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DIAGNOSIS OF CHRONIC IMPACTS OF ESTUARINE DREDGING

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ABSTRACT

A method for identifying environmental impacts to estuarine sediments has been developed and applied to Coos Bay, Oregon. This approach is directed towards early phases of environmental impact assessment and appears to be effective for promoting truly interdisciplinary efforts. Physical, chemical and biological characteristics are sketched on a two-dimensional plot of organic content of the sediment (OCS) versus rate of sediment turnover (RST). These plots are overlayed to given common characteristics. Movements of stations on the plane are identified as chronic impacts.

INTRODUCTION

The assessment of chronic environmental impacts in estuaries is difficult and often poorly understood; as such, most assessments have focused on short-term acute alterations. To overcome some of these difficulties, a general assessment approach for dredging-related impacts has been developed. This approach provides a simplified, but practical methodology for impact assessment; it can be used to predict general alterations of the chemical, biological and physical characteristics of the top 20 cm of estuarine sediments. The data summarized herein that illustrate the use of this approach were obtained from an interdisciplinary research study of Coos Bay, Oregon [1].

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A DIAGNOSTIC APPROACH

The Need for a Diagnostic Approach

Interdisciplinary impact assessment is widely recognized as an essential activity to aid society in coping with its expanding technological capacity to impact ecological systems. However, it appears that truly interdisciplinary efforts often tend to fail in that their actual accomplishments fall far short of their ambitions [2, 3]. Many of these failures seem to result from a lack of identification of a useful conceptual framework during the initial phases of the assessment. This early phase of an assessment study is required before information needs are identified and data collection undertaken. It should proceed concurrently with impact identification.

The technical literature provides little information about this early phase of projects because such publications typically present only the end results. In general, the end results of studies tend to be more precise and detailed than the earlier conceptual frameworks that lead to the successful results. The initial phases often involve disagreement, disorder, accidents, conflicts, failures, mistakes and much imprecise or "fuzzy" thinking, particularly in the case of interdisciplinary efforts. These early phases are important because they can lead to the identification of important questions, tasks and unifying conceptual frameworks. Too often, however, interdisciplinary impact studies try to establish the order associated with the end product too soon. The imposition of such order at the beginning of the project may result in the project being based on a conceptual framework that is inappropriate for the problem being studied.

Diagnosis Applied to Environmental Assessment

The term "diagnosis" is used herein to imply an early process of information gathering and decision making. Consider a visit to a family doctor. The doctor reviews the records, asks a few questions and proceeds with an examination that typically includes a few simple measurements. The data collected may be unsophisticated; yet based on this brief assessment, the doctor usually arrives at a reasonable decision. In comparison, environmental scientists and engineers often appear to be confused and lost when asked to "diagnose" the impacts within an ecological system.

It appears that the doctor's initial diagnostic approach involves the collection of a set of information, much of which is general and imprecise; the assemblage of this information into general patterns that correspond to a diagnostic condition (such as "flu"); and speculation as to the nature of the condition and its seriousness, causes, unrecognized symptoms, and possible remedies. Based on this initial diagnosis, the doctor can call for more tests, dismiss the problem as not serious, recommend a remedy, or seek help from a specialist.

It appears that impact assessments call for a similar diagnostic approach.

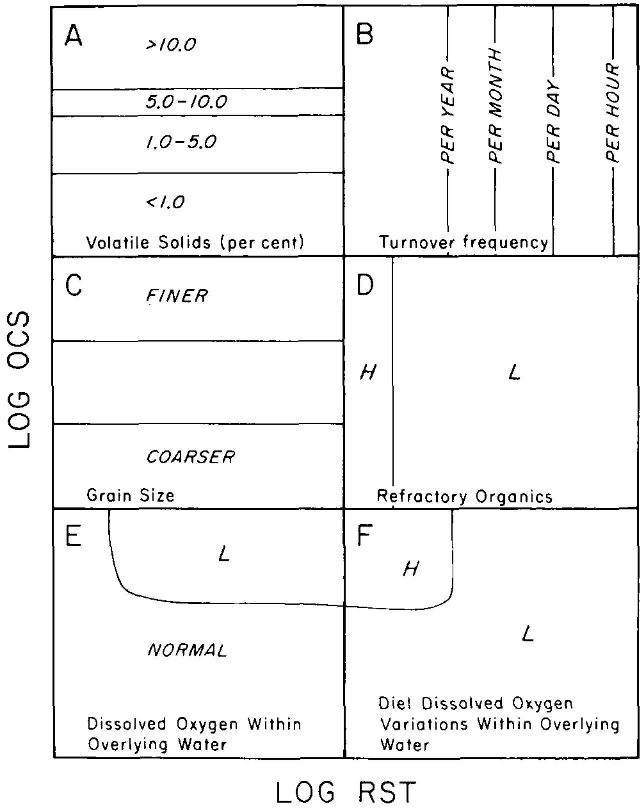
Such an approach would provide an important and possibly essential direction to a study so that important questions can be asked, information needs identified, potential problems assessed, possible causes described and possible remedies suggested. Such a diagnostic paradigm will *not*, however, define precise answers or eliminate the need for detailed disciplinary work. Similar to the doctor's diagnostic paradigm, the environmental diagnosis would deal with a set of information, much of which is imprecise; identify some patterns within this information; and associate such patterns with conditions for which causes, symptoms and remedies can be initially identified. Another important characteristic of such a diagnostic paradigm would be its ability to accommodate a wide range of disciplinary views particularly during the early phases of an environmental impact assessment.

The approach presented herein is concerned with the chronic impact of dredging; as such, focus is directed toward the sediments of estuaries. In general, impacts in the water column tend to be more acute than those associated with the sediments. Two sediment characteristics receive particular attention: the organic content of the sediments (OCS) and the rate of sediment turnover (RST). OCS relates to the organic matter present as mg organics/mg sediment. RST relates the frequency of disruption or hydraulic flushing of the sediments; its units are 1/time. This frequency is estimated from the frequency of the disrupting mechanism (e.g., storms, tides, bioturbation, ship traffic, sedimentation). It is not necessary to precisely define or measure these characteristics. Remember, a doctor does not have a flu meter or flu units; rather, the illness, flu, is identified through general patterns of symptoms and behaviors. So it is with OCS and RST.

