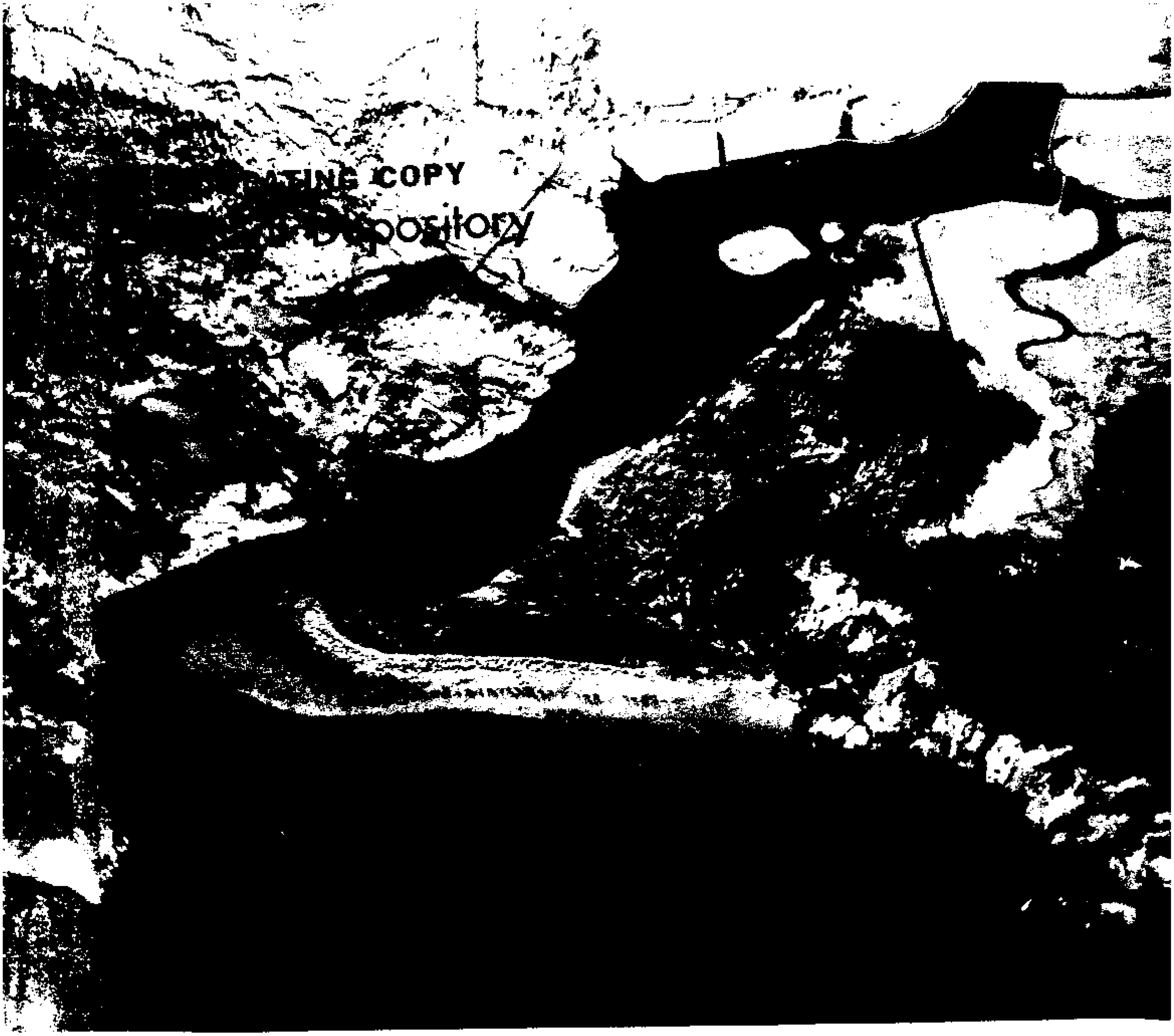

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Proceedings 1971 Technical Conference on Estuaries of the Pacific Northwest

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Preface

Estuaries are the natural focal point for many industrial and recreational activities; their uses should be recognized. We realize that estuaries are the rearing areas for many marine animals and that land fill and pollution have wiped out many estuaries on the shores of North America. Many life forms and the valuable aesthetics of the remaining estuaries of the Pacific Northwest are in danger. Thus, it is timely to review the problems involved in the preservation and proper utilization of the estuaries in this region.

Speakers were invited to address themselves to a wide range of subjects -- some of a legal-political nature and others emphasizing estuarine technology. Sessions were devoted to modeling, hydrodynamics, sediment transport, the ecology of estuaries, state and national legal policies and standards affecting developments of estuaries. It was demonstrated that very competent talent exists in the Pacific Northwest in governmental organizations, educational institutions, industry, and consulting firms to effectively handle technical problems concerning development and preservation of estuaries. However, the interactions between local groups and governmental groups at all levels needs to continue in order to effect needed standards and regulations to reduce the complex conflicts of use of the coastal zone.

On the following pages appear the texts of papers delivered by the invited speakers to this first Technical Conference on Estuaries of the Pacific Northwest. Grateful acknowledgement is directed to those who participated in the program and open discussions during the conference. Additional conferences are being planned to be held on an annual basis at Oregon State University to continue to promote greater understanding of our Pacific Northwest estuaries.

Corvallis
1971

John N. Nath
Research Engineer
Department of Oceanography

Larry S. Slotta
Director
Ocean Engineering Program
School of Engineering

Contents

Opening Address

by
Robert W. MacVicar
President
Oregon State University

I would like to say a few words about the importance I attach to the subject that you are examining. The estuarian problems of the Pacific Northwest clearly are critical as far as the whole marine area is concerned. It is this relatively fragile band where the land meets the sea that is critical for the entire marine biota. Particularly here in the Pacific Northwest and especially in Oregon so much of this confrontation is brutal, involving rocky headlands and spectacular scenery that is elegant to look at but not very useful for anything else. It is the estuaries that make this joining of land and sea useful for the human beings that inhabit the planet.

It is for this reason that it seems to me the coastal zone and particularly the estuaries represent a very important resource that must be both preserved and protected. These two words, preservation and protection, mean different things to different people. I would like to suggest that the word preservation might be more intended to imply that there will be certain selected areas in peculiar locations which are so critical to marine life, or so important in other respects or so valuable an economic resource that they should be henceforth preserved without significant change from their natural state.

In other areas this is not feasible if we are to make expected use of our marine resources, but in these areas we should be sure that we exercise appropriate protective measures. In using the valuable interface of land and the sea we do not so intact upon the estuaries that they cease to be as valuable and significant as they otherwise could be. Protection becomes a very essential ingredient for long-term use.

It seems to me that for at least a great many of you in this room today, these are the objectives that you seek in your respective organizations. This is what the organizations that you are here representing are focusing their attentions upon. I might suggest that it seems to me if we are to engage meaningfully in this dual action of preservation and protection that we need to do two things.

One is we need to know a great deal more about the fragile interface than we now know. There is, of course, massive research both biological, physical, oceanographic that has been accumulated over time. It has been my experience in a few brief months in Oregon that when the questions have arisen, when the public policy issues have been raised that very frequently the best answer that you could give to a concerned individual, or a group, or a legislative assembly was: "We do not know." This, of course, is not good enough of an answer; hence the expanded and continuing research of all kinds, including engineering research, is in my opinion an absolute necessity if we are to achieve the dual goal of preservation and protection.

It seems to me a second thing, that it is absolutely essential that we must put this knowledge to work. Knowledge unused is, as far as I am concerned, knowledge that for all practical purposes does not exist. Unless someone is aware of it and it is put into some functional purpose there is little reason for it to be buried in the library. Hence in the fields of planning, in the fields of organization and administration and enforcement of both statues and codes, the availability of information of appropriate accuracy and the implementation of appropriate planning and procedures is a critical matter indeed.

You are here to examine some of the most recent studies that have been undertaken relating to estuarian problems. You are here to discuss some of the public policy issues this research and other research is bringing to us. You are here to examine what changes in procedures and policies and agency directives might be helpful. You are here probably more than anything else to be with one another to share ideas in the informal situation as well as to listen to formal presentations.

I will not, therefore, consume further of your time except to say that I am confident that this first conference cannot achieve the objectives we seek. I would hope that this is not the first time I will be extending greetings from this University, inviting you to use our resources while you are here, and encouraging your planning group to consider what will be appropriate for 1972.

The Potential of Physical Models to Investigate Estuarine Water Quality Problems

by
Henry Simmons
Assistant Chief, Hydraulic Division
Waterways Experiment Station
Army Corps of Engineers
Vicksburg, Mississippi

ABSTRACT

Four physical models of Pacific Northwest estuaries are described. These include the Columbia, Umpqua, Grays Harbor and Tillamook estuaries; in addition some discussion is given to San Francisco Bay, San Diego Bay and New York Bay. These models have been verified to reproduce tides, tidal and river currents, and salinities for prototype conditions. Tests of pollutant release and dispersion have been conducted to simulate flushing capabilities on these and other models. Salinity intrusion, navigation, dredging and shoaling problems are typical of the studies conducted on these models.

The theme of this technical conference is management and planning for water quality in the Pacific Northwest estuaries, and my particular subject is related to the potential of physical models for water quality investigations. Possibly because the Pacific Northwest was developed and exploited by man at an appreciably later date than were the Atlantic and Gulf Coasts of the United States, and thus has not been exposed to manmade pollutants for so great a period of time, much greater use of physical models has been made to date for water quality studies in the Atlantic and Gulf Coast regions than in the Pacific Northwest. This is no reflection on the potentials of physical models for such investigations, but perhaps emphasizes that more needs to be done before estuarine pollution becomes as critical in this area as in some other regions of the United States.

At the present time four physical models of Pacific Northwest estuaries are in existence at the U. S. Army Waterways Experiment Station that have good potential for water quality studies, and some of these have already been used to a limited extent for such purposes. The oldest of these is the Columbia River model (Fig. 1) constructed in 1962, which reproduces the lower 52 miles of the Columbia River and adjacent offshore areas to linear scale ratios of 1 to 500 horizontally and 1 to 100 vertically. Following construction, the model was adjusted carefully so that tides, tidal currents in both plan and vertical, and salinities in both plan and vertical agreed closely with measurements made in the field for model verification purposes. The principal studies made to date in the Columbia River model were concerned with navigation improvements and the reduction of maintenance dredging quantities and costs, and in these respects the model has contributed much valuable design data for both engineering and operations efforts by the North Pacific Division and the Portland District of the Corps of Engineers.

In addition to these principal studies, a few supplemental studies have been made in the Columbia River model that were directly related to water quality. In 1964, a series of tests was performed in cooperation with USGS to gain some insight as to the rate of flushing of pollutants released in the lower Columbia River and to determine the gross effects of upland discharge on flushing rate. Figure 2 presents a summary of the results of two tests involving reproduction of a mean tide, an upland discharge of 600,000 cfs, and the release of simulated contaminents (2 flourescent dyes) at mile 47 above the river entrance. One dye tracer was released at strength of flood current, and the second was released at strength of ebb current. The two graphs in Fig. 2 show the concentrations in parts per billion of the two dye tracers as measured at middepth along the navigation channel centerline at high water slack of the tidal current at times corresponding to 2, 4 and 6 diurnal tidal cycles following release of the tracer. The initial concentration of the dye tracers was 100,000 ppb. You will note that the peak dye concentration observed after two tidal cycles was in the vicinity of river mile 12 for the release during flood current and in the vicinity of river mile 6 for the release during ebb. In the subsequent tidal cycles, most of the dye tracers had moved completely out of the river entrance, and only very low concentrations were noted in the lower twelve miles of the estuary.

Figure 3 shows the results of two similar tests except that the upland discharge was reduced to 200,000 cfs. At four tidal cycles following release of the tracers, peak concentrations of both tracers were observed in the vicinity of river mile 18, and lesser but significant concentrations were observed in the lower river 6 and 8 tidal cycles after release. The results of these tests illustrate the extremely rapid flushing rate that occurs in the Columbia River and further illustrates the significance of the upland discharge on flushing rate. For example, the tests with an upland discharge of 600,000 cfs showed that the peak concentration moved downstream some 35 to 41 miles in two diurnal tidal cycles, whereas the tests with 200,000 cfs indicated downstream movement of about 26 miles in 4 tidal cycles. Thus, the rate of downstream movement of the peak concentration at the lower upland discharge was less than half the rate for the higher discharge.

In 1966, a series of tests was made in the Columbia River model to determine the upstream limits of salinity intrusion at high-water slack for a wide range of upland discharges. Figure 4 shows the bottom salinity distribution in the estuary for conditions of a mean tide and upland discharges of 400,000, 200,000, 120,000 and 40,000 cfs. It may be noted from these data that upland discharge is a highly significant factor in controlling the extent of saltwater intrusion. The maximum penetration of salt water was to river mile 20 for a discharge of 400,000 cfs, to mile 24.5 for a discharge of 200,000 cfs, to mile 31.5 for a discharge of 120,000 cfs, and to mile 38 for a discharge of 40,000 cfs. The probability of upland discharges in the range of 40,000 cfs or less is fairly remote in the Columbia River, but these tests illustrate the major advance of saltwater intrusion to be expected should the discharge be reduced to or below that value.

The Umpqua River model (Fig. 5) was constructed in 1966 to study navigation and shoaling problems in the entrance to this estuary. The model is built to linear scale ratios of 1 to 300 horizontally and 1 to 100 vertically and reproduces all of the tidal portions of the Umpqua River and tributaries, along with adjacent offshore areas. Portions of the Umpqua River and tributaries upstream from Reedsport were bent into a labyrinth form to conserve space and reduce costs; however, the cross sectional areas and the tidal prisms of these streams were faithfully reproduced. The entire model has been verified for tidal elevations and phases and, in addition, it has been verified for velocity and salinity distribution in both plan and vertical from the seaward ends of the jetties upstream to Winchester. No water quality studies have been performed to date in the Umpqua River model, but the model has great potential for such studies if and when required. There are no immediate plans to dismantle the Umpqua River model; however, at some future date it is inevitable that the space now occupied by this model will be needed so urgently for other models that it will probably have to be destroyed. If there are water quality studies planned for the Umpqua estuary that could be implemented by model tests, serious consideration should be given to scheduling such tests at the earliest practicable date.

The Grays Harbor Model (Fig. 6) was constructed in 1968 to study a number of existing navigation and dredging problems in the estuary and to investigate the effects of possible future changes in channel alignments, channel dimensions, and structures. This model is constructed to scale ratios of 1:500 horizontally and 1:100 vertically and reproduces the entire estuary along with pertinent offshore areas. Like the Umpqua River model, the upstream portions of the Chehalis River and other tributaries are reoriented to conserve space and reduce costs, but the significant characteristics of these streams have been preserved. The model has been carefully adjusted for tides, tidal currents, and salinities throughout the entire estuary, making use of measurements made in the field especially for that purpose, and is presently being used to investigate the effects of suggested modifications to the north and south jetties at the harbor entrance on hydraulic and other conditions in the estuary.

Some rather detailed water quality studies are planned during the comprehensive testing program scheduled for the Grays Harbor model, involving detailed studies of flow patterns and velocities, salinity intrusion and salinity distribution, and flushing rates and patterns throughout the estuary. Detailed data on these subjects have been developed for existing conditions, and the basic tests will be repeated for conditions representing any major modification to be given serious consideration. Thus, direct comparison of the results of such tests will define in detail the changes to existing water quality parameters to be expected should the modifications under study be selected for construction in the prototype.

Dye dispersion tests have been made using injection points at opposite ends of the estuary. In the first, dye was released at mid-depth in the Chehalis River near Cosmopolis, Washington, over a complete 24 hr 50 min tidal cycle at a rate equivalent to 25.5 mgd and with an initial concentration of 10,000,000 ppb. In the second test, dye was released at the bottom of the natural entrance channel adjacent to the outer end of the south jetty over half a tidal cycle at the rate of 92.7 mgd and with an initial concentration of 10,000,000 ppb. These tests were actually conducted simultaneously using different flourescent dyes.

Figure 7 shows plots of dye concentration in parts per billion as measured at middepth along the navigation channel centerline at the times of high-and low-water slacks of the tidal current for the upstream dye release. Curves are presented for conditions at tidal cycles 2, 5, 9, 12 and 16 after release of the dye. It can be seen that the position of the peak concentration rapidly moved downstream to about station 40 at high-water slack and station 65 at low-water slack, but the subsequent downstream movement was quite slow.

Similar plots for the downstream dye injection are presented in Fig. 8. In this test the position of the peak concentration is not very well defined, since the tops of the concentration curves are rather flat. It can still be seen, however, that the initial upstream movement of the peak was quite rapid, whereas the subsequent downstream movement of the peak was quite slow. The results of these tests illustrate the relatively slow flushing rate of Grays Harbor, especially when compared with the Columbia River.

The fourth North Pacific estuary model at WES is the Tillamook Bay model which was constructed in 1970 (Fig. 9). This model is built to linear scale ratios of 1 to 500 horizontally and 1 to 100 vertically and reproduces all of Tillamook Bay, the tidal portions of significant tributaries, and pertinent offshore areas. The principal studies being performed on this model are to investigate the effects of jetty and channel modifications at the estuary entrance on hydraulic and shoaling phenomena. However, supplemental studies are planned to determine the effects of such modifications that might appear desirable on water quality parameters throughout the estuary.

The model has been verified carefully for tides, tidal currents, and salinities, and tests are in progress to study various alignments and lengths for the new south jetty now under construction at the entrance. Since significant scour has occurred off the end of the completed jetty section, these studies are being extended to investigate the effects of leaving temporary gaps in some portions of the structure to minimize scour, then filling these gaps as the final stage of jetty construction. The water quality studies in Tillamook Bay model are still in the future, since not even tentative decisions have yet been reached as to the jetty or entrance channel plans to be recommended for construction; however, when this point in time is reached the water quality studies will be made to determine changes to be expected in tides, flow patterns, velocities, salinities, and flushing characteristics throughout the bay as a whole. Should detrimental effects on water quality parameters be disclosed by the results of such tests, in all probability the project design would then be modified as necessary to minimize or eliminate such effects.

It might be worthwhile to note the existence of two additional models of Pacific coast estuaries, although neither estuary is located in the northwest. One is the San Francisco Bay model (Fig. 10), located in Sausalito, California, and operated by the San Francisco District of the Corps. This model was constructed in 1956 to study navigation and shoaling problems in San Francisco Bay and to evaluate the effects of the many saltwater barriers proposed for the bay at that time. Within the past year or two, this model has been extended to include the entire channel complex within the Sacremento - San Joaquin Delta, and it will be used in the future to study in detail the effects of the comprehensive California Water Plan on water quality throughout the delta and bay complex. The second model is the San Diego Bay model (Fig. 11) located at WES. This model reproduces San Diego Bay and adjacent offshore areas and has been used to study the effects of possible second entrances to the bay on the hydraulic and flushing characteristics of the bay. The results of water quality studies performed in this model were reported in some detail in a recent paper by Simmons and Herrmann presented at the FAO Conference on Marine Pollution in Rome, Italy, in December 1970.

As an example of comprehensive use of a physical model in water quality studies, I would like to summarize the results of a recently completed study at WES concerned with proposed construction of a new inlet across Sandy Hook Peninsula about 5 miles south of the entrance to New York Harbor. The new inlet, known locally either as Shrewsbury or Sandy Hook inlet, has authorized dimensions of 250 ft in width and 15 ft in depth at mlw.

The principal purpose of the new inlet is to provide a safer and shorter route for recreation and charter boats between the Shrewsbury-Navesink River complex and the popular fishing grounds lying offshore and to the southeast. Boats presently going to the fishing area go north through Sandy Hook Bay, around the tip of Sandy Hook, thence south to the fishing grounds. The authorized inlet would reduce travel distance and time by more than 50 percent and eliminate the need to pass through the rough waters of Sandy Hook Bay, thus providing a much safer passage.

Before constructing the new inlet, it was considered essential to know its effects on tides, currents, salinities, temperatures, and the flushing characteristics of Sandy Hook Bay and the Shrewsbury-Navesink River complex so that the effects of the project on environmental factors throughout the area could be fully evaluated. Since such effects could not be predicted with full confidence by analytical methods, the U.S. Army Engineer District, New York, requested WES to conduct the necessary physical model experiments to define the effects.

Two physical models were used for the studies. The first was an undistorted 1:100 scale model (Fig. 12) of the area in which the new inlet would be constructed, including appropriate portions of the ocean and bay approaches to the inlet, and this model was used to define the hydraulic characteristics of the inlet, to study the details of channel and jetty locations and dimensions, and to determine the amount of wave energy that would be transmitted through the new inlet into Sandy Hook Bay, with specific reference to the locations of marinas near Highlands, New Jersey. The second model used was the existing comprehensive model of New York Harbor (Fig. 13), constructed to linear scales of 1:1000 horizontally and 1:100 vertically, which was extended especially for this study to include the Shrewsbury-Navesink Rivers and appropriate offshore areas. The comprehensive model was used to determine the effects of the new inlet on normal tides, hurricane surges, tidal currents, salinities, temperatures, and the concentrations of pollutants in the study area for various input sources of pollution.

The extended portion of the New York Harbor model was first verified to insure that tides, tidal currents, and salinities observed in the field were faithfully reproduced. Once verification of the model was established, tests to define the effects of the new inlet on each environmental factor of concern were initiated. The procedure followed involved two identical tests, made under the same carefully controlled test conditions, except that one test was made for existing conditions and the second was made with the new inlet installed in the comprehensive model. Therefore, direct comparison of the results of the two tests established the effects of the inlet on the environmental factor being investigated.

The results of the model tests have been summarized to provide a quich appraisal of the effects of the new inlet on various environmental factors. Figure 14 shows the effects of the new inlet on average salinities in the major compartments of the study area (Sandy Hook Bay, Shrewsbury River, and Navesink River), and you will note that the maximum change in average salinity amounted to about 0.3 - parts per thousand.

Figure 15 shows the effects of the new inlet on normal tides at three locations in the study area, and it will be noted that normal tides were relatively unaffected. Figure 16 shows the effects on water surface elevations for a test involving reproduction of the November 1950 hurricane surge in the harbor. You will note that the maximum elevation of the surge was no greater with the new inlet installed than for existing conditions, but outflow through the new inlet allowed surge elevations to drop slightly faster than for existing conditions.

Figure 17 shows current velocities over a complete normal cycle at three locations in the model. You will note that current velocities were not changed significantly by the new inlet, although the time phasing of the current at a station near the new inlet was modified slightly. This information, together with the tidal data in Figs. 15 and 16, show conclusively that the new inlet would not change existing flow rates and volumes of inflow and outflow between Sandy Hook Bay and Shrewsbury and Navesink Rivers. The control inflow and outflow remains in the relatively small channel connecting Sandy Hook Bay with the

Shrewsbury and Navesink Rivers, and dredging of the new inlet would not change this control section in any way.

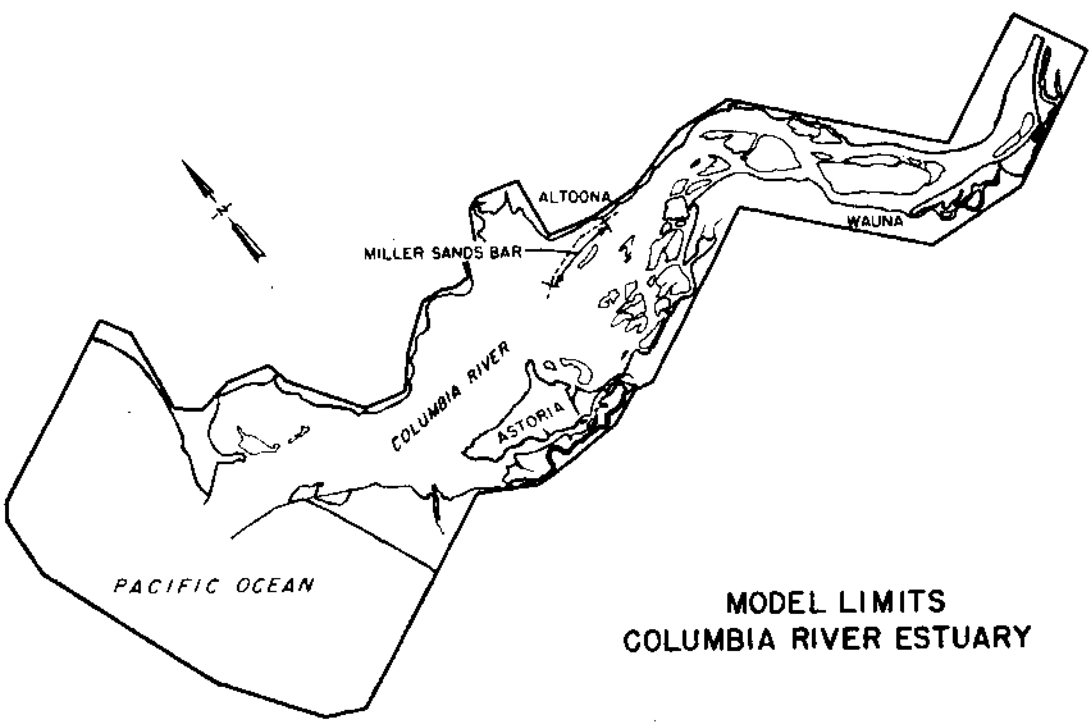
Figure 18 shows the effects of the new inlet on the rate of change in temperature in the study area for conditions simulating an upwelling of cold ocean water off Sandy Hook, which is a fairly common occurrence. You will note that the rate at which water temperatures decreased in the study area because of such upwelling was essentailly the same with the new inlet installed as for existing conditions, thus indicating that the new inlet would have no significant effects on water temperature.

Three separate tests were made to evaluate the effects of the new inlet on pollution concentrations in the study area. For the test data shown in Fig. 19, a pollution source in Raritan Bay was simulated, representing the effluents discharged from the Middlesex County Trunk Sewer Outfall. You will note that pollution concentrations from that source were lower in all three of the major water bodies of the study area with the new inlet installed, thus showing that the new inlet would reduce the influx of Raritan Bay wastes to the study area. Figure 20 presents the results of a similar test series, but simulating the major sewer outfalls in Upper N.Y. Bay. You will note that, for this source of pollution, concentrations in all three major water bodies of the study area were increased slightly. Figure 21 presents the results of the third pollution test series in which the local sources of pollution input in the Shrewsbury and Navesink Rivers were simulated, and you will note that, for conditions of these local sources, concentrations throughout the study area were substantially reduced.

The reduction in pollution concentrations in the study area from Raritan Bay source is attributed to the fact that tidal flow in and out of the new inlet reduces the present exchange of flow between Lower New York Bay and Sandy Hook Bay, and thus less of the polluted water of Lower New York Bay is drawn into the study area. The increase in pollution levels in the study area from Upper New York Bay pollution sources is attributed to the fact that pollutants from this source diffuse largely into the ocean, from which a small percentage of this waste is then transferred to the study area by tidal exchange through the new inlet. The substantial reduction in pollution in the study area from local sources is attributed to the fact that pollutants flowing out through the new inlet during ebb currents do not completely return during the subsequent flood currents, and thus the rate of flushing of such pollutants is much faster with the new inlet in place. In summary, the new inlet would reduce pollution concentrations in the study area from two of the three principal sources, would slightly increase concentrations from the third major source, and the net effect on pollution concentrations would be beneficial.

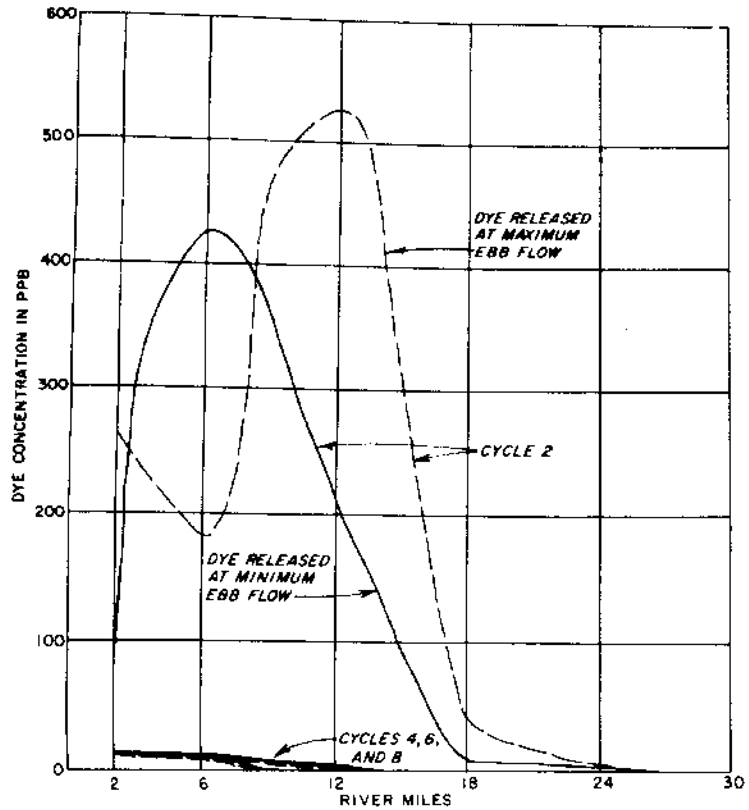
In addition to studies of environmental factors just described, the two models were used to define the optimum dimensions and alignment of the navigation channel in the interests of navigation and maintenance; to study various lengths, locations, and spacing between jetties at the ocean end of the inlet in the interests of providing safe navigating conditions for small craft; and to conduct tests to define the amount of ocean wave energy that would pass through the new inlet and reach critical locations along the Highlands shoreline. As a matter of interest, it was found that wave energy passing through the new inlet under very severe wave action in the ocean produced maximum wave heights of only 0.2 ft along the Highlands shoreline.

While time today would permit only a very brief presentation of these test data in summary form, I would like to emphasize that the actual test data obtained from the model were very comprehensive in nature. Tides, current velocities, and salinities were measured at hourly intervals or less over complete tidal cycles at many stations throughout the study area, and current velocities and salinities were measured at several points in the vertical at each station. In the dye tracer tests simulating pollutants, surface and bottom samples were obtained for analysis at well over 100 stations in and adjacent to the study area. Time exposure photographs showing surface current patterns and velocities were obtained at hourly intervals throughout the tidal cycle in the new inlet and in all adjacent areas where flows could be affected by the new inlet. All of these test data have been furnished to Federal, state and local agencies concerned with the effects of the inlet on the water quality. The significant point here, and the one I would like to emphasize in conclusion, is that reliable data showing conditions as they now exist, as well as those to be expected following construction at the new inlet, have now been developed and are available to the environmental oriented scientists as the basis for making a sound evaluation of the impact of the new inlet on the total environment.



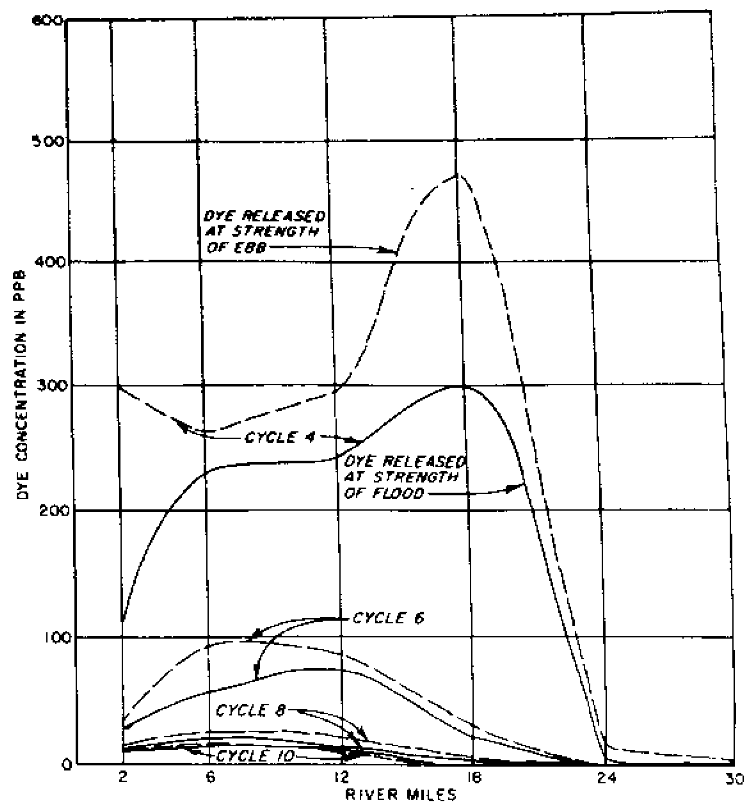
MODEL LIMITS
COLUMBIA RIVER ESTUARY

FIG. 1



DYE CONCENTRATION PROFILES (MIDDEPTH)
FRESH-WATER DISCHARGE = 600,000 CFS

FIG. 2



DYE CONCENTRATION PROFILES (MIDDEPTH)
FRESH-WATER DISCHARGE = 200,000 CFS

FIG. 3

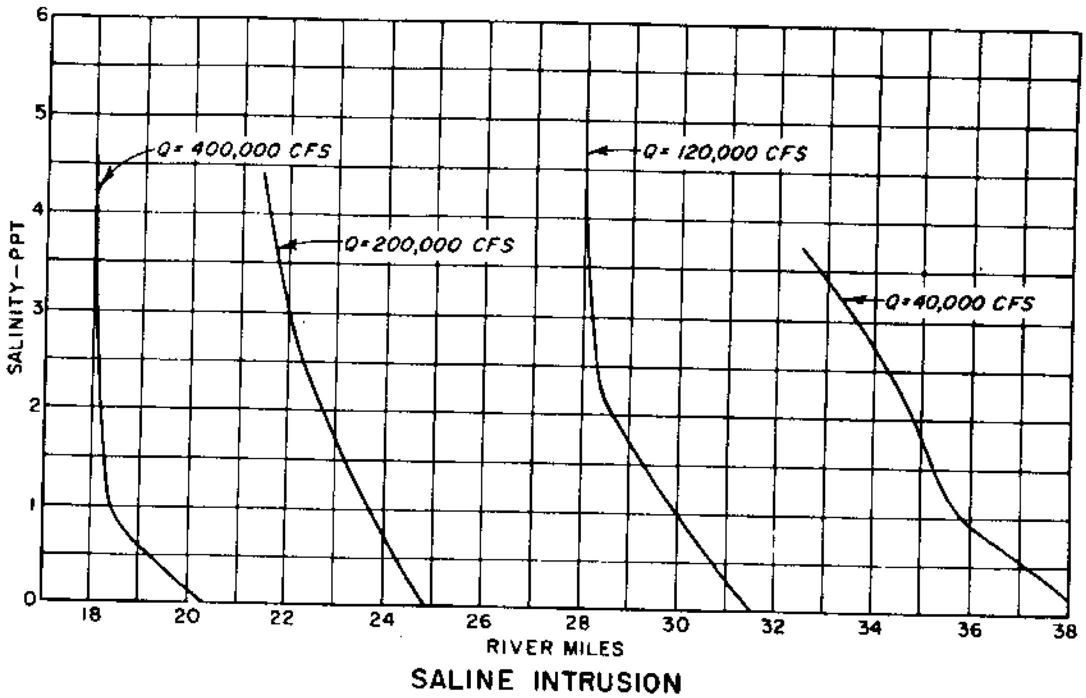

Q= 400,000 CFS
Q= 200,000 CFS
Q= 120,000 CFS
Q=40,000 CFS
SALINITY—PPT
RIVER MILES
SALINE INTRUSION

FIG. 4

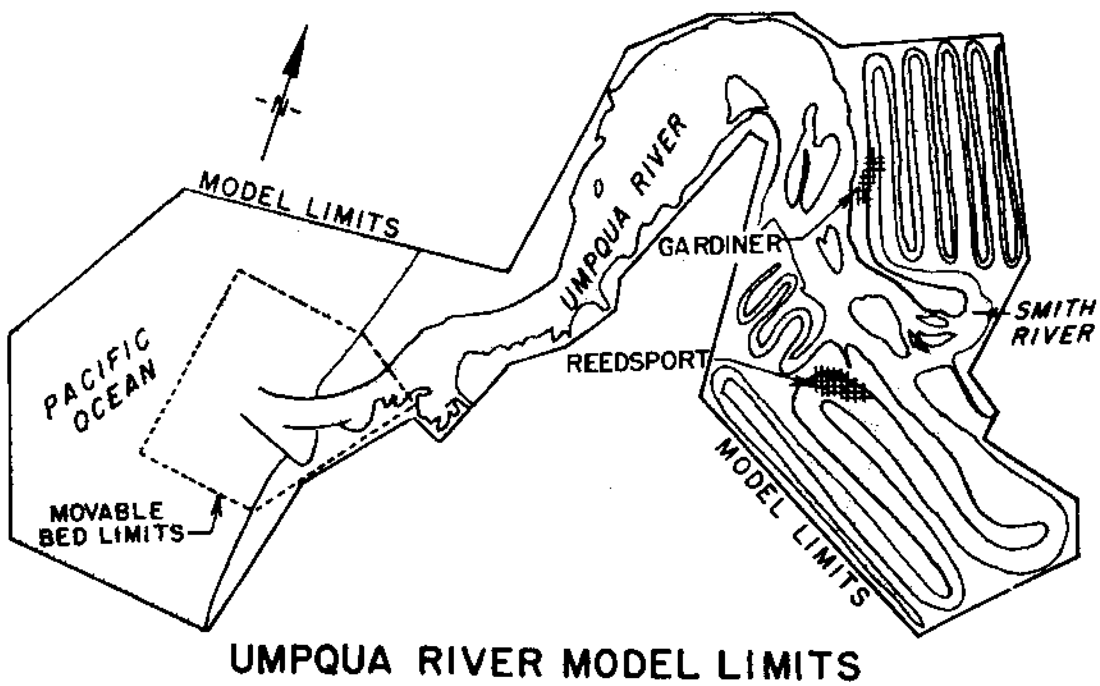
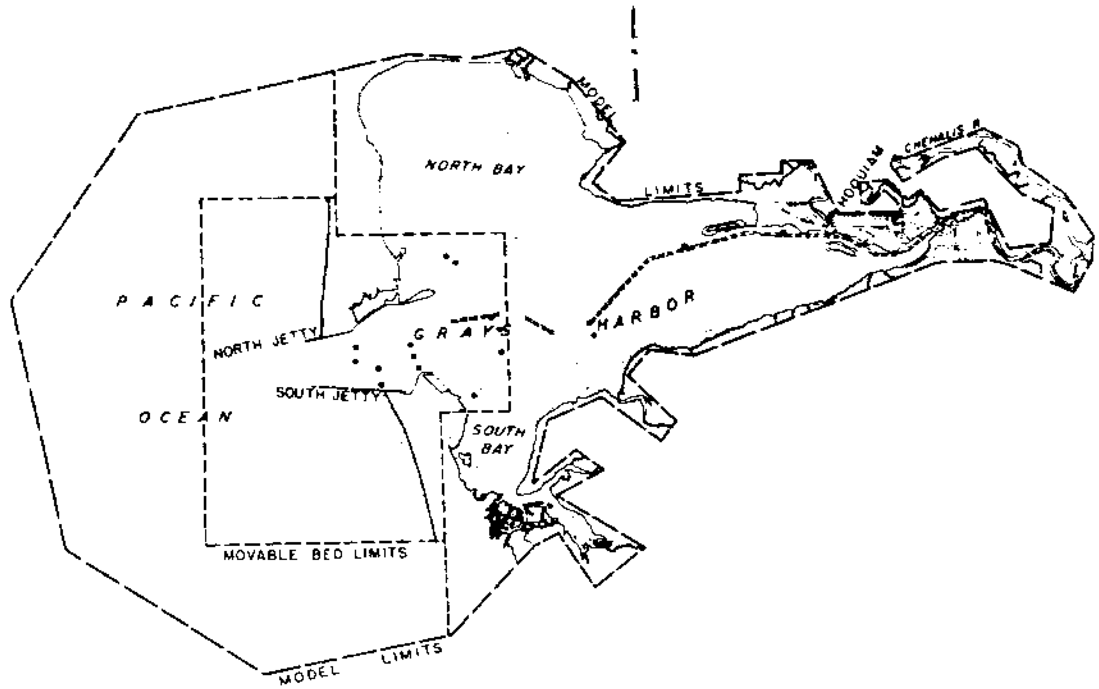
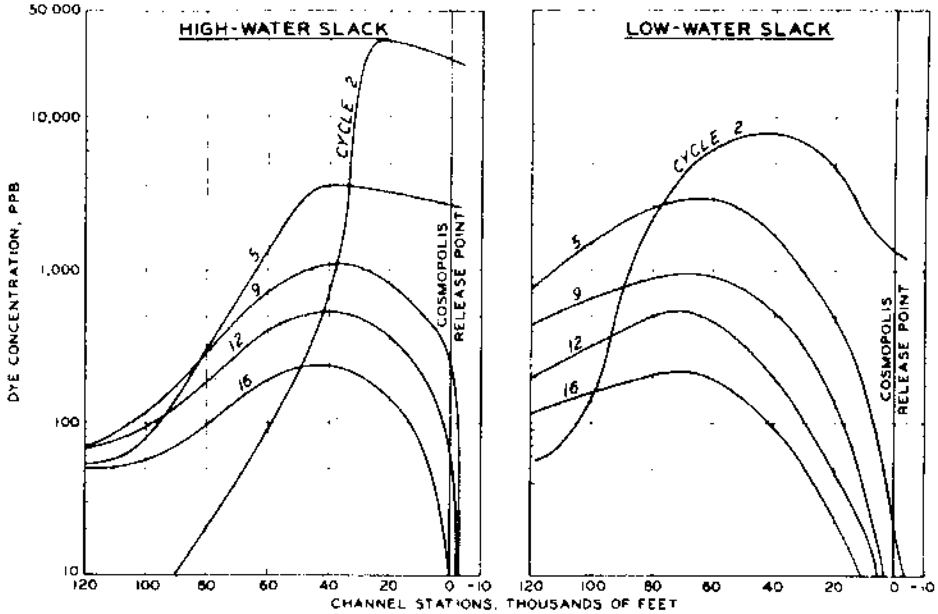

N
MODEL LIMITS
PACIFIC OCEAN
UMPQUA RIVER
GARDINER
REEDSPORT
SMITH RIVER
MODEL LIMITS
MOVABLE BED LIMITS
UMPQUA RIVER MODEL LIMITS

FIG. 5



GRAYS HARBOR MODEL LIMITS

FIG. 6



MODEL TEST DATA

TIDE	MEAN
FRESHWATER DISCHARGE	11,400 CFS
SOURCE SALINITY (TOTAL SALT)	33.0 PPT
INITIAL CONCENTRATION	10,000,000 PPB
INJECTION RATE	25.5 MGD

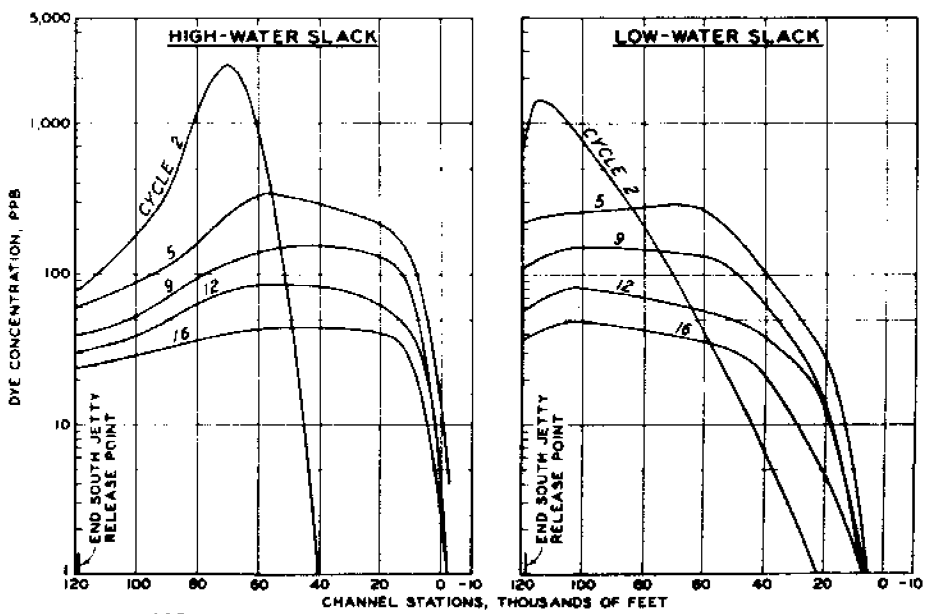
GRAYS HARBOR MODEL

DYE CONCENTRATION PROFILES

COSMOPOLIS RELEASE (MID-DEPTH)

BASE TEST CONDITIONS - MID-DEPTH

FIG. 7



MODEL TEST DATA

TIDE	MEAN
FRESHWATER DISCHARGE	11,400 CFS
SOURCE SALINITY (TOTAL SALT)	33.0 PPT
INITIAL CONCENTRATION	10,000,000 PPB
INJECTION RATE	92.7 MGD

GRAYS HARBOR MODEL

DYE CONCENTRATION PROFILES

SOUTH JETTY RELEASE (BOTTOM)

BASE TEST CONDITIONS - MID-DEPTH

FIG. 8

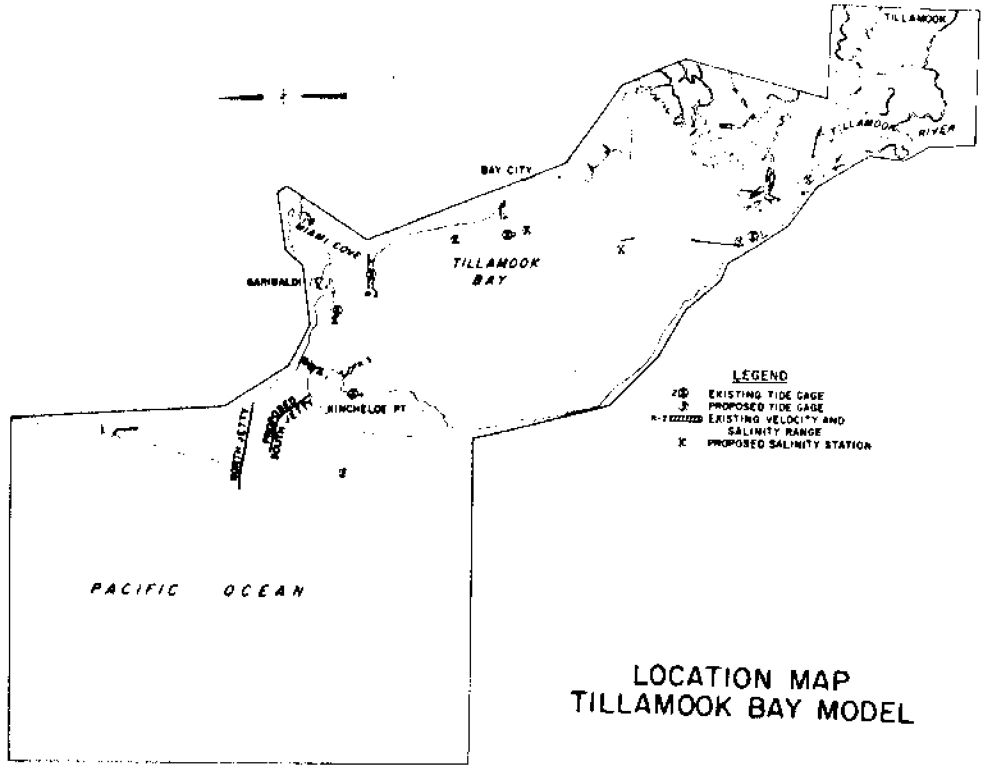

TILLAMOOK
TILLAMOOK RIVER
BAY CITY
MIAMI COVE
GARIBALDI
TILLAMOOK BAY
KINCHELOE PT
NORTH JETTY
PACIFIC OCEAN
LEGEND
EXISTING TIDE GAGE
PROPOSED TIDE GAGE
EXISTING VELOCITY AND SALINITY RANGE
PROPOSED SALINITY STATION
LOCATION MAP
TILLAMOOK BAY MODEL

FIG. 9

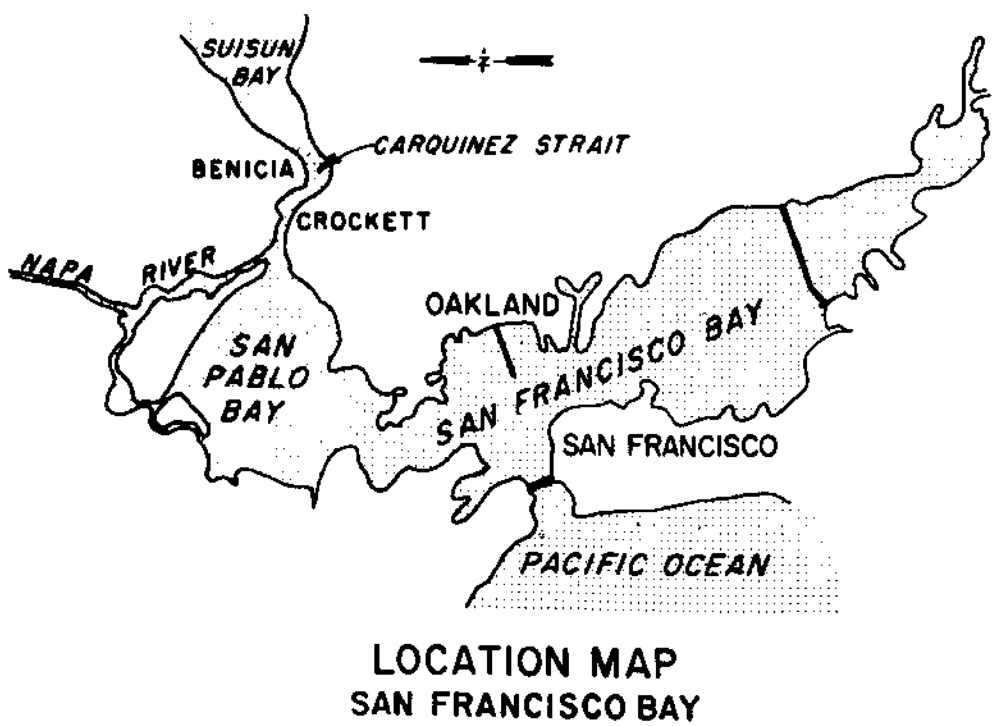

SUISUN BAY
CARQUINEZ STRAIT
BENICIA
CROCKETT
NAPA RIVER
SAN PABLO BAY
OAKLAND
SAN FRANCISCO BAY
SAN FRANCISCO
PACIFIC OCEAN
LOCATION MAP
SAN FRANCISCO BAY

FIG. 10

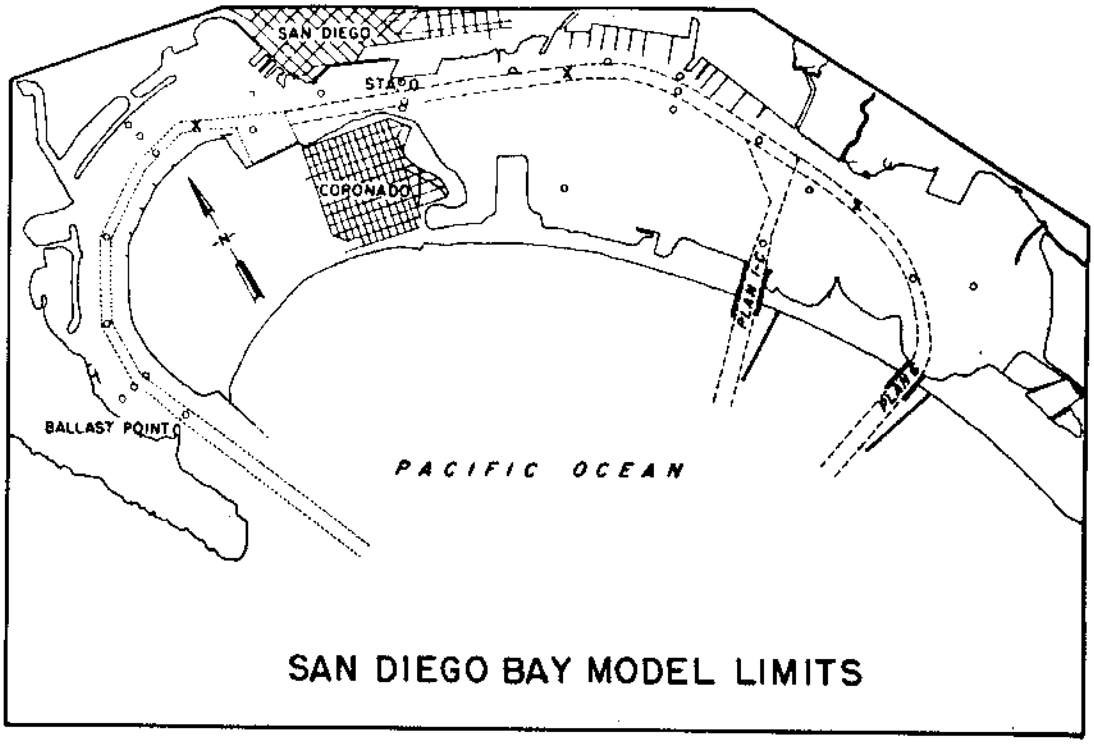

SAN DIEGO
CORONADO
BALLAST POINT
PACIFIC OCEAN
SAN DIEGO BAY MODEL LIMITS

FIG. 11


SANDY
HOOK

FIG. 12

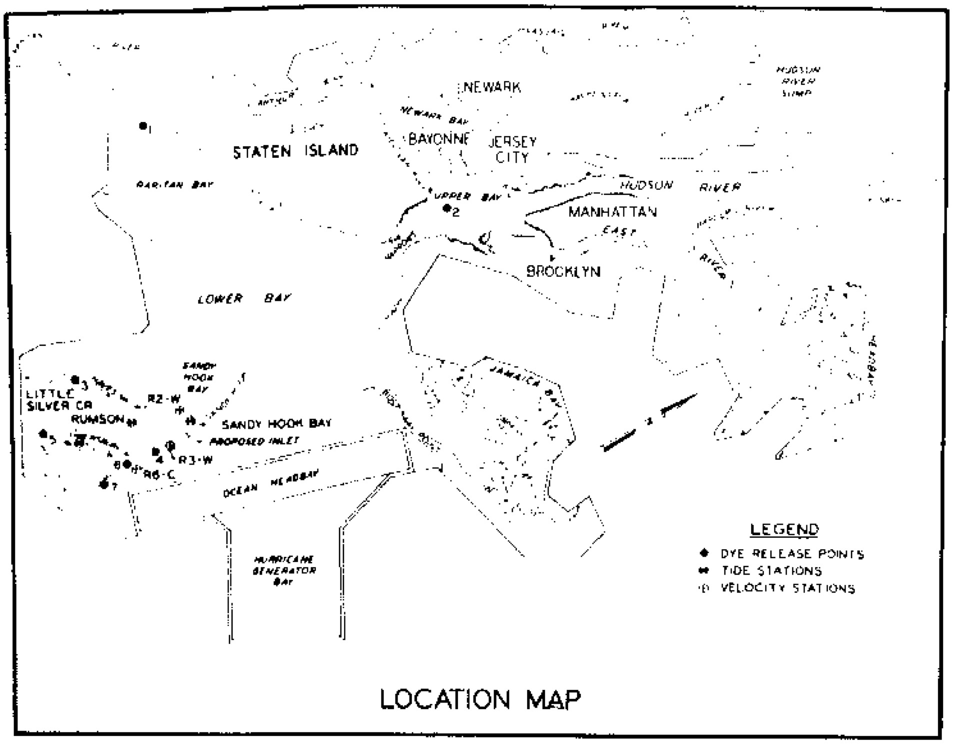


FIG. 13

SHREWSBURY INLET STUDY

EFFECTS OF PLAN 3 ON AVERAGE SALINITIES

PPT CHLORIDES

TEST	SANDY HOOK BAY	NAVESINK RIVER	SHREWSBURY RIVER
BASE	16.0	14.3	14.9
PLAN 3	16.1	14.0	15.1

FIG. 14

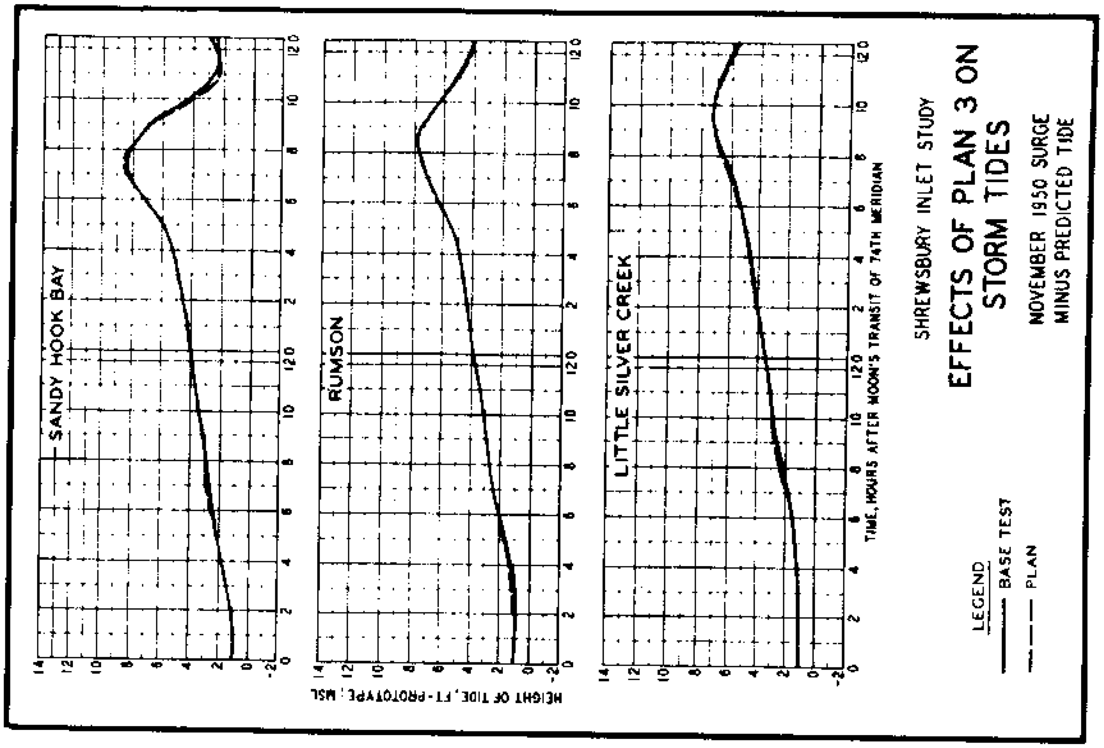

SANDY HOOK BAY
RUMSON
LITTLE SILVER CREEK
HEIGHT OF TIDE, FT-PROTOTYPE; MSL
TIME, HOURS AFTER MOON'S TRANSIT OF 74TH MERIDIAN
LEGEND
BASE TEST
PLAN
SHREWSBURY INLET STUDY
EFFECTS OF PLAN 3 ON STORM TIDES
NOVEMBER 1950 SURGE
MINUS PREDICTED TIDE

FIG. 16

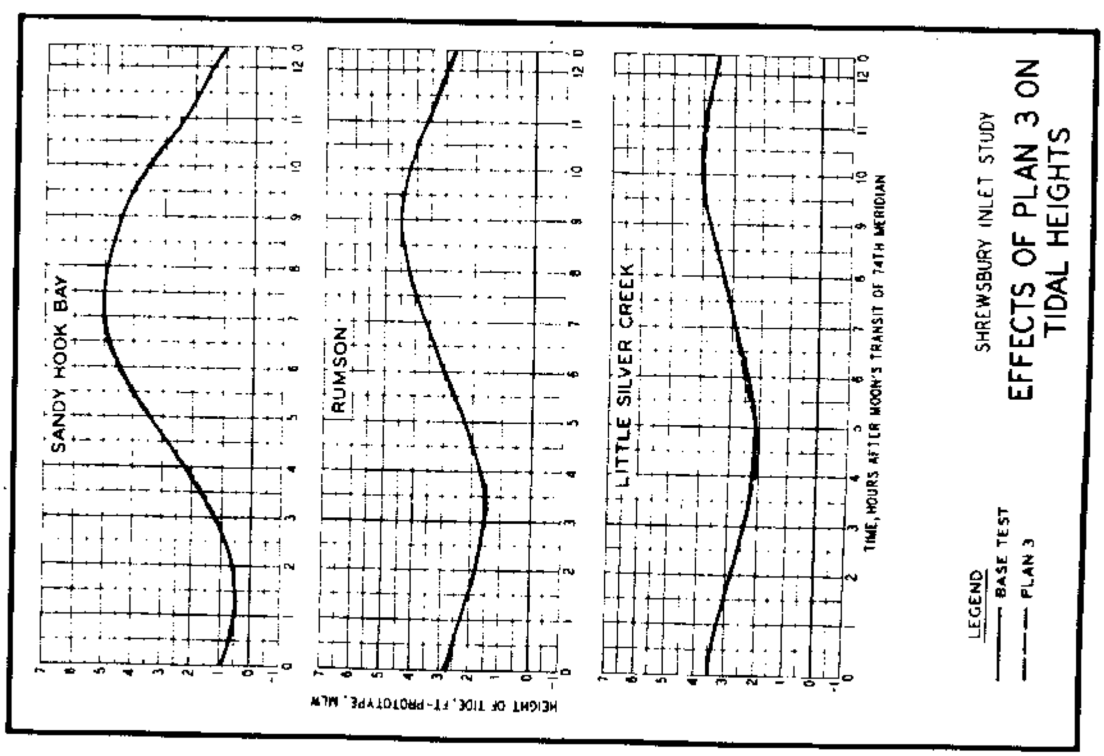
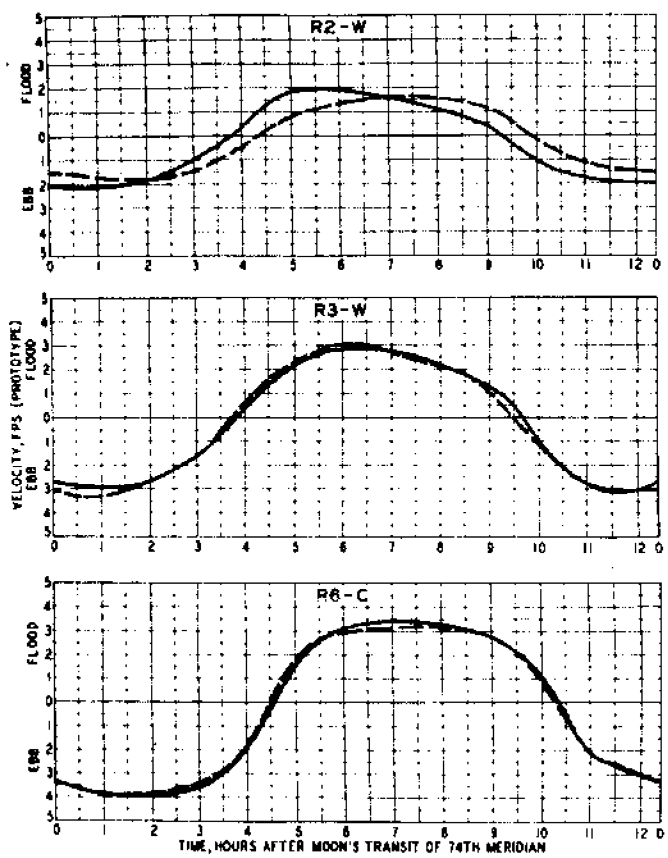

SANDY HOOK BAY
RUMSON
LITTLE SILVER CREEK
HEIGHT OF TIDE, FT-PROTOTYPE, MLW
TIME, HOURS AFTER MOON'S TRANSIT OF 74TH MERIDIAN
LEGEND
BASE TEST
PLAN 3
SHREWSBURY INLET STUDY
EFFECTS OF PLAN 3 ON TIDAL HEIGHTS

FIG. 15



LEGEND
—— BASE TEST
— — PLAN

SHREWSBURY INLET STUDY

EFFECTS OF PLAN 3 ON SURFACE CURRENT VELOCITIES

FIG. 17

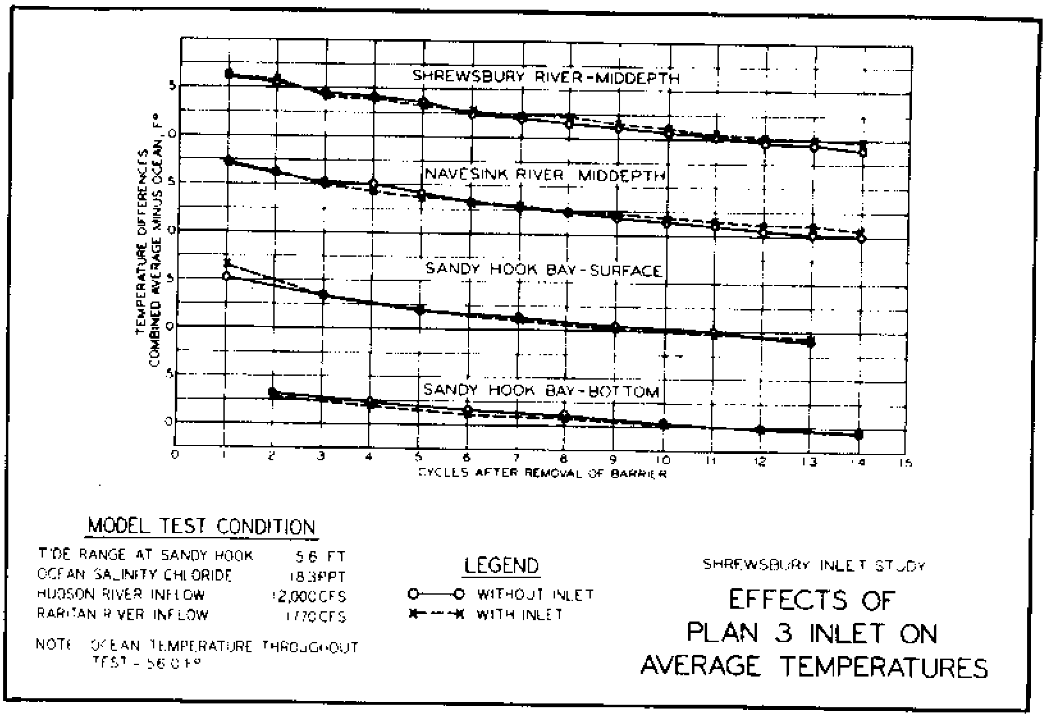


FIG. 18

SHREWSBURY INLET STUDY

EFFECTS OF PLAN 3 ON AVERAGE DYE CONCENTRATIONS

POLLUTION SOURCE IN RARITAN BAY

TEST	SANDY HOOK BAY	NAVESINK RIVER	SHREWSBURY RIVER
BASE	186	99	102
PLAN 3	174 (-6%)	94 (-5%)	96 (-6%)

DYE CONCENTRATIONS ARE IN PARTS PER BILLION

INITIAL DYE CONCENTRATIONS = 100,000 PARTS PER BILLION

FIG. 19

SHREWSBURY INLET STUDY

EFFECTS OF PLAN 3 ON AVERAGE DYE CONCENTRATIONS

POLLUTION SOURCE IN UPPER NEW YORK BAY

TEST	SANDY HOOK BAY	NAVESINK RIVER	SHREWSBURY RIVER
BASE	1039	649	694
PLAN 3	1072(+3%)	862(+33%)	854(+23%)

DYE CONCENTRATIONS ARE IN PARTS PER BILLION
INITIAL DYE CONCENTRATIONS = 100,000 PARTS PER BILLION

FIG. 20

SHREWSBURY INLET STUDY

EFFECTS OF PLAN 3 ON AVERAGE DYE CONCENTRATIONS

POLLUTION SOURCE IN SHREWSBURY AND NAVESINK RIVERS

TEST	SANDY HOOK BAY	NAVESINK RIVER	SHREWSBURY RIVER
	NAVESINK RIVER SOURCE		
BASE	55	372	82
PLAN 3	45(-18%)	285(-24%)	39(-53%)
	SHREWSBURY RIVER SOURCE		
BASE	71	129	634
PLAN 3	48(-33%)	75(-42%)	356(-44%)

DYE CONCENTRATIONS ARE IN PARTS PER BILLION
INITIAL DYE CONCENTRATIONS = 100,000 PARTS PER BILLION

FIG. 21

Applications of Some Numerical Models to Pacific Northwest Estuaries

by

R. J. Callaway

Water Quality Office

Environmental Protection Agency

Pacific Northwest Water Laboratory

Corvallis, Oregon

ABSTRACT

Physical-chemical features of some Oregon and Washington estuaries are discussed in relation to existing or potential pollution problems. Available mathematical models of flow and dispersion phenomena are reviewed and applications of a steady-state, a time-variable, and a box model are presented. The effects of estuaries on oceans are illustrated via examples on the Columbia River and Cook Inlet.

INTRODUCTION

This paper considers estuarine processes from the deterministic viewpoint and emphasizes numerical solutions of differential equations via the digital computer rather than the analog-hybrid or hydraulic model approach.

It is recognized that the hybrid computer may prove highly useful for large scale, multi-dimensional, diffusion problems especially when these include n^{th} order kinetic reactions. The hydraulic model will remain an extremely useful tool in a variety of situations such as sediment loading, scour, etc. (See Fischer and Holley, 1971, for a discussion of their use in dispersion studies.)

Briefly reviewed are some recent modeling efforts on two aspects of the simulation of estuarine processes. These are: (1) the representation of currents, and water levels, and (2) the representation of diffusion and the local change of concentration due to currents, diffusion, and source-sink terms. The source-sink terms represent waste loadings, bottom demands, growth-death rates, phytoplankton grazing, etc., and are considered more in the light of ecological modeling. Sets of coupled equations are necessary for dealing with ecological processes and these must also include the two aspects listed above; hence, while the modeling of the ecology of a system is usually highly dependent on the physical processes the reverse situation is only rarely true.

Users who develop and apply models must be aware of the numerical pitfalls involved in applying finite difference approximations which are usually involved in the study of real-life pollution problems. They must also be able to represent the fluid motion in complex estuarine waters with its tidal currents and changing water levels; i.e., the advection and diffusion processes which exist. The simulation of these processes requires employment of numerical techniques and consideration of stability and mass and momentum conservation. This paper is directed mainly to the user although numerical and fluid dynamical problems are also discussed.

A summary of the state-of-the-art for simulation of pollution problems and controls in estuaries has been presented by Baumgartner and Callaway (1970). Their paper was based on an assessment of pollution control capabilities performed by the TRACOR Corporation (1971) under contract to the Environmental Protection Agency. Emphasis in the above papers was on deterministic models rather than on empirical or stochastic approaches and should be examined for a general view of present day estuarine modeling capabilities.

Estuarine-Riverine Zones

The commonly used definition of an estuary is that it is a semi-enclosed body of water having free connection with the open ocean and whose waters are measurably diluted by fresh water drainage. Some of our Pacific Northwest estuaries, as will be shown, are completely flushed out by fresh waters during periods of high runoff hence, under a strict application of the above definition, should probably be treated as tidal rivers when such conditions exist.

A large river system, such as the Columbia, has essentailly three separate zones: (1) a saltwater portion which, for the Columbia, penetrates a maximum of 20-25 miles upstream of the entrance, (2) a freshwater, current reversal zone upstream of the salt section and, (3) a run-of-the-river section upstream of the latter zone where current direction is always directed seaward but which might exhibit vertical, tidally induced, oscillations, usually on the order of inches. The transition region between successive zones migrates longitudinally and depends on source salinity, tide range and duration, tributary and mainstream flow, and winds. For the Columbia, all three zones have been modeled (Callaway et al., 1969). While the simulation of such a large system results in a rather complex grid for the flow network it does simplify upstream boundary conditions as they may be held constant or allowed to vary with observed tailwater elevations at upstream points (e.g., Bonneville Dam for the Columbia).

The saltwater portion of a coastal river is significant from the point of view of its ecological setting. The dynamics of this zone are complicated by the fact that gravitational convection (see Hansen and Rattray, 1965), due to the density difference between fresh and salt waters, can set up circulation patterns that are difficult to simulate. The so-called 1-dimensional model imposes no horizontal or vertical deviations in velocity or salinity or pollutant. Slight vertical changes in salinity (density) are enough to generate convection currents which will in turn modify the distribution of a pollutant in the estuary. It may be that this contribution to the pollutants' distribution is minor but the modeler must be aware of the existence of such things if only to aid in understanding reasons for discrepancies, if they occur, between model and prototype.

Flow Regimes

If an effluent is discharged to an estuary through a canal or pipe it may approximate a point source. The discharge may be continuous or periodic; the volume of flow and the mass of pollutant discharged may vary at the same or different rates. The velocity of flow and dimension of the orifice may indicate that the momentum of the discharge will be enough to carry it some distance into the receiving water. The density difference between the effluent and the ambient stream and the depth of discharge may also contribute to the path the effluent follows before the ambient currents and turbulence dominate the flow.

In general, three flow regimes exist (see Baumgartner and Trent, 1970): (1) a zone of flow establishment; (2) a zone of established flow, and (3) a zone of drift flow. The first two zones are related to the initial momentum and/or buoyancy of the discharged fluid relative to the ambient fluid. If these zones are small in area it may be possible to approximate them by denoting one or more of the grid areas as sources--(assuming ambient conditions have taken over). If the zones are dominant or the numerical grid unsuitable, then models incorporating these features must be used. Typical of the models which do this are those of Brooks (1959), Okubo (1967), and Koh and Fan (1970).

ADVECTION-DIFFUSION PROCESSES

Specialists in a given field often work around a surprisingly few basic differential equations. In estuarine work we usually concern ourselves with a fixed grid system and predict the local time change of concentration of a substance. The concentration is presumed modified in transit by advection and diffusion; the total amount in a closed system remains constant unless it degrades naturally or is modified by chemical or biological processes.

The so-called advection-diffusion (AD) equation can be written as:

$$(1)\quad \frac{\partial s}{\partial t} + u\frac{\partial s}{\partial x} + v\frac{\partial s}{\partial y} + w\frac{\partial s}{\partial z} - \frac{\partial}{\partial x}\left(K_x\frac{\partial s}{\partial x}\right) - \frac{\partial}{\partial y}\left(K_y\frac{\partial s}{\partial y}\right) - \frac{\partial}{\partial z}\left(K_z\frac{\partial s}{\partial z}\right) = \Sigma S$$

where s = concentration of substance

u = velocity in the x-direction

v = velocity in the y-direction

w = velocity in the z-direction

K_x, K_y, K_z = eddy coefficients

ΣS = sum of the sources and sinks

The terms containing velocity components make up the advective transport part of the equation; terms with eddy coefficients make up the turbulent transport. The source and sink terms define pollutant additions, phytoplankton growth and death rates, etc. If more than one substance enters into a reaction then two or more equations will be coupled through feedback or feedforward mechanisms in the source and sink terms.

Difficulties exist concerning all the terms in the equation; the physical processes are sometimes difficult to express as functions and must be solved numerically (and usually separately) before inclusion in the equation. This can cause problems relating to the conservation of mass in the numerical process and constitutes a large area of research pursued by numerical analysts and fluid dynamicists.

Presently more intractable, however, is the role of the source and sink terms, both from the viewpoint of the experimentation needed to delimit certain coefficients and the non-trivial mathematical representation of several interacting components in an ecological chain. The TRACOR (1971) report should be referred to here for a more thorough discussion of the above topics.

