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Estimating Freshwater Inflow Needs for Texas Estuaries by Mathematical Programming

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As mandated by the Texas State Legislature, the Texas Department of Water Resources conducted studies of the effect of freshwater inflows upon the bays and estuaries of Texas. Developed as part of these studies, a mathematical programming model is described for computing estimates of the monthly and seasonal freshwater inflows necessary to meet specified environmental conditions in each of the major estuaries of the Texas Gulf Coast. The optimization model relates freshwater inflow to the key estuarine indicators of salinity, marsh inundation, and commercial fisheries harvests. Three management proposals are formulated for each estuary, corresponding to ecosystem subsistence, maintenance of fisheries harvests, and fisheries harvest enhancement. Linear and nonlinear mathematical programming techniques are used to determine the optimal inflows for each of these three management alternatives in all but one of the seven major estuaries, where only one of the management proposals could be solved.

INTRODUCTION

In 1975 the 64th Texas Legislature enacted Senate Bill 137, a mandate for comprehensive studies of the effects of freshwater inflow upon the bays and estuaries of Texas. These studies were to address the relationship of freshwater inflow to the living estuarine resources (e.g., finfish and shrimp) and to present methods of providing and maintaining a suitable ecological environment. This paper presents a mathematical optimization model used to determine estuarine freshwater inflow needs in studies conducted by the Texas Department of Water Resources (TDWR), the predecessor agency of the Texas Water Development Board (TWDB), for seven major Texas bays and estuaries (Figure 1). The estuaries studied were Sabine-Neches, Trinity-San Jacinto, Lavaca–Tres Palacios, Guadalupe, Mission-Aransas, Nueces, and Laguna Madre. Each of the individual estuarine studies are described in detail in separate reports [*TDWR*, 1980*a*, *b*, 1981*a*, *b*, *c*, 1982, 1983]. These studies were conducted over a 6-year period by numerous persons on the TDWR staff and under contract at universities, at other Texas State agencies, or in private industry. In the analyses of each estuarine system, physical, chemical, and biological factors were conceptually and empirically related. Many estuarine needs were directly associated with freshwater inflow and associated water quality constituents. This paper first describes briefly the general methodology used in these studies and then discusses the formulation and application of a mathematical programming model, developed by the author and other TDWR staff, to estimate estuarine freshwater inflow.

KEY INDICATORS OF ESTUARINE CONDITIONS

Many complicated interactions govern the biological productivity of Texas bays and estuaries other than the quantity of freshwater inflows. However, freshwater inflows and their associated nutrients and sediments are recognized as one of the primary factors in estuarine productivity [*Snedaker et al.*, 1977; *Wohlschlag*, 1979; *May*, 1974; *de la Cruz*, 1973, 1980; *Turner and Chadwick*, 1972]. In order to estimate freshwater inflows necessary to sustain Texas estuarine ecosystems, some assumptions must be made. The main premise underlying these assumptions is that the relationships and interactions between freshwater inflows and estuarine productivity can be indirectly examined through analyses of "key" indicators [*Odum*, 1971, p. 138].

One "key" indicator, the frequency of marsh inundation, is based on the recognition that coastal marsh areas associated with river deltas are important sources of nutrients for the estuaries [*Heinle et al.*, 1977; *de la Cruz*, 1973, 1980]. The nutrients are transported into the estuaries through inundation by periodic overbanking of river flows. Timing and extent of the inundation and dewatering processes are influenced by seasonal river flows, flooding, and tidal conditions and constitute a natural environmental function of the respective deltas and estuarine complexes in terms of waste assimilation, nutrient cycling, and maintenance of "nursery" habitats for young, growing organisms such as juvenile fish and shrimp.

Salinity of estuarine water is a second significant indicator, since important commercial estuarine-dependent organisms are critically dependent upon salinity levels for viable growth and reproduction [*Wohlschlag*, 1979]. Salinity preference ranges vary between species, as well as for different times in the life cycle of a species.

The third "key" indicator utilized in the assessment of freshwater inflow needs is the historical commercial fishery harvests. Annual harvest statistics, along with associated seasonal freshwater inflows, are the only available data with which to estimate relationships between the timing and quantities of freshwater inflows and associated fishery productivity. Further, such harvests have been used in other studies as surrogates for estimating the level of estuarine fishery productivity [*Gunter and Hildebrand*, 1954; *Turner and Chadwick*, 1972].

