R. Gonzales
P-314

Federal Emergency Management Agency
Region X Federal Regional Center Bothell, Washington 98011

OCT 4 1984

Charlie Trammell
Mail Stop 428
Nuclear Regulatory Commission
Washington, D.C. 20555

Dear Charlie:

Following up our recent telephone conversation, enclosed you will find one copy of the U.S. Geological Survey's report entitled, "Impact of an Outburst of Spirit Lake on the Columbia River." This report further substantiates information provided to you in an earlier letter from Les Laird, the District Chief of the State Office of the U.S.G.S. in Tacoma. Please contact either Dick Donovan or me if you need additional information.

Sincerely,

Charles L. Steele

Charles L. Steele, Chief
Natural and Technological
Hazards Division

Enclosure

UNITED STATES
DEPARTMENT OF THE INTERIOR
GEOLOGICAL SURVEY
Water Resources Division
Pacific Northwest District
1201 Pacific Avenue - Suite 600
Tacoma, Washington 98402

September 24, 1984

Ms. Joan Hodgins
Federal Emergency Management Agency
Region X
Federal Regional Center
Bothell, Washington 98011

Dear Ms. Hodgins:

As discussed in our recent telephone conversation, enclosed is one copy of the USGS report "Impact of an Outburst of Spirit Lake on the Columbia River."

Sincerely yours,

L. B. Laird
District Chief

Enclosure

UNITED STATES
DEPARTMENT OF THE INTERIOR
GEOLOGICAL SURVEY

IMPACT OF AN OUTBURST OF SPIRIT LAKE ON THE COLUMBIA RIVER

U.S. GEOLOGICAL SURVEY

Water-Resources Investigations Report_____

Prepared in cooperation with the

U.S. FEDERAL EMERGENCY MANAGEMENT AGENCY

UNITED STATES
DEPARTMENT OF THE INTERIOR
GEOLOGICAL SURVEY

IMPACT OF AN OUTBURST OF SPIRIT LAKE ON THE COLUMBIA RIVER

By W. G. Sikonia

U.S. GEOLOGICAL SURVEY

Water-Resources Investigations Report_____

776-7476

Prepared in cooperation with the

U.S. FEDERAL EMERGENCY MANAGEMENT AGENCY

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UNITED STATES DEPARTMENT OF THE INTERIOR

WILLIAM P. CLARK, Secretary

GEOLOGICAL SURVEY

Dallas L. Peck, Director

For additional information write to:

District Chief
U.S. Geological Survey
1201 Pacific Avenue - Suite 600
Tacoma, Washington 98402-4384

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The Trojan Intake is located at mile 72.4

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IMPACT OF AN OUTBURST OF SPIRIT LAKE ON THE COLUMBIA RIVER

By William G. Sikonia

ABSTRACT

A one-dimensional sediment-transport computer model was used to study the effects of an outburst of Spirit Lake on the Columbia River. According to the model, for an average flow of 233,000 cubic feet in the Columbia River, flood sediment discharge to the Columbia from the Cowlitz would form a blockage to a height of 44 feet above the current streambed of the Columbia River, corresponding to a new streambed elevation of -3 feet, that would impound the waters of the Columbia River. Water surface elevations would continue to increase for 16 days after the blockage has been formed. The river elevation at the Trojan nuclear power plant, 5 miles upstream of the Cowlitz River, would rise to 32 feet, compared to a critical elevation of 45 feet, above which the plant would be flooded. For comparison, the Columbia River at average flow without the blockage has an elevation at this location of 6 feet. Correspondingly high water surface elevations would occur along the river to Bonneville Dam, with that at Portland, Oregon, for example, rising also to 32 feet, compared to 10 feet without the blockage. If there were a simultaneous 2 year flood of 410,000 cubic feet per second on the Columbia River, the river elevations would rise for 14 days to elevations of 38 feet at Trojan and 39 feet at Portland, compared to elevations of 11 and 16 feet respectively, for such a Columbia River flood without the blockage. For a simultaneous 100 year flood of 850,000 cubic feet per second on the Columbia River, water surface elevations would continue to rise for 10 days to elevations of 44 feet at Trojan and 45 feet at Portland, compared to 21 and 26 feet respectively, for such a flood without the blockage.

INTRODUCTION

Devastating inundation along the Toutle and Cowlitz Rivers (figure 1), resulting from a hypothetical outburst of Spirit Lake through the debris avanlanche that currently contains it, has been predicted by earlier modeling efforts. Swift and Kresch (1983) described the effects on the Toutle and Cowlitz Rivers to the confluence with the Columbia, and Kresch and Laenen (1983) investigated the effect such an outburst would have on the Trojan Nuclear Power plant on the Columbia River in Oregon. Bissel and Hutcheon (1983) studied these reaches also, as well as the lower Columbia River that is the subject of this report, but did not model the dynamics of the sediment transport there. The focus of the present study is the distribution and timing of the sedimentation and flooding along the entire lower Columbia, which need to be better defined in order to assess the impact upon public safety and the regional economy.

Figure 1

This study is being done at the request of the Federal Emergency Management Agency (FEMA), so that they can plan for the disruption such an event would cause. A sediment transport model is used to investigate the impact of such an outburst flood on the Columbia River from Bonneville Dam to its mouth. The application is part of a longer-term project to develop a sediment transport model, or set of models, that allow more comprehensive and accurate modeling than is now possible with existing models. A one-dimensional sediment transport model written by D. L. Fread of the National Weather Service was chosen, and was edited and modified in bringing it to bear in this situation. The model's base is the Operational Dynamic Wave Model (DWOPER) (Fread; 1978, 1982) used by the National Weather Service for flood and day-to-day river forcasting, to which sediment tranport has been added.

ASSUMPTIONS

Swift and Kresch, and Kresch and Leanen made assumptions that would produce some of the worst flooding and inundation levels along the Toutle and Cowlitz Rivers. The aim of the present study is to arrive at a likely scenario based on more probable conditions. Swift and Kresch assumed a bulk volume of 2.4 billion cubic yards (bcy) of debris material would be entrained by an outburst of Spirit Lake, based on adding enough debris material to 0.51 bcy of water from Spirit Lake to yield 65 percent sediment concentration by volume. Based on field measurements, the debris porosity and degree of saturation were assumed to be 32 and 50 percent, respectively, so the 2.4 bcy of bulk debris material added 2.4 bcy x (1. - 0.32) = 1.63 bcy of solids, and 2.4 bcy x 0.32 x 0.50 = 0.38 bcy of pore water. The degree of saturation of the debris is presently (1984) 90, rather than 50 percent, and it would be impossible to bulk the flow to 65 percent sediment concentration as in the earlier study. Even inclusion of the entire 3 bcy of avalanche material, which is not anticipated, would provide 3 bcy x (1.-0.32) = 2.04 bcy of solids, but would add 3 bcy x 0.32 x 0.90 = 0.86 bcy of water to the 0.51 bcy from Spirit Lake, for a solids concentration of 2.04/(2.04 + 0.86 + 0.51) = 60 percent by volume. This study will assume the value of 1.3 bcy of bulk material as a reasonable fraction of the total avalanche material of 3 bcy to be scoured and entrained in the flow on its path down-valley from Spirit Lake, but will include the water contained in this material, namely 1.3 x 0.32 x 0.90 = 0.37 bcy in the total volume flowing downstream. To summarize, it will be assumed that 1.3 bcy x (1. - 0.32) = 0.88 bcy of solids, and 0.37 + 0.51 = 0.88 bcy of water, will be incorporated in the flood at the debris avalanche, for a total volume of 1.76 bcy and a sediment concentration of 50 percent by volume.

In their study Swift and Kresch, making largely conservative assumptions, considered no sediment deposition from a mudflow along the Toutle and Cowlitz valleys. This study will assume that 60 percent of the solids will be deposited in the these valleys. This deposition would seem to follow the pattern that can be ascertained from previous mudflows (Dinehart, 1984). For example, for the March 19-20, 1982 mudflow, 12 percent of the fines (material less than 0.062 millimeters in diameter) and 46 percent of the larger material, for an average of 36 percent of the total material, was deposited in the reach of the North Fork Toutle and Toutle Rivers between Kid Valley and Highway 99, a distance of 20 miles. From Highway 99 to the confluence of the Columbia River is another 21 miles, and although the tracking the small event of March 19-20, 1982 became difficult in this lower reach because of mixing with the flow of the Cowlitz River, a large mudflow due to the outburst of Spirit Lake could be expected to form additional deposits there. Note the preferential deposition of the larger sediment particles of the March 19-20, 1982 mudflow: at Kid Valley, fines account for 29 percent of the sediment in transport, and larger material the remaining 71 percent. When the mudflow reaches Highway 99, the fines account for 40 percent of the transported material.

The deposition of the larger particle sizes can also be deduced theoretically using Shield's criterion for incipient motion of sediment particles (Graf, 1971), given by

$$F = t/((w_s - w)\, d) \qquad (1)$$

where

$$t = w\ h\ S \qquad (2)$$

is the shear stress on the bed, and

w_s = specific weight of the sediment particles

w = specific weight of water

d = particle diameter

h = hydraulic radius

S = slope

F = fct(u* d/v) = a dimensionless function

u* = shear velocity

v = fluid viscosity

For application to the Toutle and Cowlitz Rivers, F can be taken as 0.047, and we also assume that w can be generalized to specfic weight of the mixture, for the hyperconcentrated flows under consideration here, rather than just the specific weight of water. The specific gravity of the sediment particles is approximately 2.65. For a sediment concentration of 50 percent by volume, the specific gravity of the mixture is 1.83, and for a sediment concentration of 42 percent, it is 1.69. Solving equation x for d provides the following estimates of maximum particle sizes that one can expect to be transported.

Table 1 >

Table 1 again points out that, at least for hyperconcentrated flow, as opposed to debris flow, the larger particle sizes will be deposited before the flood reaches the Columbia River. The composition of the debris avalanche, from U.S.G.S. Professional Paper 1250, is 40 percent coarse (greater than 5 millimeters), 40 percent sand (0.062 to 5 millimeters), and 20 percent fine (less than 0.062 millimeters. Table 1 suggests that the larger particles entrained in the flood near Spirit Lake will be deposited before it reaches the Columbia River. This picture must be modified somewhat in that the front of the flood may be of higher concentration than average, and more in the nature of a non-Newtonian mudflow than the hyperconcentrated flow for which the analysis is valid, since such a rock-matrix supported flow tends to produce deposits that are more unsorted in size. The picture is, however, one to be expected for the flood-averaged sediment concentration. The estimated deposition for the purposes of this study is therefore taken as 60 percent of the material entrained near Spirit Lake. This figure is subject to considerable uncertainty, and an estimated 15 percent standard error would not be unreasonable. Thus the deposits include 0.88 bcy x 0.60 = 0.53 bcy solids, and also retain (0.43/(1.-0.43)) x 0.53 bcy = 0.40 bcy of water in the pore spaces, where a sediment deposition porosity of 43 percent has been used based on sediment samples taken May 20, 1980 (U.S. Army Copra of Engineers, 1981) and recent sediment studies on the Cowlitz River (Lombard, 1984). The remaining material actually entering the Columbia River is 0.88 - 0.53 = 0.35 bcy of sediment, and 0.88 - 0.40 = 0.48 bcy of water, for a total volume of 0.83 bcy, and a sediment concentration of 42 percent by volume.

Swift and Kresch assumed that 30 percent of the sediment reaching the Columbia would be wash load of fine material in suspension that would be carried through to the lower Columbia. In this study, the finest 25 percent of the sediment will be assumed to be wash load. However, the context is somewhat different for this study than in theirs. Wash load usually refers to sediment with particle sizes smaller than represented by the bed material, and subject to uncertain introduction by upstream sources such as bank erosion. For this situation, the material introduced from upstream sources, that is, by the outburst flood, does have a complete size distribution into finely-grained material (that less than 0.062 millimeters). It essentially becomes the bed material of question for this problem, and the pre-existing bed is of little concern. Thus the wash load for this study is not related to vagaries of source, but rather to possible inadequacies of the sediment transport relation to treat very fine material properly when giving the balance between material in the bed, and sediment in transport.

Prior mudflows can provide some guide to the proportion of fine material transported and deposited. On May 19, 1980, the 39 percent of the material in transport was fines of less than 0.062 millimeters (Dinehart, 1984). Analysis of sediments (U. S. Army Corps of Engineers, 1981) showed that in the Cowlitz River at the confluence with the Columbia, 28 percent of the deposited sediment was fines, while in the Columbia River at the confluence, essentially none of the deposited sediment was less than 0.062 millimeters. This difference in deposition of fines is presumably related to the differing sediment transport capacities of the smaller Cowlitz River versus the Columbia River. For the situation modeled in this study,

the sediment deposit itself forms a blockage that substantially reduces, and even reverses, the discharge of the Columbia, so that we c n expect that the Columbia River deposits will contain more fines, and be more like those of the Cowlitz river of May 19, 1980 than seen in the Columbia River for that mudflow. For this reason, and because of the connection between assumed wash load and the adequacy of the sediment transport relation to describe fines, an estimated wash load for this study is set at 25 percent. The uncertainty in this value is quite high, estimated to be given by a standard error of plus or minus 10 percent.

THE COMPUTER MODEL

The computer model used in the study (Fread; 1978, 1982) is based on a four-point implicit finite difference scheme. The water discharge modules have been in use by the National Weather Service, the Corps of Engineers, and the Geological Survey for one-dimensional modeling for flood, dam-break, and day-to-day river forcasting. Because of the application of this model in similar previous studies, and because of its standard treatment of the relevant equations, it was chosen as the model for this study. This water discharge core of the program is known as the Operational Dynamic Wave Model, or DWOPER model, and contains the full non-linear development of the Saint Venant equations, and capability to treat a limited river network involving first order tributaries via an iterative scheme. The Saint Venant equations consist of the conservation of total mass, that is, of water plus sediment,

$$\frac{dQ}{dt} + \frac{d(A+Ao)}{dt} - q = 0 \qquad (3)$$

and the conservation of momentum equation,

$$\frac{dQ}{dt} + \frac{d(Q^2/A)}{dx} + gA\left(\frac{dh}{dx} + Sf + Se\right) + L + Wf\ B = 0 \qquad (4)$$

where

$$Sf = \frac{n^2\ |Q|Q}{2.21\ A^2\ R^{4/3}} \qquad (5)$$

$$Se = \frac{Ke}{2g}\ \frac{d(Q/A)^2}{dx} \qquad (6)$$

$$L = -q(Vl - Q/A) \qquad (7)$$

$$Wf = -Cw\ |Vw \cos a - Q/A|\ (Vw \cos a - Q/A) \qquad (8)$$

In these equations,

x = distance along the longitudinal axis of the waterway

t = time

Q = total (water + sediment) discharge

A = active cross sectional area

Ao = inactive (off-channel) storage area

q = total (water + sediment) lateral
inflow (positive) or outflow (negative)

g = gravity acceleration constant

h = water surface elevation

B = wetted top width of cross section

L = momentum effect of lateral inflow

Sf = friction slope computed from Manning's equation

n = Manning's coefficient

Se = local loss slope due to sudden
channel expansion or contraction

Wf = wind term

R = hydraulic radius

Ke = expansion (negative) or contraction (positive) coefficient

Vl = component of lateral flow velocity in downstream direction

Cw = dimensionless wind coefficient

Vw = wind speed

a = angle between wind vector and downstream channel direction

The unknown variables for the model are thus total discharge Q, and water surface elevation h. Channel geometry at a selection of cross sections is approximated by piecewise-linear functions as part of the input data. The active and off-channel areas, and the wetted top width corresponding to h are determined at each Newton-Raphson iteration within each time step. Thus, irregular channel topography is taken into account in the equations, even though the model is referred to as a one-dimensional model (in longitudinal river coordinate x). Higher dimensional models would provide the details of the velocity distribution over the cross section, but at the expense of increased computer time.

Recently modules for sediment transport and sediment conservation have been added to the model, including the approaches of Yang, Colby, Toffaleti, Myer-Peter and Muller, DuBoys, and sediment transport ratings as functions of stage or discharge. The sediment continuity equation is

$$\frac{dQs}{dx} + \frac{d}{dt}(Cs(A+Ao-As)) + \frac{d}{dt}((1-p)\ As) - qs = 0 \qquad (9)$$

where

Qs = sediment discharge

Cs = sediment concentration by volume

As = sediment deposition (positive) or scour (negative) cross sectional area

p = porosity of sediment deposit

qs = lateral sediment inflow (positive) or outflow (negative)

A space-integrated form of this sediment continuity equation, similar to what would be used in a finite-element analysis, is used that provides a full n equations for the n values of cross sectional deposition or scour.

In this study, the Yang sediment transport equation (Simons and Senturk, 1977) was employed; it is a simple, easily used equation for total bed material load. Explicitly, the equation is as follows:

$$\log Ct = 5.435 - 0.286 \log (wD/v) - 0.457 \log (U*/w) + (1.799 - 0.409 \log (wD/v) - 0.314 \log (U*/w)) \log((US/w) - (Ucr\ S/w)) \tag{10}$$

where

Ct = total sediment concentration in parts per million by weight

D = median sieve diameter

S = water surface slope or energy slope

U* = shear velocity

U = average water velocity

Ucr = critical average water velocity at incipient motion

v = kinematic viscosity

w = terminal fall velocity

The term Ucr/w can be calculated as

$$Ucr/w = 2.5 / (\log (U_* D) - 0.06) + 0.66 \qquad (11)$$

when

$$1.2 < (U_* D/v) < 70 \qquad (12)$$

and

$$Ucr/w = 2.05 \qquad (13)$$

when

$$70 <= (U_* D)/v \qquad (14)$$

The sediment discharge is provided by the sediment transport relation even at the upstream and downstream cross sections, which, in effect extrapolates conditions within the modeled reach to just above the first cross section, and just below the last.

In the computer model, the sediment transport equations and hydrodynamic equations are solved sequentially rather than simultaneously during the linear approximation of the Newton-Raphson iteration, keeping one of the two sets of variables fixed during the solution of the linear system for the other. However, the Newton-Raphson loop is repeated, within each time step, until the full nonlinear set of equations, dependent on both sets of variables, is suitably approximated. While such a scheme may not be quite as desirable as the simultaneous solution of the corresponding linear approximation for both sediment transport and hydrodynamic variables simultaneously, implementation of such a high degree of coupling in the solution process would be made difficult by the complexity and variety of sediment transport equations.

The computer model allows variety of boundary conditions. For this application, they consist of input discharge hydrographs to the modeled reach of the main river and its tributary, the tidal water surface elevation, in time, at the lower boundary, and input lateral total (water plus sediment) and sediment discharge hydrographs to represent the flooding of the breach. The momentum equation, and continuity equations must of course, balance at tributary junctions and in reaches with lateral inflows. Continuity of the water surface elevation at tributary junctions is maintained by the iterative scheme within each time step that sequentially solves each river of the problem.

In applying the program to this problem, the code was edited to clarify the flow of logic. For example, there were almost no comment cards in the entire program, and these were added to indicate what was being done within sections of the program, and what hydrodynamic, sediment transport, or numerical analytic equations were being employed. The program was also is still in a developmental state, and a general housecleaning of the code clarified the flow of the logic within it. There were in addition some modifications that were necessary to correct errors, and examples of these are as follows:

a. In the Yang sediment transport module, sediment concentration by weight was calculated, but was used as concentration by volume.

b. In several places in the program, the possibility of negative (that is, upvalley) water surface slopes was not allowed for.

c. In the formation of the momentum equation, the total cross section area was incorrectly reduced by the sediment deposition area, but actually the latter is part of the former.

d. In the momentum equation, the contribution due to lateral flow was given as -q Vl, where q is the discharge of the lateral flow, and Vl the component of its velocity in the downstream direction. The correct expression is -q (Vl - U), where U is the average flow velocity in the river into which the lateral flow is taking place.

e. The initial estimates used in the Newton-Raphson scheme should be prevented from resulting in spurious negative areas, or the iterations stop because of invalid numerical operations like trying to find the logarithm of a negative number, and never restart correctly.

f. In the momentum equation, one wants integral average values for the terms over a river element delta x, and time element delta t. In particular, for the friction slope term Sf, it is a (weighted) average of Sf(Q,A) that is desired in the four-point implicit formulation, and because of the nonlinear way that discharge Q and cross sectional area A enter the expression, that is not the same as Sf(Qav, Aav), where Qav and Aav are average values of Q and A (see equation 5). The expression Sf(Qav, Qav) that had appeared in the four-point evaluation of the friction slope was replaced by (Sf(Q,A))av.

g. In the momentum equation, the term due to sudden channel expansions or contractions had been combined with the convective term. This had been done by replacing

$$A\, d/dx\, ((Q/A)^2) \qquad \text{with} \qquad d/dx(Q^2/A) \qquad (1)$$

The expansion term was replaced by the (correct) first expression, averaged over the delta x - delta t interval.

h. In several places in the program, nested do loops ended on the same CONTINUE statement. Transfer of control within the outer loop before reaching the inner loop will result in continuation of execution within the inner loop using the current index of the outer loop, rather than what is probably desired, namely to go to the start of the outer loop, increment the index, and continue there. For this reason, such multiple-duty ending statments either are already producing unwanted program flow, or potentially can with the addition of such control transfers during program development.

i. The wind friction term was stated as

$$Wf = Cw \, (Vw \cos a)^2 \qquad (15)$$

and the documentation stated that Vw is the velocity of the wind relative to the velocity of the channel flow. What is needed is that Vw cos a be relative to channel flow speed, and the requirement that it be such a relative velocity means that wind velocity cannot be specified independently of the (a priori) unknown water velocity. In addition, as the expression is stated, the coefficient Cw must change sign depending on the direction of this relative velocity, and will be negative for the case of a downchannel relative velocity. This expression should be replaced by

$$Wf = -Cw \, |Vw \cos a - Q/A| \, (Vw \cos a - Q/A) \qquad (16)$$

where now Vw is actual wind speed.

j. The sediment deposition width was not calculated in a consistent manner in the various locations that it appeared in the program.

k. The accumulated sediment deposition depth SDZ was updated at an incorrect location so that output did not reflect the correct time step.

