AN ABSTRACT OF THE THESIS OF

SCOTT MORGAN NOBLE for the degree of MASTER OF OCEAN ENGINEERING

in Civil Engineering presented on September 7, 1976

Title: USE OF BENTHIC SEDIMENTS AS INDICATORS OF MARINA FLUSHING

Redacted for Privacy

Abstract approved:

Dr. Larry S. Slotta

This report presents the findings of a sediment analysis program formulated to determine the flushing potential of various shaped small boat marina basins. Chemical tests regarding volatile solids, Kjeldahl nitrogen, grease and oil, and sulfides were performed with the results compared to established sediment quality criteria. These results were used to estimate the relative state of pollution of several Oregon marinas. Existing criteria were used in normalizing laboratory test results into pollution indices. The marinas were characterized via dimensionless numbers composed of several physical parameters indicative of the basin's geometry on which the flushing ability of estuarine and riverine enclosures might depend.

From a general statistical examination of the benthic sediment quality data, models were developed representing sediment quality indices and flushing phenomena. Comparing the relative differences in pollution indices between stations in one basin provided useful information concerning the confidence that can be regarded about assumptions made in the problem solving technique.

Five dimensionless basin parameters were assigned limiting values that were felt optimum to obtain adequate flushing for marina basins. A nomogram for use in the design process for marina sitings was developed. Using this tool one can predict whether adequate flushing of enclosed basins would be ensured with the effect that existing water quality would be high.

It is felt that this method of research, using sediments in describing a hydraulic system, has a potential for further use in examining marina flushing ability. Suggestions for future work are proposed.

Use of Benthic Sediments as Indicators of Marina Flushing

by

Scott Morgan Noble

A THESIS

submitted to

Oregon State University

in partial fulfillment of
the requirements for the
degree of

Master of Ocean Engineering

Completion September 7, 1976

Commencement June 1977

APPROVED:

Redacted for Privacy

Professor of Civil Engineering
in charge of major

Redacted for Privacy

Head of Department of Civil Engineering

Redacted for Privacy

Dean of Graduate School

Date thesis is presented September 7, 1976

Typed by Deanna L. Cramer for Scott M. Noble

ACKNOWLEDGEMENTS

I wish to express my appreciation to Maryann and Erin, my wife and daughter, for continued encouragement throughout the three years I have been at Oregon State University, and especially Maryann's help in editing segments of my thesis and booting me out of the house at all hours of the night so I would complete my research on time. I also want to acknowledge the support of my mother, father, sisters and brothers in reassuring me that I would make it, and the occasional and timely support needed to continue.

Scholastically, I want to thank Dr. Larry S. Slotta for his helpful suggestions, continued encouragement and support in my thesis endeavor. Also, in regard to my thesis, I appreciate the help provided by Dr. Ken Williamson during the sample testing, Dr. Dave Thomas for helpful suggestions concerning the statistical analyses, Craig Delphey for doing the total sulfides analysis when I was running short on time, and Scott Boley and Shirly Tang for collecting the sediment samples. In general, I want to thank the Ocean Engineering and Civil Engineering staff for providing me with an exceptional education.

Not least of all, a substantial help to me over the past year has been the Environmental Protection Agency Trainee position I have held.

ENGLISH - SI CONVERSION FACTORS

To convert	To	Multiply by
Meters (m)	feet (ft)	3.28
Square meters (m^2)	square feet (ft^2)	10.76
Cubic meters (m^3)	cubic feet (ft^3)	35.31

TABLE OF CONTENTS

APPENDICES

LIST OF TABLES

LIST OF FIGURES

List of Figures (continued)

Use of Benthic Sediments as Indicators of Marina Flushing

INTRODUCTION

This study is an attempt to unfold the important functions of small scale estuarine circulation patterns by using benthic sediments as indicators of marina flushing. Specifically, the research has tried to identify physical parameters that are influential in providing the flushing necessary to preserve a high state of water quality within small estuarine marina basins. In the quest to accomplish this goal, a modus operandi other than a classical engineering approach of strict fluid mechanics has been employed.

With the ever increasing interest in estuaries and coastal shorelines, and the desire to be able to control or predict the effect of man's inputs into these systems, the interest in the importance of small basins as a pollutant trap has intensified. The historical approach to the design of small boat marinas has been dominantly to provide the best protection from the environment as possible. The best marina has been a calm one, where it makes all the difference between disaster and success in launching, loading, boarding, mooring, and maneuvering a boat. As the emphasis on clear waters has increased, it has come to the forefront in marina management that because marinas were designed for the greatest protection, they also inherently were designed for the lowest amount of recirculation with the main body of water. As a consequence, boat basins in most cases act as a temporary or permanent sink for material in suspension or in solution which might wander into its protected area. The current attempt is to try and determine basin shapes that will be best for recirculation capabilities while still maintaining adequate protection.

Most engineering approaches in studying this problem would undertake a field study of the basin hydraulics and/or a mathematical model of the hydraulic system. As a different approach, this study examines sediment characteristics to determine whether the flushing potential of a number of Pacific Northwest marina basins could be isolated on the basis of marina geometry. Sediment samples were taken from thirteen marinas along the Oregon coast, all within the confines of an estuary or at least an enclosed bay. Table 1 lists the marinas, by a common name they were referred to throughout the whole study and the estuary or bay in which they exist. Figure 1 shows the location along the Oregon coast where the marinas are located. Figures 2 through 14 show plan views of the

Table 1. Marinas studied.

Name	Location
Astoria	Columbia River - Youngs Bay
Hammond	Columbia River - Youngs Bay
Garibaldi	Tillamook Bay
Netarts	Netarts Bay
Depoe Bay	Depoe Bay
Newport	Yaquina Bay
Waldport	Alsea Bay
Florence	Siuslaw River
Winchester Bay	Umpqua River
Charleston	Coos Bay
Bandon	Coquille River
Gold Beach	Rogue River
Brookings	Chetco River

marinas with respect to the associated main body of water and the locations where the sediment samples were taken.

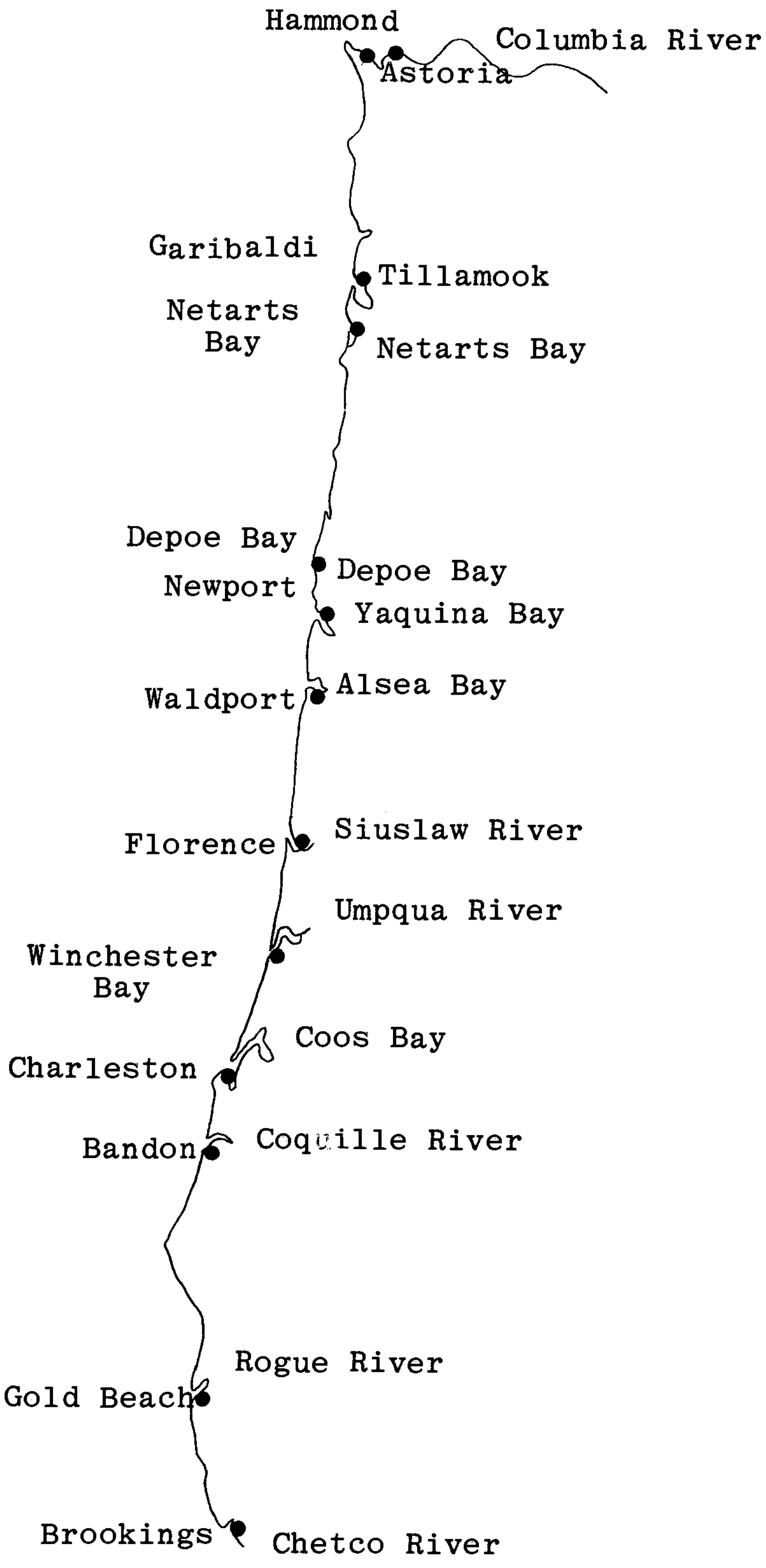

Figure 1. Marina location map.

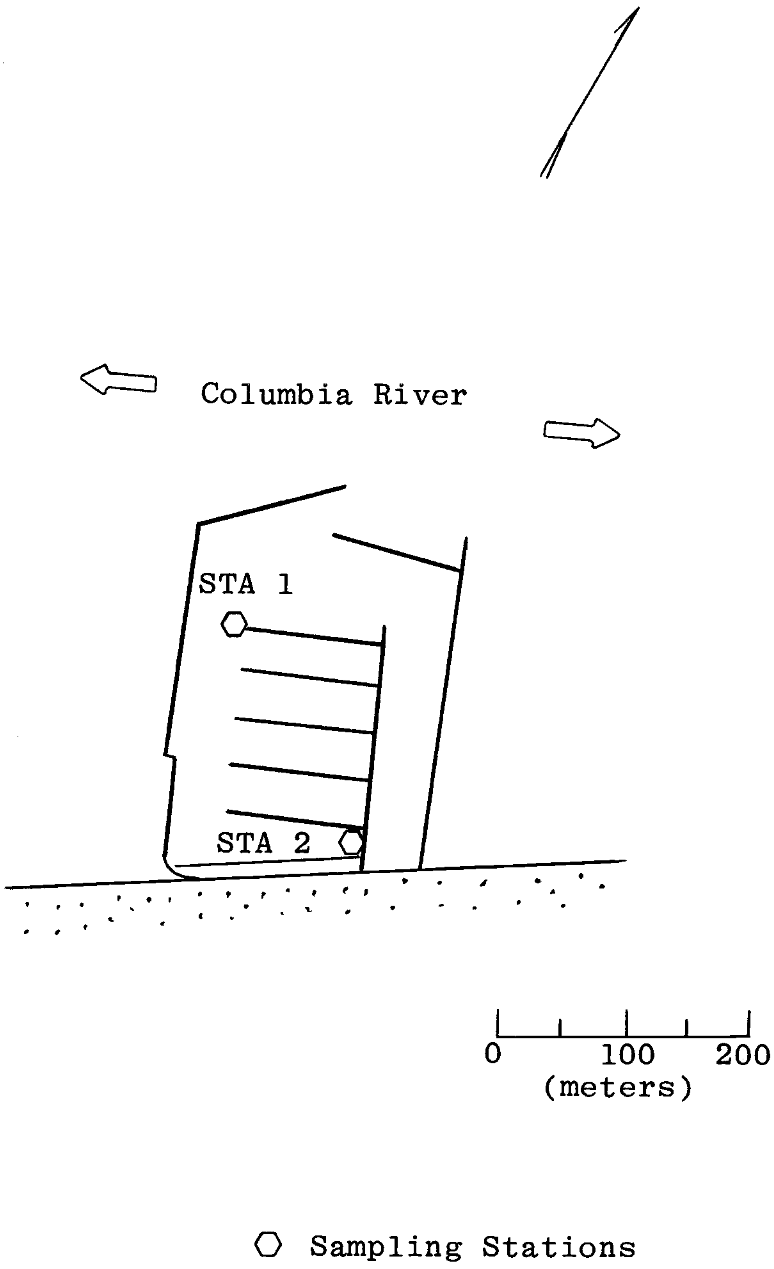

Figure 2. Astoria marina.

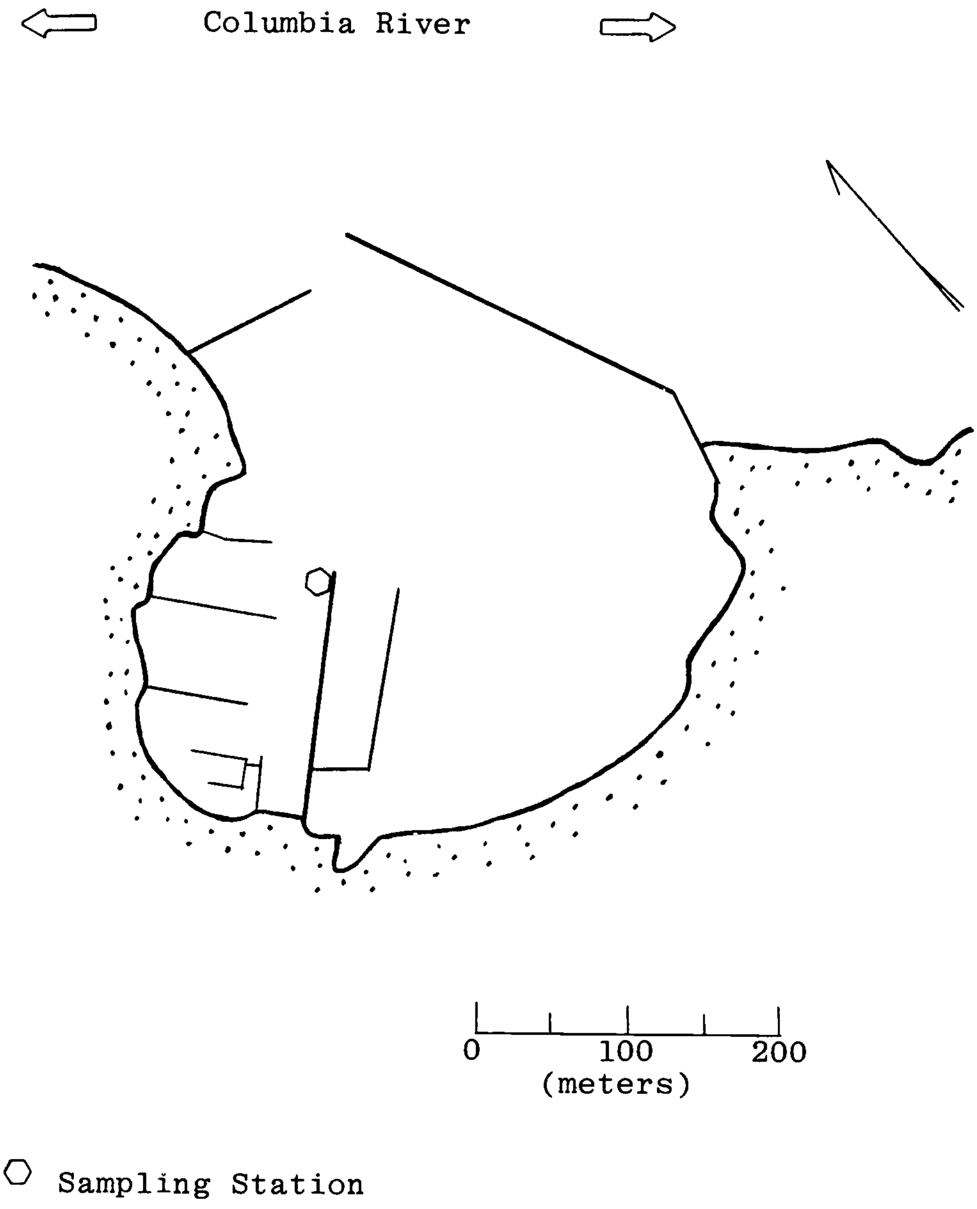

Figure 3. Hammond marina (U.S. Army Corps of Engineers, 1976).

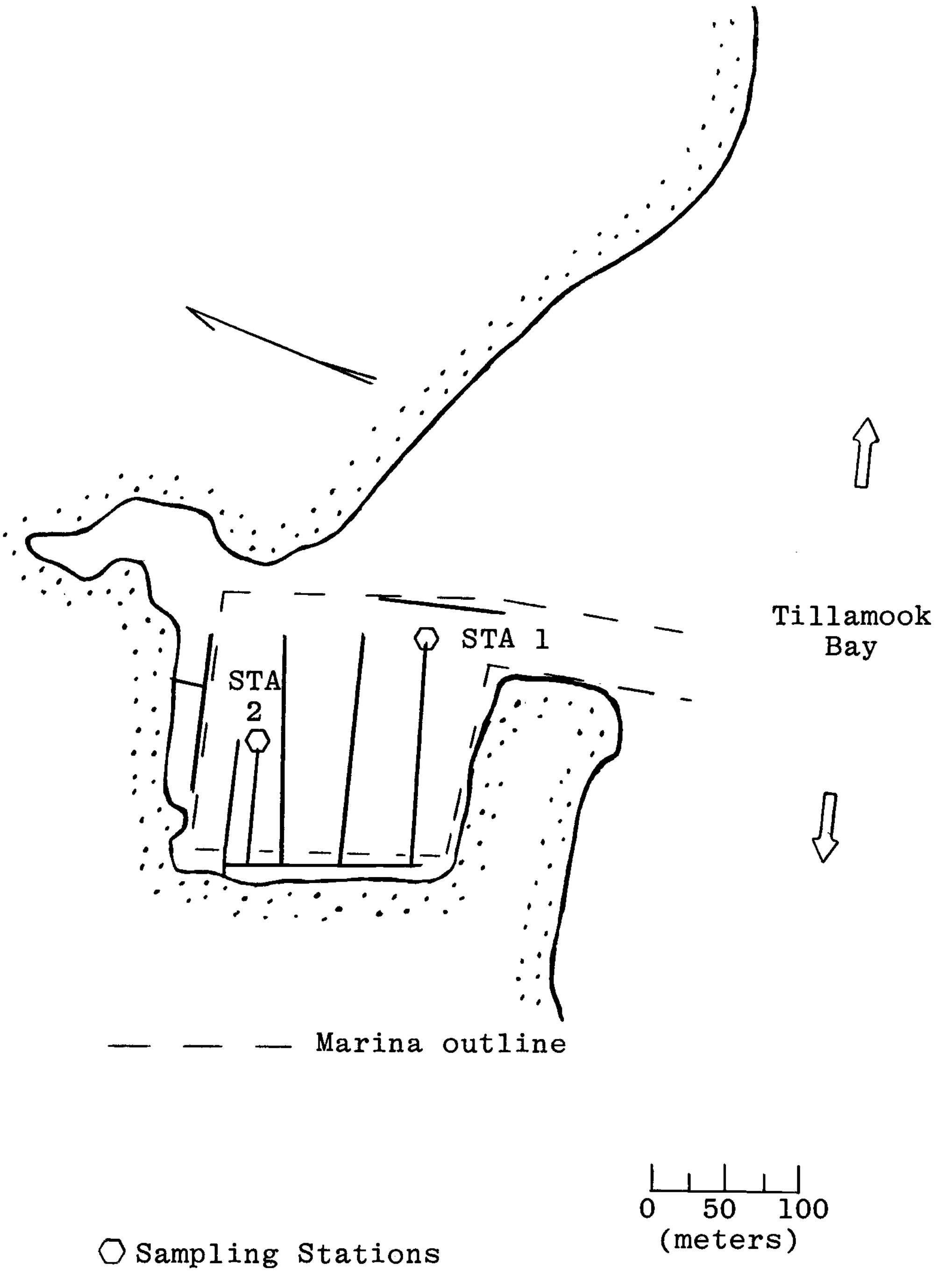

Figure 4. Garibaldi marina (U.S. Army Corps of Engineers, 1974).

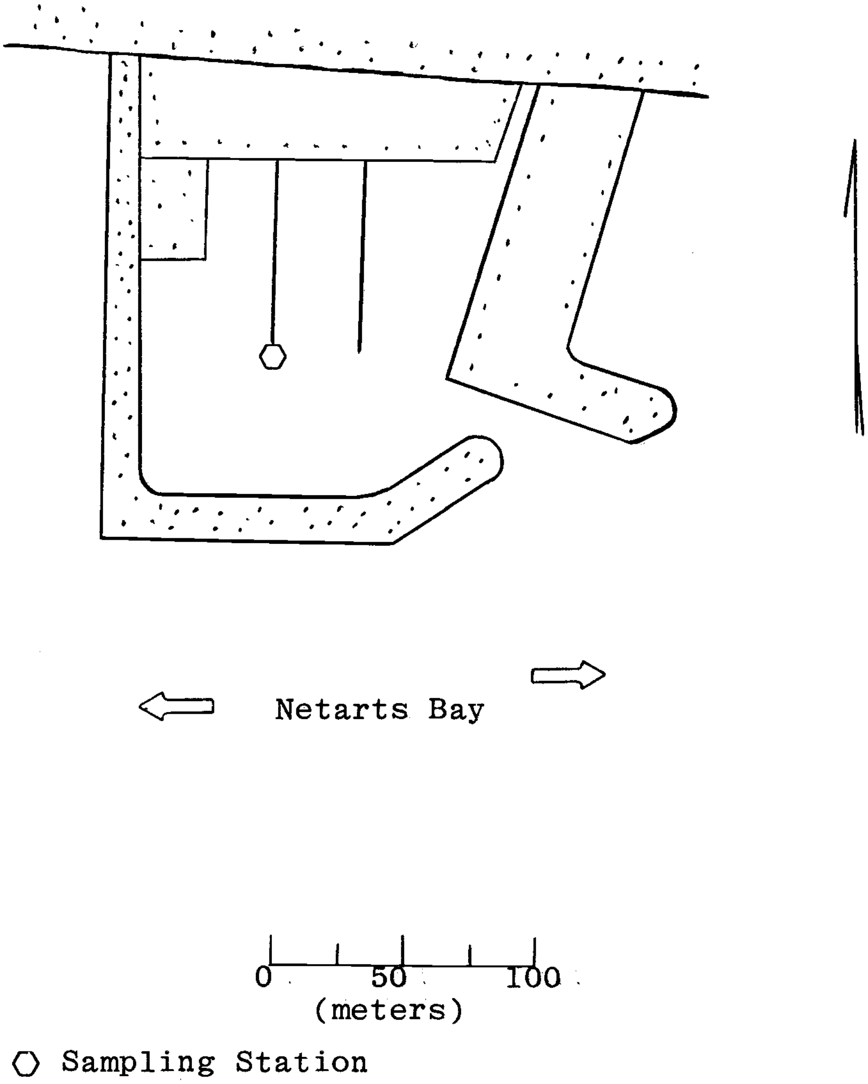

Figure 5. Netarts Bay marina (Plan of Netarts Moorage Basin, 1960).

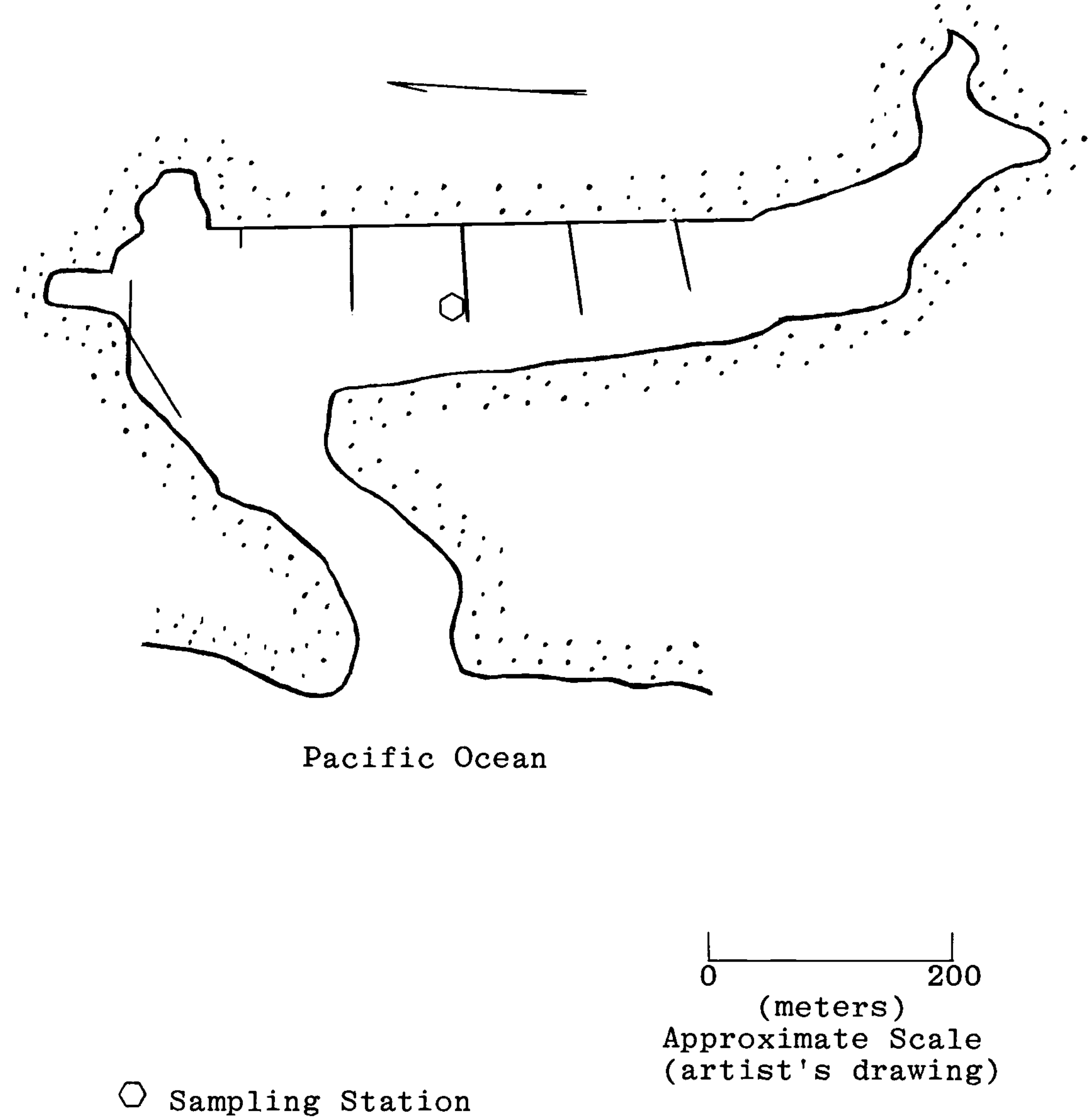

Figure 6. Depoe Bay marina (State of Oregon Division of Lands, 1975).

