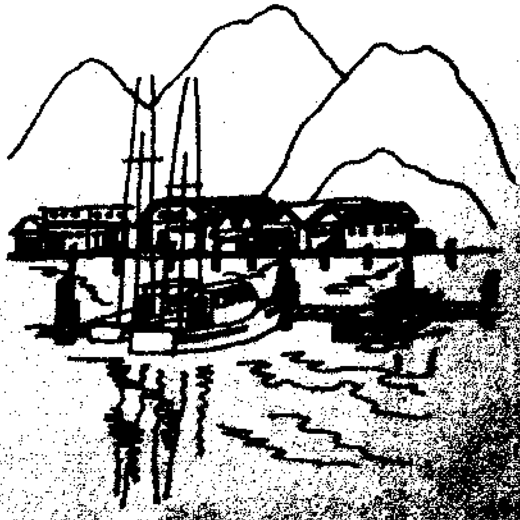
use of BENTHIC SEDIMENTS as indicators of MARINA FLUSHING

L. S. Slotta
Scott M. Noble



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related publication

OREGON'S ESTUARIES by Katherine L. Percy, Chet Sutterlin, David Bella and Peter C. Klingeman. 1974. 294 pp. ORESU-H-74-001. $2.00. Summarizes known information about 13 Oregon estuaries, excluding only the Columbia River. Intended as basic reference for those involved in coastal planning.

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abstract

This report presents the findings of a sediment analysis program formulated to determine the flushing potential of various shaped small boat 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 in normalizing laboratory test results into pollution indexes. 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 indexes and flushing phenomena. Comparing the relative differences in pollution indexes 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 where 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.

contents

introduction

This study is an attempt to understand the important functions of small scale estuarine circulation patterns by using benthic sediments as indicators of marina flushing. Specifically, research was done to identify physical parameters influential in providing the flushing necessary to preserve a high state of water quality in small estuarine marina basins. A *modus operandi* other than the classical engineering approach of strict fluid mechanics was employed.

An increased interest in estuaries and coastal shorelines, and a desire to control and predict the effect of unnatural inputs into these systems, has increased interest in small basins as a pollutant trap. Historically, boat basins were designed to provide protection in the marina from the environment. The best marina was the calm one, a critical factor when launching, loading, boarding, mooring or maneuvering boats. Increased emphasis on clear waters has brought to the forefront the fact that, in marina management, marinas are designed for the greatest protection, which also affords the least 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 any material in suspension or solution which washes into the protected marina. We will attempt to determine basin shapes best suited for recirculation capabilities while maintaining adequate protection.

Most engineering approaches to this problem would include a field study of the basin hydraulics and/or a mathematical model of the hydraulic system. Instead, this study will examine sediment characteristics to determine if 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 13 marinas along the Oregon coast, all within the confines of an estuary or an enclosed bay. Table 1 lists the marinas by common name, as they were referred to throughout the study, and by the name of the estuary or bay in which they exist. Fig. 1 shows where the marinas are located on the Oregon Coast. Figs. 2-14 show the marinas with respect to the main body of water, and also the locations where the sediment samples were taken.

ENGLISH - SI CONVERSION FACTORS

	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

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

Table 1. Marinas studied.

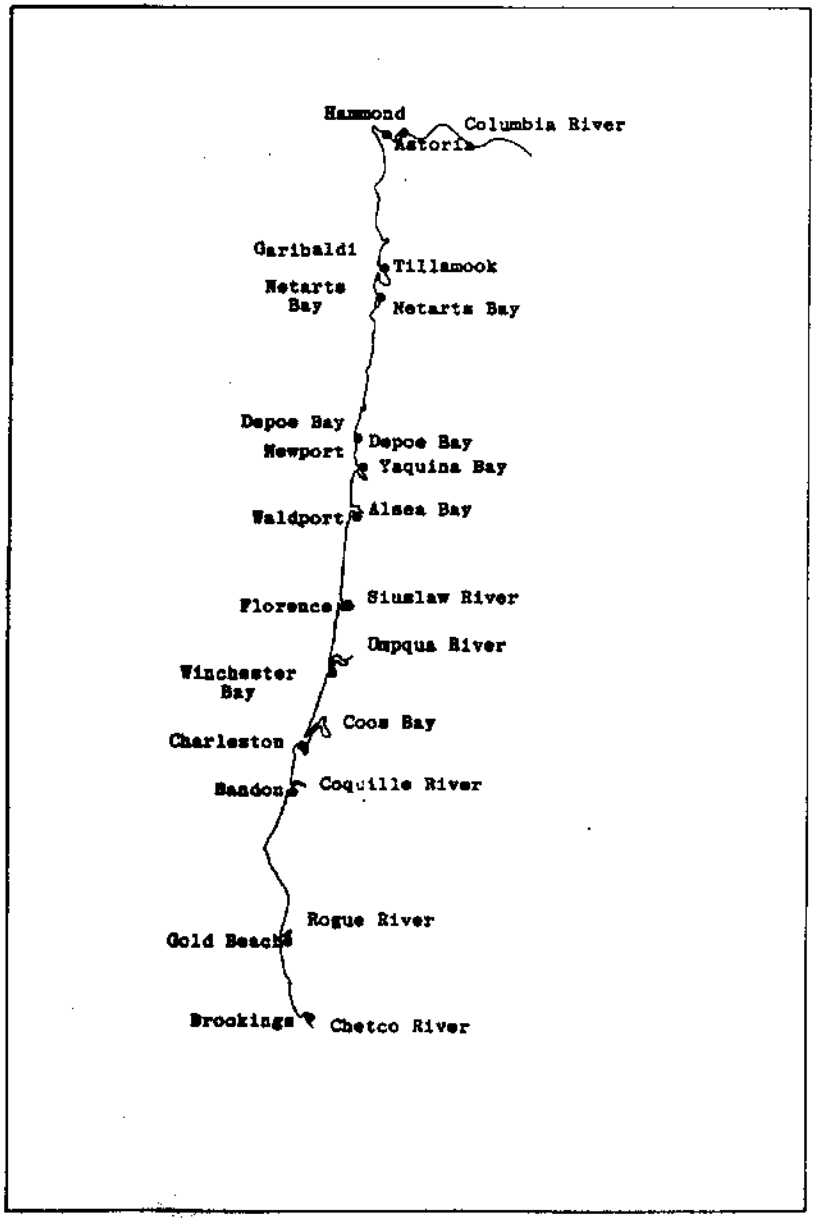

Fig. 1. Marina location map

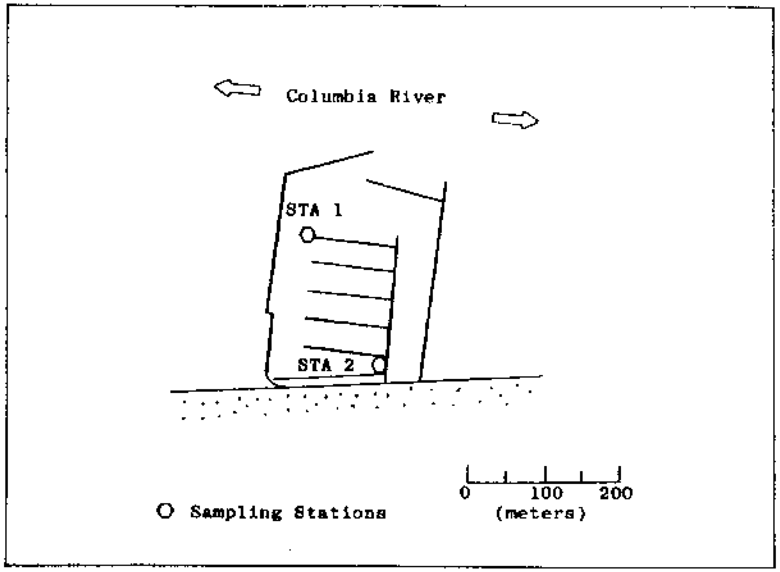

Fig. 2. Astoria Marina

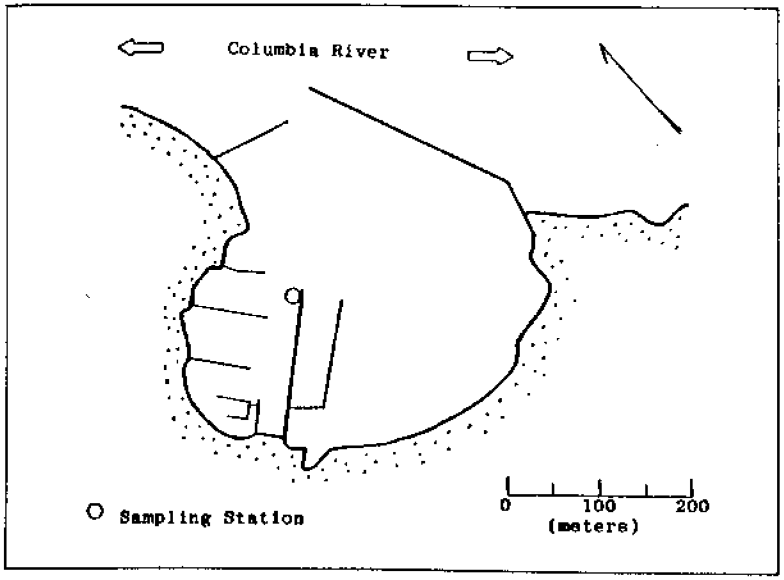

Fig. 3. Hammond marina (U.S. Army Corps of Engineers 1976)

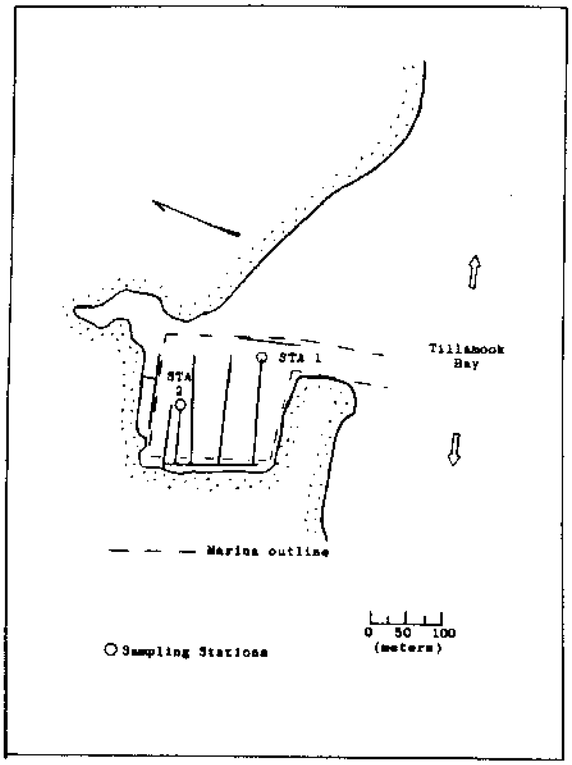

Fig. 4. Garibaldi marina (U.S. Army Corps of Engineers, 1974)

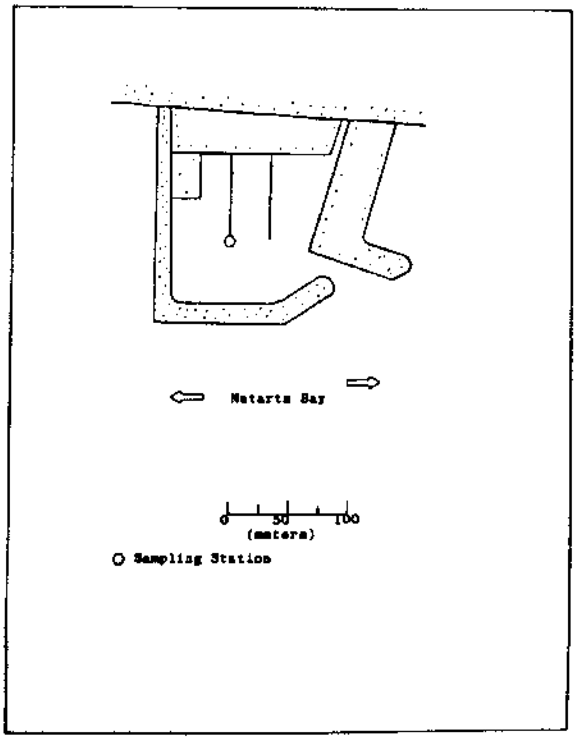

Fig. 5. Netarts Bay marina (Plan of Netarts Moorage Basin, 1960)

