University of Washington
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TIDAL CIRCULATION AND FLUSHING IN FIVE WESTERN WASHINGTON MARINAS

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Water Resources Series
Technical Report No. 63
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by

Ronald E. Nece, H. Norman Smith and Eugene P. Richey

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The model testing described was conducted in the Charles W. Harris Hydraulics Laboratory of the Department of Civil Engineering, University of Washington. The project was carried out under the supervision of Professors R.E. Nece (Principal Investigator) and E.P. Richey (Co-Investigator). Model construction and data acquisition system design were performed by Mr. H.N. Smith, Research Engineer. Mr. J. Rhee, Research Assistant, participated in the model tests and data reduction. The manuscript was typed by Ms. Janet Steadman-Chadwick. The report text was prepared by the Principal Investigator.

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I. INTRODUCTION

For some time it has been recognized that if better ways are to be obtained for estimating the water quality in small-boat harbors which have been proposed for future construction, first it will be necessary to obtain relationships between observed water quality and measurable hydraulic characteristics of existing marinas. Tidal flushing, one such characteristic that can be determined through hydraulic model studies, is assumed to be a dominant factor in the quality of water within such harbors (also known as marinas or small-boat basins) relative to that of the ambient waters with which they connect. The laboratory study reported here was part of a program designed to investigate the linkage between tidal flushing and water quality in marinas.

The state of Washington Department of Fisheries conducted a field sampling effort in the summer of 1979, measuring certain water quality parameters in five existing marinas in western Washington. The same five marinas were studied by physical hydraulic models. In each marina gross tidal flushing coefficients were determined over a range of tides, and local exchange coefficients were determined at a number of points (approximately 100) for a mean tide range. Emphasis in the present study was on the lower tidal ranges which are of more concern because they produce correspondingly low tidal exchanges.

A range or marina types was selected for the study by the Department of Fisheries. Des Moines Marina and Edmonds Marina, located to the south and north of Seattle, respectively, are single-entrance marinas largely enclosed by rubble mound breakwaters. Squalicum Small Boat Harbor, in Bellingham, also is enclosed by a breakwater on the seaward side but has two water entrances. Flounder Bay (on Fidalgo Island, near Anacortes) and Lagoon Point Marina (on Whidbey Island) are residential marinas; each has a different arrangement of individual lobes, or finger-canals, leading from a central bay which is in turn connected to the ambient water by a short channel. The locations of the five marinas are shown on Figure 1, and details are given in Chapter II.

Before the laboratory model tests could be conducted, and which indeed did provide a measure of relative exchange in various parts of the marina, it was necessary to decide on the locations of the field sampling stations. The objective in locating the sampling stations within the marinas (external control stations were also established at each marina) was to obtain a range of local exchange conditions which could be compared with the field measurements in order to determine if indeed differences in local tidal flushing behavior are tracked by corresponding differences in water quality. These sampling stations were located mainly on the basis of visual observations made in prior model studies, with the aim of selecting points within each basin covering a range from poor to good of local flushing action. The validity of the location selections will be examined later in this report, in the light of the numerical data obtained.

All but one (Squalicum) of the five existing marinas had been studied before by hydraulic model studies, and a proposed expansion of Squalicum had been modeled. The earlier studies of Des Moines, Edmonds, and Lagoon Point each had two major differences from the present investigation. First, the fluorescent dye technique used to measure the basin-averaged tidal exchange was capable of yielding only the gross, or basin-average, tidal exchange coefficients; local exchange characteristics could not be quantified. Second, these earlier studies determined the tidal flushing on the basis of how much water within the marina at high tide was still in the marina at the time of the subsequent high tide; the present and more recent studies have been based on conditions at low tide. For some of the marinas the quantitative results, expressed in terms of flushing coefficients, are quite different for the two conditions. Significant differences from results published earlier are discussed in a later chapter. Discussion and conclusions in this report are limited to tidal flushing characteristics, and do not consider water quality questions *per se*.

The prior model studies of the five marinas have been presented in earlier reports. They are listed below for reference purposes; more details are given in the bibliography.

Des Moines: Lewis, 1972; Nece and Knoll, 1974.

Edmonds: Nece and Knoll, 1974.

Lagoon Point: Nece et al., 1975.

Squalicum: Richey and Smith, 1977a.

Flounder Bay: Nece and Richey, 1979.

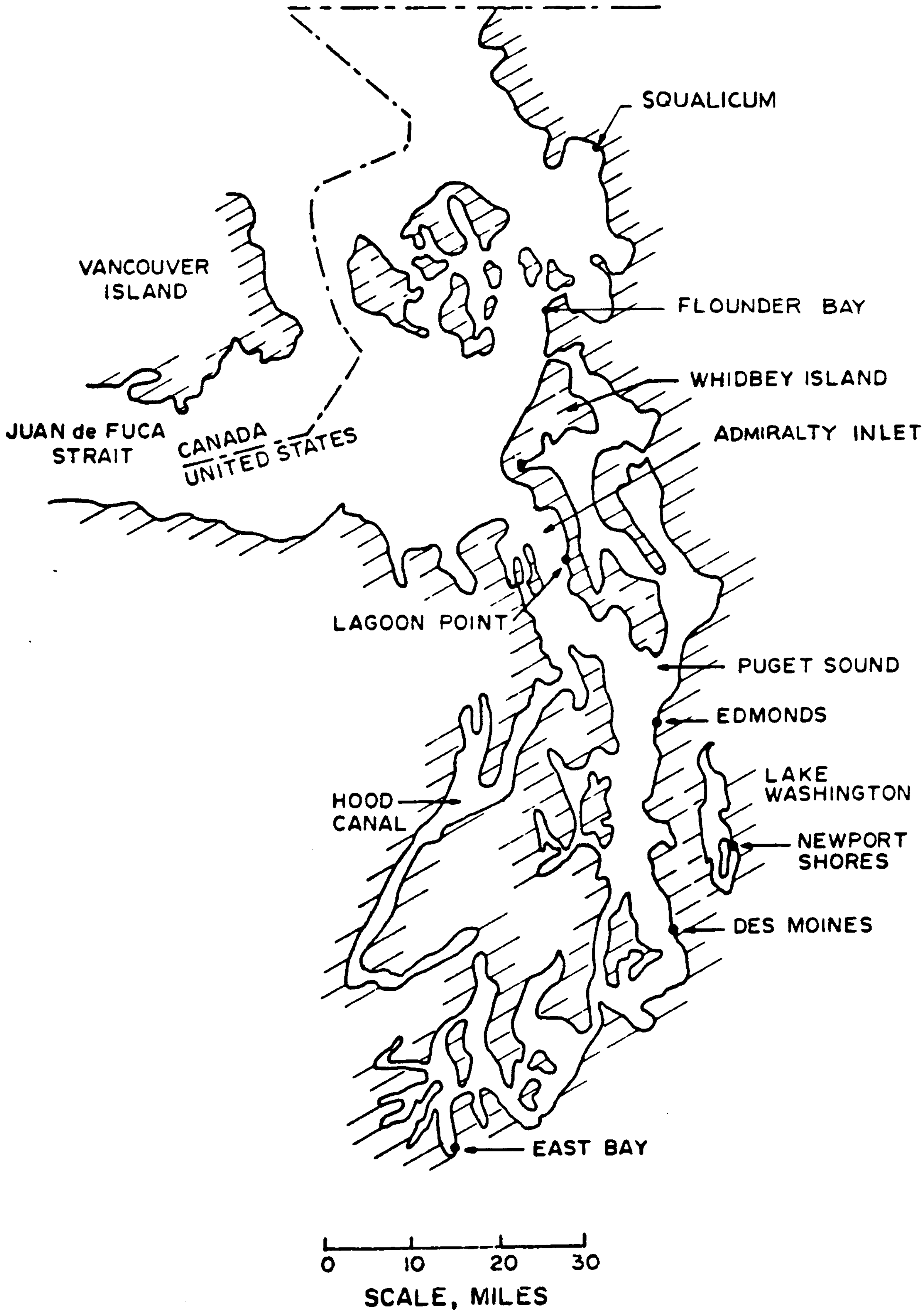


Figure 1. Locations of Marinas Studied

II. MARINAS STUDIED

The five marinas investigated are shown, respectively, in Figures 2 through 6. Shown on each figure are the sampling station locations selected for the field program.

Des Moines

The Des Moines Marina is basically rectangular in planform, with a single, well-defined entrance. The surface area is approximately 20 acres. The floating piers which provide berths for 682 boats are not shown on the drawing. The piers are connected to the eastern bulkhead, so the main interior navigation channel is adjacent to the rubble mound breakwater. Most of the floating piers are covered, so that approximately 25 percent of the total water surface within the marina is shaded. Comparison of drogue tests made in the field and in the hydraulic model (Nece and Richey, 1972) showed the floats to have negligible effect on current patterns within the marina.

Tide ranges are: mean, 8.0 feet; diurnal, 11.7 feet. Mean tide level is 6.8 feet. Mean Lower Low Water (MLLW) is the datum for all five marinas. Strong long-shore tidal currents exist off the entrance.

Edmonds

The Edmonds Marina is effectively a two-basin enclosure with a common entrance; the total surface area is 25 acres. Floating piers accomodating 825 berths shade approximately 25 percent of the surface. As at Des Moines, drains from the marina parking lot empty into the basin; the outfall from the municipal sewage treatment plant empties into Puget Sound just north of the marin; storm drains empty just to the north and south of the marina.