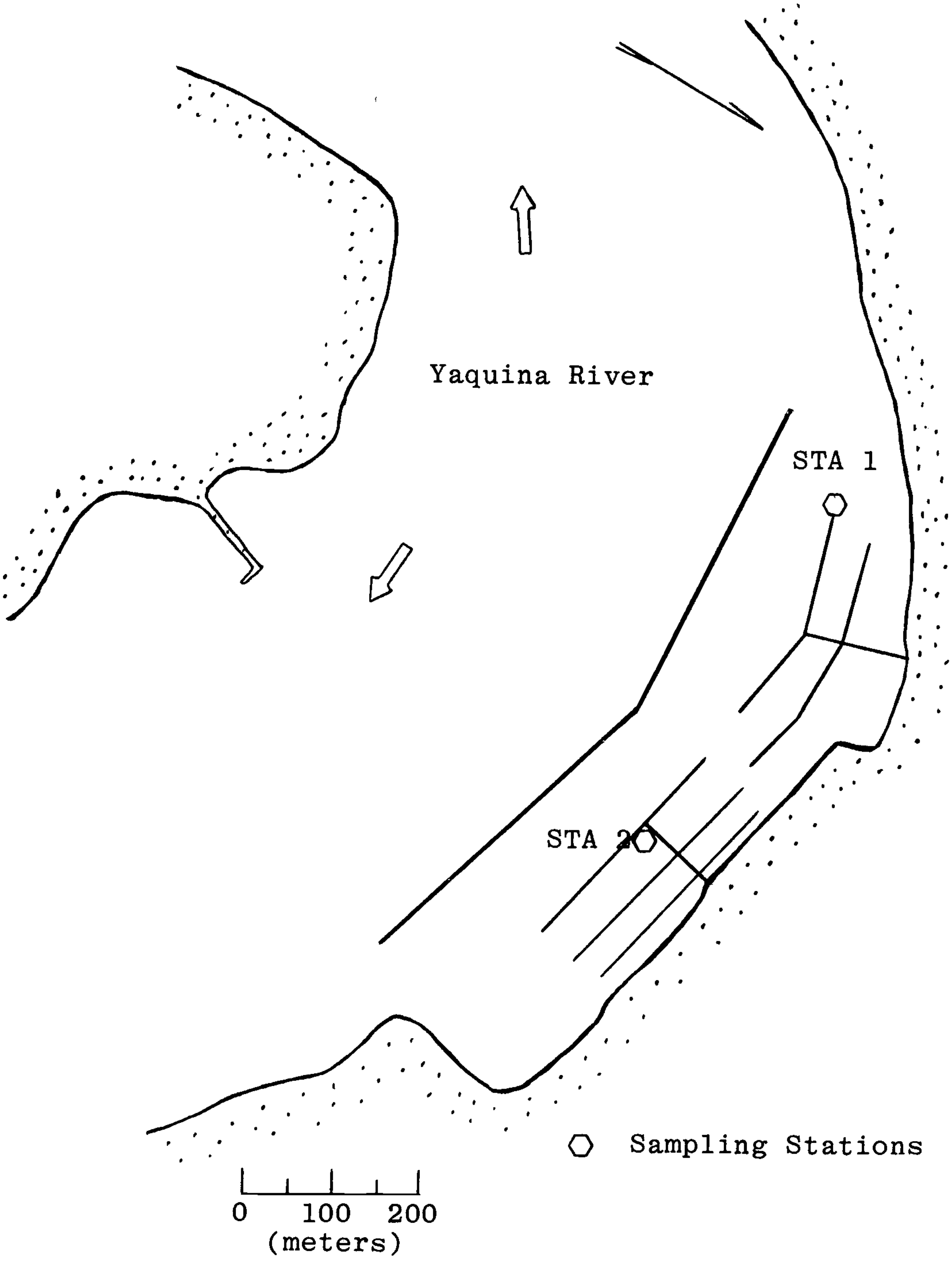

Figure 7. Newport marina (U.S. Army Corps of Engineers, 1974).

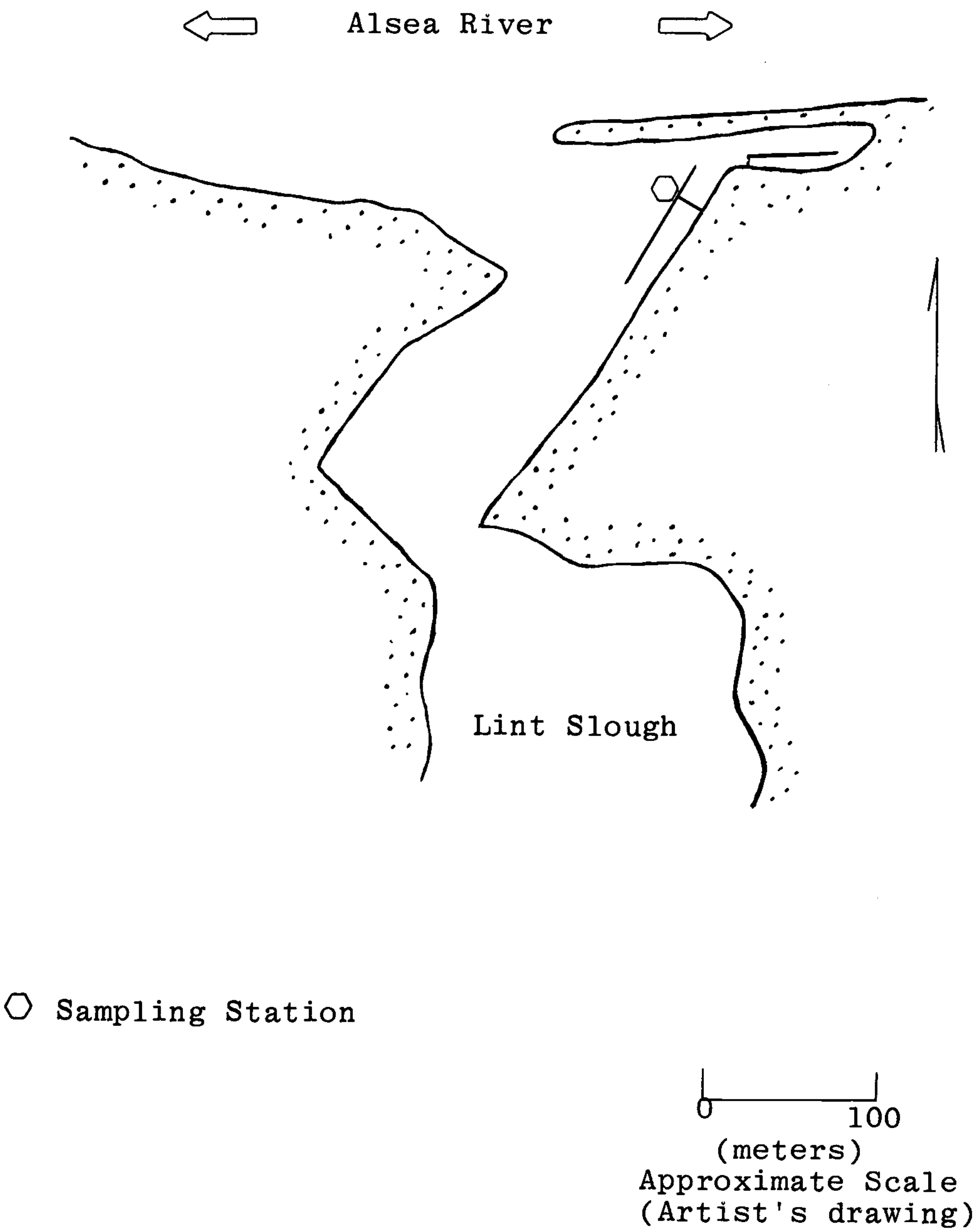

Figure 8. Waldport marina (only part of Lint Slough is shown).

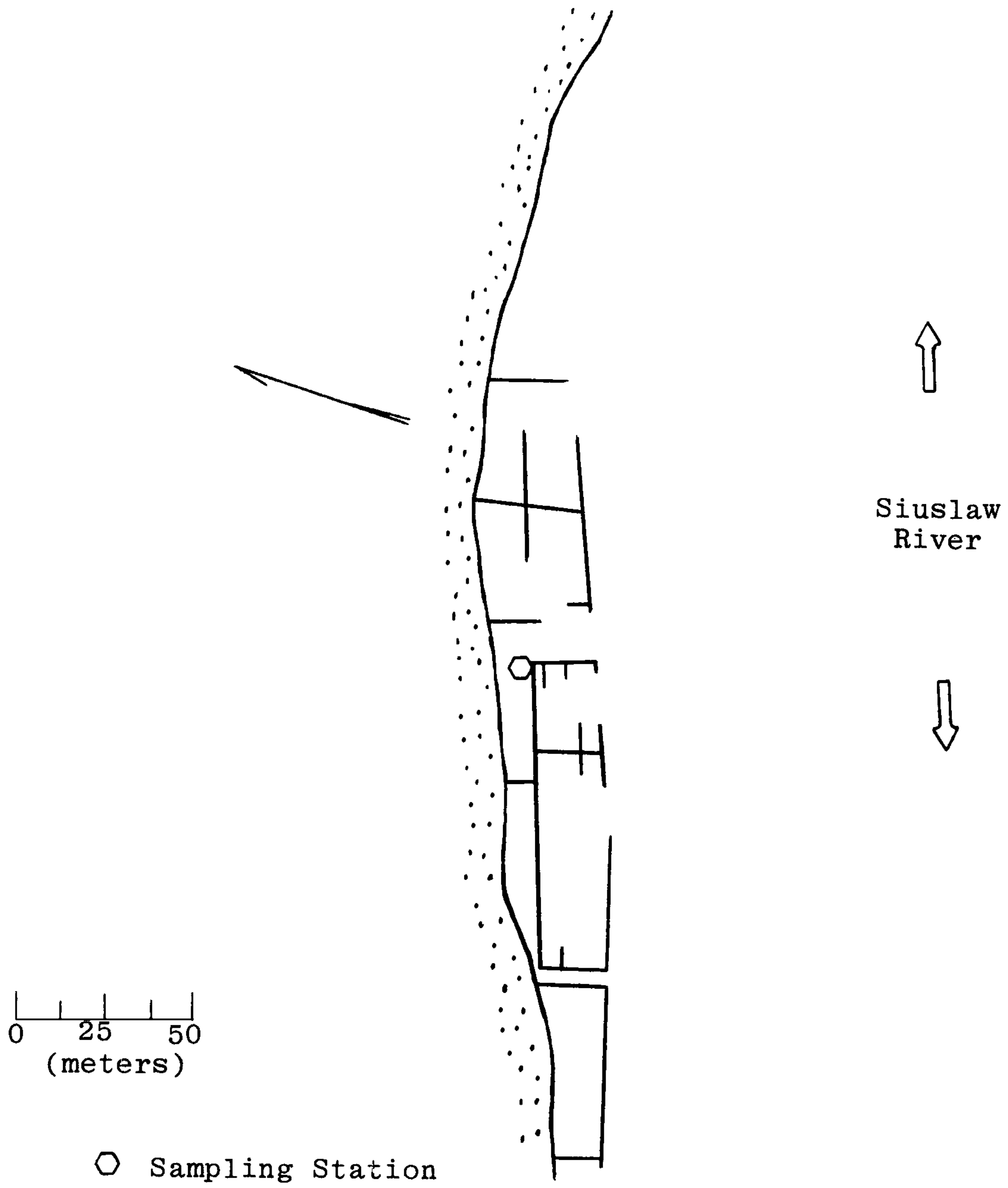

Figure 9. Florence marina (U.S. Army Corps of Engineers, 1973).

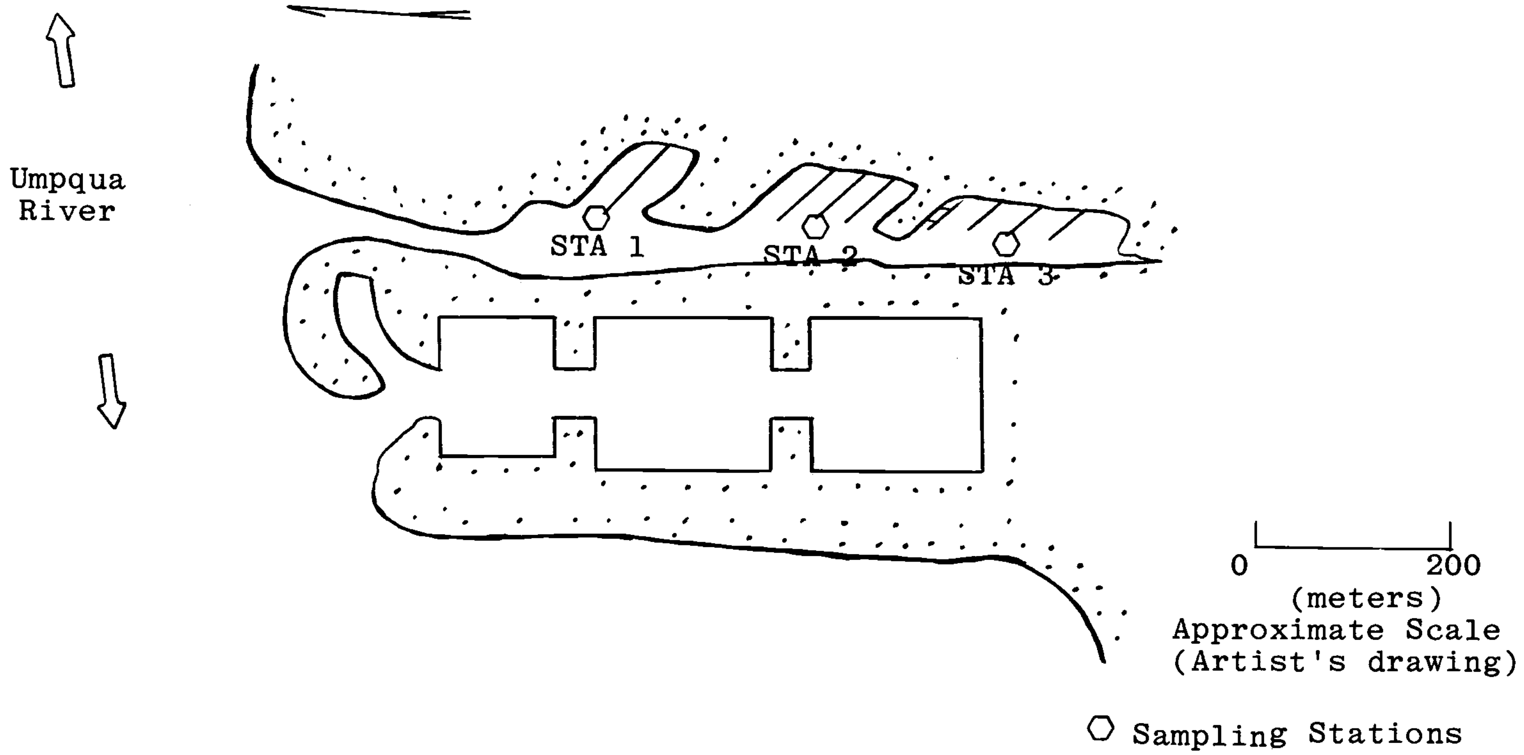

Figure 10. Winchester Bay marina.

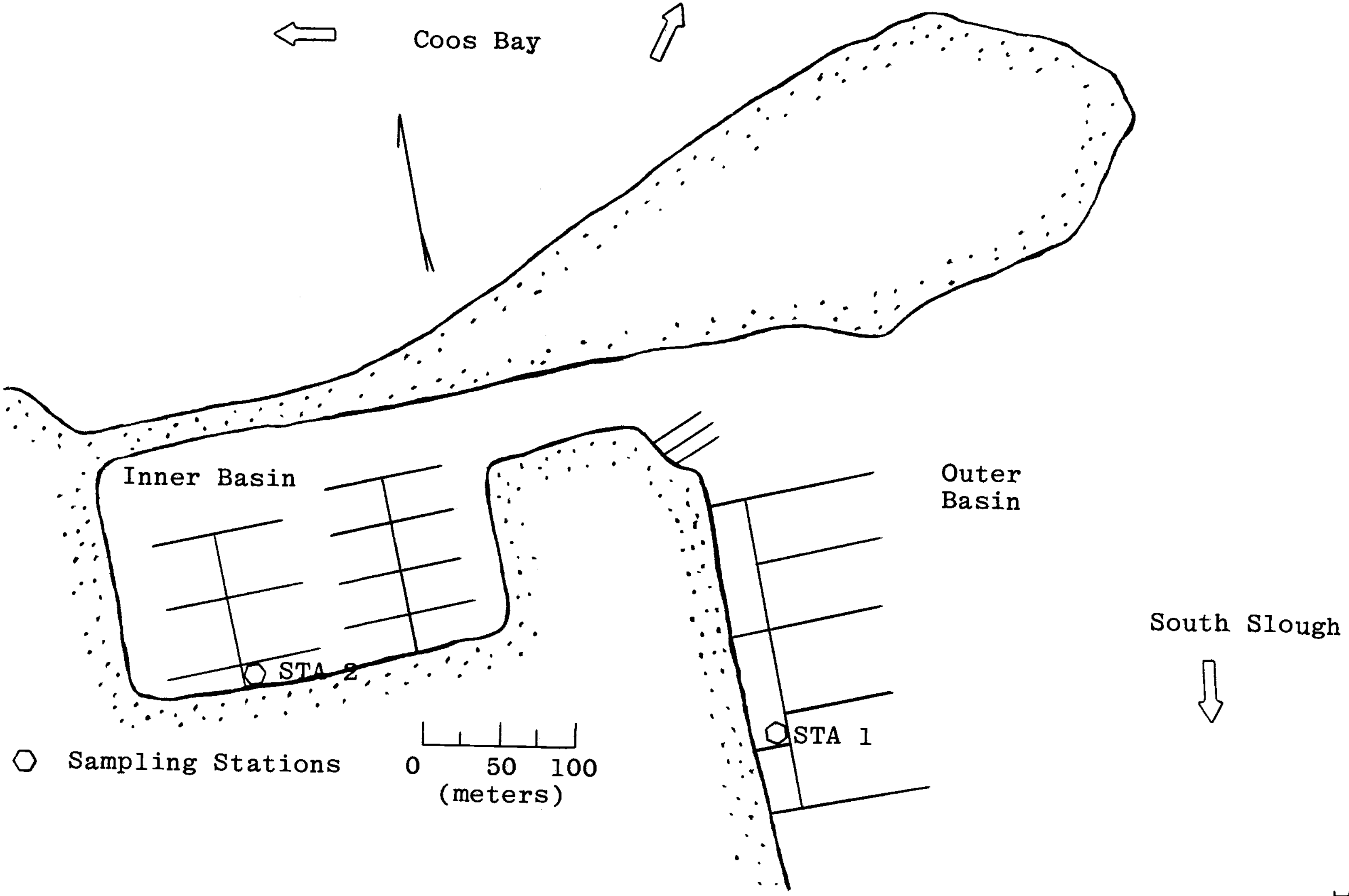

Figure 11. Charleston marina (U.S. Army Corps of Engineers, 1976).

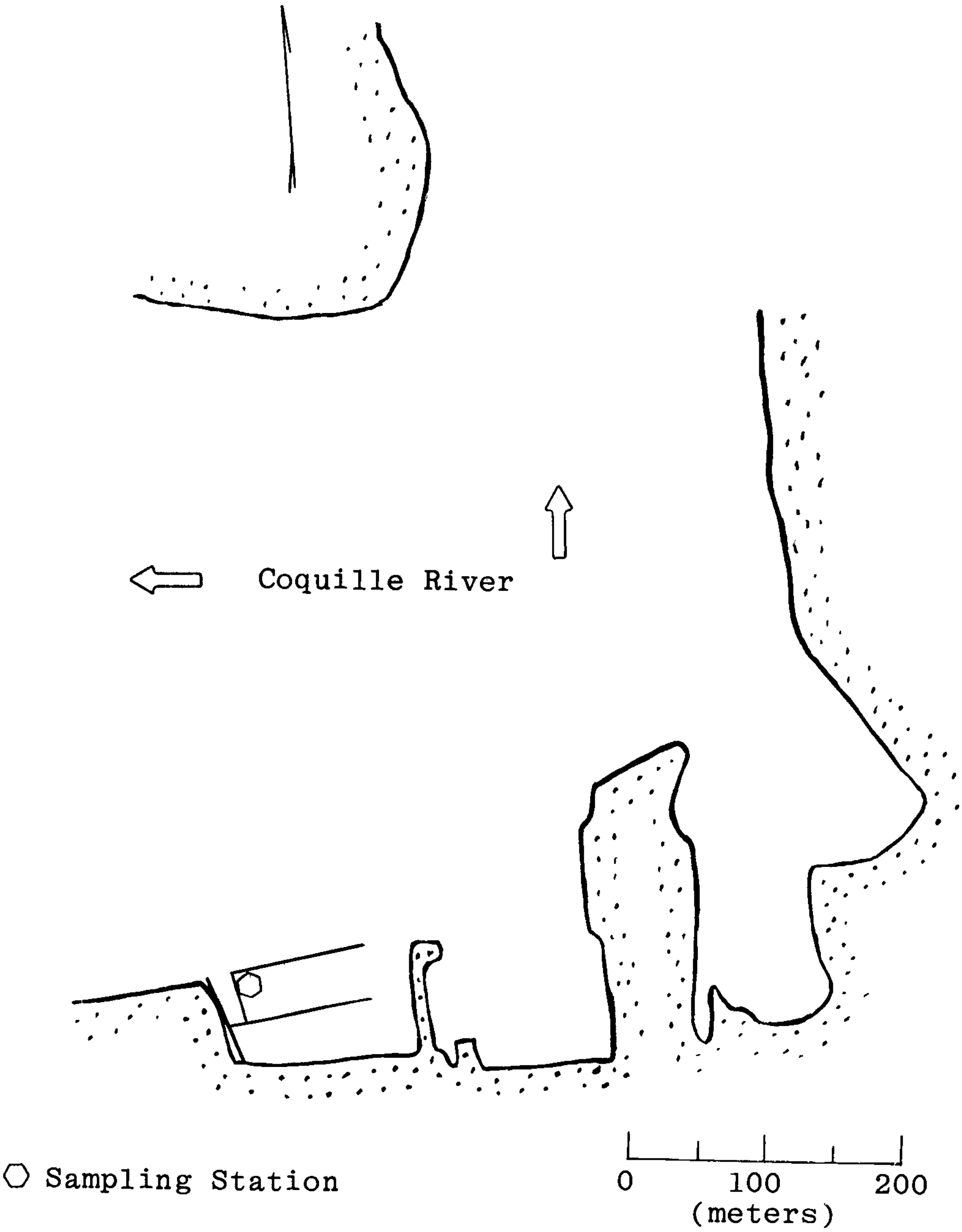

Figure 12. Bandon marina (U.S. Army Corps of Engineers, 1975).