MATHEMATICAL PROGRAMMING MODEL

The methodology adopted in the TDWR studies for estimating freshwater needs (Figure 2) consists initially of analyzing six basic data bases and developing statistical relationships between the key indicator parameters of salinity, commercial fishery harvests and marsh inundation, and historical

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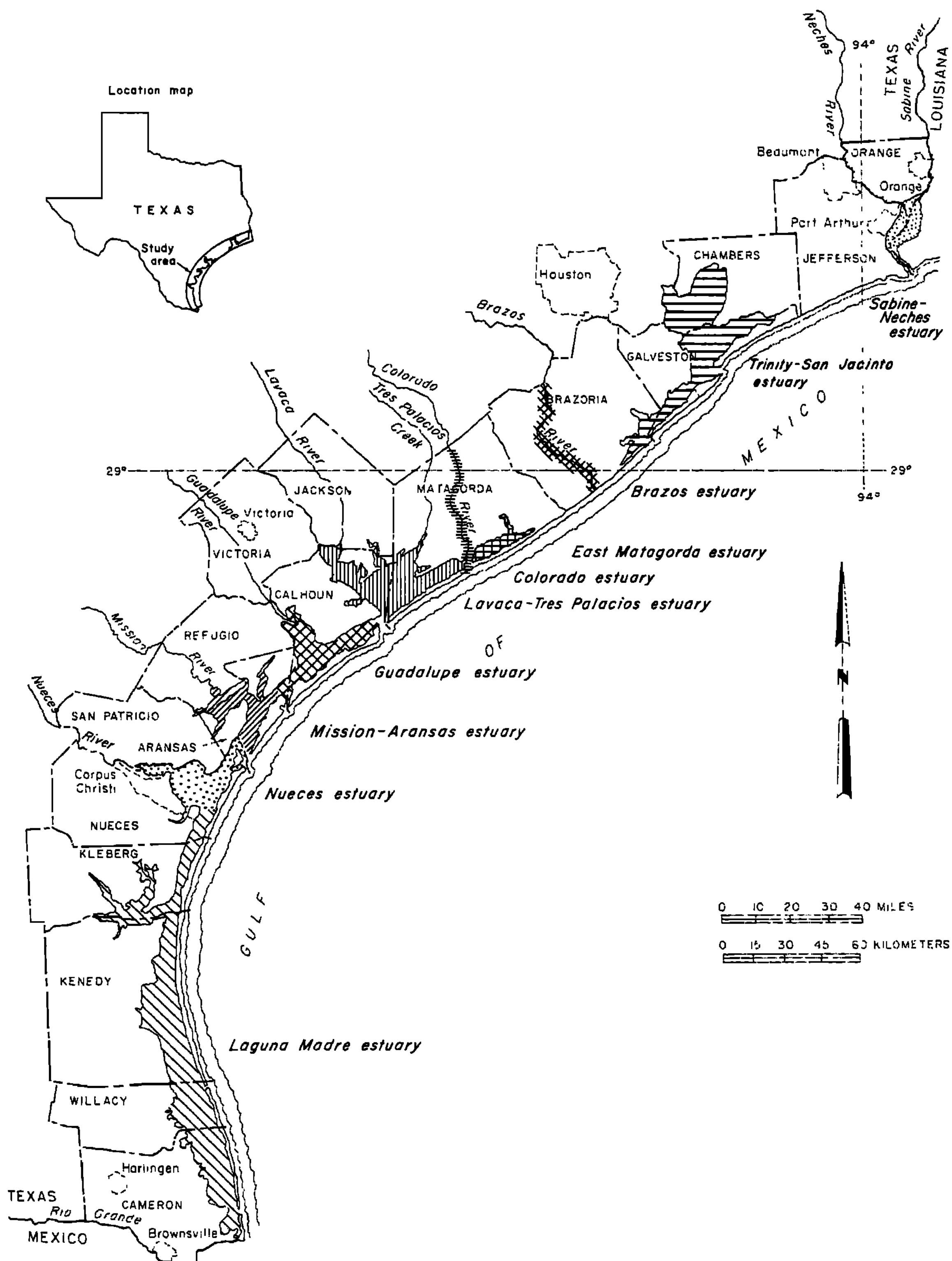

Fig. 1. Location of Texas estuaries.

monthly and seasonal freshwater inflows. These relationships are incorporated into a mathematical programming model, which is solved to establish an optimal set of freshwater inflows for the desired performance objective and constraints.

