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A METHODOLOGY FOR IMPACT ASSESSMENT IN THE ESTUARINE/MARINE ENVIRONMENT

Kendall F. Haven

October 31, 1975

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A METHODOLOGY FOR IMPACT ASSESSMENT IN THE ESTUARINE/MARINE ENVIRONMENT

Abstract

Impacts on the estuarine/marine environment can be assessed in economic terms by tracing the impact flow out of the economic sector through the marine environment and back into the economic sector as changes in natural resource availability. An impact can then be measured by the changes created in the economic sector by changes in resource availability. Primary emphasis is placed on the development of an appropriate

ecological model of the estuarine environment for this purpose. Two types, an ecological input/output model and a dynamic (difference equation) model, are proposed. Acceptability criteria for these models include the ability to track lethal and sublethal, direct and indirect (food web), and short- and long-term effects of a variety of pollutants related to the production and use of various energy resources.

Introduction

The goal of this effort is to develop a methodology capable of assessing and evaluating the impact of present and future energy-related activities on the marine/estuarine environment. For this purpose, an impact is defined as a change in either the quality or quantity of a marine resource as the result of a given action and the value of that change. Thus impacts associated with energy-related activities will arise directly from the effluent loading of point and nonpoint discharges associated with the generation and end use of the various forms of energy, and indirectly from the changes in other economic sectors induced by changes in energy-related industries and the increased effluent loading associated with those changes.

An overall concept for impact identification and assessment in the estuarine

environment is shown in Fig. 1. In this figure regional economic and aquatic ecological parameters are shown in an intrasectional input/output (I/O) matrix format, with intersectional transfer functions used to transmit flows between the two sections. This conceptual framework is a somewhat simplified form of the more complete regional analysis framework depicted in Fig. 2. This figure shows four general intrasectional models with full interconnecting intersectional transfer functions. The simplification from Fig. 2 to Fig. 1 is based on the following premises:

1. Pollutants introduced into the marine/estuarine aquatic environment will have a negligible impact on human health, and thus that section can be disregarded.
2. Since there is sufficient independence between the aquatic and nonaquatic environments, the aquatic environment can

	Economic sectors	Physical, chemical, and environmental parameters	Biotic ecosystem	R	Y
Economic sectors	I/O Matrix	Hydrological dispersion and sediment transfer			
Physical, chemical, and environmental parameters	Weighting system	Ecological model (dynamic or I/O)			
Biotic ecosystem					

Fig. 1. Environmental/economic interaction concept.

	Economic	Environmental	Human health	Social/political
Economic	Economic intrasectional transfer model	Economic → environmental transfer model	Economic → human health transfer model	Economic → social/political transfer model
Environmental	Environmental → economic transfer model	Environmental intrasectional model set	Environmental → human health transfer model	Environmental → social/political transfer model
Human health	Human health → economic transfer model	Human health → environmental transfer model	Human health intrasectional model	Human health → social/political transfer model
Social/political	Social/political → economic transfer model	Social/political → environmental transfer model	Social/political → human health transfer model	Social/political intrasectional model

Fig. 2. Regional impact analysis framework.

be studied in a separate regional analysis.

3. Effects in the social/political sector can be externalized in the form of scenarios and thus need not be internalized within the model.

Let us look first at the intersectional portion of Fig. 1. The economic sector I/O model has been widely used for economic regional analysis for a number of years (Isard, 1972; Stoenener et al., 1972; Kunin et al., 1975). All outputs listed as products from the various economic sectors are reconsumed by other sectors or exported outside the model area (column Y), so that the output flow from the economic sector into the environmental sector consists entirely of waste flows. Aqueous waste flows (the sole concern of this study) are transported into the local ecosystem through water-column advective pollutant dispersion and sediment transport. The environmental sector can be viewed as being very similar to the economic sector. Each element (environmental parameter, pollutant, or taxon) transfers a portion of its output biomass through food-web transfers or pollutant uptake to some other sector element (taxon). Again all products are consumed by other elements within this sector or are exported outside the

model limits. The flow from the environmental sector back into the economic sector is made up of the natural resources used as inputs to the various economic sectors. From estuarine and coastal zone waters this list of resources includes fish and other edible products, cooling and cleaning waters, salt, sand, gravel, transportation and recreational media, waste-assimilative capacity, and so forth.

Once this entire system has been modeled, an impact analysis can be performed as follows: An action to be studied (e.g., inclusion of a new industry or activity, or an increase in an existing one) is inserted into the economic sector I/O model and allowed to perturb that model. The resultant change in total effluent flow is then transmitted into the ecosystem model through the hydrodynamic, dispersion, and sediment-transport models. The change in sector effluent input is then allowed to perturb throughout the ecosystem model. A weighting system, which will be discussed in more detail later, is then applied to the resulting changes in natural-resource availability to measure the impact on the local economic sector of these resource-availability changes. The total value of this latter impact is, then, the value, or an assessment, of the original action's impact on the aquatic environment.

Model Methodology

A functional methodology for the development of the ecological model and two transfer functions listed in Fig. 1 is shown in Fig. 3. The desired characteristics of this methodology include the following:

1. An ability to assess pollutant impacts, including both lethal and sublethal, direct and indirect.
2. A segmented "block" design to allow creation and use of each segment individually.

Fig. 3. Methodology for San Francisco estuary impact analysis.

3. The ability to readily incorporate results of future research into any segment.

4. The ability to use all model segments with existing incomplete data and still obtain meaningful results.

The economic section I/O model is not included in this methodological diagram except for the identification of sector effluent flows.

In order to better comply with characteristic 4, a somewhat limited methodology has been developed. The complete methodological approach would require initial inclusion of food-web relationships in all bay segments over all seasons and of the uptake characteristics and toxic effects of all known toxins entering the bay. The limited methodology is designed to limit

food-web consideration spatially and temporally, and to focus attention on a certain group of effluent pollutants associated with a given action or industry.

As shown in Fig. 4, this limited plan first requires the identification of an industry for consideration (i.e., petroleum refining, hydroelectric, etc.). Transport and dispersion models are then run, first with all known effluents and second without the effluents associated with the given industry. A comparative analysis of these two runs will reveal the areas, seasons, and specific pollutants for which this industry has a discernible effect on water quality. The ecological model then need only be structured for those specific areas, seasons, and pollutants. Within these limitations the ecological model

Fig. 4. Limited-scope methodology for San Francisco estuary impact analysis.

itself will be as complete as the more general model and will have all of its analytical capabilities. Thus the use of either methodology for any given specific action or industry should yield an identical impact assessment. The difference is in model construction and run time.

This brevity is gained at the cost of an additional model assumption--namely, that the mortality and behavior of the taxa included in the model food web are not dominated by factors external to the limited model (i.e., pollutants not associated with this industry) and that these

taxa will respond to changes in the modeled pollutants in a predictable way.

The long-range goal of this study is to develop the general methodology.

Whether or not this additional assumption associated with the interim use of the limited methodology will prove troublesome is not yet known.

Ecological Model Development

There are several hydrodynamic and dispersion models for the San Francisco Bay system, the first developmental area for this methodology (Chen and Orlob, 1975; Nelson and Lerseth, 1972; Water Resources Engineers, Inc., 1965). There has also been substantial documentation of bay sediment movements (Enstein and Krone, 1961; U.S. Army Corps of Engineers, 1975, Appendices F and I), and more study is currently under way at several locations.

As a result, the principal effort of this study is the ecological model development. It is desired to keep this model as simple as possible without losing the ability to track pollutant buildup, pollutant effects, and the impact on the ecosystem of those effects. Two types of ecological models are currently being considered, both based on a food-web submodel. As with the ecological model as a whole, the goal here is to reduce the number of taxon entries actually included in the food-web model as far as possible by generalizing the species and families included within each taxon entry. The limiting criteria tentatively planned for this simplification process are as follows:

1. All included species must occupy a similar position within the local food web (same sources, same predators).

2. All included species must display similar or complementary spatial or temporal distributions.

3. All included species must demonstrate similar uptake characteristics for all toxins modeled from each toxin source (food, water column, sediments).

4. Each taxon must represent a significant element within the bay ecosystem.

The desirability of this simplification process is rooted in this study's concept that an ecosystem is not an impact analysis end point but rather a transmission path of the impact flow.

INPUT/OUTPUT ECOLOGICAL MODEL

Two types of ecological model are currently being considered:

1. Input/output model (designed for direct compatibility with the rest of the full methodological submodels).

2. Dynamic model (using finite differences and differential equations to track the rapid variation in water quality and taxon populations common in an estuarine environment).

An I/O model concept is shown in Fig. 5. In actual operation mass transfer (indicated by an X) would be shown in a quantitative form derived from the mass balance of the food web. Direct pollutant and nutrient uptake from both sediments and the water column can be simultaneously entered. Environmental parameters (temperature, salinity, turbidity, etc.) can be entered as time-step negative mass

transfers into the taxa based on the local suboptimality of that parameter at a given time step and its negative effect on overall taxa biomass and taxa activity (respiration increases, feeding reduction, mortality increases, etc.). Once an initial steady-state condition matrix is created, perturbations from that equilibrium condition can be inserted into one or more system parameters, and their total impact on the ecosystem can be measured by techniques to be discussed later in this section.

I/O Model (direct effects)

	P1	P2	Z1	Z2	B1	B2	F1	F2	Export
Light	X	X							
Nutrients	X	X							
Temperature, etc.									
Pollutant 1		X	X				X	X	X
Pollutant 2	X				X	X			
P1			X	X					X
P2			X	X					X
Z1						X	X		X
Z2					X	X			X
B1						X			X
B2							X	X	X
F1									X
F2									X
Import			X		X			X	

Fig. 5. Ecological model 1.

The principal advantages of this model include the following:

1. An I/O analysis yields a numerical value for the relative impact of unit changes in each element on the entire ecosystem.

2. An I/O format for the ecological sector would be directly compatible with both the methodology and the format of the economic sector model and with the weighting system model. With this format, each element of the ecosystem could be assigned a single numerical coefficient reflecting the value to the local economy of the impact on the entire ecosystem of unit changes in that element from some initial steady-state condition caused directly by changes, or actions, in the local economy. This could be a powerful decision-making tool.

3. The I/O format can produce a good approximation of small changes from an initially modeled condition.

However, there are also four important limitations on the use of an I/O ecological model:

1. Spatial homogeneity of each species throughout the region modeled is assumed. An I/O model is not a point model, but rather an area model. Thus most subregional impact definition is lost. This is rarely critical if the entire I/O analysis is confined to a limited spatial area such as an individual estuary or segment of coastline, but it can prevent the application of the model on a large scale.

2. An I/O analysis is not particularly compatible with a time-step progression analysis. The I/O matrix cannot easily be revised and updated at each time step without loss of much of its meaning.

3. For the point in time established as the base, or initial, condition that is reflected in the initial model, all model parameters must be known. Taxa biomasses and internal pollutant concentration are the most critical of this set of required information; however, these are rarely, if ever, known for a large estuarine system like San Francisco Bay. It does not appear to be as much of a limitation outside the highly variable estuarine environment.

4. An I/O analysis is linear. This does not require that abiotic-biotic relationships or taxa pollutant uptake rates be linear; however, it does require that, once an initial-condition point on a curvilinear relationship has been established and put into the I/O matrix, changes from that condition be linear.