MODELING

The input total (water + sediment) hydrograph developed by Swift and Kresch (1983) for the Cowlitz River at the confluence of the Columbia River was adjusted to have a reduced total volume of 0.83 bcy, added to an assumed pre-existing Cowlitz River flow of 20,000 cubic feet per second, during the 28 days of the study. The resultant hydrograph for the total (water plus sediment) discharge is shown in figure 2. The origin of the time scale is when the breach of Spirit Lake through the retaining debris avalanche begins. The resultant flood reaches the confluence with the Columbia at 9 hours after the breach, and has a peak discharge of 409,025 cubic feet per second at 16 hours. Bed material sediment discharge (figure 3) was 30 percent of this total discharge, and wash load fine material comprised 10 percent of the total discharge. The input discharge at Bonneville Dam was taken to be 200,000 cfs, and an average discharge of 33,000 cfs as input to the Willamette; these were assumed constant during time modeled. The 200,000 cfs input to Bonneville includes average flow of 194,000 cfs measured on the Columbia River at The Dalles, combined with an average 1,000 cfs measured on the Hood River and an average 5,000 cfs measured on the Lewis River. The Lewis River is actually downstream of both Bonneville and the confluence of the Columbia with the Willamette, but the river is not germane to this study, and its flow was added at Bonneville as a modeling simplification. This provided a combined average flow of 233,000 cfs downstream of the confluence of the Columbia and Willamette Rivers, and in particular at the confluence of the Columbia and Cowlitz Rivers. The modeled reach (figure 1) extended to Tongue Point near the mouth of the Columbia, with tidal water surface elevations as a function of time from NOAA tide tables used as downstream boundary condition there

(figure 4). Manning's "n" values ranged from 0.0170 to 0.0410, based on a calibration of the model to historical flood elevations done by the Corps of Engineers (1983) during a their study of flood elevations to be produced by a failure of Bonneville Dam during a concurrent Columbia River flood. A mean sediment diameter of 0.2 millimeters, and porosity for sediment deposition in the Columbia River of 43 percent, were assumed based on sediment samples taken May 20, 1980 (U.S. Army Corps of Engineers, 1981) and recent sediment studies on the Cowlitz River (Lombard, 1984). Water temperature as 51 degrees Fahrenheit, based on water temperature data at Vancouver, Washington. The computational time step delta t was 3 minutes for most of the run, but was decreased to 36 seconds during most of the time 1.5 to 2.5 days after the breach, and within that time interval was decreased even further, to 7.2 seconds, between 54 and 56 hours.

Figures 2-40

The results of the modeling at a Columbia River average flow of 233,000 cubic feet per second are shown in the plots of figures 5 to 36. Figures 5, 6, 7 and 8 show hydrographs for Columbia River mile 53.4, 12.7 miles downstream of the crest of the blockage. At this location, the effect of the blockage is a reduction in total discharge, followed by a gradual return to 233,000 cfs as the Columbia River is impounded behind it. Sediment deposition takes place gradually after the flood, as blockage material is transported to this location from upstream.

Figures 9, 10, 11 and 12 show hydrographs for river mile 66.1, at the crest of the blockage. The effect here is basically a rapid deposition of the sediment during the flood from the Cowlitz River that blocks flow on the Columbia.

Trojan is at RM 72.4

Figures 13, 14, 15 and 16 show hydrographs for river mile 69.1, which is 3.1 miles upstream of the crest of the blockage. The discharge on the Columbia River at this location is reversed during the flood by the sediment blockage itself that is cresting downstream at river mile 66.1, that is, the flood from the Cowlitz is diverted upstream. The sediment deposition of the blockage continues through this location, and a large amount of channel filling occurs during the flood itself. The water surface elevation continues to increase gradually after the flood, as the Columbia River is impounded behind the blockage.

Figures 17, 18, 19 and 20 show hydrographs for river mile 75.1, which is 9 miles upstream of the crest of the blockage. The sediment deposition of the blockage does not extend upstream this far, and the effect is one of gradual filling by the Columbia River of the impoundment area behind the blockage.

Figures 20 and 21 show hydrographs for river mile 106.5, at the Interstate 5 highway bridge at Portland, Oregon. The effect here is again one of gradual water surface rise due to filling behind the blockage.

Figures 23 through 40 show a time sequence of longitudinal profiles along the Columbia River, from Tongue Point to Bonneville Dam, as the sediment blockage is formed and the waters of the Columbia River subsequently are impounded behind it. Sediment deposition takes place during the flood at the location of the blockage, with crest at river mile 66.1. Subsequent flow then carries sediment from the blockage to downstream of the crest. The deposition depth downstream of the flow, and corresponding scour upstream, are averages over the channel width at the location. This width is much larger upstream of the blockage than below, and this is the reason the scour upstream is just barely perceptable on the plots; the corresponding sediment volumes do match as required by continuity.

The figures thus indicate the formation of a large sediment blockage in the Columbia river at the confluence with the Cowlitz, and subsequent impoundment of upstream flood waters behind this blockage. This results in a slowly rising stage that at the Trojan Power Plant, 5 miles upstream of the Cowlitz River, reaches a maximum elevation of 32 feet at 16 days. This compares with an elevation for the same location of 6 feet at an average Columbia River discharge of 233,000 cfs without the blockage. High water surface elevations could similarly be expected in the impoundment area behind the blockage in the entire reach up to Bonneville Dam, with the elevation at Portland, Oregon, for example, rising also to 32 feet, compared to 10 feet without the blockage. Due to the large channel storage volume of this reach of the Columbia River, the river levels continue to rise for 16 days after the blockage is formed.

As indicated in Table 2, these water surface elevations are generally higher than levees (U.S. Army Corps of Engineers, 1978) from the blockage near the mouth of the Cowlitz at river mile 66.1, upstream to river mile 103.1 just above the confluence with the Willamette, and flooding of low-lying areas along the Columbia and Willamette Rivers would result. The Vancouver Lake area and Sauvie Island area would be flooded. Upstream of river mile 103.1, low areas are in general protected by levees if it is assumed that they will not fail at the anticipated water surface elevation of 32 feet. However, the Corps of Engineers gives a safe elevation for levees near the interstate bridge at river mile 106.5 as about 18 feet even though the levee crest is about 35 feet, and a safe elevation for levees near river mile 114.7, just upstream of Portland International Airport, as 33 feet, even though the levee crest is about 41 feet. Downstream from the mouth of the Cowlitz, flooding is prevented by the blockage itself, even during peak flow from the Cowlitz into the Columbia River. Thus maximum water surface elevations at river mile 53.4, which is 12.6 miles downstream of the interstate bridge at Longview, Washington, are actually modeled some 14 days after the breach, due purely to a high tide at that time.

Table 2 >

Table 2 also presents the water surface elevations that would occur at higher Columbia River flows. The additional cases presented are identical in input to the modeling as for the 233,000 cfs, average flow case, except that the input discharge to the Columbia River at Bonneville Dam was adjusted upward, to produce the indicated flood discharges when combined with a flow of 35,000 cfs from the Willamette. As in the average flow case, these input discharge to the Columbia and Willamette Rivers were considered constant during the time period modeled. The modeling for these higher flows gives results that are similar to the average flow case, except that the waters from the concurrent Columbia River flood stack to higher water surface elevations behind the blockage, and cause more extensive flooding as additional levees are overtopped. Thus, during a concurrent Columbia River flood of 410,000 cfs, the levees near the Portland, Oregon Interstate 5 Bridge at river mile 106.5 would be overtopped, and this would, for example, flood Portland International Airport. For a concurrent flood of 610,000 cfs, all of the levees between the blockage at river mile 66.1, and Bonneville Dam at river mile 145.5 would be overtopped. It is to be noted again, that safe elevations for the levees are in general less than crest elevations. The sediment blockage as deposited during these higher flows is very similar to that of the average flow case. As shown in table 3, the crest is almost as high. The time to the maximum crest elevation is reduced for higher flows, because the impoundment behind the blockage fills more quickly, to restore the Columbia river discharges, and sediment transport and scour associated with these higher flows.

Table 3

CONCLUSION

The one-dimensional sediment transport model used in this study indicates that an outburst of Spirit Lake would cause a sediment deposit blockage of the Columbia River at the confluence with the Cowlitz. This would result in impounding the river's flow behind this blockage, and would cause flood-level water surface elevations upstream. There would be little, if any adverse effect downstream of the blockage. The water surface elevations are, to be sure, subject to considerable uncertainty because of uncertainty regarding the total volume of sediment which would first of all be entrained in such a breach of the debris avalanche, and which then actually would reach and be deposited in the Columbia River, rather than along the Toutle and Cowlitz Rivers.

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Table 1
Particle Size for Incipient Motion from Shield's Criterion.

River	Specific Gravity w_s / w_w	Slope S	Hydraulic Radius h (meters)	Particle Diameter d (millimeters)
N. F. Toutle	1.8	0.006 to 0.007	12	1900 to 2200
Toutle	1.8	0.0045	12	1400
Cowlitz	1.7	0.00006 to 0.0004	18	33 to 220

Table 2.
Maximum water surface elevations.

[x, Columbia River mile. yc, levee crest in feet. ys, safe water surface level for levee. t, time in days after breach. y, water surface elevation in feet with respect to National Geodetic Vertical Datum. yo, water surface elevation in feet at the same Columbia River discharge, but without the blockage. Columbia River discharges in cubic feet per second, together with recurrence interval.]

Columbia River Mile		crest of levee	safe water level for levee	Columbia River Discharge														
				233,000 (average)			410,000 (2 year)			610,000 (10 year)			750,000 (50 year)			820,000 (100 year)		
x	Approximate Location	yc	ys	t (time)	y (w.s.El.)	yo (w.s.El w/o blockage)	t	y	yo	t	y	yo	t	y	yo	t	y	yo
17.50	Tongue Point, OR			14	7	-1	14	7	-1	14	7	-1	14	7	-1	14	7	-1
23.36	Svensen, OR			14	7	0	14	7	0	14	7	0	14	7	0	14	7	1
30.15	Three Tree Pt., WA			14	7	1	14	7	1	14	7	2	14	8	3	14	8	3
34.63	Skamokawa, WA	12	8	13	8	1	14	8	2	14	8	4	15	8	4	15	9	5
41.60	Wauna, OR	12	8	14	8	2	14	8	3	14	9	6	14	10	7	14	10	8
53.40	Oak Point, WA	17	11	14	9	4	14	10	6	14	12	10	15	14	12	28	15	13
66.10	Longview Bridge	23/29	18/18	28	28	5	28	34	9	28	38	14	28	40	17	28	41	19
69.06	Cowlitz River			16	32	6	14	38	10	13	41	15	11	43	18	11	44	20
72.50	Trojan, OR			16	32	6	14	38	11	12	41	16	10	43	19	10	44	21
75.05	Kalama, WA			16	32	7	14	38	12	12	41	17	10	43	20	9	44	22
84.00	Columbia City, OR	28	25	16	32	8	14	38	13	12	42	19	10	44	22	9	45	23
92.50	Ridgefield, WA	30	23	16	32	9	14	38	14	12	42	20	10	44	23	9	45	25
100.00	Vancouver, WA	30/33	16/29	16	32	9	14	39	[illegible]	12	42	21	11	44	24	9	45	25
103.10	Willamette River	27	16	16	32	10	14	39	16	12	42	21	10	44	24	10	45	26
106.50	Portland I-5 Bridge	35	18	16	32	10	14	39	16	12	42	22	10	45	25	10	45	26
114.70	Portland Airport	41	33	16	32	11	14	39	18	12	43	25	10	45	28	9	46	30
122.90	Washoughal, WA	42	36	16	33	14	14	39	22	12	44	28	10	46	32	10	47	33
131.95	Bridal Veil, OR			16	33	16	14	40	25	12	44	31	10	47	34	10	48	36
141.00	Warrendale, OR			16	33	17	14	40	27	14	45	34	11	48	38	10	50	40
143.25	N. Bonneville, WA	41	36	16	33	18	14	41	28	12	47	37	11	50	43	9	52	44
145.50	Bonneville Dam			16	34	20	14	41	29	12	48	38	10	52	45	10	53	47

Table 3.
Crest of Sediment Blockage.
At Columbia River Mile 66.1, or 0.1 mile upstream of the interstate bridge at Longview, Washington. The pre-blockage channel depth is -47 feet. Elevations are with respect to National Geodetic Vertical Datum.

Columbia River Dischage (cfs)	Recurrence Interval (years)	Time at Highest Crest Elevation (days after breach)	Crest Elevation (feet)
233,000	Average	28	-3
410,000	2	5	-3
610,000	10	12	-3
750,000	50	6	-4
820,000	100	5	-5

Figure 1. Location map.

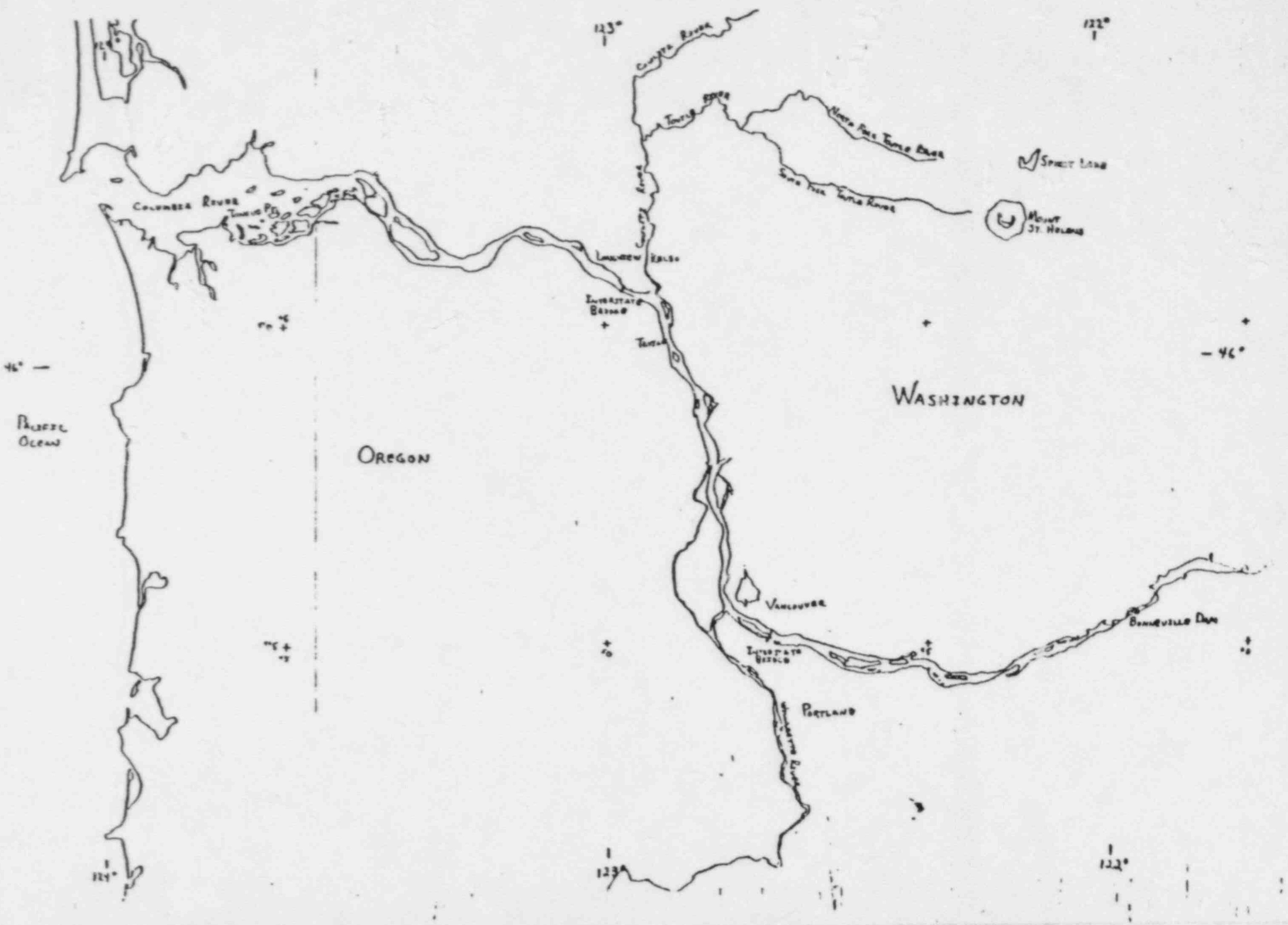


Figure 2
Cowlitz River at Confluence with Columbia River
Total Discharge

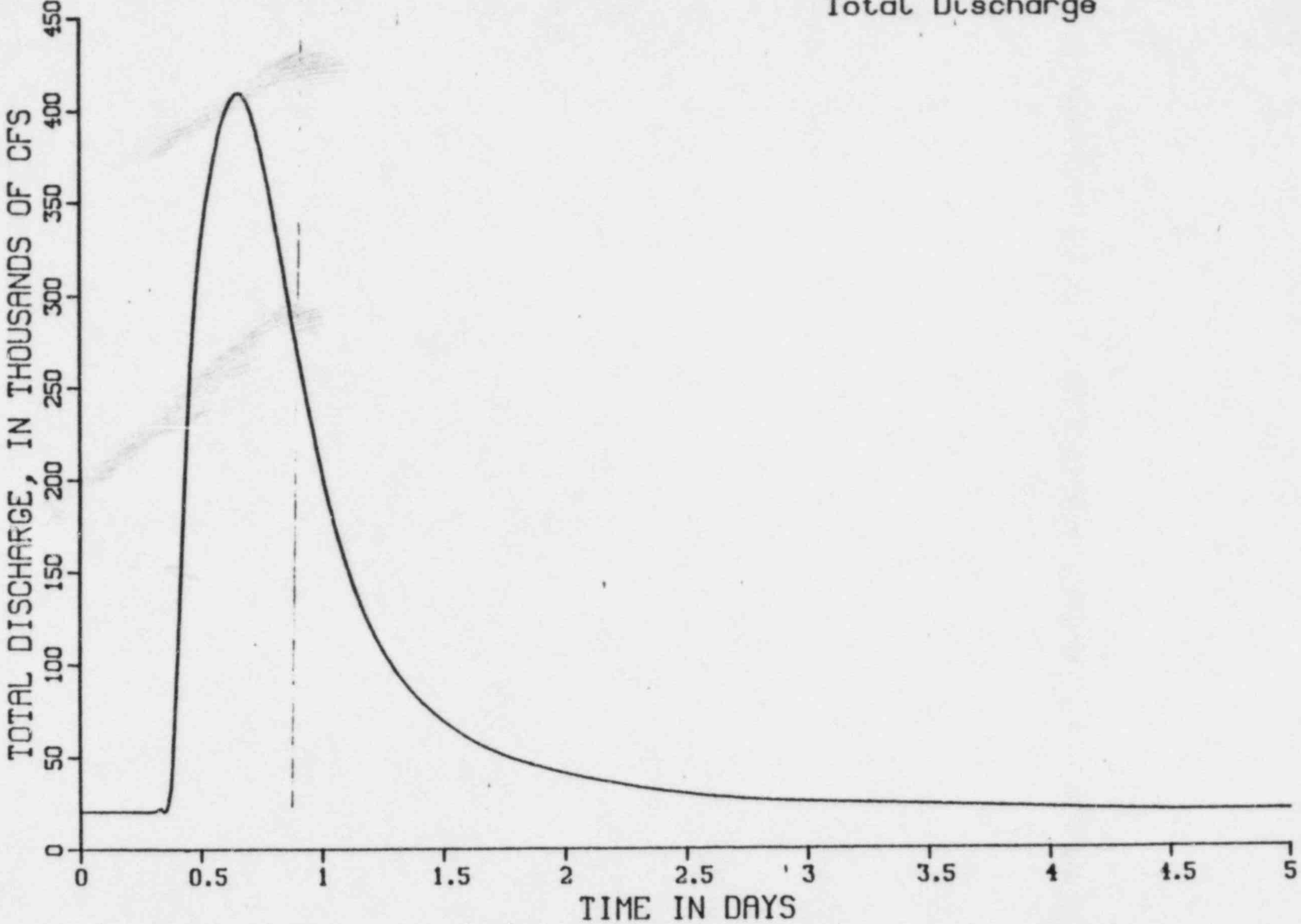


Figure 3
Cowlitz River at Confluence with Columbia River
Sediment Discharge

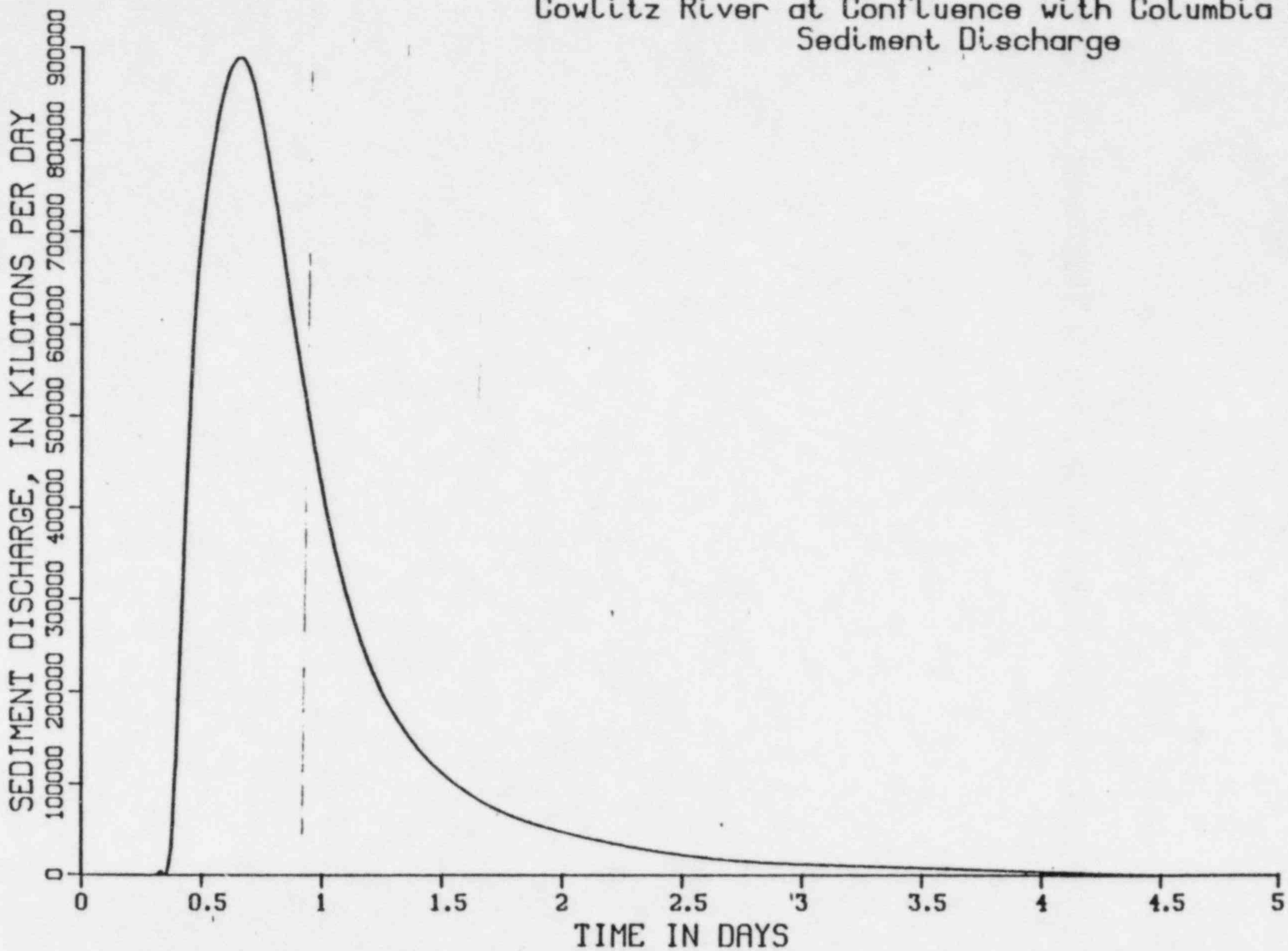


Figure 4
Columbia River at Mile 17.5
Tidal Water Surface Elevation
Tongue Point, Oregon

