CHAPTER 143

FLUSHING CHARACTERISTICS OF SMALL-BOAT MARINAS

by

Ronald E. Nece[1] and E. P. Richey[2]

ABSTRACT

Results are presented for a laboratory study investigating the effectiveness of using a small-scale laboratory model to predict tidal flushing patterns in small-boat marinas. Laboratory results are compared with field measurements taken in an existing small-boat harbor.

Model limitations are indicated, but it is concluded that simple, small-scale models can constitute an effective, economical tool in the evaluation of designs of small, enclosed basins where water quality problems associated with circulation patterns in the basin are important. Some implications are made concerning the effect of basin planform upon circulation patterns.

INTRODUCTION

Most coastal engineering projects reported in the current literature are of such magnitude that design studies usually incorporate one or both of the following: a large-scale laboratory model study, in conjunction with a comprehensive program of field data acquisition needed for both model input and verification; or, a computer numerical model study of the harbor or estuary area concerned, again making use of field data to provide boundary conditions leading to solutions for currents, tidal elevations, and sometimes pollutant motions. As questions of water quality assume ever greater importance in coastal engineering works the continued use of the above methods, and especially the growth of numerical modeling, is both anticipated and logical. On the other hand, there will continue to be projects of a much smaller order of magnitude which do not justify the expense of a large-scale model study, for which two-dimensional numerical models with their required detailed field data input might represent a very uneconomical exercise in mathematics, and for which one-dimensional mathematical models would not be detailed enough and would mask significant local effects. For such lesser projects the use of small-scale laboratory models may be worthwhile and justified in project evaluation.

This paper reports on a preliminary study in which small-scale models are considered as a tool in the design and evaluation of small-boat harbors with respect to their flushing characteristics. In order to determine the

1. Professor of Civil Engineering, University of Washington, Seattle, Washington.
2. Professor of Civil Engineering, University of Washington, Seattle, Washington.

effectiveness of small laboratory models in describing water motions associated with harbor flushing, a model of an existing installation was constructed. Prototype vs. model performance could be obtained fairly simply by taking advantage of the conveniently located, small, well defined and relatively manageable tidal water body of the field installation.

Previous emphasis on small-boat basins, or marinas, has been on protection from wave action, but more marina installations will be examined in the future with special attention to their environmental impact. Concerns include how marinas respond to pollution sources and if marinas themselves constitute pollution sources, knowledge of current patterns for use in oil spill protection and/or cleanup, and how well marinas are self flushing.

The study reported here was influenced by regional needs in the Puget Sound area of the State of Washington, U.S.A. A 1968 study projected an increase in the number of permanent winter rental moorages in Puget Sound and adjacent waters from an existing 11,600 in 1966 to 74,300 in the year 2000 (1)[1]. While more recent demographic estimates may be more conservative, the magnitude of the problem still is large. It also has been estimated (1) that an average of 3 feet of shoreline is utilized at present for each moorage, and that approximately 200 miles of shoreline in Puget Sound are considered suitable for potential marina developments. Optimum siting and design of future marinas therefore will be of considerable environmental importance in the Puget Sound area, which can be considered representative of other coastal regions in terms of small-boat use.

Another factor bearing upon future installations is that many existing marinas no longer could be built in their present configurations under regulations enacted recently. In the State of Washington, marina bulkhead and/or breakwater configurations can have significant effect upon the mortality rate of migrating juvenile salmon because the migrating fry may be forced away from their desired shallow water routes into deeper water where they become subject to predator fish. Fisheries agencies have adopted revisions in breakwater and bulkhead standards (2); the effects of these revisions, which may require multiple harbor entrances, detached breakwaters, or navigation breaches in some cases, need investigation.

Many small-boat harbors allow a number of simplifications in model studies. Stratification is often negligible; breakwater-enclosed marinas typically are built where there is little or no fresh water inflow to the basin, and up to half of the tidal prism may be exchanged on a typical high tide. Wave effects are minimal, by design and by the small absolute size of the installation. Wind effects, while obvious on surface floatables and surface currents, are negligible on major currents. Tides are the dominant mechanism for producing water motions. Bottom frictional effects are not significant in the gross current patterns of the relatively short and deep water bodies. Consequently, model construction and operation can be simplified. Limitations on interpretation of model results then must be kept in mind; these will be discussed later.

