A Land-Use Planning Model For Coastal Zone Management

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"A Land Use Planning Model For Coastal Zone Management"

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In this paper we consider a linear programming model for assessing the aggregate impact of land use activities scattered over a large area upon the resultant pollutant concentrations in coastal waters. The dispersion to coastal waters of the adverse environmental loads generated by the land uses is described by a set of transport coefficients which measure the attenuation of pollutants, such as industrial BOD, carried to the coast along surface drainage basins. Further dispersion in the waters due to tidal action is then described by the simple procedure known as "pollution susceptibility". The model seeks to minimize the steady state concentrations of pollutants by establishing an optimal spatial configuration of residential, commercial, and industrial land uses. This configuration is constrained by a number of restrictions based on local and regional targets for growth and development. The methodology discussed in the paper is intended to be useful to regional planners and is based on a study conducted for the Long Island area.

Introduction

In this paper, we discuss a model of coastal zone management designed for use by land use planners. To the authors' knowledge, there is no general methodology for assessing the aggregate impact of land use activity scattered over a large area upon the resulting pollutant concentrations in coastal waters. Nor is there a known tool for assessing land use strategies to reduce pollutants in coastal waters. In this paper, we describe a planning model designed to fill this gap. This work is part of a larger study [1] carried out for the Office of Policy Development and Research, Department of Housing and Urban Development.

The basic outputs of our model are concentrations of pollutants in coastal waters together with the spatial land use configuration of land use activities which give rise to these pollutants. These activities include residential, commercial, and industrial sectors and are spatially "located" by specifying a set of zones into which the entire region is fragmented. The dispersion to coastal waters of the adverse environmental loads generated by the land uses is described by a set of "transport" coefficients which measure the attenuation of pollutants, such as organic wastes from industrial sources, carried to the coast along surface drainage basins. Further dispersion in the coastal water due to tidal action is then described by a simple procedure called "pollution susceptibility"[2].

The model is formulated as a linear program which is readily converted to a computer code using any one of a number of programming packages available at most computing centers around the country[3]. It draws only on environmental ideas familiar to planners and relies on data which is readily available from topographic maps of the region as well as from comprehensive plan information. It is a technical tool capable of answering such questions as:

> How much reduction in pollutant concentration can be achieved by the spatial shifts of land uses?
>
> What are the relative environmental benefits of implementing different strategies (land use changes vs. technical alternatives vs. environmental modifications alternatives) for the solution of specific water quality problems?

Such questions as these form the background for policy decisions and, for example, it is in this context that the model has been successfully applied in the Long Island area.[4] It is of direct and practical assistance in the general planning process, particularly the evaluation of environmental impacts of alternative land use options.

Brief Description of the Model

The model described below is a tool for predicting average, steady state pollutant concentrations resulting from certain levels and distributions of land uses. Conversely, beginning with given average water quality goals, the model may be used to establish optimal spatial configurations of residential, commercial, and certain other land uses which meet the desired goals.

Fundamental to the model is the following description of the impact of pollutant emission from inland sources upon the coastal environment. Consistent with available data, we choose to represent source emissions of organic pollutants from residential, commercial, industrial, and other uses in lbs./acre/yr. of BOD and nitrates. Coastal impact is measured through concentration in parts-per-million of these pollutants in coastal waters. The transport mechanism by which source emissions find their way to the coastal environment is primarily surface flows within drainage basins. We neglect deep flows of pollutants from source into the ground water, and thence back up into the coastal waters because the time constants are very long and pollutants are generally not conserved, nor is much known of the physical transfer mechnism itself. When pollutants empty from a basin into coastal waters, they are dispersed through tidal action and, as a result, pollutants from one land area have impacts on nearby coastal waters. The ratio of pollutant concentration at points in the coastal zone to source emissions from land use activity is defined as a <u>transport coefficient</u>. In fact, this coefficient measures both the flow of pollutants from source to coast and their subsequent dispersion in coastal waters. This transport coefficient sums the impact of many land use activities upon one coastal area and so local water quality becomes dependent upon land uses scattered over a large area.