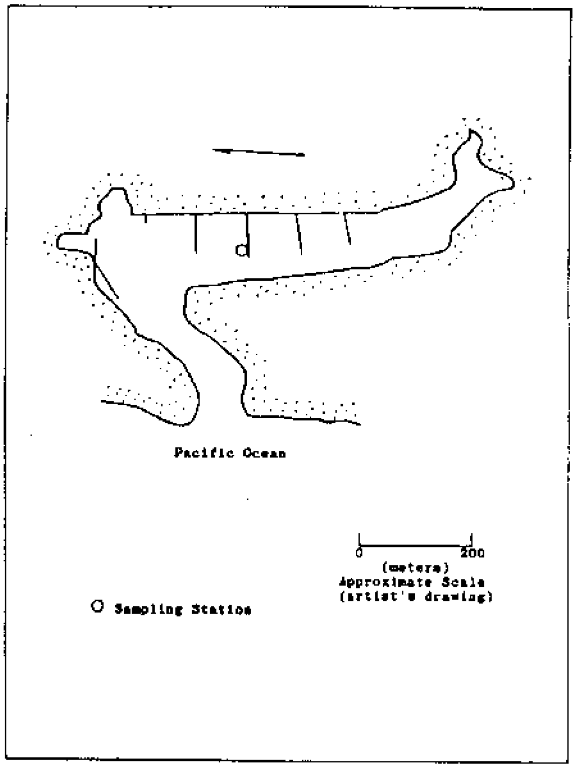

Fig. 6. Depoe Bay marina (State of Oregon Division of Lands, 1976)

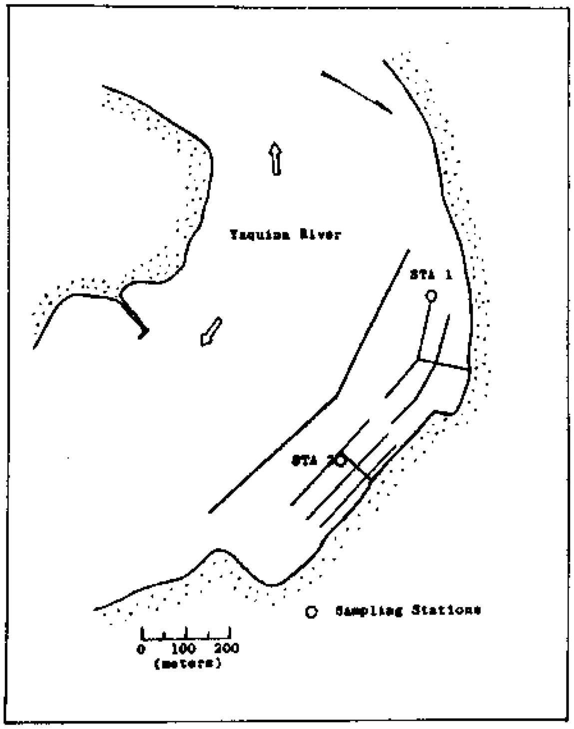

Fig. 7. Newport marina (U.S. Army Corps of Engineers, 1973)

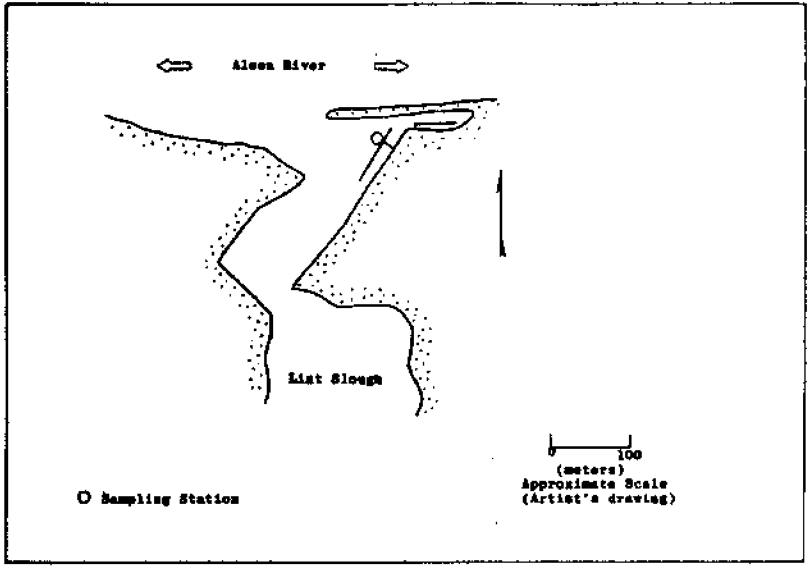

Fig. 8. Waldport marina (only part of Lint Slough is shown)

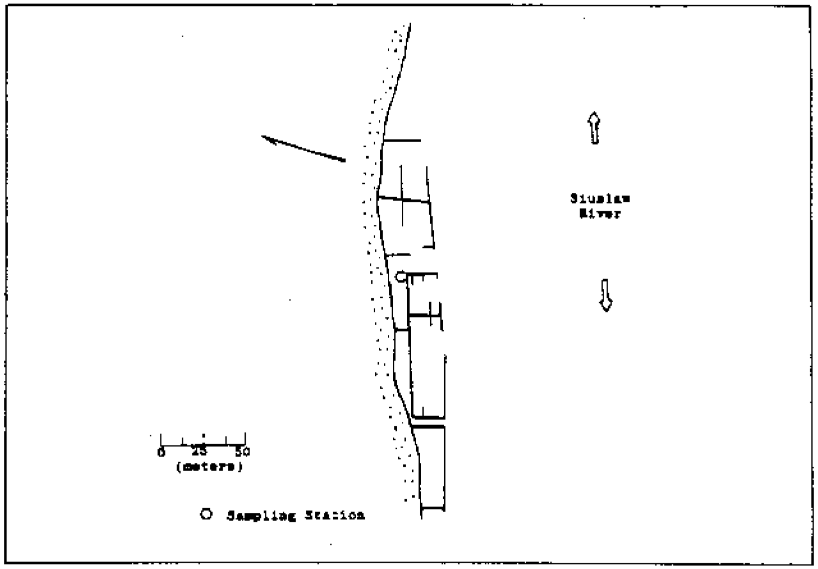

Fig. 9. Florence marina (U.S. Army Corps of Engineers, 1973)

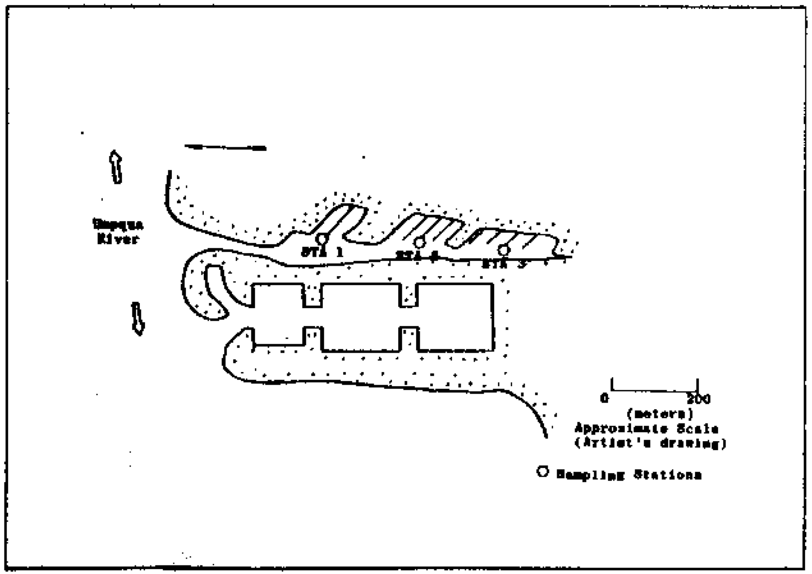

Fig. 10. Winchester Bay marina

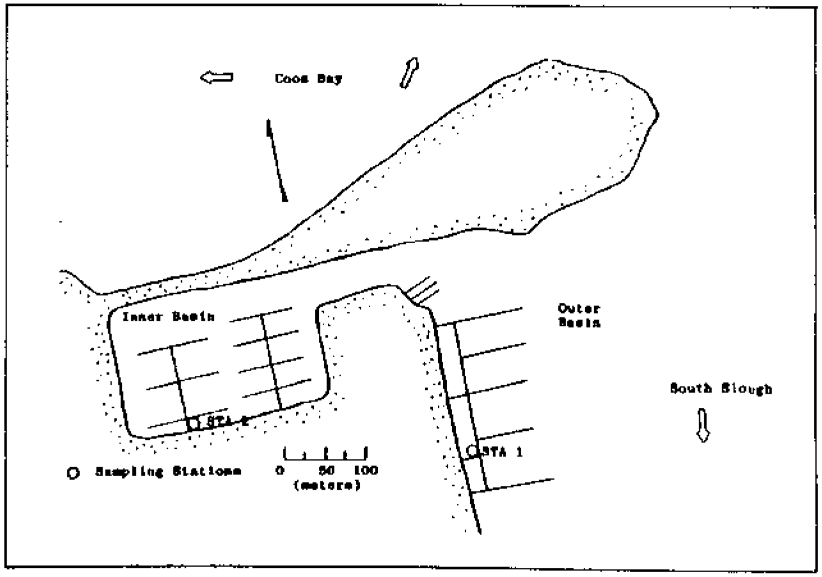

Fig. 11. Charleston marina (U.S. Army Corps of Engineers, 1976)

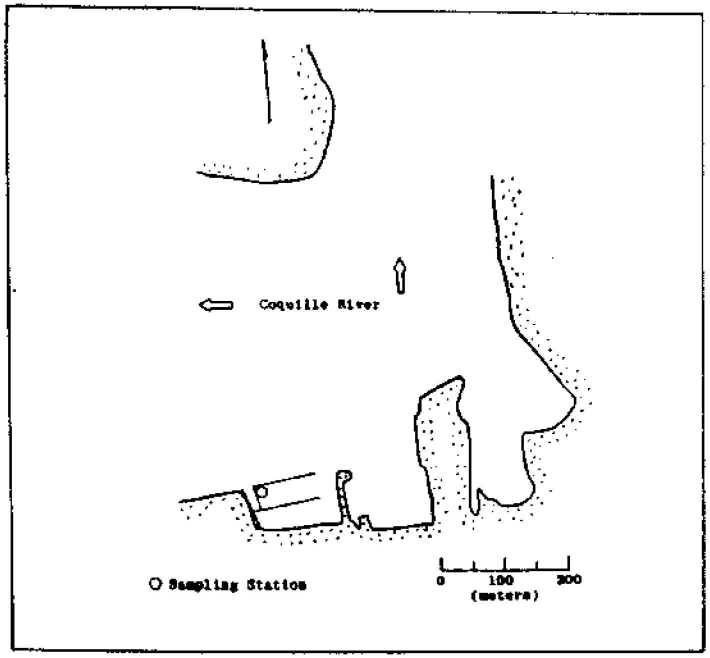

Fig. 12. **Bandon marina** (U.S. Army Corps of Engineers, 1975)