THE LINEARITY REQUIREMENT

Within the framework of this study the linearity requirement is much easier to live with than is normally supposed. Food-web consumptive transfers do tend toward linearity. With the addition of certain control criteria, the inclusion of non-linear abiotic-biotic transfer relationships with the I/O matrix can be limited to those that can be closely approximated by linear change. This limiting-factor criterion is diagrammatically illustrated in Fig. 6. The principle involved in the criterion is the analysis of the present, or initial, condition and each resulting abiotic-biotic relationship to determine (1) whether each biotic taxon and its abiotic-biotic relationships would be entered into the I/O matrix and (2) whether changes from this position could be linearly approximated by I/O procedures.

Fig. 6. Graphical representation of limiting-factor concept.

Figure 6 relates the most typical curvilinear relationship between deviation from optimal conditions for environmental parameters and for pollutant concentrations, and the resulting negative impact on taxon biomass. Although other characteristic curve shapes are possible, the limiting-factor analysis remains the same. Figure 6 identifies five zones within which the initial-condition relationship could lie. These zones can be defined as follows:

Zone 1 (maximum effect). In general, the maximum deleterious effect of any pollutant corresponds with taxon elimination. As a result, neither this taxon nor this abiotic-biotic relationship should appear in the I/O matrix, since the taxon will not be entered in the initial-condition food web.

Zone 2 (no effect). This corresponds closely with taxon optimum environmental conditions and with near-zero pollutant concentrations. Inclusion of these relationships in the matrix can be prevented by identification of environmental response and by setting an arbitrary minimum pollutant concentration for consideration. One possible approach is to tie this minimum to the known LD₅₀ levels for each taxon by using, for example, (LD₅₀)/1000 as a minimum concentration for consideration.

Zone 3 (small population). It is anticipated that pollutant populations and environmental parameter populations that fall within this range can be initially omitted through the taxon inclusion criteria, especially through criterion 4 (see page 6). If existing conditions are such that a given population has been so suppressed by the action of an existing pollu-

tant that the relationship between that pollutant and that taxon falls within this nonlinear range, then that population should be so small that it will not be included as a separate taxon. This taxon will then be included into some more general taxon where the nonlinear effects of this particular relationship should be minimized. Though this will not guarantee elimination of all such relationships, it will minimize both their number and their importance.

Zone 4 (minor effect). The only available means of excluding zone 4 from the linear I/O table is by careful selection of the pollutant concentrations and environmental parameter limits mentioned under zone 2. This selection will be based on the result of an ongoing literature search.

With these four zones essentially excluded, all relationships, or transfers, listed in the abiotic-biotic section of the ecosystem I/O model should fall within the fairly linear region labeled zone 5. It should also be noted that relationships within this region are those of prime concern. No single action or industry will create extremely large changes in the physical/chemical environmental quality in a large estuarine or marine system (such as San Francisco Bay, Long Island Sound, or Chesapeake Bay). This near-linear region is the area in which relatively small changes in total pollutant concentration will create the largest changes in the biotic community.

A flag system will have to be incorporated into the overall ecological model to compare the position of each physical/chemical pollutant parameter to its "allowable" range of values at each time step. Should any parameter transgress the bounds

of this linear range, all transfers based on that parameter will require appropriate modification or matrix exclusion, as appropriate.

NUMERICAL ADVANTAGES OF THE MODEL

Having established that linearity is an acceptable limitation over relatively small intervals of change even within a nonlinear system, such as a complex ecosystem, we can now discuss the numerical advantages of this model. Similar procedures, using one of the control methods discussed below, have been used in ecological modeling by Isard and his discussions (Isard, 1960, 1972) are referenced as a more thorough coverage of the basic numerical techniques.

Transfers from the supply (X_i) side of the ecological I/O matrix to the demand or consumer side (X_j) can be analyzed in three ways.

1. Transfers may be demand controlled. This type of transfer, which is the normal economic sector control mechanism, specifies that the mass of a transfer (x_{ij}) is proportional to the demand or to the biomass of the consumer taxon (X_j). Thus the analytical element of concern is the amount of transfer per unit consumer biomass ($a_{ij} = x_{ij}/X_j$). This type of transfer control is found ecologically only when food supplies are large in comparison to the consumer mass (as with a plankton "bloom").

2. Transfers may be supply controlled. The normal assumption of an ecological food web is that the mass of each species is food limited. This transfer control is then the basic ecological control of concern, and the appropriate analytical

element is the mass transfer (x_{ij}) per unit mass of food supply (X_i), or

$$a_{ij} = x_{ij}/X_i.$$

3. Transfer control may be unspecified in a near-steady-state condition. The amount of biomass gained by any taxon as a result of feeding is then directly proportional to the amount of food consumed. Thus in a steady state (or near steady state), with transfers x_{ij} held constant, the mass of each consumer taxon (X_j) will become proportional to the transfer mass itself. Here the element of concern is the consumer biomass per unit transfer, or $a_{ij} = X_j/x_{ij}$.

All previous work located used the first, or normal, economic control mechanism (Isard, 1972), and the seemingly more applicable ecological control mechanisms (types 2 and 3) appear to be conceptual innovations of this study.

Mathematically the matrix analysis based on any of these control mechanisms is identical, and the resulting equations are identical in form. What will change is the numerical value of the elements of the $\bar{A}$ matrix reflecting variations in system sensitivity to changes in the availability and demand of a given taxon with changes in the control mechanism of its transfers.

The fundamentals of this potential analysis are shown in Fig. 7. Here X_i can be defined as the biomass of each taxon at time step t and X_j as the biomass of each taxon at time step ($t + 1$). This latter definition is not entirely accurate, as taxon X_j assimilates into new biomass only a small fraction (about 10%) of its total consumption $\sum_i x_{ij}$. Therefore X_j in the I/O matrix literally represents the mass available to taxon X_j for conversion into

new taxon mass. Once this conversion has been completed, the resulting biomass becomes X_i for the subsequent time step.

The export_i term on Fig. 7 can be defined as the sum of all mass and energy leaving X_i and not being consumed by some other element X_j within the model. This term then includes advective export, mi-

gration, respiration, excretion, and natural mortality unless some or all of these terms are internalized within the model. The import_j term can similarly be defined as the sum of all mass and energy consumed by some element X_j within the model that does not come directly from some other element X_i within the model system.

With these definitions, X_i can be expressed as follows:

$$X_i = \sum_j x_{ij} + Y_i. \quad (1)$$

Substituting, we obtain

$$X_i = \sum_j X_j a_{ij} + Y_i, \quad (2a)$$

$$X_i = \sum_j X_j a_{ij} + Y_i, \quad (2b)$$

depending on the control mechanism used (i.e., depending on the definition of a_{ij}).

As discussed by Isard (1960), this can be expanded to

$$\bar{X} = \bar{X}\bar{A} + \bar{Y},$$

or

$$\bar{X} = (\bar{I} - \bar{A})^{-1} \bar{Y}, \quad (3)$$

where $(\bar{I} - \bar{A})^{-1}$ is called the inverse matrix and evaluates the impact of unit changes in either supply or demand of one element on the entire system.

The impact of unit changes in the availability of one or more system elements, which is the focus of this study, can now

Approach 1:

$$a_{ij} = \frac{x_{ij}}{X_j}, \quad a_{ij} = \frac{x_{ij}}{X_j}, \quad \text{or} \quad a_{ij} = \frac{X_j}{x_{ij}},$$

depending on transfer control, and

$$X_i = \sum_j X_j a_{ij} + Y_i \quad \text{or} \quad \sum_j \frac{X_j}{a_{ij}} + Y_i$$

as appropriate.

Approach 2:

For steady-state conditions, $X_i = X_j$ for $i = j$ and for the n th element

$$\sum_j x_{n,j} + Y_n = \sum_i x_{i,n} + Z_j$$

or

$$\sum_{i,j(i \neq j)} (x_{n,j} - x_{i,n}) = Z_n - Y_n.$$

Fig. 7. Input/output analysis methodology.

be evaluated as follows: impact of unit changes in $X_i \equiv \text{Imp}_i$,

$$\text{Imp}_i = \sum_j (i_{ij} - a_{ij})^{-1}. \quad (4)$$

The impact on an ecosystem of some external action is then

$$\begin{aligned} \text{impact} &= \sum_i \Delta X_i \text{Imp}_i \\ &= \sum_i \Delta X_i \sum_j (i_{ij} - a_{ij})^{-1}. \end{aligned}$$

Defining $\bar{M} = (\bar{I} - \bar{A})^{-1}$, this can be rewritten as

$$\text{impact} = \sum_i \Delta X_i \sum_j m_{ij}, \quad (5)$$

where ΔX_i is the magnitude of the initial change in the availability of each system element, X_i , as defined by the change in effluent flow and the first intersectoral transfer function.

The second analytical approach available assumes at least a temporary steady-state condition within the ecosystem (see Fig. 7). Under this condition, the taxon biomass will remain constant over any time interval and $X_i = X_j$ for $i = j$. We know that

$$X_i = \sum_j x_{ij} + Y_i + R_i$$

and

$$X_j = \sum_i x_{ij} + Z_j,$$

where R_i is energy export by respiration ($R_j = 0$, as no taxa except primary producers directly import energy, and this

energy term will be internalized). Hence an equality can be established for the n th element as

$$X_n^{\text{in}} \equiv X_j,$$

$$X_n^{\text{out}} \equiv X_i,$$

and

$$\sum_i X_{i,n} + Z_n = \sum_j x_{n,j} + Y_n + R_n. \quad (6)$$

Expanding, we obtain

$$\begin{aligned} (x_{1,n} + x_{2,n} + \dots + x_{m,n}) + Z_n \\ = (x_{n,1} + x_{n,2} + \dots + x_{n,m}) + Y_n + R_n, \end{aligned}$$

and on rearranging we find that

$$\begin{aligned} \sum_{i,j(\text{for } i=j)} (x_{n,j} - x_{i,n}) \\ = Z_n - Y_n - R_n. \end{aligned} \quad (7)$$

Now substituting for $a_{ij} \equiv X_j/x_{ij}$ for a steady-state system, we get

$$\sum_{i,j(\text{for } i=j)} \left(\frac{X_i}{a_{n,j}} - \frac{X_n}{a_{i,n}} \right) + R_n = Z_n - Y_n. \quad (8)$$

In this equation several noteworthy concepts are included:

1. The quantity $Z_n - Y_n$ is the net mass import of the n th element in the ecosystem. This gives an indication of which taxa tend to introduce new substances (such as recently released pollutants) into the local

ecosystem food web and which will tend to export such existing substances out of the local system.

2. The term $X_j/a_{n,j}$ measures the impact of unit changes in the mass transfer from n to the rest of the local ecosystem.

3. The term $X_n/a_{i,n}$ measures the impact of unit changes in the mass transfer into n from the rest of the local ecosystem.

4. The term

$$\sum_{i,j \text{ (for } i=j)} \left(\frac{X_i}{a_{n,j}} - \frac{X_n}{a_{i,n}} \right)$$

then measures the net system impact (or importance) of the n th element, including the importance to the rest of the ecosystem of transfers into and out of that element.

While both of the analytical models discussed above show potential value for elucidating the sensitivities of a system, the first is better able to express the total impact of an economic action and is also more compatible with the other elements (economic sector I/O matrix and weighting system) of this impact analysis concept.