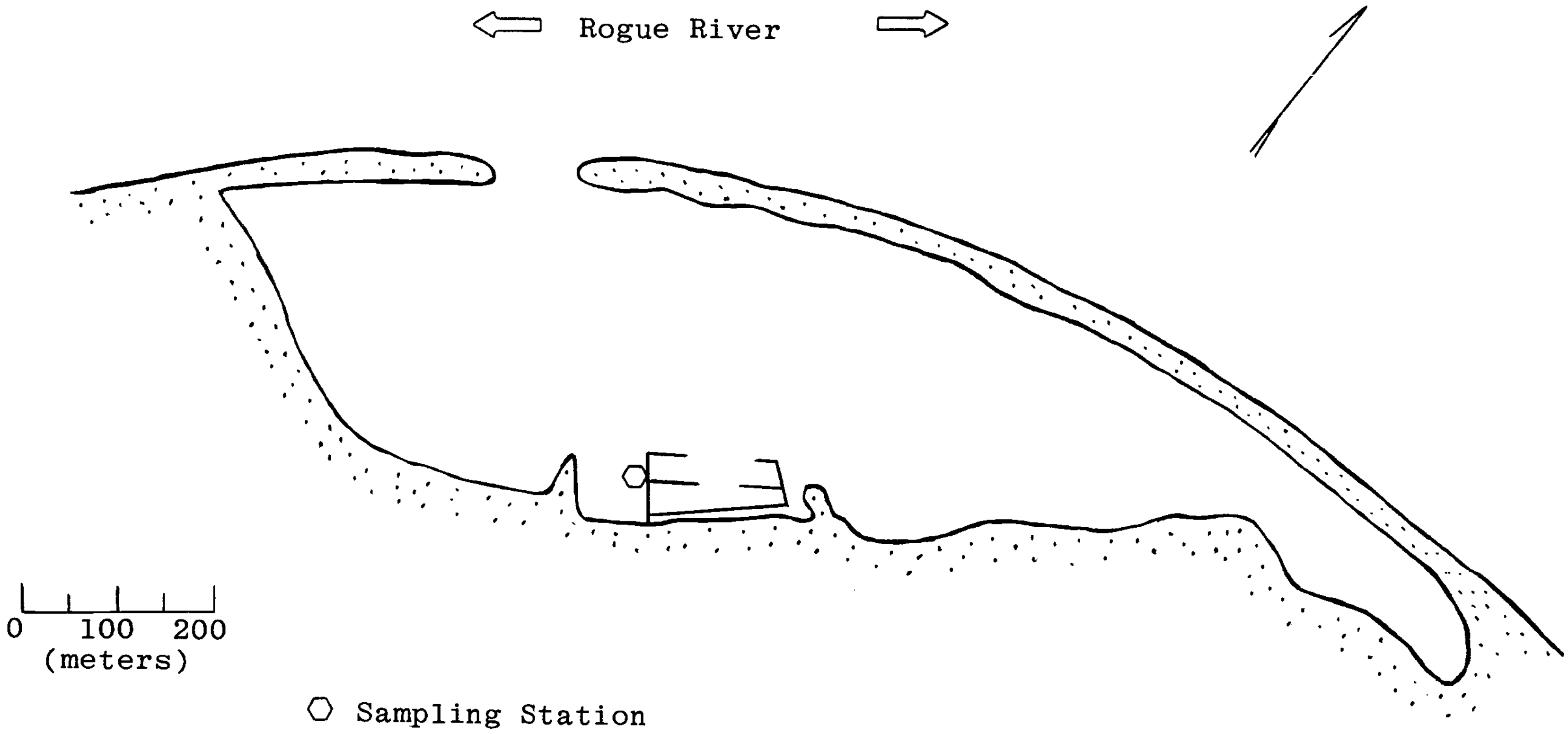

Figure 13. Gold Beach marina.

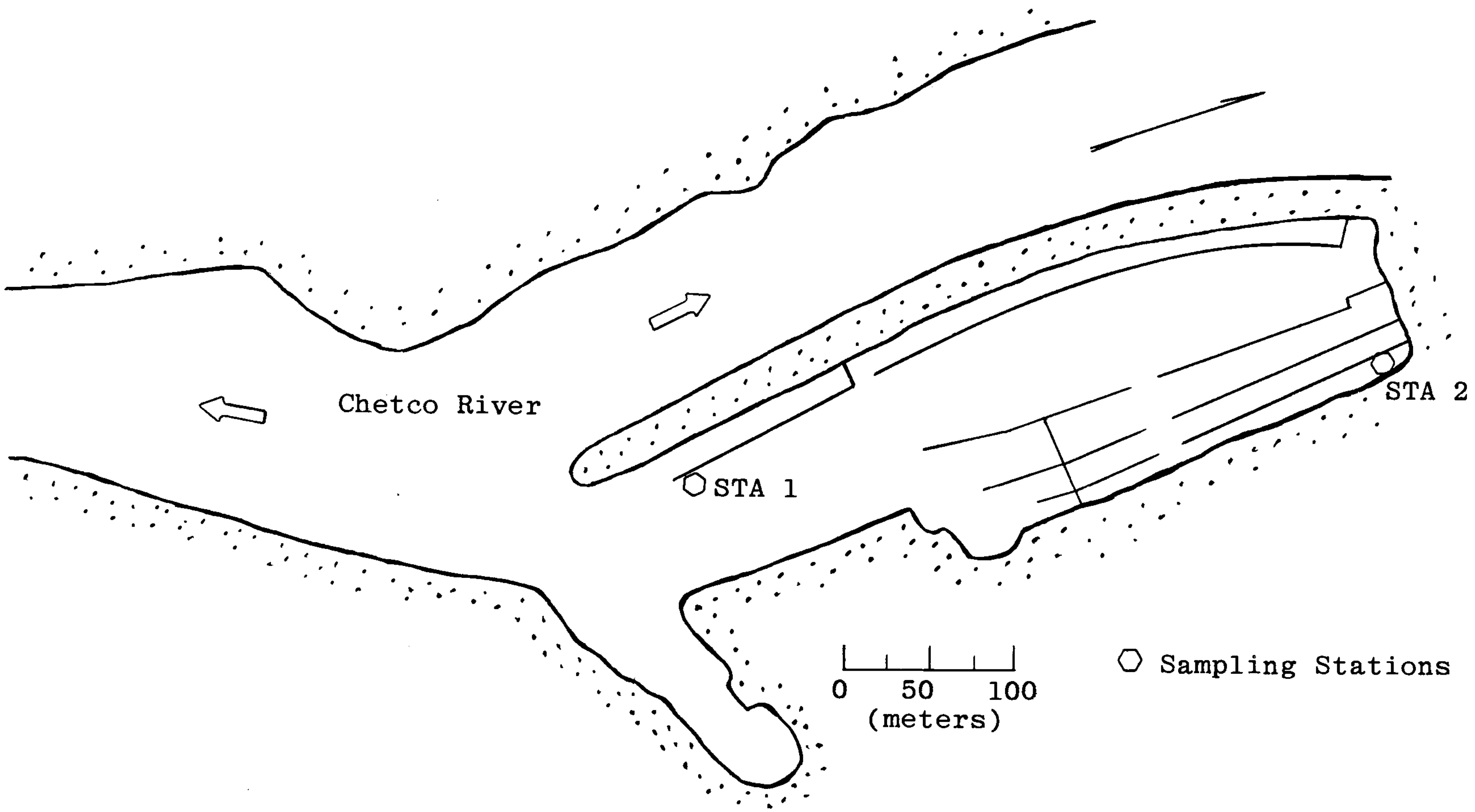

Figure 14. Brookings marina (U.S. Army Corps of Engineers, 1975).

DISCUSSION

Literature Survey

In a study similar to the present one, Yearsley (1974) of the Environmental Protection Agency (EPA), Region X, Seattle Office, attempted to relate water quality in various basins on Puget Sound to the shape of the marinas. The purpose of his work was to derive criteria for the design of small boat basins to ensure a maintenance of unpolluted waters. The work was divided into two efforts: one which extensively studied five marinas; and the other, which took a brief look at another five.

The indepth part of Yearsley's study looked at Edmonds, Squalicum, Shilshole, Kingston and Port Townsend marinas. From the water quality data obtained, a score was assigned based on a comparison of the water quality data to either Washington water quality criteria or to the control station (a sample taken outside of the marina enclosed). A maximum score of ten represented water of highest quality. Table 2 is a retabulation of Yearsley's composite water quality score with the marinas listed in order of decreasing score. The Results Section of this thesis will apply these five basins to models derived in the present work and compare the results of the two findings.

Table 2. Composite water quality score for marinas in Yearsley's study.

	Kingston	Shilshole	Port Townsend	Edmonds	Squalicum
Bacteria	9	7	9	8	1
Dissolved Oxygen	9	5	1	7	0
Temperature	1	5	2	1	3
Grease	10	9	10	7	2
Pesticides	10	9	10	5	8
Aesthetics	8	7	7	7	3
Total	47	42	39	35	17

Reference: Yearsley, 1974.

The brief study entailed a one day trip covering Port Angeles, Skyline, Cornet Bay, Anacortes, and Port Defiance marinas. Total coliforms, total grease and oil, and bioassays using Pacific oyster larvae were conducted.

For the maintenance of existing water quality, Yearsley suggested that the siting, design and operation of marinas should be carried out with consideration of the following characteristics: mixing and exchange; adjacent water use; adjacent land use; number and orientation of openings; opening size and aspect ratio; and pier length, spacing and design.

Yearsley's mixing and exchange were described by a renewal time (τ). To quantify τ a mass balance approach was applied and the following was coined:

$$\frac{1}{\tau} = \frac{1}{\tau \text{ diff}} + \frac{1}{\tau \text{ tide}} + \frac{1}{\tau \text{ fresh}}$$

where,

τ diff = Exchange due to diffusion = $\frac{\text{Vmllw Lmax}}{D_L \text{ Aw}}$

τ tide = Exchange due to tidal flow = $\frac{\text{Vmllw}}{\text{Qtide}}$

τ fresh = Exchange due to river flow = $\frac{\text{Vmllw}}{\text{Qfresh}}$

and where,

Aw = The cross-sectional area of the entrance

Lmax = The distance between the opening and the furtherest point in the marina

Qtide = The average tidal discharge into the basin

Qfresh = The discharge into the basin from the sources other than the tides

Vmllw = The mean lower low water (mllw) volume of the basin

D_L = The coefficient of eddy diffusivity.

Yearsley later made use of a relationship empirically determined for D_L,

$$D_L = 4.64 * 10^{-4} \ Lc^{4/3}$$

where,

Lc = The characteristic size of some eddy in meters, and taken as the minimum dimension of the basin (Lmin).

Defining the aspect ratio as $\lambda = \frac{Lmax}{Lmin}$, the exchange due to diffusion was finally characterized by Yearsley as,

$$\tau \ diff = \frac{Vmllw * \lambda}{Aw * 4.64 * 10^{-4} * Lmin^{1/3}} ,$$

Another way to quantify flushing time is via the Classical Tidal Prism Method (Dyer, 1973, p. 109-110) in which,

$$Te = \frac{Vmhhw}{Vp} ,$$

and

$$Vp = Vmhhw - Vmllw$$

where,

Te = flushing time in tidal cycles

Vmhhw = mean higher high water (mhhw) basin volume

Vp = basin tidal prism

One would expect Te to be greater than τ because the classical method assumes total mixing with tidal flow solely accounting for flushing, whereas Yearsley's expression also includes a flushing term due to diffusion and from flows other than tidal flow; and because the classical method determines the time to completely replace the high tide volume as opposed to Yearsley's approach which determines the time to replace the low tide basin volume. Figure 15 relates the flushing time from both methods to the composite water quality score referred to earlier. Intuitively, one would expect the water quality score to decrease, representing worse water quality, as the flushing increased, and in fact both methods tend to show this relationship. The figure reconfirms the idea that $Te > \tau$, with all basins, except Squalicum which shows $Te < \tau$.

At the end of the 1974 Yearsley study, a set of criteria were proposed to maintain adequate water quality within small boat basins. The recommendations for criteria were:

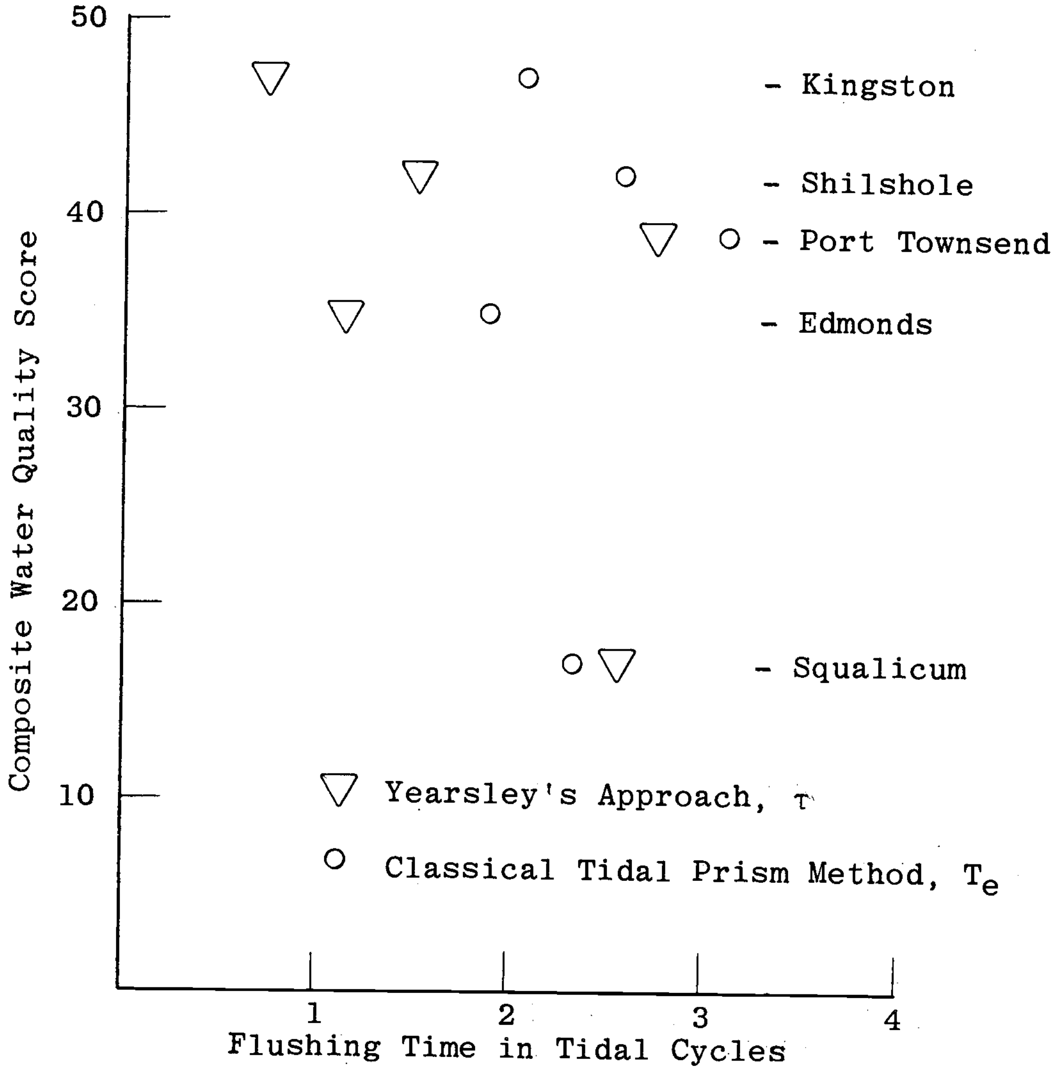

Figure 15. Flushing time vs. composite water quality score.

1. Marinas should be sited in areas where exchange and mixing characteristics are adequate. The mixing time, τ, should be less than one day.
2. Land and water use adjacent to the proposed marina site should be of high quality.
3. Marinas should contain multiple openings. These openings should be oriented in such a way so as to obtain maximum flow through efficiency. Physical and/or numerical models should be used to determine the best opening orientation.
4. Cross-sectional area of openings between the marina and open water should be as large as practicable. The aspect ratio, or ratio of maximum length dimension to minimum length dimension should be near one.
5. The diffusion time, τ diff, should be less than one day.
6. Pier lengths should be less than one-half the minimum length dimension of the marina and pier spacing should be greater than the pier length.

Richey (1971) discussed flushing mechanisms in marinas, with particular mention made of two approaches to estimate entrance velocity. He explained that considering the size of marina basins with respect to the main body of water, the fact that rivers do not empty into marinas, and that the basin depth is normally on the order of magnitude of the tidal range, water stratification effects can be excluded from an analysis of basin kinematics. These assumptions justify a one-dimensional approach to water motions within the basins.

The two approaches to computing basin entrance velocity are: a conservation of volume approach, and an approach making use of the energy equation. The conservation of volume approach gives the entrance velocity (V) as

$$V = (A/A_e)(dz/dt)$$

where,

A = the marina plan area

A_e = the entrance cross-sectional area

z = the water surface height

t = time

To facilitate the above computations, the tide curve represented by dz/dt, can be assumed to be a cosine curve. The cross-sectional area is obtained by multiplying the entrance width (b_e) by the water depth at the entrance (z), z being

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

where,

B = entrance depth, mllw

H = tide range

T = tide period.

The entrance velocity then becomes

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

In the approach using the energy equation, Richey assumed the only loss to be the kinetic energy loss through the entrance. Also noting that the atmospheric pressure doesn't change significantly over the area of concern, the energy equation can be written as

$$V^2/2g + z = Y$$

or

$$V = [2g(Y - z)]^{\frac{1}{2}}$$

with

g = gravitational acceleration
Y = water surface elevation outside the marina

Richey found the two velocity models to be in close agreement when used in a hypothetical case. He did not compare the models using field data. Layton (1971) studied, under Richey's direction, the hydraulic characteristics of Edmonds marina on Puget Sound and applied the conservation of volume model to compute tidal entrance velocities. Good agreement was found in comparing computed with measured velocities averaged over the depth. Layton also found that the tidal range inside the basin to be undiminished from the driving tidal range outside the basin.

Westrich (1976) derived a spatially one-dimensional mathematical model, supported by a physical model, to predict time dependent concentrations of a tracer mass within dead zones of basins having rectangular shape. With basin length to breadth ratios (L/B) less than six, the hydrodynamically defined dead zone, the region bounded by the sides of the basin and the dividing streamline of the river, can be approximated by the geometrically defined dead zone. In the region $0.3 < L/B < 6.0$ the exchange process is satisfactory with the consequence being that turbulent flow exists and mixing occurs within the dead zones. However, when $L/B < 0.3$ a secondary eddy tends to be created which is less diffusive than the primary eddy. If the secondary eddy is of a larger area than the primary one, then the exchange between the main flow and the dead zone may be very low. Figure 16 is a graphical representation of four basins ranging in size from $L/B = 6.0$ to $L/B = 0.3$. Figure 16 gives a visual idea of the basin shapes that Westrich studied.

For steady flow conditions, the mass exchange between the basin and stream is influenced by lateral turbulent velocity fluctuations and by the mass concentration gradient across the interface. Considering these different processes, Westrich worked with functional relationships concerning concentration ratios and normalized flows and geometries:

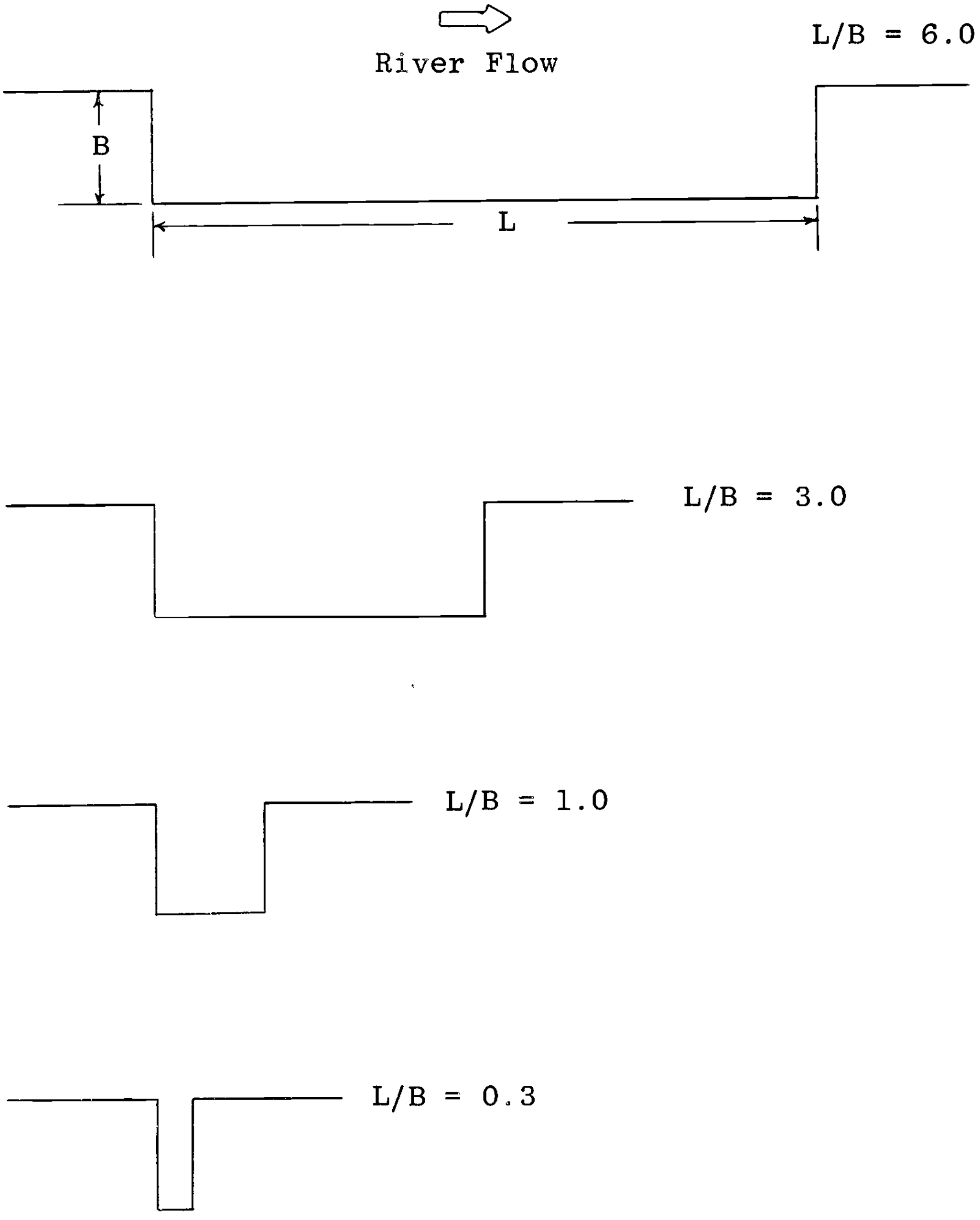

Figure 16. Graphical representation of various length-width ratio enclosures.

$$\frac{c}{c_o} = f\left\{\frac{U_t}{B}, \frac{L}{B}, \frac{U*}{U}, \frac{L}{H}\right\}$$

where,

B = width of the dead zone

c = concentration of the mass in the dead zone

c_o = initial concentration in the dead zone

H = steady river water surface elevation

L = length of the dead zone

U = mean river velocity

U* = wall shear stress

t = time

Westrich focused his attention to examining the ratios Ut/B and L/B and their effect on influencing bay-marina water exchange.

Westrich found two processes in unsteady flow that were influencing the exchange mechanism: 1) During the inflow cycle, when the river surface is higher than the basin surface, a dilution of the mass in the dead zone occurs, assuming zero tracer concentration, with a resulting smaller exchange with the main body on the outflow cycle than in the steady case; and conversely, 2) The increased entrance velocity over steady flow would cause a higher lateral velocity across the interface and hence a more intense mixing of the enclosed basin. Westrich concluded that unsteady flow effects are most important in basins of increasing volume and decreasing exchange surface, where large residence times occur.

Figure 17 presents Westrich's physical hydraulic model test results which shows the influence of L/B on the half-life residence time ($Ut_{\frac{1}{2}}/B$) of some conservative tracer. When L > B, the half-life time appears to be constant, suggesting that the exchange process is independent of L for L/B > 1.0. Note that the width of the exchange surface also has dimension of size L; so as L increases, the exchange interface also increases. As L/B approaches zero the effect of a secondary eddy becomes much more predominant, and consequently the half-life time increases.

In a study by Watters *et al.* (1973) an investigation into the efficiency of the hydraulics of waste stabilization ponds with respect to hydraulic and geometric parameters was conducted. Of interest is their discussion of dead space within the ponds.

> In any flow vessel there are generally regions where mixing is less active than desirable. Generally, this occurs in corners of the vessel. These regions of poor mixing will be called dead spaces if the fluid moving through these spaces takes 5 to 10 times as long to pass through the vessel as does the main flow.
>
> If the flow through the vessel has a minimum of dead space then the mean residence time $\bar{t}_c$ will approach the detention time and $\bar{\theta}_c$ (mean dimensionless resident time) will approach 1.0. If there are substantial dead water regions in the flow, then a large portion of the tracer will leave

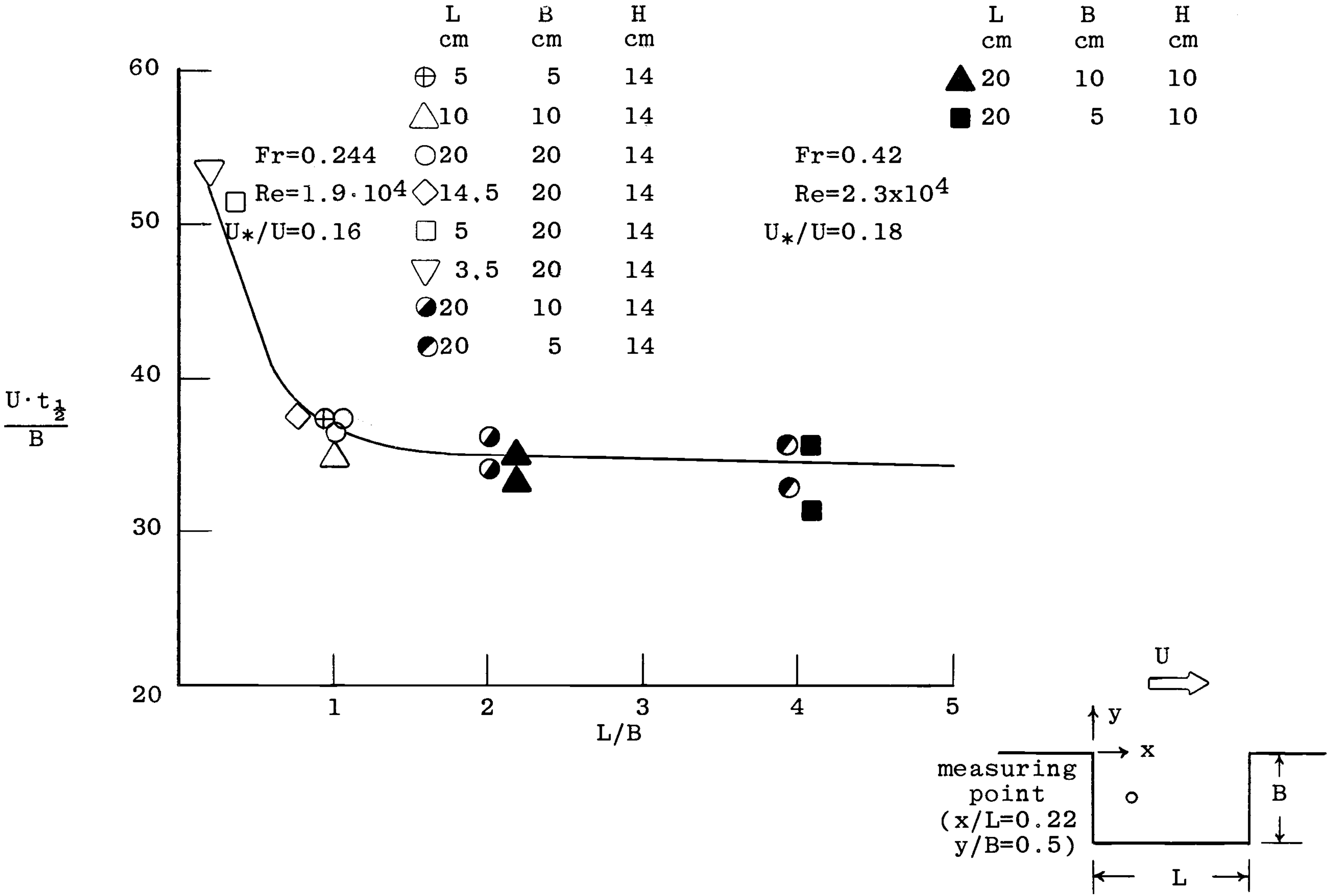

Figure 17. Length-width effects on the half-life of a tracer (Westrich, 1975).