The general approach involves a diagnostic plane with OCS and RST as the axes. A variety of physical, chemical and biological characteristics (symptoms) are described on this plane. Each location or station on the OCS-RST diagnostic plane is characterized by a particular pattern or set of physical, chemical and biological "symptoms." Thus, one can "diagnose" the location of an estuarine sediment on the OCS-RST plane by examining such patterns of symptoms. Natural estuarine sediments tend to fall within certain regions of the OCS-RST plane and normal patterns of symptoms or system characteristics can be expected. Dredging and other human activities tend to force an estuarine sediment out of the natural OCS-RST region and, as a result, new patterns of symptoms result. The impact of such dredging is estimated as the shift away from normal patterns to the new or abnormal patterns.

The System Patterns

Some general patterns of system characteristics as related to OCS and RST are shown in Figure 1; these patterns are generalized results of more detailed studies [1]. A variety of different approaches were used to obtain these patterns. As an


A
>10.0
5.0-10.0
1.0-5.0
<1.0
Volatile Solids (per cent)
B
PER YEAR
PER MONTH
PER DAY
PER HOUR
Turnover frequency
C
FINER
COARSER
Grain Size
D
H
L
Refractory Organics
E
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NORMAL
Dissolved Oxygen Within Overlying Water
F
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Diel Dissolved Oxygen Variations Within Overlying Water
LOG OCS
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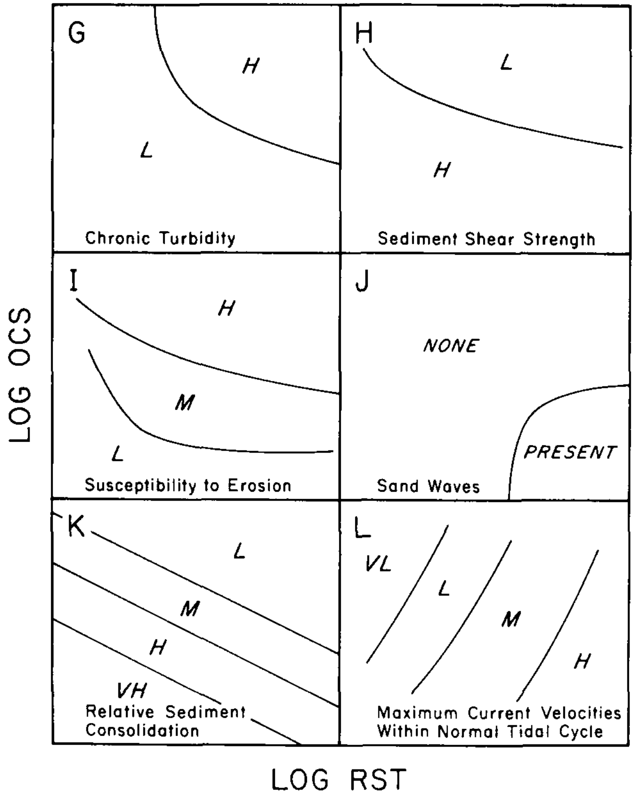
G
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Sand Waves
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Maximum Current Velocities Within Normal Tidal Cycle
LOG OCS
LOG RST

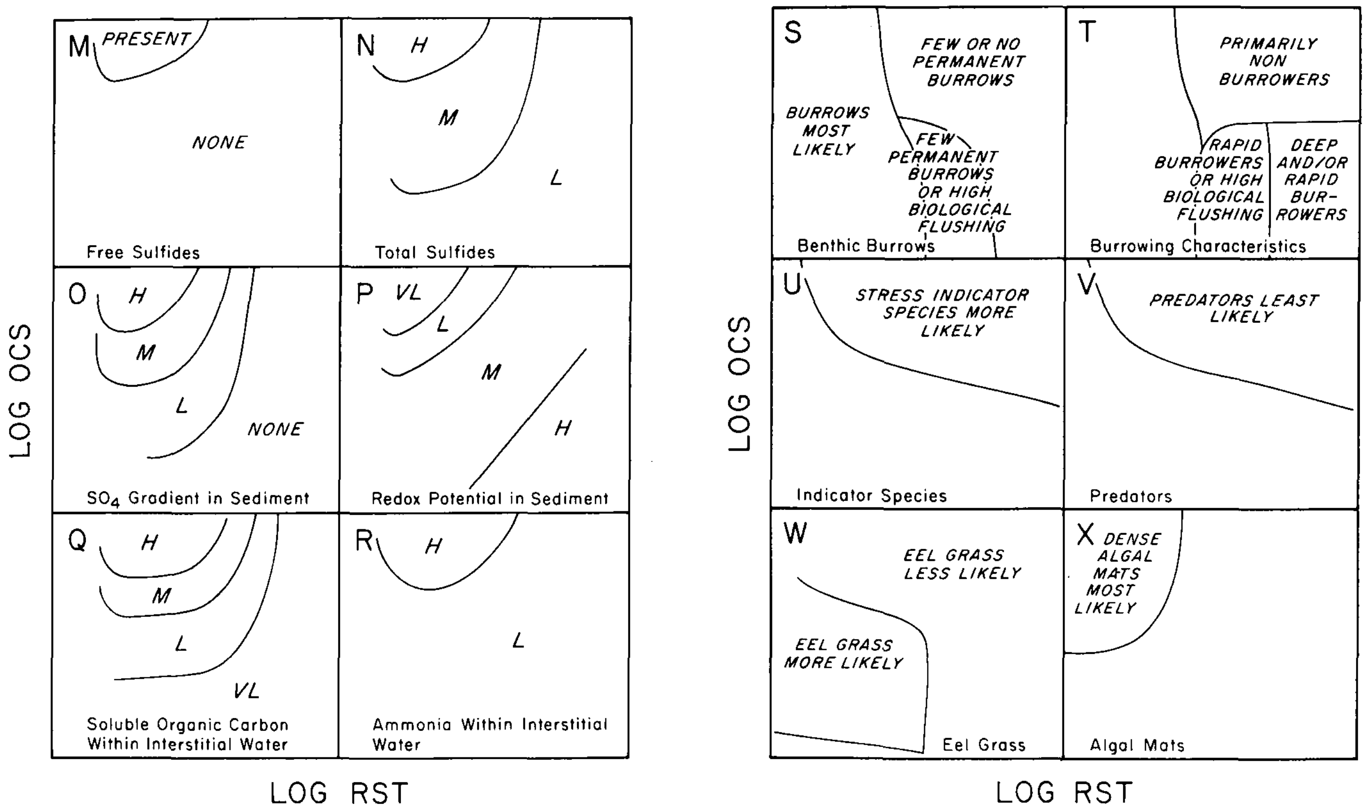

Figure 1. Physical, chemical and biological characteristics of regions on the OCS-RST diagnostic plane. (H = high, M = medium, L = low, VL = very low, VH = very high.)