The mathematical programming model considers salinity conditions at important fishery nursery locations in an estuary near the mouths of major rivers. The current salinities at such points are closely related to current freshwater inflows. The salinities in the middle of a major estuary are influenced by freshwater inflowing during many previous months and seasons and cannot be incorporated as dependent variables in the programming model. However, proper salinity conditions in the large primary bays of an estuary are important to the environmental health of estuarine ecosystems.

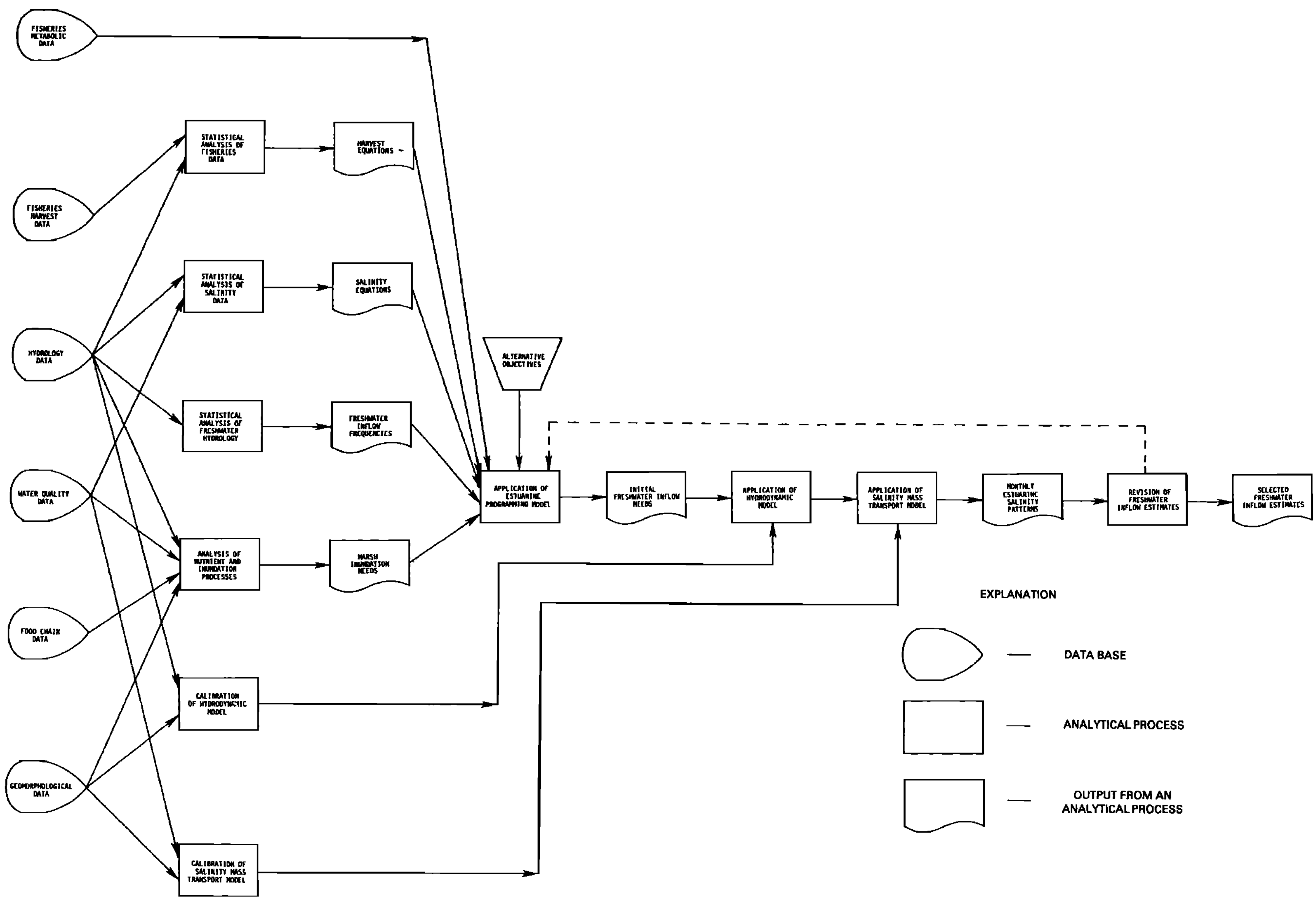

Fig. 2. Schematic diagram of methodology for estimating estuarine freshwater inflow needs under a management alternative.

