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Correlated Studies of Vancouver Lake - Hydraulic Model Study

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CORRELATED STUDIES OF VANCOUVER LAKE-
HYDRAULIC MODEL STUDY

By

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ABSTRACT

The effects of possible modifications to the Vancouver Lake-Columbia River system on the hydraulic characteristics of that system were tested in a physical hydraulic model. A mathematical model was developed for predictive analysis and to expand the results of the hydraulic model study. Alternate methods for improving flushing action through Vancouver Lake by use of a conduit were investigated.

The theories, assumptions, test procedures, data analysis and results as presented in this report are directed towards arriving at conclusions and recommendations regarding proposed hydraulic engineering works and their effects on the hydraulic regime and water quality conditions in Vancouver Lake. The tests were conducted to determine the hydraulic characteristics and the flushing efficiency of pollutants by using a fluorescent dye to simulate the soluble conservative pollutants in the prototype. In addition, the hydraulic model study provided information on the dispersion, mixing, dilution rates and detention times which are important factors influencing water quality.

This is Part 1 of a two-part study entitled "Correlated Studies of Vancouver Lake, Washington." The other part of the study is Water Quality Prediction conducted by the Sanitary Engineering Section of the College of Engineering Research Division at Washington State University under Project Number 16080 ERQ, details of which are covered in a separate report.

This report was submitted in fulfillment of Project Number 16080 ERP under the partial sponsorship of the Environmental Protection Agency.

CONTENTS

FIGURES

TABLES

CONCLUSIONS

1. On the basis of five progressive stages of model investigations, technically feasible prototype modifications for enhancement of the Vancouver Lake system have been developed.

2. Fluorescent dyes were used in the hydraulic model to simulate conservative prototype pollutants, and these tests furnished information on the flushing efficiency of the Vancouver Lake system under a variety of existing and modified conditions.

3. Dredging of Vancouver Lake and its outlet into Lake River will delay the accumulation processes from which the lake is currently suffering, but this modification by itself will not enhance water quality in the lake because it will increase the volume of the lake and therefore the detention time.

4. The introduction of flushing water from the Columbia River through a conduit, a general term for water conveyance structures, either an open channel and/or buried culverts, into the southwest quadrant (upstream end) of Vancouver Lake is a necessary step for enhancing the quality of Vancouver Lake.

5. An open channel or closed conduit (culverts) may be used, but the open channel has the disadvantages of high construction cost, the transport of floating trash and debris into the lake and interference with land transportation.

6. The use of culverts for the introduction of the Columbia River water into the southwest quadrant of Vancouver Lake has the advantages of less ground surface disturbance, fewer construction problems and the culverts can be equipped with counterbalanced gates to keep Vancouver Lake water from returning directly to the Columbia River during ebb tide.

7. The use of culverts with gates allows the flushing of the system to be one-directional, i.e., from south to north out of Vancouver Lake by way of Lake River, rejoining the Columbia River near Ridgefield.

8. The construction of a downstream channel near Post Office Lake between the Columbia River and Lake River has detrimental effects on the flushing efficiency and the flow in Lake River.

9. Small islands could be used for aligning the inflow to reduce stagnation areas around the shores of the lake, but they do not significantly improve the gross flushing characteristics in the system.

10. The hydrodynamic mathematical model developed from field and physical hydraulic model data accurately simulates prototype conditions and was used to significantly extend the analysis of alternatives beyond conditions tested in the physical model. The hydrodynamic model provided the basis for the water quality prediction model in project number 16080 ERQ and was linked to the dissolved oxygen parameter through detention time of the flushing flow.

RECOMMENDATIONS

This study has included an evaluation of the relative efficiency of flushing Vancouver Lake under existing and modified conditions. The comparison of the advantages and disadvantages of the alternatives is directed towards developing a set of guidelines for engineering design and decision-making. Some combinations of the first three alternatives must be developed in order to optimize the enhancement of the Vancouver Lake system.

Enactment of only one, or even two, of the first three recommendations will not achieve the potential project benefits.

1. Dredge Vancouver Lake to remove nutrient-rich bottom sediments and to increase the volume of the lake; dredging will increase the potential use of the lake for recreation.

2. Introduce the Columbia River water into the southwest quadrant by the use of culverts equipped with counterbalanced gates on the lake end.

3. Curtail existing and future pollution entering Vancouver Lake from upland portions of the drainage basin.

4. During and after any modification to the system, a carefully designed monitoring program should be initiated for future use including the evaluation of this study and for the improved design of similar projects.

It should be emphasized that dredging will increase the detention time of the lake. The lake quality will not be enhanced if flushing water is not introduced and pollution sources are not curtailed.

INTRODUCTION

This report describes a series of experiments conducted with a hydraulic model of portions of the Vancouver Lake-Columbia River system shown in Fig. 1. The major objective of the investigation was to provide information on mixing and flushing characteristics of Vancouver Lake and the effect of certain proposed modifications on the hydraulic regimen of the system. Emphasis was placed on the determination of the hydraulic behavior and relative "flushing efficiency" under different geometric and flow conditions. The flushing efficiency was measured in terms of the percentage of dye concentration remaining at various sampling stations in the lake as time elapsed. This information was supplied to project number 16080 ERQ for water quality prediction.

The model, constructed of a cement-vermiculite mixture, covered a surface area of approximately 2100 sq ft. The test program was comprised of five progressive stages: 1) existing conditions; 2) upstream channel and turning basin in the lake excavated; 3) Vancouver Lake dredged uniformly; 4) downstream channel excavated; and 5) Lake River dredged and widened.

By distorting the model (distortion index 10:1) in the vertical direction, more accurate depth and velocity measurement could be made. Principles covering the effects of distortion on dispersion were considered in designing the model. The lake is so large compared to the amount of inflow, and tidal action creates such uniform mixing during ebb flow, that good prototype prediction is anticipated. A view of the hydraulic model looking north is shown in Fig. 2.

Certain areas of the model were sealed with a plastic paint to improve flow visualization and photographic records, and to prevent the dye from being absorbed by the model. A fluorescent dye was used to simulate the soluble pollutants in the lake. The water samples were taken with syringes at eight sampling stations (see Fig. 6, page 16), and the corresponding times were recorded. A precalibrated colorimeter was used to determine the dye concentration of the samples. Most of the tests were conducted with river flows which occur in the summertime because this is the critical period for water quantity and quality conditions.

Sinusoidal tides were generated in the hydraulic model and the stage hydrographs were obtained with automatic level recorders. The operation of the model was verified against prototype data for water surface tidal fluctuations and discharges at various points in the system. Following model verification, tests were run to determine the influences of the various modifications on velocities, flow patterns, tidal effects, and dilution throughout the system.

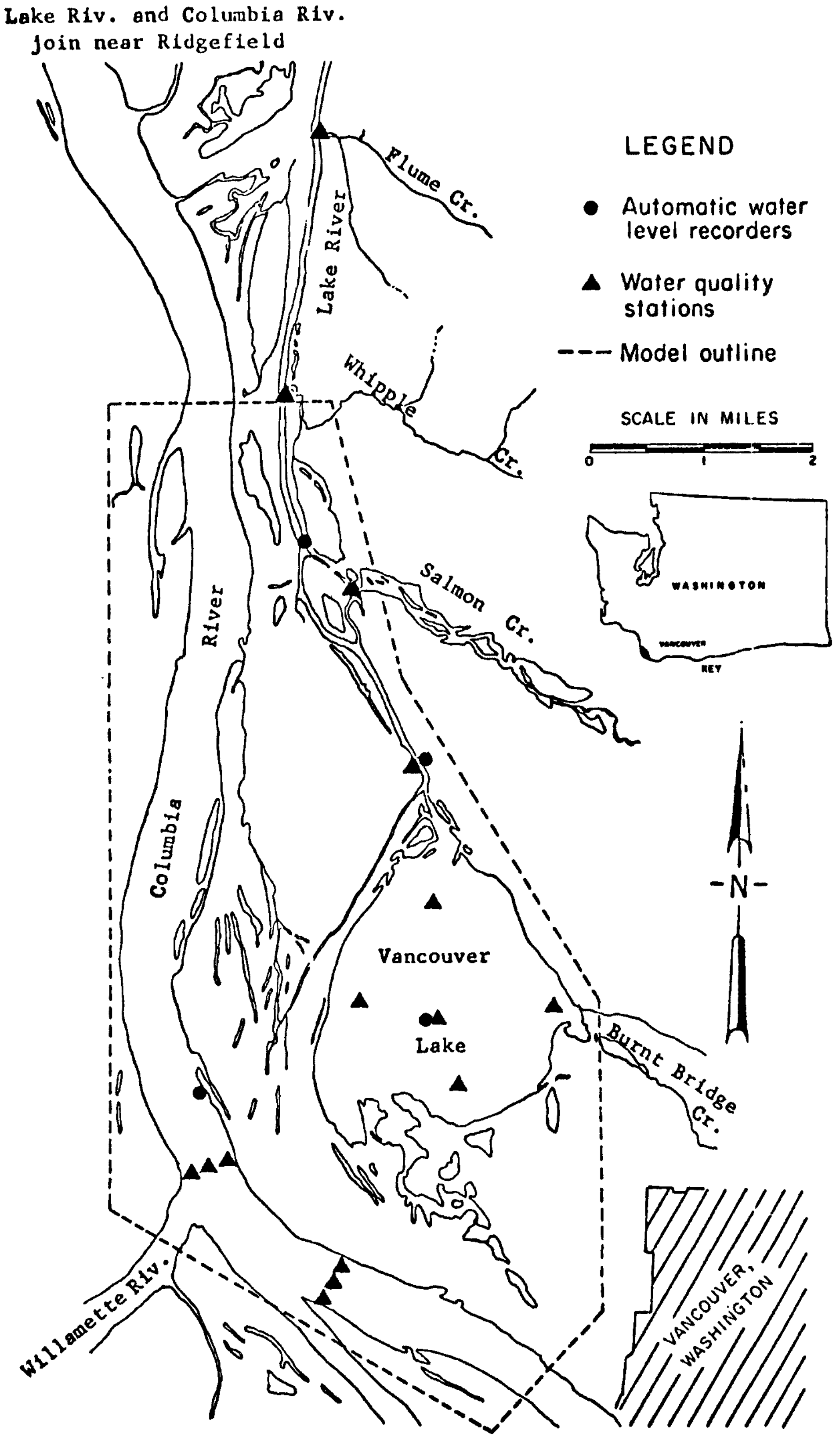


Fig. 1. Vancouver Lake-Columbia River Hydraulic System

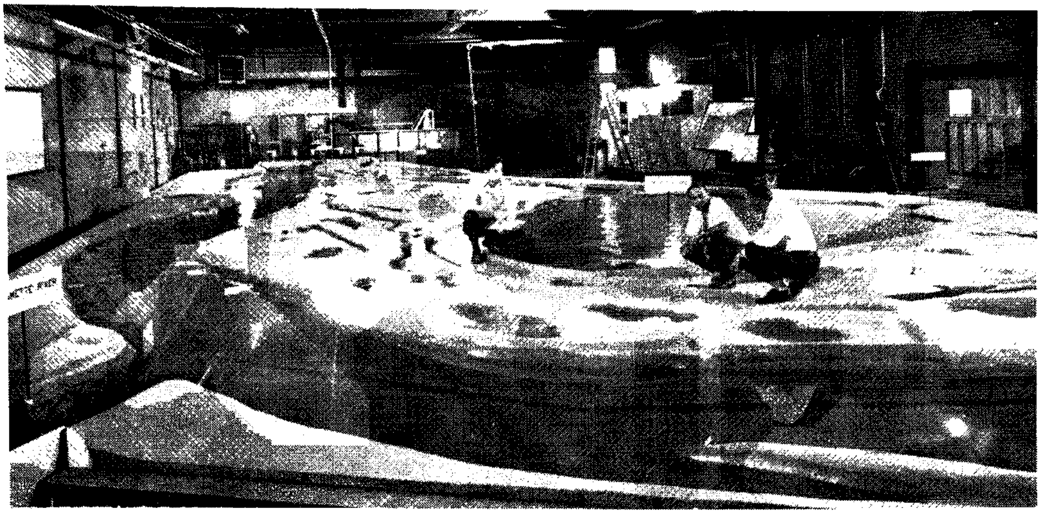


Fig. 2. View of Hydraulic Model Looking North (70 ft long by 40 ft wide)--Existing Conditions, Columbia River in the Foreground

A mathematical model, the hydrodynamic computer model, was formulated as a basis for the theoretical analysis of the flow regime in the system before and after the dredging of the lake and the construction of the flushing water conduit. Simulated results were obtained by numerical solution of the mathematical model with a digital computer. The validity of the hydrodynamic computer model was verified with the available data from the Vancouver Lake Hydrographic Study. Figure 3 shows the flow chart of all pertinent Vancouver Lake studies.

Predictive analyses were made with the hydrodynamic computer model to cover reasonable variations in width and length of an open channel; size, number, type and length of culverts; tidal amplitude of the Columbia River; and dredging depth of Vancouver Lake. Applications of the mathematical model are discussed in the section entitled "Computer Analysis and Data Extension" beginning on page 37. The computer program description is given in Appendix B. The response of water levels in Vancouver Lake to changes in river and creek discharges can be expressed by a water budget. For conservation of mass the change in volume of the lake must equal the net flux to the lake. This yields a continuity equation for the lake given by

$$\frac{d\forall}{dt} = Q_i - Q_o + P_r - E_v + Q_{in} - Q_{ou} \qquad (1)$$

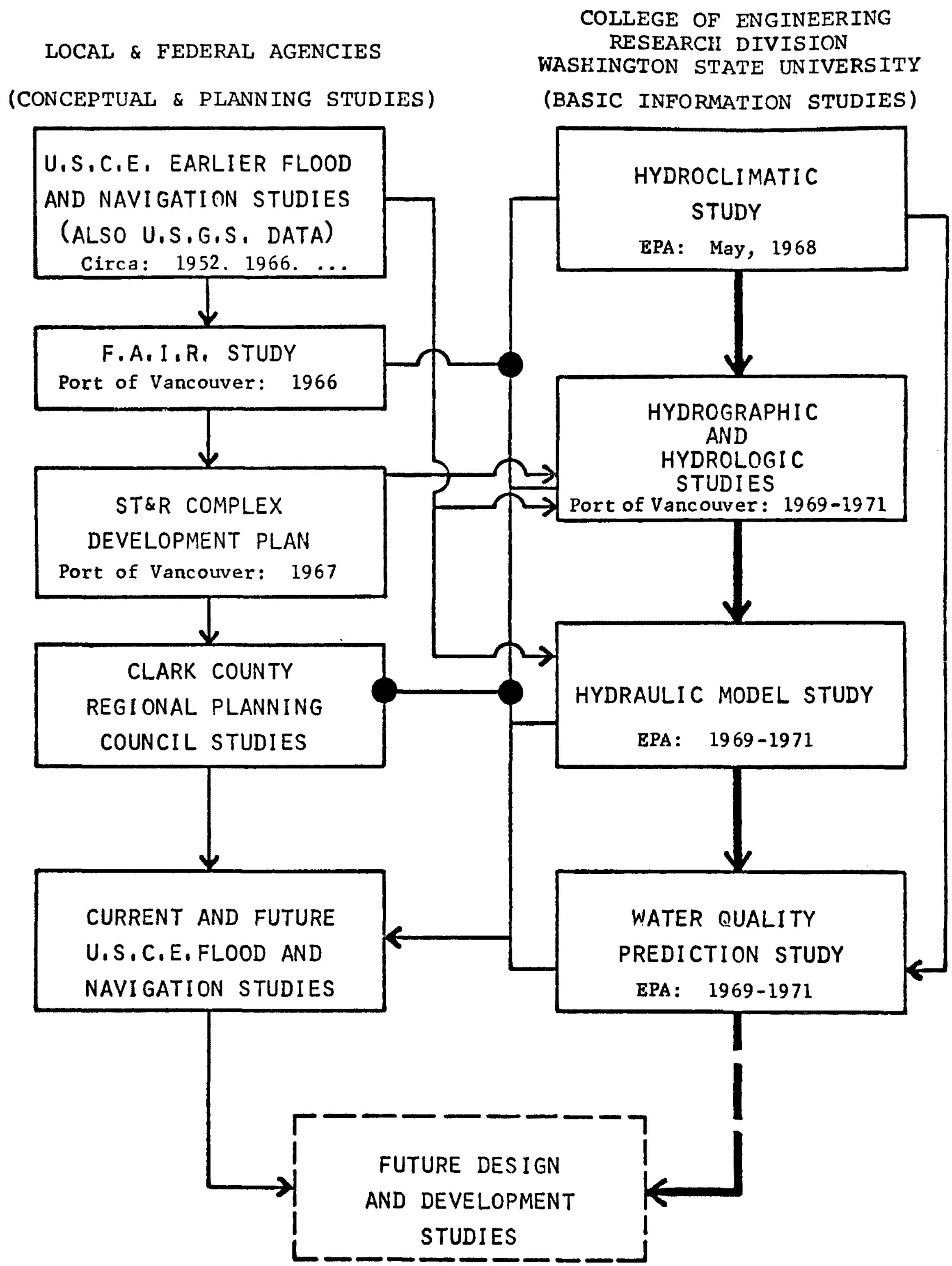


Fig. 3. Flow Chart of Vancouver Lake Studies

in which $\forall$ is the total lake volume, t is time, Q_i the inflow rate to the lake, Q_o the outflow rate from the lake, Q_{in} and Q_{ou} are local inflow and outflow rates via ground-water seepage, P_r the precipitation rate onto the lake, and E_v the evaporation rate from the lake. An average E_v value for the study area based on available data was used for each incremental period.

The inflow and outflow rates are those from Burnt Bridge Creek, Lake River, and a man-made conduit, expressed as Q_B, Q_L, and Q_c, respectively, and Eq. (1) becomes

$$\frac{dH}{dt} = \frac{Q_B \pm Q_L \pm Q_c + Q_{in} + P_r - E_v - Q_{ou}}{A} \tag{2}$$

in which the positive sign means influx to the lake, H is depth of the lake, and A is the area of lake water surface. For existing prototype conditions, Q_c is equal to zero, Q_B is small compared to Q_L and assumed to be 50 cfs, Q_{in} is estimated to be about 20 cfs, and Q_{ou} is assumed to balance Q_{in} due to lack of information. The volume of the lake at a depth of 6 ft is approximately $640 \times 10^6 ft^3$ and the annual flow from Burnt Bridge Creek used in this model amounts to $1578 \times 10^6 ft^3$. This indicates an average flushing time to be about five months for complete mixing and, if storage were available to release Q_B, at a constant rate.