Recent Work on the AD Equation

Table 1 summarizes the terms included in some, but not all, of the numerical models of the AD process in estuaries. Such a representation can be misleading since the programs for running the models are usually easily expanded or modified to include extra phenomena. For purposes of this exposition the documentation of the programs or descriptive papers available to the author was examined in order to make up the table. The progress indicated in the table in estuary (and/or coastal) models is noteworthy. Starting from Stommel's steady-state, first-order kinetics model, in the relatively computer-free times of 1953 to Thomann's first computer model in 1963 the expansion progressed in the main, to a non-steady state, one-day average, simulation of the BOD-DO system of a very large, complex tidal river. Two-dimensional vertically integrated cases are now handled by Leendertse's model although by no means routinely. Although there is still much to be learned in the vertically integrated case, progress is even more wanting in the representation of the vertical distribution of currents and pollutants.

TABLE 1. SOME RECENT APPROACHES TO MODELLING OF THE ADVECTIVE-DIFFUSION EQUATION

Author	Local	Advective Transport			Turbulent Transport			Source-Sink and Remarks
	$\frac{\partial s}{\partial t}$ +	$u\frac{\partial s}{\partial x}$ +	$v\frac{\partial s}{\partial y}$ +	$w\frac{\partial s}{\partial z}$ -	$\frac{\partial}{\partial x}\left(Kx\frac{\partial s}{\partial x}\right)$ -	$\frac{\partial}{\partial y}\left(Ky\frac{\partial s}{\partial y}\right)$ -	$\frac{\partial}{\partial z}\left(Kz\frac{\partial s}{\partial z}\right)$	= ΣS
Stommel (1953)		✓			✓			First order kinetics. Vel. = Q/A. Diffusion from salt conc.; relaxation solution.
O'Connor (1960)	✓	✓			✓			Analytical solution. BOD-DO. Vel. = Q/A. Diffusion as above.
Thomann (1963) (Jeglic, 1967)	✓	✓			✓			BOD-DO. First order kinetics. Vel. = Q/A. Diffusion via eddy exchange coeff.
Shubinski et al. (1965)	✓	✓			✓			BOD-DO. First order kinetics. Vel. from cont. & momentum. Diffusion from scale (depth) of channels.
Okubo (1967)	✓	✓			✓	✓	✓	Analytical solution. First order decay. Includes velocity shear.
Callaway et al (1969)	✓	✓			✓			As in Shubinski; + temp. Surface heat exchange.
Leendertse (1970)	✓	✓	✓		✓	✓		Vel. from mom & continuity. Diffusion as a function of current speed, friction, depth + wind-wave relationships. Nth order kinetics.
DiToro et al. (1970)	✓	✓						Box model of phytoplankton dynamics. Michaelis-Menten kinetics.
Shankar and Masch (1970)	✓	✓	✓		✓	✓		Vel. terms based on Reid-Bodine model. Conserv. distribution.
Fisher (1970)	✓	✓	✓		✓	✓		2-D hydraulics by Leendertse model; 1-D by characteristics. First order kinetics. Diffusion by attempt to incorporate shear in 2-D program.

One point should be made in relation to the way equation 1 and the Table express the advective transport. Any correct method of solving a given equation should lead to the same answer. Unfortunately, some seemingly correct finite difference approximations of the continuous processes assumed in the equations can badly represent the intent of the approximation. Illustrative examples are given by Crowley (1968) who has shown the improvement in the use of fourth-order over second-order approximations (referring to the Taylor series truncation) and more significantly, improvement in using the conservation form of the advection equation. The latter consists in writing the equation:

$$(2) \qquad \frac{\partial s}{\partial t} + u \frac{\partial s}{\partial x} + v \frac{\partial s}{\partial y} = 0$$

as

$$(3) \qquad \frac{\partial s}{\partial t} + \frac{\partial (su)}{\partial x} + \frac{\partial (sv)}{\partial y} - s \left(\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y}\right) = 0$$

The gain in accuracy is due to the fact that the former equation does not necessarily conserve mass during the iteration process; neither does the latter (exactly) but it is much better behaved. This topic has been discussed rather extensively by Leendertse (TRACOR, 1971); he has also treated the numerical problems involved in both the hydraulic and AD equations.

HYDRAULIC EQUATIONS

The velocity terms in equation 1 are usually computed independently at short time intervals (seconds to minutes), output to a disc or tape and then averaged over a longer time period. The average values (minutes) are input to the equation upon demand. Diffusion terms are expressed as functions of a characteristic scale, as functions of the variance of an observed spreading of material, as a random process, etc. As the advection process is more closely approximated at shorter time intervals the magnitude of the diffusion term becomes less--relative to the advective transport process--and can sometimes be neglected.

Table 2 shows terms in the x-direction equation of motion. As in the table before, some recent reports concerning computation of the velocity terms have been examined as to the assumptions implied by the terms included or excluded. This is not represented as a complete summary; it is meant to relate to investigations whose primary objective was for use in estuaries or which have since been modified for such use.

Trouble arises in the explicit methods of solution (marching methods) because of the short time periods required to ensure stability and the general problem related too in the AD equation concerning mass conservation. In this case momentum conservation can be violated resulting in abnormal velocity and water transport volumes. These problems are quite real but can be modified by judicious selection of computing schemes, such as the alternating direction implicit scheme of Leendertse (1970).

All of the methods above revolve around the primitive equation of motion except for Okubo's. (The continuity equation has to be solved

TABLE 2

EQUATION OF (X-DIRECTION) MOTION EMPLOYED BY VARIOUS RECENT INVESTIGATIONS

Author	Inertial	Convective		Potential	Coriolis	Bottom Friction	Wind	Viscous	Atm. Pressure
	$\frac{\partial u}{\partial t}$ +	$u\frac{\partial u}{\partial x}$ +	$v\frac{\partial u}{\partial y}$ +	$g\frac{\partial h}{\partial x}$ −	fv +	$\frac{gu\sqrt{u^2+v^2}}{C^2(h+d)}$ =	F_x +	$\mu\left(\frac{\partial^2 u}{\partial x^2}+\frac{\partial^2 u}{\partial y^2}\right)$ −	$\frac{\partial p_o}{\partial x}$
Hansen, W.[1/] (1962)	✓			✓	✓	✓	✓	✓	2/
Shubinski and Scheffey [3/] (1966)	✓	✓		✓		$K\|u\|u$ [4/]	5/		
Leendertse (1967)	✓	✓	✓	✓	✓	✓	5/		
Reid and Bodine (1968)	✓			✓	✓	✓	✓		
Masch, et al. (1969)	✓			✓	✓	✓	✓		
TRACOR (In Press)	✓			✓	✓	✓	✓		

1/ Multi-level models in preparation

2/ Has been included in large-scale grid models

3/ Quasi-2-dimensional

4/ Manning representation rather than de Chezy

5/ Has been incorporated in other versions in conjuction with the finite difference approximations. Okubo's is an analytical solution.) Okubo has included lateral and vertical shear in the x-direction velocity term, prompted by the fact that dye releases are usually observed to elongate in the direction of the current rather than spread radially about the center of mass. Inclusion of the velocity shear terms enables one to more nearly simulate instantaneous and continuous source releases (Okubo and Karweit, 1969). As have many things, the original work on the importance of shear (Saffman, 1962) was generated by meteorologists. They have an unfair advantage, of course, in that their observations are sinfully easy to obtain and reproduce compared to oceanographic measurements. This has resulted in their making relatively great advances in entering the 3-dimensional space domain by employing multi-level, global, models of circulation.

FEATURES OF SOME OREGON-WASHINGTON ESTUARIES

Burt and McAlister (1959) reviewed the hydrography of Oregon estuaries and classified them on the basis of their vertical salinity profiles. Hansen and Rattray (1966) have classified estuaries on the basis of circulation and stratification parameters at given cross-sections of an estuary. Dimensionless ratios of net surface current to mean freshwater velocity (u_s/U_f) and top-to-bottom salinity difference ($\delta S/S_0$) are used to exhibit the physical significance of different systems.

Figure 1 shows the classification in terms of the above ratios. The examples given by Hansen and Rattray are replotted with an abbreviated description of the different types (1-4). West coast waters shown are the Columbia (C); Straits of Juan de Fuca (JF); and Silver Bay, Alaska (S). A point for the Yaquina River (Y) at mile 14 has been added to the graph from data collected by the author. The Yaquina data were taken during a 25-hour survey; the stratification parameter equals 0.12, and the circulation parameter is 1.64. The coordinates of the point place the estuary at this river mile, at this time, in type 1b, a case of "...appreciable stratification." The nearly vertical line of dots through the point was obtained by computing individual hourly circulation and stratification parameters in order to obtain an idea of the range of values that might be expected under the prevailing conditions. As can be seen, the dots extend into higher stratification values (as shown by an increase in $\delta S/S_0$) and also range into type 1a "...the archetypical well-mixed estuary in which the salinity stratification is slight...."

Vertical profiles of salinity and current (used in computing the above parameters) and dissolved oxygen are given in Figure 2a which shows

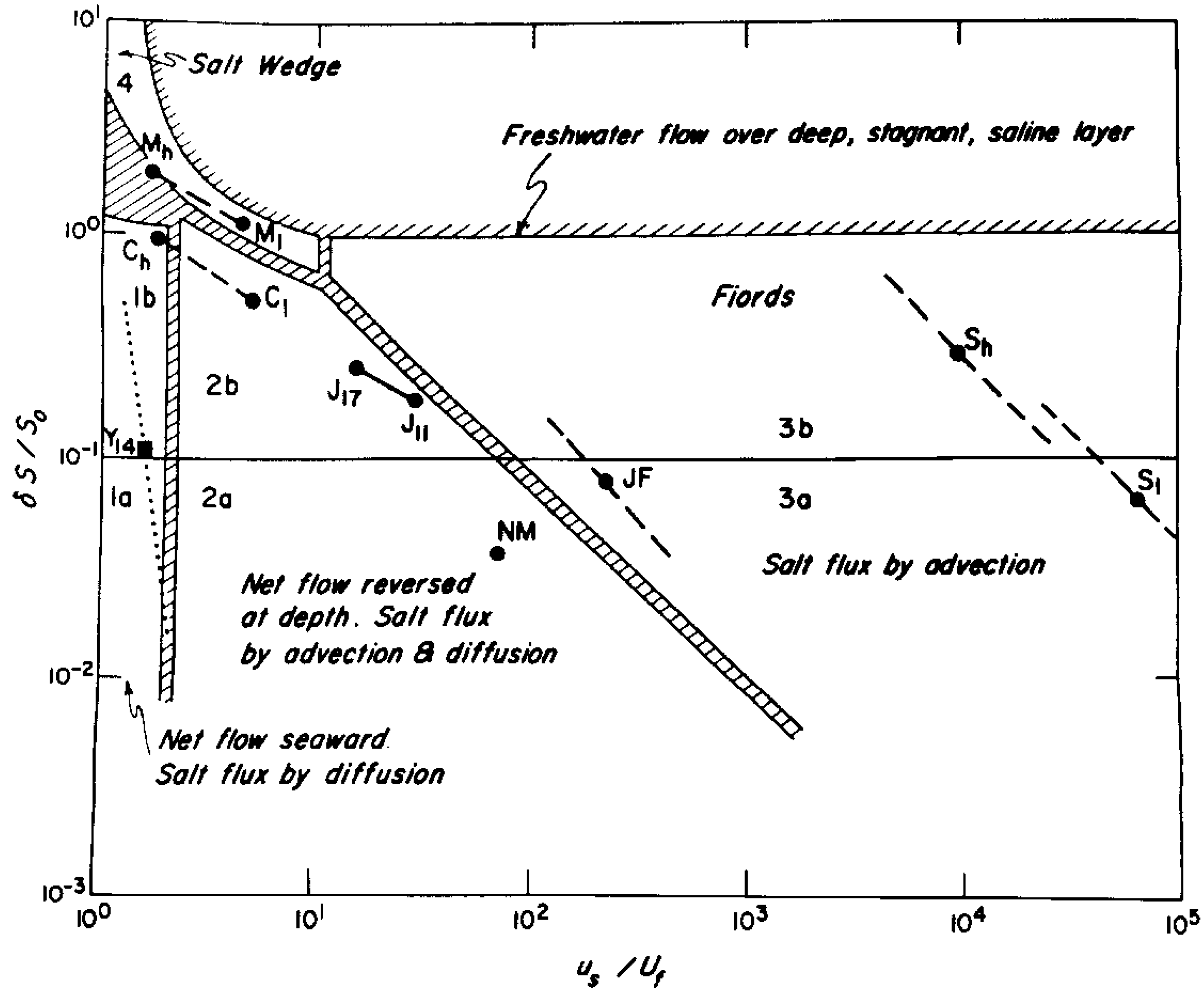
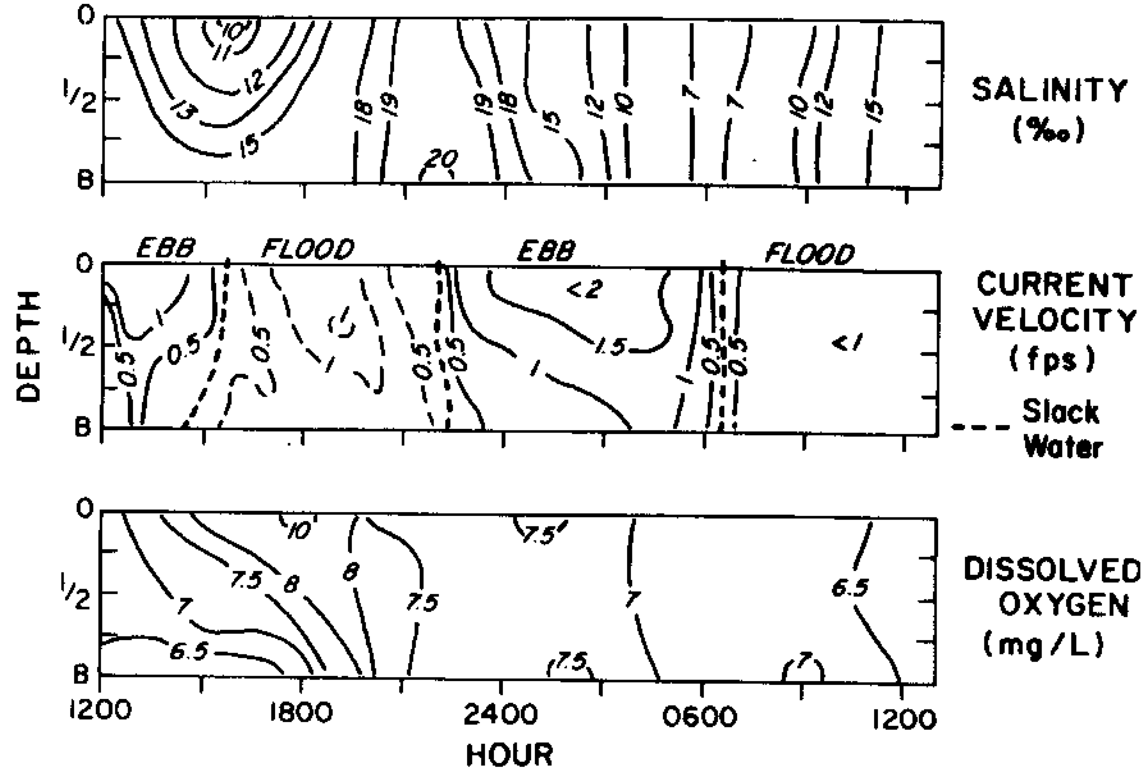
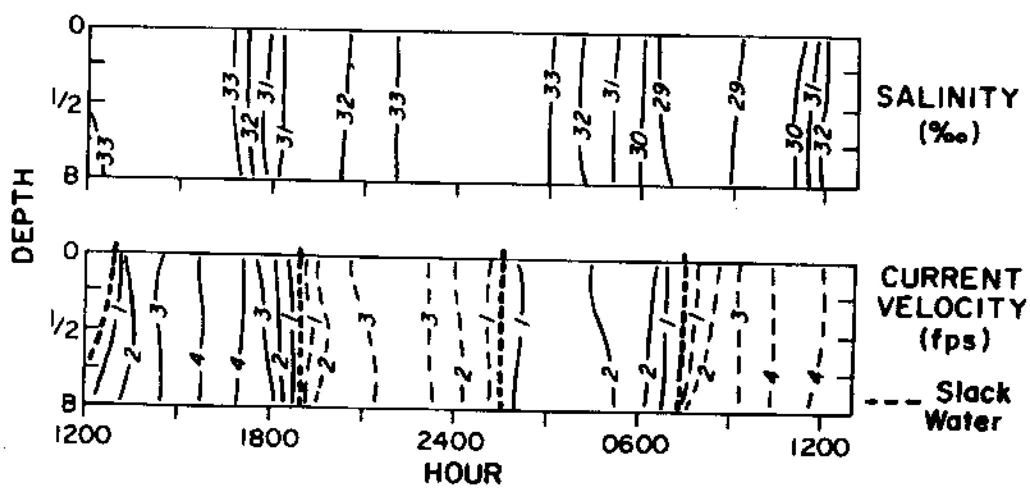


Fig. 1. Estuary type classification according to Hansen and Rattray (1966). See text.



YAQUINA RIVER ESTUARY R.M. 14 AUGUST 1-2, 1967
(EPA DATA, UNPUBLISHED)



COOS BAY R.M. 8 SEPTEMBER 20-21, 1960
(From W.B. McAlister and J.O. Blanton, 1963)

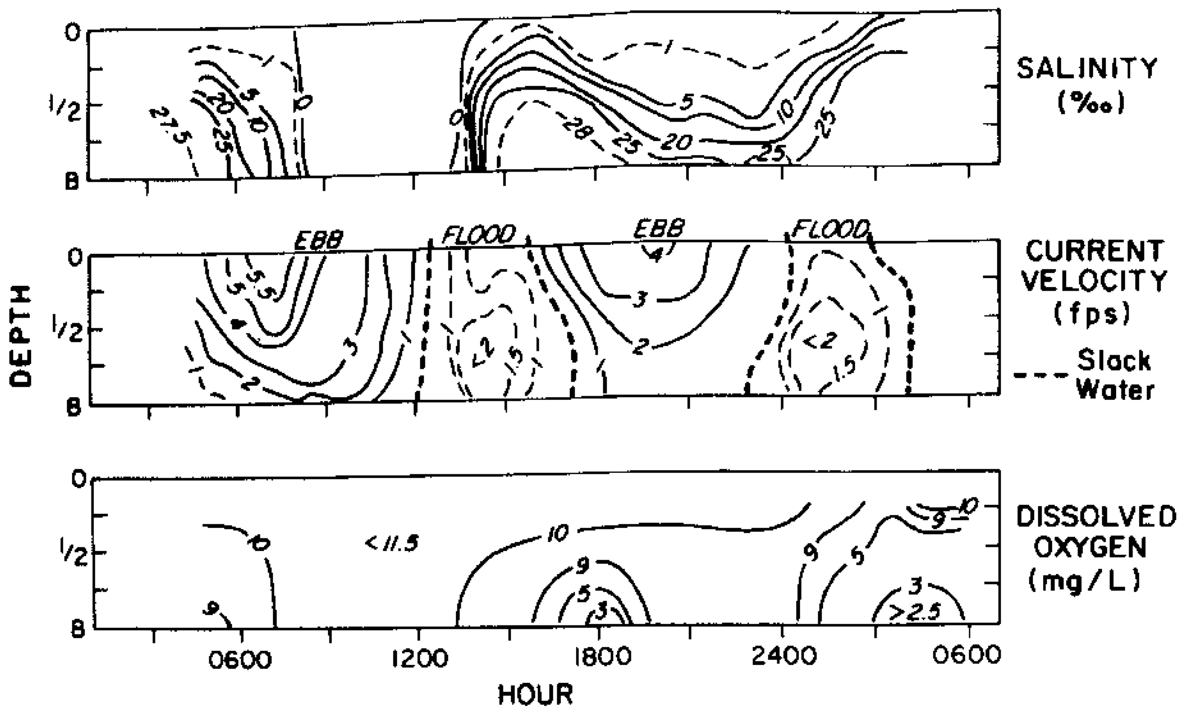
Fig. 2. Time-series of data collected over one tidal cycle.
Fig. 2a-upper, 2b-lower.

periodic stratification of salinity (and oxygen) in the first eight hours followed by well-mixed conditions for the remainder of the time. Oxygen stratification is apparent at the same time but the gradient is directed upward rather than downward as shown at about 1500 hours. If salinity were expressed in terms of the amount of freshwater rather than saltwater, the gradients would be in the same direction; more important, however, is the fact that contours of different substances will rarely be matching. A description of this type of disparity is impossible to rectify by conventional mathematical models and recourse must be made to models that incorporate terms--aside from diffusion--to at least account for photo-synthesis and respiration. The discrepancy is put into perspective by noting that sources of freshwater and oxygen, e.g., are distinctly separate mechanisms. The freshwater source is upriver while atmospheric oxygen can be supplied locally at the surface by reaeration and from within by photosynthesis. The sinks are also different, freshwater decreasing by seepage through the bottom and evaporation while oxygen decreases primarily by within-stream BOD, respiration and bottom demand.

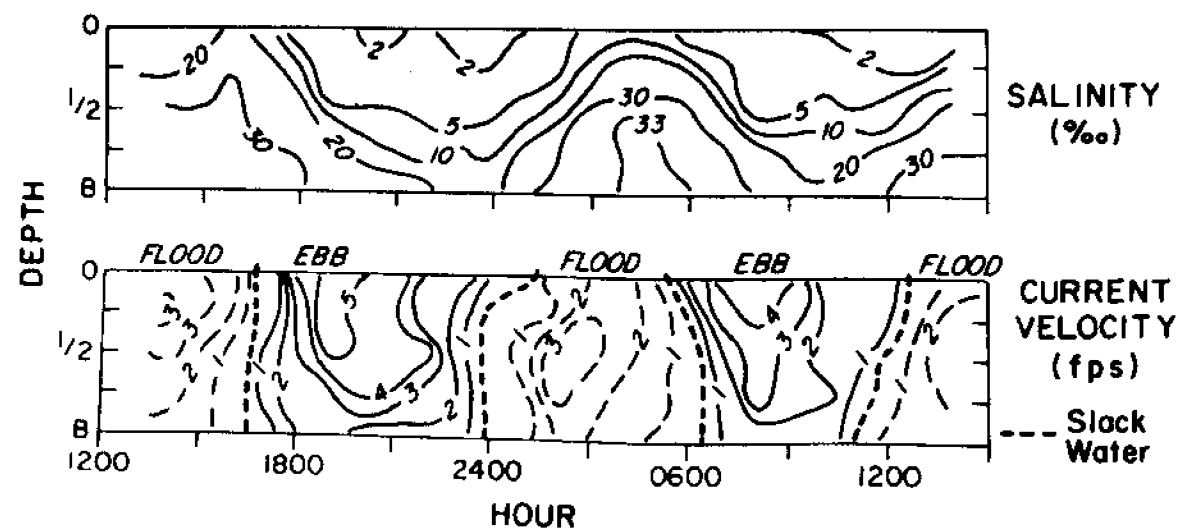
The use of 1-dimensional, longitudinal models implies that the estuary is well-mixed vertically and laterally. (See Ward and Fischer, 1971, for additional comments on the limitations of 1-dimensional models). The Yaquina is well mixed part of the time, but averaged over a tidal cycle it still exhibits stratification. In general, increasing the period of averaging serves to smooth out intra-tidal fluctuations. This rationale has been employed in order to average out diurnal tidal fluctuations in some models, primarily for ease of computation and to keep the problem within computing bounds. The above example shows that an anomalous condition can obtain; namely, a short-term average and computing interval would well suit 1-dimensional qualifications while a long-term average would put the system into the partically stratified calss. Borderline cases such as the above are not all that rare and pronouncements of 1-dimensionality should be made cautiously.

Figure 2b shows vertical profiles of salinity and current speed at river mile 8 in Coos Bay. Coos Bay at this time lies well within class 1a; profiles are of the modeler's dream-come-true variety exhibiting very little variation from top to bottom. There is no guarantee that the well-mixed condition applies to the whole estuary all the time and it is again emphasized that a well-mixed salinity-velocity profile by no means ensures a well-mixed oxygen, nutrient, plankton or any other profile. If the pollutant or substance under study enters the estuary from the ocean or river end of the estuary in the same manner as the salt or freshwater and behaves in the same fashion, then its prediction can be assumed to be as assured as the salt distribution. If on the other hand, the substance interacts within the estuary or is subject to conversion to other forms then these mechanisms have to be modeled. In the latter case, coupled sets of equations will need to be used. The point to be made here is simply that one should be aware of the fact that one man's well-mixed condition may be another man's stratification.

Figure 3a presents data collected by the author at river mile 2.3 in the Umpqua estuary during a period of high runoff. The latter condition is exhibited in the salinity profile as a complete flushing of the estuary from about 0800-1300 hours followed by a rapid influx



UMPQUA RIVER ESTUARY R.M. 23 MARCH 21-22, 1961
(Callaway, 1961)



COLUMBIA RIVER R.M. 5 SEPTEMBER 22-23, 1959
(From U.S.A.C.E. DATA: RANGE 2 STATION C, U.S.A.C.E., 1960)

Fig. 3. Time-series of data collected over one tidal cycle.
Fig. 3a-upper, 3b-lower.

of salt in along the bottom to about 28 ppt. The surface speeds associated with buildup of freshwater were in excess of 4-5.5 fps decreasing to 1.5 fps at the bottom during the ebb cycles. The flood speeds were somewhat less with the maximum speeds being located at depth. This was also a period of upwelling; the two flood cycles brought in water low in oxygen at depth, some 7-8 mg/l less than that in the surface. Mathematically modeling this sort of condition would obviously not be a trivial exercise, although two-layer modeling is now being carried out (see, e.g. Vreugdenhil, 1970).

Finally, data for the Columbia River at river mile 5 are shown in Figure 3b. This again typifies high runoff conditions although at this river mile complete flushing does not occur as in the Umpqua example. Similar features are apparent, however, such as the submerged velocity peak on the flood cycle and surface maxima on the ebb. The duration of the ebb cycle is greater than the flood, the difference becoming less disparate with depth i.e., ebb begins earlier in the surface layers and ends later.

In summary, it should be stated that 1-dimensional models of hydraulic phenomenon are rather well developed. Amplitudes and phases of tides may be represented rather faithfully but this in no way ensures that the pollution problems associated with the dispersion of an effluent is reproduced in any such satisfying fashion. This is mainly due to the fact that most non-conservative substances usually show some degree of stratification, especially when surface boundary conditions are in effect and when interactions within the water column and at the sediment-water interface are likely to occur.

TIDES AND CURRENTS AS BOUNDARY CONDITIONS

Tidal information is of interest in the modeling of estuarine pollution problems for a number of reasons: (1) tidal heights or currents are sometimes required as natural boundary conditions; (2) the tide range provides an indication of the amount of energy available for mixing--being proportional to the square of the range; (3) local tidal heights determine the amount of water available for dilution; (4) the excursion of pollutants depends on the range and duration of the ebb and flood tides; (5) in conjunction with (2) above, the vertical salinity profile can be determined in advance given the runoff and tidal prism.

Information on tides in the Yaquina, Alsea, Siletz and Coos estuaries has been presented by Neal (1966), Goodwin, et al. (1970), and Blanton (1970).

Prediction of tidal heights by harmonic analysis is well-established; discrepancies from predicted heights occur due to storm surges and freshets due to local precipitation. Tidal current prediction is less well-behaved from the viewpoint of predictability (as exemplified by ESSA publications); unlike heights they are subject to cross-stream variations and are also markedly affected by winds, local runoff conditions. Both currents and heighths are affected by channel modifications.

Prediction of tidal heights and currents becomes less certain with distance upstream as the damping effect of the estuary becomes less dominant. The linearized equations of motion, or the equations where the non-linear terms are neglected altogether, may be quite adequate in the ocean or coastal regions, but definitely cannot be employed in shallow water cases where topographic effects, friction and the Bernoulli acceleration govern the shape of the wave.

Of the three general methods (the harmonic, characteristic, or numerical method) of solving the equations of tidal motion, the numerical scheme is probably best suited for incorporating variable river flow inputs, winds and irregular topography; the examples given later utilize the numerical scheme.

Tidal Constituents

First of all, consider the tide generating constituents if only to provide a basis for correctly specifying the tide as a boundary condition.

Tidal constituents are the result of trying to account for perturbations in the orbits of the sun and moon. Each constituent represents, in effect, a miniature planet revolving about the earth exerting an attractive force on the earth's water surface. At any given prediction station the constituent is expressed as a periodic sinusoidal elevation of the surface and has an associated amplitude, period and phase; these terms are computed by harmonic analysis of time-series data. The synthesis of the harmonic constituents with reference to a specific datum gives the local tide height; prediction tables usually report the time of high or low water and the water level and the times of slack waters and maximum ebb and flood speeds.

The principal constituents are designated as M_2, S_2, N_2, K_1, O_1, P_1, etc., where the subscript ($_1$) refers to the diurnal and the ($_2$) refers to the semi-diurnal nature of the constituent. The relative amplitude of the various constituents determines the type of tide that will occur, i.e., whether it will be semi-diurnal with two nearly equal highs and lows per day or "mixed" with unequal highs and lows, or "diurnal" with only one high and one low per day.

In Table 3, constituent amplitudes, H, phase angles, K, and mean tide level elevations are given for Oregon-Washington ports 1/. Also shown is the ratio $(K_1 + O_1)/(M_2 + S_2)$ 2/; for values of this ratio less than 0.25 the tide is semi-diurnal; between 0.25 and 1.25, it is mixed. It is diurnal for ratios greater than 1.25. It can be seen that the coastal ratios all indicate mixed tides. In the approaches to Puget Sound, however, the ratio indicates diurnal tides as is shown as an example for the Friday Harbor station.

1/ Abstracted from U. S. Coast & Geodetic Survey data supplied by LCDR L. Swanson, NOAA.

2/ The ratio $(K_1 + O_1)/M_2$ is sometimes used.

TABLE 3

Tidal Constituents - Oregon-Washington Coast

Place and Position	Constant	K_1	O_1	P_1	Q_1	M_2	S_2	N_2	K_2	M_4	M_6	Z_0 ft.	$\frac{K_1 + O_1}{M_2 + S_2}$
Crescent City, Ca. 41°45'N	H (ft)	1.276	0.785	0.386	0.145	2.334	0.579	0.500	0.145	0.006	0.008	3.7	0.708
124°12'W	k_o (deg)	104	088	100	080	323	343	297	329	052	303		
Brookings, Or. 42°03'N	H	1.319	0.808	0.397	0.135	2.399	0.615	0.512	0.158	0.003	0.009	3.7	0.706
124°17'W	k_o	103	088	097	081	325	346	298	344	286	243		
Port Orford, Or. 42°44'N	H	1.402	0.866	0.413	0.152	2.451	0.625	0.515	0.160	0.005	0.005	4.0	0.737
124°30'W	k_o	107	091	103	083	328	351	303	348	045	298		
Bandon, Or. 43°07'N	H	1.221	0.762	0.372	0.130	2.404	0.613	0.496	0.156	0.011	0.009	3.6	0.657
124°25'W	k_o	112	098	109	095	335	000	310	351	244	299		
Coos Bay, Or. 43°23'N	H	1.148	0.658	0.315	0.110	2.433	0.536	0.436	0.152	0.147	0.094	4.0	0.608
124°13'W	k_o	137	124	137	132	019	055	003	044	227	068		
Gardiner, Or. 43°44N	H	1.176	0.681	0.323	0.114	2.322	0.523	0.445	0.167	0.059	0.034	3.6	0.653
124°07'W	k_o	131	117	130	126	008	040	346	020	245	063		
Florence, Or. 43°58'N	H	1.162	0.648	0.312	0.101	2.220	0.517	0.422	0.155	0.033	0.024	3.5	0.661
124°06'W	k_o	128	115	124	125	003	034	344	018	255	041		

TABLE 3 (Cont'd)

Tidal Constituents - Oregon-Washington Coast

Place and Position	Constant	K_1	O_1	P_1	Q_1	M_2	S_2	N_2	K_2	M_4	M_6	Z_0 ft	$\frac{K_1 + O_1}{M_2 + S_2}$
Waldport, Or. 44°26'N 124°04'W	H (ft)	1.314	0.773	0.387	0.121	2.607	0.669	0.516	0.181	0.044	0.047	4.1	0.637
	k_o (deg)	121	105	118	104	354	023	331	017	193	348		
Newport, Or. 44°38'N 124°03'W	H	1.386	0.843	0.426	0.141	2.778	0.728	0.566	0.190	0.044	0.021	4.3	0.636
	k_o	116	100	110	093	347	015	323	012	115	291		
Astoria, Or. Youngs Bay 46°10'N 123°51'W	H	1.326	0.798	0.346	0.130	3.129	0.746	0.586	0.216	0.054	-	4.5	0.548
	k_o	130	116	125	115	012	044	348	027	294			
Raymond, Wn. Willapa R. 46°41'N 123°45'W	H	1.405	0.828	0.417	0.137	3.503	0.902	0.686	0.192	0.133	0.106	5.3	0.507
	k_o	133	118	128	122	016	049	353	035	193	041		
Toke Point, Wn. Willapa Bay 46°42'N 123°58'W	H	1.383	0.841	0.430	0.154	3.147	0.813	0.635	0.235	0.059	0.033	4.7	0.562
	k_o	127	111	122	105	006	036	340	024	196	034		
Aberdeen, Wn. 46°58'N 123°51'W	H	1.336	0.790	0.394	0.145	3.418	0.856	0.672	0.252	0.168	0.134	5.6	0.497
	k_o	132	118	130	115	015	052	353	049	242	061		
Friday Harbor, Wn. Oceano. Lab. 48°33'N 123°00'W	H	2.463	1.413	0.768	0.231	1.827	0.423	0.394	0.114	0.063	0.010	4.6	1.723
	k_o	157	136	156	126	125	151	097	162	351	228		

STEADY STATE MODELS

Deterministic models of the environment are either steady-state or time-varying, the steady-state assumption implying no time change term in the AD (or hydraulic) equations. The effluent is discharged at a constant rate, and has come into equilibrium with the receiving waters; freshwater inflow and other characteristics of the environment are also steady. The topography of the estuary can be modeled quite closely, e.g., tide level cross-sectional areas can be incorporated to show the irregular nature of the geographic setting. However, the effect of tidal height variations on cross-sectional areas (hence, water volume changes) and tidal current fluctuations cannot be modeled here except by repeated application of the steady-state case, in which case there would evolve a process of simulation. The upstream distribution of an effluent from its source is provided for by a form of exchange coefficient. Simulation of various reaction rates, river flows, diffusion and reaeration rates is a logical extension of the steady-state assumption and perhaps the best justification for its use, since the expected range of concentration of a given pollutant can be easily explored. Input information to a complex area can be obtained from existing hydrographic charts, flows can usually be extracted from Federal or local government publications or files. The actual use of a developed steady-state model, as opposed to the judgment necessary to carry out a realistic simulation, is elementary. Modeling tidal flat areas which are periodically exposed is an exceedingly complex undertaking; properly done it will consist of aerial photogrammetric surveys and precise leveling.

In the highly industrialized setting of the Delaware Estuary the steady-state case has been used as the foundation of a linear programming method of meeting certain water quality standards. For instance, for wastes of known volume, concentration, and reaction rates discharged at various locations along some miles of an estuary and a dissolved oxygen standard of, say, 5 ppm, the linear programming concept can be used in conjunction with the steady-state case to ensure that this goal will be met a given percent of the time and at the least expense to the parties involved. Various external constraints are, of course, involved here, but the tools are available for the exercise of logical and unarbitrary decision making.

Two steady-state models are described below in order to exhibit some of the uses of this approach to estuarine problems. Both models were applied to Grays Harbor.

Grays Harbor, Washington

The Grays Harbor entrance is about two miles in width, but shoals extending southward from Point Brown contract the navigable channel to a width of 0.4 miles (Fig. 4). From the entrance, the bay extends eastward for 15 miles to the mouth of the Chehalis River. The bay is filled by shoals and flats which are bare at low water and cut by numerous channels.

The mean range of tide at Aberdeen is 7.8 feet. The range between mean lower low water and mean higher high water is 9.9 feet and a spring range of about 14 feet occurs. The flushing rate at 700 cfs was calculated by the tidal excursion-prism method to be 5.5 days.

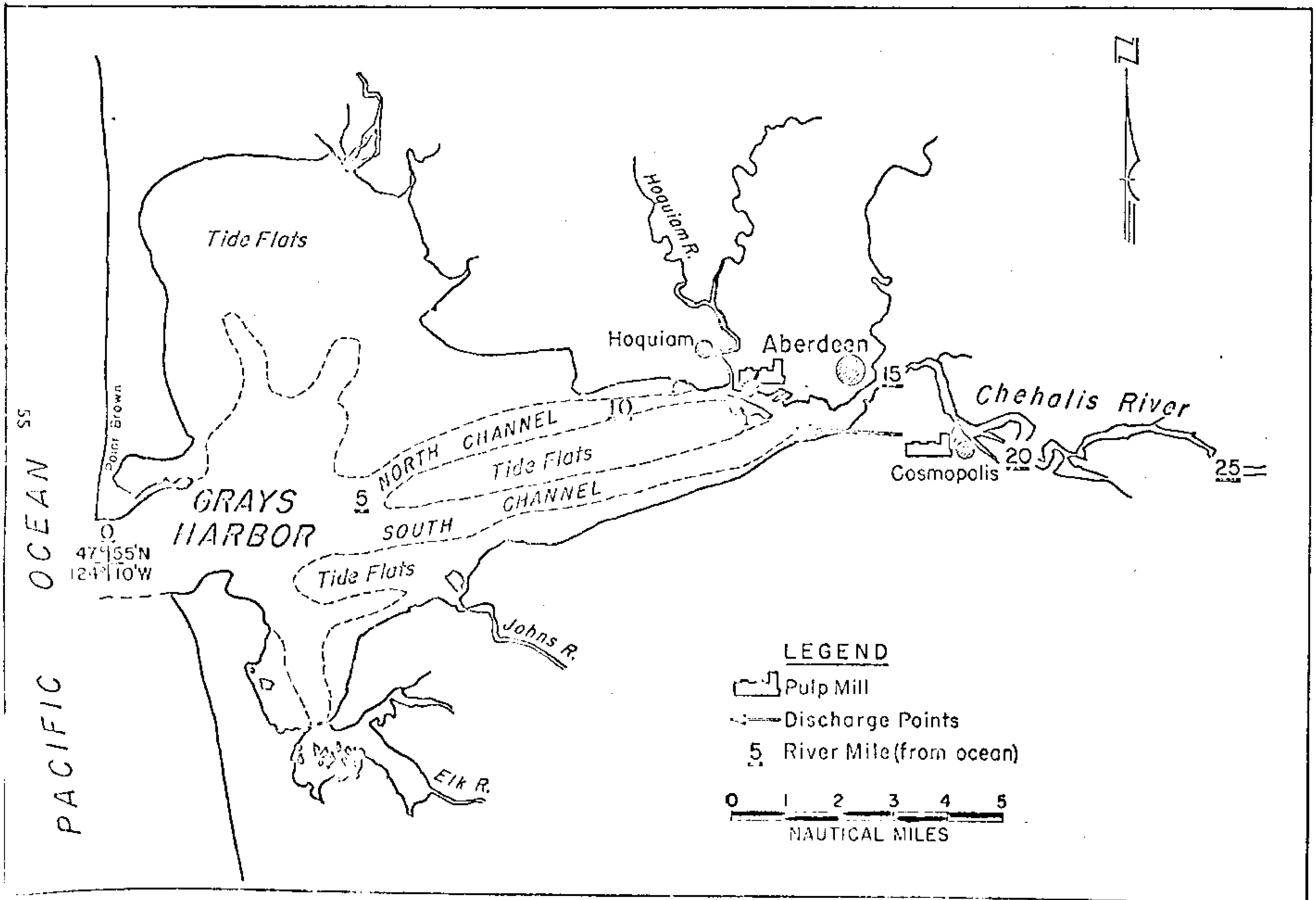


Figure 4. Location map, Grays Harbor, Washington.

Eriksen and Townsend (1940) have presented data available for calculation of eddy diffusivities from the longitudinal salinity profile in the harbor. During a period of a constant flow of 700 cfs well-mixed, essentially 1-dimensional, conditions existed.

The influence of the extensive tide flat areas on the distribution of waste effluents is unknown, and the computational error introduced by their presence cannot be evaluated at this time. (Dr. Bella's paper on the influence of tidal flats or water quality should provide some insight on this subject.) The tide flats were tacitly included in the model by using cross-sectional areas based on mean tide level.

Two pulp mills in the area discharge partially treated wastes directly to the estuary or to holding lagoons for discharge at high flow periods. The discharge of oxygen-demanding wastes naturally contributes to the oxygen deficit in addition to bottom demands and plant respiration. Another factor which enters and which frequently occurs on the West Coast of the United States is the process of upwelling. During periods of sustained northerly winds, surface waters are transported away from the coast and replaced by waters at depth. The dissolved oxygen content of the deeper waters may be as low as 1 to 2 mg/l and have been observed as penetrating into the harbor (Pearson & Holt, 1960). Prevailing winds that induce upwelling generally occur during the low river runoff period and can compound the effect of low dissolved oxygen concentrations resulting from estuarine waste discharge practices.

When only one industrial or municipal sewage facility affects an environment, the problem of a desirable level of waste treatment is fairly straightforward if water quality objectives are stated. When two or more facilities discharge into the same system, then an amenable treatment level requires that the contribution of each facility to the total stream waste load be capable of isolation. Examination of field data alone cannot separate the concentration distribution observed in the waterway into individual facility components, since the concentration at any point depends not only on the amount but also upon the location of waste discharge. Upwelling compounds the situation.

Stommel's Model

A model for treating the distribution of a pollutant in a well-mixed, 1-dimensional tidal estuary was given by Stommel (1953) as:

$$(4) \qquad F(x) = QL - SA\frac{dL}{dx}$$

where F(x) = net seaward flux of pollutant across a section

A = turbulent eddy diffusivity ($L^2 T^{-1}$)

Q = river flow ($L^3 T^{-1}$)

L = concentration of substance (M/M)

S = channel cross-sectional area (L^2)

The steady-state equation (4) for a non-conservative pollutant may be written as:

$$(5a) \qquad \frac{d}{dx}\left(QL-SA\frac{dL}{dx}\right) + K_1 SL = 0$$

or

$$(5b) \qquad \frac{d}{dx}\left(QL-SA\frac{dL}{dx}\right) + K_1 SL = J$$

at an outfall where J is the rate of flow of pollutant (MT^{-1}) at the outfall, and the reaction term, $K_1(T^{-1})$, is taken as a constant throughout the estuary. Burt and Marriage (1957) employed equations (5) in a study of the potential pollution of Yaquina Bay, Oregon.

Stommel's relaxation solution of n linear differential equations was replaced by a matrix algebra solution by Callaway (1966) which was first employed by Dorrestein (1960) and later extended to the time-variable case by Thomann (1963). After expressing equations (5) in finite difference form they become, utilizing matrix notation:

$$(6) \qquad [A]\,[L] = [J]$$

where [A] is an n x n matrix which includes the advection, diffusion and decay terms, [L] is a column vector of dimension n representing BOD concentration and [J] is a column vector of dimension n representing forcing functions of waste discharges. Equation (6) is easily solved by matrix inversion on a digital computer:

$$(7) \qquad [L] = [A]^{-1}\,[J]$$

The output $[A]^{-1}$, which is the inverse of [A], is multiplied by [J] in a given section where an outfall is situated. If outfalls are located along the estuary the resulting outputs may be added to give the total longitudinal output since the system is linear and superposition of solutions applies.

Longitudinal DO Profile

The computation of the steady-state DO profile is somewhat more complex than that for describing the distribution of a conservative or non-conservative pollutant and was not treated by Stommel. The basic dissolved oxygen equation, avoiding finite difference formulation and neglecting photosynthesis and sludge bed demand, is:

(8) $$\frac{d}{dx}\left(QC - SA\,\frac{dC}{dx}\right) = K_2\,S(C_s - C) - K_1\,SL$$

where C = dissolved oxygen concentration (ML^{-3})

C_s = saturation concentration (ML^{-3})

K_2 = reareation coefficient (T^{-1})

and the other terms are as before. Modifying equation (5a) for the distribution of pollutant or BOD:

(9) $$\frac{d}{dx}\left(QL - SA\,\frac{dL}{dx}\right) + K_1\,SL = F$$

where F is the forcing function.

Upon differentiating equation (8) with respect to *x* and rearranging, we have:

(10) $$\left[Q\,\frac{d}{dx} - \frac{d}{dx}(SA)\,\frac{d}{dx} - SA\,\frac{d^2}{dx^2} + K_2\,S\right] C = K_2\,SC_s - K_1\,SL$$

for dissolved oxygen distribution, where *L* is determined from (11) as:

(11) $$\left[Q\frac{d}{dx} - \frac{d}{dx}(SA)\,\frac{d}{dx} - SA\,\frac{d^2}{dx^2} + K_1\,S\right] L = F$$

In equation (10), the terms in brackets represent a system of operations, or transfer function, which transforms the forcing functions $K_2\,SC_s$ and $K_1\,SL$ into an output *C*. Similarly, the forcing function *F* in equation (11) is the BOD discharged at an outfall section somewhere in the estuary which is transformed by the advection, variable diffusion and constant reaction terms within brackets to a longitudinal BOD distribution. At each end of the model $C = C_s$, and eddy diffusivity at the river (freshwater) end is taken as zero. Although Stommel's model is applicable to tidal freshwater streams, the evaluation of eddy diffusivity would have to be made through the use of dye releases or some other substance beside salinity as used here.

Writing equation (10) in matrix notation for the system of equations:

$$(12) \quad [B] [C] = [K_2 SC_s - K_1 SL]$$

and solving for [C]:

$$(13) \quad [C] = [B]^{-1} [K_2 SC_s] - [B]^{-1} [K_1 SL]$$

In equation (11) when F = 0, L = 0 and equation (8) reduces to $C = C_s s$ since it is assumed that there is no longitudinal variation in C_s (first and second derivatives of C with respect to x are zero). Then equation (B) is written as:

$$(14) \quad [C] = [C_s] - [B]^{-1}[K_1 SL]$$

Solving for [L] in equation (11) and substituting in (14):

$$(15) \quad [C] = [C_s] - [B]^{-1}[A]^{-1}[K_1 F]$$

which is the synthesized DO profile equation.

Twenty-three sections were used in the 700 cfs model, no attempt was made to assess temperature effects on the BOD rate constant: C_s (= 7.5mg/l) was taken as constant in the estuary. (The forcing functions used in the above derivations have awkward dimensions which can be resolved by dividing the equation by the cross-sectional area term.)

Salinity Profile

Figure 5 shows the computed and observed longitudinal salinity distribution in the estuary at 700 cfs. Computed results were taken from the matrix inversion of the system represented by equations (5) with $K_1 = 0$. Observed salinity at the ocean end of the model was taken as the input forcing function.

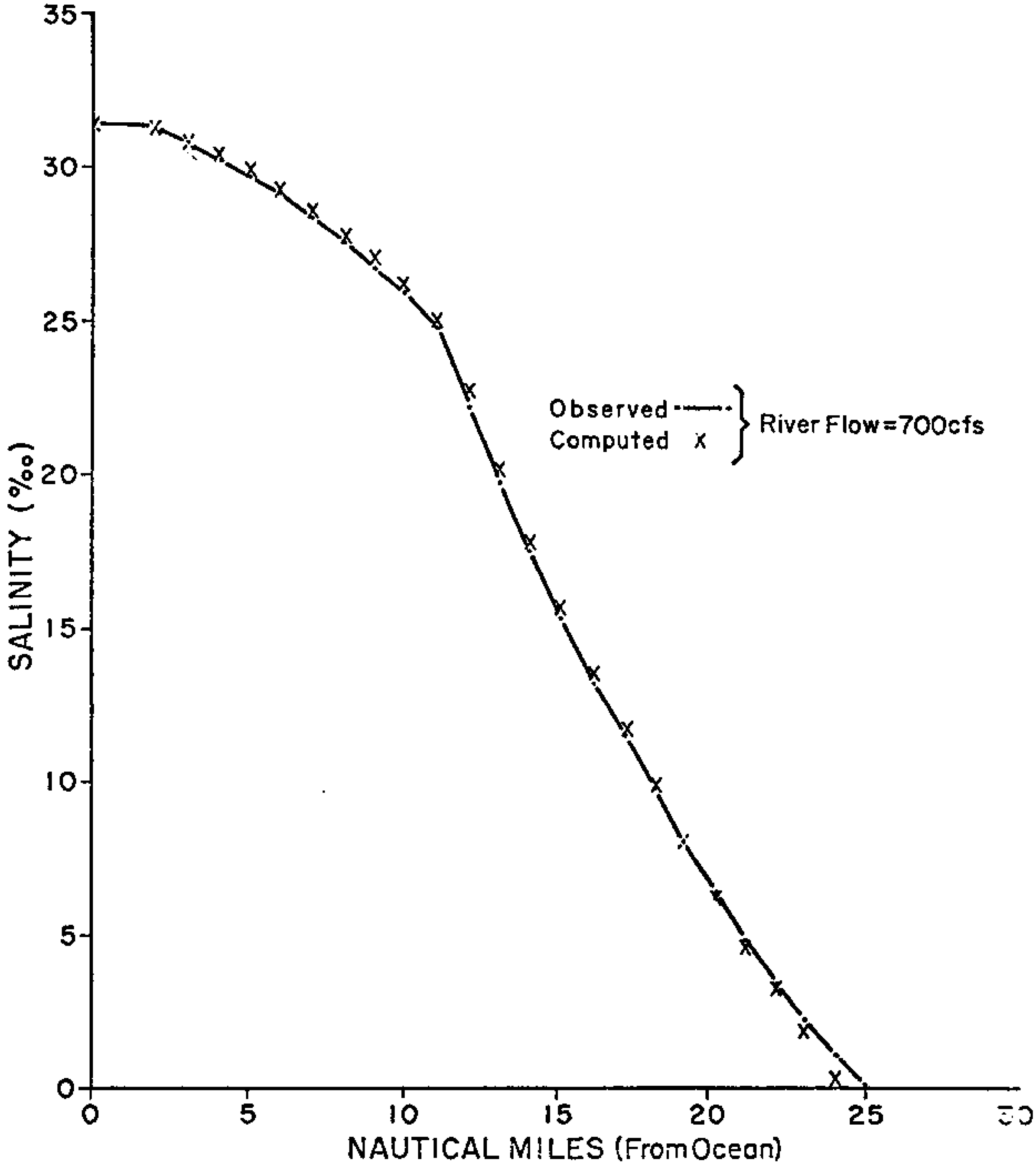


Fig. 5. Salinity profiles, Gray's Harbor.

was taken as the input forcing function. The "computed" salinity serves mainly as a check on the calculation of the coefficients in (9) since the observed salinity data were used in the calculation of eddy diffusivities. Diffusivities calculated for Q = 700 cfs averaged 2.6 square miles per day.

Upwelling

At the ocean end of the model upwelling is introduced as an initial oxygen deficit (C_s - C) subject to reaeration only. Work by Sverdrup and Fleming (1941) and Barnes and Collias (1958) suggests that waters at depth in the ocean and in fjords have very slow deoxygenation rates. Barnes and Collias find average rates of 0.016 ml/l/day in the fjord-like waters of Puget Sound while Sverdrup and Fleming reported 0.005 ml/l/day at a depth of 200 meters off the California coast. In estimating the upwelling contribution to low DO conditions, then, K_1 has been taken as negligible.

Figure 6 shows an initial oxygen deficit of 5.5 mg/l in the ocean subject to reaeration rates of 0.15 and 0.30 per day within the estuary. In the absence of a pollution source in the estuary the deficit would decrease upstream (C would approach C_s, shown by the dashed line). The upwelling effect for K_2 = 0.15/day is superimposed on an observed DO profile (solid line, Eriksen and Townsend, op.cit.). The dash-dot line shows the superposition of the two deficits; during periods of upwelling, interpretation of field data extending only from mile 8 upstream would attribute the entire oxygen sag to the BOD sources located in the middle of the estuary if the possibility of an upwelling effect were not recognized.

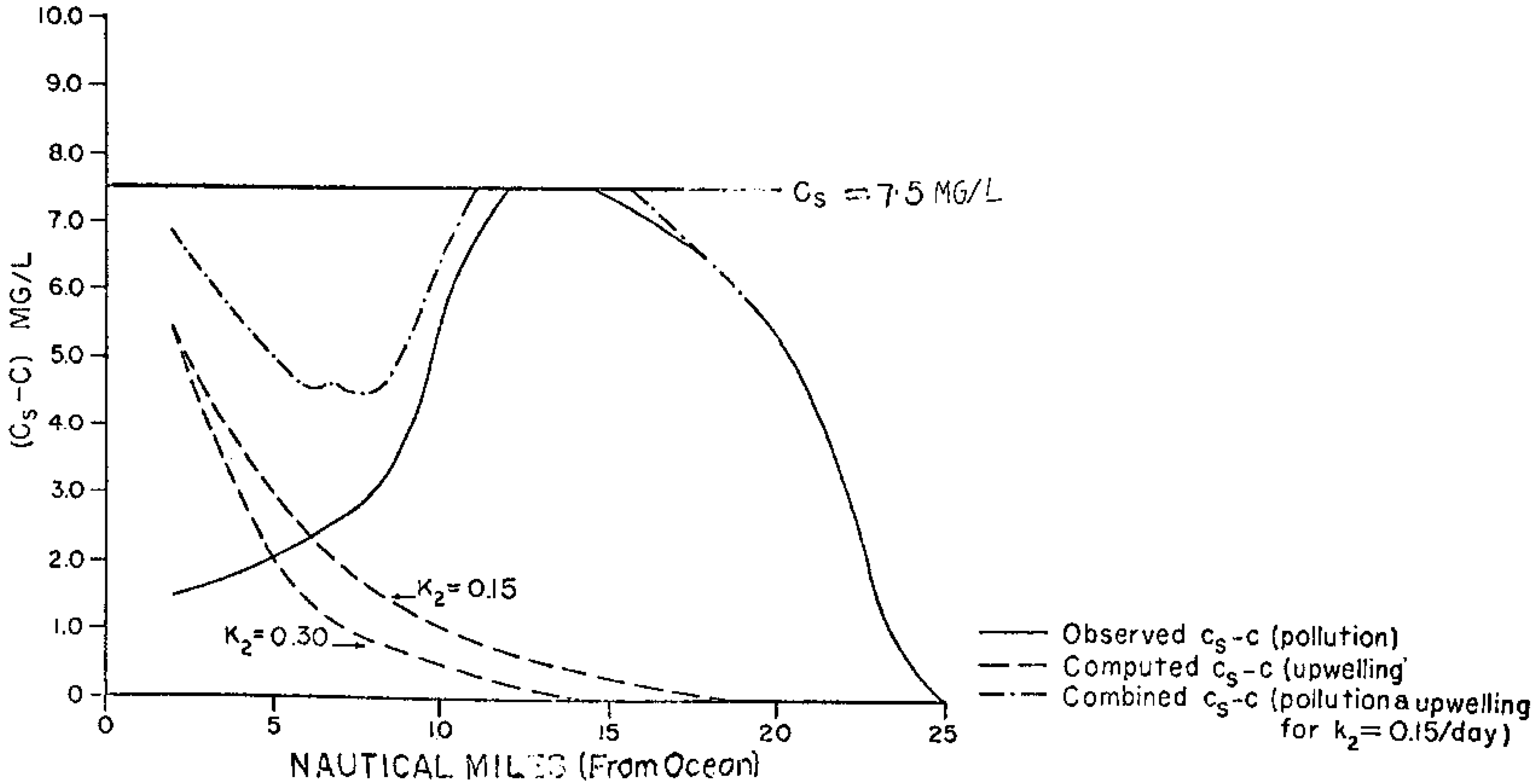


Figure 6. Oxygen deficits (C_s-C) resulting from pollution (observed), upwelling (calculated) and pollution plus upwelling.

Thomann's Model

The Thomann model (Thomann, 1963, Thomann and Sobel, 1964) also goes by the name of DECS III (for Delaware Estuary Comprehensive Study); it has been extensively documented by Jeglic (1967).

Some features of the model are similar to Stommel's, but there are enough differences to warrant discussion before the results are presented.

The time variable case is explained below; the examples shown, however, are steady-state.

In matrix form the differential equations for BOD (L) and dissolved oxygen (C) are:

$$[B]\,[L] + \left[\frac{dL}{dt}\right] = [J] - [L_b]$$

$$(17) \qquad [A]\,[C] + \left[\frac{dc}{dt}\right] = [r]\,[c_s] + [P] - [D]\,[L] - [C_b]$$

where at any given time j the matrices [A] and [B] are square, tridiagonal matrices of order n, the nonzero coefficients of which are defined as:

$$A_{i,\,i-1} = B_{i,\,i-1} = \frac{\alpha_{i,\,j}\,Q_{i,\,j} + E_{i,\,j}}{V_{i,\,j}} \qquad [i = 2, 3, 4 \ldots n]$$

$$A_{i,\,i} = \frac{\varphi_{i,\,j}\,Q_{i,\,j} - \alpha_{i+1,\,j}\,Q_{i+1,\,j} - E_{i,\,j} - E_{i+1,\,j}}{V_{i,\,j}} - r_j \qquad [i = 1, 2, 3 \ldots n]$$

$$B_{i,\,i} = \frac{\varphi_{i,\,j}\,Q_{i,\,j} - \alpha_{i+1,\,j}\,Q_{i+1,\,j} - E_{i,\,j} - E_{i+1,\,j}}{V_{i,\,j}} - d_j \qquad [i = 1, 2, 3 \ldots n]$$

$$A_{i,\,i+1} = B_{i,\,i+1} = \frac{E_{i+1,\,j} - \varphi_{i+1,\,j}\,Q_{i+1,\,j}}{V_{i,\,j}} \qquad [i=1, 2, 3 \ldots (n-1)]$$

where the i subscript denotes the i^{th} interval in a 1-dimensional grid ($\underline{n}$ grids) and the j subscript represents a time interval. The other variables are as below:

j_i = waste load to segment i

r_j = reaeration coefficient

d_j = decay coefficient

P_j = other sources and sinks of oxygen

V_i = volume of segment i

Q_j = net flow

$E_{i,j}$ = eddy exchange coefficient

α_i, ϕ_i = advection factors

The exchange coefficient is:

$$E_{i,j} = \frac{K_{i,j} \cdot A_{i,j}}{\frac{1}{2}(L_i + L_{i+1})}$$

where $K_{i,j}$ = eddy diffusion coefficient

$A_{i,j}$ = cross-sectional area

L_i = segment length

The advection factors are:

$$\varphi_{i,j} = \frac{1}{2}\left(\frac{E_{i-1,j}}{Q_{i-1,j}} + \frac{E_{i,j}}{Q_{i,j}}\right)$$

$$\text{If } \frac{E_{i-1,j}}{Q_{i-1,j}} > \frac{E_{i,j}}{Q_{i,j}} \text{ then } \varphi_{i,j} = \frac{E_{i,j}}{Q_{i,j}}$$

If $\varphi_{i,j} \geq 0.5$ then $\varphi_{i,j} = 0.5$, and

$$\alpha_{i,j} = 1 - \varphi_{i,j}$$

The role of the advection factor is similar to the weighting function (discussed, e.g., in Smith, 1965, p.23). The implicit method of solution ensures stability (but not necessarily accuracy); the advection factors minimize numerical errors which resemble diffusion.

The time variable Thomann model does not solve for short-term tidal fluctuations, hence, upstream dispersion is accomplished through the exchange coefficient and not through advection.

Steady-state solutions of equation (17) are shown in Figure 7 as the oxygen deficit per 100,000 pounds BOD discharged at various points in the estuary under various specified conditions. Figure 7a shows the effect of adding 100 cfs increments of flow to the head of the estuary with eddy diffusion calculated from the salinity profile. As can be seen the peak concentration is reduced and moves further downstream. The deficit at sections 14 and above, however, are slightly greater as a result of the increased flow. Figure 7b shows the effect of placing the outfall at different points in the north channel with a 550 cfs flow and specified diffusion rate.

Figures 7c and 7d show the effect of a doubling of the reaeration coefficient with the same decay coefficient in each case. The areas under the individual curves for a release point are greatly reduced for a reaeration coefficient increase from 0.15 to 0.30 per day.

Because the profiles have not been verified the above should be considered as examples of numerical experimentation rather than of actual conditions. A very important (and difficult) part of modeling lies in verification of the model output. Verification, or adjustment, is largely a matter of judgment; unfortunately there is little agreement or precedent upon which to go except in the simplest of cases in which analytical solutions can be simulated.

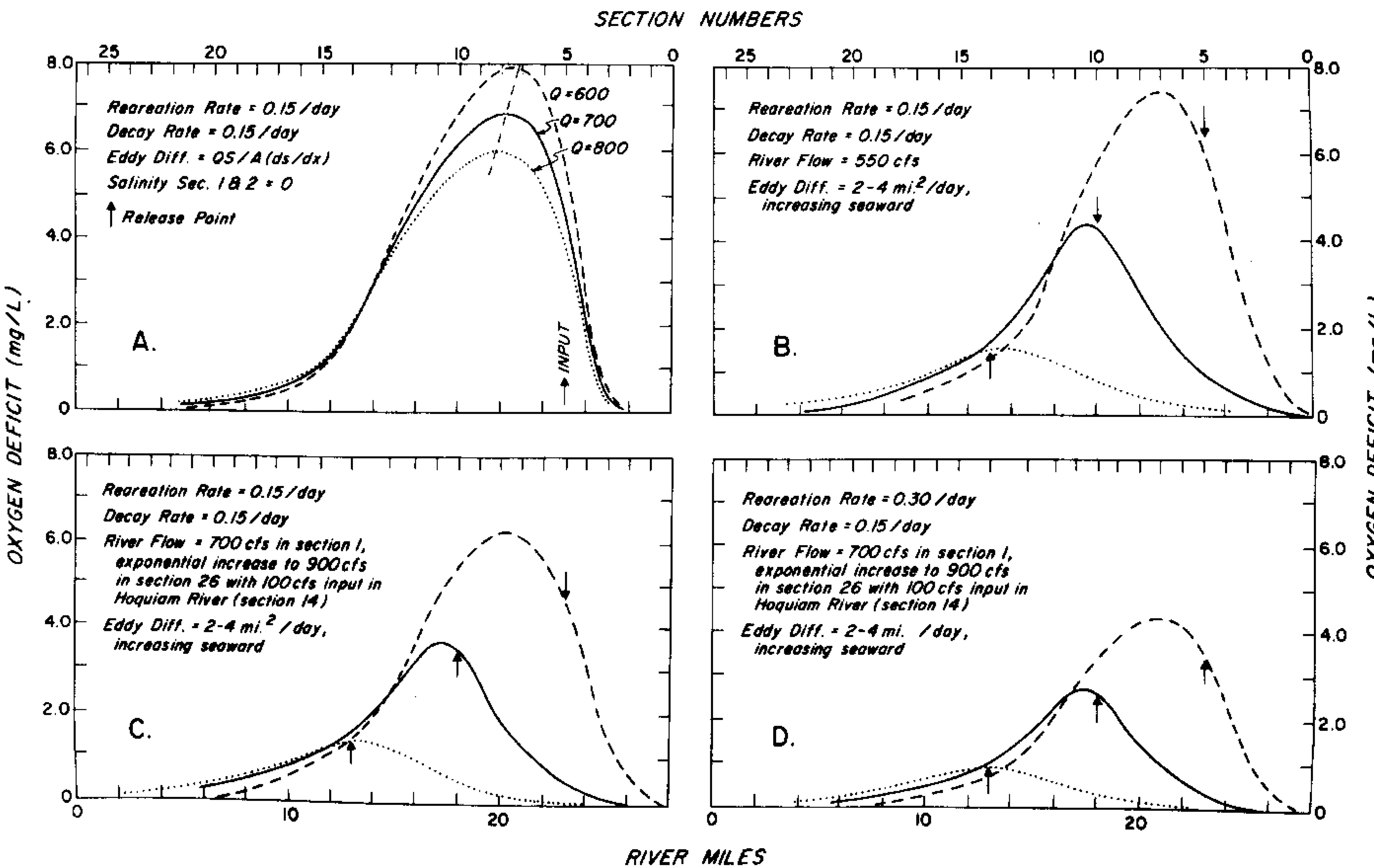


Fig. 7. Computed oxygen deficits, Gray's Harbor, per 100,000 lbs BOD.

TIME VARIABLE MODELS

Columbia River Tides and Currents

The mathematical methods for predicting tides and currents in the Columbia River from the Pacific Ocean to Bonneville Dam have been presented by Callaway, et al. (1969). Briefly, an explicit solution of the 1-dimensional equations of motion and continuity was utilized in a finite element formulation of the geometry of the system; the algorism used is due to Shubinski and Sheffey (1965). The input requirements for the model are channel lengths, widths, cross-sectional areas, and frictional resistance coefficients, and junction surface areas. Boundary conditions consist of the time varying tidal heights which can be expressed as a Fourier series or equally spaced points and tributary and mainstream river flow data. The model also treats conservative and non-conservative substances and temperature with a surface boundary exchange.

The next few paragraphs deal with verification attempts (Callaway and Byram, 1971); by this is meant duplication (primarily by adjustment of friction) of predicted heights and currents. We were not overwhelmed with actual field data and relied mainly on USC&GS tide tables for verification of the hydraulics. Stage elevations at Bonneville Dam were taken from a report by Bonneville Power Administration.

At the upper boundary condition the flow from the junction representing Bonneville Dam was input. Water elevation above datum was then approached as the channel depths responded to the amount of discharge. At the outset of this study, we were not sure just what the elevations should be and it was pleasurable to find that the computed elevations fell within 1 to 2 inches of observed, even when the difference in tailwater elevations for two flows was about seven feet.

In Figure 8, computed and observed co-range lines are given. Also shown in the figures are "observed" ranges as taken from the C&GS tide tables. In general, the agreement between computed and observed values is excellent.

Figure 9 shows a longitudinal section of computed and observed ranges. Note the agreement in the lower river which shows an increase in mean diurnal range with distance upstream, passing through 6 feet about mile 5 and again at mile 25. The agreement is rather good along the entire river stretch with the exception of from about mile 70 to 100. The reason for this discrepancy is not known, but could be due to channel modifications made after the USC&GS computations base data were collected but which are incorporated on the charts from which the input data was taken.

The 1959 flow data were chosen as representative of a "normal" low flow period. Starting at river mile 27, a wave with 6 foot range, Manning coefficient of 0.02 $ft^{1/6}$ and a 12.5 hour period was input at a river level of 3.8 feet (as determined from Corps of Engineers data for the flows used). It was assumed that 25 hours would be sufficient for convergence, hence these output data (first 25 hours) were discarded. Figure 10 shows the progression of the wave with distance upstream. Agreement between computed and Tide Table phase lags and amplitudes was very good.

Clark and Snyder (1969) published a note on their observations of current reversal 70 miles upstream from the mouth of the Columbia

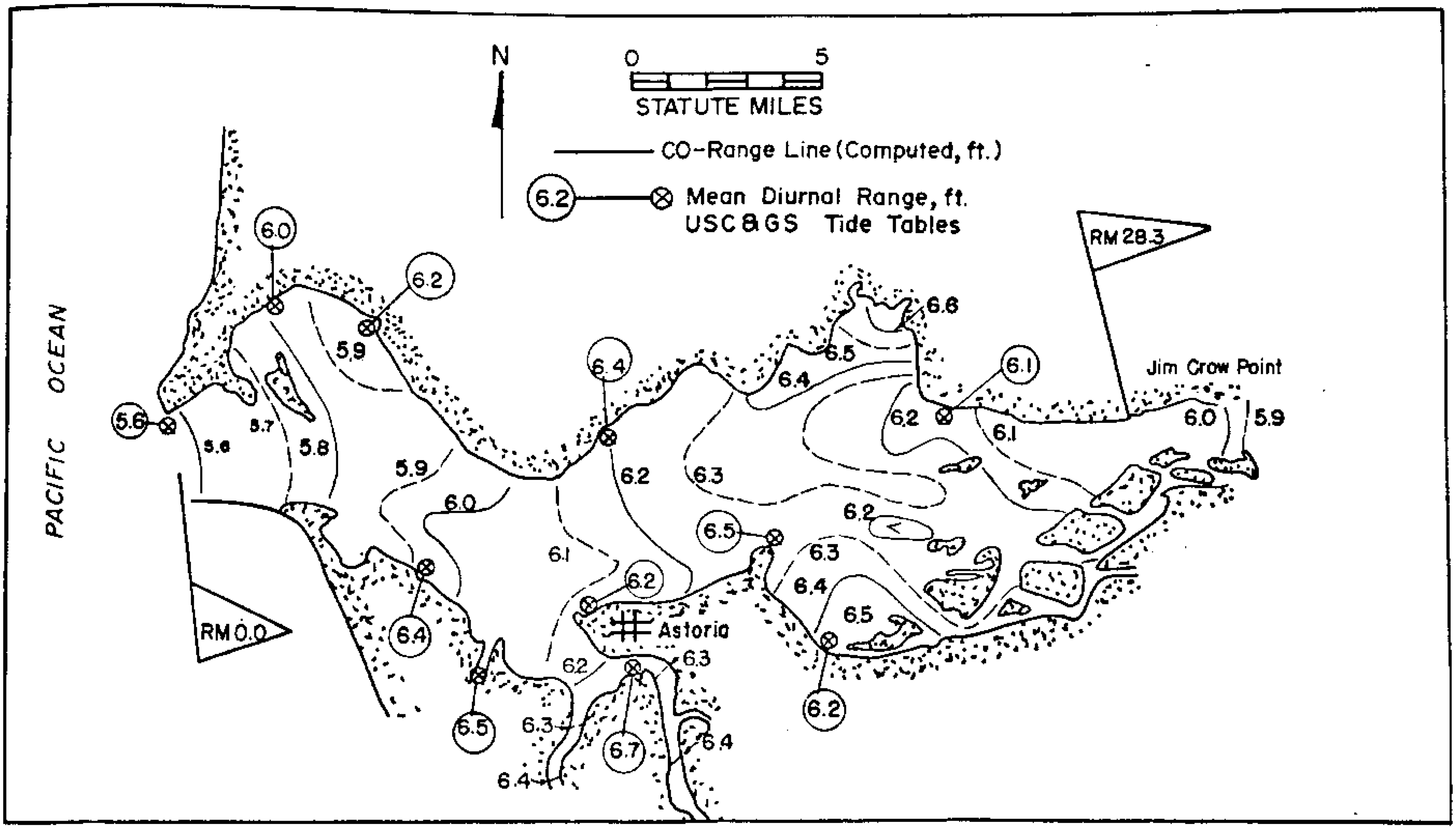


Fig. 8. Computed and observed tidal ranges, Columbia River, miles 0-30.
From Callaway and Byram (1971).

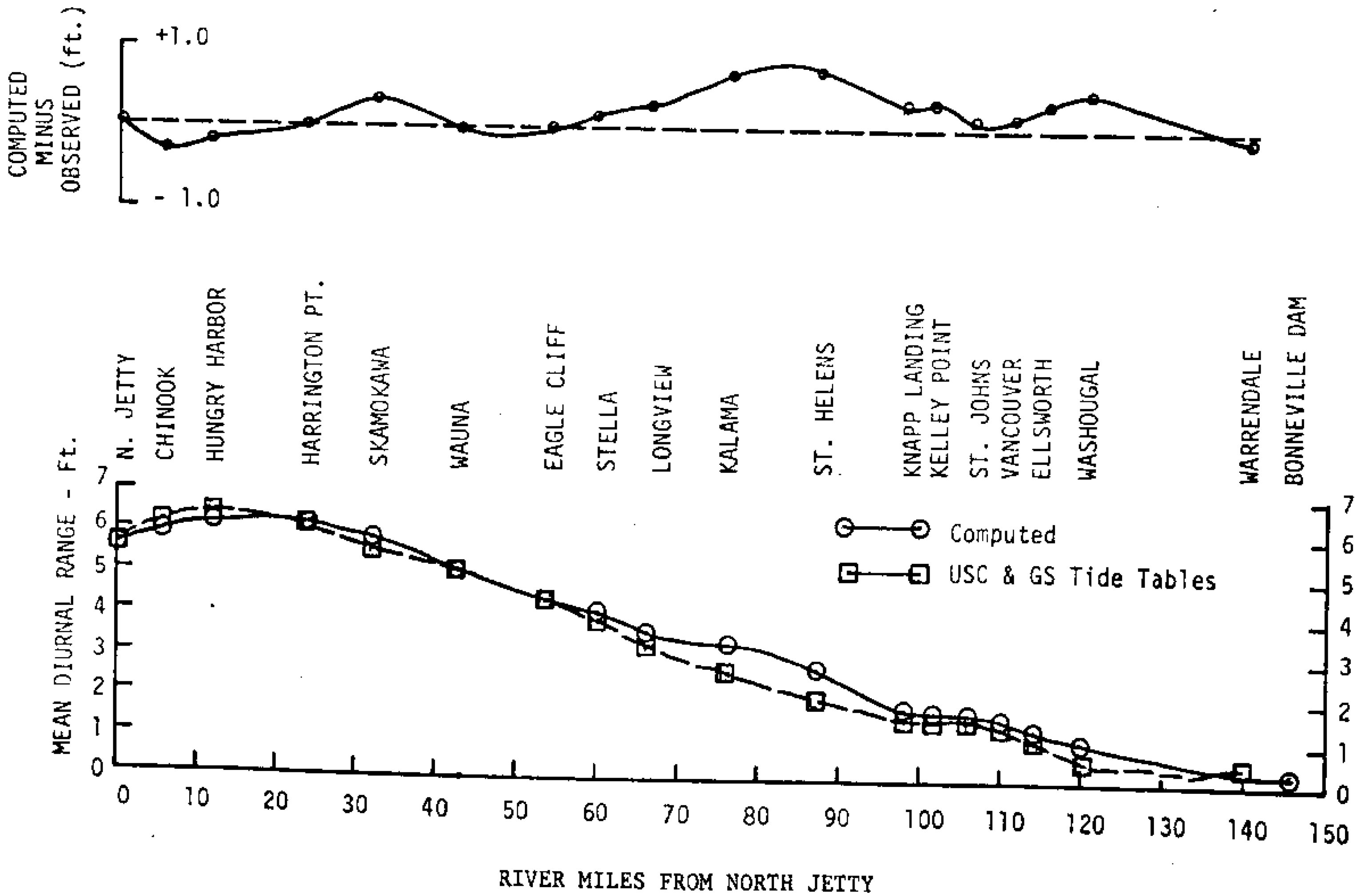


Fig. 9. Computed and observed tidal ranges, mid-channel Columbia River, Pacific Ocean to Bonneville Dam. From Callaway and Byram (1971).