Weighting System

The weighting-system model will be discussed next because of its direct design compatibility with the I/O ecological model. The purpose of any weighting system is to apply various temporal and spatial perspectives to the changes in resource availability identified by the ecological model. The use of these various temporal and spatial perspectives (short-term, long-term, bay segment, entire bay, California, or western United States) will allow full evaluation of the significance of identified resource changes. Long-term evaluations may be based on such parameters as community stability, resilience, changes in primary elemental cycling patterns, and changes in taxon diversity. Short-term impacts will be measured by the interaction of these resources with the economic sectors. The spatial zone of concern for this analysis will be defined by local economic boundaries. For San Francisco Bay, this is most of the nine-county area around the bay.

The weighting system designed for this analysis is shown on Fig. 1 as the final intersectional transfer for the impact flow pathway. Its purpose is to apply to the environmental impacts identified by the ecological model a value that can then be used as an input to the decision-making process. The value concept chosen is the value each element of the ecosystem obtains as a natural-resource input to the local economy. This evaluation can be accomplished by establishing a transfer matrix for marine natural resources to various economic sectors. This transfer matrix is identical with an I/O matrix, except that it records transfers in only one direction. While an I/O matrix reflects transfers from each sector to and from each other sector, a transfer matrix shows only transfers from one set of sectors to some other set without indicating the return flow.

For the purposes of this model, a transfer matrix is constructed showing mass

transfers from each element of the natural environment into each sector of the local economy. By using the demand-controlled-transfer mathematical techniques mentioned earlier, this matrix can be made to yield the relative impact of unit changes in the availability of each individual resource on the economy. In order to better represent a true value estimation, each economic sector is weighted by the total dollar value output of that sector. Thus the weights obtained reflect the relative dollar value of unit change in the availability of each resource. These weights can then be applied to changes in taxon availability and water quality revealed by the ecological model to obtain a relative dollar value for the impact on the natural environment of specified industries or actions within the local economy. The matrix format for this weighting system is shown in Fig. 8.

Fig. 8. Impact weights. Here $a_{j,k} = x_{j,k}/X_j$ = quantity of j th resource used per unit product of the k th economic sector.

Numerical operations with the addition of a weighting factor are as follows:

$$X_j = \sum_k x_{j,k} + Y_j = \sum_k X_k a_{j,k} + Y_j, \quad (9)$$

where

$$a_{j,k} = x_{j,k}/X_k,$$

$x_{j,k}$ = mass of resource j used in total production of product h ,

X_k = total resource consumption by the k th economic sector,

Y_j = amount of resource j not harvested,

X_j = total mass of resource j as calculated by the ecological model,

Y_k = nonnatural resource factor inputs to sector k .

This can be processed to the point where

$$\bar{X} = (\bar{I} - \bar{A})^{-1} \bar{Y}. \quad (10)$$

The value of the impact of unit changes in the availability of X_j can now be given as

$$\text{Imp}_j = \sum_k (k_{j,k} - a_{j,k})^{-1} w_k, \quad (11)$$

where w_k is the output dollar value or value added of sector k .

This impact can be defined as the value weight of the j th element in an ecological

model based on the value of that element to the local economy, or

$$w_j = \text{Imp}_j = \sum_k m_{j,k} w_k \quad (12)$$

This weight can now be inserted into Eq. (5) as a weight acting on $m_{i,j}$, so that the total value impact of an action in the economic sector can now be given by

$$\text{impact} = \sum_i \Delta X_i \sum_j m_{i,j} w_j,$$

or

$$\text{impact} = \sum_i \Delta X_i \sum_j m_{i,j} \sum_k m_{j,k} w_k, \quad (13)$$

where i denotes all elements (X_i) of the ecological model measured on the supply side of the matrix, j denotes all elements (X_j) of the ecological model measured on the demand side of the matrix and simultaneously all elements on the resource-

supply side of the weighting-system matrix, k denotes all economic sectors listed by SIC codes, and $m_{i,j}$, $m_{j,k}$, w_k , ΔX_i are as previously defined.

Equation (13) traces the impact flow and the value of that impact from the effluent in the economic sector through the environmental sector and back to the economic sector based on changes from an initial steady state. It is apparent that this type of predictive information has the potential to be a powerful decision-making tool.

It should be noted that by defining ΔX_i as the quality or availability of ecological element X_i after the economic activity under analysis minus that before the activity, net reductions in the quality or quantity result in numerically negative impact. Conversely, increases in resource availability result in positive impact. Thus this methodology for impact assessment will track both the relative magnitude and the direction of an impact.

Dynamic Ecological Model

The first three limitations listed for the I/O ecological model may prove to be prohibitively limiting when applied into an extremely dynamic estuarine environment. Environmental parameter gradients may be too steep and changes in gradient slope too rapid for application of the I/O model. Furthermore, taxon variation is much wider and the food web is generally less structured in an estuarine environment (Green, 1968; Lanff, 1967; McLusky, 1971; Perkins, 1974). As a result, a dynamic ecological model is being developed. Its position and function within

the overall assessment concept will be identical with those of the I/O model; however, the dynamic model will consist of a set of dynamic finite-difference equations that will be discussed in detail.

A schematic diagram of the dynamic model is shown in Fig. 9. Initial hydrological, dispersion and sediment-transport models are identical with those previously mentioned. Innovations included in this approach are the following:

1. Where taxon inclusion criteria allow, separation of larval and juvenile

Fig. 9. Ecological model for San Francisco estuary.

stages from adult stages with the inclusion of a recruitment term in the biomass equation. This allows differentiation of pollutant-uptake rates by larvae and by adults, differentiation of larval and adult reactions to given pollutant concentrations, and deletion from the feeding and

predation terms of the biomass equation of a "fudge factor" parameter used to characterize changes in feeding habits and rates as a function of mean taxon age.

2. Inclusion of local physical/chemical environmental tolerance/preference on local biomass. This influence will be felt pri-

marily in the "migration/advection" term in the biomass equation and secondarily in the mortality, respiration, and feeding terms.

3. Inclusion of other than lethal pollutant effects in other than the mortality term of the biomass equation. As indicated in Fig. 9, pollutant effects will be included in a number of the biomass-equation terms.

With these additions the dynamic model will consist of difference equations for primary production, detritus, and taxon biomass and differential equations to track pollutant concentrations within each taxon. This ecological model, as designed, cor-

rects all limitations listed for the I/O model, with the creation of only one new disadvantage. In most areas more initial data is required for the dynamic model, especially for model parametrization. It must be noted, however, that actual mass-transfer data for food-web links is not required. This information is generated by the biomass equation.

It is still a goal of this model-development effort to simplify each equation and term as far as possible and still provide adequate transmission of the impact flow. An attempt is being made to reduce and externalize each term not closely associated with impact transmission.

Tentative Dynamic Equations of State

The remainder of this paper is devoted to a discussion of the tentative form of each of the principal dynamic model equations. This developmental effort is neither finalized nor complete, and this presentation is designed primarily to indicate the direction it is anticipated these equations will take.

As stated, there will be four basic state equations in the dynamic ecological model. These are the biomass equation, internal pollutant-concentration equation, detritus equation, and phytoplankton or primary production equation, shown in their conceptual form in Fig. 10. Before the tentative equation form of each of these is detailed, the general subscript plan should be defined. Three subscripts can be applied to any term: a taxon-identification subscript, a time-step subscript, and a spatial, or node identification, subscript. Temporal subscripts

used are limited to either the past time step (t) or the time step being currently analyzed ($t + 1$). Three separate subscripts will be used in association with each of the spatial and taxon-identification system:

1. Taxon identification:

i indicates the taxon that is under analysis or whose biomass is currently being calculated.

j indicates a predator taxon--either all predators of taxon i or of all prey taxa k .

k indicates a food source, or prey, taxon--either all prey of taxon i or all prey of a general predator taxon j .

2. Spatial identification:

l indicates the node at which analysis is currently being conducted.

1. BIOMASS:

$$\text{Biomass}_{t+1} = \pm \text{recruitment} \pm \text{advection} + \text{biomass}_t (1 + \text{feeding growth} - \text{excretion} - \text{respiration} - \text{predation} - \text{mortality})$$

2. PRIMARY PRODUCTION:

$$\text{Biomass}(P)_{t+1} = \text{biomass}(P)_t (1 + \text{photosynthetic growth} \pm \text{advection} - \text{excretion} - \text{respiration} - \text{predation} - \text{mortality})$$

3. DETRITUS:

(a) As an external model element

$$\text{(b) Detritus}_{t+1} = \text{detritus}_t + \sum_i \{ \text{excretion}_i + \text{mortality}_i + \text{settling}_i \} + \text{net water column import} + \text{net sediment column import} - \text{decomposition} - \text{predation}$$

4. POLLUTANT CONCENTRATION:

$$\begin{aligned} \text{Total pollutant}_i \text{ in taxon } i = & \text{BIO}_{i,t} [C_{p,t} + (C_{p_{\text{water}}} u_{i_w} + C_{p_{\text{sed}}} u_{i_s} + C_{p_{\text{food}}} u_{i_f}) - \\ & \text{excretion}] - C_{p,i,t} (\text{bio loss}_i) - a [C_{p,i,t} (\text{out recruitment})] \\ & + C_{p,i,t} (\text{bio gain}) \end{aligned}$$

$$\text{Pollutant concentration} = (\text{total pollutant}_i \text{ in taxon } i) / (\text{biomass}_i)$$

Fig. 10. Equation summary for the dynamic ecological model.

m indicates all nodes from which nontidal flow flows toward node l.

n indicates all nodes to which nontidal flow flows from node l.

m may also be used to indicate all nodes connected to l when flow direction is immaterial.

Taxon identifiers j and k will also be used in association with the recruitment process. The taxon from which taxon i recruits is j, and k is the taxon that recruits from taxon i.

As examples of this system, $\text{BIO}_{i,t,l}$ is defined as the biomass of taxon i at time step t at node l, and $\text{BIO}_{j,t+1,m}$ is defined as the biomass of predator j at time step t + 1 at node m.

Subscripts may also be used to indicate the direction of an action. Thus

$$Q_{m \rightarrow l}$$

is defined as the mass flow rate from node m to node l, and

$w_{j \rightarrow k}$

is defined as the preference by predator j for taxon k as a food source.

Not all three subscripts need be included on each parameter. The identification of individual subscript as to taxon, temporal, or spatial definition should be self-evident in each application.

BIOMASS EQUATION

The terms included in the biomass equation are

$$\begin{aligned} \text{biomass}_{i,t+1} = & \text{biomass}_{i,t} \pm \text{recruitment} \\ & \pm \text{advection/migration} \\ & + \text{feeding} - \text{excretion} \\ & - \text{respiration} - \text{predation} \\ & - \text{mortality}. \end{aligned}$$

More specifically, all terms except recruitment and migration are based on specific, or unit mass, rates. Thus

$$\begin{aligned} \text{BIO}_{i,t+1} = & \pm \text{recruitment} \pm \hat{\text{advection}} / \\ & \text{migration} + \text{BIO}_{i,t} \\ & (1 + \hat{\text{feeding}} - \hat{\text{excretion}} \\ & - \hat{\text{respiration}} - \hat{\text{predation}} \\ & - \hat{\text{mortality}}), \end{aligned} \quad (14)$$

where $\hat{\text{feeding}}$ indicates the unit mass feeding rate.