1. Numbers in parentheses refer to entries listed in the References.

PHYSICAL CHARACTERISTICS OF MODEL AND PROTOTYPE

Prototype

The installation selected for the study was the City of Des Moines Small Boat Harbor, located on the east shore of Puget Sound about 15 miles south of the city of Seattle. The marina, built in 1970, was constructed on a tide flat area which was dredged to sufficient depth to allow movement of shallow draft pleasure motor and sail boats. Design dredging depths range from -8 feet MLLW at the south (closed) end of the marina to -13 feet MLLW at the entrance. Enclosing the marina is a rubble mound breakwater extending 500 feet seaward from the shoreline and then northward for 1,950 feet. The space between a timber pile breakwater and the northern end of the rubble mound breakwater provides a 175-foot entrance width at MWL. Fourteen floating piers within the marina provide 682 boat berths. Figure 1 is an aerial view of the installation.

Tides in Puget Sound are of the mixed type, with unequal lows. Mean sea level at Seattle is 6.8 feet above MLLW; the mean tide is 8.0 feet, and the average diurnal tide is 11.7 feet (3). At Des Moines there is zero height correction for low water, a 0.4-foot additive correction for high water, and an average lag of 6 minutes on Seattle for times of high and low water. The only direct fresh water inflow to the basin is sporadic and comes from storm sewer drains servicing streets immediately adjacent to the marina complex.

Model

The distorted laboratory model had a horizontal scale $L_r = 1{:}500$ and a vertical scale $Z_r = 1{:}50$. The corresponding velocity and time ratios were: $V_r = Z_r^{1/2} = 1{:}7.07$, and $t_r = L_r/V_r = 1{:}70.7$. The model, constructed primarily of plywood, was located in a tank having overall dimensions of 8 feet by 12 feet. For purposes of economy and simplicity of both construction and operation the enclosing breakwater was made impervious, the basin bottom was constructed to design dredging depths, and no attempt was made to simulate the floating piers or boats. Because currents in Puget Sound offshore from Des Moines are weak, there was no effort to model exterior currents. The model is shown in Figure 2.

Constant amplitude, constant period tides only, were produced in the model. The tidal generator was a variable-elevation waste weir, driven by a small motor through appropriate gear reducers and a Scotch yoke mechanism to obtain harmonic motion, and fed by a constant-rate water supply. Economy dictated this choice of a simple tide generator. The model tides were verified to be very nearly sinusoidal.

The model scale so selected was known to violate equality between protype and model of some similarity parameters important in the modeling of pollutant motions in tidal basins, as summarized by Carstens (4). Despite the presence of jets and wakes formed by the tidal flows past the vertical breakwater at the entrance and past other sharp corners in the boundary planform, much of the model basin flow was in the laminar regime and had Reynolds numbers $\mathbb{R} = Vd/\nu$ (V = local depth-averaged velocity, d = corresponding water depth) considerably below the 1,000 value commonly associated with the lower limit of turbulent free surface flow. In addition, there was no attempt to scale overall diffusion coefficients; hence, there was no reproduction of diffusion processes in the model.

Consequently, the small-scale model could not be utilized to reproduce either pollutant diffusion or the detailed velocity fields of the prototype; the model utility then had to be judged on how well it reproduced the gross tidal current structure of the prototype.

EXPERIMENTAL PROCEDURES

Tide Selection and Correlation

Tide curves showing typical spring tides occurring in one period during which field data were obtained are shown in Figure 3. The repetitive tide selected for use in the model had a nominal 10-foot (prototype) amplitude and a 12.4-hour (prototype) lunar tidal period; corresponding model values were 0.2 foot and 10.52 minutes, respectively.

Field current data were reduced to a common denominator for comparison with model measurements by the following process:

$$\frac{V_{ref}}{V_f} = \frac{\frac{h}{T_0}}{\frac{H}{T}} = \frac{h}{H}\,\frac{T}{T_0} \tag{1}$$

where: V_{ref} = reference velocity, expressed in prototype units of feet/minute

V_f = current velocity measured in the prototype

h = equivalent prototype height of the model tide

H = $\frac{E + F}{2}$, the average of the prototype large ebb amplitude E and large flood amplitude F

T = time between high water levels enclosing the low water ebb slack tide

T_0 = equivalent prototype time of the model tidal period.

All current magnitudes shown on Figure 8 are given as values of V_{ref}, in feet/minute, prototype; times at which the velocities obtain are expressed in terms of the dimensionless time t/T, as defined on Figure 3. All field data were taken on the large ebb, E, or the large flood, F, in order to obtain more readily measurable current magnitudes.

Current Measurements

All current measurements in both model and prototype were taken with the use of drogues, or floats, which were tracked over time and space.