The treatment of local, short-term, transient water quality problems are not within the design or purpose of the model. It is also important to recognize that the model does not measure environmental damage, as such, but in fact works with a surrogate measure of quality which is simply the level of concentration of pollutants in marine waters.

Model Formulation

In order to describe the shifts in land use from one spatial pattern to another, it is convenient to assign land uses to "zones". These should be consistent with the pollutant transport mechanism and so an initial choice of zones would be simply surface drainage basins. However, political or geographic considerations are often important constraints. Accordingly, the final spatial unit of land use, the zone, is then the intersection of surface drainage basin areas with these designated geographic sectors.

Zones which consist of inland valleys are presumed to drain directly to groundwater. These zones exhibit no transfer of pollutants to the coastal waters. From the standpoint of coastal water quality, it matters little what land use occurs here. Such zones are called "hinterlands". All other zones drain to coastal waters, either because they border directly on the coast or because they contain a stream or river.

Several characteristics of future land use are built into the model. First, there is some existing land use inventory within each zone which will be largely, but not entirely, preserved into the future. Redevelopment of built-up areas proceeds slowly. Second, total land use growth in each zone cannot exceed developable acreage in that zone. Finally, since town industrial commissions, planning boards, and the like establish preferred patterns of growth, there are region-wide and local development targets for growth. Overall, these factors prohibit the model from establishing unrealistic land use patterns.

A brief formal statement of the mathematical model is based on the flow of pollutants represented in Figure 1. For the reader who is less interested in mathematical formalism, the model description given below may be safely omitted. A glance at Figure 1 provides an understanding of how the model works which is sufficient to interpret the results and applications discussed later.

For each land use zone indexed by $\ell = 1, 2, \ldots$ let $x_{\ell i}$ denote the number of acres devoted to activity $i = 1, 2, \ldots$ (such as residential high density, residential low density, commercial, industrial, etc.). Then $L_{\ell i}$ will indicate the present levels of such activities (that is, at the time that the study is being conducted). This is the amount of land for each activity that is preserved into the future and so we write:

$$x_{\ell i} \geq L_{\ell i} \tag{1}$$

The total acreage open for development in the future in each zone ℓ imposes an upper bound on development there. Call this quantity A_ℓ Then

$$\sum_i x_{\ell i} \leq A_\ell \tag{2}$$

Let u_i denote the number of acres anticipated for each land use activity of type i . This quantity is generally obtained from the comprehensive plan of the region. This aggregate target development translates into the following mathematical statement:

$$\sum_\ell x_{\ell i} = u_i \tag{3}$$

The comprehensive plan of a region also gives certain clusters of zones which by themselves form natural targets of development. Thus, for example, all zones which collectively constitute a township might well be such a cluster. Lable these zone aggregates by a = 1, 2, . . . and let v_i^a be the acreage devoted to activity i which is anticipated or desired in the sector a . Then

$$\sum_{\substack{\text{for all } \ell \\ \text{in sector } a}} x_{\ell i} \leq v_i^a \tag{4}$$

To understand the computation of transport coefficients, we briefly review the mechanism of pollution susceptibility [2]. Pollution susceptibility p_m is defined as the concentration of pollutant in parts per billion (ppb) which results from an average discharge of one ton per day into the waters of coastal zone m. In Figure 2, which illustrates a general case, the bay has an ocean inlet at the downstream point A. Flushing action is most active at A and decreases as we move upstream to the point B. This is shown by increasing pollution susceptibility due to weaker tidal flow as one moves towards B. If pollution enters the bay at site S_i for i = 1, 2, 3, 4 (as shown) then, assuming that the pollutants are miscible and that their flow is conservative, one unit entering at S_i will, in a steady state, affect all upstream locations equally as at S_i whereas it will dilute in moving to downstream locations in proportion to the ratio of susceptibilities. For example, one ton of BOD at S_2 will yield a concentration of 500 ppb in the bay at any location to the right of the arc S_2, S_2' but will have a value one fifth of that at the arc S_3, S_3' (100 ppb) and one tenth the value at S_4, S_4' (50 ppb).