The flow rate in Lake River, Q_L, is calculated by using the Manning formula for open channels. As a first approximation, the water-surface slope was used instead of the energy slope to evaluate the flow rate in Lake River as

$$(Q_L)_1 = \left(W_2 \frac{Z + H}{2}\right) \left(\frac{1.49}{n_2}\right) R_z^{2/3} S_{wz}^{1/2} \tag{3}$$

where W_2 is the width of Lake River, Z and H the water depth of Lake River and Vancouver Lake, respectively, n_2 the Manning roughness factor in Lake River, R_z is the average hydraulic radius and S_{wz} is the average slope of the water surface. Hydraulic radius is defined as the ratio of the water flow area to its wetted perimeter. Considering an equivalent rectangular channel to the actual cross-sectional geometry of Lake River, $R_z = W_2 Z/(W_2 + 2Z)$. As W_2 becomes large, 2Z becomes less important, i.e., $W_2 \gg 2Z$, $R_z \rightarrow Z$. The hydraulic radius is defined by

$$R_z = \frac{Z + H}{2} \tag{4}$$

for a wide channel and

$$S_{wz} = \frac{Z_w - H_w}{L_2} \tag{5}$$

where Z_w and H_w are the water levels of Lake River and Vancouver Lake above mean sea level, and L_2 is length of the reach. A wide, open channel is defined as a rectangular channel whose width is greater than ten times the depth of flow. Figure 4 shows the prototype geometries used in this analysis. Substitution of Eqs. (4) and (5) in Eq. (3) yields

$$(Q_L)_1 = \frac{1.49\ W_2}{n_2(2)^{5/3}(L_2)^{1/2}} (Z + H)^{5/3}(Z_w - H_w)^{1/2} \tag{6}$$

with the first approximated value, $(Q_L)_1$, velocities in the upstream and downstream ends of the reach are calculated as follows

$$u_u = \frac{(Q_L)_1}{A_u} \quad \text{and} \quad u_d = \frac{(Q_L)_1}{A_d} \tag{7}$$

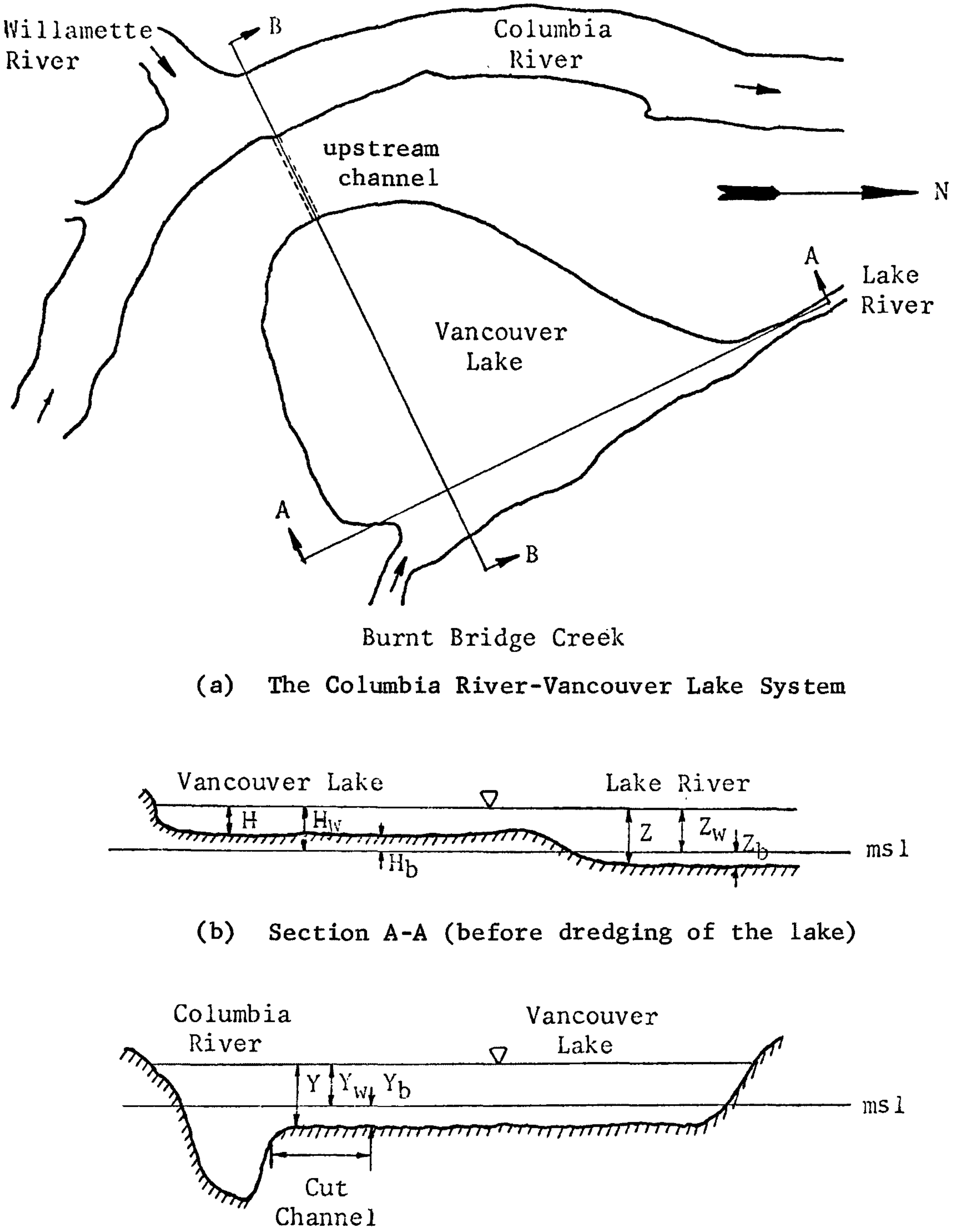
in which A_u and A_d are the cross-sectional areas at the upstream and downstream ends of the reach. Therefore, the second approximation of the energy slope can be evaluated by

$$S_{ez} = \frac{(Z_w - H_w) + (u_u^2 - u_d^2)/2g}{L_2} \tag{8}$$

and then the final calculation of the flow rate becomes

$$Q_L = \left(W_2\ \frac{Z + H}{2}\right)\left(\frac{1.49}{n_2}\right) R_z^{2/3}\ S_{ez}^{1/2}\ . \tag{9}$$

By the same token, the flow rate for the upstream channel for introducing flushing water, Q_{ch}, is given by



(a) The Columbia River-Vancouver Lake System

(b) Section A-A (before dredging of the lake)

(c) Section B-B (after cutting a channel and dredging of the lake)

Fig. 4. Geometries of the System Used for the Hydraulic Analysis

$$Q_{ch} = \left(W_1 \frac{Y + H}{2}\right)\left(\frac{1.49}{n_1}\right) R_c^{2/3} S_{ec}^{1/2} \qquad (10)$$

where Y is the depth in the channel. Both R_c, the hydraulic radius of the channel, and S_{ec}, the energy slope in the channel, have similar definitions as defined in Eqs. (4) and (8). Sinusoidal tide cycles in the Columbia River and Lake River were assumed and used in the hydraulic model and for the prediction studies as follows.

$$Y = Y_o + a_1 \sin(4\pi t) \qquad (11)$$

$$Z = Z_o + a_2 \sin(4\pi t) \qquad (12)$$

where a_1 and a_2 are half of the tidal amplitudes of the Columbia River and Lake River respectively, and Y_o and Z_o are respectively the mean initial depth in the channel and Lake River. Magnitudes of the mean tidal amplitude were obtained by statistical analysis of the field hydrographic data. Figure 5 presents the comparison between sinusoidal and actual tides over two complete tidal cycles (about 25 hrs).

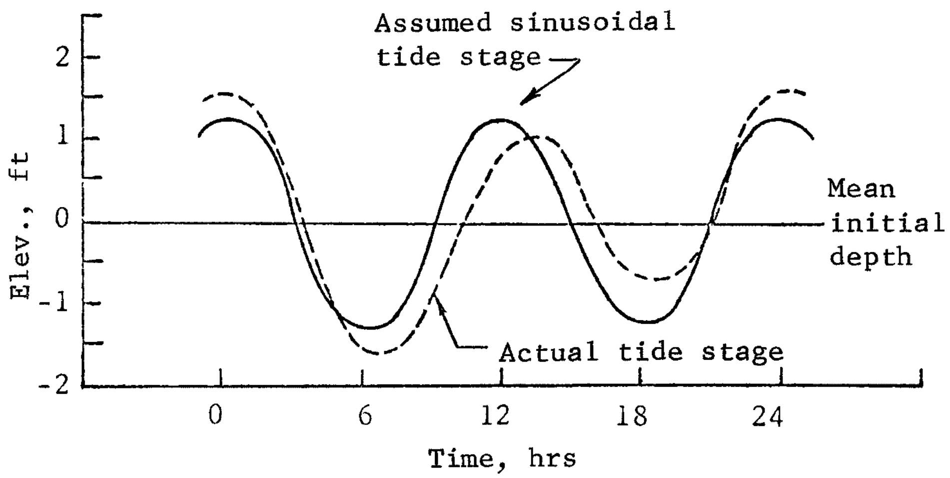


Fig. 5. Comparison of Sinusoidal and Actual Tides over Two Complete Tidal Cycles--Prototype

An alternative for introducing flushing water is a submerged culvert system. The flow through a culvert system was analyzed by the Darcy-Weisbach equation as

$$\Delta H = \left(K_e + K_x + \frac{fL_c}{D_c}\right) \bar{V}^2/2g \qquad (13)$$

in which ΔH is the continuously changing difference in water level between the Columbia River and Vancouver Lake, D_c is the inside diameter of culvert, L_c the length of culvert, K_e the entrance loss coefficient of 0.5, K_x the exit loss coefficient of 1.0, and f the friction factor in the culvert. Rearranging Eq. (13) and solving for the average velocity in the culvert yields

$$\overline{V} = \sqrt{\frac{2g\Delta H}{1.5 + fL_c/D_c}} \tag{14}$$

Therefore, the total flow rate through any number of culverts, N_c, into the lake, when the water surface in the river rises above Vancouver Lake, is expressed by

$$Q_{cu} = N_c A_c \overline{V} \tag{15}$$

where A_c is the cross-sectional area of a culvert.

Note that for the upstream channel, if Y_w is greater than H_w, Q_{ch} is positive and inflow to the lake occurs (or if it is negative, outflow occurs). For culvert construction, Q_{cu} is always positive because of the flap gates on the Vancouver Lake end. Therefore, if ΔH is negative, i.e., when the river falls below Vancouver Lake, the gates will automatically close and Q_{cu} becomes zero.

Both the mathematical and physical hydraulic models were important tools in the analysis of the effects of alternative modifications to the Vancouver Lake-Columbia River System. In addition, the laboratory and predicted results are providing guidelines for design and decision making to achieve the enhancement of Vancouver Lake. The methodology developed in this study will provide a useful experience record for others wishing to improve the quality of some of the thousands of lakes which can be restored through dredging, flushing and curtailment of pollution sources.

DESCRIPTION OF MODEL

The area modeled included the Columbia River from near the Vancouver Bridge, Vancouver Lake, and Lake River downstream to just below Post Office Lake. The confluences and short sections of the Willamette River, Burnt Bridge Creek, and Salmon Creek were included in the model. Figure 6 shows the model and monitoring stations in the model and prototype lakes. In order that dynamic similarity be maintained it is necessary to satisfy the Froude model law, i.e., the Froude number must be equal in model and prototype. By this relationship it is possible to establish the various geometric, kinematic and dynamic similitude relationships between the model and the prototype.

By definition, the Froude number F can be expressed as

$$F = V/\sqrt{gD} \tag{16}$$

where V is the average longitudinal velocity in a cross section, D is the characteristic depth, and g is the gravitational acceleration. Let the subscript r denote prototype-to-model ratios, and m and p refer to model and prototype, respectively. Then

$$F_p = F_m \tag{17}$$

or

$$(V/\sqrt{gD})_p = (V/\sqrt{gD})_m \tag{18}$$

and therefore

$$V_r = D_r^{1/2} \tag{19}$$

If A represents a cross-sectional area and L is a characteristic length, the discharge and time ratios can be expressed as

$$Q_r = A_r V_r$$

$$= (L_r D_r)\ (D_r)^{1/2}$$

or

$$Q_r = L_r (D_r)^{3/2} \tag{20}$$

and

$$T_r = L_r / V_r$$

or

$$T_r = L_r / (D_r)^{1/2} \tag{21}$$

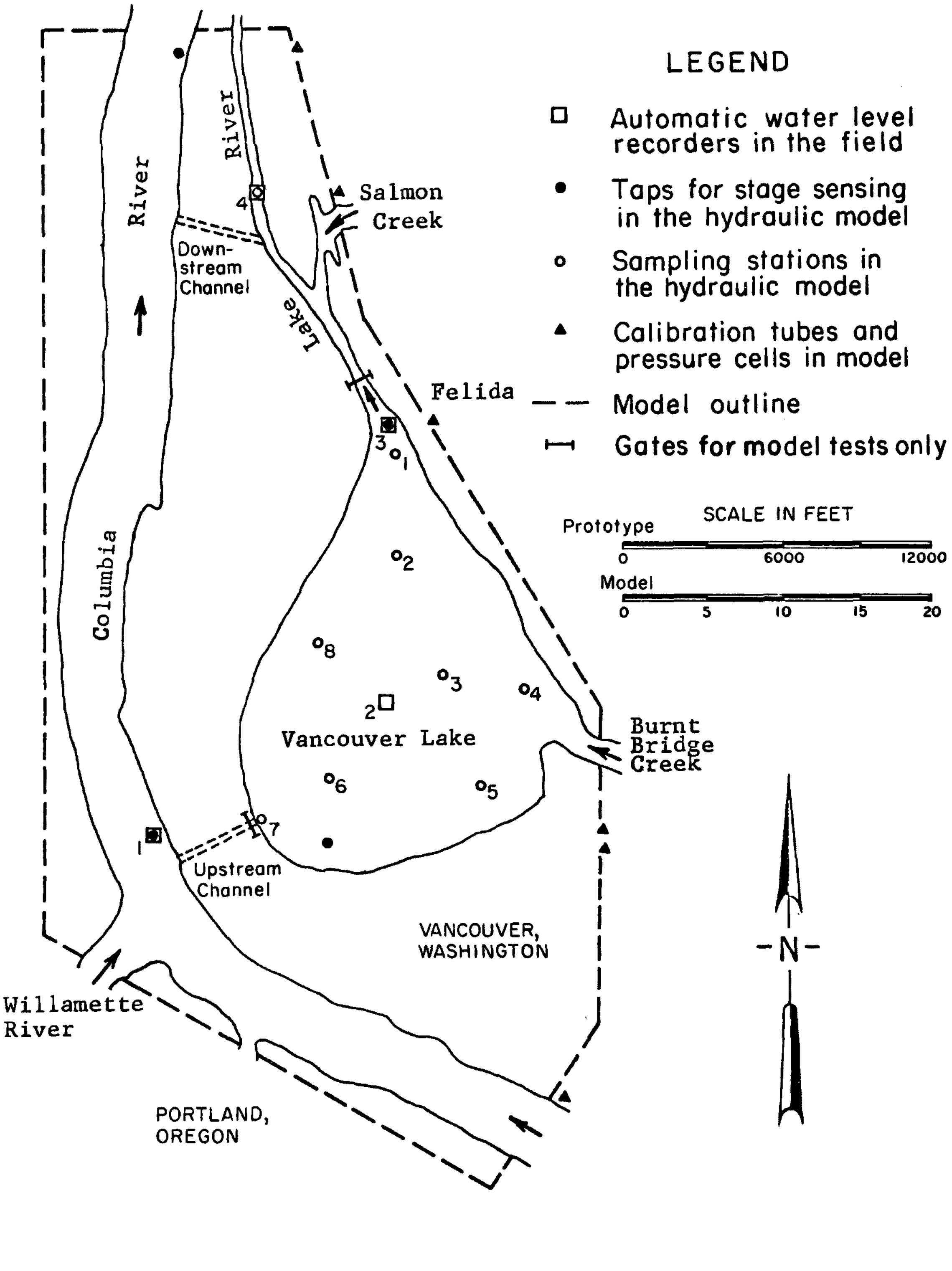


Fig. 6. Hydraulic Model and Sampling Stations

When model scales in length and depth are chosen, then the other related similitude ratios can be calculated. Table 1 shows the prototype-to-model ratios used in the Vancouver Lake model study.

Table 1. Model Scale Ratios Used in the Vancouver Lake Model Study

Item	Definition	Relation	Scale Ratio
Horizontal length	L_r	L_r	600:1
Vertical depth	D_r	D_r	60:1
Velocity	V_r	$D_r^{1/2}$	7.75:1
Discharge	Q_r	$L_rD_r^{3/2}$	279,000:1
Time	T_r	$L_rD_r^{-1/2}$	77.5:1
Distortion ratio	L_r/D_r	L_r/D_r	10:1

The model topography was constructed of vermiculite concrete. A base pour was made, contours laid out on this base, small (≦ 1/4" ϕ) metal rods were driven into the base and cut to proper elevation, the shaping pour was made, and the model was then sealed with a neat cement paste.

The Columbia and Willamette river head tanks were designed to minimize large-scale turbulence at their entrances. The tail tank and tide generators were designed as a unit. The tide generator consisted of a hydraulic motor coupled to a camshaft with reduction gears and chain drives. The cam lifted a vertical gate to generate the tidal water level change at the tail tank by raising and lowering the crest over which the outflow passed. Separate tide gates and power takeoffs were used for the Columbia and Lake Rivers. The height of the crest, the time of a cycle, and the cam throws were variable. The cam used for these studies provided a sine wave motion to the tide gates. The pool upstream of the tide gate for Lake River was provided with a source of make-up water to insure flow over the tide gate during a rising tide cycle. The large amount of flow in the Columbia River made such a control unnecessary there. The Columbia and Lake River tides could be generated independently except for the time of the cycle, which was common.

Flows for the Columbia and Willamette Rivers were measured with magnetic flowmeters. Burnt Bridge Creek and Salmon Creek flows were measured with "Rotometer" units and a propeller meter. The water levels in the model were measured with Consolidated 4-312 ±5 psid pressure cells. The signal conditioning and recording were done on Brush equipment.

Rhodamine WT dye was used for pollution tracing and concentrations were measured with a B & L Spectronic 20 colorimeter. The dye was photographed to provide visual dispersion records not possible to obtain with concentration sampling techniques. In those areas where photographs of the dye were needed, the model was painted with white epoxy paint to increase visibility and reduce staining of the topography. A Statham 0.5 psid pressure cell was used to obtain differences in water levels between the Columbia River Gage 1 and the Vancouver Lake Gage 2.

The modifications to the construction of the model were comprised of five progressive stages:

Stage I was for existing conditions in the prototype for model verification.

Stage II consisted of construction of an upstream channel 400 ft wide between the Columbia River and Vancouver Lake (see Fig. 6). An area was deepened in the proposed docking and turning area along the west shore of Vancouver Lake.

For Stage III the channel was narrowed to 200 ft. The bottom of the channel and the "dredged" area in the lake were maintained at -10 ft msl as shown in Fig. 7.