This biomass equation is designed to be sufficiently general to allow application to all taxa except phytoplankton. Each term within this equation is discussed separately below.

Recruitment

Recruitment terms are based on historical year-class estimates, available field data, and laboratory data on reproduction.

Based on such data, a basic recruitment equation is

$$\text{recruitment}_i = (Rr_i) (\text{BIO}_{j,t=t_0}), \quad (15)$$

where Rr_i is the daily recruitment rate for taxon i measured as the recruited mass per unit of "parent" taxon biomass per day. This may be a constant daily rate or may follow a Gaussian or some other distribution, depending on the taxon in question. The other term in Eq. (15), $\text{BIO}_{j,t=t_0}$, is the biomass of taxon j from which taxon i recruits at time t_0 , defined as the time step corresponding with the start of recruitment or spawning season, whichever is applicable to the recruitment process in question.

The use of parent biomass on the initial time step of recruitment may appear somewhat simplistic. However, the resultant recruitment biomass errors should be small and, more important, available data relates original standing stock to biomass of resulting larval or year-class entrants. Thus the form presented here allows maximum utilization of existing data.

Three external factors can modify this relationship: temperature, pollutant concentration, and "parent" taxon biomass.

Temperature - Long-term (seasonal) temperature regime changes (such as at the outfall of a power plant) will affect recruitment (Clark and Browell, 1973). The first effect will be to reduce the time interval between spawning and recruitment; the second effect will be to reduce initial larval survival as a result of early recruitment. If temperature-dependent time

controls can be used for these reproductive activities, then the temperature effect of initially reduced survival could be disregarded. This second effect is much smaller than either the first temperature effect or the effect of increased predation caused by temperature-induced early arrival of a specific larval taxon. This increased predation will be automatically picked up by predation terms in the biomass equation if temperature control of the time of recruitment can be included.

Pollutant Effects - Pollutant effects will be considered primarily on the spawning and larval recruitment term. Thus effects on reduction of spawning-adult fecundity, effects of increased pollutant concentration in eggs, and resultant decreased hatch rate will all be incorporated into a single effect term applied to the larval recruitment term. Secondly, pollutant effects on larval molting success will be considered. The exact form of this relationship has not yet been determined and will be based on an extensive literature search.

Population Effects - When data for local taxon-carrying capacity are known, a population-dependent term based on that figure can be inserted. The effect of this term has been well established (Park et al., 1974; Shugart et al., 1974). Large parent populations result in reduced reproduction rates. Without analyzing the basis for this reduction, we can incorporate it into the larval recruitment process--the only recruitment affected by this population phenomenon. The resulting form of this equation normally presented is (Park et al., 1974)

$$\text{reduced recruitment}_i = b_i \left(\frac{K_{c,j} - \text{BIO}_{j,t=t_0}}{K_{c,j}} \right),$$

where b_i is a constant, dependent on the characteristics of the taxon involved and $K_{c,j}$ is the local carrying capacity of the environment for taxon j from which taxon i recruits.

However, the functional shape of this expression is applicable only for $\text{BIO}_j > \text{BIO}_j^*$ (where BIO_j^* is the minimum population level for these population-density effects to be felt). The critical population is then that portion of the total taxon population in excess of BIO_j^* . Thus a more representative equational form is

recruitment reduction factor into taxon i

$$\begin{aligned} &= 1 \text{ for } \text{BIO}_{j,t=t_0} < \text{BIO}_j^*, \\ &= b_i \left(\frac{K_{c,j} - \text{BIO}_{j,t=t_0}}{K_{c,j}} \right) \end{aligned} \quad (16)$$

for $\text{BIO}_{j,t=t_0} > \text{BIO}_j^*$.

In this equational form it is critical that the parameters $K_{c,j}$ and BIO_j^* be known. However, for the marine/estuarine environment these terms have not been calculated beyond primary process levels. Furthermore, the terms are neither spatially nor temporally constant as a result of the variability of an estuarine environment.

This study will therefore use the equational form

recruitment reduction into taxon i

$$= A_i \exp \left(- \frac{\text{BIO}_i^2}{\text{BIO}_{j_0}^2} \right), \quad (17)$$

where BIO_{j_0} represents a constant popula-

tion level (the half-saturation constant) that with the constant A will be determined by parametrization of existing data.

This function more closely mirrors the natural functional form over the full range of BIO_j . Since these population effects are felt on larval recruitment only, a coefficient (b_i) must be inserted to reduce this term to unity in the recruitment expression for nonlarval stages.

Since the recruitment process involves mass transfer from one taxon to another, each taxon recruited from must be assessed a mass loss during the appropriate periods (e.g., spawning seasons for the adult-to-larval recruitment process). This mass loss must be equal to or larger than the mass recruited into the recruiting taxon to account for mass released from one taxon (such as portions of eggs not wholly consumed, eggs not hatched, eggs consumed by predators, energy losses during hatching and incubation) and not accepted as new biomass into the appropriate receiving taxon. In the case of most spawning adults, and especially for some benthics, this additional loss is very large (Fillice, 1958; Altman and Dittmer, 1962; Park et al., 1974). With most larvae molting into adults, the additional loss is small or negligible. This loss can be estimated by calculating the mass recruited into the taxon recruiting from the taxon in question multiplied by a taxon specific additional loss factor. Equationally, this loss per time period, or per day, is

$$\text{loss}_i = \frac{Rr_{i \rightarrow k} S_k L_i}{S_i}, \quad (18)$$

where $Rr_{i \rightarrow k}$ = daily recruitment rate by

k from i during k's recruitment season, S_k is the length (in days) of the recruitment season of taxon k, S_i is the length of spawning season of taxon i, and L_i is a taxon-specific additional spawning loss coefficient, approximately unity for adult recruitment stages and greater than unity for larval recruitment.

The final recruitment term of the biomass equation is as follows for taxon i:

$$\begin{aligned} \text{Recruitment} = & Z_1 (f_{\Sigma p}) (Rr_{j+1}) (BIO_{j,t=\tau_0}) \\ & \times b_i A_i \exp\left(-\frac{BIO_j^2}{BIO_{j0}^2}\right) \\ & - Z_2 \left(\frac{L_i Rr_{i \rightarrow k} S_k}{S_i}\right), \quad (19) \end{aligned}$$

where Z_1 and Z_2 are temperature-dependent timing functions and are equal to unity if recruitment into or out of taxon i, respectively, is ongoing and equal to zero if not. Mean daily temperature levels will be used to modify the number of days between a shift of Z_1 or Z_2 from 0 to 1 or from 1 to 0. The coefficient b_i in Eq. (19) is defined as

$$b_i = A_i^{-1} \exp\left(+\frac{BIO_j^2}{BIO_{j0}^2}\right)$$

for adult-stage recruitment and

$$b_i = 1$$

for larval-stage recruitment.

Feeding

Under the assumption and limitations defined for the I/O model, the mass trans-

fer from the i th taxon to the j th taxon (feeding by j on i) is represented by x_{ij} , with X_i and X_j representing the standing stock or the biomass of each of these taxa, respectively. It was further shown that, if X_i represents a nonlimiting food supply for j and if the demand for X_i by X_j was unencumbered, or nonelastic (i.e., demand by any one organism within X_j does not affect the ability of other organisms to fulfill their demand for X_i), then the transfer x_{ij} was linearly proportional to X_j and a meaningful term, a_{ij} , would be established as

$$a_{ij} = \frac{x_{ij}}{X_j} \equiv \frac{\text{Biomass}_{i \rightarrow j}}{\text{Biomass}_j},$$

with the total demand for food, or total feeding, by $X_j = \sum_i a_{ij} \text{BIO}_j$. This amount of feeding represents an optimum, or maximum, amount of feeding that X_j can perform. Furthermore, $\sum_i a_{ij}$ can be called the maximum feeding rate (FR_j) per unit biomass of j , so that

$$\text{feeding}_j = \text{FR}_j \text{BIO}_j.$$

To generalize away from this ideal feeding situation, factors must be included in the equation to account for suboptimal environmental feeding conditions. Thus

$$\text{feeding}_j = (\text{FR}_j) (\text{BIO}_j) (f_{\Sigma p}) (f_{\Sigma \text{env}}) \times (f_{\text{BIO}_j}) (f_{\text{BIO}_i}), \quad (20)$$

where $f_{\Sigma p}$ is the effect on feeding of pollutant concentration present in taxon j , $f_{\Sigma \text{env}}$ is the effect of a suboptimal envi-

ronment, f_{BIO_i} is the effect of a limited food supply, f_{BIO_j} is the effect of encumbered feeding.

Analyzing these in reverse order, it has been well established that large feeding populations reduce unit mass feeding regardless of food-supply availability (Park et al., 1974; De Angelis, 1975; Fox, 1975). This may be a result of increased cannibalism or of physical interference. However, the phenomenon definitely exists. The general functional shape of this effect is shown in Fig. 11. The equation form of this graph is

$$\text{Feeding} = x_{ij} = A_{j+1} \exp\left(-\frac{\text{BIO}_j^2}{\text{BIO}_{j0}^2}\right)$$

Differing mathematical forms of the phenomenon have been based on the "carry capacity" of the local environment for a given taxon. However, this parameter has not been identified for the widely varying estuarine environment. Half-saturation constants--or that population size for which unit mass feeding is reduced to one-half of the maximum feeding rate--have

Fig. 11. Dependency of unit feeding rate on taxon biomass.

been established for a number of species and are more easily obtainable by direct experimentation (Chen and Orlob, 1975).

The parameters $A_{j \rightarrow i}$ and $BIO_{j,0}$ must be determined experimentally for each feeding taxon and feeding link.

The effect of a limited food supply is to limit total feeding for small-food-supply biomasses. Complicating this relationship is the fact that the estuarine food web is very loosely structured, each predator having a variety of potential food sources. The general effect of food-supply size on total feeding is shown in Fig. 12.

Fig. 12. The relationship between food-supply biomass and predator feeding.

This relationship can be expressed as (Isaacs, 1972)

$$\text{feeding}_j = \sum_k \left(\frac{BIO_{j \rightarrow k} w_{j \rightarrow k}}{C + \sum_k BIO_{j \rightarrow k} w_{j \rightarrow k}} \right), \quad (21)$$

where $BIO_{j \rightarrow k}$ is the biomass of the k th food source or prey for predator j , C is a constant (may be the half-saturation constant for X_j feeding on X_i), and $w_{j \rightarrow k}$ is a parameter that represents the predator (j) preference for, and ability to catch, food source k . Numerically it is the relative amount of k that would be consumed by a unit mass of j over some specified time period

if j were simultaneously presented with an equal biomass of each potential food source (O'Neill, 1969).