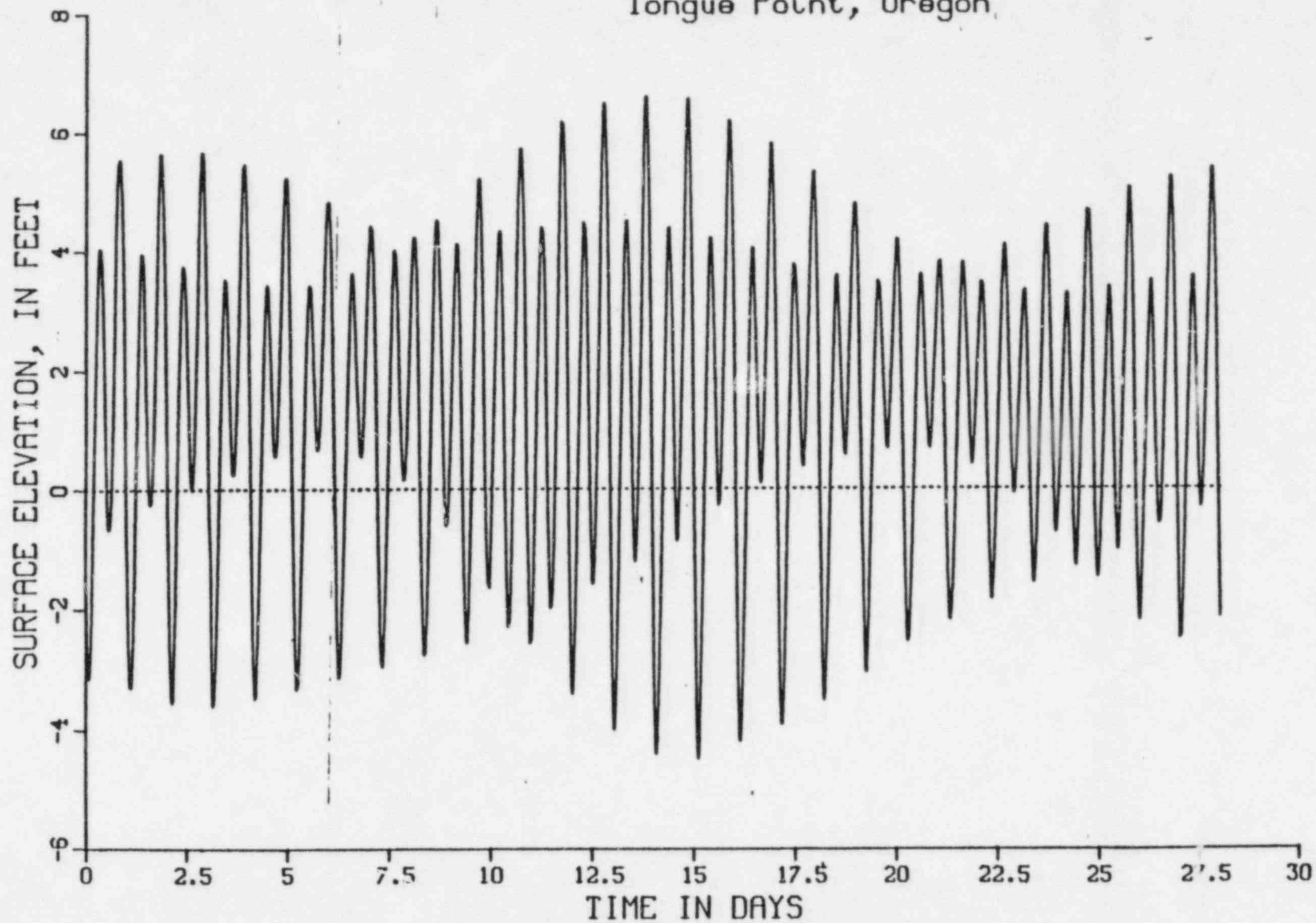


Figure 5
Columbia River at Mile 53.4
Water Surface Elevation
12.6 Miles Downstream of Interstate Bridge
at Longview, Washington

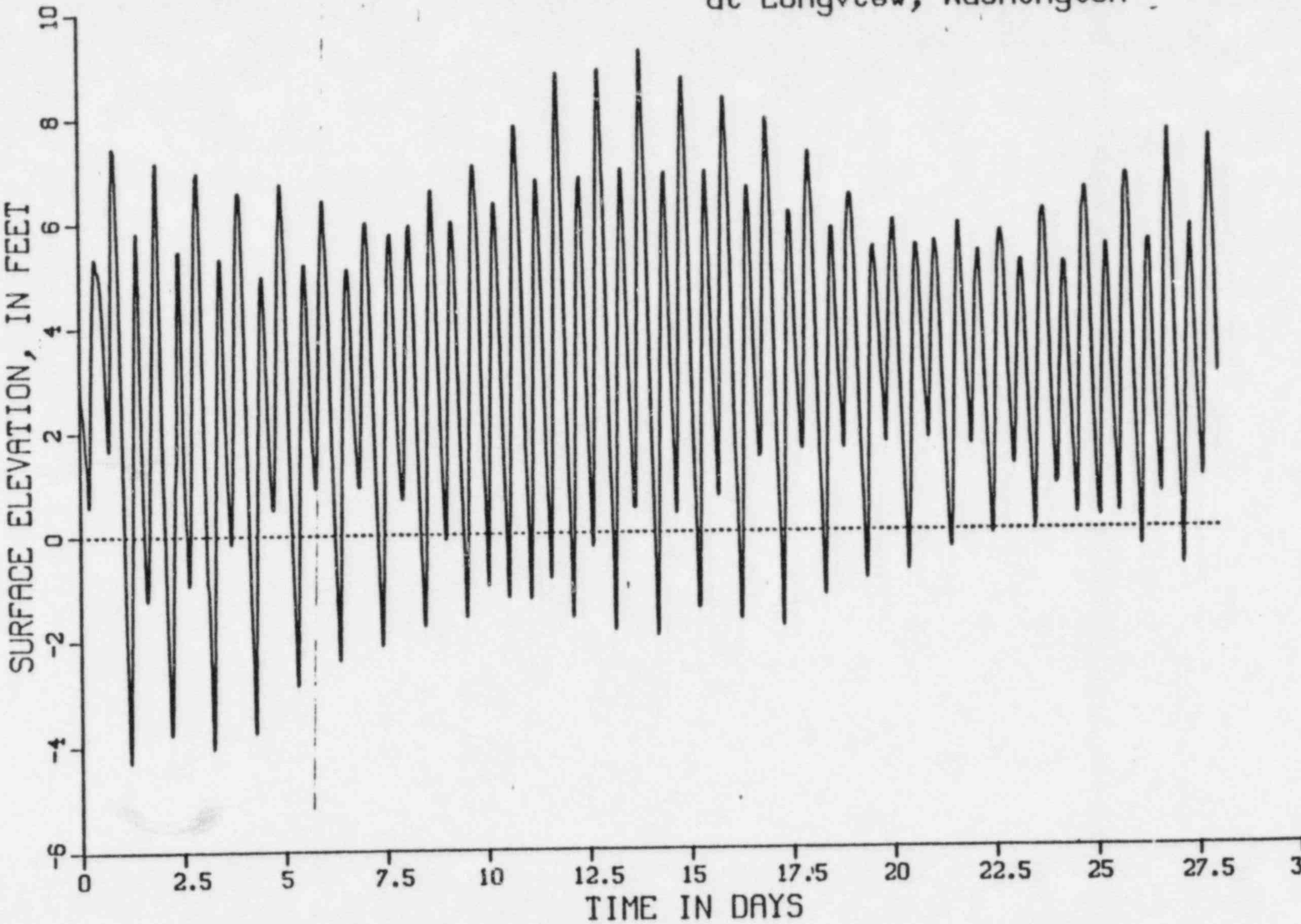


Figure 6
Columbia River at Mile 53.4
Total Discharge
12.6 Miles Downstream of Interstate Bridge
at Longview, Washington

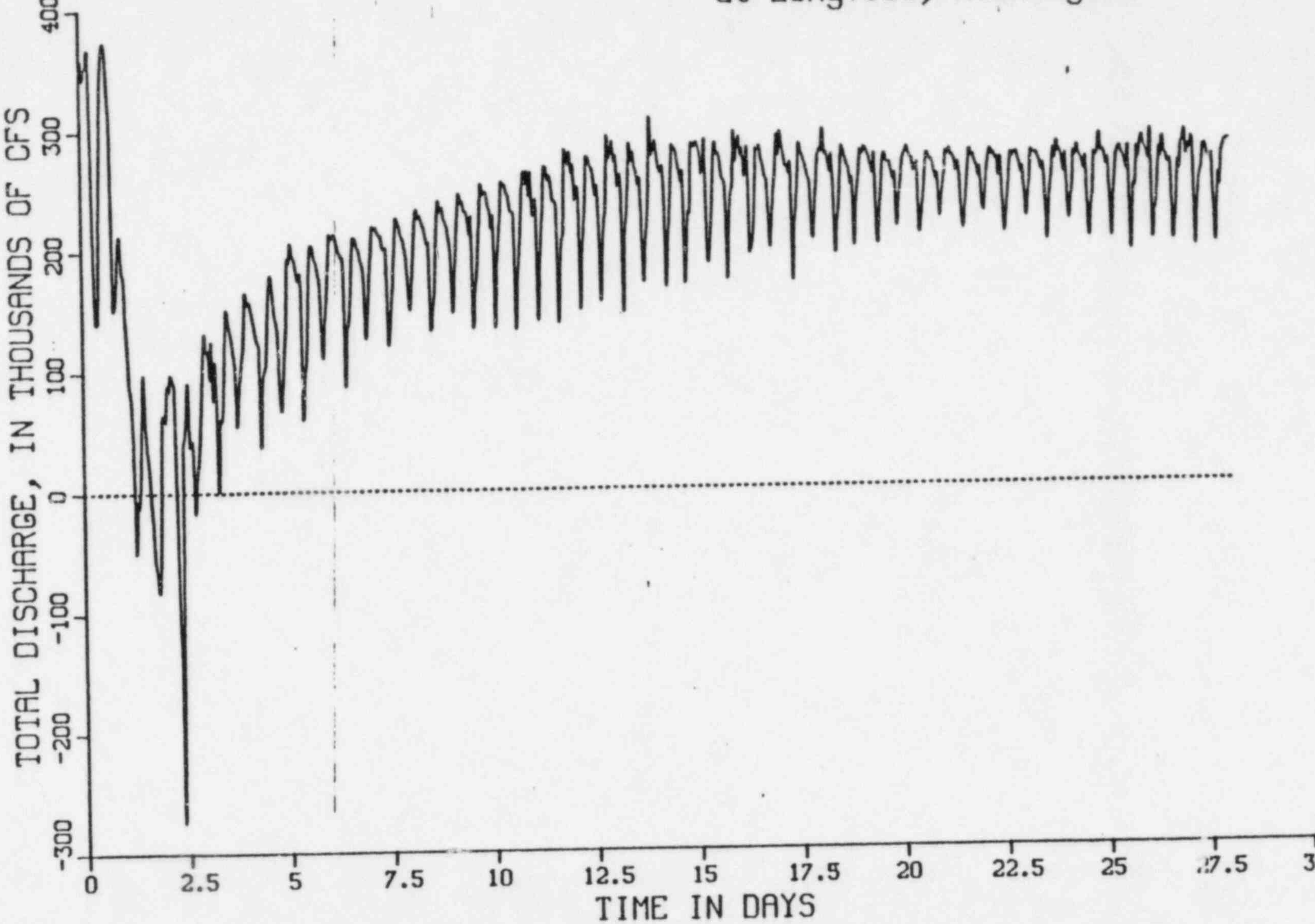


Figure 7
Columbia River at Mile 53.4
Bed Elevation
12.6 Miles Downstream of Interstate Bridge
at Longview, Washington

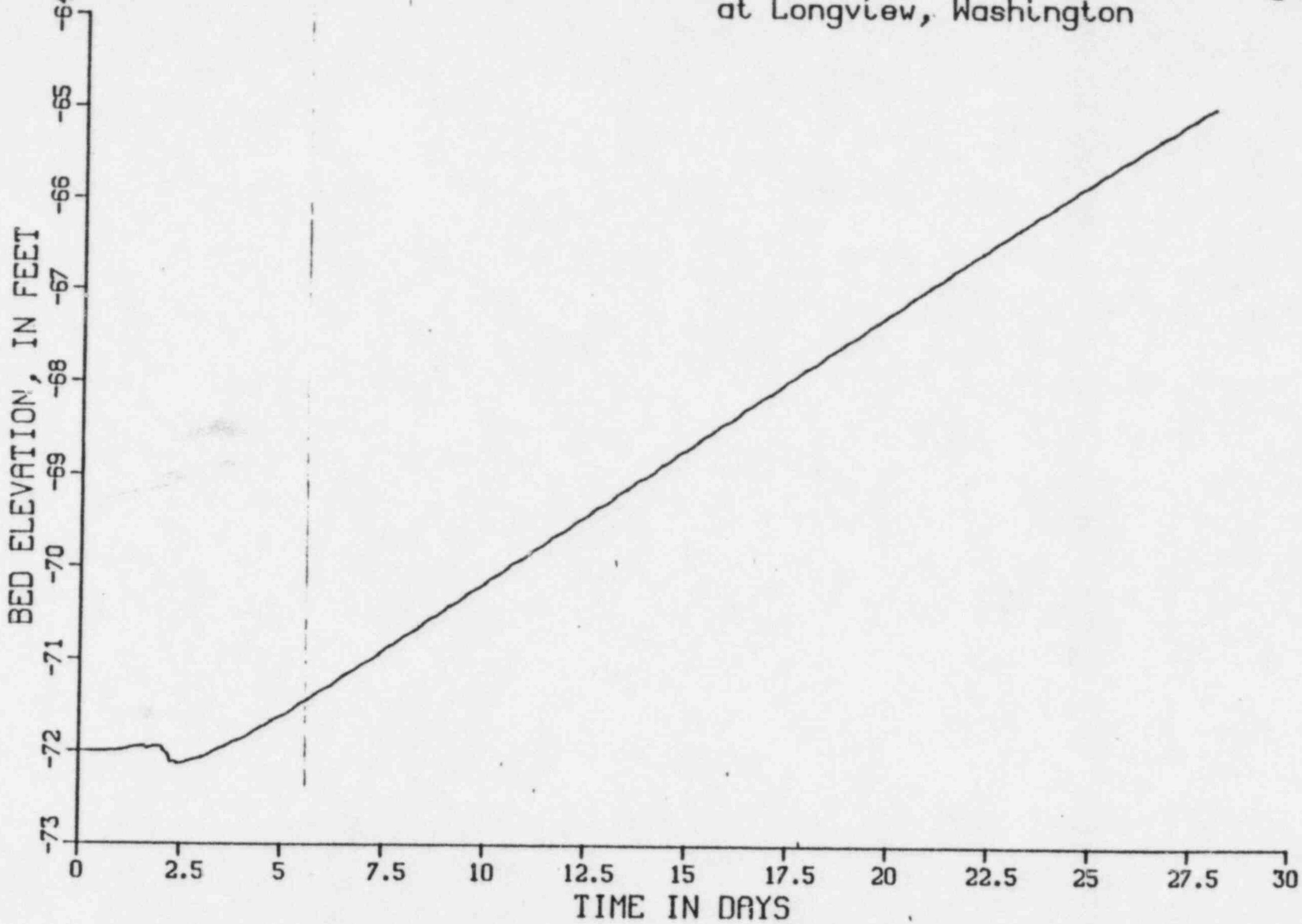


Figure 8
Columbia River at Mile 53.4
Sediment Discharge
12.6 Miles Downstream of Interstate Bridge
at Longview, Washington

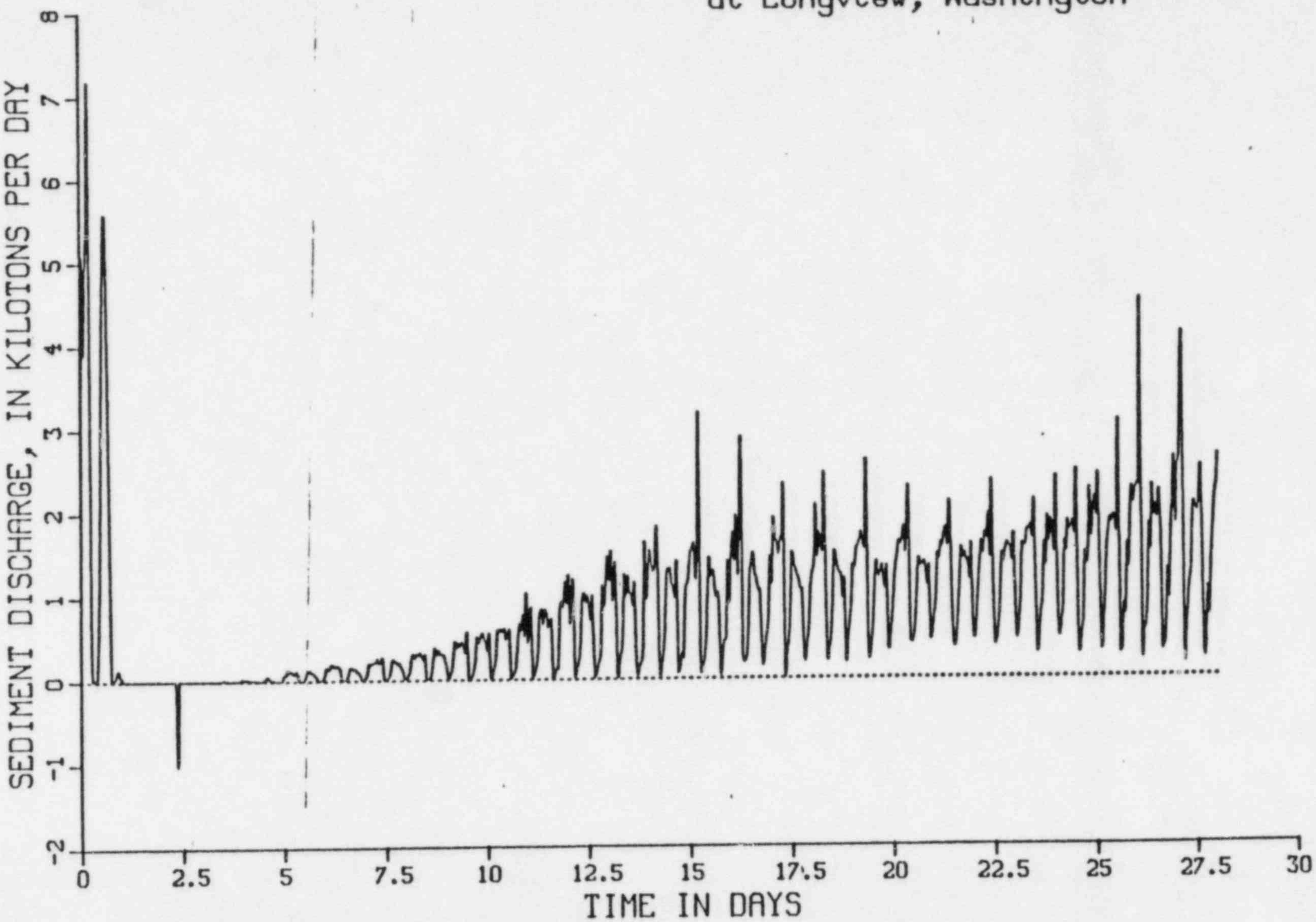


Figure 9
Columbia River at Mile 66.1
Water Surface Elevation
Longview, Washington
0.1 Mile Upstream of Interstate Bridge

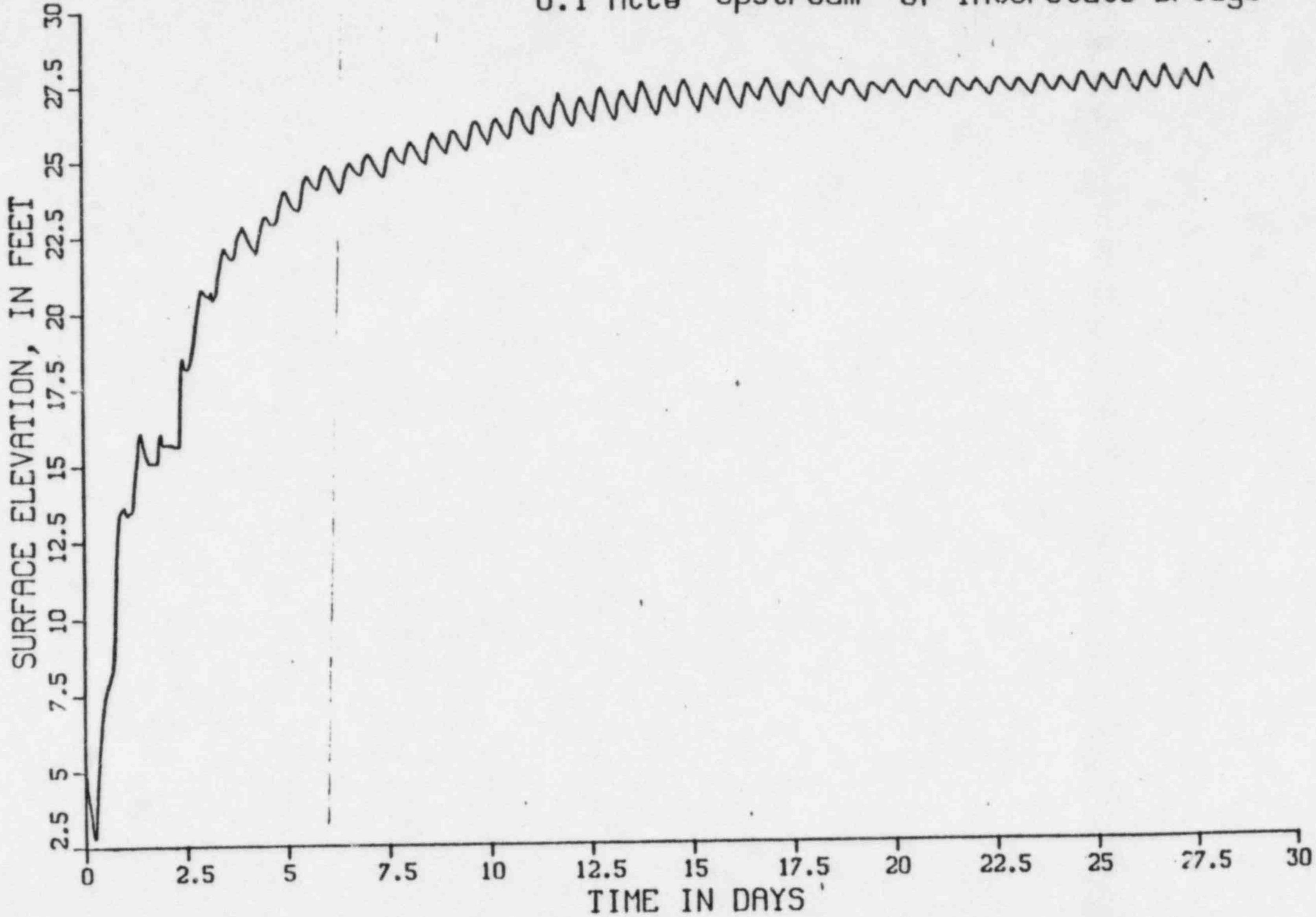


Figure 10
Columbia River at Mile 66.1
Total Discharge
Longview, Washington
0.1 Mile Upstream of Interstate Bridge