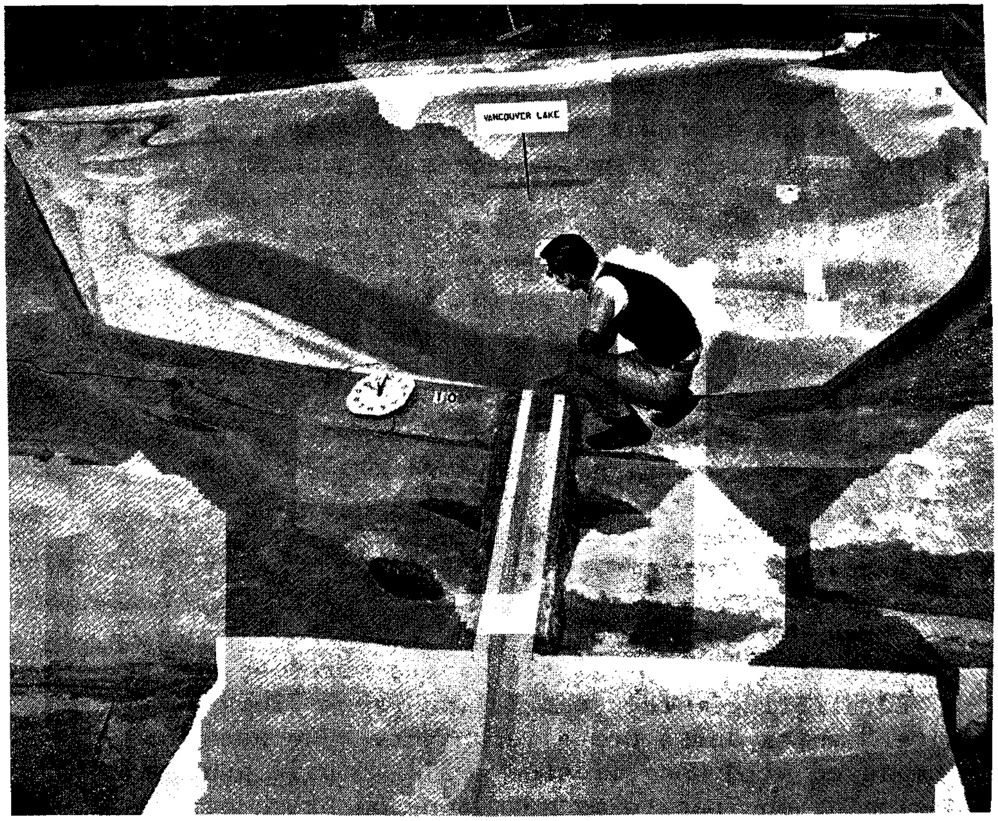


Fig. 7. Upstream Channel Test of Hydraulic Model with West Side of Lake Dredged--Stage III

For Stage IV the entire Vancouver Lake was " dredged" to -10 ft msl. An island was installed in Vancouver Lake to evaluate the feasibility of using such an island for improving circulation within the lake. No significant improvement was observed. A 10-ft diameter (prototype) culvert was tested in lieu of the upstream channel to evaluate its relative effectiveness in flushing the lake.

Stage V consisted of additional "dredging" and widening of Lake River to a downstream channel from Lake River to the Columbia River (see Fig. 6). This channel was constructed just upstream of Post Office Lake. The width was 200 ft and beds were excavated to -10 ft msl for both Lake River and channel cross sections.

The model was verified by comparing model gage heights versus time with prototype data for the same discharge conditions under which the field data were taken (Fig. 8). Gage data of Vancouver Bridge were obtained from the USGS and others were taken by visual observation of staff gages by Clark College (Vancouver, Washington) students under the direction of the project hydrologist. The verification was considered acceptable for the available range of prototype data and the sinusoidal model tide generation.

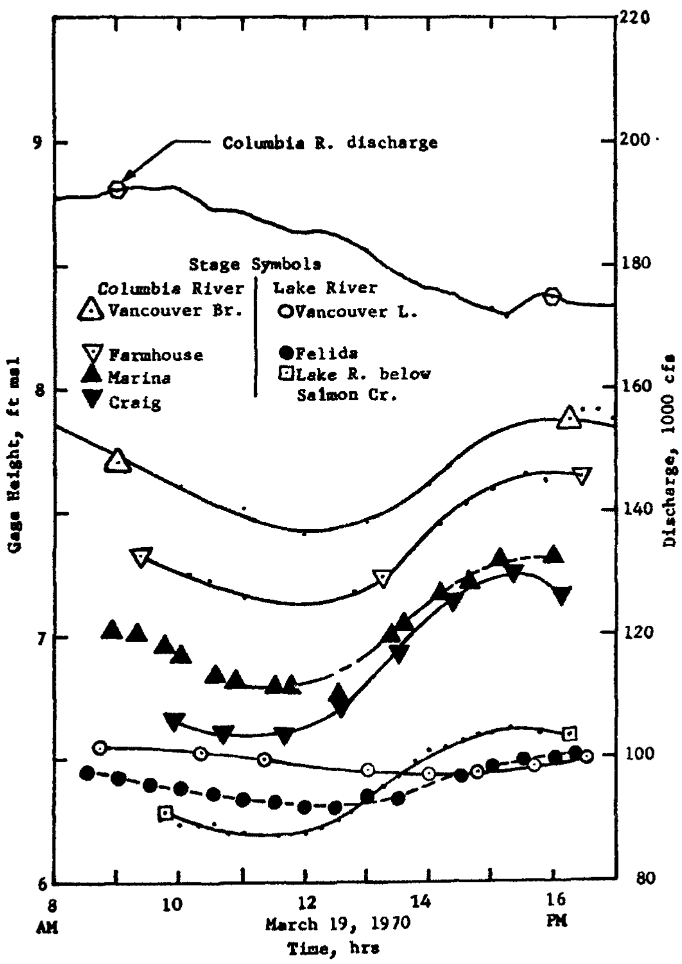


Fig. 8. Prototype measurements Used to Verify the Physical Model-Sample

TESTING PROCEDURES

Testing was restricted to the most severe conditions available from examination of the prototype data. The extreme tide variation for the Columbia Gage 1 was selected and the concurrent streamflows were determined. Model streamflows were established and the tide generator adjusted to produce the desired tide range. Some additional adjustment in phasing and range was necessary on the Lake River tide system. With these controls all set, the model was ready for testing in the Stage I condition. For subsequent conditions, the control settings were not changed. This was required to establish a controlled basis in the model for evaluating effects for future conditions (i.e., the dredged upstream channel).

Data taken included photographs, samples of the water, velocity measurements, flow rates, and recorded stages. All data were related on a common time base. Velocities were low and their measurement was restricted to timing the movement of floats or dye. Velocities were taken throughout a tide cycle, and three locations were selected for measurements: 1) in Lake River downstream of the lake outlet near Felida; 2) in the upstream channel, and 3) in the downstream channel.

In general it was necessary to run through five or six tide cycles before stable repetitive water levels were achieved. A testing modification was necessary for reliable pollution tracing. For the modified conditions with channels, temporary gates were used in the upstream channel and Lake River to isolate the Vancouver Lake pollution. The isolated area was filled and mixed uniformly with dyed water to a depth consistent with the test conditions. The water levels were selected so there was no differential head across the gates. At the null point where the tide was starting to rise and there was no movement of water in or out of Vancouver Lake, the gates were removed.

Eight sampling points were selected in the Vancouver Lake area and samples were taken with syringes at the end of the ebb tide cycle (Fig. 6). The corresponding times were recorded. A precalibrated B & L Spectronic 20 colorimeter was used to read the percent of transmittance. By using the calibration curve the relative concentration of each sample was determined. The calibration curve was obtained by the following steps: 1) consider the initial concentration C_o of dye water in the lake to be 100 percent corresponding to percentage of transmittance T_o (note that the clearer the water, the higher is T_o); 2) by successive dilution to the desired concentration C, the percent of transmittance T was read from the colorimeter; and 3) plot C versus T to one of the curves using T_o as a parameter as shown in Fig. 9.

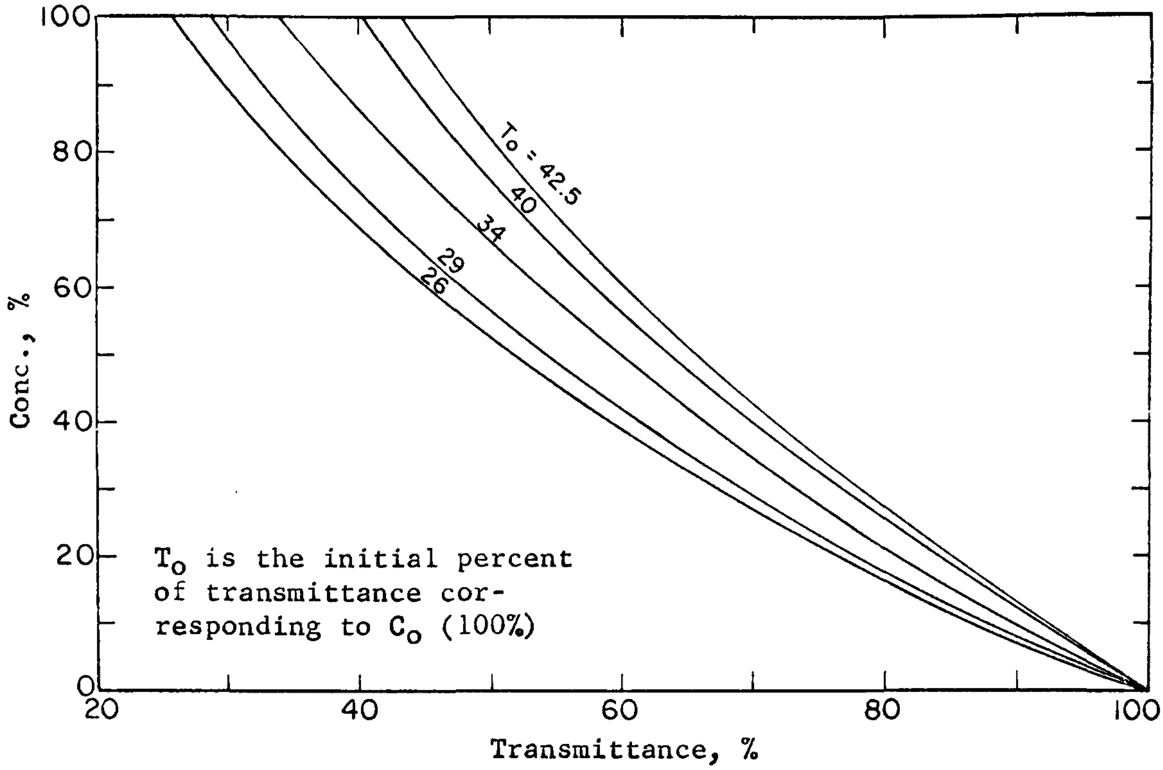
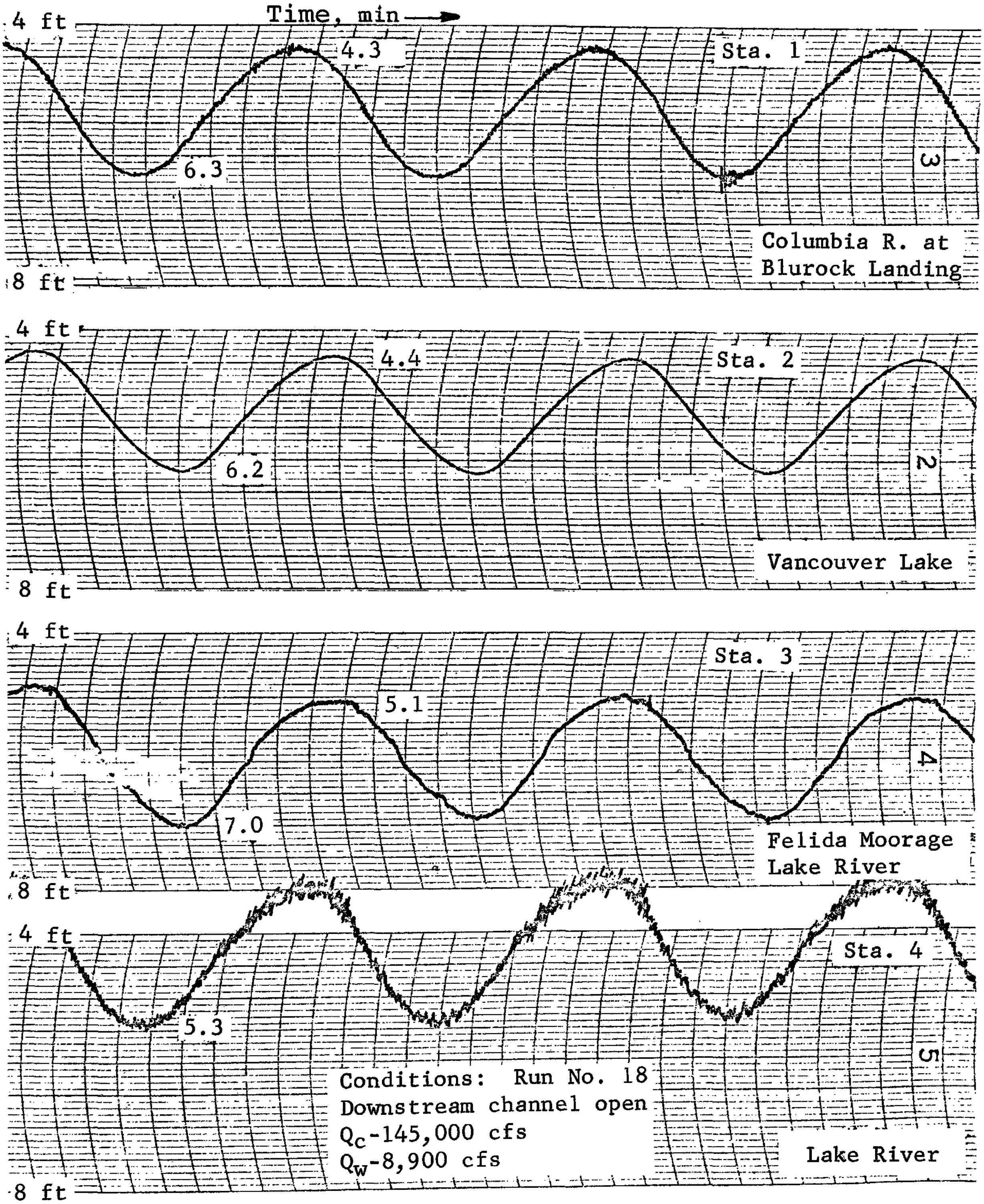


Fig. 9. Calibration Curve for B & L Spectronic 20 Colorimeter (Rhodamine WT Dye)

Photographs were taken to record the changes in lake color, and stages were recorded continuously. Figure 10 presents strip charts for gage stations in Vancouver Lake model. Differential water stages between the Columbia Gage 1 and the Vancouver Lake Gage 2 were recorded for one tide cycle.

In the "as-is condition," without the channels being open, additional pollution studies were made by injecting dye into Burnt Bridge Creek and Salmon Creek flows. Samples were taken at Felida and two locations in the lake. Dye injection was started or commenced to be concurrent with the highest, lowest or intermediate level of Vancouver Lake water stage, with the lake being initially clean for those exploratory tests.

Dye tracing was done photographically to determine: 1) under what conditions the Willamette River would enter the upstream channel; 2) the flow rate from Salmon Creek which causes reversal of the Lake River flow back into Vancouver Lake during ebb tide; 3) flow patterns with the island; and 4) various other flow patterns in the model.



Note: Chart speed (horizontal) 1cm-2min (model time)
Chart scale (vertical 1cm-1 ft (prototype)

Fig. 10. Strip Charts for the Gage Stations in the Vancouver Lake Hydraulic Model

DESCRIPTION OF TESTS AND DATA ANALYSIS

Prior to initiating the test program, the hydraulic model was verified against prototype conditions for water surface tidal fluctuations and discharges at various points in the system. Following model verification, tests were conducted to determine the influences of the various test conditions on velocities, flushing action, and dilution throughout the system. Table 2 summarizes the conditions for the various tests.

TABLE 2 . SUMMARY OF TEST CONDITIONS AND DATA ACQUISITION

TEST NO.	FLOW CONDITIONS: RIVER FLOWS (cfs)				CHANNELS OPEN[a]			LAKE CONDITIONS[b]				DATA MEASUREMENTS: DYE STATIONS[c]		VELOCITIES[d]			PHOTOGRAPHS[e]			TIDE[f]	ΔH[g]
	Columbia	Willamette	Burnt Bridge	Salmon	U	L	C	N	DD	D	LR	Source	Sampled	U	F	L	U	F	L		
1			1037					•				BBC	1							•	
2	Preliminary Tests		1031					•				BBC	1,3							•	
3	on Burnt Bridge		1037					•				BBC	1,3							•	
4	and Salmon Creeks		1037					•				BBC	1,3								
5				2565				•				SC	1,3							•	
6				2565				•				SC	1,3							•	
7				2510				•				SC	1,3							•	
8	145000	7500	0.2	1.6	400			•	•			U	1,3,7				•			•	
9a	145000	5000			400			•	•			↓					•			•	
9b	75000	75000			400			•	•			WR					•			•	
9c	50000	100000			400			•	•			CR					•			•	
9d	25000	125000			400			•	•			U ↓					•			•	
10	145000	5000			200			•	•			VL	1-8	•	•					•	
11a	145000	5000			200			•	•			↓					•			•	
11b	75000	75000			200			•	•			WR					•			•	
11c	50000	100000			200			•	•			CR					•			•	
11d	25000	125000			200			•	•			U ↓					•				
12a	145000	7000			200					•		VL	1-8	•	•		•			•	•
12b	145000	7000		5230†	200					•		-								•	•
12c	348000	50000			200					•		-								•	•
12d	232000	26000			200					•		-								•	•
13	145000	7500			200			Island		•		U					•			•	•
14	VOID	--	--	--	--	--	--	-	-	-	-	-	-	-	-	-	-	-	-	-	-
15	145000	7500			200	200				•	•	VL	1-8		•	•	•	•	•	•	•
16	145000	7500				200				•	•	VL	1-8		•	•	•	•	•	•	
17	145000	8900					•			•	•	VL	1-8	•			•			•	•
18	145000	8900				200	•			•	•	VL	1-8	•		•	•		•	•	•
19	145000	8900	500		200	200				•	•	VL	1-8	•	•	•	•		•	•	•
20	145000	7000	500							•	•	VL	1-8	•			•			•	•
21	145000	7000	500		200					•	•	VL	1-8	•	•		•			•	•
22	145000	7000			200					•	•	VL	1-8	•	•		•			•	•

[a]CHANNELS OPEN: U, upstream channel near Blurock Landing opposite Willamette River
L, downstream channel south of Post Office Lake near mouth of Salmon Creek
C, 10-ft diameter single culvert placed in upstream channel position
For location of channels, see Fig. 6
200 and 400 are channel widths in feet

[b]LAKE CONDITIONS: N, natural existing conditions
DD, docking area dredged along west shore of lake (15 ft)
D, Vancouver Lake dredged to 15-ft depth (-12 ft msl)
LR, Lake River widened to 200 ft and dredged to 15 ft

[c]DYE STATIONS: Source: BBC, Burnt Bridge Creek; SC, Salmon Creek; U, upstream channel; CR, Columbia River; WR, Willamette River
Sampled: Stations 1 through 8 as shown in Fig. 6

[d]VELOCITIES measured at: F, Felida in Lake River; U, upstream channel; L, downstream channel

[e]Photographs taken at same locations as in Note d above

[f]TIDE means the tides for Columbia River and Lake River were generated in the model

[g]ΔH means that the differential elevation between water surfaces in the Columbia River and Vancouver Lake was recorded

†Minimum flood flow at which Salmon Creek moves upstream in Lake River and enters Vancouver Lake against an ebb tide

Tests in the hydraulic model are divided according to different modification stages as follows:

Stage I (Tests Nos. 1-7): Preliminary tests on Burnt Bridge and Salmon Creeks--the introduction of larger than average flows was to simulate flood-flow effects and possible future storage released from Salmon and/or Burnt Bridge Creeks. Continuous dye was injected at Salmon and Burnt Bridge Creeks in order to trace their flows into and out of the lake.

