CHAPTER 142

FIELD AND LABORATORY STUDIES; NAVIGATION CHANNELS OF THE COLUMBIA RIVER ESTUARY

M. P. O'BRIEN

Dean Emeritus, College of Engineering
University of California
Berkeley

INTRODUCTION

A model of the estuary of the Columbia River was built and tested at the University of California, Berkeley, during the years 1932 to 1936, to study the effects of proposed changes in the navigation channels on the currents and sediment movement. The project was sponsored by the North Pacific Division of the Corps of Engineers, and the engineering results were reported at that time in internal memoranda. The basis for the selection of the scale ratios and other factors affecting the design of the model were reported in some detail (O'Brien, 1935), but only a brief note was published regarding the operation and the accuracy of the model (Johnson, 1948). In some respects this model is still unique, and a description of it may be of interest to the coastal engineers.

This paper deals primarily with the model itself and not with the practical problems of channel maintenance and improvement, but some information regarding the regimen of the Columbia is necessary background for understanding the problems which were to be studied in the model. Figure 1 shows the configuration of the estuary, the jetties, and the ship channel. The river was then unregulated; the freshwater discharge exhibited an annual cycle with an average annual flow of 235,000 second-feet, an average summer freshet discharge of 660,000 second-feet, and an average low-water flow of 70,000 second-feet. The tide shows a diurnal inequality, with the long run-out following higher high water; the diurnal range of tide is 8.5 feet, and the average range is 6.5 feet. Freshet flows affect the range and lag of tide in the river section above the estuary to such a degree that the published USC and GS Tide Tables were valid only for the months September through May and not for the freshet season. The range of tide is approximately constant from the ends of the jetties to Harrington Point; the lag over this reach is approximately two hours. At low river stages the tide is evident as far as Bonneville, 140 miles from the mouth; the tide wave progresses with steadily decreasing amplitude and there are no nodal points. The tidal prism varies both with range of tide and river stage; at low river stages, the prism corresponding to an 8 foot range is between 600,000 and 700,000 acre feet.

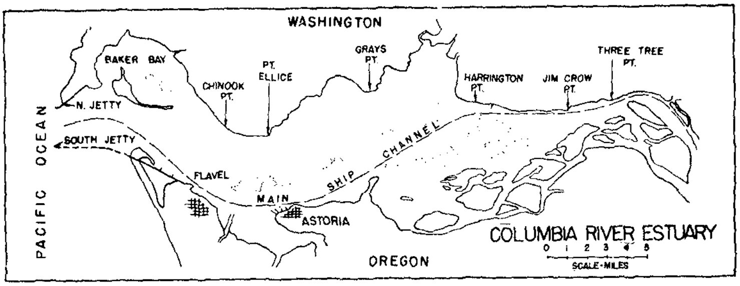

Fig. 1--Area covered in Columbia River Estuary model

The average annual suspended sediment load at the Dalles at that time, when the river was unregulated was 10,000 tons per year. The gradient of the river and the current velocity decrease, and the depth increases, below the Dalles; some of the suspended load at the Dalles probably moves as bed load in the lower river. At an average flow of 235,000 second-feet throughout the year, the average concentration of suspended material must be approximately 50 parts per million to transport 10,000,000 tons per year in suspension. However, the concentration in the estuary reached this level only at high freshet stages and was materially less throughout the remainder of the year. If the estimate of suspended load at the Dalles was correct, and if this load was transported through the estuary, high rates of net movement as bed load must occur there.

Two independent samplings of the bottom of the entire estuary showed the median diameter of a composite sample to be 0.0096 inches. The median diameter of samples from the beach and offshore was 0.0075 inches. The settling velocity of the estuary bottom material ranged from 0.10 to 0.15 ft. per sec.

OBJECTIVES OF THE MODEL STUDY

When model scale experiments were proposed, there were two unrelated problems in the area near the mouth of the Columbia; one concerned the channels in the estuary and the other the erosion of the ocean shore just south of the south jetty.

During the early stages of construction of the south jetty the shoreline of Clatsop Spit built seaward rapidly and the desired crest elevation of the jetty was attained with a lighter section than designed. Accretion continued for a few years but erosion followed; if erosion continued the light section at the base of the south jetty might be breached. It was thought that a scale model might provide the basis for correction of this problem. However, field studies of the movement of sand by wind on the flat shore of Clatsop Spit and correlation of winds measured at the beach with those measured concurrently at North Head and at the Lightship showed that the observed erosion was caused by onshore winds transporting sand from the beach across the spit and into the lagoon (O'Brien and Rindlaub, 1934). Consequently, erosion of the outer beach was omitted from the program.

An interesting consequence of these studies of wind drift was a program of dune building and stabilization which was carried on for almost ten years. Its success was indicated by a recent paper (Kidby and Oliver, 1966) which reported that the dunes south of the south jetty are stabilized at about +25 ft. MLW and that the erosion of this shore appears to be approaching a terminal position asymptotically.

The other problem to be studied in the model was the location of the navigation channel between Harrington Point and the jetties. As it then existed, the ship channel made a sweeping curve, crossing the estuary to Tongue Point and following the south shore to the entrance (Fig. 1). A straight channel from Harrington Point to the entrance would be both shorter and easier to navigate, but this alignment would require dredging through the shoal area west of Harrington Point. Other less drastic changes were also under consideration.

At the time there was little experience with models involving both waves and tides, and the first question to be resolved was whether or not a scale model would furnish information regarding the currents and sediment movement in the estuary with the necessary accuracy, and in sufficient detail, to evaluate the proposed changes. The first phase of the study (O'Brien, 1935) was planned as a test of the validity of the model technique. It was anticipated that at least two horizontal scale ratios and several vertical scale ratios would be modeled and tested in the course of the program. The first model, built to a horizontal scale ratio of 3600, was thought to be the smallest in physical size which might yield reliable results.

FIELD INVESTIGATION

Elimination of the beach erosion problem from the scope of the model study considerably simplified the boundary conditions to be represented because it became unnecessary to reproduce ocean waves and this fact, in turn, permitted much greater flexibility in the choice of the horizontal and vertical scale ratios.

Reproduction of the currents required modeling of the entire estuary and river to the end of tide water. Surveys had been made frequently in the navigation channels, but the shoal areas, a major fraction of the area of the estuary, had been surveyed only infrequently. There was available a fairly complete survey made in 1935 and this survey was supplemented by local surveys made at other times; these surveys formed the basis for the fixed-bed model (Univ. of Calif., 1936). Depths over the shoals probably show some seasonal variation, especially after the freshet season, and this fact should be kept in mind in appraising the reliability of this model.