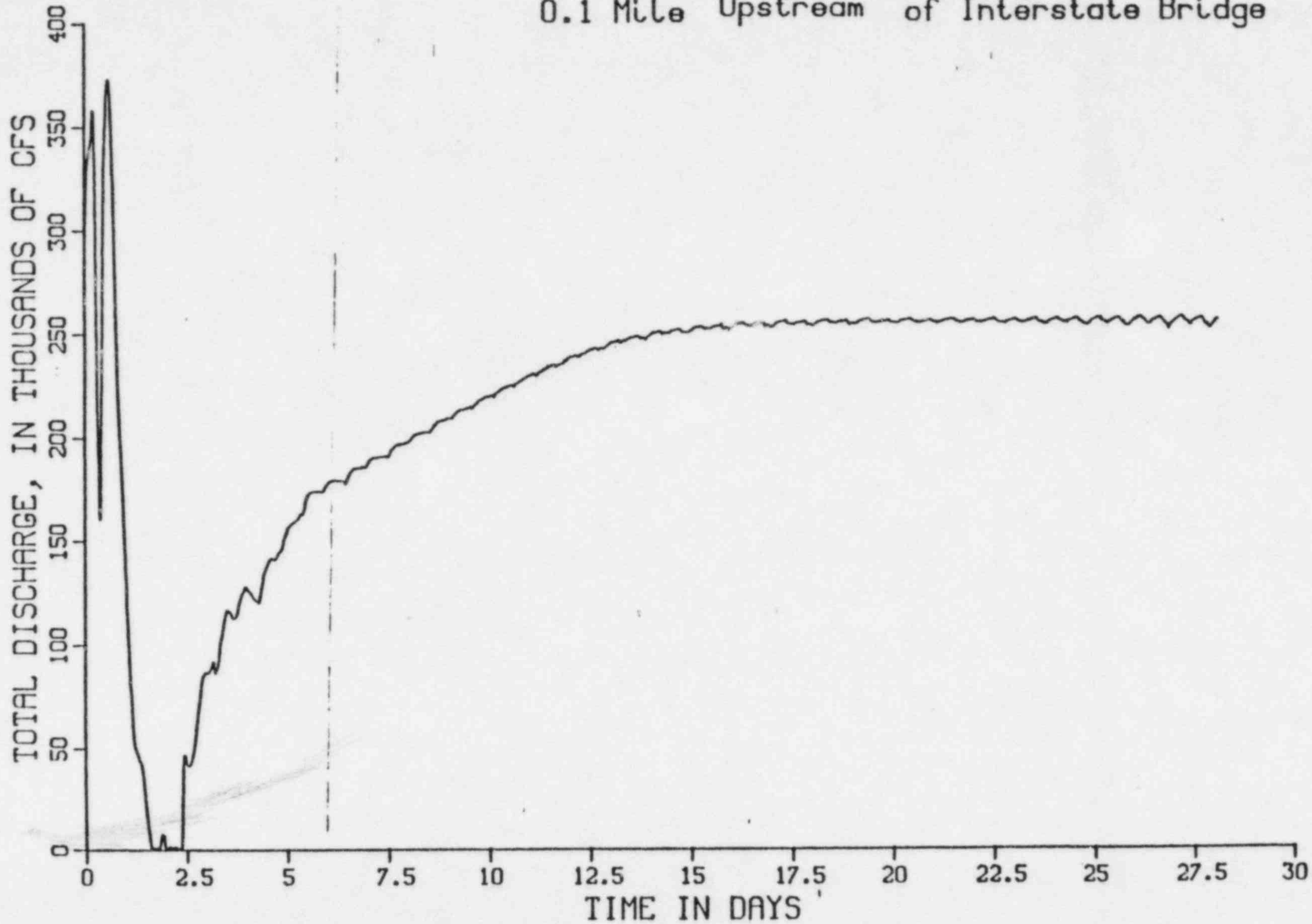


Figure 11
Columbia River at Mile 66.1
Bed Elevation
Longview, Washington
0.1 Mile Upstream of Interstate Bridge

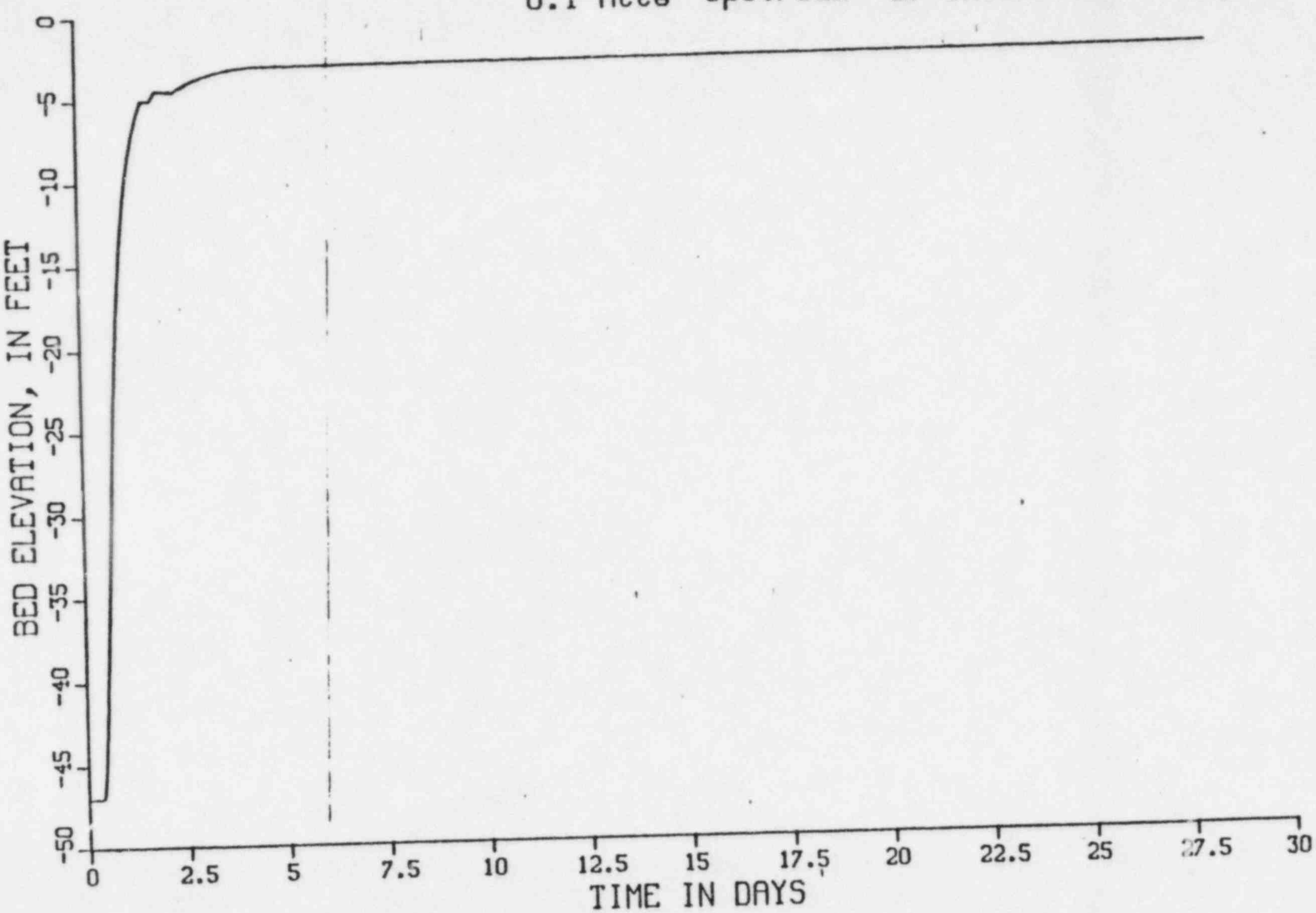
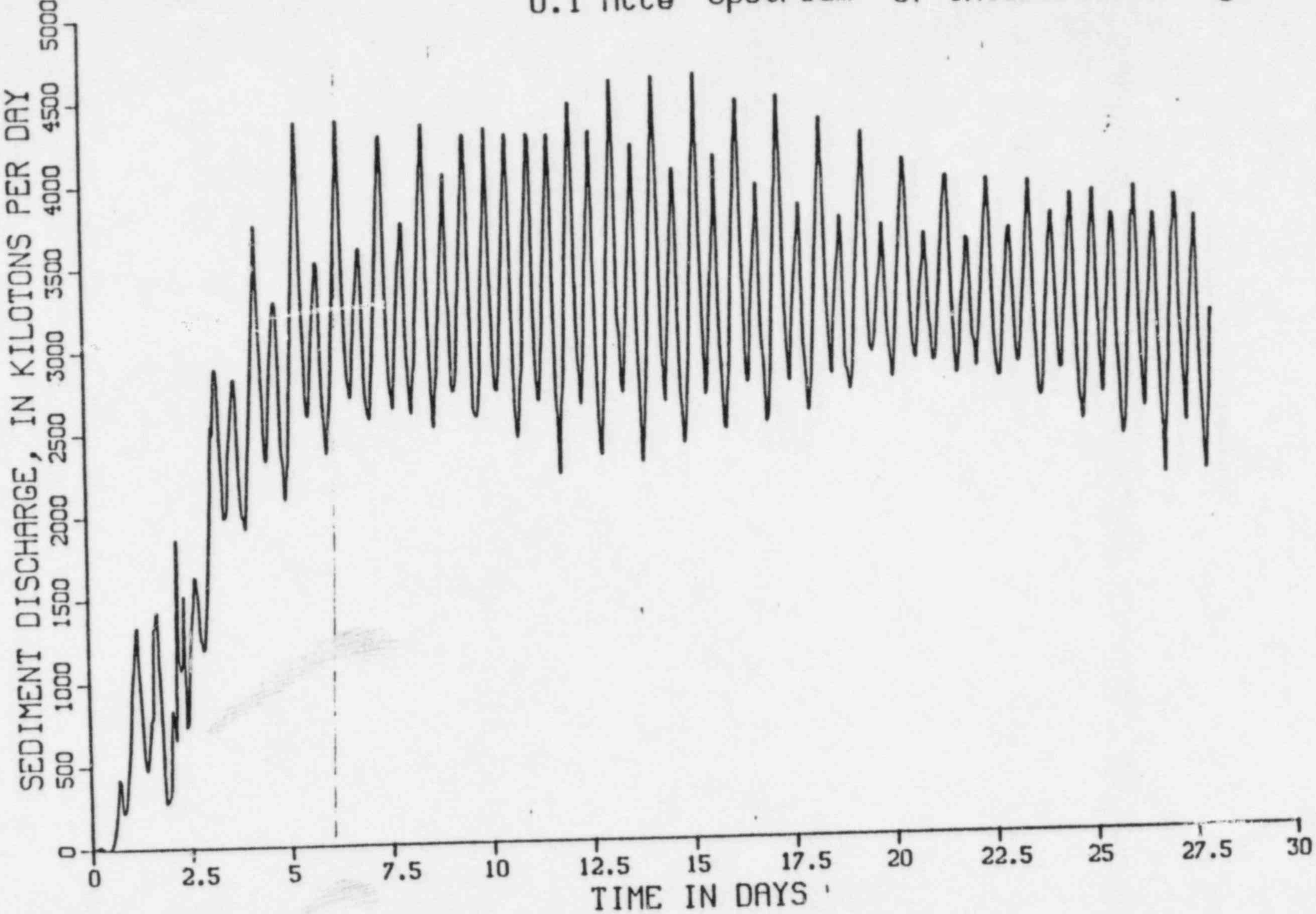


Figure 12
Columbia River at Mile 66.1
Sediment Discharge
Longview, Washington
0.1 Mile Upstream of Interstate Bridge



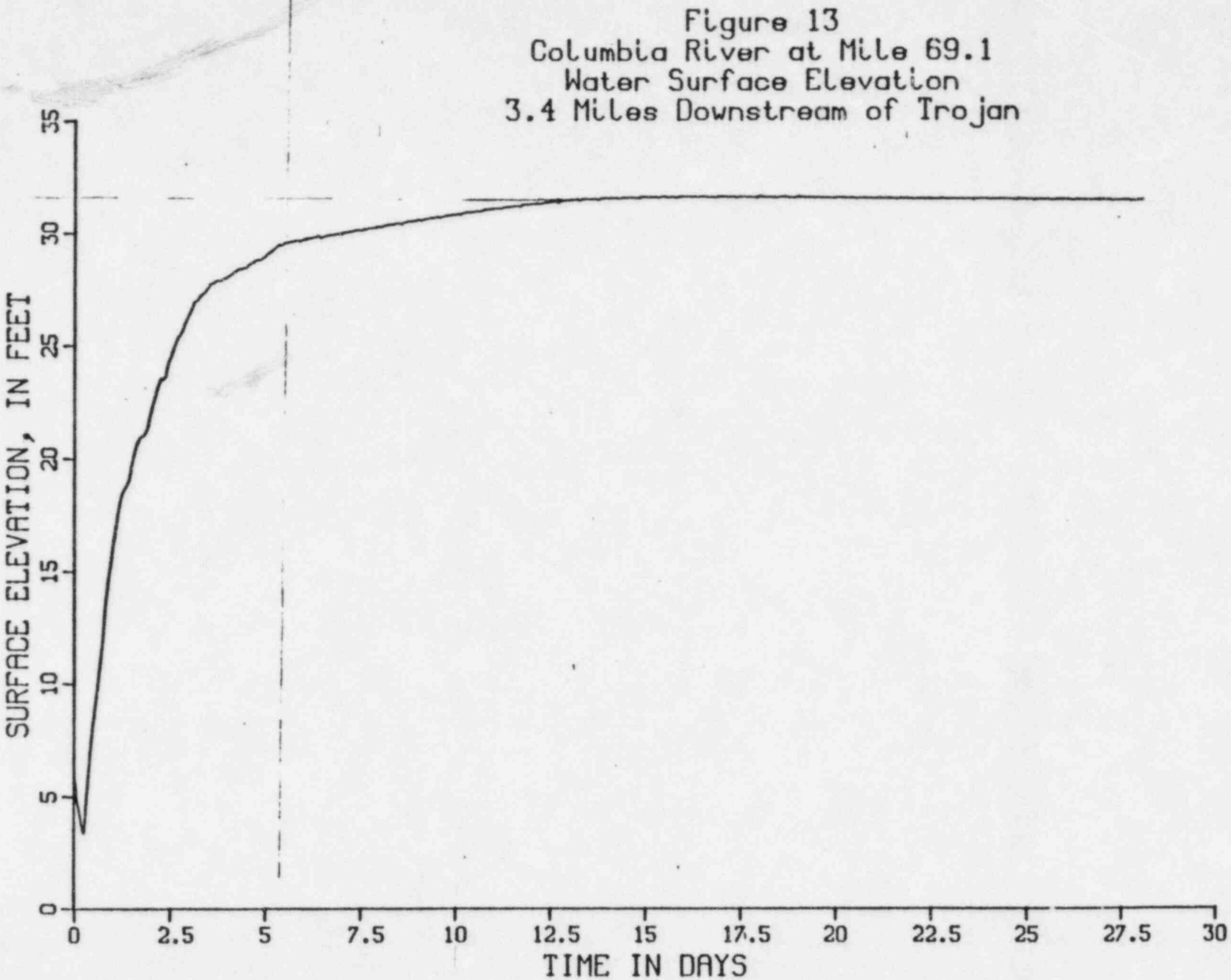


Figure 13
Columbia River at Mile 69.1
Water Surface Elevation
3.4 Miles Downstream of Trojan
SURFACE ELEVATION, IN FEET
0
5
10
15
20
25
30
35
0
2.5
5
7.5
10
12.5
15
17.5
20
22.5
25
27.5
30
TIME IN DAYS

Figure 14
Columbia River at Mile 69.1
Total Discharge
3.4 Miles Downstream of Trojan

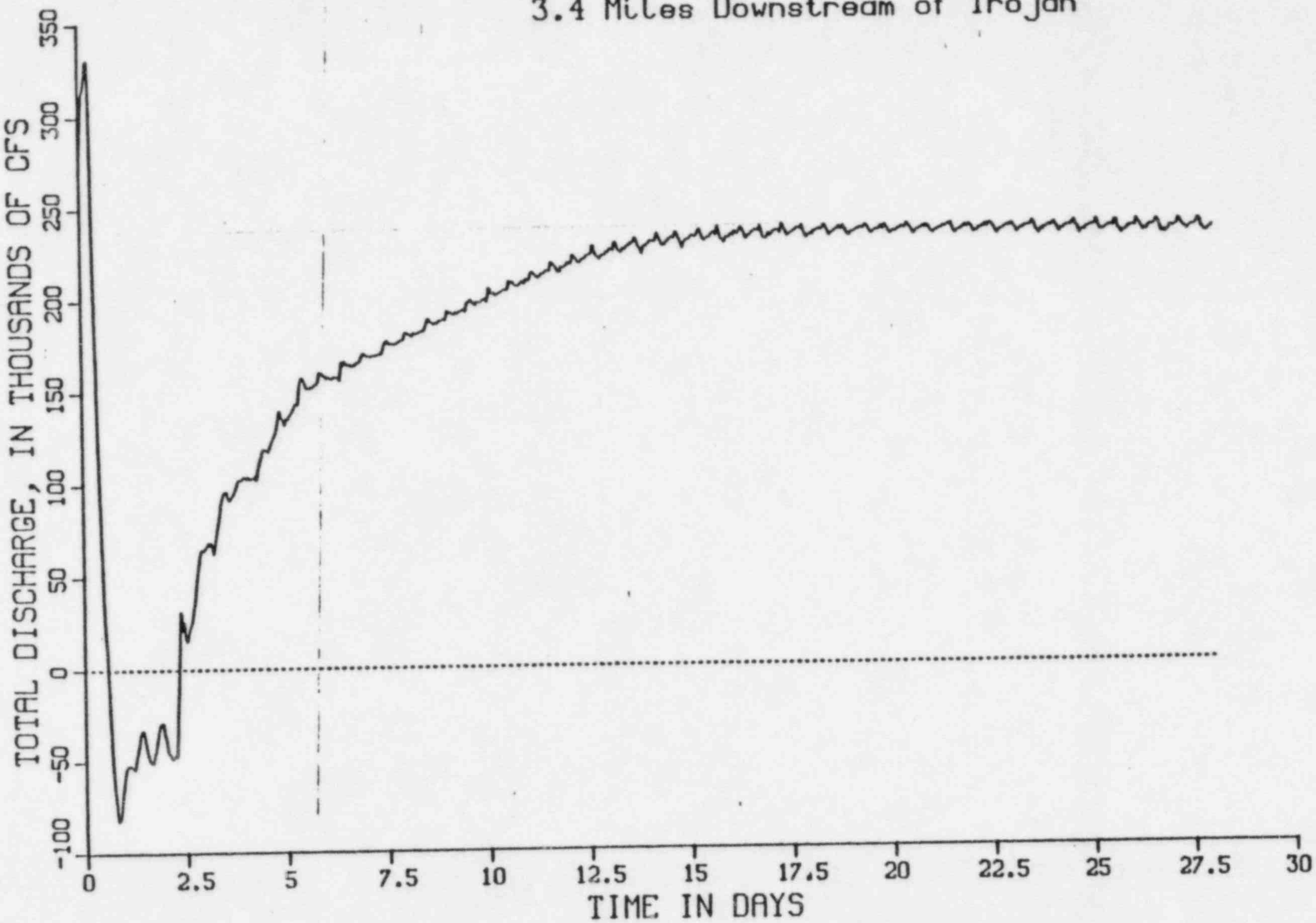


Figure 15
Columbia River at Mile 69.1
Bed Elevation
3.4 Miles Downstream of Trojan

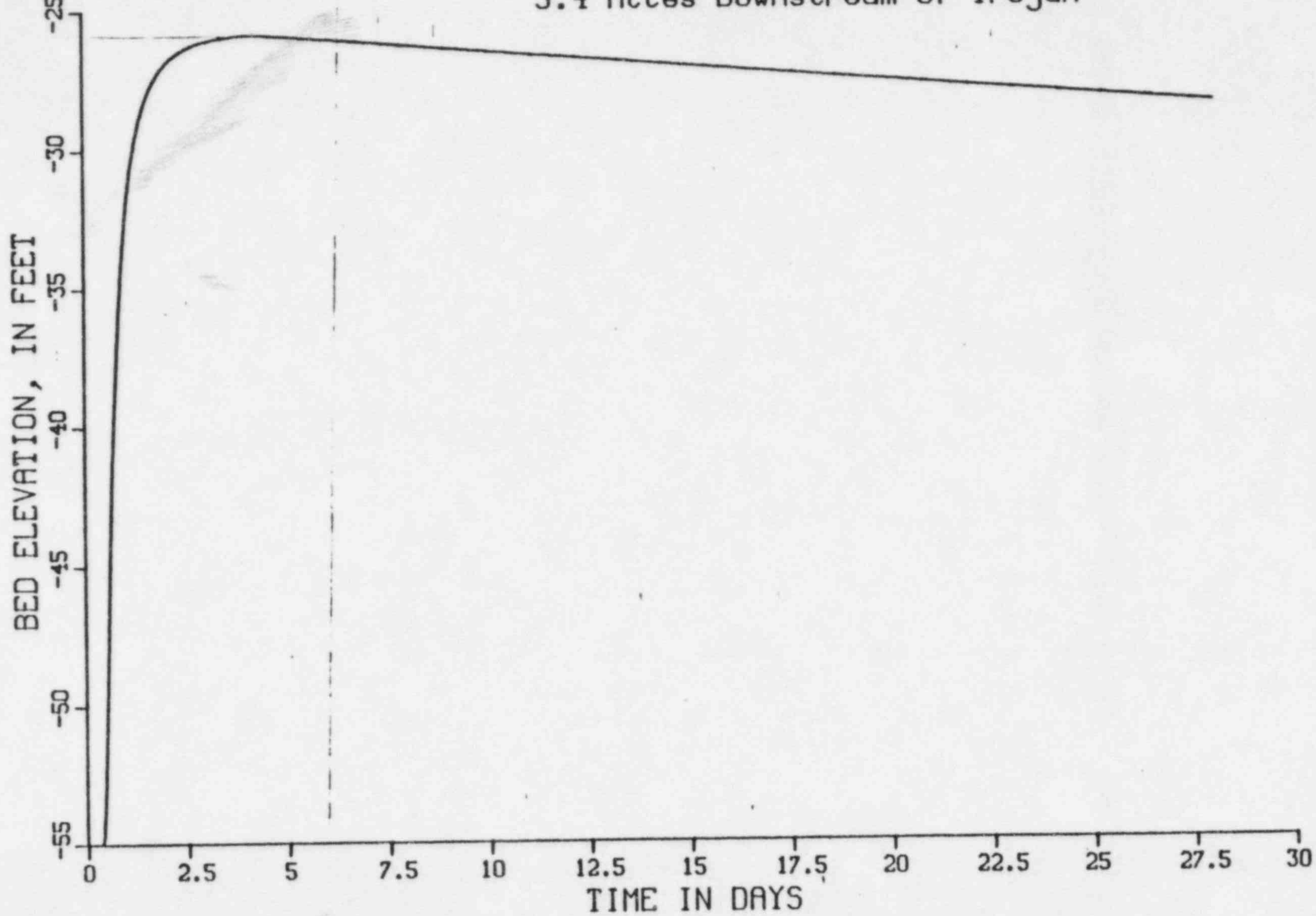


Figure 16
Columbia River at Mile 69.1
Sediment Discharge
3.4 Miles Downstream of Trojan