To properly estimate salinity conditions throughout an estuary, the TWDB supported development of estuarine hydrodynamic and salinity transport models [*F. D. Masch and Associates*, 1971]. These models solve finite difference approximations of the basic partial differential equations governing surface water flow and the movement of conservative water quality constituents. Each estuary is segmented in a rectangular grid of discrete spatial elements. External hydrological, meteorological, and water quality conditions are imposed on the models, and they simulate the temporal and spatial behavior of circulation and salinity patterns in an estuary.

To consider the impacts upon an entire estuary, the resulting monthly freshwater inflows from the programming model are utilized as input data to digital estuarine hydrodynamic and salinity transport models to simulate the salinity distribution throughout an estuary. If this distribution is not within desired limits, then the mathematical programming model (generally a linear program) is reformulated with modified constraints and again solved. This reformulation process is by trial and error. Fortunately, the inflows calculated by the programming model were sufficient in all cases to keep salinities in the middle areas of each estuary within the broad range of 10–20 or 25 ppt, depending upon the estuary.

The mathematical representations of each of the key indicators is described below, followed by the general formulation of the estuarine management model.

Estuarine Water Salinity and Freshwater Inflows

Changes in the salinity of estuarine waters are a function of several variables, including the magnitude of freshwater inflow, tidal mixing, density currents, wind-induced mixing, evaporation, and salinity of source inflows. In the absence of highly saline inflow and neglecting wind effects the volume of antecedent freshwater inflow and the volume of tidal mixing are the most important factors affecting salinity. Salinities immediately inside the passes between the Gulf of Mexico and an estuary vary markedly with flood and ebb tide; the influence of tidal mixing attenuates with distance traveled inside the estuary from the gulf pass.

The dominance of the effect of freshwater inflow on estuary salinity increases with an increase in proximity to freshwater inflow sources. The areal extent of the estuary influenced by freshwater inflow varies in proportion to the magnitude of freshwater inflow except during conditions of extreme drought. Regression analyses of measured salinities versus freshwater inflow were carried out by TDWR staff to verify and quantify such relationships in locations near the mouths of the major rivers entering Texas estuaries. Such areas are major nursery ground for juveniles of important fishery species.

Average monthly salinities near each major river delta were related to the average monthly flows from the associated river using one of two equation forms:

$$S_i = c_{0i} Q_i^{c_{1i}} \tag{1}$$

$$S_i = c_{0i}(Q_i + Q_{i-1})^{c_{1i}} \tag{2}$$

where S_i is the average salinity for month i (in parts per thousand), Q_i is the average river flow to the delta in month i (in cubic feet per second), c_{0i}, c_{1i} are the constant coefficients for the month i equation. A separate equation was generated for each of the 12 months.

Commercial Fisheries Harvests and Freshwater Inflows

The influence of freshwater inflows upon the fisheries production of an estuary is a complex and imperfectly understood process. A sufficiently detailed, reliable causal mathematical model of the interactions in this process could not be created based upon current information. In addition to freshwater inflows the factors that have been identified as influencing commercial fishery harvests include fishery profitability and effort, water temperature, ocean currents, meteorological conditions, salinity, and habitat area [*Turner*, 1979; *Ulanowicz et al.*, 1982; *Walker and Saila*, 1984; *Hayman and Tyler*, 1980]. *Ulanowicz et al.* [1982] developed predictive equations of fisheries landings using predictor values of salinity, air and water temperatures, and daily precipitation. *Walker and Saila* [1984] derived white and brown shrimp annual harvests equations based upon principal component analysis using river discharges, salinity, water temperature, and shore current direction as basic variables.

Statistically significant linear regression equations were developed by TDWR staff relating freshwater inflows in each of five "seasonal" monthly groupings and, where data were available, annual fishing effort to annual commercial harvests of the important species and species groups in each estuary. The seasonal inflow terms were required to be biologically meaningful. The general equation for the annual harvest H_k of fisheries group k as a function of the freshwater inflow from a source j is

$$H_k = a_{0j} + \sum_{m=1}^{5} a_{mj} QS_{mj} + b_k E_k \tag{3}$$

or

$$H_k = a_{0j} \prod_{m=1}^{5} QS_{mj}^{a_{mj}} E_k^{b_k} \tag{4}$$

where a_{0j}, a_{mj}, and b_k are constants; QS_{mj} is the mean monthly freshwater inflow in season m from freshwater source j; and E_k is the annual harvest effort in daily trips per year for harvest group k. The harvest effort E_k was generally not available as data to use in (3) and (4).