Stage II (Tests Nos. 8-9): Excavation of an upstream channel 400 ft wide in the vicinity of Blurock Landing in the Columbia River opposite the mouth of Willamette River to Vancouver Lake, and the dredging of a docking terminal area along the west shore of the lake to a mean depth of 15 ft.

Stage III (Tests Nos. 10-11): Same conditions as Stage II except reducing the upstream channel to 200 ft of width.

Stage IV (Tests Nos. 12-13): Dredging of entire Vancouver Lake bottom to approximately 10 ft below mean sea level and widening of the entrance to Lake River. The flow conditions in the Willamette and Columbia Rivers were tested at which the Willamette would enter the upstream channel. (Only when $Q_W \geq Q_C$. This condition occurs rarely and only at times when the Willamette River is in flood.) A small island was placed in the lake near the upstream channel outlet to divide the inflow and observe any changes in flushing pattern. Test No. 14 was voided.

Stage V (Tests Nos. 15-22): Additional dredging and widening of Lake River downstream (north) as far as the second (downstream) by-pass channel to a width 200 ft and a bottom elevation of 10 ft below mean sea level. Various dye experiments were conducted in the hydraulic model with the upstream and/or downstream channels in operation and a single culvert was used as an alternative to the upstream channel.

To display test results, selected data from Tests 12,15,17,18,19,20 and 22 are presented in Figs. 11 through 17. These show similar concentration decay curves. In order to evaluate the relative effectiveness of each test, comparison was made of the relative "flushing efficiency" which was measured in terms of the percentage of dye concentration remaining in the lake as time elapsed. The lower the relative concentration C/C_O, the more efficient is the flushing action. Figure 18 presents the test results (average of all eight sampling stations) plotted on semilog paper. A functional relationship between these tests is given by

$$\frac{C}{C_o} = \exp(-kt) \qquad (22)$$

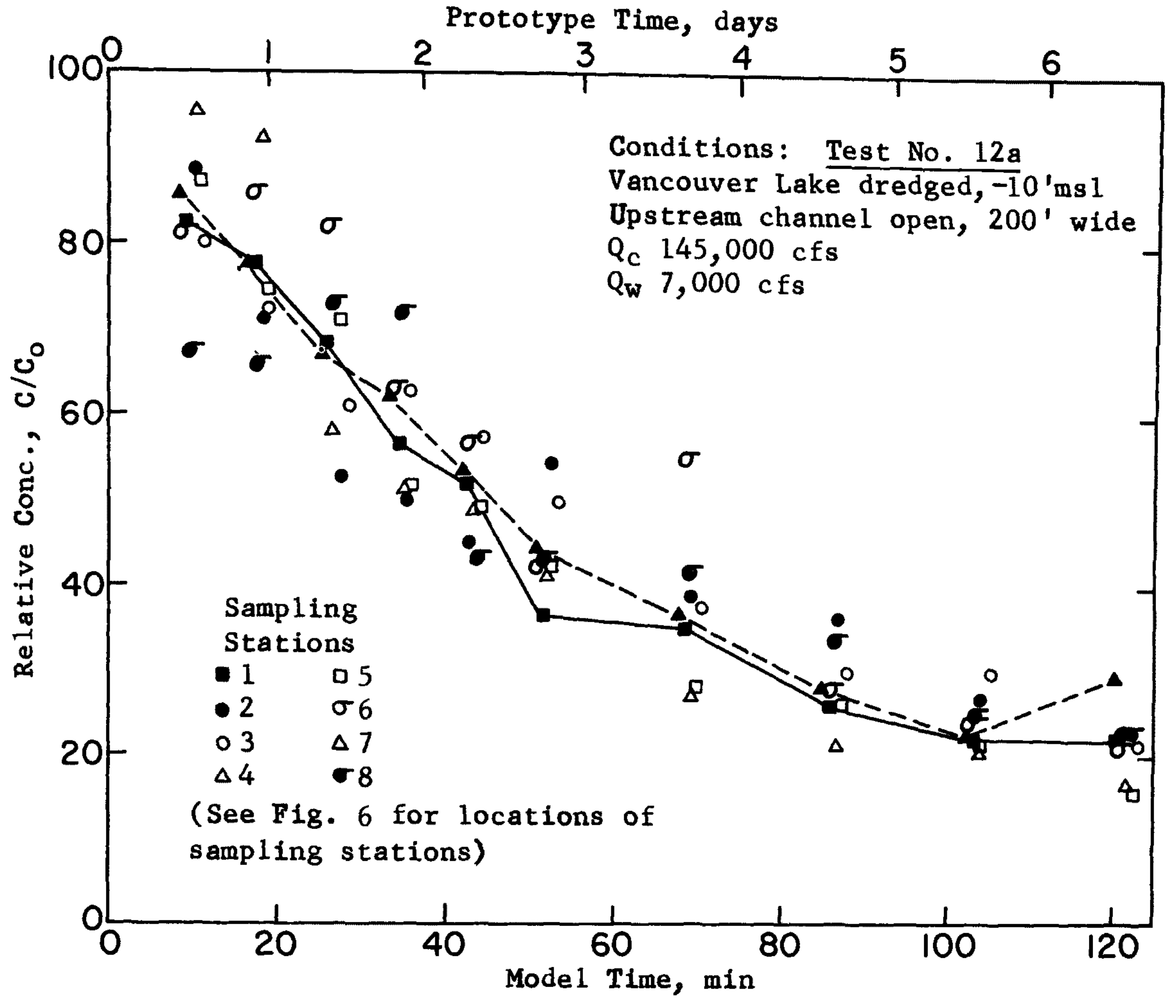


Fig. 11. Test No. 12: Relative Concentration of Dye in Vancouver Lake Model as Function of Time

where C_o is the initial dye concentration in the lake, C the dye concentration at any time t, and k the dilution rate coefficient. Equation (22) indicates that the larger k values are associated with higher flushing efficiencies.

All test results have not been reproduced because some of the changes in test conditions (i.e., the introduction of 500 cfs from Burnt Bridge Creek in Test No. 21) did not significantly change the results from other tests (i.e., Test No. 22 compared to 21). Therefore, graphs of these insignificant tests have been deleted. A summary of the results of individual tests and test series follows:

Test No. 1-7: Purposes: to evaluate model operation and dye dispersion throughout system for flows in Burnt Bridge and Salmon Creeks on the

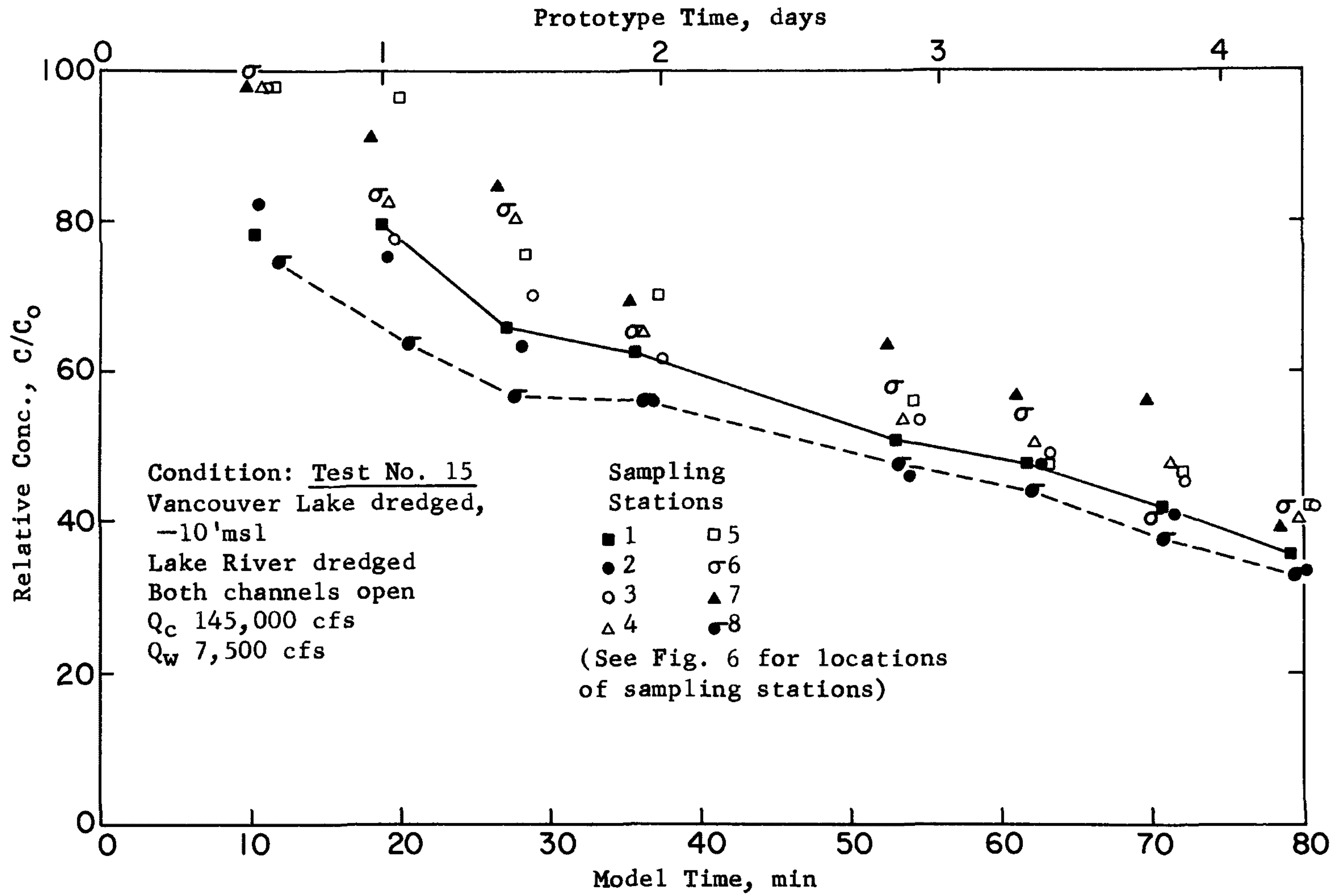


Fig. 12. Test No. 15: Relative Concentration of Dye in Vancouver Lake Model as Function of Time

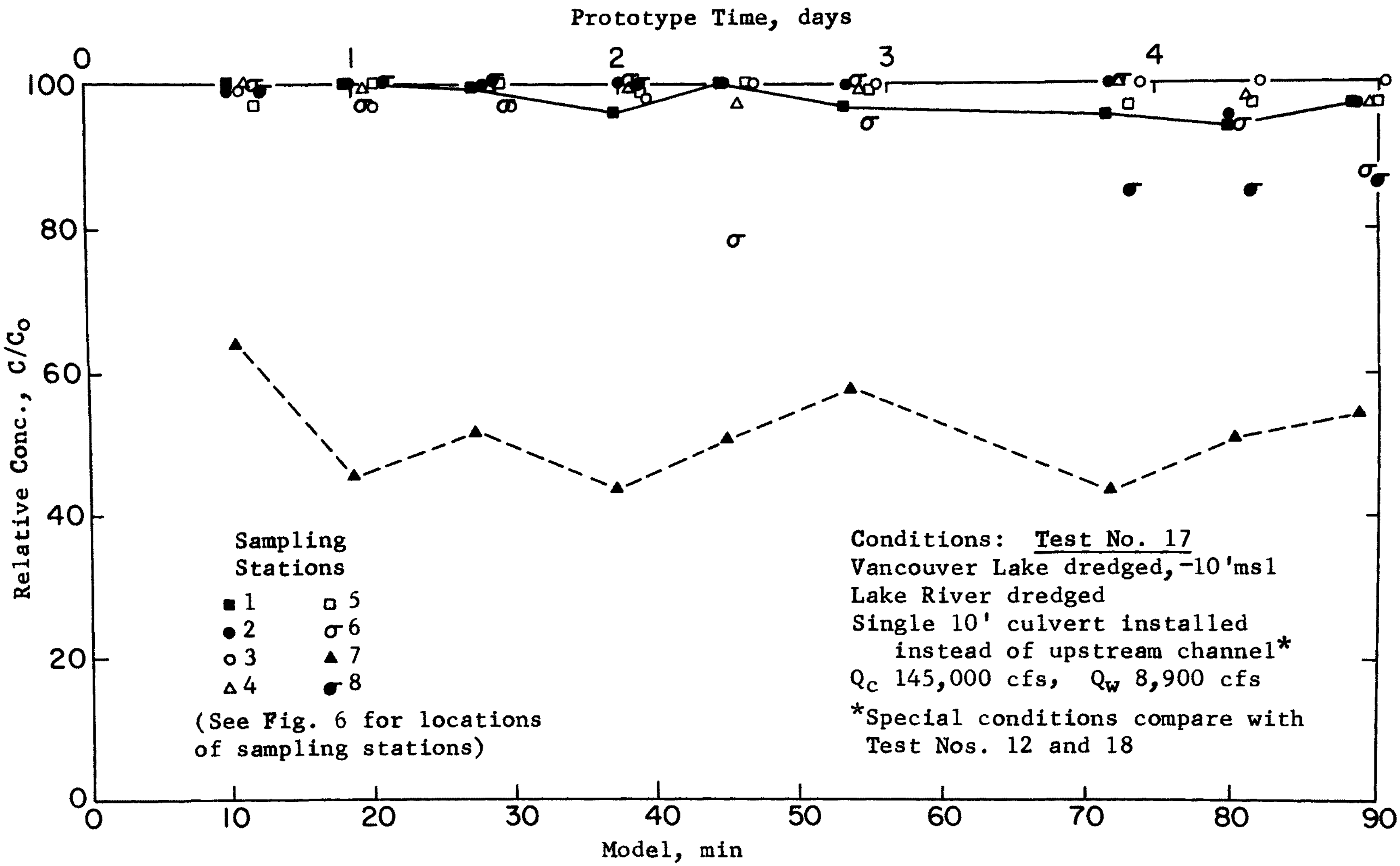


Fig. 13. Test No. 17: Relative Concentration of Dye in Vancouver Lake Model as Function of Time

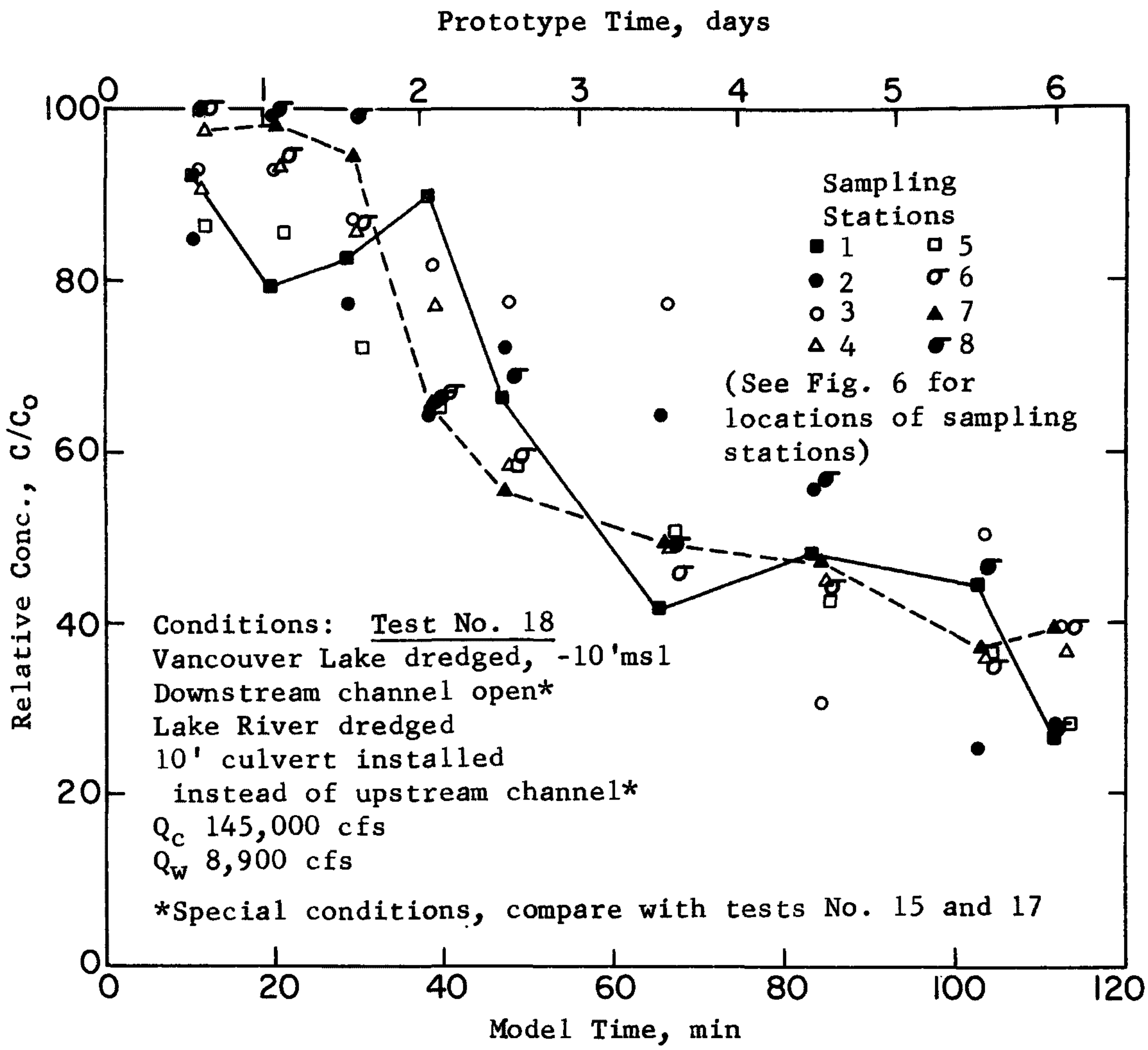


Fig. 14. Test No. 18: Relative Concentration of Dye in Vancouver Lake Model as Function of Time

order of flows which would enter through a channel. Results: shakedown and testing procedures evaluated; effects of tides determined on existing conditions and model verified against prototype conditions.

Test Nos. 8-11: Purposes: to evaluate effects of wide and medium open channels on partially dredged lake (west side); to provide channel flow information for hydrodynamic computer model; to evaluate influence of Willamette River flows. Results: flushing action very efficient in shallower portions of the lake; flushing delayed in dredged area when Lake River flowing in and channel flow forced to south edge of lake away from dredged area. Willamette River flows were found to enter the upstream flushing water channel when discharges in the Willamette and Columbia Rivers are almost equal. This event usually occurs in the winter when water quality and temperature are not problems, and the Willamette River quality is being improved.