Consider now a source zone ℓ which impacts at a coastal zone m'. Let $t_{\ell m'}$ be a number between zero and one indicating the fraction of source emissions in land use zone ℓ which flow to coastal zone m'. Order all coastal zones by increasing indices m' as shown in Figure 2, moving from the last upstream location toward the first downstream location at the inlet. Then, for upstream locations m with pollution susceptibility p_m; $m \leq m'$ (or $p_m > p_{m'}$) one ton of pollutant originating at ℓ has a concentration of $t_{\ell m'}\ p_{m'}$ ppb at coastal site m. However, its value at downstream location $m > m'$ is $t_{\ell m'}\ p_{m'}\ \frac{p_m}{p_{m'}} = t_{\ell m'}\ p_m$ ppb. Since zone ℓ can impact on several or even all possible coastal locations, a matrix o transport coefficients $T_{m\ell}$ is found by summing up over all m':

$$T_{m\ell} = \underset{\substack{m' \leq m \\ \text{(downstream)}}}{\sum} t_{\ell m'}\ p_m + \underset{\substack{m' > m \\ \text{(upstream)}}}{\sum} t_{\ell m'}\ p_{m'} \qquad (5)$$

In the particular case that each zone ℓ is a single drainage basin, then ℓ impacts only the coastal waters which abut that zone. That is, $m' = \ell$ and the computation of $T_{m\ell}$ reduces to

$$T_{m\ell} = \begin{cases} t_{\ell\ell}\ p_m, & \text{if } m > \ell \\ t_{\ell\ell}\ p_\ell, & \text{if } m \leq \ell \end{cases}$$

We now let the source loads of pollutant emissions be denoted by s_{ij} to indicate the tons of pollutant j which is the result of land use activity i. The concentration of pollutant j in coastal zone m, which is denoted by z_{mj}, is the sum of contributions from source emissions in many land use zones:

$$z_{mj} = \sum_{\ell} \sum_{i} T_{m\ell} \; x_{\ell i} \; s_{ij} \tag{6}$$

For those bay areas in which tidal flow, and hence pollution susceptibility, diverges from the mainstream into "arms" or branches, we need to extend Equation (5). Figure 3 illustrates a bay with two interacting systems flushed by a single inlet, a bay configuration typical of that found in many coastal waters. The bay running from A to B (right branch) interacts at A with the one moving from A to B' (left branch). Following the procedure outlined above to determine transport coefficients, one computes concentrations in the right branch in the usual way, ignoring all coastal areas left of A and then adds to these values the concentrations at A due to loadings which impact on the left branch. Thus a half-ton loading at S_3 gives a concentration of 25ppb at S_4 (that is, at A) and, therefore, a value of 25 ppb at S_5 and at S_6. Its value at S_1 is 500 ppb. The computation for the left branch is the converse of this example. The actual computations are obtained by indexing all coastal zones from the upstream point at B to A by $m = 1, \ldots, M$ and all other zones from B' to A by $m = M + 1, \ldots M + N$ (where M is the number of coastal zones in the right branch and N is the number in the left branch (in Figure 3, M = 4, N = 2). Assume, for simplicity, that a zone ℓ has a non-zero transport to coastal zones in the right fork or in the left fork but not both. Then, if ℓ impacts zones in the right fork,

$$T_{m\ell} = \begin{cases} \sum_{m' \leq m} t_{\ell m'} \; p_m + \sum_{m' > m} t_{\ell m'} \; p_{m'}, & 1 \leq m \leq M \\ \sum_{m' \leq m} t_{\ell m'} \; p_m, & M + 1 < m < M + N \end{cases} \tag{7}$$

An analogous formula holds when ℓ impacts zones in the left fork. More complicated interacting coastal systems involving several "arms" can be treated in a similar way.

