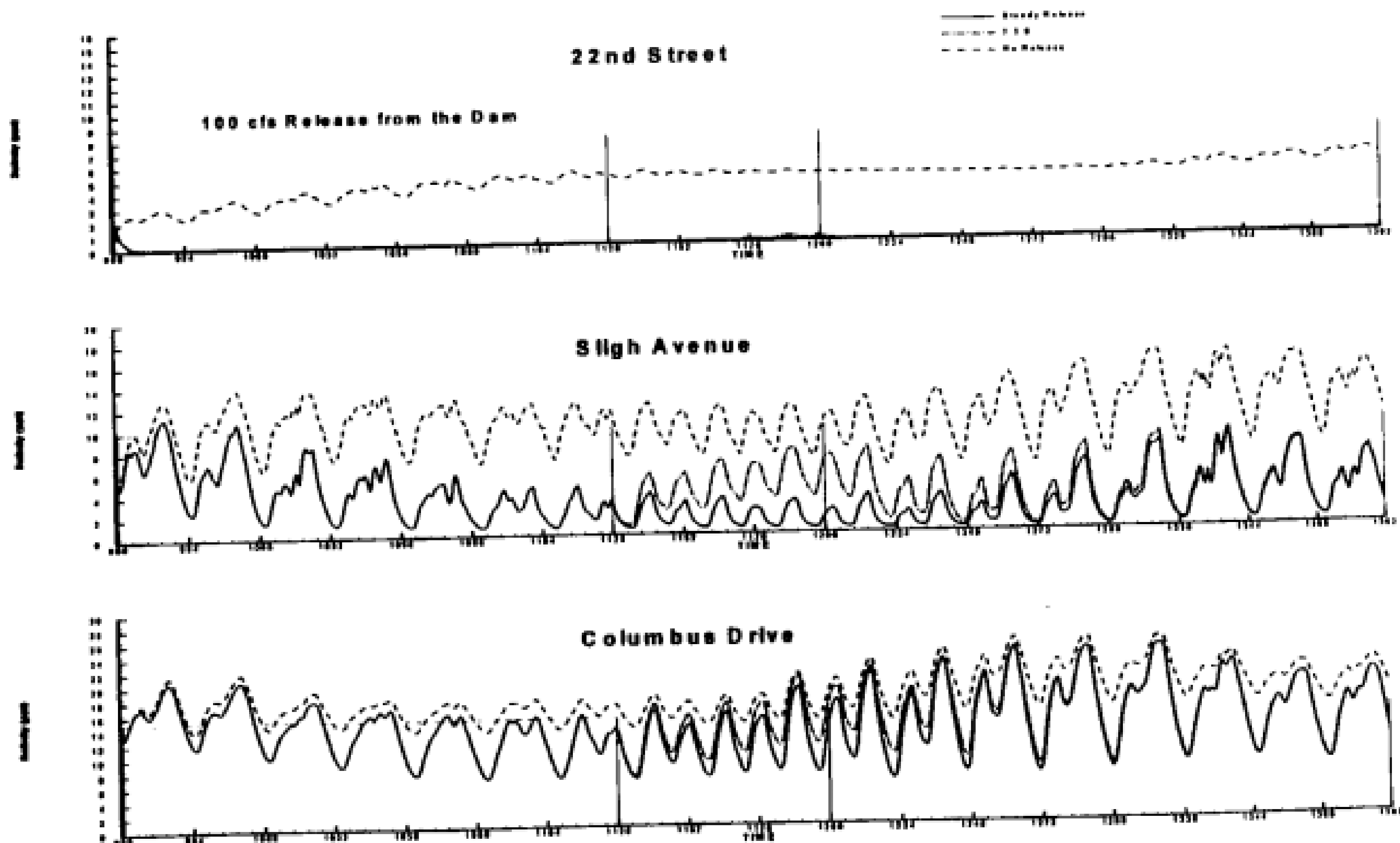


Figure D-15 Comparisons of simulated salinity for Schedule 3e (100 cfs in the first seven days and 0 cfs in Days 8 through 9, and 100 cfs for Days 10 through 18) to those of continuous releases of 100 cfs and 0 cfs.