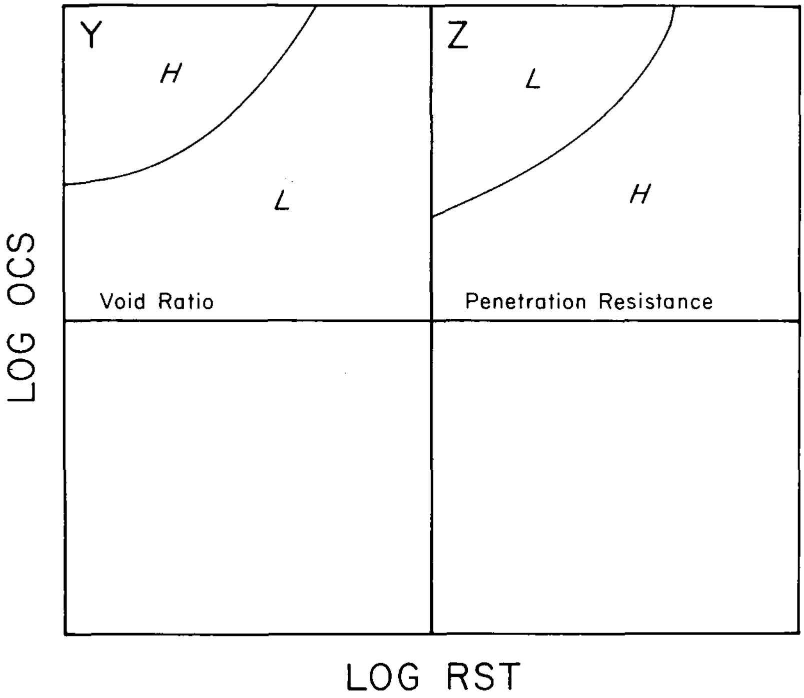

Figure 1. (Cont'd.)

example, the characteristic regions shown in Figure 1(M) through (Q) were selected, in part, on the basis of a mathematical model simulation [4]. Other relationships shown in Figure 1 were drawn through less involved analysis. As an example, the region "Dense Algal Mats Most Likely" shown in Figure 1(X) was located on the plane by estimating the RST that would prevent algal mat development and some minimum OCS that the algal mats themselves would cause. The presence of sand waves (Figure 1(J)) was determined by knowing the frequency of the disrupting mechanism (storms, 1/month(s)) and by estimating the allowable OCS to maintain a sand wave front.

Some adjustment to these shapes were done in response to field operations; however, the general patterns shown in Figure 1 are based upon theoretical and conceptual reasoning having general applicability. Thus, these general patterns are believed to have utility beyond the particular locations examined in the Coos Bay study.

The characteristic regions shown in Figure 1 are not intended to be precisely fixed. In fact, the dimensions of RST and OCS are intentionally removed to emphasize the low-detail, high-perspective nature of these planes. As explained later, some degree of judgment is required in their use.

Natural Positions on the RST-OCS Plane

The OCS and RST within the top 20 cm of the sediments will vary throughout the estuary. There are theoretical reasons to expect that OCS and RST levels within an estuary will display a functional relationship, such as:

$$\mathrm{OCS} = f\left(\frac{1}{\mathrm{RST}}, \frac{1}{F_o}, I_o\ D_o\right) \tag{1}$$

in which OCS = the organic content of the upper portions of a sediment,
RST = the rate of turnover within the upper portions of a sediment,
F_o = the hydraulic flushing rate (primarily advective transport) of suspended organics away from the sediment's location,
I_o = the input rate of organics to the sediment's location, and
D_o = the decay rate of organics.

On a mass basis, the OCS is primarily refractory in nature and, as such, D_o is assumed to be near zero.

The OCS consists of organic material originating from a wide range of sources, including primary production within the estuary, sewage effluents and land runoff. The RST is an indicator of the frequency of sediment turnover from such disruptions as storms, waves, tidal currents, dredging operations, ship traffic and bioturbation. The term, I_o, refers to the input of organics into a given region. As an example, a sewage outfall could result in a significant input of organic material into a given region. The OCS of the region would be higher because of this input rate. Thus, Equation 1 assumes that OCS varies directly, but not necessarily linearly, with I_o.

The hydraulic flushing rate, F_o, describes the transport of suspended material out of a given region. If a sediment is overturned and F_o is low, the suspended material will tend to settle within the same region. If F_o is high, however, the suspended material will be transported away from the location. The term, F_o, can be interpreted as the probability of a suspended organic particle being removed from a given location, with its magnitude depending upon the settling velocity. Obviously, suspended sand will tend to be transported away from an area at a lower rate than suspended organic material. Thus, a high level of F_o would indicate a relatively high transport away from a location of suspended organics (and other fines) in comparison to the coarser inorganics.

Assume that the OCS is temporarily constant throughout an entire estuarine system and the inputs of organics are spread throughout the system. Those regions with high RST and F_o then could be expected to lose organics to those

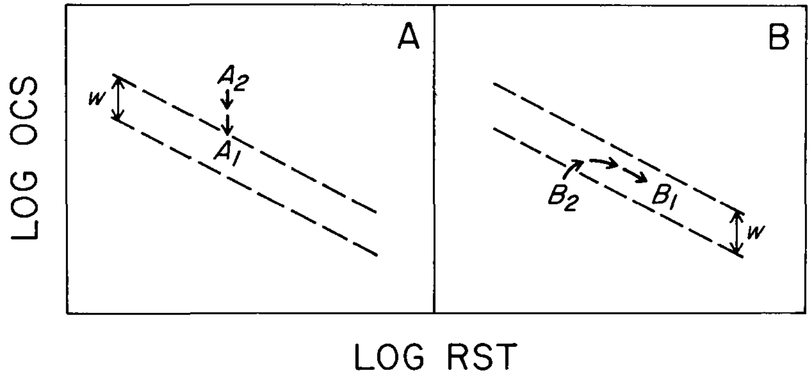

Figure 2. Equilibrium band (dashed lines) and shifts back to equilibrium band.

regions with low RST and F_0. After a period of adjustment the OCS levels within the estuarine system would tend to vary inversely with RST and F_0 as implied by Equation 1. Thus, Equation 1 suggests that sediments within a natural estuary will tend to fall within an equilibrium band on the OCS-RST plane as shown in Figure 2. The slope of this band reflects the inverse relationship between OCS and RST and the width, w, reflects the additional influence of F_0 and I_0 variations upon OCS.