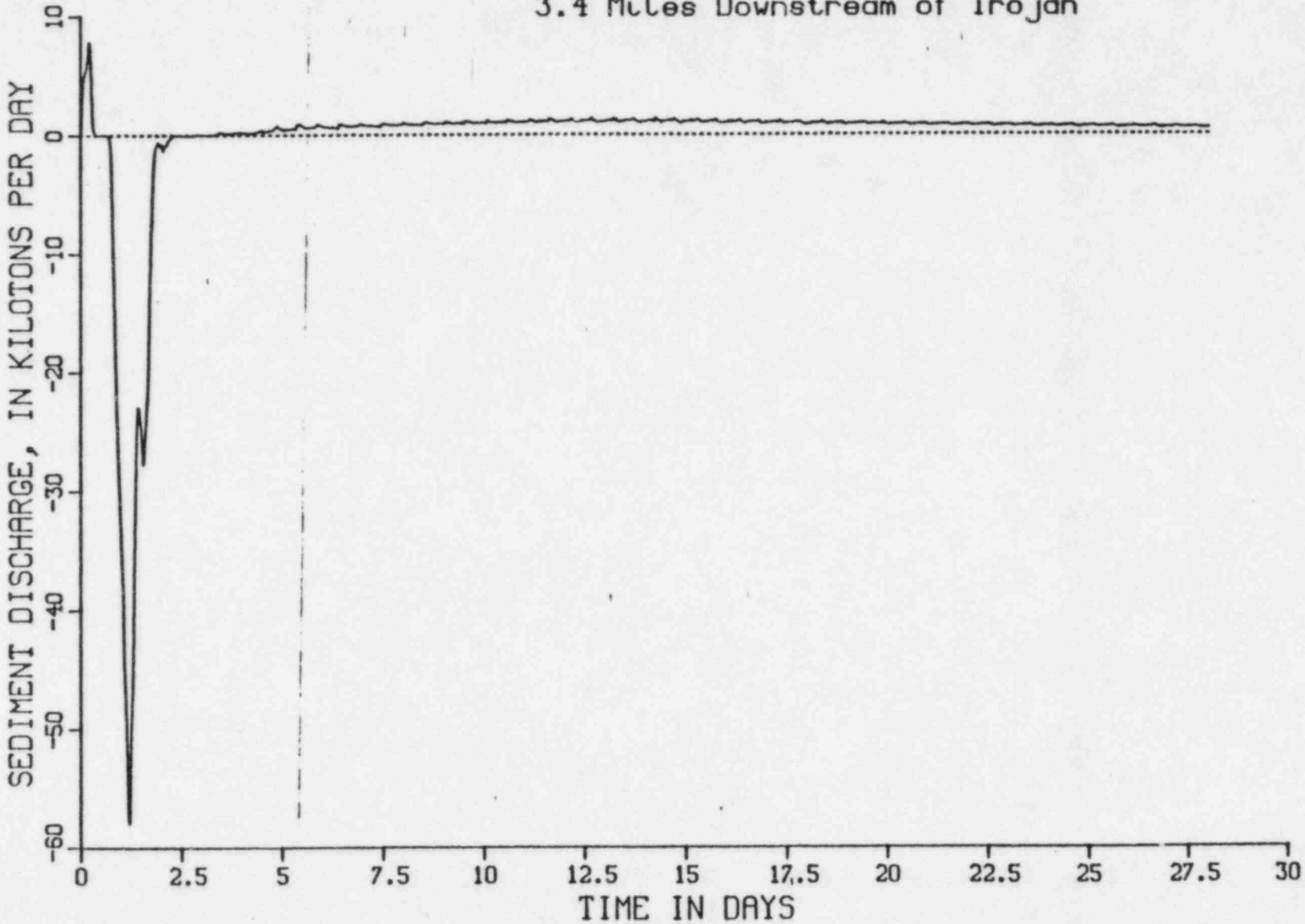


Figure 17
Columbia River at Mile 75.1
Water Surface Elevation
2.6 Miles Upstream of Trojan

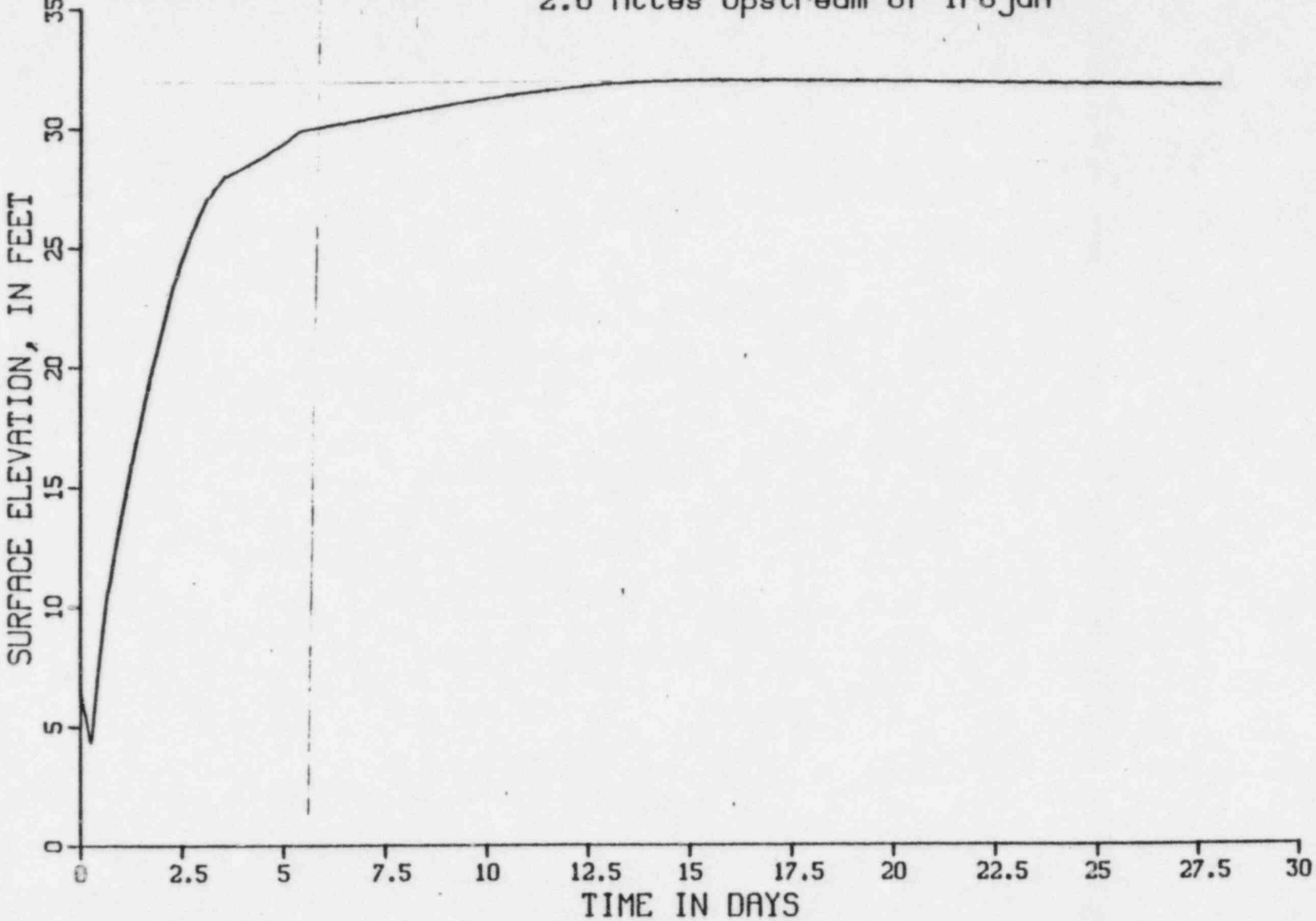


Figure 18
Columbia River at Mile 75.1
Total Discharge
2.6 Miles Upstream of Trojan

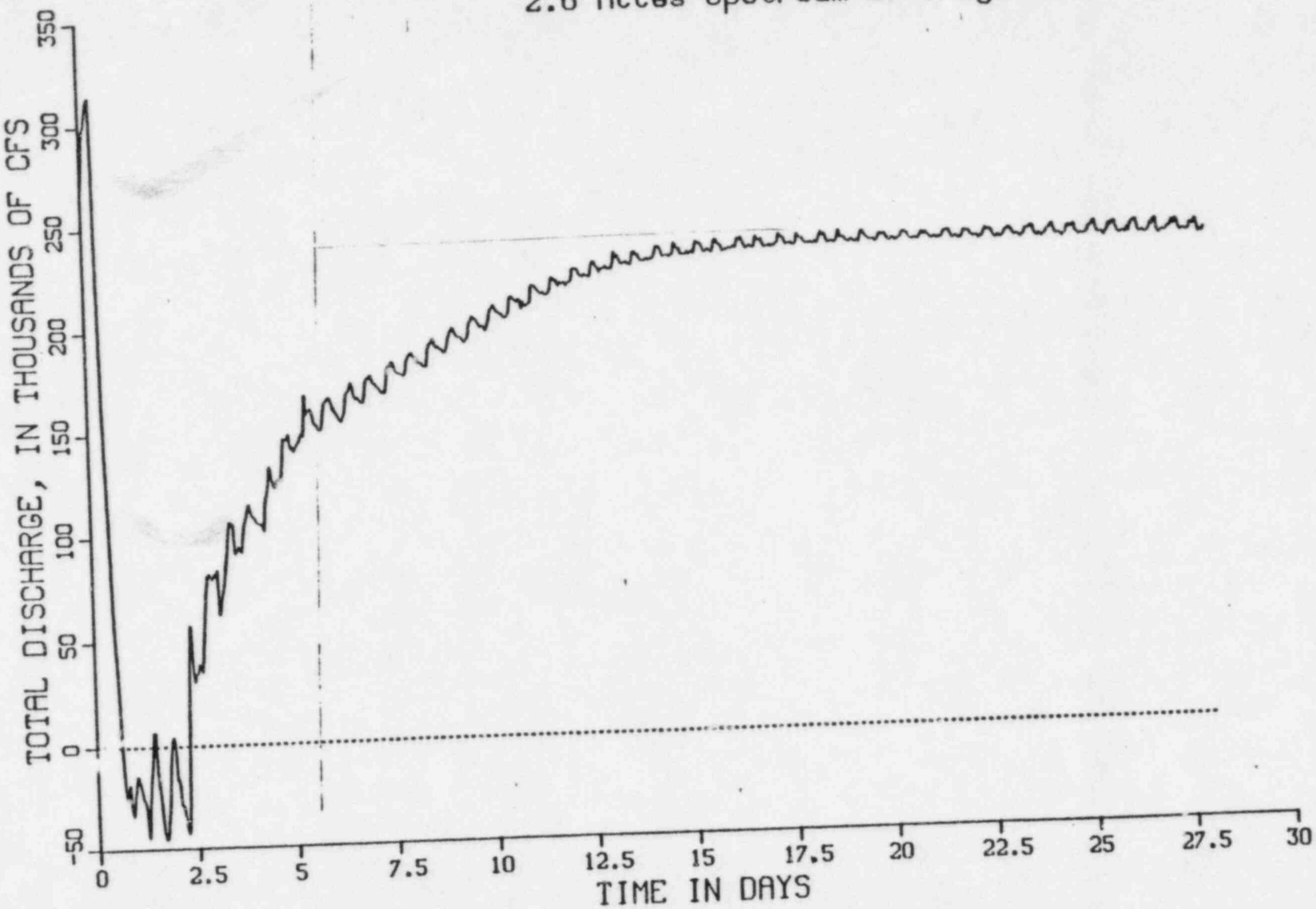


Figure 19
Columbia River at Mile 75.1
Bed Elevation
2.6 Miles Upstream of Trojan

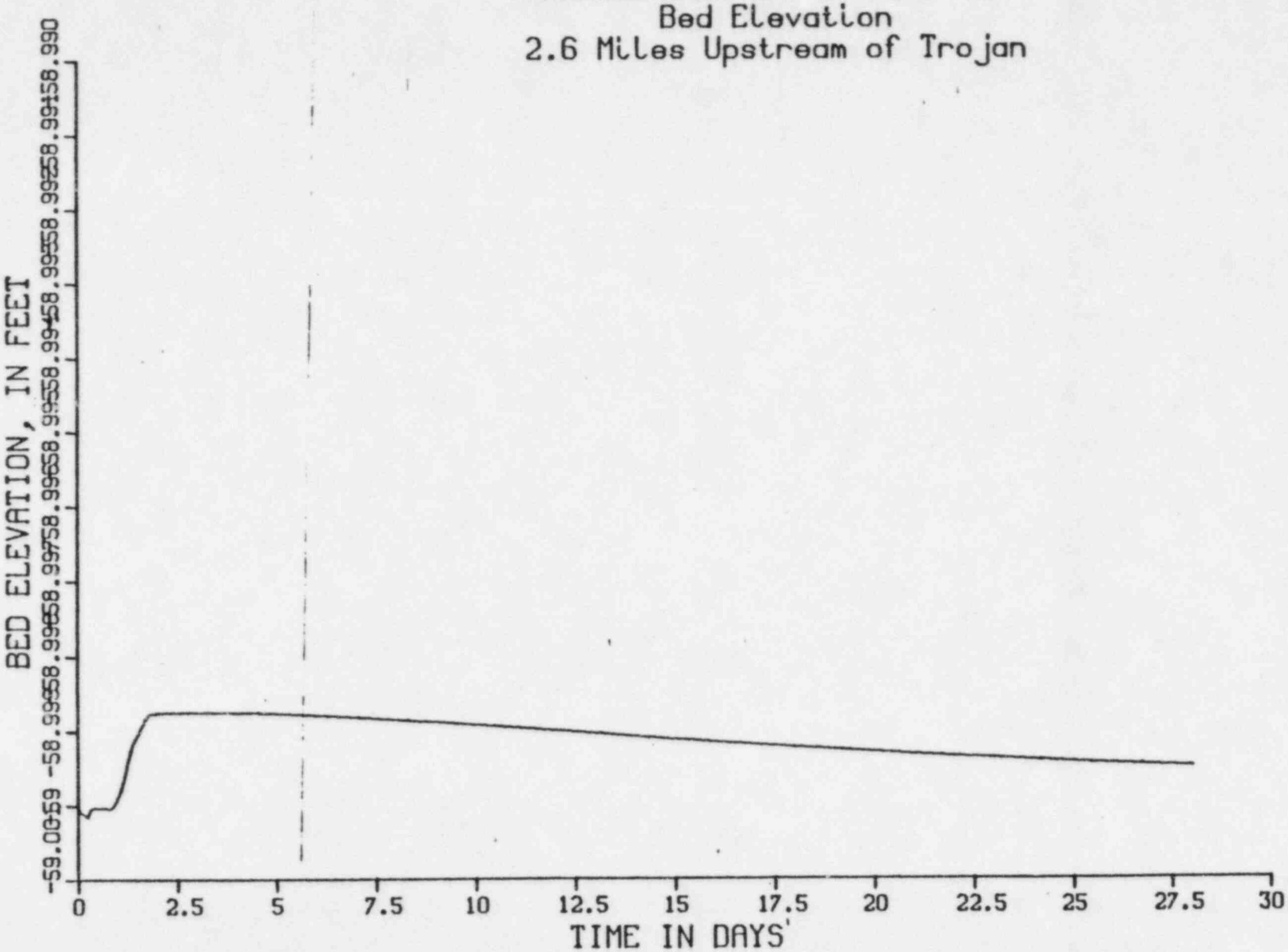
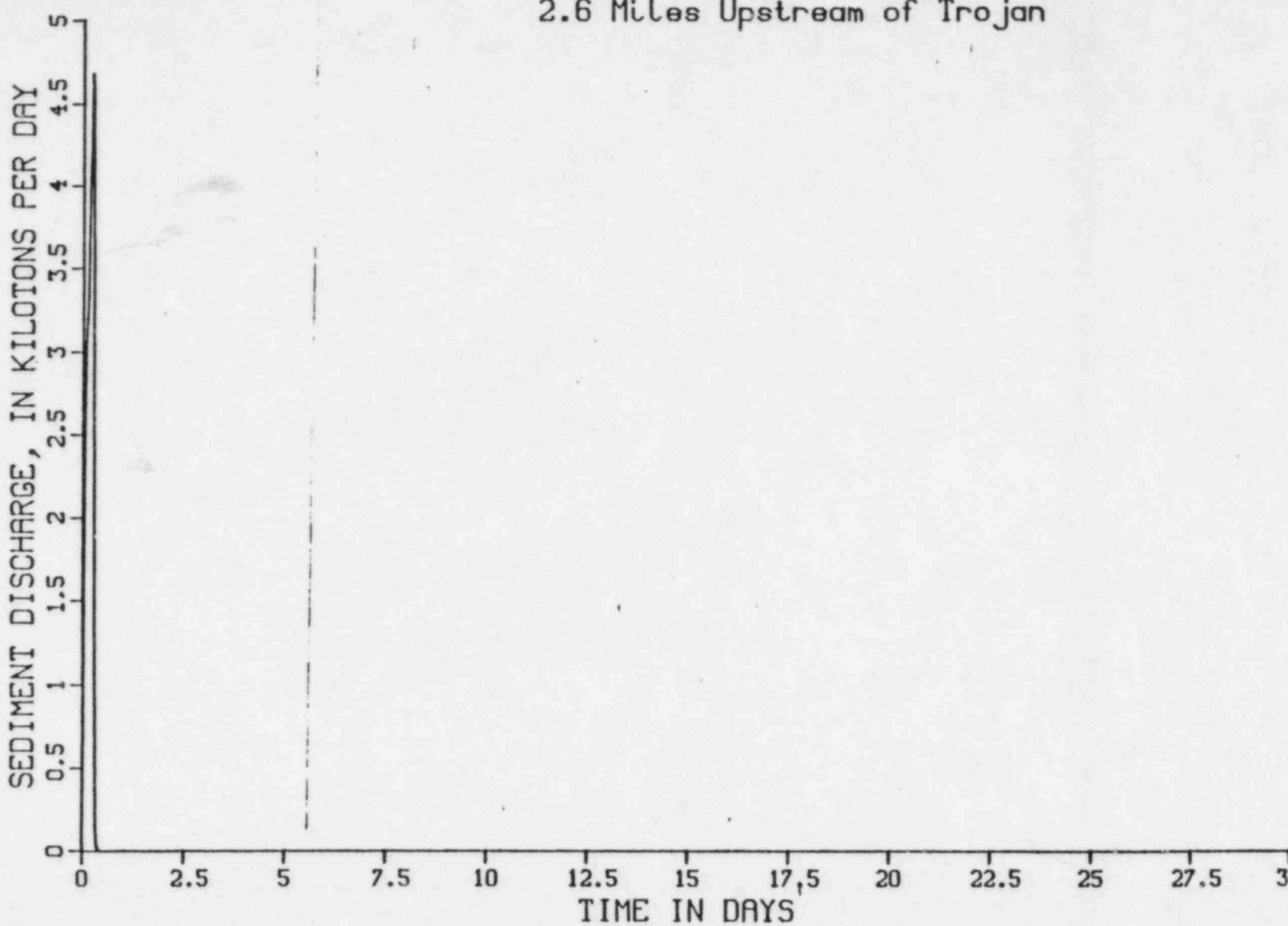


Figure 20
Columbia River at Mile 75.1
Sediment Discharge
2.6 Miles Upstream of Trojan



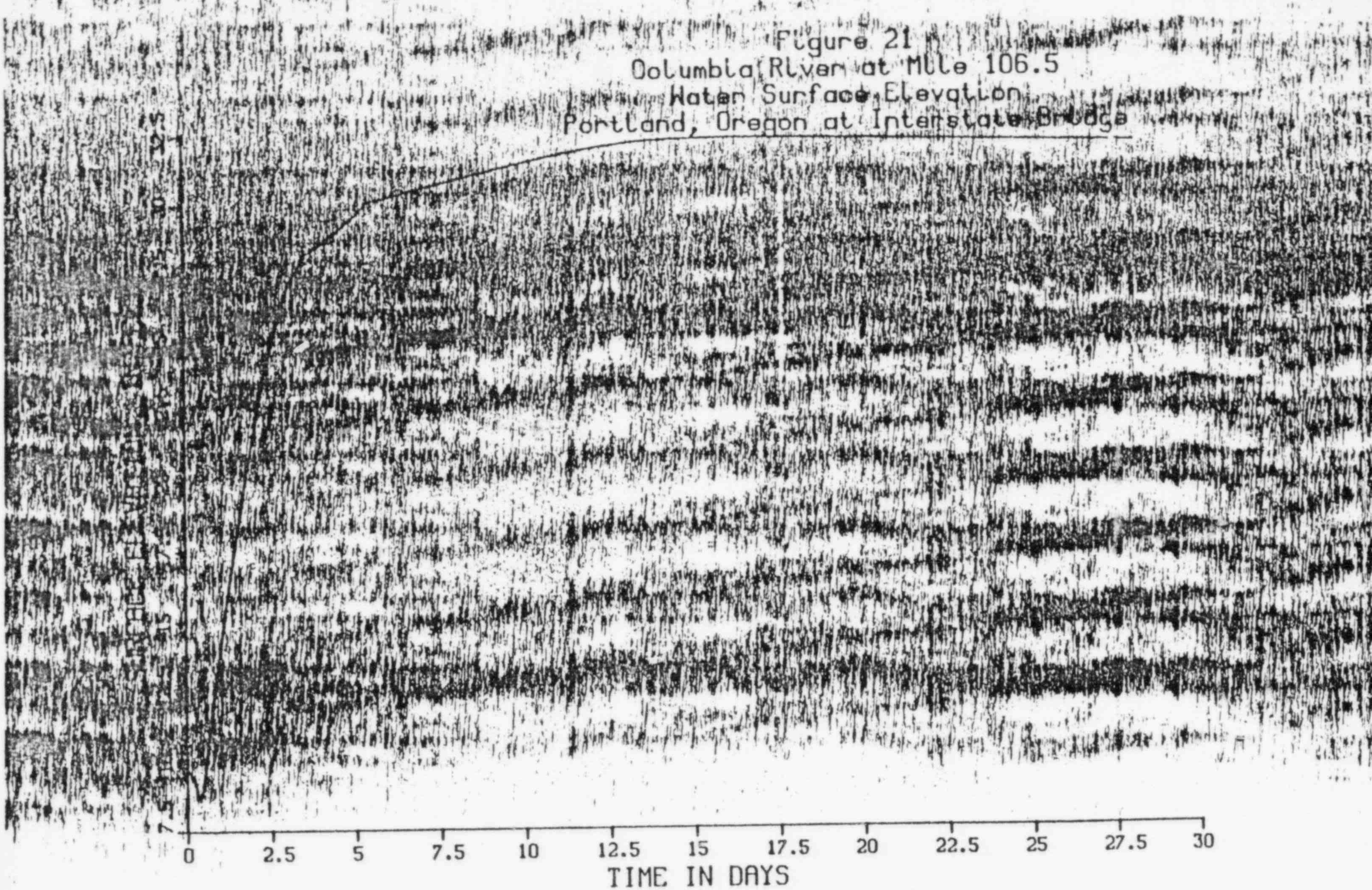


Figure 21
Columbia River at Mile 106.5
Water Surface Elevation
Portland, Oregon at Interstate Bridge
0
2.5
5
7.5
10
12.5
15
17.5
20
22.5
25
27.5
30
TIME IN DAYS