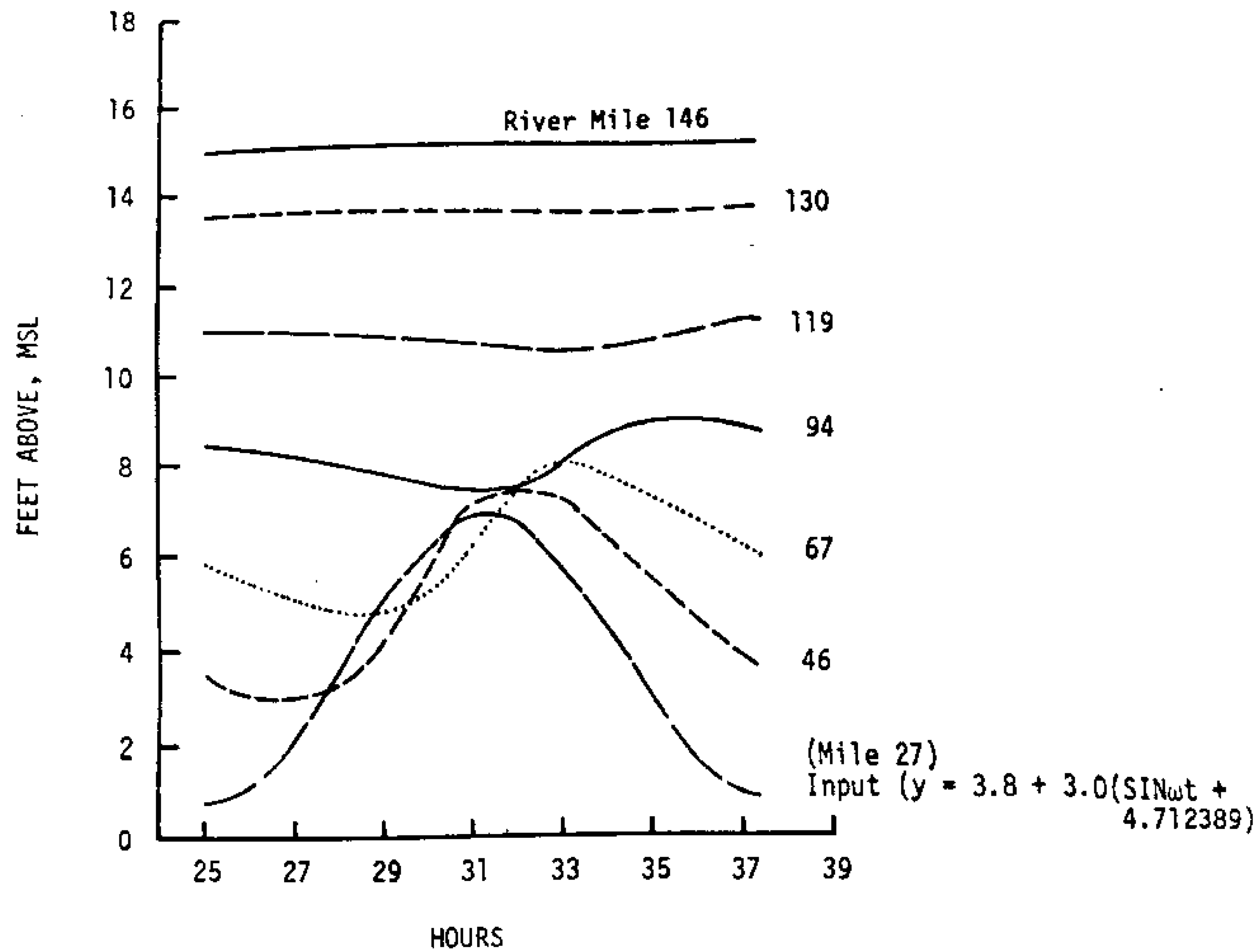


Fig. 10. Computed stage elevations versus time, mile 27-146. From Callaway and Byram (1971).

River, near the proposed site of two thermal electric power plants. The particular river stretch was chosen because heated cooling water returned to the stream might interfere with the endemic and anadromous fishery, especially if there were to be periods of low current speeds as during a current reversal. The purpose of their study was thus to determine if reversal occurred, and if so, to measure its duration during a very low flow period (84,500 cfs at Astoria) of less than half the river's mean annual discharge. The low flow occurring during their study was the result of filling the then just-completed John Day Reservoir. A rather extensive field study using dye dumps and fluorometry was reported; in summary, they found that reversal occurred over a four-hour period from about 3:50 a.m. to 8:00 a.m. on April 16-17, 1968.

A sine wave with a period of 12.5 hours and range of 7.5 feet, the diurnal range at the North Jetty, was input at the ocean end of the model. A Manning coefficient of 0.02 ft $^{1/6}$ was employed and conditions simulated for two tidal cycles.

Figure 11 is a computer plot of tidal elevations, velocities and flows at river miles 67 to 74. The somewhat erratic traces in the first few hours of simulation are due to convergence of the numerical solution from the given set of initial conditions. In this case, convergence was complete in about 10 hours. The open circles on the figure are tidal elevations as taken from Clark and Snyder and adjusted so that the computed second high water maximum is in phase with the observed.

Even though no attempt was made to input the existing mixed tide at the entrance (although it could easily have been at the expense of more computer time) the computed curve is in good agreement with the observed.

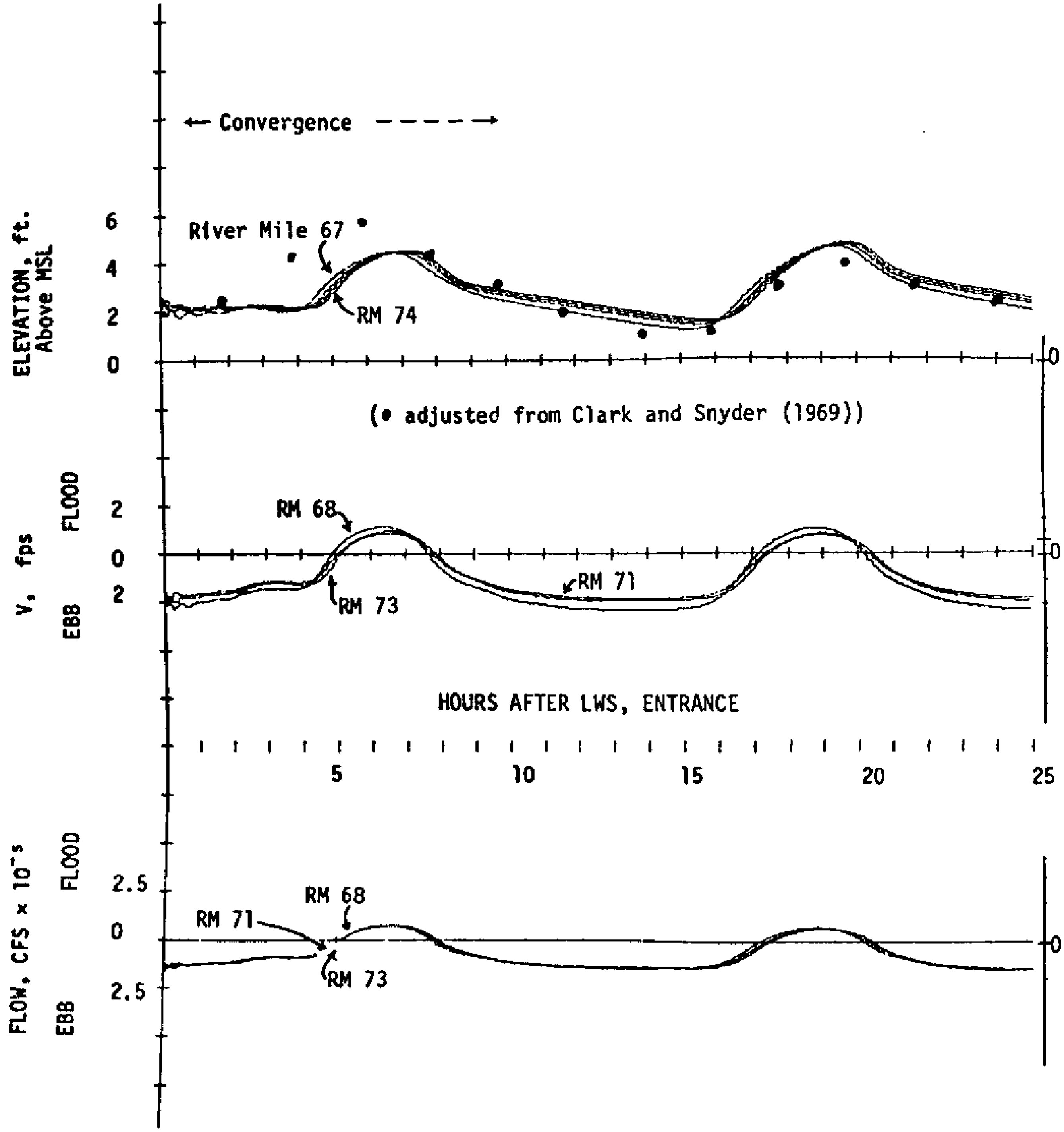


Fig. 11. Computed tidal elevation, current velocity and flow. Columbia River at about river mile 70 for low flow conditions. From Callaway and Byram (1971).

It can be seen that the frictional and non-linear term in the equation of motion have distorted the ocean input sine wave to the output shown near Prescott. Computed tide reversal (middle figure) occurs for about three hours as compared with four hours observed, the difference due mainly because a uniform friction coefficient was used in the model. Computed maximum flood velocity was 1.2 fps; maximum ebb velocity was 2.1 fps. These velocities are integrated vertically across channel and will generally be lower than observed peak velocities in mid-channel.

Computed transport through the channels is shown in the lower part of the figure. New flow in the Columbia channels for the last 12.5 hours of the run was 78,606 cfs; the remaining flow being diverted north through another channel. For the low flow period of 1968, Figures 12 and 13 show computer plots of head, velocity, and volume of flow with river mile upstream for the tidal cycles. These results have not been "verified" as such but are given here as additional examples of output.

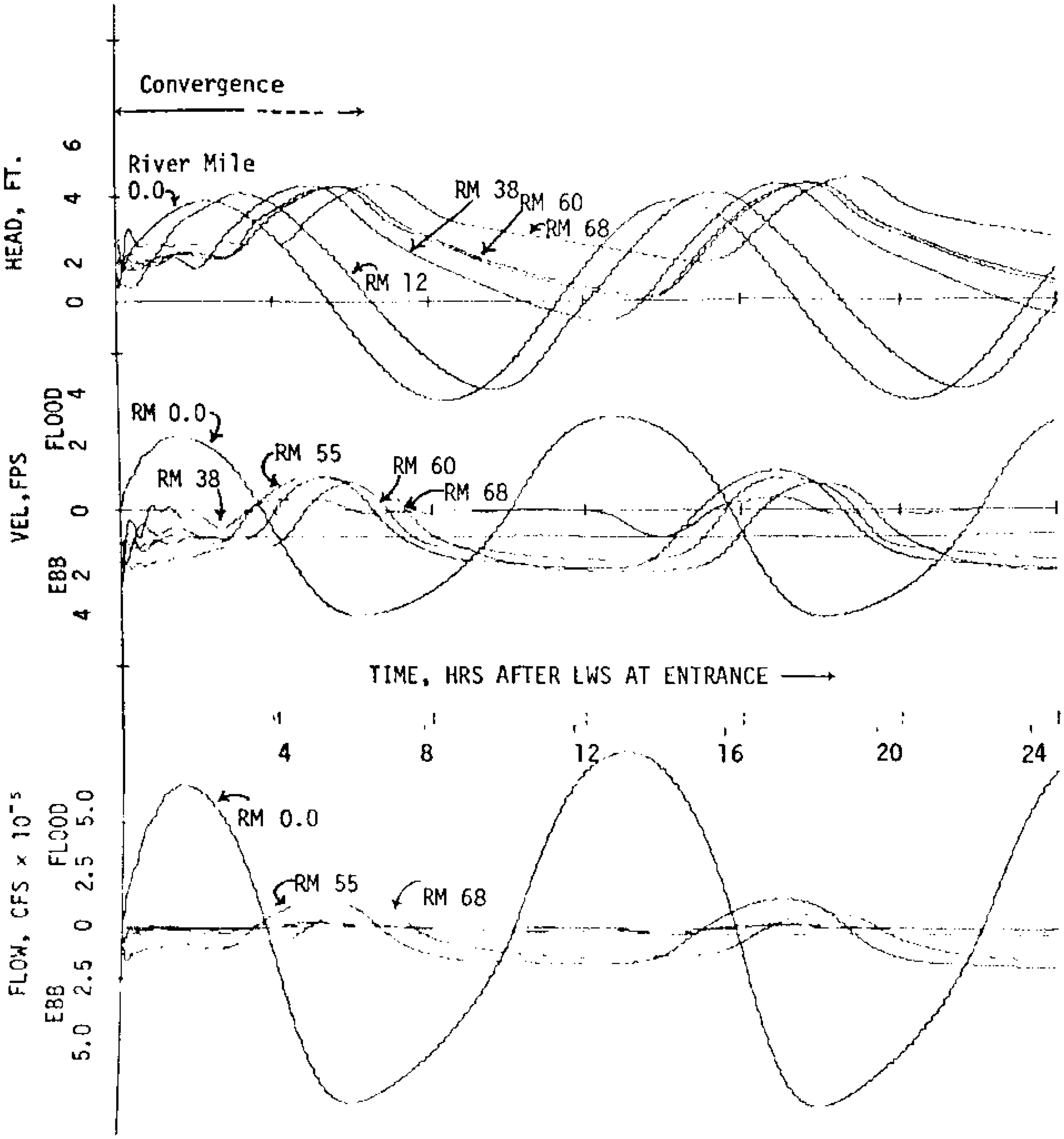


Fig. 12. Computed tidal elevation, velocity and flow. River mile 0-68, Columbia River, low flow conditions. From Callaway and Byram (1971).

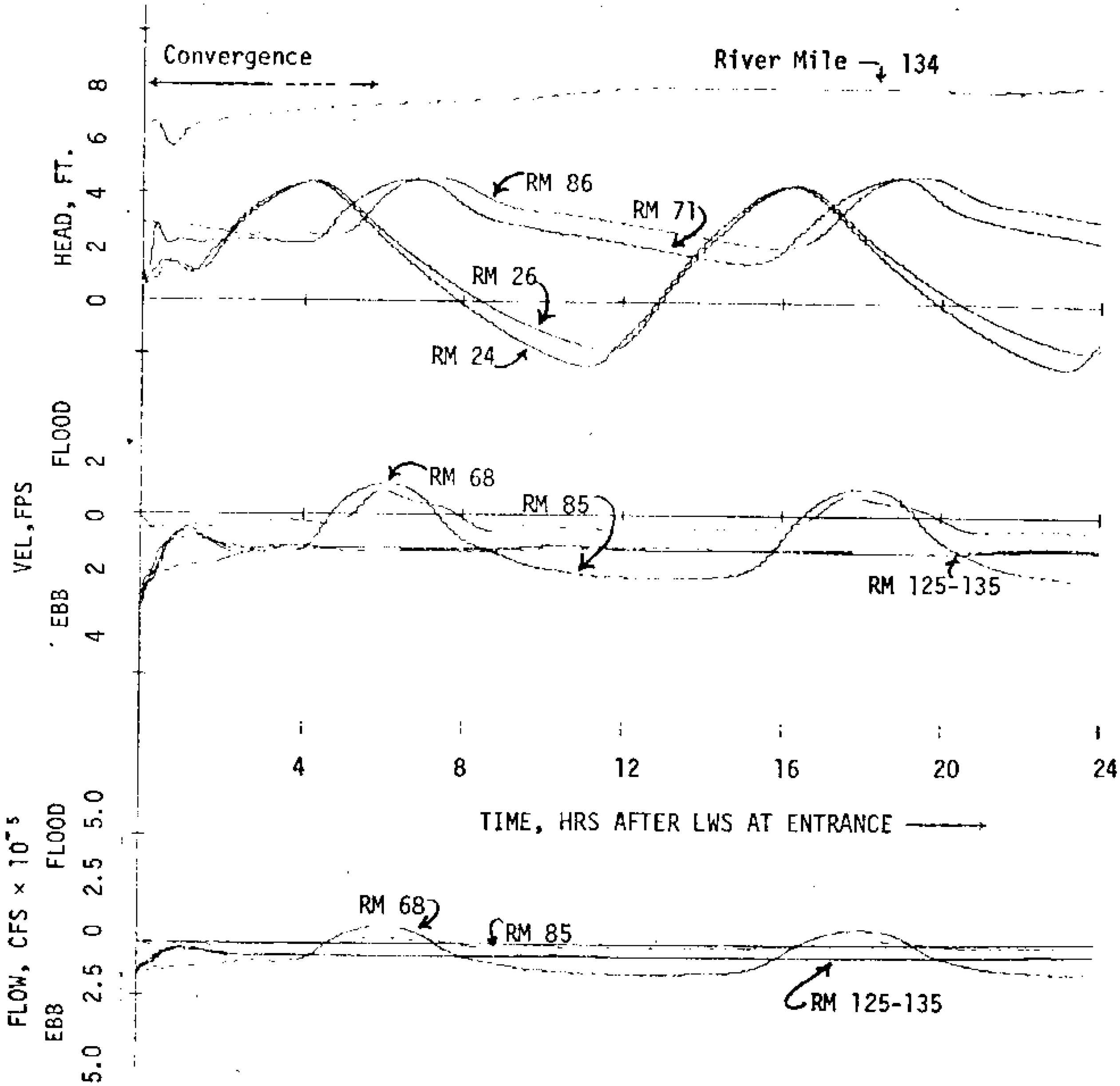


Fig. 13. Computed tidal elevation, velocity and flow. River miles 24-134, Columbia River, low flow conditions. From Callaway and Byram (1971).

FLUSHING

The residence time of pollutants in estuaries depends primarily on the freshwater runoff to the estuary. Calculation of the time required to remove dissolved substances results in a flushing rate and/or time. If the pollutant is discharged in or near the primary freshwater source, then the salinity distribution can be used for this computation; if not the distribution of the pollutant may have to be used.

Machine Calculations of Flushing

Once dynamic steady-state has been achieved in a time-varying model, i.e., after the pollutant has been distributed by allowing the program to run long enough, the flushing of a continuous release can be easily observed. The given distribution at time t is simply used as the initial distribution (t = 0) on a second run; the waste input is set to zero and the concentration decrease followed as long as need be.

For an instantaneous release, one sets the initial distribution in a given section or grid of the model to a certain level with no further inputs and allows the program to run (assuming the hydraulic portion, if any, of the model has achieved convergence).

Point source releases cannot be exactly simulated with a finite sized grid system, for the instantaneous or continuous case, of course.

Direct Observation

The response of an estuary to a sudden increase in streamflow can be quite dramatic as seen in Figure 14, a time-series of salinity in the Yaquina River Estuary (Callaway et al., 1970). Rainfall in inches per day is shown in the upper inset and the combined runoff from the Yaquina

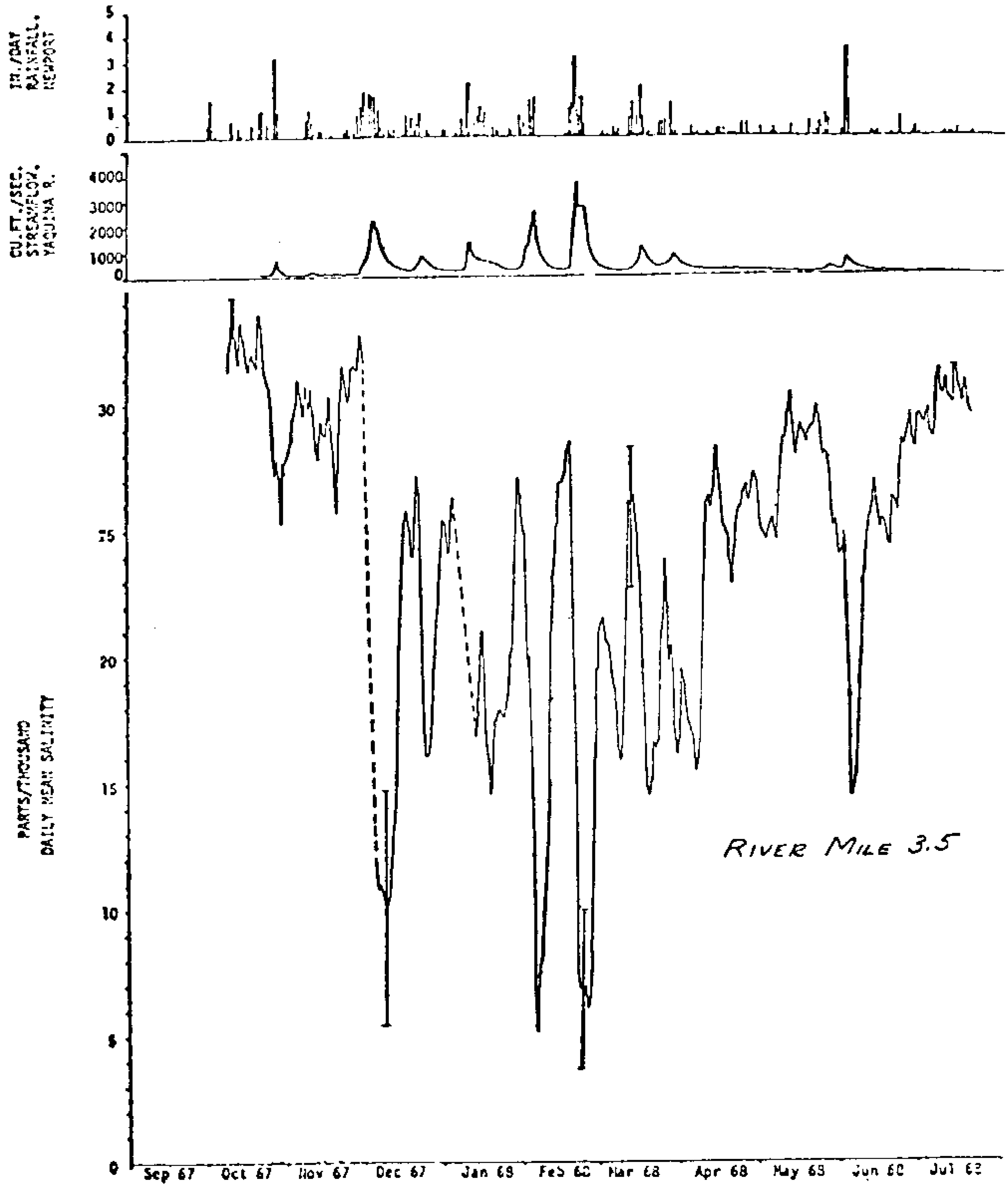


Fig. 14. Daily averages for selected parameters. From Callaway et al., (1969).

River and Elk Creek are shown below it. Coincident with the rainy season (starting in November, 1967) the salinity at mile 3.5 drops from about 33 ppt to 10 ppt.

With the succession of rainy periods during the winter, about 5 months are required until the higher salinity is achieved again (May, 1968). In June, 1968, a single intense storm of short duration lowered the salinity to about 15 ppt. It would appear from the hydrograph that local rainfall was effective in lowering the salinity as was the upstream runoff. In essence, then, flushing can be extremely fast and may at times sweep out the entire estuary.

Tidal Prism Method

The flushing rate of Grays Harbor was calculated by the tidal prism method described by Ketchum (1951). Here, the excursion length of the flood tide was used to divide the estuary into segments. Exchange ratios for each segment were calculated from:

$$r_n = \frac{P_n}{P_n + V_n}$$

where n = segment number

r_n = exchange ratio

P_n = tidal prism volume

V_n = low tide volume

Constant river flow was assumed (700 cfs) and a flushing time of 5.5 days was found.

The ratio of freshwater discharge during a half tidal cycle (12.4 hours) to P_n can be used to determine the type of vertical salinity distribution that is likely to occur:

$$\left\{ \int_0^T Q\,dt \right\} / P_n$$

where T = tidal period

Q = runoff

General, but not infallible, guides to vertical stratification were postulated by Schultz and Simmons (1957) who found that well-mixed estuaries have ratios of about 0.1; partly-mixed about 0.2-0.5; stratified conditions are found for values greater than 0.5 with 2-layer conditions being found at values near 1.0 or more. P_n/Q provides a measure of the flushing time.

Box Models

The "box" or "reservoir" model as used in oceans and estuaries has been described by Keeling and Bolin (1967) and Okubo and Pritchard (1969). In brief, one box or several connecting boxes are postulated as containing completely mixed fluids with exchange allowed within a box and between them at their mutual interface. Objections can be raised as to the loss of rigor when using the box model approach, i.e., replacing the appropriate differential equation with intuitive ideas on exchange processes and fluxes. However, when the system studied is complicated the box model method can prove a valuable tool, and perhaps the only tool, for studying processes between water masses and also between the water-air or water-sediment interface.

In a sense, all numerical models, i.e., finite sized grid models, are box models in that exchanges take place between grids at certain time steps. One difference between the "numerical" and the "box" model is that in the former case the governing equations are in terms of diffusion coefficients while in the box model diffusion processes are expressed as rates. As Okubo and Pritchard (op. cit) put it, "The exchange rate constants in the box model have ... no clearly defined physical basis, but, to be honest about it, neither do the eddy diffusivities."

As an example, the box model approach is used for evaluation of the flushing rate of sulfite waste liquor (SWL) in Bellingham Bay. Flushing, as evidenced by a decrease in the surface concentration of SWL, can be accomplished by seaward advection of the surface layer, diffusion downward, and biodegradation. Data on the distribution of SWL emanating from a pulp mill in the northeast corner of Bellingham Bay have been described in U.S. Department of Interior (1967), which includes data collected by the author during and after a mill closure as shown in Figure 15. Collias et al. (1966) give an extensive analysis of the flushing mechanism in the Bay.

The Bay is considered to be a box with a depth, d, of 10 feet (the upper mixed layer), length, l, of 12 nautical miles, and width, b, of 5 nautical miles. Rates are expressed as (1) seaward advection through the south vertical plane, (2) vertical diffusion through the bottom horizontal plane, and (3) decay within the box.

The rate of change of SWL can thus be expressed as:

$$\frac{ds}{dt} = -\left(\frac{Q}{V} + \frac{K_z}{A} + K\right)s$$

where s = SWL concentration (ppm)

Q = net seaward advection ($L^3\ T^{-1}$)

V = volume of the box (L^3)

K_z = vertical eddy diffusivity ($L^2\ T^{-1}$)

A = area of the horizontal plane (L^2)

K = decay rate of SWL (T^{-1})

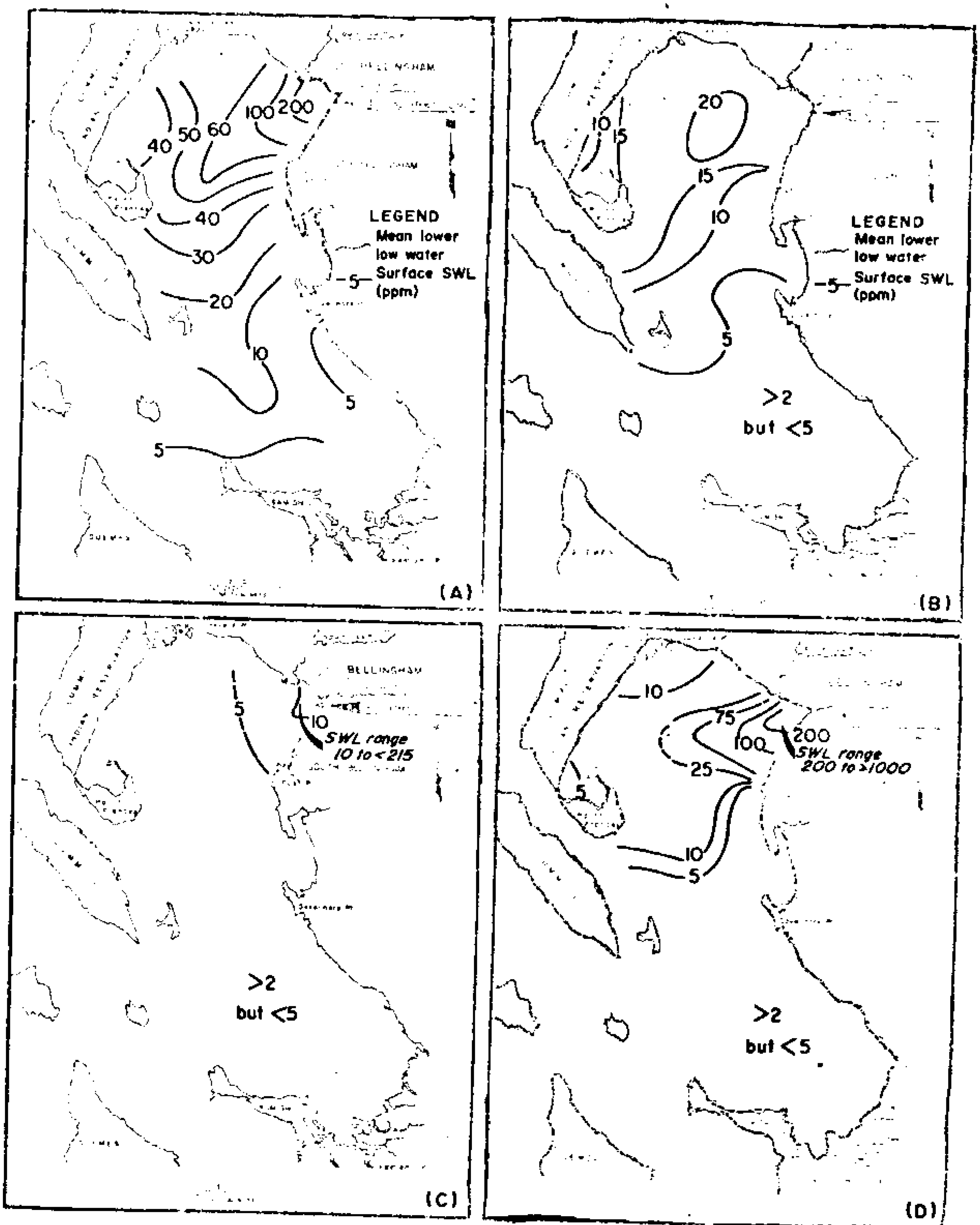


Fig. 15. Surface SWL: (A) average for the period Nov. 1959-Nov. 1961; (B) observed on Nov. 18, 1964; (C) observed on Nov. 25, 1964, and (D) observed on Dec. 1, 1964. From U. S. Dept. Int. (1967).

Seaward advection was estimated from net surface tidal velocities found at the entrances to the Bay by the USC&GS. Uncertainty exists as to the depth of the surface layer which for this example was chosen from an examination of vertical SWL profiles (Figure 16). Net velocities, passage widths, and depths result in a mean advective velocity, $\bar{U}$, of 0.1 ft. sec^{-1}. Since $Q = \bar{U}\, bd = 3.04 \times 10^4$ cfs, the rate of advection, $Q/V = 1.37 \times 10^{-6}\ sec^{-1}$. The primary tributary, Nooksack River, has daily flows ranging between 595 and 46,200 cfs with a mean daily flow of 3,700 cfs. The latter value of Q would put $\bar{U}$ at 0.012 ft. sec^{-1}. Both estimates of Q will be used in the order of magnitude analysis.

Vertical flux was estimated from the steady-state expression:

$$\bar{U} \frac{\partial s}{\partial x} = K_z \frac{\partial^2 s}{\partial z^2}$$

and K_z was computed from:

$$K_z = (\bar{U} \frac{\partial s}{\partial x})/(\frac{\partial^2 s}{\partial z^2})$$

The horizontal SWL gradient, $\partial s/\partial x$, was found to be 0.009 $ft.^{-1}$, and the vertical term, $\partial^2 s/\partial z^2$, to be 0.06 ft^{-2}, as displayed in Figures 15 and 16. For $\bar{U} = 0.1$, $K_z = 0.015\ ft^2\ sec^{-1}$. The half-life ($t_{1/2}$) of sulfite waste liquor in lagoons has been reported as 1 week by Lindsay et al. (1960). Assuming first order decay, the rate constant can be found from the expression $K = (t_{1/2})^{-1} \ln 0.5$.

For the lower advection rate (Q = 3,700 cfs) the magnitudes of the terms are:

$$Q/V = 0.17 \times 10^{-6}\ sec^{-1}$$

$$K_z/A = 6.09 \times 10^{-11}\ sec^{-1}$$

$$K = 1.09 \times 10^{-6}\ sec^{-1}$$

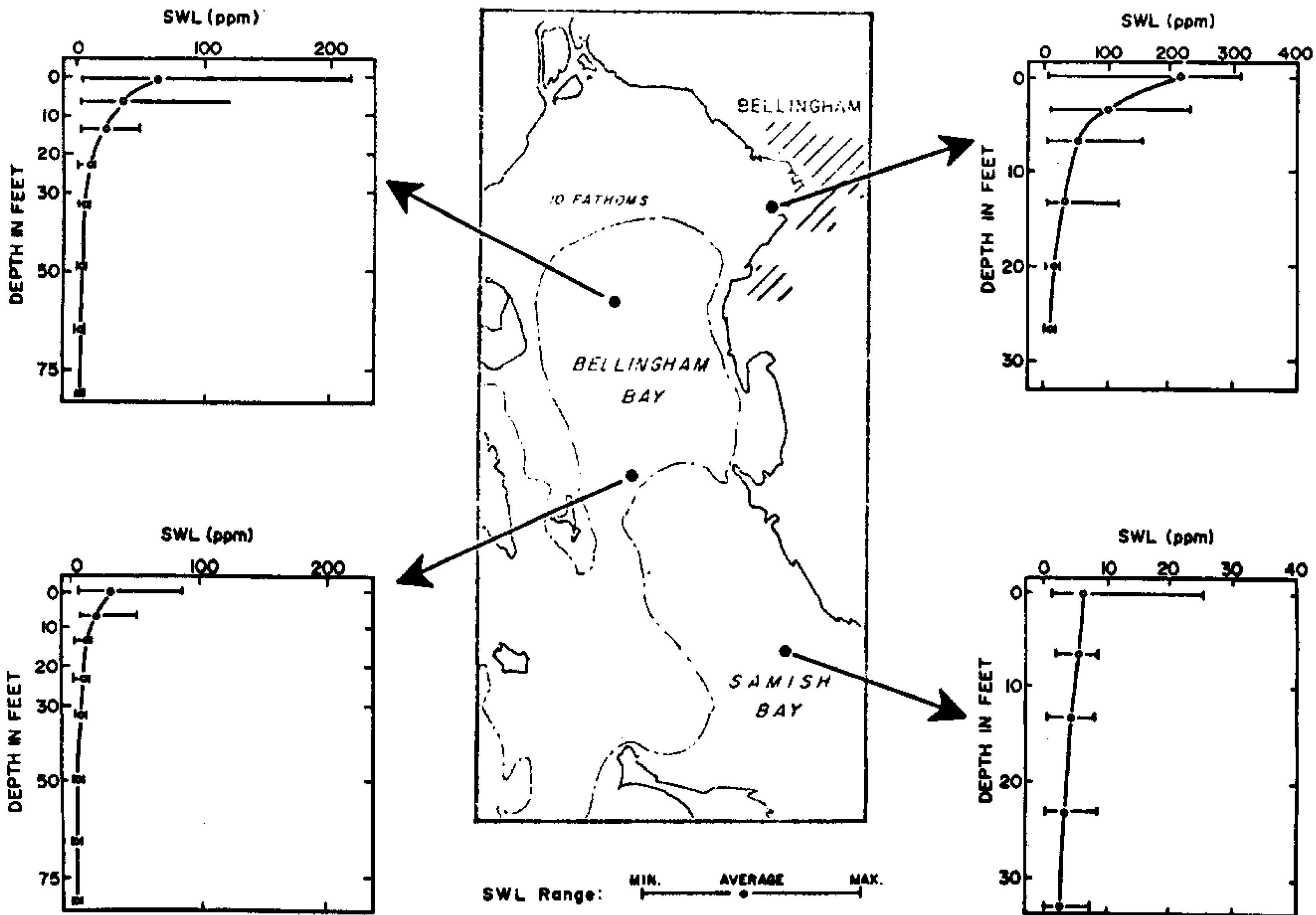


Fig. 16. Vertical distribution of average, maximum, and minimum SWL concentrations in Bellingham Bay. Data from Univ. of Wash. as given in U.S. Dept. Int. (1967).

From this analysis it can be seen that the loss by diffusion downward (for the box depth used) can be neglected relative to the other processes. The loss of measureable SWL by decay cannot be neglected at the flows used; however, as the size of the box decreases, K becomes negligible and Q/V becomes dominant.

Writing equation 18 in terms of the half-life of the distribution, taken as the time when the area (rather than the concentration) enclosed by the 5 ppm contour decreases to half that of the initial area:

$$\left(\frac{Q}{V} + K\right) = \frac{0.693}{t_{1/2}}$$

Upon substitution it is found that $t_{1/2}$ = 6.4 days for Q = 3700 cfs. For Q = 24000 cfs, $t_{1/2}$ = 3.6 days. For Q = 48000 cfs (the upper limit observed) $t_{1/2}$= 6 hours. The half-life found by planimetering the areas in Figure 15 was 2 days. The computed value seems reasonable considering the assumptions made.

In an attempt to calculate the rate, the word of warning mentioned at the beginning of this section was violated in obtaining a figure for the advection rate, namely, that the source of the effluent and the primary flushing source were in the same location. This is probably no worse a violation than the other assumptions such as complete mixing, etc.

In summary, it can be seen that a rapid estimate of flushing can be obtained via the box model approach but the data demands are no less stringent than a more sophisticated approach.

EFFECTS OF ESTUARIES ON OCEANS

The freshwater entering a river system eventually enters an estuary and is then discharged to sea. En route, losses may occur through seepage, evaporation or withdrawals, and agricultural or other diversions.

Water originally very pure in the headlands may, on its passage to the sea, accumulate substances which are detrimental. Some of the materials transported in this manner may precipitate out upon mixing with saltwater in the estuary, or be lost by deposition, by uptake of organisms, by evaporation, etc. Eventually, however, discharge of substances to the ocean will occur. When runoff is large, the plume of freshwater can be traced far offshore by observing the salinity distribution as shown for the Columbia, for example, by Duxbury et al. (1968). Work on the coastal distribution of Zn^{65} suggests that the best time to study its effects and to separate the Columbia from other coastal river discharges is during the winter when the Columbia is confined nearshore and directed northward; razor clam uptake of Zn^{65} is high at this time. At other times the Columbia plume is directed offshore.

Except in well-mixed estuaries, net flow landward along the bottom will occur, balancing the outflow in the surface layers by advection and entrainment of saline waters into the fresher surface layer. Offshore waters at depth will move inshore towards an estuary (the dynamics of this situation are different than these due to wind-related coastal upwelling) as has been demonstrated experimentally on the west coast for the Columbia River and San Francisco Bay; it appears to be a reasonable assumption for Cook Inlet waters. Coincident with this net shoreward movement are pollution problems associated with offshore dumping and barge disposal (see Callaway, 1970).

Tamai et al. (1969) exhibited the variation of salinity concentration in the Pacific Ocean resulting from the jet action of the Columbia during the spring and summer as a plot of ratios of seawater, jet axis, and river mouth salinities versus the dimensionless ratio of axis distance (x) divided by the width of the river mouth (D_0). These data are plotted in Figure 17 as is the relation found by Jen et al. (1966) for comparison. The latter was derived from laboratory experiments to determine the characteristics of a warm water jet discharged horizontally into initially resting deep water; D_0 was 0.036 feet.

Pak et al. (1970) have presented data on light-scattering measurements in the Columbia River plume (D_0 = 2 n. miles) and were able to trace the plume for 200 km; they deduced that the scatterers were contained in the plume water for at least 30 days. Their data are also plotted on the figure.

The salinity distribution along the south coast of Alaska and Shelikof Island (D_0 = 30 n. miles) and the Aleutian Island chain was calculated in a like manner and is shown in the figure for the summer of 1957 (Callaway, 1963) and 1958 (Dodimead et al., 1963). Average combined river flow of the Susitna River and from Knik Arm in Cook Inlet are reported (Wagner et al., N.D.) as about 52,800; 102,000; 124,000; and 111,000 cfs during May, June, July, and August, respectively. The June through August values are in the range of low Columbia River flows.

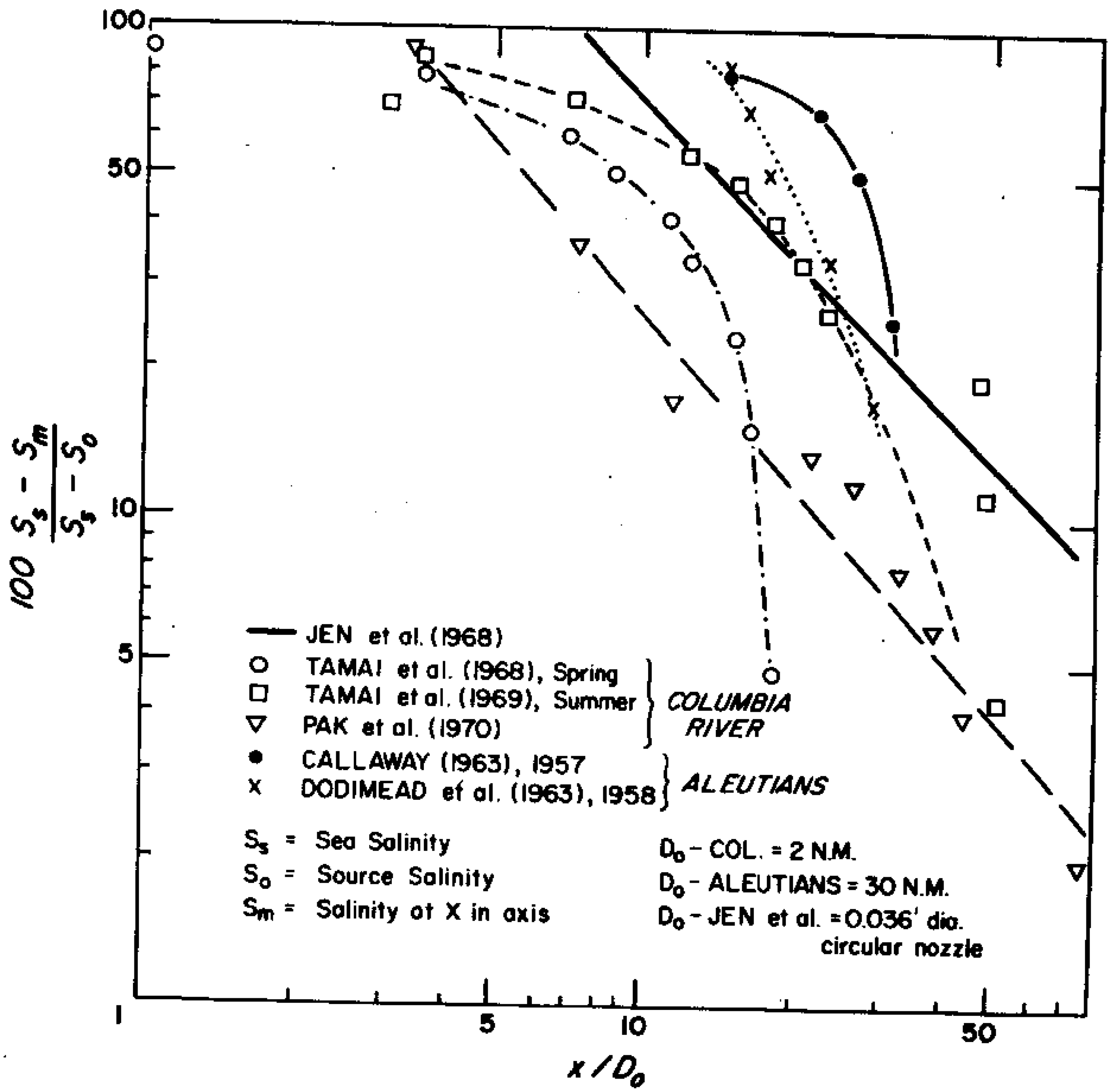


Fig. 17. Salinity or particle scattering along the jet axes of various water bodies.

The slopes of the four cases are somewhat similar. The ratio in the ordinate does not begin to fall off for the Aleutians until x is about equal to 10 D_0, unlike the Columbia, suggesting less horizontal and/or vertical entrainment with distance from the orifice. Since the coast and islands prevent entrainment of less saline waters to the north and since current direction south of the chain is into Bristol Bay, entrainment will be less than that of a plume directed into the ocean (as for the Columbia) where it can occur on both sides of the plume.

Less dramatic effects will be exhibited by estuaries fed by smaller river systems; however, it should be clear from the above brief discussion that the estuary and ocean are interacting systems with the potential to affect each other in adverse as well as beneficial ways. The upwelling model given for Grays Harbor provides one example of the oceans affect on the estuary.

DISCUSSION

A rather broad view of models has been presented with emphasis on the physical processes in estuaries. Of course, the real problems concern ecology and the effect of pollutants and natural substances on animal and plant communities.

Some examples of model use have been given ranging from a slide rule approximation of flushing to a time varying digital computer solution of an estuary-river system. Applications to Pacific Northwest estuaries serve to point out the usefulness of steady-state ways of looking at things while anticipating full scale, at least 2-dimensional, simulation of our rather small but highly complex systems. The main waters of Puget Sound have been avoided in this discussion for lack of actual computational examples rather than to suggest that they are uninteresting or unimportant. The Sound is anything but that; hopefully it is not a setting awaiting its overdue succession of disasters. Visions of one large, uncoordinated, city subdivided into an array of political fiefdoms spreading from Olympia to Canada occur.

Pollution problems are difficult to solve. The more we learn about what were once thought to be rather straightforward relationships the more mysteries we uncover. If the problems relating to our estuaries are to be solved in a short time span then recourse will necessarily have to be made to models of some sort. As before, the complexity of a model has no real bounds; we must utilize the simplest, largest scale, model possible to attack existing problems rather than devoting too much attention to a virtually limitless collection of microcosmic structures. Information exchange among practicing engineers actually using models or requiring them to make management decisions and theoretical and applied engineers and scientists is a necessity if we are to continuously narrow the gap between overly simplified models (what is practical) and those of the forefront variety (what is possible).

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Mathematical Modeling of Estuarine Benthal Systems

by
David A. Bella
Assistant Professor
Department of Civil Engineering
Oregon State University
Corvallis, Oregon

ABSTRACT

The use of mathematical models in a study of estuarine benthal systems is discussed. The mechanisms within the benthal systems which result in a reduction of dissolved oxygen and a release of free sulfides are discussed. A mathematical model which describes the relationships between soluble organics, insoluble organics, sulfates, dissolved oxygen, and free sulfides within the deposits and overlying waters is presented.

INTRODUCTION

Aquatic ecosystems contain a wide variety of species. This diversity of species has been considered to be of great ecological importance, particularly in maintaining the stability of the ecosystem. Similar species compete for similar resources such as food, space and light. There is a tendency for the more efficient species to eliminate from the system the less efficient species (1). Because a high species diversity is desirable, a question that should be asked with reference to water resource management is, "what are the environmental conditions which allow competitor species to coexist and how can these conditions be preserved?".

Environmental variations, both in time (2)(3)(4) and space (3)(5)(6) are factors which can contribute to the coexistence of competitors within a given ecosystem. Reduction of natural environmental variations can thus contribute to the reduction of species diversity.

Consider a cross section of a typical estuary as shown in Figure 1. The estuary has been divided by the vertical solid line into two general sections: the main channel section (left side) and the tidal flat section (right side). These two sections have been further subdivided into four general regions. Regions A and A' consist of the main water bodies of each section. Regions B and B' are the water regions which extend several centimeters above the bottom. Vertical mixing in these regions is low and thus the chemical properties of regions B and B' are often quite different from the chemical properties of regions A and A'. The upper interstitial waters of the bottoms (waters containing dissolved oxygen) comprise regions C and C'. Deeper interstitial waters, lacking dissolved oxygen, make up regions D and D'.

Though varying in relative size, each of these eight general regions is of great ecological importance. Organisms which persist in one particular region would likely not survive in the remaining regions. Environmental conditions and variations with time are different for each of these regions. These differences are important as they contribute to the overall species diversity. (There are additional important variations within each of the defined regions, of course). Despite the ecological importance of all of

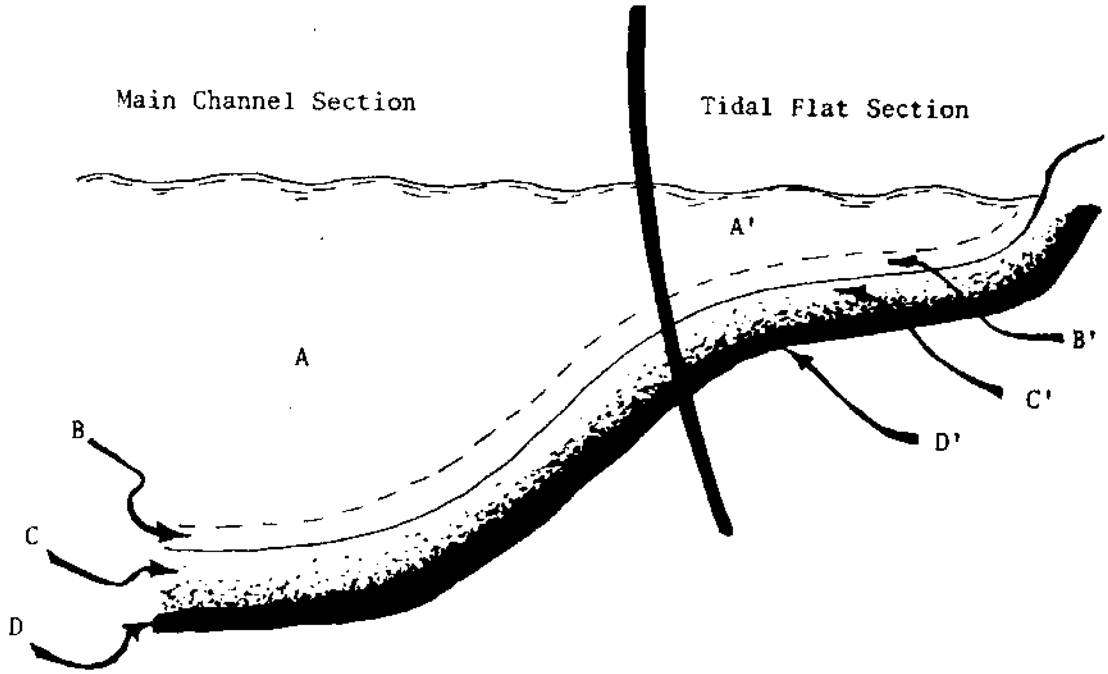


Figure 1.- Different Regions Within a Cross-section of a Vertically Well Mixed Estuary

these regions, water quality standards are written primarily for region A. Water quality monitoring by regulatory agencies is done almost exclusively in region A. Most research of water quality is concerned with region A. Most mathematical models involve only region A and occasionally region A'.

It is the purpose of this paper to discuss several aspects of the less frequently studied regions of estuarine ecosystems. Particular emphasis will be given to the role mathematical models have played in a current research project being conducted at Oregon State University. This paper will seek to not only present results of past observations, but, will attempt to give some insight as to the future directions of this study. Before proceeding to discuss observations of this research, however, the views from which the observations were taken will be discussed.

DETAIL AND PERSPECTIVE

The real world appears to be organized into an intergrated series of organizational structures. On an extremely small scale, atoms are organized to form molecules. On a large scale, the planets and sun are organized to form the solar system. Large numbers of intermediate structures, some obvious and some not, are of course present. The definitions of different structures and the disagreements of these definitions will not be pursued. Rather, the point to be made is that a given structure or entity is both made up of components and is also a component of a higher structure.

In order to understand the natural world, man has found it necessary to group what appear to be natural structures into larger groupings. As an example of a functional grouping, individual organisms with similar functions have been grouped into trophic levels. This grouping has enabled man to study the relationships between large groups of organisms. Such a grouping thus enables one to gain perspective, yet because of this larger grouping, one looses detail. This same real world systems may be studied at finer levels of resolution. That is, smaller groupings may be employed. As an example, individual organisms may be grouped into species. Such groupings permit one to gain detail, yet, because of the larger numbers of groups, one now has great difficulty in obtaining perspective. Thus, the same real world systems may be studied at different levels of organization (that is, different levels of resolution; different degrees of grouping). A fine resolution leads to a gain in detail with a sacrifice of perspective while a low resolution leads to a gain in perspective with a sacrifice in detail (precision).

Once a given investigator has defined what he feels to be the most important components of the particular real world system being studied, he then seeks to define the relationships between these components. In this manner, he hopes to form a conceptual model that will describe, within acceptable limits, specific real world phenomena by a logical arrangement of general, simple, and acceptable concepts.

Investigators of different professional background, both studying the same real world system, often form models of different levels of organization. Thus, for, a microbiologist, a level of resolution sufficiently fine to describe the numerous and different types of bacteria is essential. For an engineer or ecologist, most of these bacteria, as well as certain other organisms, can be grouped into a single category of "decomposers". The microbiologist argues that the larger grouping of "decomposers" omits detail which is essential to understanding the system. The ecologist and engineer, however, argue that if one divides the "decomposer" component into separate components for each species, or possibly for each individual organism, the number of components will be so large that it will be impossible to define the relationships between the components. In a sense, both arguments are correct for the increase in detail is gained by a loss in perspective while a gain in perspective results from a sacrifice in detail. While such different professions often appear to be separated by the traditional levels of organization used by each in viewing the real world, their views and observations should compliment each other and provide a means of understanding both detail and perspective.*

*Authors Note: Some information may require both detail and perspective simultaneously. Such information may be essentially unattainable. At this time, however, the rather philosophical question of "ecological uncertainty" will not be pursued.

The research project upon which this paper is based, from the start, has studied benthal systems (loosely defined structures having, however, some unique characteristics) from two general views (i.e. at two general levels of organizations.) Related component parts which make up benthal systems were studied. In addition, larger estuarine systems, of which the benthal systems are components, were also studied.

Feedback occurred between the results gained from the different views; that is, results gained at one level of organization influenced the direction of work done at the other level of organization. As an example, the percent of fine particles within the benthal deposits appear to be important. This result came from investigating the components of benthal systems within tidal flat regions (fine level of resolution). A wide range of man's activities might lead to a significant increase in the percent of silts and clays. These activities may be studied at lower levels of resolution; by studying the estuarine-river system. Upstream dams tend to hold back larger particles while suspended particles (colloidal and near colloidal) can proceed downstream. A large portion of these particles may then flocculate and settle out in the more saline estuarine waters.

Dredging operations tend to suspend large amounts of bottom materials. The larger particles settle quickly and are thus eventually picked up by the dredge. Often, currents at the lower depths within estuaries have a net velocity in the landward direction. Thus, dam's and dredging may contribute to along term increase in the percent of fine material within benthal deposits. A study of the larger river-estuary system would be needed to investigate the extent of this possible increase in fines. Thus, a study conducted at a fine level of resolution (benthal system) is now leading to questions that must be answered by a study at a lower level of resolution (river-estuarine system).

The remainder of this paper will emphasize benthal systems (particularly those in tidal flat regions). It must be recognized, however, that the behavior of benthal systems depends not only on the relationship of their sub-systems but also on the relationship of the benthal systems within the larger estuarine systems.

MATHEMATICAL MODELS

Conceptual models often lead to the development of mathematical models. Such use of mathematics results in two benefits.

First, mathematics is a precise language and thus it forces an investigator to precisely state the basic concepts of the model.

Second, having defined the concepts in the precise language of mathematics, one can manipulate the symbols by following a precisely defined set of rules. Such manipulation of symbols is a logical manipulation of the concepts expressed by the symbols. Thus, one may interact concepts to form new concepts.

The difficulty in the use of mathematical models most often arises when the symbols of the mathematical model are translated back to concepts. In order for such concepts to be reasonable and justified, the translator must be cognizant of the assumptions which had been made in translating the original concepts into the mathematical language.

The worth of a mathematical model, of course, depends on the worth of the concepts upon which the model was built. The worth of these original concepts, as well as the worth of the translation of the mathematical symbols into new concepts, rests on real world observations and the understanding of these observations. That is, mathematical models and experimental observations compliment each other. As an example, the oxygen demand of benthal deposits, particularly within tidal flat regions, was recognized in this study from the start as an important consideration. First, laboratory studies were made to study the benthal uptake (7). Next, a simple mathematical model was developed. From this model, an _in situ_ benthal respirometer was designed, built and run. The results from the _in situ_ benthal oxygen uptake rate studies appeared to be affected by leakage from the respirometer. A mathematical model of the respirometer system was developed and, from that model, correction for the leakage was made (8). The corrected benthal oxygen uptake rates were then studied. The mathematical model results indicated that the experimental results could only be explained if a substantial portion of the measured oxygen uptake rate was due to the release of a material which was oxidized rather quickly (half life of several hours or less). Both of these processes suggested that a large portion of the benthal uptake (not including benthal plant respiration) was due to a quickly oxidizing material; the material being oxidized either within the aerobic region of the deposit or within the overlying water. The literature suggested that free sulfides might be such materials. Because free sulfides (particularly hydrogen sulfide) are quite toxic, their presence within the water might often be of greater significance than the low DO values which result, in part, from the oxidation of the free sulfides. It was generally felt at the time, however, that the rapid rate at which free sulfides are oxidized in estuarine waters would prevent their presence in waters containing measurable DO. Thus, it was felt that the free sulfides which were released from the anaerobic regions of the deposit would normally be completely (or near completely) oxidized within the aerobic zone of the deposits. The literature also appeared to reflect this notion. A mathematical model of the aerobic zone of the deposits was developed (9). This model included the downward diffusion of DO, the upward diffusion of free sulfides and the reaction between the two. The model results indicated that under certain conditions, the free sulfide concentrations would likely be significant. Experimental methods were then developed and significant concentrations of free sulfides were measured in certain areas (9). Field studies and an exhaustive literature review then led to the following qualitative description of what appears at this time to be the important processes leading to both the oxygen uptake and the release of free sulfides (9)(10).

QUALITATIVE DESCRIPTION OF BENTHAL SYSTEM

The sulfur cycle has been described in some form in nearly every textbook on ecology. Its importance in benthal ecosystems has been stressed (11)(12), yet, it has often received only superficial attention. Significant processes which occur within benthal systems are illustrated in figure 2. In Figure 2, the overlying water has not been divided into the two regions shown in Figure 1. This omission was done for simplicity and thus the significance of these two regions should not be overlooked.

Various sulfur compounds occur within the water column overlying benthal deposits. In most brackish water which is oxygenated, these are usually in an oxidized state, with sulfates being the most abundant. Those sulfur species which are soluble may diffuse across the sediment-water interface and enter the sediments. Within the water and upper aerobic layer of the deposits, inorganic sulfur compounds may be utilized by sulfur oxidizing bacteria, such as those belonging to the genus Thiobacillus, which produce sulfates.

Hydrogen sulfide occurs in aqueous solution as part of the pH dependent system

$$H_2S \rightleftarrows HS^- + S^= \qquad (1)$$

At a pH of approximately 6.5-7, free sulfides are equally divided between H_2S and HS^- with $S^=$ being negligible. In the following discussion, all components of equation (1) will be referred to as 'free sulfide'. Free sulfide orginates within the anaerobic layer where it is primarily produced by heterotrophic sulfate reducing bacteria which utilize the sulfates as hydrogen acceptors (12). The sulfates diffuse downward from the overlying water. When sulfates are available, biological stabilization will likely occur through sulfate reduction rather than through methane fermentation (13).

Free sulfides may also be produced during anaerobic putrefaction of sulfur containing amino acids, but this process is felt to be of lesser importance in the marine environment (11)(14). The fate of the free sulfides thus produced will depend upon the physical and chemical characteristics of the deposits. If sufficient amounts of metal ions, such as iron, are present, the sulfide will form insoluble precipitates. If removal of these insoluble sulfur compounds does not take place, either by resolubilizing or through transport out of the area, the levels of total sulfide, which include free, soluble, and insoluble forms, may reach significant proportions in the sediments.

If the rate of sulfide production exceeds the rate at which it can be converted to nondiffusible forms, such as ferrous sulfide or insoluble sulfur, it may diffuse upward into the aerobic region and possibly into the water column. Here it will be oxidized to sulfite, sulfate, thiosulfate, or insoluble sulfur (14)(15)(16).

The chemical reaction of sulfides with oxygen in aqueous solutions has been studied by many investigators. Half lives of free sulfides ranging from 15 minutes to 70 hours have been reported (14)(15)(16) (17)(18)(19). Several studies have described the oxidation of free sulfides to occur by a second order reaction (14)(15)(16), however, such a description is a simplification of an extremely complex system (16). Studies done in sea water have indicated that pH, temperature, dissolved oxygen concentration and free sulfide concentration are all factors affecting the rate of oxidation (14)(15). The oxidation of free sulfides is catalized by the presence of metallic ions such as Ni, Mn, Fe, Ca, and Mg and is accelerated by some organic substances such as formaldehyde, phenols, and urea (16). These results suggest that oxidation of free sulfides in estuarine water may be more rapid than in distilled water due to the presence of such catalysts. During the past year, several experiments were conducted to investigate the rate of sulfide oxidation using aged, 0.2 micron-filtered sea water (salinity of 33 parts per thousand and initial pH at 8.2). Sulfide was measured with a sulfide membrane electrode on samples withdrawn from the system and fixed with a sulfide antioxidant buffer solution. While results varied with initial concentrations of oxygen and sulfide, half lives ranged from 10 minutes to one hour. These limited results are in fair agreement with other studies done in sea water in which half lives in the range of approximately 15-25 minutes were reported (14)(15)(19).

If the aerobic layer of the sediment is thin enough to allow light to penetrate to the anaerobic zone, photosynthetic purple and green sulfur bacteria may utilize the sulfides, producing free sulfur as a by-product. This often occurs below a layer of benthic algae and is possibly due to the lower compensation point for photoreduction, and to the ability of the photosynthetic bacteria to utilize longer wavelength light than the algae (11)(20). At one study site, a light purple color, believed to be caused by the presence of purple sulfur bacteria, was noticable on portions of the mud surface and immediately below mats of benthic blue-green algae which covered large portions of the site. The purple growth was identified as belonging to the purple sulfur bacteria, but as yet has not been classified as to genus.

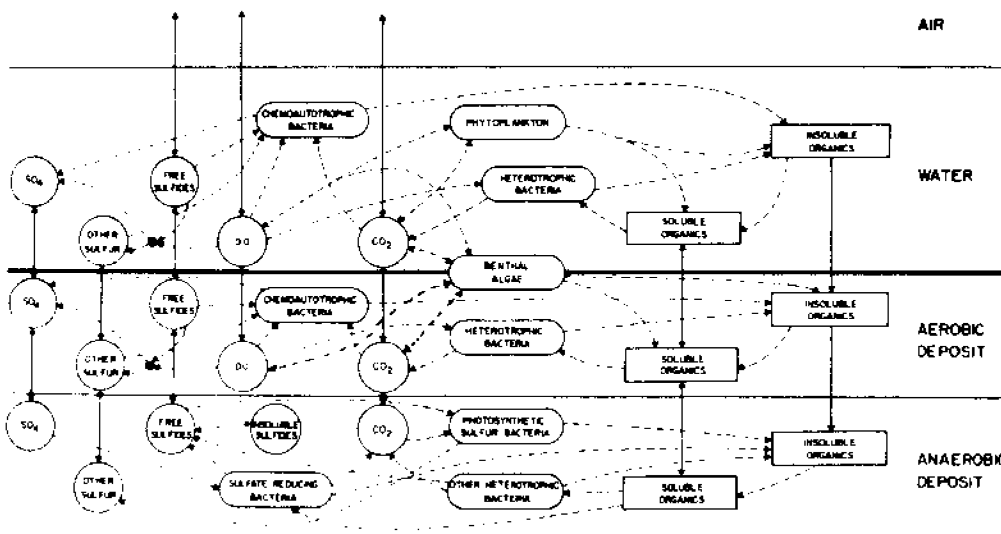
The dissolved oxygen within the water overlying the deposits may originate from reaeration and photosynthesis. In tidal flat regions, wind and wave action will have a major influence on the air-water transfer of dissolved oxygen. This transfer may occur either into or out of the water, depending upon the relative partial pressures of oxygen on each side of the interface.

During daylight hours, oxygen is produced photosynthetically by planktonic and benthal green plants through photolysis of the water molecule. The extent of photosynthesis depends on light, nutrients, temperature, and standing crop. Photosynthesis results in the production of organic material which may accumulate in the upper regions of the deposit. During the night hours, photosynthesis ceases, but respiration continues, resulting in a nocturnal decrease of DO. Diel DO variations between 14 mg/L and 6 mg/L are not uncommon within tidal flat regions.

The high reaction rate between free sulfides and dissolved oxygen in estuarine waters has contributed to the general assumption that free sulfides released from the anaerobic layers of the deposit will be essentially completely oxidized within the aerobic layer of the deposit. Significant concentrations of free sulfides within waters containing normal dissolved oxygen concentrations has been generally considered as a transient condition due to dredging, scour, or other similar major benthal disruptions. In general, the continued presence of significant concentrations of free sulfides in waters containing dissolved oxygen has been considered improbable. Because of the relatively high toxicity of free sulfides, principally H_2S, the presence of free sulfides might often be a more serious water quality problem than the lower DO values resulting from the oxidation of the sulfides (21).

Under certain conditions, free sulfide concentrations within tidal flat waters were measured at concentrations of approximately 1 mg/l even within waters containing 4 mg/l or more of dissolved oxygen (9). These levels of free sulfides will most likely be quite harmful to many desirable species (11)(21). The presence of silt and clay particles, large amounts of organics within the deposits, shallow water depths, available sulfates, low dissolved oxygen concentrations, poor drainage and low water velocities all appear to contribute to higher concentrations of free sulfides within the overlying waters.

It is intended that continued research employing a feedback between experimental and mathematical model results will better define the extent and significance of free sulfide release and the conditions contributing to this release.



(a) VERTICAL LINES REPRESENT PHYSICAL TRANSFER PROCESSES
(b) CHEMICAL REACTION NOTED BY (●)

Figure 2. - Diagram of Estuarine Benthal System.

GENERAL BENTHAL DEPOSIT MODEL

General

In this section, a model is developed which more closely desc the processes illustrated in Figure 2 than did previous models. S principal assumptions used in the model are listed below.

1. The model will be one-dimensional; considering only variations in the vertical direction.

2. The model will assume an equilibrium between sorbed and non sorbed materials.

3. The model will assume an initial distribution of organics and no addition of total organics will be included. The addition of organics through settling primary production and other sources will later be included as an expansion of the model.

4. It will be assumed that adapted microorganisms are available to carry out biological reactions. In addition, substances which effect biochemical reacti but are not included within the model are assumed to have a constant influence.

5. As in all models, many different substances will be grouped into large catagories. As an example, solub organics will be grouped into two catagories (degrada and nondegradable). If necessary, these groupings ma be further broken down.

6. Several additional assumptions can be observed by inspection of the model. Because of assumptions 2 and 4, the model will better describe slow, long term variations than sudden, short term, variations.

General Notation

The following general notation will be utilized.

1. G proceeding a second symbol will signify a rate chan per unit volume of water. The second symbol, followi the G, will define the substance changing.

2. R will signify a maximum rate for a particular reaction, assuming no limiting materials and no inhibition. Subscripts on R will define the particular reaction.

3. The star superscript (*) will signify a coefficient pertaining to an aerobic reaction.

New specific notation will be defined as the model is developed. Organic material will be quantified by the COD through a different measury may later be needed due to measurement difficulties.

General Description of Soluble Materials

Consider a vertical section of deposit and overlying water of horizontal area A. Positive depth z, is measured from the water surface downward. Taking a mass balance on a slice of depth dz within the deposit leads to

$$\frac{\partial(AndzS')}{\partial t} = F_i - F_o + n(GS')Adz) \qquad (2)$$

in which n is the fraction of the deposit filled with water, S' is the concentration of a soluble substance, F_i is the total flux of this substance into the slice, F_o is the flux of the substance out of the slice and (GS') is the sum of the addition and removal rates per unit volume of water of S' within the slice.

The flux of S' due to advection and dispersion is taken as

$$F = - D_{s'}Am \frac{\partial S'}{\partial z} + UAmS' \qquad (3)$$

in which $D_{s'}$ is the vertical dispersion coefficient for S', U is the vertical velocity (positive downward) and m is the fraction of A open to diffusion and convection. Let

$$F_o = F_i + \frac{\partial F}{\partial z} dz \qquad (4)$$

Substituting equations (3) and (4) into equation (2) leads to

$$\frac{\partial (AnS')}{\partial t} = \frac{\partial (D_S{}'Am\partial S'/\partial z)}{\partial z} - \frac{\partial (UAmS')}{\partial x} + n(GS')A \qquad (5)$$

Assuming A to be constant with distance and time and n to be constant with time reduces equation (5) to

$$\frac{\partial S'}{\partial t} = \frac{1}{n} \frac{\partial (D_S{}'m(\partial S'/\partial z)}{\partial z} - \frac{\partial (UmS')}{\partial x} + (GS') \qquad (6)$$

which is taken as the general equation for a soluble material within the vertical slice. Equation (5) can be used within both the deposit and the overlying water. In the overlying water n and m will equal unity, while both will have lower values (approximately 0.4) within the deposit. In addition, $D_S{}'$ will be substantially greater within the overlying water.

General Equation for Insoluble Materials

For the present, no insoluble materials will be included in the overlying water. Thus, following a similar mass balance as above, one obtains the general equation for insoluble materials shown below:

$$\frac{\partial I'}{\partial T} = (GI') \qquad (7)$$

in which I' is the concentration of the insoluble materials and (GI') is the sum of the sources and sinks of insoluble materials at a particular depth.

Promoters and Inhibitors

The primary differences between the various substances included in the mass balance will be expressed in the terms (GS') and (GI'). Differences in D_S, may also be expected particularly when dispersion is reduced to molecular diffusion.

Reaction rates which determine (GS') and (GI') will be determined by the concentrations of two types of substances; substances which promote the reaction and substances which inhibit or retard the reaction.

As an example, DO would promote aerobic biological reactions and inhibit anaerobic biological reactions. Let P be the concentration of a substance which promotes the reaction while I is the concentration of a substance which inhibits or retards the reaction.

Considering a unit volume of water, biological reaction promotion will be expressed by the common Michaelis-Mention equation shown below:

$$G = R\left(\frac{P}{K_p + P}\right) \qquad (8)$$

in which G is a given reaction rate per unit volume of water, R is the maximum reaction rate which occurs when P is large, and K_p is the concentration of P when G equals one half R, assuming no other promoters or inhibitors reduce the reaction rate. A star (*) superscript will denote K values applicable to aerobic reactions. When multiple promoters occur equation (8) will be expanded to

$$G = R\left(\frac{P_1}{K_{P_2} + P_1}\right)\left(\frac{P_2}{K_{P_2} + P_2}\right)\left(\frac{P_n}{K_{P_n} + P_n}\right) \qquad (9)$$

Promoters will generally classified into substrates and hydrogen acceptors.

Inhibition of a biological reaction will presently be expressed by the equation

$$G = R\left(1 - \frac{I}{F_I + I}\right) \tag{10}$$

in which F_I is the concentration of I at which the reaction is reduced by one half. The sharpness of the inhibitor effect can be adjusted by raising I and F_I to higher powers. In the following presentation of equations, higher powers will not be shown. That is, equation (10) will be used as shown for the sake of simplicity. It is anticipated that a better method of including the effect of inhibitors will be developed as the system is better understood. For the present, however, equation (10), with higher powers of I and F_I used as needed, will serve to describe the inhibitor effects.

Insoluble Organics

The source and sink term for insoluble organics is given by

$$GIO = -\ (GIO)_1 - (GIO)_2 \tag{11}$$

in which $(GIO)_1$ is the aerobic breakdown rate of insoluble organics and $(GIO)_2$ is the anaerobic breakdown rate of insoluble organics.

The following equations will be applied.

$$\begin{aligned} (GIO)_1 &= R^*_{IO}\left(\frac{b^*IO}{K^*_{IO} + b^*IO}\right)\left(\frac{O}{K_O + O}\right)\left(1 - \frac{S}{F^*_S + S}\right) \\ (GIO)_2 &= R_{IO}\left(\frac{bIO}{K_{IO} + bIO}\right)\left(1 - \frac{O}{F_O + O}\right)\left(1 - \frac{S}{F_S + S}\right) \end{aligned} \tag{12}$$

in which O is the concentration of dissolved oxygen, S is the concentration of free sulfides, IO is the concentration of insoluble organics and b is the fraction of the insoluble COD that can be broken down.

Soluble Organics

The source and sink term for soluble organics is given by

$$\begin{aligned}(GSO) = {} & f(GIO)_1 + f^*(GIO)_2 \\ & - (GSO)_1 \\ & - (GSO)_2 \\ & - (GSO)_3\end{aligned} \tag{13}$$

in which f is the fraction of the biodegradable COD remaining after the conversion of insoluble to soluble, SO is the concentration of soluble organics, $(GSO)_1$ is the breakground rate of SO per unit volume of water due to aerobic decomposition, $(GSO)_2$ is the breakdown rate of SO due to sulfate reduction and $(GSO)_3$ is the breakdown rate of SO due to other anaerobic processes.

The following equations will be applied

$$(GSO)_1 = R_{SO*}\left(\frac{SO}{K^*_{SO} + SO}\right)\left(\frac{O}{K_O + O}\right)\left(1 - \frac{S}{F^*_S + S}\right)$$

$$(GSO)_2 = R'_{SO}\left(\frac{SO}{K_{SO} + SO}\right)\left(\frac{SUL}{K_{SUL} + SUL}\right)\left(1 - \frac{O}{F_O + O}\right)\left(1 - \frac{S}{F'_S + S}\right)$$

$$(GSO)_3 = R_{SO}\left(\frac{SO}{K_{SO} + SO}\right)\left(1 - \frac{O}{F_O + O}\right)\left(1 - \frac{S}{F_S + S}\right) \tag{14}$$

In which R'_{SO} denotes the maximum rate of SO removal per unit volume of water due to sulfate reduction while R_{SO} applies to all other anaerobic processes. SUL is the concentration of sulfates (SO_4) and $F_{S'}$ describes the inhibition of S on sulfate reduction.

<u>Sulfates</u>

The reaction of sulfates is given by

$$(GSUL) = - Y_{SUL}(GSO)_2 \tag{15}$$

in which Y_{SUL} is the mass of sulfate utilized per mass of COD oxidized by sulfate reduction. It is assumed that the source of SUL resulting from the biological and chemical oxidation of sulfides can be ignored when compared to the dispersion of SUL downward.

<u>Sulfides</u>

Let

$$\begin{aligned}(GS) = {} & Y_S\ (GSO)_2 + Y'_S\ (GSO)_3 \\ & - (GS)_1 \\ & - (GS)_2 \\ & - (GS)_3\end{aligned} \tag{16}$$

in which Y_S is the mass of sulfides released per mass of COD removed through sulfate reduction, Y'_S is the mass of sulfide released per mass of COD removed anaerobically (non sulfate reduction), resulting from the sulfur within the organic materials (putrification), $(GS)_1$ is the loss rate of sulfides (S) per unit volume of water due to the chemical reaction with DO, $(GS)_2$ is the removal rate of S due to the anaerobic photosythetic sulfur bacteria and $(GS)_3$ is the removal rate of S due to the aerobic autotrophic bacteria.