Current measurements had been made by means of both current meters and surface floats. Current meter measurements were made at several boat stations across sections near Clatsop Spit in 1932 and near Clatsop Spit and Flavel in 1933; recordings were continuous at five points in the depth and over several days at each boat station. Float runs had been made at many points in the estuary over the years. In short, field data on the currents were sufficiently detailed and extensive that it was possible to construct a reasonably complete pattern of the currents at different ranges and phases of the tide. However, the current measurements were not made at the same time as the base survey.

The fresh water flow of the Columbia is relatively large, especially in the freshet season, and salinity gradients might possibly affect the currents in the estuary. No quantitative information was available on the salinity in the estuary and its spatial and temporal variations. Several salinity traverses were made along the ship channel at different river flows to establish the approximate magnitude and position of the maximum horizontal and vertical salinity gradients within the estuary proper. Since the heavier saline water tends to move inward along the bottom and the freshwater to move outward on the surface, the effects of a strong salinity gradient might have been appreciable on the currents and a major factor in the bottom sediment movement. Later, after the currents had been measured in the model, it was possible to correct the position of the isohalines to a constant phase of the tide and to determine the approximate horizontal motion of the salt wedge during a tidal cycle (Univ. of Calif., 1936); O'Brien, 1952). A study of the vertical variations in velocity at the current meter stations gave unmistakable evidence of net salinity currents, inward at the bottom and outward at the surface. Calculations from the field measurements showed that the inward salinity flow was approximately 100,000 sec. ft.

Earlier, extensive studies had been made at Berkeley of the movement of salt water through fresh water (O'Brien and Cherno, 1934), and this experience led to the conclusion that although salinity currents undoubtedly existed in the Columbia River estuary, representation of this phenomenon in this model would introduce severe complications, both in operation and in the interpretation of the results. There was no field evidence then available that flocculation occurred in the zone of increasing salinity or that the bottom salinity currents caused shoaling at particular points. Salinity effects were not represented in the model.

The internal summary report of these model studies (Univ. of Calif., 1936) contained this statement:

> "As regards the reliability of the model, it appears certain that failure to reproduce the salinity effects results in an error which is greatest in the region of the greatest rate of change of salinity... If the model were to be used to study the currents between the jetties, the effect of the salinity gradient would require more

careful study. However, the salinity survey showed that the salinity gradient is probably of negligible importance in the areas under study. Furthermore, comparison of model and prototype currents showed good agreement."

In recent years the currents near the Columbia River jetties have been studied in a model in which the salinity gradient was reproduced (Herrmann and Simmons, 1968).

Tongue Point in Astoria, Oregon is the primary reference tide station for this portion of the Pacific Coast, and a long period of tidal measurements was available. The tide generator in the model permitted continuous variation of range and duration and specific sections of the tide record could have been reproduced but at a considerable cost and delay of operations. An analysis was made of the frequency of different tidal ranges and of the duration of phase and it was found that the duration did not change appreciably with range and that range was the dominant variable. The energy transmitted by the tidal wave is proportional to the square of the range and this transmitted energy measures the capacity of the tide to generate currents and move bed material. Accordingly, the standard range reproduced in the model was the root-mean-square of the ranges, which was 8 ft., approximately the diurnal range. A standard tide curve was prepared for the model by averaging a number of consecutive tide cycles at Astoria measured concurrently with the 1932-33 Current Survey to obtain a curve representing percentage of range versus percentage of duration.

The tidal prism varies both with range and river flow. Adequate field data on river stage and tide range at points along the river to the limit of tidal effects were available for adjustment of the friction in the model to conform to the prototype.

In brief, the hydrographic and dynamic boundary conditions to be represented in the model were adequately defined and a valid appraisal of the accuracy or inaccuracy of the model was assured.

DESIGN AND CONSTRUCTION OF THE MODELS

Osborne Reynolds (1887) has pioneered the use of movable-bed tidal models with apparently valid results. In Table I (O'Brien, 1935), the characteristics of a number of earlier tidal models are compared with the <u>first</u> model of the Columbia River. By this comparison, the model seemed conservative but it represented a substantial extrapolation beyond the scale ratios and distortion of the few river models built in this country. For this reason, the first Columbia River model incorporating a movable bed was regarded more as an experiment on models than as a working model of the estuary. The extensive studies made as a basis for designing the movable-bed model were reported at the time (O'Brien and Rindlaub, 1934; O'Brien, 1935) and will only be summarized here.

The primary problems of designing a movable-bed tidal model are to select a material which will be moved by the tidal currents and to select vertical and horizontal scale ratios which will produce natural patterns of currents throughout the tidal cycle in those portions of the estuary under investigation, at velocities which will move this material, and at

Table I

CHARACTERISTICS OF IMPORTANT ESTUARY MODELS BUILT UP TO 1935

(From O'Brien, 1935)

Prototype	Mersey	Mersey	Seine	Rangoon	Severn	Columbia[a]
Experimenter	Reynolds, 1885	Vernon-Harcourt, 1886	Vernon-Harcourt, 1886	Alexander Gibbs and partners, 1932	A. H. Gibson, 1932	U. S. Engineers, 1934
Purpose	Effect of regulating works	Effect of regulating works	Channel-improvement	Channel through outer bar	Effect of barrage on silting and currents	Estuary-and bar-channels
Range of tide (ft)	.....	......	24	16-21	21-41	8
Diameter of sand in prototype (in)	0.008	......	.....	.....	0.009	0.008
Diameter of sand in model (in)	0.006	0.0065	.....	Same as Rangoon River	0.007	0.0076
Horizontal scale	31800 10600	30000	40000	8068 7050	8500	3600
Vertical scale	960 396	500	400	192	200	64
Period of tide in model (sec)	40 80	......	25	76	74	99
Reproduction of tides	Hinged trough	Hinged trough	Hinged trough	Plunger	Plunger	Pumping and gravity
Waves	Used in part	......	No	By fans	No	Yes

[a]Scales and sizes of model refer to first series of experiments.

a single scale ratio of volumetric transport. These are severe specifications and, clearly, cannot be fully realized. The practical question is whether bed material and scale ratios can be found which will yield acceptably close agreement with the prototype. The test of the validity of the model is to subject the model to proper boundary conditions of tide range and river flow and compare the model hydrography with past surveys in nature. If the model is thus verified, the assumption is made that changes in the configuraiton of the model will produce changes in its bed which will be predictive of corresponding conditions in the prototype.