Figure 22
Columbia River at Mile 106.5
Total Discharge
Portland, Oregon at Interstate Bridge

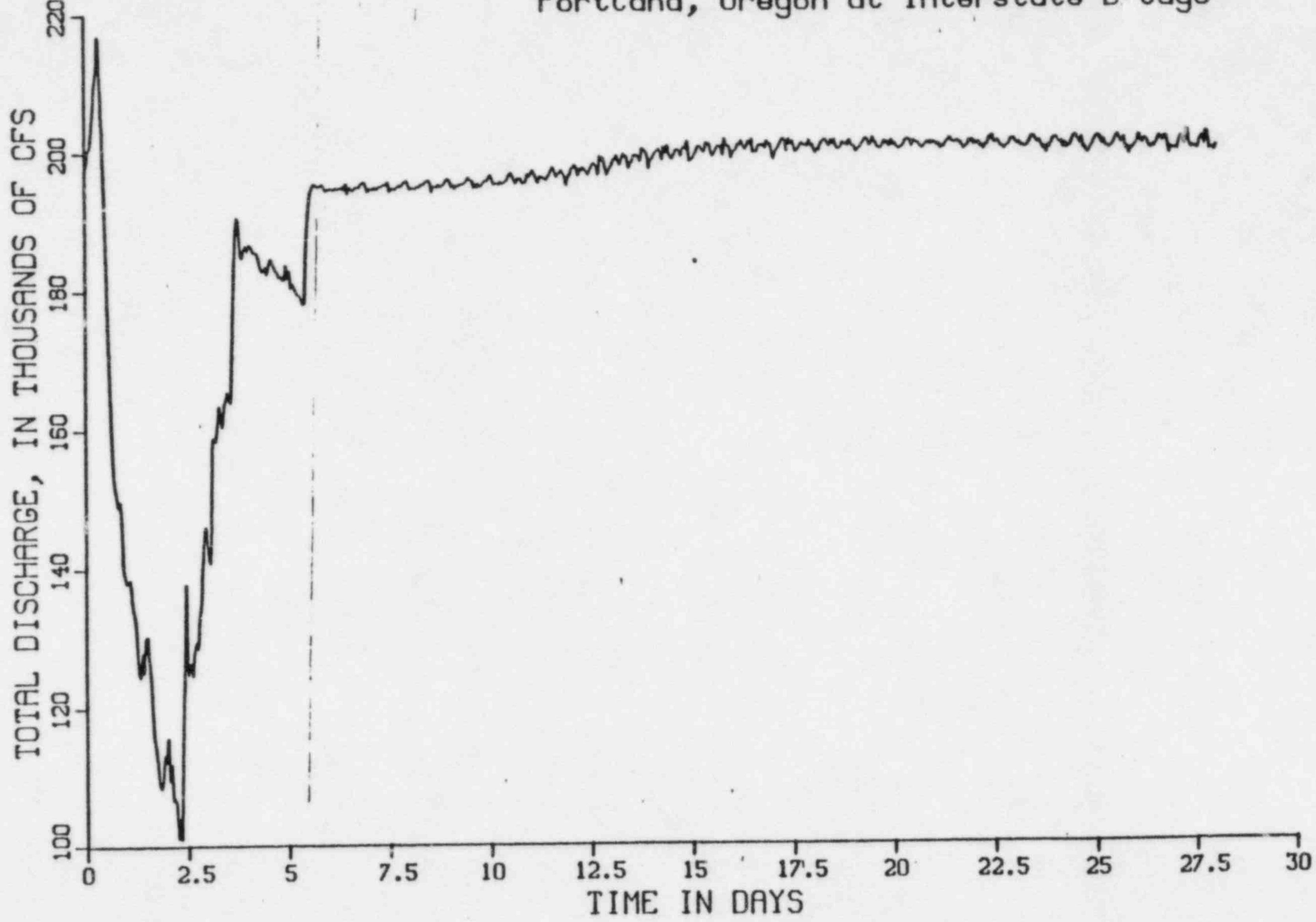


Figure 23
Columbia River
Water Surface and Bed Profiles
at 0.25 Day

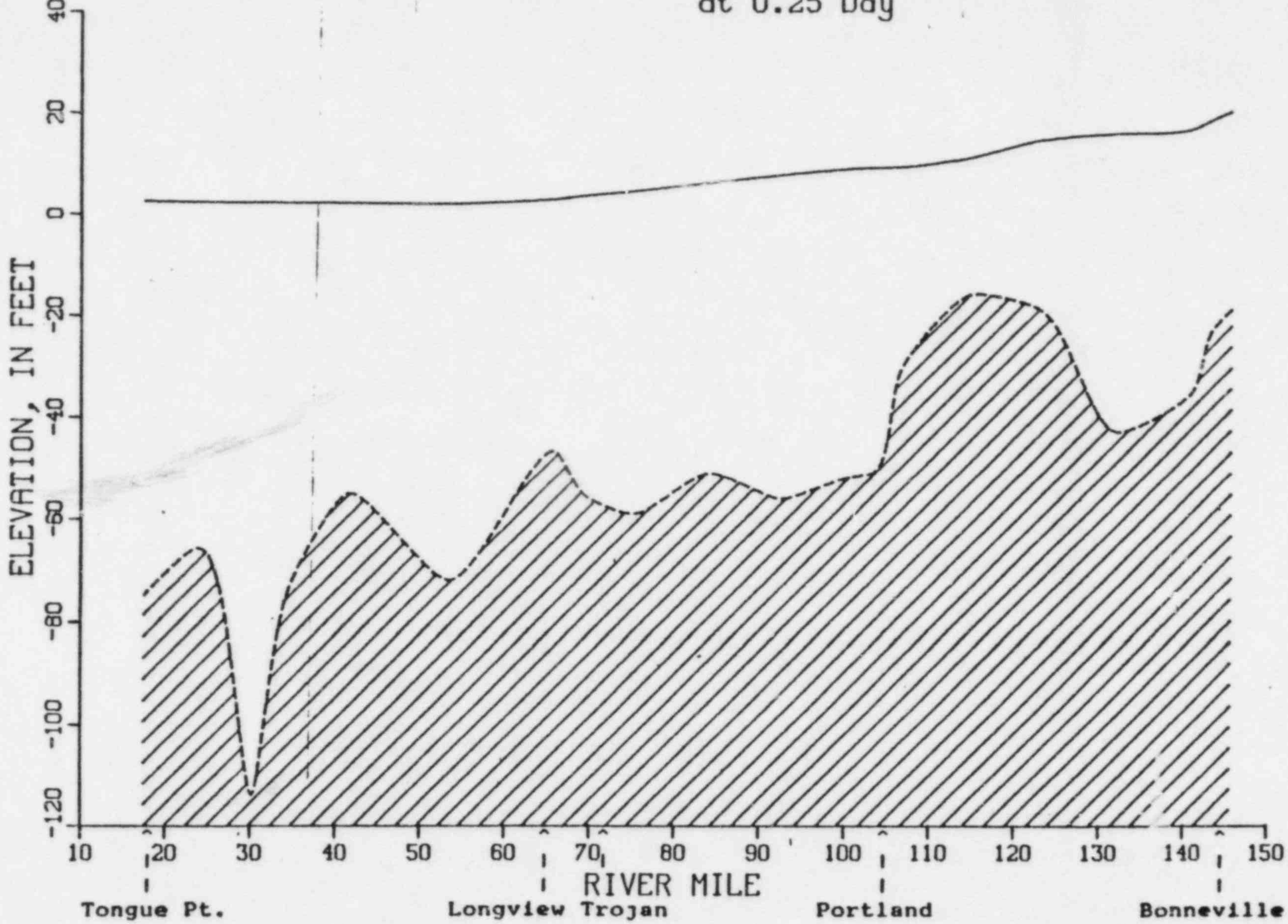


Figure 24
Columbia River
Water Surface and Bed Profiles
at 0.50 Day

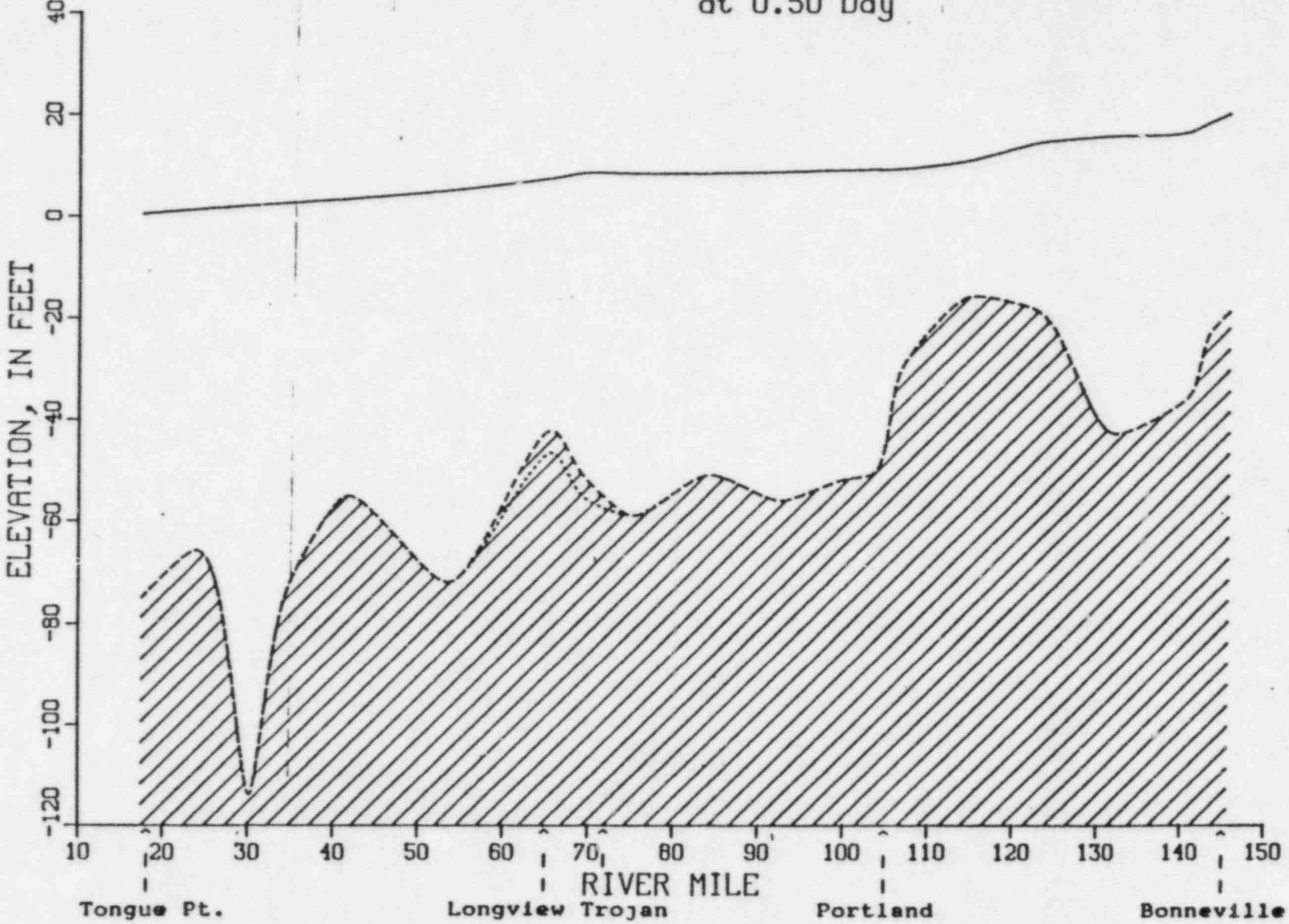


Figure 25
Columbia River
Water Surface and Bed Profiles
at 0.75 Day

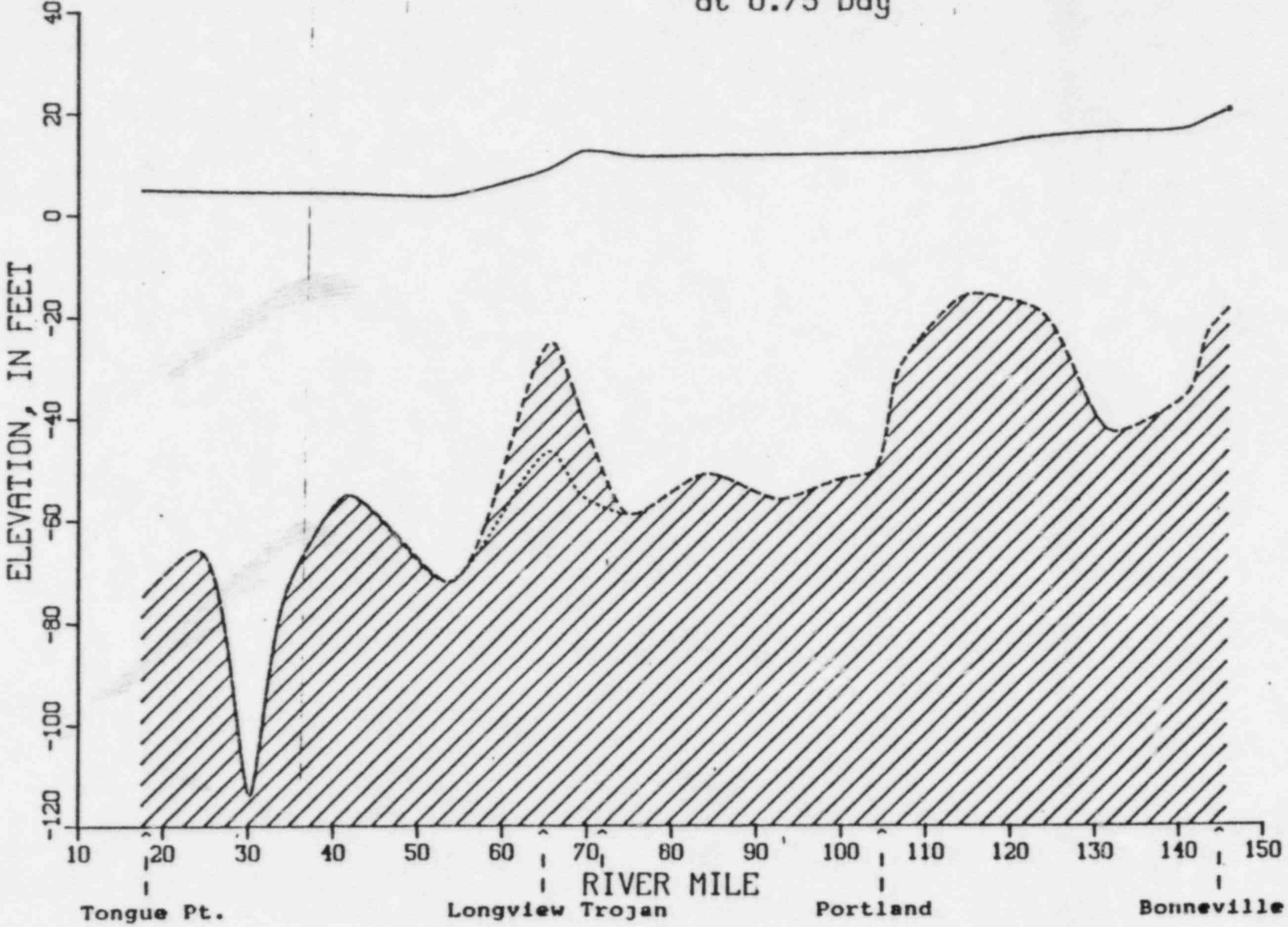


Figure 26
Columbia River
Water Surface and Bed Profiles
at 1 Day

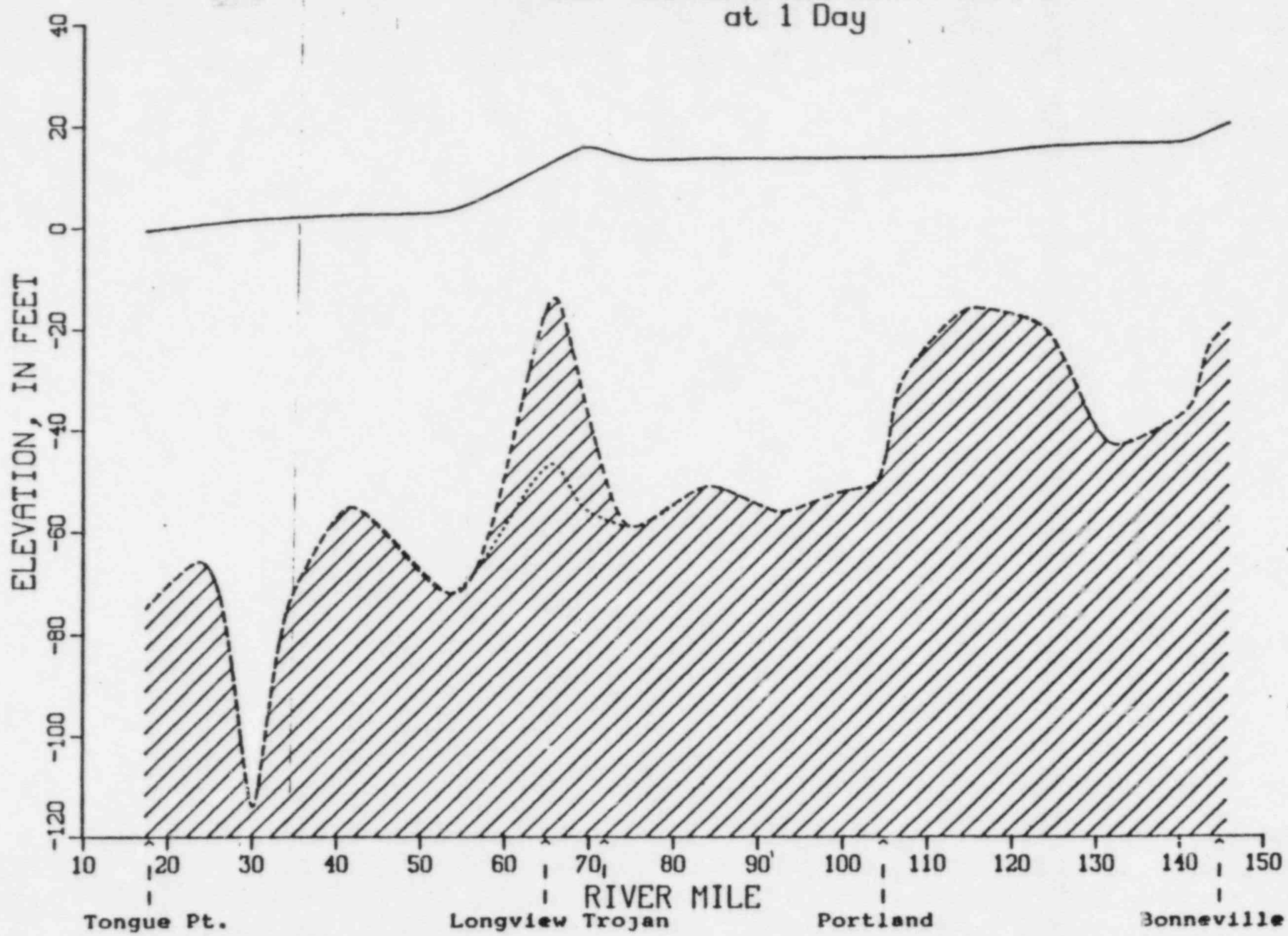


Figure 27
Columbia River
Water Surface and Bed Profiles
at 1.25 Days

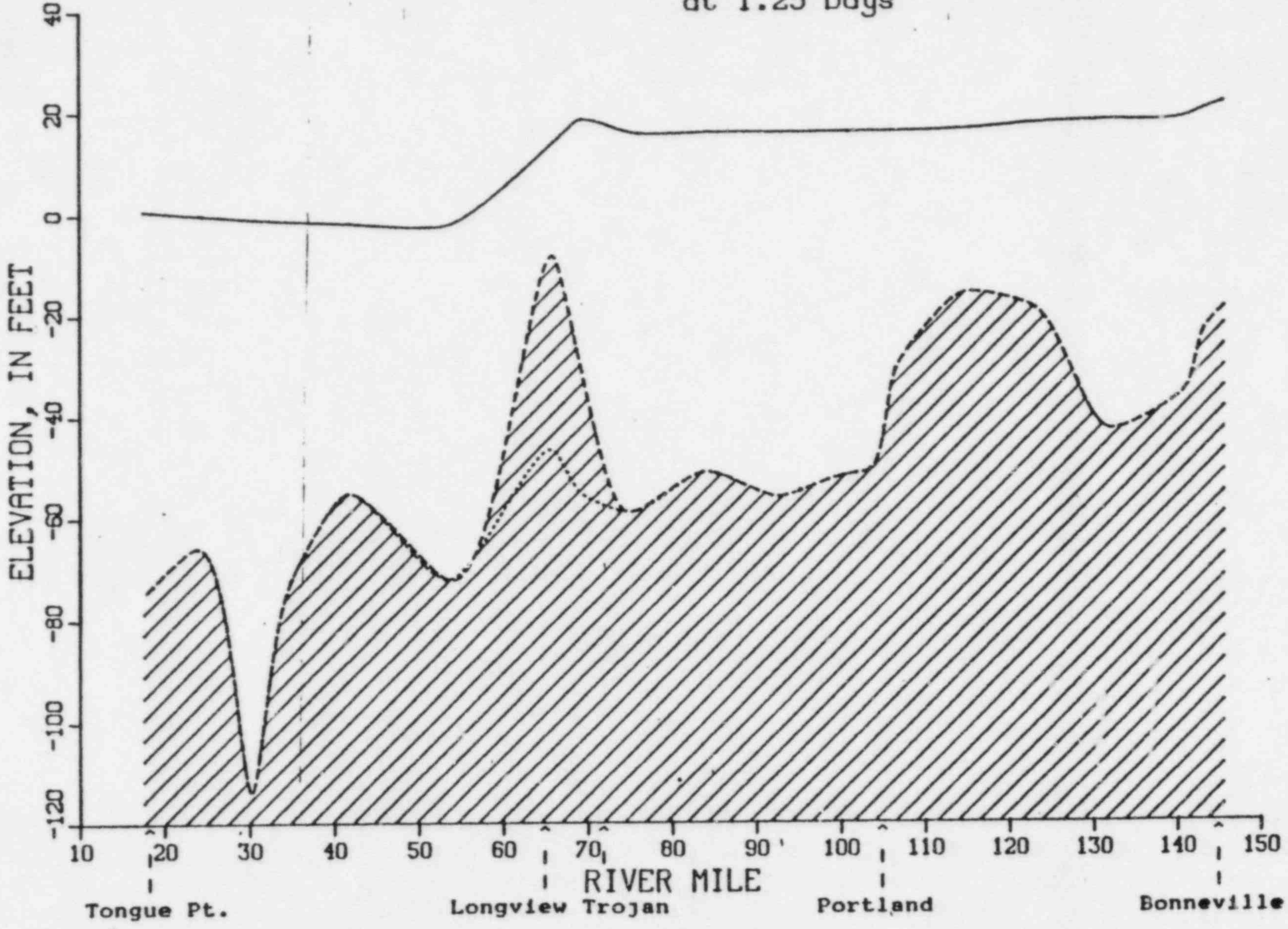