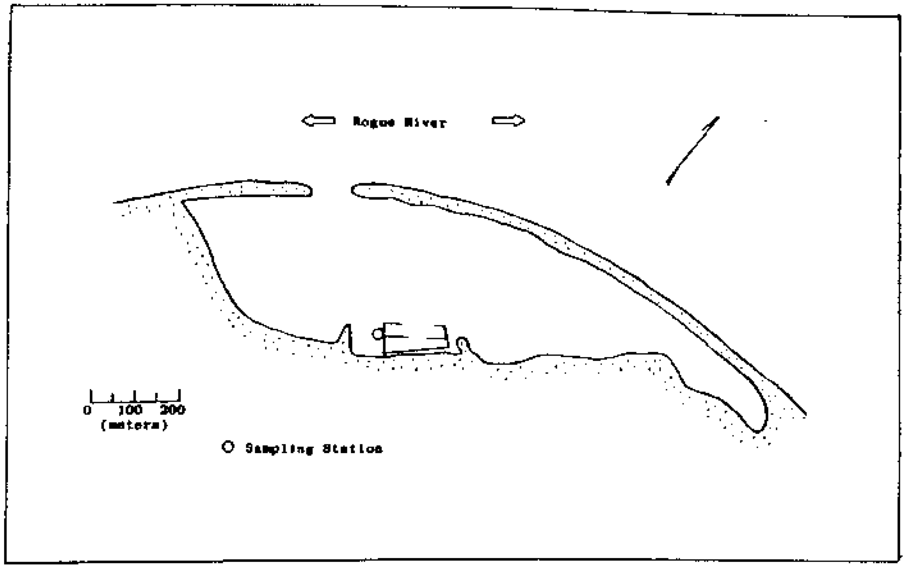

Fig. 13. Gold Beach marina

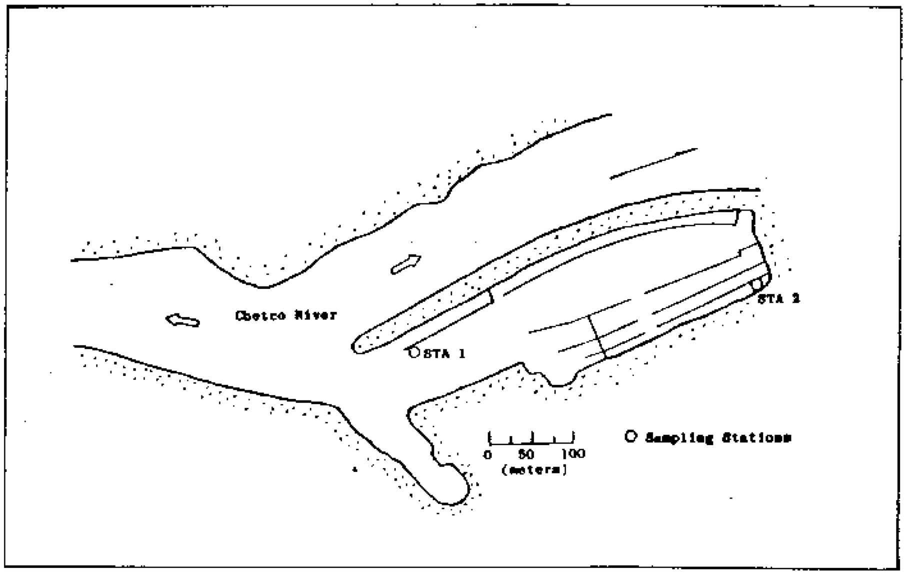

Fig. 14. **Brookings marina** (U.S. Army Corps of Engineers, 1975)

discussion

LITERATURE SURVEY

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

The in-depth part of Yearsley's study looked at Edmonds, Squalicum, Shilshole, Kingston and Port Townsend marinas. A score was assigned from the water quality data obtained. Comparisons of the water quality data were based on either Washington water quality criteria or the control station, a sample taken outside the enclosed marina. 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 compare these five basins to models derived in the present work and compare the results of the two findings.

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

To maintain existing water quality, Yearsley suggested that the siting, design and operation of marinas be carried out in consideration of the following characteristics: Mixing and exchange, adjacent water usage, adjacent land use, number and orientation of openings, opening size, aspect ratio, pier length, spacing and design.

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

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

	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.

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

where

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

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

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

and

Aw = cross-sectional area of the entrance

Lmax = distance between the opening and the furthest point in the marina

Qtide = average tidal discharge into the basin

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

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

D_L = coefficient of eddy diffusivity

Yearsley later made use of a relationship empirically determined for D_L

$$D_L = 4.64 * 10^{-4}\ Lc^{4/3} \qquad (2)$$

where

Lc = the characteristic size of some eddy in meters, 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

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

Another way to quantify flushing time is via the Classical Tidal Prism Method (Dyer 1973)

$$Te = \frac{Vmhhw}{Vp} \qquad (4)$$

and

$$Vp = Vmhhw - Vmllw \qquad (5)$$

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. Yearsley's expression also includes a flushing term due to diffusion and flows other than tidal flow. Because the classical method determines the time to completely replace high tide volume, it is opposed to Yearsley's approach, which determines the time to replace the low tide basin volume. Fig. 15 relates 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. In fact, both methods tend to show this relationship. The figure reconfirms the idea that Te > τ, in all basins except Squalicum, which shows Te < τ.

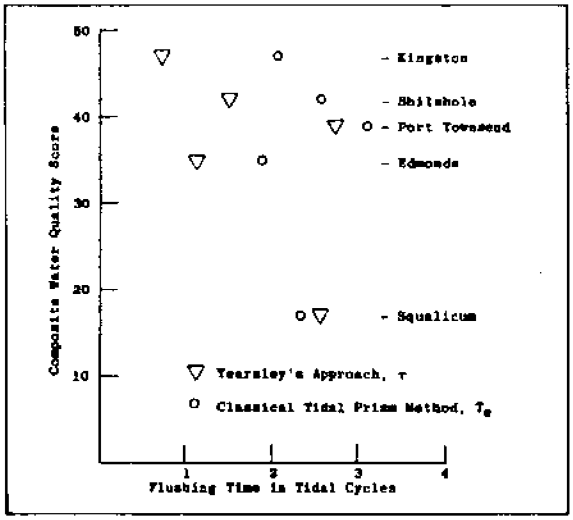

Fig. 15. Flushing time vs. composite water quality score

At the end of the Yearsley (1974) study, a set of criteria were proposed to maintain adequate water quality in small boat basins. Recommendations for criteria follow:

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 areas 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 a ratio of 1 : 1.

5. The diffusion time, τ diff, should be less than one day.

6. Pier lengths should be less than half the minimum length dimension of the marina. Pier spacing should be greater than pier length.

Richey (1971) discussed flushing mechanisms of marinas, particularly two approaches for estimating entrance velocity. Considering the size of marina basins with respect to the main body of water, the fact that rivers do not empty into marinas and the fact that 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

$$V = (A/A_e)(dz/dt) \tag{6}$$

where

A = marina plan area

A_e = entrance cross-sectional area

z = 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

$$z = B + (H/2)\cos(\pi t/T) + H/2 \tag{7}$$

where

B = entrance depth, mllw

H = tide range

T = tide period

The entrance velocity then becomes

$$V = (A/A_e)(\pi/T)(H/2)\sin(\pi t/T) \tag{8}$$

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

$$V^2/2g + z = Y \text{ or}$$
$$V = \{2g(Y - z)\}^{1/2} \tag{9}$$

where

g = gravitational acceleration

Y = water surface elevation outside the marina

Richey found the two velocity models to be in close agreement using a hypothetical case. He did not compare the models using field data. Layton (1971) studied the hydraulic characteristics of Edmonds marina on Puget Sound and applied the conservation of volume model to compute tidal entrance velocities. Computed velocities agreed with measured velocities averaged over the depth. Layton also found 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 in dead zones of basins having a 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. A consequence is 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 the exchange between the main flow and the dead zone may be very low. Fig. 16 is a graphic representation of four basins ranging in size from L/B=6.0 to L/B=0.3. Fig. 16 gives an idea of the basin shapes Westrich studied.

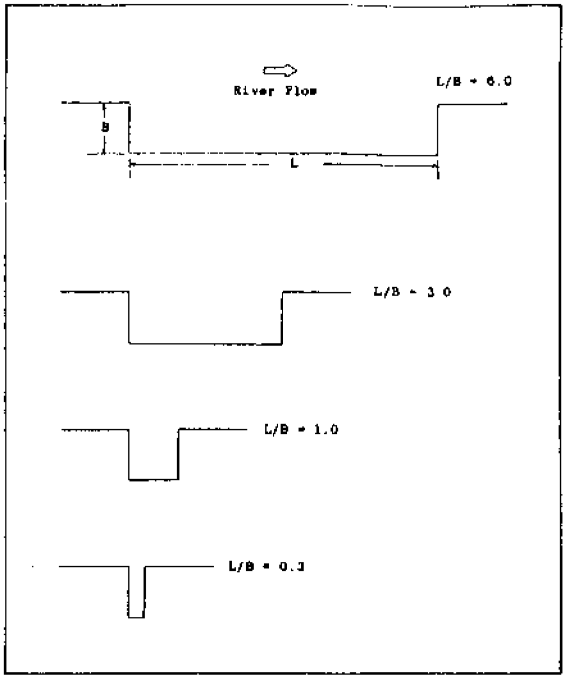

Fig. 16. Graphical representation of various length-width ratio enclosures

For steady flow conditions the mass exchange between 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

$$\frac{c}{C_o} = f\left\{\frac{Ut}{B}, \frac{L}{B}, \frac{U^*}{U}, \frac{L}{H}\right\} \qquad (10)$$

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 on the ratios Ut/B and L/B and their affect on bay-marina water exchange.

Westrich found two processes in unsteady flow that influenced 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 in the basin there is a resulting smaller exchange with the main body on the outflow cycle than in the steady case.

2. Conversely, 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.

Fig. 17 presents Westrich's physical hydraulic model test results which show the influence of L/B on the half-life residence time ($Ut_{1/2}/B$) 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. The width of the exchange surface also has a dimension of size L. 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 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.