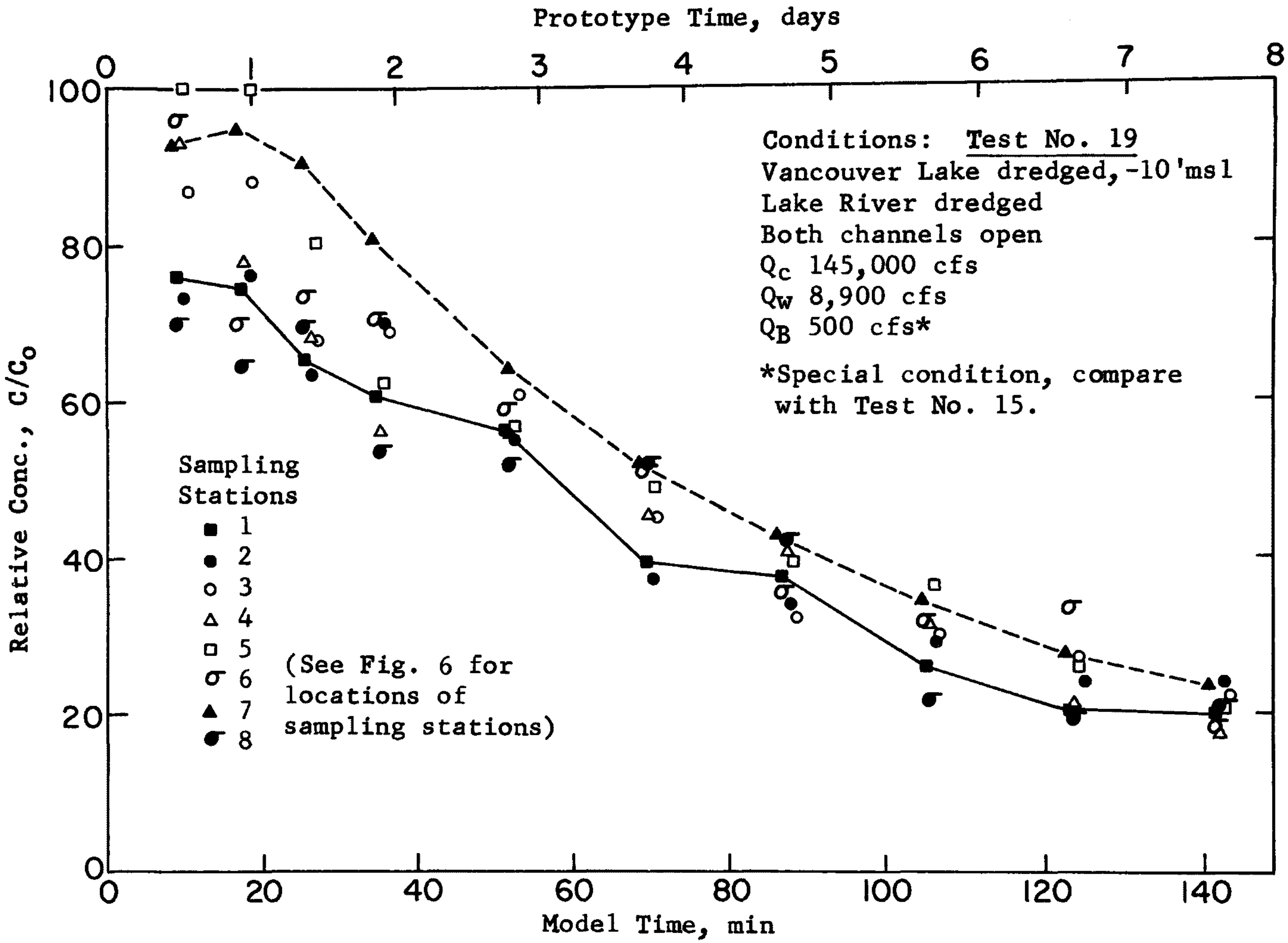


Fig. 15. Test No. 19: Relative Concentration of Dye in Vancouver Lake Model as Function of Time

Test Series No. 12: Purposes: to determine Salmon Creek flood flow which would block the tidal flow in Lake River from entering and leaving Vancouver Lake; and to explore the effects of higher flows in the Columbia River on tidal effects for a fully dredged lake. Results: Salmon Creek flood flow determined that would block the tidal action in Lake River, and model verified for field tide data at higher flows (see Fig. 11 for results of Test No. 12a).

Test No. 13: Purpose: to evaluate effectiveness of island in lake near outlet of upstream channel on flushing efficiency. Results: the island assisted in dividing the flow in such a way as to improve the flow characteristics along the south shore part of the time. But the path of the inflow is strongly influenced by the tidal action, and the amount of inflow is so small in comparison to the volume of the lake, that the use

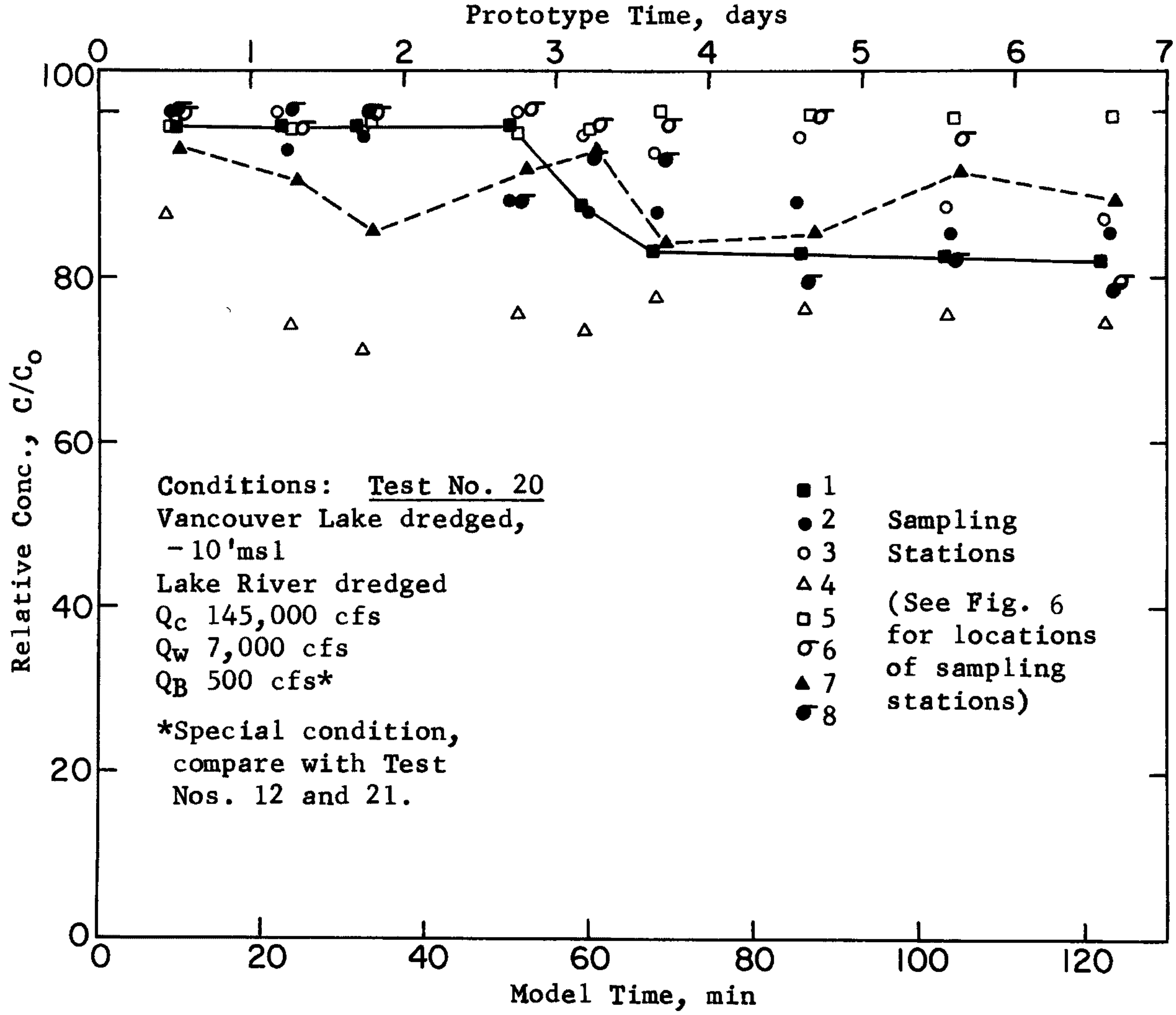


Fig. 16. Test No. 20: Relative Concentration of Dye in Vancouver Lake Model as Function of Time

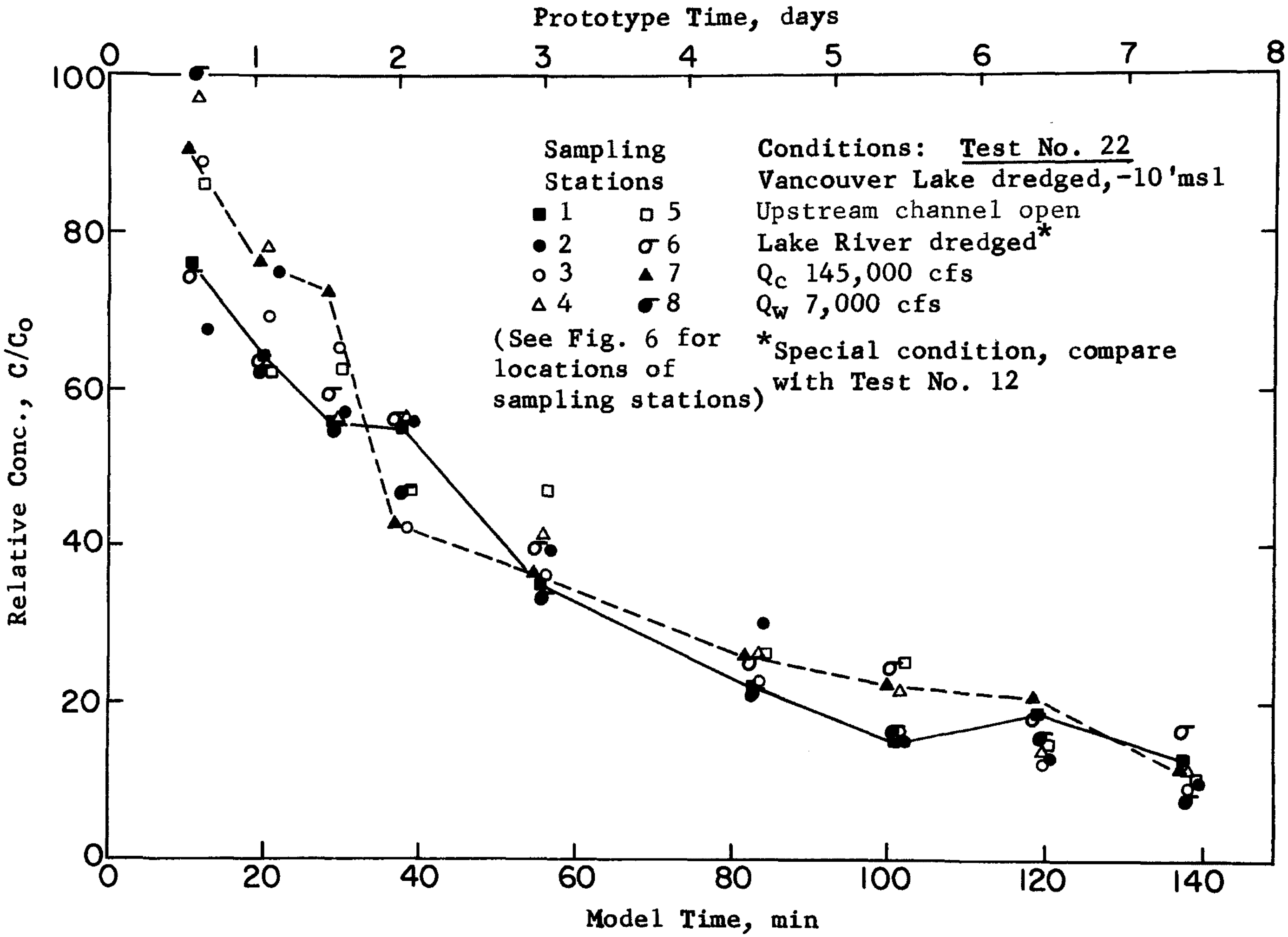


Fig. 17. Test No. 22: Relative Concentration of Dye in Vancouver Lake Model as Function of Time

of an island was deemed insignificant in trying to influence flushing efficiency.

Tests Nos. 15 and 16: Purposes: to test downstream channel operating in conjunction with the upstream channel and test the action of the downstream channel with the upstream channel closed. Results: the downstream channel short-circuits the Columbia River tidal flow into Vancouver Lake via Lake River. Its flow blocks the tidal action coming up Lake River towards Vancouver Lake and holds back water in the lake. The downstream channel is detrimental to the flushing of Vancouver Lake by the upstream channel. This is obvious when Fig. 12 (Test No. 15) for both channels open is compared with Fig. 17 with only the upstream channel being open.

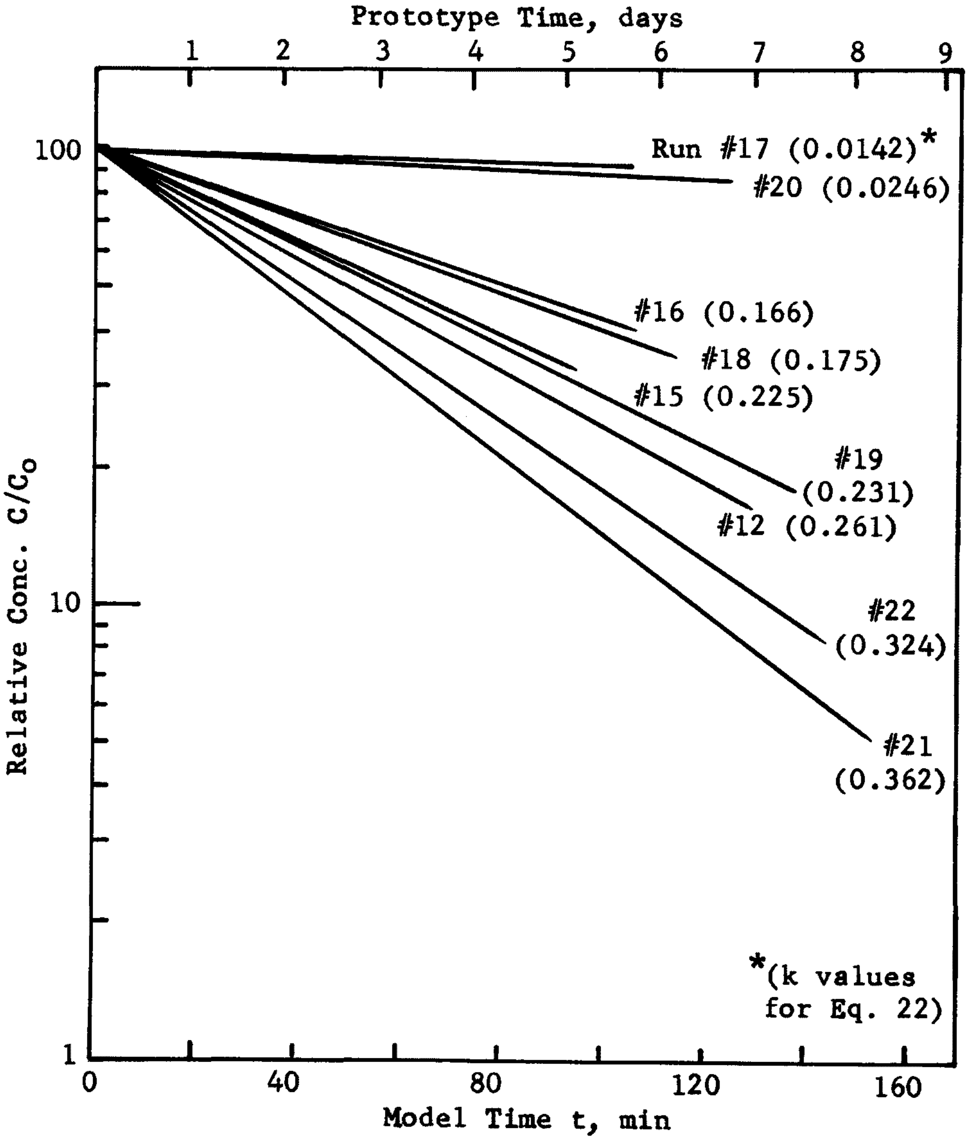


Fig. 18. Summary of Vancouver Lake Model Tests for Post-Development Study

Tests Nos. 17 and 18: Purposes: to evaluate single culvert and the downstream channel. Results: Fig. 13 shows how inefficient a single culvert is, and Fig. 14 shows how the downstream does help flush the lake, but in a cyclic fashion as caused by the tides. Also, the lower channel allows no opportunity for flow through the lake, only in and out.

Tests Nos. 19, 20 and 21: Purpose: to evaluate the influence of a larger-than-normal discharge from Burnt Bridge Creek with various conditions of channel openings. The tests were done to evaluate the suggestion of possibly storing water in the Burnt Bridge Creek basin and releasing it over a short time period in the summer. Results: Fig. 16 shows that the flushing efficiency of Burnt Bridge Creek is quite low.

Test No. 22: Purpose: to evaluate the effect of dredging Lake River (near the outlet of Vancouver Lake) on the flushing efficiency with the upstream channel open. Results: by comparing Figs. 17 and 12, a slight improvement in flushing efficiency due to widening and deepening of Lake River can be observed for Test No. 22.

Hydraulic characteristics in the model were obtained by recording continuous stage hydrographs and by measuring velocities in the channels and in Lake River near Felida. Figure 19 shows the surface velocity variations in Lake River near Felida and Fig. 20 presents the variations in the upstream channel velocities.