The following equations will be applied

$$(GS)_1 = \mu(O)(S)$$

$$(GS)_2 = R'_S \left(\frac{S}{K_S + S} \right) \left(\frac{L}{K_L + L} \right) \left(1 - \frac{O}{F_O + O} \right) \tag{17}$$

$$(GS)_3 = R^*_S \left(\frac{S}{K_S + S} \right) \left(\frac{O}{K_O + O} \right)$$

in which μ is the second order coefficient for the chemical oxidation of S and L is the light intensity.

Dissolved Oxygen

Let

$$\begin{aligned}(GO) = &- (1-f)(GIO)_1 \\ &- (GSO)_1 \\ &- Y_{OS}(GS)_1 \\ &- Y_{SO}(GS)_3\end{aligned} \tag{18}$$

in which Y_{OS} is the mass of O utilized per unit mass of S chemically oxidized, and Y_{SO} is the mass of O utilized per unit mass of S oxidized by aerobic sulfur bacteria. It is assumed that the COD loss in the anaerobic solubilization would result in an insignificant loss of O.

Combined Equations

Equations (6) through (18) combine to form a model of an estuarine benthal system. All of these equations may be included both within the interstitial water and within the overlying water. Interstitial and overlying water differ principally by the values of D, n, and m. The lower boundary will likely be relective, while the upper boundary condition at the water surface will be relective except for gases which transfer between the water and the atmosphere.

The model serves to quantitively express concepts concerning the processes that occur within an estuarine benthal system. The limitations of the concepts of course are not removed when these concepts are put in mathematical form. Thus, proper use of the model involves a continual evaluation of its limitations. The model, hopefully, will permit one to develop new concepts which arise by the interaction of the basic concepts from which the model was built. Sensitivity studies with the model will eventually serve to estimate which factors have the greatest influence on behavior of the benthal system. The model can thus indicate where experimental effort might most profitably be exerted. Ultimately, it is anticipated that the model will serve to describe (through probably not to a high degree of accuracy) the benthal response to a given environmental change, be it man-made or natural.

Finite-difference procedures (22) will be used to obtain approximations to the solutions of equations (6) through (18). At the present date, the complete model has not been programmed, though portions of the model have . Currently, experiments are being conducted to better define the processes expressed within the model; particular attention is being devoted to reactions $(GIO)_2$, $(GSO)_1$, $(GSO)_3$, and $(GS)_1$. As a result of model, laboratory and field experiments, the model will likely change as the benthal system is better understood. In particular, micronutrients may play a significant role in controlling biological reactions. As an example, lack of iron within the depths of the deposit may decrease sulfate reduction. If this is found to be significant, inclusion of iron within the model may be necessary. In addition, certain soluble organics may not be directly available to the sulfate reducing bacteria. Conversion of these organics to more available forms may be necessary. At present, it does not appear advisable to further divide the organics into two or more soluble components though this possibility will be considered as more experimental results become available. In the model's present form, certain complex soluble organics which are not available to the sulfate reducing bacteria may be included within the "insoluble organics" component.

SUMMARY

The use of mathematical models in conjunction with field and laboratory experiments for the study of estuarine benthal systems was discussed. The importance of dissolved oxygen and free sulfides was stressed. A mathematical model which includes important aspects of the benthal system was presented. It is intended that use of this model along with field and laboratory studies will lead to a better understanding of the estuarine benthal system and in particular, the influence of man's activities on this system.

ACKNOWLEDGMENTS

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Remote Sensing Acquisition of Tracer Dye and Infrared Imagery Information and Interpretation for Industrial Discharge Management

by

J. R. Eliason, D. G. Daniels, and H. P. Foote

Pacific Northwest Laboratories

A Division of Battelle Memorial Institute

P. O. Box 999

Richland, Washington 99352

ABSTRACT

Techniques have been developed at Battelle-Northwest to predict detailed patterns of waste movement in surface water by digital modeling techniques utilizing data collected from an aerial platform. Data is collected from a light aircraft flying at speeds greater than 100 miles per hour. Systems have been developed to conduct tracer dye tests with a sensitivity to ∿1 ppb and to map temperature patterns with 0.5°C accuracy. Techniques for computer reduction of the data collected have been developed. Data collected with the aerial imaging system is presently being utilized for computer model verification and input. Output from the models is in the form of isoconcentration or isothermal plots of the pollutant distribution with time in the water body. This information is invaluable for assessing the environmental impact of wastewater discharges and for providing data needed for industrial plant siting.

INTRODUCTION

Innumerable tracer and thermal studies of surface waters have been conducted to determine the dynamic parameters of water bodies. These studies in the past have relied primarily on contact sampling devices and aerial photography for quantitative and qualitative evaluation of the tests. In areas where rapid dynamic changes within the water body are taking place, it has been impractical to attempt to obtain enough measurements during a single test to quantitatively define the system characteristics. Remote sensing systems developed over the past several years are now able to provide the coverage necessary to conduct detailed studies of these dynamic changes which must be considered in evaluation of an industrial site. Limitations on discharge of industrial wastes into surface water bodies of all types are now being imposed by state and federal regulations which may be severely limiting because of lack of ability to accurately predict the impact of waste discharges on the environment. Advanced remote sensing systems developed by Battelle-Northwest are now capable of providing information on diffusion and dispersion of tracer dyes and accurate measurements of thermal patterns which are valuable input for evaluating existing industrial waste discharges and proposed industrial sites. This type of information will provide a sound basis for evaluating the effects of existing sites and will provide invaluable data needed to evaluate the impact of proposed sites.

Remote sensing systems used to collect data are mounted in a Cessna 206 aircraft. These systems include a dual channel optical mechanical imaging system operating in the visible spectrum for collection of tracer dye data, a single channel optical mechanical imaging system operating in the far infrared spectrum for collecting two-dimensional surface thermal data and an infrared radiometer operating in the far infrared spectrum for collecting radiometric temperature traverses. Data from these systems is recorded on a wide band magnetic tape recording unit for subsequent computer analysis. A block diagram of the aircraft and data analysis systems is shown in Figure 1. Output can be obtained as isothermal or isoconcentration plots produced directly by

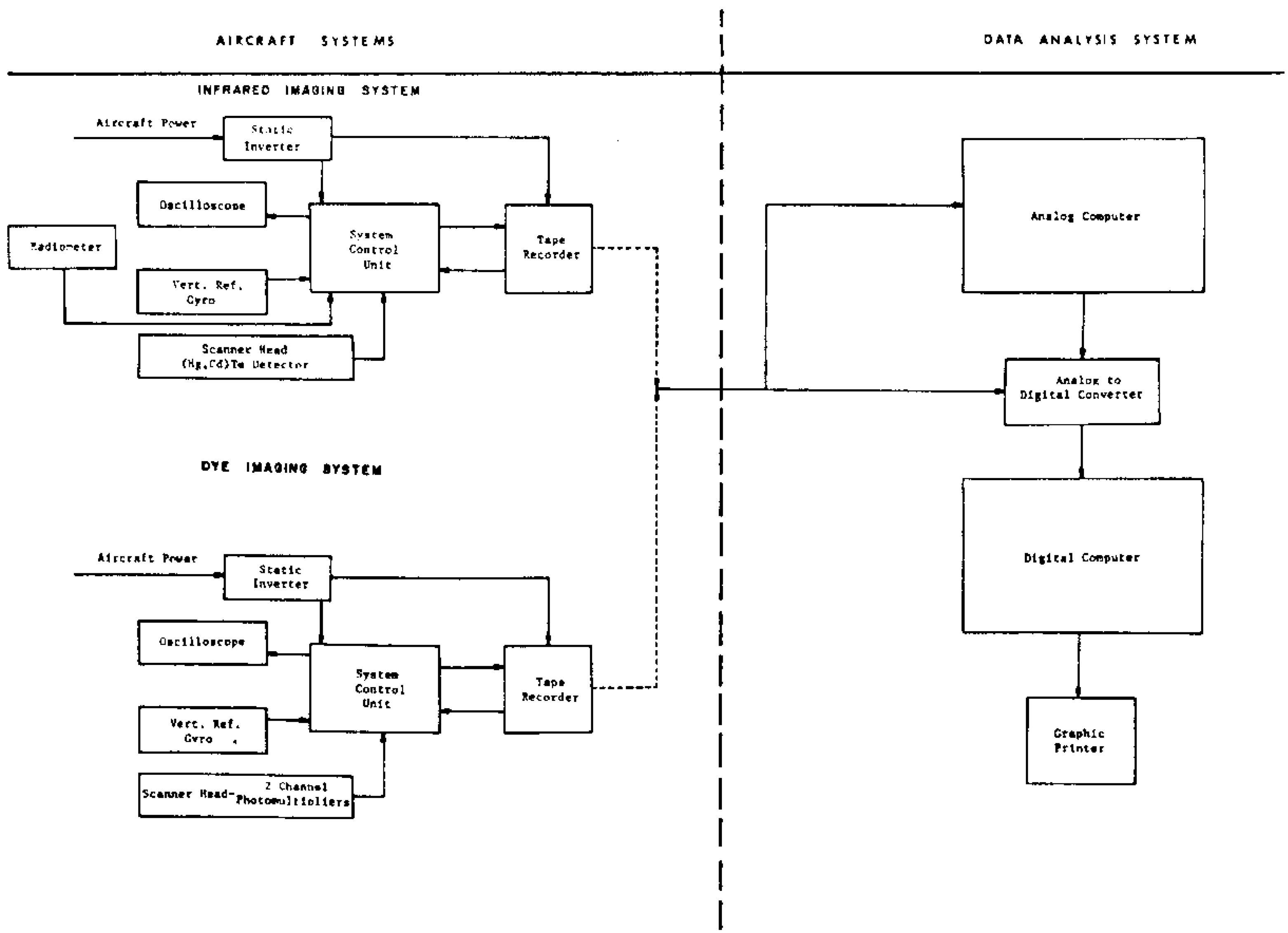


FIGURE 1. Block Diagram of Aircraft and Data Analysis Systems

the computer or the data can be output on digital tape, paper tape, or computer cards for subsequent computer analysis.

Subsequent analysis of the above described data yields input which is necessary for computer simulation of the temperature or concentration fields that would exist in the vicinity of an industrial effluent discharge. From the remotely sensed dye concentration data, lateral and longitudinal eddy diffusivities are calculated. A computer program has been written to solve the equations of motion in simplified form and output from this program is the predicted current velocity field in the vicinity of the plant effluent discharge outside the turbulent mixing zone caused by momentum and buoyancy of the effluent jet. Dye velocity measurements, taken during dye studies, are compared with the predicted velocity field for verification.

Within the turbulent mixing zone due to the momentum and buoyancy of the effluent jet, a separate jet model is used to predict the temperature or concentration and velocity fields. These temperatures or concentrations and velocities are used as boundary conditions in the simplified equations of motion and in the water transport model. Final output is in the form of predicted isothermal or isoconcentration plots that can be used for advanced planning and determination of the effects of the industrial discharge on the environment. Also temperature or concentration surfaces can be projected on paper for qualitative evaluation.

REMOTE SENSING INSTRUMENT SYSTEMS

Remote sensing systems developed by Battelle-Northwest are now capable of providing data on diffusion and dispersion of tracer dyes and accurate measurements of thermal patterns. The basic data collection system is an optical mechanical scanner which is operated from a light aircraft. Data is recorded directly on magnetic tape which can be input to a computer system for analysis. Output can be obtained as isothermal or isoconcentration plots produced directly by the computer or the data can be output on digital tape, paper tape, or computer cards for subsequent computer analysis.

The optical mechanical imaging systems scan an area normal to the aircraft flight path and 45 and 60 degrees either side of nadir. Figure 2 shows a typical scanner sweep path and the instantaneous field of view of the scanner, illustrating the relationship of the scanning system to the ground. Figure 3 shows a generalized diagram of an optical mechanical imaging system. This system consists of several basic units. The control and recording unit consists of a magnetic tape recorder section that records the signal (and other synchronizing pulses) generated in the systems. The system monitor and control section displays the signal on an oscilloscope for visual monitoring purposes. The intensity-modulated film recorder section uses the signal to modulate the intensity of an oscilloscope that sequentially scans and produces an image of the surface on film with

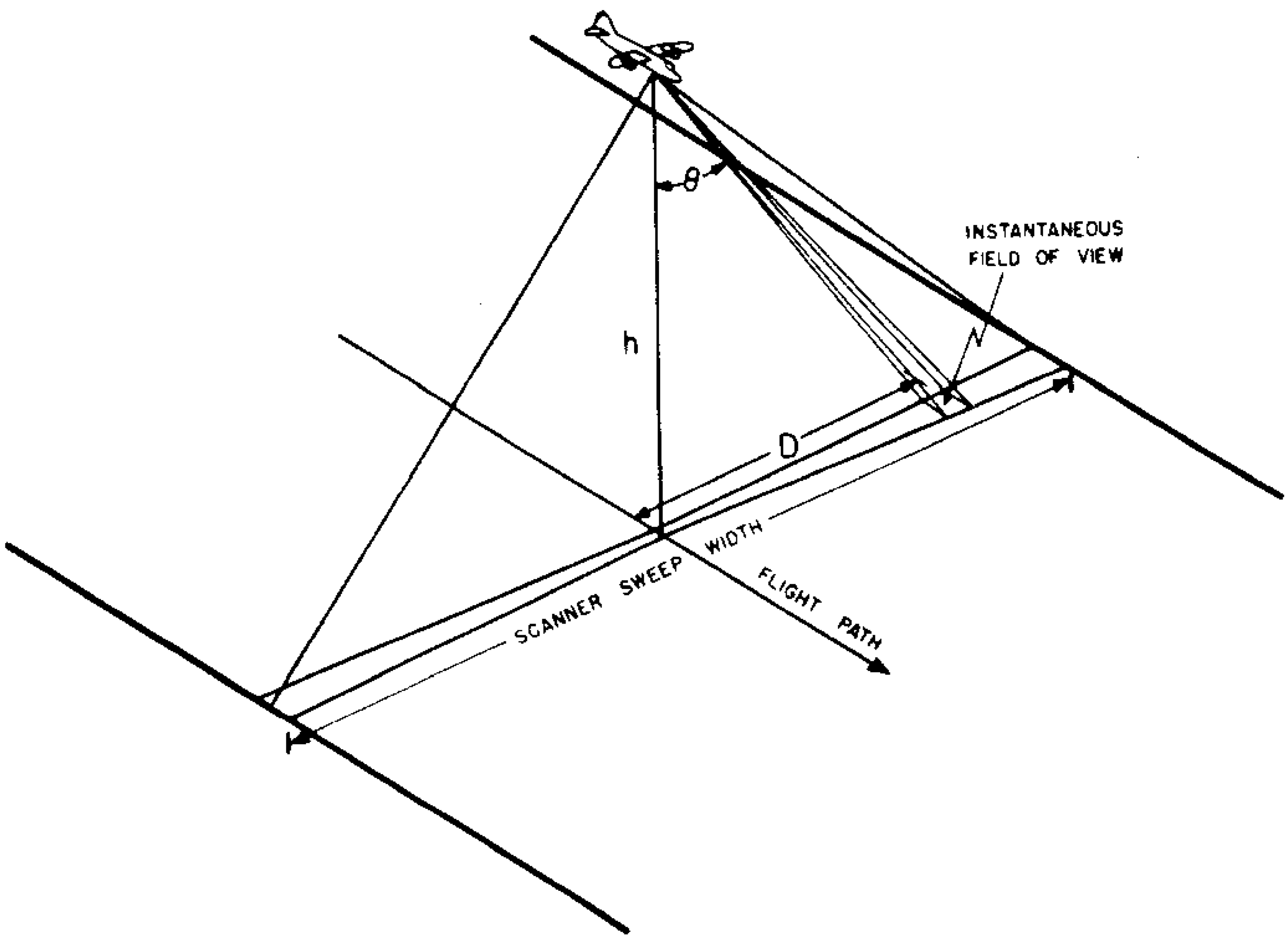


FIGURE 2. Imaging System Relationship to the Ground

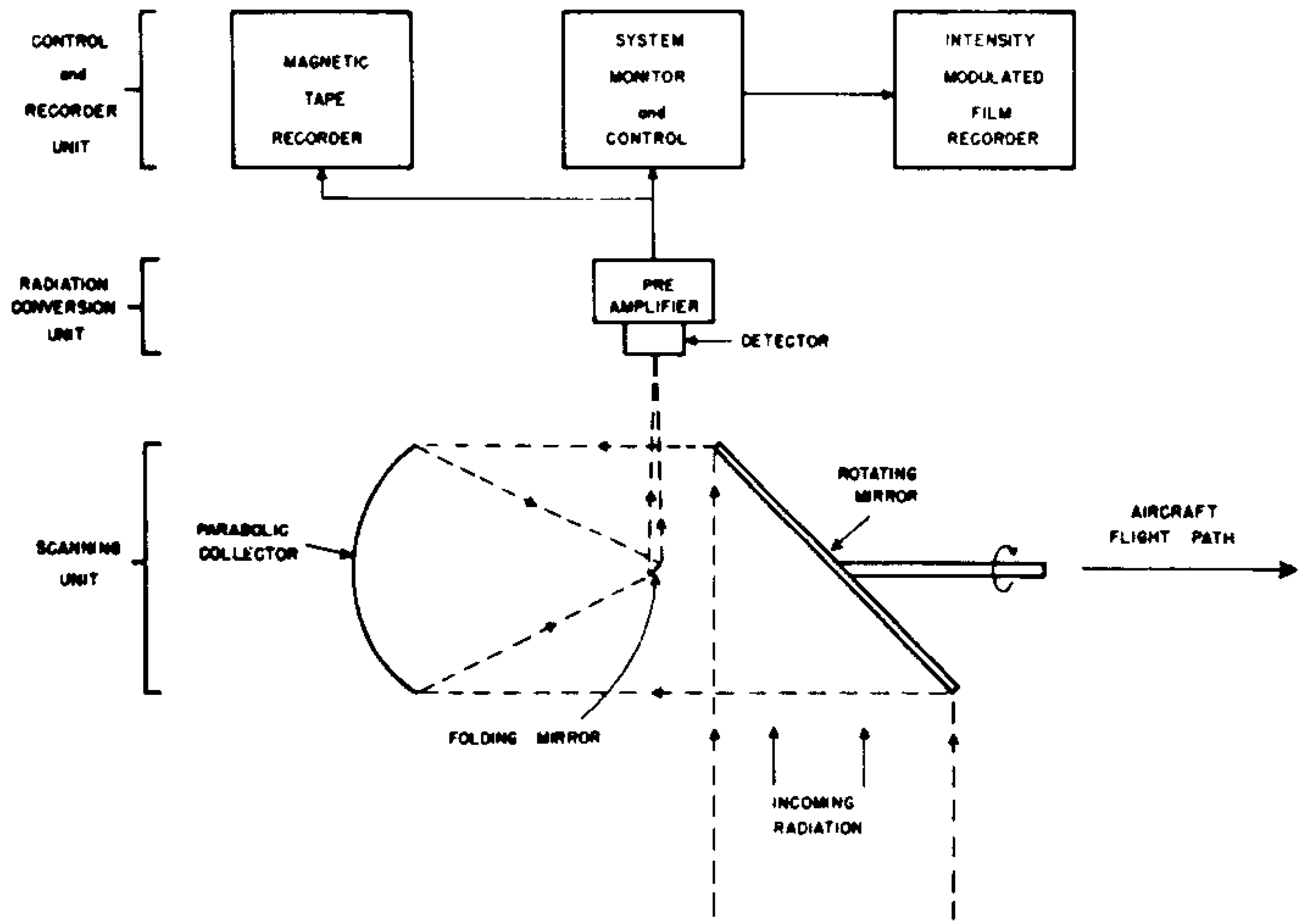


FIGURE 3. Optical Mechanical Imaging System

the position on the film corresponding to the scanner's position on the surface. The radiation conversion unit consists of a detector (photomultiplier or infrared detector) that responds to the radiation (fluorescence or radiant energy) to produce a signal that varies in amplitude with variations in the radiation intensity, and a pre-amplifier which amplifies the output of the detector. The scanning unit consists of a rotating mirror system that scans a segment of the surface normal to the flight path, and an optics system that collects and focuses the incoming radiation on the detector.

The dye tracer system and the infrared thermal system are passive systems which collect the electromagnetic radiation emitted by the fluorescent dye due to solar pumping and the long wavelength electromagnetic energy emitted by objects due to their temperature. The basic scanner is used in both systems with the dye system utilizing photomultipliers for the detectors and the thermal system having a photoconductive long wavelength detector sensitive to 8 to 14 μ infrared radiation (mercury cadmium telluride).

Optical mechanical imaging systems normally have a nonlinear ground scanning rate due to the scanner rotating at a constant angular rate. The relationship of the altitude to the distance from the center line of the scan is $D = h \operatorname{Tan} \theta$, where D is the distance from the center line and h is the altitude (Figure 2). The output plots produced by the computer system are rectified to account for this factor. General radiation intensity patterns are not changed, but the removal of the distortion allows overlays to be made for direct comparison to maps of the study area which aids in interpretation of the data.

The systems are being flown in a light aircraft. Figures 4 and 5 show the imaging head and the system monitor and control unit installed. One of the primary sources of distortion in data collected with an optical mechanical imaging system is the instability of the aerial platform itself. Using light aircraft, it has been necessary to correct the imagery for aircraft roll. This is achieved by recording the output of a vertical reference gyro on one track of the magnetic tape. In the computer analysis of the data, the roll compensation signal is used to displace the scan lines in proportion to the aircraft roll. An example of roll compensated and uncompensated imagery is shown in Figure 6.

Thermal Imaging System

The thermal imaging system consists of an optical mechanical imaging system equipped with the long wavelength mercury cadmium telluride detector which provides a temperature sensitivity to $<0.5°C$, a magnetic tape recording system, and computer data analysis programs. Data collected with this system is representative of the near-surface, <0.1 mm, temperatures. A complete two-dimensional pattern is collected as the aircraft traverses the target area. The optical resolution is dependent on aircraft altitude with a system

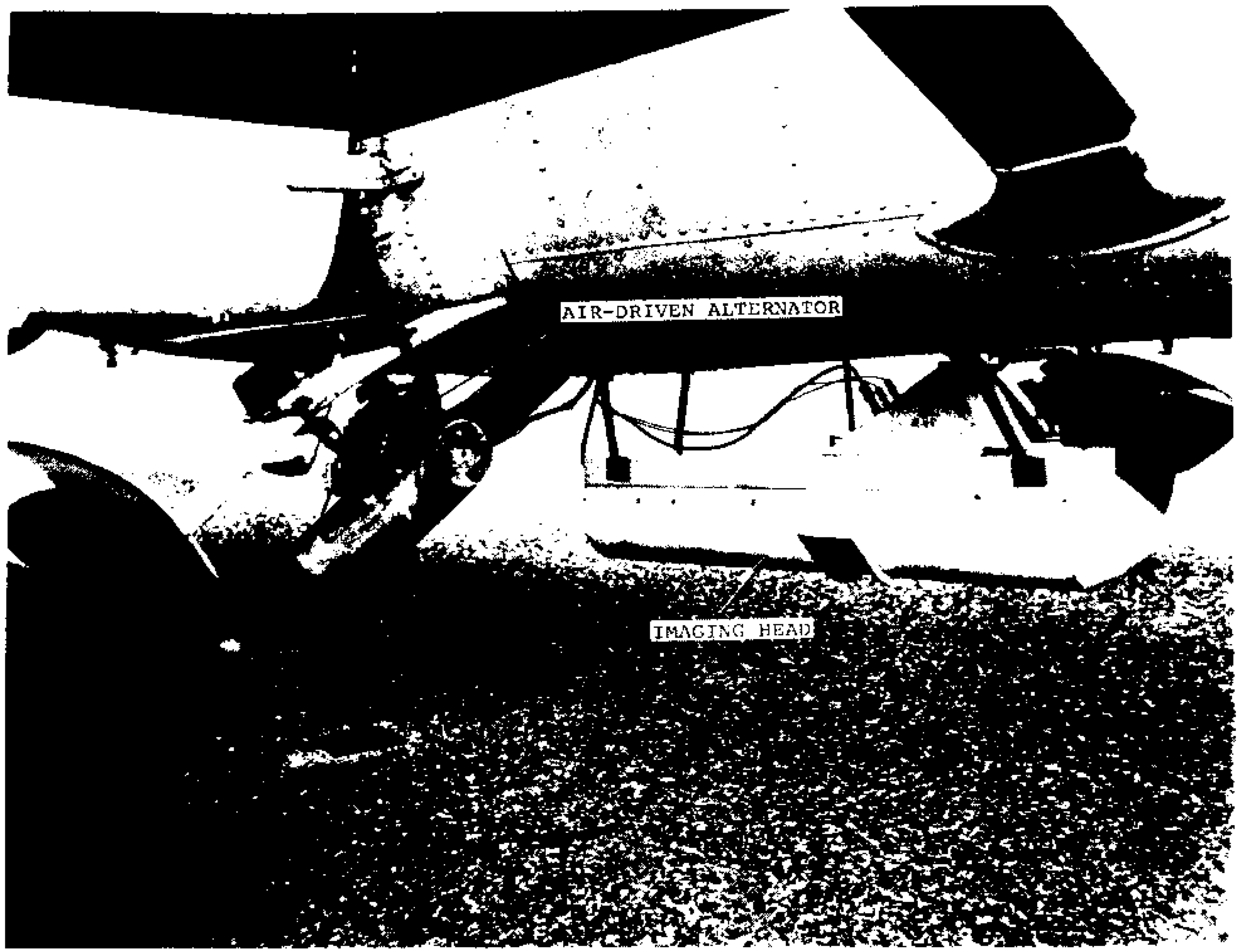


FIGURE 4. Imaging Head and Auxiliary Alternator

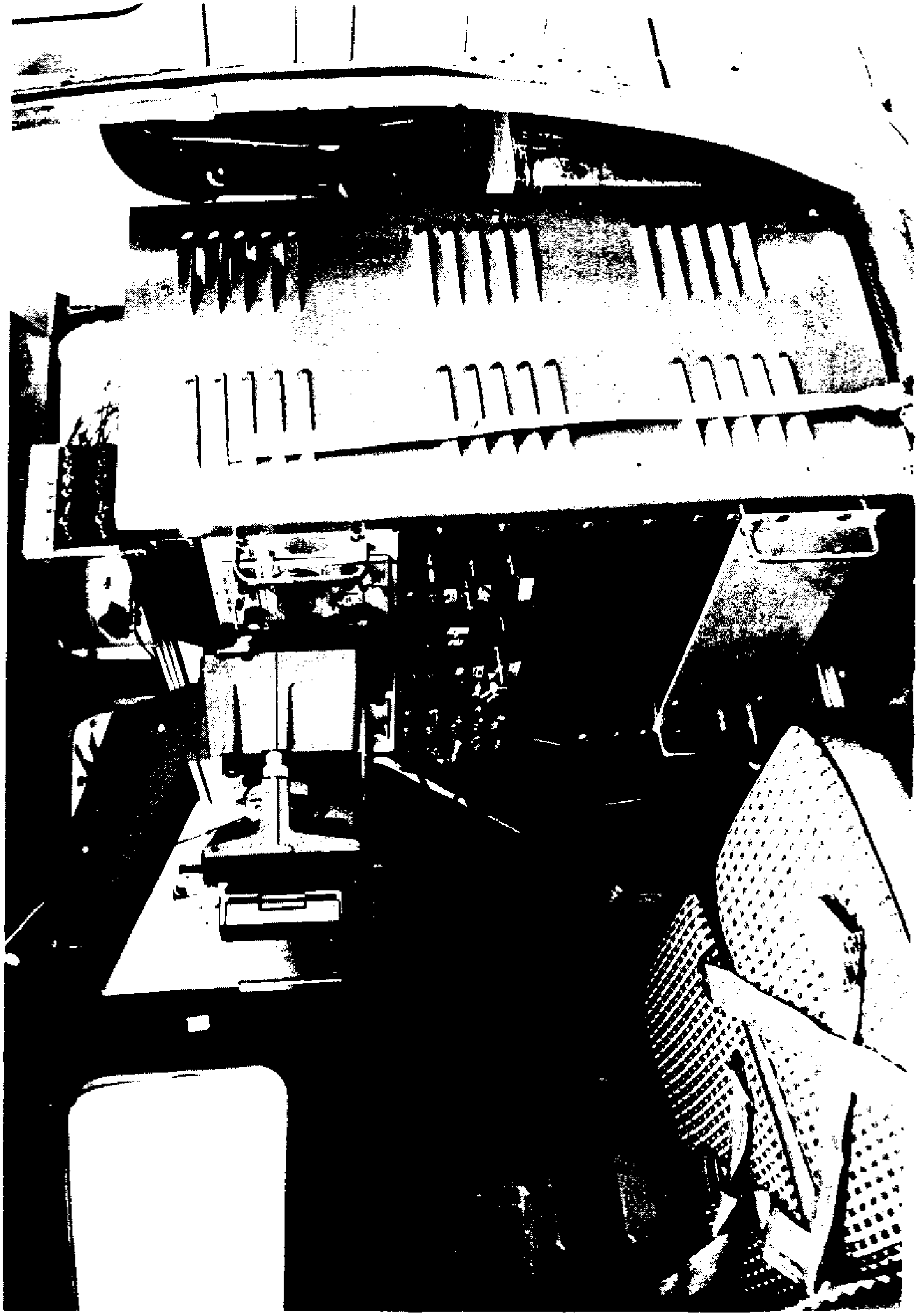


FIGURE 5. Imaging System Monitor and Control Unit

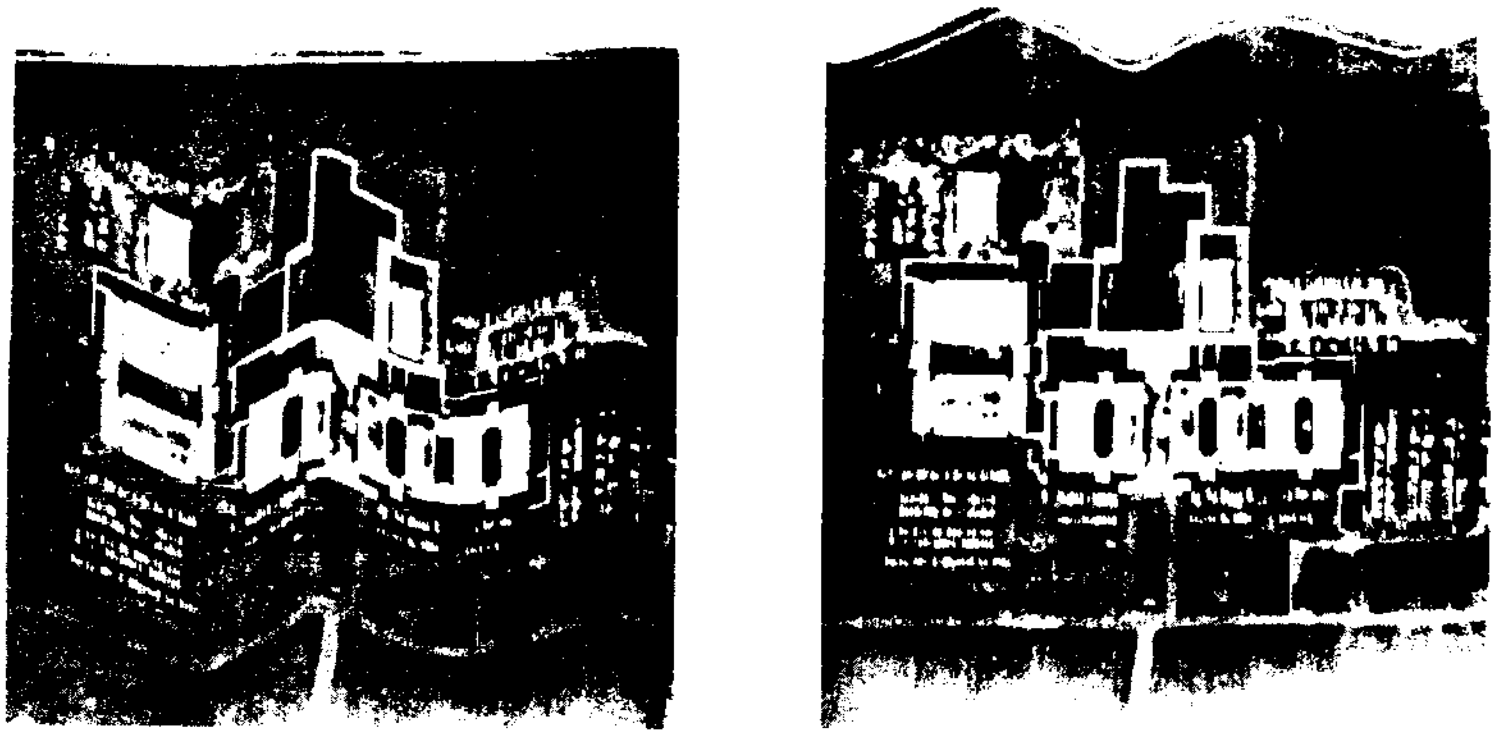


FIGURE 6. Roll Uncompensated and Compensated Image of the Battelle-Northwest Laboratory

divergence of <3 milliradians which would limit the instantaneous field of view to approximately a 3 foot diameter spot at 1,000 foot altitude. In order to quantitatively evaluate the imagery, it is necessary to collect surface temperature measurements during each survey. These measurements are then used to scale the signal level during the data processing sequence. The computer generated plots of the data are coded isothermal levels (Figure 7) which can be individually identified even in the complex patterns which develop near thermal discharge points. Also the magnetic tape record can be used to produce intensity modulated two-dimensional images of the thermal patterns (Figure 8).

Tracer Dye Imaging System

The tracer dye system as it is presently being operated consists of a dual channel optical mechanical imaging system, a magnetic tape recording system, and a computer data analysis program (Figure 9). The optical mechanical imaging system developed for the dye surveys is a dual channel system utilizing a branched fiber optic light guide to divide the incoming radiation into the two channels (Figure 10). Narrow band pass filters in the imaging system are centered at the fluorescence emission maximum for the tracer dye and for a reference at longer wavelengths beyond the fluorescence emission of the dye. Data from the fluorescence channel is corrected for reflectance variation by using the longer wavelength reference channel. Figure 11 shows typical output from the fluorescence channel A, reflectance channel B and

FIGURE 7. Computer Generated Thermal IR Analysis

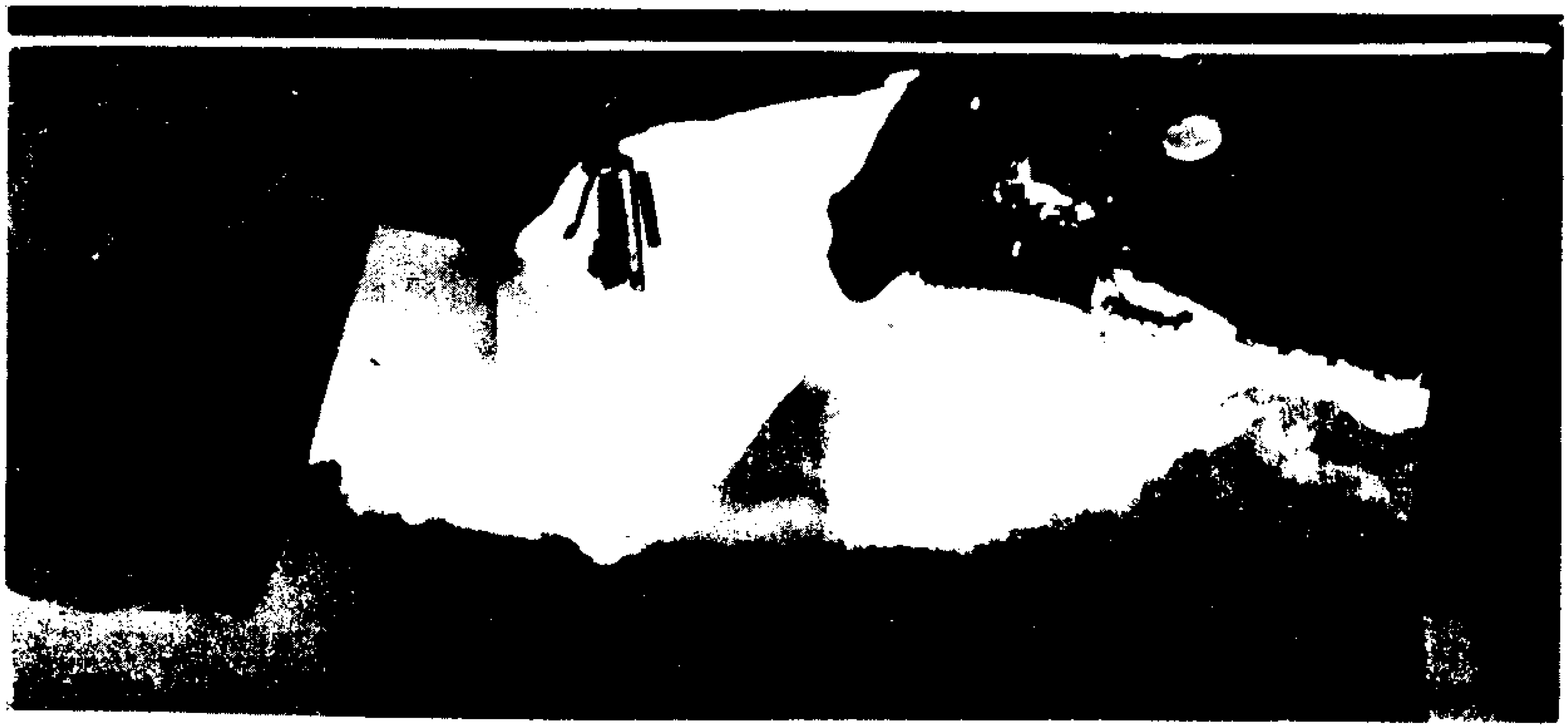


FIGURE 8 . Intensity Modulated Two-Dimensional Infrared Image

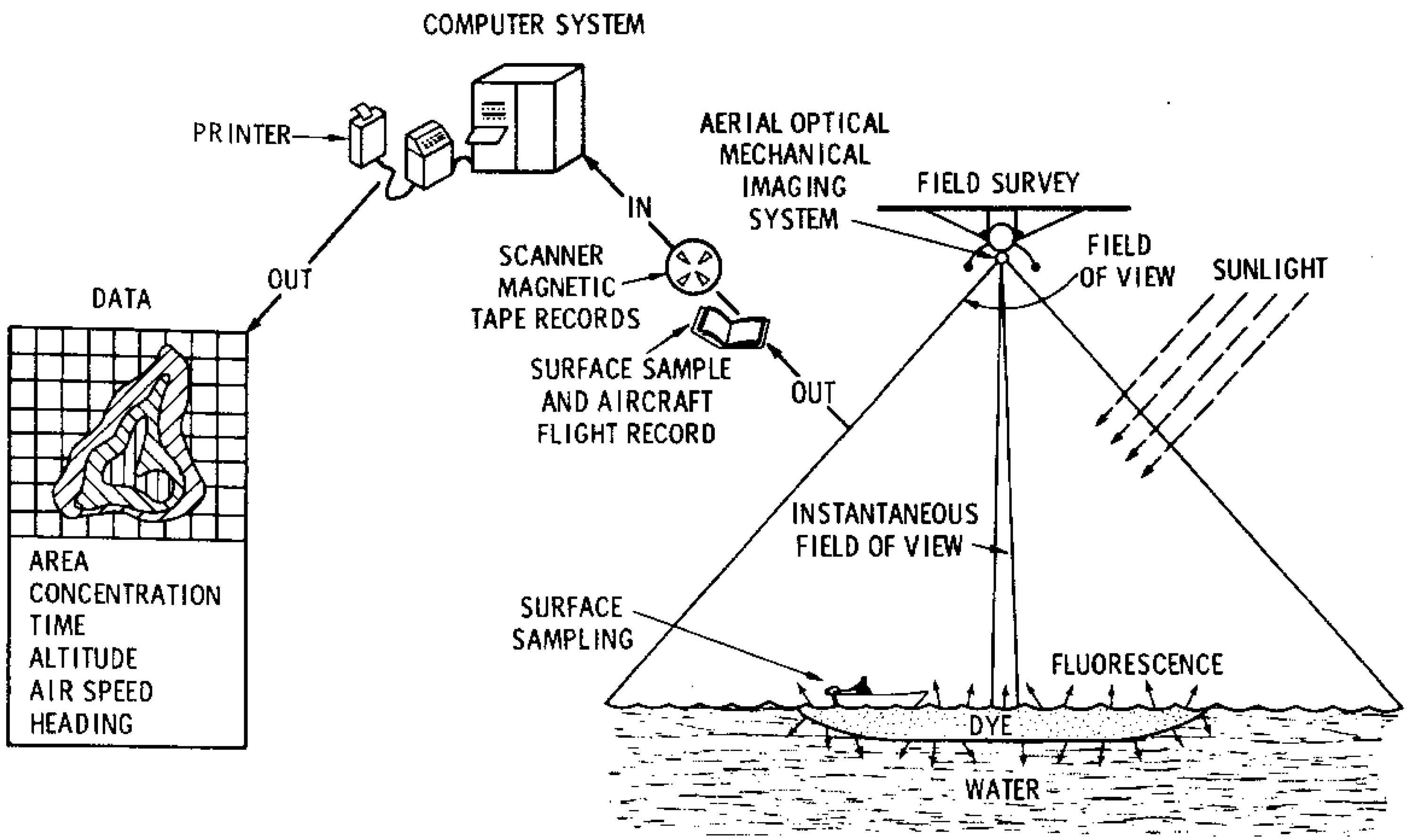


FIGURE 9. Aerial Dye Survey and Analysis System

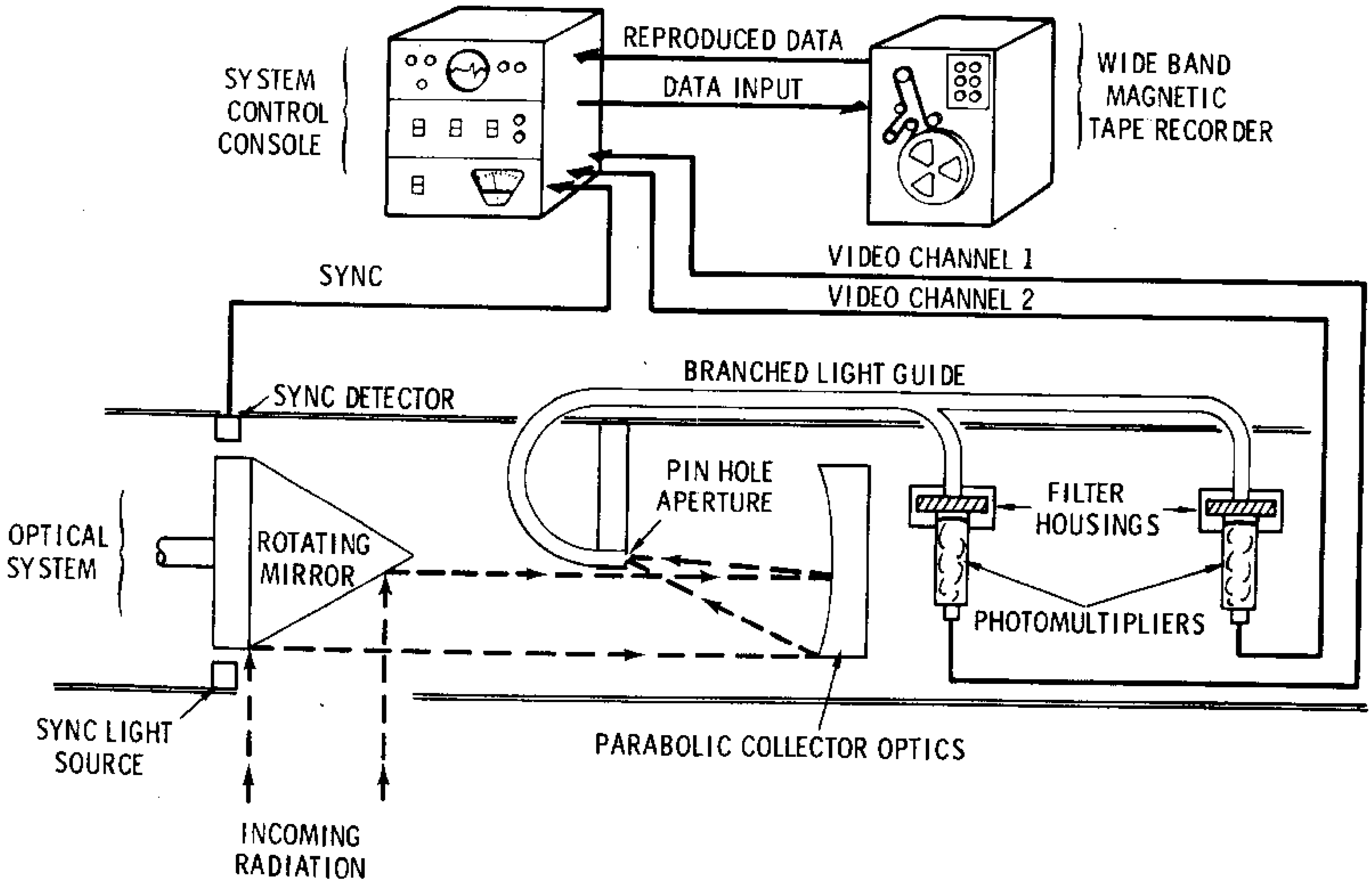
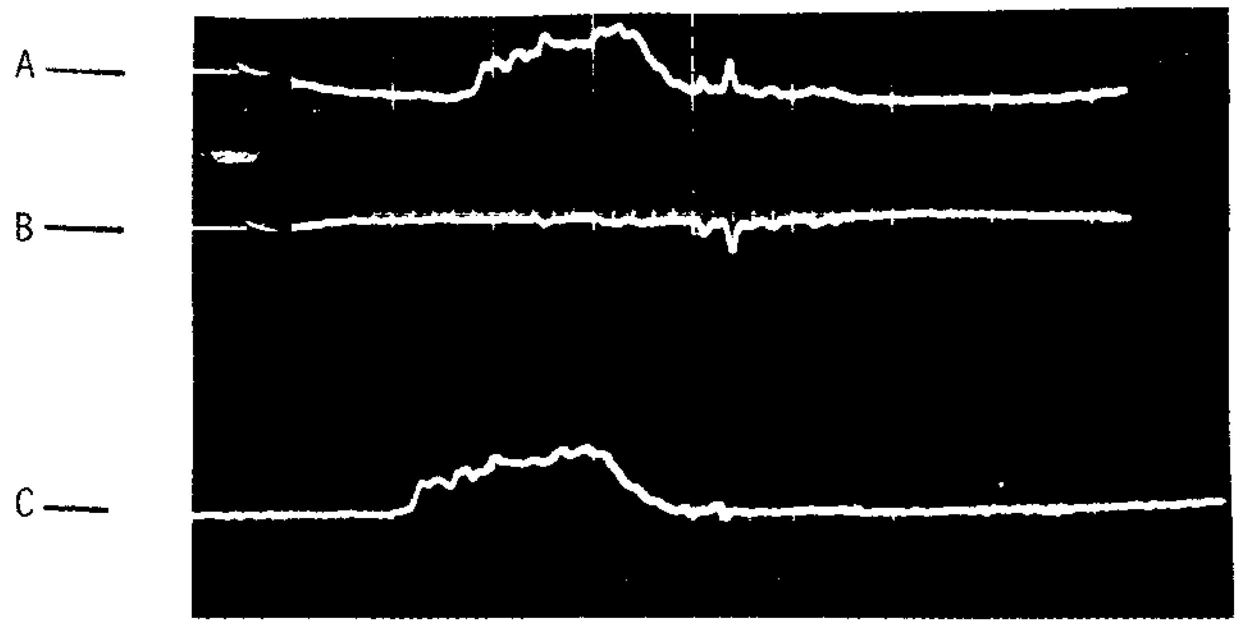


FIGURE 10. Optical Mechanical Scanner Dye Test Configuration



A - FLUORESCENCE SIGNAL

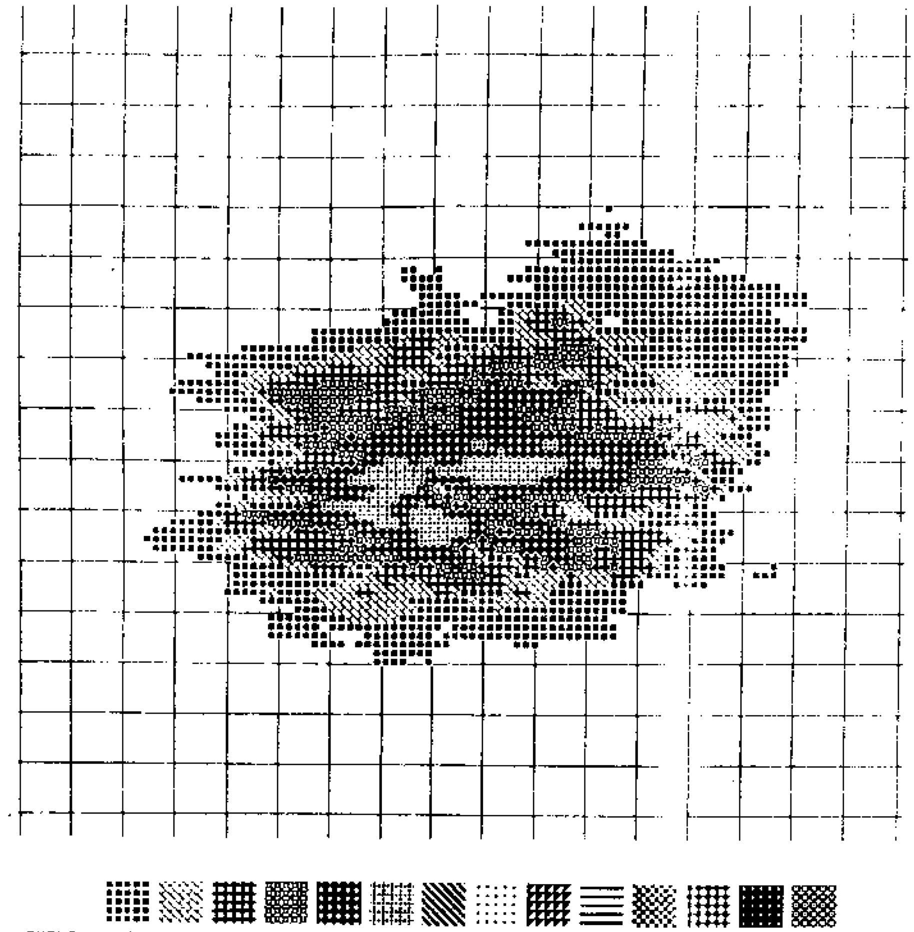
B - REFLECTANCE SIGNAL

C - SUMMATION OF A AND B

FIGURE 11. Typical Signals Produced by the Dye Imaging System

the combined output C. Magnetic tape recordings of the data are collected and processed by a computer program which produces a display of selected dye concentration ranges which are individually coded (Figure 12). The computer generated displays are rectified to correct for aircraft roll and scanner distortion; also the displays are superimposed on a reference grid and the integrated areas for each concentration range can be printed out. The imaging system produces a signal which is proportional to dye concentration and to which quantitative values are assigned from the field samples which are collected at the surface and with depth. These samples provide a point measurement of the dye concentration and an estimate of the depth of the dye. In the analysis sequence, an effective depth for each survey time is input and, based on the amount of dye released, a mass balance is calculated. The mass balance calculation and field sample results provide a cross check on the dye concentration plots produced. Figure 13 diagrams a typical dye release, the sampling technique, and the effective depth which would be used in the analysis sequence.

Several advancements over presently available instruments conducting dye tracer studies have been achieved with the system. The two-dimensional scanning provides essentially real-time coverage of a dye plume in that a complete survey of the plume can be obtained in the time (several seconds) required to fly the length of the plume. This can be contrasted to the need for collection of innumerable samples



LEVELS 1 2 3 4 5 6 7 8 9 10 11 12 13 14

LEVEL	CON. RANGE (PPB.)	NUMBER OF AREA ELEMENTS	AREA (SQ.FT.)
1	0 - 100	998	70146
2	100 - 200	305	21437
3	200 - 400	386	27130
4	400 - 600	287	20172
5	600 - 1000	321	22561
6	1000 - 2000	108	7590
7	2000 - 4000	0	0
8	4000 - 6000	0	0
9	6000 - 8000	0	0
10	8000 - 10000	0	0
11	10000 - 15000	0	0
12	15000 - 20000	0	0
13	20000 - 30000	0	0
14	30000 - 40000	0	0

AREA OF ONE ELEMENT (SQ. FT.) = 70.29
TIME OF PASS = 1232
ALTITUDE (FEET) 750
HEADING (DEG. FROM NORTH) 50
SPEED (MPH) 105
DISTANCE SCALE (100 FEET BETWEEN MARKS) I
D/S TEST 10/4/70

FIGURE 12. Computer Generated Tracer Dye Analysis

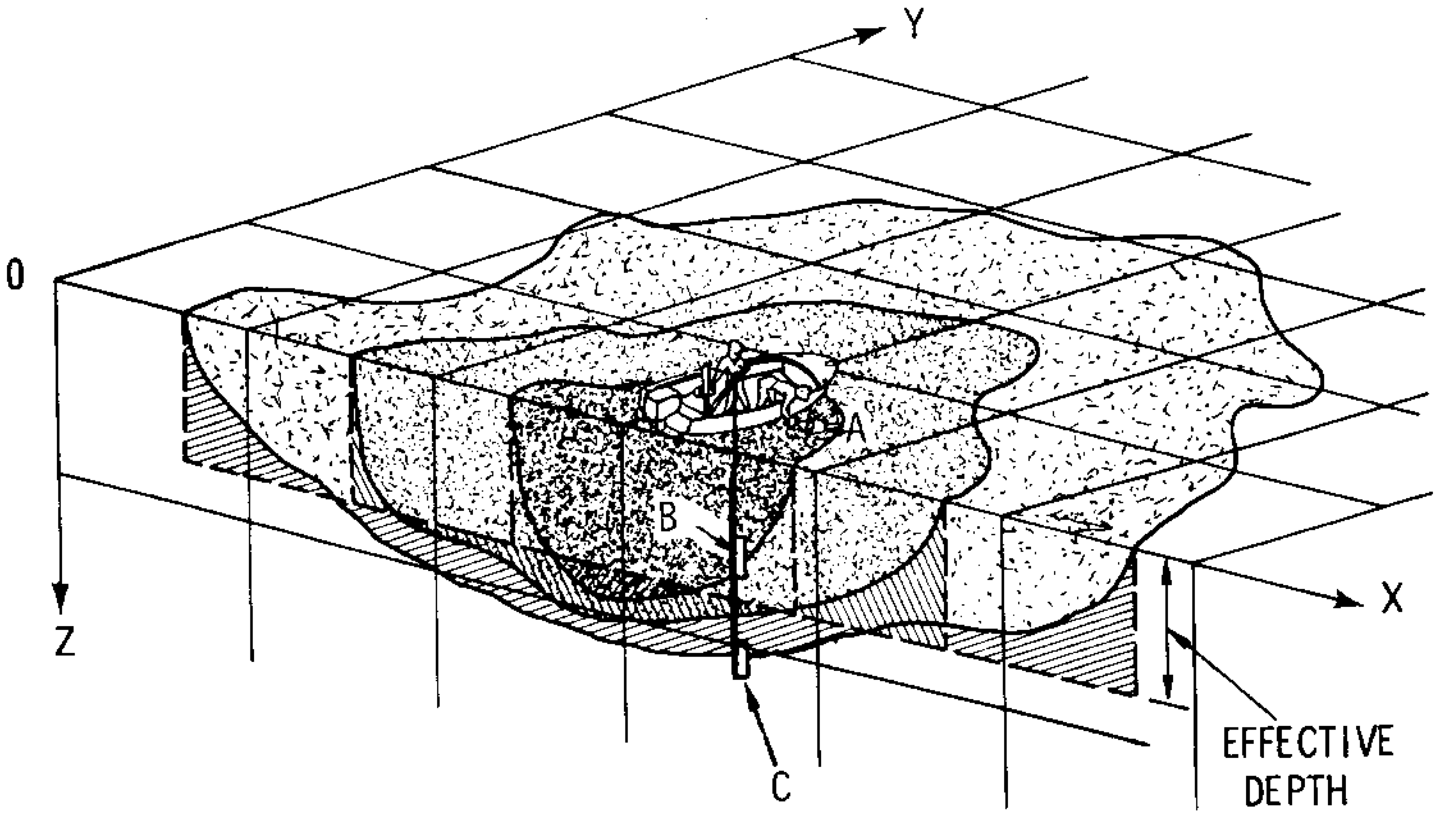


FIGURE 13. Schematic Diagram of a Typical Dye Distribution Pattern and Sampling Techniques

from surface vessels during an ever changing dye pattern. Concentration patterns derived from directly sampling the dye plume are limited by the lack of detail necessary to evaluate detailed current dynamics and dispersion. Initial studies indicate that a high signal-to-noise ratio can be obtained at very low dye concentrations using rhodamine or fluorescein dye as the tracer. This system eliminates the need for using radar tracking or other aerial navigation aids in that the imagery produced provides a detailed picture of shoreline features or other landmarks (e.g., nearshore roads, buildings, jetties, etc.). On open waters, reference buoys and boats have been used as navigation aids. Correlation of surface samples to data can be achieved by relating the scanner signal level at the boat, which can be identified, to the measured sample concentration. The system has been operated under various weather conditions with the only limiting requirement being uniform lighting of the dye plume. Cloud ceilings as low as 500 feet have not limited the system's operation. The system's sensitivity would be affected by extremely heavy cloud cover which would significantly lower the overall daylight level.

Computer Analysis System

The computer system serves to simplify the analysis of recorded data and facilitate presentation of the information in an understandable and usable fashion. The recorded analog signals for video, sync, and roll are input to the digital computer by use of analog to digital converters. From 600 to 800 points are digitized in each recorded scan line depending on the fraction of the scan line containing information of interest. For example, if a dye patch occupied only 10° of the field of view, only that part of the scan line would be digitized. Additionally, the program uses aircraft altitude and speed to calculate the number of scan lines that must be averaged for processing. The same information is used to determine the spacing for the background reference grid (Figure 12). This grid size may be varied over a wide range, but is always calculated to match the scale of the display.

After the correct number of scan lines have been averaged, a correction is applied to correct for the distortion caused by the constant angular scanning rate of the scanner. For example, a 5° portion of the field will represent a larger distance when the scanner is looking near the horizon rather than directly below the aircraft. The correction is incorporated through a weighted averaging method. The averaged scan line is reduced to 133 points each of which is at one of 15 levels proportional to the signal level. This form of the line is stored on a magnetic drum memory. The process continues until the desired surface area has been recorded by analysis of the appropriate number of scan lines.

At this point, the results can be viewed on a high resolution memory oscilloscope. If a dye signal is being processed, the computer calculates the total mass of dye based on an effective depth for the patch. This check maintains a mass balance on the dye between time planes.

An editing program is available for adding or removing features desired on the data displayed on the oscilloscope. For example, land areas can be edited into the display to provide actual reference features in the final output. The processing is then complete and the picture ready for printing.

There are three forms of output available. The first output utilizes a number of different patterns to represent either temperature levels or dye concentrations (Figures 7 and 12). The patterns are chosen for maximum recognition and also to have an alternating density. Thus, one level would tend to be light and the next dark. This variation facilitates differentiation of one level from the next. By using a unique pattern for each level, it is possible to determine the level of every point in the picture. Additionally, there is a background grid for reference which does not overlap the character patterns. The second output form is a standard contour plot. The contour levels may be identified by overlaying this map on the pattern coded output. The contour map can be produced in two views that form a stereo pair. In this form, it is easy to distinguish the contour levels viewed in stereo even with complex patterns. The third output form is similar to the first but uses density coded characters. The higher levels are darker producing a picture similar to a normal photograph. All three outputs are in the same scale and may be overlapped in any combination.

In addition to the pictorial type of output, the character types are printed along with their levels. The number of characters at each level is listed and the total area at each level is printed. The altitude, speed, heading, grid scale, time of flight, and location are also listed (Figure 7).

Intensity modulated pictures can be produced from the recordings for qualitative evaluation of the data (Figure 8). This type of display provides detail which is not apparent in the computer generated displays. Particularly in the case of infrared, it is often interesting to see the fine structure of the temperature variations. Oblique projection of the thermal surface can also be made (Figure 14). These provide a quick qualitative feeling for the relative significance of the temperature variations.

THE WATER TRANSPORT SYSTEM

The water transport system is used to predict the temperature or concentration patterns that would exist in the vicinity of an industrial discharge and is based on the concept depicted in Figure 15. Modeling the temperature or concentration and flow distribution in the region affected by effluent jet momentum and buoyancy is done with an outfall jet plume model developed by D. S. Trent[1]. The velocity boundary conditions from this model are input to a potential flow model responsible for predicting the flow field in the

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1 Baumgartner, D. J., and D. S. Trent. "Ocean Outfall Design - Part I, Literature Review and Theoretical Treatment." U. S. Department of the Interior, Federal Water Quality Administration, April 1970.

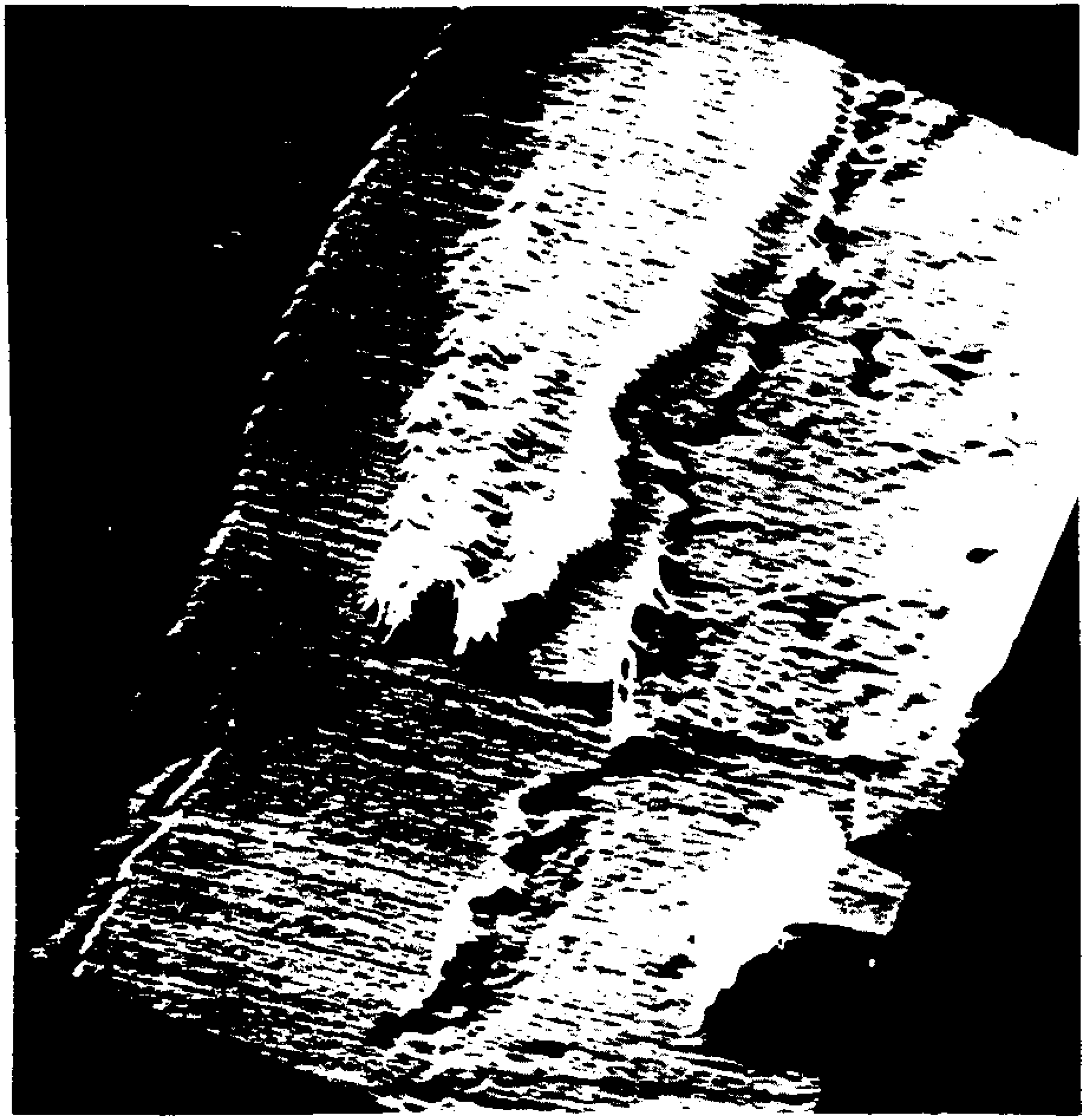


FIGURE 14. Oblique Projection of an IR Image Collected Over a Reactor Discharge Into the Columbia River

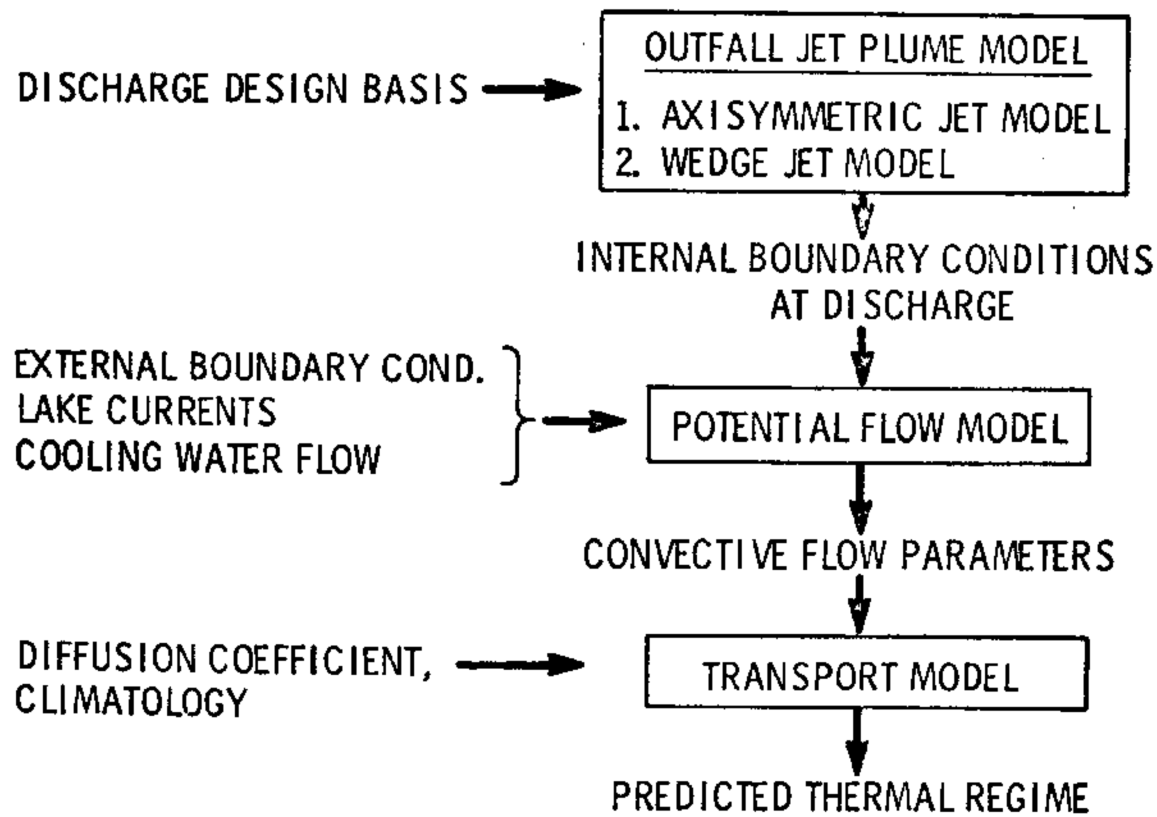


FIGURE 15. The Water Transport System

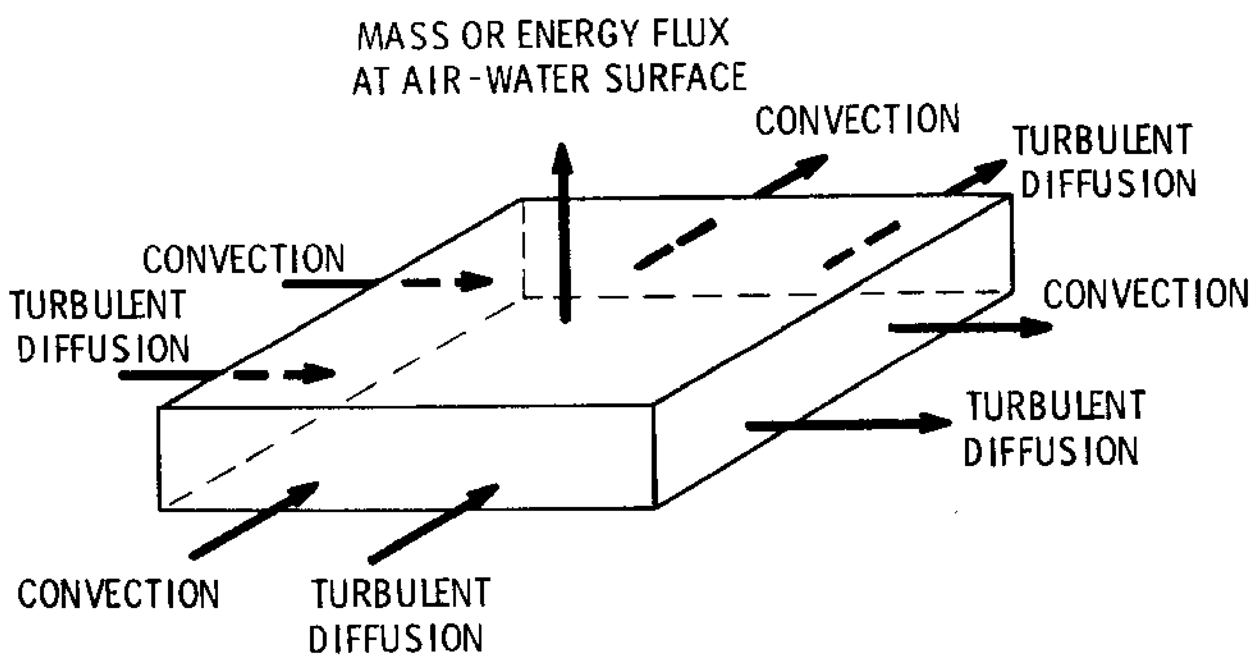
region affected by the industrial discharge together with external boundary conditions, ambient currents, and cooling water flow. The velocity field calculated by the potential flow model is input to the transport system together with diffusion coefficients calculated from remotely sensed dye data and climatology. This transport system is responsible for predicting the temperature or concentration field due to the input conditions.

This water transport system is based on the mass or energy conservation equation described conceptually in Figure 16. This equation states that the rate of mass or energy entering a system less the rate of mass or energy leaving a system must equal the rate of accumulation of mass or energy within the system.

Now if the system is treated as a block as shown in Figure 1, the conservation equation can be written. When this block is reduced to infinitesimal size the conservation equation becomes

$$\frac{\partial S}{\partial t} = -u\frac{\partial S}{\partial x} - v\frac{\partial S}{\partial y} + D_x\frac{\partial^2 S}{\partial x^2} + D_y\frac{\partial^2 S}{\partial y^2} + S_t \qquad (1)$$

which includes convective, diffusive, and source terms for a two-dimensional, transient system with variable velocity field. Equation 1 cannot be solved analytically for a variable velocity field, but has been solved numerically by writing in finite difference form using an alternating direction implicit algorithm. A detailed description of this



RATE OF ACCUMULATION = RATE IN-RATE OUT + SOURCE TERMS

$$\frac{\partial S}{\partial t} = -u\frac{\partial S}{\partial x} - v\frac{\partial S}{\partial y} + D_x\frac{\partial^2 S}{\partial x^2} + D_y\frac{\partial^2 S}{\partial y^2} + S_T$$

FIGURE 16. Mass or Energy Balance on a Cell

algorithm is given in a recent publication by Oster, Sonnichsen, and Jaske[2].

The system to be modeled is divided into a set of cells by a rectilinear grid system and the finite difference algorithm is applied to each cell. The assumptions necessary to write Equation 1 in finite difference form include:

- Velocity is constant across a cell face
- Eddy diffusivity is constant within the system
- All internal source or sink terms can be described by S_t
- Turbulent diffusion is treated analogous to microscopic diffusion but on a larger scale.

Determination of Input Parameters for the Water Transport System

In order to solve Equation 1, eddy diffusivity and velocity must be known for the system. The velocity field may vary in time and space; the diffusivity field is assumed to be constant with respect to time and space. Eddy diffusivity data are obtained from the remotely-sensed dye tracer data and velocities are calculated from the equations of motion, using measured dye plume velocities to check these calculated velocities.

The lateral and longitudinal eddy diffusivities are calculated directly from the remotely-sensed dye concentration data as previously described. This is done by assuming the dye plume is vertically homogeneous and that the

[2] Oster, C. A., J. C. Sonnichsen and R. T. Jaske. "Numerical Solution to the Convective Diffusion Equation," Water Resources Research, Vol. 6, No. 6, pp. 1746-1752, December 1970.

concentration patterns follow a bivariate normal distributi in the lateral and longitudinal directions. The second assumption implies that the dye disperses according to the conservation equation described by Equation 1. If the velocity components and eddy diffusivities are assumed constant with respect to spatial coordinates and time, the conservation equation has an analytical solution

$$S = \frac{W_d}{2\pi\sigma_x\sigma_y} \exp \left\{ - 1/2 \left[\left(\frac{x-ut}{\sigma_x} \right)^2 + \left(\frac{y-vt}{\sigma_y} \right)^2 \right] \right\} \quad (2)$$

where $$\sigma_x = \sqrt{2\ D_x t} \quad (3)$$

$$\sigma_y = \sqrt{2\ D_y t} \quad (4)$$

and S refers to dye concentration.

The eddy diffusivities can be calculated by examining changes in the dye plume concentration as it moves and disperses with time. For example, by following a dye plume and obtaining successive detailed dye concentration pattern in time* with the remote sensing instruments, the effective average eddy diffusivities responsible for dispersal of the dye plume between successive time planes can be calculated. If the time difference between successive time planes is short and the dye plume does not extend over too large an area, the assumptions necessary to write Equation 2 are nearly satisfied.

---

* Hereafter referred to as time planes.

The eddy diffusivities can be calculated from variance data obtained between adjacent time planes as

$$D_x = \frac{\sigma_{x_2}^2 - \sigma_{x_1}^2}{2(t_2 - t_1)} \qquad (5)$$

$$D_y = \frac{\sigma_{y_2}^2 - \sigma_{y_1}^2}{2(t_2 - t_1)} \qquad (6)$$

where subscripts 1 and 2 refer to variances calculated at the first and second time planes, respectively.

The evaluation of the lateral and longitudinal variances follows from the development of Equation 2 by Diachishin in 1963[3]. By examining the isoconcentration lines within the dye plume and measuring the surface areas of the regions enclosed within each isoconcentration line, one can plot the area versus the logarithm of the corresponding concentration line enclosing the area as shown in Figure 17. Examination of the table accompanying each remotely-sensed dye concentration pattern (as in Figure 12) will show that by summing the right-hand column (which tabulates the area of each separate concentration range) and noting the lower limit of each concentration range, the above information is immediately available.