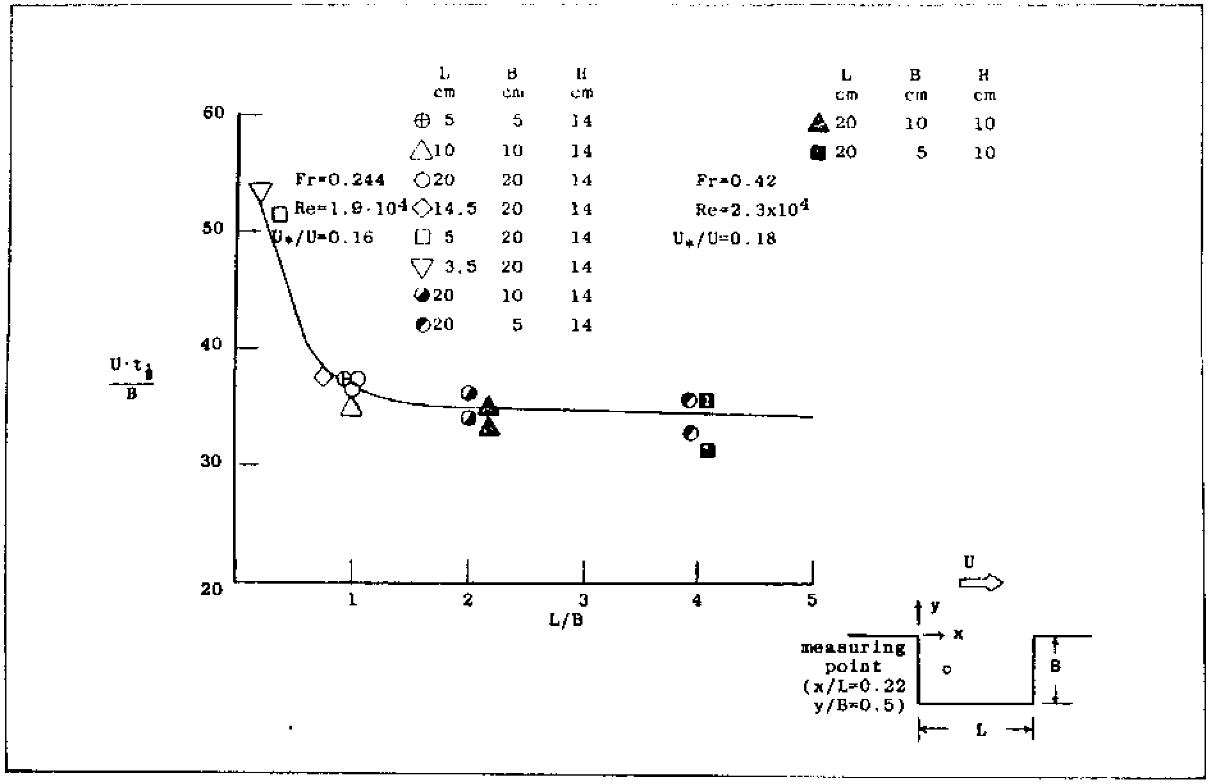

Fig. 17. Length-width effects on the half-life of a tracer (Westrich, 1975)

> If the flow through the vessel has a minimum of dead space then the mean residence time 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 the vessel before θ (dimensionless time ratio of time to theoretical detention time) = 1.0. (Watters *et al.* 1973)

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, 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 water will tend to be trapped with little flow through.

Just as 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 both describe how long the water mass stays inside respective enclosures. The difference is in the treatment process where it is desirable to increase the detention time to the point of maximum treatment. For the marina, it is desirable to decrease the flushing time so water within the marina will exchange rapidly with the open body of water, enhancing water quality in the enclosure.

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

$$V_d = V - V_f \tag{11}$$

with the dead space parameter as

$$\bar{V}_d = V_d/V = 1 - \bar{\theta}_c(F)_{\theta=2} \tag{12}$$

where

V = pond volume

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

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

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

The F age function is the fraction of dye material occurring 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 established. The cell caused flow to be one direction on one side of the pond and another on the opposite side.

Tests were made with constant density and with stratification. The modeling criterion for the unstratified case was the Reynolds number; in the stratified case it was the densimetric Froude number. 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 studied in the density stratified tests were:

1. The density of the water flowing into the pond (ρ_{in}) was greater than the density of water in the pond (ρ_{pond}).

2. With $\rho_{pond} > \rho_{in}$ Watters *et al.* found in the first case that inflow occurred along the bottom with low velocities and consequential low mixing. In the second case the inflow along the surface generated a mixing action in the pond and increased turbulent diffusion.

Major changes in the hydraulic efficiency of waste stabilization ponds were the result of alterations in length to width ratios. Large ratios were most efficient. Effects from different depths, Reynolds numbers and densimetric Froude numbers were 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 inconclusive as to where the openings in marinas should be. 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 common to measure changes in salinity concentration over a tidal cycle of 0 to 30 parts per thousand.

Water quality is also subject to seasonal changes in environmental conditions. An example of annual variation in water quality is the change in dissolved oxygen concentration (DO) caused by changes in water temperature. Artificially induced seasonal changes in water quality may occur due to industrial effluent discharge deviations.

A study designed to determine the 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. Thus they may be acceptable indicators of the trend in basin water quality.

Three types of exchange processes affect the transfer of materials between water and sediments: 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 the exchange of materials between water and sediments. Concerning the physical exchange of materials, Lee said water currents in the overlying water played a prominent role. When the current velocity is high enough, bottom sediments become suspended, catalyzing exchange mechanisms such as:

1. Increased chemical reactions due to increased sediment surface area.

2. Release of material in the interstitial water.

3. Advection of the suspended sediments.

Currents also remove substances by decreasing concentrations of particular compounds which enhance the probability of chemical equilibrium reactions occurring.

Another physical factor which affects mass exchange is the mixing of sediments, a process which allows materials in 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 by physical attachment of material to the organism and as a 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 the above ways (Bella 1975). The mixing that occurs in surface sediments is theorized by many investigators, as referenced in Lee (1970), to occur in the top 5 to 15 cm, depending on sediment type and environmental conditions.

Another event that enhances the mixing of sediments is the result of bubbling gases produced in anaerobic fermentation, carbon dioxide and methane in particular (Lee 1970). Oregon State University investigators (Slotta *et al.* 1974) have used a rate of sediment turnover in describing characteristics of benthic deposits, illustrating the importance of mixing in sediments.

Biological factors that affect the 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 and Bella 1975). Two examples of organic decomposition may be illustrated using the nitrogen and sulfur cycles. Organic nitrogen, on degradation by bacterial action, is released as ammonia. If the sediment environment is anaerobic the ammonia will eventually be released to the water column where green plants will use the ammonia as protein building blocks (Brezonik 1973). In the presence of an aerobic benthic environment, bacteria such as *Nitrosomonas* and *Nitrobacter* will nitrify the ammonia to nitrate, which can be used by green plants or undergo further transformation (Mitchell 1974 and Reid 1961).

Sediments are usually considered anaerobic because oxygen is used 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 and Mitchell 1974). 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 may 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 influences precipitation reactions. Biological processes indirectly alter exchange reactions by affecting DO utilization and nutrient uptake 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 lowers the concentration of these substances, allowing nutrients bound in the sediment to be solubilized.

Chemical reactions are direct exchange mechanisms where materials move from sediment to water body and vice versa. It is reasonable to assume that since chemical reactions are pH responsive, exchange mechanisms are pH dependent. The influence of precipitation reactions is hard to measure because of the many elements that influence the reactions. Lee (1970) 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 water and sediments also have an influence on what types of reactions take place (oxidizing or reducing) and what types of material exchanges take place.

For example, in an oxidizing environment ferrous sulfide may be oxidized to elemental sulfur that reacts with ferrous sulfide to form pyrite, a sink for available iron. Ferrous sulfide would otherwise 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. Nitrate appears to have no sorption tendencies towards clay. In contrast, the ammonium ion is reported to be rapidly sorbed by sediments (Brezonik 1973).

Exchange mechanisms are complex and not well understood. The above discussions show that many types of exchanges take place between the overlying water and the sediment and that each are responsive to conditions in the other. It therefore seems probable that benthic deposits represent trends in water quality that can be analyzed to gain a perspective of the water quality in marina basins.

Extensive studies concerning the interrelations of mud quality and benthic ecology have been reported in *An Examination of Some Physical and Biological Impacts of Dredging in Estuaries* by an OSU research team (Slotta *et al.* 1974). In this study the organic content of sediment and rate of sediment turnover (OCS-RST) correlation was proposed for classification of benthic systems. The classification scheme began in 1972; quantitative delineation of different systems by the OCS-RST measures remain somewhat subjective. Using volatile solids in the sediments as a measure of OCS and various environmental conditions as measures of RST, the following categories were defined: Low OCS, 0-1.5 per cent volatile solids (VS) on a dry basis; medium OCS, 1.5-8.0 per cent VS; high OCS, greater than 8.0 per cent VS; low RST, greater than one year turnover frequency; medium RST, one year to one month; and high RST, less than one month.

Fig. 18 is a partial reprint from the above-mentioned report of a figure illustrating uses of the OCS-RST scheme. A low water velocity represents high organic content and low sediment turnover rate, an undesirable condition. The DO schematic shows that low DO can be expected in the same system as the undesirable condition in the water velocity illustration. Other schematics portray similar situations. The importance of the figures is that they show high volatile solids and sulfide concentrations to be undesirable, particularly as a result of low water velocities.

Plant and animal life and numerous types of industrial waste are sources of organics to natural waters. Organic material affects the water quality as it is 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:

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

Stored energy in the form of adenosine triphosphate (ATP), is acquired by the microorganism. Two ways of increasing oxygen demand are by letting the organics increase so the microorganisms will tend to consume more and then the environment will be able to support a larger microorganism population. The DO demand is commonly referred to by sanitary engineers as biochemical oxygen demand (BOD).

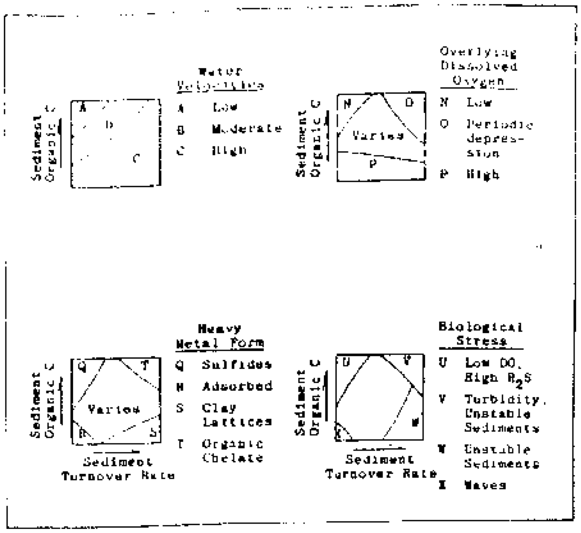

Fig. 18. Four cases of classification by se sediment organic content and sediment turnover rate (Slotta *et al.*, 1974)

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

Nitrogen, an essential component in amino acids or the protein building blocks, is found in many different organic compounds. The breakdown of organic nitrogen into ammonia is called ammonification. Phytoplankton appear to prefer ammonia as their inorganic source of nitrogen instead of nitrate because of its reduced state (Brezonik 1973). If the ammonia is not used by these photosynthetic plants, it is nitrified to nitrite and nitrate under aerobic conditions. Low oxygen concentrations allow denitrifying bacteria to convert nitrate to nitrous oxide or gaseous nitrogen. Otherwise nitrate will remain stable and be used by green plants and some bacteria.

Concentrations of ammonia in the water over 2.5 mg/l are harmful to certain organisms (Reid 1961). Fish canneries are notable sources of nitrogen in water bodies (Soderquist 1974). Because of continued recycling of inorganic nitrogen, one would expect low concentrations of ammonia and nitrate nitrogen. However, nitrogen measurement can be a valuable aid to 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) are found 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 dependent on the availability of iron. In the presence of iron, ferrous sulfide will be formed. When all available iron is used, concentrations of free sulfides will increase, a toxic condition for many marine and aquatic organisms (Slotta *et al.* 1974). When sediments are overturned the ferrous sulfide is oxidized, increasing the concentration of available iron (Bella, 1975). Recycling available iron is part of the iron-sulfur relationship.

The importance of the iron-sulfur relationship has been characterized and used by OSU investigators to determine sediment quality. Total sulfide capacity (TSC), sulfide capacity (SC) and total sulfides (TS) were used 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 in free sulfides may occur. If the sulfide capacity is near the TSC measure it is likely that the sediments were recently overturned and ferrous sulfide oxidized resulting in increased available iron.

MARINA FLUSHING PREDICTIONS

This study used the tidal prism method to predict flushing times in marina basins, 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 during each tidal cycle. Using this method, predicted flushing times will generally be lower than those 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 Fig. 15). It was felt that 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 13 Oregon marinas considered (3.2 tidal cycles) occurred at the Garibaldi basin. Calculated flushing times for Florence and Charleston (outer basin) were not necessary because both marinas are exposed to the main body of flowing water and experience a continuous change of water. The Newport marina has two entrances so the flushing time cannot be accurately calculated using the tidal prism approach. However, since both openings were nearly parallel to the river, it was felt that the river flow would have considerable influence on flushing. For this reason the Newport basin was ranked higher than the rest of the enclosed basins. The Waldport basin does not appear in this table because basin data was not available.