In general, the upper sediments of natural estuarine systems can be expected to fall within such an equilibrium band. Estuaries, of course, are not static systems. They are continually changing and adjusting; nevertheless, the general tendency is toward the equilibrium band. After shifting an estuarine sediment out of this equilibrium band, it will tend to return to its original position. As an example, if a large amount of organics were placed within the sediment at a given location, the OCS would increase. This would result in a shift as shown in Figure 2(A) from Position A_1 to position A_2. The continued overturning of the sediments, however, would result in the relative loss of sediment organics from this location to other locations. Thus, the OCS would decline with time and the location would tend to return to the equilibrium band.

As another example, imagine that a depression occurs at a particular location that has a high RST. The RST and F_0 at the bottom of the depression would now likely be lower than at the surface prior to its formation. The surface sediments would have shifted as shown in Figure 2 from location B_1 to B_2. The hole would begin to fill, probably at first with higher organic content material; thus, its OCS might increase. As it filled, it would become more subject to periodic scour and its RST and F_0 would increase. The increased RST and F_0 would result in a greater removal of organics and, thus, the surface region OCS would decrease. This location would tend to shift back to the equilibrium band and, with time, would shift back toward its original position (see Figure 2(B)).

DIAGNOSING DREDGING IMPACTS

Dredging activities change the shape of an estuary, typically by deepending the main channel. However, dredging can also involve actions such as the construction of dikes, spoil islands, jetties and other fills. The change in the shape of an estuary can lead to changes in the RST from natural and human causes and changes in F_o within the altered estuarine region. The shipping that a dredged channel makes possible can also result in an increase in the RST due to propwash and anchor drag [5]. A dike, spoil island or fill can shelter an area and decrease its RST and F_o. The industrial and commercial activities that shipping serves also can lead to an increase in the organic input (I_o) to an estuarine system. In the Coos Bay area, timber activities have resulted in a substantial input of wood chips, bark and sawdust. Thus, dredging activities can result in a shift of an estuarine region out of the equilibrium band on the OCS-RST diagnostic plane.

An example of such a shift is the dredging of a new channel. The deepending of the channel would promote a more stratified flow regime in which net estuarine currents near the channel bottom tend to be directed upstream. Such currents lead to the trapping of suspended material [6]. Thus, the hydraulic flushing of suspended organics (and other fines), F_o, may decrease significantly. The OCS would tend to increase as the channel filled with higher organic sediments. The RST might remain the same or even increase due to ship traffic in the channel. The sediment might remain highly unconsolidated and, as a result, would become subject to more frequent turnover. Continued dredging might "mine" the coarser material from the system, thus further aggravating the unconsolidated condition. In short, such a dredged system would have a higher OCS and possibly a higher RST, and would be shifted out of the equilibrium band.

This system would tend to adjust back toward the equilibrium band, but such a shift is contrary to the objectives of maintaining a dredged channel. As a consequence, maintenance dredging is needed to stop the readjustment of the system back towards the equilibrium band. The necessity of maintenance dredging demonstrates that the condition that dredging seeks to maintain is not an equilibrium condition.

At present, the shifts on the OCS-RST plane caused by a particular dredging activity cannot be accurately predicted. However, the directions of such shifts due to different types of dredging activities can be indicated. These directional shifts can be used to diagnose the kinds of impacts that a dredging activity might cause. They can also be used to diagnose existing problems, design assessment studies, establish monitoring programs and, in some cases, indicate ways of minimizing and correcting impacts.

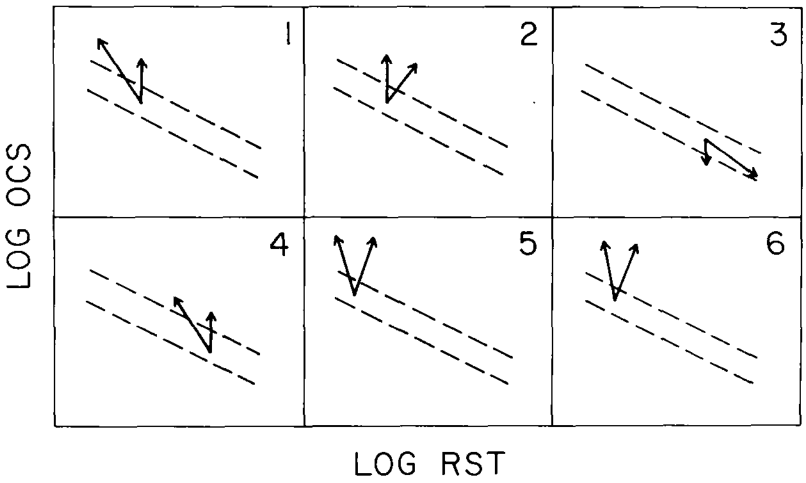

Figure 3. Shifts on diagnostic planes due to different dredging and fill activities (numbers refer to activities described in Table 1).

Six types of dredging and fill activities are identified in Table 1. The general influence upon RST and F_0 are indicated for each activity. The general direction of OCS changes (see Equation 1) and RST changes indicate the directional shift on the OCS-RST plane (see Figure 3).

When dredging activities shift an estuarine region on the OCS-RST plane, the chronic chemical, physical and biological changes resulting from this activity can be estimated by referring to Figure 1(A) to (Z). By locating the pre-dredged estuarine region on the OCS-RST plane and then estimating the shift on the plane caused by the dredging activity, the chemical, physical and biological properties for the new, shifted location can be estimated. The difference in the properties of the original OCS-RST location and the new location due to dredging provide an estimate of some chronic impacts.

Application to Coos Bay

Data were collected at ten stations within the Coos Bay system on the Oregon Coast. A summary of categorized data from these ten stations is provided in Table 2. The data as presented are not highly detailed; a single measurement or even several measurements from Table 2 would likely provide very little useful information. Collectively, however, such information can be used to locate stations on the OCS-RST plane. This imprecise information can be used to diagnose the RST-OCS location of different stations by identifying general

Table 1. Dredging and Fill Activities; Their Relationship to RST and F_o

Dredging activity (1)	*Consequence (2)*	*Change in RST*[a] *(3)*	*Change in* F_o *(4)*	*Indicator (5)*
1. Upstream estuarine channel is deepened. Shipping remains the same.	Greater density stratification, less sediment disruption from prop wash and anchor drag.	Same or decrease	Decrease	Maintenance dredging required; fines and organics in dredge spoils.
2. Upstream estuarine channel is deepened.	Greater density stratification. Sediment disruption from prop wash and anchor drag remains the same or increases.	Same or increase	Decrease	Maintenance dredging required though possibly less than Activity 1; fines and organics in dredge spoils; persistent turbidity near bottom.
3. Channel near estuary mouth is deepened.	Inlet and channel tends to be self-scouring.	Same or increase	Increase	Little maintenance dredging needed; sediments become coarser.
4. Channel near estuary mouths is deepened.	Inlet chokes. Channel fills.	Same or decrease	Decrease	Maintenance dredging needed.
5. Dike or fill constructed which partially enclose an area such as a tidal flat.	Area tends to act as a settling basin.	Decrease or increase[b]	Decrease	Area fills with fines and organics.
6. Deepen areas next to docks, side channels, or boat basin.	Areas tend to fill.	Decrease or increase[b]	Decrease	Area fills with fines and organics; maintenance dredging needed.