If the feeding term is now divided by BIO_j to present feeding per unit biomass of j , we have, for feeding by j th predator on all prey:

$$\begin{aligned} \text{unit feeding}_j &\equiv \text{feeding}_j / BIO_j \\ &= (FR_j) \left[A_j \exp \left(- \frac{BIO_j^2}{BIO_{j,0}^2} \right) \right] \\ &\times \left(\frac{\sum_k \frac{BIO_{j \rightarrow k} w_{j \rightarrow k}}{C + \sum_k BIO_{j \rightarrow k} w_{j \rightarrow k}}}{\sum_k \frac{BIO_{j \rightarrow k} w_{j \rightarrow k}}{C + \sum_k BIO_{j \rightarrow k} w_{j \rightarrow k}}} \right) \\ &\times (f_{\Sigma_p}) (f_{\Sigma_{env}}). \quad (22) \end{aligned}$$

The $f_{\Sigma_{env}}$ term can be expanded to

$$f_{\Sigma_{env}} = f(\text{temperature, salinity, dissolved oxygen, turbidity, current, pH}). \quad (23)$$

Two general functional relationships may be used to characterize the effect on feeding of each of these environmental parameters. These are illustrated in Fig. 13.

Fig. 13. Generalized environmental parameter modification of unit feeding.

The general equational form of each of these relationships is easily established. However, no additional work is anticipated on defining which of the above mentioned environmental parameters will be included, or on parametrization of the various constants associated with the mathematical form of these relationships, until specific areas and seasons of concern have been defined (see Fig. 4). At that time an appropriate effort can be made to define the physical environmental regions and abiotic-biotic relationships associated with it.

Finally, $f_{\Sigma P}$, or $f(P_1, P_2, \dots, P_n)$ has an effect on feeding for each $f(P_i)$ similar to that defined for turbidity and current. Again, no additional effort will be expended on this term until "pollutants of concern" have been defined by the hydrodynamic, dispersion, and sediment-transport models and by an extensive literature search on pollutant uptake and effects.

With feeding thus defined, the addition of biomass into the i th taxon can be defined as

$$\text{unit increased biomass } i = \mu_i (\text{feeding}_i), \quad (24)$$

where μ_i is the assimilation rate of mass consumed to resultant biomass increase. The value of μ_i varies between about 7 and about 15% for most marine and estuarine species.

Thus the feeding term for the i th taxon in the biomass equation can be summarized as follows:

unit increased biomass i

$$= \mu_i \left\{ (FR_i) \left[A_i \exp \left(- \frac{BIO_i^2}{BIO_{i0}^2} \right) \right] \right\}$$

$$\times \sum_k \frac{BIO_{i+k} w_{i+k}}{C + \sum_k BIO_{i+k} w_{i+k}} (f_{\Sigma P})(f_{\Sigma env}) \quad (25)$$

Advection and Migration

Two separate terms are used to define change of taxon biomass at any given node due to biomass flow across nodal boundaries: advection and migration. Advection is involuntary movement as a result of advective current flow. Migration is voluntary self-induced movement from one node to another. Advection requires that organisms float but cannot swim; migration requires a swimming or crawling ability. These two types of biomass redistribution would seem to be mutually exclusive. There are, however, a large group of organisms (including many larval stages, zooplankton, and some benthics) that can swim but not well enough to overcome many advective current flows. Thus their movement is a function of both choice and current flow.

Advection - The advection term is a simple nodal mass and flow balance:

$$\Delta BIO_{i,t+1,l} = \left[\sum_m (\rho_{i,t,m} Q_{m \rightarrow l}) (f_{i,m \rightarrow l}) - \sum_m (\rho_{i,t,l} Q_{l \rightarrow m}) (f_{i,l \rightarrow m}) \right], \quad (26)$$

The quantity ρ_i is the density of taxon i , and $Q_{m \rightarrow l}$ is the net nonfidal mass flow rate from node m to node l at time t . These "link" flow rates are a normal parameter already generated by the hydrodynamic program. The last term in Eq. (26), $f_{i,l \rightarrow m}$, is a dependency factor of

taxon i on current movement along link ℓ to n .

This factor is current velocity dependent for some taxa (i.e., those that are partially dependent on current movements for migration). It is zero for sessile taxa, unity for planktonic taxa with no swimming ability, and $(1 > f_i \geq 0)$ for all other taxa.

Gamefish, commercial fish, and commercial crustaceans will probably be assigned $f_i = 0$, even though the current does have some effect on their movement (Perkins, 1974).

Migration - The migration term will be based on the form of human migration used in regional economics (Isard, 1960):

$$\text{migration}_{i,m \rightarrow \ell} = \frac{\text{population}_{i,m}}{\text{distance}_{m \rightarrow \ell}} \quad (\text{desirability}_{\ell}), \quad (27)$$

so that net migration between two nodes, m and ℓ , is

$$\text{net migration}_i = \frac{(\text{BIO}_{i,m})(\text{desirability}_{\ell})}{\text{distance}_{m \rightarrow \ell}} - \frac{(\text{BIO}_{i,\ell})(\text{desirability}_m)}{\text{distance}_{\ell \rightarrow m}} \quad (28)$$

Applying this equation to the nodal/link system being used in this model, in which all link lengths are known, the biomass of taxon i at time t is known for each node, the net migration into node ℓ is defined as $\text{migration}_{i,t+1,\ell}$, and where m denotes all nodes linked to ℓ , we obtain

$\text{migration}_{i,t+1,\ell}$

$$= \sum_m \left[\frac{(\text{BIO}_{i,t,m})(Z_{i,\ell}) - (\text{BIO}_{i,t,\ell})(Z_{i,m})}{\text{distance}_{m \rightarrow \ell}} \right] (1 - f_{i,m \rightarrow \ell}), \quad (29)$$

where $Z_{i,\ell}$ is the desirability to taxon i of migrating to node ℓ and $(1 - f_{i,m \rightarrow \ell})$ is that part of the movement by taxon i that is not controlled by advective flow along link $m \rightarrow \ell$ or that part of its movement that is controlled by individual choice. It has been established, especially for pelagics, that even minor migrational movements are not totally random in nature but have some net directionality (Harden Jones, 1968). Thus the concept of "choice" does have definite meaning here even when applied to feeding movements.

The term $Z_{i,\ell}$ requires additional explanation. It is anticipated that this term will be a function of environmental parameters, pollutant concentration, and food supply. If one or more of these factors are more desirable (closer to optimum for the taxon) at node ℓ than at node m , a migration will be induced for taxon i from m to ℓ that is proportional to the increased desirability of ℓ . The term Z_i is expanded as follows:

$$Z_i = Z(\text{temperature, salinity, turbidity, food supply, } \Sigma p) \quad (30)$$

Each of these five parameters, varying between 0 and 1, defines the relative desirability of a given node for that one environmental parameter. Their product is $Z_{i,\ell}$. The functional form of the relationship between node desirability and each of

these parameters is the same as that between feeding and the parameters discussed in the preceding section on feeding. Their graphical form and functional range are shown in Fig. 14.

Fig. 14. Generalized relationship between Z_i and various environmental factors. (C_p denotes pollutant concentration for a given pollutant p .)

Using the equational forms of these relationships listed in the section on feeding, we obtain

$$Z_{i,l} = \left(\frac{\sum_k \text{BIO}_{i \rightarrow k} w_{i \rightarrow k}}{C + \sum_k \text{BIO}_{i \rightarrow k} w_{i \rightarrow k}} \right)^{b_f} \times \left[\prod_i A_i \exp \left(- \frac{C_{p,i}^2}{C_{p,i,0}^2} \right) \right]^{b_p} \times \left\{ \prod_i A_i \exp \left[- \frac{(\text{Env}_{\text{opt}} - \text{Env}_i)^2}{(\text{Env}_{\text{opt}} - \text{Env}_{i,0})^2} \right] \right\}^{b_{\text{env}}}, \quad (31)$$

where b_f , b_p , and b_{env} are the weighting factors for the relative importance of food

supply, pollutant concentration, and environmental quality, respectively. A minor error is potentially introduced here by assuming that temperature and salinity effects are symmetrical about the parameter optimum condition. Should this error prove excessive, the equational form can be skewed.

The distance term, also needs further definition. In order to maintain units conceptually compatible with the rest of the biomass equation, this "distance" will be measured in time units. Thus d will be measured in units of days, and

$$d_{m \rightarrow l} = \frac{\text{length of link } m \text{ to } l \text{ (feet)}}{\bar{u}_{m \rightarrow l}}, \quad (32)$$

where $\bar{u}_{m \rightarrow l}$ is the nontidal advective current over the link $m \rightarrow l$ measured in feet per day. The advection and migration term can now be summarized as follows:

net change in biomass $_{i,t+1,l}$

$$= \left\{ \left[\sum_m (\rho_{i,m} Q_{m \rightarrow l}) (f_{i,m \rightarrow l}) - \sum_n (\rho_{i,l} Q_{l \rightarrow n}) (f_{i,l \rightarrow n}) \right] + (1 - f_{i,m \rightarrow l}) \times \left[\sum_m \frac{\text{BIO}_{i,m} Z_{i,l} - \text{BIO}_{i,l} Z_{i,m}}{d_{m \rightarrow l}} \right] \right\}, \quad (33)$$

where $Z_{i,l}$ is given by Eq. (31).

Excretion

For the purposes of this study excretion is defined as all mass that is eaten and does not become new taxon biomass. Thus excretion can be written as

$$\text{excretion}_i = (1 - \mu_i)(\text{feeding}), \quad (34)$$

where u_i and feeding are as defined in the section on feeding.

This simplified view of excretion and u_i ignores both additional losses in the form of energy required for digestion and utilization and the form of the excreted matter (Park, 1974). In a more rigorous treatment, u_i would normally represent the percentage of food ingested (and would be larger than the u_i used here). Respiration rates would then be increased as a function of ingestion to reflect digestive and utilization processes, and excretion would be reduced by this same amount. This more rigorous approach is not being taken here for two reasons:

1. Ease of data acquisition. The u_i used here is far easier to determine experimentally and is already available for many species.

2. No error is generated in the biomass equation as a direct result of this simplification. If the energy losses being ignored here are represented collectively as M_e , conversion to the more detailed system would be as follows:

$$b_{i, \text{detailed}} = b_i + M_e,$$

and

$$\text{respiration}_{i, \text{detailed}} = R_i + M_e,$$

where u_i is as included in the feeding term. Since the biomass equation includes the terms (+ feeding) and (- respiration), the M_e term is canceled out. An error is generated here as an overestimation of excretory mass. Should this generate significant additional errors (as overestimation of detritus food supply), a constant fac-

tor can be applied to excretion to reflect these energy losses, and

$$\text{excretion}_i = C_i(1 - u_i)(\text{feeding}_i). \quad (35)$$

Respiration

As indicated in the preceding section, the definition of respiration used here is a somewhat simplified one. Respiration is taken to depend on temperature only, so that

$$R_i = \hat{r}_{i, T_0} \theta_i^{(T - T_0)}, \quad (36)$$

where $\hat{r}_{i, T_0}$ is the specific respiration rate at temperature T_0 (normally taken between 18 and 20°C), θ is the taxon-dependent temperature coefficient ranging from 1.02 to 1.06 (Chen and Orlob, 1975), and T is the ambient water-column temperature.