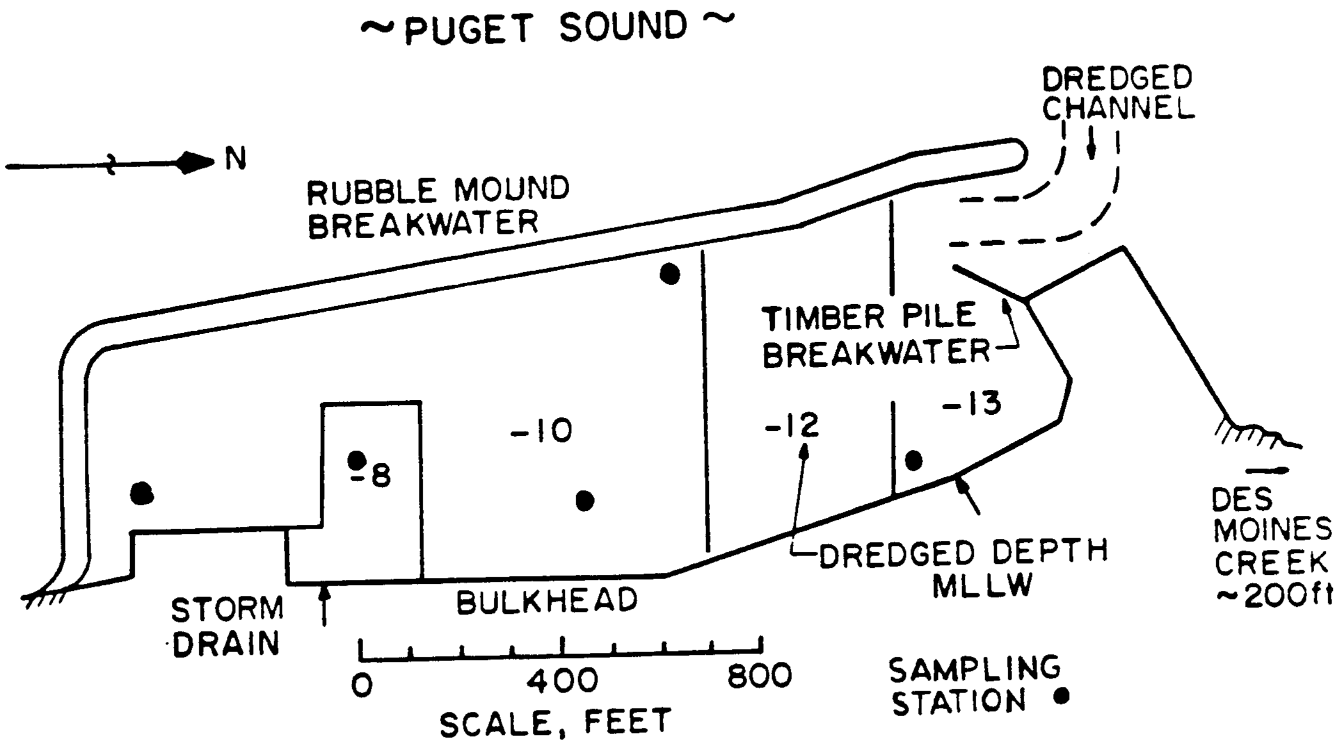


Figure 2. Plan View of Des Moines Marina

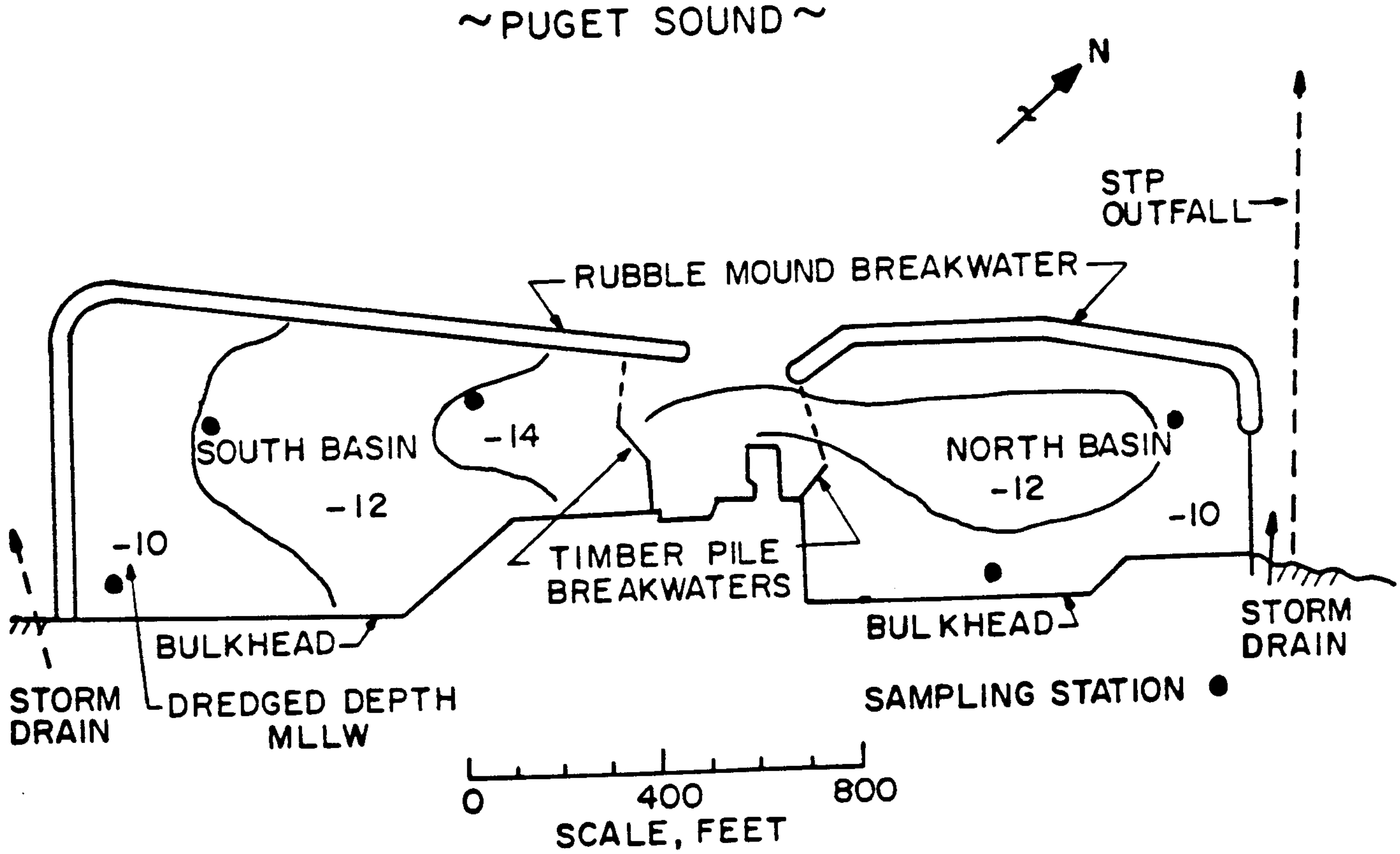


Figure 3. Plan View of Edmonds Marina

Tide ranges are: mean, 7.2 feet; diurnal, 10.9 feet. Mean tide level is 6.4 feet. Again, strong long-shore tidal currents are present off the entrance. Some stratification, associated with Snohomish River outflows, has been noted in the marina entrance (Layton, 1971).

Squalicum

The existing Squalicum Small Boat Harbor has a planform area of approximately 55 acres. The basin contains 620 permanent moorage spaces, 200 of which are allocated to commercial vessels. The layout of the main floating piers is indicated on Figure 4; very little of the surface area is shaded by covered moorages. Mean depths in the basin range from -12 to -15 feet MLLW. Squalicum Creek enters the bay just to the north of the north breakwater.

Tide ranges are: mean, 5.2 feet; diurnal, 8.6 feet. Mean tide level is 5.2 feet. The tidal currents in Bellingham Bay have little velocity; waters and currents ambient to the basin are affected by salinity gradients, freshwater inflow from the Nooksack River and local creeks, and wind stresses.

Flounder Bay

Flounder Bay was planned in part as a residential development. It has four lagoon-type appendages, or "lobes", attached to the central basin which in turn connects to Burrows Bay via a single narrow entrance. The water surface area is approximately 26 acres. Part of the central basin is occupied by a commercial marina operation, and individual moorages are located in the lobes. Shading by covered floating moorages is very small. The bottom depth in most of the central basin is from -10 to -12 feet (MLLW); one hole close to the entrance has a bottom elevation of about -30 feet. The lobes are dredged to -8 feet.

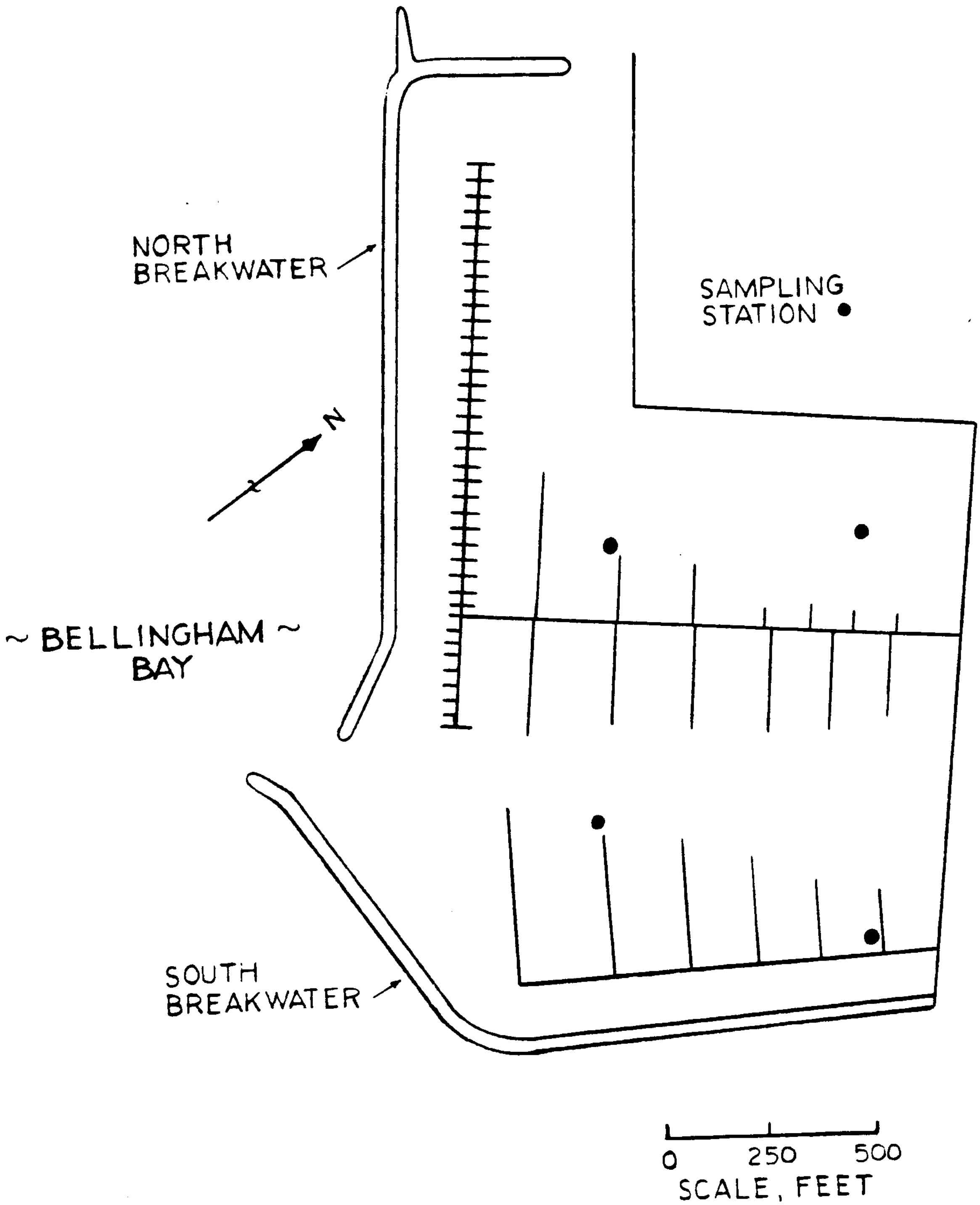


Figure 4. Plan View of Squalicum Small Boat Harbor

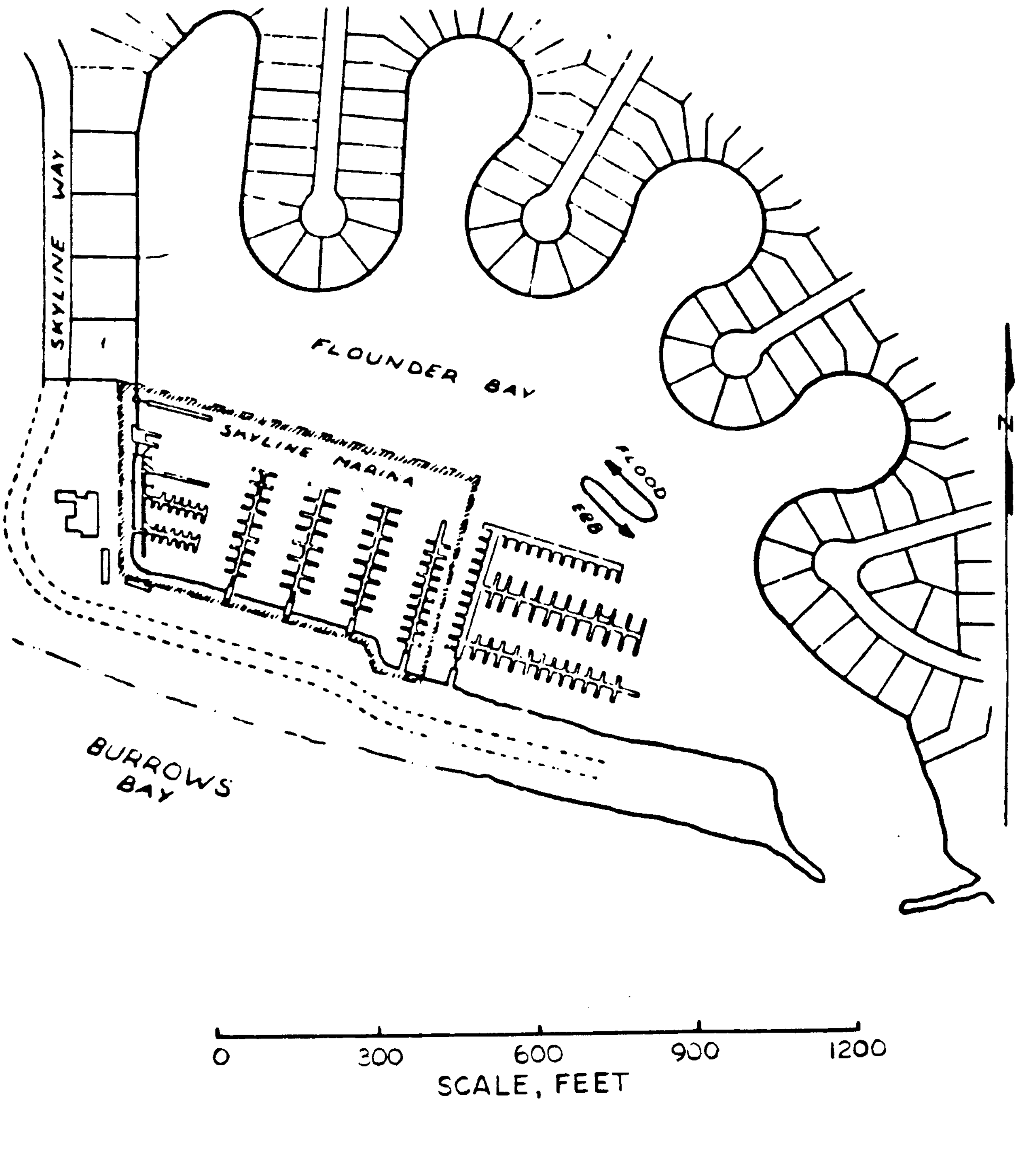


Figure 5. Plan View of Flounder Bay

Tide ranges are: mean, 5.0 feet; diurnal, 8.1 feet. Mean tide level is 4.8 feet. Long-shore tidal currents off the mouth of the marina are strong; currents from the southeast appear to dominate the circulation across the mouth of the entrance and have caused sediment transport into the basin. The entrance channel has been dredged to deeper depth.

Lagoon Point

At Lagoon Point Marina two relatively long and narrow channels have been dredged from a marshland and connected to Admiralty Inlet by a short header channel. The surface area of each canal is about 7 1/2 acres, with nominal depths to -10 feet MLLW. The narrow entrance channel through the jetties has a 20-foot bottom width and bottom elevation of -5 feet (Murray, 1980); the small entrance cross-sectional area leads to high inflow currents into the header channel. The prior entrance configuration included a sill inside the jetties, at elevation -1 foot MLLW, so that at low water on larger tidal ranges the marina discharge was by gravity flow over the sill. The brackish lagoon lake drains into the header channel at low tide. Individual floating slips are located along the two long canals, serving respective residences.

Tide ranges are: mean, 5.6 feet; diurnal, 8.8 feet. Mean tide level is 5.3 feet. Strong tidal currents exist off the mouth of the marina.