Riverine Delta Inundation and Freshwater Inflows

The quantitative role of river flooding of riverine deltaic marshes to the ecological health and productivity of Texas estuaries is not fully understood. However, riverine flooding is regarded as essential to the maintenance of river delta marshes, which are considered by many estuarine ecologists to be important sources of nutrients [*de la Cruz*, 1973, 1980; *Heinle*, 1977] and areas of fish and wildlife habitat [*May*, 1974] in an estuary.

To formulate a water management program incorporating deltaic inundation, it is necessary to determine both the frequency and magnitude of historical flood events for the delta. If what has happened naturally in the past has been sufficient to maintain the productivity of the estuary, incorporation of historical patterns into a management plan will most likely provide inundation sufficient to maintain productivity in the future. This assumption is recognized as being an incomplete treatment of the quantification of the water needed for marsh inundation. However, ignoring the identified need for flood inflows is inconsistent with maintaining the ecological health of the estuary.

Historical streamflow records were used to determine past flood events in each of the major river deltas of Texas. On the basis of these results and biological information, freshwater needs for marsh inundation in each estuary were assigned by TDWR staff to individual months to reflect the past median magnitude and seasonal distribution of flood events, as well as timing for ecosystem biological needs. The monthly freshwater needs for marsh inundation are expressed as lower bounds $QIND_{ij}$ on the inflow Q_{ij} in month i from freshwater source j:

$$Q_{ij} \geq QIND_{ij} \quad (5)$$

Mathematical Problem Statement

The estimated freshwater inflow needs of an estuary are determined by finding the 12 monthly inflows from each of the major contributing river basins which either minimizes the total annual inflow or maximizes the annual fisheries harvest subject to constraints on average monthly salinities, annual commercial fisheries harvests, and monthly inflows. This formulation represents the general form of the freshwater inflow need estimation problem. Not all constraints need to be used in determining inflow needs. For example, if fisheries harvests are not considered, then the lower limits on these harvests may be set to zero.

Let i correspond to one of 12 months and j to one of the major rivers contributing freshwater to an estuary (NB). Further, let k correspond to one of the fisheries species groups harvested in the estuary (NS) and E_k, the annual fishing effort to harvest species of fisheries group k, be fixed at a specific value. Also, let **Q** be the matrix of all Q_{ij}, where Q_{ij} is the total inflow to the estuary in month i from river basin j. The set of monthly freshwater inflow needs for the estuary are the values of Q_{ij}, which

$$\min_{\mathbf{Q}} F(\mathbf{Q}) \quad (6)$$

subject to (1) upper and lower limits on monthly average salinities,

$$SMIN_{ij} \leq S_{ij} \leq SMAX_{ij} \quad (7)$$

$$i = 1, \cdots, 12 \qquad j = 1, \cdots, NB$$

(2) monthly average salinity definition,

$$S_{ij} = f_{ij}(Q_{ij}, Q_{ij-1}) \quad (8)$$

$$i = 1, \cdots, 12 \qquad j = 1, \cdots, NB$$

(3) lower limits on annual fisheries harvests by species,

$$HMIN_k \leq H_k(\mathbf{Q}) \qquad k = 1, \cdots, NS \quad (9)$$

(4) lower limits on monthly inflows for inundation needs,

$$QIND_{ij} \leq Q_{ij} \qquad i = 1, \cdots, 12 \qquad j = 1, \cdots, NB \quad (10)$$