Most field measurements were made with the miniature drogues shown in Figure 4. The 4-inch by 3-inch cross-form plexiglass drogues could be positioned at any desired depth below the water surface; the color-coded fishing floats, which provided the necessary buoyancy as well as drogue identification, provided minimal exposure to wind drag above the water surface. Drogues were tracked by observers in small boats or standing on the piers; the piers provided ample reference points for distance and angle measurements. Except for the entrance region, velocities shown on the data figures are taken from drogues operating at a 6-foot depth, below the region of reduced velocities caused by the draft of the floating piers and moored boats.

Pathlines and velocities were measured on ebb flows near the outlet. For this purpose, the larger drogue shown in Figure 4 was used. A plane table and alidade, set up on the shore and used in conjunction with the thin stadia rod projecting above the water surface, allowed single-instrument determination of location vs. time of the drogue, from which local velocities at the 4-foot depth could be determined. The path followed by the drogue when it was released at the tip of the vertical timber breakwater provided the shape of the free streamline of the discharge jet at the marina mouth.

A simple visual method was used in the model in lieu of the more common streak photographs of confetti placed on the water surface to measure currents. Length of small, 0.10-inch diameter plastic-coated drinking straws, sealed and weighted at the bottom but open at the top, and with an equivalent prototype depth penetration of 10 feet, acted as drogues responding to an effective average velocity over the water column. Drogue locations were plotted at discrete time intervals by marking pen on a horizontal plexiglass sheet mounted above the model; the requirement that an observer sight down the open vertical bore of the straw cylinder was an effective method of reducing parallax errors. Individual drogues could be inserted at any location and at any time of the tidal cycle; drogue insertions at the same time and place, but on different tidal cycles, yielded pathlines in very close agreement and indicated model consistency.

MODEL-PROTOTYPE COMPARISONS

Ebb Flow at Entrance

Flow conditions in the harbor entrance area are such as might lend themselves to a first analysis utilizing ideal fluid, two-dimensional, free streamline methods if frictional resistance and effects of changing depth are neglected. Such an approach was used by French in considering the velocity distribution in the entrance region of a tidal flow through a relatively short channel into a lagoon (5).

In the present work, limited attention was given to the ebb flow only, in the vicinity of the timber breakwater. One set of drogue tracking data gave field observations of velocities and pathlines at the 4-foot depth. The observed separation streamline of the exit jet was compared with an estimated free streamline location determined by an (interpolated) adaptation of von Mises' two-dimensional contraction coefficients (6). No exact solution was attempted. An effective approach width of b = 175 feet between MWL on the rubble mound breakwater and the tip of the timber breakwater was selected, as shown on Figure 5. The interpolated contraction coefficient $C_c = 0.58$ gave a predicted jet width of 100 feet. A flow net construction then gave the shape of other streamlines in the predicted jet.

Comparison between predicted and observed separation streamlines on Figure 5 shows that the predicted contraction was overestimated. The laboratory observation was closer to agreement with the predicted location. It is also very clear, however, that the separation streamline past the breakwater is indeed independent of the shape of the dredged channel.

Figure 5 indicates how predicted velocities, all based in part on the predicted free streamline location, compared reasonably well with field measurements. The predicted velocities were calculated by the one-dimensional continuity equation,

$$V = \frac{A_{basin}\left(\frac{dz}{dt}\right)}{a_{exit}} \tag{2}$$

where: A_{basin} = total surface area of the marina behind the plane of a_{exit} ($A_{basin} = 1.05 \times 10^6$ sq. ft)

(dz/dt) = fall rate of water surface, from tide curves

a_{exit} = cross-sectional area of plane normal to the assumed uniform, one-dimensional velocity distribution in the jet where the jet surface width has become equal to $C_c b$.

Exit velocities measured in the model, while not shown on Figure 5, agreed well with field values.

Circulation Patterns within Marina Basin

The well defined basin geometry presented the temptation to treat ebb flows by potential flow methods -- i.e., by constructing a flow net for the basin configuration and extending Eq. 2 to yield local velocities at all points and at all times on the ebb flow. This procedure, a one-step refinement of rather common one-dimensional methods, could then yield water particle detention times. Both field and model observations confirmed the fallacy of such an approach.