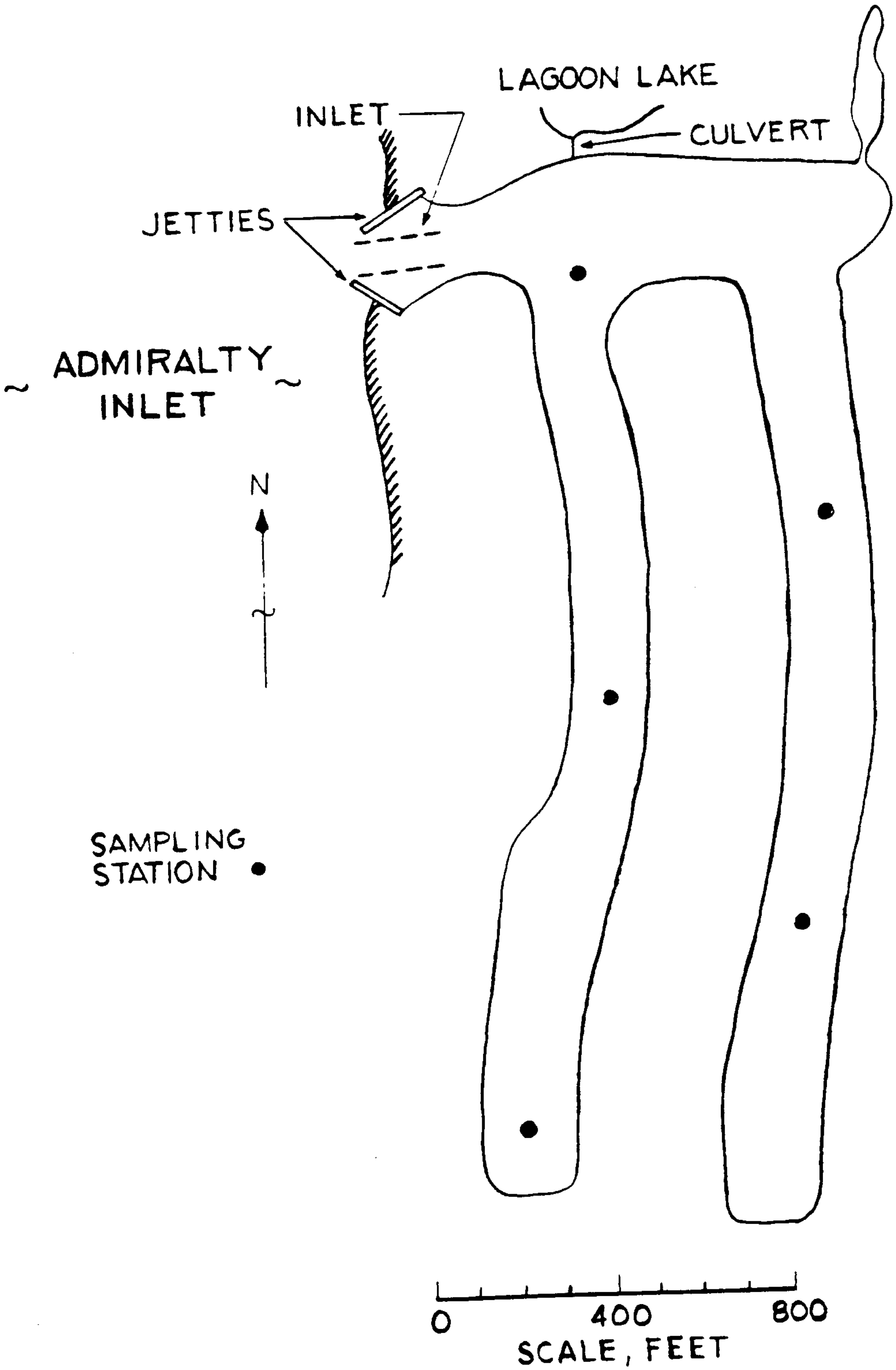


Figure 6. Plan View of Lagoon Point Marina

III. EXPERIMENTAL METHODS

Data Sought

The specific information to be determined and quantified in this study was the relative exchange of water within each of the respective marina basins with ambient water due to tidal flushing of the basin. This information is presented in the form of an "exchange coefficient".

The average per-cycle exchange coefficient, which indicates that fraction of water in a basin or a segment of the basin which is removed (flushed out) and replaced with ambient water during each tidal cycle (defined in this report as the time from low water to following low water), is represented by the equations

$$E = 1 - R$$

and

$$R = (C_n/C_o)^{1/n}$$

where

E = average, per cycle, exchange coefficient

R = average, per cycle, ~~exchange~~ retention coefficient

C_o = initial tracer concentration

C_n = tracer concentration after n cycles, where n is an integer.

The above equations assume repetitive, identical tides and consequent identical exchanges on each of the cycles. In this report, the local value of exchange coefficient for a particular segment of the basin is designated by E, while the spatial average coefficient applicable to the entire basin is designated as $\overline{E}$.

Although $\overline{E}$ and $\overline{R}$ could be defined using any starting time on the tidal cycle, it is most convenient to use either high water or low water slack as the condition for which they apply. In this study, low water slack was used. The low water definition was chosen because at this position on the tidal cycle the residual currents caused during the flood portion, very much in evidence at high water, have diminished during the subsequent ebb flow. This condition presents two advantages: first, from an experimental standpoint, conditions are more likely to be repeated in more detail from one cycle to the next; second, the spatial distribution at low tide of relative concentrations of water originally in the basin at the prior low tide should be more indicative of the effective flushing within the basin over an entire tidal cycle. Since effective "flushing times" would be of concern in water quality models, the low water evaluation is more appropriate for the application of the tidal exchange data.

Model Basin Tide Tank

All of the physical hydraulic model studies were carried out in a laboratory basin having an overall plan size of 8 feet by 12 feet, with an 18-inch working depth. Repetitive constant amplitude, constant period tides were produced by a tide generator which 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 entering the tank through a perforated manifold. Tide ranges and mean water levels could be adjusted by cams and threaded rods, respectively, on the weir drive mechanism; the variable speed gear box gave provision for tide period changes. The single-fluid test facility is not capable of generating controlled stratified flows, so model simulation is limited to fully mixed conditions in the prototype.

The five laboratory models were all constructed with distortion ratio between vertical and horizontal dimensions, and the conventional practice of equating Froude numbers in model and prototype led to the particular scale relationships in each model. Horizontal scale ratios in each case were dictated by the need to fit the model into the existing tank, making the marina basin itself as large as possible while at the same time providing ample space in the tank exterior to the marina so that ambient currents ("boundary conditions" for the marina model) were reporduced adequately.

The Des Moines, Edmonds, Flounder Bay, and Lagoon Point models were built to the following scale ratios:

L_r = horizontal length ratio = 1:500

Z_r = vertical depth ratio = 1:50

Distortion ratio = 10:1 (conventional practice)

V_r = velocity ratio = $Z_r^{1/2}$ = 1:7.07

T_r = time ratio = $L_r/V_r = L_r/Z_r^{1/2}$ = 1:70.7

The repetitive, sinusoidal 12.42 - hour, semi-diurnal tides assumed for the prototype were then simulated in the model tests by tides of constant period equal to 10.54 minutes.

The Squalicum model had L_r = 1:600, Z_r = 1:48 (12.5:1 distortion). The smaller scale on this latter model resulted from the fact that the model of the existing basin was reconstructed from the model tested earlier (Richey and Smith, 1977a) for studying a proposed expansion of Squalicum Small-Boat Harbor; the prototype planform area in the earlier model was larger, necessitating a smaller horizontal scale ratio.

Experimental Methods

A photographic technique utilized and described by Richey and Smith in two 1977 reports was used to obtain the values of E. The procedure tracks the change of tracer dye concentration with time at selected grid points in the basin by measuring the density of dye at the points at specified times on sequent tidal cycles. Dye density values were measured directly from 35-mm black-and-white negatives, using a Tobias Associates Model TBX photodensitometer equipped with a digital readout. The camera was mounted above the basin; the camera was automated to take a photo each quarter-point in a tidal cycle. The photo flood lamps providing the necessary lighting were controlled by the same circuit, and were illuminated only long enough for the picture to be taken by the camera before they were extinguished; one objective in this operation was to minimize the possibility of heating the water in the model by the lamps and thus introducing stratification effects which could destroy the single fluid, unstratified conditions desired. The procedural steps utilized in the tests were:

1. With water level in the tide tank at low water slack (low tide) elevation, insert a temporary barrier dam across the entrance, separating basin and ambient waters.
2. Photograph the model when filled with clear water (at low tide level) to establish a background light level, at C = zero percent. Standard black, gray, and white strips are placed in the camera field of vision for control purposes.
3. The basin is dosed with a suitable water-soluble dye (Mrs. Stewart's bluing was used). Insert dye in equal increments until the final dosage (C_o = 100%) is reached. A photograph is taken at each dosage level after the dye has been thoroughly mixed into the marina water and the water has then been allowed to become quiescent. This produces, at each grid point, a calibration curve of densitometer reading vs. dye concentration. Separate calibration curves must be determined for

various points in the model because of differences in lighting from point to point, depth effects, etc.

4. Remove the barrier dam and simultaneously start the tide generator.
5. Take photographs at quarter-cycle points until the desired number of cycles has been run. Four complete cycles were used; the readings at low water at the end of the fourth cycle give the C_n values ($n = 4$).
6. At low water slack corresponding to $n = 4$, stop the tide generator and simultaneously replace the barrier dam. Thoroughly mix the water in the basin, allow it to become quiescent, and take a final photograph which indicates the spatially averaged tracer dye concentration in the basin.
7. Develop the negatives, set up a grid overlay, and measure the dye densities C_o and C_n with the photodensitometer. The equations given earlier are used to determine E.

The negatives constitute an easily-stored permanent data record. A reader board and an automated "clock" located within the camera field of view contained necessary particulars for each test: date, tidal range, marina identification, and camera settings.

The choice of four tidal cycles was partly pragmatic; after more cycles the amount of tracer dye remaining in the basin usually drops to such a low concentration that the densitometer calibration curves tend to become more non-linear and hence introduce greater possibility for error. The $n = 4$ case has been tested for both E and $\overline{E}$ evaluation using the apparatus and procedures used in the present study; repetitive overall behavior was obtained within 4 cycles, and the use of $n = 4$ in the equations for E and R was validated (Nece et al., 1979).

Presentation of Results

Each tide range for each of the five marinas was run in three separate tests; data given in this report represent the run producing the lowest exchange coefficient values. Results presented, therefore, are deliberately on the conservative side.

The three runs were made in each case to check on the repetitiveness of the testing procedure. Past experience has shown that the testing procedure is sensitive to variations in room temperature, lighting, etc., which may produce some slight degree of stratification. In the model and in the prototype, stratification leads to higher tidal exchange than if the water is fully mixed. Therefore, in keeping with the objective of simulating fully mixed conditions, the run showing lowest exchange values was selected. The damming of the model at low tide, $n = 4$, was performed while the model was in a transient state of operation, so small time differences from one run to another in the time of the dam installation could lead to small differences in $\overline{E}$. The results for the three separate runs at the same tide condition did agree well, in fact, verifying that the testing procedure does give results which are satisfactorily reproducible. Still, instead of averaging the three runs to obtain $\overline{E}$ values, the lowest result was used for the reasons indicated. This approach has been adopted in a recent study of some generalized geometry effects on tidal flushing of marinas (Nece et al., 1979).

Data are presented in three separate figures for each of the three marinas tested. One figure shows the distribution of local E values for the mean tide range only. Each E value shown on the figure is calculated from a densitometer reading from the negative of the photograph taken at low tide, $n = 4$. The densitometer eye used for these readings had a 1-mm diameter eye. The negative areas thus scanned did not overlap but in some cases were nearly tangent. Isopleths of per-cycle E values are shown on these exchange contour diagrams, in incremental steps of 0.05.

The second figure for each marina shows the E value for each tide range tested, and the local $\overline{E}$ value at each of the proposed sampling locations for each tide range. These latter values were obtained with a 2-mm aperture, so that a larger local region was being sampled that in turn might better match the area within which the field sampling was to be performed.

The third figure is a plot of $\overline{E}$ versus tide range. For all except Squalicum, results are compared with results of previous model studies. These earlier results have been summarized (Nece and Richey, 1979), so where numerical differences are found these differences are discussed.

In the tabulated results, the tidal prism ratio is identified for each flushing run. The tidal prism ratio is the ratio of the water volume between high tide and low tide level to the total volume of water in the basin at high tide. The tidal prism ratio can be computed from geometric data alone; it is a measure of the potential exchange of basin water within one tidal cycle. In equation form,

$$\text{TPR} = \frac{\text{Basin volume at high tide - Basin volume at low tide}}{\text{Basin Volume at high tide}}$$

The tidal prism approach (a "box model") assumes the basin to be mixed thoroughly with ambient water during each cycle, yielding an optimum mixing condition.

An additional parameter, the "flushing efficiency", has been defined as

$$\eta = \frac{\overline{E}}{\text{TPR}}$$

and compares measured gross exchanges with those predicted by the simple tidal prism theory. For a marina in which the ambient water entering the basin on the flood tide is completely and uniformly mixed with the water in the basin at low tide, the exchange coefficient should equal the tidal prism ratio, i.e., $\eta = 1.0$.

For purposes of uniformity, the following procedure was utilized in all tests in the present study. In all cases, the mean water level was set at the mean tide level for each respective marina, and the sinusoidal, repetitive tides were centered about this level. All tidal prism ratio and flushing efficiency calculations were based on this approach. Where different approaches may have been utilized in prior studies the differences are indicated in the discussions of results for the respective marinas presented in the next chapter.

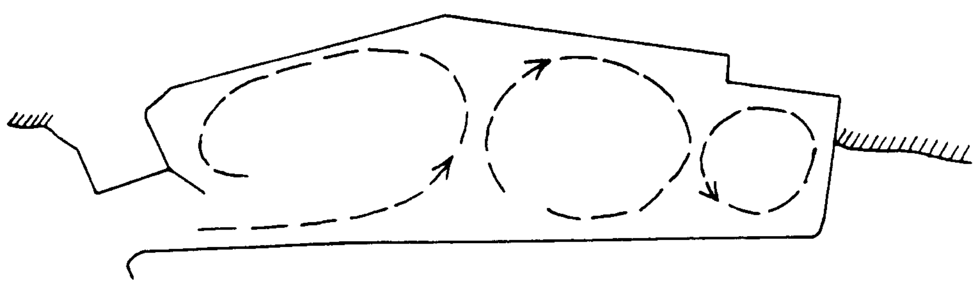
All values of TPR, $\overline{E}$, and η are presented to two places only, commensurate with experimental accuracy.

IV. EVALUATION OF EXPERIMENTAL RESULTS

Des Moines

Results are presented in Figures 7 through 9, and in Table 1.