(5) upper limit on total annual inflow from each river,

$$\sum_{i=1}^{12} Q_{ij} \leq QT_j \qquad j = 1, \cdots, NB \quad (11)$$

(6) upper and lower limits on seasonal inflows from each river,

$$SQMIN_{jm} \leq \sum_{i=L(m)}^{L(m+1)-1} Q_{ij} \leq SQMAX_{jm} \quad (12)$$

$$m = 1, \cdots, 5 \qquad j = 1, \cdots, NB$$

(7) upper and lower limits on monthly inflows from each river,

$$MQMIN_{ij} \leq Q_{ij} \leq MQMAX_{ij} \quad (13)$$

$$i = 1, \cdots, 12 \qquad j = 1, \cdots, NB$$

where

- f salinity equation defined by equation (1) or (2);
- F objective function of the monthly freshwater inflows;
- H_k annual commercial harvest function for harvest category k, defined by equation (3) or (4);
- $HMIN_k$ minimum allowable annual commercial harvest for fishery category k;
- $L(m)$ beginning month of season m, where $m = 1, \cdots, 5$ and $L(6) = 13$;
- $MQMAX_{ij}$ maximum inflow allowed for month i from river basin j;
- $MQMIN_{ij}$ minimum inflow allowed for month i from river basin j;
- **Q** array of all monthly inflows Q_{ij};
- Q_{ij} inflow to the estuary in month i from river basin j;
- $QIND_{ij}$ minimum inflow for inundation purposes in month i from river basin j;
- QT_j maximum annual inflow from river basin j;
- S_{ij} average salinity in month i in an area of the estuary near the inflow point for river basin j;
- $SMAX_{ij}$ maximum average salinity allowed in month i in a key area of the estuary near the inflow point for river basin j;
- $SMIN_{ij}$ minimum average salinity allowed in month i in a key area of the estuary near the inflow point for river basin j;
- $SQMAX_{jm}$ maximum inflow allowed in season m and from river basin j;
- $SQMIN_{jm}$ minimum inflow allowed in season m from river basin j.

Equations (12) and (13) represent the allowable range of seasonal and monthly inflows from each river so that the inflows remain with the range of flows for which regression equations (1)–(4) were developed.

Solution Procedure

Generally, the mathematical programming problem given by (6)–(13) is a nonlinear programming problem and was solved either by a steepest descent, gradient algorithm, or the GRG2 nonlinear programming algorithm [*Lasdon et al.*, 1980]. When the problem has only linear terms, it is a linear programming problem and was solved by the revised simplex algorithm [*Dantzig*, 1963], using a computer program developed by *Clasen* [1967].

ESTIMATES OF FRESHWATER INFLOW NEEDS

Specification of Estuarine Management Alternatives

Numerous estuarine management problems may be posed using the general problem formulation given in (6)–(13). To demonstrate the method for alternative formulations, three alternative management problems were proposed for each Texas estuary. The three alternatives were selected to provide estimates of freshwater inflow needs over a wide range of possible estuarine conditions, particularly those of fisheries harvest. With regard to commercial fisheries harvest, it is assumed that the profitability of fishing remains at the levels of the period 1962–1976, for which fisheries landings data were used.

The subsistence alternative (alternative I) considers the marsh inundation and salinity characteristics of an estuary