> the vessel before θ (dimensionless time ratio of time to theoretical detention time) = 1.0. (Watters, et al., 1973, p. 11).

If there are dead spaces then the residence time will be shortened for a large part of the basin and bacteria won't have enough time to break down the waste, thus causing the pond to be hydraulically inefficient from a waste treatment point of view. Analogous to the sanitary engineering problem, dead space in marinas means that water will tend to be trapped with little flow through.

As the detention time is a measure of the hydraulic efficiency of the treatment process, the flushing time is a measure of the hydraulic efficiency, bay-marina water exchange, of the marina system. Detention time and flushing time are similar in that they both describe how long the water mass stays inside of the respective enclosures. The difference is that in the treatment process it is desirable to increase the detention time to the point of maximum treatment, whereas for the marina it is desirable to decrease the flushing time so that the water within the marina will exchange rapidly with the open body of water, enhancing the water quality within the enclosure.

The ideal situation for both of these engineering systems is to have a completely mixed system with no dead space, i.e. where $\overline{\theta}_c = 1.0$. Following Watters et al., the volume of dead space can be defined as

$$V_d = V - V_f \ ,$$

with the dead space parameter as

$$\overline{V}_d = V_d/V = 1 - \overline{\theta}_c(F)_{\theta=2}$$

where,

V = pond volume

V_f = ficticious pond volume; an effective volume that has no dead space

$(F)_{\theta=2}$ = the F age distribution at time $\theta = 2$

$F(\theta) = 1 - \exp(-\theta)$.

The F age function is the fraction of dye material that occurs at the outlet as a function of dimensionless time θ.

In the pond hydraulic model study, as in Westrich's work, a circulation cell was found to be established. The effect was for flow to be one direction on one side of the pond and another direction on the opposite side of the enclosure.

Tests were made with constant density and with stratification. The modeling criterion for the unstratified case was the Reynolds number, while in the stratified case it was the densimetric Froude number. The results of the unstratified flow tests showed: the effect of increasing depth was to increase the mean dead space $\overline{V}_d$, thus decreasing hydraulic efficiency; the amount of dead space only increased slightly as the Reynolds number was increased; and, for an increasing length to width ratio, the hydraulic efficiency also increased. Two general cases that were studied in the density stratified tests were: the density of the water flowing into the pond (ρ_{in}) was greater than the density of water in the pond (ρ_{pond}); and, with $\rho_{pond} > \rho_{in}$. Watters et al. found in the first case that the inflow occurred along the bottom with low velocities and consequential low mixing, whereas in the second case the inflow along the surface generated a mixing action in the pond and an increased turbulent diffusion.

The major changes in hydraulic efficiency of the waste stabilization ponds were the results of alterations in length to width ratios. Large ratios were found to create the best efficiency. Effects from different depths, Reynolds numbers, and densimetric Froude numbers were considered small. Even though some changes due to various inlet and outlet locations were observed, the basic difference of openings between ponds and marinas makes any analogous comparison as to where the openings should be located in marinas inconclusive. However, changes in circulation cells may occur in marinas due to various entrance configurations as inferred from Watter's findings on inlet-outlet variations in stabilization ponds.

Sediments

Sediments were used to characterize the water quality of small boat marina basins because benthic deposits are not subject to large variations in quality due to short term changes in the chemical composition of the overlying water. Changes in water composition in an embayment or estuary are most noticeably due to the diurnal tide cycle. In estuaries it is very common to measure changes in salinity concentration over a tidal cycle of from 0 to 30 parts per thousand. The water quality is also subject to seasonal changes, caused by seasonal changes in environmental conditions. An example of annual variation in water quality is the change in dissolved oxygen concentration (DO) caused by a change in water temperature. Man induced seasonal changes in water quality may occur due to industrial effluent discharge deviations. A study designed to determine water quality in basins using water data would require numerous sampling efforts to characterize the situation. Relative to changes in water quality, sediments are only minutely affected by diurnal and seasonal changes, and thus may be acceptable indicators of the trend in basin water quality.

There are three types of exchange processes affecting the transfer of materials between water and sediments, including: physical factors (hydrodynamic and sediment mixing effects), biological factors, and chemical factors (acid-base reactions, precipitation, complexation, oxidation-reduction and sorption reactions).

Lee (1970) discussed the factors which affect exchange of materials between water and sediments. Concerning the physical exchange of materials, Lee listed water currents in the overlying water as playing a prominent role. When the current velocity is high enough, bottom sediments become suspended, catalyzing exchange mechanisms such as: 1) an increase in chemical reactions due to an increase in sediment surface area; 2) release of material in the interstitial water; and 3) advection of the suspended sediments. Currents also in effect remove substances by decreasing concentrations of particular compounds which will enhance the probability that chemical equilibrium reactions will occur.

Another physical factor which affects mass exchange is the mixing of sediments, a process which allows materials that are in the surface layers of the sediment to be moved into a position where exchange is more likely to occur with the water column. Mixing of sediments and movement of materials by burrowing organisms occurs both by physical attachment of material to the organism and as a secondary consequence of biochemical reactions where substrate material is excreted in a location other than where it is consumed. Various worms are an example of estuarine benthic organisms which transport material in these ways (Bella, 1975, p. 22). The mixing that occurs in the surface sediments has been speculated by many investigators, as referenced in Lee (1970, p. 7-9), to occur in the top 5-15 cm depending on sediment type and environmental conditions. Another event which enhances mixing of sediments is the result of the bubbling of gases produced, carbon dioxide and methane in particular, in anaerobic fermentation (Lee, 1970, p. 12). Oregon State University investigators (Slotta *et al.*, 1974) have used a rate of sediment turnover (RST) in describing characteristics of benthic deposits, illustrating the importance of mixing in sediments.

Biological factors that affect exchange of materials between water and sediment are all directly or indirectly related to metabolism. The most significant changes are due to bacterial decomposition of organic material (Slotta *et al.*, 1974, p. 19; Bella, 1975, p. 14). Two examples of organic decomposition may be illustrated with the nitrogen and sulfur cycles. Organic nitrogen upon degradation by bacterial action is originally released as ammonia. If the sediment environment is anaerobic, the ammonia will eventually be released to the water column where green plants will utilize the ammonia as protein building blocks (Brezonik, 1973, p. 94). In the presence of an aerobic benthic environment, bacteria such as *Nitrosomonas* and *Nitrobacter* will nitrify the ammonia to nitrate, which can be utilized by green plants or undergo further transformation (Mitchell, 1974, p. 175; Reid, 1961, p. 187). Sediments may in most cases be considered anaerobic because of the oxygen utilization where there is any oxygen, and because of the low capability of oxygen recharge. With an anaerobic environment and low concentrations of nitrate, the principal hydrogen acceptors are sulfate reducing bacteria such as Desulfovibrio (Bella, 1975, p. 14; Mitchell, 1974, p. 187). Sulfates from organic material are reduced to hydrogen sulfide, H_2S, which make-up part of the free sulfides in a benthic system. Free sulfides then may either be combined with metals, most commonly iron, to form insoluble compounds, they may accumulate if no metals are available, or they may move into the water column with subsequent oxidation.

Biological reactions such as photosynthetic activity and respiration will affect the pH of the water, which will have an influence on precipitation reactions. These biological processes will indirectly alter exchange reactions by affecting DO utilization and uptake of nutrients in the water. Dissolved oxygen concentrations affect redox reactions, which may affect concentrations of materials in solution with subsequent exchange between the sediment and water. An uptake of nutrients by photosynthetic plants will lower the concentration of these substances, allowing nutrients bound in the sediment to be solubilized.

Chemical reactions are direct exchange mechanisms whereby materials will move from sediment to water body and vice versa. It is reasonable to assume that since chemical reactions are pH responsive then exchange mechanisms are pH dependent. The influence of precipitation reactions is very hard to measure because of the influence of all the elements present on these reactions. Lee (1970, p. 26, 28) points out that some theoretical reactions based on equilibrium criteria may not occur because the proposed aggregates have not been isolated. Other precipitation reactions do occur, but they are hard to generate and isolate in the laboratory. Redox conditions in the water and sediments will also have an influence on what type of reactions take place (oxidizing or reducing), and consequently, on what types of material exchange take place. For example, in an oxidizing environment ferrous sulfide may be oxidized to elemental sulfur to react with ferrous sulfide to form pyrite, a sink for available iron; otherwise, ferrous sulfide would remain in equilibrium with other free sulfides. Another important chemical factor in exchange mechanisms controlling material movement are sorption reactions. Lee provided a bibliography covering studies concerned with sorption; clay sediments were listed to have a large capacity for sorption, with phosphorous and certain pesticides being the specific cases of interest. Nitrate appears to have no sorption tendencies towards clay. In contrast, the ammonium ion has been reported as being rapidly sorbed by sediments (Brezonik, 1973, p. 94).

Exchange mechanisms tend to be complex and little understood. The above discussions have served to show that many types of exchanges do take place between the overlying water and the sediment, and that each are responsive to conditions in the other. It appears justified then that benthic deposits do represent the trends in water quality, and can be analyzed to gain perspective of the water quality in marina basins.

Extensive studies concerning interrelations of mud quality and benthic ecology have been reported in <u>An Examination of Some Physical and Biological Impacts of Dredging in Estuaries</u> by an Oregon State University research team (Slotta <u>et al</u>., 1974). In this study the organic content of sediment and rate of sediment turnover (OCS-RST) correlation was proposed for classification of benthic systems. This classification scheme is in its infancy (1972-76); quantitative delineation of different systems by the OCS-RST measures remains somewhat subjective. With use of volatile solids in the sediments as a measure of OCS, and the use of various environmental conditions as measures of RST, the following categories were defined: low OCS, 0-1.5% volatile solids (VS) on a dry basis; medium OCS, 1.5-8.0% VS; high OCS, greater than 8.0% VS; low RST, greater than one year turnover frequency; medium RST, one year to one month; and, high RST, less than one month. Figure 18 is a partial reprint from the above mentioned report of a figure illustrating uses of the OCS-RST scheme. In the schematic concerning water velocities, a low velocity represents a high organic content and a low sediment turnover rate, an undesirable condition. The DO schematic shows that low DO can be expected in the same system as in the undesirable in the water velocity illustration. The other schematics portray similar situations. The importance of the figures is that high volatile solids and sulfide concentrations have been acknowledged as definitely undesirable, and that low water velocities may be expected to partially cause this result.

Sources of organics to natural waters are plant and animal life, and numerous types of industrial wastes. Effects that organic material have upon the quality of water is most directly related to oxygen demand. An increase in respiration occurs with the bacterial breakdown of organics in an aerobic environment. Oxygen is used as the electron acceptor in the reaction

$$\text{organics} + O_2 \rightarrow H_2O + CO_2 + \text{energy} \cdot$$

Stored energy, in the form of Adenosine Triphosphate (ATP), is the benefit derived by the microorganism. Two ways of increasing the oxygen demand are: as the organics increase the microorganisms will tend to consume more and, the

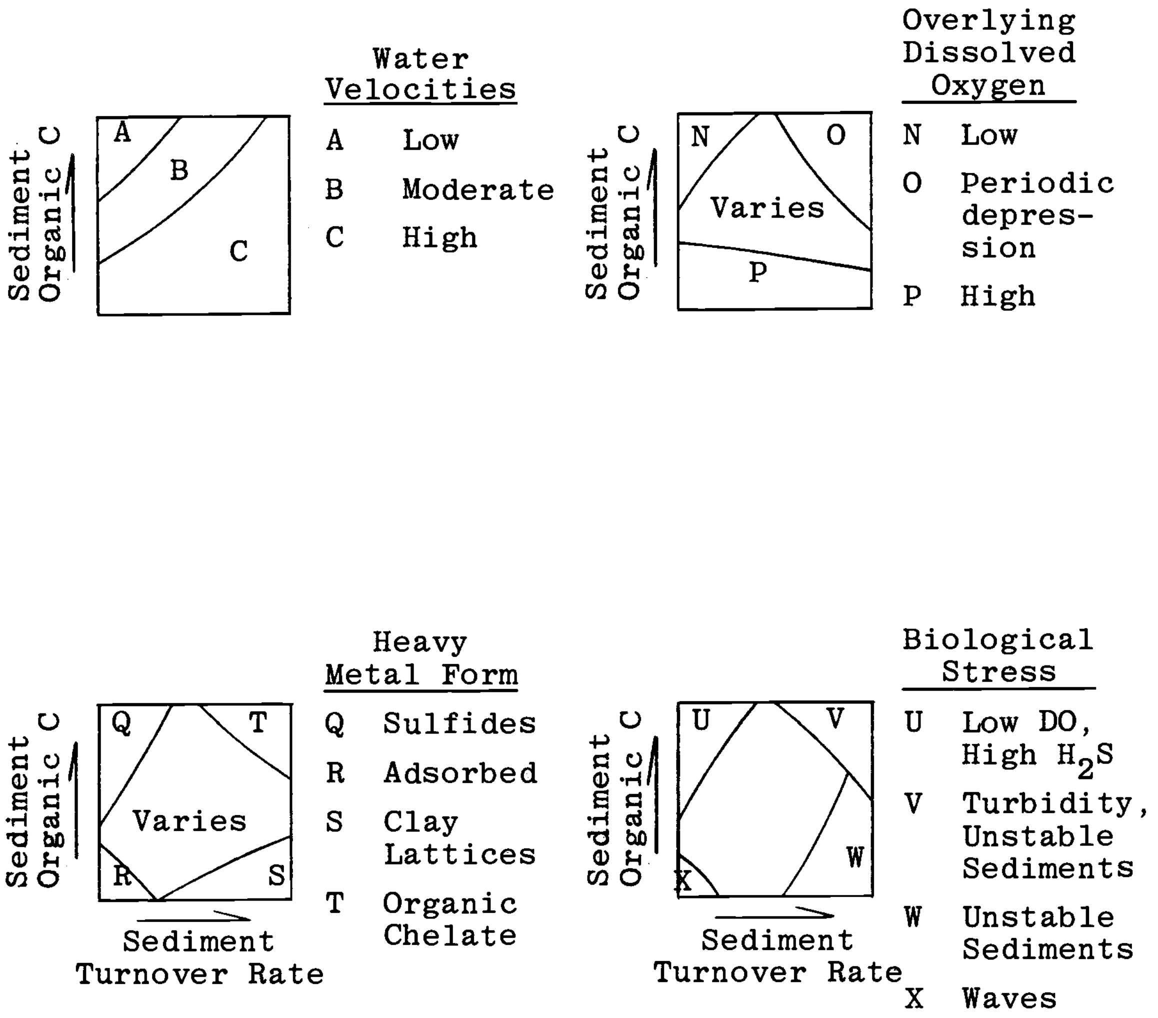

Figure 18. Four cases of classification by sediment organic content and sediment turnover rate (Slotta <u>et</u> <u>al</u>., 1974).

environment will be able to support a larger microorganism population. The amount of DO demand is most commonly referred by sanitary engineers as biochemical oxygen demand (BOD).

An increase in organic concentration will also indirectly affect water quality. Bi-products of bacterial breakdown of organics are inorganic nutrients, such as nitrogen and phosphorus. These nutrients can be utilized by photosynthetic plants and by select microorganisms in their growth cycles. With an overabundance of nutrients, plants will increase significantly, thereby increasing the organic content to the system. The result is a loss of oxygen in the bottom waters where decomposition occurs. Examples of tests that can be employed to measure the organic content of solids are volatile solids, chemical oxygen demand (COD), total organic carbon, and organic nitrogen.

Nitrogen is an essential component in amino acids, the protein building blocks, and is thus found in many different organic compounds. The breakdown of organic nitrogen into ammonia is termed ammonification. Phytoplankton appear to prefer ammonia as their inorganic source of nitrogen instead of nitrate because of its reduced state (Brezonik, 1973, p. 10, 11). If ammonia is not utilized by these photosynthetic plants, then it is nitrified to nitrite and nitrate under aerobic conditions. If low oxygen concentrations exist, nitrate will be acted upon by denitrifying bacteria and converted to nitrous oxide or gaseous nitrogen, otherwise the nitrate will remain stable and be utilized by green plants, and some bacteria. Concentrations of ammonia in the water over 2.5 mg/l are harmful to certain organisms (Reid, 1961, p. 185). Fish canneries are notable sources of nitrogen to water bodies (Soderquist, 1974, p. 366). Because of the continued recycling of inorganic nitrogen, one would expect to find low concentrations of both ammonia and nitrate nitrogen. However, a measurement of nitrogen can be a valuable aid in determining water quality.

In the study by Slotta *et al*. and a work by Bella (1975), the importance of the sulfur cycle in benthic deposits is stressed. Because sediments are usually in an anaerobic condition, organic degradation occurs predominantly by bacterial sulfate reduction. Other possible electron acceptors such as nitrates and carbon dioxide (Brock, 1970, p. 116) are in far lower concentrations than sulfates so they are less important. The bacteria that mainly convert sulfates to sulfides are from the genus *Desulfovibrio*. Depending on the pH of the system, free sulfides may exist in three states shown by the following equilibrium equation

$$H_2S \rightleftarrows HS^- \rightleftarrows S^= .$$

Further movement of free sulfides is highly dependent on the availability of iron. In the presence of iron, ferrous sulfide will be formed. When all of the available iron is used then concentrations of free sulfides will increase, a condition which is toxic to many marine and aquatic organisms (Slotta *et al*., 1974, p. 16, 19). When sediments are overturned the ferrous sulfide is oxidized, increasing the concentration of available iron (Bella, 1975, p. 18). A recycling of available iron is part of the iron-sulfur relationship.

The importance of the iron-sulfur relationship has been characterized and utilized by the Oregon State investigators in determining the quality of the sediments. Total sulfide capacity (TSC), sulfide capacity (SC), and total sulfides (TS) were used in their studies to determine mud quality. Total sulfide capacity is the total amount of ferrous sulfide that can be formed, including available iron (SC) and precipitated ferrous sulfide (TS). As the total sulfide content approaches the TSC value, an increase of free sulfides is likely to occur. If the sulfide capacity is near the TSC measure, then it is likely that the sediments have been recently overturned and the ferrous sulfide has been oxidized with the result that available iron has increased.

Marina Flushing Predictions

The model used to predict flushing times in marina basins in this study was the tidal prism method, mentioned earlier with regard to Yearsley's (1974) work. The method assumes a completely mixed system, with a volume of water in the marina, equal to the tidal prism, replaced over each tidal cycle. With this method, predicted flushing times will generally be lower than found in reality. The tidal prism method was chosen over Yearsley's flushing prediction method because Yearsley's method produced even lower values than the tidal prism approach (see Figure 15), and thus it was felt that the tidal prism calculations would more closely approximate reality.

The predictions as calculated from the prism approach are tabulated in Table 3. The longest predicted flushing time of the thirteen Oregon marinas considered (3.2 tidal cycles) occurs at the Garibaldi basin. It was not necessary to calculate flushing times for the Florence and Charleston (outer basin) because these marinas are both exposed to the main body of flowing water and so they experience a continuous change of water. The Newport marina has two entrances and so the flushing time can not be calculated accurately enough by the tidal prism approach. However, with the two openings both aligned nearly parallel to the river, it was felt that the river flow would have a

Table 3. Ranking of marinas by flushing time using tidal prism approach.

Oregon Marina Boat Basins	Flushing (Tidal Cycles)*
Florence	exposed**
Charleston (outer)	exposed
Newport	river influenced***
Netarts	2.1
Hammond	2.3
Depoe	2.4
Astoria	2.8
Bandon	2.9
Gold Beach	3.0
Charleston (inner)	3.0
Winchester	3.0
Brookings	3.1
Garibaldi	3.2

*A tidal cycle is commonly 12.4 hours for the Pacific Northwest coast.

**Exposed: located in main stream of flow, continually flushed.

***River influenced: two entrances allows considerable flushing from river, prediction approach not applicable.

considerable influence on its being flushed. For this reason, the Newport basin was put higher in the ranking than the rest of the enclosed basins. The Waldport basin does not appear in this table because basin data was not available.

DATA

Sampling Techniques

On September 16, 17 and 18, 1975 a field survey consisting of bottom sediment grab samples and various water quality measurements was conducted at the thirteen Oregon small boat marina basins studied. Up to three stations were sampled at each marina depending upon the size of the basin and the accessibility to various locations within the basin. As each bottom sample was taken, the time was recorded and pH, dissolved oxygen, turbidity, water depth, and salinity were measured.

The method used to obtain the bottom samples consisted of a metal bucket which was weighted along one side so that the bucket would sink with the opening faced downward. With the weights situated on one side, a sample was easily collected as the bucket was dragged along the bottom. A line attached to the bucket was used to retrieve the sample, which was immediately placed in plastic bags, identified as to basin and station, and put in an ice box of dry ice. The dry ice freezes the samples, and because very few organisms survive freezing conditions (Mitchell, 1974, p. 25), microbial activity will decrease. The samples were later stored in an ice box until the tests were conducted.

The following methods or instruments were used in measuring the water quality data:

pH - Corning Scientific Instruments Model 5 pH meter

Dissolved Oxygen - Samples were tested using the Winkler Method Azide Modification as outlined in Standard Methods 13th Edition (1971)

Turbidity - Water samples tested in the lab with a Hach Model 1860 Turbidimeter.

Water Depth - A lead line was used.

Salinity - Samples analyzed in the lab with a Hytech Model 6220 Portable Laboratory Salinometer

Analytical Tests

Four analytical tests were used to obtain a representative measure of the pollution load in the sediments. The tests chosen for the experiments were: volatile solids, Kjeldahl nitrogen (broken up into ammonia nitrogen and organic nitrogen), grease and oil content, and total sulfides. Table 4 presents a matrix of the tests that were considered.

The purpose of the study was not to determine the sediment quality per se, but to use the sediment quality as an index to flushing. It was felt that trace metals

Table 4. Test matrix.

Test	Tested	Not Applicable to Study	Too Difficult	Not Accurate	Results Overlap Other Tests
Volatile Solids	x				
Kjeldahl Nitrogen	x				
Grease and Oil	x				
Chemical Oxygen Demand				x	x
Mercury			x		x
Lead			x		x
Phosphorous					x
Total Organic Carbon					x
Sulfides	x				
Iron					x
Cadmium		x	x		x
Chromium		x	x		x
Pesticides			x		x

would not yield any additional information concerning flushing and thus the efforts were considered unwarranted. The total organic carbon test, one of many ways of measuring organic content was also consequently considered repetitious. The chemical oxygen demand test is yet another way of measuring organic content, although not limited to substrate material utilizable by biological organisms. It was felt that the interference from chlorides in the test (chlorides being readily oxidized by the chemical oxidizing agent used in the test) could not clearly represent a measurement of organics. Other tests were excluded for the reasons checked in the matrix of Table 4.

Volatile Solids

By heating a sample to a specific temperature for a specified time interval, organic constituents in the sample ignite and thus the sample becomes lighter. The temperature and time specified in the Great Lakes Region Chemistry Laboratory Manual Bottom Sediments (1968) is 600° Centigrade (°C) for one hour. The change in weight of the sample is expressed as a ratio of the dry solids content of the sample and recorded as percent volatile solids with respect to dry weight. The dry weight may be determined separately to or in combination with the volatile solids test by heating the sample at approximately 105°C overnight. The standard procedure in both of these tests is to place the samples in a desiccator directly out of the oven until they are at the ambient temperature, avoiding the moisture absorbing characteristic of a warm sample that would increase the weight of the sample and result in an inaccurate reading. As with all the tests a blank was carried through the procedure. As another check on the accuracy of the results, duplicate testings of all samples were executed. In the case that the results of the duplicates varied significantly, another set of duplicate tests were conducted.