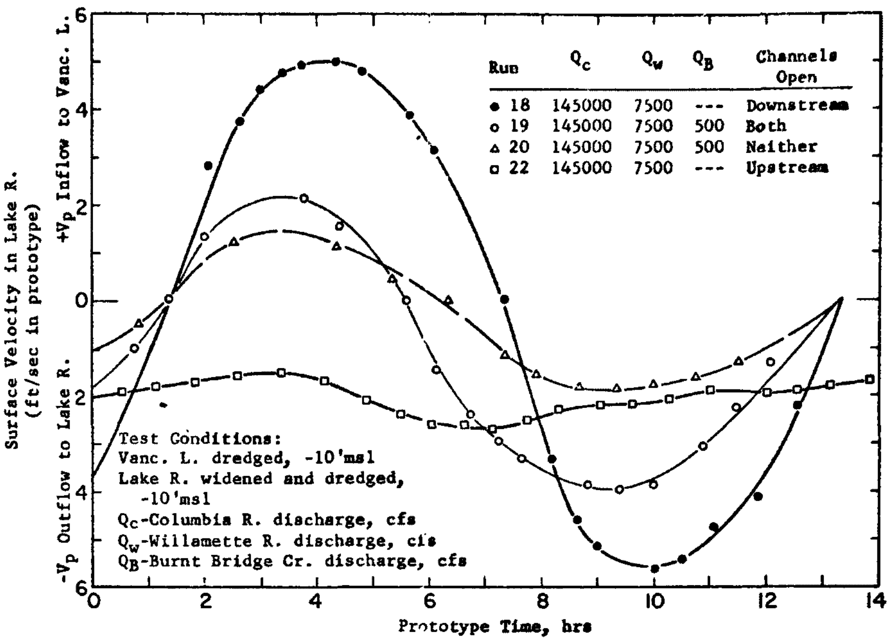


Fig. 19. Surface Velocity in Lake River near Felida (near Gage 3) (Model measurements converted to prototype)

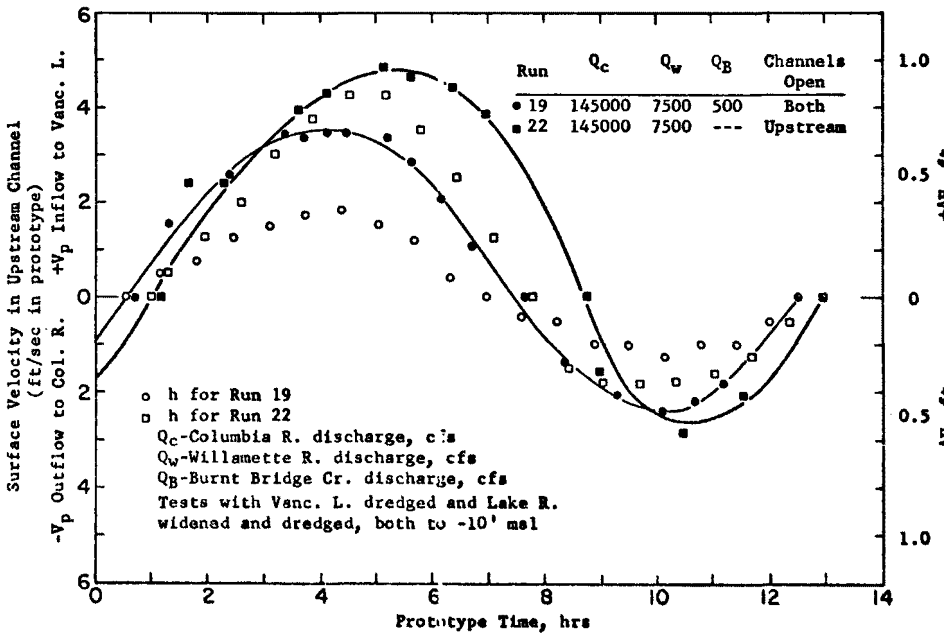


Fig. 20. Surface Velocities and Differences in Elevation for Upstream Channel (Model measurements converted to prototype)

COMPUTER ANALYSIS AND DATA EXTENSION

Mathematical modeling was the basis of the hydrodynamic computer model used to extend the results of the physical hydraulic model study. Details of the hydrodynamic model are given in Appendix C. Under the assumptions of: a) constant lake surface area, b) average evaporation rate from the lake, c) constant Burnt Bridge Creek inflow, d) constant seepage inflow to and outflow from the lake, and e) sinusoidal tide cycles in the Columbia and Lake Rivers, the response of water levels in Vancouver Lake to changes in river and creek discharges were obtained by the water budget concept.

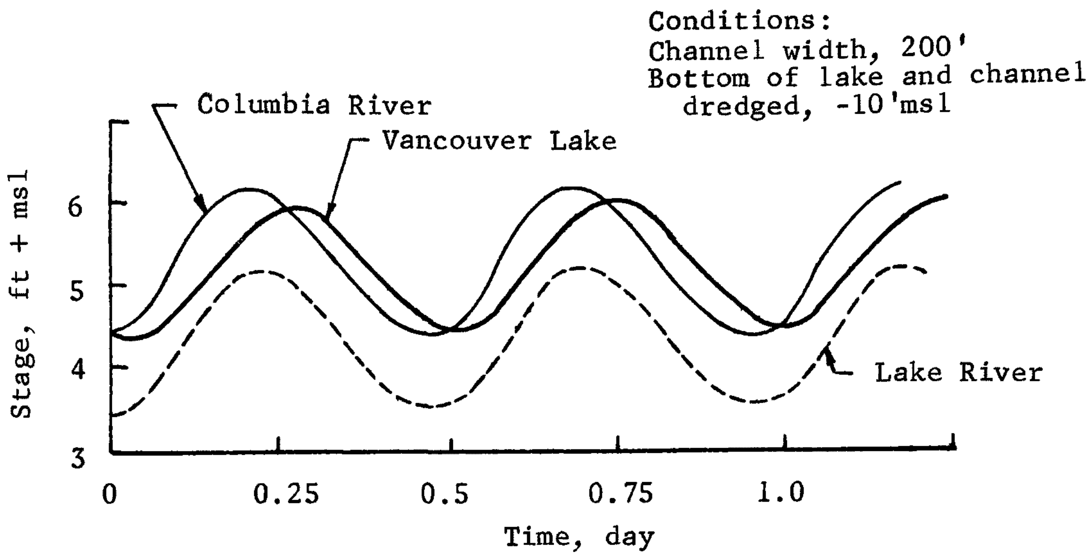
The flow rates in Lake River and the upstream channel were calculated by using the Manning formula. An alternative to the upstream channel for introducing flushing water was a submerged culvert system as analyzed by the Darcy-Weisbach equation for the pipe flow velocity based on the differential head loss between the Columbia River and Vancouver Lake.

The numerical integration of a set of differential equations was achieved by explicit difference approximation. The solution proceeds in steps of time increment of one hour until the desired total simulation time has been reached. The validity of the hydrodynamic computer model was verified with data from the field and the hydraulic model. Figure 21 gives the stage hydrograph recorded and velocities measured in the physical hydraulic model with the upstream channel 200 ft wide and Vancouver Lake dredged to 15 ft deep (bottom -10 ft msl). Figure 22 presents the predicted results of the hydrodynamic model for the inflow-outflow stage and discharge relations in the system at the same conditions. The comparison between simulated values and those obtained from the hydraulic model is shown in Table 3.

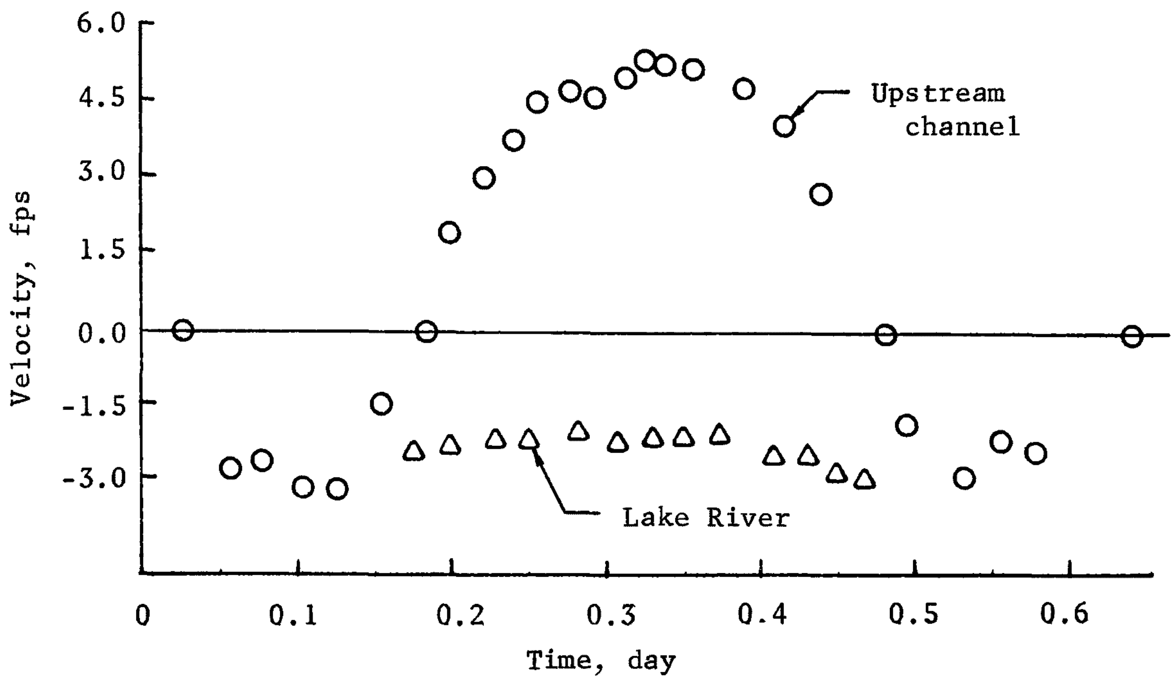
Table 3. Comparison of Results between Predicted Values and Those from the Hydraulic Model

Characteristics	Range	Computer Program	Hydraulic Model
Depth of Vancouver Lake (ft)	max	15.9	16.0
	min	14.3	14.4
Velocity in Lake River (ft/sec)	max	-3.0	-3.0
	min	-1.5	-1.9
Velocity in the channel (ft/sec)	max	4.8	5.1
	min	2.0	2.4

Notes: Conditions--channel width=200 ft; bottom of lake and channel dredged, -10ft msl. Negative sign means outflow from the lake. Model velocities measured with surface floats and are therefore greater than the average velocity by 5% to 10%.



(a) Stage versus Time (recorded in the physical hydraulic model)



(b) Velocity Profile (measured in the physical hydraulic model)

Fig. 21. Prototype Inflow-Outflow Stage and Discharge Relations Obtained from the Physical Hydraulic Model

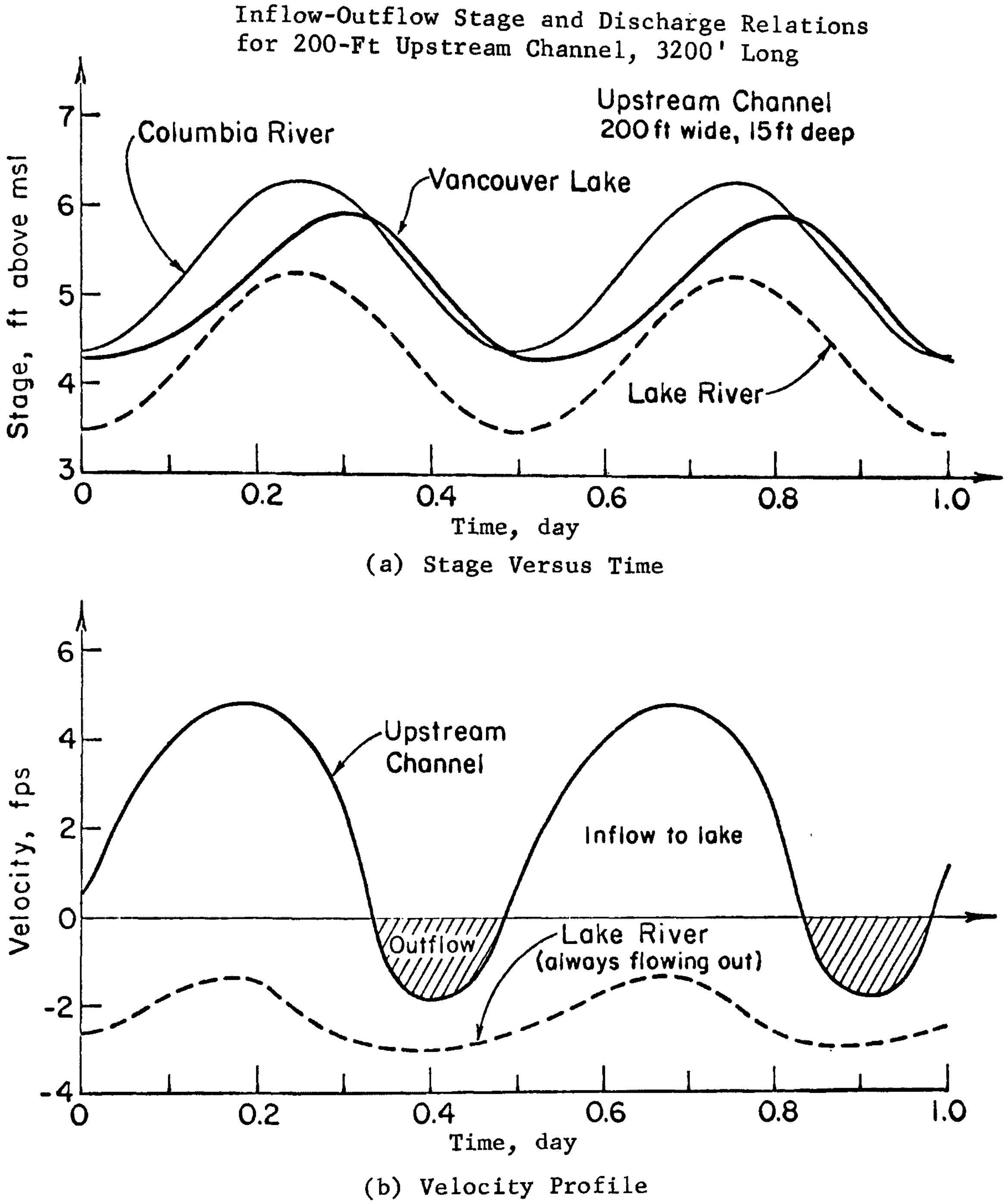


Fig. 22. Typical Example of Upstream Channel Flow Analysis for One Set of Width and Depth Conditions

Upon validation of the existing prototype conditions, numerous simulation runs were made by the hydrodynamic model to examine the influence of possible modifications to the system on hydraulic characteristics.

First, various widths of the upstream channel were tested to determine the width and corresponding flow rate at which Lake River could be kept from discharging into Vancouver Lake. Under these conditions the tidal flow from Lake River into Vancouver Lake would be reversed. Flow would always be out of Vancouver Lake via Lake River to the Columbia River near Ridgefield. The results for widths of 100, 150 and 200 ft are plotted in Fig. 23. It was found that Lake River will always flow out of the lake if the width of the upstream channel is 150 ft or greater.

Then, various combinations of channel length; size, number, type, and length of the culvert; tidal fluctuation of the Columbia River; and dredging depth of the lake were tested to determine their effects on detention time of flow entering the lake. As an example, the influence of various types of culvert materials (i.e., various friction factors) on the average flow rate (or detention time) through culverts is shown in Fig. 24. Finally, functional relationships were obtained for conduit discharge as a function of each variable. Common conditions for the simulation runs were: a) bottom of Vancouver Lake dredged to 10 ft below mean sea level, b) initial lake depth of 15 ft, and c) constant lake surface area equal to 105×10^6 sq ft.

Figure 25 shows the detention time (t_d) of flow into the lake as function of the upstream channel width (W_1) and the Columbia River tidal fluctuation (Δh). The functional relationship is

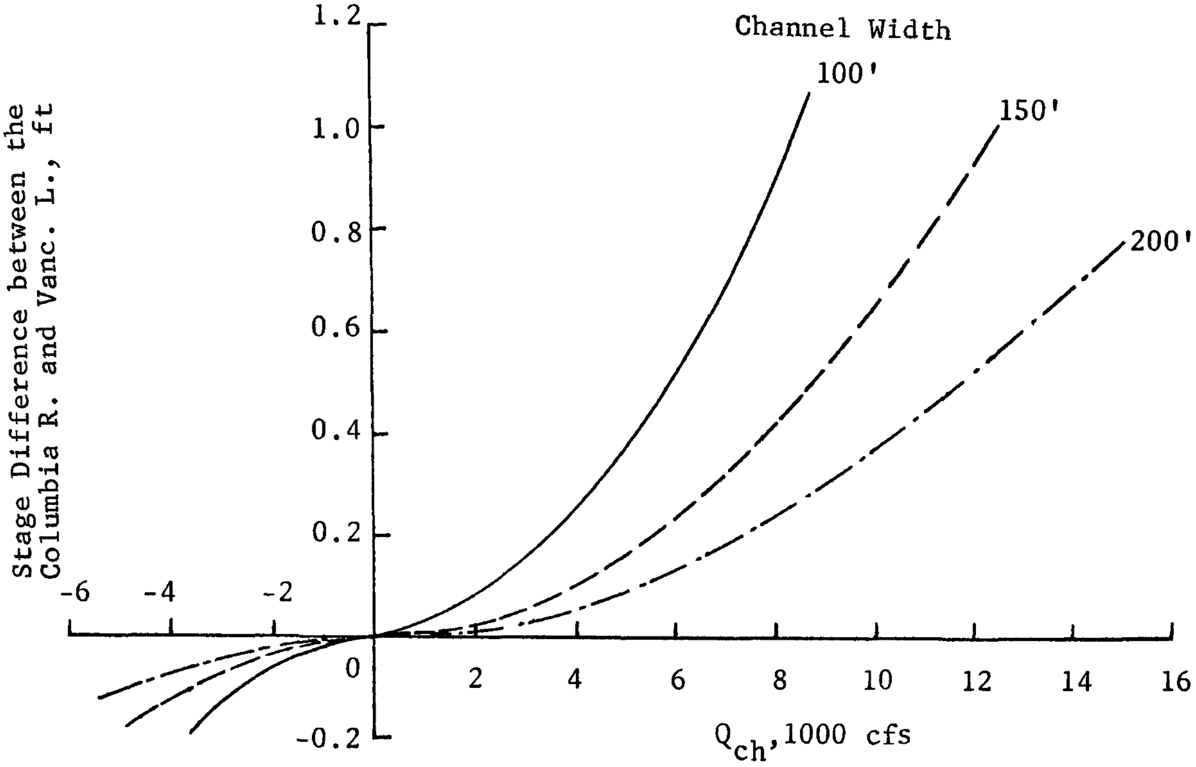
$$t_d = \frac{2170 - 300(\Delta h)}{(W_1)^{1.4}} - \frac{2.0}{(\Delta h)^{0.75}} \quad . \tag{23}$$

Figure 26 gives the detention time of flow into the lake as a function of the number of upstream 10-ft diameter culvert (N_{c10}) and the Columbia River tide fluctuation (Δh). The functional relationship is