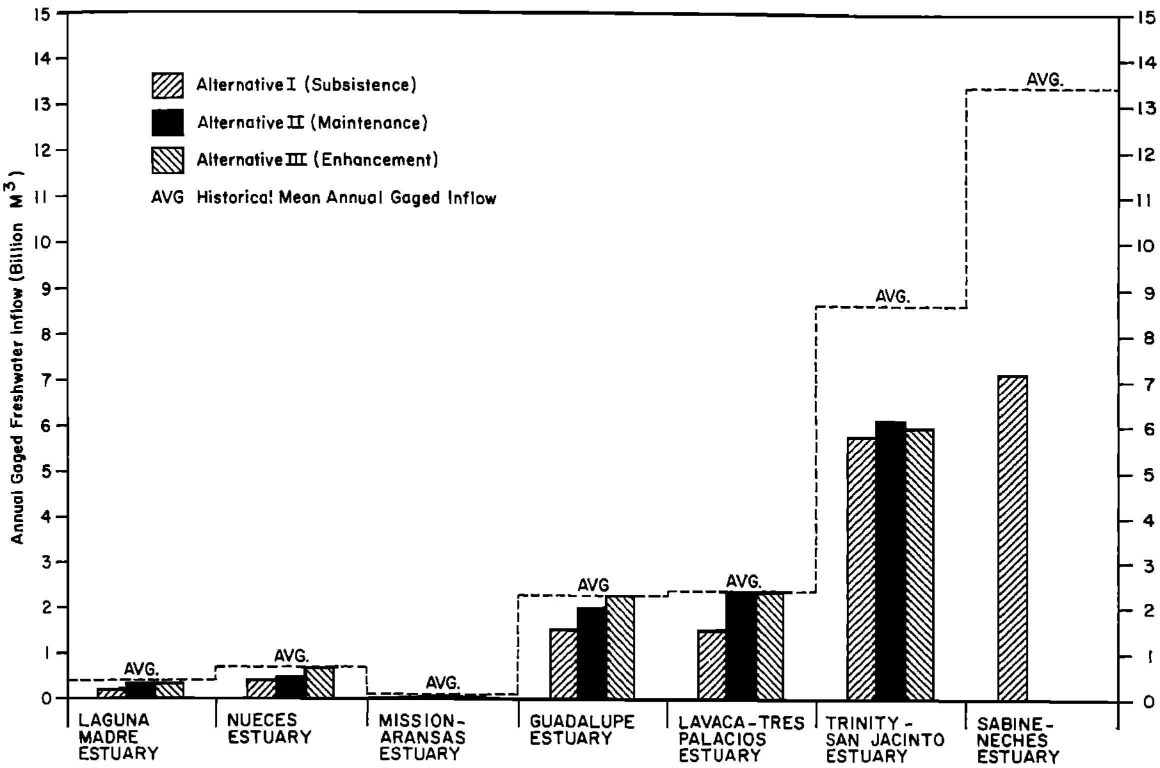

Fig. 3. Estimated annual gaged freshwater inflow needs and mean annual gaged historical freshwater inflows for seven Texas estuaries (1941–1976).

and establishes minimum monthly inflows for the basic purposes of nutrient transport, habitat, and salinity level control. Constraints (7), (8), (10), and (13) are used in this alternative, with minimization of an objective function (6) equal to the total annual freshwater inflow.

The estimated annual freshwater inflow need for the fisheries harvest maintenance alternative (alternative II) is the least annual inflow, distributed appropriately on both a monthly and a seasonal basis, such that this level of inflow satisfies the constraints of the subsistence alternative and also provides sufficient freshwater to support annual commercial fisheries harvests for each of the major species harvest categories in each respective estuary at levels equal to or greater than average annual catches over the period 1962–1976. The constraints used in this alternative are (7)–(10), (12), and (13).

A third alternative, termed fisheries harvest enhancement (alternative III), is considered in order to provide estimates of monthly and seasonal freshwater inflows needed to satisfy the constraints of the subsistence alternative and to maximize the harvest of a specific species of commercially harvested fish (which differs with the estuary considered). The total annual freshwater inflow is constrained under this alternative at a level not to exceed the mean annual historic inflow over the period 1941–1976. This alternative uses constraints (7)–(13).

Estimated Annual Freshwater Inflow Needs

The estuarine mathematical programming model was solved for each of the three management alternatives for each of the seven major Texas estuaries, with one exception. Inflow estimates for the Sabine-Neches estuary were not derived for the maintenance and enhancement alternatives, since the relationships between recorded inflows and fisheries harvests could not be utilized with validity over a range of inflows consistent with the subsistence alternative constraints. Such fisheries harvest estimates were required in order to determine inflow needs for alternatives II and III.

The estimates of estuarine freshwater inflow needs are expressed in terms of the annual volume of water passing the most downstream river-gaging station and represent the estimated volumes needed to satisfy the three alternative estuarine objectives described above. Ungaged inflows from the coastal basins to the estuaries are largely unregulated and are assumed, for total inflow accounting, to be at their computed historical average monthly rates for the 1941–1976 period. The ungaged inflow contributions from the major river basins are estimated based upon statistical relationships derived from recorded data which relate monthly total basin inflow to the gaged basin inflow component of total inflow.

The estimated annual gaged freshwater inflow needed, in addition to the ungaged inflow, for the Sabine-Neches and Trinity–San Jacinto estuaries under the three alternatives stated above are significantly less than the historical (1941–1976) mean annual gaged inflow to these estuaries (Figure 3). However, the gaged inflow needs for the estuaries along the drier central and southern portion of the Texas Gulf Coast (the Lavaca–Tres Palacios, Guadalupe, Mission-Aransas, Nueces, and Laguna Madre estuaries) are generally only slightly less than or equal to the 1941–1976 period average annual inflow for alternatives II and III (Figure 3). Excluding the Sabine-Neches estuary, the estimated total annual gaged inflow needs are approximately 9.4, 11.2, and 11.5 × 10^9 m^3 for alternatives I, II, and III, respectively. The inflow need of the Sabine-Neches estuary for the subsistence alternative amounts to approximately 7.0 × 10^9 m^3 annually. The