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

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

*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 allow considerable flushing from river, prediction approach not applicable.

data for samples and analysis

SAMPLING TECHNIQUES

On Sept. 16, 17 and 18, 1975 a field survey consisting of bottom sediment grab samples and various water quality measurements was conducted at the 13 Oregon small boat marina basins studied. Up to three stations were sampled at each marina depending on the size of the basin and the accessibility of various locations within the basin. For each bottom sample collected the time was recorded and pH, dissolved oxygen, turbidity, water depth and salinity were measured.

Bottom samples were collected with a metal bucket weighted on one side so the bucket would sink with the opening facing down. With the weights 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 froze the samples. Because few organisms can survive freezing conditions (Mitchell 1974), microbial activity decreased. The samples were later stored in an ice box until 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 - Lead line 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 would not yield any additional information concerning flushing so the efforts were considered unwarranted. The total organic carbon test, one of many ways to measure organic content, was also considered repetitious. The chemical oxygen demand test is another way of measuring organic content, although not limited to substrate material used by biological organisms. It was felt that interference from chlorides in the test (chlorides being readily oxidized by the chemical oxidizing agent used in the test) would not allow clear representation or measurement of organics. Other tests were excluded for the reasons checked in the matrix of Table 4.

Volatile Solids

Heating a sample to a specific temperature for a specified time interval causes organic constituents in the sample to ignite, making the sample lighter. The temperature and time specified in the Great Lakes Region Chemistry Laboratory Manual Bottom Sediments

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

Table 4. Test matrix.

(1968) is 600°C (1292°F) 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 or in combination with the volatile solids test by heating the sample at approximately 105°C (221°F) overnight. The standard procedure in both 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 tests of all samples were executed. Another set of duplicate tests were conducted in case the results of the duplicates varied significantly.

Kjeldahl Nitrogen

A measure of ammonia nitrogen and organic nitrogen constitutes the Kjeldahl nitrogen. By distilling ammonia out of the sample into approximately 0.02 N boric acid, ammonium borate is formed, which is then titrated with approximately 0.005 N H_2SO_4 to determine the nitrogen content of the sample. Standard Methods 13th Edition (1971) suggests using 0.02 N H_2SO_4 as the titrating reagent, but a lower normality was used to give a system more sensitive 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 of organic nitrogen was then distilled and titrated as was 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 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 completely remove grease, extracting the grease with hexane for four hours, distilling away the hexane, steam drying the flask and weighing the cooled grease content of the sample. The end representation is a percent concentration grease of the dry weight of the sample. Completely drying the sample so that no free water is available to combine with the grease and sediment in a bound state is important.

Total Sulfides

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

BASIN GEOMETRY

To correlate mud quality data with the basins it was necessary to define pertinent characteristics of each basin. Obvious parameters 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 ( ), 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. All variables are listed in Appendix A. Fig. 19 presents a definition sketch of some of the parameters.

Most physical data were obtained from U.S. Army Corps of Engineers photographic charts. These charts were derived from aerial photographs with bathymetry in the channels superimposed from field studies performed at various intervals. 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 the soundings cover the entrance to the marinas, making it possible to draw an entrance cross-section. In other cases the information provided an estimate of entrance depth; which then provided an estimate of an entrance cross-sectional area.

Though the study was interested in mean basin depth, corps data were often insufficient to provide this information. It was impossible to obtain the basin geometry and

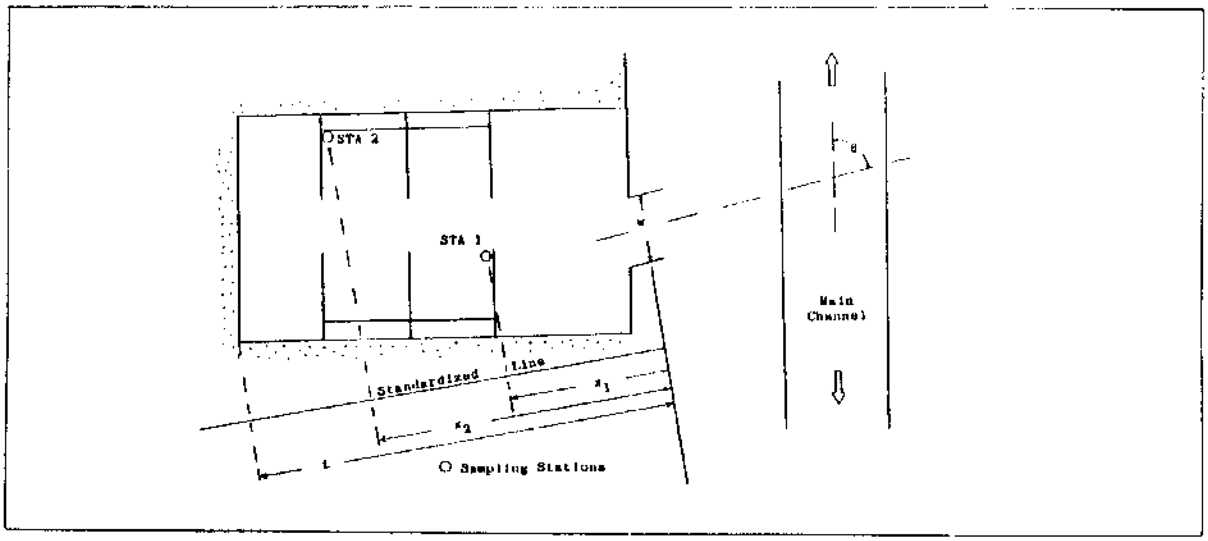

Fig. 19. Definition sketch of various basin characteristics

bathymetry data without independently surveying each marina. Because of the various basin shapes, the plan form distance measurements were standardized so that variability in measurement techniques could be avoided.

In all entrances except the Astoria entrance a "standardized line" was drawn perpendicular to the entrance. Normal lines were constructed from the standard line to the point in question. The final distance measurement was between the entrance and intersection of the normal and standardized lines (see Fig. 19). Due to the orientation of the Astoria entrance, the standardized line was arbitrarily drawn perpendicular to the west breakwater facing the river. The angle of the entrance to 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 of these two lines delimits θ. The mean tidal range was taken for the location nearest to each marina from *Tide Tables West Coast of North and South America* (1975). Physical characteristics of each basin are tabulated in Appendix B.

As mentioned previously, some basin parameters of interest in this study were computed using measured physical characteristics. The calculated parameters were determined using hydraulic characteristics of the basins such as characteristic velocity through the entrances (v) and tidal prism of the basins (P). In computing the velocity it was assumed that the entire basin experienced 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

$$v = \frac{2RA}{T\bar{a}} \tag{13}$$

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

$$P = RA \tag{14}$$

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 of reality. However, the accuracy is comparable to other approximations in the original data that were considered acceptable. The goal of this study, which is to suggest general marina siting guidelines, and the inappropriateness of defining each basin in detail with commensurate multiple sediment sampling, justifies the approximations. A few cases not strictly applicable to our definition of basin tidal prisms are at Newport, Florence and the outer basin at Charleston. Since the Newport marina has two entrances the definition-implied fact that tidal prisms move in and out over a tidal cycle through an area does not apply. It is not certain what the tidal prism would be in this case. The other two basins have no real entrances; they are fully exposed to the main body of water. Their entrance areas were derived from a characteristic depth along the exposed frontage and the distance of exposure. However, at Newport the conservation of volume approach was used to get an estimate of the entrance velocity. At Florence a mean river velocity was used as an approximation to a characteristic velocity. At Charleston (outer basin) the velocity of the inner basin was used as a first approximation.

DIMENSIONAL ANALYSIS

To derive an adequate representation of the flushing phenomenon in an enclosed basin it was necessary to decide how the sediment quality data could best be compared to basin parameters.

One way would be to relate sediment quality to each basin characteristic thus indirectly relating to flushing potential.

Another approach would be to conduct a dimensional analysis of the important variables, which in turn would derive a set of dimensionless expressions independent of any measurement system. Applying the laws of dimensional analysis the original expressions were studied and considered independently, combined with others or excluded in order to originate a final set of expressions to describe the flushing characteristics of small boat basins.

The dependent variable in the analysis was flushing time (F) and the important independent variables considered 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

$$\frac{Fv}{a^{1/2}} = f_1 \{\frac{\ell}{a^{1/2}}, \frac{A}{a}, \frac{w}{a^{1/2}}, \frac{d_1}{a^{1/2}}, \frac{d_2}{a^{1/2}}, \frac{P}{a^{3/2}}, \frac{V}{a^{3/2}}, \frac{u}{v}, \frac{R}{a^{1/2}}, \frac{x}{a^{1/2}}, \frac{a^{1/2}g}{v^2}, \frac{\mu}{a^{1/2}v\rho}, \theta\} \qquad (15)$$

Regrouping these expressions gives the final list of dimensionless expressions

$$\frac{Fv}{a^{1/2}} = f_2 \{\frac{x}{\ell}, \frac{A}{a}, \frac{A}{wa^{1/2}}, \frac{P}{V}, \frac{u}{v}, \frac{R}{a^{1/2}}, \frac{Ax}{a\ell}, \frac{v^2}{a^{1/2}g}, \frac{va^{1/2}\rho}{\mu}, \theta\} \qquad (16)$$

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

The idea behind the sampling program was to assume the quality of the mud was indicative of the respective flushing capabilities 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, relating the mud quality to the basin parameters, was the next course of action. In other words, the mud quality was considered synonymous to flushing potential, 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, oil and sulfides. The EPA criteria generally used for deciding whether the release of dredge spoil can be permitted, served as a reference for classifying samples. The EPA criteria comes from a study by O'Neal and Sceva (1971), who 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 five per cent were considered lightly polluted and those that had volatile solids greater than 10 per cent were considered heavily polluted. A table was constructed giving the ranges and means of all parameters tested. Using the lightly polluted group data as justification, they proposed their criteria from seven of their tests. Table 5 is a list of "the basic seven" with the corresponding limiting value for marine or aquatic disposal of dredge spoil. The criteria states that a violation of any one of the tests means the spoil does not meet the criteria for discharge or release. The seven criteria 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.

Sediments in Fresh and Marine Waters	Conc. Percent (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

Table 5. Basic seven sediment pollution criteria.

Reference: O'Neal and Sceva 1971.

The use of the "basic seven" in this study was twofold. First, the criteria provided a number that could be used as a cut off in determining which basins were acceptable and which were not. Second, the information was used to normalize data 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, once normalized, constituted a pollution index for each basin. All stations have an index for each test and, because the data were standardized, the indices of the tests were linearly combined to form a total pollution index. Mud quality data was tabulated and used for analysis based on:

1. Pollution index for each test and each station.

2. Total pollution index for each station.

Table 6 contains sample data from four of the conducted tests.

METHOD OF DATA ANLYSIS

Three basic approaches to analyze and relate the sediment data with the basin data were:

1. An intrabasin comparison between stations;

2. A grouping of basins into polluted and nonpolluted categories

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 that problem. The second and third methods were used to derive generalizations about basin flushing; in essence, to construct a model that would yield information about other marinas.

Intrabasin Analysis

Intrabasin analysis was first used with the Kjeldahl nitrogen data. A unique feature of the Kjeldahl data was that only one station was "polluted." If this data were used exclusively one could conclude that no Oregon marinas were polluted during 1975 and each marina shape was satisfactory according to current EPA guidelines. Such a conclusion would contradict other tests that definitely place some Oregon marinas in the polluted category.