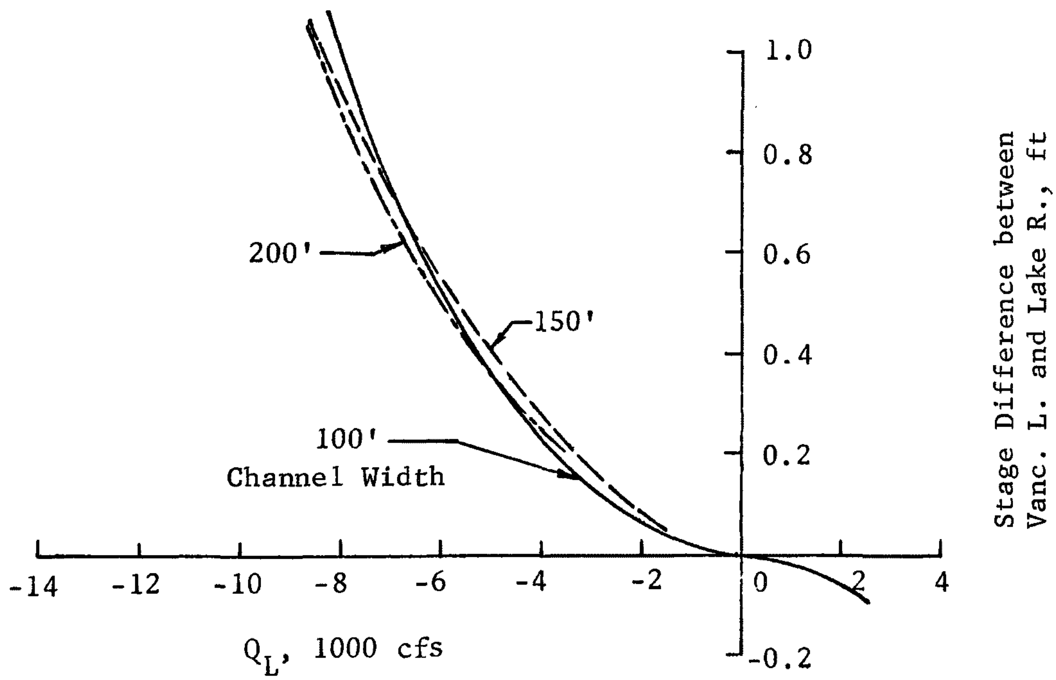
$$t_d = \frac{129}{(\Delta h)^{0.4}(N_{c10})^{0.98}} \quad . \tag{24}$$

The plot of the detention time versus average discharge ($\bar{Q}$) for culverts or the upstream channel, using lake bottom elevation of H_b ft below mean sea level as a parameter, is shown in Fig. 27. The functional relationship is

$$t_d = \frac{1850(H_b)}{\bar{Q}} \quad . \tag{25}$$



(a) Upstream Channel Stage Difference and Flow Rate Relation



(b) Lake River Stage Difference and Flow Rate Relation

Fig. 23. Simulated Results of Upstream Channel and Lake River Flow Analyses for Various Channel Widths

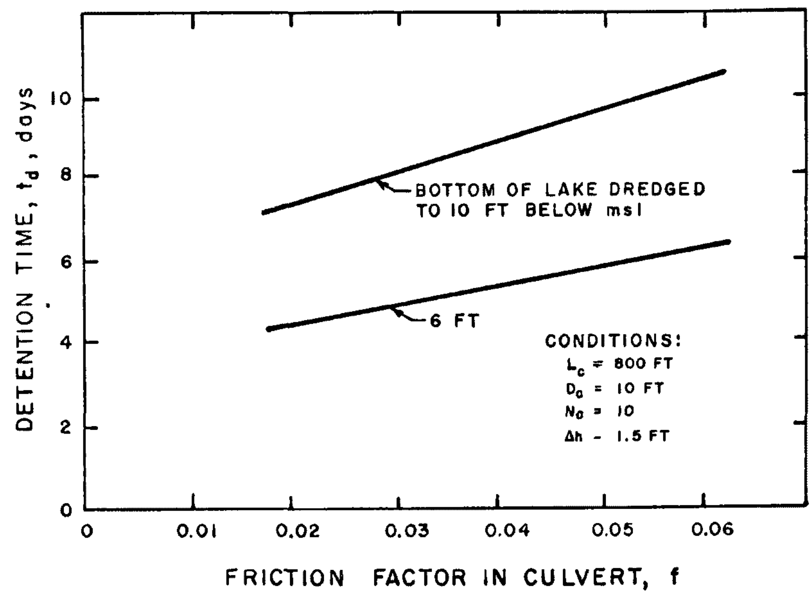


Fig. 24. Detention Time as a Function of Friction Factor and Depth of Lake

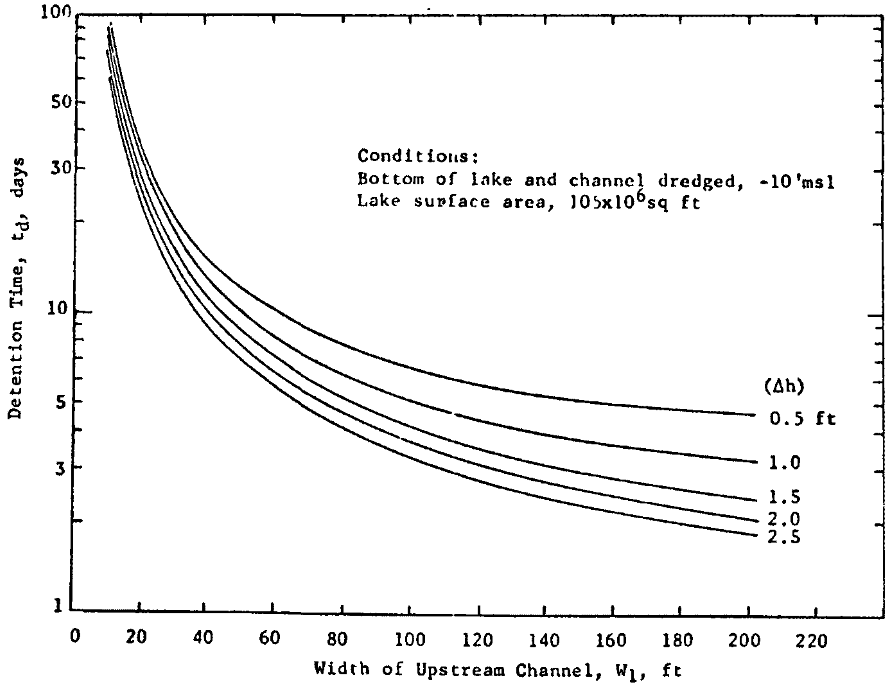


Fig. 25. Detention Time versus Width of Upstream Channel Using the Columbia River Tidal Amplitude as a Parameter

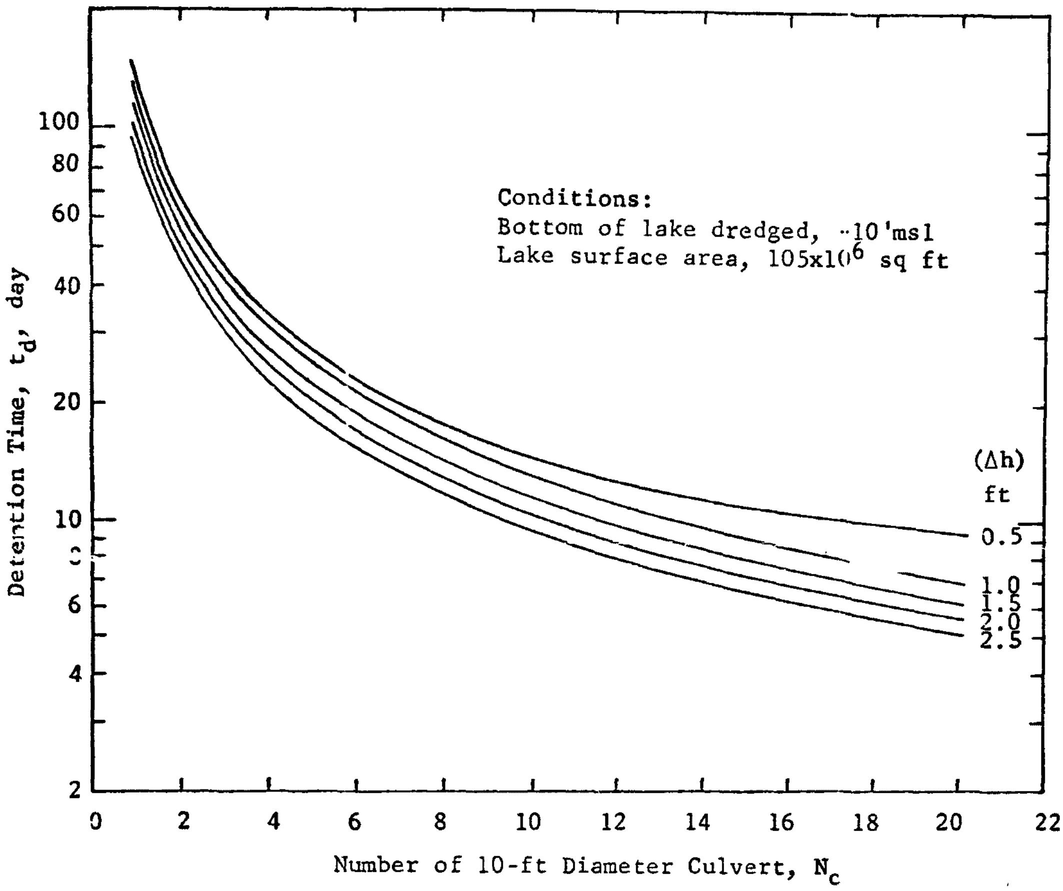


Fig. 26. Detention Time versus Number of 10-ft Diameter Culvert Using the Columbia River Tidal Amplitude as a Parameter

Figure 28 gives the detention time as a function of the culvert length (L_c) and diameter (D_c) under the conditions of 1.5-ft Columbia River tidal fluctuation, and ten culverts. The functional relationship is

$$t_d = \frac{125(L_c)^{0.33}}{(D_c)^{2.25}} \tag{26}$$

Figure 29 shows the average discharge through one culvert as a function of culvert length (L_c) and diameter (D_c) under the condition of 1.5-ft Columbia River tidal fluctuations. The functional relationship is

$$q_{lc} = \frac{43}{(L_c)^{0.5}} (D_c)^{\exp\left[1.3(L_c)^{0.08}\right]} \tag{27}$$

These predicted results can be used to select the geometric dimensions of the conduit and thus provide information for initial considerations as well as for final design stages.

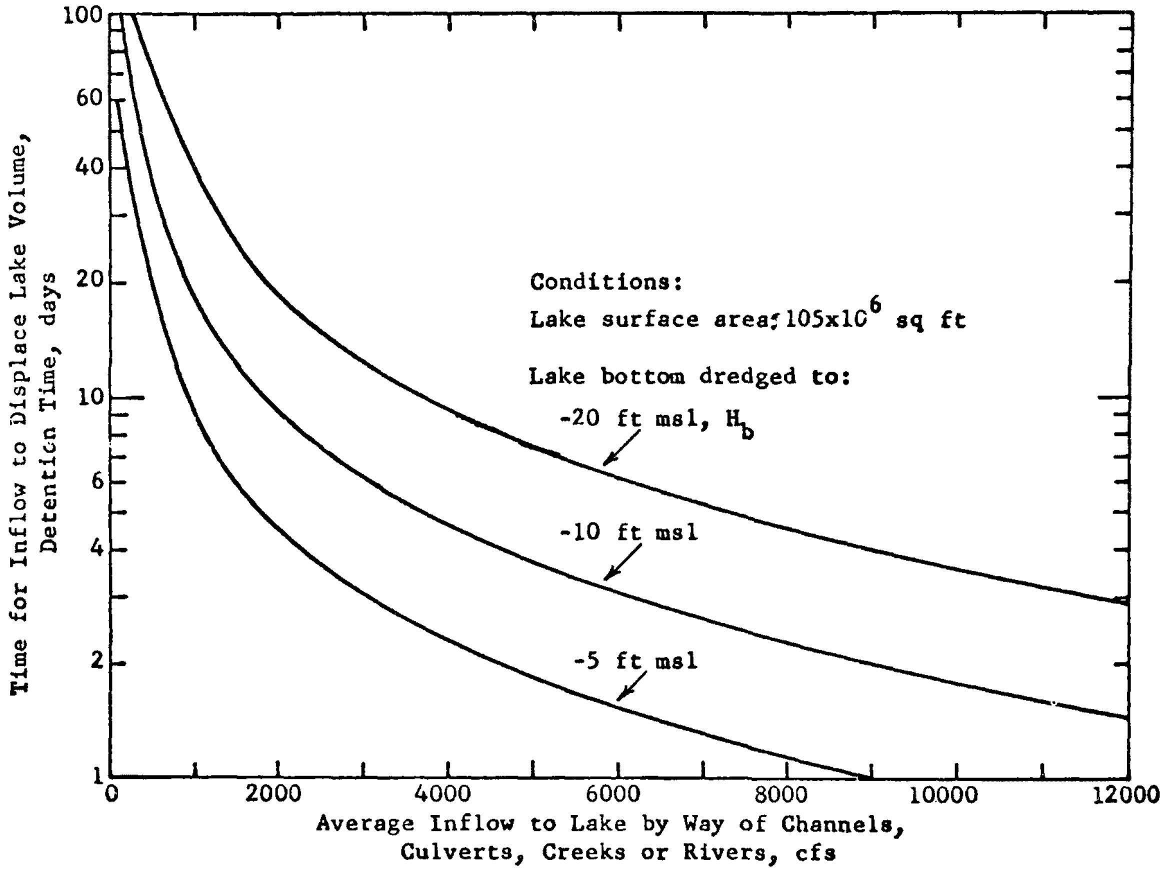


Fig. 27. Lake Detention Time and Average Inflow through Any Kind of Conduit(s)

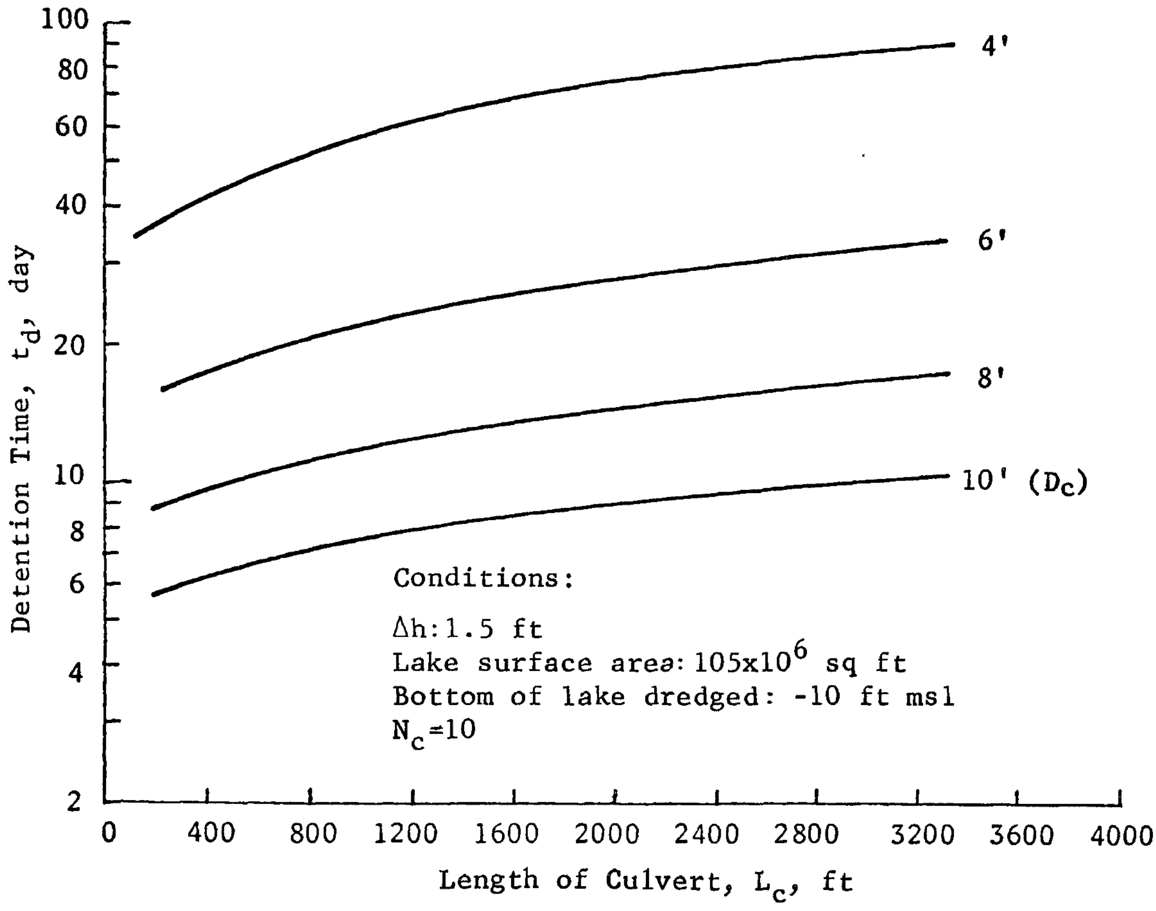


Fig. 28. Detention Time versus Length of Culvert for Various Culvert Diameters

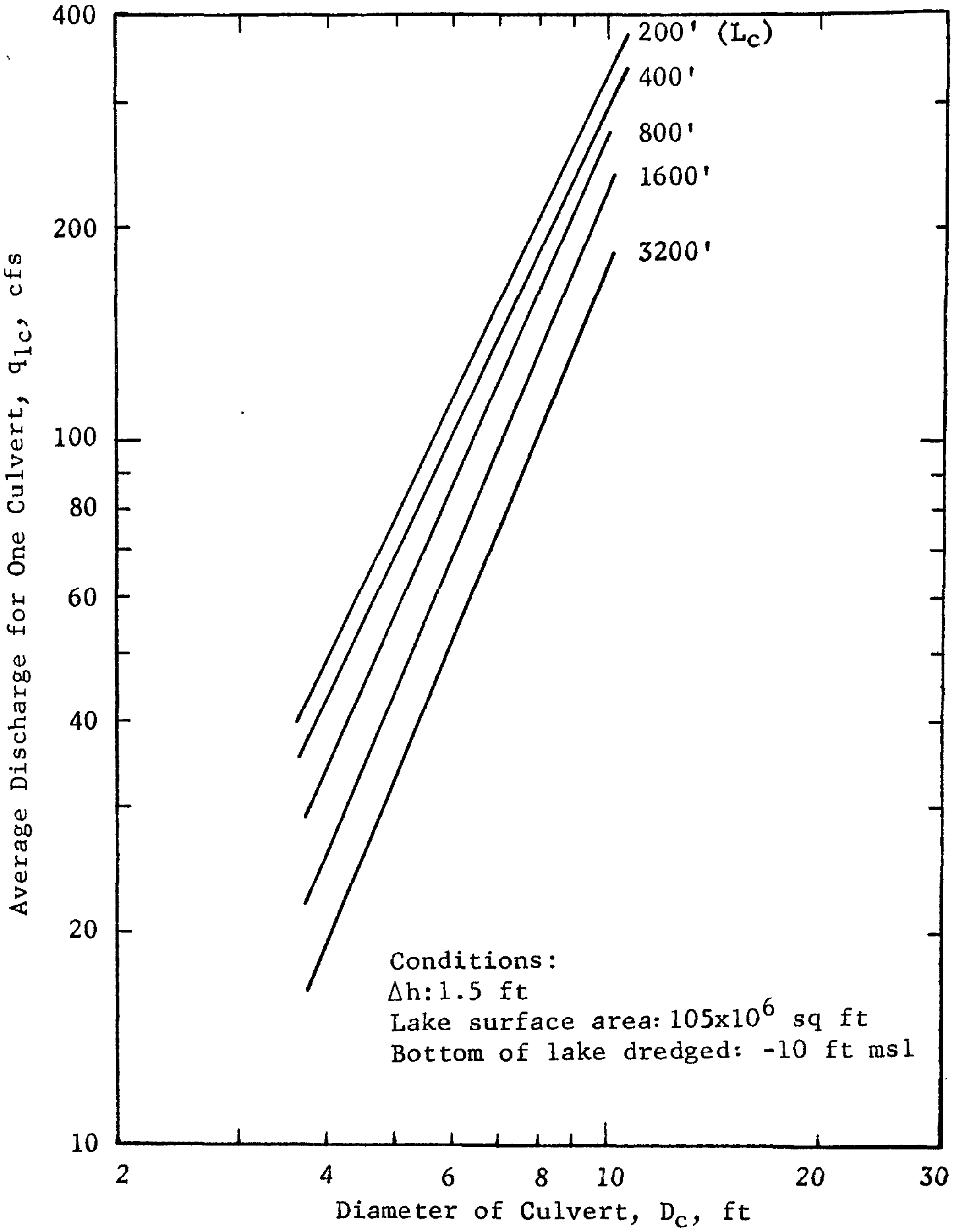


Fig. 29. Average Discharge through One Culvert versus Diameter of the Culvert

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APPENDICES

APPENDIX A. PROJECT BIBLIOGRAPHY

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APPENDIX B. NOTATION

The following symbols were used in this study:

a	tidal half amplitudes, feet
A	area of lake water surface; cross-sectional area; square feet
C	dye concentration at any time t, second
C_o	initial dye concentration in the hydraulic model lake
D	depth, feet
D_c	nominal inside diameter of culvert, feet
E_v	evaporation rate from the lake, cubic feet per second, or inches per year
f	pipe flow friction factor
F	Froude number, $F/\sqrt{gD}$
g	acceleration due to gravity, feet per second^2
Δh	Columbia River tidal amplitude, feet
H	water depth of Vancouver Lake, feet
H_b	dredged lake bottom elevation below mean sea level, feet
H_w	lake water surface elevation measured from mean sea level, feet
k	dilution rate constant
K	minor loss coefficient
L	characteristic length, feet
L_c	length of culvert, feet
m	subscript refers to model
n	Manning roughness coefficient
N_{c10}	number of 10-foot diameter culverts
p	subscript refers to prototype