[a] For OCS-RST changes, see Figure 3.
[b] Increase may be due to increase sedimentation rate with high organic material.

Table 2. Summary of Field Data for Ten Stations

Figure 1	Characteristic	Stations 1	2	3	4	5	6	7	8	9	10
A	Volatile Solids	M[a]	M	M	M	H	LM	L	H	H	H
B	Primary Turnover Mechanism[b]	B	AB	BE	A-B	D-E	F	A	C	C	D-E
	(approximate freq.)[c]	(yr-mo)	(mo)	(yr)	(mo)	(dec +)	(wks)	(hr-dys)	(mos)	(mos)	(dec-yr)
C	Grain Size	coarse	coarse	coarse	coarse	fine	coarse	very coarse	fine	fine	very fine
D	Refractory Organics	—	—	—	—	—	—	—	—	—	—
E	Dissolve Oxygen Within Water[d]	H	H	H	H	H	H	H	L	L	V
F	Diel Dissolved Oxygen Variations	L	L	L	L	L	L	L	L	L	H[e]
G	Chronic Turbidity[f]	No	No	No	No	No	No	No	Yes	Yes	No
H	Shear Strength[f]	H	H	H	H	H	H	H	L	L	L
I	Susceptibility to Erosion[g]	M	M	M	M	L-M	M	L-M	—	H	—
J	Sand Waves	none	none	none	none	none	none	present	none	none	none
K	Relative Sediment Consolidation	M-H	M-H	M-H	M-H	M-H	M-H	M-H	L	L	M
L	Tidal Currents	M	M	M	M	VL	M	H	L	L	VL
M	Free Sulfides	none	none	none	none	none	none	none	none	none	present
N	Total Sulfides	M	L	M	M	M	L	VL	M	M	H
O	SO_4 Gradient	L	L	L	L	M	L	VL	M	M	H
P	Redox Potential	M	M	M	M	L	M	H	M	M	VL
Q	Soluble Organic Carbon	—	L	M	M	L	L	L	M-H	M	H

R	Ammonia	L	L	L	L	L	L	L	M-H	M	H
S	Permanent Animal Burrows	present	none	present	none	present	present	none	none	none	present
T	Burrowing Characteristics	deep	rapid	deep	rapid		HBT[h]	rapid	highly motile	highly motile	fine
U	Stress Indicator Species	—	—	—	—	HR[i]	—	—	HR	HR	HR
V	Carnivorous Predators	present	present	present	present	IA[j]	present	present	none	none	none
W	Etel Grass	present	none	present	none	none	none	none	none	none	none
X	Algal Mats	none	none	none	none	less dense brown	none	none	none	none	very dense green
Y	Void Ratio	L	L	L	L	L	L	L	H	H	H
Z	Penetration Resistance	H	H	H	H	L	L[k]	—	L	L	L

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[a] L = Low, M = Moderate, H = High, V = Variable, — = Information not available.

[b] A = Tidal Action, B = Storms, C = Ship Traffic Anchor Drag, D = Sedimentation, E = Rare Storms, F = Bioturbation.

[c] Relative approximations, at depths less than 10 cm would be higher.

[d] Based on fall sampling, 1974 and 1975.

[e] Reference 1 and fall sampling, 1975.

[f] Based primarily upon diver observations.

[g] Based on in-situ scour tests.

[h] High biological turnover, ghost shrimp bed, many burrows.

[i] High reproductive capacity species.

[j] Infauna absent, motile species present.

[k] Influenced by the high biological turnover.

patterns. This diagnosis is accomplished through the use of Figure 1(A) to (Z). Each of these figures express some characteristic or property of an estuarine sediment or the water overlying this sediment. A particular station is located on that part of the OCS-RST plane where its measured characteristics and properties correspond most closely to those shown in Figure 1.

A useful procedure for locating a station on the RST-OCS plane involves the use of transparent overlays of the Figure 1(A) to (Z). Each overlay is constructed with the same RST and OCS scales. For each figure, those regions of the plane not corresponding to the measured characteristics of the station being studied are darkened. As an example, Table 2 shows free sulfides were not present at Station 2; thus, on the overlay of Figure 1(M), the region of the RST-OCS plane indicating that free sulfides were "present" would be darkened. The remainder of that particular overlay would be left clear. As a result, a series of partially darkened transparent overlays would be obtained for each station as shown in Figure 4.

A semi-transparent darkening is most useful. The clear regions of the overlay indicate possible locations of the station on the OCS-RST plane. Any single overlay would have a wide portion of the plane clear. However, when all the overlays are placed on top of each other, only a small portion of the plane remains clear. This small clear region describes the most probable location of the station on the OCS-RST plane and is compatible to the pattern of characteristics and properties measured at that station. This approach was used for all ten Coos Bay stations and their locations are shown in Figure 5. These results suggest the general pattern shown in Figure 6.

Of the ten stations shown on Figure 5, four were influenced by dredging and fill activities (Stations 7, 8, 9 and 10). The remaining stations are located within the South Slough which is relatively undeveloped and has been designated as the first national estuarine sanctuary. These stations (1 to 6) are clustered within an equilibrium band as shown in Figure 6.

Station 7 is located within the outer main channel of the Coos Bay system. It appears that channel dredging has shifted this location on the diagnostic plane in a manner shown within Figure 3 for Activity 3 (see Activity 3, Table 1).

Stations 8 and 9 are located within the upper main dredged channel of Coos Bay with Isthmus Slough. These sediments were found to be periodically overturned by the anchor drag associated with the shipping in this area. The RST-OCS shift of these stations due to dredging and the secondary impacts of dredging appears to be best described within Figure 3 for Activity 2 (see Activity 2, Table 1). The principal impacts appear to be chronic turbidity (Fig. 1(G)), unconsolidation (Fig. 1(K)) and few permanent-burrowing species (Fig. 1(S)).