Predation

While feeding is a measure of a given predator taxon's consumption of a number of separate prey taxa, natural predation is a measure of the consumption of a given taxon by a number of separate predator taxa. More specifically, it is the sum of the portion of each predator taxon's total feeding that consists of a given prey species, or

$$\text{predation on } i = \sum (\text{total predation by each predator taxon } j) \\ (\text{percent of each predator's consumption representing taxon } i).$$

Under the discussion of feeding, an expression was developed to describe total feeding by any taxon. Also in that section

there was developed an expression for the percentage of a predator taxon's total diet comprised by a given taxon. From these expressions we obtain

$$\begin{aligned} \text{predation on } i = & \sum_j \left(\frac{\text{BIO}_i w_{j \rightarrow i}}{\sum_k \text{BIO}_{j \rightarrow k} w_{j \rightarrow k}} \right) \\ & \times (\text{FR}_j) \left[A_j \exp \left(- \frac{\text{BIO}_j^2}{\text{BIO}_{j0}^2} \right) \right] \\ & \times \left(\sum_k \frac{\text{BIO}_{j \rightarrow k} w_{j \rightarrow k}}{C + \sum_k \text{BIO}_{j \rightarrow k} w_{j \rightarrow k}} \right) \\ & \times (f_{\text{LP} \rightarrow j}) (f_{\text{LEnv} \rightarrow j}) \cdot (37) \end{aligned}$$

Total predation equals natural predation plus human harvest. Human harvest can be included in any of several ways as follows:

1. As an externally defined constant based on recorded fish landings.
2. As an exogenous variable defined for any taxon in any given manner to allow management-decision control of fisheries.
3. As a percent of total available taxon biomass based on historical records.

Since this study does not now include any fisheries-management objectives, option 2 will not be considered. Option 3 requires additional data on actual game and commercial species biomass. Although these data are collected for a few extremely important species (e.g., striped bass) at the state level in California and stored for computer analysis, it is not generally known on a year-by-year basis for all harvested species. Thus option 1 will be used initially, but the ability will be retained to shift to a size-dependent expression involving mass and year class should the nec-

essary data become available. A parameter of legality and marketability (f_l) will be used to modify human harvest. This term will range from 0 to 1 based on pollutant and toxin concentrations within each harvested taxon and will reflect both reduction in marketability for such reasons as tainting or higher oil and grease content, and legal closures of certain fisheries (e.g., clam or oyster) when pollutant-concentration health limits are exceeded. Normally a legal concentration of pollutant is exceeded before the species is naturally unmarketable.

In assessing the parameters associated with the mathematical form of this relationship (shown in Fig. 15), several economic simplifications have been made. Specifically, demand elasticity and product substitution rates will be ignored. Parametrization of this function will be based largely on gamefish tainting tests conducted by the California State Department of Fish and Game (Kopperdahl, 1971; Hazel et al., 1971).

Fig. 15. Pollutant modification of human harvest.

Thus human harvest can be expressed as

$$\text{harvest}_i = (f_l)(P_h), \quad (38)$$

where P_h is the human-harvest predation and may become a biomass-dependent term. Total predation is thus equal to $P_i + f_{l,i} P_{h,i}$, where P_i is given by Eq. (37).

Mortality

Mortality is the nonpredation loss for any taxon. It is considered here as a dependent function of the natural mortality rate, pollutant and toxin concentration, temperature, and feeding rate. Temperature is included here only for analysis of thermal-discharge effects. Temperatures within the natural estuarine system do not tend to approach lethal limits (Pearson et al., 1965, 1967; Kaiser Engineers, 1969). Population size is not included as a determinant of mortality since it is felt that the effects of overcrowding are found primarily in association with reduced potential unit feeding. Thus resultant increased mortality can be related more successfully to a critical minimum feeding rate than to the population size, which is only one determinant of feeding rate. Salinity has not been included, even though many species, especially microbenthos and plankton, have rather sharp, well-defined limits on salinity tolerance. This exclusion is based on the taxon-inclusion criteria listed on page 6, especially on criterion 2. It is anticipated that planktonic species will be lumped into a single listing over wide estuarine segments or, possibly, over the entire estuary. The same is true for microbenthic species. Thus a taxon consisting of spatially integrated salinity-sensitive species will have a similar representation at any salinity level since an integration across the horizontal spatial dimension of an estuary is also an integration over the full range of

potential estuarine salinity levels. The probable result of this is that natural mortality levels (α_i) for these taxa will be somewhat higher than indicated by the mortality levels of each individual species. This rise will account for salinity-induced kills resulting from advective migration of a species out of a desired salinity range.

The functional relationship between mortality and the three independent variables within the mortality term are shown in Fig. 16. Relative normal bay limits (Pearson et al., 1967) for temperature are indicated relative to the mortality rate

Fig. 16. Generalized influence of temperature, feeding rate, and pollutant concentration on taxon unit mortality.

curve to show the absence of its influence on mortality under normal conditions. Thermal-discharge influence is depicted to identify the portion of the temperature-mortality curve of concern. Though each taxon has different temperature limits and temperature sensitivities, the relationships depicted are typical of many estuarine species (Green, 1968; McLusky, 1971; Perkins, 1974).

It is currently anticipated that the effects of each of these influences will be linearly additive. This does not mean that potential synergistic effects in the presence of more than one pollutant are discounted--only that the total pollutant-induced kill, the temperature-induced kill, and starvation kills will be additive. Even this, in fact, may not be true, and low feeding rates may leave an organism more susceptible to pollutant toxicity. However, at this time the general form of the mortality term is

$$\begin{aligned} \text{mortality}_i = \alpha_i & \left\{ 1 + \prod_j A_{P_{j+1}} \right. \\ & \times \exp \left[- \frac{(C_{P_{\max+1}} - C_{P_i})^2}{(C_{P_{\max+1}} - C_{P_{i0}})^2} \right] \\ & + A_{F_i} \exp \left(- \frac{F_i^2}{F_{i0}^2} \right) \\ & \left. + A_{T_i} \exp \left[- \frac{(T_{i,\text{opt}} - T_i)^2}{(T_{i,\text{opt}} - T_{i0})^2} \right] \right\}, \end{aligned} \quad (39)$$

where F is the unit mass feeding rate, C_{P_0} and T_0 are the 96-hour LD_{50} levels for

taxon i , and $C_{P_{\max+1}}$ is the concentration of pollutant j for the 96-hour LD_{100} for taxon i .

The entire biomass equation is shown in Fig. 17.

PRIMARY PRODUCTION

Within the estuarine environment, primary production is essentially limited to phytoplankton production. Major exceptions, such as eel-grass beds, are not significantly present in San Francisco Bay except along the northern fringe marshes (Pearson et al., 1966; Kaiser Engineers, 1969), which will be kept external to the model and treated as import terms. A basic equation for phytoplankton biomass is similar to the general biomass equation and can be expressed as follows:

$$\begin{aligned} BIOP_{i,t+1,l} = BIOP_{i,t,l} & \left(1 + \hat{\mu}_i f_{\Sigma P} f_{\Sigma env} \right. \\ & - \sum \text{predation} - R_i f_{temp} \\ & + \text{advection}_i - \text{excretion}_i \\ & \left. - \text{mortality}_i f_{\Sigma P} f_{temp} \right). \end{aligned} \quad (40)$$

The only term not represented here is a recruitment term. Obviously, primary producers will not recruit either into or out of a given taxon. Provision has been made in this equation for more than one phytoplankton taxon, as it is most probable that lumping of all planktonic species into a single taxon will not be possible.

In the primary production equation, the principal term is the growth term $(\hat{\mu}_i f_{\Sigma P} f_{\Sigma env})$, where $\hat{\mu}_i$ is defined as the specific maximum growth rate for that taxon.

$$\begin{aligned}
\text{BIO}_{i,t+1,l} = & \underbrace{\left[Z_{i,l} (f_{\text{Ep}}) (R_{j \rightarrow i}) (\text{BIO}_{j,t=t_0}) b_i A_i \exp \left(- \frac{\text{BIO}_{i,l}^2}{\text{BIO}_{j_0}^2} \right) - Z_{i,l} \left(\frac{L_i R_{i \rightarrow k} S_k}{S_i} \right) \right]}_{\text{recruitment}} \\
& + \underbrace{\left\{ \left[\sum_m (\alpha_{i,m} Q_{m \rightarrow i}) (f_{i,m \rightarrow i}) - \sum_n (\alpha_{i,n} Q_{i \rightarrow n}) (f_{i,i \rightarrow n}) \right] + (1 - f_{i,m \rightarrow i}) \left[\sum_n \frac{\text{BIO}_{i,m} Z_{i,l} - \text{BIO}_{i,n} Z_{i,m}}{d_{m \rightarrow i}} \right] \right\}}_{\text{advection/migration}} \\
& + \underbrace{\text{BIO}_{i,t,l} \left(1 + \mu_i \left\{ (FR_i) \left[A_i \exp \left(- \frac{\text{BIO}_{i,l}^2}{\text{BIO}_{j_0}^2} \right) \right] \sum_k \frac{\text{BIO}_{i \rightarrow k} w_{i \rightarrow k}}{C + \sum_k \text{BIO}_{i \rightarrow k} w_{i \rightarrow k}} (f_{\text{Ep} \rightarrow i}) (f_{\text{Env} \rightarrow i}) \right\} \right)}_{\text{feeding}} \\
& - \underbrace{\left((1 - \mu_i) \left\{ (FR_i) \left[A_i \exp \left(- \frac{\text{BIO}_{i,l}^2}{\text{BIO}_{j_0}^2} \right) \right] \left[\left(\sum_k \frac{\text{BIO}_{i \rightarrow k} w_{i \rightarrow k}}{C + \sum_k \text{BIO}_{i \rightarrow k} w_{i \rightarrow k}} (f_{\text{Ep} \rightarrow i}) (f_{\text{Env} \rightarrow i}) \right) \right] \right\} \right)}_{\text{excretion}} - \underbrace{\left[\hat{e}_{i,t_0} \theta_i (T - T_0) \right]}_{\text{respiration}} \\
& - \underbrace{\left[\sum_j \left(\left(\frac{\text{BIO}_{i,j} w_{j \rightarrow i}}{\sum_k \text{BIO}_{j \rightarrow k} w_{j \rightarrow k}} \right) (FR_j) \left[A_j \exp \left(- \frac{\text{BIO}_{j,l}^2}{\text{BIO}_{j_0}^2} \right) \right] \left(\sum_k \frac{\text{BIO}_{j \rightarrow k} w_{j \rightarrow k}}{C + \sum_k \text{BIO}_{j \rightarrow k} w_{j \rightarrow k}} (f_{\text{Ep} \rightarrow j}) (f_{\text{Env} \rightarrow j}) \right) \right] \right)}_{\text{predation}} + f_{i,l} \text{Ph}_i \\
& - \underbrace{\left(\alpha_i \left[1 + \prod_j A_{p_{j \rightarrow i}} \exp \left[- \frac{(C_{p_{\text{max} \rightarrow i}} - C_{p_i})^2}{(C_{p_{\text{max} \rightarrow i}} - C_{p_{i_0}})^2} \right] + A_{F_i} \exp \left(- \frac{f_i^2}{f_{i_0}^2} \right) + A_{T_i} \exp \left[- \frac{(T_{i,\text{opt}} - T)^2}{(T_{i,\text{opt}} - T_{i_0})^2} \right] \right] \right)}_{\text{mortality}}
\end{aligned}$$

where $Z_{i,l}$ is defined as

$$Z_{i,l} = \left(\frac{\sum_k \text{BIO}_{i \rightarrow k} w_{i \rightarrow k}}{C + \sum_k \text{BIO}_{i \rightarrow k} w_{i \rightarrow k}} \right)^{b_f} \left[\prod_i A_i \exp \left(- \frac{C_{p_i}^2}{C_{p_{i_0}}^2} \right) \right]^{b_p} \left\{ \prod_i A_i \exp \left[- \frac{(\text{Env}_{\text{opt}} - \text{Env}_i)^2}{(\text{Env}_{\text{opt}} - \text{Env}_{i_0})^2} \right] \right\}^{b_{\text{env}}}$$

Fig. 17. The complete biomass equation.