From the point of view of optimization, we may choose a single objective which is to minimize the aggregate pollutant concentrations,

$$\min \sum_{j} \sum_{m} z_{mj} \tag{8}$$

Of course, one might also use weighting factors to represent the relative importance of various pollutants in different zones. This type of single objective analysis proved most useful within the context of the Long Island studies described below. There are some inherent limitations in the model that we want to summarize here. First, numbers generated from any model are only as good as the numbers which go into it. No amount of numerical manipulation can possibly augment the accuracy or validity of the data used in constructing the model. This is an obvious point but worth reaffirming. Second, the model is a device for obtaining the inter-zone substitutions of land uses so as to reduce coastal environmental impact but it does not determine land uses intra-zones. That is, the zone is the smallest parcel of land for which land uses can be defined. Third, coastal impact is described in terms of the Weyl study and therefore is subject to the same limitations to be found in that work. That is, coastal pollution is characterized only for those pollutants which are miscible and transported along coastal waters in a conservative fashion. This leaves out of consideration such items as turbidity of waters or pollution by heavy metals. Fourth and perhaps most damaging is that the model uses a number of simplifying assumptions regarding the transport mechanism of loadings. This is an area that should be looked at more carefully in order to develop useful 'rules of thumb' which can be applied simply and widely to determine how certain pollutants enter coastal regions and with what attenuation. For example, setting the transport coefficients to a value of one for coastal zones is probably an overestimate since source load calculations include pollutants carried off by runoff and by sewage. But sewage is not completely transported to the coast since some of it permeates down to the ground water. Also, the use of a unit coefficient ignores the fact that some pollutants, such as BOD, are attenuated somewhat before reaching the coast.

Application to the Long Island Area

The model has been used as a planning tool in the Nassau/Suffolk Counties of New York with specific emphasis upon the area known as Great South Bay. The bay configuration is shown in Figure 4 and inscribed on it are the pollutio susceptibility indixes that we used, as obtained from computations in (ref. 1). This coastal area is actually two interacting bay systems with an inlet (as indicated) through which all tidal flushing action occurs. This required us to utilize the method of calculating transport coefficients that was described in Equation (7).

Appropriate values of source loadings for BOD emissions associated with the various land use activities and values of pollution susceptibility are given in Table 1. BOD values are given for runoff alone and for runoff plus sewage (denoted BOD +). Nitrogen concentrations were also studied, with results similar to the discussion of BOD below.

A summary of the BOD concentrations computed by the model for selected land use and engineering alternatives is given in Table 2. The two values for each zone represent estimated upper and lower bounds on concentration. The first, labelled simply as BOD, consists of all pollution generated from runoff and collected within each drainage basin. However, since a certain amount of BOD is carried to the coast through ground water flows we also measured the contribution due to sewage assuming the same attenuation (transport coefficient) assigned to runoff. This clearly is an overestimate but it provides a measure of the worst pollution levels which are likely to occur. Pollution concentrations from runoff plus sewage we designate as BOD+. Concentrations are averages measured at the center of the bay along the curves displayed in Figure 4. They do not represent concentrations at the shoreline itself where even higher levels of pollution generally occur. Assuming an average saturation value of dissolved oxygen of about 9 ppm implies, by subtraction from our BOD values, dissolved oxygen levels which vary mostly between 8.5 to 2.5 ppm.

The land use and engineering alternatives selected for analysis (as shown in Table 2) were the following:

1975 - current land uses in the region.

1985 - the spatial configuration in the Comprehensive Plan of the Nassau/ Suffolk Region for 1985.

Land Use - land use rearrangements. The Comprehensive Plan can be perturbed to allow for spatial shifts between each of the projected target areas as well as within them. Shifts of up to 1,000 additional acres of each residential type, industrial, or commercial development are permitted.

Recharge - assume the 1985 Comprehensive Plan. In addition, for Zones 20 and 21 recharge reduces all source loads by 50%.

Dredging - assume the 1985 Comprehensive Plan. In addition, the inlet in Zone 28E is dredged to improve tidal flushing action. Current tidal range is .66'. The inlet is widened to permit a tidal range of 1.3'.

The western portion of the bay is considerably more populated than the eastern so that the opportunity for optimal land use shifts in Zones 34/28W is correspondingly less than it would be in Zones 21/20. In fact, the difference between present inventory and future (1985) development, vacant land, is roughly 3% of total acreage in Zone 34 and 20% in Zone 20.