The construction of a dike that partially encloses the tidal flat area at Station 10 appears to have shifted this location on the diagnostic plane as shown in Figure 3 for Activity 5 (see Activity 5, Table 1). Log storage in this area also appears to have increased the inputs of organics. The principal environmental

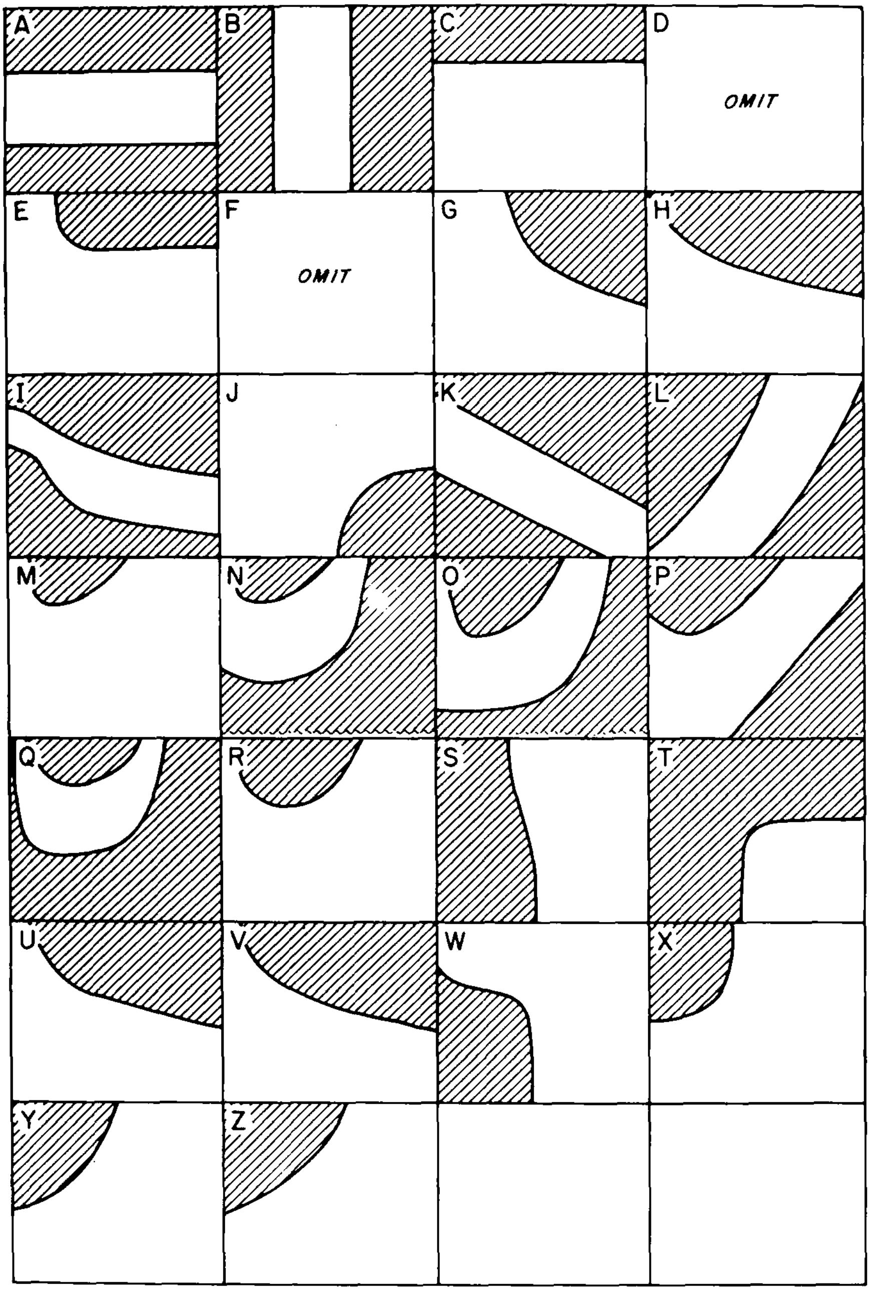

Figure 4. Overlays for Station 4 (refer to Figure 1 and Table 2).

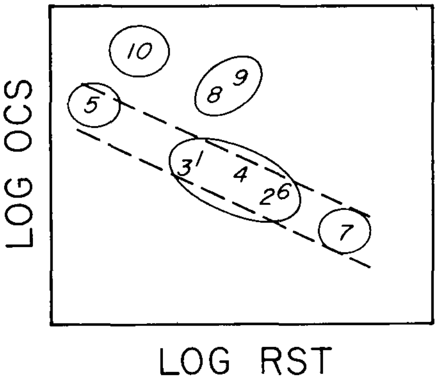

Figure 5. Locations of ten stations (see Table 2) on diagnostic plane (light solid lines indicate biological clusters).

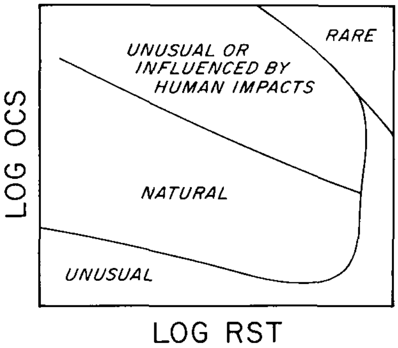

Figure 6. General conditions of sediments on the RST-OCS diagnostic plane.

impact appears to be high levels of free sulfides within the interstitial waters (Figure 1(M)), the release of free sulfides to the overlying water [7], and the release of hydrogen sulfide to the atmosphere. Station 10 was found to have the lowest species diversity of all ten stations [3] which is likely a biological response to free sulfide toxicity.

Cluster analysis [3] revealed that benthic infauna were divided into the following biologically similar clusters: (Cluster 1) Stations 1, 2, 3, 4 and 6; (Cluster 2) Station 5; (Cluster 3) Station 7; (Cluster 4) Stations 8 and 9; and (Cluster 5) Station 10. This biological similarity corresponds to the locational clustering on the RST-OCS plane (see Figure 5).

The Need for Judgment

The use of this diagnosis methodology requires some degree of judgment. As an example, it must be decided, when shading in the individual overlays, how extensive to darken the plane. Figure 1 does not provide precise definitions for each region, although it does provide general indications. If too much area is darkened and only small regions are clear on each overlay, then the composite overlay may not show any clear regions. At the other extreme, the composite overlay may display too large an area of the OCS-RST plane.