Granular material is moved by water at rates which depend upon the tractive force of friction, which is in turn related to the average velocity and the depth. Experiments indicated that there is a critical velocity at the bed below which a material is not moved and that critical velocity reaches a minimum value below which it increases with decreasing diameter of material, probably because the grains are so small as to be submerged in the laminar layer. In order to attain velocities in the model as large as possible, and necessarily above the critical velocity, over all areas of the estuary under invesitgation, the depths and range of tide in the model should be as large as possible, that is, the vertical scale reduction should be small. However, if this requirement is met and the same scale factor is applied to the horizontal dimension, the area of the model generally becomes too large and costly to be feasible. The usual solution of this dilemma is to distort the model by applying different scale ratios to all horizontal and vertical dimensions, both hydraulic and hydrographic.

Distortion of a model introduces many sources of discrepancy between model and prototype in addition to those inherent in small, undistorted models.

- The skin friction drag or hydraulic gradient will be less than that corresponding to the scale ratios. In the first Columbia River model, the friction slope in the model was approximately four times that in nature, whereas it should have been in the ratio of 3600/64. The tractive force on the bottom is correspondingly distorted.
- All of the bottom slopes will be greater in the model than in nature, and the form drag in the model will be relatively greater than in nature - by an unpredictable amount.
- Eddies with vertical axes may occur in the model behind projecting point at which the slope of the bottom has been greatly distorted but not in nature.
- The natural angle of repose of the model material and the bottom slopes in nature set a limit on the permissible distortion, if similarity is to exist.
- Ripple spacing and height appeared to depend on material size and current velocity, and hence would probably be related to the vertical scale ratio; ripple lengths would probably be relatively too large in the model.

These possible complications and the problem of selecting a suitable bed material led to much study and speculation before the design was completed.

If the velocities in the model are sufficient to move the material selected, turbulent flow will probably occur and the head losses will be approximately proportional to the square of the velocities, thus following the vertical scale ratio as requried. However, the magnitude of the energy loss in the estuary and the balance between skin friction and form drag on the bottom would affect the model response. The energy transmitted into the estuary by the tidal wave is proportional to WLH^2, where W is the width of the channel, H is the tide range, and L is the length of the tide wave in water of constant depth. Comparing the energy at the jetties and that at the entrance to the river at Harrington Point showed that the loss of energy in the estuary was approximately 75 percent of the 4×10^{12} ft lbs/tide which entered. Calculation of the loss by bottom friction gave 3×10^{12} ft lbs/tide, which is in agreement with the first calculation.

There was no evidence of appreciable reflection. Thus, it was established with reasonable accuracy that friction within the estuary plays a major role in determining the magnitude and distribution of the current velocities.

A possible type of hydraulic distortion which would increase the model velocities was to shorten the duration of the model tidal cycle. The velocity of advance of the tide is fixed by the depth, and the distortion would alter the phase relationship between elevation and velocity at different points along the channel but, since the vertical curvature of the surface is small, the cycle of current direction and phase might remain unaltered at each point with only an increase in velocity. Experiments on the model, with the tidal cycle shortened from 100 to 60 seconds, indicated that this technique is feasible technically, but this model tide duration proved to be too short for accurate control and measurement.

The time scale for the movement of corresponding volumes of sediment may be distorted by increasing the number of tidal cycles in a model year if the pattern of velocities in the model corresponds to the prototype and if the material in the model is kept in motion over the same fraction of the tidal cycle. This scale ratio can be determined empirically by operating the model until there is movement of volumes corresponding to measured changes in nature.

Consideration of the general model laws, the special factors mentioned, the space available, and the cost, the decision was made to model, with vertical boundaries, the high-water line of the estuary, river, and ocean shore to a scale of 3600. This arrangement would permit modeling different vertical scales without altering the plan form. The material used had approximately the same mean diameter as the weighted average of the material in the estuary*. The river section above Three Tree Point was represented by a labyrinth in which the bottom elevation and the width corresponded approximately to those of the river. The friction loss in the river section was adjusted by metal strips until the range and lag of the tide at each range of tide and river flow agreed with the prototype.

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*Private communication from Prof. A. H. Gibson (dated Jan. 5, 1934) who had assisted Prof. Reynolds in the Mersey experiments:

> "As regards the question of sands for the bed materials, all models on which we have been working for the last 7 years or so have been those of tidal estuaries in which the flow has taken place alternately in both directions. We have, in these cases, determined the best bed material experimentally; that is, by choosing two surveys at a sufficiently long period apart, moulding the bed to the first survey, and running the appropriate number of tides and then re-surveying. We have then chosen the material which gave closest agreement with the second survey. In the case of our Severn model, we tried 12 materials of different grain sizes and densities, and finally adopted a sand whose mean diameter was about 25% less than that of the actual sand in the estuary.
>
> As it happens, the sands in the other estuaries which we have had to investigate were not very different in fineness from those in the Severn, and as a result we used the same type of bed material for these also."

MOVABLE BED MODEL

The movable bed model was built and operated to a vertical scale ratio of 64. The initial bed was leveled at an elevation corresponding to the average depth over the whole estuary. The average annual river flow of 235,000 sec-ft and the weighted tide range of 8 feet were applied. No measurement of the bed transport into the estuary had been made; the rate fed into the model at the river end was adjusted to maintain a constant bed level there. This rate, converted to prototype quantities at the model scale ratio, was 29 x 10^6 tons per year, which seemed high but possible, when compared to a suspended load of 10^7 tons per year at the Dalles.

The movable bed model was operated until the bed reached equilibrium. A good channel had developed along a straight line from Harrington Point to the jetties and there was no channel in the model corresponding to the navigation channel in the prototype. This negative result was discouraging at the time and it was concluded that a reliable movable-bed model would require a much larger horizontal scale. The decision was made to rebuild the model with a fixed bed to a vertical scale of 128.

Subsequent studies of the movement of powdered coal (specific gravity = 1.33; median diameter = 0.0041 inches) in the fixed-bed model showed that the sediment load brought down in the freshet season is deposited on the shoal area between Harrington Point and Point Ellice and that it is gradually moved out between the jetties during the remainder of the water year. The channel indicated by the model probably was in a good location under average conditions but it would have been closed completely after the freshet each year. Under regulated river flow, this straight channel might be feasible.

FIXED-BED MODEL

The 3600-scale model was molded in roughened concrete to a vertical scale of 128; the remainder of the program was carried out in this model. The bed conformed to the hydrographic survey made in 1935 which included most of the area of the estuary. Gaps in this survey were filled in from surveys made at other times. Depths in the estuary change both seasonally and from year to year, especially in the shoal areas where freshet flows deposited large quantities of sediment, and these deviations from the 1935 survey would affect current velocities and directions measured at other times.