Figure 28
Columbia River
Water Surface and Bed Profiles
at 1.50 Days

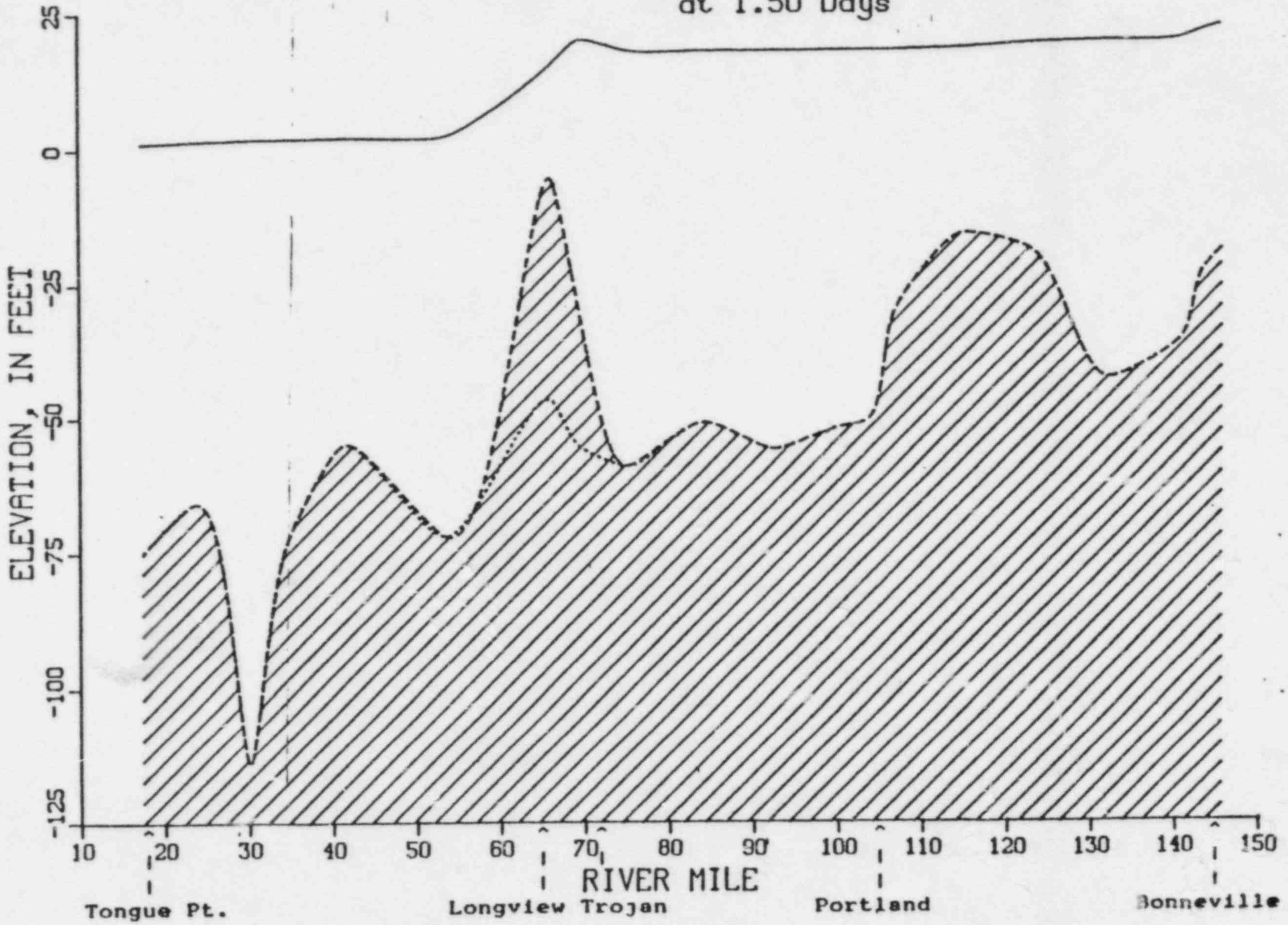


Figure 29
Columbia River
Water Surface and Bed Profiles
at 1.75 Days

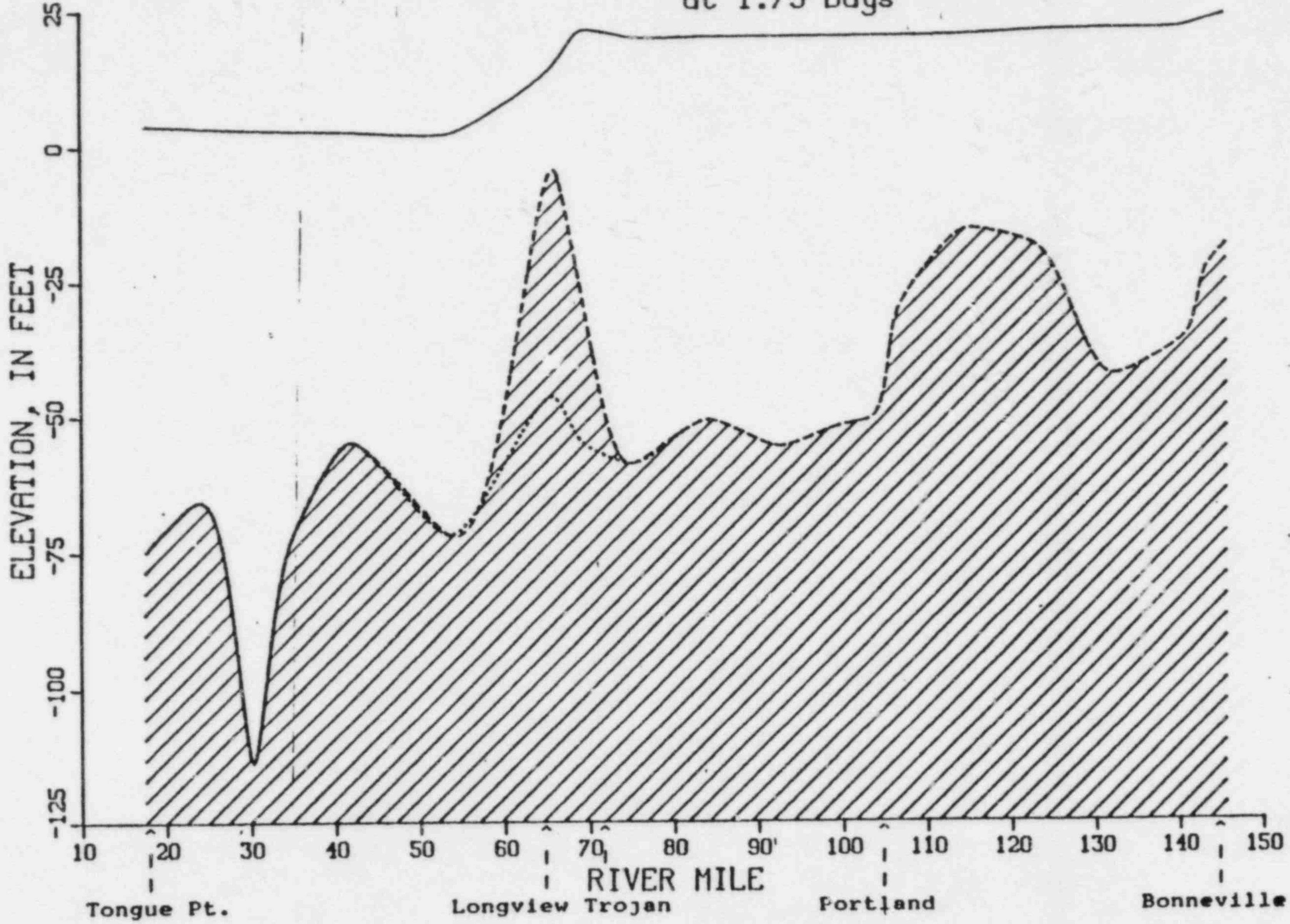


Figure 30
Columbia River
Water Surface and Bed Profiles
at 2 Days

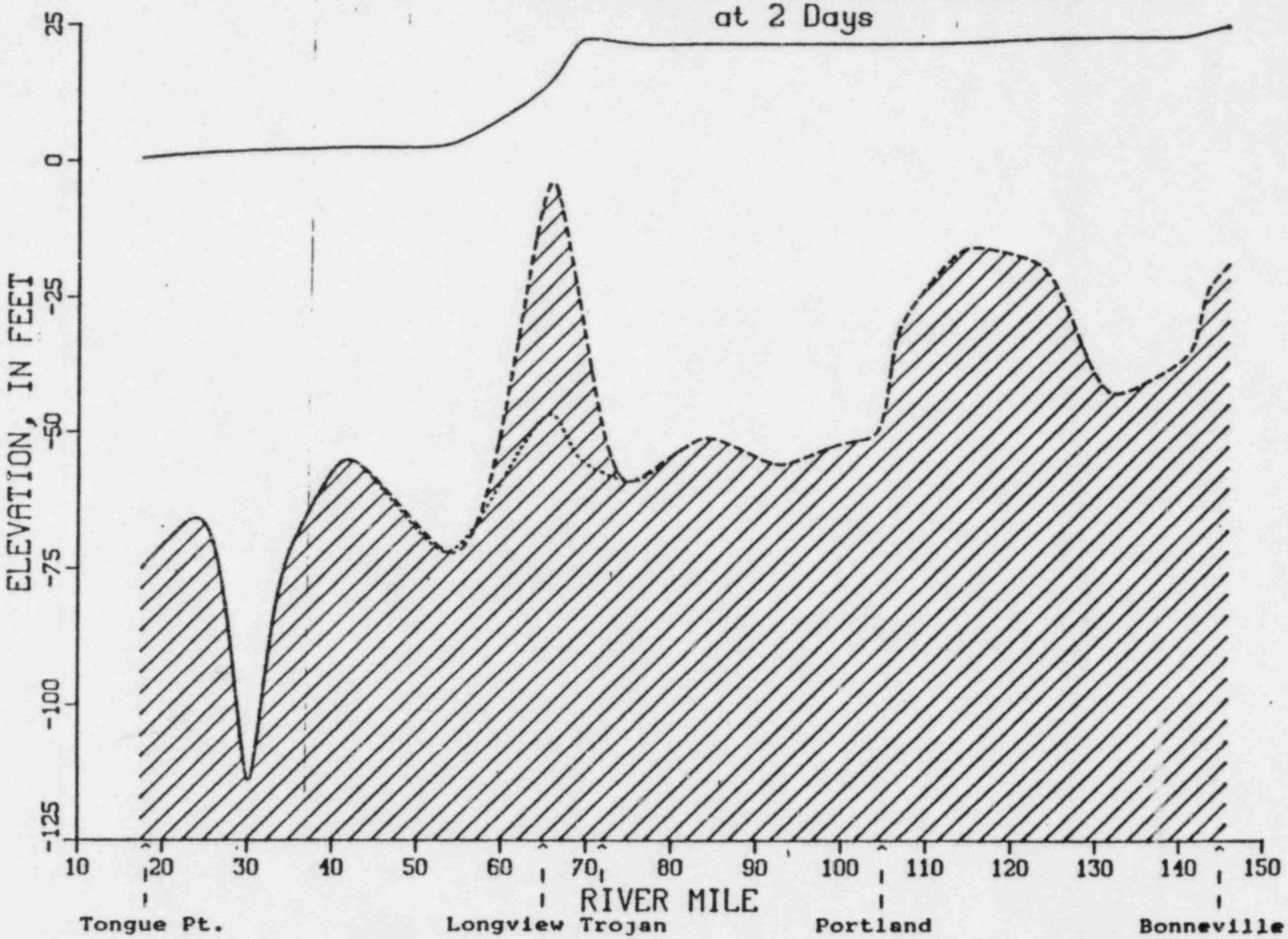


Figure 31
Columbia River
Water Surface and Bed Profiles
at 3 Days

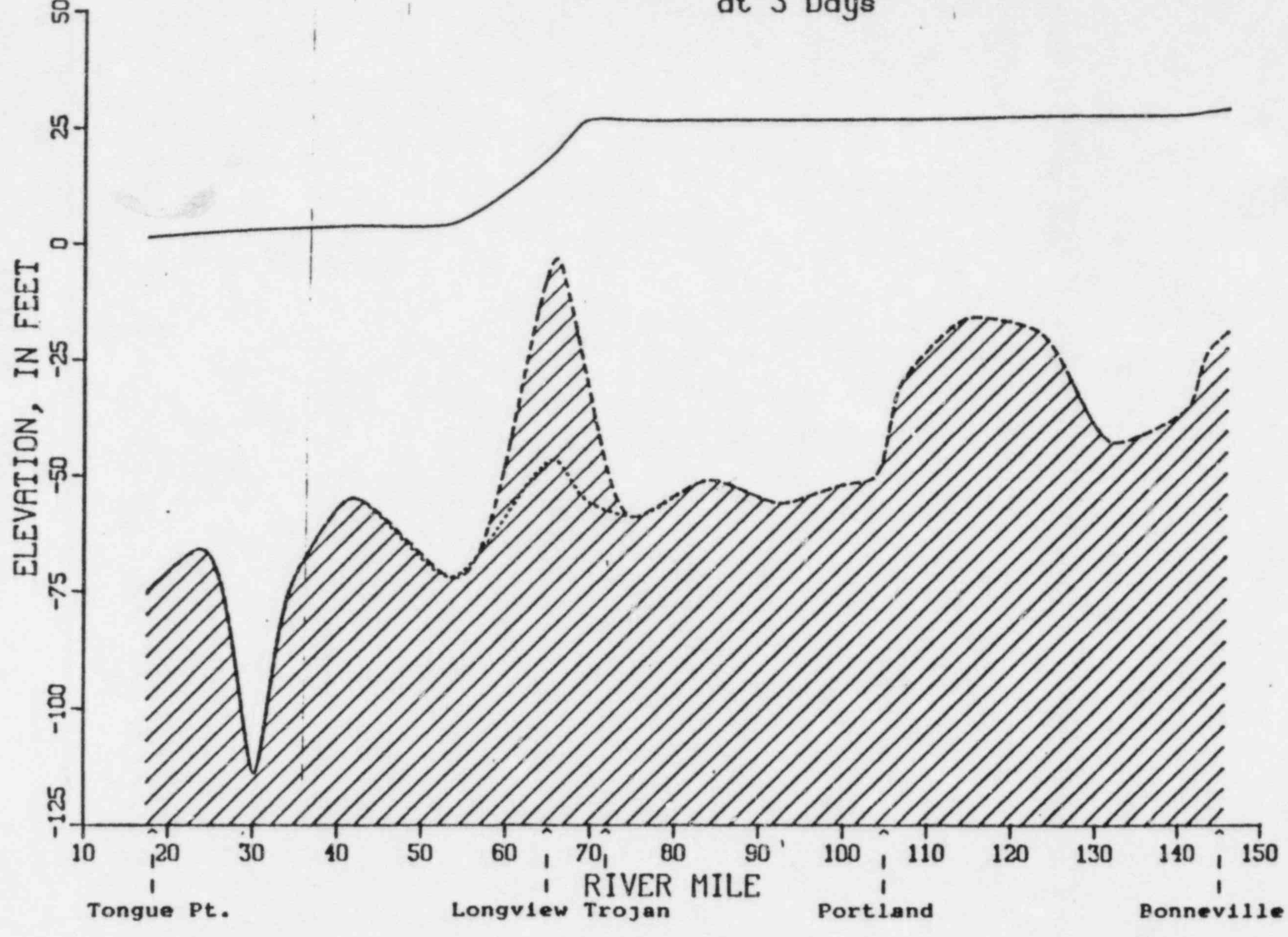


Figure 32
Columbia River
Water Surface and Bed Profiles
at 4 Days

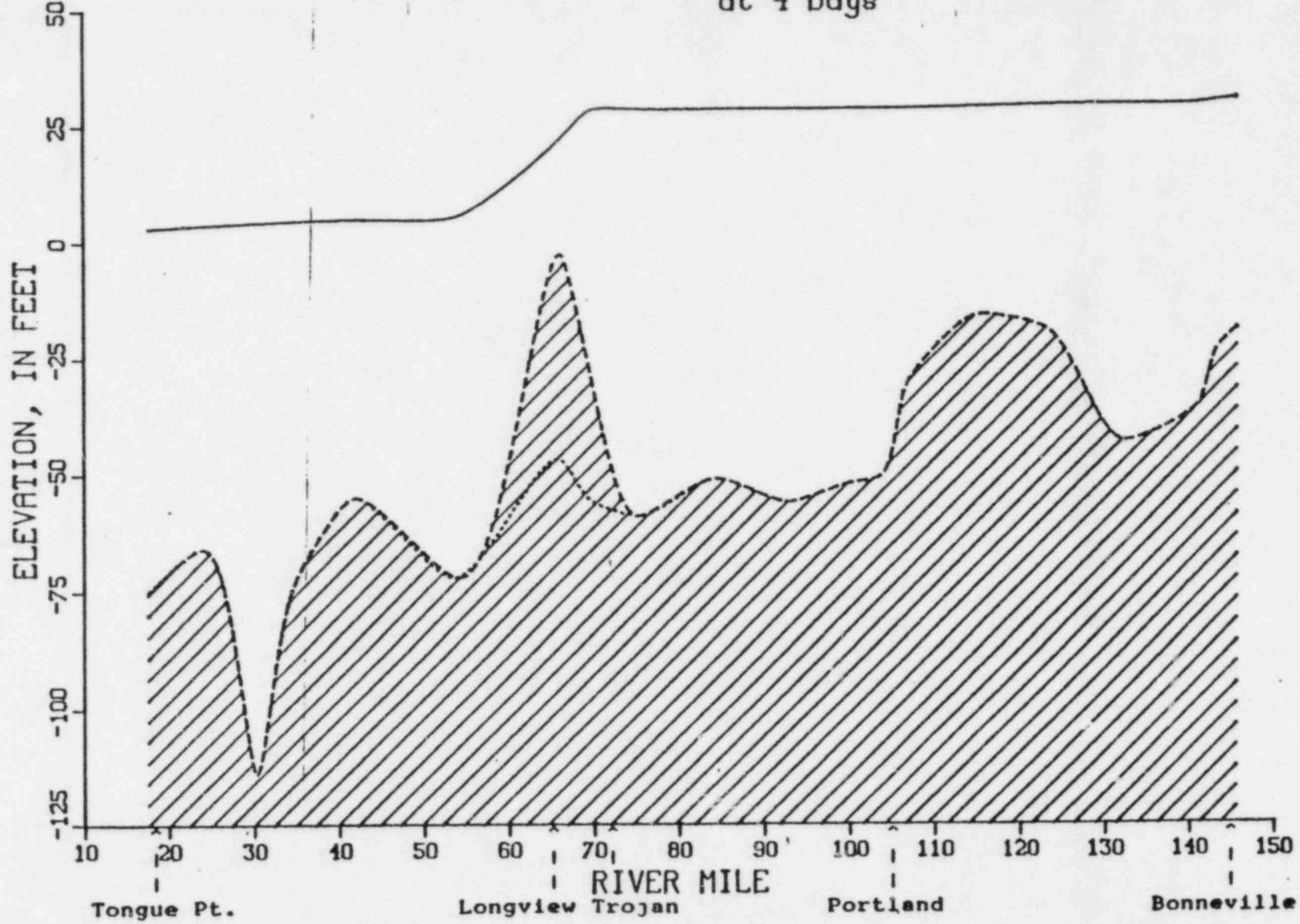


Figure 33
Columbia River
Water Surface and Bed Profiles
at 5 Days

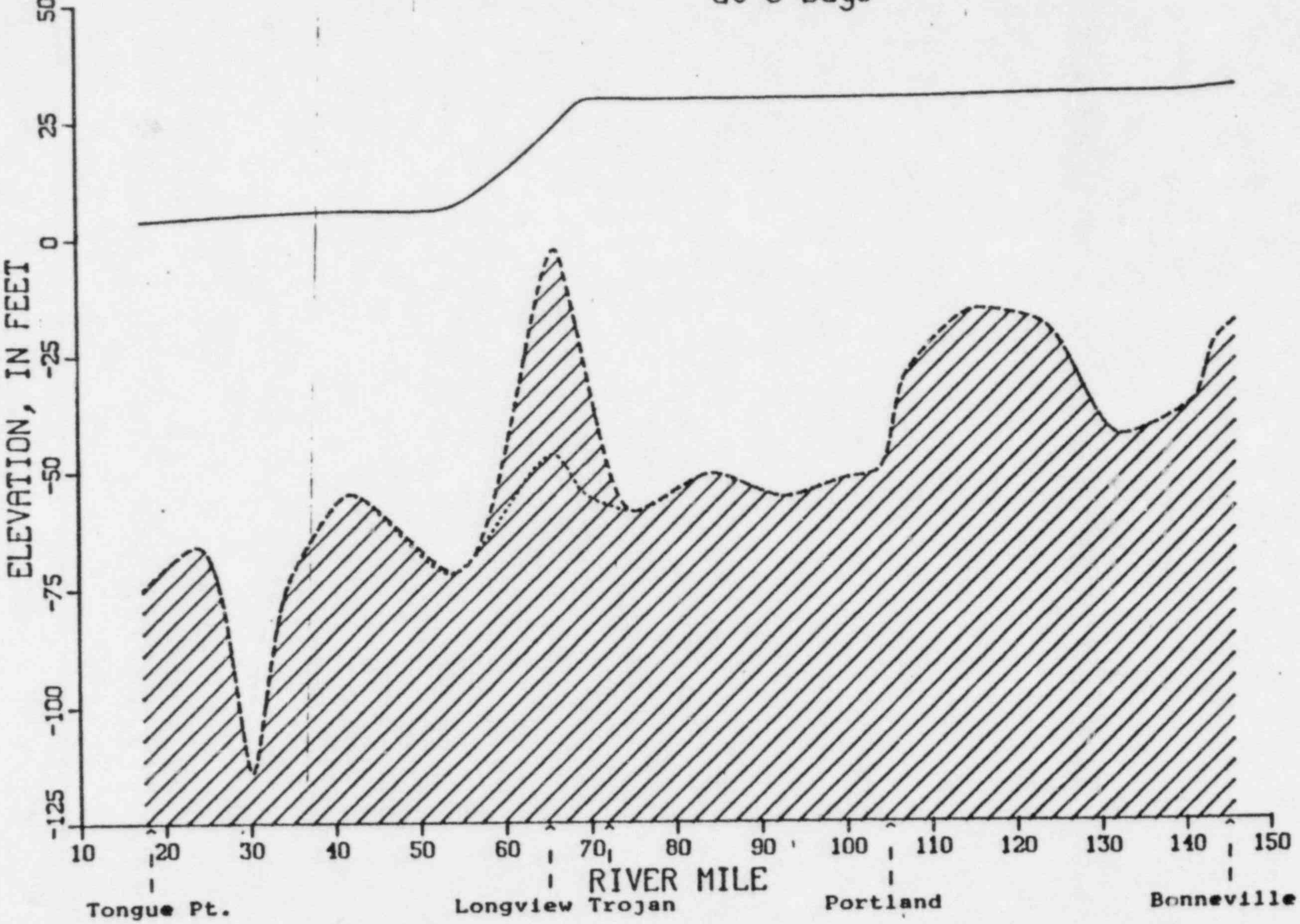


Figure 34
Columbia River