Kjeldahl Nitrogen

A measure of the ammonia nitrogen and organic nitrogen constitutes the Kjeldahl nitrogen. By distilling ammonia out of the sample into approximately 0.02 $\underline{N}$ boric acid, ammonium borate is formed, which is then titrated with approximately 0.005 $\underline{N}$ H_2SO_4 to determine the nitrogen content of the sample. Standard Methods 13th Edition (1971) suggests using 0.02 $\underline{N}$ H_2SO_4 as the titrating reagent, but a lower normality was used to have a more sensitive system to the range of values expected. After the ammonia nitrogen was determined, a digestion reagent was used to release the organic nitrogen as ammonia. This percentage was then distilled and titrated as previously done for the ammonia nitrogen determination.

Grease and Oil

The grease and oil content of a sample, hereafter referred to collectively as grease, is defined as that quantity which is extracted by a particular solvent, in this case hexane. Grease consists of a variety of organic compounds. Some of the lower molecular weight substances and substances with high vapor pressures are lost in the procedure. The technique, as described in Standard Methods, involves drying a sample with $MgSO_4 \cdot H_2O$, acidifying to pH 1.0 to release the fatty acids, pulverizing the dried sediment to accomplish total grease removal, extracting the grease with hexane for four hours, distilling away the hexane, steam drying the flask and weighing after cooled the grease content of the sample. The end representation is percent concentration grease of the dry weight of the sample. Of extreme importance is completely drying the sample so that no free water is available to combine with the grease and the sediment in a bound state.

Total Sulfides

Basically, sulfides are stripped from the sample and reacted with zinc acetate. Excess iodine solution reacts with the zinc solution under acidic conditions. Thiosulfate is then used as a titrating agent to measure the remaining iodine. Results are expressed as mg sulfide per kg sample. Percent solids of the sample is then used to express the final results as percent dry concentration total sulfides.

Basin Geometry

To correlate the mud quality data with the basins it was necessary to define pertinent characteristics of each basin. Obvious parameters that were defined were: plan area (A), entrance (mllw) cross-sectional area (a), entrance width (w), mean depth (mllw) at the entrance (d_1), mean depth (mllw) of the basin (d_2), standardized length of the basin (ℓ), standardized distance to the sample location (x), angle of entrance orientation with respect to the main channel in the estuary (θ), and the mean tidal range (R). Other parameters were defined as a combination of the above because of insufficient field data. A list of all variables is listed in Appendix A. Figure 19 presents a definition sketch of some of the parameters.

Most of the physical data were obtained from U.S. Army Corps of Engineers photographic charts. These charts are derived from aerial photographs, with bathymetry in the channels superimposed from field studies that are performed at various intervals in time. A planimeter was used to determine plan areas. Because the Corps is mainly interested in navigation, almost all of the bathymetry is confined to channels in the main body of water. In most cases

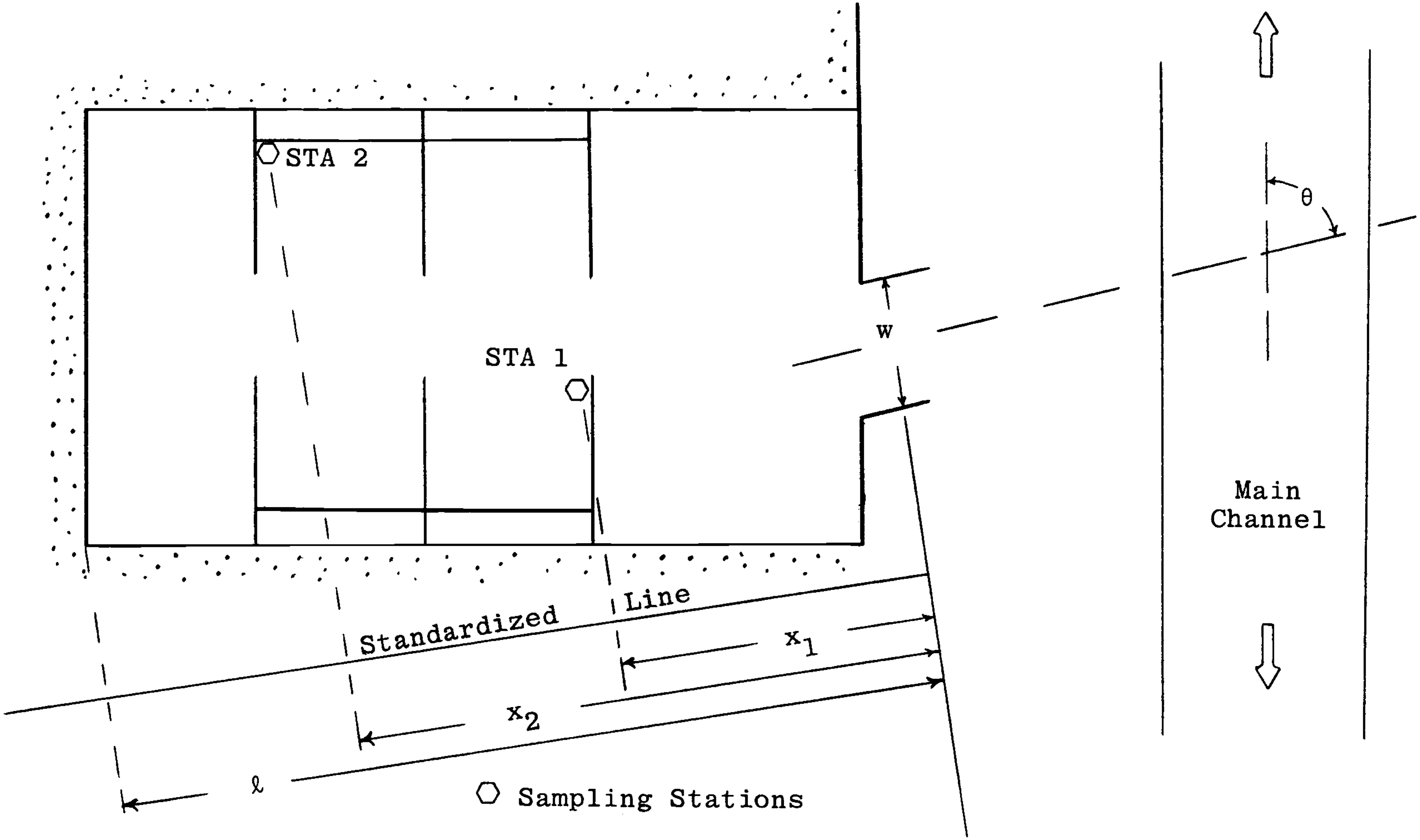

Figure 19. Definition sketch of various basin characteristics.

the soundings cover the entrance to the marinas so that it was possible to draw an entrance cross-section. In other cases the information provided an estimate as to what the entrance depth was, and then a rectangular cross-section was assumed to compute an entrance cross-sectional area. Even though the study was interested in a mean basin depth, the Corps data were often insufficient in providing this information; it was impossible to obtain the basin geometry and bathymetry data without independently surveying each marina. Because of the various shapes of the basins, it was decided to standardize the plan form distance measurements so that variability in measurement technique would be avoided. In all cases except Astoria a "standardized line" was drawn perpendicular to the entrance. Normal lines were then constructed from the standard line to the point in question, with the final distance measurement being that between the entrance and the intersection of the normal and standardized lines (see Figure 19). Due to the orientation of the Astoria entrance, the standardized line was arbitrarily drawn perpendicular to the river-fronting west breakwater. The angle the entrance makes with open water was evaluated by drawing a line perpendicular to the entrance and intersecting a line parallel to the channel in the main body of water. The acute angle these two lines make delimits θ. The mean tidal range was taken from Tide Tables West Coast of North and South America (1975) for a location nearest to each marina. The physical characteristics of each basin are tabulated in Appendix B.

As mentioned previously, some of the basin parameters of interest in this study were computed using measured physical characteristics. The calculated parameters are hydraulic characteristics of the basins such as characteristic velocity through the entrance (v), and tidal prism of the basin (P). In computing the velocity, it was assumed that the whole basin experiences the same tidal range, the tidal period (T) was 12.4 hours, the entrance cross-section was constant and equal to the mean tide level (mtl) area ($\bar{a}$), and the slope of the sides of the basin did not cause a change in plan area between high and low waters. These assumptions allow a velocity to be defined such that

$$v = \frac{2RA}{T\bar{a}} .$$

Richey (1971) and Layton (1971) have shown this approach to be valid. Under the same assumption, the tidal prism may be shown to be

$$P = RA .$$

The velocity may thus be described as the flow of the tidal prism over half a tidal cycle per cross-sectional area, a conservation of volume approach. This definition is an approximation to reality. However, the accuracy is comparable to other approximations in the original data and thus was considered acceptable. The goal of this study, to suggest general marina siting guidelines, and the inappropriateness of defining each basin in detail with commensurate multiple sediment sampling, justifies the approximations that are made. A few cases that will not strictly apply to this definition of basin tidal prism are Newport, Florence, and the outer basin at Charleston. Since there are two openings to the Newport marina, the definition implied fact that the tidal prism moves in and out over a tidal cycle through an area does not strictly apply. It is not certain what the tidal prism would be in this case. The other two basins have no real entrance but are rather fully exposed to the main body of water. Their entrance areas have been derived from a characteristic depth along the exposed frontage and the distance of exposure. However, for Newport, the conservation of volume approach was used to get an estimate of the entrance velocity. For Florence a mean river velocity was used as an approximation to a characteristic velocity. For the Charleston (outer basin) the velocity for the inner basin was used (as a first approximation).

Dimensional Analysis

To derive a model that would adequately represent the flushing phenomenon of an enclosed basin, it was necessary to decide in what way the sediment quality data could best be compared to the basin parameters. One avenue would be to relate sediment quality, and in so doing indirectly relate flushing potential, to each basin characteristic. Another approach, would be to conduct a dimensional analysis of the variables that were considered important, and in so doing derive a set of dimensionless expressions that were independent of any measurement system. In applying the laws of dimensional analysis, the original expressions were studied and either considered independently, combined with others, or excluded, to originate a final set of expressions with which to describe the flushing characteristics of small boat basins.

The dependent variable in the analysis was flushing time (F), while the independent variables considered of importance were A, a, w, d_1, d_2, ℓ, x, θ, R, v, P, basin mllw volume (V), mean river velocity (u), gravitational acceleration (g), density of water (ρ), and the molecular viscosity of water (μ). With a, v, and ρ as repeating variables, the first set of expressions relating a flushing parameter to the various variables yielded:

$$\frac{Fv}{a^{\frac{1}{2}}} = f_1 \{\frac{\ell}{a^{\frac{1}{2}}}, \frac{A}{a}, \frac{w}{a^{\frac{1}{2}}}, \frac{d_1}{a^{\frac{1}{2}}}, \frac{d_2}{a^{\frac{1}{2}}}, \frac{P}{a^{3/2}}, \frac{V}{a^{3/2}}, \frac{u}{v}, \frac{R}{a^{\frac{1}{2}}},$$

$$\frac{x}{a^{\frac{1}{2}}}, \frac{a^{\frac{1}{2}}g}{v^2}, \frac{\mu}{a^{\frac{1}{2}}v\rho}, \theta\} .$$

A regrouping of these expressions brought forth the final list of dimensionless expressions,

$$\frac{Fv}{a^{\frac{1}{2}}} = f_2 \{\frac{x}{\ell}, \frac{A}{a}, \frac{A}{wa^{\frac{1}{2}}}, \frac{P}{V}, \frac{u}{v}, \frac{R}{a^{\frac{1}{2}}}, \frac{Ax}{a\ell}, \frac{v^2}{a^{\frac{1}{2}}g}, \frac{va^{\frac{1}{2}}\rho}{\mu}, \theta\} .$$

The term $\frac{Fv}{a^{\frac{1}{2}}}$ can be termed a dimensionless flushing number which is unique for each marina. The final list of expressions were thought to relate the basin characteristics and some factors of the sampling to the flushing potential of the marina.

The idea behind the sampling program, as mentioned previously, was to use the quality of the mud as being indicative of the respective flushing capability of the basins. Ramifications of this hypothesis will be explored later in the report. Realizing that flushing times are theoretically based with little possibility of a distinct measurement, it was evident that the course of action was to relate the mud quality to the basin parameters. In other words, the mud quality was considered synonymous to flushing potential, and so the goal was to relate the sediment data to the basin data.

Sample Data

It was previously acknowledged that the marina sediment samples were analyzed for volatile solids, Kjeldahl nitrogen, grease and oil, and sulfides. The EPA criteria that are generally used for deciding whether the release of dredge spoil can be permitted served as a reference for classifying the samples. The outgrowth of the EPA criteria comes from a study by O'Neal and Sceva (1971), where they analyzed many sediment samples for a number of characteristics. In their study, samples were divided into two groups; those that had a volatile solids concentration of less than 5% were considered lightly polluted, and those that had a volatile solids greater than 10% were felt to be heavily polluted. From these two groups a table was constructed of ranges and means of all parameters tested. Using the lightly polluted group data as justification, they proposed their criteria from seven of the tests they executed. Table 5 is a list of "the basic seven" with the corresponding limiting

Table 5. Basic seven sediment pollution critiera.

Sediments in Fresh and Marine Waters	Conc. % (dry wt. basis)
Volatile Solids	6.0
Chemical Oxygen Demand (COD)	5.0
Total Kjeldahl Nitrogen	0.10
Oil-Grease	0.15
Mercury	0.001
Lead	0.005
Zinc	0.005

Reference: O'Neal and Sceva, 1971.

value for marine or aquatic disposal of dredge spoil. In the criteria it is stated that a violation of any one of the tests means the spoil does not meet the criteria for discharge or release. It was stated that these seven are not an all inclusive list for determining whether a spoil is polluted, other tests may also be used to determine the quality of the sediment.

The utilization of the "basic seven" in this study was two fold: firstly, the criteria provided a number which could be used as a cutoff in determining which basins were acceptable and which were not; and secondly, the information was used to normalize the data both for comparisons of magnitude between the different tests and so that a combination of the test data could be used in the analysis of basin characteristics to mud quality. The test data upon being normalized constituted a pollution index for each basin. Thus, all stations have an index for each test, and because the data had been standardized, the indices of the tests were linearly combined to form a total pollution index. The mud quality data was tabulated and used for analysis based on: 1) pollution index for each test and each station; and, 2) total pollution index for each station. Table 6 contains the sample data for the four tests conducted.

Table 6. Pollution indices for each test.

Station		Volatile Solids (VS)	Kjeldahl Nitrogen (KJDN)	Grease Oil (GO)	Total Sulfides (SULF)
Astoria	1	1.25	0.51	1.15	0.97
	2	1.48	0.57	1.29	2.17
Hammond		1.67	0.85	0.89	1.70
Garibaldi	1	2.15	0.56	0.77	1.20
	2	1.93	0.35	1.41	1.47
Netarts		1.82	0.42	0.51	1.13
Depoe		2.22	0.33	0.68	0.38
Newport	1	0.72	0.10	0.43	0.17
	2	1.25	0.39	0.19	0.56
Waldport		2.43	0.88	3.70	6.85
Florence		2.23	0.86	0.91	0.26
Winchester	1	1.83	0.60	1.49	4.81
	2	1.78	1.19	1.10	3.61
	3	1.75	0.67	1.06	3.50
Charleston	1	2.15	0.44	1.17	2.31
	2	0.58	0.15	0.23	0.60
Bandon		1.77	0.32	1.54	2.22
Gold Beach		0.42	0.19	0.17	0.04
Brookings	1	0.87	0.22	0.64	1.31
	2	1.45	0.28	2.41	1.98

Method of Data Analysis

There were three basic approaches that were taken to analyze and relate the sediment data with the basin data. These were: 1) an intrabasin comparison between stations; 2) a grouping of basins into polluted and non-polluted categories; and 3) a statistical analysis of the data. The first approach was used to explain variations that occur between tests, and to suggest hidden complexities of the initial problem and the approach to solving the problem. The second and third methods were used to derive generalizations about basin flushing, in essence to construct a model which would yield information about other marinas.

Intrabasin Analysis

This approach surfaced when first looking at the Kjeldahl nitrogen data. A unique feature of the Kjeldahl data is that only one station was "polluted." If this data were used exclusively one would conclude that all of the Oregon marinas were unpolluted during 1975 and each of the shapes is satisfactory for meeting current EPA guidelines. Such a conclusion would be contradictory to other tests that show some marinas definitely in the polluted category.

Realizing the shortcoming of using the Kjeldahl data exclusively and yet having good data proved to suggest the first method of analysis. For instance, at the marinas where multiple stations were sampled, a comparison of the change in pollution index between the stations and the different tests renders especially unique and beneficial information to this study. Such an analysis would show which measurements are a result of pollution from within or from without the basins. If for example the change in pollution readings between stations for all tests is approximately the same, then it can be concluded that these particular stations have been subjected to some unit load which enters the basin: because the circulation pattern of a marina is not dependent upon the type of test conducted, one would expect for a particular pollutional load in the main body of water and a characteristic exchange between the main body of water and the basin, a constant difference of pollution index between specific stations for all tests. Alternatively, for a load that is introduced in some location within the basin, some proportion of the load may accumulate in a particular part of the basin, and thus the sediment in this area may act as a pollutant trap and other parts of the marina might not experience the same percentage of the load as from a unit impulse outside the marina. The movement of a mass inside the basin is also much more dependent on the time of dumping with respect to tidal movement than a pollution source outside the enclosure. Further, inside the basin different proportions of various pollutants may be introduced and thus if one pollutant is heavily dumped in the marina, the test that detects this pollutant may show a very high value at one station while registering a low value at another station. This test might not compare with changes in pollution index between stations from other tests. The input location of the pollutant thus becomes an important independent variable which can be inferred qualitatively by analyzing the data.

It is helpful in making a comparison between tests to have a common reference datum. The data were compared by taking the ratio between stations for each particular test. For a particular exchange property between the main body of water and the enclosure, the percentage of the pollutant concentration between locations inside of the basin should remain approximately constant for all constituents. This assumes a constant exchange function between the water and sediment, which for the initial purposes of this study were sufficient.

Grouped Data

The first method of grouping data was similar to O'Neal and Sceva's 1971 approach for determining the Basic Seven Criteria. This was done by dividing the basins into a polluted and a non-polluted group as based on the test results. Since a basin may not be polluted in all of the tests, it was a subjective problem to decide what the cutoff for the groups would be. Table 7 is a ranking by test of the most to the least polluted Oregon marina. Also illustrated in the table is the cutoff point for the critical pollution index, i.e. PI = 1.0.

The value of Table 7 is seen in the case of the Astoria marina where the volatile solids for both stations were slightly above the critical value, while being below the critical value for Kjeldahl nitrogen, slightly above in the grease test, and split in the sulfides determination. Since most stations were above the 1.0 value for volatile solids, Astoria, because of its marginal location in the first ranking, would be rated acceptable for the first two tests; however, the above normal rating in the grease test, in which an even distribution about the critical value occurs and a definite leaning toward a pollution status from sulfides, would put this basin in the lower end of the polluted group. Once the two groups were formed, it became the task to note similarities in the groups and dissimilarities between the groups.

Statistical Analysis

Use was made of the prepared programs of Oregon State's CDC-3300, OS3, Statistical Interactive Programming System, SIPS, for the analysis of the data. Multiple regression analyses were used to build models for describing the flushing mechanism of small boat marinas. This was

Table 7. Station ranking by pollution index.

Increasing Pollution Index →

Test			
Volatile Solids	Kjeldahl Nitrogen	Grease	Total Sulfides
Waldport	Winchester 2	Waldport	Waldport
Florence	Waldport	Brookings 2	Winchester 1
Depoe	Florence	Bandon	Winchester 2
Garibaldi 1	Hammond	Winchester 1	Winchester 3
Charleston 1	Winchester 3	Garibaldi 2	Charleston 1
Garibaldi 2	Winchester 1	Astoria 2	Bandon
Winchester 1	Astoria 2	Charleston 1	Astoria 2
Netarts	Garibaldi 1	Astoria 1	Brookings 2
Winchester 2	Astoria 1	Winchester 2	Hammond
Bandon	Charleston 1	Winchester 3	Garibaldi 2
Winchester 3	Netarts	Florence	Brookings 1
Hammond	Newport 2	Hammond	Garibaldi 1
Astoria 2	Garibaldi 2	Garibaldi 1	Netarts
Brookings 2	Depoe	Depoe	Astoria 1
Astoria 1	Bandon	Brookings 1	Charleston 2
Newport 2	Brookings 2	Netarts	Newport 2
Brookings 1	Brookings 1	Newport 1	Depoe
Newport 1	Gold Beach	Charleston 2	Florence
Charleston 2	Charleston 2	Newport 2	Newport 1
Gold Beach	Newport 1	Gold Beach	Gold Beach

________ Signifies separation by critical pollution index, i.e. PI = 1.0.

accomplished by regressing the dependent pollution indices on the dimensionless basin parameters. Statistical tests were utilized in a systematic manner to determine which expressions should be built into the flushing model from the given data. Trends indicated by scatter plots of the parameters occasionally suggested that an algebraic transformation of the data would offer a more highly correlated linear model. Transformations take the form of simple algebraic manipulations, e.g. square root, square, logarithms, etc.

A delineation between the limitations and power of statistical analysis is essential in order to fully appreciate the meaning of the results from this analytical approach. The degree to which a statistical model can be used for prediction is highly dependent upon the sampling program, both in numbers and randomness, the independent variables chosen to represent the response variable, and the range over which the original data spans. As the number of samples increase, the ability of statistics to explain variation among the samples improves. Important in any sampling program is where or when to sample; a sampling in one particular area, even if a number of times, might exclude possible samplings that may represent a true picture of the function that is being studied. Even if the data are representative, a deletion of important independent variables in the model may result in an inefficient description of the function. As in any analysis, the results are only as good as the original data. This statement applies to prediction from regression analysis by confining the soothsaying to the range over which the original data extends: there is no assurance and statistical basis that the model applies to regions outside the initial information.

The above reflection is only meant to caution the reader that the results in this study must be taken in perspective of the whole study. Because thirteen marinas were studied, the complete sampling of all basins was both prohibitive and not suggested in the context of the work planned. A further limiting factor was not attempting to quantify the magnitude of pollution source to each basin. Statistically, the generalness of most studies means that if another set of samples were taken, the regression function may be different than the first derived. A regression line from a second set of data may be different from the original regression line, with the explanation being that the confidence intervals on the function which explains the mean response are larger than if a more complete sampling program had been initiated originally. The importance of the limitations related to the marina siting analysis is not meant to downgrade the results of this study, but only to provide the results in a proper perspective.

RESULTS

Marina basin characteristics were grouped dimensionlessly and were assigned appropriate names. A list of the basin variables is tabulated in Table 8 with the corresponding name; also tabulated are the names assigned to the test variables and combinations of the test variables.

Intrabasin Comparison

A comparison was made of pollution indices among sampling stations in basins where multiple samples were taken. Table 9 is a tabulation of pollution indices, PI, differences in pollution indices between the stations for each test, and the ratio of pollution indices between the stations. The value of this table is that it illustrates the relationship between the stations. A simple differencing will not take into account the relative differences of each chemical constituent in the water body. However, the mass dispersal in a basin should be constant on the average, and thus the ratio of concentrations should be constant unless there is a point source within the basin.

In the case of Astoria, station 1 has a lower pollution index, PI, than station 2 over all tests. The ratio of concentrations is essentially the same in the first three tests, being somewhat lower in the fourth test.

Table 8. Basin variable names and test names.

Dimensionless Basin Parameter	Variable Name
A/a	AREA
x/ℓ	DIST
$A/(wa^{\frac{1}{2}})$	ENTR
$R/a^{\frac{1}{2}}$	RA
$(x/\ell)\sin\theta$	DTHA
$(va^{\frac{1}{2}})/\nu$	*REY
$v^2/(ga^{\frac{1}{2}})$	*FR
θ	THETA
$(va^{\frac{1}{2}})^2/\nu^2$	*SQREY
Test(s)	Name
Volatile Solids	VS
Kjeldahl Nitrogen	KJDN
Grease	GO
Total Sulfides	SULF
VS + KJDN + GO	PI3
VS + KJDN + GO + SULF	PI4
VS * KJDN * GO	PI23
VS * KJDN * GO * SULF	PI24

*In analyses and discussions, factors of 10^5, 10^{10}, and 10^{-5} are left off for REY, SQREY and FR, respectively.

Table 9. Comparison of pollution indices among multi-station basins.

Station		PI				ΔPI				Ratio			
		VS	KJDN	GO	SULF	VS	KJDN	GO	SULF	VS	KJDN	GO	SULF
Astoria	1	1.25	0.51	1.15	0.97	-0.23	-0.06	-0.14	-1.20	0.84	0.89	0.89	0.45
	2	1.48	0.57	1.29	2.17								
Garibaldi	1	2.15	0.56	0.77	1.20	0.22	0.21	-0.64	-0.27	1.11	1.60	0.55	0.82
	2	1.93	0.35	1.41	1.47								
Newport	1	0.72	0.10	0.43	0.17	-0.53	-0.29	0.24	-0.39	0.58	0.26	2.26	0.30
	2	1.25	0.39	0.19	0.56								
Winchester	1	1.83	0.60	1.49	4.81	0.05	-0.59	0.39	1.20	1.03	0.50	1.35	1.33
	2	1.78	1.19	1.10	3.61	0.03	0.52	0.04	0.11	1.02	1.78	1.04	1.03
	3	1.75	0.67	1.06	3.50	0.08	-0.07	0.43	1.31	1.05	0.89	1.41	1.37
	1	1.83	0.60	1.49	4.81								
Charleston	1	2.15	0.44	1.17	2.31	1.57	0.29	0.94	1.71	3.71	2.93	5.09	3.85
	2	0.58	0.15	0.23	0.60								
Brookings	1	0.87	0.22	0.64	1.31	-0.58	-0.06	-1.77	-0.67	0.60	0.79	0.26	0.66
	2	1.45	0.28	2.41	1.98								

Garibaldi exhibits a mixed trend, probably due to differences in source of pollution.