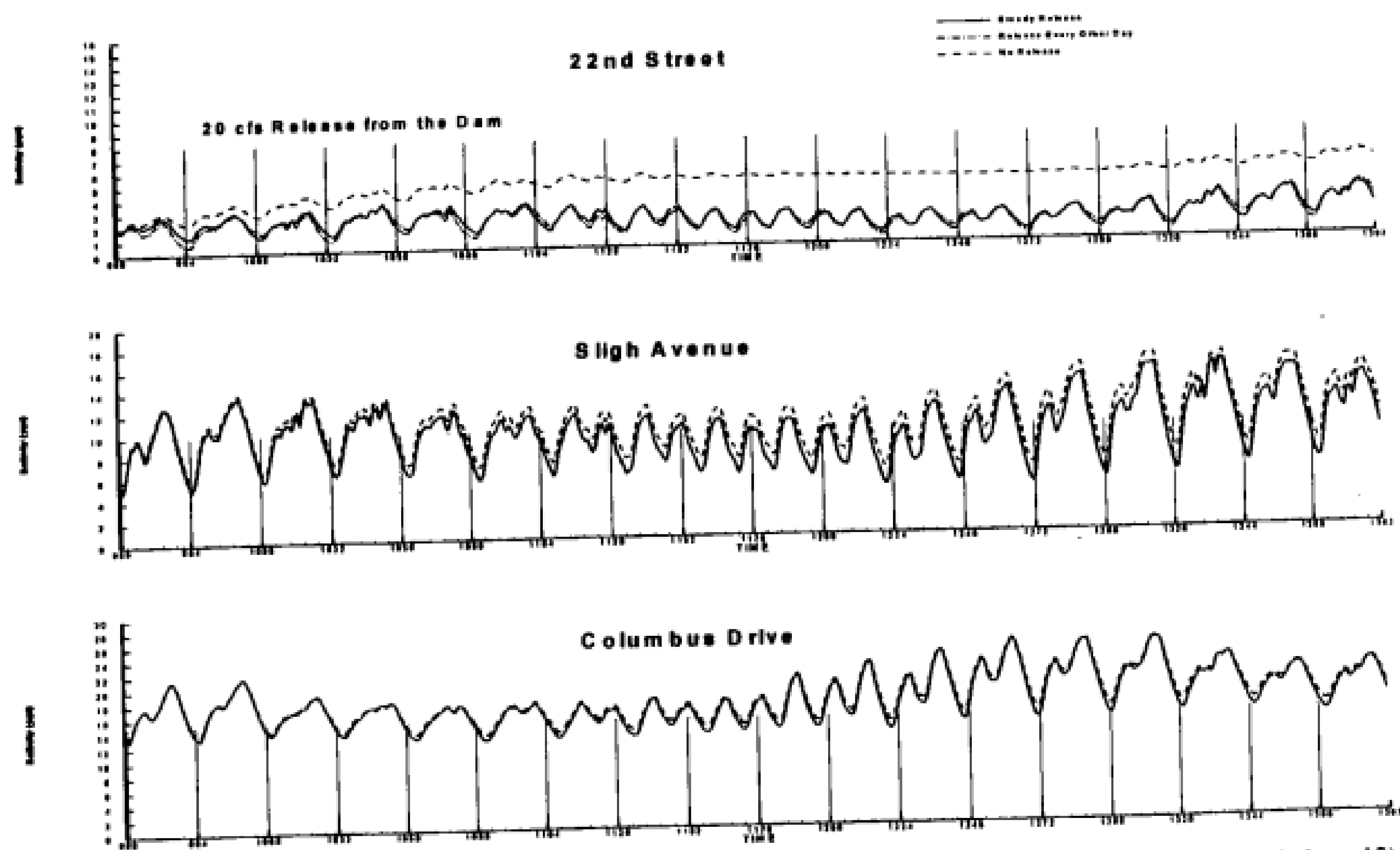


Figure D-16 Comparisons of simulated salinity for Schedule 4a (20 cfs on Days 1, 3, 5, ..., 17, and 0 cfs on Days 2, 4, 6, ..., 18) to those of continuous release of 10 cfs and 0 cfs.