The dominant feature of current patterns within the basin was the establishment of circulation cells initiated by flow separation around the timber breakwater on flood flows. Currents reversed direction almost everywhere in the channel at or very close to low water slack ($t/T = 0.5$). On the following inflow, separation flow past the timber breakwater created a counter-clockwise cell in the area behind the breakwater; this cell grew until it occupied about 40 percent of the basin area, and a second (clockwise) cell was formed and which filled most of the southern part of the basin. (A third, small counter-clockwise cell which formed at the extreme southern end of the enclosure contributed very little to general circulation patterns, but could lead to very long detention times for pollutants introduced in this part of the basin). When the two primary cells were well established, by $t/T \approx 0.75$, the primary inflow current near the middle of the basin was directed inshore and almost normal to the major axis of the marina.

This cellular flow structure is indicated by the float pathlines on Figure 6. Model and field pathlines at comparable t/T times show good agreement. Pathlines in the prototype are limited in length because the floats could not travel beneath piers. For repetive model tides, t/T values of 0.08 and 1.08 have the same meaning.

Angular momentum established during flood tide flows persisted into ebb flows. Outward flows were established in the main channel by the southerly of the two primary circulation cells prior to the time of high water slack. This effect is illustrated in Figure 7, where limited field tests were used to check the flow patterns observed in the model.

Slight errors were introduced in the model by making the exterior breakwater impermeable. Flows through the porous rubble breakwater were confirmed by dye observations in the field, and small head differences were measured by manometers between the interior and exterior faces of the breakwater during tidal flows. Pending the general lack of information in the literature on head loss relationships for flow through porous media of large 'grain' size, no attempt was made to calculate discharges through the breakwater. It is considered that any resulting discrepancies would be confined to regions adjacent to the breakwater and would have little if any effect upon general circulation patterns.

Existence of the two primary circulation cells is shown clearly in Figure 8, which indicates current patterns at $t/T = 0.75$. Although no direct comparison was reached between field and laboratory velocities at exactly the same time and place, agreement between model and prototype is adequate. Model-determined velocities shown at nearby points in Figure 8 are an indicator of the degree of consistency and reproducibility between repetitive tidal cycles as obtained by the simple visual observation procedures used in the laboratory.

CONCLUSIONS

The small single-entrance tidal water body studied has well defined boundaries; wind and stratification effects are negigible, so that tidal action is the dominant flow-producing mechanism. Despite the well defined boundary conditions, water motions within the basin are not easily predictable and cannot be treated by simplified calculation methods. Computation procedures such as those outlined by Leendertse (7), modified to incorporate the important separation effects, might be used to predict water motions; however, in terms of project sizes and costs as typified by the marina reported upon here, such methods might not be justified in terms of cost vs. useful output.

Planform geometry is seen to have a significant effect upon circulation patterns within the marina. Sharp corners, with resultant flow separation, promote circulation and mixing which may be helpful in the elimination of pollutants from the basin; effects of this additional mixing upon detention times of pollutants inserted at different locations in a basin likewise would depend upon basin geometry. Asymmetry of single entrances appears to be advantageous in terms of promoting circulation within the marina. The number of circulation cells within a tidal basin would seem to be dependent largely upon entrance asymmetry and the length: width ratio of the plan-form. Investigation of the effects of such geometry parameters would be fruitful in considering designs of future, largely enclosed, marinas.

The laboratory model tested was found to give satisfactory reproduction of the gross velocity patterns within the existing marina. It is concluded that such small-scale models are a useful and economical tool to be used in the design and evaluation of proposed small-boat harbors.

ACKNOWLEDGMENT

Partial financial support for the laboratory activities was obtained from the Water Quality Training Program of the U.S. Department of the Interior. M. Maher, L. Lewis, T. Kearns, and C. Tweedt, graduate students at the University of Washington, contributed to various phases of the program.

REFERENCES

1. "Pleasure Boating Study, Puget Sound and Adjacent Waters, State of Washington", Report prepared for Puget Sound Task Force of Pacific Northwest River Basins Commission by Seattle District, U.S. Army Corps of Engineers and Pacific Northwest Region, Bureau of Outdoor Recreation, November 1968.

2. "Criteria Governing the Design of Bulkheads, Land Fills, and Marinas in Puget Sound, Hood Canal, and Strait of Juan de Fuca for Protection of Fish and Shellfish Resources", Washington State Department of Fisheries, Olympia, Washington, February 1971.

3. United States Coast and Geodetic Survey, "Tide Tables, West Coast North and South America", 1971.

4. Carstens, T., "Physical Modeling of Residence Times in Ocean Basins", Proc. 1972 Technical Conference on Estuaries of the Pacific Northwest, Oregon State University, Corvallis, Oregon, March 1972 (in press).