The terms $f_{\Sigma p}$ and $f_{\Sigma env}$ act as suboptimal condition modifiers of that growth rate (Park et al., 1974). The term $f_{\Sigma p}$ is anticipated to play a minor role in retarding marine photosynthetic growth; however, insufficient research has been conducted to date to allow its total deletion. The term $f_{\Sigma env}$ can be expanded to

$$f_{\Sigma env} = \prod_j \hat{c}_j f_{temp}, \quad (41)$$

where (based on Chen and Orlob, 1975)

$$\hat{c}_j = \frac{C_j}{K_{0j \rightarrow i} + C_j},$$

C_j being the concentration of nutrient j at node i and time t and $K_{0j \rightarrow i}$ being the half-saturation constant for nutrient j on taxon i and $f(T)$ as shown in Fig. 18.

Fig. 18. Relationship between phytoplankton growth and temperature.

As indicated in Fig. 18, growth increases exponentially to some T_{max} and then falls off very sharply (Nielsen, 1964; Department of Fish and Game, 1972). The temperature for maximum growth, T_{max} , is rarely reached or exceeded within the normal estuarine temperature regime.

Therefore the expression ψ^{T-T_0} is often used as a simplified temperature-effect form. However, this study will incorporate investigation of thermal discharges that may locally exceed T_{max} . Therefore the full expression for this functional relationship must be used. This relationship is, referring to Fig. 18, as follows:

For $T \leq T_{i,max}$, the temperature effect for taxon i , $E_{T,i}$, is

$$E_{T,i} = A_{T,i} \exp \left[- \frac{(T_{i,max} - T)^2}{(T_{i,max} - T_{i0_1})^2} \right], \quad (42a)$$

and for $T > T_{i,max}$,

$$E_{T,i} = A_{T,i} \exp \left[- \frac{(T_{i,max} - T)^2}{(T_{i,max} - T_{i0_2})^2} \right], \quad (42b)$$

where T_{i0_1} and T_{i0_2} represent the half-saturation or half-growth constants for taxon i .

The use of a half-saturation constant for light should be explained. The amount of light available for photosynthesis is actually a function of variable incident light and exponentially decaying light strength with depth, turbidity, depth of the photic zone, the quantity of organic matter in the water column, and so forth (Nielsen, 1964; Hardy, 1965, Vol. 1). However, it must be remembered that one-day time steps will be used in this model and that the photic zone in San Francisco Bay is often less than 4 feet deep. Under

these conditions the use of water-column and time-averaged light-intensity figures is justifiable, and the half-saturation constant becomes applicable.

The predation term of the primary production equation is identical with the predation term of the biomass equation [see Eq. (37)].

Respiration can be represented by a specific respiration rate times a temperature function:

$$\text{respiration}_i = \hat{r}_i f(T). \quad (43)$$

Respiration, as opposed to feeding, does increase exponentially over the full temperature range (Green, 1968). Thus respiration can be expressed as

$$\text{respiration}_i = \hat{r}_i \theta_i^{T-T_0}, \quad (44)$$

where $\hat{r}_i$ is the specific respiration rate measured at T_0 and θ is a taxon-specific constant between 1.02 and 1.06 (Chen and Orlob, 1975).

The advection term is also as shown in the biomass equation. It must be remembered that, as each taxon represents large spatial integrations, salinity variations from node to node need not be considered. Advection is thus represented by

$$\begin{aligned} \text{advection}_i &= \sum_m \rho_{i,m} Q_m \\ &- \sum_n \rho_{i,n} Q_{n \rightarrow i}. \end{aligned} \quad (45)$$

The $f_{i,m \rightarrow l}$ term need not be included, as phytoplankton have no choice of movement and, by definition, $f_{i,m \rightarrow l} = 1$.

The excretion term is proportional to

net photosynthetic growth, where the net growth is equal to total growth minus respiration (Park et al., 1974). As a result, the total growth and respiration terms are often combined into single net photosynthetic term:

$$P_{\text{net},i} = \hat{\mu}_i f_{\Sigma p} f_{\Sigma env} - r_i \theta_i^{T-T_0}. \quad (46)$$

Excretion, Ex_i , is then

$$Ex_i = \begin{cases} a_i' \text{net}_i & \text{for } P_{\text{net},i} > 0, \\ 0 & \text{for } P_{\text{net},i} \leq 0, \end{cases} \quad (47)$$

where a_i' is the fraction of net photosynthate lost per time step.

Under conditions of low photosynthesis and/or high respiration rates (such as at elevated temperatures) excretion goes to zero and all energy losses are through respiration.

The final term, mortality, includes both actual cell destruction within the euphotic zone and mass settling out of the euphotic zone. Where available, a single coefficient representing total planktonic mass loss, d_i , can be used:

$$\text{specific mortality} = d_i f(T) f_{\Sigma p}. \quad (48)$$

Where the combined data are not given and data on actual cell death rate and settling rates are available, mortality can be expressed by

$$\begin{aligned} \text{specific mortality}_i &= \left(\alpha_i + \frac{S_v}{Z_{\text{photic}}} \right) \\ &\times f(T) f_{\Sigma p}, \end{aligned} \quad (49)$$

where α_1 is the actual unit mass cell-death rate, S_v is the node average settling velocity, and Z_{photic} is the mean depth of the photic zone at a given node.

The relationship between temperature and mortality is essentially the reverse of that between temperature and feeding and has been previously discussed. The general shape of this relationship is shown in Fig. 19. The actual temperature levels for the onset of temperature-induced mortality are, of course, a function of each individual taxon. However, for the fairly limited temperature regime of San Francisco Bay [normal surface limits are about $7^\circ\text{C} \leq T_{\text{Bay}} \leq 18^\circ\text{C}$ (Kaiser Engineers, 1967)], limits on Fig. 19 are typical of many estuarine species.

Fig. 19. Relationship between water temperature and phytoplankton mortality.

If symmetry about T_{opt} is assumed, then the temperature influence on the mortality of taxon i is given by

$$M_{T_i} = A_{T_i} \exp - 1 \frac{(T_{\text{opt},i} - T)^2}{(T_{\text{opt},i} - T_{0_i})^2}, \quad (50)$$

where A_{T_i} can easily be determined by making T very large and assuming that the

total population kill T_{0_i} , is the LD_{50} temperature for the i th taxon and T_{opt} is the optimum temperature for the taxon.

The mathematical form of the pollutant effects for this equation will also be left until the specific pollutants of concern have been determined and until a more thorough literature search has been made.

The primary production equation is summarized in Fig. 20.

DETRITUS

Detritus has no direct impact importance. Thus the goal of this study in dealing with detritus is to externalize and simplify detrital mapping as much as possible. The principal limiting factor in this simplification process is the requirement to track pollutant concentration through detrital material and into the food web. Estimates of detrital biomass in a large shallow estuary are very tentative at best, especially for settled detrital material whose availability must be measured against depth of burial into the sediment column, depth of the aerobic layer of sediment, and depth of the sediment column experiencing tidal and non-tidal advective forces (Trevallion, 1967). As an alternative to actual detrital biomass estimation at each time step, the assumption that enough detrital material in its various forms is present and available so that all food-web transfers out of detritus are limited by demand may have some merit. With this assumption the term

$$\sum_k \left(\frac{\text{BIO}_{j \rightarrow k} w_{j \rightarrow k}}{C + \sum_k \text{BIO}_{j \rightarrow k} w_{j \rightarrow k}} \right)$$

goes to unity for all detritus eaters and

$$\begin{aligned}
\text{BIOP}_{1,t+1,i} = & \sum_m c_{1,m} Q_{m \rightarrow i} - \sum_n c_{1,n} Q_{i \rightarrow n} + \text{BIOP}_{1,t,i} \left\{ 1 + \left[\hat{c}_1 \left(\prod_j \frac{c_j}{K_{0,j+1} + c_j} \right) f(T)_1 \right] \right. \\
& \xleftarrow{\text{advection}} \quad \xleftarrow{\text{old biomass}} \quad \xleftarrow{\text{growth}} \quad \xrightarrow{\quad} \\
& \left. - \left[\sum_j \left(\frac{\text{BIO}_{1,j+1}}{\sum_k \text{BIO}_{j \rightarrow k} w_{j \rightarrow k}} \right) \left\{ (FF_j) \left[A_j \exp \left(- \frac{\text{BIO}_{j+1}^2}{\text{BIO}_{j,0}^2} \right) \right] \left(\sum_k \frac{\text{BIO}_{j+1+k}}{C + \sum_k \text{BIO}_{j \rightarrow k} w_{j \rightarrow k}} \right) (f_{\text{Env} \rightarrow j}) (f_{\text{Env} \rightarrow j}) \right\} + f_{2,i} P_{h1} \right] \right\} \right. \\
& \xleftarrow{\text{predation}} \quad \xrightarrow{\quad} \\
& \hat{P}_{1,i} Q_i^{T-T_0} - E_{x1} - \left(a_1 + \frac{S_v}{Z_{\text{photic}}} \right) A_1 \exp \left[-1 \frac{(T_{\text{opt},1} - T)^2}{(T_{\text{opt},1} - T_{1,0_1})^2} \right], \\
& \xleftarrow{\text{respiration}} \quad \xleftarrow{\text{mortality}} \quad \xrightarrow{\quad}
\end{aligned}$$

where

$$f(T)_1 = A_{T_1} \exp \left[- \frac{(T_{\text{opt},1} - T)^2}{(T_{\text{opt},1} - T_{1,0_1})^2} \right] \text{ for } T \leq T_{\text{opt}},$$

$$f(T)_1 = A_{T_1} \exp \left[- \frac{(T_{\text{opt},1} - T)^2}{(T_{\text{opt},1} - T_{1,0_2})^2} \right] \text{ for } T > T_{\text{opt}},$$

and the excretion term is

$$E_{x1} = \begin{cases} a_1 P_{\text{net},1} & \text{for } P_{\text{net},1} > 0, \\ 0 & \text{for } P_{\text{net},1} \leq 0, \end{cases}$$

with $P_{\text{net},1}$ being the total photosynthetic production minus respiration.

Fig. 20. The complete primary production equation.

total consumption is limited primarily by taxon biomass. In conjunction with this assumption, it can be assumed that the pollutant concentration of detritus removed from the water column is equal to that of the water column and that detritus removed from the sediment column has a concentration equal to that of the sediment. Detrital decomposers and the inorganic nutrients they produce can also be externalized by assigning a fixed rate of nutrient production as a model import. Nutrients are rarely a principal limiting factor in an estuarine system, and thus any error generated in total nutrient availability will be of little importance.

Should additional studies indicate that this treatment of detritus is inadequate, detritus mass-balance equations can be generated. Figure 21 illustrates the estuarine detrital cycle in which four detrital components are specified (Shugart et al., 1974). These are suspended dissolved organic matter (DOM), suspended particulate organic matter (POM), settled DOM, and settled POM. Each of these components could be tracked and balanced separately. However, this would require reconstruction of the excretion term of the biomass equation, inclusion of a decomposer mass-balance equation, and far more detailed information on sediment-water column interactions than is available at this time.