Diachishin has shown that each graph of the above described data should have a slope of $-2\pi\sigma_x\sigma_y$. For example, a plot of some of these data is shown in Figure 18. With

[3] Diachishin, Alex N. "Dye Dispersion Studies," J. of the Sanitary Engineering Division, Proceedings of the ASCE, pp. 29-49, January 1963.

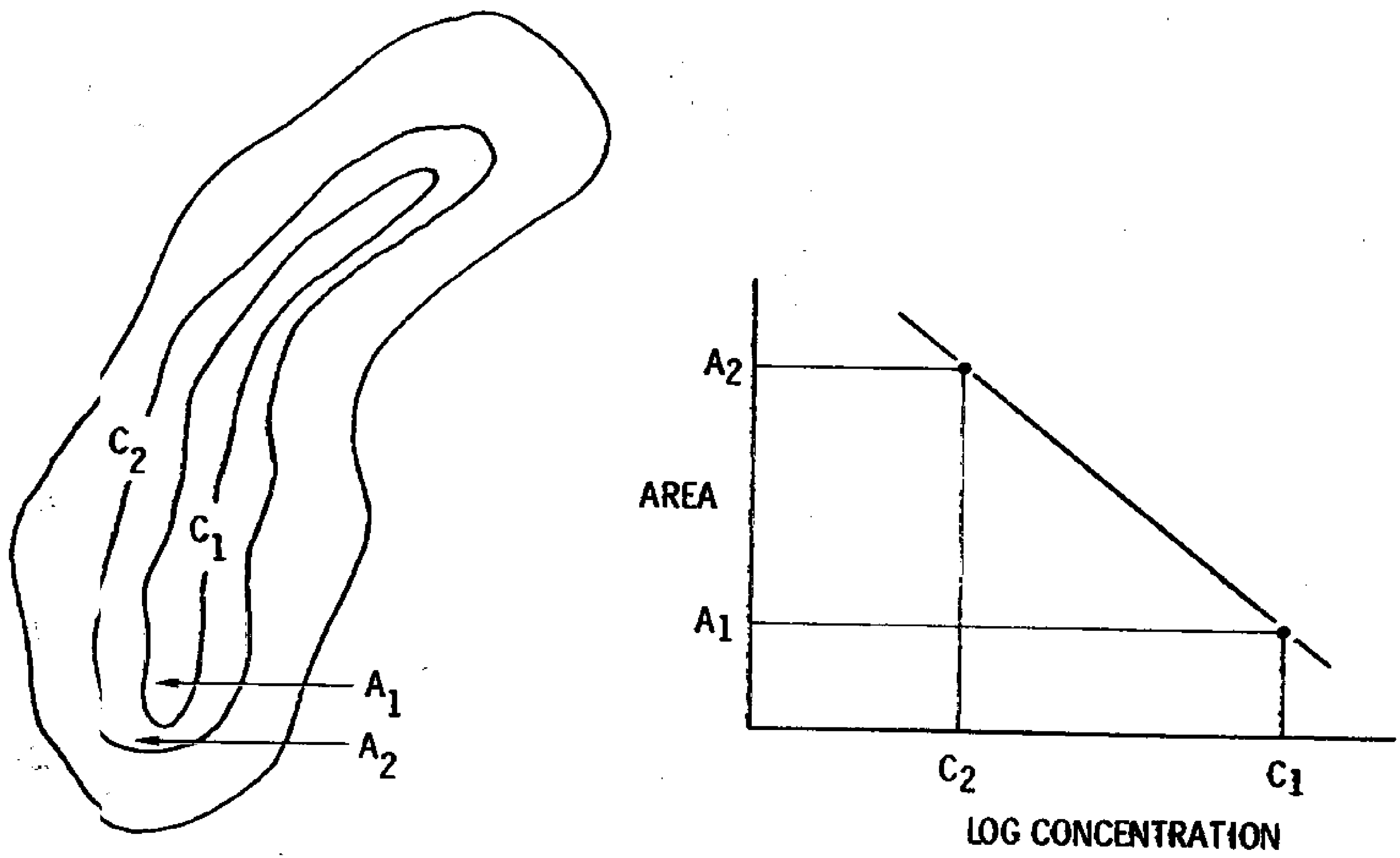


FIGURE 17. Idealized Dye Concentration Pattern

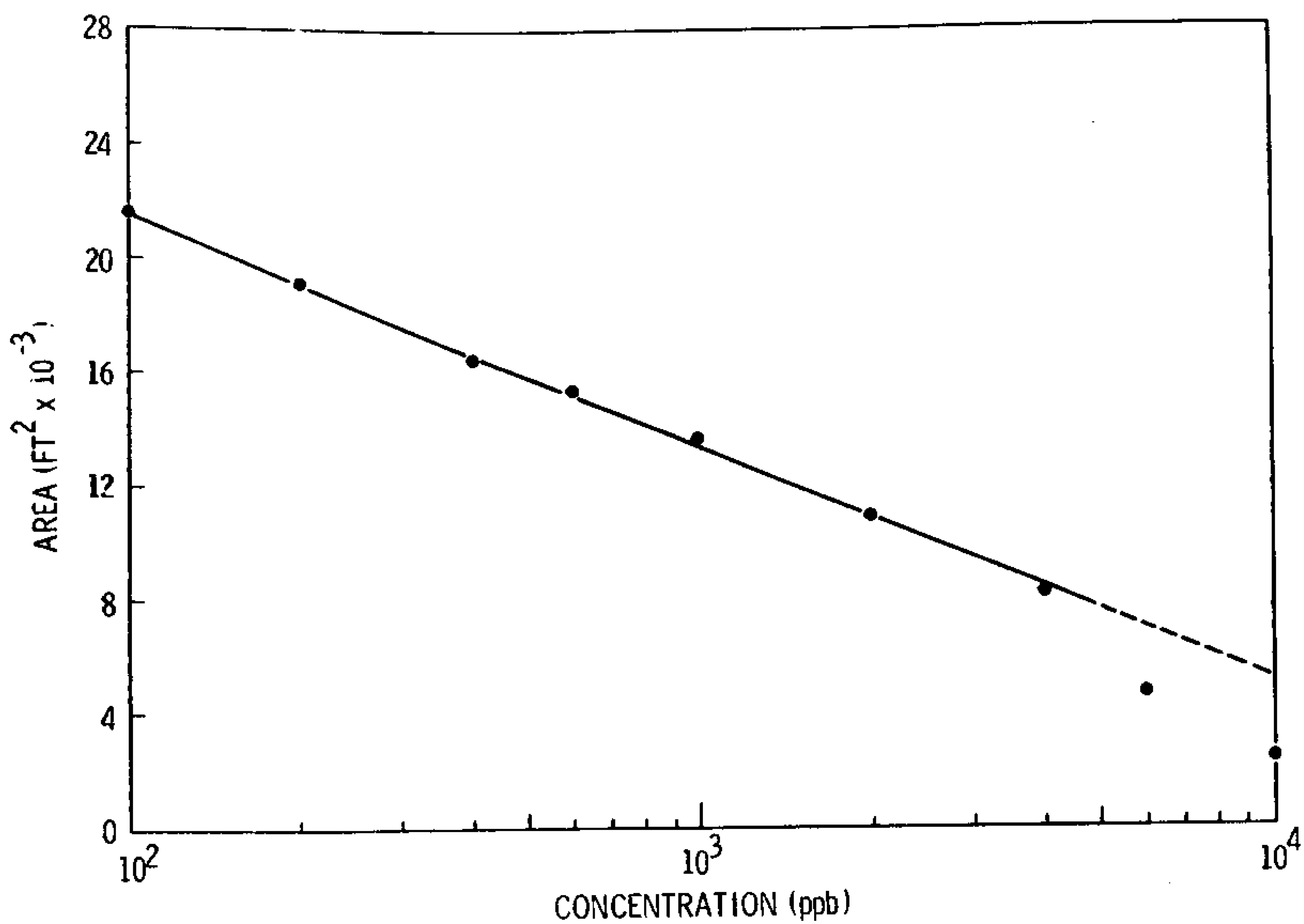


FIGURE 18. Dye Plume Surface Area as a Function of Concentration

further information regarding the ratio of σ_x and σ_y, which is obtained from the overall length and width of the dye plume, it is possible to calculate σ_x and σ_y for each time plane represented. From these variances, longitudinal and lateral eddy diffusivities can be calculated between successive time planes using Equations 5 and 6.

Generally accepted theories of transport phenomena in turbulent systems (e.g., the Prandtl mixing length theory) conclude that values of eddy mass diffusivity and eddy thermal diffusivity are essentially the same for systems in which the molecular rate of transport of mass and heat are comparable in magnitude. This is true for water and, consequently, the eddy mass diffusivities derived from dye data are used directly in solving Equation 1 for mass concentration or thermal energy distribution.

The velocity information necessary to solve Equation 1 is calculated from a simplified set of equations of motion. At present, these simplifications are based on the following assumptions:

- Steady flow
- Coriolis forces are negligible
- Buoyancy forces are small
- Frictional forces are negligible
- Two-dimensional lateral irrotational flow.

With these assumptions, the equations of motion can be written as follows:

$$u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} = -\frac{1}{\rho_o}\frac{\partial P}{\partial x} \qquad (7)$$

$$u\frac{\partial v}{\partial x} + v\frac{\partial v}{\partial y} = -\frac{1}{\rho_o}\frac{\partial P}{\partial y} \qquad (8)$$

It can be shown that Equations 7 and 8 are satisfied by

$$\nabla^2\phi = o \qquad (9)$$

where ϕ is a scalar potential given by

$$u_i = \frac{\partial\phi}{\partial x_i} \qquad (10)$$

Velocities for the dye plume are calculated by measuring the dye plume movement with time according to the following equations

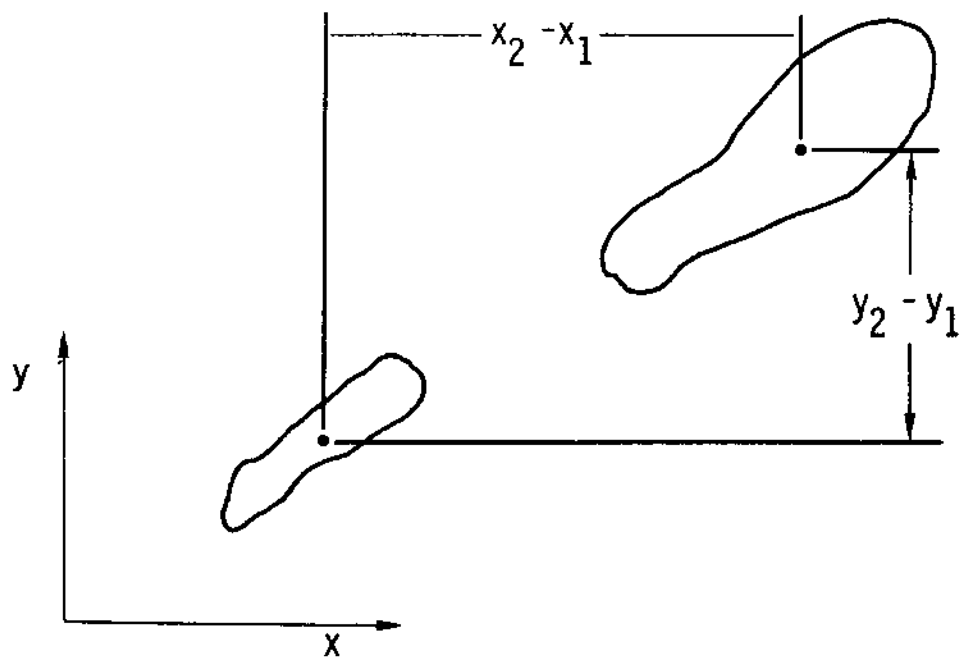
$$u = \frac{x_2 - x_1}{t_2 - t_1} \qquad (11)$$

$$v = \frac{y_2 - y_1}{t_2 - t_1} \qquad (12)$$

A diagram of this relationship is given in Figure 19. The x and y coordinates are measured from an arbitrary origin and represent the point in the dye plume with the maximum concentration. These measured velocities are compared with calculated velocities and boundary potentials are adjusted until a reasonable comparison is obtained.

Modeling the Region Affected by Effluent Jet Momentum and Buoyancy

The one region in the flow field that cannot be treated with reasonable accuracy using the potential flow theory described by Equation 9 is the region near the outfall where considerable rotation, mixing, and buoyancy are associated with a jet discharge of warm water.



$$u = \frac{x_2 - x_1}{t_2 - t_1} \qquad v = \frac{y_2 - y_1}{t_2 - t_1}$$

FIGURE 19. Velocity Determination From Dye Studies

In this region, the flow field is modeled with a two-part outfall model and the results of this model are entered as boundary conditions in the potential flow field. This two-part outfall model is composed of an initial mixing model responsible for transporting the effluent water from the discharge to the surface or to the elevation where the mixed jet density is the same as the ambient water. From this point downstream the plume is treated as a horizontal wedge.

This initial mixing model is based on a similarity solution of the conservation equations for a horizontally-discharged buoyant jet. Figure 20 illustrates this model. Assuming an axially symmetric jet, the governing equations for the jet are

Momentum along jet axis:

$$\frac{dE}{dS} = \frac{3}{4F_i} S R \sin \theta \tag{13}$$

Conservation of buoyancy:

$$\frac{dR}{dS} = 0.109 \; SE^{1/3} \frac{d\rho_\infty{}^*}{dS} \tag{14}$$

where $\rho^* = \dfrac{\rho_\infty}{\rho_o - \rho_j}$

Dilution:

$$S_m = 1/4 \; E^{1/3} \; S \tag{15}$$

Angle of plume centerline trajectory:

$$\theta = \cos^{-1} \frac{E_e}{E}^{2/3} \cos \theta_e \tag{16}$$

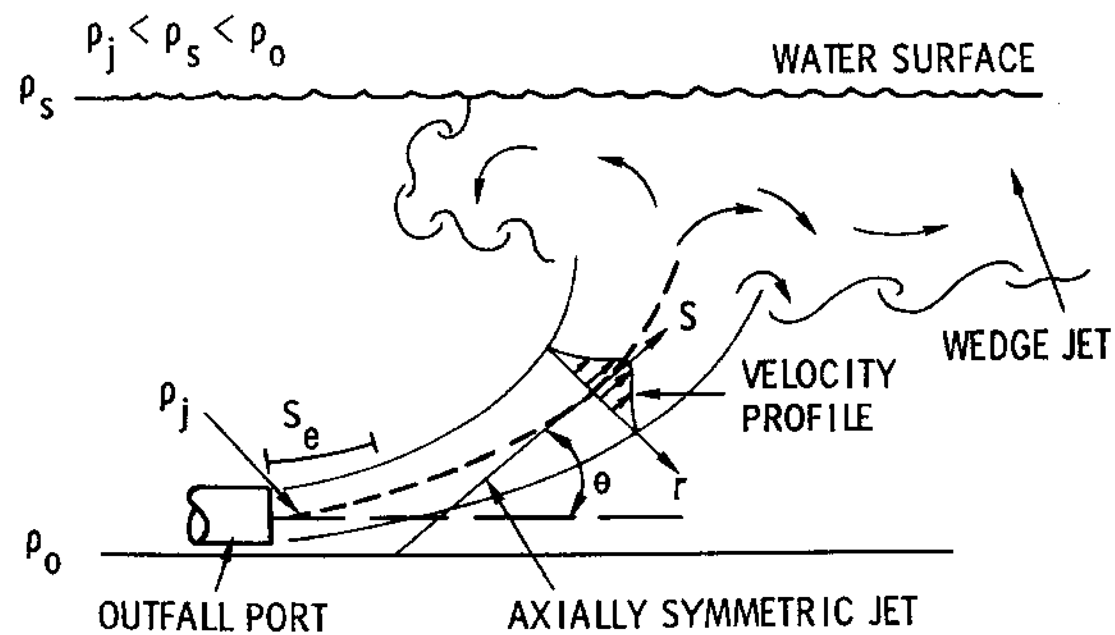


FIGURE 20. Horizontal Plume Issuing Into a Stagnant, Density Stratified Fluid

along with the additional geometric relationships

$$\frac{dx}{dS} = \cos\theta \tag{17}$$

$$\frac{dz}{dS} = \sin\theta \tag{18}$$

In Equations 13 and 14

$$E \sim (V_m S)^3 \tag{19}$$

$$R \sim (V_m \Delta_m s^2) \tag{20}$$

The subscript j refers to the condition at the discharge port, o refers to the receiving water at the port elevation, and e refers to conditions along the plume centerline where flow is completely established.

Beyond this initial mixing model, the water is treated as a horizontal wedge moving at the elevation of its equilibrium density.

In this wedge jet, the plume relationships are

$$V = \frac{3.16}{\sqrt{X}} \tag{21}$$

$$S = 0.2\sqrt{x} \tag{22}$$

$$W = 0.43x \tag{23}$$

$$Q = 263\sqrt{x} \tag{24}$$

This wedge jet is carried to an arbitrary distance (∿1500 ft) beyond the point where the axially symmetric jet reaches its equilibrium elevation. The velocities around this wedge jet and the temperatures calculated within this wedge jet are used as boundary conditions in the potential flow model.

Water Transport System Output

Using the eddy diffusivities calculated from the remotely-sensed dye concentration data and the velocities calculated with the simplified equations of motion and source terms as input to the finite difference form of Equation 1, mass concentrations or temperatures can be calculated for a particular problem.

An example is a simulation of the temperature distribution around a proposed industrial site. Figure 21 describes the potential contours calculated around the outfall of this plant located on the rectangular island. The streamlines run normal to the potential contours and in the direction of increasing potential. Figure 22 is a description of the temperature excess isotherms calculated for this case.

Figure 23 is a two-dimensional projection of the three-dimensional temperature excess surface described by temperature contour lines in Figure 22. To give some idea of the scale in Figure 23, the long side of the island is about 2800 feet long and the temperature spike near the center of the depicted surface is 3.5°C.

CONCLUSIONS

Advanced remote sensing systems being developed by Battelle-Northwest are capable of conducting detailed tracer and thermal surveys of surface water bodies near existing and proposed industrial sites. The detail obtainable far exceeds that obtainable by field sampling or contact measuring

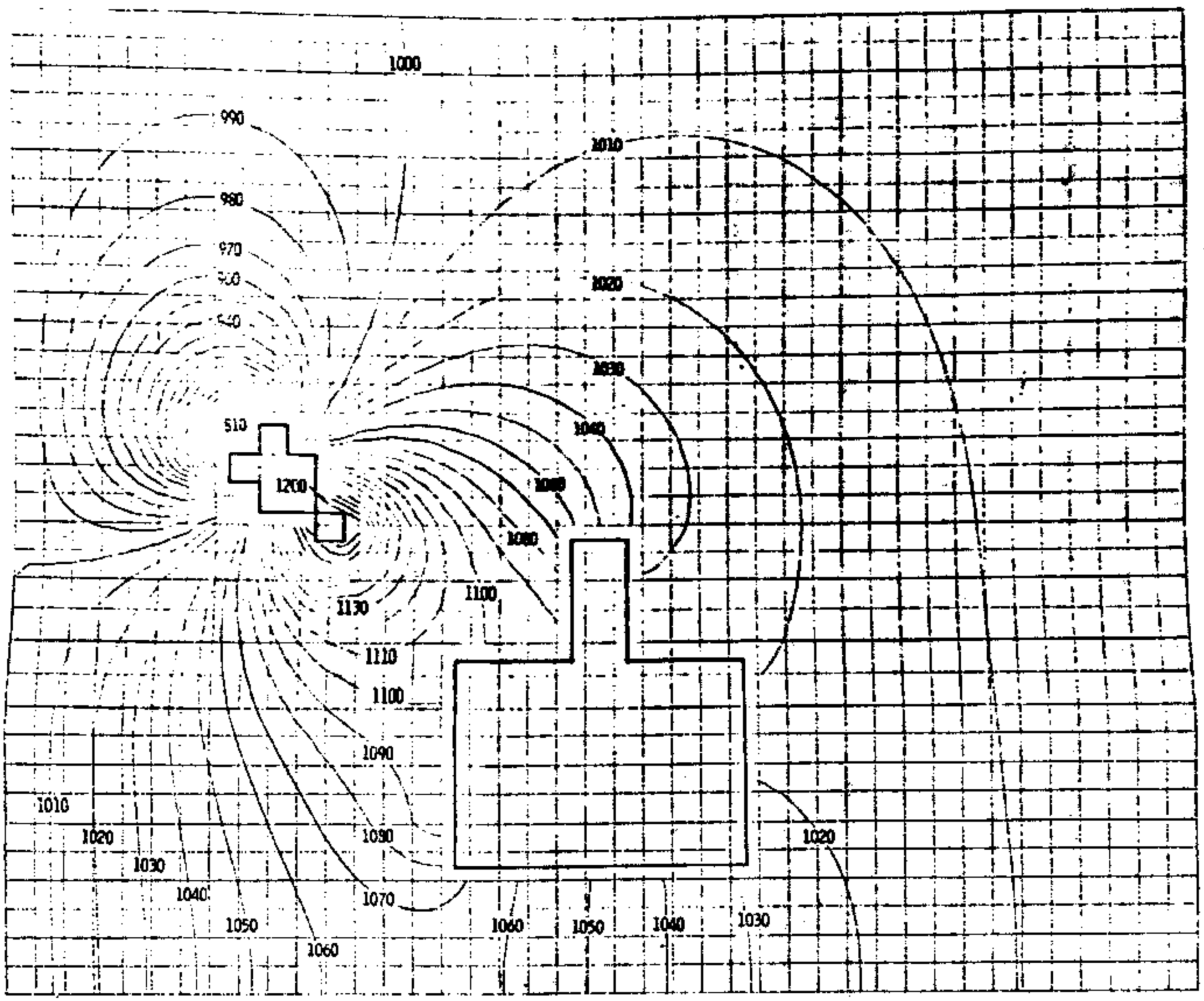


FIGURE 21. Calculated Potential Contours

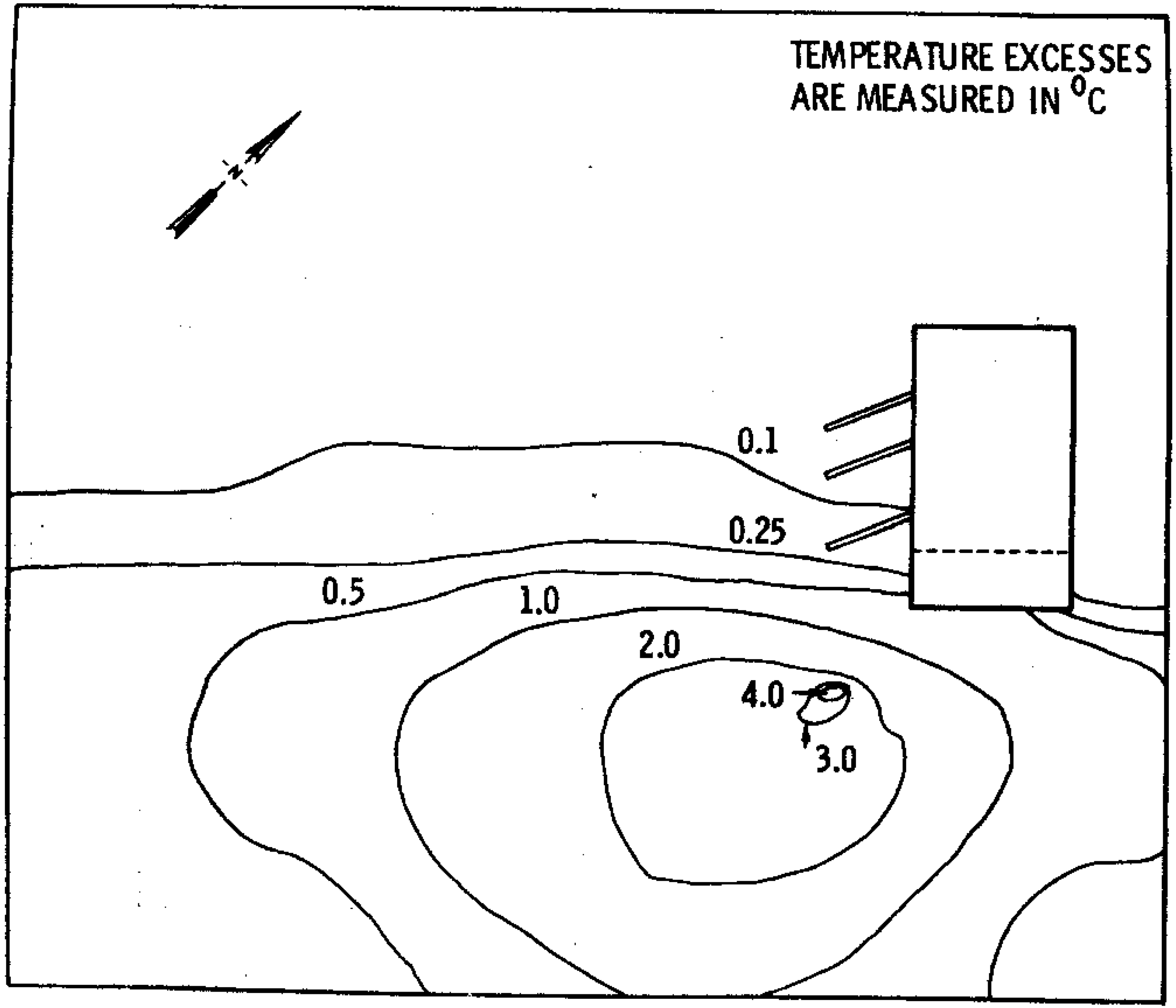


FIGURE 22. Temperature Excess Isotherms

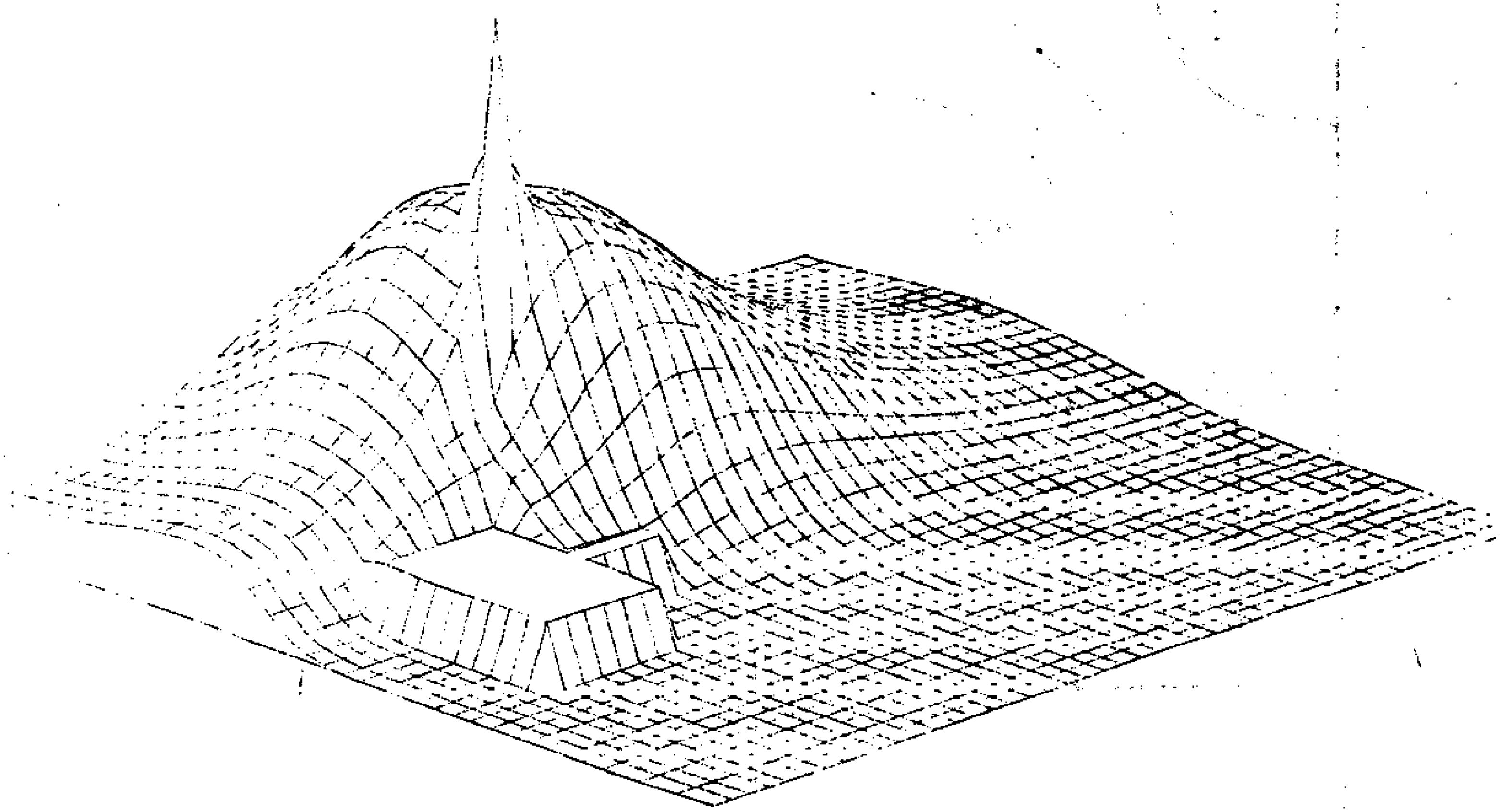


FIGURE 23. Temperature Excess Surface

systems. Tracer dyes, fluorescein and rhodamine, have been used in studies in fresh and salt water bodies. The use of advanced remote sensing systems and computer analysis techniques to conduct studies of surface water movement has provided data which could not be collected by other techniques. Data collected and analyzed by the systems developed at Battelle-Northwest are versatile, providing displays which can be used directly by engineers and scientists or the data can be produced in a format which can be submitted directly to advanced computer analyses or modeling programs.

The concentration and thermal data produced are being analyzed to obtain lateral and longitudinal eddy diffusivities and velocity information. These data, together with velocities calculated with a program used to solve a simplified form of the equations of motion, are input to a water transport system capable of predicting temperature or concentration fields that would occur due to an industrial effluent discharge.

The direct use of data acquired with the remote sensing instrument systems in conjunction with the predictive water transport system to simulate the water effects of an effluent discharge on a body has been accomplished for the first time in the comprehensive system described herein. More advanced methods of utilizing the remotely-sensed data and of modeling the water systems are being developed.

NOMENCLATURE

S	Temperature or concentration field, °C or ppm, respectively
t	Time, seconds
D_x, D_y	Eddy mass and eddy thermal diffusivity in the x and y directions, respectively, ft^2/sec
σ_x, σ_y	Variances in the x and y directions, respectively, ft
W_d	Dye release parameter, ppm/ft^2
S	Distance along jet centerline where not referring to temperature or concentration field, ft
x, y, z	Position coordinates directed east, north, and vertically upwards from an arbitrary origin
u, v, w or u_1, u_2, u_3	Velocity components in the x, y and z directions, respectively, ft/sec
ρ	Density, lbm/ft^3
ρ_∞	Ambient density, lbm/ft^3
ρ_o	Density of receiving water at intake or outfall elevation, lbm/ft^3
ρ_j	Density of effluent at discharge port, lbm/ft^3
V	Average axial velocity in jet, ft/sec
V_m	Axial velocity along jet centerline, ft/sec
Δ_m	Centerline plume velocity, ft/sec
W	Plume width, ft
Q	Jet flow, ft^3/sec

Legal Protection of the Pacific Northwest Estuaries

by

Nelson H. Grubbe

Director, Regulatory Programs

Northwest Region, Water Quality Office

Environmental Protection Agency

Portland, Oregon

OUTLINE

- Common law history of administrative regulation of water use.
- Restricted by statute and judicial guidelines, administration is primary protector of estuaries.
- Federal role in standard setting -- E.P.A. goals...
- State and Federal water quality standards. Enforcement conference in Puget Sound. Citizen suits.
- Ocean dumping policy -- dredging precautions.
- Proposed new legislation --
- N.E.P.A. clearly points the way to placing burden upon user to prove that he is not abusing the estuary. Outlook favorable.

There are forty or more agencies that exercise some legal jurisdiction over the Pacific Northwest estuaries. But as one TV commercial points out, "You are just polishing the polish", unless you use Brand X. The opportunity for duplication is tremendous. The chances that no agency will make the important decision for protection are also present. The legal protection available for Pacific Northwest estuaries is however encouraging.

Legal protection of estuaries does not mean that the wetlands cannot or will not be used. Legal protection, at its best, means enforceable rules to assure that there will be no abuse. The definition of no abuse, however, I leave to this conference. Legal protection can be no better than the scientific input upon which it is based. Maybe non-use is the answer in many sensitive areas.

Maybe there will develop out of this conference a new standard to protect the estuaries of the Pacific Northwest.

Jurisdiction over the control and regulation of estuaries has been a long and continuing struggle. It is going on today. The privately-owned title to land, the rights of water use, the police powers of the state, the constitutional powers of the Federal government, all have engaged in the battle in the overall struggle for jurisdiction. A newcomer to this battleground may be referred to as the "concerned citizen" who is interested in his "public rights".

The Federal role in regulating the nation's water has not yet been clearly defined. The public interest, however, is reflected in the common law development over the past several years. As a starting point, I would like to read a policy of the Board of Trade, in Great Britain:

> "In a country as crowded as England is, where the preservation of every open space is of the highest importance for the public health and enjoyment; in a maritime country, where facilities for navigation, for fishing, boating, beaching, landing, and shipping are essential to our trade and to the well-doing of our maritime population -- it is of the greatest moment that the control of the public and of the Government over the bed of the sea and the strip of common which lies between land and open sea should be preserved so

that it may be used for the furtherance of the important interests above referred to, and so that nothing may be done with it which is inconsistent with those interests. To sell it to private persons because a high price is offered, without reference to those interests, would be as absurd as it would be to sell Dover pier or to include or build in the London Parks . . . "

(Memorandum of Board of Trade, 1866)

The Constitution of the United States places considerable power in Congress to regulate commerce and to provide for the general welfare (Article I, Section 8). The early Acts by Congress were based upon the commerce clause.

Legal protection of estuaries is not accomplished by statutes alone. Judicial interpretation on a case-by-case basis may give us guidance but its application is often limited. Legal protection of our estuaries is accomplished for the most part by administration of state and Federal programs. The administrative agency is the protector. The administrative agency makes the decision that spells wise use or dumb abuse. Recent examples of the effects of the Executive Branch upon estuaries are President Nixon's order establishing a Federal permit system and Governor McCall's order banning construction on the coast which might block estuaries.

Administrative decisions have, by far, the greatest impact upon the regulation of the use of these sensitive areas. The treatment requirements in a municipal system before approving a grant; the criteria established for the protection of shellfish; the anti-degradation policy of each state to protect pristine waters. All of these decisions made by the administration have a direct and sometimes drastic effect upon the estuaries.

Out of the forty agencies I mentioned that have a concern for estuaries, the Environmental Protection Agency stands out. This agency, formed in late 1970, is charged by Congress with the administration of the laws relating to noise, air, pesticides, radiation,solid waste and water. It has transferred people and responsibility from 15 other programs. Its purpose is to better analyze and regulate the environmental forces in these six fields. E.P.A. administrators, with your help, will set rules and regulations for the wise use and not abuse of estuaries and other resources.

This agency is in the forefront of the revolution described by President Nixon in his recent State of the Union Message. That revolution is crying out that the smokestack which was once the symbol of community prosperity is now a monument of its pollution. That revolution is telling us that the economic benefits that helped us overlook water quality degradation is no longer strong enough to support the continuation of pollution. The voice of the people and the voice of this conference tell us the same thing -- we must find a new way to do business -- that the environmental ethics of the past, however valid they might have seemed in the first half of this century, are no good for the Age of Aquarius. Such a philosophy shapes the policies of this agency.

The regulation of water quality standards in interstate and coastal waters is carried out by first establishing state and Federal water quality standards, classifying streams, defining criteria, and establishing implementation schedules. Classification of water uses brings us to the Pacific Northwest estuary. Waters valuable for shellfish propagation; waters used for fish and wildlife purposes; water use of the ocean as it may affect the estuary. This is the area to be protected -- this is the area where evidence of abuse haunts us daily. This is the area of your concern.

Congress provided for the establishment of criteria, implementation plans and enforcement procedures in the Federal Water Pollution Control Act of 1965 (33 USC 466). Under this Act, the State of Oregon has established standards for the marine and estuarine waters of the State. The criteria for water quality provide that no waste discharge or activity shall cause the dissolved oxygen to fall below 6 milligrams per liter or cause concentrations of coliform bacteria to exceed 70 MPN per 100 milliliters; that the pH range remain between 7. and 8.5 for shellfish waters in marine and estuarine areas; that turbidity not exceed 5 JTU above natural background, except during authorized dredging and that temperature changes cause no adverse effect.

The State of Washington has classified certain streams as AA Extraordinary. These are to receive the most stringent protection. Among other criteria, the total coliform organisms shall not exceed 50 in fresh water or 70 in marine water. D.O. shall exceed 9.5 milligrams per liter in fresh water and 7.0 mg/l in marine water. Temperature ranges are specified not to exceed 60^{0} F (fresh water) or 55^{0} F (in marine water).

Alaska has established similar criteria for the protection of its estuaries. An interesting note on these standards relates to water classified for growth and propagation of fish and other aquatic life. The restriction on residues is "None alone or in combination with other substances or waste as to make receiving water unfit or unsafe for the use indicated, except that no waste oils, tars, grease or animal fats are permitted."

The Federal government has approved these standards --

The implementation and construction of treatment facilities is worked out on a case-by-case basis. Each municipality and industrial discharger was given notice of the requirements. The large majority of these entities are well along on the preventive job that must be done.

In Puget Sound we have worked long and hard with the pulp and paper industry. A State and Federal conference for enforcement of the standards was held at the request of Governor Rosellini in 1962. Thereafter, a joint study of the effect of the pulp mills was completed in 1966. This detailed survey included a number of different studies on the effect of pulp mill wastes on oysters and oyster larvae, juvenile salmon, fish food organisms as well as waste contribution and sludge bed distribution. The conference was reconvened in 1967. The implementation plan is well underway but not without its exceptions.A complaint was filed in the U.S. District Court for the Western District of Washington against Georgia-Pacific Corporation at Bellingham. This effectively reduced mercury discharges into the Sound. Litigation has been recommended against ITT-Rayonier at Port Angeles because there has been no agreement concerning the treatment facilities to be installed. The legal protection of these waters has not been as effective as we would like. The decision of the administrator of E.P.A. here, however, has been to take the firm line and insist upon the highest and best practicable treatment now known to the industry.

In addition to the efforts of the State and Federal agencies, two suits have been filed against pulp mills in Puget Sound by citizens who alleged a right under the Refuse Act of 1899. One of these has been dismissed and one is now pending. Citizen suits have been authorized in the Clean Air Act of 1970 and water standards may be the subject of such suits if the proposal now before Congress is enacted.

One of the practices that certainly has an impact upon estuaries is the discharge of waste into the ocean. These discharges include industrial and municipal sources -- solid as well as liquid. This practice has recently undergone extensive studies by the Council on Environmental Quality, the President's Advisor on Environment. In their report dated October, 1970, several important recommendations were made:

(1) New legislation needed

(2) Ban unregulated ocean dumping of all materials harmful to the marine environment,

(3) High priority to protect the marine environment which is biologically active; namely, the estuaries and the shallows, nearshore areas in which many marine organisms breed and spawn,

(4) Corps of Engineers should dredge highly polluted areas only when absolutely necessary.

The Federal Water Quality Improvement Act of 1970 established the current requirements for the handling of oil. Absolute liability for cleanup of oil spills has been legislated. (Up to $14 million). A national contingency plan was established and approved by the President in June, 1970. The most advanced scientific knowhow of oil cleanup is assured. Teams have been formed. Equipment has been centralized. The military-like preparation has been made. Each Region has supplemented this plan with 24-hour on-the-scene preparedness. We continue to have serious oil spills but the calamity crew has improved.

The requirement of the past year for the transportation of oil has been considerably strengthened. Preventive measures have been taken by the industry. Some evidence of this, locally, is the sophisticated ballast treatment plant to be built at the Southern terminus of the Alaska Pipeline. E.P.A. engineers have worked on the specifications for this plant for some time.

As further evidence that the administrator makes the important day-to-day decisions that protect our estuaries, we in the Regional Office of E.P.A. work closely with the Corps of Engineers in their dredging program and in their permit program.

The Columbia estuary, as well as many on the Washington coast, require constant dredging to keep them free for commercial traffic. The E.P.A. laboratory here in Corvallis now conducts many of the sludge analyses prior to dredging. There is in my own shop in Portland close review and cooperation in deciding upon the disposal of contaminated dredge spoils. From this conference and others like it, we hope to assure the wise use of our estuaries -- not dumb abuse.

Private dredge and fill operations can no longer be made as a matter of right. An important judicial announcement was made in the case of Zabel vs. Tabb, 5th Circuit - 1970. Tabb was the District Colonel for the Corps of Engineers at Jacksonville, Florida. Zabel and others applied for a permit to dredge and fill navigable waters to develop a trailer park. Although no navigational harm could be shown, the Corps refused the permit on the basis of the recommendation of the Department of the Interior relating to damage to fish and wildlife habitat. The U.S. District Court ordered the permit to be issued. The U.S. Court of Appeals reversed the District Court and agreed with the Corps that it need not issue the permit unless satisfied that the requested activity would not harm the environment. Thus opened wide the door for the Corps of Engineers to be influenced by the sciences of environmental protection.

Under Section 13 of the Refuse Act, the President has announced a Federal Waste Discharge Permit Program. This is another effort at the Federal level to exercise broader jurisdiction and control over these sensitive waters. This program, whereby the Corps of Engineers will issue permits to each industrial discharger will be backed up by our water scientists in E.P.A. The states will also have an opportunity to require safeguards - so the time for indiscriminate uncontrolled devastating pollution of the coastal waters is hopefully drawing to a close. One of the high priority studies to precede a Section 13 permit is now underway in the fish processing industry. The seagulls may have to go further out for their gourmet dinners.

Congress has long recognized the need to give special attention to estuaries. In August, 1968, (PL 90-454) they authorized a study to be made directed to the need to protect, conserve and restore estuaries. This Act recognized the interest of the states and urged cooperation between the Federal and State agencies. This study, carried out by the Department of Interior, was released in January, 1970. It is a 7-volume work entitled National Estuary Study. The Federal Water Quality Administration, then in Interior, also released early last year three volumes entitled, "National Estuarine Pollution Study". Most of you here, no doubt, are familiar with these studies.

One of the most far-reaching and significant Congressional Acts that will surely have a beneficial effect upon the care and feeding of wetlands is the National Environmental Policy Act signed by President Nixon on January 1, 1970. I have provided you with a copy of Section 101 of that Act which recites the basic direction of public land and water management in the future. The Act also requires all Federal agencies to consider the environmental impact of their activities. This requirement should be felt at the estuary level during the forthcoming permit program that will authorize the use of navigable waters for industrial waste. Here again the decision of the Administrator of E.P.A. in setting treatment requirements will be the protection to the resource involved. Certainly a heavy load in this case and one in which we are frantically seeking the technical answers from you folks.

Now for a look at the legal protection in the wings that we can expect tomorrow. There has been introduced in the current session of Congress a bill entitled "National Coastal and

Estuarine Zone Management Act of 1971." The bill provides for Federal aid in assisting states in management of these zones. It also provides for authority to purchase lands for research and protection within these zones. The bill was developed after the studies authorized by Congress in 1968. On February 4, 1971, Senator Hollings from South Carolina advised the Senate of the need for this new legislation. He said:

> "Mr. President, the coastal and estuarine zones of the United States are among the most productive natural areas found anywhere and are under great pressure from our increasing population and development. It is essential to concentrate environmental and resource management in those areas, management geared to their special needs, management that differs markedly from terrestrial areas farther inland...
>
> "There is heavy public interest in both the environment and the resources of the coastal and estuarine zones. Thirty million people turn to the coasts annually for swimming; 11 million to fish; 8 million to sail. And the greatest contests between public and private interests for the scarce resources in these areas take place there...
>
> "No more politically complex areas exist in the United States than in our coastal and estuarine zones. The

political authority extends from the local, to state, Federal, and international. But there is no overall management by the states nor any national guidance in this critical area. Yet strategically, the coastal and estuarine zones are the key to preservation and use of the ocean's environment and resources."

Additional Federal statutes have been introduced in the current session of Congress. These include:

Amendment to Section 7 - a grant program for State planning

Amendment to Section 8 - a two fold increase in construction grants to provide for Federal assistance of $6 billion over the next 3 years to be granted on an equal matching basis

Amendment to Section 10 - to strengthen the enforcement of water quality standards and to broaden jurisdiction to all navigable waters

Marine Production Act - authorize E.P.A. to issue permits and control ocean and coastal dumping

CONCLUSION

Out of this jurisdictional struggle comes the legal protection of the estuaries. Federal influence is increasing -- E.P.A. has the expertise that is critical to protection. Our administrator has pointed the way.

Your efforts to emphasize the importance of these have paid off -- the local agency, the State government, Congress, and best of all, the general public, have commenced to talk about estuaries. All Federal agencies must build and administer their programs so as to take into account the environmental impact of their activities. States have come a long way in wise land use planning. The water user now has the burden of showing that proposed activity will not damage the resource.

The outlook is promising.A bit of order is shining through the chaos. But we have a lot of work to do. The techniques of protection developed at this conference will be the backbone of "Legal Protection". If we are to insist upon wise use we must have the scientific background to justify our administrative decision.

Congratulations on your approach to estuary protection. You have made a bold beginning toward a hospitable environment for today and for tomorrow.

NATIONAL ENVIRONMENTAL POLICY ACT

Public Law 91-190
January 1, 1970

SEC. 101. (a) The Congress, recognizing the profound impact of man's activity on the interrelations of all components of the natural environment, particularly the profound influences of population growth, high-density urbanization, industrial expansion, resource exploitation, and new and expanding technological advances and recognizing further the critical importance of restoring and maintaining environmental quality to the overall welfare and development of man, declares that it is the continuing policy of the Federal Government, in cooperation with State and local governments, and other concerned public and private organizations, to use all practicable means and measures, including financial and technical assistance, in a manner calculated to foster and promote the general welfare, to create and maintain conditions under which man and nature can exist in productive harmony, and fulfill the social, economic, and other requirements of present and future generations of Americans.

(b) In order to carry out the policy set forth in this Act, it is the continuing responsibility of the Federal Government to use all practicable means, consistent with other essential considerations of national policy, to improve and coordinate Federal plans, functions, programs, and resources to the end that the Nation may --

(1) fulfill the responsibilities of each generation as trustee of the environment for succeeding generations;

(2) assure for all Americans safe, healthful, productive, and esthetically and culturally pleasing surroundings;

(3) attain the widest range of beneficial uses of the environment without degradation, risk to health or safety, or other undesirable and unintended consequences;

(4) preserve important historic, cultural, and natural aspects of our national heritage, and maintain, wherever possible, an environment which supports diversity and variety of individual choice;

(5) achieve a balance between population and resource use which will permit high standards of living and a wide sharing of life's amenities; and

(6) enhance the quality of renewable resources and approach the maximum attainable recycling of depletable resources.

(c) The Congress recognizes that each person should enjoy a healthful environment and that each person has a responsibility to contribute to the preservation and enhancement of the environment.

Studies of Sediment Transport in the Columbia River Estuary

by

D. W. Hubbell

J. L. Glenn

H. H. Stevens, Jr.

Water Resources Division

U. S. Geological Survey

Portland, Oregon

ABSTRACT

Information on sediment transport and deposition in the Columbia River estuary has been obtained by measuring and sampling the flow, surveying the bed with acoustic techniques, and determining radionuclide levels. Flow measurements and water-sediment samples show that temporal and spatial variations in suspended-sediment concentrations and in suspended-sediment discharges are large and are affected significantly by a turbidity maximum that develops and migrates longitudinally in the estuary. Side-scan sonar records obtained during a period of relatively low river flow indicate predominantly landward transport of sediment along the bottom in deep channels upstream from the mouth to about mile 14 and predominantly seaward transport on shallow slopes marginal to the channels downstream to about mile 5. A mass-balance equation that considers the amount of ^{65}Zn in the estuary bed and the net inflow of ^{65}Zn to the estuary suggests that approximately 30 percent of the silt and clay that enters the estuary from the river is retained there. Because of the complex character of estuary flows, detailed information on transport can be obtained only by making observations throughout tidal cycles and over extended periods of time.

INTRODUCTION

For the past several decades the Columbia River has received radionuclides from nuclear fallout over its drainage basin and from the release of low-level radioactive effluents at the U.S. Atomic Energy Commission's Hanford Reservation near Richland, Wash. Although many radionuclides decay during transport or are sorbed by river bottom sediments, some radionuclides are conveyed in solution and in association with particulate matter downstream to the estuary and thence to the ocean. In late 1963, the U.S. Geological Survey, in cooperation with the U.S. Atomic Energy Commission,

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1/ Publication authorized by the Director, U.S. Geological Survey.

2/ Research Hydrologist.

3/ Research Hydraulic Engineer.

initiated an investigation of the transport and disposition of the radionuclides in the Columbia River estuary. In order to quantify transport rates of radionuclides and to better understand radionuclide transport phenomena, water discharges have been measured and sediment data, as well as radionuclide data, have been collected. This paper briefly describes several different collection and analysis techniques that have been used to obtain data during the investigation and discusses aspects of the data that relate to sediment transport in the estuary. In particular, data on spatial and temporal variations in suspended-sediment transport are presented; trends of sediment movement along the bottom as inferred from acoustic records of bottom topography are discussed; and general conclusions about sediment transport derived from the radionuclide data are described.

For the purposes of the overall investigation, the estuary has been defined as the part of the Columbia River between Longview, Wash., CRM (Columbia River mile) 66, and the mouth CRM 0 (fig. 1). The discussion of sediment transport in this paper, however, mainly pertains to the part of the estuary seaward from Harrington Point, CRM 23, which is the part subjected to salt-water intrusion. The width of the estuary in this part varies from about 10 miles just below Harrington Point to about 2 miles between the jetties at the mouth. Tides are the mixed type, and at the mouth the mean tidal range is 5.6 feet and the mean diurnal range is 7.5 feet (U.S. Coast and Geodetic Survey, no date, p. 172-173). On the basis of long-term records at The Dalles, Oreg. (U.S. Geol. Survey, 1968), upland flow (fresh-water flow) at Vancouver, Wash., CRM 107, averages about 200,000 cfs (cubic feet per second). During 1963-67, discharge at

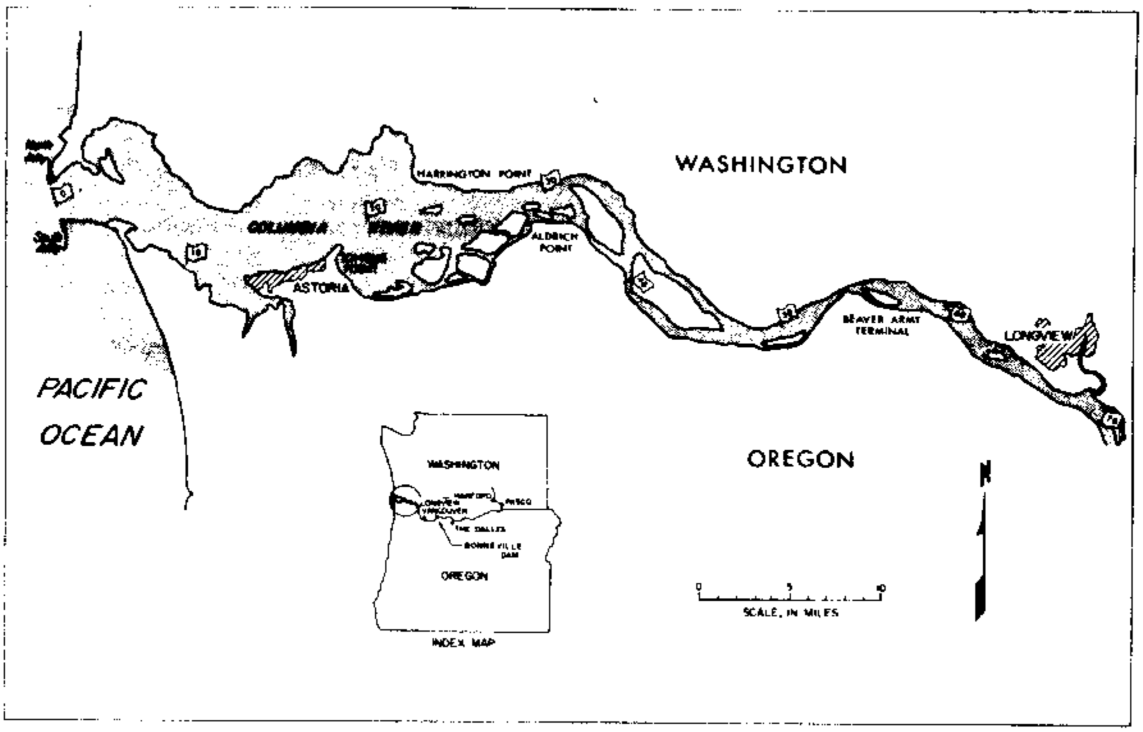


Figure 1.--Columbia River estuary. Flags show Columbia River mile. River mile 0 is on line with ends of north and south jetties. (From Hubbell and Glenn, 1971.)

Vancouver ranged from about 80,000 cfs to 675,000 cfs (U.S. Geol. Survey, 1968). These flow rates represent roughly from 1/10 to 1/3 of peak instantaneous ebb discharges measured at Astoria, Oreg., CRM 13. Salinity distributions usually vary more or less gradually in the vertical and longitudinal directions, and at times a lateral gradient that decreases from north to south exists in the vicinity of Astoria. Because of these distributions, the estuary usually is classified as "partially mixed."

SUSPENDED-SEDIMENT TRANSPORT

Measuring and Sampling Techniques

In order to define, on a continuous basis, rates of suspended-sediment transport, samples of water and suspended sediment were collected periodically from cross sections at Astoria and at the former Beaver Army Terminal, CRM 53, and routinely from single fixed sites at these locations. The samples provide information on the temporal and spatial variations of suspended-sediment concentration in the transition part of the estuary (Astoria), where fresh and salt water mix, and in the fluvial part of the estuary (Beaver Army Terminal), where only fresh water is present but where the tide significantly influences the flow. In addition, total water discharges were measured at the two cross sections to provide data for adapting and calibrating a mathematical model (Lai, 1965) to compute instantaneous total discharges throughout time. The combination of instantaneous concentrations and water discharges gives continuous records of suspended-sediment transport through the two cross sections. A more synoptic view of transport in the estuary, however, is provided by data,which were obtained on two occasions, on the longitudinal distribution of suspended sediment.

For water discharge determinations, flow was measured from a continuously moving boat by using equipment and a technique (Prych and others, 1967) that provides for the rapid collection of data for defining velocity profiles (magnitude and direction) throughout the total depth. By measuring repetitively during the daylight hours at about 20 verticals, spaced roughly according to discharge across the width of the estuary, and by combining the discharges from several adjacent verticals, the time variation of discharge through individual segments of the width was defined. Summing discharges for common times from the hydrographs for all segments of the width yields the discharge hydrograph for the entire cross section.

Suspended sediment was sampled by two different techniques. To obtain information on the vertical distribution of suspended sediment, the point-integrated sampling technique was used. Either 3- or 6-gallon samples were collected from various points throughout the depth with a vacuum-actuated pumping unit that has a streamlined sampling assembly with a horizontal nozzle which orients into the flow. The pumping rate was regulated so that the velocity within the nozzle nearly equaled the ambient velocity at the sampling point. Sampling at ambient velocity insures that all particles in suspension, regardless of their size, are collected according to their concentration in the flow. When samples were obtained primarily for suspended-sediment discharge computations, the techniques of depth integration was employed. With this technique, a sampler with a horizontal nozzle that collects water-sediment mixture at stream velocity is traversed at a uniform rate throughout the total depth. Thus, in each increment of depth, an incremental volume of water-sediment mixture is collected which is proportional to the water discharge through the increment. The resultant concentration of the sample then is discharge weighted and can be multiplied directly with the appropriate water discharge to yield the suspended-sediment discharge through the width assumed to be represented by the sample.

In the following discussions, the sampling technique employed to obtain the samples will be mentioned. An important point with both techniques is that the sample is collected at stream velocity; thus, sand particles that may be transported in suspension near the bed, as well as finer sediments, are collected in proportion to their true concentration in the flow.

Temporal and Spatial Variations in Transport

In the Columbia River estuary, depending on location, velocities near the surface vary during the flood from zero to about 4 fps (feet per second) and during the ebb from zero to about 8 fps. Suspended-sediment concentrations vary over a relatively wide range in response to these velocities. The variation in the concentration of depth-integrated samples obtained at a routine sampling site on the south side of the navigational channel in the vicinity of CRM 13 is shown in figure 2 for a 25-hour period on September 14-15, 1969. Total water discharge, water-surface elevation (stage), salinity 1/, and suspended-sediment discharge 2/

1/ The term "salinity" is used to designate the dissolved-solids content, in parts per thousand (ppt). Salinities were determined by converting measured conductivities and temperatures to dissolved solids by means of laboratory calibration data.

2/ Suspended-sediment discharge at any given time is determined by multiplying 0.0027, which is a units-conversion constant, by the product of the concentration and water discharge at that time.

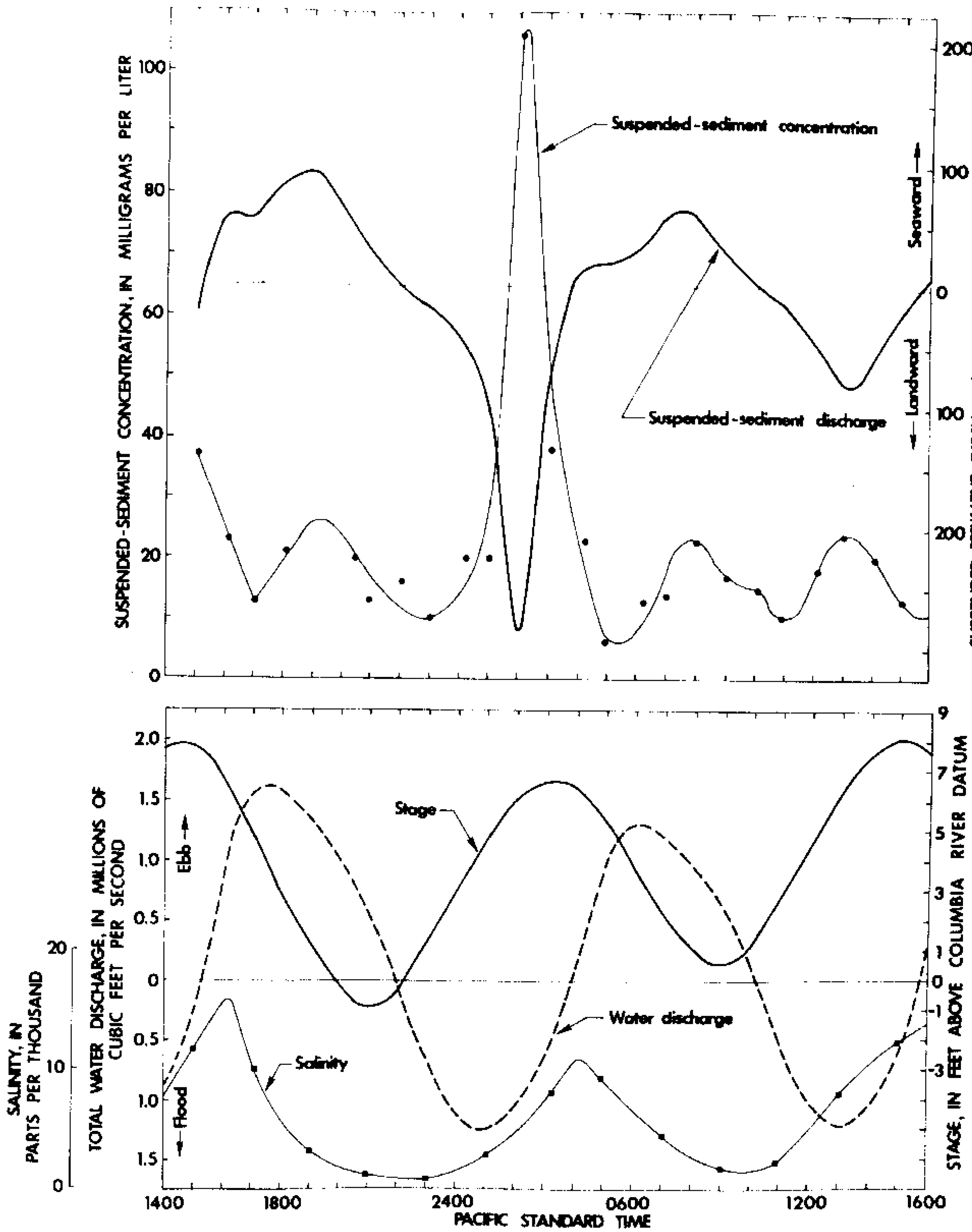


Figure 2.--Temporal variations in total water discharge, water-surface elevation (stage), salinity, and the concentration and discharge of suspended sediment at CRM 13 on September 14-15, 1969. Suspended-sediment concentrations and salinities were determined from depth-integrated samples from the routine sampling site.

(computed from concentrations and water discharges given by the curves) also are illustrated. Integration of the suspended-sediment discharge over the tidal cycle (24.8 hours) gives a net landward transport of sediment of 7,400 tons. For the tidal cycle depicted in figure 2, the maximum suspended-sediment concentration occurred during a flood. At another time, May 23-24, 1970 (fig. 3), at the same location, the maximum concentration occurred during an ebb. The suspended-sediment concentration was fairly constant during the floods but increased significantly during the ebbs to produce a net suspended-sediment transport over the tidal cycle of 50,000 tons seaward.

Temporal variations in suspended-sediment concentrations at any particular location in the estuary are affected significantly by the character and areal distribution of the so-called "turbidity maximum" which is a characteristic feature in many estuaries. In the part of the estuary subjected to salt-water intrusion, flow throughout the entire depth is alternately conveyed landward and seaward; however, a net circulation pattern (called the estuarine circulation pattern) is developed such that a landward flow of dense salt water predominates in the lower layers and a seaward flow of less-dense fresh water predominates in the upper layers. Similarly, suspended sediment alternately is transported landward and seaward by the flow. Particularly during slack water, some of the particles in suspension in the upper layers settle into the lower layers and subsequently are transported back upstream (landward) as a result of the upstream flow. This action over many tidal cycles causes sediment to accumulate in the zone where net flow near the bed is zero. Hence, whenever velocities in the zone are sufficient to transport sediment, a turbidity

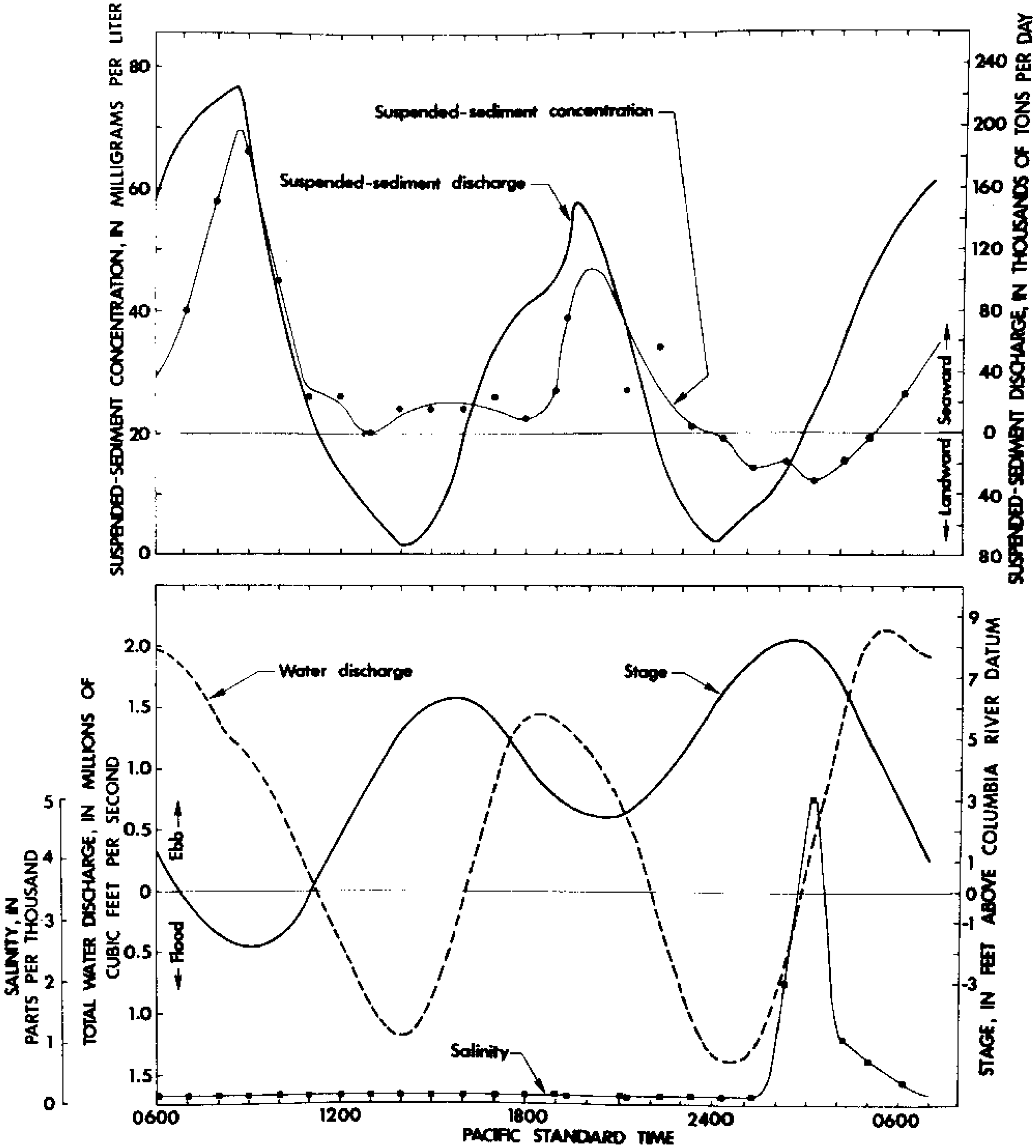


Figure 3.--Temoral variations in total water discharge, water-surface elevation (stage), salinity, and the concentration and discharge of suspended sediment at CRM 13 on May 23-24, 1970. Suspended-sediment concentrations and salinities were determined from depth-integrated samples from the routine sampling site.

maximum is developed wherein the suspended-sediment concentrations are considerably higher than they are in either the river water upstream or in the highly saline water downstream.

The character of the turbidity maximum in the Columbia River estuary was investigated on two different occasions by collecting data during 3-day periods when the tidal patterns and upland discharges were relatively constant. In each 3-day period, point-integrated suspended-sediment samples were collected 5 feet above the bed and 10 feet below the water surface and vertical distributions of velocity, salinity, and temperature were measured at seven stations that were located about 2 miles apart along the navigational channel. On each day, data were collected at three adjacent stations from a single vessel that repetitively occupied each station about every 2 hours during the daylight hours. On the second day of each 3-day period, the occupied stations were located in the middle part of the study reach and the upstream and downstream stations corresponded, respectively, to the downstream station on the first day and the upstream station on the last day. Measurement data were combined according to the relative time of collection in the tidal cycle to give distribution curves that show the time variations of variables at all stations on the second (middle) day. The distribution curves for the two stations where duplicate data were collected are defined relatively well because the data combined to provide measured values about every hour. The well-defined curves, in turn, served as guides for the preparation of distribution curves at the other stations.

The longitudinal distribution of suspended-sediment concentration 5 feet above the bed during different times in the tidal cycle on

May 23, 1970 is shown in figure 4. The mean daily flow through the cross section at Astoria on this day was about 468,000 cfs. At 0800 hours, about 2 hours after the time of high ebb velocities, concentrations were fairly high all along the reach and the peak concentration in the turbidity maximum was at about CRM 8. At 1100 hours, during the low slack, the general level of concentrations had diminished and the peak concentration was seaward from the study reach. At 1430 hours, about 1 hour after the peak flood velocity, the turbidity maximum again was well developed and the highest concentration was at about CRM 9.5. At 1700 hours, during the high slack, transport was nil, material in suspension settled, and the concentration decreased to a relatively low level.

Concentration distributions on September 14, 1969 (fig. 5), when the mean daily flow through the cross section at Astoria was 231,000 cfs, show the same general distribution patterns for essentially the same relative times as are illustrated in figure 4; but, the turbidity maximum was roughly 10 miles upstream. Approximately 1½ hours after high ebb velocities (0630 hours) concentrations generally were low and the peak concentration was at about CRM 19. At low slack (0930 hours) concentrations were low and they varied somewhat throughout the reach. Soon after high flood velocities (1230 hours), the turbidity maximum again was well developed and peaked at CRM 16.5. At high slack (1630 hours) concentrations again had diminished appreciably throughout the reach.

The textural composition of the suspended sediment (table 1) varies as the turbidity maximum develops and abates, and it also varies from one time to another. On September 14, 1969, the concentration of a sample collected 1½ hours after the peak ebb velocity was 17 mg/l (milligrams

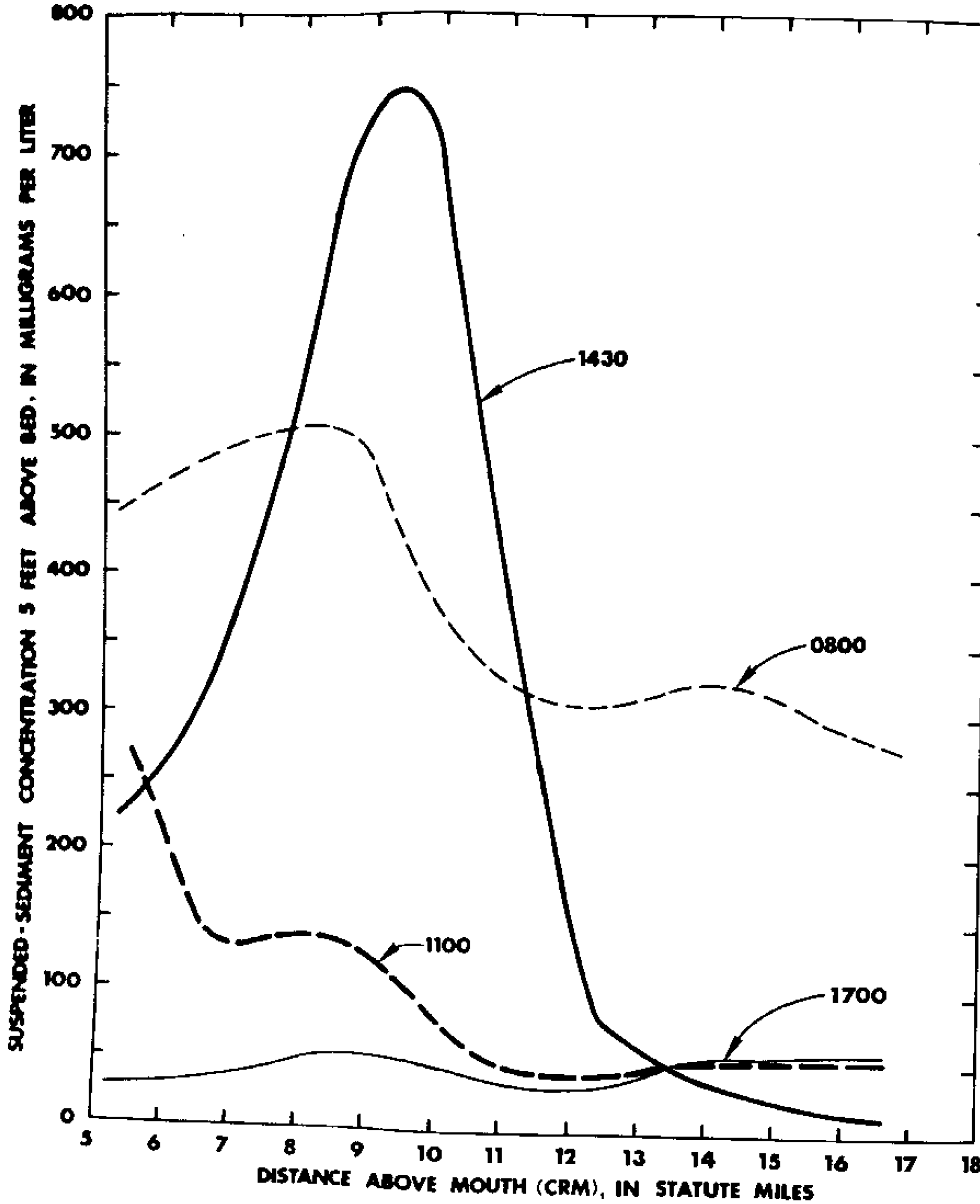


Figure 4.--Longitudinal distributions of the concentration of suspended sediment 5 feet above the bed at various times on May 23, 1970. Indicated times are Pacific Standard time.

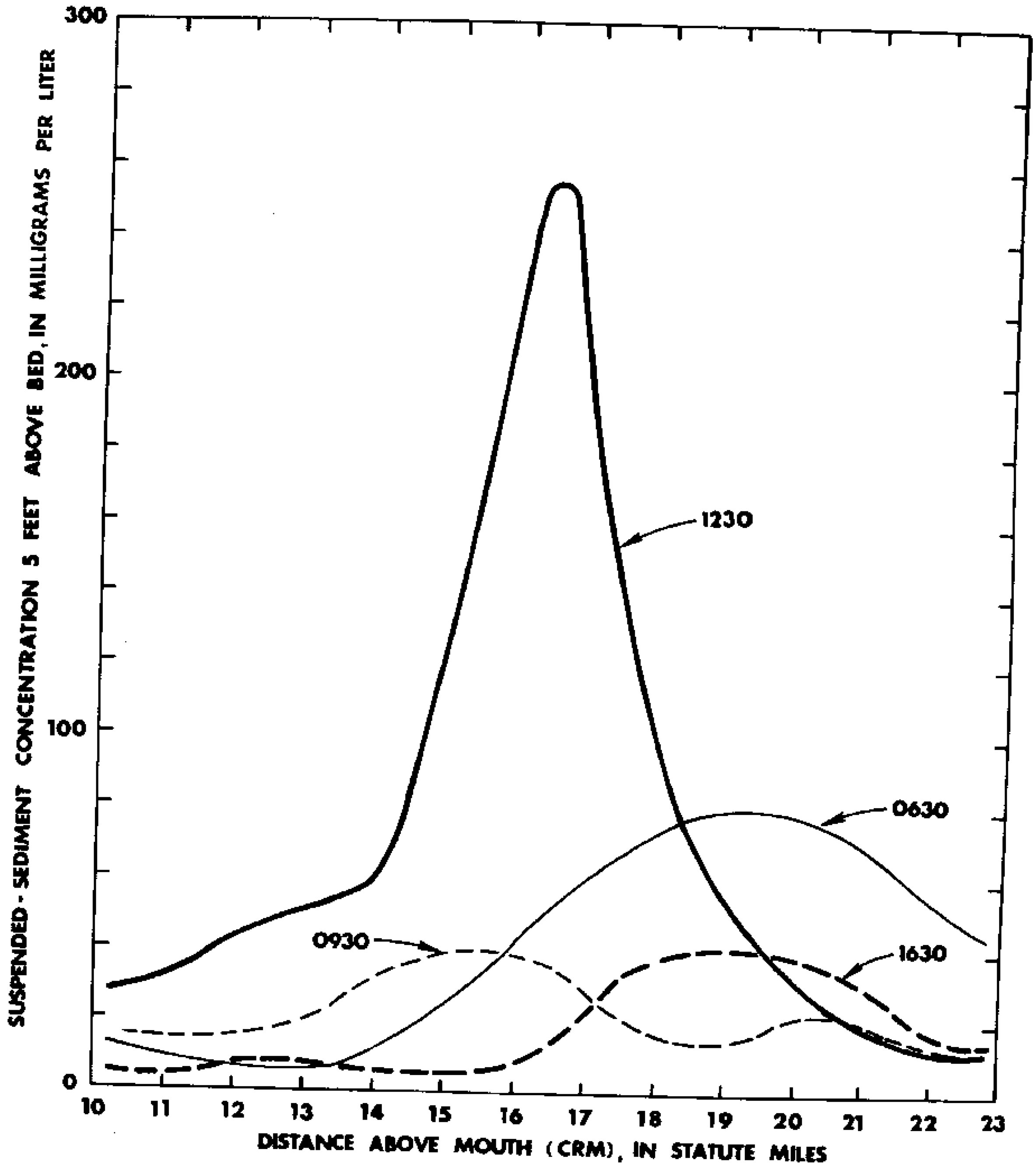


Figure 5.--Longitudinal distributions of the concentration of suspended sediment 5 feet above the bed at various times on September 14, 1969. Indicated times are Pacific Standard time.