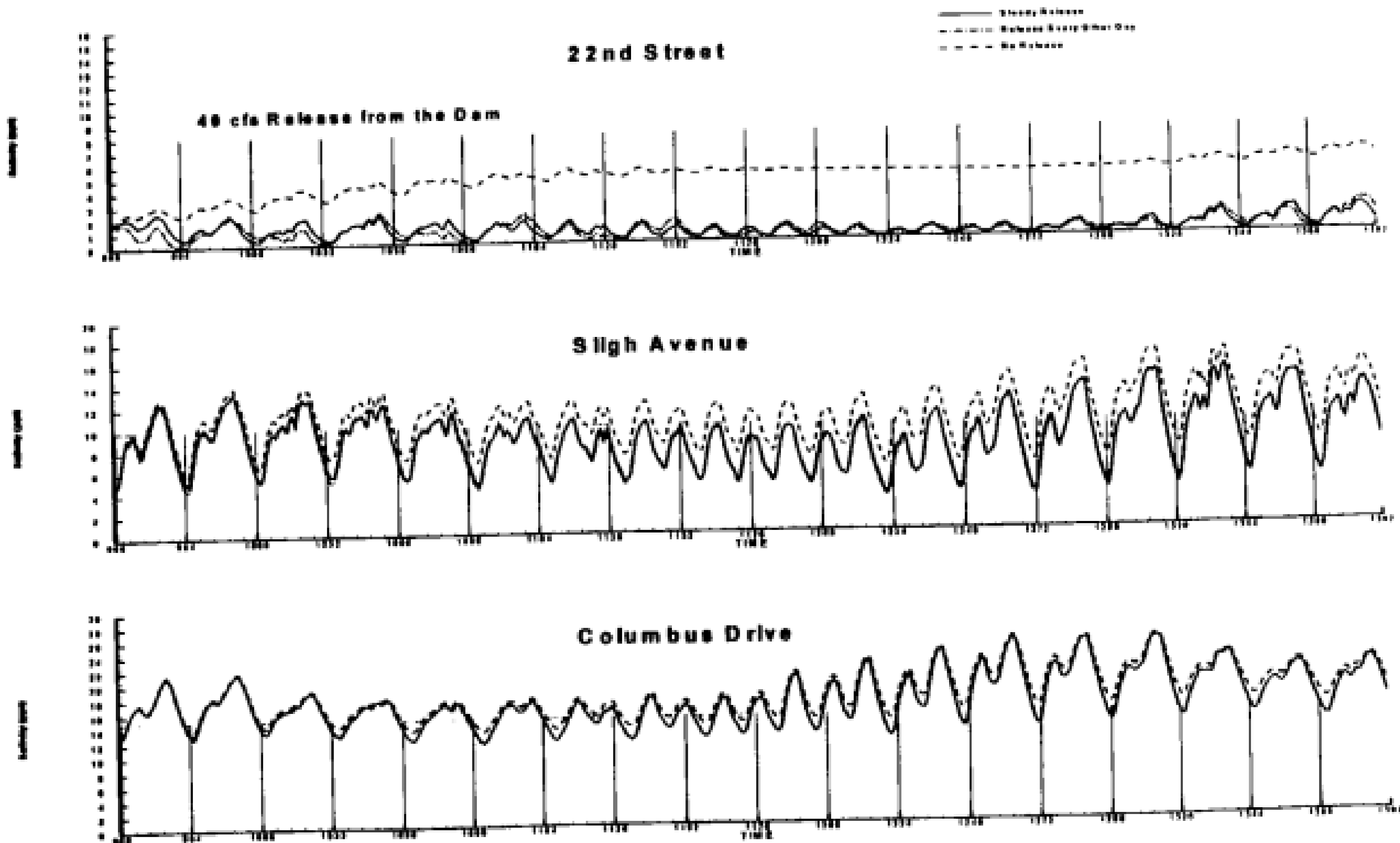


Figure D-17 Comparisons of simulated salinity for Schedule 4b (40 cfs on Days 1, 3, 5, ..., 17, and 0 cfs on Days 2, 4, 6, ..., 18) to those of continuous release of 20 cfs and 0 cfs.