Significant reductions in pollutant concentrations can be achieved by spatial rearrangement of the various land use activities. Most of these occur in Zones 20 and 21 and in Zone 34 - that is, the extreme ends of the bay. Meager reductions occur in the middle of the bay but that is of little significance since the pollution susceptibility is already low there. In addition, other computer runs not shown here indicate that land growth as it actually evolved in the western end of the Great South Bay area was not favorable to coastal water quality.

The model output includes the marginal change in aggregate BOD concentration per 1,000 acre increment in land use (ppm/1,000 acres). These indicators are known as "shadow prices" in economic terms and are summarized in Table 3 for the two extreme Zones 20 and 34 as well as for the low pollution susceptibility Zone 28E. For runoff alone, it happens that high density residential, industrial and commercial development have the same marginal values since each has the same BOD source load (lbs. per year per acres), but this is no longer true in the case of BOD+. The greatest benefits in land use reductions occur in Zones 20 and 34. A 1,000 acre change there has far greater impact on aggregate BOD concentrations than it does in Zone 28E or in any other low susceptibility area. For example, a 1,000 acre shift of land use activity in Zone 20 from high density residential (-.19 ppm) to open space (+.06 ppm) results in a net decrease in BOD level of .13 ppm in the bay system as a whole. This represents a 3% reduction of the 5.23 ppm projected BOD load for 1985 shown in Table 2. This suggests the plausible rule of thumb that as much as possible land development should be shifted away from zones with high pollution indices to others with low indices. Table 3 also shows the impact of reducing high density development in terms of attenuating BOD+. For example, a 1,000 acre shift to open space in Zone 20 yields a 5.10 ppm net decrease in overall BOD+ levels of the bay.

For the engineering alternatives, we focus our interest on Zones 20 and 21 since there is still sufficient vacant land there to seriously consider recharge options during future development. As we see from Table 2, a 50% recharge in those zones results in about a 30% reduction in overall BOD levels in the bay. (Although not shown, a 50% recharge option for Zone 20 alone results in only a 20% aggregate BOD reduction.) Dredging on the other hand achieves the same BOD reduction in Zone 20 (.49 ppm) but it also improves overall water quality more noticeably - a 70% reduction. Of course, most of the payoff in dredging occurs in areas of low susceptibility near the inlet.

The model formulation and analysis described above has provided the basis for a series of changes in the Comprehensive Plan for the Nassau/Suffolk region. Its implementation in the Great South Bay area lead to specific changes in recommended land uses for Zones 20 and 21.[4]

References

1. Integration of Regional Land Use Planning and Coastal Zone Science - A Guidebook for Planners, prepared by the Nassau/Suffolk Regional Planning Board for the Office of Policy Development in Research, HUD (June, 1976).
2. P. Weyl, "Polution Susceptibility: An Environmental Parameter for Coastal Zone Management", . Vol. 2 (1976), pp. 327 - 343
3. Computer programs and full documentation are available from the Nassau-Suffolk Bi-County Regional Planning Board, Hauppauge, N.Y. 11787
4. "Regional Plan Changed for Ecology", Newsday, May 21, (1976).

SOURCE LOADINGS

(lbs. per year per acre)

Land Use	BOD	BOD +
High density	84.0	2,250.0
5 - 10 acre	61.9	510.0
2 - 4 acre	45.4	256.0
0 - 1 acre	34.3	87.0
Low density	23.3	49.6
Farm	—	1,760.0
Utility	1.6	5.2
Institutional	61.9	607.0
Commercial	84.0	204.0
Open (recreational)	24.0	42.0

POLLUTION SUSCEPTIBILITIES

(ppb per ton of pollutant)

Zone	Tidal Range .66'	Tidal Range 1.3'
20	1,000	500
21	500	150
26	200	50
27	100	20
28E	50	10
28W	500	100
34	1,000	500

TABLE 1

(data taken from Ref. 1)