5. French, J.L., "Tidal Flow in Entrances", Committee on Tidal Hydraulics, U. S. Army Corps of Engineers, Technical Bulletin No. 3, January 1960.

6. Rouse, H., "Elementary Mechanics of Fluids", J. Wiley & Sons, New York, 1946 (p.57).

7. Leendertse, J. L., "Use of a Computational Model for Two-Dimensional Tidal Flow", Proc. Eleventh Conference on Coastal Engineering, London, 1968, pp. 1403-1420.

Fig. 1. Des Moines Small-Boat Harbor

Fig. 2. Laboratory Model

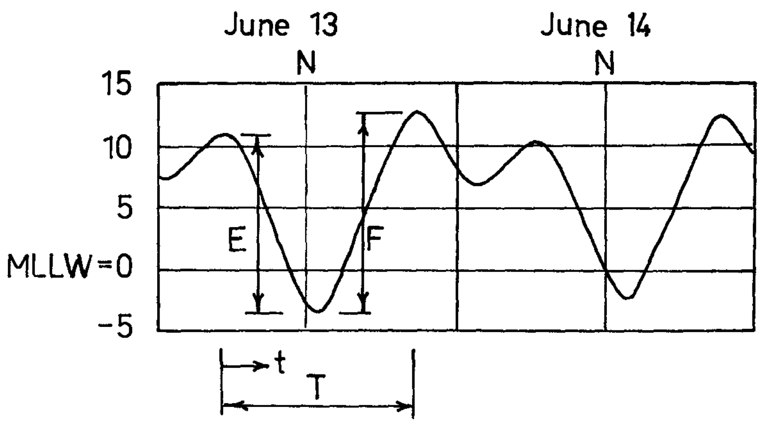