The Newport stations have a similar relationship to each other in three out of four tests with station 1 less "polluted" than station 2. This relationship is expected because station 1 is near the entrance, where the best flushing is likely to take place, while station 2 is inside the basin. In the grease determination however, station 1 has twice the concentration as the other station. This indicates that the input of grease compounds is influencing grease distribution within the basin and not just the hydraulic features of the basin.

The Winchester marina is an interesting case in point. For the volatile solids test the stations decrease in PI further into the basin from the mouth; however, the values are very similar. For the Kjeldahl determination, station 2 is much more polluted than the other two. The grease test again shows the decreasing trend in PI versus length into the basin, but in this test, station 1 is much more polluted than the others. The sulfide results are analogous to the grease results. A look at the ratio shows a constant relationship between stations 2 and 3 except in the nitrogen case. Station 1 tends to be higher than the other two. In this marina there does tend to be some specificity between test and location.

The Charleston marina, divided into two cases points out a peculiar feature. The outer basin (used for moorage since 1958), which is much more exposed to flushing action than the inner basin (constructed in 1965), is much more highly polluted in all cases. This finding is counter to what one might expect. The explanation for this trend is that there are three fish canneries located in Charleston, one being directly adjacent to the outer basin anchorages (Percy et al., 1973, p. 56). Since fish cannery wastes are usually high in organic content, grease and oils, and organic and ammonia nitrogen (Soderquist, 1974, p. 91, 115), it is reasonable for the outer basin to translate these trends. The outer basin will tend to be an irregular case in the rest of the analyses discussed, exhibiting the unexpected. The fact that the inner basin has low pollution indices in all cases suggests that its narrow entrance does not allow a significant portion of cannery wastes to enter, nor does it have its own source of pollution.

At Brookings marina station 1 shows a lower PI in all cases, with ratios between the stations ranging from 0.26 to 0.79.

In summary, a few significant points can be made. There seems to be definite sources of pollution from within the basins whose distributions throughout the basin are very dependent on where the pollutant is introduced. Therefore consideration should be given to the siting of facilities within a basin. Although in most cases a sample taken closer to the entrance is less polluted than other sample locations this is not always the case. As displayed in the Charleston case, marina design for optimal water quality is not just dependent on flushing potential but is also very sensitive to siting location.

Grouped Data Analysis

Reference is made to Table 7, station rankings for each test, which was used to group the Oregon marinas as to acceptability. Table 10 indicates the respective grouping of the marinas with the average pollution index for all tests and all stations indicated numerically. Surprisingly, Charleston occurs in both groups. The reason for this is that the marina is made up of two distinct areas of moorage,

Table 10. Grouping of marinas: Acceptable or unacceptable.

Acceptable		Unacceptable	
Netarts	0.97*	Astoria	1.29
Depoe	0.90	Hammond	1.28
Newport	0.95	Garibaldi	1.23
Florence	1.06	Waldport	3.46
Charleston (inner)	0.39	Winchester	1.95
Gold Beach	0.20	Charleston (outer)	1.52
Brookings	1.14	Bandon	1.46

*Number denotes the average pollution index for each marina.

one enclosed from and the other exposed to the main stream of flow separating South Slough and the main channel of Coos Bay. In deciding their relative placement, consideration was given to the range of values in each test and their proximity to the critical value in the ranking. Marinas such as Netarts and Brookings are marginal in this pollution index classification scheme.

Ranking of the marinas based on classical tidal prism flushing times was made for comparison with that of the pollution index ranking shown in Table 10. Table 11 indicates that the joint rankings have few real correlations.

Table 11. Comparison of predicted to measured basin ranking.

Predicted	Measured
Florence	Gold Beach
Charleston (outer)	Charleston (inner)
Newport	Depoe
Netarts	Newport
Hammond	Netarts
Depoe	Florence
Astoria	Brookings
Bandon	Garibaldi
Gold Beach	Hammond
Charleston (inner)	Astoria
Winchester	Bandon
Brookings	Charleston (outer)
Garibaldi	Winchester
	Waldport

One of the reasons for few real correlations is that the predicted ranking does not take into account the various pollution loads in the different estuaries, whereas it is inherent in the measured rankings.

Following grouping the marinas as acceptable or unacceptable, an inspection was made of plots of pollution indices for each individual test and as a combination of the tests against the dimensionless variables depicting basin shape. Most of the graphs displayed a rather random scattering of the two groups. However, in the plots of two basin variables, AREA and ENTR, lines could be drawn dividing the groups for all of the tests. Figures 20 and 21 show the grouped marinas as a function of AREA and ENTR, respectively. A dividing line is drawn between the two groupings. In both figures, two unacceptable basins were found to lie in the acceptable zone. These two marinas are the Charleston (outer basin) and Bandon marinas. The Charleston (outer basin) marina has already been shown to be an irregular case due to its proximity to canneries. Similarly, the Bandon basin is affected by siting location. This marina is next to the Bandon secondary sewage treatment plant and also to a saw mill that tends to cause a pollution problem (Percy *et al.*, 1973, p. 70).

Utilizing Figures 20 and 21 as a basis for comparing the marinas, limiting values of AREA = 400 and ENTR = 100 are considered dividing lines between acceptable and

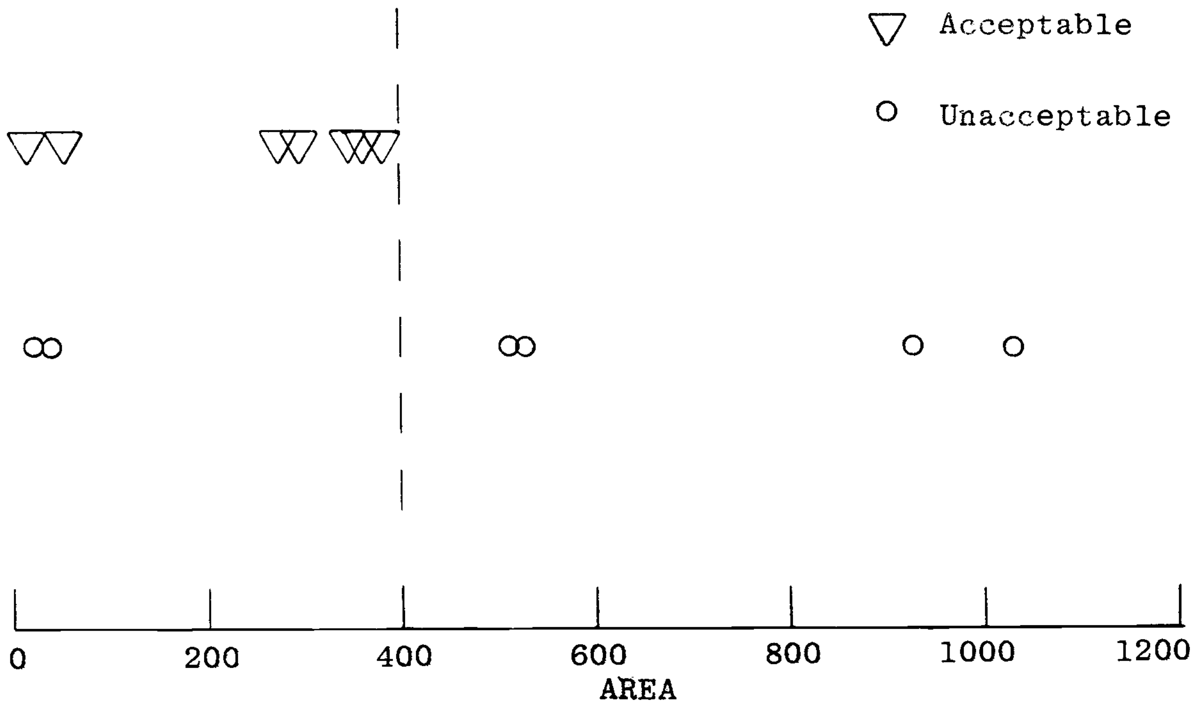

Figure 20. Marinas with respect to acceptability and AREA.

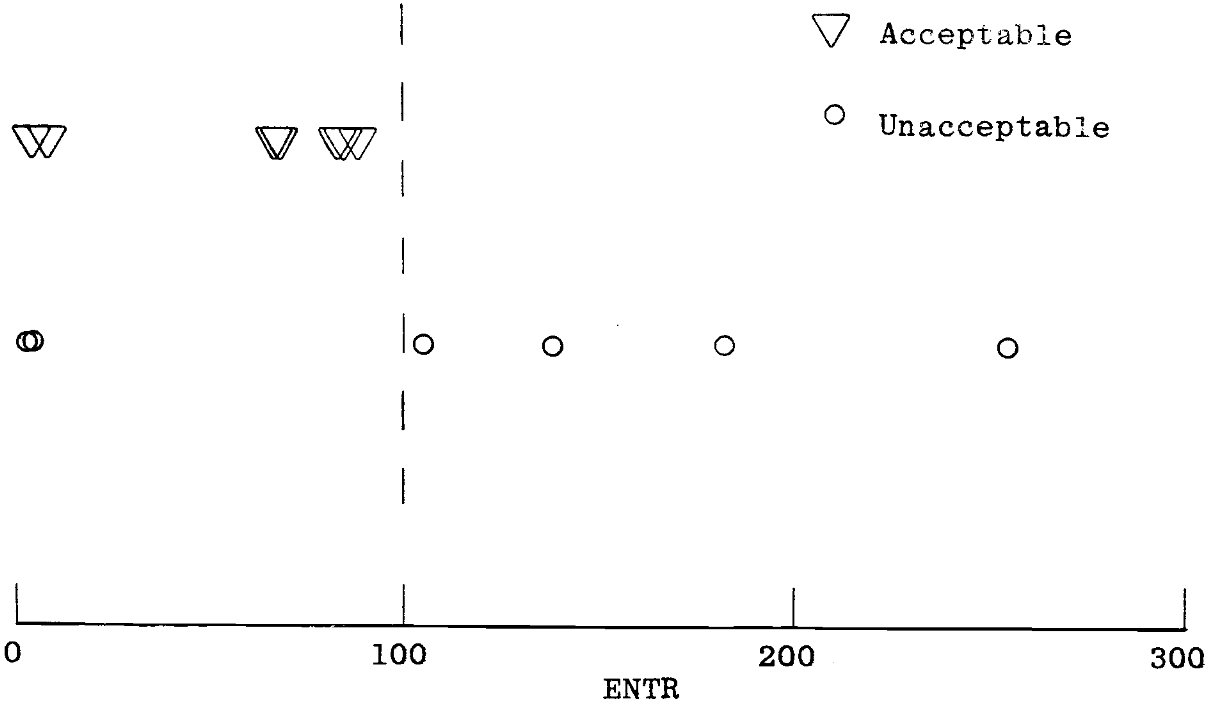

Figure 21. Marinas with respect to acceptability and ENTR.

unacceptable groups. These critical values are founded from what has been stipulated as being acceptable, i.e. from sediment quality criteria.

Before going further into a treatise of these preliminary limiting basin parameters, a discussion of other analytical approaches will follow, with the objective that after all of the analyses have been portrayed, a final set of recommendations will be presented. The applicability of any suggested limiting criteria will accordingly be presented.

Statistical Analyses

Partial Correlations

Partial correlation coefficients can be used to obtain a measure of the correlation of variables among themselves and to aid in the interpretation of statistical models. Table 12 is a matrix of correlation coefficients of the variables used in the statistical analyses. The sign determines whether two variables relate positively or negatively to one another. A perfect correlation is designated by a +1.0 or -1.0, while two variables said to be completely uncorrelated will have a correlation coefficient of 0.0. A perfect correlation signifies that a plot of the two variables will lie on a straight line, whereas a coefficient of 0.0 means the data will be scattered randomally about the graph.

Table 12. Partial correlation coefficients of sediment and basin variables.

	VS	KJDN	GO	SULF	PI4	PI24	AREA	DIST	ENTR	RA	DTHA	REY	FR	THETA
VS														
KJDN	.550													
GO	.431	.216												
SULF	.362	.501	.582											
PI4	.662	.631	.751	.913										
PI24	.339	.661	.458	.925	.851									
AREA	.119	.557	.192	.627	.530	.658								
DIST	.122	.156	.115	.025	.097	.092	-.055							
ENTR	.053	.451	.135	.349	.317	.348	.857	-.097						
RA	.214	.124	.048	-.041	.060	-.091	.317	-.132	.559					
DTHA	-.250	.141	-.154	.250	.064	.313	.401	.442	.294	.117				
REY	.226	.645	.026	.209	.275	.359	.385	.151	.228	-.292	-.038			
FR	.209	.654	.176	.409	.431	.439	.798	-.062	.834	.315	.180	.454		
THETA	-.061	.170	.034	.424	.271	.446	.391	-.037	.222	.060	.775	-.122	.178	
SQREY	.284	.604	-.000	.077	.198	.230	.137	.179	.000	-.316	-.108	.942	.295	-.158

If two independent variables are highly correlated then the use of both these variables in a model might be misleading. In helping to explain this point, let us look at the general form of a multiple regression model (where two independent variables will be used for simplicity, but the argument applies to larger models as well),

$$Y' = b_0 + b_1X_1 + b_2X_2 .$$

In this model, Y' is the fitted response variable, X_1 and X_2 are independent variables with b_1 and b_2 the corresponding regression coefficients, and b_0 is a regression coefficient inherent in most models with the implied variable equal to 1.0. If X_1 and X_2 are highly correlated then the use of both variables in the model may tend to affect the regression coefficients b_1 and b_2. For the most accurate model, regression coefficients should remain nearly constant when new independent variables are added to the model. This is reasoned from the concept that each independent variable has a particular effect in reality upon the response function; the addition of another variable should have no effect on other independent variables in the theoretical model, only upon the response function. In interpreting models that may contain highly correlated variables, an examination of the regression coefficients as the variables are added will aid in assessing the impact upon the regression coefficients. If there is an impact on the coefficients, then it may be desirable to drop one or more of the variables. Another way of measuring which variables should remain in the model is to make statistical tests on each regression coefficient in the model. Both of the above techniques were used in the statistical analyses of the data.

The independent variables which had the highest correlation among each other were AREA and ENTR (coefficient of partial correlation r = 0.857), AREA and FR (r = 0.798), ENTR and FR (r = 0.834), DTHA and THETA (r = 0.775), and REY and SQREY (r = 0.942). One would expect DTHA and THETA, and REY and SQREY to be highly correlated because the two variables in both cases are defined similarly, i.e. SQREY for instance is the squared value of REY. Conversely, there is one case of independent variables that is completely uncorrelated, ENTR and SQREY (r = 0.000). There is no obvious explanation for this uncorrelated example.

In the case of the dependent variables, one might expect PI4 and PI24 (total pollution indices as defined in Table 8) to be highly correlated with the other response variables since they both are defined as a combination of the others; this was confirmed.

Glancing at the coefficients between test variables and basin variables in Table 12 shows that KJDN, SULF, and PI24 seem to have the highest degree of correlation with the independent variables. At the opposite end of the scale, GO appears to have the lowest relationships, with the correlation coefficient with SQREY equal to -0.000. All of the negative correlations have absolute coefficients less than 0.3 and thus are not very significant.

Three Test Variable Regression

To gain a subjective feel for the effect of the number of tests on the resultant model, two analyses were performed. One in which three tests (volatile solids, Kjeldahl nitrogen, and grease) were used to form the total pollution index; and the other which added the effect of the total sulfides test into the total pollution index. It was hoped that the difference in the resulting models from adding another set of test results would give an idea of the sensitivity of this type of problem solution to the resultant models.

This subsection deals with the analyses performed using the first three test data. It might be noted that any model produced with only one of these three as the response variable will not be affected by additional data in the form of another test. What will be altered is the total pollution index. Also note a model can be created with the new test data alone. Since the tests conducted have no impact on basin flushing, one would expect the addition of data from another test to only slightly alter any model conceived from three test data.

The variables DIST and DTHA are given particular mention. Even though these variables were not significant when compared with the other variables, attempts were made to initially add these to the models irregardless of their statistical relevancy. The idea was for the model to take into account the different sampling locations within the basins. In applying these models for predictive purposes, the two variables DIST and DTHA were considered unimportant and so were assigned the value 0.0. The basic approach was to include effects of the sampling program into the model, but since the model was only to deal with flushing potential, which is not a function of DIST and DTHA, it was sufficient to ignore the variables by equating them to 0.0.

There were two total pollution indices formed that were a combination of the test data. One was a simple addition of the pollution indices from the volatile solids, Kjeldahl nitrogen, and grease data, given the symbol PI3; and the other was the product of the same three tests, given the symbol PI23.

The attempt to create a model using volatile solids (VS) as the sole response variable was unsuccessful. Table 13 is a tabulation of statistical data, termed TVALUES, which was used in determining which variables would be added to the model, and if the regression coefficients were significant at the 90% level. The tabulation is divided into two groups: the first giving variables in the model

Table 13. Volatile solids regression statistics.

(1)

Variable	S.E. of Regr. Coef.	T	Critical T
Constant	0.128	0.120	1.734

Variable	Partial Correlation	T	Critical T
AREA	0.119	0.492	1.740
DIST	0.122	0.508	
ENTR	0.053	0.219	
RA	0.214	0.905	
DTHA	-0.250	-1.063	
REY	0.226	0.955	
FR	0.209	0.883	
THETA	-0.060	-0.250	
SQREY	0.283	1.219	

(2)

Variable	S.E. of Regr. Coef.	T	Critical T
Constant	0.301	4.666	1.740
DIST	0.455	0.508	

Variable	Partial Correlation	T	Critical T
AREA	0.126	0.510	1.746
ENTR	0.066	0.263	
RA	0.234	0.964	
DTHA	-0.341	-1.453	
REY	0.211	0.864	
FR	0.219	0.898	
THETA	-0.056	-0.226	
SQREY	0.268	1.112	

with the corresponding standard error and t-statistic for the regression coefficient; the second listing the variables not in the model, with the corresponding partial correlation coefficients (based on the correlation of adding the particular variable with the existing model) and the t-statistic of the regression coefficient, if that variable were to be added. Also appearing in Table 13 is the 90% level critical t-statistic by which the significance of the variables was determined. As variables were added, the degrees of freedom of the model decreases, thereby affecting the critical t-statistic. With only the constant in the model, the degrees of freedom is equal to n-1, n being the sample size, and as each variable is added, one degree of freedom is lost.

Table 13 relates the TVALUE statistics both with and without the variable DIST being added to the model irrespective of its significance. In both cases it is clearly apparent that none of the variables would meet the critical statistic when added. It was therefore concluded that no model with VS alone could be derived.

When trying to regress the additive pollution index, PI3, on the basin parameters, the same result occurred as with the VS model. None of the regression coefficients were significant at the 90% confidence level with or without DIST in the model. This was somewhat contrary to what was expected, since it was believed a combination of the test results would be the best for model building. The regression on the multiplicative combination was found to yield much better results.

Also contrary to correlation expectations, the grease data, GO, furnished a satisfactory model, after some manipulation. DIST was added and no variables had high enough t-statistics to warrant their addition. However, when DTHA was added, the TVALUE data showed that variables were significant enough to add to the model. Consequently, THETA was added, with the effect that the t-statistics on the regression coefficients were all above 2.0 (the critical value at this degree of freedom being 1.753). There was also evidence that other variables should be added. Thus, ENTR came into the model. Table 14 lists the TVALUES for the case when only DIST is in the model, and when the model is complete. This table shows that after DIST is in the model the variables are still not significantly correlated, but with further manipulation the regression coefficients become significant. It should be noted that with the limited degrees of freedom available in this study (nineteen data points), the number of variables that can be added to a model safely is severely restricted. The final model should accordingly be viewed with some reservation.

Two of the response functions for GO are graphed in Figure 22. One curve contains the variables DIST, DTHA, and THETA in the model, while the other has these three

Table 14. Grease regression statistics.

(1)

Variable	S.E. of Regr. Coef.	T	Critical T
Constant	0.300	2.734	1.740
DIST	0.453	0.477	

Variable	Partial Correlation	T	Critical T
AREA	0.200	0.815	1.746
ENTR	0.148	0.597	
RA	0.064	0.258	
DTHA	-0.239	-0.946	
REY	0.009	0.036	
FR	0.184	0.750	
THETA	0.039	0.156	
SQREY	-0.021	-0.085	

(2)

Variable	S.E. of Regr. Coef.	T	Critical T
Constant	0.440	-0.904	1.761
DIST	0.581	3.148	
ENTR	0.002	2.068	
DTHA	0.830	-3.493	
THETA	0.351	3.107	

Variable	Partial Correlation	T	Critical T
AREA	0.134	0.489	1.771
RA	0.089	0.322	
REY	-0.191	-0.703	
FR	-0.154	-0.563	
SQREY	-0.226	-0.835	

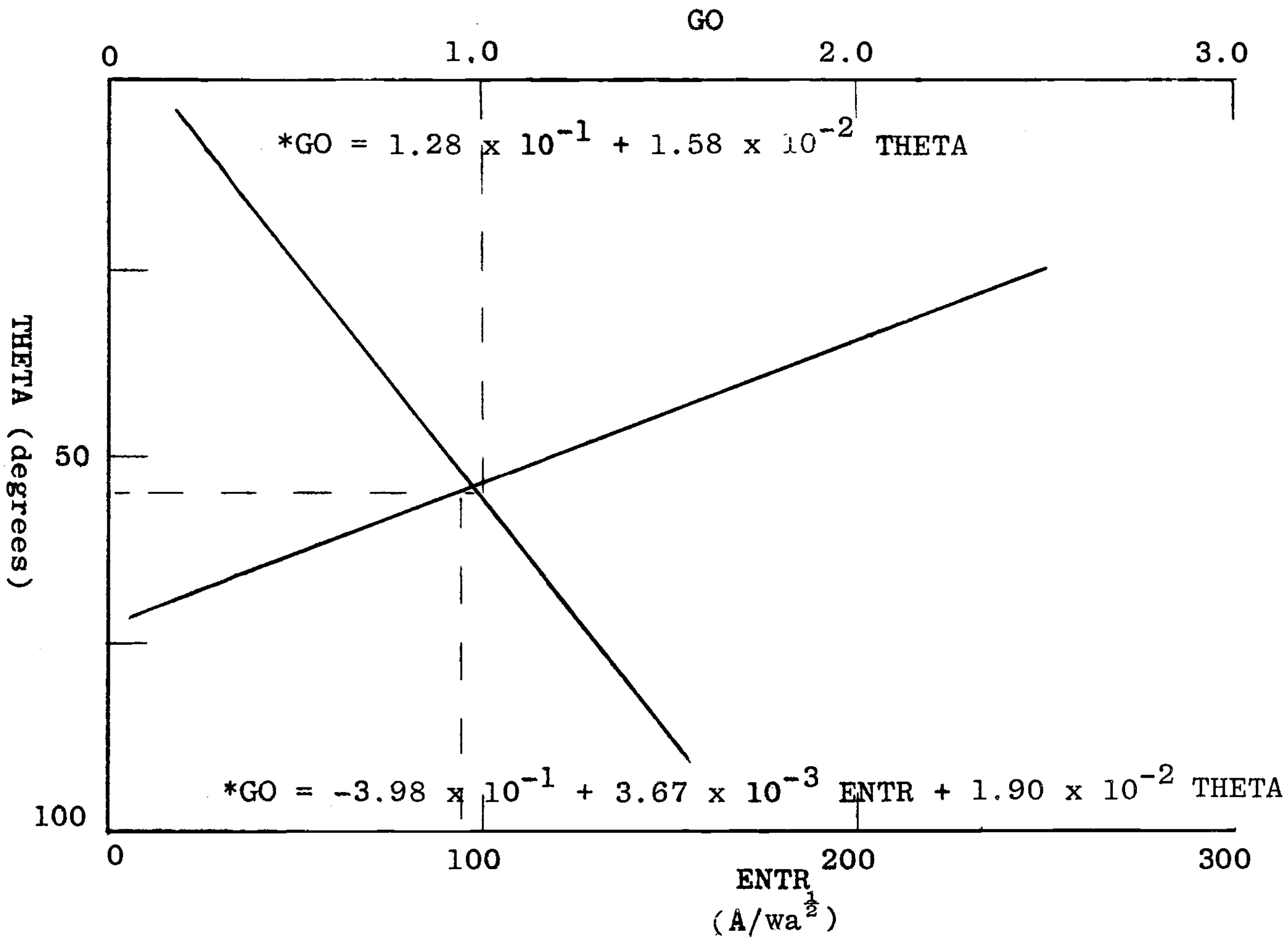

Figure 22. Response curve of GO to THETA and ENTR (*DIST and DTHA assigned the value of 0).

with ENTR added. The plot of both curves assigns the variables DIST and DTHA the value 0.0 for the reasons stated earlier. The first function is a plot of GO vs THETA, and the second curve is a plot of the isoline GO = 1.0 (limiting criteria) with ENTR vs THETA. The regression equations, minus the two sampling variables, are indicated adjacent to the appropriate curve. It is interesting to note that with the addition of ENTR, the regression coefficient of THETA changes only slightly. This shows that there is a correlation between the two variables (r = 0.222 from Table 12), but not enough to greatly alter the model.

The interpretation of these two models is that when applying the limiting criteria for grease content in benthic deposits (GO = 1.0), a maximum angle of basin entrance orientation should be about 55 degrees (this interpretation is printed as a dashed line in Figure 22). The value of the second curve is to relate ENTR to THETA. We have already determined that a maximum THETA = 55 degrees should be observed, this corresponds to an ENTR approximately equal to 95 (again, a dashed line represents this interpretation).