Table 1.--Textural composition of suspended sediment 5 feet above the bed at various times in the tidal cycle and at various longitudinal positions in the estuary

Date	Relative time in tidal cycle	Location (Columbia River Mile)	Suspended-sediment concentration (mg/l)	Texture					
				Percentage in class			Concentration in class (mg/l)		
				Sand	Silt	Clay	Sand	Silt	Clay
1969									
Sept. 14	$1\frac{1}{5}$ hr. after peak ebb velocity----	14.0	17	0	63	37	0	11	6
Do----	Low slack--------	14.0	24	1	71	28	0	17	7
Do----	---do------------	18.2	11	0	56	44	0	6	5
Do----	$\frac{1}{5}$ hr. before peak flood velocity--	14.0	59	9	81	10	5	48	6
Do----	---do------------	18.2	87	3	83	14	3	72	12
Do----	$1\frac{3}{4}$ hr. after peak flood velocity--	14.0	85	3	85	12	3	72	10
Do---	$\frac{1}{2}$ hr. before high slack-----------	18.2	60	0	70	30	0	42	18
Do---	$\frac{3}{4}$ hr. before peak ebb velocity----	14.0	67	0	83	17	0	56	11
Do---	---do------------	18.2	34	0	88	12	0	30	4
1970									
May 23	$\frac{1}{5}$ hr. before peak flood velocity--	5.6	310	7	46	47	22	142	146
Do---	Peak flood velocity--------	10.7	344	8	71	21	28	244	72
Do---	$\frac{3}{4}$ hr. after peak flood velocity--	8.5	638	1	65	34	6	415	217

per liter); about 63 percent of the sediment or approximately 11 mg/l was silt[1/] and about 37 percent or 6 mg/l was clay[2/]. Approximately the same silt-clay content existed during low slack water. When concentrations increased during the flood, some sand[3/] (3-5 mg/l), as well as increased amounts of silt and clay, were suspended in the flow. During high slack, the sand and coarse silt apparently settled, but the fine-sediment content increased slightly, possibly because of an increase in the organic-matter content. As with the previous ebb, the particle size distribution remained essentially unchanged from the slack except that the clay content decreased. During the tidal cycle, apparently most of the sediment that was resuspended was silt, except during the time of high flood velocities when some sand was resuspended.

On May 23, 1970, somewhat before and during the time of the peak flood velocity, up to 28 mg/l of sand (approximately 8 percent) and 146 mg/l of clay were in suspension. As the velocities decreased, the quantity of sand in suspension diminished, but the clay content increased to 217 mg/l.

Graphs of the change with time in the vertical distributions of velocity, salinity, and suspended-sediment concentration at a central location within the zone of the turbidity maximum conveniently illustrate relations between these three variables. Concentrations, velocities, and salinities on May 23 at CRM 8.5 are shown in figure 6. On this day,

1/ Inorganic and organic material whose fall diameter is ≥4 microns and <62 microns.

2/ Inorganic and organic material whose fall diameter is <4 microns.

3/ Inorganic and organic material whose fall diameter is ≥62 microns.

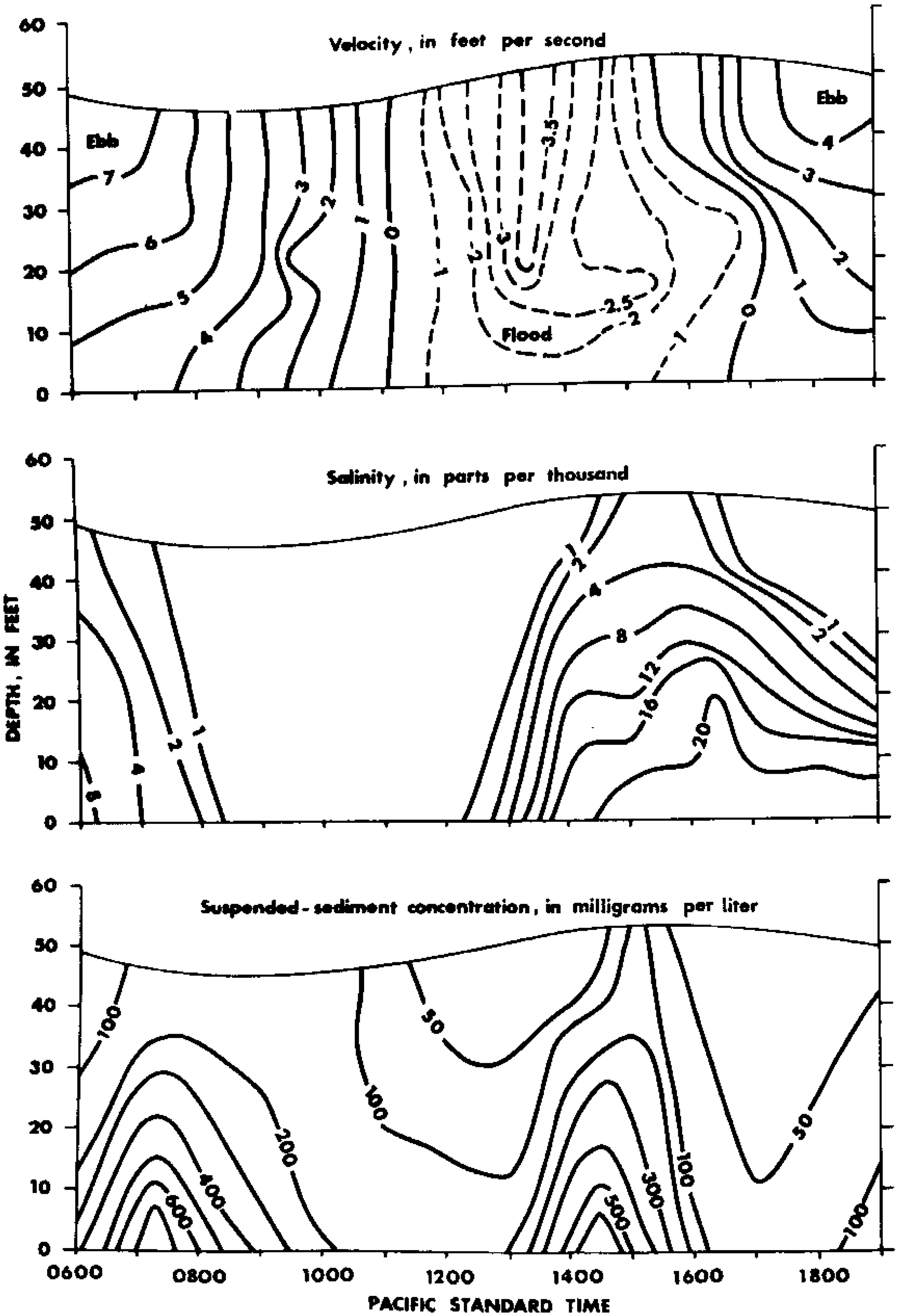


Figure 6.--Vertical distributions of velocity, salinity, and suspended-sediment concentration at CRM 8.5 on May 23, 1970.

highest suspended-sediment concentrations occurred somewhat after the peak ebb velocity and when the salinity was about 1-3 ppt. During the flood, the peak suspended-sediment concentration, which was slightly lower than the peak concentration during the ebb, also lagged the peak velocity, but occurred when the salinity was about 20 ppt at the bed. On September 14 at CRM 16.2 (fig. 7), measurable salinities persisted near the bed throughout the day. With this condition, the peak concentration occurred at about the same time as the peak flood velocity and when salinities still were low. During the ebbs, the peak concentrations remained relatively low. The data do not cover completely the ebb periods; however, it appears that the peak concentrations may have occurred at times of maximum velocity and moderate (2-8 ppt) salinities.

Meade (1968) has observed in some Atlantic Coast estuaries that the maximum concentration follows the fresh water-salt water transition as it moves back and forth with the tide. These measurements indicate that, in general, this is also the case in the Columbia River estuary. Certainly, the reach of the estuary where the turbidity maximum occurs varies throughout the year and corresponds approximately with the reach over which saline water at the bottom oscillates with the tide. Whereas, in many estuaries peak concentrations coincide with low salinities (Meade, 1968) and lag peak velocities (Postma, 1967), the variations in hydrodynamic conditions in the Columbia River estuary apparently are so extreme that no consistent and simple relations exist among concentrations, velocities, and salinities.

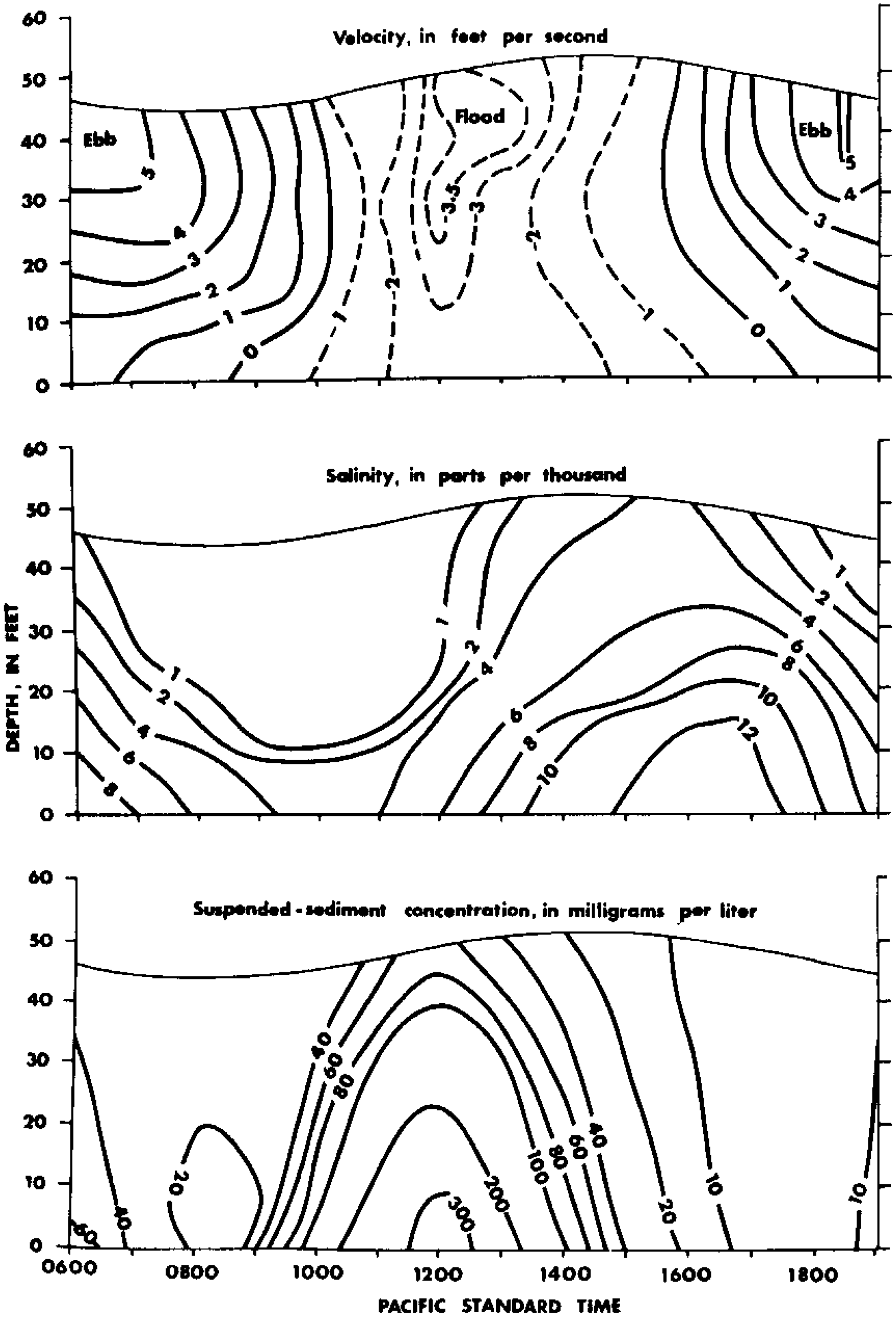


Figure 7.--Vertical distributions of velocity, salinity, and suspended-sediment concentration at CRM 16.2 on September 14, 1969.

SEDIMENT TRANSPORT ALONG THE BOTTOM

Unlike suspended-sediment transport, the transport of sediment along the bottom is difficult to measure directly by sampling. Acoustic equipment and techniques that provide information on the topography, texture, and stratigraphy of bottom sediments, however, can be applied to study transport at the bed. Side-scan sonar is particularly useful because it provides an areal view of the surface composition and topography for fairly long distances on either side of a cruise track.

Side-scan sonar records from parallel cruise tracks that were about 500 feet apart are shown in figure 8. By maintaining the same velocity over the bottom along each cruise track it was possible to provide data that could be matched to produce a record that showed bottom topography over a 1,000-foot width of the estuary. This particular figure shows the bed in the main channel near CRM 53. The upper two sections were produced along one cruise track and the lower two were produced along a second parallel cruise track. Each section shows features to one side of the cruise track. The zero line on the travel-time and slant-range scales represents the position of the submerged towing unit that housed the transmitting and receiving transducers. The first heavy line represents the reflection from the water surface and the irregular line represents the topography of the bed directly below the transducers. The remainder of the record shows the strength of the reflected sound waves at all points on the bed surface from below the transducer unit outward to a selected full-scale range of 247 feet. Strong reflections appear as dark areas in the record and weak reflections appear as light areas; hence, surfaces that are approximately normal to the sound waves and that act as

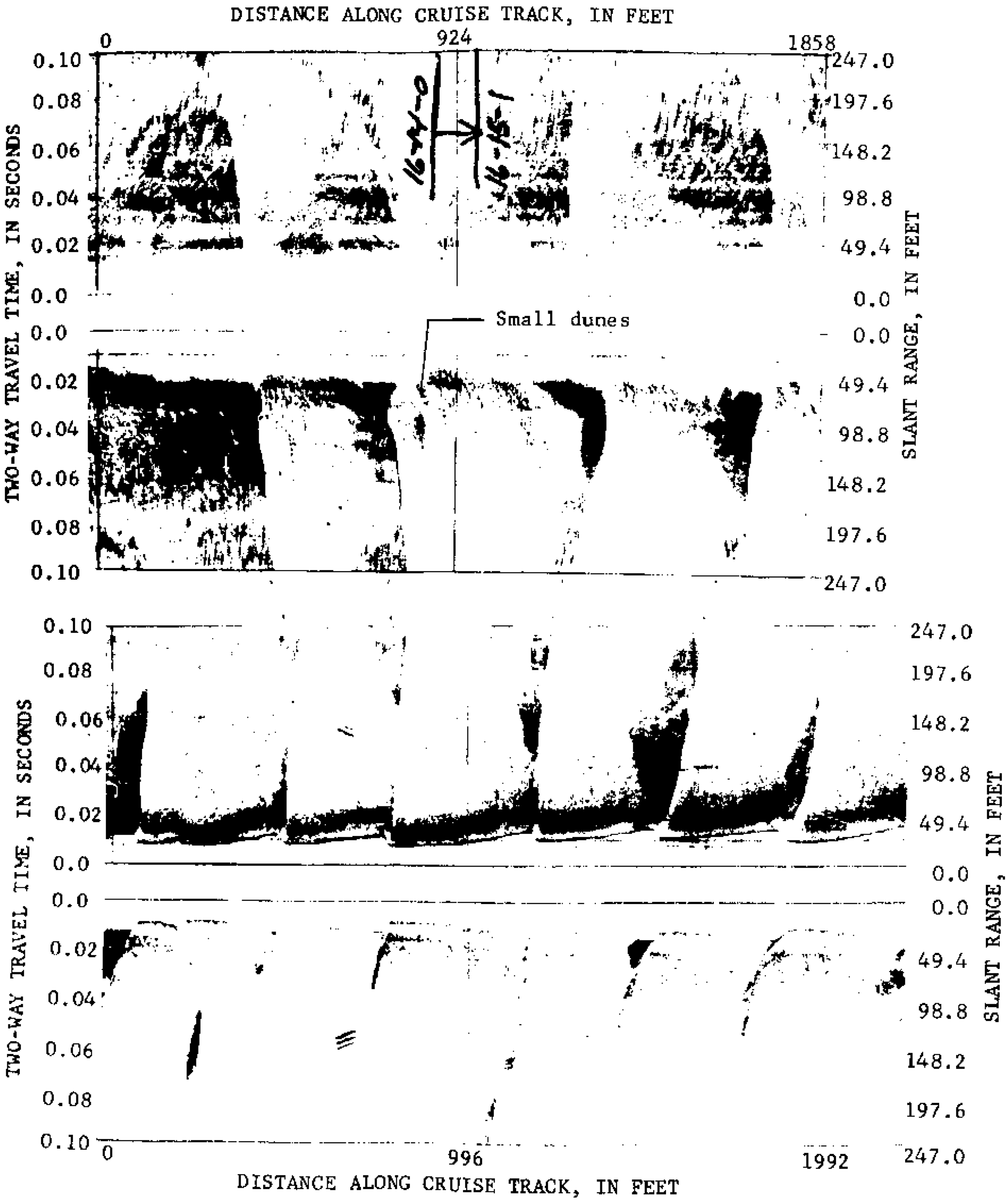


Figure 8.--Side-scan sonar records showing the characteristics of a dune field in a deep fluvial channel. Seaward (downstream) direction is to the left.

good reflectors show up as black, whereas, surfaces that are in the so-called acoustic-shadow zone appear white. In figure 8 it is evident that dune crests are approximately parallel to one another and that they extend for the full 1,000-foot width of the record. The black areas in the troughs between dune crests are strong reflections from areas where sub-bottom profiles indicate that bedrock is present.

Because side-scan sonar records show the topography of large areas of the bed, they can be used to study the orientation and shape of dunes that commonly form the estuary bed. These characteristics, in turn, reveal the dominant direction of sediment movement along the bottom of the estuary. The side-scan record shown in figure 9 was obtained during a run across the navigational channel at CRM 7. The shallow flats at either end of the record are essentially free of large relief features, as are the steep and deep parts of the slopes on either side along the navigational channel. Within the navigational channel, the foreward slopes of dunes cause acoustic shadows (thin circuitous bands of white) in the port record and strong reflections (thin circuitous bands of dense black) in the starboard record. This pattern indicates that the foreward slopes of dunes in the channel are toward the top of the record, which is the landward direction. On the gentle and shallow parts of the slopes on either side of the navigational channel, however, the acoustic shadows and the strong reflections are reversed and appear in the starboard and port records, respectively. This pattern indicates that the foreward slopes of the dunes are oriented seaward. From this record it appears that at the time of the survey the dominant sediment transport along the bottom of the navigational channel was

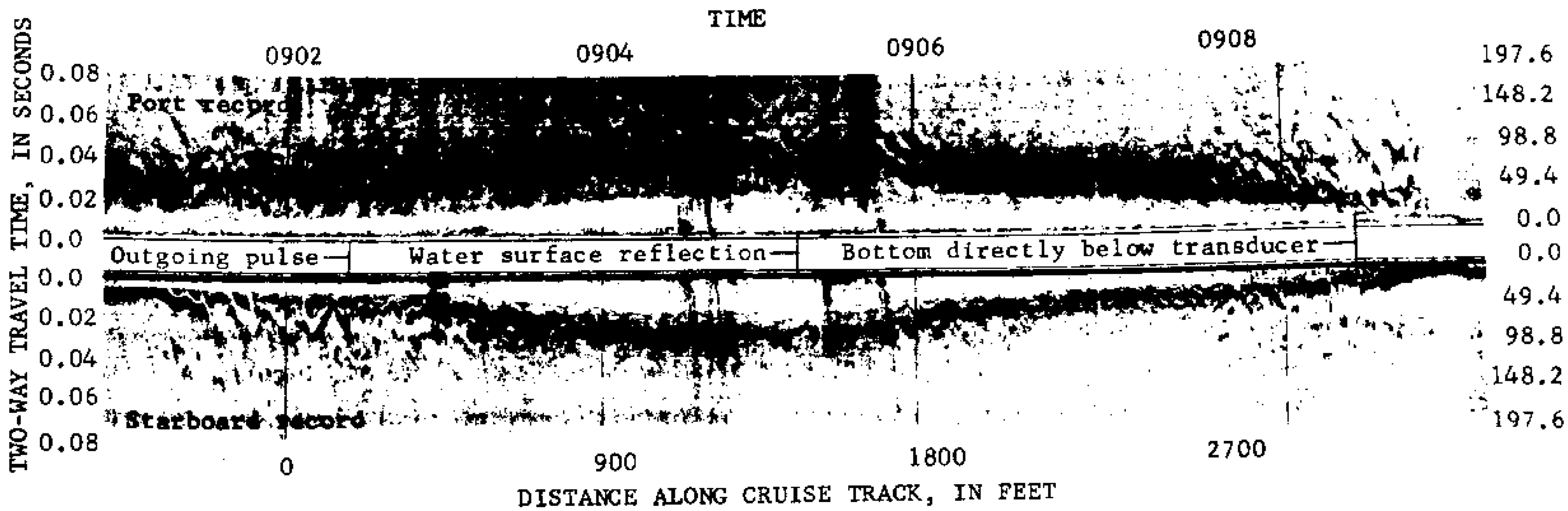


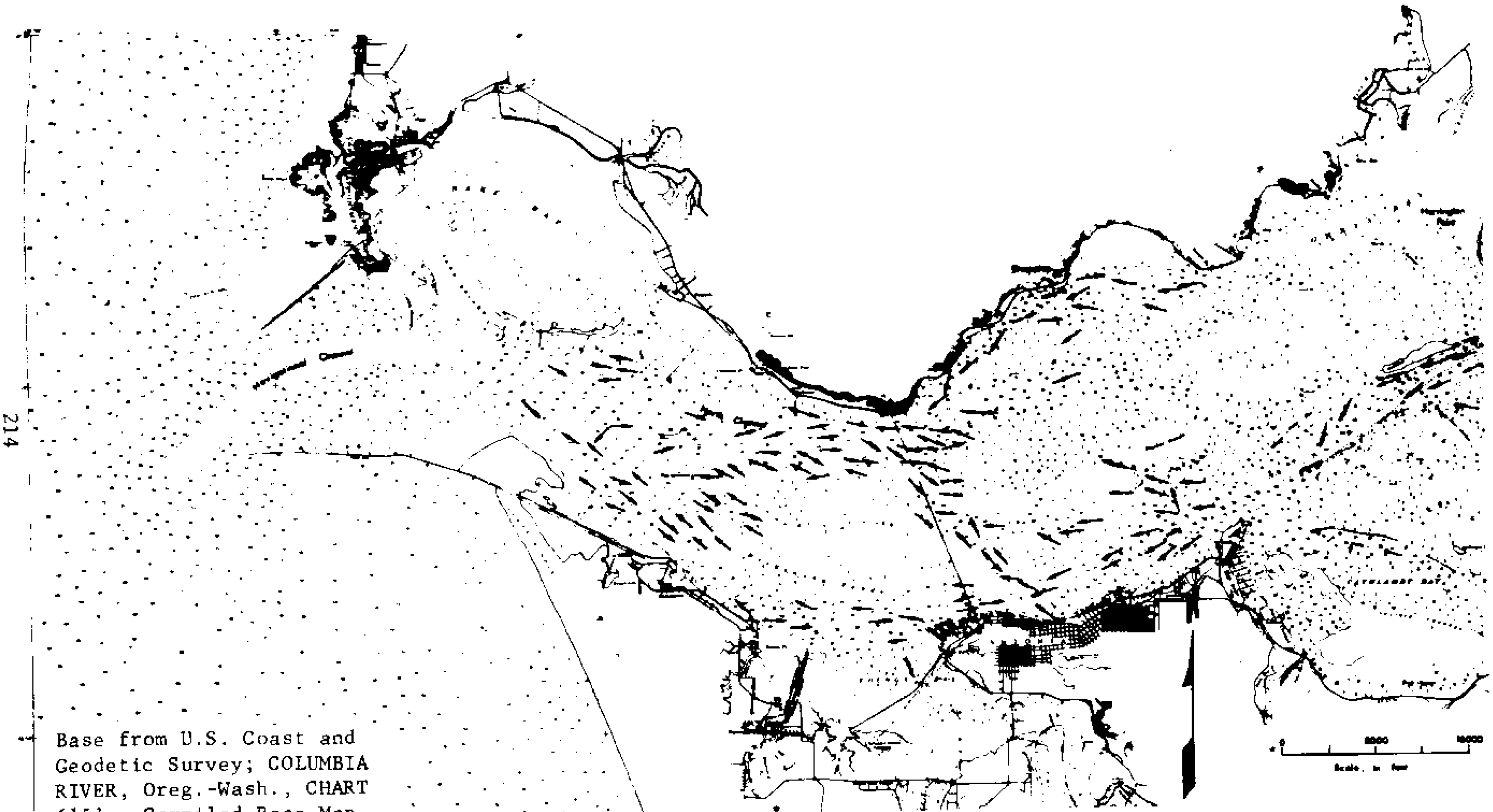
Figure 9.--Side-scan sonar record obtained during a lateral traverse of the navigational channel in the transition-marine part of the estuary. Landward (upstream) direction is toward the top of the record.

landward; whereas, on the slopes adjacent to the navigational channel the sediment movement along the bottom was seaward. Prentice and others (1968) reported similar transport patterns of bottom sediment in the Thames estuary; Nichols and Poor (1967) observed that suspended-sediment transport was upstream in the main channel of the Rapahannock estuary and downstream on the adjacent flats.

By analyzing side-scan records obtained throughout the estuary, a generalized qualitative pattern of sediment movement along the estuary bottom has been developed (fig. 10) for a period of relatively low upland flow (early fall of 1968). The pattern shows that between Harrington Point and Tongue Point, sediment movement along the bottom was seaward and was confined mostly to the vicinity of the navigational channel. Downstream from Tongue Point, transport along the bottom in the navigational channel was dominantly landward; whereas, transport on the slopes marginal to the channel was seaward at least as far downstream as CRM 5. On the north side of the estuary, transport along the bottom was dominantly landward in the deep channel, but occurred in both directions on slopes. Lateral transport in the old ferry channel at Astoria was in a northerly direction at the south end of the channel and in a southerly direction at the north end.

The pattern shown in figure 10 corresponds generally to that suggested by Lockett (1967). Studies at other times of the year, no doubt, would show somewhat different patterns.

CRM 7.



Base from U.S. Coast and Geodetic Survey; COLUMBIA RIVER, Oreg.-Wash., CHART 6151. Compiled Base Map Unit, Menlo Park. 11-13-68.

Figure 10.--Generalized patterns of sediment movement along the bottom of the Columbia River estuary below Harrington Point, September 1968. Arrows run at right angles to the trend of the dune ridges and point in the direction of sediment movement. Double-headed arrows indicate "neutral" bed forms.

Comparison between the dominant direction of flow near the bed and the orientation of bed forms sometimes can be used to infer the relative magnitude of sediment transport along the bottom. A relation (fig. 11) for flow predominance at a point 5 feet above the bed in the center of the north channel just above the Columbia River Bridge at Astoria (CRM 13), which was developed from velocity profiles measured sequentially over parts of tidal cycles during 1966-70, indicates that approximately 80 percent of the total flow back and forth past this point at the time of the side-scan sonar survey (discharge at Vancouver ≈ 120,000 cfs) was in a seaward direction. Because the orientation of the bed forms at the same location also was seaward, it seems reasonable to assume that some seaward transport may have occurred; however, since the bed forms below the bridge were oriented upstream, the transport probably was low. At higher flows, presumably, landward transport along the bottom would commence. In the navigational channel just above the bridge, landward flow appears to predominate near the bed (fig. 11) at low discharges, but seaward flow predominates at higher discharges. At this location during the side-scan sonar survey, flow near the bed apparently was dominantly upstream as was the orientation of the bed forms. This correspondence would tend to indicate that some sediment was being transported along the bottom in a landward direction.

IMPLICATIONS OF SEDIMENT TRANSPORT FROM RADIONUCLIDE DATA

The association between sediments and radionuclides in the estuary provides a unique means for tracing the movement of sediment particles and for quantifying long-term average values of sediment transport variables in the estuary. Unfortunately, not all analyses that might be made appear

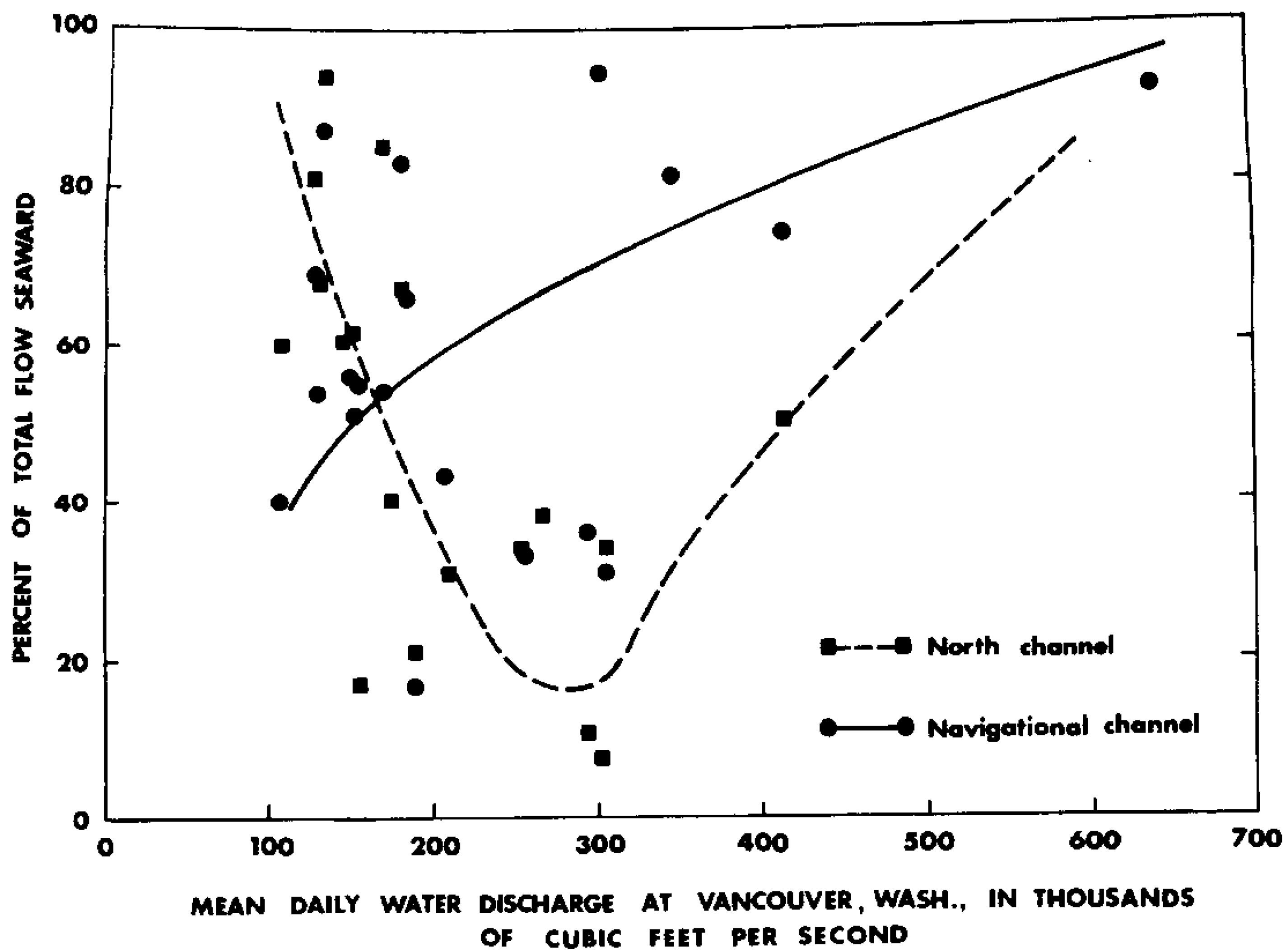


Figure 11.--Flow predominance 5 feet above the bed in the north channel and in the navigational channel just above the Columbia River Bridge at Astoria (CRM 13).

to be valid because of the influence of sorption and desorption phenomena and of the complexities of sediment movement.

According to computations in a recent report (Hubbell and Glenn, 1971), approximately 2,060 curies of ^{65}Zn resided on sediment in the bed of the estuary in June 1965. This value, together with information on the discharge of ^{65}Zn at Longview, has been used (Hubbell and Glenn, 1971) to estimate the fraction of fine sediment retained in the estuary. The calculation is based on equation 1, which states that the change with time in the amount of a radionuclide in the estuary equals the difference between the net rate of inflow (inflow minus outflow) to the estuary and the rate of decay of the radionuclide in the estuary.

$$\frac{dA}{dt} = \left(C_s Q_w\right)_I - \left(C_s Q_w\right)_O + \left(C_f Q_f\right)_I - \left(C_f Q_f\right)_O + \left(C_c Q_c\right)_I - \left(C_c Q_c\right)_O - \lambda A \qquad (1)$$

where

- A is the amount of the radionuclide in the estuary at any given time, t;
- C_s, C_f, C_c are the concentrations of the radionuclide in solution and associated with the fine and coarse sediment[1/], respectively;
- Q_w, Q_f, Q_c are the discharges of water and of fine and coarse sediment, respectively;
- I, O are subscripts denoting a quantity that is coming in or going out of the estuary, respectively; and
- λ is the decay coefficient for the radionuclide.

1/ Fine sediment is all material, including biota, whose diameter is ≥ 0.45 micron and < 62 microns. Coarse sediment is all material ≥ 62 microns in diameter.

In equation 1

$$\left(C_fQ_f\right)_O = C_{f_O}Q_{f_O} \quad \text{and} \quad \left(C_fQ_f\right)_I = C_{f_I}Q_{f_I}.$$

Thus, by setting

$$\frac{\left(C_sQ_w\right)_O}{\left(C_sQ_w\right)_I} = k, \qquad \frac{C_{f_O}}{C_{f_I}} = c$$

and dividing by $\left(C_fQ_f\right)_I$, equation 1 becomes

$$\frac{dA}{dt} = \left(C_fQ_f\right)_I\left[R_s\ (1-k) + 1 - c(1-P) + R_c - \frac{\left(C_cQ_c\right)_O}{\left(C_fQ_f\right)_I} - \frac{\lambda A}{\left(C_fQ_f\right)_I}\right] \qquad (2)$$

where

$$\frac{\left(C_sQ_w\right)_I}{\left(C_fQ_f\right)_I} = R_s, \quad \frac{\left(C_cQ_c\right)_I}{\left(C_fQ_f\right)_I} = R_c, \text{ and}$$

$$\frac{Q_{f_I} - Q_{f_O}}{Q_{f_I}} = P \text{ or } Q_{f_O} = Q_{f_I}\ (1-P).$$

If equation 2 is applied to the transport and storage of ^{65}Zn in the estuary, it can be reduced with several simplifying assumptions. In the reach between Pasco and Vancouver, the amount of ^{65}Zn in the streambed is essentially constant throughout the year (Nelson and others, 1966; fig. 6). Similarly, limited data indicate that ^{65}Zn in the bed of the estuary was essentially the same in 1965 as it was in 1964 (Hubbell and Glenn, 1971; fig. 23). Since the amount of ^{65}Zn in solution and in association with the suspended-particulate matter in transport in the estuary at any given time is insignificant compared to the amount of ^{65}Zn in the streambed sediments, $\frac{dA}{dt} \cong 0$. Also, the outflow of ^{65}Zn in association with coarse sediment probably can be considered to be negligible; evidence in this report (fig. 10) and data in Lockett (1967) suggests that little coarse sediment leaves the estuary. With these assumptions, equation 2 reduces to

$$P = \frac{c + k\,R_s - \left[R_s + R_c + 1 - \frac{\lambda A}{\left(C_f Q_f\right)_I}\right]}{c} \qquad (3)$$

in which P is the fraction of the ^{65}Zn-bearing fine sediment inflow that must be retained in the estuary in order to maintain a constant amount of ^{65}Zn in the bed.

Equation 3 can be solved with measured data by further assuming that (1) the ratio of the discharges of ^{65}Zn in solution coming in and going out of the estuary, k, is relatively constant; (2) the ratio of the concentrations of ^{65}Zn associated with the fine sediment coming in and going out of the estuary, c, is relatively constant; and (3) the ratio of the concentrations of ^{65}Zn associated with the fine and coarse sediment respectively, coming in the estuary, C_{f_I}/C_{c_I}, averages about 5.0. (See Hubbell and Glenn, 1971, app. VI for supporting data.) Pertinent basic data and computed values of the fraction of fine sediment retained in the estuary for calendar years 1963-65 are listed in table 2. Because of the grossness of several parameters in equation 3, average annual percentages and average annual daily ^{65}Zn discharges were used in the computations. Included in table 2 are values for P in 1964 that were computed by using hypothetical amounts of ^{65}Zn in the bed that are 20 percent higher and 20 percent lower than the measured amount of 2,060 curies. In all computations, values of c and k were taken as 0.97 and 1.15, respectively. These values were selected because approximately 3 percent of the ^{65}Zn

Table 2.--Computation of fraction of fine sediment (P) retained in the Columbia River estuary

Year	Inflow data: Percent of total sediment discharge1/		Inflow data: Percent of total ^{65}Zn discharge1/		Inflow data: Daily ^{65}Zn discharge	Inflow data: $\frac{C_{f_I}}{C_{c_I}}$	Inflow data: R_s	Inflow data: R_c	$(C_fQ_f)_I$	$\left(\frac{\lambda A}{C_fQ_f}\right)_I$	P
	<0.062 mm	>0.062 mm	In solution	On sediment	(curies/day)				(curies/day)		
1963	80	20	17	83	2/22	5	0.22	0.05	17.4	0.33	0.29
1964	62	38	20	80	1/18	5	.28	.12	12.8	.45	.35
1965	72	28	18	82	1/22	5	.24	.08	16.7	.35	.28
1964	62	38	20	80	1/18	5	.28	.12	12.8	3/.36	3/.26
1964	62	38	20	80	1/18	5	.28	.12	12.8	4/.53	4/.43

1/ Written communication (W. L. Haushild, 1968).

2/ From Foster (1964).

3/ Based on ^{65}Zn content in bed 20 percent lower than 2,060 curies.

4/ Based on ^{65}Zn content in bed 20 percent higher than 2,060 curies.

associated with the fine particulate matter might be displaced in the presence of sea water (Johnson, Cutshall, and Osterberg, 1967) and, if this displacement occurred, the outflow of ^{65}Zn in solution would be approximately 15 percent higher than the inflow since the amount of ^{65}Zn in transport associated with the particulate matter is roughly 4 to 5 times greater than the amount in solution. (See table 2.)

With these assumptions, the average of values of P computed for 1963, 1964, and 1965 was 0.31. Apparently, P is a relatively insensitive variable. Although the mean daily inflow of ^{65}Zn associated with fine sediment decreased 26 percent between 1963 and 1964, the computed percentage of fine sediment retained increased only 6 percentage points. Similarly, amounts of ^{65}Zn in the bed 20 percent higher and 20 percent lower than the measured amount, changed the percent retained by only 8 or 9 percentage points, respectively. Although the computations are far from conclusive, they suggest that on the average approximately 30 percent of the fine sediment which enters the estuary is retained there. Quantitatively, the computations indicate that approximately 1.8, 4.0, and 4.7 million tons of fine sediment were retained in the estuary during 1963, 1964, and 1965, respectively.

Radionuclide data also afford the opportunity to make other kinds of computations relative to sediment transport and deposition. For instance, the longitudinal attenuation in the concentrations of radionuclides associated with sediment particles in given size ranges in the bed has been used (Hubbell and Glenn, 1971) to compute the net transport velocity of particles of those size ranges. Computations were made by two methods. In one method, the time required for particles to move between two given locations was equated to the time required for the ^{65}Zn concentration at one location to decay to a concentration the same as that at the other location. In the second method, the time required for particles to move between locations was equated to the time required for the ratio of two radionuclides (^{65}Zn and ^{60}Co) at one location to change, through decay, to a ratio the same as that at the other location.

Velocities computed by either of the above methods seem to be high. For example, the average velocity of particles in the 0.5 to 1.0 millimeter size range was computed to be about 2,400 feet per day. The high computed velocities suggest that decay is not the only factor causing a change in radionuclide concentrations between locations; hence, other underlying assumptions of the analysis (see Hubbell and Glenn, 1971) are being violated.

Information on the vertical distribution of radionuclides associated with sediment within the bed can be used to compute rates of sediment deposition. As with the computations of particle velocity, the time required to deposit sediment between elevations, H_1 and H_2, is assumed to be the same as the time required for the ratio of two radionuclides to change, as a result of different rates of decay, from the value at H_1 (the highest elevation) to the value at H_2. One important assumption in this technique is that the sediment at H_1 had the same ratio of radionuclide concentrations at the time it was deposited as the sediment at H_2 had when it was deposited. In an environment where the elevation of the bed surface varies periodically and where particles at depth are exposed, transported, and redeposited, this assumption probably is not true and the technique is invalid. However, in an environment where deposition is continuous, the technique may be useful. The variation in the ratio of ^{65}Zn to ^{60}Co with depth in a core collected from such an environment in the estuary above Tongue Point is shown in figure 12. The net deposition rate determined from the length of time necessary for the ratio at the surface to become equal to the ratio at the 11.5-inch depth is 3.4 inches per year (Hubbell and Glenn, 1971). Of course, this rate of deposition applies for that particular core location only and not for the estuary in general.

SUMMARY

Sediment transport and deposition in the Columbia River estuary has been studied by utilizing data obtained by several different techniques. Probably the single most significant characteristic of sediment transport is its variability, both in time and space. To adequately define transport rates and to understand transport phenomena, observations must be made throughout tidal cycles and for extended periods of time so as to reflect the wide range of hydrodynamic conditions.

In the part of the estuary affected by salt-water intrusion, suspended-sediment transport is affected significantly by a turbidity maximum that develops in response to the estuarine circulation pattern and that intensifies, abates, and translates back and forth with the tides and with the season. Sediment movement along the bottom in this part of the estuary also is highly influenced by the estuarine circulation pattern and tends to be landward in deep channels and seaward in shallow areas.

The landward transport of sediment along the bottom tends to cause coarse sediment to be trapped in the estuary. Similarly, computations based on radionuclide data suggest that about 30 percent of the fine sediment transported into the estuary by the river may be retained in the estuary.

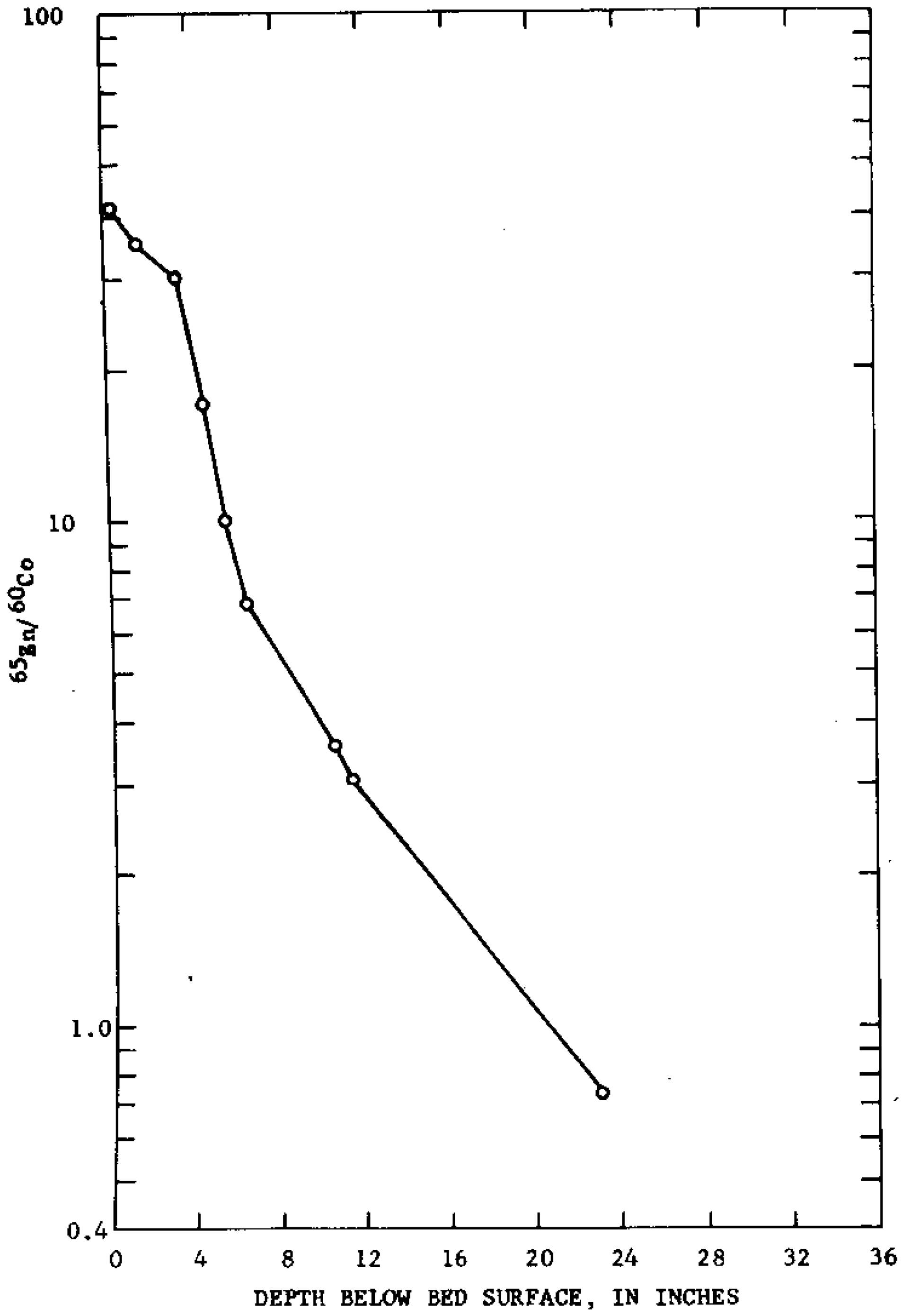


Figure 12.--Variation of $^{65}Zn/^{60}Co$ ratio with depth in a core from the estuary above Tongue Point. (From Hubbell and Glenn, 1971.)

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A Study of Sediments from Bellingham Harbor as Related to Marine Disposal

by

James A. Servizi

Director

Cultus Lake Laboratory

International Pacific Salmon Fisheries Commission

British Columbia

ABSTRACT

Sediments from Whatcom Waterway, Bellingham were studied in response to a proposed dredging and disposal program. Laboratory study indicated that two types of sediment were involved. Sediment from the inner harbor consisted primarily of putrefying pulp fibers which exerted a significant oxygen demand, created substantial turbidity, and were toxic to juvenile sockeye salmon because of their hydrogen sulfide content. Various methods of widespread dispersal to dilute the sediment appeared impractical, and it was concluded that land disposal of inner harbor sediment would be necessary to protect fish stocks. Sediment from the outer harbor was a natural silt, not containing hydrogen sulfide, but exerted an oxygen demand and created a highly turbid mixture which settled very slowly. Because dumping of this sediment at the proposed site could also prove harmful to fisheries, hydraulic dredging and local disposal adjacent to the outer harbor was recommended.

INTRODUCTION

In 1968, it was proposed that a part of Bellingham Harbor, Whatcom Waterway, be dredged and the sediment dumped in an area southeast of Lummi Island, Washington (FIGURE 1). Since the proposed disposal area was on the general migratory routes of Fraser River sockeye (Oncorhynchus nerka) and pink salmon (O. gorbuscha), it was the responsibility of the International Pacific Salmon Fisheries Commission, under its terms of reference, to investigate possible harm to these fisheries from the project and to recommend alternatives if necessary.

Whatcom Waterway, the principal harbor facility of the Port of Bellingham, consists of an inner and an outer harbor (FIGURE 2). The entire waterway is subject to shoaling by river silt and sediments from the adjacent area. Bottom deposits have accumulated in the inner harbor primarily by deposition of pulp fiber from the Georgia-Pacific Corporation

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sulfite pulp, board and paper mills; a smaller contribution of sediment has originated from the Bellingham sewage treatment plant and Whatcom Creek (Fed. Water Pollution Control Admin. and Wash. State Pollution Control Comm., 1967). Sediment in the outer harbor has accumulated largely from the silt load of the Nooksack River.

To maintain adequate depth for seagoing vessels, Whatcom Waterway has been dredged several times in the past. Sediment removed during the past decade was transported on flat barges and washed overboard in the vicinity of Post Point, south of Bellingham, where a shoal was eventually created and disposal discontinued in that area (FIGURE 2). Land disposal was also used, with the sediment utilized for land fill at the site of the present Georgia-Pacific Corporation chlorine plant. Because of its high organic content and low sand content (less than 10%), the material was not suitably compacted for more than 5 years.

The project proposed by the Port of Bellingham and the U.S. Army Corps of Engineers called for removal of approximately 62,600 cu yd of sediment from the inner harbor area and 69,000 cu yd from the outer harbor. The dredged material was to be transported in bottom dump barges and released in 47 fathoms of water at a site southeast of Carter Point, off Lummi Island.

The proposed disposal site is important from the fisheries standpoint. Many of the adult sockeye and pink salmon bound for the Fraser River pass through the area during their summer and autumn migration and thus would be subject to any adverse conditions created by sediment disposal. Any substance which would be harmful or cause fish to detour from their historic migration route would result in an economic loss to the commercial purse seine, gill net and reef net fisheries in the area. The reef net fisheries, located along the west side of Lummi Island between 4.5 and 7 miles from the proposed disposal site, obtain fish from schools which turn northwest as they enter the general area of Lummi Island. Reef net fishermen could be especially affected by increased turbidity caused by sediment disposal, not only because of their stationary gear, but also because visual observation to a depth of 15 ft is necessary in order to fish effectively.

Juvenile sockeye salmon from the Fraser River migrate seaward in April, May and June, primarily along a route through Haro Strait and thus would not be expected in significant numbers near the proposed dumping site. A few juvenile pink salmon of Fraser River origin might be present in the proposed

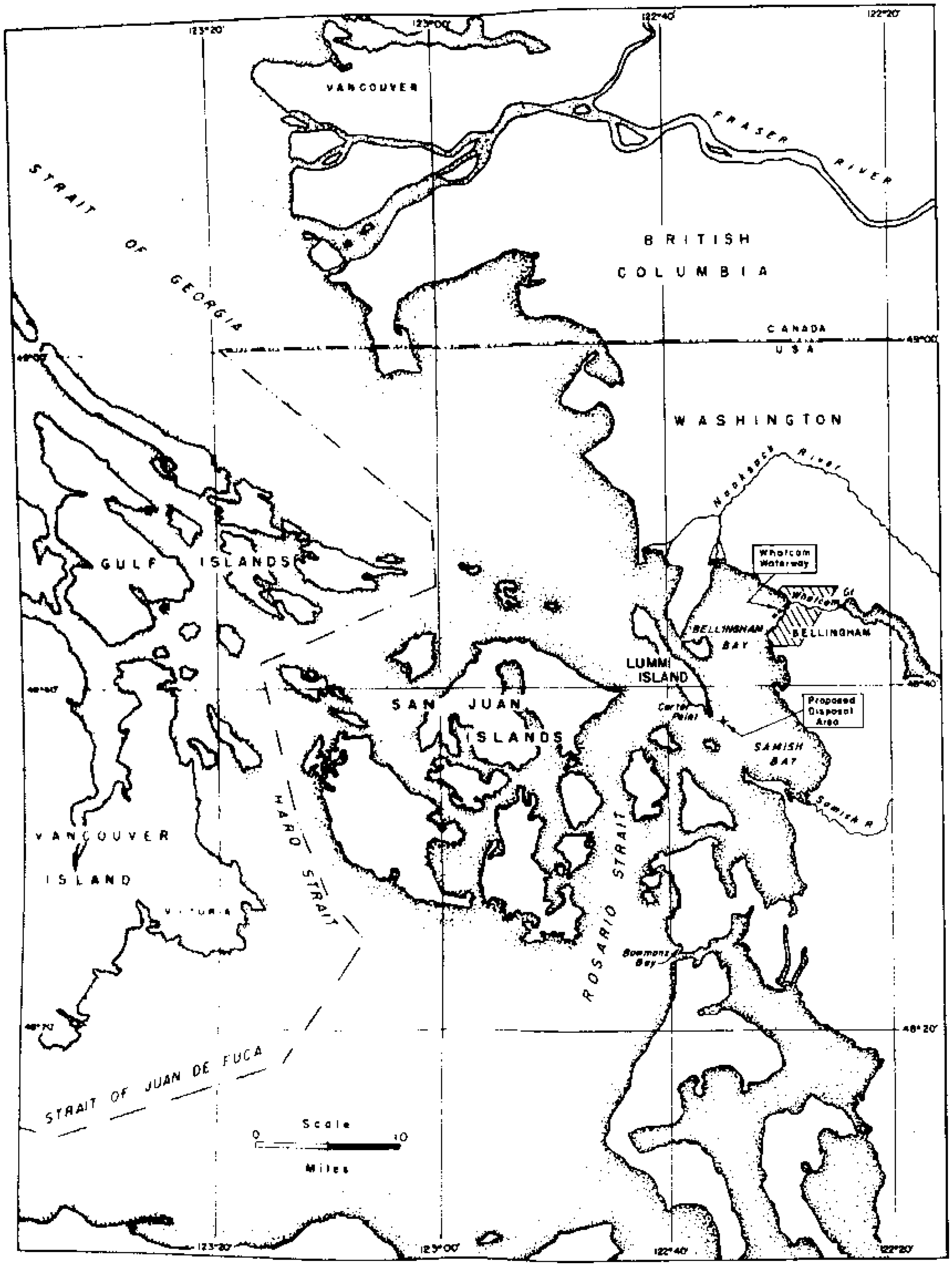

FIGURE 1 - Waters south of the Fraser River showing Whatcom Waterway and the proposed sediment disposal area.

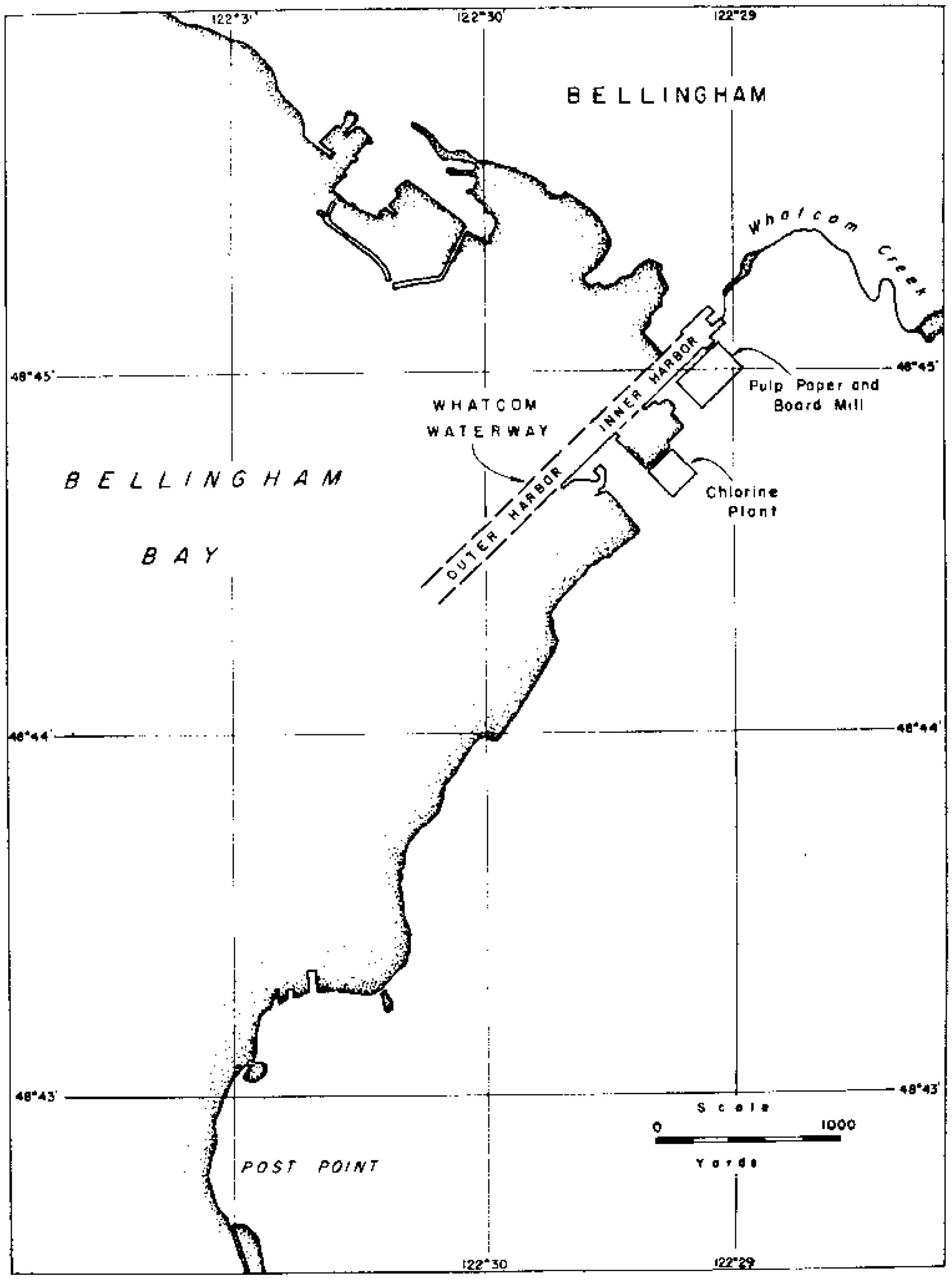

FIGURE 2 - Whatcom Waterway showing inner and outer harbor areas.

disposal site, but the majority spend their first spring and summer farther west in the Gulf and San Juan Islands.

The proposed disposal area is also of importance to chinook (O. tshawytscha), coho (O. kisutch), chum (O. keta) and pink salmon from the Nooksack and Samish Rivers, both adult and juvenile fish, which move through the area on their historic migrations during spring, summer and autumn. Chinook, coho and chum salmon from the Fraser River also may migrate through this area. Pacific herring (Clupea harengus pallasi) are taken commercially during winter months in the proposed disposal area and a bottom trawl fishery operates throughout most of the year. Finally, the area is a commercial crab fishing ground during winter (E. Limbacher, personal communication).

Previous surveys indicated that sediments in the inner harbor would contain considerable hydrogen sulfide and would be devoid of normal benthic organisms such as crabs and clams (F.W.P.C.A. and W.P.C.C., 1967). Hydrogen sulfide, a respiratory depressant, has been reported lethal to salmon and trout at concentrations above 0.3 ppm (McKee and Wolf, 1963) and thus it was advisable to investigate whether toxic conditions might arise during sediment disposal. Other factors, such as oxygen demand of the inner harbor sediment and turbidity which might be created during dumping, were of concern as well.

The aforementioned survey found sediment in the outer harbor to support a benthic community typical of a muddy marine bottom. Crabs, clams, and starfish were noted, and hydrogen sulfide was not detected. These characteristics suggested that sediment in the outer harbor was less hazardous than that from the inner area. However, its oxygen demand and potential for creating turbidity were unknown and required investigation.

An experimental study was conducted to answer the various questions raised above and a summary of the results and recommendations for sediment disposal are described herein. Readers interested in details of experimental methods and results are referred to Servizi, Gordon and Martens, 1969.

RESULTS

Physical Characteristics of Sediments

Inner Harbor Sediment

All sediment samples collected from the inner harbor were slurries consisting primarily of pulp fibers. A strong odor of hydrogen sulfide was present and sediment was black. Bubbles of gas were seen rising continually throughout the inner harbor area on all sampling trips and a group of bubbles was released whenever a sample of sediment was taken with the Ekman dredge. Presumably the bubbles consisted of hydrogen sulfide, carbon dioxide and methane (A.E. Werner, Fish. Res. Bd. Canada, personal communication). No bottom organisms such as crabs, worms, or algae were evident in the 35 dredge samples collected during the course of the study.

The sediment was 11% solids, of which 27% were volatile solids, and the specific gravity was 1.02 (TABLE 1). When air-dried outdoors the sediment was similar to dewatered pulp fibers taken from a typical pulp mill settling pond.

TABLE 1 - Physical characteristics of sediments.

Sediment Origin	Total Solids %	Volatile Solids %	Specific Gravity
Inner Harbor	11	27	1.02
Outer Harbor	47	5	1.35

Outer Harbor Sediment

Sediments throughout the outer harbor appeared to consist of natural silt deposits. The odor of hydrogen sulfide was not evident in the samples upon collection. Small crabs and worms were noted in the samples and these remained alive during a 14-day storage period. The sediment was 47% solids with a volatile solids content of 5%; the specific gravity was 1.35 (TABLE 1).

Turbidity Created by Sediments

Sediment may create turbid conditions when dumped, depending upon the degree of mixing and break-up of particles. Measurements were conducted to determine the amount of turbidity formed and clarification time of different concentrations of sediment in sea water at 50°F.

Inner Harbor Sediment

Initial turbidity of inner harbor sediment decreased considerably during the first 1.5 hr and then more slowly thereafter (FIGURE 3). After 24 hr, turbidity of sediment concentrations from 0.5 to 10% ranged between 7 and 96 ppm and remained proportional to initial sediment concentration. A fraction of the sediment, probably natural silt originating from Whatcom Creek, was finely divided and settled very slowly.

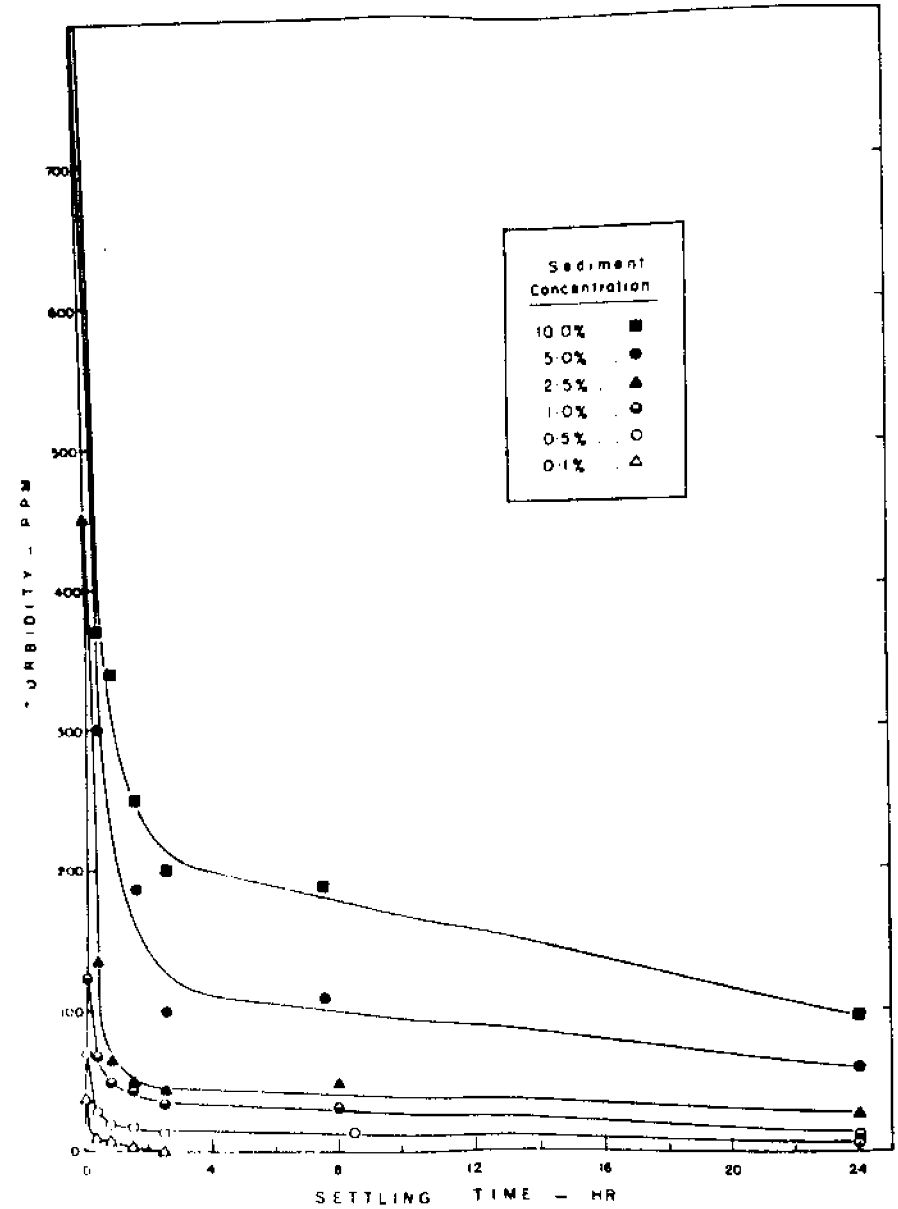

FIGURE 3 - Turbidity of inner harbor sediment.

Outer Harbor Sediment

Outer harbor sediment created much higher initial turbidities than did the inner harbor sediment (FIGURE 4). However, the outer harbor sediment settled rapidly during the first 1.5 hr and turbidities were in the same general range as those created by inner harbor sediment. Following the initial 3-hr period of rapid sedimentation, turbidity declined very slowly and after 24 hr was between 5 and 20 ppm. It is of interest to note that the 0.1% concentration of outer harbor sediment did not clarify as did the inner sediment, but had a turbidity of 5 ppm at 24 hr.

Oxygen Demand and Hydrogen Sulfide Content of Sediments

Inner Harbor Sediment

The oxygen demand and hydrogen sulfide concentrations of 2% mixtures (by volume) of inner harbor sediment were measured at 50°F in sea water on two identical 3-liter samples mixed continuously with a mechanical stirrer at 70 rpm. Oxygen declined rapidly at first in each sample, decreasing to 5 ppm within 25 min in sample I and within 35 min in sample II (FIGURE 5). The oxygen demand apparently equaled the supply after about 90 min when oxygen stabilized at 2.3 and 3.2 ppm in the two samples.

Hydrogen sulfide concentrations in the two samples showed a rapid increase in the first 5 min, followed by a steady decline. The initial increase was probably created by dissolution of hydrogen sulfide as the particles of sediment were dispersed during initial mixing.

There was a close correlation between oxygen demand and dissipation of hydrogen sulfide, indicating oxidation of hydrogen sulfide to the harmless sulfur state. However, the oxygen demand probably consisted of biochemical oxygen demand exerted by microorganisms as well as the chemical demand of hydrogen sulfide oxidation.

Outer Harbor Sediment

Although hydrogen sulfide was not detected, the outer harbor sediment also exerted a significant oxygen demand. Dissolved oxygen concentrations of 5, 3, 2 and 1% sediment mixtures (by volume) were measured at 50°F in sea water for a 2-hr period in the absence of fish. Each 3-liter mixture was continuously mixed with a mechanical stirrer at 70 rpm. Oxygen dropped to about 5 ppm within 2 min in a 5% concentration and reached 0.1 ppm after 2 hr (FIGURE 6). Oxygen demands were proportionately less at lower sediment concentrations.

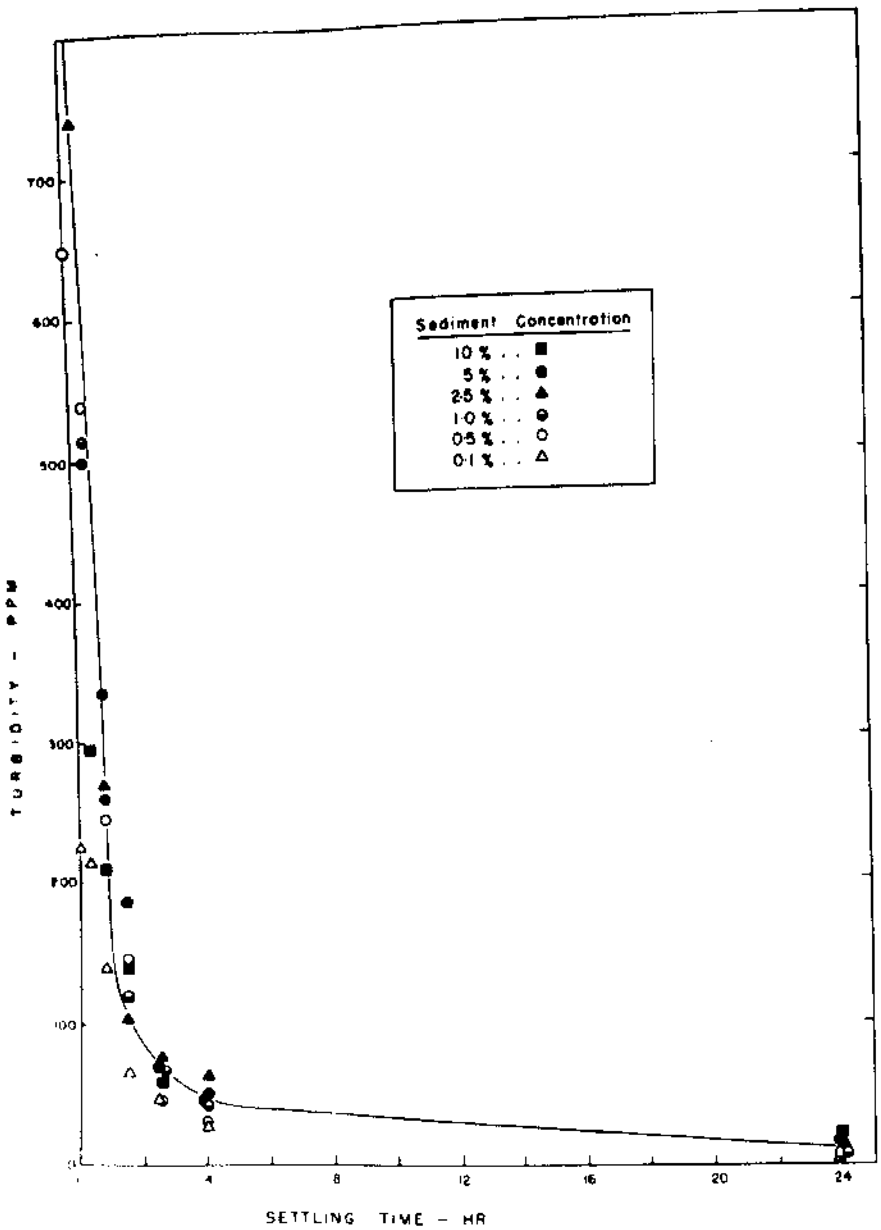

FIGURE 4 - Turbidity of outer harbor sediment.

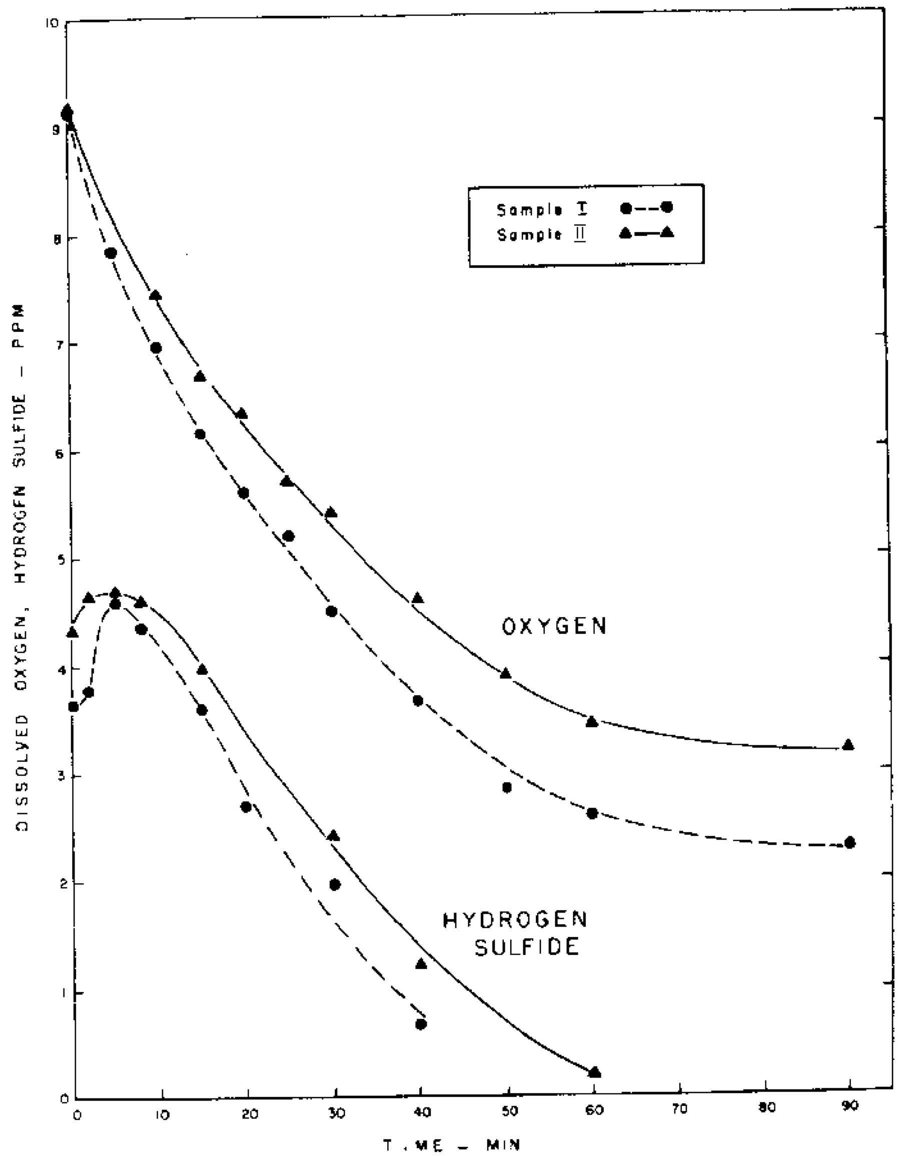

FIGURE 5 - Oxygen demand and hydrogen sulfide content of 2% concentrations of inner harbor sediment. (Continuous mixing, fish not included.)