The local E values shown on Figure 7 (for the tide range = 6.0 feet), as in the comparable figure for each of the other four marinas, reflect residual effects of the circulation pattern established by the flood tide inflow that still persist at low water slack. The flow patterns in the basin are complex; the three-gyre pattern (Nece and Richey, 1972) is indicated schematically in the sketch below.



Low local E values can be detected in the central regions of the two larger gyres. The exchange in the innermost, and weakest, gyre is poor. The length:width ratio of the roughly rectangular planform basin is larger than 3:1, which is a value which has been found to approximate the limit between single-gyre and multiple-gyre tidal circulation patterns in single, asymmetric entrance small harbors (Nece et al., 1979).

That gyre strengths and hence local E values change with tide range is shown in Figure 8. Although the local E values at the five sampling station locations all increase with increasing tide range R, the changes in E are not in the same proportion at the various locations. The two stations near the east bulkhead (refer to Figure 2) lie in regions supplied by the flood flow jet after it has penetrated about one-half of the major-axis length of the marina and then has moved laterally across the basin to the eastern boundary where it bifurcates, establishing the two larger gyres. Only that sampling station which has E = 0.16 at the 6.0-foot tide range can be considered as lying near the central region of a circulation cell, or gyre. For all tide ranges tested the five sampling stations provide a good range of local E values; the locations can be considered satisfactory.

Differences between using high tide and low tide conditions for evaluating $\overline{E}$ are shown clearly in Figure 9. The first and most obvious conclusion is that mixing within the basin is not complete and uniform, as assumed in the simple tidal prism approach; if tidal mixing were indeed complete and uniform, the same exchange coefficient values would be determined using either high tide or low tide conditions. The earlier high tide evaluations give larger $\overline{E}$ values because at high water slack all of the "new" ambient water is within the basin whereas between high water and low water much of this same water has passed around the outermost gyre without full mixing and has been exhausted from the basin. The result for the entire marina, where the inner regions do not participate fully in direct exchange, is a lower $\overline{E}$ value.

The difference is shown clearly in Table 1. Tidal exchange efficiencies η are more uniform with range when based on the low tide evaluation. The value of $\eta > 1.0$ for the low range, using the high tide conditions, reflects the fact that the ambient water which enters on the flood has displaced "old" basin water that is exhausted on the ebb, from the outer gyre, without much mixing.

It should be noted that one other difference exists in the two sets of data shown in Figure 9 and Table 1. For the present study, tide ranges were about the mean tide level of 6.8 feet for all tests, as indicated in the concluding paragraphs of Chapter III. For the earlier tests, a different procedure was utilized which attempted to account for the large diurnal inequalities between the heights of succeeding low tide levels associated with the mixed tides in Puget Sound. For model study purposes basic tidal data were extracted from tidal prediction tables (U.S. Department of Commerce, 1969, 1970) covering a period of two consecutive years. Values for Seattle were corrected to Des Moines (Lewis, 1972). It was assumed that on the average the quarter-monthly tidal range extremes (spring and neap tides) occurred within 36 hours of the respective moon phase. Within each time bracket four successive ranges (two large and two small) and their respective high and low water levels were selected. The data were categorized with respect to type of tide (spring and neap) and type of range (large and small), producing four sets of data representing four kinds of tidal conditions; the 3.5-foot and 13.3-foot ranges listed in the present report correspond to "spring-large" and "neap-small" tides so determined. The arithmetic means of the four sets of data were used to derive the "average" tidal conditions. These average values (7.9-foot range, 6.97-foot mean tide level) then differed from the U.S. Department of Commerce "Tide Table" values listed in Chapter II and used in the present tests. The differences, however, are considered sufficiently small to be neglected in interpretation of test results; they are noted here for completeness of record. They have little effect on TPR and η calculations.

Edmonds

Results are presented in Figures 10 through 12, and in Table 2.

The two basins each act as a basin with a single, asymmetric entrance, and each contains a single gyre. This pattern is shown schematically in the

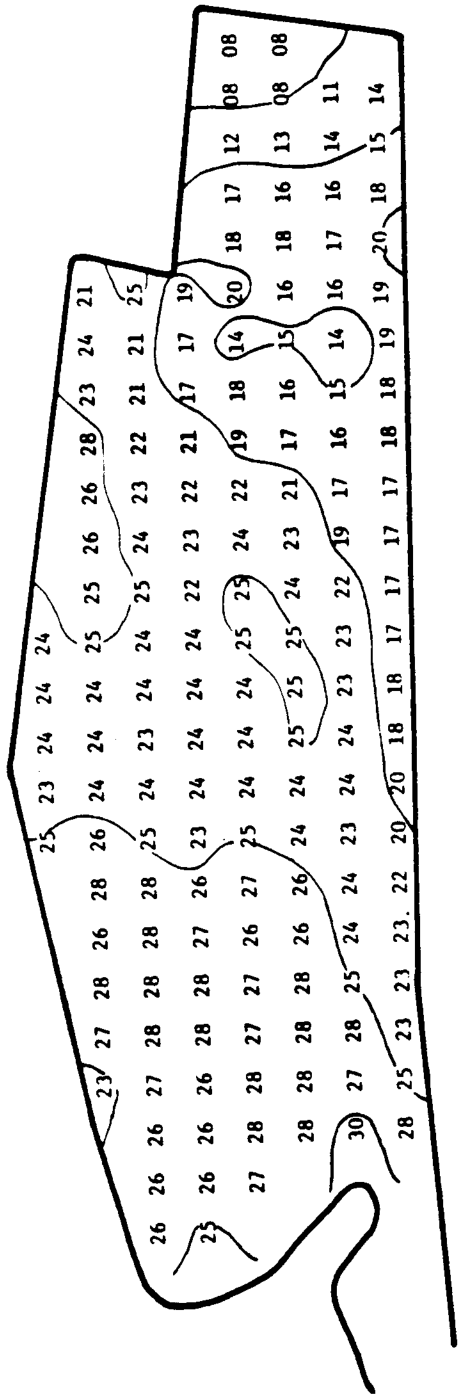


Figure 7. Des Moines Marina Local Exchange Coefficients R = 6' $\overline{E} = 0.22$

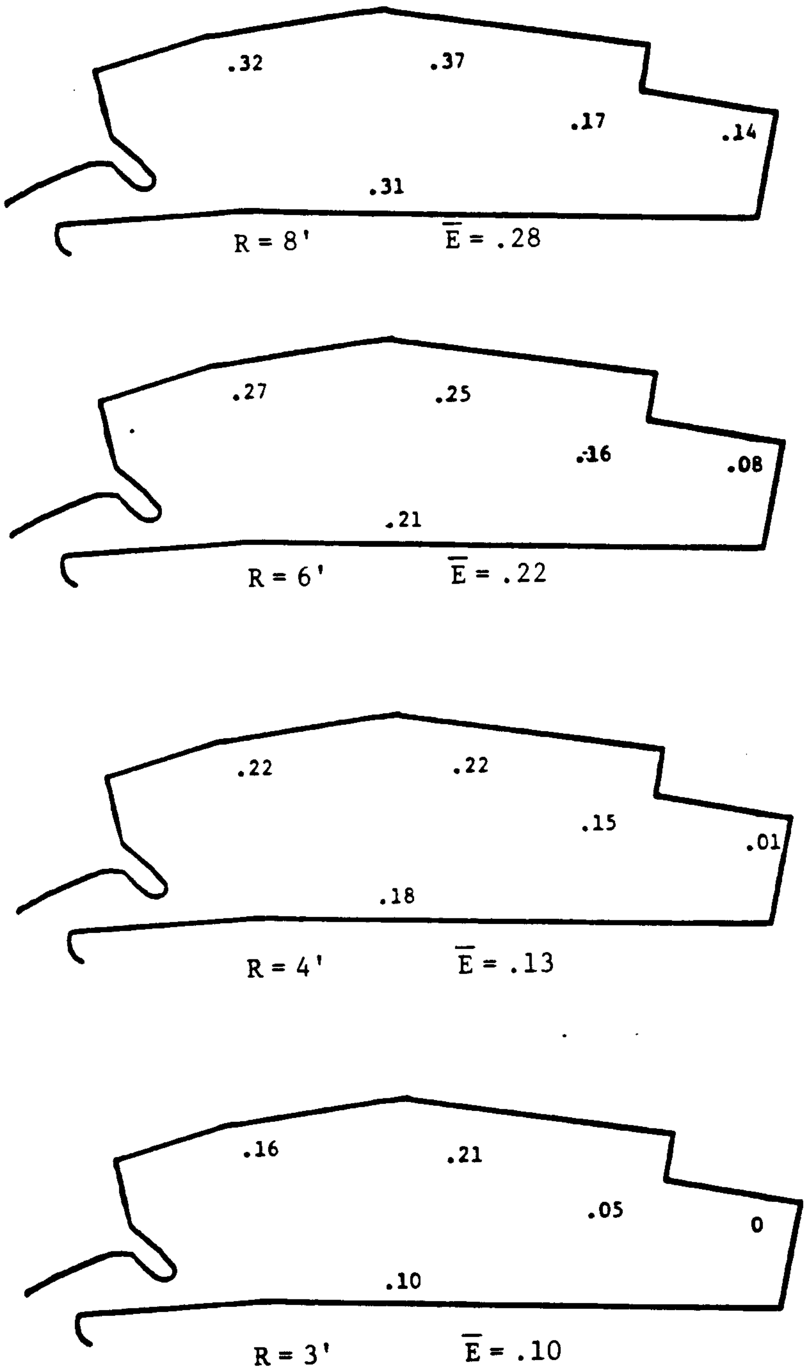


Figure 8. Des Moines Marina Exchange Coefficients $\bar{E}$ and E at Sampling Station Locations

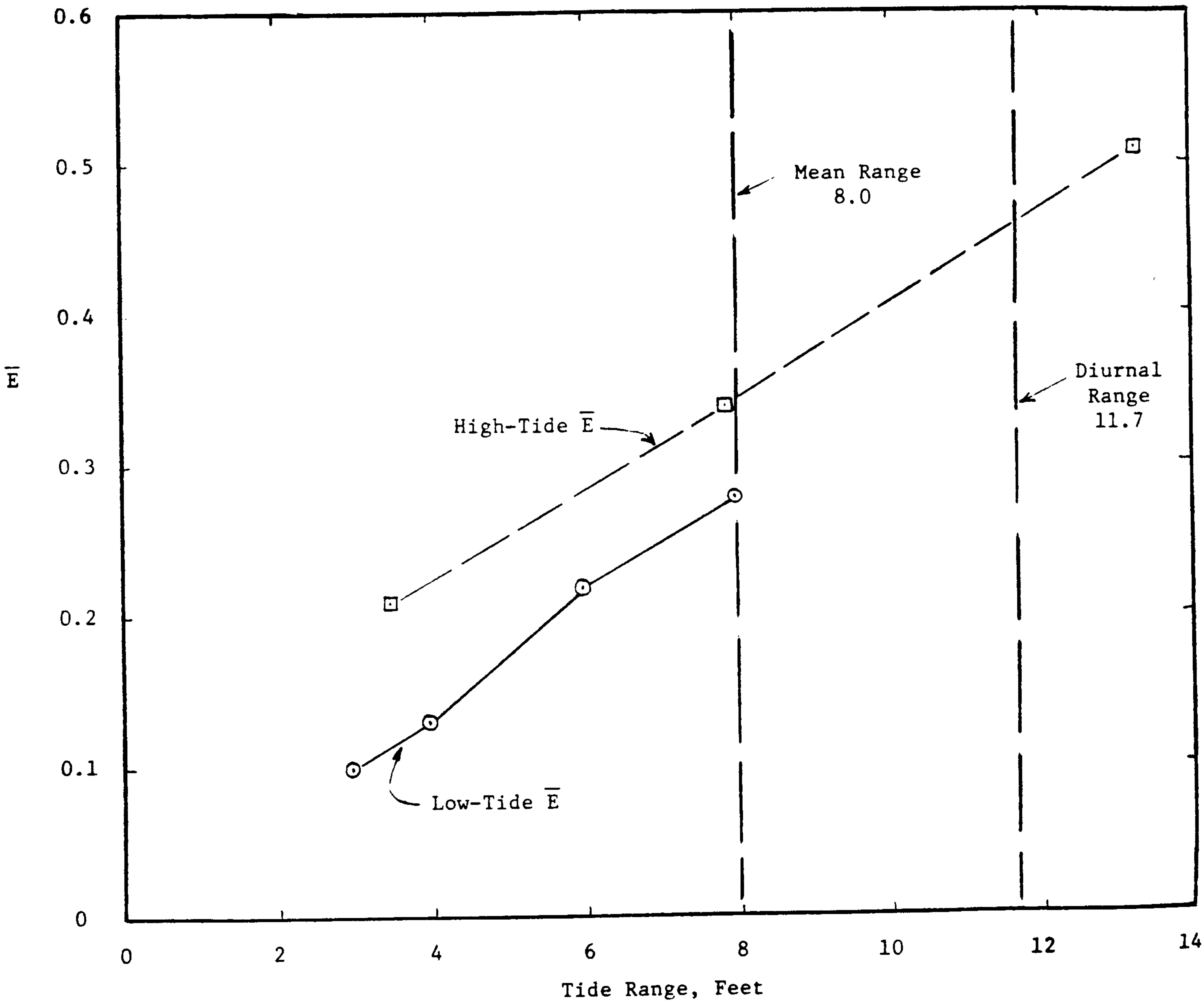
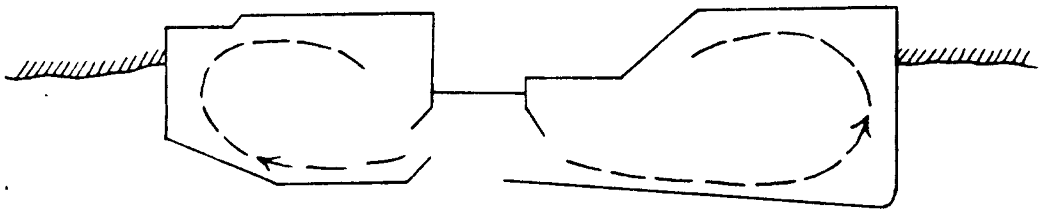


Figure 9. $\overline{E}$ vs. Tide Range, Des Moines Marina

sketch below (Nece and Knoll, 1974).