P_r precipitation rate onto the lake, cubic feet per second or inches per year

q_{1c} average discharge through one culvert, cubic feet per second

$\bar{Q}$ average discharge, cubic feet per second

Q_B flow rate in Burnt Bridge Creek, cubic feet per second

Q_c discharge through conduit, cubic feet per second

Q_{ch} discharge through man-made channel, cubic feet per second

Q_{co} flow rate in the Columbia River, cubic feet per second

Q_{cu} flow rate through culverts, cubic feet per second

Q_i inflow rate to the lake, cubic feet per second

Q_{in} local inflow rate including both surface runoff and ground-water contribution, cubic feet per second

Q_L flow rate in Lake River, cubic feet per second

Q_o outflow rate from the lake, cubic feet per second

Q_{ou} local outflow rate from the lake to ground-water storage, cubic feet per second

Q_w flow rate in Willamette River, cubic feet per second

r subscript means prototype-to-model ratio

R hydraulic radius, feet

S slope of water surface, bed, or energy line

t time, second

t_d detention time of inflow into the lake, days

T percent of transmittance at any time t

T_o percent of transmittance corresponding to C_o

T_r time ratio prototype-to-model

u local velocity, feet per second

V average longitudinal velocity in a cross section, feet per second

$\mathbf{\overline{V}}$ volume of lake, cubic feet

W width of the channels and rivers, feet

Y depth in a channel, feet

Z depth of Lake River, feet

APPENDIX C. HYDRODYNAMIC MODEL

1. Identify initial values of H_i, Y_i, and Z_i; then calculate $(Q_L)_i$ by Eq. (15), and $(Q_c)_i$ by Eq. (16) for open channel calculation and Eq. (21) for pipe flow calculation.

2. Calculate the subsequent values by using initial values. At time $t_{i+1} = t_i + \Delta t$, use Eqs. (17) and (18) to obtain Y_{i+1} and Z_{i+1}. Calculate $(Q_L)_{i+1}$ and $(Q_c)_{i+1}$ by using Eqs. (15), (16), or (21), and then obtain the change in lake depth by Eq. (8) as

$$\Delta H = [(Q_L)_i + (Q_c)_i + Q_B + Q_{in} + P_r - E_v - Q_{ou}]\,\Delta t/A \quad .$$

   Therefore, we can evaluate

$$H_{i+1} = H_i + \Delta H \quad .$$

3. Using the results of the previous steps as initial values, the procedure is repeated.

Actual tidal records were used instead of assuming the sinusoidal tidal cycle. Tabulated field data were used in input information and the same procedure of calculation was followed. The flow chart for the Combined Hydrodynamic and DO models is shown in Fig. 30.

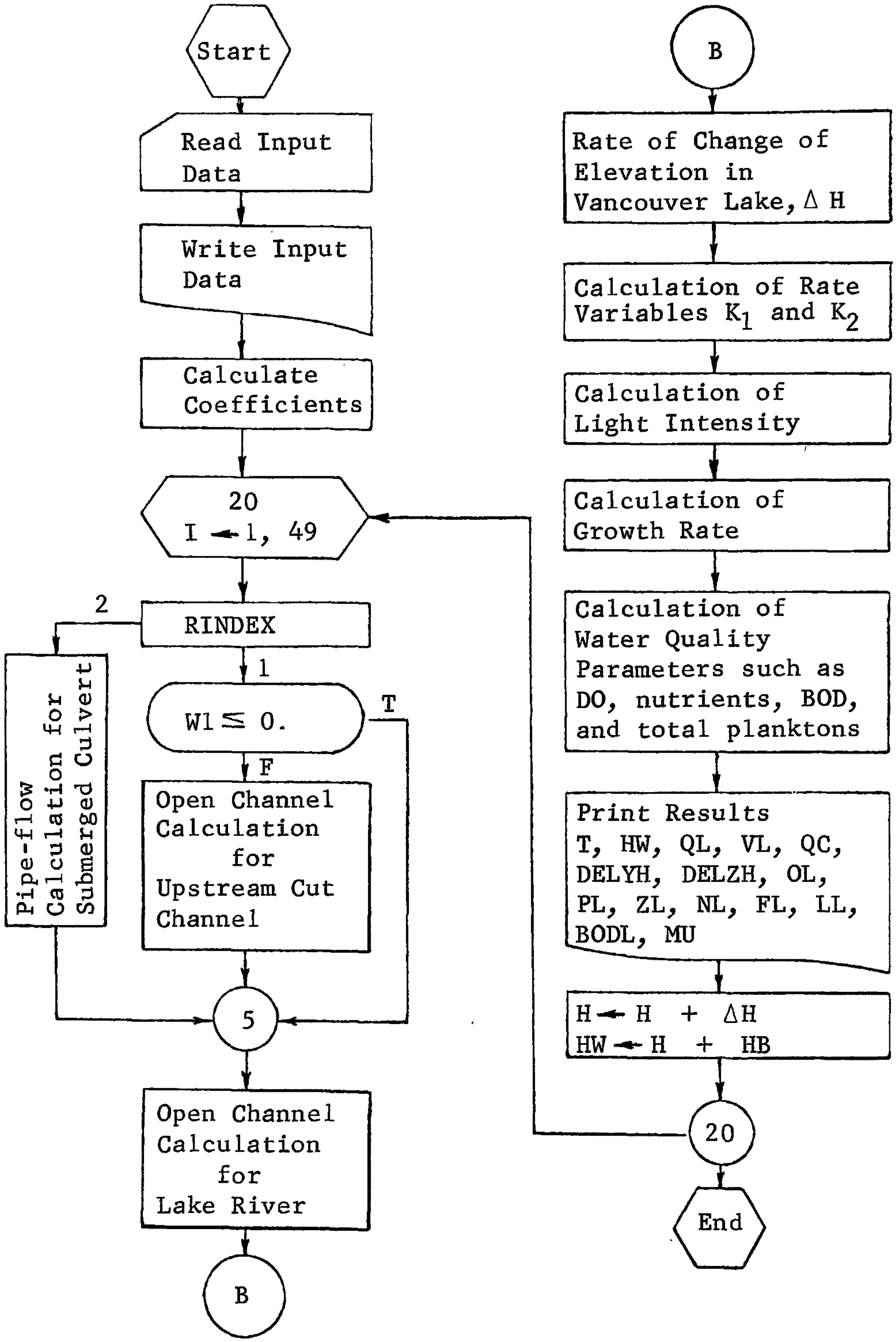

Fig. 30. Flow Chart for Hydrodynamic and/or DO Computer Models

```
C
C                           ************************
C                           *  HYCRCCYNAMIC MCDEL  *
C                           ************************
C
C
C
C
C      ...................................................................
C      . HYDRODYNAMIC PRCGRAMMING : WATER BUDGET FCR VANCOUVER LAKE-     .
C      . RIVER SYSTEM BY USING THE CONTINUITY CCNCEPT.                   .
C      .    1.  MANNING FORMULA (IN FT-SEC UNIT) -- FOR UPSTREAM CUT CHANNEL .
C      .    2.  DARCY-WEISBACH EQUATION -- FOR SUBMERGED CULVERTS        .
C      . THIS PROGRAM WAS PREPARED AND REVISED BY MARCUS C. N. LIN       .
C      . IN MARCH, 1971 AT WSU                                           .
C      ...................................................................
      DIMENSION TEMP(400),ZW(400),YW(400),V(400)
100   READ(5,1,END=1000) ZG,YB,HW,HB,F1,F2,W1,W2,D1,D2,A,DCT,RNT,F3,D3,
     1RINDEX
1     FORMAT (8F10.2)
      WRITE (6,300) ZG,YB,HW,HB,F1,F2,W1,W2,D1,D2,A,DCT,RNT,F3,D3,
     1RINDEX
300   FORMAT (1H1,'HYDRAULIC CHARACTERISTICS CF LAKE RIVER SYSTEM  ',//,
     1' ZG =',F7.2,10X,'YB =',F8.2,10X,'HW =',F7.2,10X,'HB =',F7.2,//,
     2' F1 =',F7.3,10X,'F2 =',F8.3,10X,'W1 =',F7.2,10X,'W2 =',F7.2,//,
     3' D1 =',F10.2,7X,'D2 =',F10.2,8X,' A =',F14.2,//,6F20.3)
      INDEX=RINDEX
      INDEX1=3.
      C=4.*3.14159
      PR=0.
      COL=0.
      CIN=0.
      QB=50.
      EV=0.
      DT=0.005
      CV1=(1.49*W1)/(F1*D1**0.5*2.**1.6667)
      CV2=(1.49*W2)/(F2*D2**0.5*2.**1.6667)
      CV3=SQRT(64.4/(1.5+F3*D3/DCT))
      CVI=1.0*CV2
      CVO=1.00*CV2
      DB1=YB-HB
      DB2=ZG-HB
      HH=HW
      H=HW-HB
      WRITE (6,9)
9     FORMAT (///,' OUTPUT LISTINGS ARE:')
      WRITE (6,10)
10    FORMAT (///,' TIME (DAY) C CF CH1   DEL C-V    Q OF L.R.  DEL L-V
     1  VEL OF CH1 VEL OF L.R.   QC/QL      Y OF C.R.  Y OF L.R.  Y OF V.
     2L.')
      COUNT=0.
      HSUM=0.
      QSUM=0.
      COSUM=0.
```

```
      QLSUM=0.
      DO 20 I=1,201
      RI=I
      T=(RI-1.)*DT
      THETA=C*T
      GO TO (90,91,92,93,94),INDEX1
90    YW(I)=4.89-1.25*COS(THETA)
      ZW(I)=4.47-0.8*COS(THETA)
      GO TO 95
91    YW(I)=4.89-1.0*COS(THETA)
      ZW(I)=4.47-0.55*COS(THETA)
      GO TO 95
92    YW(I)=4.89-0.75*COS(THETA)
      ZW(I)=4.47-0.3*COS(THETA)
      GO TO 95
93    YW(I)=4.89-0.5*COS(THETA)
      ZW(I)=4.47-0.1*COS(THETA)
      GO TO 95
94    YW(I)=4.89-0.25*COS(THETA)
      ZW(I)=4.47-0.05*COS(THETA)
95    Z=ZW(I)-ZG
      DELZH=ZW(I)-HW
      GO TO (2000,3000),INDEX
2000  IF (W1 .LE. 0.) GO TO 55
C
C     FLOW RATE AND VELOCITY IN THE UPSTREAM CUT CHANNEL
C
      Y=YW(I)-YB
      DELYH=YW(I)-HW
      AC=W1*(Y+HW-YB)/2.
      TD1=Y-H+DB1
      COO=(W1/(W1+Y+H))**0.6667
      IF (TD1 .LT. 0.) GO TO 4
C
C     FIRST APPROXIMATION IN UPSTREAM CUT CHANNEL
C
      QC=CV1*(Y+H)**1.6667*TD1**0.5
      IF (W1 .GT. 200.) GO TO 405
      QC=QC*COO
C
C     FINAL CALCULATION IN THE UPSTREAM CUT CHANNEL
C
405   VC1=QC/(W1*Y)
      VC2=QC/(W1*H)
      DV=(VC1+VC2)*(VC1-VC2)/64.4
      TEST=TD1+DV
      IF (TEST .LT. 0.) GO TO 11
      QC=CV1*(Y+H)**1.6667*(TEST)**0.5
      IF (W1 .GT. 200.) GO TO 12
      QC=QC*COO
      GO TO 12
11    QC=-CV1*(Y+H)**1.6667*(-TEST)**0.5
      IF (W1 .GT. 200.) GO TO 12
      QC=QC*COO
12    VC=QC/AC
      GO TO 5
```

```
4      QC=-CV1*(Y+H)**1.6667*(-TC1)**0.5
       IF (W1 .GT. 20C.) GC TC 410
       QC=QC*COQ
410    VC1=QC/(W1*H)
       VC2=QC/(W1*Y)
       DV=(VC1+VC2)*(VC1-VC2)/64.4
       TEST=-TD1+DV
       IF (TEST .LT. C.) GC TC 22
       QC=-CV1*(Y+H)**1.6667*(TEST)**0.5
       IF (W1 .GT. 20C.) GC TC 23
       QC=QC*COQ
       GC TC 23
22     QC=CV1*(Y+H)**1.6667*(-TEST)**0.5
       IF (W1 .GT. 20C.) GC TC 23
       QC=QC*COQ
23     VC=QC/AC
       GC TC 5
55     QC=C.
       VC=C.
       DELYH=C.
       GO TC 5
3000   IF (DCT .LE. C.) GC TC 55
C
C      FLCW RATE ANC VELOCITY IN CULVERTS (SUBMERGED CONDITION ANC
C      INFLCW TC VANCCUVER LAKE CNLY)
C
       DELYH=YW(I)-HW
       IF (DELYH .LT. C.) GC TC 55
       AT=C.785*DCT**2.
       QC= AT*RNT*CV3*DELYH**0.5
       VC=QC/(RNT*AT)
C
C      FLCW RATE AND VELOCITY IN LAKE RIVER
C
5      AL=W2*(H+Z)/2.
       AI=1.0*AL
       AC=1.0C*AL
       TD2=Z-H+DB2
       IF (TD2 .LT. 0.) GO TC 6
C
C      FIRST APPPOXIMATICN IN THE LAKE RIVER
C
       QL=CVI*(Z+H)**1.6667*TD2**0.5
C
C      FINAL CALCULATICN IN THE LAKE RIVER
C
       VL1=QL/(W2*Z)
       VL2=QL/(W2*H)
       DV=(VL1+VL2)*(VL1-VL2)/64.4
       TEST=TD2+DV
       IF (TEST .LT. C.) GC TC 44
       QL=CVI*(Z+H)**1.6667*(TEST)**0.5
       VL=QL/AI
       GO TC 45
44     QL=-CVO*(Z+H)**1.6667*(-TEST)**0.5
45     VL=QL/AO
```

```
      GO TO 7
6     QL=-CVO*(Z+H)**1.6667*(-TD2)**0.5
      VL1=QL/(W2*H)
      VL2=QL/(W2*Z)
      DV=(VL1+VL2)*(VL1-VL2)/64.4
      TEST=-TD2+DV
      IF (TEST .LT. 0.) GO TO 33
      QL=-CVO*(Z+H)**1.6667*(TEST)**0.5
      VL=QL/AO
      GO TO 34
33    QL=CVI*(Z+H)**1.6667*(-TEST)**0.5
34    VL=QL/AI
C
C     CHANGE OF ELEVATION IN VANCOUVER LAKE
C
7     DH=DT*(QIN+QO+QL+QB+PR+EV+CCU)*86400./A
      IF (QL .EQ. 0.) GO TO 8
      RATIO=QO/QL
      GO TO 50
8     RATIO=9999.999
C     PRINT AND LIST THE RESULTS
50    WRITE (6,30) T,QO,DELYH,QL,DELZH,VO,VL,RATIO,YW(I),ZW(I),HW
30    FORMAT (F9.3,F11.2,F10.4,F12.2,F10.4,F11.3,F11.3,F11.2,F13.4,F11.4
     1,F10.4)
      IF (QO .LE. 0.) GO TO 666
      COUNT=COUNT+1.
      QSUM=QSUM+QO
      HSUM=HSUM+HW
C     WATER LEVEL IN VANCOUVER LAKE
666   H=H+DH
      HW=H+HB
20    CONTINUE
      QAVG=QSUM/COUNT
      HAVG=HSUM/COUNT
      DETIME=(HAVG-HB)*A/(QAVG*86400.)
      WRITE (6,5000) QAVG,HAVG,DETIME
5000  FORMAT (////,3F20.3)
      GO TO 100
1000  WRITE (6,40)
40    FORMAT (///,' END OF CALCULATION')
      RETURN
      END
```

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16. *Abstract* The effects of possible modifications to the Vancouver Lake-Columbia River System on the hydraulic characteristics of that system were tested in a physical hydraulic model. A mathematical model was developed for predictive analysis and to expand the results of the hydraulic model study. Alternate methods for improving flushing action through Vancouver Lake by use of a conduit were investigated.

The theories, assumptions, test procedures, data analysis and results as presented in this report are directed towards arriving at conclusions and recommendations regarding proposed hydraulic engineering works and their effects on the hydraulic regime and water quality conditions in Vancouver Lake. The tests were conducted to determine the hydraulic characteristics and the flushing efficiency of pollutants by using a fluorescent dye to simulate the soluble conservative pollutants in the prototype. In addition, the hydraulic model study provided information on the dispersion, mixing, dilution rates and detention times which are important factors influencing water quality.

This is Part 1 of a two-part study entitled "Correlated Studies of Vancouver Lake, Washington." The other part of the study is Water Quality Prediction conducted by the Sanitary Engineering Section of the College of Engineering Research Division at Washington State University under Project #16080 ERQ, details of which are covered in a separate report.

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