Realizing the shortcomings of using the Kjeldahl data exclusively and yet having good data suggested the first method of analysis. For instance, at marinas where multiple stations were sampled, a comparison of changes in the pollution index between the stations and different tests renders unique and beneficial information. Such an analysis shows which measurements are a result of pollution from within or without the basins. For example, if the change in pollution readings between stations for all tests is approximately the same 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 on the type of test conducted, a constant difference of pollution index between specific stations for all tests is expected. This accounts for a particular pollution load in the main body of water and a characteristic exchange between the main body of water and the basin.

Alternatively, for a load introduced within the basin, some proportion of the load may accumulate in a particular part. Thus, the sediment in this area may act as a pollution trap; 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 more dependent on the time

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 Bay		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

Table 6. Pollution indices for each test.

of dumping with respect to tidal movement than a pollution source outside the enclosure. Inside the basin, different proportions of various pollutants may be introduced. If one pollutant is dumped in large quantities in the marina, the results of the test that detects this pollutant may show a very high value at one station while registering a low value at another station. These results might not compare with changes in pollution index between stations as shown from other types of tests. Therefore, the input location of the pollutant becomes an important independent variable that can be inferred qualitatively by analyzing the data.

It is helpful when 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 the basin should remain approximately constant for all constituents. This assumes a constant exchange function between the water and sediment, which is sufficient for the initial purposes of this study.

Grouped Data

The first method of grouping data was similar to O'Neal and Sceva's (1971) approach for determining the seven basic criteria. This was done by dividing the basins into polluted and nonpolluted groups based on the test results. Since a basin may not show pollutants in all the tests, it was a subjective problem to decide the cutoff for each group. Table 7 ranks, according to test results, from most to least polluted Oregon marinas. Also given in the table is the cut off 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, 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, was 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 there is a definite leaning toward pollution status from sulfides, would put this basin in the lower end of the polluted group. Once the two groups were formed, similarities and dissimilarities between the groups were noted.

Statistical Analysis

Use was made of the prepared programs of OSU's CDC-3300, OS3, Statistical Interactive Programming System (SIPS) for data analysis. Multiple regression analyses were used to build models describing the flushing mechanism of small boat marinas. This was accomplished by regressing the dependent pollution indices on the dimensionless basin parameters. Statistical tests were used to systematically determine what 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 to fully appreciate the meaning of the results from this analytical approach. A statistical model for prediction is dependent on the sampling program, both in numbers and randomness, the independent variables representing the response variable and the range the original data spans. As the number of samples increases, the ability of statistics to explain variation among the samples improves. In any sampling program it is important where and when samples are taken. Sampling one area, even a number of times, might exclude possible samplings representing a true picture of the function 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. Regression analysis should be confined to predictions of the original data. There is no assurance and/or statistical basis that the model applies to regions outside the initial information.

Results of this study should be taken in perspective to the whole study. Because 13 marinas were studied, complete sampling of all basins was prohibitive and not suggested in the context of the work planned. Another limiting factor was that no attempt was made to quantify the magnitude of pollution source in each basin. Statistically, the general nature of most studies means that if another set of samples is taken, the regression function may be different. A regression line from a second set of data may be different from the original regression because the confidence intervals on the function that explains the mean response are larger than if a more complete sampling program had been initiated originally. The importance of limitations to the marina siting analysis is not meant to downgrade results of this study, but to provide the results in a proper perspective.

	Test			
	Volatile	Kjeldahl Nitrogen	Grease	Total Sulfides
Increasing Pollution Index	Waldport	Winchester 2	Waldport	Waldport
	Florence	Waldport	Brookings 2	Winchester 1
	Depoe Bay	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	Garbaldi 1
	Astoria 2	Garibaldi 2	Garibaldi 1	Netarts
	Brookings 2	Depoe Bay	Depoe Bay	Astoria 1
	Astoria 1	Bandon	Brookings 1	Charleston 2
	Newport 2	Brookings 2	Netarts	Newport 2
	Brookings 1	Brookings 1	Newport 1	Depoe Bay
	Newport 1	Gold Beach	Charleston 2	Florence
	Charleston 2	Charleston 2	Newport 2	Newport 1
	Gold Beach	Newport 1	Gold Beach	Gold Beach

Table 7. Station ranking by pollution index.

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

results

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

INTRABASIN COMPARISON

Pollution indices among sampling stations were compared in basins where multiple samples were taken. Table 9 tabulates pollution indices, differences in pollution indices between the stations for each test and the ratio of pollution indices between the stations; it illustrates the relationship between the stations. A simple differencing will not take into account the relative differences of chemical constituents in the water body. However, the mass dispersal in a basin should be constant on the average and the ratio of concentrations should be constant unless there is a point source within the basin.

In the case of Astoria, Station 1 had a lower pollution index than Station 2 in all tests. The ratio of concentrations was essentially the same in the first three tests and somewhat lower in the fourth test. Garibaldi exhibited a mixed trend, probably due to differences in the source of pollution.

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

Winchester marina is an interesting case in point. The volatile solids test shows the station's decrease in pollution index

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

Table 8. Basin variable names and test names.

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

farther into the basin away from the mouth, yet the values stay very similar. The Kjeldahl determination shows Station 2 as more polluted than the other two. The grease test again showed a decreasing trend in pollution index vs. length into the basin, but in this test Station 1 was more polluted than the others. The sulfide results were 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 tends to be some specificity between test and location.

The divided Charleston marina illustrates a peculiar feature. The outer basin (used for moorage since 1958) is more exposed to flushing action than the inner basin (constructed in 1965) and is more highly polluted in all cases. This finding was counter to expectations. The explanation is that three fish canneries are located at Charleston. One is directly adjacent to the outer basin anchorages (Percy *et al.* 1973).

Since fish cannery wastes are usually high in organic content, grease, oils and organic and ammonia nitrogen (Soderquist 1974), it is reasonable for the outer basin to translate these trends. The outer basin tends to be irregular in the rest of the analyses discussed, giving unexpected results. The inner basin has low pollution indices in all cases, suggesting 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 pollution index in all cases, with ratios ranging from 0.26 to 0.79.

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

GROUPED DATA ANALYSIS

Reference is made to Table 7, which has station rankings for each test and is 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. Charleston occurs in both groups because the marina is made up of two distinct areas of moorage. One area is enclosed from and the other is exposed to the main stream of flow separating South Slough and the main channel of Coos Bay. In deciding their relative

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	.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								

Table 9. Comparison of pollution indices among multistation basins.

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

Table 10. Grouping of marinas: Acceptable or unacceptable.

*Number denotes the average pollution index for each marina.

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

One reason for this is that the predicted ranking does not take into account various pollution loads in different estuaries, whereas it is inherent in the measured rankings.

After grouping the marinas as acceptable or unacceptable an inspection was made of plots of pollution indices for each test and of a combination of the tests against the dimensionless variables depicting basin shape. Most of the graphs displayed a

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

Table 11. Comparison of predicted to measured basin ranking.

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 the tests. Figs. 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 in the acceptable zone: Charleston (outer basin) and Bandon marinas. The Charleston (outer basin) marina is an irregular case due to its proximity to canneries. The Bandon basin is also affected by siting location. It is next to the Bandon secondary sewage treatment plant and a sawmill with a pollution problem (Percy *et al.* 1973).

Using Figs. 20 and 21 as a basis for comparing the marinas, limiting values of AREA=400 and ENTR=100 are considered to be the dividing lines between acceptable and unacceptable groups. The critical values were taken from previously acceptable standards, i.e. sediment quality criteria.

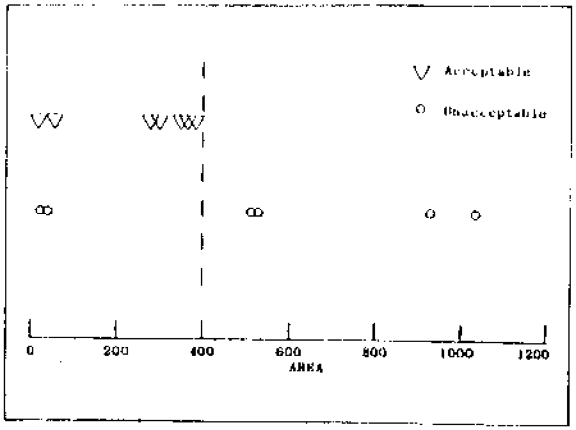

Fig. 20. Marinas with respect to acceptability and AREA

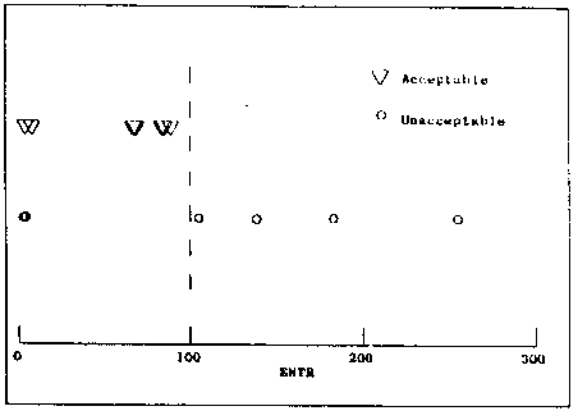

Fig. 21. Marinas with respect to acceptability and ENTR

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 the 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. Two variables said to be completely uncorrelated 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 on the graph.

	VS	KJON	GO	SULF	PI4	PI24	AREA	DIST	ENTR	RA	DTHA	REY	FR	THETA
VS														
KJON	.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	.139	.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

Table 12. Partial correlation coefficients of sediment and basin variables

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

$$Y' = b_0 + b_1X_1 + b_2X_2 \qquad (17)$$

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 on the response function. The addition of another variable should have no effect on other independent variables in the theoretical model, only on 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 on the regression coefficients. If there is an impact on the coefficients, 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 the above techniques were used in statistical analyses of the data.

Independent variables with 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 is the squared value of REY. Conversely, one case of independent variables that are completely uncorrelated are ENTR and SQREY (r=0.000). There is no obvious explanation for this uncorrelated example.

In the case of 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 are both defined as a combination of the others. This correlation was confirmed.

Coefficients between test variables and

basin variables in Table 12 show KJDN, SULF and PI24 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 of SQREY=-0.000. All negative correlations have absolute coefficeients of less than 0.3 and 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 used three tests (volatile solids, Kjeldahl nitrogen and grease) to form the total pollution index; the other 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.

Analyses were performed using the first three test data. Any model that produced results with only one of the three response variables was not affected by additional data in the form of another test. However, the total pollution index was altered. Note that 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 the three test data.

The variables DIST and DTHA were not significant when compared with the other variables. Attempts were made initially to add these to the models regardless of their statistical relevancy. The idea was for the model to take into account different sampling locations in the basins. In applying these models for predictive purposes the two variables DIST and DTHA were considered unimportant and assigned the value 0.0. The basic approach was to include effects of the sampling program in the model. However, since the model only dealt 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.

Two pollution indices were formed combining the test data. One was a simple addition of pollution indices from the volatile solids, Kjeldahl nitrogen and grease data with the symbol PI3; 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 tabulates statistical data (TVALUES) used to determine which variables should be added to the model and to determine if the regression coefficients are significant at the 90 percent level. The tabulation is divided into two groups: The first gives variables in the model with the corresponding standard error and t-statistic for the regression coefficient. The second lists 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 percent level critical t-statistic which determines the significance of the variables. As variables were added the degrees of freedom of the model decreased, affecting the critical t-statistic. With only the constant in the model the degrees of freedom are equal to n-1, n being the sample size. As each variable is added, one degree of freedom is lost.

Table 13 relates the TVALUE statistics with and without the variable DIST being added to the model, irrespective of its significance. In both cases it is apparent that none of the variables would meet the critical statistic when added. It was 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. No regression coefficients were significant at the 90 percent confidence level with or without DIST in the model. This was somewhat contrary to expectations since a combination of the test results was thought to be the best for model building. Regression on the multiplicative combination yielded much better results.