The Kjeldahl regression yielded some of the most significant statistics. Variables other than the ones important in the GO regression were found significant. Table 15 is a listing of the TVALUES with all the pertinent variables in the models. One case included DIST, whereas the other

Table 15. Kjeldahl nitrogen regression statistics.

(1)

Variable	S.E. of Regr. Coef.	T	Critical T
Constant	0.059	4.412	1.746
FR	0.048	3.200	
SQREY	0.002	2.761	

Variable	Partial Correlation	T	Critical T
AREA	0.215	0.852	1.753
DIST	0.178	0.700	
ENTR	0.052	0.202	
RA	0.194	0.766	
DTHA	0.159	0.625	
REY	-0.088	-0.341	
THETA	0.249	0.996	

(2)

Variable	S.E. of Regr. Coef.	T	Critical T
Constant	0.106	1.885	1.753
DIST	0.151	0.700	
FR	0.049	3.209	
SQREY	0.002	2.513	

Variable	Partial Correlation	T	Critical T
AREA	0.213	0.817	1.761
ENTR	0.050	0.186	
RA	0.202	0.774	
DTHA	0.080	0.301	
REY	-0.092	-0.347	
THETA	0.249	0.964	

did not. It was again illustrated that the variables in the model were significant with respect to KJDN, and the parameters not included were not significant.

Figure 23 shows two curves, one corresponding to just FR in the model, and the other with FR and DIST. This figure illustrates two things: adding DIST to the model only slightly changes the curve, having the most affect on the constant in the equation; and that the Kjeldahl regression implies that all the basins are satisfactory with respect to flushing. This statement is made on the basis that a limiting value of KJDN just barely intersects the curves. This could be expected when remembering that the Kjeldahl test indicated but one station classified polluted according to the EPA spoil limits. In order to use the Kjeldahl data for design purposes a lower limiting value of KJDN would need to be selected, which is a somewhat subjective problem. For want of a better solution, the limiting value was chosen as the mean Kjeldahl concentration of O'Neal's lightly polluted sediment samples. This value happened to fall between the mean Kjeldahl values of the acceptable and unacceptable groups in this study. Translated, the critical KJDN becomes 0.55. This critical value corresponds to the dashed line in Figure 23. The limiting FR numbers become 1.2 for the case not considering DIST, and 1.7 when DIST is considered. Remembering that general guidelines

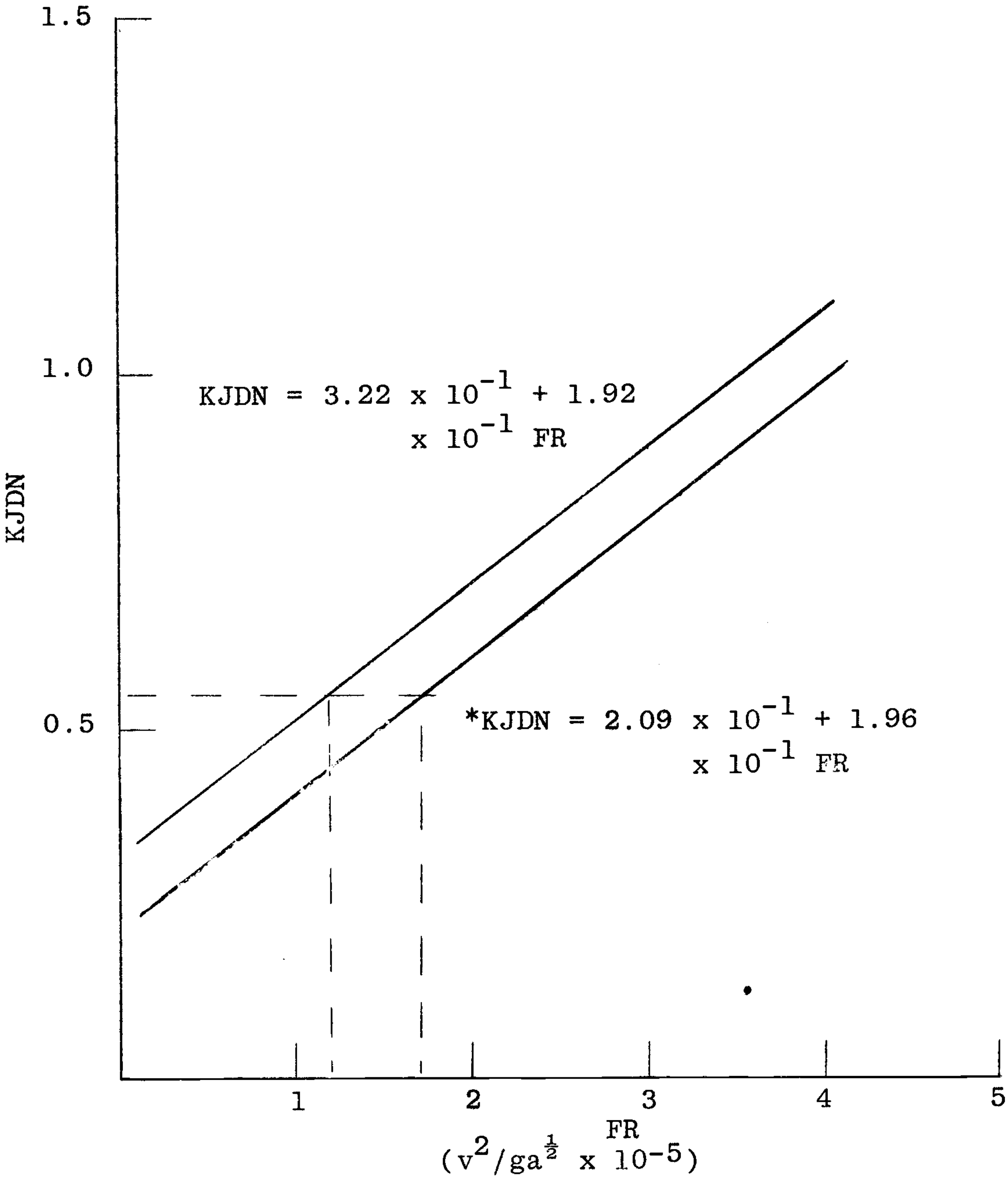

Figure 23. KJDN related to FR (*DIST assigned the value of 0).

are the goal in this report, the difference in limiting values of FR is minor.

Figure 24 contains the isolines of KJDN = 0.55 with SQREY added to the model, for the cases with and without DIST. Using the representative limiting FR numbers, the limiting SQREY values become approximately 16 without DIST and 13 with DIST.

To facilitate the use of the Kjeldahl models, it is suggested that a simple average be used to provide design guidelines. Thus, limiting values of FR = 1.5 combined with SQREY = 15 can be used as general recommendations for design criteria.

Even though no relation could be formulated using the additive total pollution index, a model was achieved using the multiplicative total pollution index for three variables (PI23). Only one basin parameter was able to be included in the model at the 90% significance level. Figure 25 shows the relationship of PI23 to REY. Also included in the graph are the 90% confidence limits on the regression line. The line with DIST included in the model was not drawn, but it would be similar in slope but lower on the graph than the one presented.

The limiting value for the total pollution index was 1.0. Even though a low critical index was used for KJDN, in the combined effect of all three equal weight was given to the total index. A critical index of 1.0 yields a

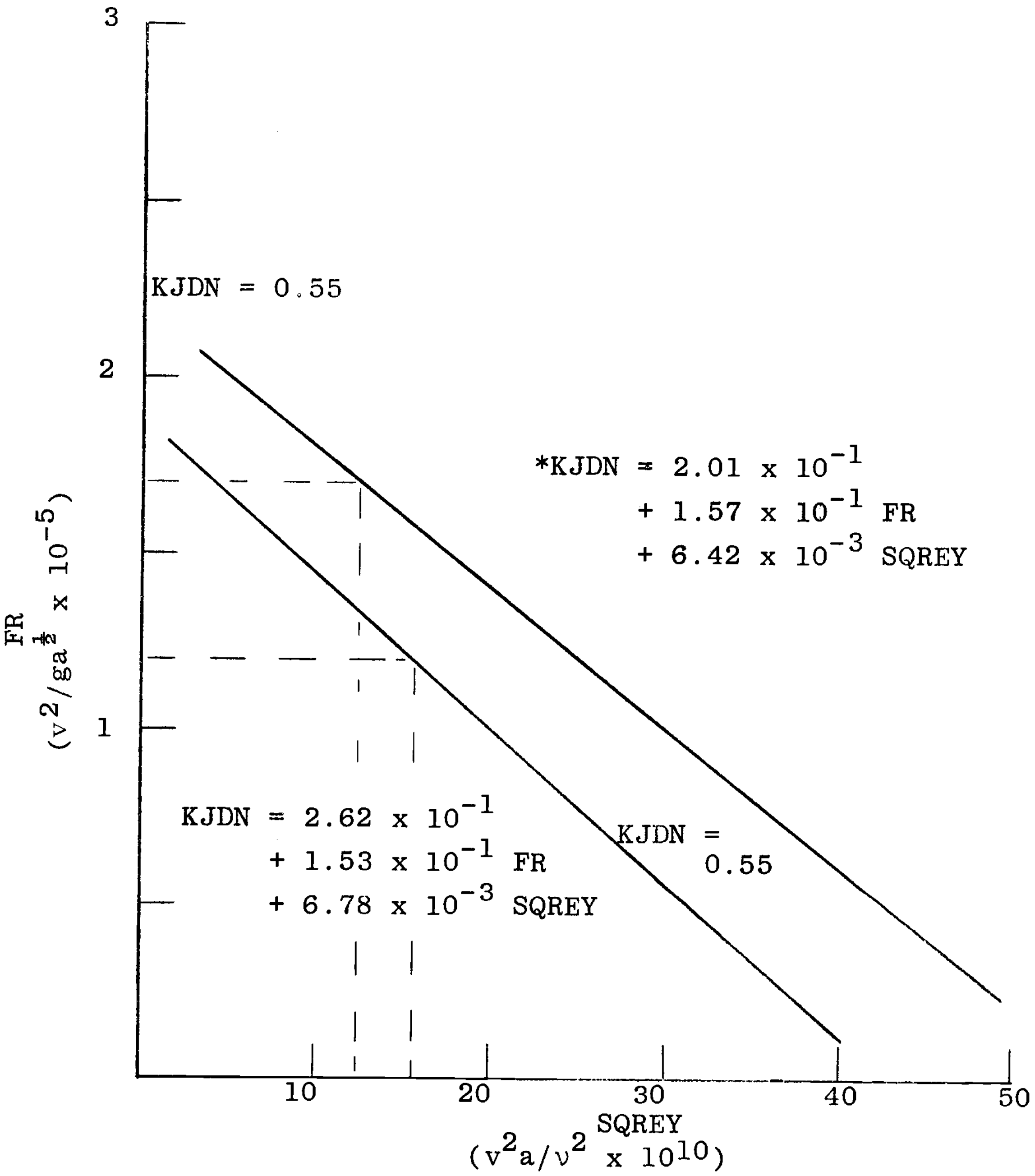

Figure 24. KJDN as a function of SQREY and FR (*DIST assigned the value of 0).

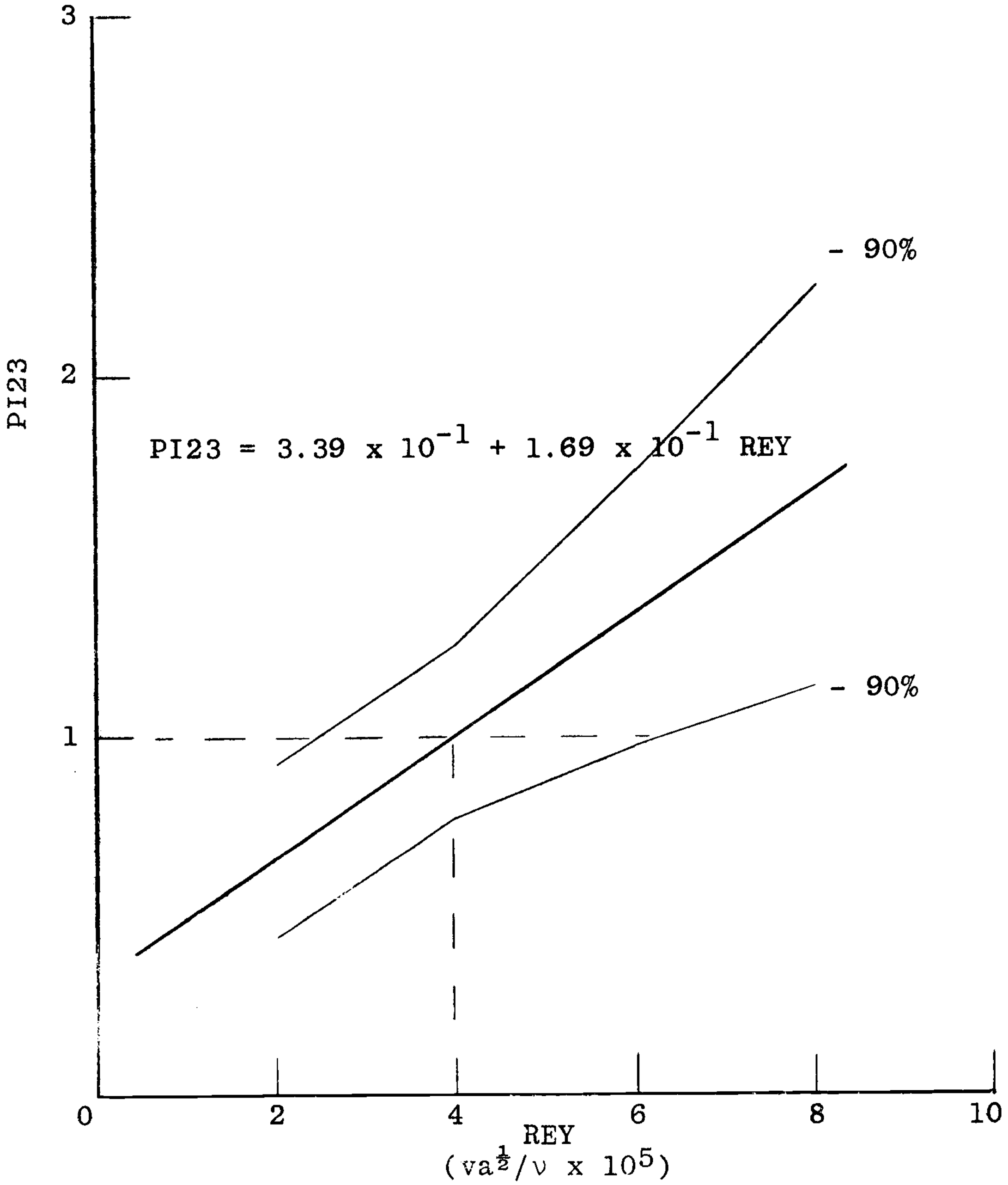

Figure 25. Total pollution index (PI23) as a function of REY).

limiting value REY number of 4.0; it would be 5.0 for the model including DIST.

Confidence limits give an indication as to the quality of the model. If for example, the 90% confidence limits gave a range of limiting REY numbers from 1.0 to 8.0, then the model would be deemed insignificant. In this case, the confidence limits give a range of limiting REY numbers of from 2.4 to 6.4. The limits are not close but they are sufficiently satisfactory for the trends in this analysis. Quantitative results indicate that the reduced marina data will provide a basis for general guidelines. The results do give a representative range, and the actual value from the regression line is sufficiently reasonable in order to make general recommendations. A maximum recommendation of approximately 4.5 for the basin parameter REY is suggested for design criteria.

Four Test Variable Regression

With the addition of the total sulfides information, three more response variables for making models are generated. These three are the sulfide function (SULF), the additive total pollution index combining four test variables (PI4), and the multiplicative total pollution index combining four test variables (PI24).

In regressing SULF on the basin variables, a new set of parameters other than FR and REY, used commonly earlier, became important. The final model involved AREA and ENTR. Table 16 shows the TVALUE statistics with just AREA and then with AREA and ENTR in the model. It will be remembered that these two variables are highly correlated among themselves (r = 0.857) so the effect they have on each other must be observed.

Figure 26 shows two curves. One curve is the isoline of SULF = 1.0 (critical value) with AREA and ENTR, and the other line is SULF plotted against AREA. A model was derived with DIST in it, but the similarity to the line without DIST warrants notice of what the limiting values are with respect to the DIST model. The critical SULF value suggests an AREA equal to approximately 205. This limiting AREA value then suggests a limiting ENTR of about 50. With DIST included, the limiting AREA is 268 with the corresponding ENTR equal to about 70. Average limiting values would be AREA equal to 240 and ENTR equal to 60.

Examining Figure 26 shows that when ENTR is added to the model, the difference in slopes of the lines (change in the regression coefficient of AREA) is substantial. In fact there is a change of about 65% in the regression coefficient of AREA between the two models. This suggests that possibly only the variable AREA should be in the model; however, other models may prove to be more useful.

In finding a model that would fit the additive total pollution index (PI4) a newly defined variable came into

Table 16. Total sulfides regression statistics.

(1)

Variable	S.E. of Regr. Coef.	T	Critical T
Constant	0.413	1.154	1.740
AREA	0.0008	3.317	

Variable	Partial Correlation	T	Critical T
DIST	0.077	0.307	1.746
ENTR	-0.470	-2.129	
RA	-0.324	-0.369	
DTHA	-0.002	-0.008	
REY	-0.044	-0.177	
FR	-0.194	-0.793	
THETA	0.250	1.032	
SQREY	-0.011	-0.045	

(2)

Variable	S.E. of Regr. Coef.	T	Critical T
Constant	0.386	1.708	1.746
AREA	0.001	3.701	
ENTR	0.006	-2.129	

Variable	Partial Correlation	T	Critical T
DIST	0.035	0.136	1.753
RA	-0.067	-0.259	
DTHA	-0.060	-0.231	
REY	-0.168	-0.660	
FR	0.042	0.163	
THETA	0.161	0.633	
SQREY	-0.139	-0.542	

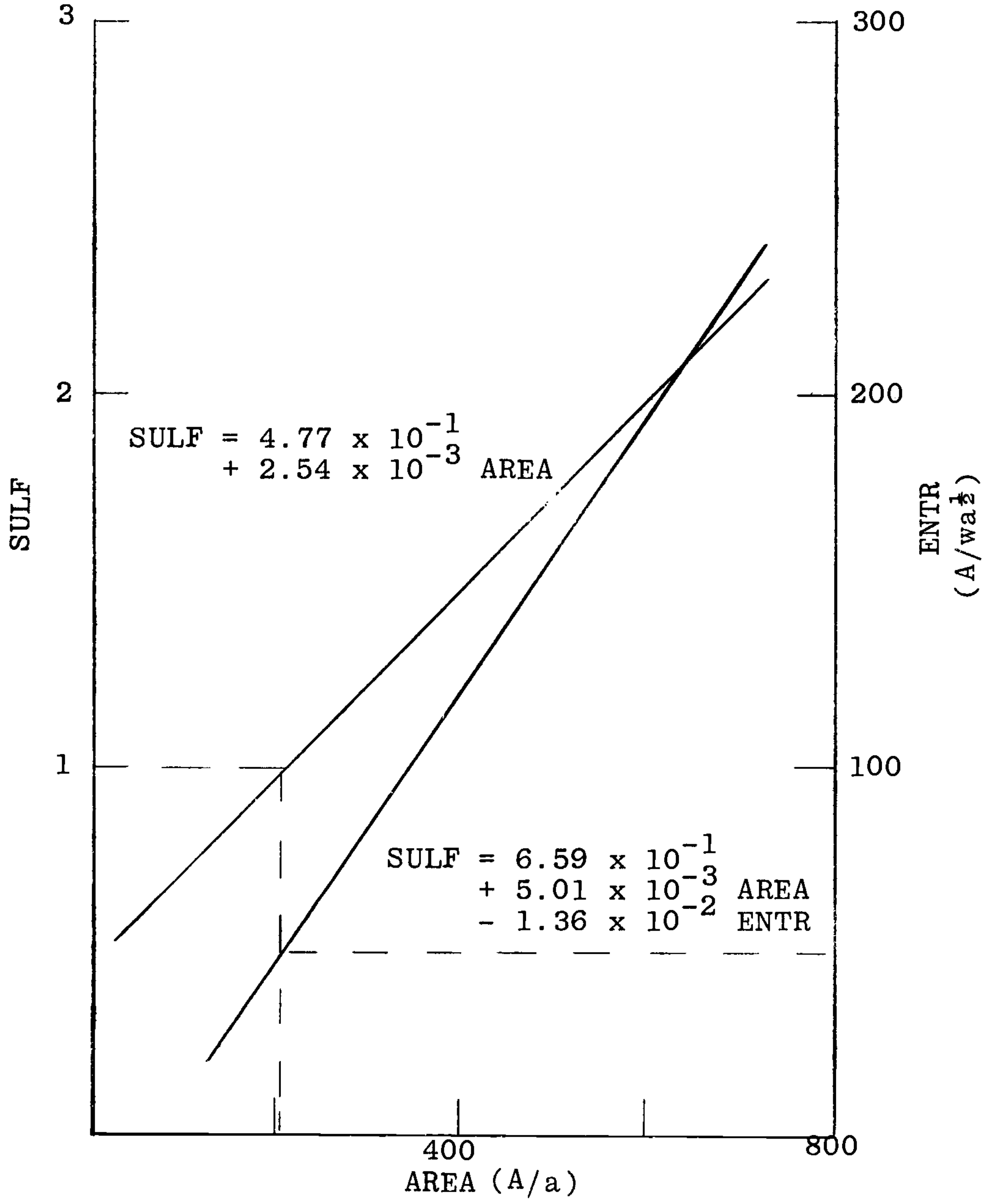

Figure 26. SULF regression lines.

use. Similar to DTHA, DTHB is equal to DIST * cos(THETA). This variable would be utilized similar to DIST and DTHA whereby it would be treated as zero when it was in the model. The best regression equation became a function of DTHA, DTHB, AREA and THETA. ENTR could have been marginally added but since it was correlated with AREA, and considering the number of variables already in the model, it was felt best to leave it out.

Table 17 lists TVALUES for the final model. Figure 27 is the corresponding graph with DTHA and DTHB set to zero. The line is the 4.0 PI4 isoline (critical value for the four variable additive index is 4.0). Also plotted on Figure 27 is the regression line with only AREA in the model. The critical index as noted by the dashed line, starting from the PI4 axis, suggests a limiting AREA of 280 and a limiting THETA of about 55 degrees. With DTHA, DTHB, and AREA in the model, the limiting value for AREA is 350, which when used in the model with THETA causes a change in the limiting THETA to about 50 degrees. Using the averaging procedure when sampling variables are added suggests limiting values of AREA = 315 and THETA = 50 degrees (taking the conservative value of two that are nearly the same).

In the analysis of the multiplicative combined index PI24, three models were derived. More than three were possible but the increases in variables added to the model made the validity of the model questionable.

Table 17. PI4 regression statistics.

Variable	S.E. of Regr. Coef.	T	Critical T
Constant	1.365	-1.190	1.761
AREA	0.001	4.212	
DTHA	1.631	-3.102	
THETA	1.154	3.942	
DTHB	1.720	3.637	

Variable	Partial Correlation	T	Critical T
DIST	0.329	1.257	1.771
ENTR	-0.451	-1.822	
RA	-0.146	-0.532	
REY	0.024	0.085	
FR	-0.241	-0.899	
SQREY	0.052	0.188	

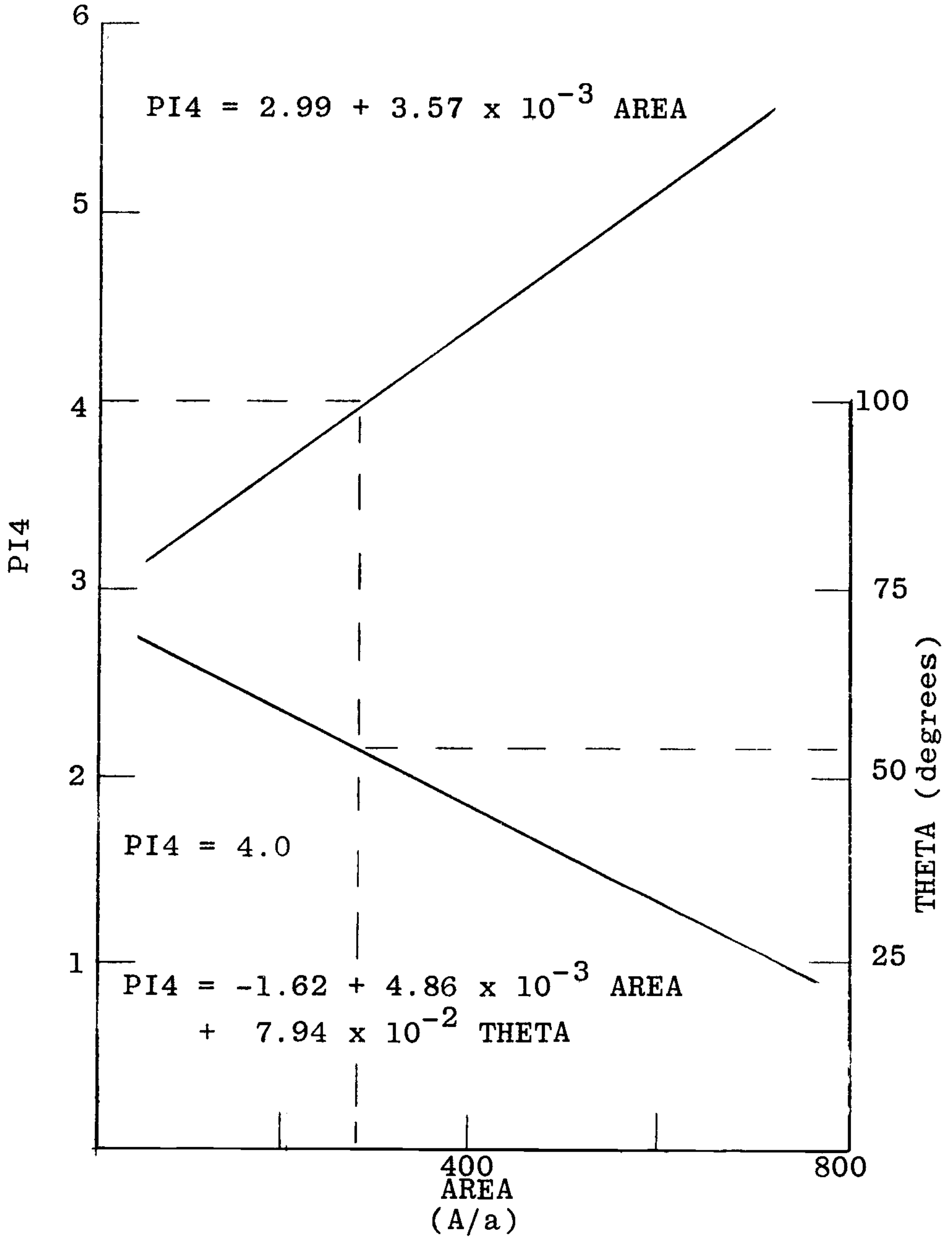

Figure 27. Additive pollution index (PI4) regression lines.