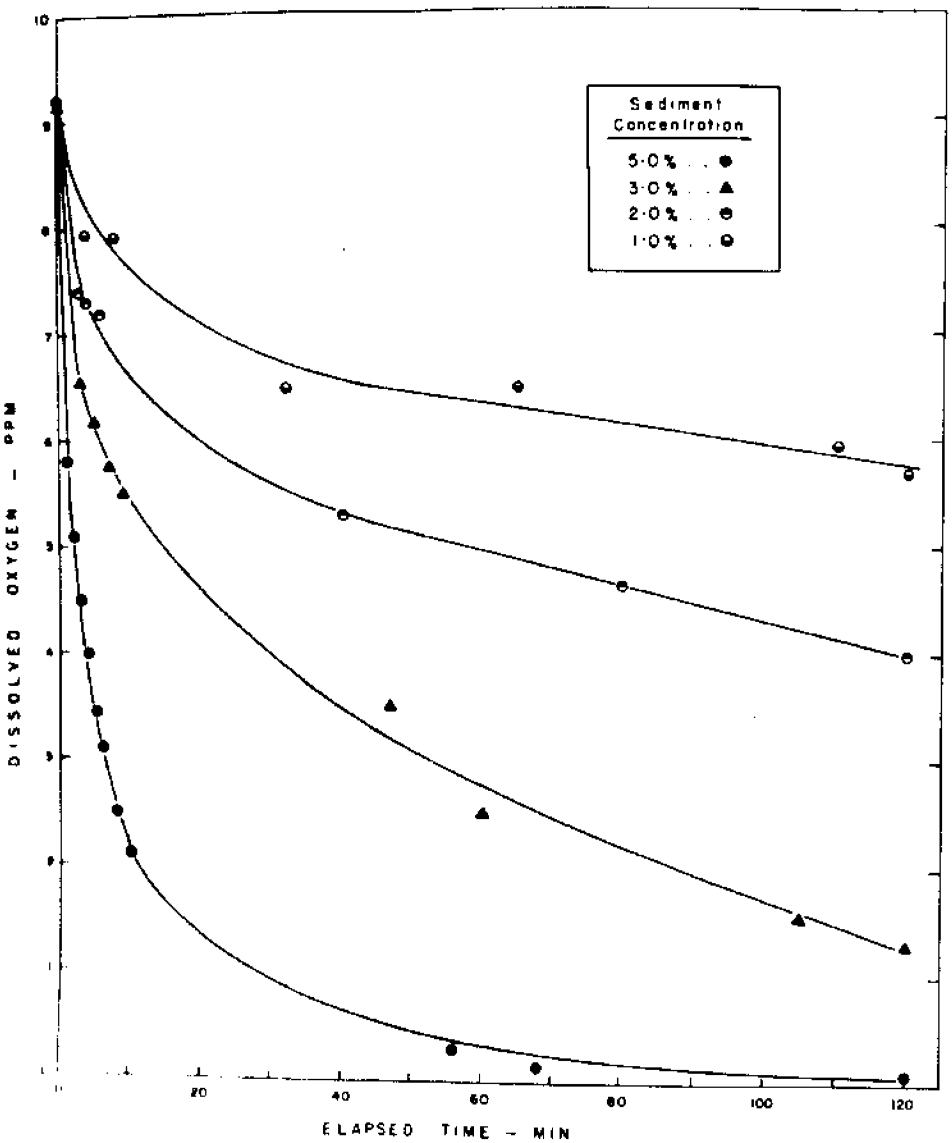

FIGURE 6 - Oxygen demand of various concentrations of outer harbor sediment. (Continuous mixing, fish not included.)

Comparison of oxygen demands of 2% concentrations of inner and outer harbor sediments in 60 min indicated the latter was 67% of the former. Oxidation of hydrogen sulfide in the inner harbor sediment probably accounted for much of the difference in oxygen demands. The rapid initial oxygen demand of outer harbor sediment was similar to that of the inner harbor sediment and indicated oxygen demand consisted of chemical as well as biochemical oxidation. However, there was no evidence of hydrogen sulfide in outer harbor sediment, which can be detected at very low concentration by its odor, nor were there any gas bubbles released to indicate the presence of other gases (e.g., methane) in the sediment. Oxidation of reduced sulfur, iron or manganese in the sediment may have been the cause of rapid chemical oxygen demand, but the topic was not pursued and should be the subject of further investigation.

Toxicity of Sediments

Inner Harbor Sediment

Sediments collected from the inner harbor were bioassayed using sockeye smolts in sea water to evaluate acute toxicity. Sediments were bioassayed initially within about 4 hr of procurement and again after sediment had been stored for several days. Details of bioassays are reported elsewhere (Servizi, Gordon and Martens, 1969).

In summary, bioassays showed that toxicity of the inner harbor sediment was related primarily to its hydrogen sulfide content. Complete mortality occurred in a few minutes at a 1% or greater concentration of inner harbor sediment when average initial hydrogen sulfide concentrations were 2.3 ppm or greater (TABLE 2). Fish were distressed at concentrations between 0.1 and 1.0% sediment where initial hydrogen sulfide concentrations were greater than 0.3 but less than 2.3 ppm. It appeared that a 0.1% sediment concentration was the incipient level for visible evidence of distress of sockeye smolts. When hydrogen sulfide was removed by aeration, distress and toxicity appeared related to clogging of gills by suspended fibers at concentrations over 1% sediment. It is likely that fiber acted to compound the respiratory problems created by hydrogen sulfide when both were present together.

TABLE 2 - Summary of toxic effect and hydrogen sulfide content of various concentrations of inner harbor sediment.

Sediment Concentration % by Volume	Average Initial Hydrogen Sulfide ppm	Toxic Effects
10	-	Mortality in approximately 5 min.
2	4.1	Mortality in approximately 15 min.
1	2.3	Mortality in approximately 20-25 min.
0.75	-	Possible mortality.
0.50	1.1	Distress - coughing - frenzied swimming.
0.25	-	Distress - coughing - frenzied swimming.
0.10	0.3	Possible distress.
0.05	0.1	No visible distress.

Outer Harbor Sediment

Bioassays of outer harbor sediment indicated no evidence of distress among fish introduced into 5, 3, 2 and 1% sediment mixtures although there was some random swimming as though the fish had become disoriented in the turbid water. Hydrogen sulfide was not detected, and thus it was apparent that the sediment exerted no direct toxic effect. However, the 5% sediment mixture exerted a significant rapid oxygen demand, as described earlier (FIGURE 6), causing dissolved oxygen to decline during bioassay to about 2 ppm in 10 min at which time the fish appeared to lose equilibrium.

Effect of Atmospheric Exposure on Hydrogen Sulfide Content of Inner Harbor Sediment

Exposure of inner harbor sediment to the atmosphere in 1-inch layers resulted in a gradual loss of hydrogen sulfide (TABLE 3). However, the low rate at which hydrogen sulfide was lost suggests that it was being produced continuously by bacteria. Temperature of the sediment would influence the rate of hydrogen sulfide production, the greater production occurring as temperature increased. Hence, the increase in temperature from 45°F to 62°F noted in TABLE 3 would have played a role in maintaining a significant hydrogen sulfide content in the sediment.

TABLE 3 - Hydrogen sulfide content of inner harbor sediment following exposure to the atmosphere.

Time of Exposure hr	Temperature of Sediment °F	Hydrogen Sulfide* ppm	Reduction %
0	45	3.28	0
1	-	1.81	45
2	-	1.86	43
4	59	1.55	53
5	57	1.60	51
7	55	0.98	70
24	54	0.29	90
28	62	0.32	90

* Measured in a 1% sediment concentration by volume in sea water.

The situation studied herein does not duplicate that expected if sediment were piled on a barge for removal and dumping, but some application of the experimental results appears reasonable. Since atmospheric contact for 5 hr reduced the hydrogen sulfide content of a 1-inch layer of sediment by less than 50%, sediment piled several feet deep on a barge would probably lose very little hydrogen sulfide before it was dumped. In fact on a warm day, solar heating of sediment on a barge could conceivably increase the hydrogen sulfide concentration owing to more vigorous bacterial metabolism.

Effect of Washing and Resettling on Hydrogen Sulfide Production of Inner Harbor Sediment

When sediment is dumped in sea water it is with the intention that it will settle to the bottom. Washing will occur as the sediment settles and it was questioned whether this might eliminate subsequent hydrogen sulfide production. If a 300 cu yd barge load of sediment were dumped at the proposed location in 47 fathoms of water it would be washed at the rate of about 40 to 1 if it descended vertically. This is a minimum value, and mixing created by tidal currents could increase the degree of washing. However, in order to assess the possible effects of mixing, a 40 to 1 washing ratio was evaluated.

Sediment from the inner harbor was washed at a ratio of 40 to 1 in sea water at 50°F, allowed to settle and the sea water discarded. Washed sediment was then added to a depth of 1.5 inch in a 1-liter graduated cylinder and to 3.0 inch depth in another. Fresh, aerated seawater was added so as not to mix the sediment and it was allowed to stand for 48 hr at 45°F. This temperature was considered a realistic estimate of that occurring on the bottom off Carter Point. Samples of supernatant were drawn from mid-depth for hydrogen sulfide and oxygen analyses and compared with a control cylinder containing only sea water.

Significant amounts of hydrogen sulfide were found in the cylinders containing sediment (TABLE 4). Furthermore, dissolved oxygen was nil in one cylinder and 2.4 ppm in the other, indicating a significant oxygen demand exerted by the sediment. Dissolved oxygen remained at 9.4 ppm in the control and hydrogen sulfide was not detected. Thus it was evident that washing during dumping would not preclude synthesis of hydrogen sulfide once the sediment resettled on the bottom. The result was not unexpected since the fiber itself is undergoing decay and would not be altered by washing.

TABLE 4 - Hydrogen sulfide and dissolved oxygen content of sea water overlying washed sediment for 48 hr.

Sediment Depth inch	Hydrogen Sulfide ppm	Dissolved Oxygen ppm
3.0	0.55	0.0
1.5	0.25	2.4
0.0	0.00	9.4

DISCUSSION

Results indicated that four factors should be considered if disposal of sediment in sea water is contemplated: (1) turbidity created during sediment disposal, (2) oxygen demand of the sediment, (3) toxicity due to hydrogen sulfide released during disposal, and (4) generation of hydrogen sulfide by sediment after it resettles. The first three factors are of direct concern to pink and sockeye fisheries while the fourth concerns bottom fisheries such as sole and crabs. All four factors are of importance insofar as disposal of inner harbor sediment is concerned, but only turbidity and oxygen demand are of importance when outer harbor sediment is considered.

The proposed disposal area for sediment is one which would affect adult Fraser River sockeye and pink salmon and possibly juvenile Fraser pink salmon, as well as local stocks of salmon and other fish. Toxicity of sediment was measured using sockeye smolts since adult fish were not obtainable, but it seems reasonable to apply the results to adult sockeye and pink salmon, bearing in mind that a safety factor should be assigned to waste disposal projects to allow for variation in tolerance because of size, species and unforeseen environmental factors.

Inner Harbor Sediment

Inner harbor sediments were found to cause considerable turbidity and had a high oxygen demand. However, the major hazard to fish was toxicity created by hydrogen sulfide which dissolved as the sediment was mixed with sea water. Hydrogen sulfide is formed in an anaerobic environment from the activity of specialized bacteria (genus Desulfovibrio) which convert sulfate to hydrogen sulfide as they metabolize organic matter (Stanier, Duodoroff and Adelberg, 1957). In this instance, sulfate was supplied by sea water and the organic matter by the fiber deposits. Hydrogen sulfide is a respiratory depressant, similar to cyanide, and at lethal concentrations reacts quickly to arrest respiratory functions (Jones, 1964). Thus the sediment was responsible for imposing the additive stresses of reduced oxygen supply, owing to its oxygen demand, and depressed respiration caused by hydrogen sulfide.

The maximum concentration of hydrogen sulfide at which salmon or trout would survive has been reported as varying between 0.3 and 1.0 ppm (McKee and Wolf, 1963). The results obtained herein fall within this range as smolts were highly distressed at 1.0 ppm hydrogen sulfide, but not visibly so at 0.1 ppm. The threshold level for visible distress of sockeye salmon smolts appeared to be around 0.3 ppm, which coincided with a 0.1% concentration of sediment (TABLE 2). There were indications that respiration of sockeye smolts may have been depressed at a 0.05% concentration of sediment (Servizi, Gordon and Martens, 1969) but this was not definite and therefore the higher concentration of 0.1% was used as the maximum tolerable level in considering disposal requirements.

Experimental studies indicated that toxicity of the inner harbor sediment would decline only slightly during exposure to the atmosphere and therefore the sediment probably would be as toxic when dumped from a barge as when first dredged. This result was to be expected since conditions for hydrogen sulfide production would remain favorable in the barge where the combination of rich organic material (fiber), sulfate (sea water) and bacteria would be maintained. In fact, solar heating could raise the temperature of sediment on a barge, increasing the rate of bacterial metabolism and consequently increasing hydrogen sulfide production and potential toxicity.

The amount of mixing and dispersion which would occur during discharge of sediment from a barge is unknown, however zones of high hydrogen sulfide, low dissolved oxygen and excessive turbidity may occur. Therefore, elimination of potential hazards to fish through adequate dilution during dumping would be necessary. Bioassay results indicated the concentration of inner harbor sediment should not exceed 0.1%. This concentration corresponds to the visible threshold of distress for salmon, exerts an insignificant oxygen demand and creates a turbid condition which would clarify within approximately 1 hr. Thus if requirements for eliminating stress and toxicity caused by hydrogen sulfide could be satisfied by dispersal and dilution, turbidity and oxygen demand would not be significant factors.

In order to not exceed a 0.1% concentration of sediment, methods must be found to dilute the sediment at a ratio of 1,000 to 1 during disposal. To obtain this dilution, each 300 cu yd barge load of sediment would need to be dispersed in a volume of 300,000 cu yd of sea water (60.6×10^6 gal). There is little knowledge to predict how the sediment would disperse and mix when released from a typical bottom dump barge with a bottom opening 16 ft wide by 65 ft long. However, towing a barge while distributing the contents in order to create a 1,000 to 1 dilution appeared impractical. Furthermore, in practice the bottom of a barge opens suddenly and cannot be controlled for uniform dispersion of the contents. Consequently, the practical method of operation is to dump the barge contents at a single site. Thus if the sediment from a single 300 cu yd barge load were mixed in the 47 fathom water column beneath the barge at the disposal site, the concentration of sediment would be about 2.8%; 28 times greater than that considered marginally safe for fishes.

These comparisons serve to illustrate the magnitude of the problem faced in obtaining safe dispersal of the sediment in sea water. Of course, the theoretical sediment concentration of 2.8% may not be reached since some material may sink quickly with little mixing. However, the theoretical concentration which could occur is so much greater than that which is considered minimally safe that a substantial risk to fish and fisheries operations could be associated with dumping.

Inner harbor sediment could also alter the character of the bottom at the disposal site and, after resettling, form a continuing hazard to bottom-dwelling species. As noted earlier, normal marine bottom life was absent from the original collections of inner harbor sediment. If the 62,600 cu yd of inner harbor sediment were redistributed over an area of 1 million sq yd (3,000 ft x 3,000 ft), it would form a deposit about 2.25 inch deep. Results showed a 1.5-inch depth of sediment exerted a significant oxygen demand and continued to produce hydrogen sulfide, a condition which could destroy normal bottom life. Dispersal of sediment over an area of 10 million sq yd (9,000 ft x 10,000 ft) would form a deposit about 0.25 inch deep which would probably be harmless. But to achieve uniform distribution of sediment over a wide area would require careful planning and further knowledge of mixing and settling of the sediment during dumping. Previous sediment dumping in Bellingham Bay created a shoal opposite Post Point.

Outer Harbor Sediment

Sediment from the outer harbor had two characteristics which are of concern when marine disposal is considered, turbidity and oxygen demand.

Turbidity may divert salmon from their usual migration route. Furthermore, turbid water seriously reduces the efficiency of reef net fishermen who require very clear water in order to see fish entering their nets at a depth of 15 ft. The turbidity of various concentrations of sediment declined sharply to between 40 and 70 ppm during the first 3 hr of settling (FIGURE 4). From that time on, the turbidity declined very slowly and there was little difference in turbidity of mixtures which had initial concentrations of 0.1% to 10% sediment. For example, after 8 hr of settling turbidity ranged between 20 and 50 ppm, a level which would interfere with reef net operations as tidal currents carried the sediment northward, since normal turbidity in the general fishing area averages 2.6 ppm and does not exceed 4 ppm (Kincaid, Wennekens and Sylvester, 1954, 1955).

A deoxygenated zone may also serve to divert salmon from their normal migration route with serious reductions in catch by commercial fishermen pursuing the fish in their accustomed places. In this regard, oxygen levels less than 6 ppm may be avoided by some coho and chinook salmon (Whitmore, Warren and Doudoroff, 1960) and presumably by sockeye and pink salmon as well. Oxygen demand of the sediment was great enough to lower dissolved oxygen to less than 6 ppm in a matter of minutes, depending upon the concentration of sediment. Thus diversion of salmon during marine disposal of sediment is a distinct possibility.

Furthermore, although most fish, including Pacific salmon, will avoid zones of low oxygen, avoidance is not necessarily complete and some salmon may enter a deoxygenated zone and perish (Whitmore, Warren and Doudoroff, 1960). The oxygen demand of a 5% sediment mixture was great enough to reduce dissolved oxygen to values less than 2 ppm in about 16 min (FIGURE 6) and such low oxygen levels led to loss of equilibrium in bioassays. Since mixing characteristics during dumping of sediment are unknown, the time required for a zone of oxygen-poor water to be reaerated through mixing with oxygen-rich water is unknown.

The impracticality of dispersing inner harbor sediment to obtain substantial dilutions was discussed earlier and applies to the outer harbor sediment as well. Thus it appears that adequate dilution to eliminate the effects of turbidity and oxygen demand could not be obtained by any practical method of widespread dispersal.

An alternative proposal to dump sediment only on ebbing tides also has certain impractical aspects. The net movement of sea water entering the area from Juan de Fuca Strait is northward through Rosario Strait past Lummi Island; the net outflow leaves via Haro Strait, westward of Rosario Strait (FIGURE 1). Because of this circulation, sediment dumped on an ebb tide would be carried away from Lummi Island initially, but material remaining in suspension would be carried past Lummi Island again on the flooding tide. Furthermore, there are only two ebb tides per day which restricts the dumping period considerably and makes the logistics of sediment disposal more complex than could be reasonably regulated or controlled. This is especially true when one considers that there would be about 230 barge loads of sediment from the outer harbor alone.

RECOMMENDATIONS

Inner Harbor Sediment

Sediment from the inner harbor was shown to be highly toxic and its disposal by dumping would be a hazard to both surface and bottom marine life. There appeared to be no practical feasible method of either detoxifying the sediment before dumping, or dispersing it to assure adequate dilution. Hence, from the standpoint of total fisheries protection, it appeared ill-advised to dump this sediment in any area inhabited by fish, crabs, or shellfish.

As noted earlier, this sediment consisted of pulp fibers in various stages of decay. When dewatered it was very much like the waste pulp dredged from settling basins or otherwise discarded by pulp mills. Such material has been used successfully for land fill. An odor problem would probably accompany land fill in the initial stages but once the sea water either drained away or was washed away by rain, the sulfate supply would be removed and hydrogen sulfide would no longer be produced. In this regard, pulp fibers have remained on the bottom of treatment plant settling basins without production of hydrogen sulfide since sulfate is in insufficient supply. Thus the odor associated with land disposal of sediment would not be continuous but would exist only during the dredging period.

Outer Harbor Sediment

Sediment from the outer harbor constituted a threat to adult sockeye and pink salmon fisheries if disposal occurred in the proposed area during the months of June through October. Furthermore, juvenile Fraser River pink salmon might be affected if dumping took place between March and August. Hence it was recommended that sediment disposal not be outside of Bellingham Bay (south of 48° 40'N or west of 122° 35') between March and October.

This sediment appeared amenable to local disposal in the northern area of Bellingham Bay as it was a naturally occurring bottom material similar to that of the immediate area and was found to support a normal bottom population in this and in other studies (F.W.P.C.A. and W.F.C.C., 1967). Some degree of hazard to fishes from low dissolved oxygen would accompany disposal, caused by the oxygen demand of the sediment. However, a previous study indicated that hydraulic (suction) dredging of a channel in Chesapeake Bay did not cause gross damage to marine life. Although some bottom animals were smothered, other species began repopulation soon after dredging (Flemer et al., 1968). Unfortunately, dissolved oxygen was not measured during the foregoing study.

In the present situation, it appeared that a hydraulic dredge could dispose of the sediment in the immediate area of the outer harbor, but outside the shallow water (4 fathoms) used by juvenile bottom fishes. This proposal, as suggested by the Washington Pollution Control Commission and Washington State Department of Fisheries, could probably be completed with minimal harm. The problem of turbidity would be minimized if the work were done during summer (as suggested by the aforementioned agencies) when Bellingham Bay is already turbid due to discharge of the Nooksack River. Additional turbidity originating from natural sediments could probably be tolerated for the few weeks required for dredging.

Subsequent to completion of the study reported here, the Washington State Water Pollution Control Commission, the Washington State Department of Fisheries, and the U.S. Army Corps of Engineers agreed on a modified dredging plan. The modified plan called for retention of the inner harbor sediment until a land disposal plan could be developed and hydraulic dredging of the outer harbor sediment with disposal in the local area during summer. The contents and recommendations of this report formed part of the testimony used in formulating the modified dredging plan.

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Hydro-Ecological Problems of Marinas in Puget Sound

by

Eugene P. Richey

Professor of Civil Engineering

University of Washington

Seattle, Washington 98105

ABSTRACT

Some new criteria for reviewing plans for new marinas and other shore-tied structures in the regions of Puget Sound and Adjacent Waters that are to be added to the traditional list for planning design considerations, are discussed as to origin and possible methods of compliance. These criteria involve limits on the extent and type of structure to maintain water quality and to minimize barriers in the path of juvenile, migratory salmon. A model is developed for describing gross kinematics in a marina of simple planform for the purposes of comparing the effect of different geometries on circulation patterns. A few marinas now in operation are reviewed as illustrations of how conventional designs conform to the new guidelines.

Introduction

The projected figures for the growth of pleasure boating in the Pacific Northwest are impressive. A study for Puget Sound (1968) estimates that pleasure craft in the area will increase to 291,000 in 1980, up 56% from the 1966 level of 186,000, and to 551,000 by the year 2000. The forecast for additional marinas, launching sites and related facilities parallels the boat-number forecast. New environmental awareness and concerns relating to the use of our water-related resources will require that designers of these facilities consider features that are not yet a part of conventional practice.

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[a] Eugene P. Richey, Professor of Civil Engineering, University of Washington, Seattle, Washington

A recent (1969) report on design practices treats the geometry, physical structures and economics of typical marinas, but treats environmental issues in a few lines as items to be checked against requirements of local agencies. The objective of this paper is to call attention to some of these local factors, water quality, the accommodation of shell fish and migratory fish, navigation, shoreline equilibrium and management, which may influence the planning and hydraulic design of the small harbors and marinas that appear in the regional growth forecast.

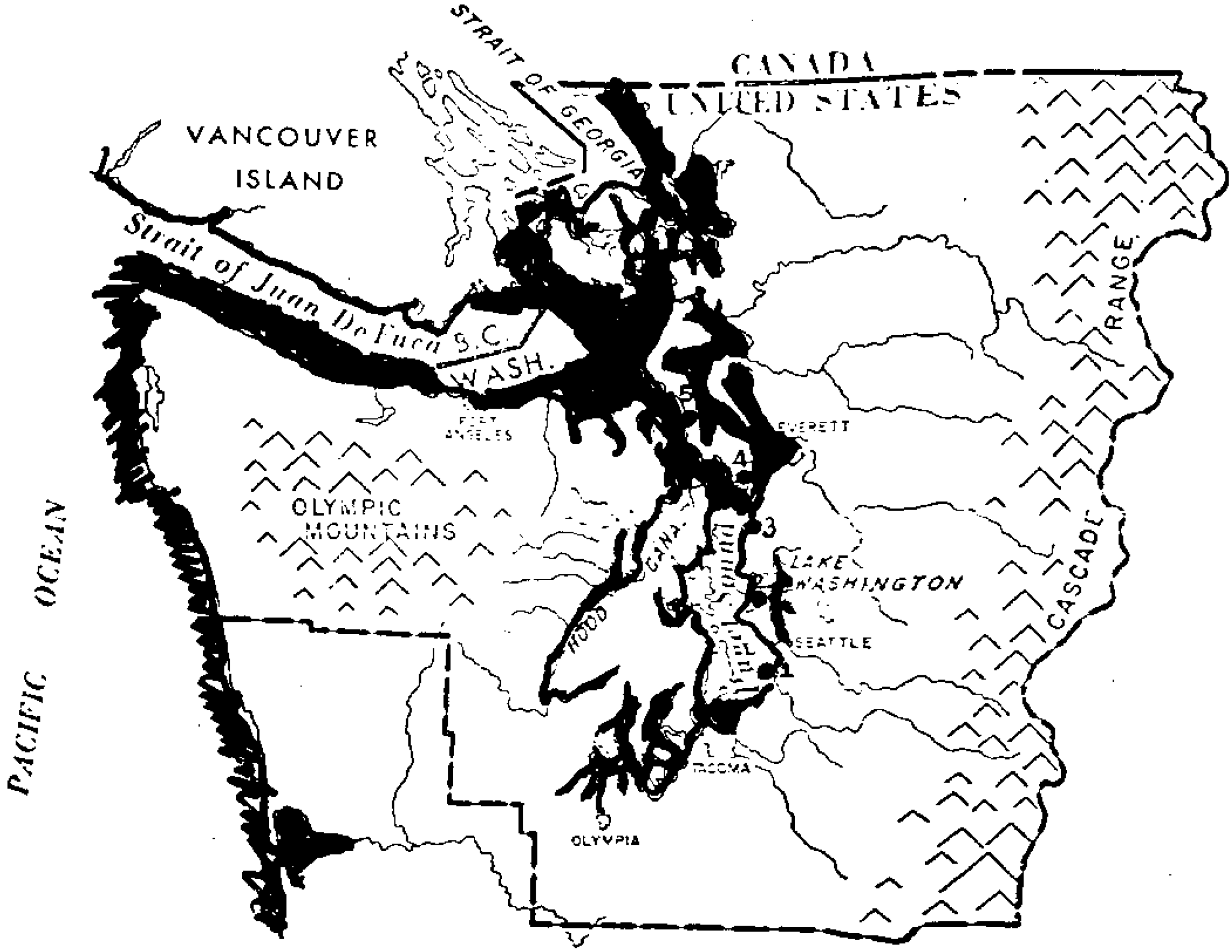
Hydrography

Puget Sound, Hood Canal, the Straits of Juan de Fuca and Georgia, approach a water area of some 2,500 square miles. Figure 1 shows their relationship to the Pacific Ocean. Although the region has many local features that tend to become lost in broadly stated generalities, there are a few descriptions applicable to the region as a whole. Tides are of mixed type with unequal lows; ranges are in the order of 10 feet, although in some places, like Seabeck on Hood Canal, the extreme range is from -4 feet to +15 feet. Northwesterly winds are typical during the summer season. The highest speeds, however, are from the southwesterly quadrant during the winter storms. Speeds of 40 knots are quite common; a burst to 70 knots is an event likely in the life of any project not topographically sheltered in some manner. Maximum wind wave heights are considered to be about six feet, except in the Strait of Juan de Fuca where much higher values superimposed on swells may occur. Data on wave heights measured by modern techniques are practically non-existent, however. The inflow from the many rivers along with the variable tidal currents and regions of great depth, give rise to important density stratifications, and regional and seasonal variations are considerable. Littoral drift patterns have been assessed in a few sensitive places, such as at Ediz Hook protecting the harbor of Port Angeles, but a regional pattern is fragmentary, and rates of drift at any one site have to be inferred from local indices and empirical wave energy relationships. In spite of gaps in basic data about Puget Sound and Adjacent Water, if a site is under study, an exhaustive literature search for relevant background material should be undertaken in the Oceanography-Fisheries Library at the University of Washington, as well as in those of the regional and state agencies; much data is on record and current research projects are bringing in more.

Tidal Flushing of Marinas

Much has been written, and more is "in press", about diffusion problems in estuaries. Bowden (1967) discusses the basic principles of circulation and mixing and summarizes several approaches to large-scale applications. However, the size of the marinas and an objective restricted to describing certain kinematic relations allow several simplifying assumptions. The diffusion process as a formal problem is not to be dealt with. The fresh water inflow to the typical marina is small, so only a single-layered system need be considered. (If the marina were to be located at the mouth of a creek of any consequence, likely it would be relocated to provide unimpeded access to migratory fish.) The usual water depth in a marina is only about twice the tidal range, so effects of stratification on gross kinematics are neglected. These assumptions admittedly may oversimplify the hydrodynamics in a given marina, but they do allow some useful first-order approximations to be obtained readily.

A first model assumes that the dominant motions in the marina may be found from a conservation of volume basis, only, as stated in Eq. 1 with no difference in surface elevations between the basin and the estuary, $dY = dz$, for the element identified on Figure 2.



Station	Total % of time wind is within MPH range 0-3	4-15	16-30
Everett	14	73	13
Seattle	35	61	4
Port Angeles	20	42	38

1 Des Moines
2 Shilshole
3 Edmonds
4 Cultus Bay
5 Lagoon Point

FIGURE 1. Puget Sound and Adjacent Waters

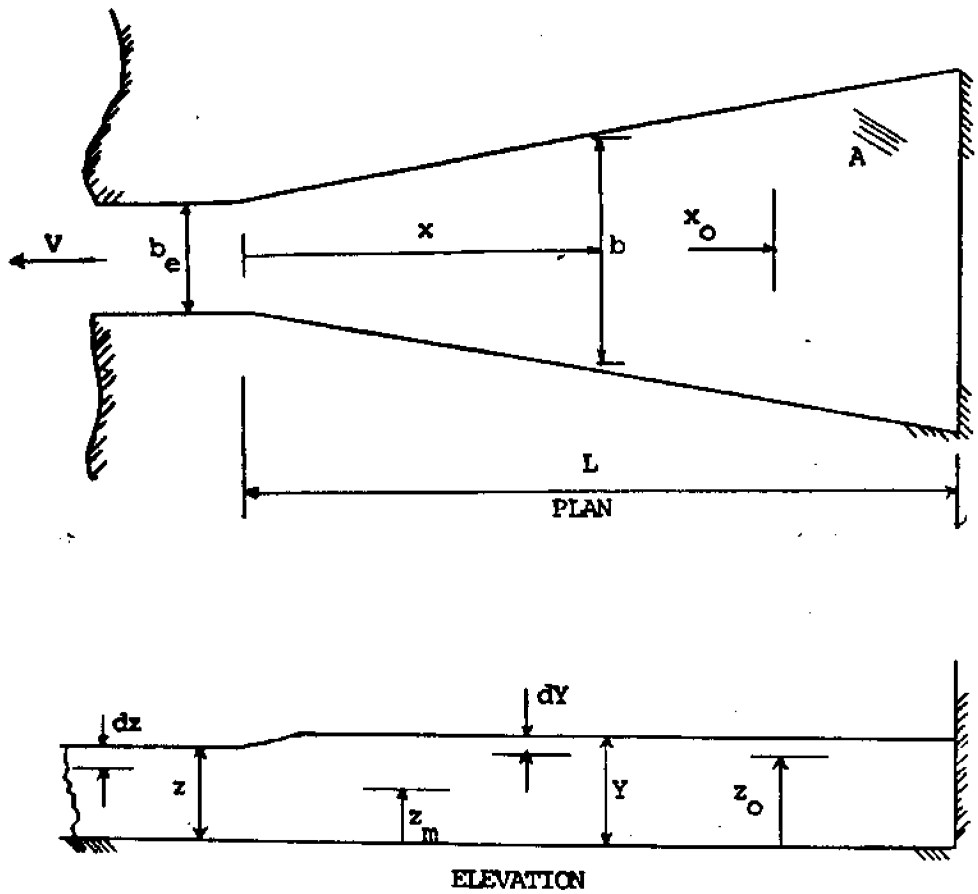
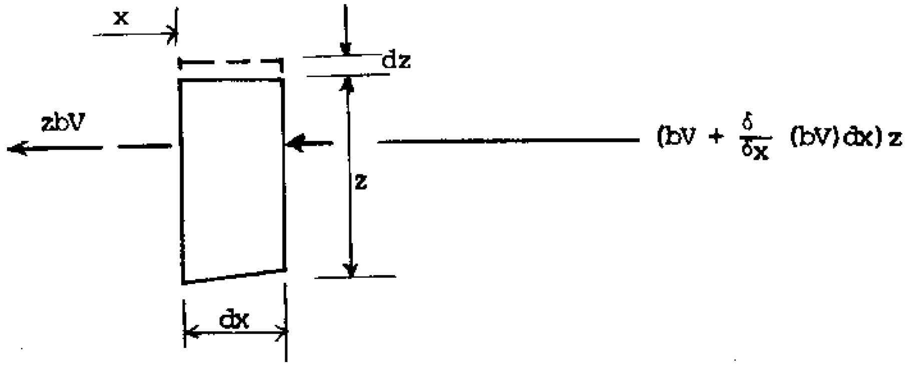


FIGURE 2. Definition Sketch



For a horizontal bottom, ($z \neq f(x)$) the volume conservation requires that

$$zbV - (bV + \frac{\delta}{\delta x} \quad (bV + \frac{\delta}{\delta x} (bV) \; dx)) \; z = -bdx \frac{dz}{dt} \tag{1}$$

$$\frac{\delta}{\delta x} (bV) \; dx \; = b \frac{dx}{z} \; \frac{dz}{dt}$$

$$\frac{d}{dx} (bV) \; = \; b \; \frac{d}{dt} \; \ln z$$

$$\int_V^o d(bV) = \frac{d \; \ln \; z}{dt} \; \int_x^L b \; dx, \text{ since } \frac{d \; \ln \; z}{dt} \; \neq f(x)$$

$$V = V \; \text{ at } \; x$$

$$V = 0 \; \text{ at } \; x = L$$

$$bVdt = d \; \ln \; z \; \int_x^L \; b \; dx$$

$$dx = -Vdt$$

$$-b \; dx \; = \; d \; \ln \; z \int_x^L b \; dx$$

$$\int_{z_o}^{z} d \; \ln \; z \; = \; - \int_{x_o}^{x} \frac{b \; dx}{\int_x^L b \; dx} \tag{2}$$

Equation 2 expresses the condition that if a parcel were at x_o when $t = 0$, and $z = z_o$ and were to travel with the fluid velocity V, then it would be at a position x when the depth becomes z.

Since the right hand side (RHS) of Equation 2 is of the form du/u,

$$\ln \frac{z}{z_o} = -\ln \frac{\int_x^L b\,dx}{\int_{x_o}^L b\,dx}$$

$$\frac{z}{z_o} = \frac{\int_{x_o}^L b\,dx}{\int_x^L b\,dx}$$

$$z \int_x^L b\,dx = z_o \int_{x_o}^L b\,dx \qquad (3)$$

For selected initial conditions, (x_o, z_o) the RHS of Equation 3 is a constant, i.e., the volume between x_o and $x = L$.

Equation 3 can be adapted to solve for

a. x, given x_o, z_o and z

b. z, given x_o, z_o and x

c. x_o, given z_o, z, and $x = 0$

Conditions in (c) allow for determining x_o such that a parcel would reach $x = 0$ in the interval that $z_o \rightarrow z$. The equation can be adapted readily to iterative methods of solution for a basin of non-regular shape so long as the assumption of a uniform velocity distribution, i.e., $V = f(x)$ only, can be made. In other words, the method does not allow for variations in velocity across the basin, nor in the vertical direction as might develop in a stratified flow.

To explore Equation 3 quantitatively, consider a marina having a rectangular planform, 750' x 1500', (about a 300-boat size), an entrance width b_e = 100 feet, and a horizontal bottom at elevation -15' MLLW. One solution of Equation 3 for this assumed geometry is shown on Figure 3, where $\underline{z_o}$ is the depth at slack flood tide, $\underline{z_m}$ is the depth at slack ebb. Then for a parcel at the midpoint $x_o/L = 0.5$, a value of $z_o/z_m = 1.9$ would be needed for the parcel to reach the basin entrance at the ebb slack time. This is a value that would be possible on a high spring tide, but not during the neap cycle.

Equation 3 may be used also to determine the ebb slack position $\underline{x}$ of a parcel that was at x_o on flood slack. For the illustrative basin, with a bottom elevation of -15 MLLW, the ratio of initial depth to final depth z_o/z_m =2.4 for a typical high spring tide and 1.5 for a neap tide; results for these tides are shown on Figure 4. The travel distances depend only upon the depth ratio, not upon the shape of the tide curve. The limitations on flushing from the upper reaches of the basin by tidal action alone become obvious. The method may be adapted to basins of irregular shape by step methods.

A definition of a flushing time $\underline{t}$ in tidal cycles is given by Bowden (1967) as $t = (V + P)/P$, where $\underline{V}$ is the water volume in the basin at low water and P the volume at high water. Complete mixing is assumed so $\underline{t}$ represents only the lower limit of flushing time; actual times may be much longer.

Entrance Velocity

The velocity at the entrance to a basin resulting from tidal exchanges is important from viewpoints such as navigation, the paths of small fish migrating along the shoreline, sediment transport and its role in a material balance, which in turn may relate to biological and shoreline equilibrium problems. A first estimate of this average velocity $\underline{V}$ as a function of time can be predicted from the continuity principle as

$$V = A/A_e(dz/dt) \tag{4}$$

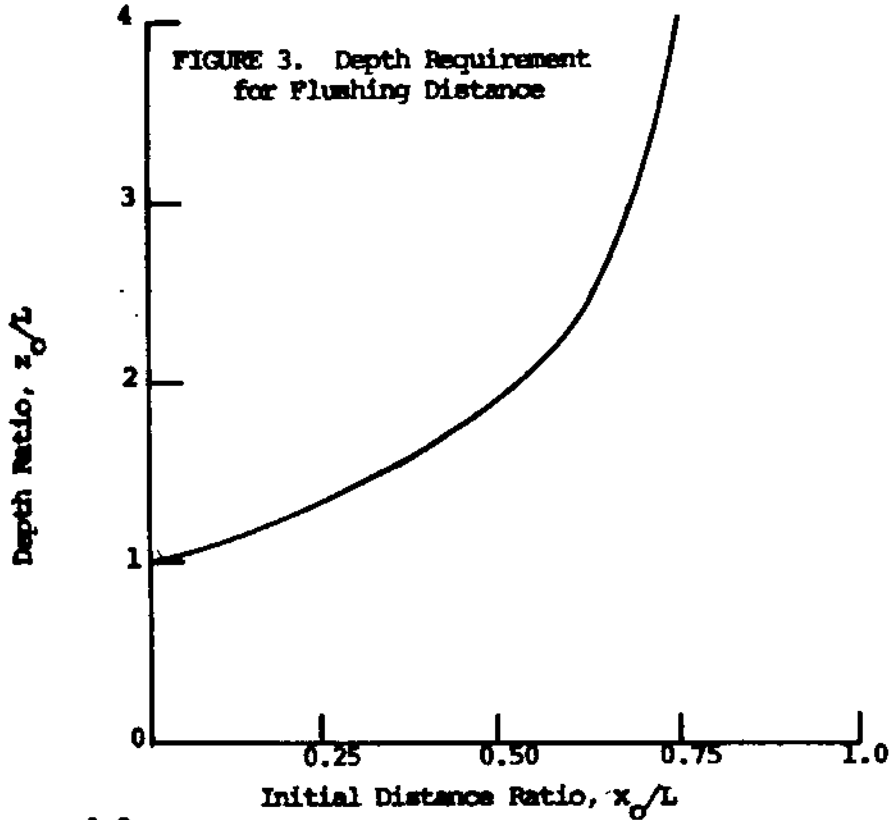


FIGURE 3. Depth Requirement for Flushing Distance

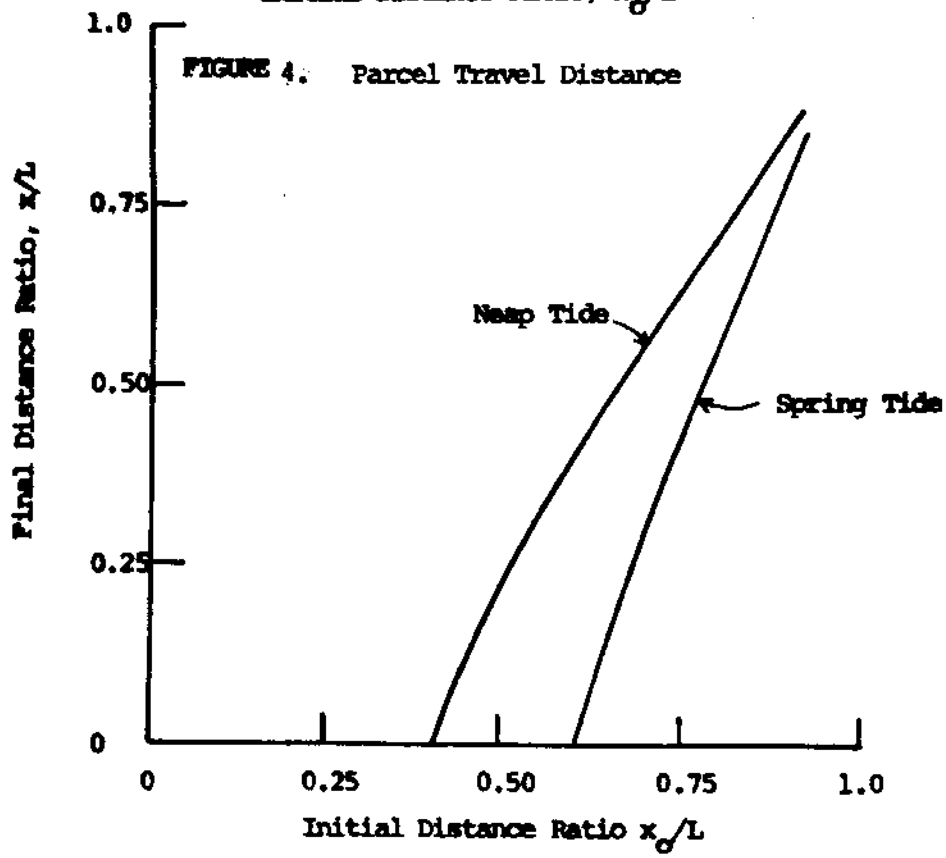


FIGURE 4. Parcel Travel Distance

where $\underline{A}$ is the planform area of the basin, $\underline{A_e}$ is the cross-sectional area of the entrance, and dz/dt the time change of tidal height, assumed in this model to be the same as the change within the basin. The model does not distinguish between incoming and outgoing currents.

The mixed tides with the unequal lows peculiar to the region require a cumbersome harmonic function to describe them throughout a complete cycle, so it is expedient to use a simple cosine curve over just a selected limb of the cycle to predict the entrance velocity. More exact functions can be used for a particular tide and place. Let the entrance depth for an ebbing tide be

$$z = B + (H/2) \cos \pi t/T + H/2 \qquad (5)$$

where $\underline{B}$ is the depth at low tide, $\underline{H}$ is the full height range, and $\underline{T}$ the time from flood to ebb slack. The average entrance velocity from Equation 4 is then

$$V = A/A_e \ (\pi/T)(H/2) \sin \pi t/T \qquad (6)$$

The predicted velocity is plotted as Figure 5 for the dimensions of the sample basin and a spring tide have H = 14 feet and T = 420 minutes. The velocity is directly proportional to the area ratio, so the first-order effects of changes in area, tidal range and period can be computed easily. It was assumed in this model that the water surface height in the basin was the same as in the estuary (Figure 2). A refinement on the "continuity" model can be made by using the Energy Equation, written between the water surface inside the basin and that in the tidal zone outside the basin entrance, to obtain:

$$V_1^2/2g + Y = V_2^2/2g + z$$

$$V_1^2/2g + Y = V_2^2/2g + z \ h_L \qquad (7)$$

where the last term is the summation of all losses. After neglecting friction, accelerations, bottom slope, velocity heads in the basin and in the estuary, and assuming the only important loss is the kinetic energy in the entrance, the entrance velocity is found to be

$$V = \sqrt{2g\ (Y - z)} \tag{8}$$

This technique has been used quite successfully by Halliwell (1967) in planning closures for estuaries. The effects of sills can be included in the analysis by considering them as possible control structures. The volume flux $\underline{Q}$ through the entrance must equal the volume drawn from the basin, so

$$Q\ dt = -A\ dY = VA_e \tag{9}$$

and A_e can be determined from the entrance geometry and Equation 5. A solution of Equations 8 and 9 for the same geometry used to solve the first velocity model is plotted for comparison on Figure 5, along with other geometries to show the relative effects of areal and tidal parameters.

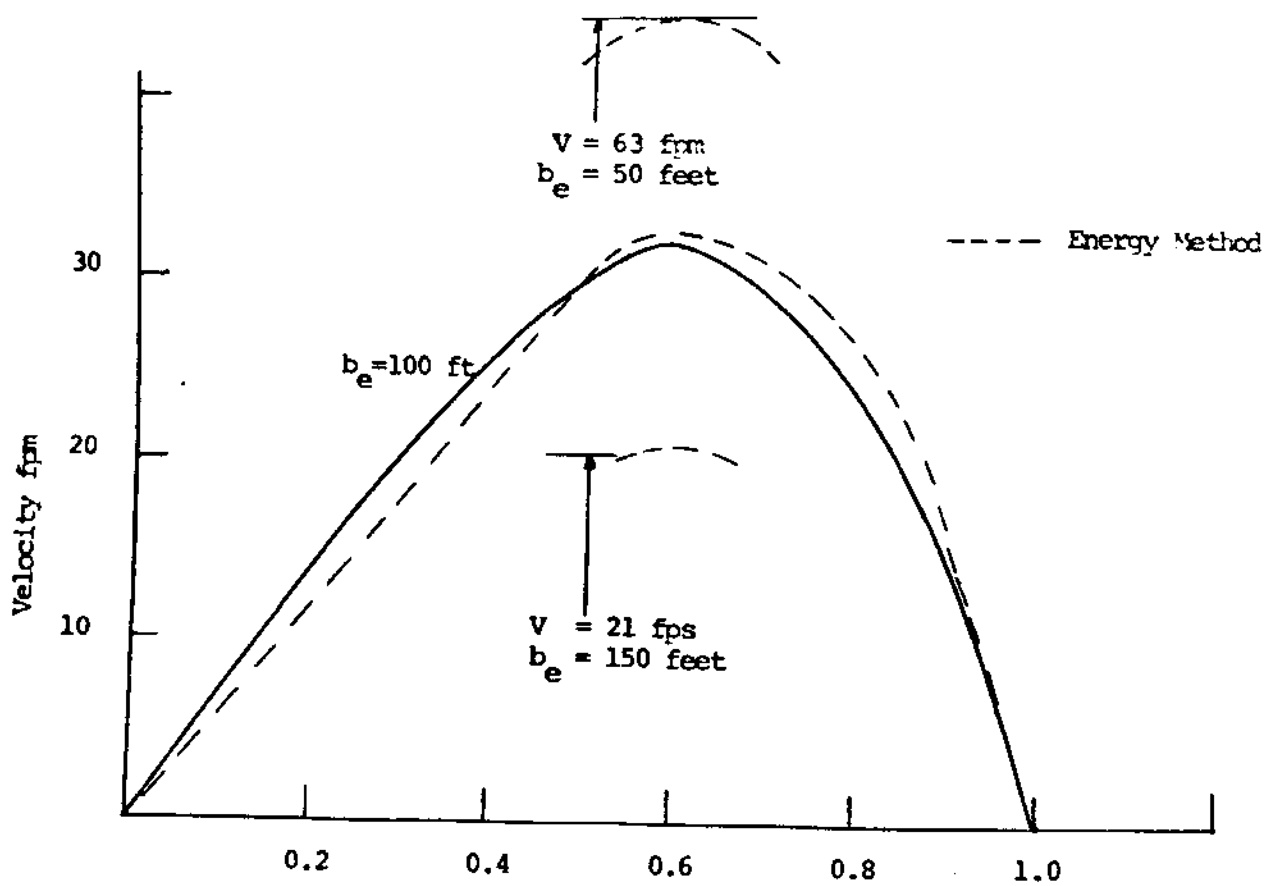


FIGURE 5. Entrance Velocity

One-dimensional flow was assumed for both prediction models in order to obtain readily the gross kinematics: effects due to alignment of entrances with respect to the main body of the basin, the particular entrance geometry, the presence of boat slips, wind stress, nor bottom configurations were included. Estimates of the effects of entrance and alignment geometry in the individual case might be obtained from potential flow theory as used by French (1960) or from some analogue technique like the fluid mapper (Moore, 1961). However, experimental data from prototype sites or physical models are needed to check the prediction models and to assess the relative importance of the secondary influences. The elementary approach provides a first approximation which may be quite adequate for some applications, but the secondary effects could be of primary importance in other cases.

Migratory Fish and Marinas

The State of Washington Department of Fisheries has released (Feb. 1971) a report which establishes guidelines ".. to govern design and construction of facilities that might affect the fish and shellfish resources under jurisdiction of the Department of Fisheries. The criteria ... will be immediately implemented in review of applications to construct facilities along the seashore, particularly bulkheads, landfills, and marinas in all marine waters lying east of Cape Flattery ..." This report follows an earlier one by Heiser and Finn (1970) on juvenile salmon in marina and bulkheaded areas. Some of the information from these two reports which relates most closely to the marina hydraulics is paraphrased here for the present discussion, but the reader should see the original reports for additional remarks on biological and water quality matters and for a full listing of the design criteria.

Pink and chum salmon fry, the species most vulnerable to predation by more vigorous fishes and susceptible to other hazards, migrate in only the upper 6-12 inches of water; they suffer increased predation when forced to move into deeper water. This trait has a direct bearing on design criteria for structures in the zones of migratory salmon, which means most of Puget Sound and Adjacent Waters, and surely will be a factor to be reckoned with in any cooling water systems in these regions, although the reports do not cover this point.

The general objective of the criteria is to maintain natural shorelines and beach slopes so far as possible, to provide adequate circulation within marinas, and to require structures that will neither force juvenile salmon into deep water nor provide a habitat favorable for predators. Some specific criteria are:

1. The construction of a bulkhead and/or land fill with a vertical face is limited in seaward extent to certain tidal elevations specified by regions, and is set at +9 feet in the area of Seattle, for instance. Construction of riprap or stepped forms may proceed further seaward to another limiting elevation, again set on regional levels, but is +6.6 in the Seattle area.

2. Breakwaters and/or bulkheading built seaward in a plane perpendicular to the shoreline shall not be allowed as a continuous one-piece structure. The tow of a shore breakwater may not extend seaward beyond the zero-tide level.

3. The beach inside a marina is subject to the same elevation limits as in (1) above.

4. No restrictions are applied to the form of isolated breakwaters, except that any breaches shall not be less than 20 feet in width, measured at the tow, and pre-project depths must be maintained.

To see how a conventional design might be altered to accommodate some of these criteria, refer to the schematic layout of Figure 6a. The bulkhead at the shore is assumed to be vertical, the bottom excavated to a constant depth. Breakwater materials and sections are chosen on the economics of structural requirements, only. The single entrance is oriented to minimize influent wave energy, and a culvert has been called for in one breakwater for circulation purposes. Under the new criteria, Figure 6B, the extent seaward of the vertical bulkhead has been limited as under (1) above, as is the beach. The construction material and sides of the two structures normal to the shoreline

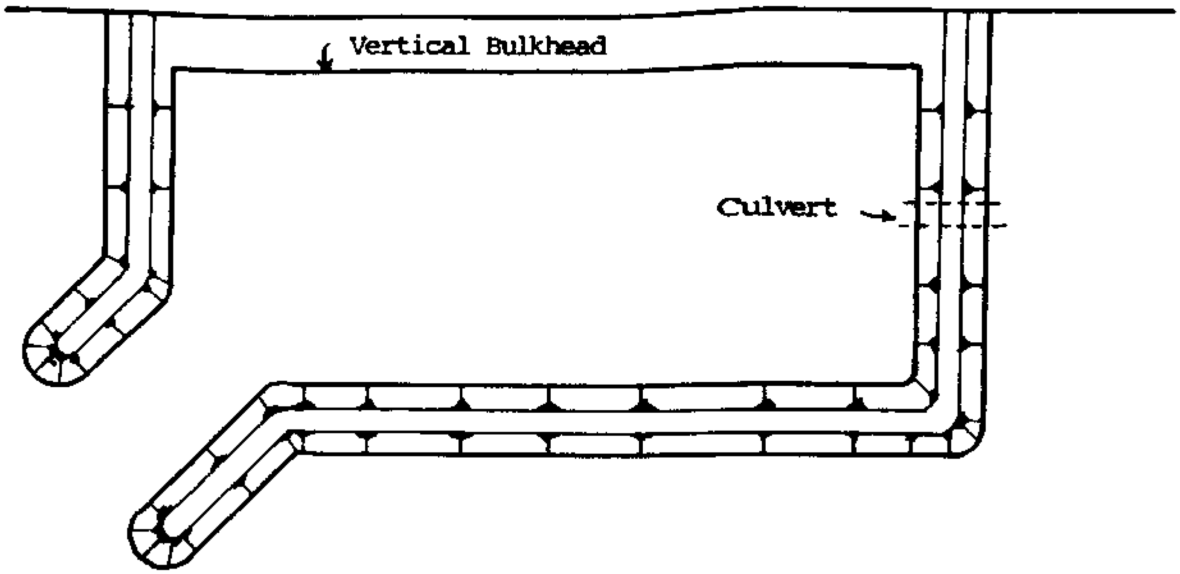


FIGURE 6a. Conventional Layout

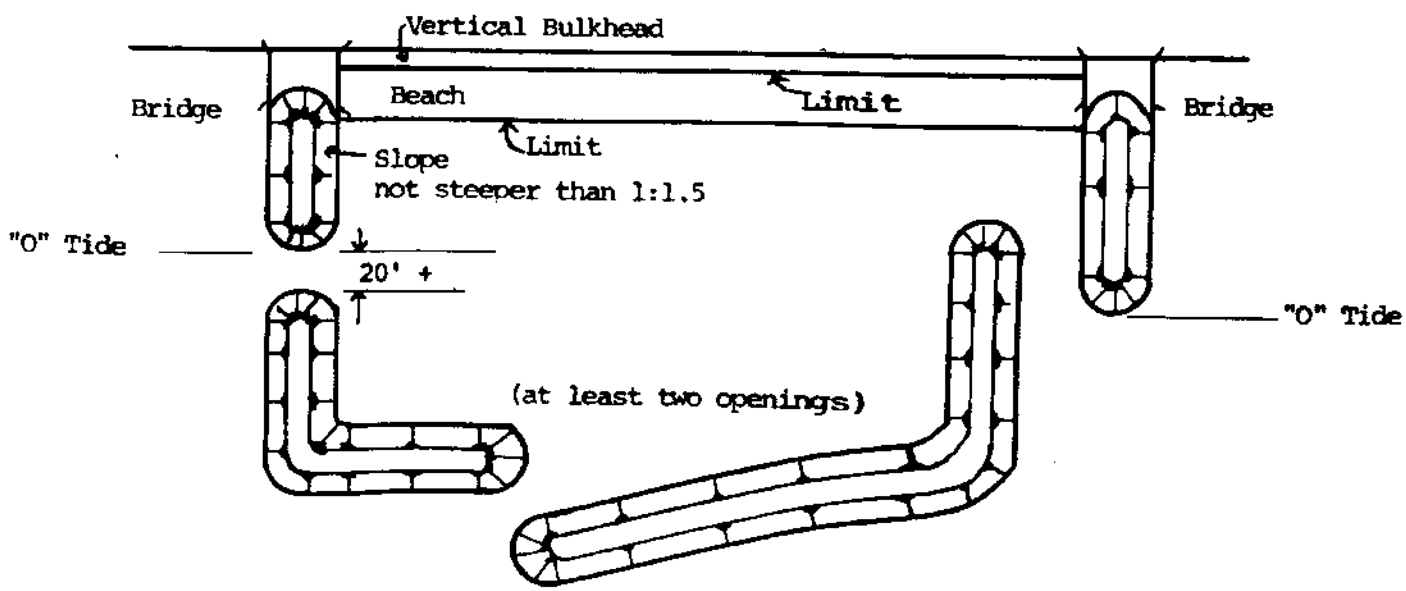


FIGURE 6b. Revised Layout

have been chosen to conform to preferred material and minimum slope, gaps have been provided on the shore ends since the fish refuse to enter a culvert, and the seaward end has been terminated at zero-tide line. The outer breakwaters have been detached with minimum gaps of 20 feet, and have multiple openings to increase water circulation. The breakwater segments have been offset to divert wave energy from the marina. Floating breakwaters would appear to be a good guardian of marinas so far as the salmon fry migration paths are concerned, and, indeed may be an economical alternative in some locations where water depths preclude a fixed breakwater and long wave lengths are excluded for some physical reason, but are not a promising solution on exposed sites.

The new criteria provide the planner and designer of shore-based facilities with long-needed guidelines. Increases in cost may be associated with the construction of some marina components. However, the market is a luxury one, though not necessarily a luxurious one, and should be able to absorb the modest cost increases to help maintain a resource that adds pleasure to pleasure boating.

The Lake Chelan Case

An action by the Supreme Court of Washington on December 4, 1969 sets forth another consideration for the planning input to shoreline developments in the state. According to Corker (1970) "The courts ordered defendants who had filled their lands, which are seasonally inundated by the waters of Lake Chelan, to remove the fill because it obstructed the rights of the plaintiffs and the public to swim, boat, fish, bathe, recreate, and navigate in the waters of the lake. This principle applies to all navigable waters of the state." Corker discusses the case at some length, and includes definitions of the terms "navigable" and "navigability". A reply to Corker's analysis by Rauscher (1970) states a contrary view with respect to both the law of tidelands and shorelands in lakes, which fluctuate only naturally, and the effect of the Lake Chelan case upon that body of law. It may be sometime before the spectrum of cases falling under the Lake Chelan ruling is fully defined. One opinion is that breakwaters to protect a marina are "aids to navigation" and therefore do not come under the ruling. However, plans for any shoreline developments need to be projected against the Lake Chelan ruling for possible conflicts.

Marina Examples

Five existing marinas (located on Figure 1) will serve as examples of possible field study sites and comparisons with some of the planform requirements of the new criteria; Heiser (1970) reports on observations of juvenile salmon in the first four of these.

The Des Moines Marina (Figure 7) has a single entrance on its northern end. This location is desirable from a wave-energy standpoint, but not from the water exchange view. Northerly winds are common during the active summer boating season, which may inhibit the outward movement of surface water. The simple kinematic model should yield reasonable results here, for the geometry is relatively simple. The effect of boat slips is unknown, of course. Very likely, under the new criteria, a second opening at the southern end would have been included in the design to increase circulation through the marina.

The Shilshole Marina, Figure 8, is discussed in some detail in Reference 1. Its detached breakwater with the two major entrances provide good tidal exchanges and movements of surface currents by winds from either of the two frequent sectors.

The Edmonds Marina (Figure 8) has a single, central opening with a reentrant breakwater wing on the north side. The marina might be analyzed in two parts, with corrections for the asymmetric geometry. Any gaps that might be suggested for either of the two breakwaters that are normal to the shoreline would have to compensate for incident wave energy on the south side and the flow from sewer outfall just off the north side.

The Cultus Bay Marina (Figure 9) is relatively long and narrow, with shallow beaches. It opens toward the north, so the water in the upper end stagnates and becomes quite warm because of the shallow depths and poor circulation.

The Lagoon Point site (Figure 10) on the western side of Whidbey Island has been developed by excavating behind the normal beachline. The channel formed by dredging the small creek that drained the marshland is the only opening. Its crossing of the beachline has been protected by two short groins. The general planform configuration does not lend itself well to a field study site.

Conclusions

The new criteria to be used by the State of Washington Department of Fisheries in the review of applications for the construction of shore facilities such as bulkheads and marinas form one more instance where ecological parameters need to be added to the ones used more traditionally in the planning and design of water-oriented structures. Two major points so far as marinas are concerned relate to limits on the seaward protrusion of shore-connected structures, and the requirements for better wave circulation. Two prediction models for assessing circulations due to tidal effects were developed; the second model showed that neglecting the exit loss would be a permissible assumption in most instances. It appears that these new criteria can be woven into the existing planning and design procedures in quite the same way as any other new regulation on navigation, safety, etc., would be handled.

Acknowledgements

Discussions with personnel in the State of Washington Department of Fisheries and their cooperation in supplying reports were essential in the preparation of this paper.

Thanks are extended to Stephen J. Burges, Assistant Professor of Civil Engineering, University of Washington for his assistance in programming work and to Marc Maher, Graduate Student, University of Washington for his marina photographs.

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FIGURE 7. Des Moines Marina

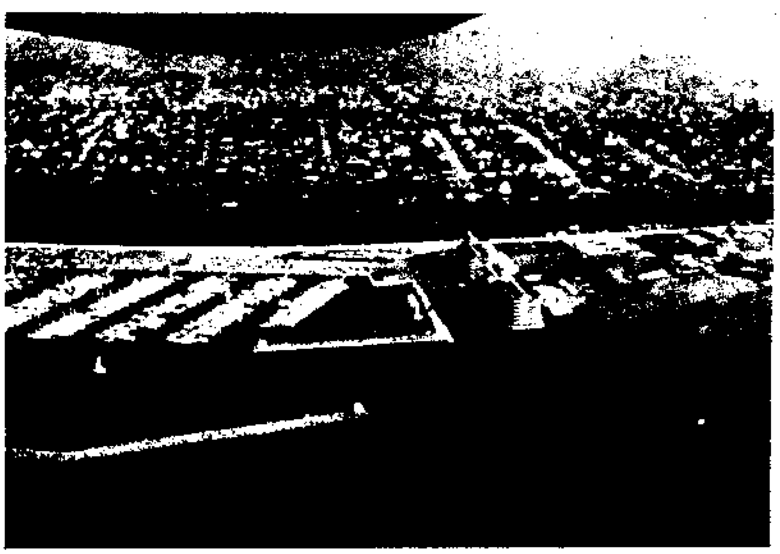


FIGURE 8. Shilshole Marina

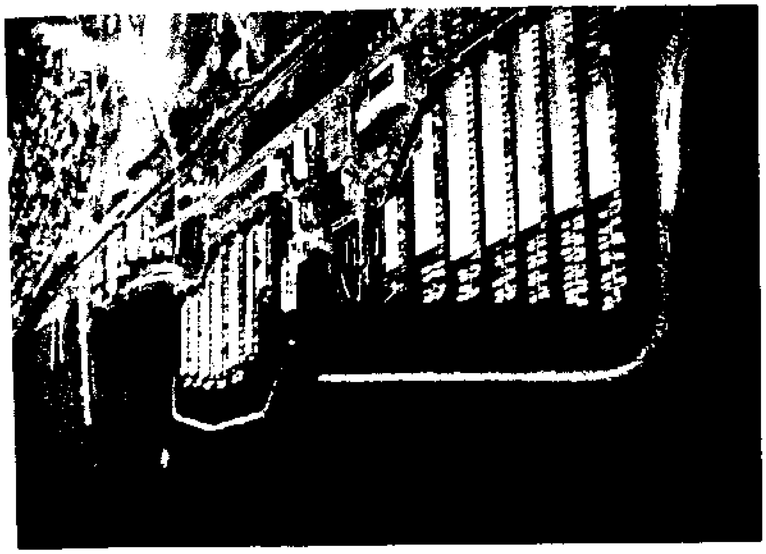


FIGURE 9. Edmonds Marina

FIGURE 10. Cultus Bay

FIGURE 11. Lagoon Point

Marine Aids to Navigation - Selection and Design

by

Commander, Charles L. Clark, USCG

Chief, Civil Engineering Branch

Thirteenth Coast Guard District

Seattle, Washington

ABSTRACT

Our modern marine aids to navigation system is designed to give the mariner maximum assistance in transiting our navigable water safely. Types of aids within the estuary include ranges, passing lights, buoys, and day-beacons. Individual aids are located, designed and maintained to serve the specific needs of the mariner. Equipment is designed to provide efficient operation without sacrificing reliability.

The first known man-made aid to marine navigation in the western world dates back 2,250 years. Even before then, sailors were undoubtedly guided by the smoke and fires of volcanoes as well as by the sun, moon and stars. In 280 B.C. a massive 400-foot tower was built on the summit in the Pharos of Alexandria, Egypt, on which a wood fire was kept burning. The tower was started by the first Ptolemy and completed by the second Ptolemy, at a total cost of 800 talents (2,400,000 shekels). The pharos of Alexandria was numbered among the Seven Wonders of the Western World, and it gave use the word "pharology," meaning the science of lighthouse design and engineering.

A modern aids to navigation system bears no resemblence to this ancient wonder, or even the aids of 100 years ago. Vast increases in the number of users, including recreational boatmen, an increase in vessel size and speed, transportation of bulk cargoes with potential adverse affects on marine ecology, have all contributed to the growth and importance of our marine aids to navigation system. The Coast Guard operates and maintains over 44,000 aids within the navigable waters of the United States. In addition to protecting the life and property of users, our system plays a key role in preserving the environment for everyone dependent on our estuaries for economic and recreational support.

To the casual observer, most aids look the same except for color and light characteristic. Selection of a specific aid is governed by operational criteria plus physical characteristics of the station. On an estuary such as the Columbia River , all types of aids are encountered by the mariner. They include lighted and unlighted buoys, lighted structures, daybeacons, and ranges. Each of these will provide the user with one or more of the following audio/visual services:

1. Daymark with visual identification.
2. Radar target.
3. Light with visual identification.
4. Audible signal.

A system of marine aids to navigation must be established and maintained according to several basic principles. Aids are installed along a coast and navigable waterways and aboard stationary vessels: to enable navigators to determine their position with relation to land, other visible objects and concealed, isolated dangers: to follow natural and improved channels; and to determine their position on the high seas. Different types of aids are used solely to meet the requirements of varying locales and navigators. The system should be based on the following principles:

1. It must be sufficient to serve the needs of the armed forces and permanent and substantial commerce of the country involved. The term "commerce" includes international and coastwise trade, commercial and recreational fishing, and recreational boating.

2. Each aid in the system must be justified in terms of public benefit to be derived therefrom.

3. It must provide a uniform, simple method of identification and distinction of one aid from another.

4. It must be reliable. Reliability is essential to the safe use of the system. Whenever a deficiency exists, the mariner must be expeditiously notified of it.

5. It is passive. An aid to navigation is only a tool of the mariner as the name "aid" applies. The aids and precautionary notes pertaining to them make available to the mariner certain valuable information. The interpretation and use of the information are left to the discretion of the mariner. He must judge for himself whether the position obtained is dependable and accurate and what steps are needed to assure his safe passage. The amateur navigator often forgets that the aid is passive and that he must act.

6. An aid to navigation by itself does not provide a mariner with all the information he needs. Proper use of a system of aids to navigation requires that the mariner seek additional information about the aid, its location and purpose by consulting up-to-date charts, Light Lists, appropriate Sailing Directions, and Notices to Mariners. Accordingly, accurate and timely information on the type, characteristics, and location of each aid must be provided the mariner through the specific publications.

The estuaries of the Pacific Northwest offer a great challenge to the officers and men responsible for providing a safe marine highway. Location of the entrances of estuaries along the Oregon and Washington Coast has given us the dubious honor of having the roughest buoy station in the entire United States (Clatsop Spit Lighted Whistle Buoy 4 on the Columbia River Entrance Bar).

As we proceed from sea, the forces and conditions change drastically and require varied solutions discussed in the following paragraphs.

BUOYS

Buoy design employs all of the principles of vessel design with the added factor of a fixed mooring under all conditions. Lighted buoys are designed with a period of roll approximately five seconds and a 35 degree maximum angle of roll to afford the mariner an opportunity to observe the light characteristic at its advertised intensity during each oscillation.

Buoys come in many shapes and sizes, each designed to support a payload under particular conditions. A buoy is required when a fixed structure is not feasible due to:

1. Water depth.

2. Local sea conditions.

3. Current.

4. Unstable channel or bottom contours.

5. Frequent contact with passing vessels, tows, or debris.

Table I shows the performance characteristics of standard lighted buoys. The lighted whistle buoy in Figure 1 is typical of the Columbia River Bar Channel buoys except 1 7/8" chain is used to withstand the tremendous loads imposed on the mooring on our bar stations. At the other end of the spectrum is the sixth class unlighted buoy similar to the type used in the upper Columbia River (Figure 2).

Selection of a particular buoy to do the job depends on the following requirements:

1. Geographic location (exposed, semiexposed, or sheltered). Exposed locations demand buoys with a large reserve buoyancy to support the vertical component of the mooring load during adverse sea conditions.

2. Operational range of the light. The height of the focal plane must be sufficient to assure the geographic range of the light equals or exceeds the operational range.

3. Visual range of daymark. Daymark areas and height to permit visual detection under standard visibility and sea conditions.

4. Comparative radar range.

5. Depth of water. Minimum depth governed by buoy underwater dimension and minimum allowable mooring. Maximum depth

PERFORMANCE CHARACTERISTICS OF 1962 TYPE LIGHTED BUOYS

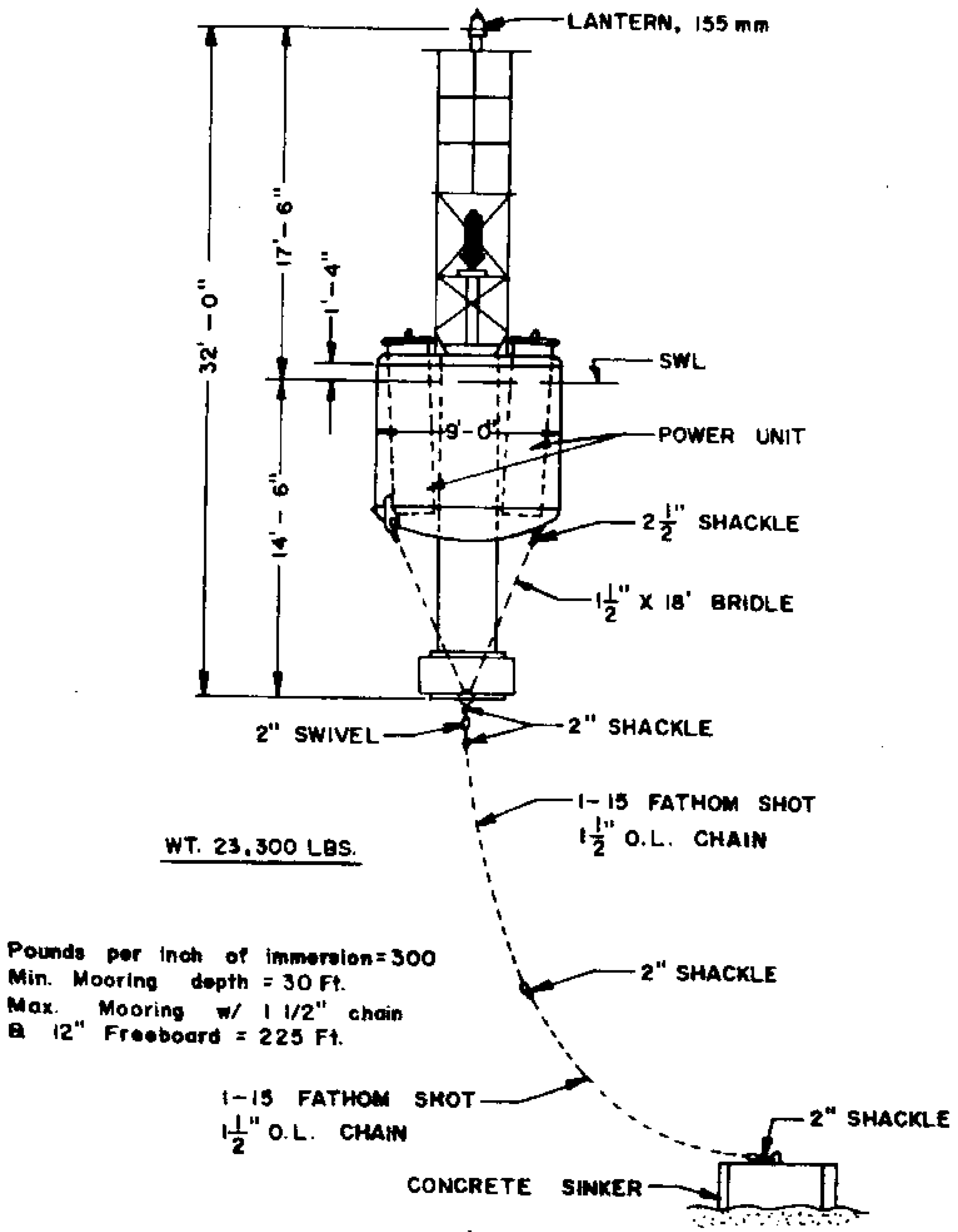
	9 x 32 LR	9 x 32 LBR	9 x 32 LGR	9 x 32 LWR	8 x 26 LR	8 x 26 LBR	8 x 26 LGR	8 x 26 LWR	6 x 20 LR	6 x 20 LBR	7 x 17 LR	5 x 11 LR	$3\frac{1}{2}$ x 8L
VISUAL RANGE OF DAY-MARKS* (NAUTICAL MILES).	2.5	2.5	2.5	2.5	2.0	2.0	2.0	2.0	1.5	1.5	1.5	1.0	0.5
COMPARATIVE RADAR RANGE (NAUTICAL MILES).	7.0	7.0	7.0	6.5	6.0	6.0	6.0	5.5	4.0	4.0	4.5	3.0	0.5
TYPE OF LOCATION FOR WHICH INTENDED.	EX-POSED	EX-POSED	EX-POSED	SEMIEX-POSED OR EX-POSED	SEMIEX-POSED OR EX-POSED	SEMIEX-POSED OR EX-POSED	SEMIEX-POSED OR EX-POSED	SEMIEX-POSED OR EX-POSED	SHEL-TERED	SHEL-TERED	SHEL-TERED	SHEL-TERED	SHEL-TERED
DEPTHS OF WATER FOR WHICH DESIGNED (FEET).	30-450	30-360	30-360	30-220	25-290	25-240	25-240	25-130	20-170	20-140	25-230	10-130	5-35
GEOGRAPHIC RANGE OF LIGHT (NAUTICAL MILES).	9.4	9.0	9.0	9.0	9.0	9.0	9.0	9.0	8.0	8.0	8.0	7.5	7.0
MAXIMUM CURRENT FOR WHICH DESIGNED (KNOTS)	4-5	4-5	4-5	4-5	3-4	3-4	3-4	3-4	3-4	3-4	3-4	3-4	3

* FIGURES ARE FOR T-0.5 PER SEA MILE, 95 % DETECTION PROBABILITY OF NOMOGRAM, MINIMUM FREQUENCY OF VISIBILITY OF 79 %, AND A 75 % MINIMUM PROBABILITY OF SEEING THE BUOY.