Water Surface and Bed Profiles
at 6 Days

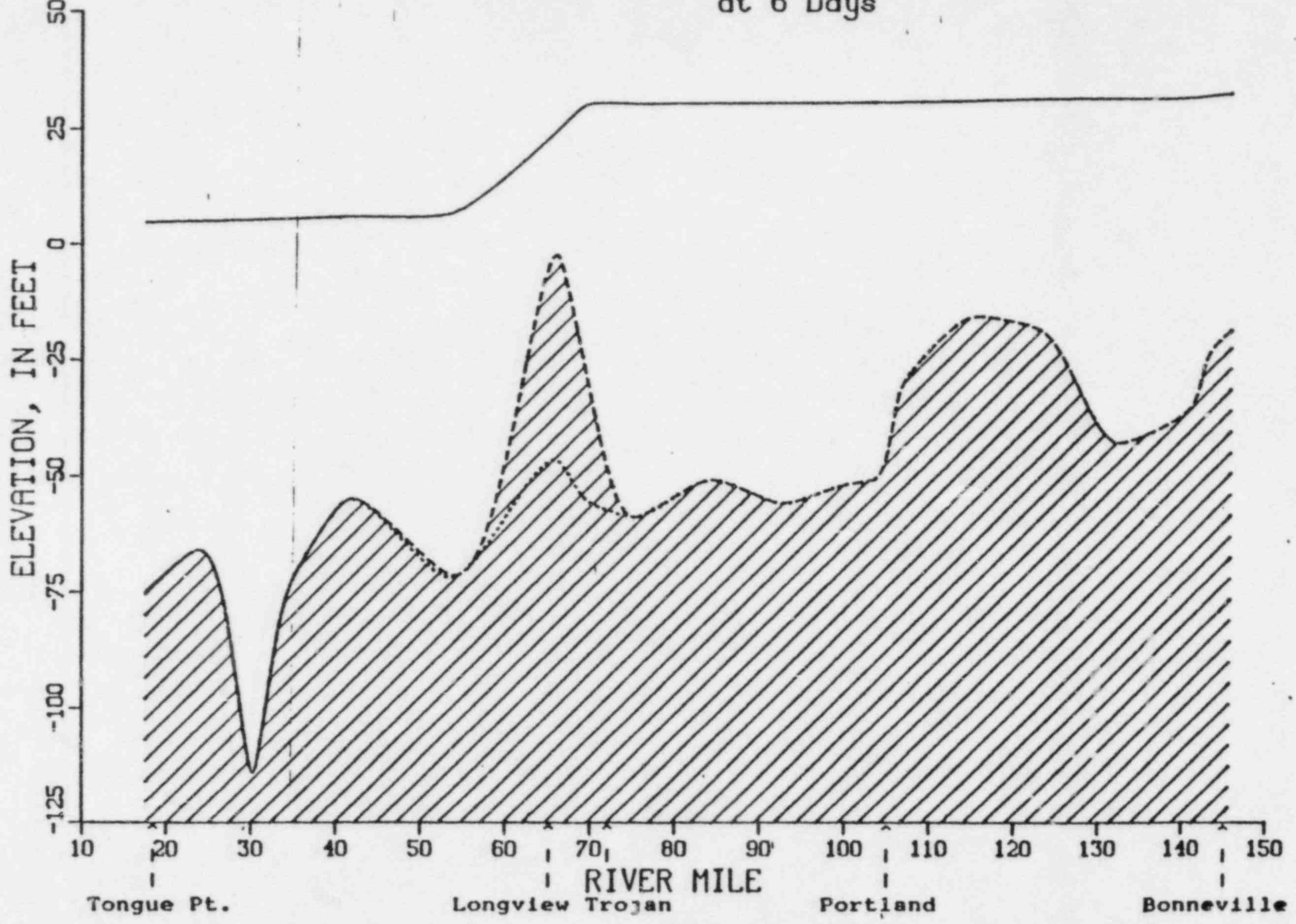


Figure 35
Columbia River
Water Surface and Bed Profiles
at 7 Days

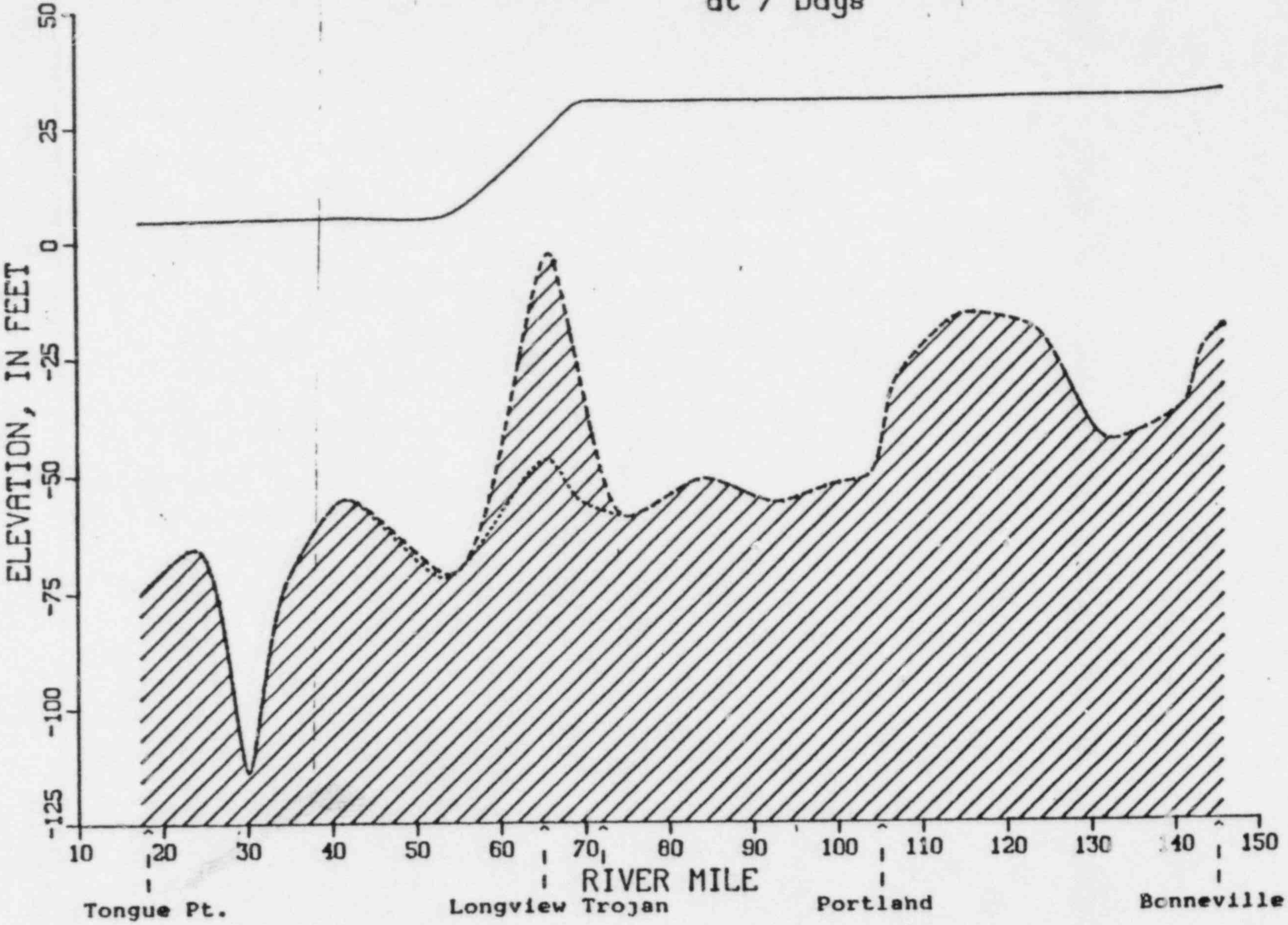


Figure 36
Columbia River
Water Surface and Bed Profiles
at 10 Days

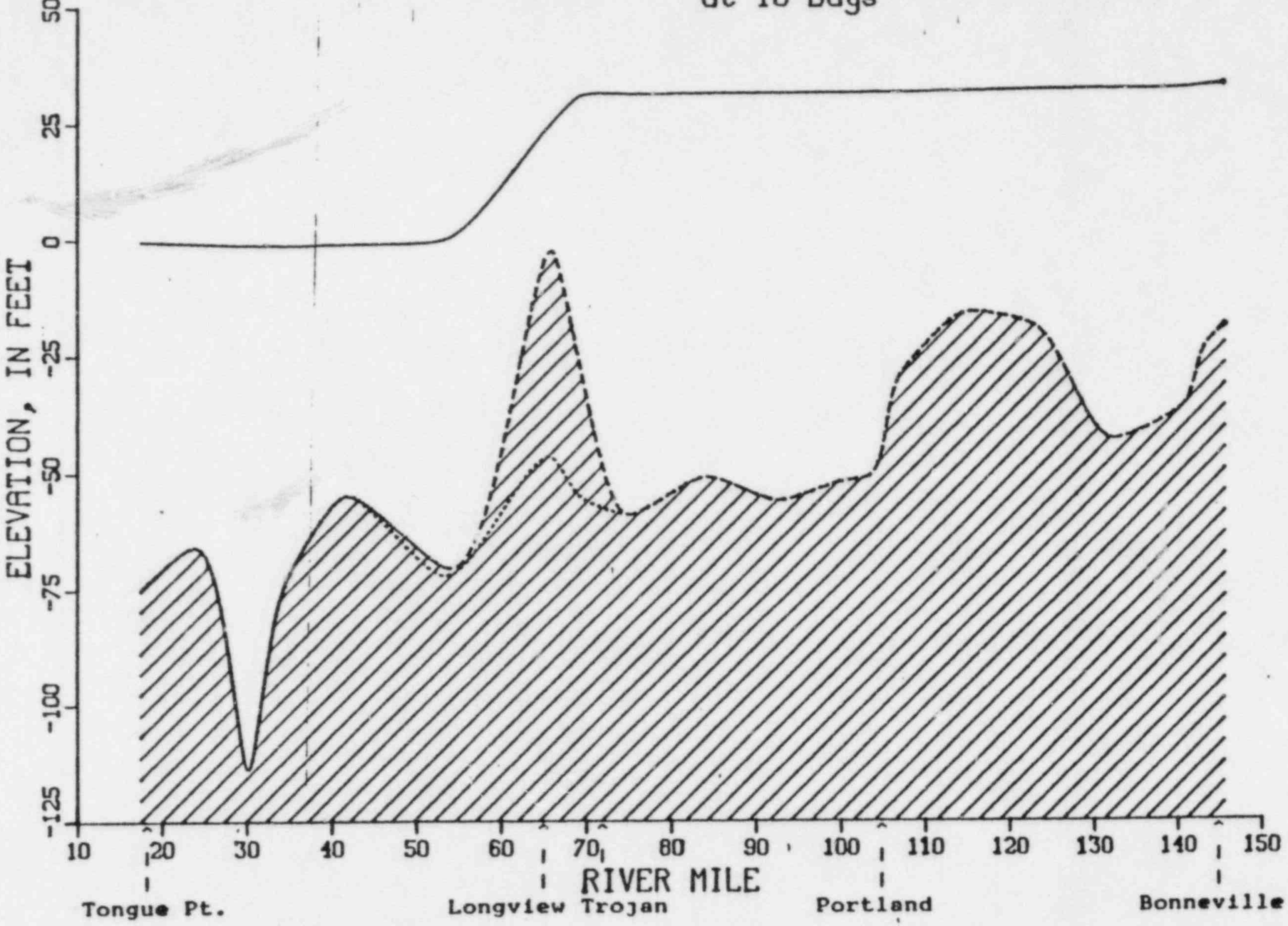


Figure 37
Columbia River
Water Surface and Bed Profiles
at 14 Days

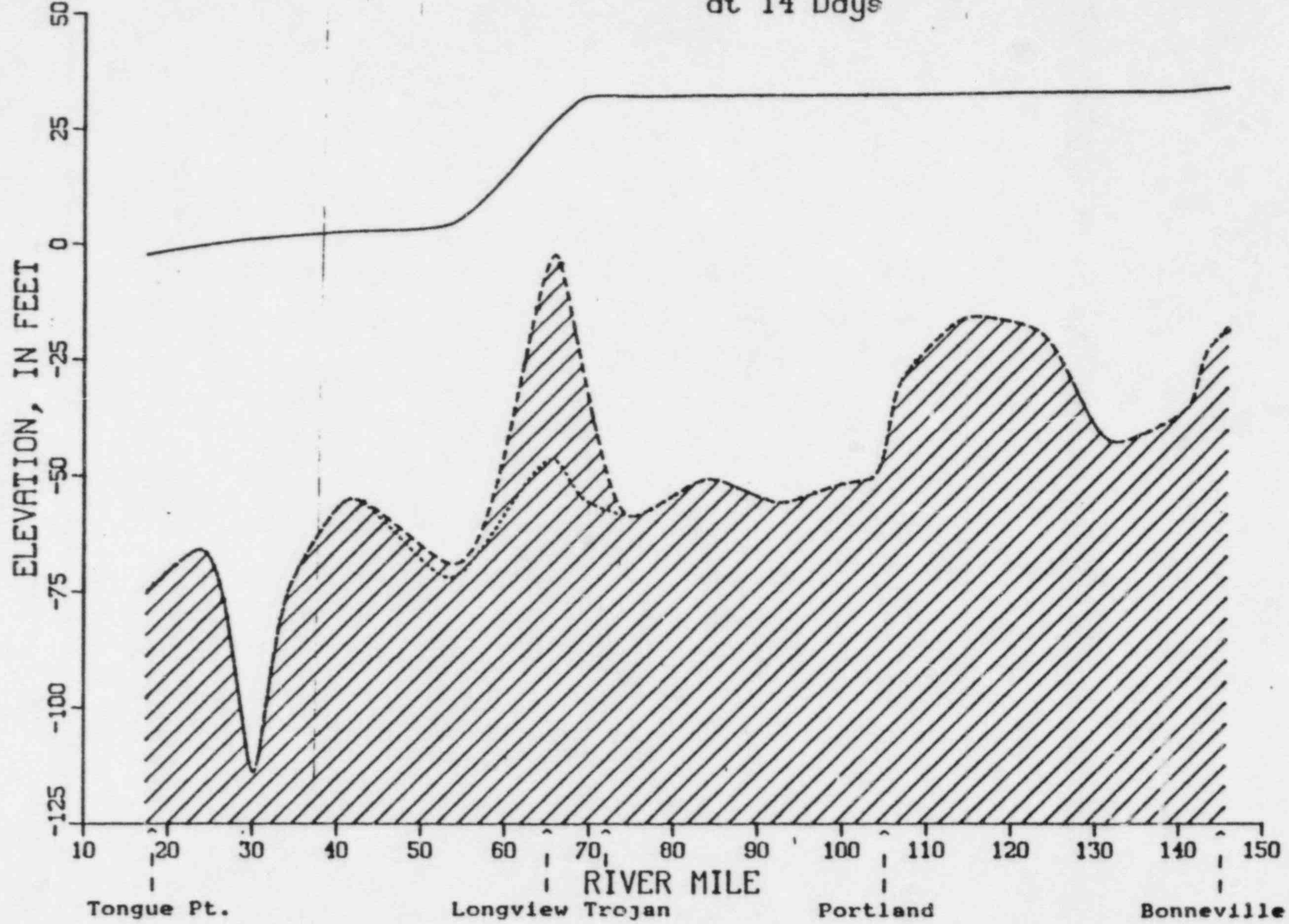


Figure 38
Columbia River
Water Surface and Bed Profiles
at 17 Days

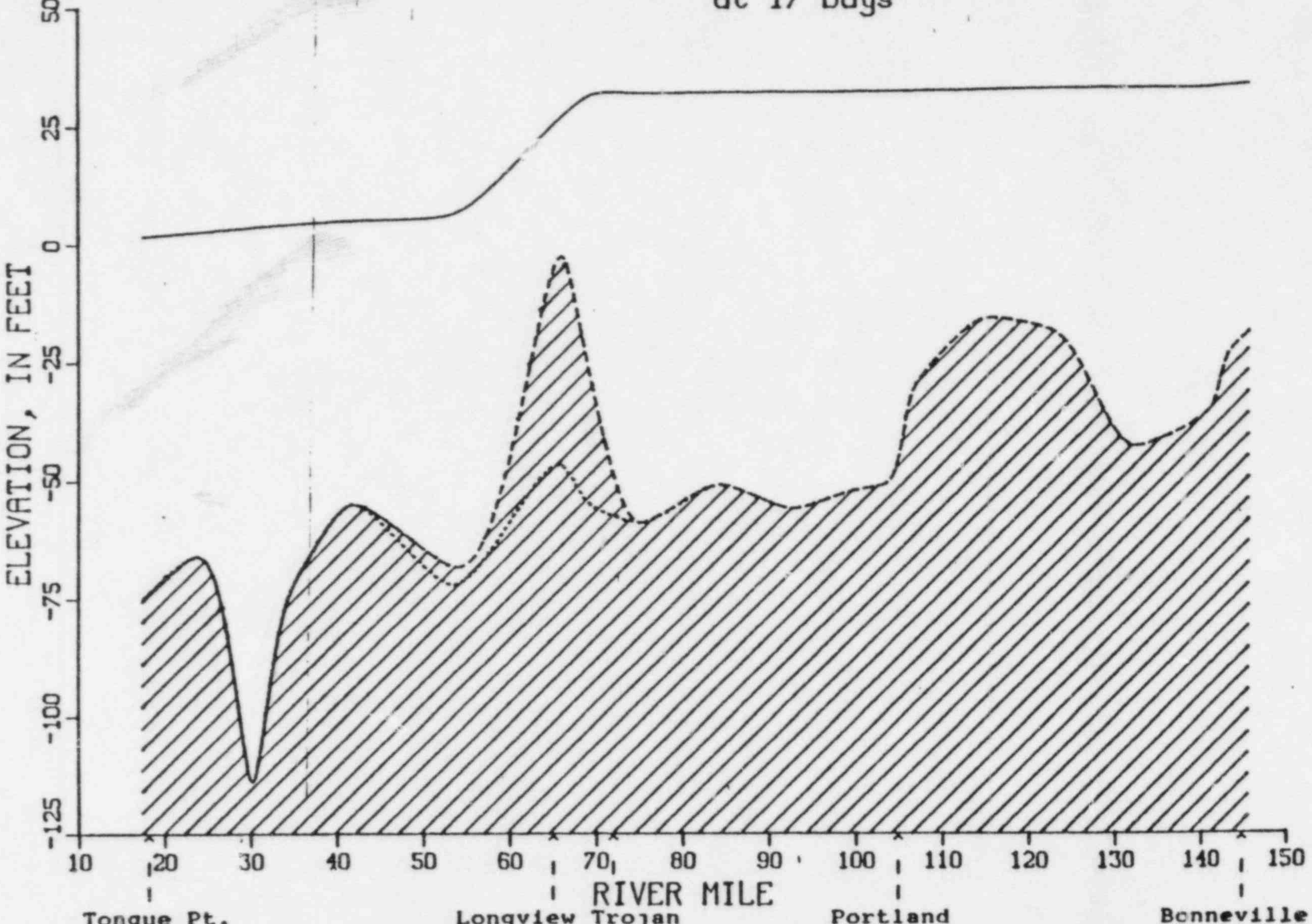


Figure 39
Columbia River
Water Surface and Bed Profiles
at 21 Days

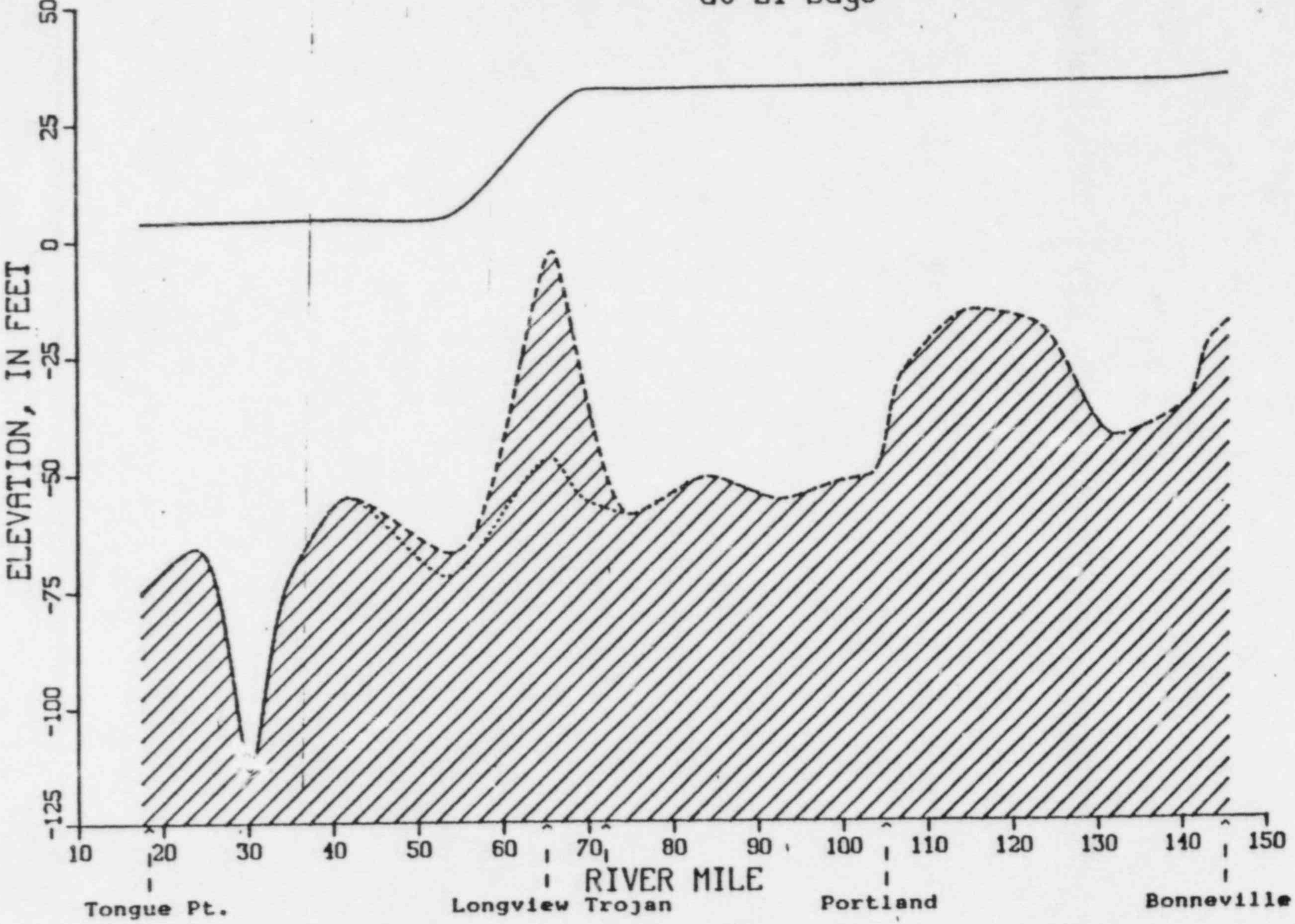


Figure 40
Columbia River
Water Surface and Bed Profiles
at 28 Days