For mass-balance purposes it will therefore be extremely advantageous to combine all detrital forms into a single biomass heading and construct a single mass-balance equation. As indicated in Fig. 21, the equation is

$$\begin{aligned} \text{detritus}_{t+1,l} = & \text{DET}_{t,l} + \sum_i E_i + \sum_i M_i \\ & + \sum_i S_i + \sum_m I_{MWC,m \rightarrow l} \\ & + \sum_m I_{LSC,m \rightarrow l} - \sum_n O_{MWC,l \rightarrow n} \\ & - \sum_n O_{LSC,l \rightarrow n} - D \\ & - \sum_j P_{j \rightarrow \text{DET}}, \end{aligned} \quad (51)$$

where

E = excretion,

M = mortality,

S = settling,

I_{MWC} = mass water column import,

I_{LSC} = link sediment column import,

O_{MWC} = mass water column export,

O_{LSC} = link sediment column export,

D = decomposition,

P = predation.

The first three mass addition terms in this equation (excretion, mortality, and settling) have already been calculated by the biomass equation for each taxon. Advective import and export terms can be calculated similarly to advective migration calculations for biotic taxa, since the forces and processes involved are identical with those that result in biotic advection.

The presence of a decomposition term in the detritus equation is required even though the decomposer populations and processes have been externalized. A given mass of detritus during each time step

Fig. 21. Estuarine detritus cycle.

will be consumed by decomposers. Given a constant specific feeding rate for decomposer organisms (averaged over a one-day time step), the size of the decomposer biomass at each time step will be proportioned to and numerically dependent on the available detrital biomass (Nielsen,

1964). Thus the mass of detritus consumed will vary according to available detrital biomass, or

$$D_{\text{DET}, t+1} = C_{\text{DET}}(\text{DET}_{t, \ell}), \quad (52)$$

where D is decomposition.

This analysis assumes that, since a variety of decomposer species exist over the full range of estuarine environmental conditions and in the presence of all currently discharged wastes, under any given environmental conditions there will be sufficient decomposers to maintain this ratio of decomposers to detritus. Furthermore, it assumes that the adverse effects of any set of pollutants will not affect all decomposer species; hence if some species are retarded by a specific pollutant action, others will emerge to maintain a normative decomposer-detritus relationship and total rate of detritus conversion. Should pollutant concentration sets be encountered that invalidate this assumption, an appropriate pollutant-concentration dependence can be included directly in Eq. (52), so that

$$D_{DET,t+1,l} = C_{DET}(DET_{t,l}) f_{LP+decomposers} \quad (53)$$

Once the detrital biomass has been reduced to a finite mass, the predation term will return to the normal, previously discussed predation form.

Since most detrital feeders are selective [i.e., consume only settled, or only suspended matter (Perkins, 1974) or consume only particulate rather than dissolved organic matter], the $w_{j \rightarrow DET}$ term in the detrital feeding equation will require adjustment. Each selective feeder will not encounter $DET_{t,l}$ amount of detritus, but rather something less than this mass, depending on the type of detritus preferred. Thus the detritus-feeders preference used in the detritus prediction equation will be

$$w_{j \rightarrow DET}^* = \sum_i (w_{j \rightarrow DET,i}) (\%DET_i), \quad (54)$$

where $\%DET_i$ is the fractional percent of total detrital mass that is of detrital type i (POM or DOM; suspended or settled); $w_{j \rightarrow DET,i}$ is predator j 's preference for detritus type i .

Finally, pollutant concentrations will be tracked through detritus consumption as previously indicated by assuming that the concentration of pollutant in detritus matches the concentration of its surroundings.

This is admittedly an extreme simplification of actual concentrations of pollutants in detritus, which depend on several factors, including the source of the detritus and the length of time it has existed in its present form. However, it is anticipated that errors generated in this manner will, when transmitted through the food web, represent a very small percentage of the total concentration levels.

POLLUTANT CONCENTRATION

At each time step, the concentration of various pollutants will be mapped in the water column, in the sediment column, and within each taxon. The goal here is to predict community response to any given level of a specific pollutant or to any given set of pollutant concentrations. While most pollutants tend to concentrate in a specific organ or muscle tissue, it is extremely disadvantageous to approach their study on this level. So far this study has considered only gross taxon biomass. It would be extremely difficult to consider individual organs within each taxon. Fortunately, this does not appear to be necessary. If pollutant effects can

be related to concentrations within an organ, and if that organ's biomass can be related to an organism biomass and this to the total taxon biomass, then the effects can be directly related to the average concentration within the taxon biomass. This integrative approach can mask local high concentration anomalies; however, this effect will be minimized by this study's *concentration on chronic low-level loading*.

With this conceptual basis, the general form of the equation for total taxon pollutant mass is given by the concentration of the previous time step plus the net uptake over one time interval plus the effect of taxon biomass changes, or

$$\begin{aligned}
 &C_{pT_{j+1,t+1,l}} \\
 &= \left\{ \text{BIO}_{i,t,l} C_{p_{j+1,t,l}} + \left[\left(C_{p_{j+water}} u_{i+j_w} \right) \right. \right. \\
 &\quad \left. \left. + \left(C_{p_{j+sed.}} u_{i+j_s} \right) + \left(C_{p_{j+food}} u_{i+j_f} \right) \right] \right. \\
 &\quad \left. - \left(E_i C_{p_{j+E_i}} \right) \right\} - \left[C_{p_{j+i,t,l}} \text{bioloss}_i \right. \\
 &\quad \left. - a_i \left(C_{p_{j+i,t,l}} \text{recruitment}_{i+k} \right) \right. \\
 &\quad \left. + \sum_{j1} C_{p_{j+j1}} \text{biogain}_{j1+i} \right], \quad (55)
 \end{aligned}$$

where u_{i+j} is the uptake rate of pollutant j by taxon i , $C_{p_{j+1,t,l}}$ is the concentration of pollutant j in taxon i at time t and node l , $C_{p_{j+water}}$ is the concentration of pollutant j in the water column at node l and time t and a_i is the pollutant-concentration factor associated with taxon reproduction activities.

The last three terms of Eq. (55) (enclosed within the brackets) correspond to the mass changes associated with the biomass equation. The biomass-equation terms associated with each mass-change term in Eq. (55) are (1) bioloss, which includes mortality, predation, as well as outadvection and outmigration; (2) outrecruitment, which includes only the outrecruitment portion of the full recruitment term; and (3) biogain, which includes inadvection and immigration as well as inrecruitment to taxon i .

The excretion term here depends only on taxon assimilative characteristics and on the pollutant concentration at the previous time step. Thus this term represents only the amount of each pollutant removed from the organism's internal system. The total pollutant load excreted is equal to this quantity plus the amount not taken up from the food consumed. This latter figure would be important only for calculation of concentration in detritus.

The u_{i+j} terms in Eq. (55) represent taxon uptake rates. Such uptake rates are dependent on the local pollutant availability, taxon characteristics, and previous internal concentrations. A typical curve for uptake as a function of time is shown in Fig. 22 (Polikarpov, 1966). For

Fig. 22. Typical pollutant uptake rates and concentrations.

many estuarine species the time (t_0) to reach the maximum pollutant concentration is much less than one day, the time-step interval of this study. Thus for many taxa the use of a simple concentration factor (final steady-state concentration) instead of the functional uptake rate may be appropriate. This interchangeability has not yet been determined.

Once the total taxon pollutant load has been determined by Eq. (55), the pollutant concentration (pollutant per unit taxon

mass) can be calculated as

$$C_{p_{j+1},t+1,\ell} = \left(C_{p_{T_{j+1},t+1,\ell}} \right) \left(B_{i,t+1,\ell} \right)^{-1}. \quad (56)$$

Curves of pollutant effects, once established, will be geared to this concentration term for each taxon. The resulting lethal and sublethal effects will be reinserted into the biomass and primary production equations for the next time-step calculation.

Ecological Model Data Requirements

It is readily apparent that operation of either of the proposed ecological models requires an extensive data base. More specifically, both the I/O and the dynamic model require identification of the following:

- All food-web links
- All link $w_{j \rightarrow k}$ values
- Specific feeding rates and conversion rates (u_i) for all taxa
- Pollutant-uptake rates for all potential pollutants by all taxa
- Pollutant effects (by concentration) to include lethal, sublethal, behavioral, and physical
- Human harvest rates
- Environmental tolerances and preferences by taxa.

Moreover, the dynamic model will also require

- Taxa half-saturation constants by pollutant and environmental parameter
- Reproductive and recruitment rates, times, controlling factors, etc.

- Advection or migration choice factors.

In addition to this list of specific relationships, the dynamic model contains a number of constants that must be specified through parametrization techniques for data fitting. This process, of course, requires multiple data points for each parameter.

Obviously many of these data are currently nonexistent. Many pollutants are just beginning to be fully explored, and an acceptable seasonal species-identification list has not yet been determined for San Francisco Bay, much less the specific food-web links. Thus fully determinant explicit operation of the models is not yet feasible.

The operational plan of this study is to estimate and extrapolate all required data that cannot be specified and to either approximate or disregard suboptimal condition modifiers (environmental, pollutant, or population effects) that are not known. In this manner the model will be made immediately available for operational use,

and specific areas for needed research will be identified. It is hoped that this will, in turn, increase the rate at which new data become available for inclusion into various model parameters.

Such an operational mode will not yield data-point-specific results on an impact analysis; but even under worst case conditions it will be able to define the direc-

tion that an impact will take, the ecological elements primarily affected, and an order-of-magnitude estimation of that impact. This may be less than an ideal output, but it is no worse than many existing inputs to the decision-making process in the public sector and should be far better than the intuitive evaluations of environmental impacts currently used in that process.

Ecological Model Omissions

As currently designed, both of the ecological models proposed here omit certain significant elements of the general estuarine ecology. The first of these is macroflora. No provision is currently made to track the growth or size of macroflora. This is not as important in the San Francisco estuary as it is in many lakes; however, estuarine eel-grass beds are uniquely important for their role in defining the estuarine fauna. Coastal seaweed beds play a similar role in that environment. Marsh grasses and swamp grasses are less critical since detritus-import terms cover much of their primary importance to the estuarine ecology. It will become desirable to include eel grasses within the ecological model because of their important base roles; however, this has not been done to date.

Waterfowl have also been disregarded in this model effort. This omission should not have a major consequence in San

Francisco Bay; yet waterfowl fill a top predator slot for which the ecological model presented here will not compensate. Should this omission prove troublesome, a predation factor for waterfowl will be incorporated into the biomass equation. It is not anticipated that waterfowl will ever be included as a set of separate taxa into this model.

Finally, intertidal species are handled in a simplified form by this model. As relatively strict intertidal zonation is present in most West Coast estuaries (Ricketts and Calvin, 1966) it would be possible to incorporate, taxon by taxon, the effects of varying exposure to air and water. However, the benefits of such an approach have been tentatively deemed insufficient to justify the added complication to benthic, zooplankton, and phytoplankton taxa that would be affected, and the added requirement for input data, equation parametrization, and air-shed modeling.

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