Differences in the behavior of the Des Moines and Edmonds flushing behavior are apparent. In each of the two basins at Edmonds, it is noted that high local E values (Figure 10) are present in the innermost parts of the basins, farthest from the entrance. The low-tide E values indicate the location of larger concentrations of "new" water, and show that much of the water entering on the flood has not mixed fully and is located far from the entrance at low water slack.

Evidently three of the five sampling stations were located at the perimeter of a gyre, and in the path swept out by the flood flow jet, and as a consequence had E values generally higher than $\overline{E}$ for the respective tides. Again, changes in jet penetration patterns with tide range R can be inferred from Figure 11. The sampling stations on the whole gave indications of higher than average exchange rates. It would have been better if one station had been located in the more clearly discernable gyre center in the north basin, for example (refer to Figure 3).

Figure 10 shows that the entire marina participates directly in the tidal process. Consequently, the $\overline{E}$ behavior is much different than at Des Moines, and as shown in Figure 12 there is much less difference at mean and lower tide ranges in the $\overline{E}$ values based on low tide and high tide evaluations. For the smallest tides the same arguments applicable to small-range exchange

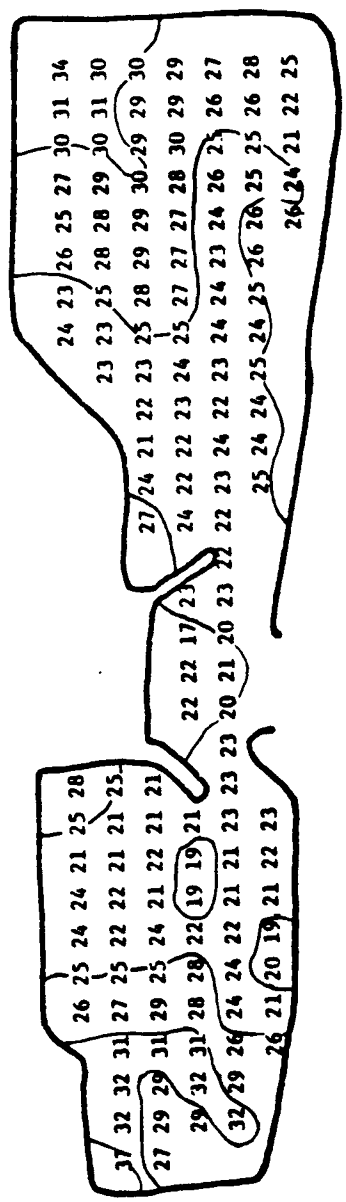
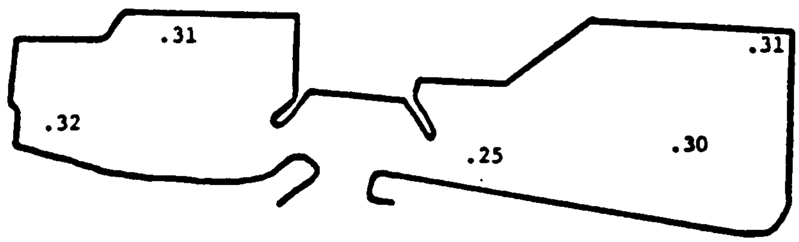
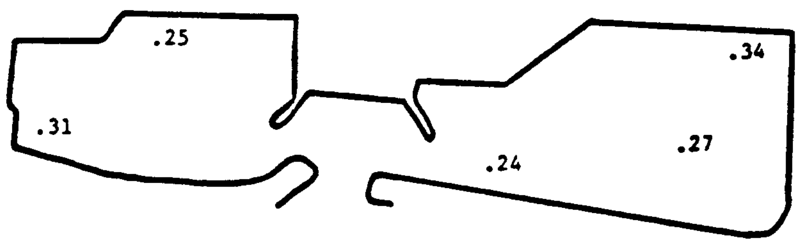


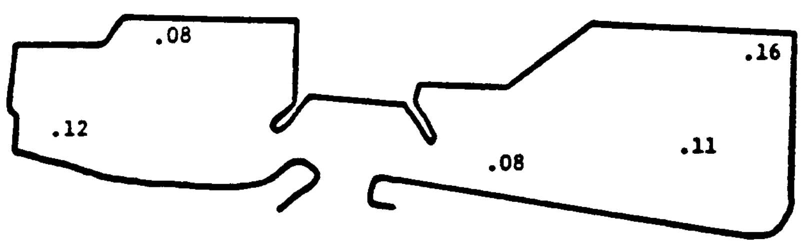
Figure 10. Edmonds Marina Local Exchange Coefficients R = 6' $\overline{E}$ = 0.26



R = 9' $\overline{E}$ = .30



R = 6' $\overline{E}$ = .26



R = 3' $\overline{E}$ = .12

Figure 11. Edmonds Marina Exchange Coefficients $\overline{E}$ and E at Sampling Locations

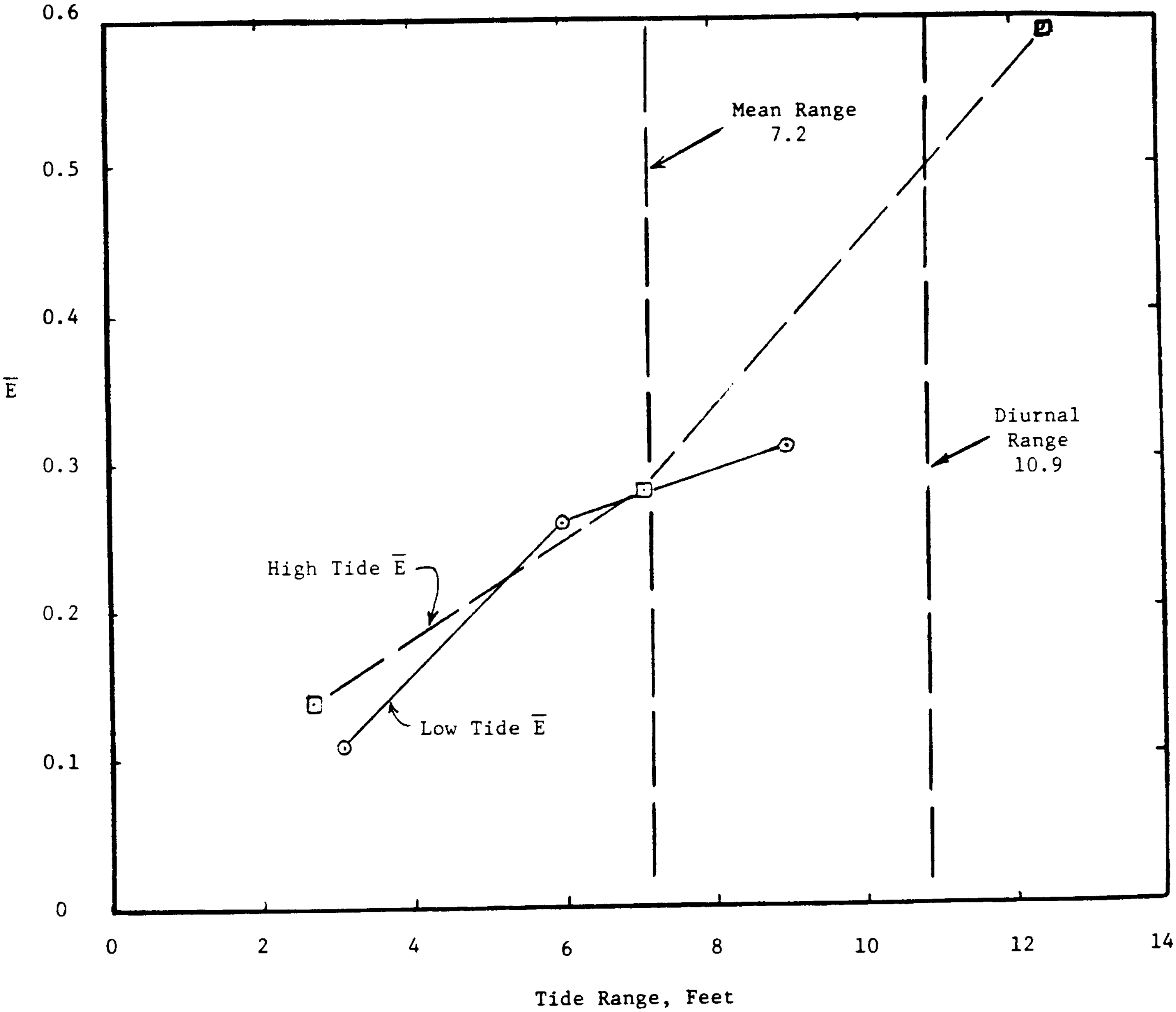


Figure 12. $\overline{E}$ vs. Tide Range, Edmonds Marina efficiency η at Des Moines apply to Edmonds, but to a lesser extent. Again, it should be noted that the high tide values shown on Figure 12 and in Table 2 were based on tide conditions determined using the same procedures, as discussed above, for Des Moines, with predicted tide conditions for Seattle being corrected to Edmonds (Knoll, 1974). The "average" values (7.1-foot range, 6.57-foot mean tide level) so determined are close to the respective values of 7.2 and 6.4 feet used in the present study, so again do not have to be considered in interpretation of test results.

Squalicum

Results are presented in Figures 13 through 15, and in Table 3. The data from the present study are the only ones for the existing basin.

The flow pattern in the marina is shown schematically in the sketch below; it is essentially a two-gyre pattern, with one gyre in each of the two portions of the harbor which connect with their respective entrances.

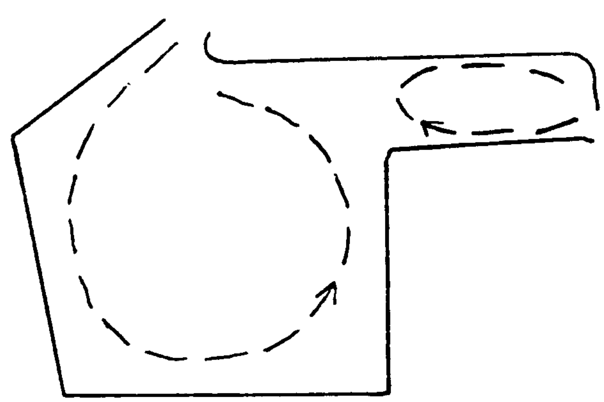


Figure 13 indicates that with the exception of the rear corner the local exchange is quite uniform over the larger of the two basins comprising the harbor. The planform arrangement of the basin and its entrance approaches an optimum configuration for single-entrance marinas (Nece, et al., 1979).

The two gyres, of unequal strength and size, do have naturally induced circulation directions which augment each other.

There has been no unanimity of opinion about the benefits of having more than one entrance to a marina. The State of Washington Department of Fisheries (1971), in developing criteria governing the design of new marinas, included the following proposal: "In the event a marina is constructed shoreward of the natural pre-existing beach line, there shall be no less than two breaches. Elsewhere, the following comments have been advanced (Nece, et al., 1979): "In general, two-entrance basins would be very sensitive to effects of persistent longshore currents ... Short-circuiting could exist if the currents are primarily uni-directional. Generalizations are dangerous for multi-entrance basins, because the interior circulation patterns are sensitive to local head levels which result from the physical configurations of the entrances, near shore, and details of the longshore current patterns."

The relatively good flushing performance of the Squalicum configuration does not contradict the above. Exterior currents in the model study were weak, so flow patterns were governed by the harbor geometry. If the multiple gyres in a two-entrance marina have opposing circulation directions instead of the supportive directions present at Squalicum, regions of poor exchange ("hot spots") could readily occur within the marina.

Most of the basin participates directly in the tidal exchange process. The harbor is relatively deep, and as a consequence the TPR values are low. The high η values indicate that during the tidal cycle "old" basin water is moved about in such a way that enough of it is exhausted on the ebb, for the high and low tide ranges tested, to produce net exchanges greater than predicted by the simple tidal prism model.