BOD CONCENTRATIONS (ppm)

		Aggregate	Zone 34	Zone 28W	Zone 28E	Zone 27	Zone 26	Zone 21	Zone 30
1975	BOD	4.30	1.28	.76	.12	.32	.36	.69	.89
	BOD +	27.32	9.56	5.70	.66	1.18	1.96	3.72	4.54
1985	BOD	5.23	1.34	.79	.14	.26	.45	.90	1.25
	BOD +	32.11	10.00	5.42	.83	1.49	2.57	5.04	6.76
Land Use	BOD	4.63	1.28	.76	.15	.27	.42	.78	.98
	BOD +	29.42	9.56	5.70	.91	1.07	.250	4.38	5.20
Recharge	BOD	3.39	1.34	.79	.08	.14	.21	.32	.49
	BOD +	22.47	10.00	5.42	.50	.84	1.27	1.78	2.65
Dredging	BOD	1.70	.59	.16	.03	.05	.11	.26	.50
	BOD +	11.46	4.98	1.32	.16	.30	.62	1.44	2.65

TABLE 2

DECREASE IN AGGREGATE BOD CONCENTRATION (ppm)
PER 1,000 ACRES DECREASE IN LAND USE,
BASED ON THE 1985 PLAN

LAND USE	ZONE	BOD	BOD +
High Density Residential	Zone 20	.19	5.20
	Zone 34	.16	1.40
	Zone 28E	.03	.70
Low Density Residential	Zone 20	.05	1.1
	Zone 34	.04	.10
	Zone 28E	.01	.02
Commercial	Zone 20	.19	.60
	Zone 34	.16	.20
	Zone 28E	.03	.08
Industrial	Zone 20	.19	.50
	Zone 34	.16	.10
	Zone 28E	.03	.06
Open Land (Recreational)	Zone 20	.06	.10
	Zone 34	.05	.03
	Zone 28E	.01	.01

TABLE 3

FIGURE CAPTIONS

Table 1 - Source Loadings
Pollution Susceptibilities

Table 2 - BOD Concentrations (ppm)

Table 3 - Decrease in Aggregate BOD Concentration (ppm) per 1,000 Acres Decrease in Land Use, Based on the 1985 Plan

Figure 1 Flow of Pollutants From Sources to Coastal Waters

Figure 2 Schematic of a Bay with Inlet

Figure 3 Schematic of Two Interacting Bay Systems Flushed By a Single Inlet

Figure 4 Map of the Great South Bay Region in Long Island
The solid lines represent contours of constant polution susceptibility, with susceptibility index values shown.