The fixed-bed model program assumed that if the model currents conformed to measurements in the estuary the changes in currents due to dredging and training works could be predicted and that the trend of changes in bed configuration could be estimated from the currents.

Over the years, many current measurements had been made in the estuary using both current meters and floats. The hydrography at the time of these measurements was not known precisely and it was necessary to assume in making comparisons of the model with nature that the bottom was the same as shown in the 1935 surveys. Differences in depth between the dates of the current measurement and the bottom survey modeled probably caused discrepancies in the comparison of velocities, particularly over the shoal areas. Other causes of disagreement between velocities in the model and in nature were:

1. Winds over the estuary are relatively strong and predominantly from the west. Some surface currents in the estuary probably were affected by winds at the time of measurement, particularly over shoal areas.

2. The model was out-of-doors. Much of the current data were obtained by timed photographs of confetti on the surface. Imperceptible air currents moved the confetti. Runs made while there were noticeable air currents were eliminated, but some remaining photographs undoubtedly were affected. These measurements in the model gave the surface current only.

3. The velocity and direction of the currents at each point varies with the phase of the tide. Comparisons must be made at the same phase of tide at each point. The celerity of the tide wave depends on the existing depth; it was difficult in some cases to determine the exact phase of the tide in nature during a specific float run.

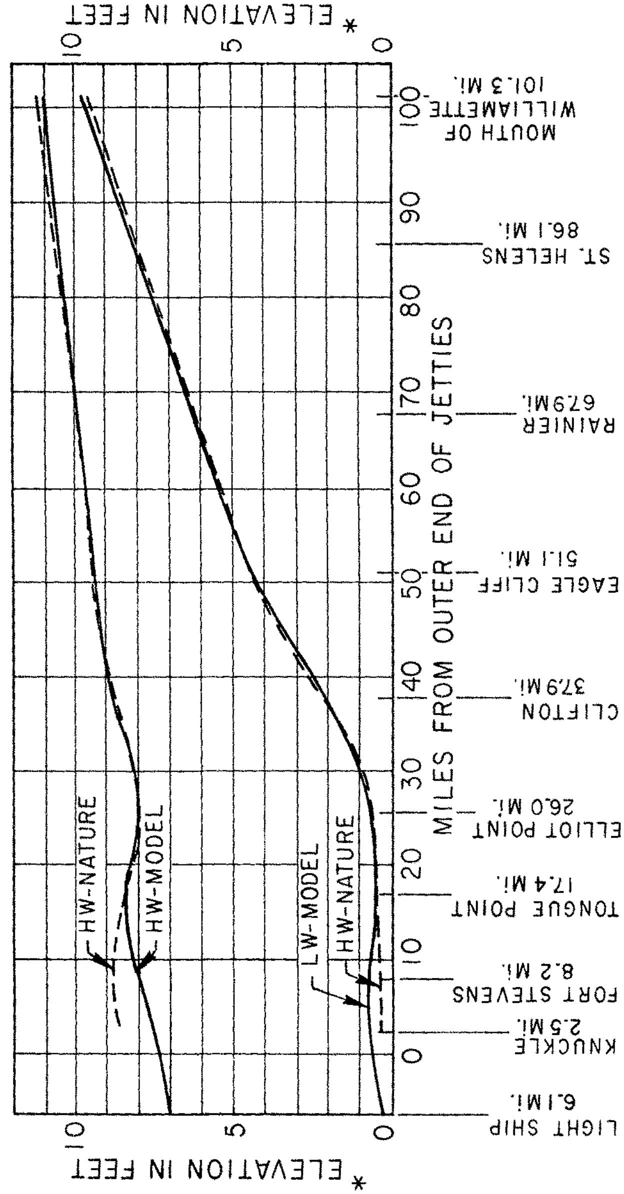
4. A miniature propeller current meter was used in some of the model tests. The tidal cycle lasted only 100 seconds. An integral number of revolutions required a finite time; the measured peak velocities were lower than the true value.

5. The ocean tide varies continually in range, and to some extent in duration; the model was operated at the tide range and duration and the river flow existing at the time of field measurements, but the preceding sequence of tides was not followed.

6. There are unavoidable errors - and some blunders - in all field or laboratory measurements.

To minimize the effect of these possible causes of discrepancies, the field measurements were segregated in time into ten phases of the tide; comparisons of model and nature were made as precisely as possible in the same phase at the same location under the same range and duration of the tide and at the same river flow. Fortunately, the number of field measurements was sufficiently large to permit meaningful averages within these concurrent brackets of conditions to minimize the errors due to wind, changes in depth, and possibly salinity variations.

The model was controlled to match the prototype tide curve at Tongue Point, the reference station of the Tide Tables, and adjusted to yield the desired backwater curve at one discharge and the range of tide in the river to the limits of tidal effects. When so adjusted and controlled, the degree of agreement in tide range and backwater elevation was shown in Figure 2. The lag of the tide, which could not be adjusted independently was as shown in Figure 3. The range at the jetties in the model was 18