Fig. 3. Typical Tide Curves for Puget Sound, and Notation Definition

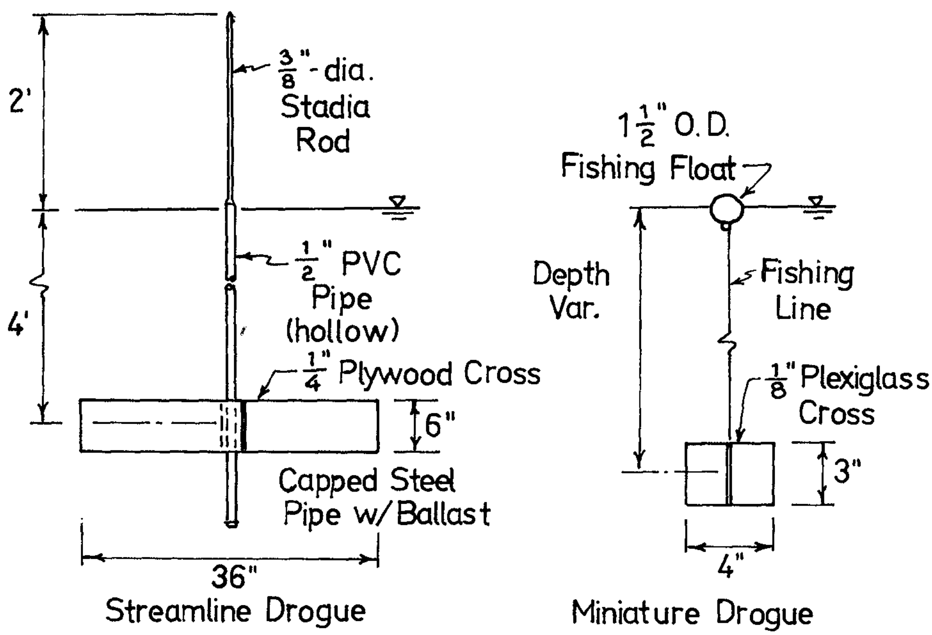

Fig. 4. Drogues Used in Field Studies

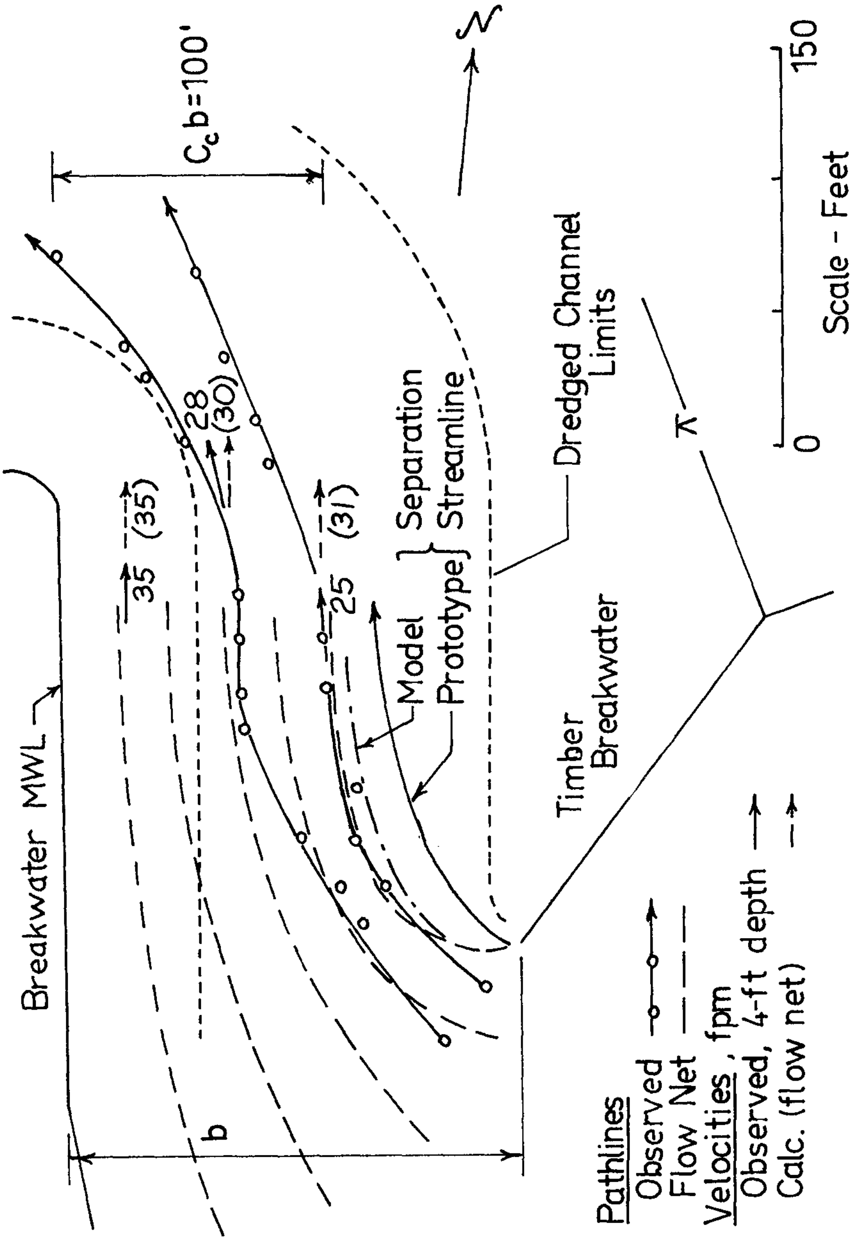

Fig. 5. Ebb Flow at Harbor Entrance

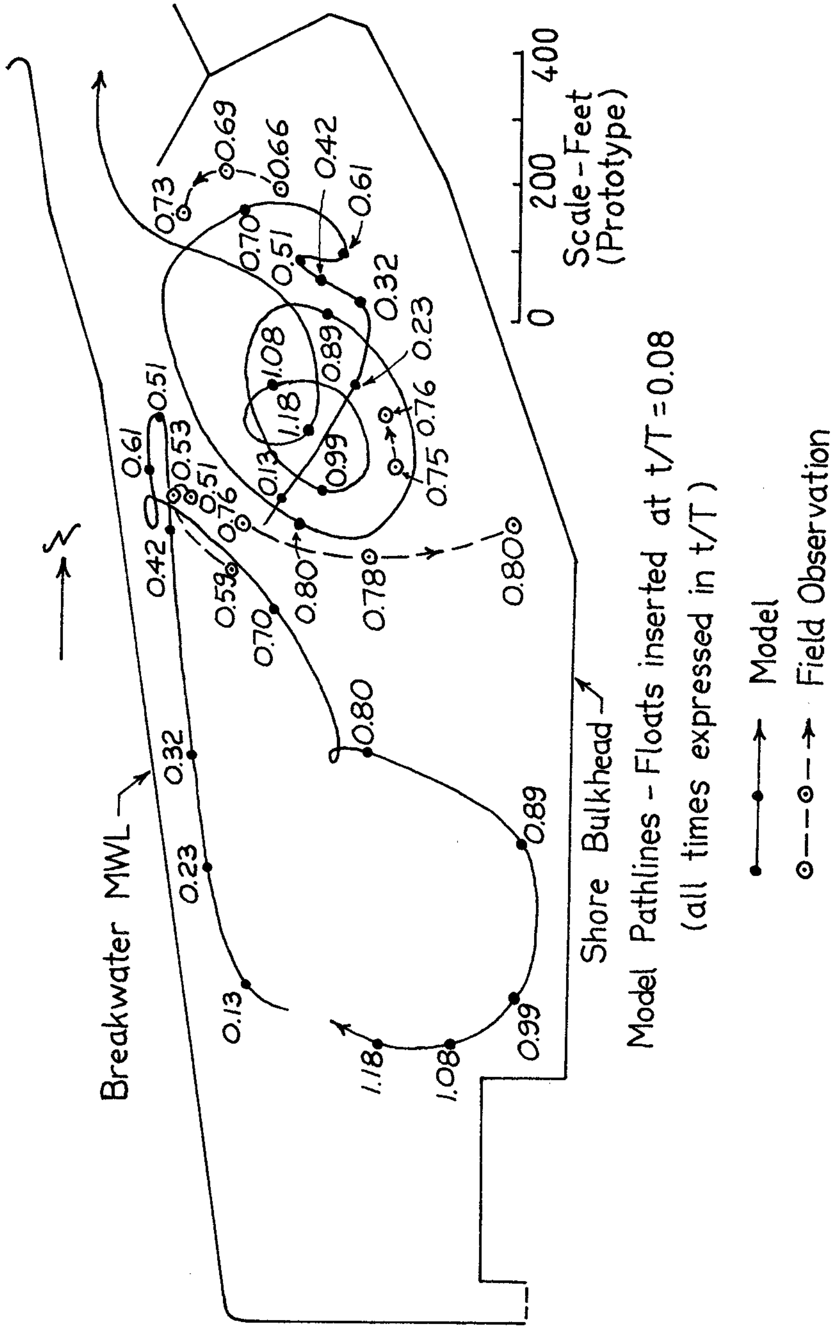