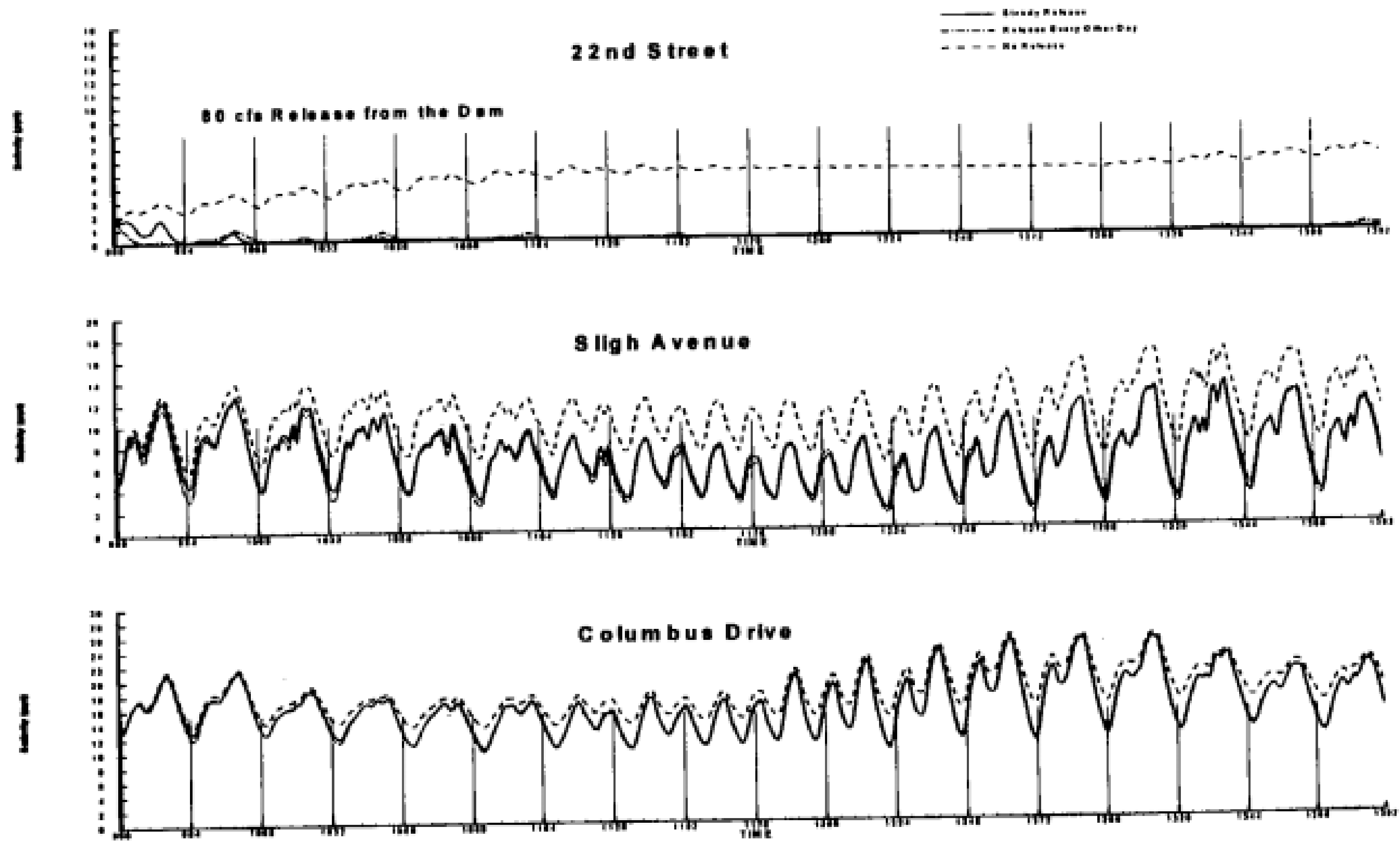


Figure D-18 Comparisons of simulated salinity for Schedule 4c (80 cfs on Days 1, 3, 5, ..., 17, and 0 cfs on Days 2, 4, 6, ..., 18) to those of continuous release of 40 cfs and 0 cfs.