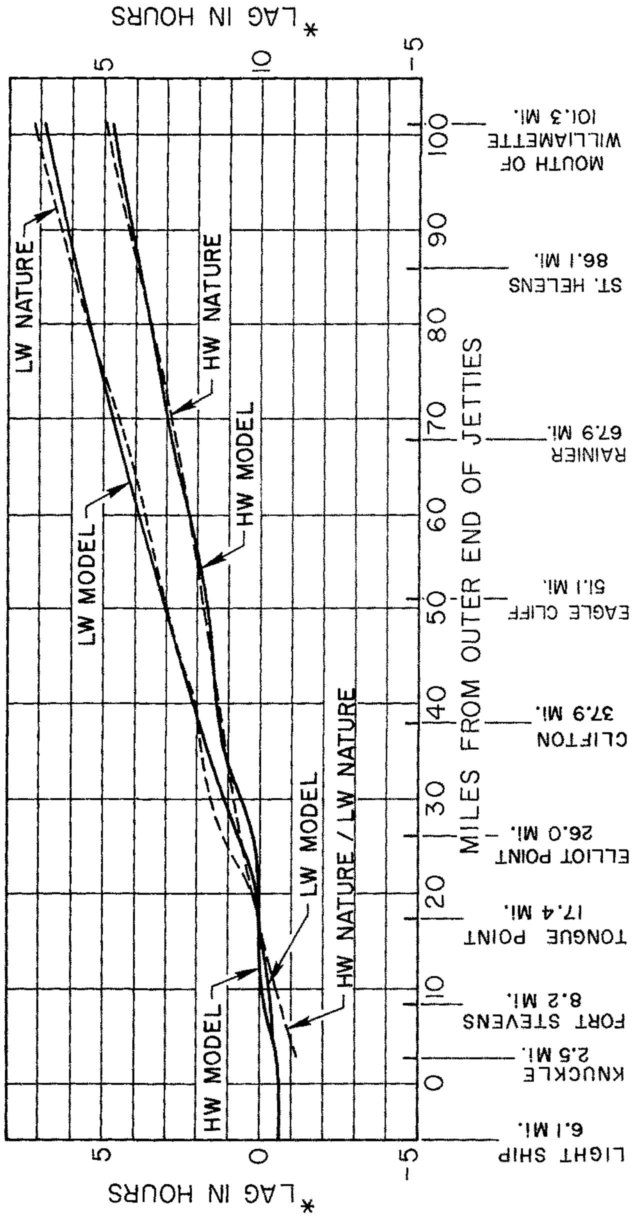


* Elevations are referred to MLLW at outer end of jetties

Model data taken from results of run Nos. 8-T-1 and 8-T-1d
Nature data from 1932 tide tables and U.S.T.M.L. dwg. Nos. D-8-1 and D-8-2

Average Normal Yearly Conditions for the Columbia and Willamette Rivers Excluding the Months of May, June and July

FIG. 2 COMPARISON OF MODEL AND NATURE, RANGE AND HEIGHT OF TIDE



* Lags are referred to time of tide at Tongue Point

Model data taken from results of run Nos. 8-T-1 and 8-T-1d
Nature data from 1932 tide tables and U.S.T.M.L. dwg. Nos. D-8-1 and D-8-2

Average Normal Yearly Conditions for the Columbia and Williamette Rivers Excluding the Months of May, June and July

FIG. 3 COMPARISON OF MODEL AND NATURE, LAG OF TIDE percent less, and the celerity of the tide through the estuary was greater than in the estuary. Similar comparisons were made at other river flows and tide ranges with similarly favorable results. The discrepancies were attributed to the relatively lower friction losses in the model which may have, among other effects, permitted some reflection of the tide seaward from the estuary, whereas no appreciable reflection was found in nature.

Many comparisons of model and prototype current velocities and directions were made and only a sampling of these results will be presented here to indicate the character of the results. Comparisons were made at corresponding tide ranges but exact duplication of tide was not always possible; the field velocities were corrected to the model range of tide by the relationship $V = V_{(\text{observed})} \times \frac{8}{\text{Range}}$.

Table II shows one such comparison of float measurements at a fixed river discharge made during the central 40 minutes and 5 minutes of the tide phase. The phase divisions are referred to the tide at Tongue Point and Phase Division One follows high water. The exposure time for the photographs of the model was 0.63 seconds, corresponding to 3.5 minutes in nature. The agreement was improved in almost each case by considering the shorter time interval.

Table III shows a comparison of velocities measured by current meter in both model and prototype at a section across the estuary at Clatsop Spit. Figure 4 compares the variation in velocity over a tidal cycle. The field measurements were made in 1932; the bed of the model corresponded to the survey of 1935.

Most of the current measurements were made by photographing confetti strewn on the water surface. The exposure time was accurately controlled (see Figure 5).

The current directions scaled from drawings of field float observation and photographs of the model agreed within the precision of the measurements. The disagreement showed no regular variation with either location or phase. The average differences in direction during the division of the tidal cycle are shown in Table IV. The probable error in the model was ± 5 degrees and in nature at least ± 2 degrees.

The comparisons of model and prototype cited were made when the reliability of the model was still in question. The results indicated that a larger model would not be required and that the measurements in this model would provide a sound basis for engineering plans. The next step was to make more precise and detailed comparisions in the areas of particular interest.

Float measurements had been made in nature in considerable detail in the area near Harrington Point. These measurements were segregated by phase division in areas judged to have common hydraulic characteristics, and the average velocity and direction were computed for each group of measurements. The center of gravity of the field float runs was determined and the velocity and direction at this point in the model were measured by current meter and direction indicator. An excerpt from the report on this comparison appears in Table V.

TABLE II

Ratio of Field and Model Velocities for Tide Ranges between 7 and 9 feet. (Surface Floats)

	Phase Division										Average
	1	2	3	4	5	6	7	8	9	10	
Mouth to Fort Stevens	--	1.09	0.85	1.71	--	--	--	0.81 (0.76)	1.25 (1.15)	0.81 (0.85)	1.09 (0.94)
Channel to Astoria	--	--	--	--	--	--	0.80 (0.79)	0.89 (0.95)	1.51 (1.19)	--	0.95 (0.93)
Channel Astoria Tongue Pt.	2.06 (1.29)	1.25 (1.25)	--	--	--	--	--	--	--	--	1.43 (1.25)
Tongue Pt. Harrington Pt.	--	--	--	--	--	--	--	1.62 (1.77)	--	--	1.62 (1.77)
Harrington Pt.	1.41 (0.94)	1.24 (0.84)	--	1.76 (0.76)	--	--	--	--	1.05 (0.97)	--	1.09 (0.86)
Miller Sands Cut-off	--	--	0.68	1.03 (1.03)	0.99 (0.99)	--	--	--	--	--	0.82 (1.01)
Shoals at Miller Sands	--	0.78	1.03 (1.00)	1.25 (1.04)	--	--	--	--	--	--	1.15 (1.03)
Snag Island Jetty	3.08 (2.25)	1.34 (1.32)	0.82 (1.00)	0.70 (0.82)	1.05	--	--	--	--	--	0.90 (0.99)
Elliott Pt.	--	--	--	--	--	--	--	--	--	1.06 (1.06)	1.06 (1.06)
Average*	1.79	1.18	0.79	1.07	1.02	--	0.80	1.03	1.22	0.88	1.04 (0.99)

* The averages are computed from the summations of all float runs and not as straight numerical averages of the figures in the body of the table.

() Figures in parenthesis show the velocity ratio taken over the central 5 minutes of the phase division. Total of comparisons, 183.