Fig. 6. Drogue Pathlines, Model-Prototype Comparison

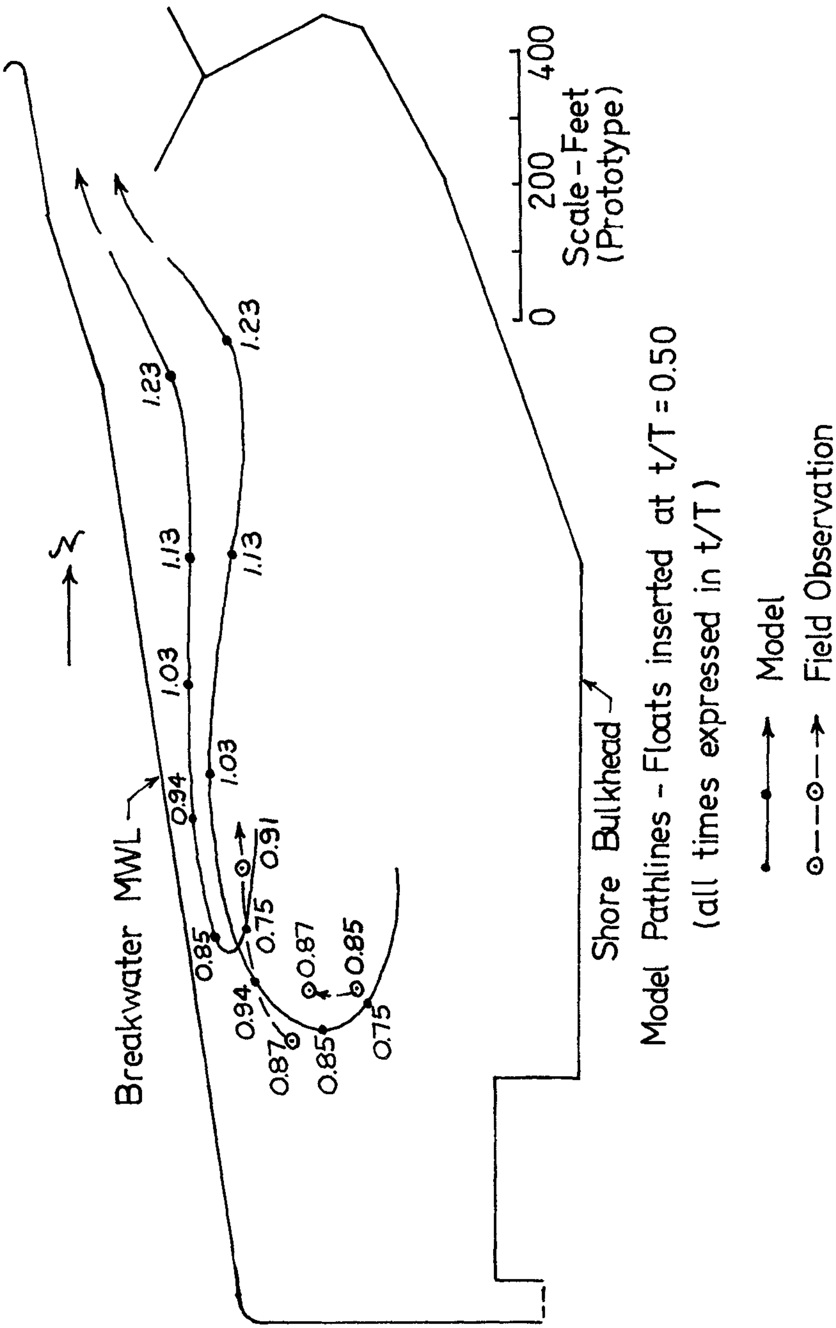

Fig. 7. Drogue Pathlines, Model-Prototype Comparison

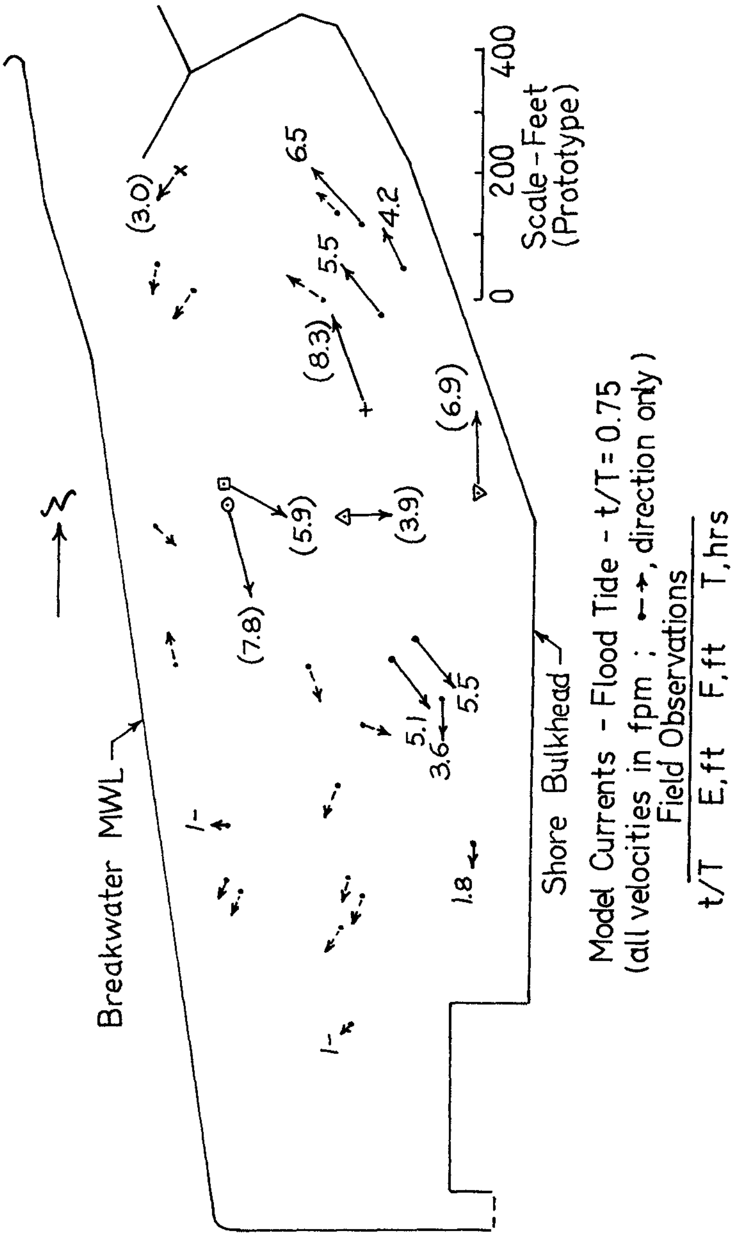

Fig. 8. Currents at t/T = 0.75, Model-Prototype Comparison