TABLE I

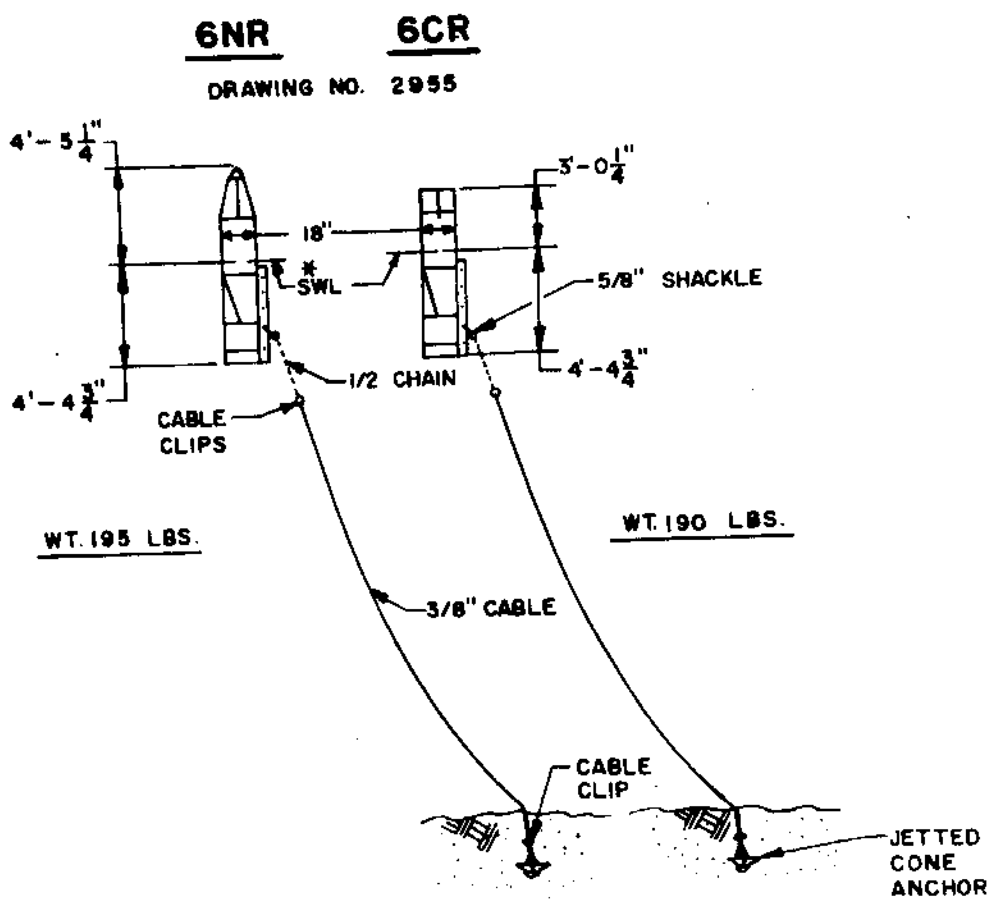
9 x 32 LWR

DRAWING NO. 107326



The freeboard shown on this buoy is the result of the weight of the moorings if suspended as shown. However, mooring should be ordered to suit local conditions with a length of chain from 1 1/2 to 3 times the depth of water. The weight of the sinker is not included in the weight of the buoy shown above.

Figure 1



Pounds per inch of immersion = 9.4 (salt water)
Pounds per inch of immersion = 9.2 (fresh water)
Min. Mooring depth = 6 Ft.
** Max. Mooring depth w/ 3/8" cable = 60 Ft.
*** Max. Mooring depth w/ 7/16" chain = 45 Ft.

The freeboard shown on these buoys is the result of the weight of the moorings if suspended as shown. However mooring should be ordered to suit local conditions with a length of cable from 1 1/2 to 3 times the depth of water. The weight of the sinkers is not included in the weight of the buoys shown above

* Freeboard with 7/16" Chain: 6NR = 3'-10 1/2" & 6CR = 2'-5 1/2"

** 3/8" Cable is used only with the Jetted Cone Anchor

*** When a Sinker is used, 7/16" H.T.S. Chain is used for the entire mooring.

Figure 2

depend on reserve buoyancy available to support maximum length of standard mooring.

6. Desired service period. Length of service period must be exceeded by Rated Battery Discharge Time. RDBT is a function of light characteristic and lamp size for a particular size of battery power unit.

Size and weight of the selected buoy determine the requirements of the servicing craft. Steel buoys will eventually give way to buoys constructed of lightweight materials such as filament-wound-glass reinforced polyester resin(Figures 3 and 4)

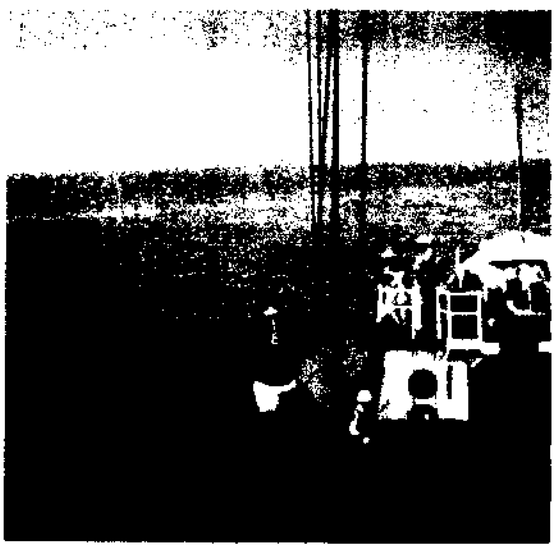


Figure 3

Figure 4

and rotationally molded high density polyethylene (Figures 5, 6, and 7). Their use will afford a more cost/effective system without reducing service to the mariner.

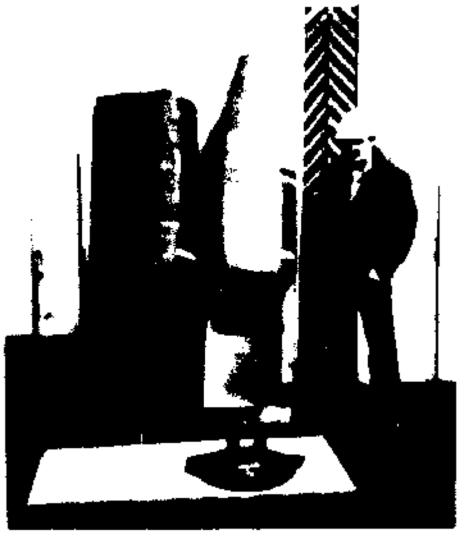


Figure 5

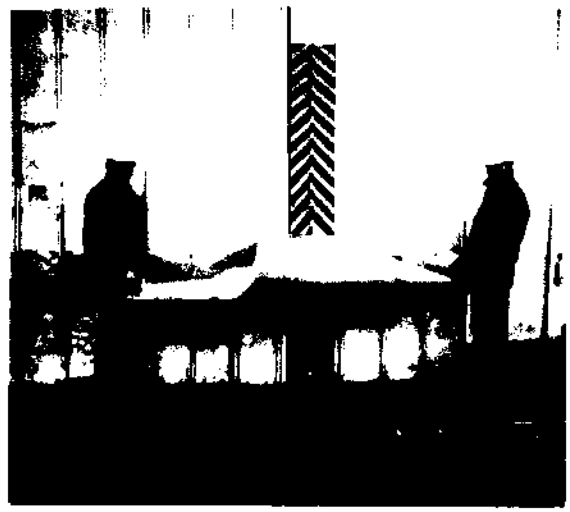


Figure 6

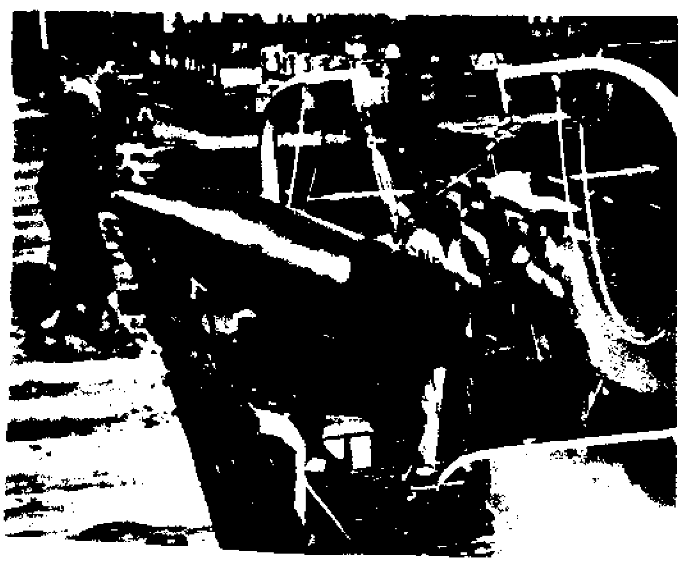


Figure 7

STRUCTURES

Lighted fixed structures and unlighted daybeacons afford the mariner an accurate reference point in determining his position relative to hidden dangers or the limits of a channel. In this respect they are a much better aid than a buoy if certain criteria can be met:

1. Location with respect to the channel or danger. A feasible site must be located close enough to the danger or channel limit to insure the mariner will remain in "good" water when passing the aid.

2. Depth of water. Limiting depth of water for marine structures is generally 30 feet.

3. Height. Elevation of the light must be sufficient to place the beam at or near the height of eye of normal users. The platform, daymark, and equipment must be above all wave action or maximum high water.

4. Bottom conditions. A structure is fixed until destroyed or moved. Therefore, it is not economically feasible to build marine structures along constantly changing portions of a channel or on land sites subject to rapid bank recession. Certain hard bottoms exclude fixed structures because of the cost of driving pile substructures.

5. Longevity. Sites that subject a structure to frequent destruction by vessels, tows, or debris prevent economical maintenance of this type of aid. Life expectancy of aids vary but a 25 year life is not uncommon in our estuaries.

6. Wind loads. The structure must withstand local wind loads on the daymark. Winds in excess of 100 miles per hour are not rare at the entrances of some Northwest estuaries.

Because the supporting structure plays no significant part in a mariners use of an aids, its construction can vary greatly to best satisfy the above criteria. Use of single concrete piles (Figure 8) or steel pipe piles (Figure 9) give a "clean"

Figure 8

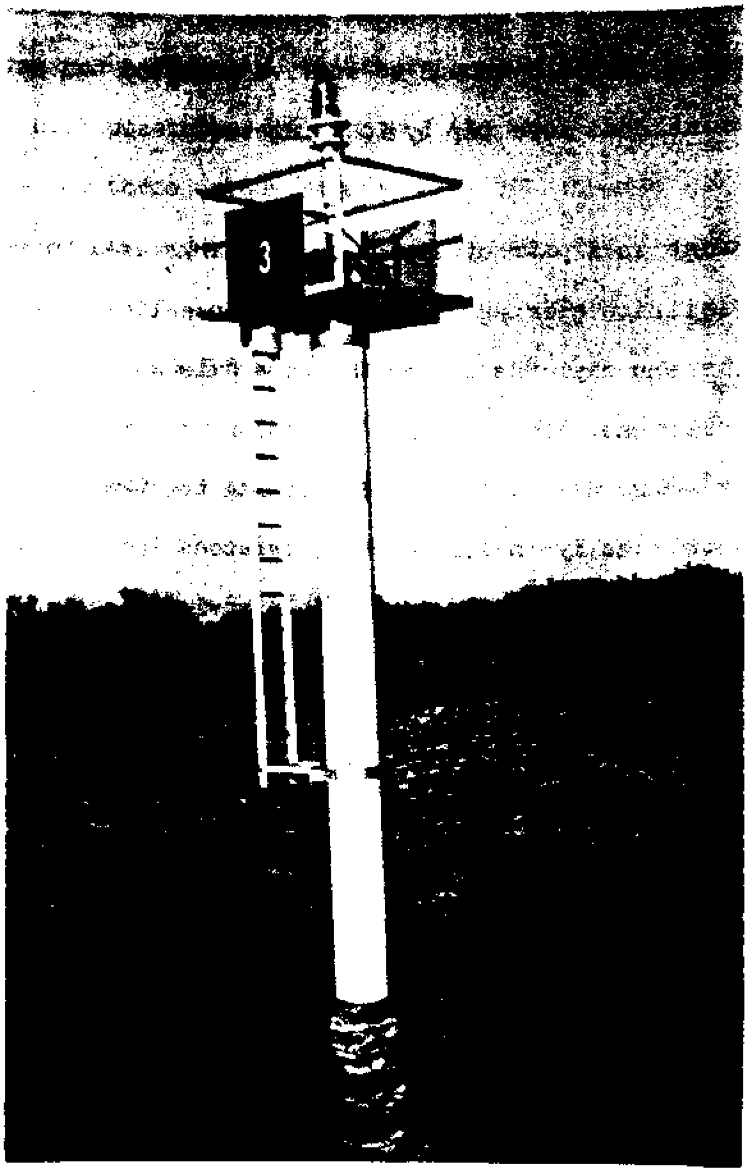
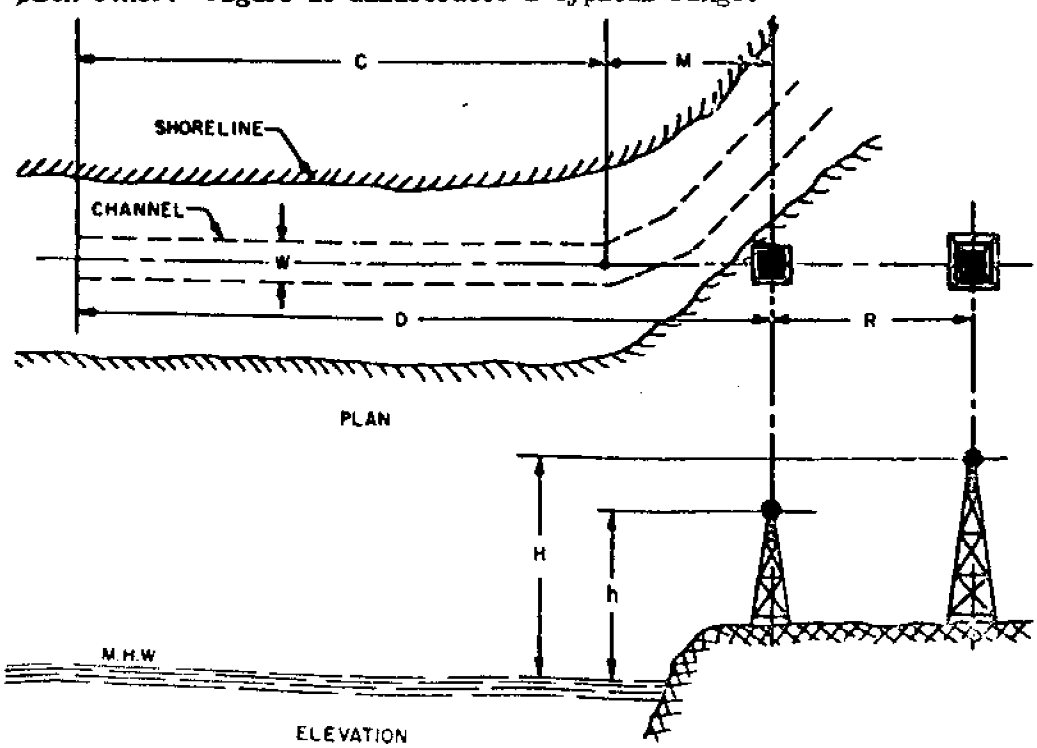


Figure 9

low-maintenance structure. Treated wood pile structures are also common. One design, a 5 pile dolphin was originated for use on the Columbia River. Its piles are unbraced and rely on a wire-rope binding at the top for structural integrity. The resulting structure is flexible enough to survive repeated contact by debris and an occasional love tap by a passing tow.

RANGES

A range is a pair of lights and daymarks used to establish a line of definite bearing, commonly the centerline of a channel. The lights and daymarks lie on the same axis as the range line and the rear ones are of higher elevation than the front. A navigator makes use of a range by keeping the two lights and daymarks vertically in line as he progresses into a channel. As he moves sideways in the channel, a navigator estimates the distance he has departed from the range line by the apparent lateral displacement of the two lights and daymarks relative to each other. Figure 10 illustrates a typical range.

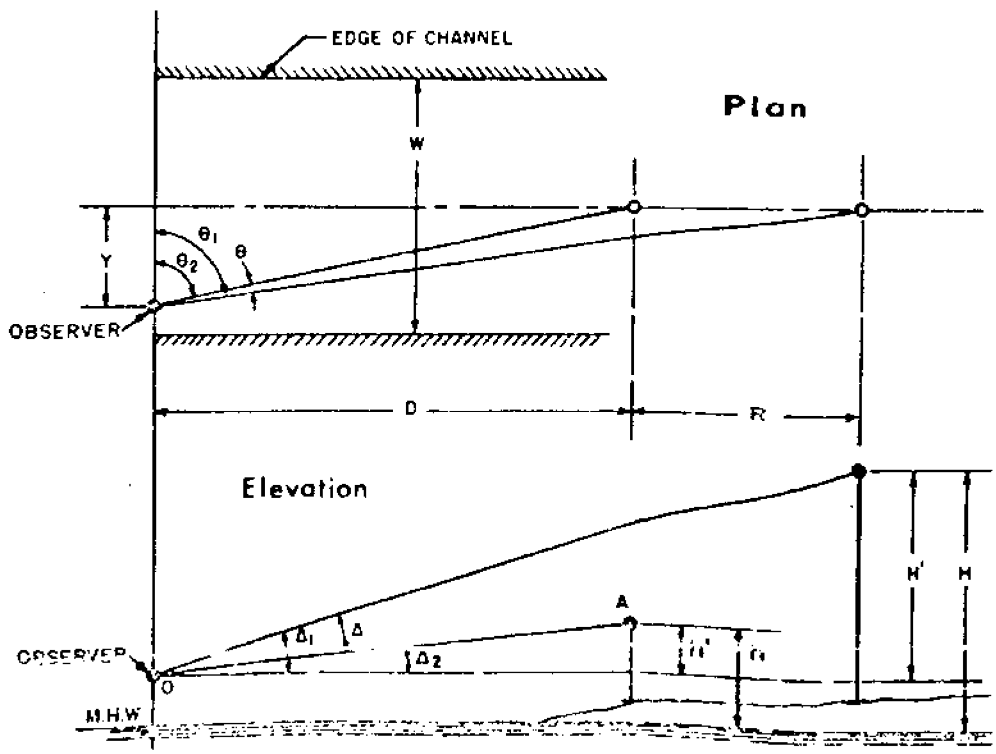


A Typical Range. Figure 10

From an economic viewpoint, a range is one of the more expensive aids to navigation, and therefore should be designed to provide the best possible service per dollar cost.

A range has three unique properties: the minimum acceptable vertical angle between the two lights or marks, the lateral sensitivity of the range measured by the coefficient K, and the relative brightness (brightness balance) of the two lights.

The vertical angle of separation of two range lights is a measure of the opening effect; that is, their ability to be resolved as two separate lights. This is the angle subtended by the two lights at an observer at the far end of the range, shown as angle Δ in Figure 11.



Vertical Angle and Lateral Sensitivity of Ranges.

Figure 11

Experience has shown that if Δ is equal to or greater than 4.5 minutes of arc a person with average eyesight will see two lights.

Lateral sensitivity is the measure of the mariner's ability to detect a change in a ship's lateral position. It is measured by the rapidity with which the lights open (deviate from a vertical line) as the ship moves crosswise in the channel.

The coefficient of lateral sensitivity, K, is computed by the formula:

$$K = \frac{WR}{D(H-h)} \quad ; \text{ where}$$

K is the coefficient of the lateral sensitivity (in dimensionless units); W is the width of the navigable channel in feet; R is the distance between the structures; H and h are the heights of the structures; D is the distance from the far end of the channel to the front structure.

The two lights of a range should appear to be of approximately the same brightness; however, an exact balance at all points along the range is impossible. The two brightnesses should not be so unequal that one light completely obscures the other. Arbitrary criteria have been established to govern the permissible "unbalance" of range lights. In general, the brightness of one light should not be more than five times the other at any point along the range.

The problem as presented to the designer is usually in the following form: it is desired to construct a range on the center-line of a channel whose length is C feet and whose width is W feet. The simplified solution is presented for the general case in the steps below.[1] All linear units are in feet.

Step 1 - Determine the minimum distance from the front structure to the near end of the channel. If the distance is called M, the D (the distance from the front structure to the far end of the channel) is equal to M plus C. Such facts as the depth of water, nearness of land at the inner end, the ability to obtain property, and the type of terrain must all be considered in locating the front structure. But there are also minimum limits set by the geometry of the range and the brightness of the lights.

The minimum value for M due to the brightness balance of the lights is determined by the following relation:

$$M_{min} = \frac{C}{\frac{\sqrt{(Q-1)}}{K \quad C} - 1}$$

where Q equals the ratio of the brightness of the rear light to the front light at the far end of the channel. The initial assumptions are that Q=5, K=0.5 and Δ=4.5'/3438 radians, so chosen to meet the minimum engineering and operational standards.

Looking at the geometric limitations it is observed that in some cases, for small values of M, the rear light will have to be very high so that at the near end at least 50% of the rear daymark is visible and the vertical angle is at least 4.5', while a much smaller structure would insure the required conditions at the far end. By choosing a larger value for M, the height of the

(1) USCG Civil Engineering Report CG-250-39

rear light can be decreased and thus the cost. At this point it cannot be determined whether or not this factor will enter into the problem so the smallest possible value for M is chosen. After having chosen the value for M that is suitable for the local conditions and that is larger than M_{min}, R is selected.

Step 2 - The distance R between the range structures is determined by:

$$R = \frac{D}{\frac{W}{K \quad D} - 1}$$

This equation will give the minimum value of R upon substitutions of the values for K and Δ which meet the minimum standards; i.e.,

$$R_{min} = \frac{D}{\frac{3438W}{4.5\ D\ K_{min}} - 1}$$

If R is chosen, due to the practical considerations of the area, to be larger than R_{min} either K or Δ or both will increase depending upon how the larger choice of R affects the other dimensions. It is best to keep R as small as possible as this will help keep the height of the rear light to a minimum.

Step 3.- The sizes of the daymarks, which are to be placed immediately below the range lights, should be determined now for they too affect the height of the structures. The charts on size, color and visual range of daymarks are given in Table II.

The front daymark should be visible at a distance D and the rear at a distance D+R. Let:

l = length of the front daymark

L = length of the rear daymark

NOMINAL DAY VISIBILITY OF RANGE DAYMARKS
(MILES)

	DAYMARK SIZE (FT)									
	3x6=18	4x8=32	5x10=50	6x12=72	7x14=98	8x16=128	9x18=162	10x20=200	11x22=242	12x24=288
BROWN FOLIAGE BACKGROUND										
KWR	1 1/2	3	3 1/2	4	4	4 1/2	4 1/2	4 1/2	5	5
KRW	1 1/2	3	3 1/2	4	4 1/2	4 1/2	4 1/2	5	5	5
GREEN FOLIAGE BACKGROUND										
KBR	1	1 1/2	2	2	2 1/2	2 1/2	3	3	3	3 1/2
KBW	1 1/2	2	2	2 1/2	2 1/2	3	3	3 1/2	3 1/2	3 1/2
KRB	1 1/2	2	2 1/2	3	3	3	3 1/2	3 1/2	4	4
KRW	1 1/2	2 1/2	3	3	3 1/2	3 1/2	4	4	4	4 1/2
KWB	1 1/2	2 1/2	3	3 1/2	3 1/2	4	4	4	4 1/2	4 1/2
KWR	1 1/2	2 1/2	3	3 1/2	3 1/2	4	4	4	4 1/2	4 1/2
SKY OR SNOW BACKGROUND										
KWR	1/2	1	1	1 1/2	2	2	2 1/2	2 1/2	2 1/2	3
KWB	1/2	1	1 1/2	1 1/2	2	2	2 1/2	2 1/2	2 1/2	3
KRW	1	1 1/2	2	2	2 1/2	2 1/2	3	3	3	3 1/2
KBW	1	1 1/2	2	2 1/2	2 1/2	3	3	3	3 1/2	3 1/2

DAYMARK DESCRIPTION CODE:

1st LETTER = K (RANGE)

2nd LETTER = MAJOR COLOR

3rd LETTER = COLOR OF STRIPE

R= FLOURESCENT RED-ORANGE

W= WHITE

B= BLACK

TABLE II

Step 4 - The height of the front structure is determined by the following considerations: the daymark must remain above the high water level, above all objects that would obstruct it from view, and yet must be as low as possible consistent with these requirements. This as-low-as-possible consideration is a major factor in an economic and still geometrically sufficient solution. The value of h, measured from MLW, is thus determined by:

h = l + "extra"

where l is the daymark length and "extra" refers to the largest "extra" positive value found of the following five terms:

1. "Extra" equals the height necessary to keep the daymark high enough above any obstructions present so that it is visible along the entire length of the channel.

2. "Extra" equals the height necessary to keep the daymark safely above the high water level and wave action. This height is also measured with reference to MLW and therefore must be at least as large as the mean range of tide, t.

3. "Extra" equals the height necessary for proper geographic range.

4. If the front structure is built on land:

"extra" equals elevation of the site above MLW

5. The only consideration given to a height of eye greater than 15' in the "extra" calculation is in the case where at the near end of the channel the ship's bow actually would hide the observer's view of the front daymark (this calls for a small

M value). In this case the bow is treated as an obstruction at this near point only and the "extra" value calculated.

Step 5 - Now that the physical dimensions of the range have been established, it is necessary to select the proper lighting equipment. First, the ratio of the effective intensities of the two lights must be determined to insure that a brightness balance of 5:1 exists at all points in the channel whenever the transmissivity is greater that some minimum value. The intensity ratio must fall between the limits given by:

$$Q \left[\frac{R+D}{D}\right]^2 \geq \frac{I_e \text{ (rear)}}{I_e \text{ (front)}} \geq \frac{1}{Q T_{min}^{R/6080}} \left[\frac{R+M}{M}\right]^2$$

where Q=5 and T_{min} is the minimum transmissivity (per sea-mile) above which a brightness balance must be maintained. If when analyzing a specific range, the numerical value of the left side of the equation is less than the right side, the brightness balance condition cannot be satisfied for all transmissivities greater than T_{min}. The operational requirements must be relaxed to allow a greater value of T_{min}, i.e., brightness balance will be achieved fewer nights of the year.

Step 6 - The minimum required effective intensities of both lights, sufficient to be seen to their operational range (generally beyond the far end of the channel) for some high percentage of the nights of the year, must now be determined. Either Allard's law

$$B = \frac{I_e \; T^X}{X^2}$$

or the Allard's Law Nomogram may be used, where the value of B is selected for the appropriate background lighting conditions.

It will now be necessary to increase the minimum required effective intensity of one of the light (generally the rear) to meet the intensity ratio established in Step 5.

Step 7 - Select the lighting equipment from the candlepower tables, Civil Engineering Report No. 12D, which furnish the required effective intensities and characteristics for the front and rear lights. This equipment will often have effective intensities somewhat larger than the minimum requirements found in Step 6.

Step 8 - Calculate the brightness of the actual lighting equipment at the near and far ends of the channel calculating the four brightnesses, form the ratios:

$$\frac{E_2}{E_1} \quad \text{and} \quad \frac{E_{22}}{E_{11}}$$

and insure that

$$5.0 \geq \frac{E_2}{E_1} > \frac{E_{22}}{E_{11}} \geq \frac{1}{5.0}$$

LIGHTING EQUIPMENT

Conversion of a minute amount of electrical energy into a reliable, intense, and indentifiable light source is no small task. The energy used in our system is generally derived from primary batteries in the buoy or on a structure. Some fixed aids use commercial power when available. The energy is metered to the incandescent lamp by two regulators (1) a photo-sensitive daylight control to activate the light only during periods of darkness or reduced visibility and (2) a solid state timing device capable of giving the light an accurate characteristic, regulating input voltage to the lamp, and sensing lamp filament failures and advance a new lamp to the burning position. The incandescent lamps used in aids to navigation are prefocused during manufacture to insure all lamps burn in the same position within the optic.

Selection of the most cost/effective lighting system is dependent upon:

1. Type of aid. The type of aid determines the lantern and lens to be used. Both buoys and fixed aids use a 360° fresnel lens to produce a narrow horizontal fan beam. Vertical divergence of the lens for a fixed aid is two degrees while the buoy lens has a five degree divergence. The useful light beam of a range is very limited so this type of aid requires a parabolic reflector combined with a lens to gain maximum light in a horizontal beam limited to 30 degrees.

2. Required luminous range. The distance between a light source and a point at which the light just stimulates a visual response is the luminous range. It is a function of effective beam candlepower, transmissivity, background lighting conditions, and the adaption of the observer's eye. Lamp size and battery requirements are determined by these factors.

SOUND SIGNALS

Sound signals can be placed on any aid, providing adequate power is available to operate the signal. Some buoys use wave actuated whistles, gongs, and bells. This type of signal is of limited value due to their extremely short range and reliance on buoy motion for output. Battery powered electric air oscillator signals are used both on buoys and fixed structures. Battery requirements generally limit this type of signal to ratings of less than one mile. Larger signals must be powered by commercial power. Selection is determined by:

1. Required range. The size of the signal and its power requirement are a function of the rated audible range.

2. Size of vessel using the signal. Background noises on large and small vessels differ appreciably and are a factor in the selection of the frequency and sound pressure level to insure detection in the presence of background noise.

3. Site conditions. Prevailing wind, local atmospheric conditions and topography have a great influence on the propagation of sound.

4. Effect on the surrounding environment. While a sound signal may be a very good aid for the mariner, it makes a very poor neighbor in a populated area. The impact on all aspects of the locale must be considered prior to establishing any sound signal.

Historical Changes of Estuarine Topography with Questions of Future Management Policies

by

John B. Lockett

Research Associate

Department of Oceanography

Oregon State University

Corvallis, Oregon

ABSTRACT

The ephemeral nature of the estuarine environment makes it essential that man's most sophisticated tool, intelligent management, be employed to preserve and develop the special resources of that environment. This paper raises a number of questions relating to future coastal zone management policies and attempts to answer these questions in a manner designed to provoke constructive thinking and discussion as a requisite to the development of an effective plan for coastal zone management.

As Dr. Russell of the Louisiana State University pointed out at the Conference on Estuaries held at Jekyll Island, Georgia, in 1964, this is an excellent time to discuss estuaries as, in a few ten thousand years from now, estuaries may be quite rare. In their place will be numerous valleys with alluvial flood plains widening seaward and, in some cases, blending into deltaic or other coastal plains. He further states that few estuaries can survive for more than a minute fraction of a geological epoch, since it appears probable that another glacial stage and lowering of the sea level will be accompanied by the disappearance of practically all estuaries and the erosional entrenchment of rivers crossing their alluvial deposits. Although neither the geologic past nor the future holds much promise for estuaries and, in many cases, today's estuaries seem headed for rapid extinction, their very existence at this stage in time provides an excellent opportunity to study their peculiar regimens and to make maximum use of their unusual resources for the further enrichment of man's present way of life.

Perhaps the ephemeral nature of estuaries may no better be illustrated than by a review of changes in topography that have occurred in one major West Coast estuary during the past century. It was my fortunate experience a few years ago to uncover the Annual Report of the Chief of Engineers, U. S. Army, for the year 1903, which contained sketches of the configurations of the Columbia River entrance area as they existed in 1885 and continuing year by year until 1902. Using these sketches and the more recent condition surveys of the Corps of Engineers it was possible to develop a color film depicting the changes occurring in the topography of the lower Columbia estuary and entrance area, which will be shown at this time. Some of these changes, it will be noted, have developed in obvious response to works of improvement for navigation while other changes seem to have more elusive origins. Depths below mean lower low water are shown in shades of blue on the film, with the darker shades of this color denoting greater depths. This film was prepared with the cooperation of the Division Engineer, North Pacific Division and the District Engineer, Portland, Oregon. In view of its brevity and the magnitude of the changes in topography involved, it will be shown twice to provide you an opportunity to recognize the significance of these changes. In this connection, your particular attention is invited to the development, by littoral drift, of land masses between the mid-point of the South jetty and Point Adams, as well as to the build-up of land behind the North jetty as this structure was extended seaward.

SHOWING OF FILM

With this background and our real, but incomplete, knowledge of the unique resources found only in our estuaries, it is only natural that we should seek the means of preserving our fragile esturaine areas and of enhancing the growth and development of their special resources, now so vital to our economy and, in another sense, so essential to man's continued enjoyment of their non-consumptive benefits. We are all aware of the inroads already made by man in the estuarine environment resulting from his past preference for short-term benefits over long-range values. This preference has upset the ecological balance of this delicate environment by the destruction of estuarine bottom areas through the filling of marsh and tidelands; alteration of the tidal prism, as well as currents by structures; introduction of unusually large quantities of sediments into the estuarine regime by deforestation, flashing run-off and poor agricultural practices in the upland areas; and the creation of sediment-trap characteristics through dredging in the interest of navigation. Further, organic enrichment, through disposal of raw domestic and industrial wastes into estuarine waters, has contributed significantly to oxygen-deficient conditions. In some estuaries, particularly along the Eastern Seaboard, practically all the rich resources these regions once harbored have been destroyed, while we, on the West Coast, find our situation not so hopeless but, nevertheless, some of our more important estuaries seriously threatened because of man's preference for short-term benefits.

Dr. Cronin, Director of the Chesapeake Biological Laboratory, states that man's past actions in estuaries have been poorly and incompletely planned, unimaginative, and frequently destructive. In view of the many important uses served by these waters, he stresses that it is imperative that a new major human force be utilized in the future - the force of intelligent management. Application of this force will require the use of many kinds of tools and techniques, ranging from original fundamental oceanographic research to regulatory changes and public education. Some of the approaches necessary for intelligent management are becoming apparent and it is perhaps timely for us to explore some of their potentials at this time. With this in mind, let us ponder a number of questions as a means of identifying and analyzing the tools for coastal and estuarine management.

1. DOES BASIC RESEARCH HAVE A PLACE IN THE MANAGEMENT PLAN?

In spite of the growing attention given to estuaries in recent years, we must admit that most of the controlling parameters are still incompletely and inadequately understood. With respect to the physical processes, only gross estimates can be developed for the patterns of flushing, circulation, vertical mixing and diffusion and for such phenomena as light absorption, sedimentation rates, current direction and velocity, and salinity intrusion. More knowledge is needed for a better understanding of chemical and geological factors affecting estuarine behavior. It is also clear that our present biological knowledge of estuaries is weak, notwithstanding the fact that these regions have been heavily utilized by man for centuries for the production of food. Other areas of research exist in the fields of economics and social science. Here, intelligent management needs a valid estimation of the economics of alternate courses of action which may modify existing patterns of human activity. Evaluation of the recreational use and potential is difficult, particularly in the non-consumptive fields of beauty, cleanliness, and personal enjoyment. In the social and political areas, the resistance man demonstrates to changes in working habits is difficult to comprehend. Thus, it appears abundantly clear that basic research is a badly needed and essential tool for the development of an intelligent plan of management of our coastal resources.

2. WHAT ARE THE GOALS OR OBJECTIVES OF AN EFFECTIVE MANAGEMENT PLAN?

There are many goals or objectives that may be selected to achieve the most desirable type of use or development, including preservation where appropriate, of our coastal zone including estuaries. These goals or objectives may stress such aspects as improvement of water quality, exploitation of their biological resources, preservation of their scenic attractions and the attainment of the maximum recreational potential, to mention a few. The question appears to resolve itself upon the present physical characteristics of each estuary being studied and the relationship of these characteristics to the integrated desires of the local, State and Federal governments. Not all estuaries, due to differing physical characteristics, offer the same opportunities for development, just as there very likely exists no uniform integrated State-wide desire for estuarine preservation and development. Goals and objectives are, nevertheless, essential choices that must be made, initially at the local level and later from the overall position of the State and Federal levels. In general, it is believed that the guiding principles for the selection of goals for coastal and estuarine management should employ the concept of fostering the widest possible variety of beneficial uses so as to maximize the net social return. Once goals or objectives have been selected, they should be vigorously pursued through the formulation of policies, projects and programs - with means of implementing all three elements.

3. HOW DO WE GO ABOUT ACHIEVING THE SELECTED GOALS OR OBJECTIVES?

Achievement of the selected goals or objectives is the primary purpose of an intelligent plan for coastal and estuarine management. The development of this plan, which is more properly a continuing process for rational management, has its roots in the desires of local government. Furthermore, this process should be an integral part of existing governmental activities, including planning and management at all levels. The State, with the advantage of overview of local problems, constitutes the natural level for coordination and supervision over the preparation of the management plan which should, of course, give due consideration to essential Federal requirements. Many states are subject to intense pressures from the county and municipal levels because management directly affects local responsibilities and interests. On the other hand, local knowledge is frequently necessary to reach rational management decisions at the State level and is also essential to reflect the interests of local governments in accommodating competitive needs. In Oregon, the State and local governments have entered into a partnership to develop and implement a coastal management process, with primary responsibility resting with local government. While this is no simple matter, we are fortunate in that we do not have the tremendous population pressures of central and southern California or the eastern seaboard. Unlike many states which are preparing coastal zone management plans primarily at state level, Oregon is fortunate to have a coastal planning program, the initiative for which is coming primarily from the local level. This bodes well for future implementation of any resultant management plan.

4. WHAT TYPE OF AGENCY SHOULD BE ESTABLISHED TO MANAGE THE COASTAL AND ESTUARINE AREAS?

Consideration is being given in some coastal states to the establishment of a State Coastal Zone Authority to coordinate plans and uses of coastal waters, including estuaries, and adjacent lands and to regulate and develop those areas. Such an authority would draw upon all available knowledge of the physical, biological and economic characteristics of a state's coast and estuaries. As the magnitude of coastal problems varies from state to state, so would the powers assigned to the Coastal Zone Authority be determined. In certain relatively undeveloped areas, only planning would be required, but in other areas the full range of State powers might be needed to preserve resources of statewide and national significance, including:

a. The development of comprehensive plans for the coastal and estuarine waters and adjacent lands, and the conduct of necessary studies and investigations.

b. The zoning and granting of easements, licenses or permits and the exercise of other necessary controls for insuring that the use of waters and adjacent lands is in conformance with the plan for that area.

c. Acquisition of lands when public ownership is necessary to control their use.

d. The provision of such public facilities as beaches, marinas, and other waterfront developments, and the leasing of lands in its jurisdiction, including offshore lands.

While Oregon has not yet felt the need for establishment of a Coastal Zone Authority, the coastal counties, in coordination with the State, have embarked upon a Coastal Program. The Program's primary working elements are four area coordinating committees - Clatsop/Tillamook Intergovernmental Council, Lincoln County Subdistrict Number 4, a special committee representing the coastal portions of Lane and Douglas Counties, and the Coos/Curry Councils of Governments. These groups are charged with developing and implementing comprehensive plans for their respective areas which, in total, will form the nucleus of a coastwide plan. The program's Oregon Coastal Conservation and Development Committee, composed of six representatives from each of the four areas and two representatives of the Governor's office, will be responsible for developing coastwide planning policies, procedures, and standards in concert with the Program's area coordinating committees and for integrating the area plans. The Committee's goal provides for the preparation, encouragement and maintenance of a comprehensive, coordinated Coastal Program for the orderly long-range conservation and development of marine and coastal resources which will insure their wise multiple-use in the total public interest. The establishment of this Committee represents a pioneering effort among the coastal states of the Nation, and there is no doubt that its future actions will be closely watched by other states as guidance in the resolution of their own coastal management problems.

5. WHAT IS THE FEDERAL ROLE IN COASTAL MANAGEMENT?

Since several Federal agencies operate in coastal waters and as their operations sometimes profoundly affect their use, it is only reasonable to expect that the Federal government will have a strong interest in the effective management of a State's coastal waters. Further, such vital interests as navigation and military security should not be endangered by State or local action. Hence, it is essential that the Federal government insure that the general national interest in effective coastal planning is protected. Federal review is possible at a number of stages, such as when a State first proposes a particular type of management authority, when the comprehensive coastal plan is developed and when Federal grants are proposed. However, in view of the multiplicity of Federal interests, Federal responsibilities for dealing with State and local authorities should be centralized to insure that the Federal government speaks with a single voice on coastal zone matters. In connection with Oregon's Coastal Program, the Federal interests are being coordinated through the Pacific Northwest River Basin's Commission, and as of this date, the Federal agencies have expressed their desire to remain in an advisory capacity, which will probably take the form of a technical advisory task force on subcommittee.

6. WHAT INFORMATION IS NEEDED FOR DEVELOPMENT OF AN EFFECTIVE MANAGEMENT PLAN?

A challenge to a State's capacity for effective planning and management is presented by the coastal zone's many uses which occur within a complex and delicately balanced biophysical system. To develop an adequate basis for decision-making in this zone, there is need for broad surveys to establish basic inventory information, for continuous and detailed studies of specific local conditions and for trained personnel. Acquisition of accurate information relative to the physical, economic and biological characteristics and potentials of the coastal zone is a first step toward more rational management. A concentrated, comprehensive effort to survey coastal zone resources will gather much needed basic data. However, this survey will not meet the needs for detailed, specific understanding of local opportunities and problems. The meeting of these needs will require systems for continuous monitoring of coastal zone phenomena as well as vigorous support for basic and applied research in local areas. It is not easy to understand the complex and often subtle biological and physical relationships and interactions in the coastal zone. Although the understanding of these phenomena has improved markedly during the past 20 years, the accellerated pace of man's activities has increased both the complexity of the coastal zone system and the urgency for greater understanding. Continuously updated data are needed by State and Federal fishery and pollution control agencies on water quality, flow circulation, salinity and biological content; and beach erosion and siltation must be monitored so as to detect changes before excessive damage is done. Monitoring of such social and economic indicators as recreation usage and fisheries production will also be required for effective management of the coastal zone. Regretably, however, too little attention has been given to the development of instrumentation for monitoring estuarine parameters and a special effort to meet this need is required. With regard to trained personnel, the existence of a strong research-oriented university group should strengthen a State's administrative ability to formulate plans, to execute a rational policy, and to assist in the training and orientation of management personnel. Successful coastal zone management will also require increased capabilities within State governments and improved understanding by the general public. Problems of alternative uses generally involve value judgments which should be reached by democratic processes. While the expert can provide information regarding the consequences of alternative actions, he can seldom furnish the complete answer. Thus, the officials responsible for action must be sufficiently trained to understand the significance and the limitations of the information available.

While many more questions may be raised on future management policies, it is obvious that a management system for the coastal zone provides only a framework within which proper development may take place. The full potential of the coastal zone will be realized only when science and technology are coupled with imagination and sound management to make existing uses more efficient and to develop new beneficial uses.

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Effects of Institutional Constraints and Resources Planning on Growth in and Near Estuaries

by

Malcolm H. Karr

Glen L. Wilfert

Battelle-Northwest

Richland, Washington

ABSTRACT

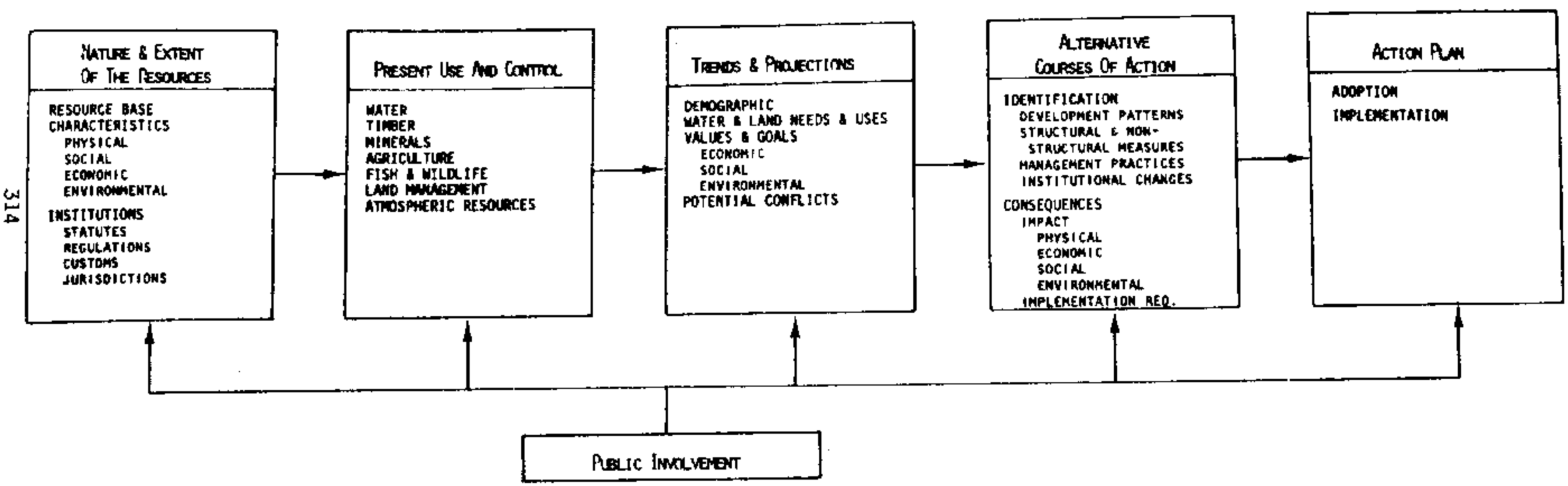
Institutional constraints, in the form of laws, statutes, regulations, customs, and political jurisdictions, are a significant element of the planning process that greatly influence the nature of management policies and practices relative to any resource, including estuaries. Many institutional constraints that are now evolving in regards to estuaries and shorelands recognize the need and provide for the development of shoreland management policies that are compatible with the overall resources management philosophy. This is essential in order to provide for necessary economic growth and opportunities while maintaining desirable social and environmental values.

In order to fully understand the significance of institutional constraints on resources development and management, whether it be estuaries or any other natural resource, such constraints must be viewed in their proper perspective relative to the total resources planning process.

Let me begin, then, by briefly outlining the key components of the planning process and their interrelationship. The figure on the next page is a simplified version of the planning steps that are considered essential today if resources management is to be truly responsive to the needs and desires of the public.

The planning process begins with a determination of the nature and extent of the resources that are available in the region under consideration. This includes: the resource base such as natural, human,

THE RESOURCES MANAGEMENT PLANNING PROCESS



and financial resources, industry, commerce, agriculture, and non-commodity lines; the many factors that identify physical, social, economic, and environmental characteristics; and the different institutional constraints such as laws, statutes, ordinances, regulations, local customs, and the arrangements of political structures and jurisdictions.

It is unfortunate that available data seldom permits treatment of these components on a comparable basis. Data on physical characteristics far outweigh, both in quantity and reliability, data for analysis of socio-economic characteristics. Although environmental quality is now receiving considerable attention, the difficult tasks of developing acceptable methodology for quantifying environmental values and integrating environmental considerations into the resources management process still remain. Institutional constraints have received the least emphasis because the mission orientation of agencies and the profit motivation of industry makes it difficult for them to undertake analysis of this nature in a fully objective and comprehensive manner.

Next in the planning process for resources management is an in-depth analysis of the present use and control of the resources and associated problems. The items listed for this step in the figure on the preceding page are those of importance in the Pacific Northwest. Each of these can be broken down into a number of components that require consideration. For example, the heading "WATER" would encompass all the beneficial uses recognized under Oregon law if the work was being done by a state agency, or all of the project functions authorized by Federal statutes if by a federal agency.

Of major importance in this step is the need to take cognizance of the interrelationship between water, land, and air, particularly where environmental quality is involved. In a like manner, surface water, groundwater, and marine and estuarine waters should be treated together as parts of a total resource even though antiquated laws pose an institutional constraint to such an approach.

These steps--inventorying the resources and analyzing the present use and control--provide the basis for the third step; the development of trends and projections of future needs and uses and determining the adequacy of the resources to meet those needs. The number of uncertainties begins to increase with this step because of the difficulty of predicting the future and because methods are lacking with which to adequately identify goals or quantify values. To respond to the current demands of the public in a meaningful manner, we can no longer go along with the practice of relegating items that are difficult to evaluate to the "intangible" category. It has become necessary to undertake the tough, down-to-earth effort that will provide the understanding to cope with the difficult as well as the obvious.

The remaining steps in the planning process leading to the adoption and implementation of action programs--identification and evaluation of the consequences of alternative courses of action--is where the greatest improvement is required. Part of the problem stems from the requirement to force-fit all components into the "benefit-cost" mold with the result that new, unique, and imaginative approaches to resources management are seldom evaluated and offered to society as alternatives from which to choose. Consequently, adequate consideration is seldom given to those societal factors that are unquantifiable in monetary terms, yet those are the factors that the public often feels are of major importance.

In addition, implementation requirements such as financing, legislation, delegation of authority, and other needed changes in institutional arrangements are not clearly identified in many cases. As a result, many good planning studies are destined to collect dust on a shelf because they do not include the intelligence of how to transform the recommendations into action plans.

Finally, an important requirement for successful resources management is involvement of the public on a continuous basis throughout the planning process. While this too leaves much to be desired, there are a few notable exceptions that demonstrate that the planning process <u>can</u> be responsive to the needs and desires of the public. And further, that desirable actions <u>will</u> receive public support if the public has a part in identifying what is desirable.

From the foregoing discussion of the resources management planning process, it is evident that consideration of institutional constraints is an integral part that must be treated in an iterative fashion with all other significant factors. It comes into play at the very start in determining the nature and extent, and present and potential use and control, of the resources of a region, including the estuaries.

And it carries through the process to become important output in the form of changes in institutional arrangements necessary to successfully implement the desired action plan for resources development and management. At this point, institutional constraints are reflected in the adoption and enforcement of resources management policies and practices.

This paper has so far shown how resources planning would have an effect on the growth of <u>any</u> region. Specific reference was not made to estuaries and the surrounding land because these areas should not be treated as separable parts of a region's resources if their management is to be compatible with the overall resources management philosophy established for the region. Rather, they should be treated as an integral part of a composite planning process that gives adequate consideration to all components of a region's resources and their interactive characteristics--physical, economic, social, and environmental. It is only in this way that a sound, long-range program can be evolved that will provide for necessary economic growth and opportunities while maintaining desirable social and environmental values.

Nevertheless, increasing attention is being paid to estuaries and coastal lands and, more recently, to all shorelands including those inland adjacent to freshwater. Part of this impetus comes from the growing demand for "quality living in a quality environment" with emphasis at one extreme on maintenance of environmental quality at all cost. This, coupled with a growing concern over the small amount of remaining shoreland accessible to the public and suitable for public enjoyment, has prompted political action at all levels of government in the form of legislation, both passed and proposed, to provide more stringent management guidelines and quality controls.

Early identification of the situation now causing widespread concern can be found in the reports of the Outdoor Recreation Resources Review Commission (ORRRC). In reference to institutional constraints, ORRRC has this to say: (1)

> "The institutional arrangements by which public agencies order their affairs have a distinct bearing on the amount and kind of services that are or can be offered. This is nowhere more true than in the provision of shoreline recreation opportunities. These arrangements, applied to the physical and current use situation..., delimit the recreation potential of the shoreline."

In describing deficiencies in institutional arrangements and identifying needed changes, ORRRC comments:

> "Increased recreation demands by the year 2000 will require substantial increase in the amount of public unrestricted shoreline, or much more efficient use of currently available shorelines, or both. ...under present (1962) policies it is highly unlikely that recreational demands will be satisfied. ...To meet this growing need most of this shoreline should be in public ownership and it will have to be managed much more efficiently than it is today. For not only will recreational demands be intense - other demands for the shoreline, pre-eminently those for transportational and industrial uses, will also be large..."

(1) <u>Shoreline Recreation Resources of the United States,</u> Study Report 4, Outdoor Recreation Resources Review Commission, 1962.

And, finally, in its conclusions ORRRC once again calls attention to the seriousness of the situation and the need for new institutional arrangements, with these words:

> "There is a crisis in shoreline outdoor recreation... there is need for coordinated, planned action - based on adequate information and upon clear statements of public policy."

Creation of the Bureau of Outdoor Recreation and several pieces of Federal legislation were the outgrowth of the work by ORRRC, but this apparently did not overcome the problems relative to coastal areas. Seven years later (1969) we find the Commission on Marine Science, Engineering and Resources reporting many of the same findings regarding institutional constraints. Of the many such references in its report,[(2)] a few selected examples are quoted below:

> "...some of the most urgent marine science problems are those of the coastal zone... Present institutional arrangements do not provide for the necessary facilities and institutions to attack these problems."

> "More imaginative attempts are required to integrate recreational projects with other uses of the coastal zone such as conservation and industrial uses."

And finally, in its conclusions the Commission ties together the planning process and institutional constraints in a manner that substantiates the approach outlined at the start of this paper, with these words:

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(2) Science and Environment, Panel Reports of the Commission on Marine Science, Engineering and Resources, Volume 1, 1969.

"In making plans and decisions to manage the coastal zone, both land and water uses must be taken into consideration... balanced management of our coastal environment requires effective planning, regulation, acquisition, and enforcement, consistently applied, to preserve and enhance both the qualitative values and the economic interests found in the coastal zone." (emphasis added)

From this has evolved recent federal legislation relative to seacoast management and estuaries. I will not say anymore about that since that is the topic for Mr. Dillon's paper which follows next.

The states have also been active in searching for better management practices. To illustrate the nature of thinking in the Pacific Northwest, we could examine the various versions of legislation for shoreland management that are under consideration in the State of Washington. Initially, the emphasis was on seacoast management, but has now been broadened to include all shorelands.

The thrust of such legislation is illustrated by the language of two sections--Declaration of Policy, and Preparation of Comprehensive Plans--in a version titled Shorelines Protection Act. Selected portions of those sections are reproduced below:

"Declaration of Policy. The people of the state of Washington hereby find: that the shorelines of this state are a valuable natural resource which is a public trust of all the citizens of the state; that haphazard development on the shorelines is reducing open space available for public recreation and aesthetic enjoyment, diminishing public access to public tidelands and shorelands, obstructing the public and residents' view of our shorelines, increasing air, water and visual pollution that threatens the public health, and destroying marine life and aqua culture that produces food necessary to the public's health and well being; that the damage from haphazard development has not and will not be met by the uncoordinated and inadequate planning that has characterized the efforts of state agencies and local governments.

The people therefore declare that it is the policy of this state that Washington shorelines be protected and managed so that to the greatest extent possible natural areas shall be preserved and all development shall be constructed so as to maximize the public's right to enjoy an unpolluted environment, access to public tidelands and shorelands, views of the state's shorelines, adequate and healthy food resources, and open space. To that end, the people hereby establish a comprehensive management system for the shorelines of the state of Washington that will coordinate the efforts of state and local governments and preserve for future generations our state's most precious and fragile resource.

Preparation of Comprehensive Plans...comprehensive plan shall include the following elements:

(a) A conservation use element for the preservation of natural resources, including but not limited to scenic vistas, water sheds, forests, soils, fisheries, wildlife and minerals, and lands and waters giving aesthetic enjoyment;

(b) A recreation use element for the preservation and enlargement of recreational opportunities, including but not limited to parks, beaches, and recreational easements;

(c) A water-oriented use element for the location and design of industries, tourist facilities, commerce and other development that must be located near water;

(d) Any other element which is necessary to accomplish the policies and goals set out under Declaration of Policy."

Institutional constraints on growth in and near estuaries is viewed somewhat differently at the local level. Let's take Grays Harbor as an example. Here the major constraint is in the form of water quality standards. The County is desperately searching for a means of improving economic conditions which have been in a state of decline for more than 20 years. Quality standards set by the Department of Ecology for the harbor will not allow for industrial expansion since the existing pulp and paper mills are presently discharging wastes into the harbor that are at or near the allowable limits. A further complication is in the offing in that the City of Aberdeen is committed to pay for M&I water to be stored in Wynooche Reservoir, now under construction, but cannot find a major water user to sell to because the quality standards constraint would prohibit any significant increase in effluents, treated or otherwise, that would eventually discharge into the estuary.

There are several potential solutions to the economic problems of Grays Harbor County. These require looking at the County's total resources, not just the estuary region, with the objective of developing a resources implementation plan that encourages sound economic growth through controlled and integrated development of resources unique to the area while maintaining desired social and environmental values.

It is encouraging to be able to conclude that many of the institutional constraints that are now evolving in regards to estuaries and shorelands recognize that there could be detrimental long-range effects if shoreland management is not compatible with the overall resources management philosophy. And that the only way to insure compatibility is to develop shoreland management policies in concert with the development of policies for the entire region.

Recent Federal Policies Affecting Marine Science and Engineering Development

by

Enoch L. Dillon

Acting Executive Secretary

National Council on Marine Resources

and Engineering Development

Executive Office of the President

Washington, D.C.

ABSTRACT

The National Land Use Policy, with emphasis on the coastal zone; waste disposal at sea; oil pollution of our beaches and estuaries; necessary power requirements for our people; coastal zone construction; land requirements met by filling of wetlands, marshes, and other marine areas; contamination of our fishery products; recreation.

Also discussion of need for the knowledge and equipment required to insure that this valuable environment is developed so that its use is properly allocated. There are many, varied and often conflicting uses of the marine environment. Careful analysis must be made of questions of suitability of the site, whether land or water, the priority of various public needs, and the cost/benefit or return on investment. Thus, not only are the uses of the coastal zone conflicting but even the standards by which we determine use are conflicting.

The Value and Problems of the Coastal Zone

This conference on the estuaries of the Pacific Northwest is most important. The problems of the coastal zone are well known to the participants of this meeting and especially to my fellow Oregonians. However, it may be appropriate to summarize briefly the impact at this point.

The thirty coastal and Great Lakes States contain more than 75 percent of our population; eighteen of our twenty-one million increase in population during the past ten years are coastal state residents; and more than 86 million Americans live in U.S. coastal counties. Ninety percent of the harvest of our domestic commercial fisheries is associated with the continental shelf environment during some or all of the resource life cycle. The recovery of ocean minerals--including the billion-dollar per year offshore oil industry--is concentrated there. The coastal zone has been the scene of an intense and diversified industrial development, which includes $40 billion in annual maritime trade. Beyond its economic significance, the coastline has become a prime recreational refuge not only for the area's ballooning population, but also for inland residents as well; thirty million turn annually to the sea to swim, eleven million to fish, and 44 million to boat.

The increased use of this limited geographical area has accentuated the adverse impact of our society upon it. Perhaps even more far-reaching than the relatively well-know pollutants such as sewage, chemicals, and mud, are the new potential threats which our technology is raising. Off shore oil terminals and airports, nuclear power plants, undersea mining, and other innovations which did not exist a generation ago must now be reckoned with.

The coastal zone has several characteristics which make it particularly susceptible to pollution. It is, in most cases, the end of the line. A river will renew itself; stop pollution, and the natural flow will in a relatively short time cleanse the stream. On a longer time-scale, and to a more limited extent, lakes may revert to their normal evolution. The inland waters, and in the case of materials which do not quickly degrade in sea water, they may remain to cause damage for unknown lengths of time.

I would like to re-emphasize the point that our 1970 census discovered that 18 of the 21 million increase in population since 1960 occurred in coastal states.

As a result of these problems it is important that not only governments at all levels, but industry, the universities and other private citizens must act on these problems and act now.

What This Paper Sets Out To Do

This paper briefly addresses, in line with your interests, those recent Federal actions concerning the following subjects:

The National Land Use Policy, with emphasis on the coastal zone;

Waste disposal at sea;

Oil pollution of our beaches and estuaries;

Necessary power requirements for our people;

Coastal zone construction;

Land requirements met by filling of wetlands, marshes and other marine areas;

Contamination of our fishery products;

Recreation.

Following the discussion of these points, this paper discusses the need for the knowledge and equipment required to insure that this valuable environment is developed so that its use is properly allocated. There are many, varied and often conflicting uses of the marine environment. Careful analysis must be made of questions of suitability of the site, whether land or water, the priority of various public needs, and the cost/benefit ratio or return on investment. Thus, not only are the uses of the coastal zone conflicting but even the standards by which we determine use are conflicting.

National Land Use Policy

Noting the need for reform of the institutional framework in which land use decisions are made, the President in his message on the Environment of February 8, 1971, stated: "I propose legislation to establish a National Land Use Policy which will encourage the States, in cooperation with local government, to plan for and regulate major developments affecting growth and the use of critical land areas. This should be done by establishing methods for protecting lands of critical environmental concern, methods for controlling large-scale development, and improving use of lands around key facilities and new communities." The proposed policy will replace and expand on the proposal submitted to the last Congress on coastal zone management--while still giving priority attention to the coastal area with the broader framework of national land use.

It should be emphasized that this program places a high priority on the role of the States and their Governors. For example, State land use programs would include methods for inventorying, designating and exercising control over the use of land within areas of critical environmental concern or areas impacted by key facilities, as well as methods for controlling large-scale development and methods for assuring that local laws and regulations do not restrict development or conservation of regional benefit, and for controlling land use around new communities.

I would like to quote the Chairman of the Council on Environmental Quality on this point:

"We have identified the fact that most land use decisions today are made by local governments, towns and counties, and yet the impact of those decisions in many cases environmentally goes far beyond the confines of that particular political entity.

"So what we are trying to do here is to strengthen the role of the States in controlling these critical land use decisions."

Many have contended that Government at many levels has become unworkable. The proposed program is designed to assure that the State governments will have a significant role to play which will both benefit the citizens of the State and help strengthen State governments. In addition, the act will require Federal projects and programs to be consistent with the State plan.

It is important to note that decisions regarding proper land use policy will require science and environmental monitoring to insure the proper decisions are made. Furthermore, new technology is needed to economically restore and maintain our coastal environment, and also new technology has created many problems for coastal areas.

Waste Disposal at Sea

During the past year we have seen a heightened interest in the problems of disposing of waste at sea. There have been studies by the Council on Environmental Quality, the National Academy of Sciences, and by the

Massachusetts Institute of Technology--the latter under contract with the National Council on Marine Resources and Engineering Development. It is interesting to note that the study by the MIT indicated that for some large metropolitan areas bordering the ocean, disposal of waste on land sites was economically competitive with disposal at sea. If these land sites are properly selected, the danger to the ecology could be less. However, objections to major metropolitan areas dumping their wastes at inland sites has not gone too well with the local citizens. For example, The State of Vermont has prohibited such disposal for the City of New York--so have many upstate counties in New York, and New York City has therefore a very grave problem. Recycling is costly and incineration is both costly and would lead to greater air pollution.

Legislation has been proposed to the 92nd Session of Congress to implement an ocean dumping policy. The legislation provides for a national policy banning unregulated ocean dumping of all materials and placing strict limits on ocean disposal of any materials harmful to the environment, and requires that a permit be granted by the Administrator of EPA for any materials to be dumped into the oceans, estuaries, or Great Lakes. Further, it authorizes the Administrator to ban dumping of wates which are dangerous to the marine ecosystem, and permits the Administrator to begin phasing out ocean dumping of harmful materials.

In passing, I should mention that the entire world community may be affected by waste disposal at sea. Over 100 nations now front the oceans and seas of the world. On the other hand, many more densely populated nations, such as England, do not have all the opportunities we have to dispose of their wastes inland rather than at sea. The problem is bound to become more complex.

Oil Pollution

Probably no dramatic pollution "event" has occupied public attention, in recent years, more than the massive oil spills that we and other nations have experienced as a result of tanker and offshore oil well accidents. The United States Government has passed legislation and developed a national contingency plan to prevent, control and mitigate such oil spills. For example, the Water Qualtiy Act recognizes that the responsibility for cleaning up spills of oil or other material which threatens the environment rests with the polluter. In those instances where the responsibility cannot be immediately assigned or the polluter cannot handle cleanup properly, the National Oil Spill Contingency Plan provides for action to be taken by the responsible Federal agencies. National strike forces are being set up in various locations by the Coast Guard, to assist upon request. Local strike forces and emergency groups of trained personnel at major ports are also being formed. The plan establishes guidelines for the use of chemicals that may be used in cleanup operations.

In addition, the United States has worked with NATO nations in developing plans for control of oil spills and for setting standards regarding the practices utilized in transporting oil at sea. Similarly, the Intergovernmental Maritime Consultative Organization is considering measures for the world shipping community. These proposals look forward to new practices such as expansion and improvement of port reception facilities for oily waste, clean ballast systems, and navigational aids, and control. In addition to these special liability provisions are currently under consideration regarding spillage of oil at sea.

The United States now has available a $20.5 million revolving fund to assist in cleanup if the polluter does not respond fast enough and which, or course, he will be required to reimburse.

Power Requirements

The need for electric power is very well known here in the Northwest where the great hydroelectric power dams have been constructed. But now all parts of the Nation are experiencing problems in providing enough power as the American consumer buys more and more electric equipment. The presence and possibility of more brownouts and blackouts could easily move public opinion to ignore the need for necessary environmental studies as these plants are constructed. We must have both. At this point, I would like to paraphrase remarks made in the fact sheet accompanying the President's environmental message regarding future power plant siting.

1. Electric utilities will be required to submit to State or regional agencies, established to balance power and environmental needs, plans providing 10-year projections of power and facilities requirements.

2. The State or regional agency will provide preliminary clearance of proposed power plant sites and transmission line routes five years prior to commencement of construction, and certification of specific sites, facilities and routes two years in advance, with public hearings at both stages.

In many of these controversises, the difference of opinion as to environmental effects are quite profound. Somebody must pay for the research to make proper decisions. At this point, I would like to emphasize that the research required for many of the activities that have been required is not solely the responsibility of the Federal Government. In fact, in many cases it should be the responsibility of others. Industry, States and local communitites must be concerned with providing adequate environmental information where needed.

Coastal Zone Construction

The National Environmental Policy Act of 1969 requires that any proposal for legislation or major action significantly affecting the quality of the human environment be preceded by a statement on the environmental effects, the relationship of the short-term uses of the environment to long-term productivity, and possible alternatives.

Of considerable significance have been several recent administrative and judicial actions during the past year, which integrate environmental considerations into existing regulatory processes. The original laws regulating activity in coastal waters through the Department of the Army were concerned primarily with the interests of navigation. More recently, under the Fish and Wildlife Coordination Act, the considerations were broadened to include the effects of proposed work on fish and wildlife.

Action by the Corps of Engineers to deny a work permit solely on the grounds of adverse effects on fish and wildlife resulted in a suit against the Corps; on appeal, it was ruled for the first time by a court that the Corps was entitled to consider ecological factors in the issuance of permits for construction or other activities in the navigable waters of the United States.

Presently, permit regulations include requirements for specific evaluation of the effects of works not only on navigation but ecology, conservation, pollution, esthetics, and indeed all factors relevant to the general public interest.

Filling of Wetlands and Marshes

Related to the problems of coastal construction but one which poses in many communities a very important and special problem is that valuable property can easily be developed from a marsh into a place where beach homes and even high-rise buildings can be constructed. We have had many experiences recently on the East Coast where the developers have been able to demonstrate that they could contribute to the economic wealth of an area by filling in a marshland while those who are concerned with conservation were unable to come forth with the type of evidence required for the zoning authorities to turn down the application. One major benefit of the new land use policy will enable States to control the zoning or strengthen the hand of local officials. For it would enable States to insure that proper land use planning and management had been developed prior to permission for any such development.

When developers of such land have been able to demonstrate improved profits and benefits to a community, there is much pressure to proceed, particularly if the information on ecological damage is scant. However, it is apparent that with filling in marshland and constructing houses, highways, stores, power lines and all the other community facilities, the development has become an irreversible act. In other words, delaying the development might cause some discomfort but keeps open the options for later development or preservation of the wetlands. If the lands are developed now, the development is, for all practical purposes, irreversible. Here again I would like to point out the necessity for a proper amount of research to assist in the decision-making process and in this connection, a proper amount of good economic research.

Development of new lands for beach homes, or coastal construction, or engineering of other kinds is supported by contentions that it enhances local profits and payrolls. These arguments must be looked at skeptically. Under the condition of a full employment economy, such investments merely transfer available capital from one income producing area to another. The funds could have been invested elsewhere with the same result. In short, one community gains but either another loses or the public in general loses. Of course, in this connection, a full employment economy is considered. Where unemployment exists, the investment could be made, if all factors are considered, for the alleviation of local unemployment.

One of the significant reasons for the involvement of the States and State Governors in the new land use policy is to insure that regional interests as a whole are considered and not just the profits and payrolls of one community.

Contamination of Fishery and Other Marine Food Products

Food from the sea is one of the best sources of protein and much of it is inexpensive. However, our Nation is not one that depends heavily upon food from the sea for our protein. Nevertheless, it is still an important part of our diet and certainly one that helps maintain low cholesterol levels. Yet only recently we have discovered in some species of fish excess quantities of mercury. Mercury, if consumed extensively, could contribute to a destruction of the nervous system. Of course, not many of us are excessive consumers of such fish, but peoples in many other places are.

This is another example of environmental concern and one that requires research and monitoring. From what little we now know, we are not always certain as to the source of the mercury, nor are we fully certain as to the long-term effects of varying levels of consumption of such fish.

Recreation

Increases in population, gross national product, median family income, mobility, and leisure time over the last several years have combined to make recreation one of the fastest-growing uses of the coastal zone.

Existing data on recreational expenditures, combined with information on population distribution, indicate that direct and indirect outlays for marine recreation have a sizeable economic impact. Sport fishing, SCUBA diving, and boating are particularly significant, because of the specialized equipment that they require. The Census Bureau has estimated the total nationwide recreational fishing expenditures in 1965 at $3 billion.

The Boating Industry Association estimates the number of U.S. boaters in 1969 at about 44 million--8.5 million recreational boats,7 million outboard motors, with over $3.2 billion spent during the year for equipment and services.

In its 1962 evaluation of the U.S. oceanic and Great Lakes shoreline, the Outdoor Recreation Resources Review Commission stated that only 1,209 miles of the 17,000 miles of contiguous shoreline suitable for recreation were so used. Since 1961, 845 miles of recreational shoreline have been added by the creation of new National Seashores and Lakeshores. The National Shoreline Study, being prepared by the Army Corps of Engineers for release in late 1971, will provide detailed information about land ownership and use.

In 1970, the Bureau of Outdoor Recreation (BOR), Department of the Interior, completed a survey of the recreational potential of the Nation's islands.

The Land and Water Conservation Fund, created in 1965, provides money to expand national, State and local outdoor recreation facilities. The strain on its resources prompted the Bureau of Outdoor Recreation, which administers the Fund, to suggest changes. Two of those implemented are an increase in the funding limit from $200 million to $300 million a year, and advance expenditure authority to permit agencies to contract for the purchase of recreation land immediately after authorization.

Science and Engineering Development

The discussion of each of these problems has indicated varying needs for science and engineering development and marine services. I would like to summarize by pointing out that a great deal remains to be done if we are to properly use our estuaries and shorelines. Your own Sea Grant program has produced a paper on the estuaries of Oregon and this report indicates problems of industrial, thermal and municipal pollution; potential reduction in fisheries and shellfish, dangers from land fill and road building, and damage from upstream uses of waters that feed the estuary. Unless those who are concerned can speak with an informed, accurate and loud voice, these conditions will continue.

Another important subject for study involves geographical and legal studies to establish true boundaries or baselines--baselines between State and State, State and Federal offshore lands, and national continental shelves' demarkation from lands not under national jurisdiction.

Federal Funds for Marine Science

For our part, the Federal Government this year is devoting close to $50 million fro marine science, technology and service specifically related to development and conservation of the coastal zone. Related marine science and technology funds for basic oceanographic research, environmental observation and prediction; mapping, charting and geodesy; ocean engineering data centers; and fisheries development will also contribute greatly. I cannot give a precise estimate of how much the $609 million in the Federal budget for marine science and technology will contribute directly and indirectly to these programs, but I think I can assure you that the present emphasis on civilian marine programs is to focus more and more on inshore problems.

In addition to these funds, there are some coastal programs of the Department of Defense and other agencies which have not been included in these figures although they are closely related to marine science and technology. Many of these programs are research and development programs with important spin-off values to the marine sciences; others are action and regulatory programs of Federal and non-Federal agencies, and private activities related to coastal problems. Examples of these activities are: channel and harbor development, $148 million; beach erosion control, hurricane protection, $22 million; pilot dredging and spoil disposal, and regulatory programs concerned with pollution, dumping and flushing, $8 million; recreational beaches and small craft harbor improvement, $16 million; environmental observations and predictions related to planning, design, construction, operations, and maintenance, $4 million; and general purpose coastal engineering, including development of improved dredging technology, $18 million.

Conclusion

This should give some idea to you of the total Federal effort oriented towards the problems being discussed at this seminar. Both the legislation and funds provided in the budget are substantial and increasing. It is our hope that other levels of government and industry will also see the importance and as this seminar demonstrates, probably see the importance better than we have.

Remarks Following the Technical Conference

by

Arvid Grant

Arvid Grant & Associates

Olympia, Washington

I would like to congratulate Oregon State University and the faculty of the School of Civil Engineering for having conceived, organized and presented this seminar. It has given so many answers to me that I have been searching for, for a long time, just in one day; and I think that many of us feel the same way. I want to express my gratitude to everybody who did the work.

Now I want to make a suggestion, but before I do this, I want to recite a newspaper story that was in our local Washington newspapers just a few days ago. It had happened that a plywood manufacturer had decided to build a new plywood mill in Centralia. In the course of building this mill he had to remove a small dam from a creek or a small river that was passing through the area. He went to the Department of Natural Resources, which apparently had jurisdiction over the place, and obtained permit to remove the little timber dam. Then he went, since fish do pass through the creek, to the Department of Fisheries or Game, I do not recall which, to obtain another permit to remove that dam; because in the course of moving that dam there will still be some fish in thestream. Then he proceeded with those two permits to remove the dam. While he was doing so, a man from the Department of Ecology happened to come by, and said he was silting up the stream and fined him $250. The mill-man got angry and said he was not going to build his plywood mill if this was the way life works in our place. He stopped the $400,000 construction project, and he fired all of the men. Then he came to the legislature, and he said, "Look, this is what the Department of Ecology has been doing with a $15,000,000 budget, now they are asking for thirty-three million and I am going to see that they do not get it."

I am impartial in this case, I merely read the newspaper account and I am not even sure the account was correct. But it does point to a problem. Now days when I want to design something that is on the waterfront, I have to go to the Department of Fisheries to obtain a permit; I have to go to the Department of Game, where likely I will have to go to the community planning and affairs agency to let them review how it will affect the total environment of the state. I probably will have to go to the Department of Health; I will have to go to the Department of Ecology, and I most likely will have to go to the Department of the Army Engineers. They all regulate the same subject matter in the same general way, in the same context, except their regulation while 90% overlaps it spreads out a little bit to the sides. I still do not know what the regulative rules are and what is right and what is wrong. Now before I start doing something my client expects me to be a professional and a knowledgeable man, and will accordingly listen to my advice. The first thing I tell him, I must tell him I do not know. I truly do not know.

Now what I would like to suggest to Oregon State University is to repeat this conference exactly as presented, exactly as thought and done, but next time to invite, not the legal men, but the department heads and the department directors from all of these departments, the key legislators plus the engineers and scientists once again. This I most sincerely wish you will follow.