TABLE III

Ratio of Currents at Five Clatsop Spit Stations in 1932-33 to the Model.
Field Velocities are the Average of Five Depths.
Range 7 to 9 feet in Nature. (Current Meters)

Date	Phase											Average
	Discharge	1	2	3	4	5	6	7	8	9	10	
9/13 to 9/15 1932	125,000	0.57	1.22	1.18	1.06	0.86	-	1.01	0.84	0.80	1.16	1.02
		Ebb phases, 1.06					Flood phases, 0.98					
4/6 to 4/8	320,000	2.16	1.32	1.19	0.99	0.77	-	0.86	0.82	0.80	0.98	1.00
		Ebb phases, 1.15					Flood phases, 0.85					

Average of all comparisons, 1.005

TABLE IV

Average Difference in Current Direction During
the Divisions of the Tidal Cycle

Phase	1	2	3	4	5	6	7	8	9	10	Average
Average difference in angle (degrees)	+3.3 (3)	-1.4 (17)	-7.0 (10)	-5.1 (19)	-0.6 (5)	-	-8.4 (5)	-2.4 (15)	+1.9 (19)	-2.6 (7)	-2.3

( ) Figures in parenthesis show number of float directions compared.

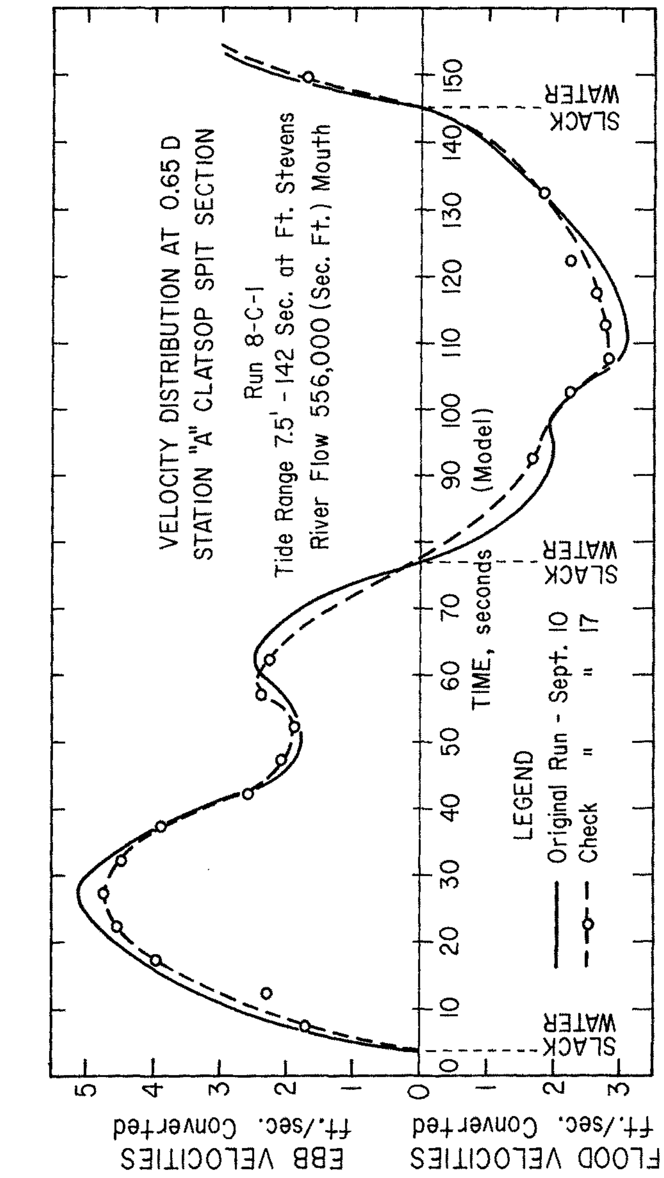


FIG. 4 MODEL MEASUREMENTS ON THE VARIATION IN VELOCITY OVER A TIDAL CYCLE

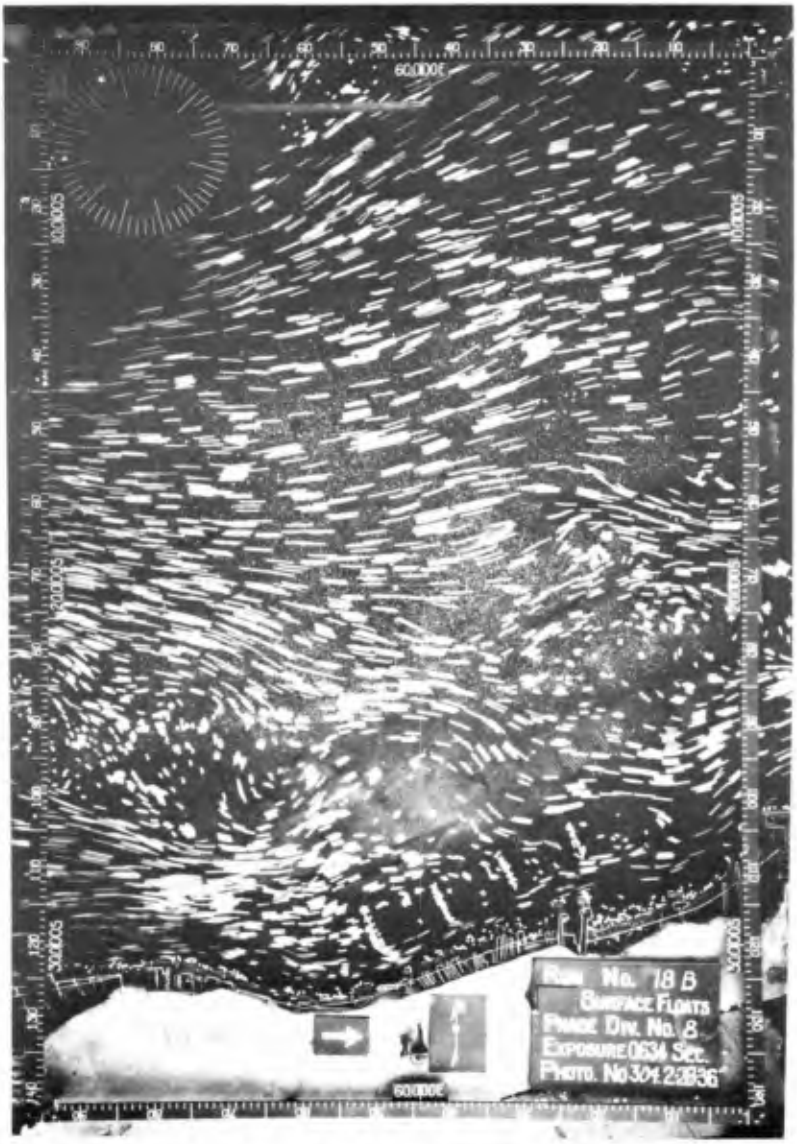


Fig. 5. Typical photograph for measurement of surface currents in the model.