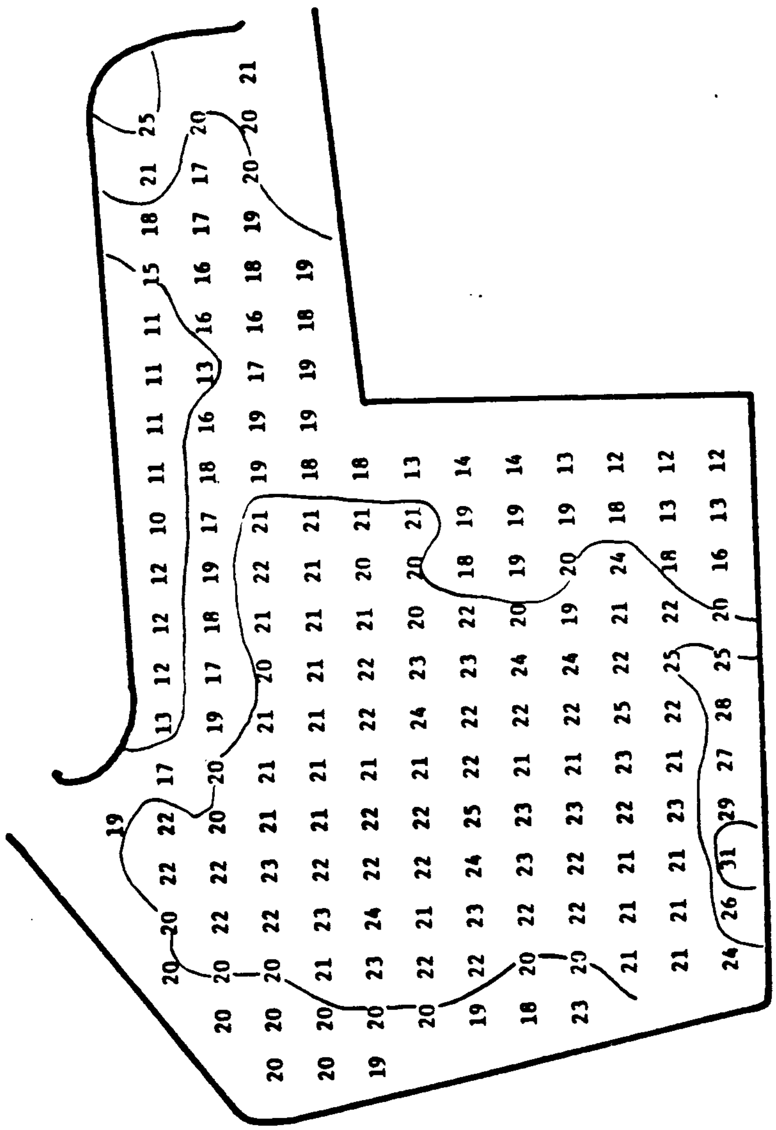


Figure 13. Squalicum Small Boat Harbor Local Exchange Coefficients
$R = 5'$ $\overline{E} = 0.21$

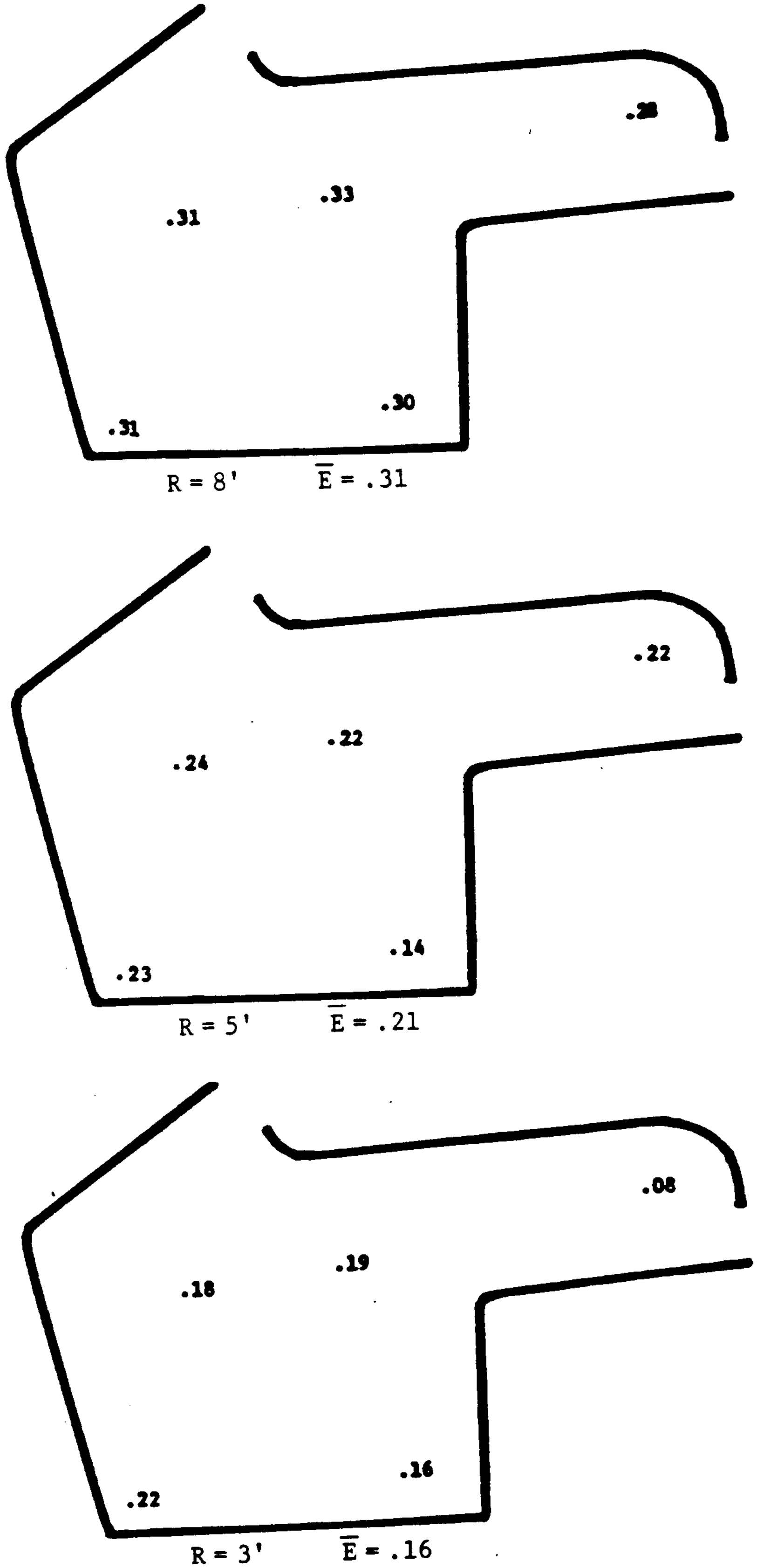


Figure 14. Squalicum Small Boat Harbor Exchange Coefficients $\overline{E}$ and E at Sampling Station Locations

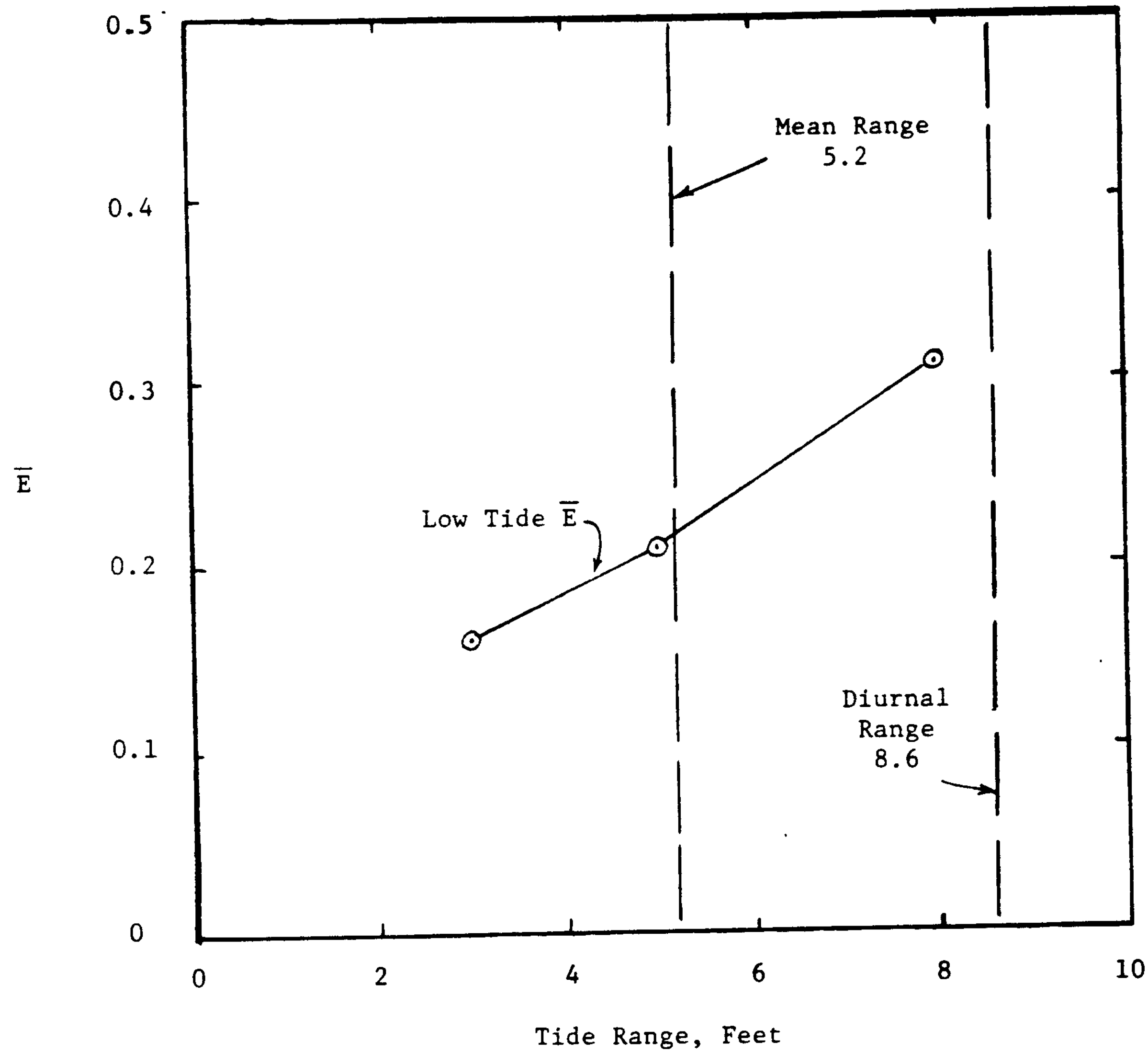


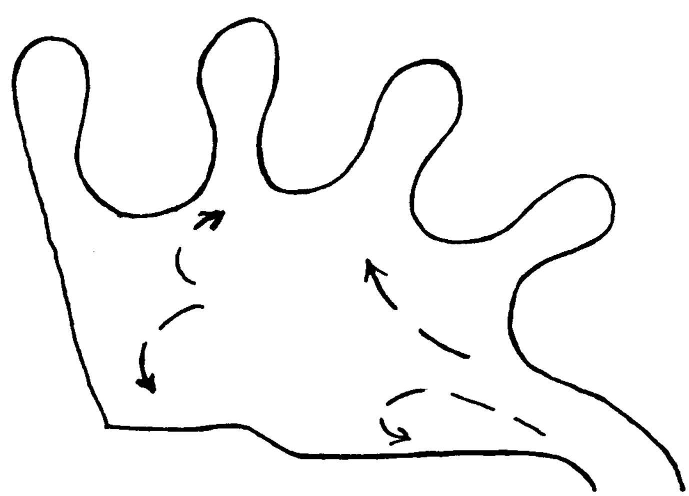
Figure 15. $\overline{E}$ vs. Tide Range, Squalicum Small Boat Harbor

Because of the relatively uniform exchange in the larger basin, the four sampling stations there did not provide much of a range in local E values, even though two of these stations were in the central region of the gyre, one was in the path of the flood jet, and one (in the rear corner) may have been subject to separation of the jet from the northeast boundary of the large basin (refer to Figure 4).

Flounder Bay

Results are presented in Figures 16 through 18, and in Table 4. The earlier tests were made with the same model used in the present study and also were conducted using the low tide evaluation for exchange coefficients; the only difference is that in the present study the harbor inlet was enlarged to match the prototype changes made between the earlier model studies and the 1979 field measurements.

The flood flow "gyre" pattern in the basin is shown schematically in the sketch below. There is no predominate single circulation cell in the harbor.



The high local values of E shown on Figure 16 inside the entrance on the southern edge of the marina (refer to Figure 5) reflect the presence of the small separation cell inside the entrance. The mixing in the main part of the harbor is reasonably uniform, and the single sampling station in this area reflects the overall $\overline{E}$ quite well.

The local E values in the two lobes farthest from the entrance are low, perhaps predictably so. The second most easterly lobe has the highest value of E of the four lobes; it also appears to be most directly impacted by water from the harbor entrance. The innermost lobes exchange with the main central basin and do not exchange directly with the external, ambient waters. The sampling stations provide a good range of local E values.

The results for the original entrance and dredged entrance tests shown on Figure 17 indicate that the dredging has slightly reduced the overall tidal exchange. Enlarging the cross-sectional entrance of the marina reduces the momentum of the flood tide inflow and hence alters the penetration and circulation characteristics of the flood jet. Again, as appears to be the case at the higher tide ranges, the resulting changes in the flow patterns and consequent changes in $\overline{E}$ can be quite sensitive. One example of this is the presence of the high E values inside the entrance at the southern border of the marina, noted above. The exchange contour plot for the same tide range but with the original entrance (Nece and Richey, 1979) indicated low local E values in the same area. These changes would appear to be associated with the momentum of the flood inflow and its consequent effects on the behavior of the separation cell. It is apparent that rather subtle boundary changes in complex-geometry harbors can produce some significant changes in internal flow characteristics.