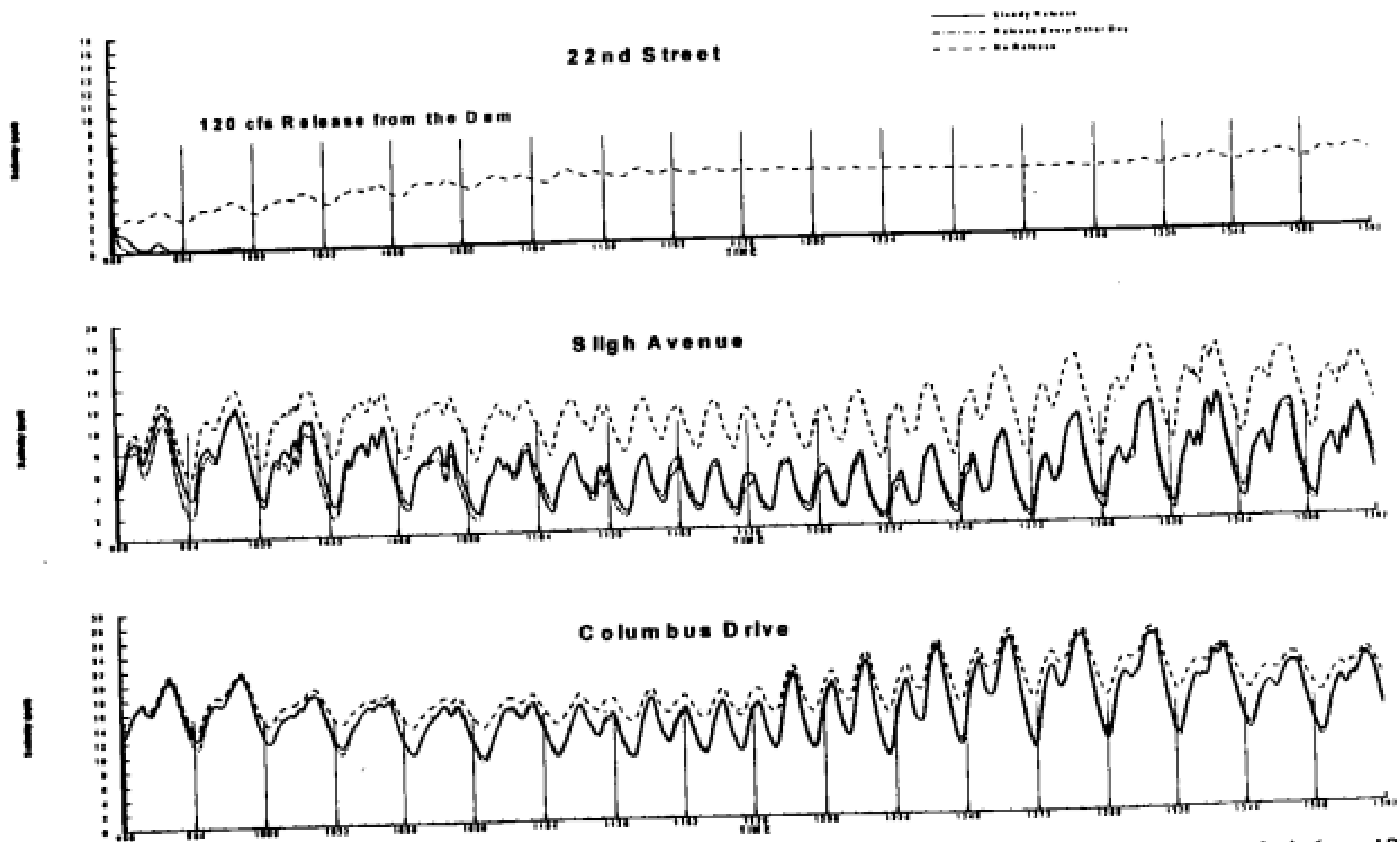


Figure D-19 Comparisons of simulated salinity for Schedule 4d (120 cfs on Days 1, 3, 5, ..., 17, and 0 cfs on Days 2, 4, 6, ..., 18) to those of continuous release of 60 cfs and 0 cfs.