TABLE V

Current Measurements at Harrington Point

Comparison of currents in model vectorially by phase divisions with those for nature given in Tech. Memo. No. 8, Low River Stage before Cutoff.

a) Run No. 9-C-D Per General Program, Run No. 9

Conditions: Corresponding to average in nature from HW at Tongue Point at 9.8 o'clock, Nov. 13 to LW at 18.7 o'clock, Nov. 16, 1933, the period during which float runs were made.

Range: 6.7 ft. at Tongue Point.
Elev. LW: 1.0 ft. at Tongue Point.
Period: 140 1/2 sec. (model)
River Flow: 152,000 sec. ft. (mouth)

Table of Comparison, Azimuths of Current Directions by Phase Divisions in Model with Directions of Velocity Vectors for Nature given in Tech. Memo. No. 8.

Area No.		Phase Divis.	Azimuth from True North			
			Model			Nature
			Start of Phase Divis.	End of Phase Divis.	Middle of Phase Divis.	
			degrees	degrees	degrees	degrees
XXI	e	9			124	125
	k	1			56	46
		2			*SW	*SW
		5			231	226
		10			57	53
XXIII	e	2	95	*SW	*SW	86
		3			281	277
		4			285	290
		8	280	102	109	94
		9			99	99
XXV	c	3			270	269
		4			272	275
		9			91	91
		10			91	93

*SW - Slack Water

b) Table of Comparison, Converted Model Phase Division Velocity Magnitudes with Nature as given in Tech. Memo. No. 8.

Area No.		Phase Divisions	Magnitude of Velocity	
			Model	Nature
			ft/sec.	ft/sec.
XXI	k	5	2.8	3.6
XXIII	e	3	3.2	1.6
		4	4.0	4.7
XXV	c	3	2.4	3.0
		4	3.1	3.4
AV.			3.2	3.3

The agreement between model and prototype was good in the channels and deeper areas at strength of flood and ebb currents. The discrepancies between model and prototype were greatest over the shoal areas and near slack water.

MOVEMENT OF BED MATERIALS

Bed-movement was simulated in the fixed-bed model by using powdered coal having a specific gravity of 1.33 and a median diameter of 0.0041 inches. Theory and the observed behavior in the model indicated that this material was relatively more difficult to move as bed-load than the sand in the estuary; it was the most suitable material available for these qualitative experiments. Another technique used was to place permanganate crystals on the model surface at key locations. The important features of the pattern of bed movement were as follows:

- Under average conditions of river flow and tide, coal placed in the ship channel off Three Tree Point was moved rapidly, spreading both upstream and downstream along the ship channel and southward over the shoals as far as Snag Island Jetty. At the end of these runs, coal was found along the Ship Channel as far as Tongue Point and only a small amount had been carried onto the shoals west of Harrington Point.

- At freshet stage, coal placed in the main channel off Elliott Point passed through both the old channel and the Miller Sands Cut-Off. Part of the coal then followed the channel towards Tongue Point, but the major portion of it was carried onto the shoals west of Harrington Point. A very large accumulation of coal occurred west of Harrington Point along the line of the proposed channel "D". With channel "D" open, a greater percentage of the material reaching Harrington Point passed along this path than with it closed. West of Tongue Point the main bed-movement is outward across the estuary along the north side.

It was these experiments with coal in the fixed-bed model which answered the major question regarding channel location. The best channel indicated by the movable bed model from Harrington Point along the north side of the estuary to the jetties would be closed by sediment after each year's freshet.

In an effort to account for sand movement through the estuary, laboratory experiments were carried out on a number of sands, including one from the Columbia River estuary (O'Brien and Rindlaub, 1934; O'Brien, 1936). The work showed that the rate of transport was a function of $(V/D^{1/4})$ for a particular sand. Samples from the estuary showed a median diameter of 0.0096 inches. Local variations in sand size could not be considered in computing the bed-movement because of insufficient bottom samples, and the computations were made assuming a uniform sand size equal to that of the estuary sample tested in the laboratory.

Table VI shows the rate of movement at several points in the estuary during representative phase division. Table VII shows the rate of movement in pounds per hour at four sections in each of the ten tide phases, the net

TABLE VI

Bed-Movement Across Different Sections in Estuary

(in thousands of pounds of dry sand per hour)

Section		Average Norman Yearly Conditions				Freshet Conditions
		Ebb (Seaward)		Flood (Inward)		Ebb (Seaward)
		Phase Division				Phase Division
No.	Location	4	5	8	9	5
I	Ends of Jetties	46	16	64	69	72
II	Clatsop Spit	230	81	292	441	580
III	Chinook Dike	100	25	218	661	1,580
IV	Flavel	185	345	141	115	1,130
V	Astoria-Knappton	246	700	455	128	1,810
VI	Tongue Pt.-Grays Pt.	670	710	100	232	2,690
VII	Tongue Pt.-Harrington. N. bank of Channel	* 820	*1,630	108	3	* 3,860
VIII	Tongue Pt.-Harrington. S. bank of Channel	80	185	1	42	* 1,378
IX	Jim Crow Point	167	205	0	0	430

* Movement occurs in both directions across section.
Figure given is not movement in seaward or ebb direction.

TABLE VII

Bed Transportation
(pounds per hour)

ase	Section I (Jetties)		Section II (Clatsop Spit)		Section III (Chinook)		Section IX (Jim Crow Point)	
	Average	Freshet	Average	Freshet	Average	Freshet	Average	Freshet
1	* 1,000	* 96,000	* 1,000	* 225,000	*2,000	*28,000	0	0
2	*27,000	*390,000	*215,000	*1,270,000	*11,000	*360,000	0	*85,000
3	*90,000	*570,000	*197,000	*1,730,000	*95,000	*1,150,000	*19,000	*295,000
4	*46,000	*760,000	*230,000	*1,170,000	*200,000	*1,300,000	*167,000	*426,000
5	*16,000	*72,000	*81,000	*580,000	*25,000	*1,580,000	*205,000	*430,000
6	0	0	0	0	0	*36,000	*41,000	*1,300,000
7	-5,000	-64,000	-78,000	-246,000	0	-38,000	*27,000	*370,000
8	-64,000	-208,000	-292,000	-840,000	-218,000	-730,000	0	*82,000
9	-69,000	-150,000	-441,000	-890,000	-666,000	-1,300,000	0	0
10	0	0	0	-41,000	-3,000	-77,000	0	0
Net Movement per tide (pounds)	*52,000	*1,830,000	-194,000	*3,700,000	-810,000	*2,900,000	*570,000	*3,720,000
Net Movement per year+ (tons)	*17,000	*625,000	-37,000	*1,260,000	-277,000	*980,000	*195,000	*1,270,000

Notes:

* Indicates movement Seaward

\- Indicates movement Inward

\+ Taken as 680 tides

movement in pounds per tide, and the annual movement in tons in a year of 680 tides under average annual and freshet river flows. Figure 6 shows the computed rates of bed transport during Phase Division 4.