Judgment is also needed to decide whether to ignore a particular overlay from Figure 1(A) to (Z) or to modify it. As an example, a low sulfate gradient may have been measured within a sediment. Based on Figure 1(O), the station would likely be located on the low OCS, high RST region of the plane. The station, however, may have been located in a low salinity region of the estuary; thus, the sulfate concentrations of the overlying water would be low. A high sulfate gradient in the sediment would not be expected even if the station did have a high OCS and a low RST. Thus in Figure 1(O), the high OCS, low RST region should not be darkened.

As another example involving judgment, consider Figure 1(X) which concerns dense algal mats. If no such algal mats are present, the area designated "Dense Algal Mats Most Likely" might be darkened. However, the absence of algal mats may be due to some factors other than OCS or RST. As an example, the sediment may be covered with turbid water that prevents sufficient light penetration. If this was the case, Figure 1(X) should be omitted from the composite overlay.

Judgment is also needed to interpret seasonal variations since Figure 1(A) to (Z) tend to best describe late summer, early fall conditions. Winter conditions might be different due to lower salinities, seasonal storms and lower light levels.

While some judgment is needed in darkening the individual overlays, the locations of stations on the diagnostic plane are relatively insensitive to fine adjustments of individual overlays. In fact, several individual overlays can be omitted and the composite overlay still provides a reasonably specific location of a station on the diagnostic plane. Often, the individual overlays can be randomly divided into several piles and the several composite overlays that result will provide essentially the same location of a station on the diagnostic plane. This implies that data requirements can be greatly reduced without loss of the ability to reach the same conclusions.

The Use of the Diagnostic Approach

This diagnostic approach is intended to assist an interdisciplinary impact assessment team, particularly in the early phases of their study. Impact studies generally are organized around the following format:

1. the description of the present state of the environment,
2. the prediction of environmental changes resulting from a human activity, and
3. the assessment of significances of these changes.

The first of these steps involves the collection and presentation of data; major difficulties include deciding which data are relevant, how such data can be collected within the study constraints, and how to present the data in a clear and concise manner. The proposed diagnostic approach can assist in addressing these difficulties. The location of estuarine regions on the RST-OCS diagnostic plane can often be done without extensive sampling efforts. The overlay approach can be used for this purpose. By defining such regions on the diagnostic plane, a rather concise description of the characteristics and conditions of these sediments (Figure 1(A) to (Z)) is obtained in much the same way as a doctor's diagnostic word, "flu," expresses a set of symptoms. Thus, the proposed diagnostic approach can significantly assist in the achievement of the first of the three steps listed previously.

The second step involves describing the changes from a human activity, in our case, estuarine dredging and its secondary activities. Under this diagnostic approach, the chronic changes due to dredging can be seen as shift of estuarine regions on the OCS-RST diagnostic plane. Our approach suggests the direction of such shifts as a result of different kinds of dredging activities (see Table 1 and Figure 3). This approach does not, however, provide a way of determining the magnitude of such shifts. This kind of information would require more detailed disciplinary work particularly in the areas of hydrodynamics and sediment transport. The approach, while not providing precise answers, does help to identify and guide the more detailed disciplinary studies toward meaningful answers.

If some reasonable estimate of the shift on the diagnostic plane due to dredging (and secondary activities) can be obtained, then the approach does provide some guidance to identify the significance of such changes (Step 3). A shift on the diagnostic plane provides an indication of the physical, biological and chemical changes resulting from the activity that caused the shift. By estimating the pre-activity and post-activity locations on the diagnostic plane, Figure 1(A) to (Z) can be referred to for guidance to assess some physical, biological and chemical changes resulting from the activity. As an example, if an activity shifted an estuarine region to the upper left portion of the diagnostic plane (such as Station 10, Figure 5), then free sulfides would likely result within the sediments (see Figure 1(M)). Hydrogen sulfide might then be released to the atmosphere, particularly from exposed tidal flat regions. Free sulfides are toxic to a wide range of organisms [6, 8, 9]. Hydrogen sulfide is also a toxic gas and thus its release from estuarine sediments could be an air pollution problem [10, 11].

As another example, dredging might result in the shift of a subtidal area toward the upper-central region of the diagnostic plane (see Stations 8 and 9, Figure 5). Such a shift would indicate the occurrence of weak, unconsolidated sediments and chronic turbidity (see Figure 1(G) and (H)). Permanent burrows would not probably be possible within such sediments (see Figure 1(S) and (T)). Thus, dredging activities might eliminate subtidal clam beds. These clam beds might be important seed areas to other tidal clam beds and thus, the impact might extend beyond the immediately impacted area [12].

In both of the examples provided above, the diagnostic approach provides initial guidance to assess the significance of possible impacts. The approach helps to identify important questions that might lead to more quantitative estimates of significant impacts. Finally, the diagnostic approach provides a concise way of describing some results of an impact study. The impact of estuarine dredging activities can be described, very briefly, as a shift on the diagnostic plane. Such a *description would be a concise, yet, information-rich description of very* complex interactions within estuaries.

BROADER CONSIDERATIONS

The RST-OCS diagnostic plane was developed as a practical aid to impact assessment. This approach has arisen, however, from some very fundamental philosophical concerns that are briefly addressed below.

The Sacrifice of Precision and Detail

The education of most scientists and engineers has inculcated certain notions concerning how problems should be "properly" solved. The most common approach is a step by step, causal chain approach that Maruyama described as the "unidirectional causal paradigm." [13] Classical geometry is an example of this approach; geometry problems are solved one step at a time, each step being precisely defined before proceeding to the next. Under this approach, the whole approach must be questioned if any step is imprecise or doubtful. A problem solution can be imagined as a chain that is as strong as its weakest link. Problems are ideally solved by precisely planning, organizing, directing, coordinating and controlling each step. Technical publications tend to follow this model; procedures, derivations and discussions are presented in a step by step manner and imprecision or "fuzziness" at any step raises doubts concerning the whole. Maruyama described impact assessment as an example of this approach; he argues, however, that this approach has serious limitations [13].