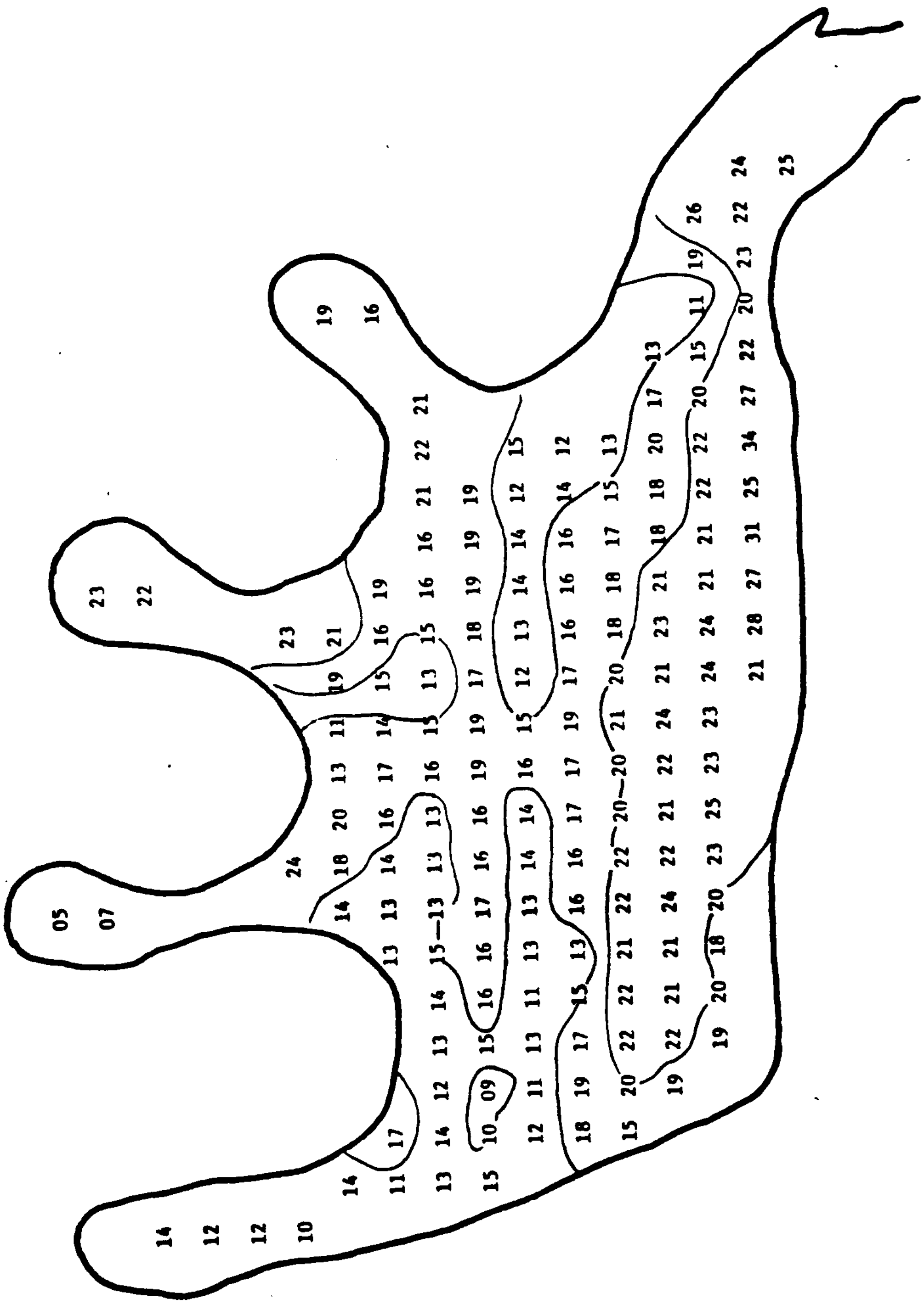


Figure 16. Flounder Bay Local Exchange Coefficients R = 5' $\overline{E} = 0.19$

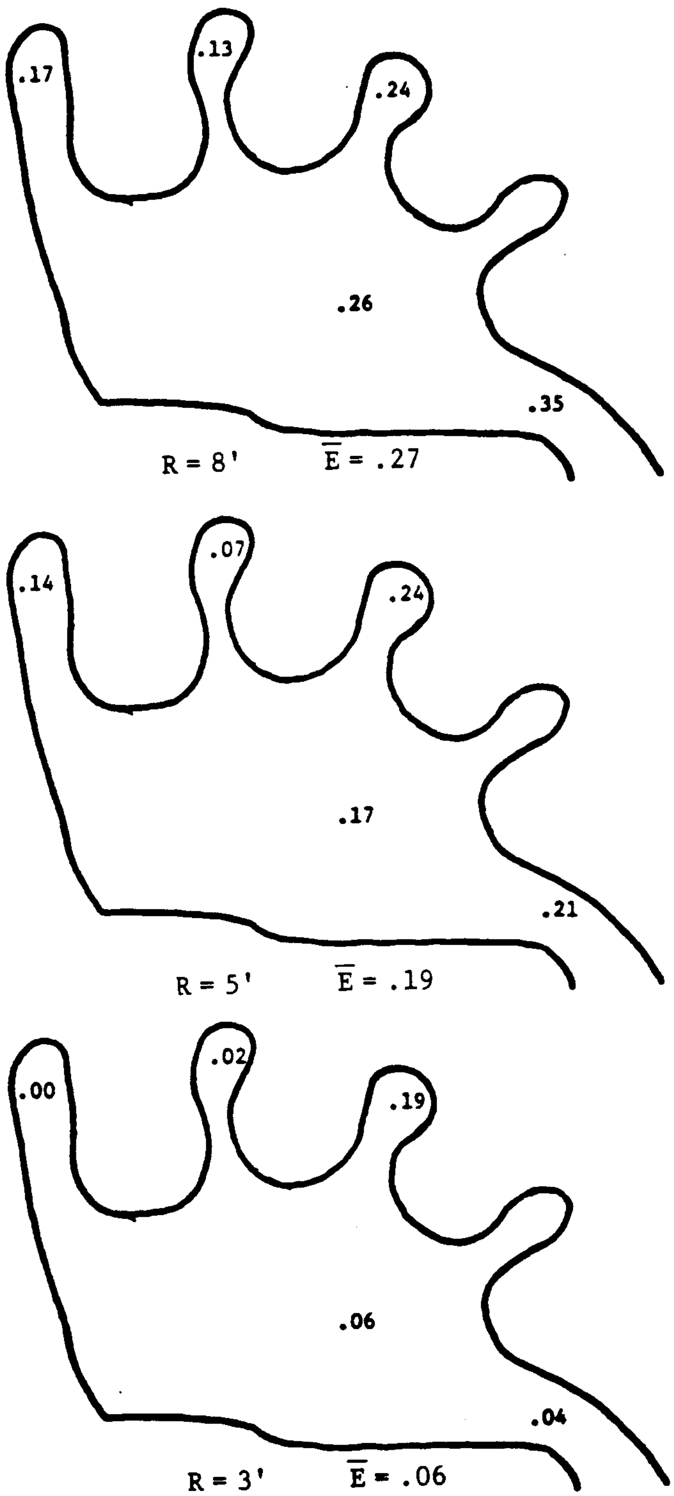


Figure 17. Flounder Bay Exchange Coefficients $\overline{E}$ and E at Sampling Station Locations

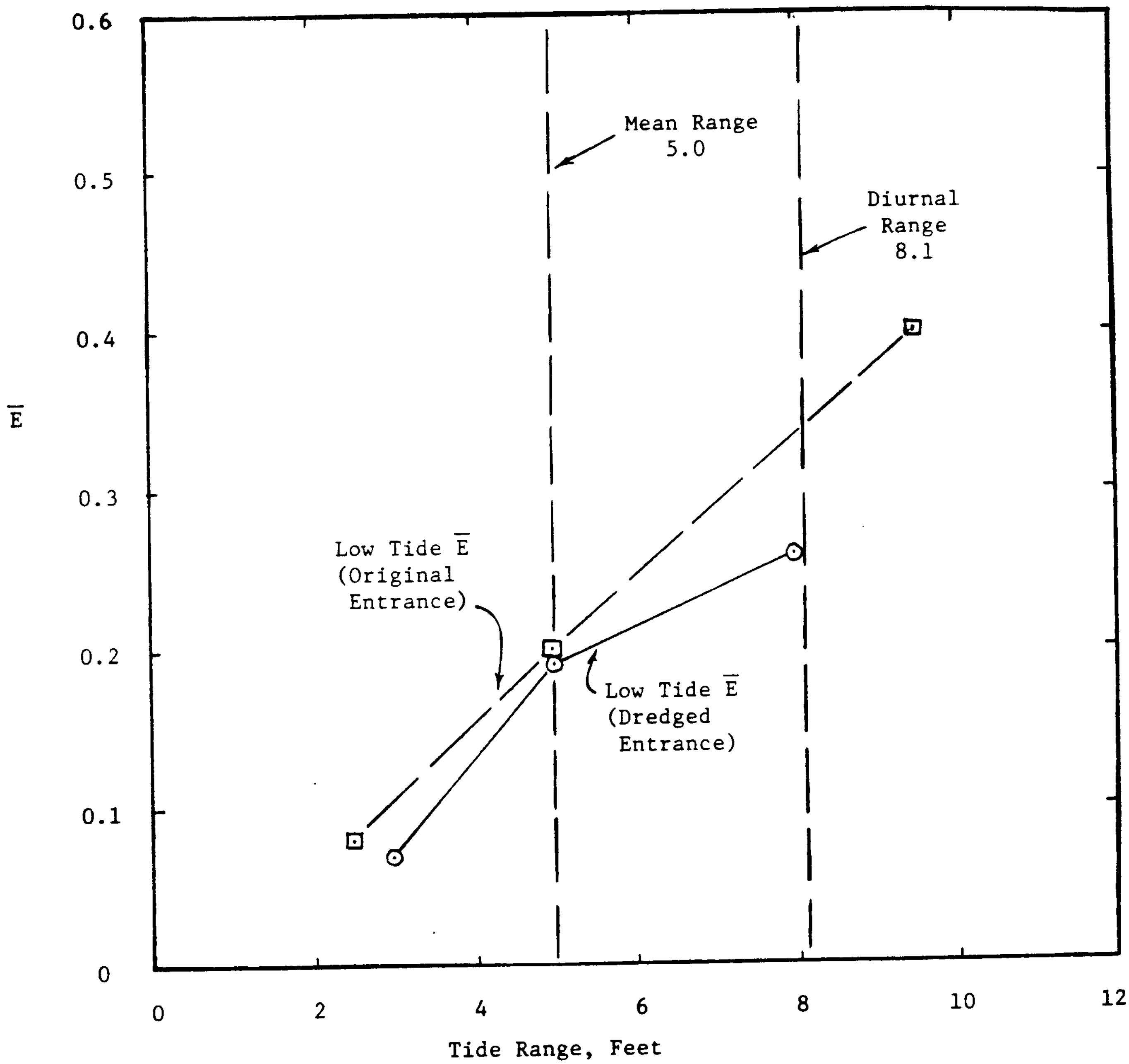


Figure 18. $\overline{E}$ vs. Tide Range, Flounder Bay

Lagoon Point

Results are presented in Figures 19 through 21, and in Table 5.

Lagoon Point Marina is very different from the other four marinas studied. Almost all of the circulatory tidal flow occurs in the header channel; flows in the two canals tend to be more one-dimensional. For this reason, no schematic sketch of the flood tide gyre pattern has been shown. A separation streamline that divides the flood flow through the inlet into two halves intersects the headland between the two canals about midway between the two canals. As a consequence there is more penetration of inflow current momentum into the inshore canal than into the seaward canal.

Relatively little of the total marina participates directly in the tidal exchange process; as a result, the overall $\overline{E}$ values are significantly lower than for the other marinas. Highest local E values occur in the header channel.

As anticipated, there are gradients of local E values along the two canals. These gradients were verified in the earlier fluorescent dye studies, but in a much more gross manner, when each canal was divided into three segments by temporary barrier dams at the end of the test and the water within each of the three sub-areas in each canal was mixed and tested for average concentration of tracer dye. Local exchanges approach zero at the closed ends of the canals, where water horizontal velocities likewise vanish in the unstratified, no wind laboratory model tests. The sampling stations, effectively distributed along the length of the canals, provide a good range of coverage of local E values.

Differences between high tide and low tide condition evaluation of $\overline{E}$ is greater at Lagoon Point than at either Des Moines or Edmonds, the other two marinas for which the comparison may be made. Again, this is due to the

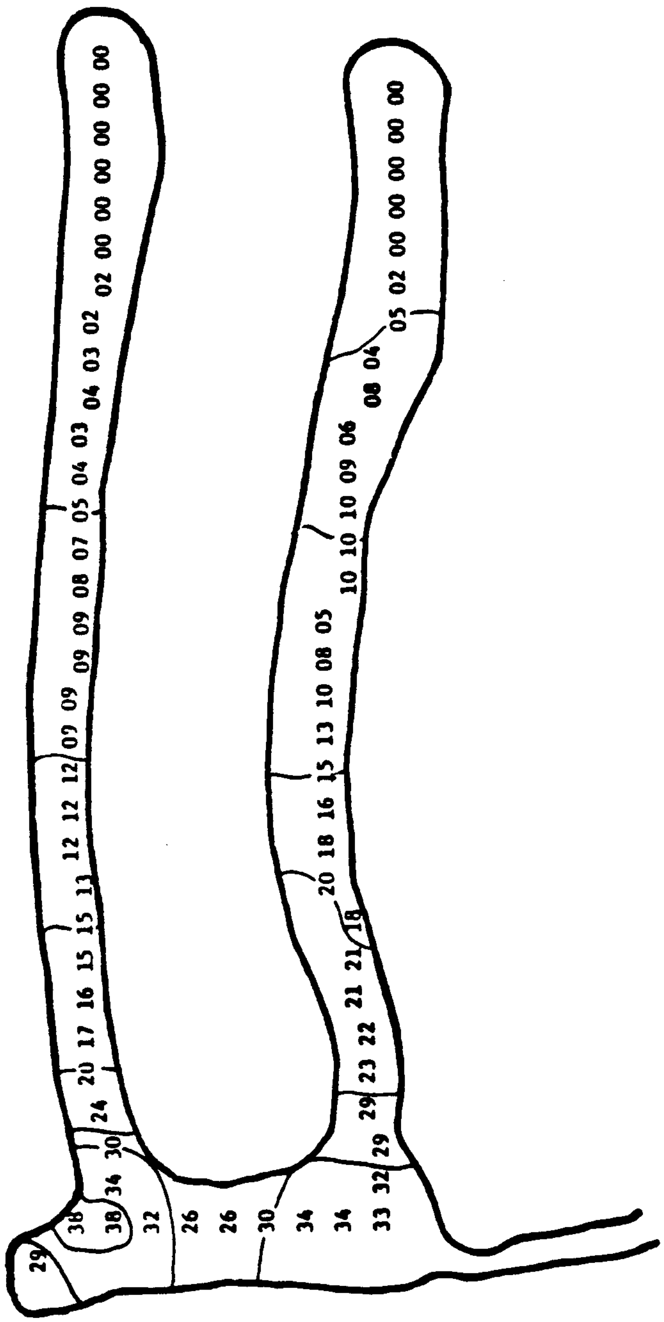


Figure 19. Lagoon Point Marina Local Exchange Coefficients. R = 6' $\overline{E}$ = 0.11