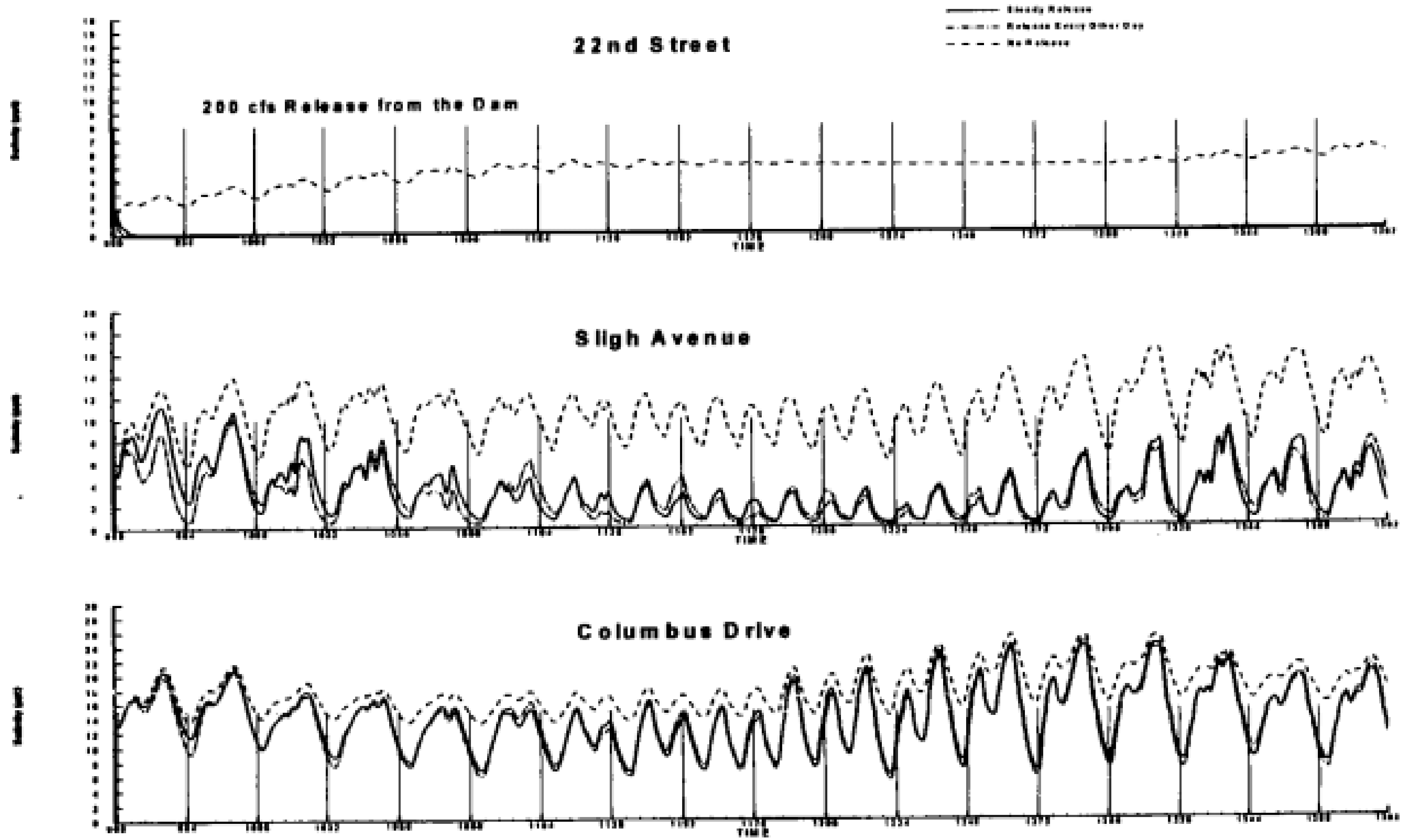


Figure D-20 Comparisons of simulated salinity for Schedule 4e (200 cfs on Days 1, 3, 5, ..., 17, and 0 cfs on Days 2, 4, 6, ..., 18) to those of continuous release of 100 cfs and 0 cfs.