Contrary to correlation expectations, the grease data, GO, furnished a satisfactory model after some manipulation. DIST was added; no variables had high enough t-statistics to warrant their addition. However, when DTHA was added the TVALUE data showed variables significant enough to add to the model. When THETA was added the t-statistics on the regression coefficients all rose above 2.0 (the critical value at this degree of freedom being 1.753).

It was evident that other variables should be added. Thus, ENTR came into the model.

Table 14 lists TVALUES when DIST was in the model and when the model was complete. It shows the model including DIST with the variables still not significantly correlated, though with further manipulation the regression coefficients became significant. It should be noted that with the limited degrees of freedom available in this study (19 data points), the number of variables that can be safely added to a model is restricted. The final model should accordingly be viewed with some reservation.

Two of the response functions for GO are graphed in Fig. 22. One curve contains the variables DIST, DTHA and THETA in the model. The other has these three with ENTR added. The plot of both curves assigns the variables DIST and DTHA the value 0.0 for reasons stated earlier. The first function is a plot of GO vs. THETA. 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

(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	

Table 13. Volatile solids regression statistics.

appropriate curve. With the addition of ENTR the regression coefficient of THETA changes only slightly. This shows 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° (this interpretation is printed as a dashed line in Fig. 22). The value of the second curve is to relate ENTR to THETA. We have already determined that a maximum THETA=55° 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

(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	

Table 14. Grease regression statistics.

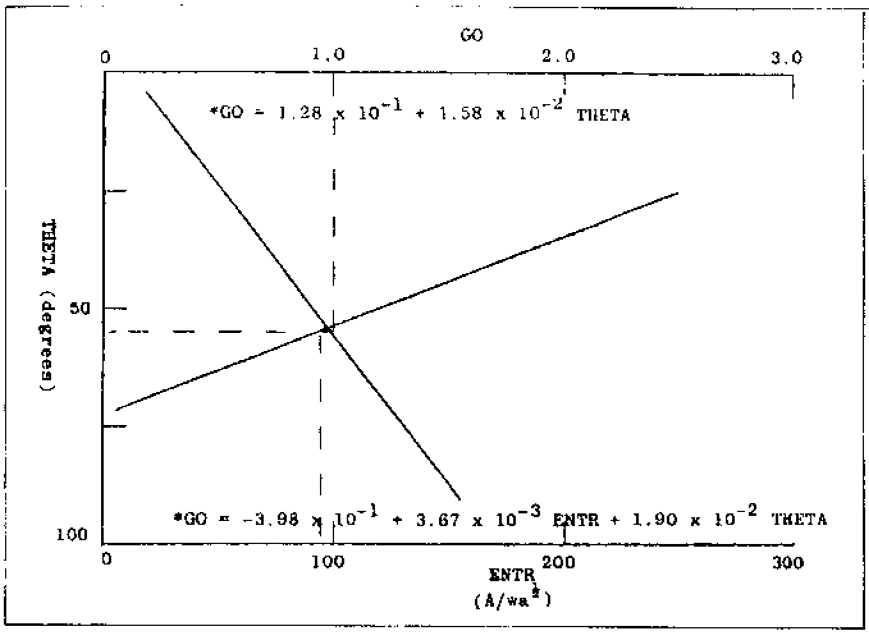

Fig. 22. Response curve of GO to THETA and ENTR (*DIST and DTHA assigned the value of 0)

other than the ones important in the GO regression were found to be significant. Table 15 lists the TVALUES and pertinent variables in the models. One case included DIST, the other did not. It was again illustrated that the variables in the model were significant with respect to KJDN. The parameters not included were not significant.

Fig. 23 shows two curves, one corresponding to FR in the model and the other with FR and DIST. This figure illustrates that adding DIST to the model only slightly changes the curve; it has the most effect on the constant in the equation. Because a limiting value of KJDN just barely intersects the curves, the Kjeldahl regression implies that all the basins are satisfactory with respect to flushing. This is to be expected because the Kjeldahl test indicates only one polluted station according to the EPA spoil limits.

To use the Kjeldahl data for design purposes, a lower limiting value of KJDN is needed, which is a somewhat subjective problem. For want of a better solution, the limiting value was chosen as 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 Fig. 23.

Limiting FR numbers become 1.2 for cases not considering DIST and 1.7 when DIST is considered. Remembering that general guidelines are the goal in this report, the difference in limiting values of FR is minor.

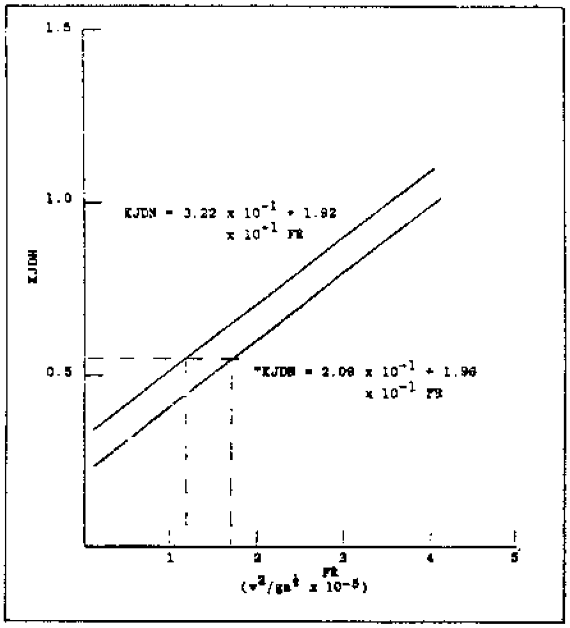

Fig. 23. KJDN related to FR (*Dist assigned the value of 0)

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

To facilitate the use of the Kjeldahl models a simple average should 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.

Though no relation could be formulated using the additive total pollution index, a model was made 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 percent significance level. Fig. 25 shows the relationship of PI23 to REY. Also included in the graph are the 90 per cent confidence limits on the regression line. The line with DIST included in the model was not drawn, but it would be similar in slope and 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 the combined effect of all three equal weight was given as the

(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	

Table 15. Kjeldahl nitrogen regression statistics.

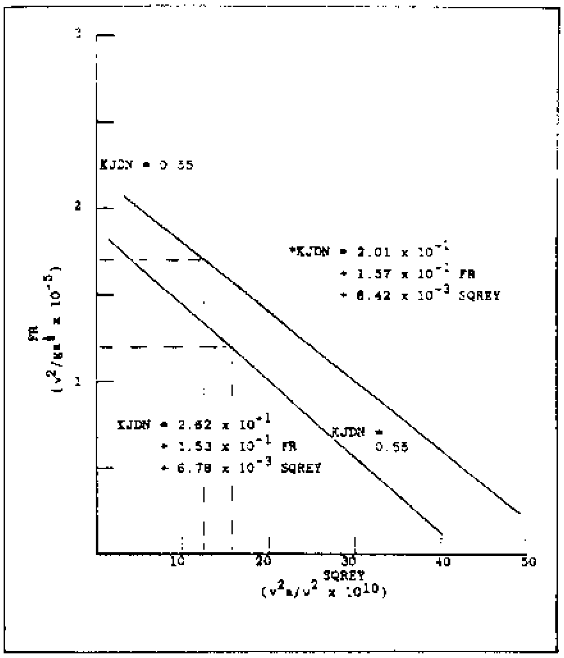

Fig. 24. KJDN as a function of SQREY and FR (*DIST assigned the value of 0)

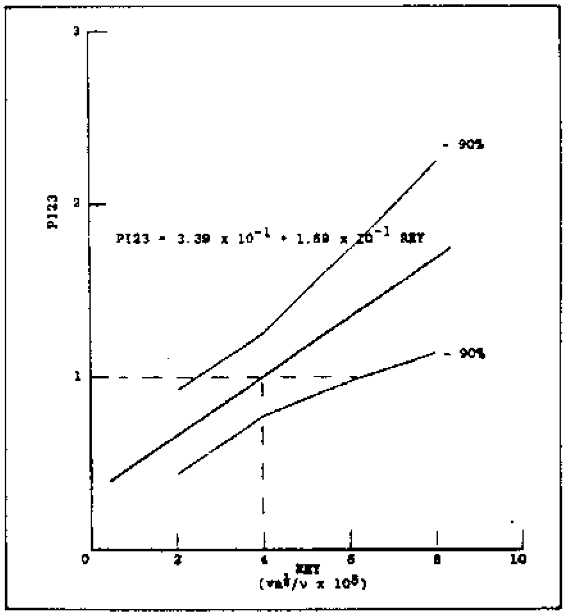

Fig. 25. Total pollution index (P123) as a function of REY)

total index. A critical index of 1.0 yields a limiting value REY number of 4.0. It would be 5.0 on a model including DIST.

Confidence limits give an indication of the quality of the model. For example, if the 90 percent confidence limits gave a range of limiting REY numbers from 1.0 to 8.0 then the model would be insignificant. In this case, the confidence limits gave a range of limiting REY numbers from 2.4 to 6.4. The limits are not close but they are satisfactory for the trends in this analysis.

Quantitative results indicate that reduced marina data will provide a basis for general guidelines. The results give a representative range, and the actual value from the regression line is reasonable enough 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 models were 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 became important. The final involved AREA and ENTR. Table 16 shows TVALUE statistics with AREA and then with AREA and ENTR in the model. Both these variables are highly correlated among themselves (r=0.857) so the effect they have on each other can be observed.

Fig. 26 shows two curves. One is the isoline of SULF=1.0 (critical value) with AREA and ENTR. The other is SULF plotted against AREA. A model was derived using DIST, but the similarity to the line without DIST shows the limiting values with respect to the DIST model. The critical SULF value suggests an AREA equal to approximately 205. This limiting AREA value 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=240 and ENTR=60.

Fig. 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, about 65 per cent in the regression coefficient of AREA between the two models. This suggests that possibly the only variable in the model should be AREA. Other models may also prove useful.

In finding a model to fit the additive

(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	-0.094	-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	

Table 16. Total sulfides regression statistics.

total pollution index (PI4) a newly defined variable came into use. Similar to DTHA, DTHB is equal to DIST * cos(THETA). This variable would be similar to DIST and DTHA; it would be treated as zero in the model. The best regression equation became a function of DTHA, DTHB, AREA and THETA. ENTR could have been marginally added but 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. Fig. 27 is the corresponding graph with DTHA and DTHB at zero. The line is the 4.0 PI4 isoline (critical value for the four variable additive index is 4.0). Also plotted on Fig. 27 is the regression line with AREA only 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°. With DTHA, DTHB and AREA in the model, the limiting value for AREA is 350. When used in the model with THETA it causes a change in the limiting THETA of about 50°. 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 an analysis of the multiplicative combined index PI24, three models were derived. More than three were possible, but the increases in the number of variables

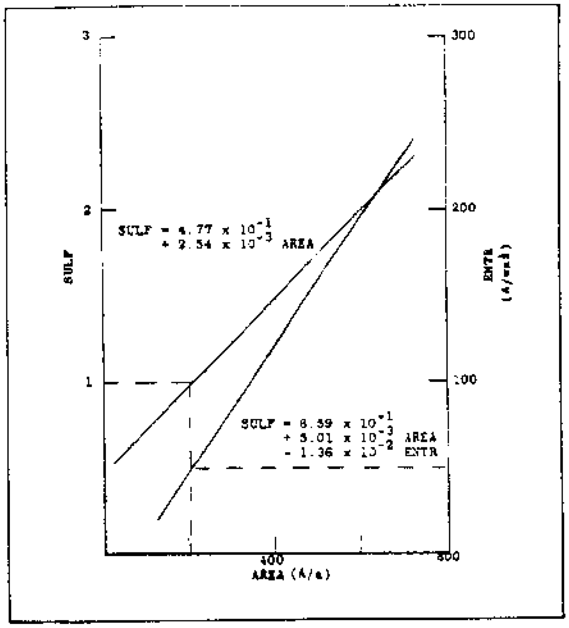

Fig. 26. SULF regression lines.