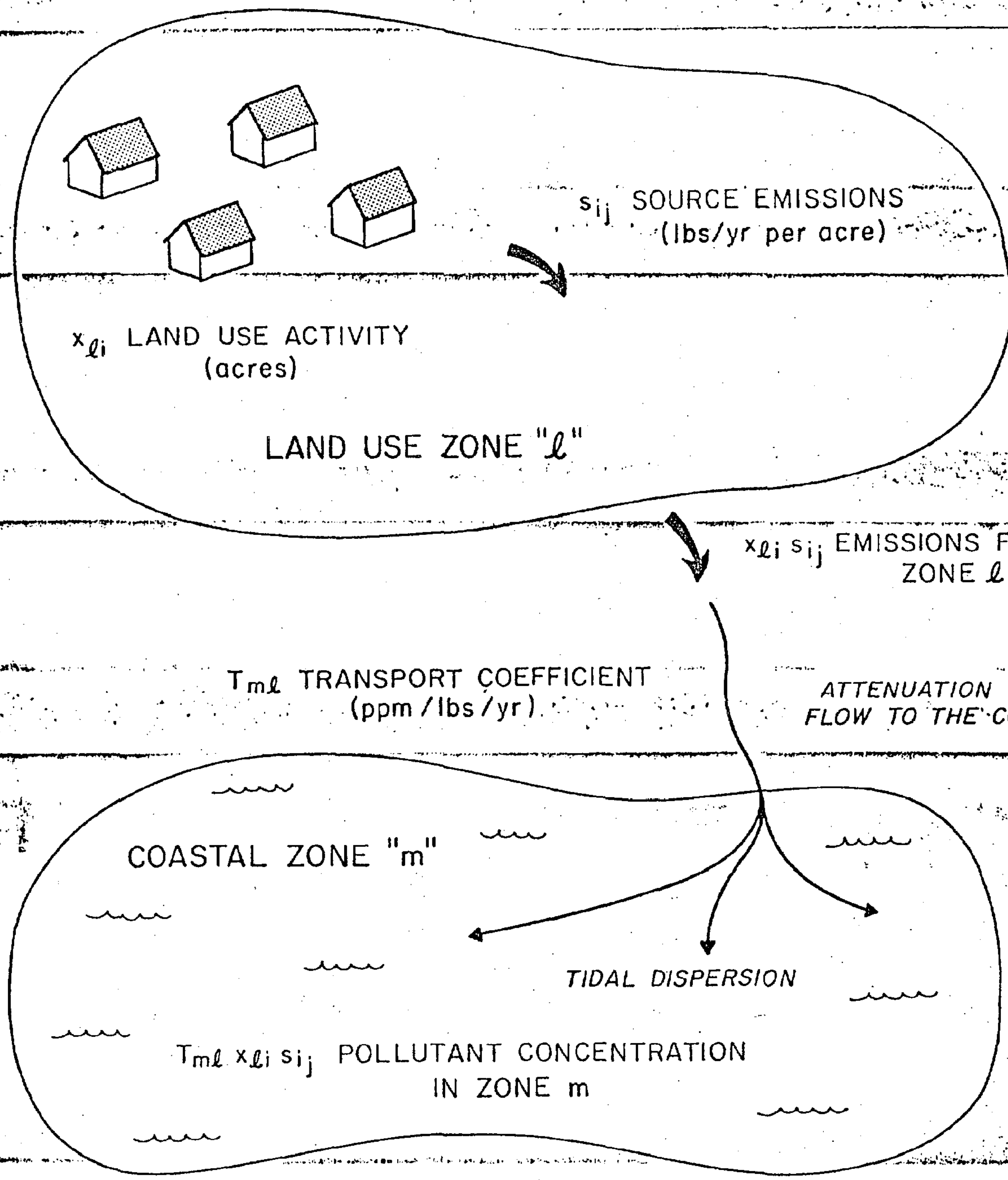

Figure 1 FLOW OF POLLUTANTS FROM SOURCES TO COASTAL WATERS

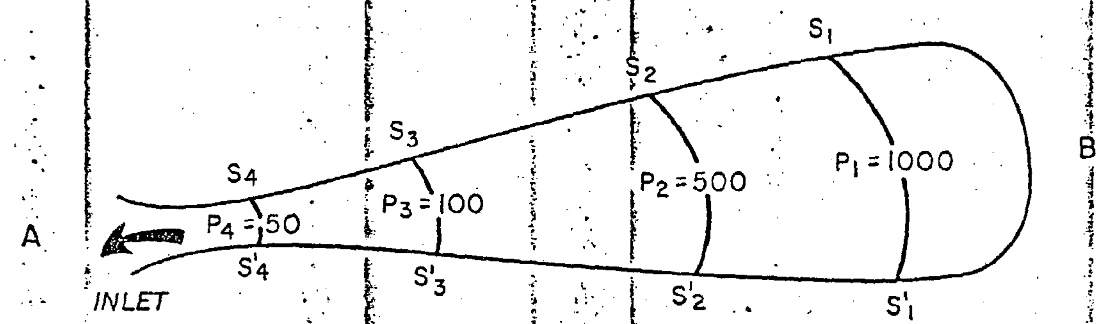

Figure 2 SCHEMATIC OF A BAY WITH INLET

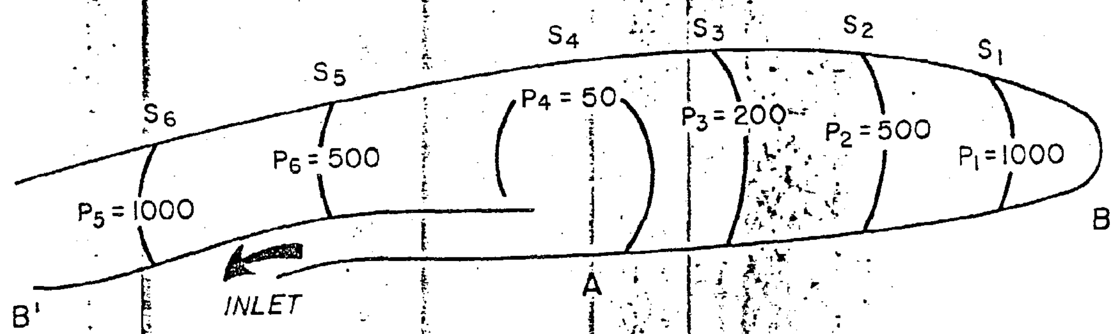