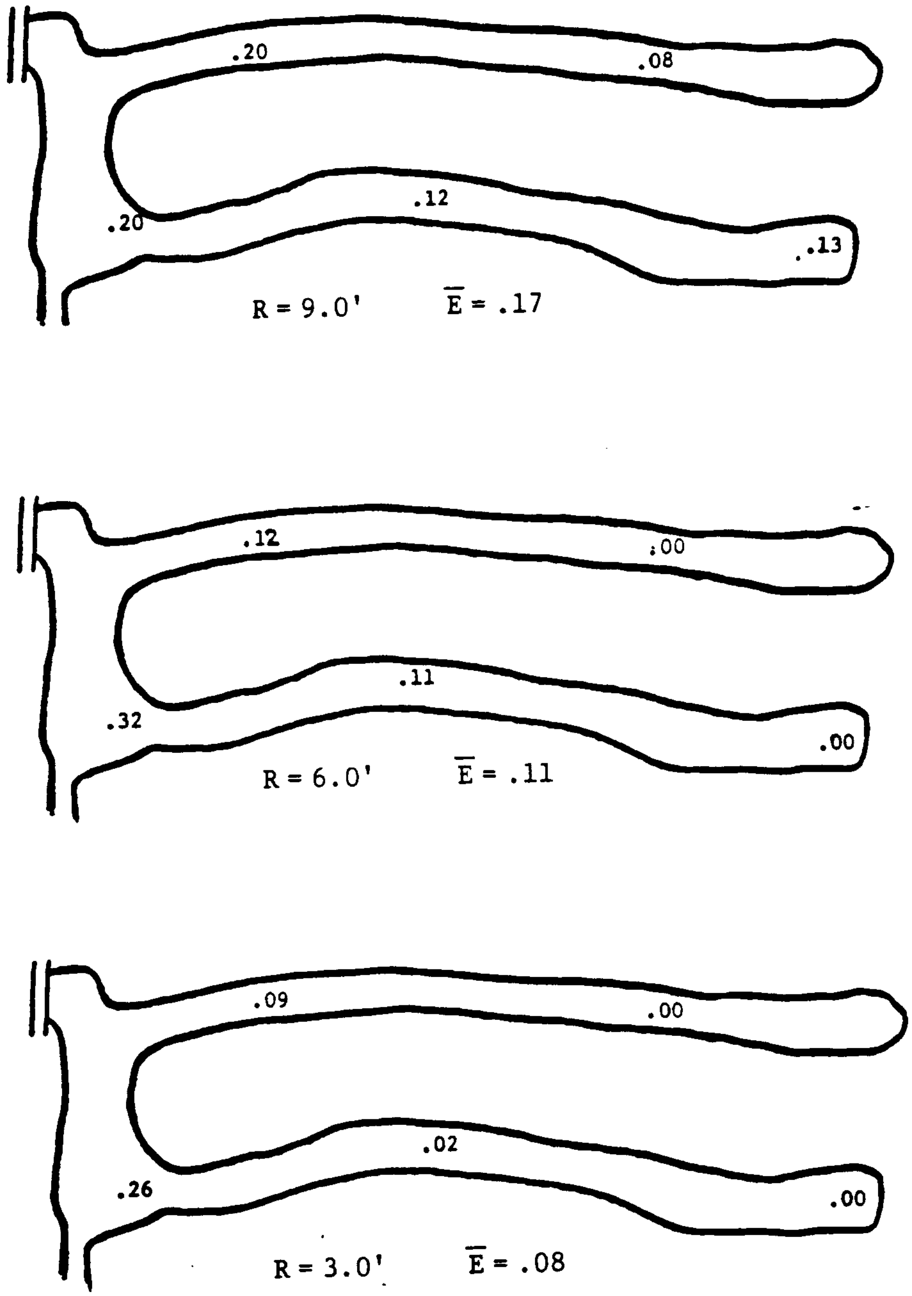


Figure 20. Lagoon Point Marina Exchange Coefficients $\overline{E}$ and E at Sampling Station Locations

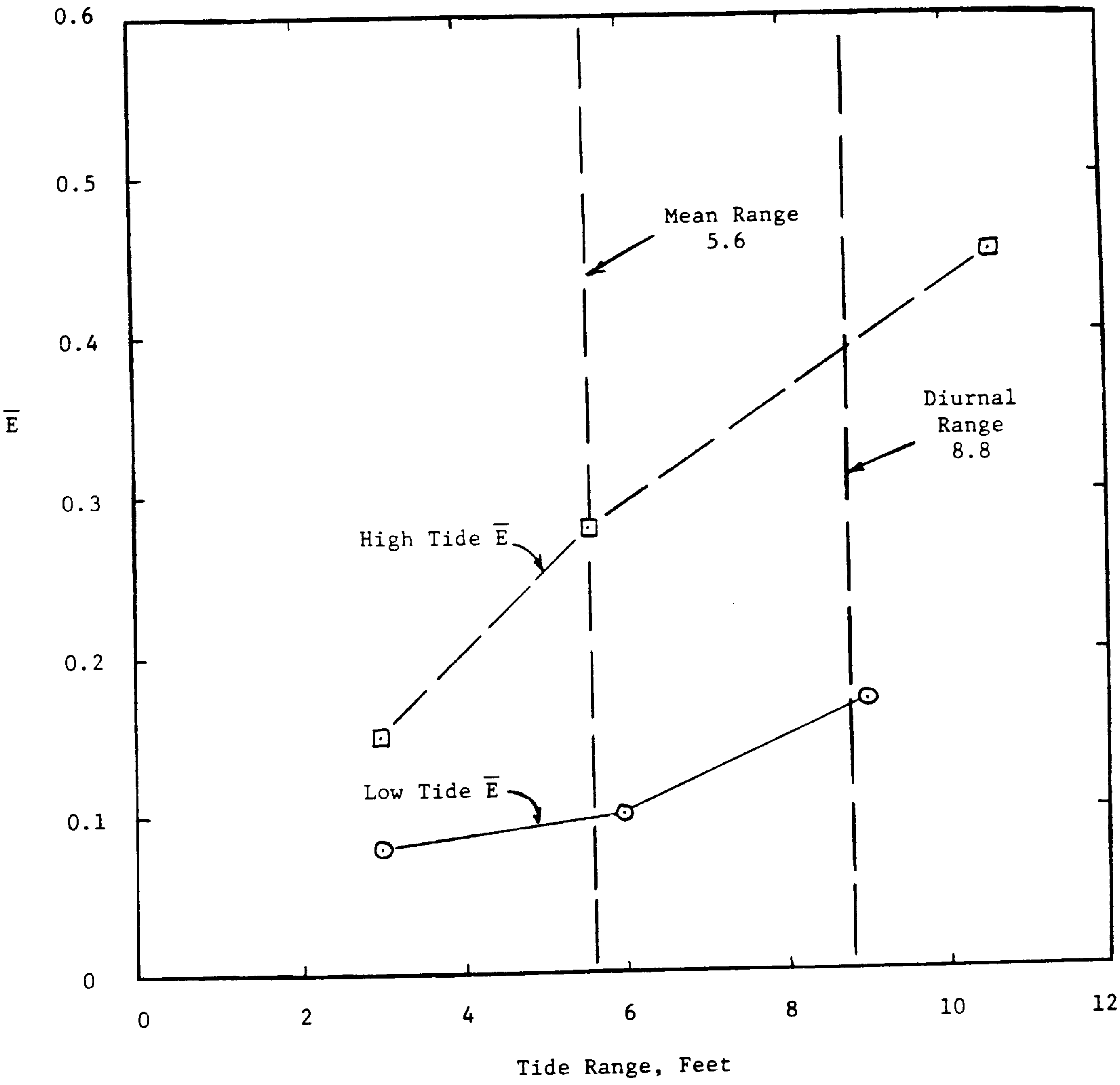


Figure 21. $\overline{E}$ vs. Tide Range, Lagoon Point Marina fact that much of the inflow on the flood tide is confined to the header channel and the connecting ends of the canals and as a consequence has little chance to mix with canal water. Consequently, $\overline{E}$ (and η) values are much higher when based on high tide conditions than when based on low tide conditions, at which time much of this relatively unmixed ambient water has been exhausted from the marina.

V. CONCLUSIONS

Results of the present study and comparisons provided with prior studies reflect changes in approach and experimental techniques in the use of physical hydraulic models for the determination of tidal flushing characteristics of salt water marinas. The present methods and evaluation procedures (e.g., low tide evaluation of $\overline{E}$) provide what is considered to be a consistent and conservative approach.

The approach has been somewhat parochial, conditioned to a large degree by regional interests in maintaining good water quality in marinas because of their potential impact on juvenile migratory salmon runs. The demand for more marinas continues in the Pacific Northwest. State and federal agencies have been active in the region in trying to achieve good marina designs, so tests such as those reported here, along with studies of more generalized planform geometries, have sought to provide the information needed by both designers and regulatory agencies.

The laboratory models will continue to provide information needed for design and decision purposes until economical computer models linking velocity fields and diffusion become available and ultimately, it is hoped, will remove the need for site-specific model studies. The photodensitometer techniques might indeed provide data which, along with velocity measurements, will serve as a basis for evaluating and testing numerical models. As evaluated in this report, the small-scale physical models can be used to provide input in planning field experiments.

The five marinas tested have a fairly wide range in planform geometries. Four of the five (Lagoon Point is the exception) fall within an "envelope" of performance when spatial average flushing is considered; the behavior of the four can be plotted within the envelope formed by the curves $\overline{E} = 0.45R$ and $\overline{E} = 0.30R$, where R is here defined as the tide range. Higher average flushing efficiencies are linked to those marinas where all or nearly all of the basin participates directly in the tidal exchange. This situation occurs when there is a single gyre in each basin or sub-basin connecting directly with an entrance. It has also been noted (Nece, et al., 1979) that this performance occurs where two gyres can occur in a basin with a centrally located entrance; each gyre connects directly with the flood inflow through the entrance.

Comparison of the tidal flushing at Flounder Bay and at Lagoon Point verifies the rather obvious conclusion that residential marinas with long canal-type segments have poor flushing characteristics. In sites such as Lagoon Point much of the flushing near the closed ends of the finger canals must depend on wind-driven circulation. Strictly tidal flushing in such configurations can be estimated by one-dimensional analyses (e.g., Brandsma, et al., 1973; Van de Kreeke and Dean, 1975) if appropriate dispersion coefficients can be selected.

The marinas tested here did behave in ways anticipated from the extrapolation of test results for generalized planform geometries (Nece, et al., 1979). While numerical $\overline{E}$ values for widely varying planform geometries cannot be predicted accurately at this time, enough is now known about relative flushing and internal circulation patterns to identify designs which should be satisfactory from a flushing standpoint and those which are not.

It still remains to link both average and local tidal exchange coefficients to a quantitative comparison of the quality of water within the marina to that of the ambient water. This information, which must be based on actual field sampling, is needed before designs can be evaluated properly and predicted water quality within a proposed marina can be compared against local water quality standards. Correlation with field measurements of water quality parameters is needed in order to answer the question of how significant hydraulic performance (tidal flushing) really is to marina water quality. The State of Washington Department of Fisheries study, the companion to the laboratory studies detailed in this report, was designed to provide such information.

Table 1. Tidal Flushing Characteristics, Des Moines Marina

Prior Results, $\bar{E}$ for High Tide Conditions

Range ft.	TPR	$\bar{E}$	η
3.5	0.17	0.21	1.23
7.9	0.37	0.34	0.94
13.3	0.59	0.51	0.86

Present Study, $\bar{E}$ for Low Tide Conditions

Range ft.	TPR	$\bar{E}$	η
3.0	0.16	0.10	0.63
4.0	0.21	0.13	0.62
6.0	0.29	0.22	0.76
8.0	0.37	0.28	0.76

Table 2. Tidal Flushing Characteristics, Edmonds Marina

Prior Results, $\bar{E}$ for High Tide Conditions

Range ft.	TPR	$\bar{E}$	η
2.7	0.14	0.14	1.00
7.1	0.36	0.28	0.78
12.5	0.59	0.54	0.92

Present Study, $\bar{E}$ for Low Tide Conditions

Range ft.	TPR	$\bar{E}$	η
3.0	0.17	0.11	0.65
6.0	0.31	0.26	0.84
9.0	0.43	0.31	0.72

Table 3. Tidal Flushing Characteristics, Squalicum Small Boat Harbor

Present Study, $\bar{E}$ for Low Tide Conditions

Range ft.	TPR	$\bar{E}$	η
3.0	0.15	0.16	1.07
5.0	0.23	0.21	0.91
8.0	0.35	0.36	1.03

Table 4. Tidal Flushing Characteristics, Flounder Bay

Prior Results, $\bar{E}$ for Low Tide Conditions

Range ft.	TPR	$\bar{E}$	η
2.5	0.17	0.08	0.47
5.0	0.31	0.20	0.65
9.5	0.53	0.40	0.75

Present Study, $\bar{E}$ for Low Tide Conditions

Range ft.	TPR	$\bar{E}$	η
3.0	0.20	0.07	0.35
5.0	0.31	0.19	0.61
8.0	0.46	0.26	0.57

Table 5. Tidal Flushing Characteristics, Lagoon Point Marina

Prior Results, $\bar{E}$ for High Tide Conditions

Range ft.	TPR	$\bar{E}$	η
3.0	0.24	0.15	0.63
5.6	0.39	0.28	0.72
10.6	0.64	0.45	0.70

Present Study, $\bar{E}$ for Low Tide Conditions

Range ft.	TPR	$\bar{E}$	η
3.0	0.23	0.08	0.35
6.0	0.41	0.10	0.24
9.0	0.54	0.17	0.31

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