The easiest model, as in all of the examples, is the dependent variable as a function of only one other variable. The variable AREA was added first and its regression coefficient has a t-statistic of 3.604 (90% critical t-statistic = 1.74). A very similar model was obtained when DIST was added with AREA. The second model contains both AREA and ENTR, with t-statistics of 4.469 and -2.684 respectively (critical t = 1.740). These are relatively high t-statistics, with those for AREA being the highest. As with the case when SULF was regressed on AREA and ENTR, one would need to be concerned with the multicollinearity effects of the two highly intercorrelated independent variables. The third model of interest contains DIST, DTHA, AREA, and THETA. All of the representative t-statistics are above 2.3 (critical t = 1.761). Because of the number of variables included in the model, caution should be applied before accepting the model. The model may contain useful information, but it must be considered in the light of the analysis.

Figure 28 is a representation of all three models. The critical index for PI24 is 1.0. This value is used to obtain a limiting value for AREA, which is used to obtain limiting values of ENTR and THETA. The dashed line on the graph delineates the limiting values. A look at the slopes between the first two cases again shows substantial effect on the regression coefficient of AREA when ENTR is brought

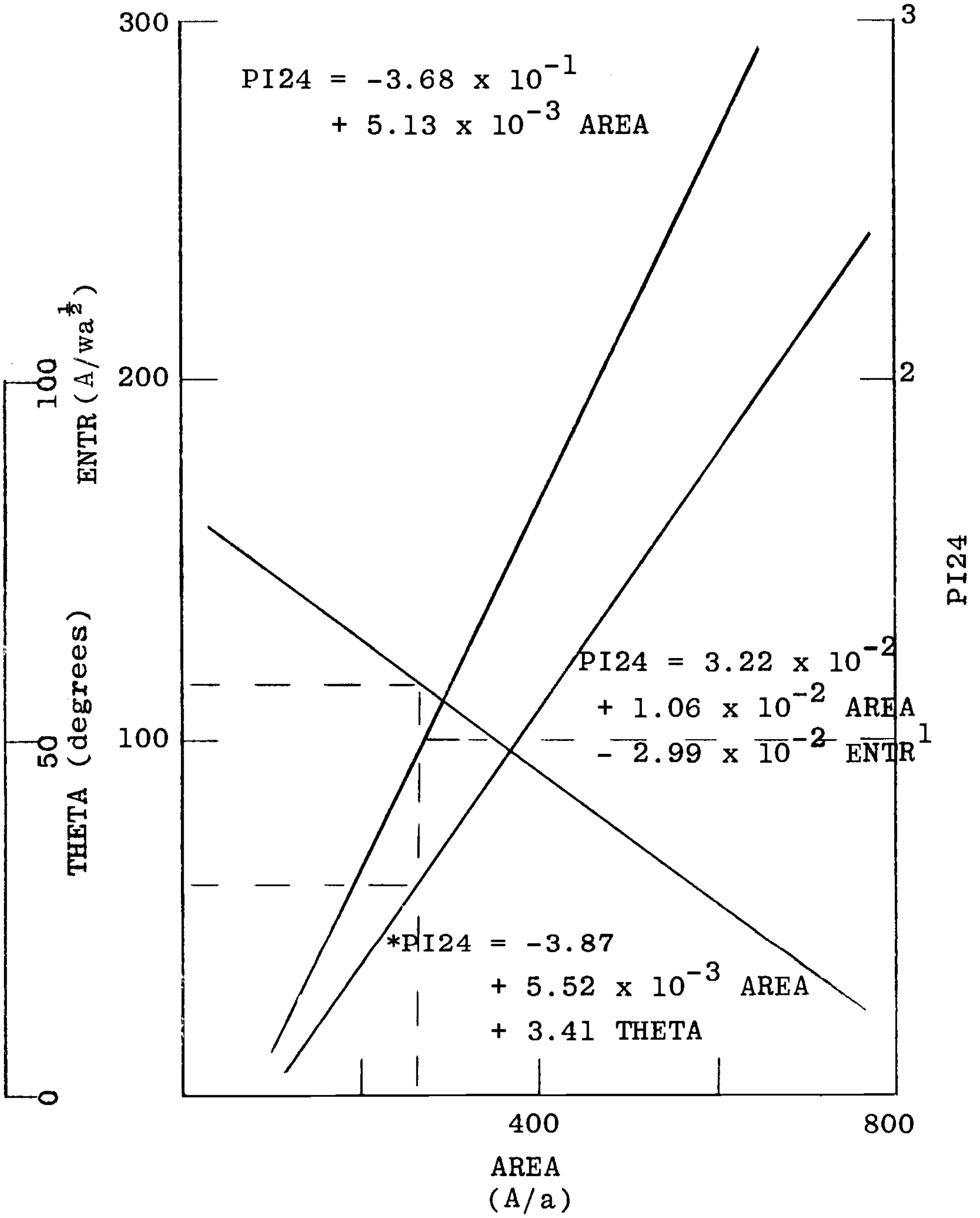

Figure 28. Total pollution index (PI24) as a function of AREA, ENTR and THETA. (*DIST and DTHA are assigned the value of 0).

into the model (the difference between AREA's coefficients is about 69%). The model with both variables included should be viewed carefully. The limiting value of AREA becomes approximately 260 with the corresponding ENTR and THETA equal to about 60 and 60 respectively.

Recommendations

The benefit of analyzing the data in several statistical ways is that comparisons can be made between the results, a process which will help in determining the reproducibility of the results. Table 18 lists the results of different analyses with the respective limiting recommendations. The asterisks denote which recommendations were the

Table 18. Marina design recommendations based on various models.

Analysis	Limiting Value for High Quality Water	
Grouped	*AREA = 400	*ENTR = 100
KJDN	FR = 1.5	SQREY = 15
GO	THETA = 55	ENTR = 95
SULF	AREA = 240	ENTR = 60
PI23	*REY = 4.5	
PI4	AREA = 315	THETA = 50
PI24	ENTR = 60 AREA = 260	THETA = 60

*Only one variable involved in analysis.

the result of an analysis of one variable, the rest occurring in a multivariable model.

The two variables that appear most in Table 18 are AREA and ENTR. These variables are highly intercorrelated, so their influence on each other may affect the model. The two times these variables occur in the same model corresponds to the lowest limiting values recommended for them. The effect of having them in the same model appears to lower each of their limiting values. This lends credence to the higher values suggested for AREA and ENTR. With this in mind, it is reasonable to set upper limiting values of AREA = 400 and ENTR = 100. Values lower than this will be conservative.

The other four variables with limiting values are THETA, REY, SQREY, and FR. THETA in all three cases is between 50 and 60. Considering this small range, an upper limiting THETA should be 60, with anything below that being conservative. The variable REY appears twice, once in the form of REY with limiting value equal to 4.5 and the other time as SQREY, which is REY squared, with a limiting value of 15. A somewhat conservative combined criteria can be given of REY $\leq$ 4.0. The variable FR appears only once, in combination with SQREY. The final limiting value for FR will stay at 1.5. The final recommendations, as tabulated in Table 19, are listed as maximum values.

Table 19. Final marina design recommendations.

Limiting Value for High Quality Water		
AREA = 400 THETA = 60	FR = 1.5	ENTR = 100 REY = 4.0

Recommendations Compared with Other Studies

Use was made of the Washington marina data of Yearsley's (1974) study to see if other marinas follow similar relationships. The ranking of the Washington marinas based on the composite water quality score assigned to them by Yearsley are given in Table 20. By computing the values of AREA, ENTR, REY, and FR, and applying the design recommendations, a ranking of marinas from least to most likely to be polluted was established. Table 20 is a list of the five marinas studied by Yearsley in order of increasing pollution susceptibility based on the limiting values of the dimensionless basin parameters. In the calculation of REY and FR it was assumed that the characteristic velocity was the same through each entrance, consequently the velocity was determined using a conservation of volume approach on the combined entrance area. In ranking the marinas, emphasis was placed on the AREA and ENTR variables because the highest degree of confidence is placed in these.

A comparison of the two rankings shows a good amount of correlation. The only marina that is somewhat displaced

Table 20. Comparison of marina rankings.

Basin Parameter Ranking		Basin Parameters				Composite Water Quality Ranking
		AREA	ENTR	REY	FR	
Kingston		52	5	3.2	0.1	Kingston
Edmonds		200	51	1.9	0.2	Shilshole
Shilshole	S	694	168	6.0	0.6	Port Townsend
	N	1051	248	4.8	0.7	Edmonds
Port Townsend		763	305	10.4	2.3	Squalicum
Squalicum	SW	870	245	4.7	1.2	
	NW	1052	306	4.3	1.3	

is Edmonds, getting a higher ranking from the basin parameter ranking than with the water quality ranking. There is no immediately apparent reason for this discrepancy, other than it is noted all of the marinas used to derive the basin parameter recommendations were located in an estuarine or riverine system; whereas the marinas studied by Yearsley were located on Puget Sound, a fairly open body of water. The agreement between the two rankings is surprisingly satisfactory.

APPLICATIONS

The purpose of this study has been to provide guidelines that can be used in the design of small boat marina basins. The focus on the guidelines has been to furnish a predictive tool that will enable an engineer to design for optimal flushing of a basin so that the water quality will remain high. In the recommendation section of the report, limiting values for optimal design were assigned to five variables. At this point it is necessary to discuss how the variables relate to each other and provide an example of how the criteria can be used to best advantage.

The most satisfactory variables, from a statistically significant point of view, number of times they appear in the models, and ease by which they are evaluated, are AREA and ENTR. They are defined by plan view area (A), mllw entrance cross-sectional area (a), and the entrance width (w), a combination of parameters that are easily varied in the design process.

The other three variables assigned limiting values are not as good as AREA and ENTR. In the case of THETA, there was quite a bit of scatter in the original data, and no real relationship existed between just the pollution indices and THETA. This particular variable was associated with ENTR and/or AREA in the models in which it appeared. The information derived from THETA is useful, however, because it does provide a general guideline. In the instance of FR and REY the velocity in each was defined strictly from a physical dimension point of view. Applying conservation of volume to compute the entrance velocity was considered acceptable because of the degree of accuracy desired and its successful use by other investigators.

The criteria based on FR and REY suggested extremely small entrance areas. For this reason and the confidence in the AREA and ENTR results, the variables FR and REY are considered to be relatively an unsatisfactory basis for a marina siting criteria.

The two most important variables, AREA and ENTR, will now be focused upon. To facilitate the use of these criteria in the design process, it was considered appropriate to originate a nomogram based on the three basin characteristics found in AREA and ENTR (namely A, a, and w). Because the suggested criteria are based on field information, the nomogram was confined to the range of values representative of the thirteen basins studied. These general ranges are: $A \leq 200{,}000\ m^2$; $a \leq 1500\ m^2$; and $w \leq 600$ m. Because of maximum values of A and a, w will be confined to a much smaller value than 600 m.

In combining the two dimensionless variables, it was informative to go back to their definition to try to integrate the two. Thus,

$$\text{AREA} = A/a \leq 400, \quad \text{ENTR} = A/(a^{\frac{1}{2}}w) \leq 100.$$

Rearranging ENTR, and then incorporating AREA yields,

$$A/(a^{\frac{1}{2}}w) * a^{\frac{1}{2}}/a^{\frac{1}{2}} = (A/a) * (a^{\frac{1}{2}}/w) = AREA * a^{\frac{1}{2}}/w \leq 100 \ .$$

Inserting the criteria of AREA, and remembering it is a maximum value gives,

$$400 * a^{\frac{1}{2}}/w \leq 100, \quad \text{or}$$
$$a \geq 0.0625\ w^2 \ .$$

The less than symbol is switched to a greater than symbol to account for the maximum AREA criteria of 400 which provides a minimum entrance area (a), given a width (w).

Figure 29 is the resulting nomogram, which can be used in the following way. In the design process the plan area may be a given, in that the marina is to provide anchorage for a certain number of boats. With A assumed, a and w may be altered to present the optimum plan. Basin bathymetry may be used to estimate a mean depth at the entrance, thus making a correlation of a and w very easy. For instance, if a plan area of 50,000 m^2 is to be used to provide a small boat marina, and the depth will be about 5 m, an entrance 40 m wide could be designed to provide a large enough cross-sectional area, 200 m^2, for adequate flushing.

The nomogram that is presented here is the result of a preliminary examination based on sediment grab samples. The nature of the study implies that the conclusions made are best considered as generalizations. For example, as

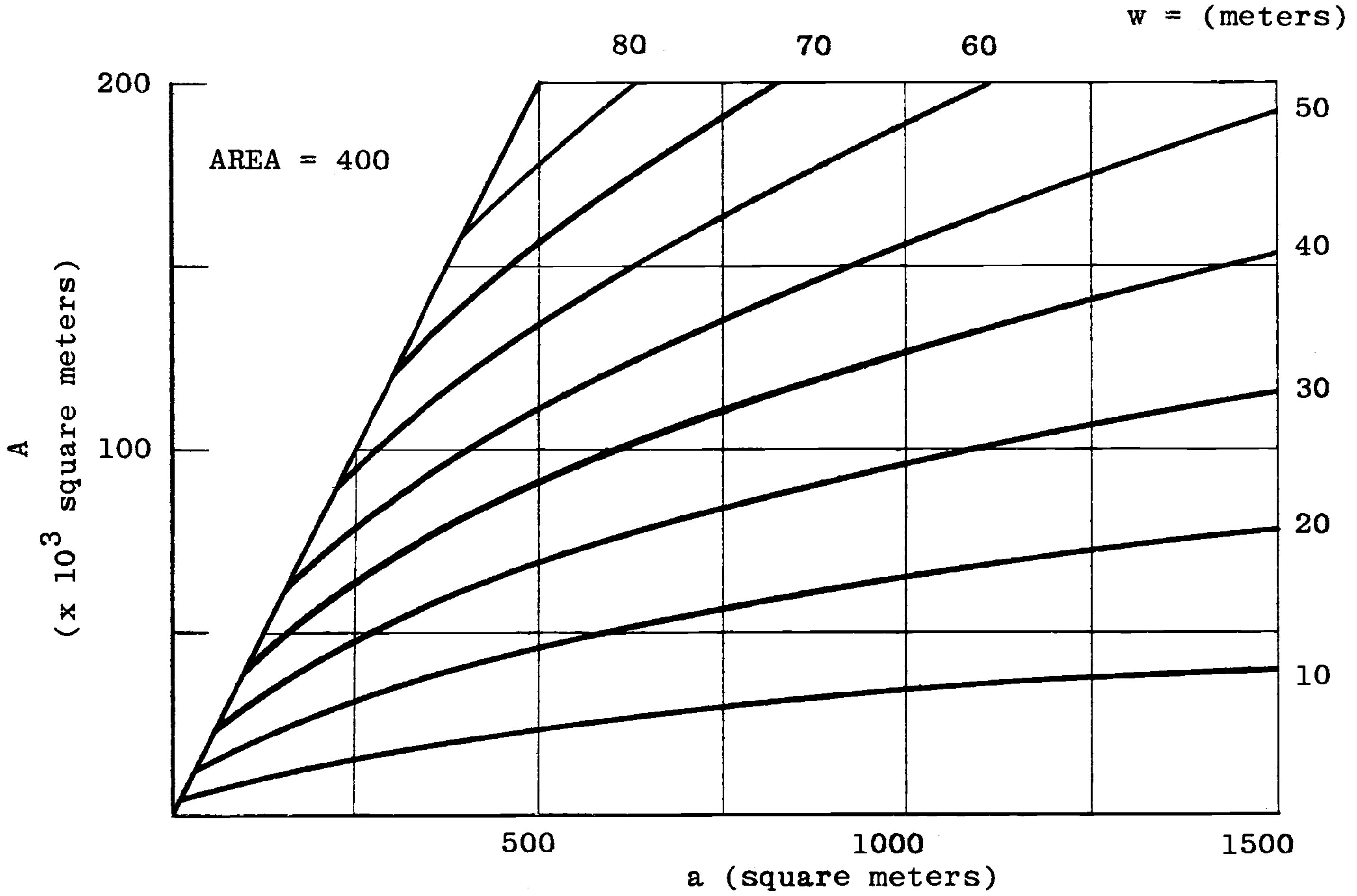

Figure 29. Nomogram of Acceptable Plan Area (A) vs Entrance Cross-Sectional Area (a) and Entrance Width (w) (A may be less than the limiting value, and a may be greater than the limiting value).

the plan area of a marina increases, there should be a corresponding increase in the entrance cross-sectional area to provide for adequate exchange with the main body of water. The nomogram suggests a general guideline for how much the entrance area should be increased based upon one set of samples taken from thirteen marinas along the Oregon coast.

Suggestions for Future Work

This study is a preliminary effort in applying sediment data to generalize the flushing ability of and circulation in marina basins. It has been shown that there is a practical utilization in an analytical approach using sediments as indicators of environmental quality. Future studies of this kind would be especially useful in supporting or suggesting changes in the conclusions of this study.

A most beneficial result of most studies is that the learning process is not confined to the problem that is being examined but extends to the study technique. From this study the following list has been compiled to assist other researchers who may venture into a similar project.

1. Several samples should be taken at each marina.
2. A formal random sampling technique should be followed.
3. Control samples outside of each marina should be examined.

4. Seasonal changes should be considered.
5. Core samples should be taken with subsequent testing of particular sediment depths from all of the samples.
6. A grain size analysis should be conducted.
7. The Kjeldahl test could be excluded with the addition of some other test.
8. When the basins were formed should be considered.

CONCLUSIONS

The following conclusions are drawn from the study reported in this thesis:

1. Sediment quality can be used to study hydraulic systems, in particular the flushing properties of small boat marina basins.
2. Basin characteristics can be combined into dimensionless numbers, which can be used to relate to sediment quality.
3. As justified by various analyses, the dimensionless variables AREA (A/a) and ENTR ($A/a^{\frac{1}{2}}w$) should be kept below 400 and 100 respectively in marina design to obtain optimal basin configuration for flushing.
4. Dimensionless variables THETA (θ), FR ($v^2/ga^{\frac{1}{2}} \times 10^{-5}$) and REY ($va^{\frac{1}{2}}/\nu \times 10^{+5}$) show a preliminary relationship to flushing (sediment quality) but should be examined further before being utilized extensively in the design process.

BIBLIOGRAPHY

American Public Health Association, Standard Methods for the Examination of Waste and Wastewater, 13th edition, Washington D.C., 1971.

Bella, D.A., Tidal Flats in Estuarine Water Quality Analysis, EPA-660/3-75-025, Environmental Protection Agency, Corvallis, Oregon, June, 1975.

Brezonik, P.L., Nitrogen Sources and Cycling in Natural Waters, EPA-660/3-73-002, Environmental Protection Agency, Washington D.C., July 1973.

Brock, T.D., Biology of Microorganisms, Prentice-Hall, Inc., Englewood Cliffs, New Jersey, 1970.

Dyer, K.R., Estuaries: A Physical Introduction, John Wiley and Sons, London, England, 1973.

Guthrie, D., Avery, C., and Avery, K., Statistical Interactive Programming System (* SIPS), Technical Report No. 36, Oregon State University, Corvallis, Oregon, May 1973.

Layton, J.A., Hydraulic and Flushing Features of a Small Craft Harbor in Puget Sound, thesis presented to the University of Washington at Seattle, Washington in 1971, in partial fulfillment of the requirements for the degree of Master of Science.

Lee, G.F., Factors affecting the transfer of materials between water and sediments, Literature Review No. 1, Federal Water Quality Administration, Washington D.C., July 1970.

Mitchell, R., Introduction to Environmental Microbiology, Prentice-Hall, Inc., Englewood Cliffs, New Jersey, 1974.

Neter, J. and Wasserman, W., Applied Linear Statistical Models, Richard D. Irwin, Inc., Homewood, Illinois, 1974.

O'Neal, G. and Sceva, J., The Effects of Dredging on Water Quality in the Northwest, U.S. Environmental Protection Agency, Region X, Seattle, Washington, July 1971.

Percy, K.L. et al., Descriptions and information sources for Oregon estuaries, Water Resources Research Institute 19, Oregon State University, Corvallis, Oregon, March 1973.

Reid, G.K., Ecology of Inland Waters and Estuaries, D. Van Nostrand Co., New York, N.Y., 1961.

Richey, E.P., Hydro-ecological problems of marinas in Puget Sound, Proceedings 1971 Technical Conference on Estuaries of the Pacific Northwest, Circular No. 42, Oregon State University, Corvallis, Oregon, 1971.

Sawyer, C.N. and McCarty, P.L., Chemistry for Sanitary Engineers, 2nd edition, McGraw-Hill Book Co., N.Y., 1967.

Slotta, L.S. et al., An examination of some physical and biological impacts of dredging to estuaries, Interim progress report to Division of Environmental Systems and Resources (RANN), Oregon State University, Corvallis, Oregon, Dec. 1974.

Soderquist, M.R., Environmental Associates, Development Document for Effluent Limitations Guidelines and Standards of Performance for the Canned and Preserved Fish and Seafoods Processing Industry, Phase II. U.S. Environmental Protection Agency, February 1974.

Soderquist, M.R., Environmental Associates, Upgrading Seafood Processing Facilities to Reduce Pollution, U.S. Environmental Protection Agency, March-April 1974.

U.S. Department of the Interior, Chemistry Laboratory Manual Bottom Sediments, Great Lakes Region, January 1968.

U.S. National Ocean Survey, Tide Tables 1975 West Coast of North and South America, Department of Commerce.

Walters, G.Z., Mangelson, K.A. and George, R.L., The hydraulics of waste stabilization ponds, PRCWRR18-1, Office of Water Resources Research, Utah State University, Logan, Utah, February 1973.

Westrich, B., Simulation of mass exchange in dead zones for steady and unsteady flow conditions, International symposium on unsteady flow in open channels, Newcastle-upon-Type, England, 12-15 April 1976.

Yearsley, J., Unpublished manuscript, U.S. Environmental Protection Agency, 1974.

APPENDICES

APPENDIX A

NOTATION

A = Basin plan area, m^2

a = Entrance mean lower low water (mllw) cross-sectional area, m^2

$\bar{a}$ = Entrance mean tide level (mtl) cross-sectional area, m^2

d_1 = Entrance mllw depth, m

d_2 = Average depth of basin, mllw, m

F = Flushing time in tidal cycles

g = Gravitational acceleration, 9.8 m/sec

ℓ = Standardized length of basin, m

P = Basin tidal prism, m^3 per tidal cycle

R = Mean tide range, m

T = Tidal period, taken as 12.4 hours

u = Mean velocity in main body of water, cm/sec

V = Volume of basin mllw

v = Mean entrance velocity, cm/sec

x = Standardized length from entrance to sample stations

μ = Absolute viscosity of water

θ = Angle of entrance orientation, degrees

ρ = Density of water

APPENDIX B

PHYSICAL DIMENSIONS OF BASINS STUDIED

Station		A (m^2)	a (m^2)	$\bar{a}$ (m^2)	ℓ (m)	P (m^3)	R (m)	w (m)	x (m)	θ ($^\circ$)
Astoria	1	55,748	109	137	307	105,921	1.9	29.5	88	45
	2								280	
Hammond		102,958	100	138	350	195,620	1.9	40.6	132	34
Garibaldi	1	44,360	84	123	311	75,412	1.7	46.0	127	90
	2								236	
Netarts		9,970	36	82	116	15,952	1.6	20.0	57	34
Depoe		31,870	109	138	248	50,992	1.6	36.2	171	0
Newport	1	196,948	552	664	731		1.8	125.0	118	17
	2								469	
Waldport*										
Florence		12,541	820		46		1.5	26.9	40	0
Winchester	1	194,570	210	282	1,112	291,855	1.5	96.5	528	90
	2								754	
	3								950	

Appendix B (continued)

Station	A (m^2)	a (m^2)	$\bar{a}$ (m^2)	ℓ (m)	P (m^3)	R (m)	w (m)	x (m)	θ (°)
Charleston (outer) 1	54,759	1,460		168		1.5	612.0	142	0
Charleston (inner) 2	50,682	147	183	401	76,023		48.0	325	90
Bandon	11,251	557	679	71	18,000	1.6	152.0	0	90
Gold Beach	9,638	182	249	381	14,457	1.5	90.0	343	79
Brookings 1	63,120	167	220	454	94,680	1.5	71	65	3
Brookings 2								441	

*No data available.

**Where no data exists, the measurement was inappropriate.