At an average flow of 225,000 second-feet throughout the year, the average concentration of suspended material must be approximately 50 parts per million to transport 10,000,000 tons in suspension - the amount indicated by measurements at the Dalles. Even at points of greatest agitation, such as over the hole off Tongue Point and around the old dikes at Harrington Point, the concentration of suspended material in the estuary reaches this value only at freshet stages. The average concentration throughout the year is believed to be materially less than 50 ppm and much of the material must move as bed-load if this annual load in the upper river is to be transported through the estuary.

The suspended load in the upper river amounted to 10,000,000 tons per year or 2,350,000 pounds per hour. At strength of ebb current under freshet conditions, with an extreme range of tides, bed movement exceeds this figure only at two sections within the estuary and is small at Jim Crow Point and Clatsop Spit.

This study of sediment movement in the estuary was not pursued farther because the other experiments described had provided answers to the engineering problems under study.

The analysis of bed-load movement indicated that regulation of the river in such manner as to reduce peak flows may have a disproportionately great influence on the channels of the river and the estuary. It has been estimated that at Wesport and Eureka bars, bed-movement is unimportant at fresh-water flows below 350,000 second-feet. Above this discharge, the transportation of material increases very rapidly and regulating the flow will reduce the total volume of material transported by the same total volume of water. The effect of such a change will vary with location in the river. Near tributaries which supply material, the average capacity to remove material will be reduced and shoaling will occur, whereas at points distant from sources of sand, depths should increase.

CONCLUSIONS

1. The movable bed model may have been more reliable than it was believed to be at the time, and this approach may have been abandoned prematurely.

2. The fixed-bed model to a vertical scale of 128 and a horizontal scale of 3600 reproduced with acceptable accuracy the range and lag of tide and the direction and velocity of the currents. The agreement was good in the channels and deepwater areas near strength of ebb and flood currents. Over shoals and around the time of slack water, the discrepancy between model and prototype was larger.

3. The movement of powdered coal in the model under average and freshet river flows appeared to agree qualitatively with the movement in the estuary.

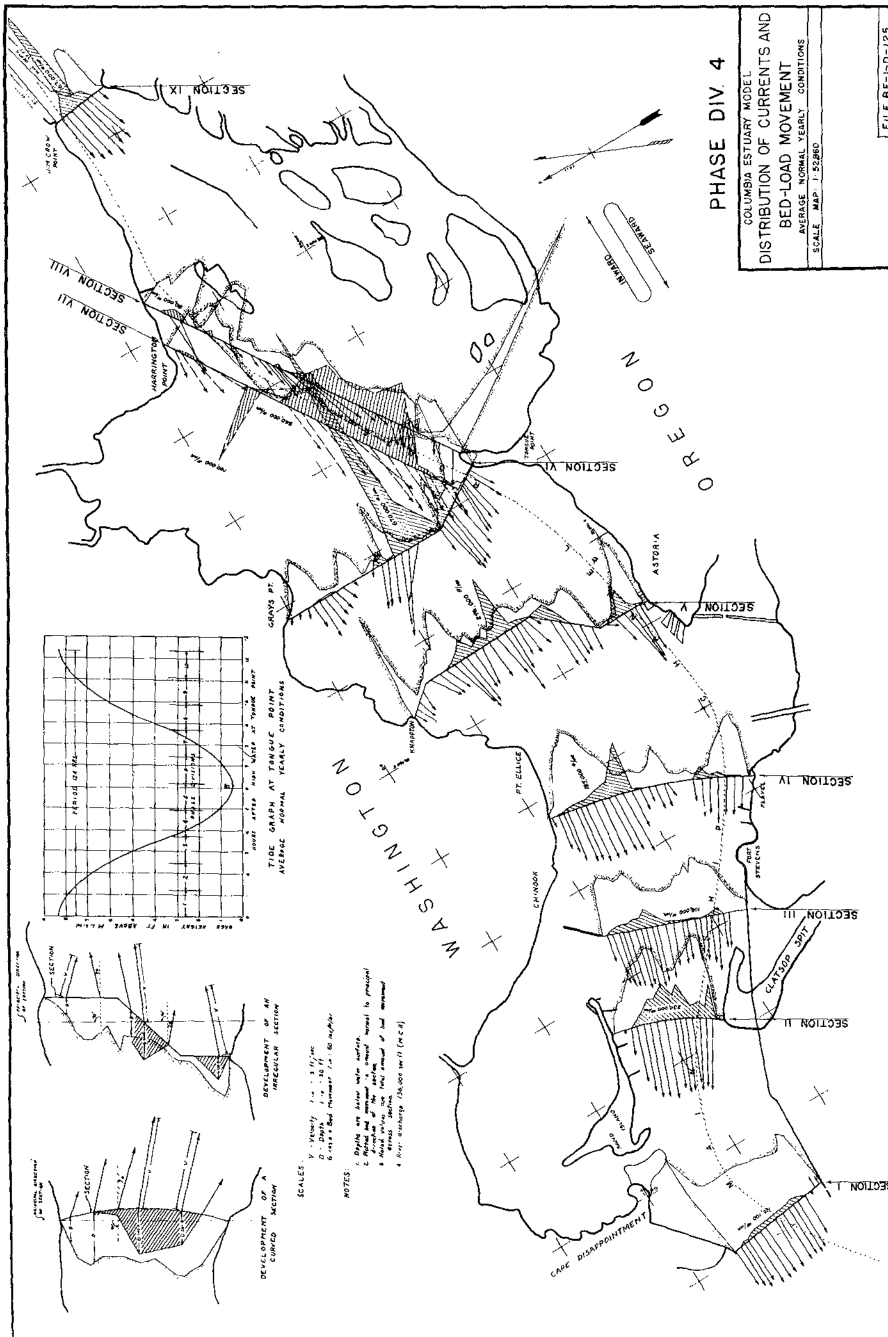


Fig. 6. Distribution of currents and bed-load movement.

4. Tidal models, which do not involve either wind waves or salinity gradients, may be modelled to small scales and large distortions with reliable results.

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