The authors' experiences have shown that, while the final results of technical environmental studies may be described in this step by step fashion, the earlier developmental stages of such studies often follow a very different, less precise process. Moreover, the authors have stated elsewhere that the broader perspective required for the interdisciplinary study of complex systems must likely involve sacrifice of detail. Zadeh expressed this concern as a "principle of incompatibility" which states that "as the complexity of a system increases, our ability to make precise and yet significant statements about its behavior diminish until a threshold is reached beyond which precision and significance (or relevance) become almost mutually exclusive characteristics." [14] It is suggested that, in an effort to proceed in a precise step by step manner, impact assessment typically has attempted to pursue step by step precision (or at least the impression of such precision) and, in doing so, it has potentially lost significance and relevance in accordance with Zadah's principle. The result has often been large impact statements containing much data, maps, charts and graphs; however, such impact statements often do not inspire confidence in their significance or relevance.

Zadah further argued that human reasoning involves "a logic of fuzzy truths, fuzzy connectives and fuzzy rules of inference" and this "not well understood logic—may well be one of the most important facets of human thinking." [14] "Viewed in this perspective," he continued, "the traditional techniques of system analysis are not well suited for dealing with humanistic systems because they fail to come to grips with the reality of the fuzziness of human thinking and behavior. Thus, to deal with such systems realistically, we need approaches that do not make a fetish of precision, rigor and mathematical formalism, and which employ instead a methodological framework which is tolerant of imprecision and partial truths."

The approach presented herein is based upon concerns similar to those stated by Zadeh [14]. Without denying the importance of precision, rigor and mathematical formalism, a "fuzzy" methodology has been presented that is particularly directed toward the earlier stages of interdisciplinary studies. The approach admittedly sacrifices precision to gain significance and relevance, a necessity implied in Zadeh's principle of incompatibility. The approach seeks to help identify which precise information would be relevant and significant, but the approach itself is not precise in the step by step manner of geometry. The approach employs fuzzy classes of variables, relationships and algorithms in which the transition from membership to nonmembership is gradual rather than abrupt. Thus, RST is a "fuzzy" variable, the relationship shown in Figure 1(A) to (Z) are "fuzzy" relationships and the changes due to dredging shown in Figure 3 are "fuzzy" algorithms.

This approach differs radically from the step by step, "unidirectional casual paradigm" which Maruyama [13] described as the basis for most impact assessment. Under this paradigm, the diagnostic approach would be judged as "unreasonable" since it does not proceed in a precise step by step manner. As an example, it has been reasoned that a number of overlays can often be taken out without significant change in the location of a station on the diagnostic plane. From the traditional step by step approach, this is tantamount to saying that it is appropriate to discard several links of the casual chain which would cause the whole chain to lose its value. But the diagnostic approach is not relevant to the chain analogy. This approach departs from the traditional "unidirection casual paradigm" and thus, as Maruyama [13] excellently described, confusion and misunderstanding will likely arise among those committed to this more traditional paradigm.

A Broader Context

It has been attempted to view (imagine, conceptualize, understand) the OCS-RST approach within a broader context to recognize its advantages and limitations. This contextual framework has been based upon a general concept of an estuary which an interdisciplinary team can share. It has been attempted to identify the word "estuary" with a general concept that can compliment the different disciplinary understandings of this word. This is important because, while different disciplines can agree on what an estuary is, the patterns of thought (structures of reasoning, paradigms) from which this work is interpreted are quite different and such differences can cause serious communication problems. The general shared concept of an estuary that has been found useful can be mentally formulated by first considering any two estuarine characteristics (e.g., temperature and salinity) that form a plane. All regions within a typical estuary could be located on such a plane. The result can be imagined as a textured or shaded two dimensional patch or blot. By adding a third dimension (e.g., dissolved oxygen) a three dimensional blot or object is obtained.

Dimensions can now be added to form an nth dimensional object that is defined by the geographical, geological, hydraulic, chemical and biological characteristics of a typical temperate estuary. In the context of our interdisciplinary team dialog, the word "estuary" called forth this concept of an nth dimensional imaginary object. This nth dimensional object, of course, is only a vague conceptual reference from which more detailed inquiry can proceed.

A team can now select two dimensions from this nth dimensional object to form a plane. There are some advantages to selecting dimensions that may be a composite of several more precise dimensions.

If one or more basic diagnostic planes are selected, then confusions and disagreements can often be resolved in the group dialog by occasionally referring to other dimensions without increasing the dimensions of the basic diagnostic planes. As an example, the presence or absence algal mats shown on Figure 1(X) depend upon more than OCS and RST. As an example, sufficient light is needed. For that particular figure, a team can imagine light and other requirements for algal mats as additional dimensions to that particular figure. Thus, the team need not reject the basic OCS-RST diagnostic plane simply because it does "not work" in all cases. Instead, it is not expected to apply in all cases because the dimensionality of the diagnostic plane is not sufficient to bring about such precision.

In the use of the OCS-RST plane, the following complimentary dimensions have been employed: temperature, salinity, tidal exposure, distance from ocean, water depth, grain size, light level, sulfide capacity, biological availability of organics, size of organic particles, depth of overturn, duration of overturn, sediment slope, depth from sediment surface, hydraulic flushing, organic input rates, and sediment input rates [1]. Such complimentary dimensions were not used to change the basic OCS-RST diagnostic plane. Rather, such dimensions were added in discussions to better understand the complications, limitations and exceptions of the OCS-RST approach.

SUMMARY

The approach presented is directed toward the chronic impacts of estuarine dredging activities that are both more important and more difficult to examine than the acute impacts that are usually examined. This is a diagnostic approach that is primarily directed toward the early phases of interdisciplinary impact studies where critical failures often occur. It appears to be an effective way of promoting truly interdisciplinary efforts, and can be an important aid to present results in a clear and concise manner. The approach holds some hope for reducing the serious problems and deficiencies of current impact studies such as interdisciplinary failure, lack of cohesion and purpose, large amounts of unused data, little advancement of knowledge, focus upon simpler though less important impacts, ineffective use of study resources, and bulky reports that are difficult to review.

The authors appreciate the limitations associated with this approach. The OCS-RST diagnostic plane is only one of many possible diagnostic planes. The characteristics described in Figure 1(A) to (Z) need to be redefined, compared to more field studies and expanded. Other dimensions and diagnostic planes need to be developed. Entirely new diagnostic approaches need to be examined and some impact study efforts must be employed to search for impacts not identified by any diagnostic approach. Given the current difficulties and problems of impact studies, however, the potential benefits of this approach appear to outweight its limitations and the risks of its misuse.

APPENDIX I

NOTATION

D_o = the decay rate of the organic content
F_o = the hydraulic flushing rate of suspended organics away from the sediment's location
I_o = the input rate of organics to the sediment's location
OSC = the organic content of the upper portions of a sediment
RST = the rate of turnover within the upper portions of a sediment

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