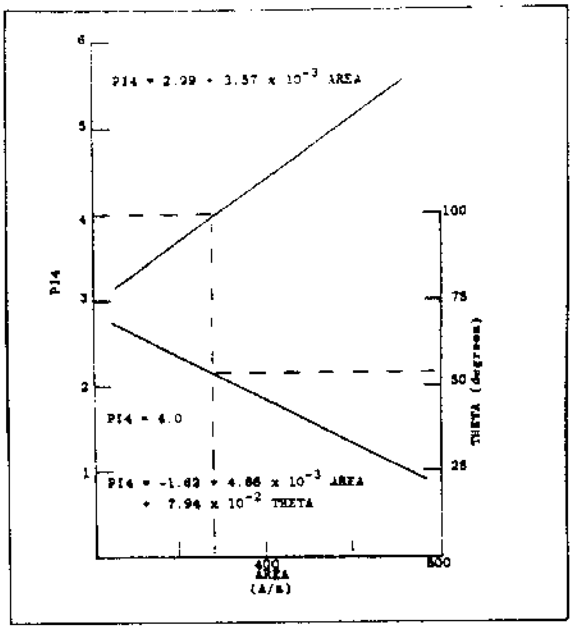

Fig. 27. Additive pollution index (P14 regression lines

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	

Table 17. PI4 regression statistics.

added to the model made the validity of the model questionable.

The easiest model, as in all 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 percent critical t-statistic=1.74). A similar model was obtained when DIST was added to 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. Those for AREA are the highest. As when SULF was regressed on AREA and ENTR, there is concern with the multicolinearity effects of the two highly intercorrelated independent variables.

The third model of interest contains DIST, DTHA, AREA, and THETA. All representative t-statistics are above 2.3 (critical t=1.761). Because of the many 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 analysis.

Fig. 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 the limiting values of ENTR and THETA. The dashed line on the graph delineates limiting values. A look at the slopes between the first two cases shows substantial effects on the regression coefficient of AREA when ENTR is brought into the model (the difference between AREA's coefficients is about 69 percent). The model with both variables should be reviewed carefully. The limiting value of AREA becomes approximately 260 with the corresponding ENTR and THETA each equal to about 60.

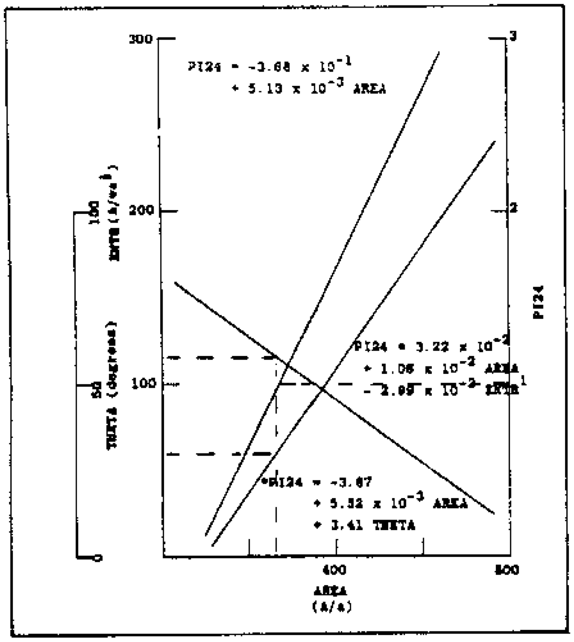

Fig. 28. Total pollution index (PI24) as a function of AREA, ENTR and THETA (*DIST and DTHA are assigned the value of 0)

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 determine 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 result of an analysis of one variable. The rest occur in a multivariable model.

The variables that appear most often in Table 18 are AREA and ENTR, two highly intercorrelated variables whose 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. Including both 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. Lower values would 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 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 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.

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 marinas, emphasis was placed on the AREA and ENTR variables because the highest degree of confidence is placed in these.

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

Table 18. Marina design recommendations based on various models

Limiting Value for High Quality Water

AREA = 400
THETA = 60
FR = 1.5
ENTR = 100
REY = 4.0

Table 19. Final marina design recommendations.

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	

Table 20. Comparison of marina rankings.

A comparison of the two rankings shows many correlations. The only marina that is somewhat displaced is Edmonds, which gets a higher ranking from the basin parameter ranking than with the water quality ranking. There is no apparent reason for this discrepancy except that all the marinas that were used to derive 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 was to provide guidelines useful in the design of small boat marina basins. The focus of the guidelines was to furnish a predictive tool that will enable engineers to design a basin with optimal flushing so the water quality will remain high. In the recommendation section, limiting values for optimal design were assigned to five variables. It is necessary to discuss how the variables relate to each other and to provide an example of how the criteria can be used to best advantage.

The most satisfactory variables (satisfactory because of statistical significance, number of times they appear in the models and ease with 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 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 the pollution indices and THETA. THETA was associated with ENTR and/or AREA in the models in which it appeared. The information derived from THETA is useful 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 from FR and REY suggest extremely small entrance areas. For this reason and because of the confidence in AREA and ENTR results, the variables FR and REY are considered to be a relatively unsatisfactory basis for marina siting criteria.

The two most important variables, AREA and ENTR, will be focused on. To facilitate the use of these criteria in the design process, a nomogram based on the three basin characteristics found in AREA and ENTR (namely A, a and w) was originated. Because the suggested criteria are based on field information the nomogram is confined to the range of values representative of the 13 basins studied. These general ranges are: $A<200,000 m^2$; $a\leq 1500 m^2$; and $w\leq 600m$. Because of maximum values of A and a, w will be confined to a much smaller value than 600m.

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

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

Rearranging ENTR and then incorporating AREA yields

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

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

$$400 * a^{1/2}/w \leq 100 \text{ or}$$

$$a \geq 0.0625 w^2$$

The 'less than' symbol is switched to a 'greater than' symbol to account for the maximum entrance area (a) given a width (w).

Fig. 29 is the resulting nomogram, which can be used in the following way. In the design process the plan area may be a given because 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, making a correlation of a and w easy. For instance, if a plan area of $50,000m^2$ is to be used to provide a small boat marina, and the depth will be about 5m, an entrance 40m wide could be designed to provide a large enough cross-sectional area, $200m^2$, for adequate flushing.

The nomogram 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 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 on one set of samples taken from 13 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 at the conclusion of this study.

A beneficial result of most studies is that the learning process is not confined to the problem 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. Time of basin formation should be considered.

9. Siltation rates or yearly maintenance dredging requirements should be included.

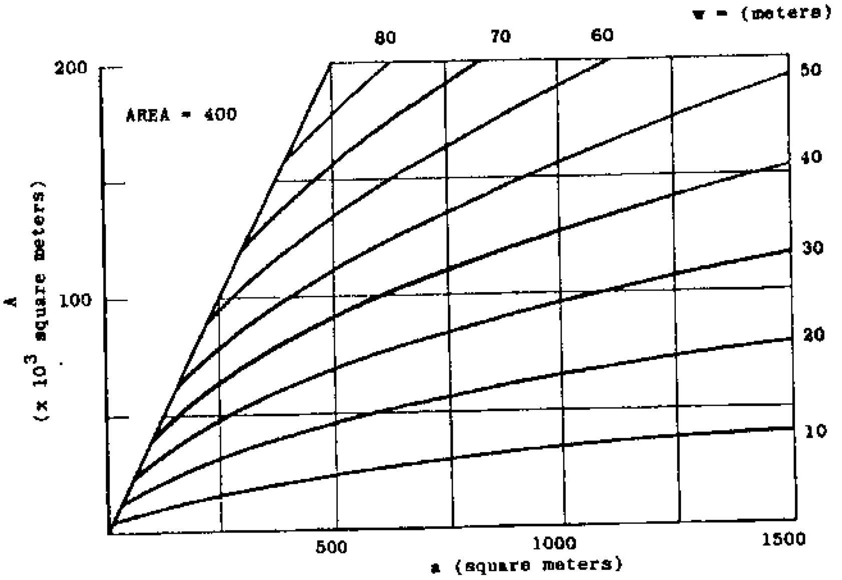

Fig. 29. Nomogram of Acceptable Plan Area (A) vs. Entrance Cross-sectional Area (a) and Entrance Width (w) (A may be less than the limiting value, and a may be greater than the limiting value)

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 used extensively in the design process.

bibliography

American Public Health Association. 1971. Standard methods for the examination of waste and wastewater. 13th Ed. Washington, D.C.

Bella, D.A. 1975. Tidal flats in estuarine water quality analysis. EPA-660/3-75-025, Environmental Protection Agency. Corvallis, OR.

Brezonik, P.L. 1973. Nitrogen sources and cycling in natural waters. EPA-660/3-73-002, Environmental Protection Agency. Washington, D.C.

Brock, T.D. 1970. Biology of microorganisms. Prentice-Hall, Inc., Englewood Cliffs, NJ.

Dyer, K.R. 1973. Estuaries: a physical introduction. John Wiley and Sons, London, England.

Guthrie, D., C. Avery and K. Avery. 1973. Statistical interactive programming system (*SIPS), Technical Report No. 36. Oregon State Univ. Corvallis, OR.

Layton, J.A. 1971. Hydraulic and flushing features of a small craft harbor in Puget Sound. Master's thesis presented to the Univ. of Washington. Seattle, WA.

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

Mitchell, R. 1974. Introduction to environmental microbiology. Prentice-Hall, Inc., Englewood Cliffs, NJ.

Neter, J. and W. Wasserman. 1974. Applied linear statistical models. Richard D. Irwin, Inc., Homewood, IL.

O'Neal, G. and J. Sceva. 1971. The effects of dredging on water quality in the northwest. U.S. Environmental Protection Agency, Region X, Seattle, WA.

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

Reid, G.K. 1961. Ecology of inland waters and estuaries. D. Van Nostrand Co. New York, NY.

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

Sawyer, C.N. and P.L. McCarty. 1967. Chemistry for sanitary engineers. 2nd Ed. McGraw-Hill Book Co. NY.

Slotta, L.S., *et al.* 1974. 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 Univ. Corvallis, OR.

Soderquist, M.R. 1974. Development document for effluent limitations guidelines and standards of performance for the canned and preserved fish and seafoods processing industry, phase II. KCM/Environmental Associates, Inc. Corvallis, OR.

Soderquist, M.R. 1974. Upgrading seafood processing facilities to reduce pollution. KCM/Environmental Associates, Inc. Corvallis, OR.

U.S. Department of the Interior. 1968. Chemistry laboratory manual bottom sediments, Great Lakes region.

U.S. National Ocean Survey, Department of Commerce. 1975. Tide tables 1975 west coast of North and South America.

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

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

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

appendices

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 A. Notation.

Station		A (m^2)	a (m^2)	$\bar{a}$ (m^2)	ℓ (m)	P (m^3)	R (m)	w (m)	x (m)	θ (°)
Astoria		55,748	109	137	307	105,921	1.9	29.5	88 280	45
Hammond		102,958	100	138	350	195,620	1.9	40.6	132	34
Garibaldi	1 2	44,360	84	123	311	75,412	1.7	46.0	127 236	90
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 2	196,948	552	664	731		1.8	125.0	118 469	17
Waldport*										
Florence		12,541	820		46		1.5	26.9	40	0
Winchester	1 2 3	194,570	210	282	1,112	291,855	1.5	96.5	528 754 950	90
(outer) Charleston	1	54,759	1,460		168		1.5	612.0	142	0
(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 2	63,120	167	220	454	94,680	1.5	71	65 441	3

Appendix B. Physical dimensions of basins studied.

*No data available.

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