Figure 3 SCHEMATIC OF TWO INTERACTING BAY SYSTEMS FLUSHED BY A SINGLE INLET

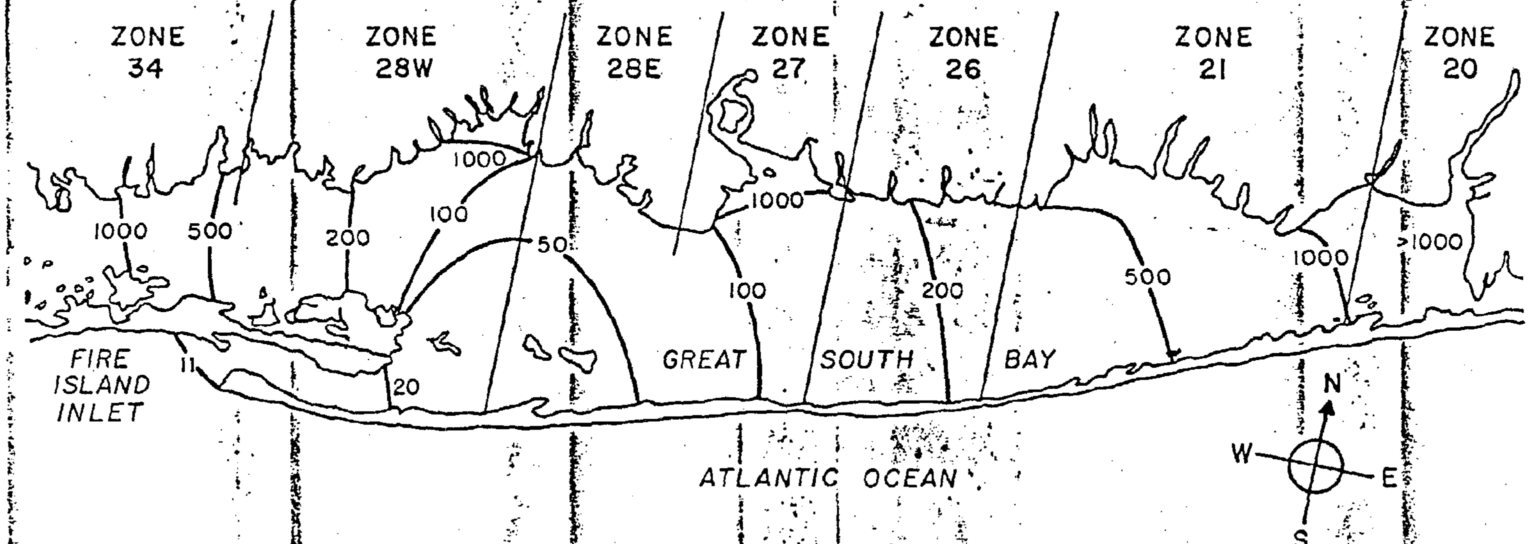

Figure 4 MAP OF THE GREAT SOUTH BAY REGION IN LONG ISLAND

The solid lines represent contours of constant polution susceptibility, with susceptibility index values shown.