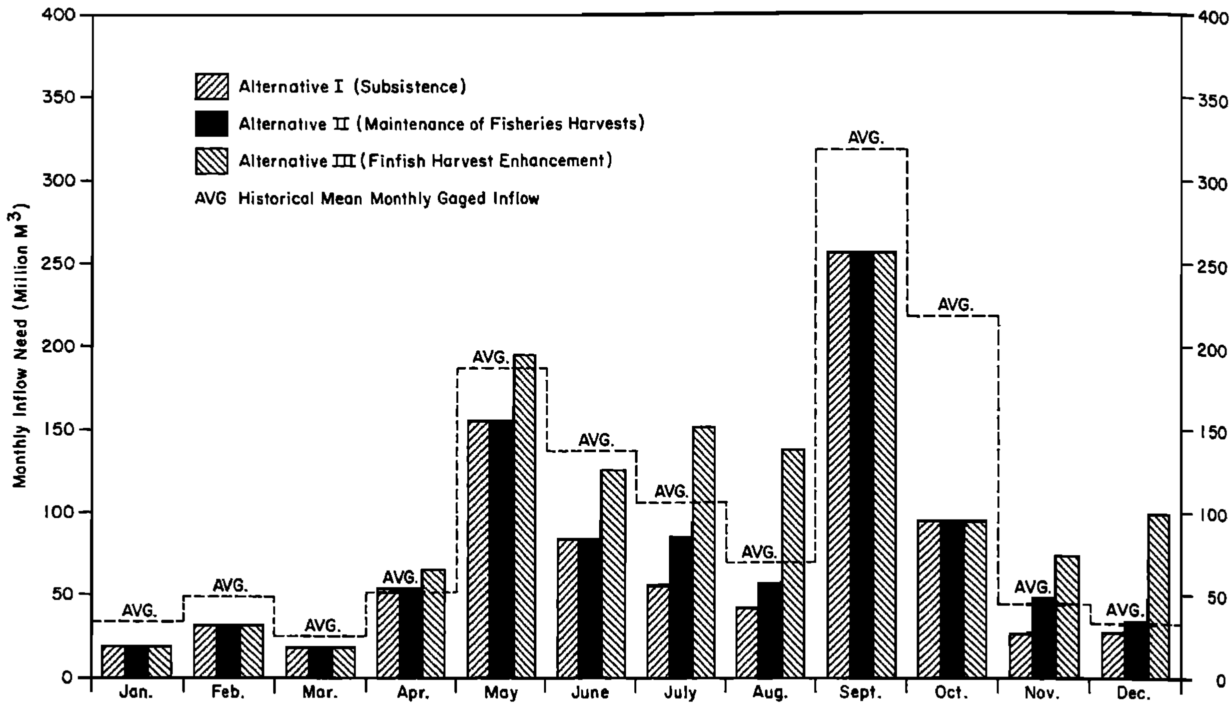

Fig. 4. Estimated monthly gaged freshwater inflow needs for the Nueces and Mission-Aransas estuaries under alternatives I, II, and III.

average 1941–1976 annual recorded gaged inflow to the seven estuaries was about 27.5 × 10^9 m^3.

Estimated Monthly and Seasonal Inflow Needs

The annual inflow needs shown in Figure 3 are derived from monthly and seasonal needs estimated for each estuary. The monthly and seasonal distribution of freshwater inflows were found to be perhaps more important to estuarine productivity than the annual volume of inflows. The importance of the seasonal timing of the inflows varies with each species in an estuary according to that species' life cycles. It was found that spring (April, May, and June) inflows were beneficial to the majority of commercially important estuarine species; however, directly opposite and conflicting relationships were detected between species in their preference for certain seasonal freshwater inflows.

To illustrate the monthly freshwater inflow needs derived for an estuary, the needs estimated for the Nueces and Mission-Aransas estuaries are shown in Figure 4 for each of the management alternatives.

Freshwater inflows estimated for alternative I total 0.85 × 10^9 m^3 annually (of which 46% is estimated from ungaged areas) to satisfy the basic salinity gradient and marsh inundation needs. This annual inflow is approximately 69% of the 1941–1976 historical average inflow.

Under alternative II (maintenance of fisheries harvests) the predicted annual commercial bay harvests of red drum, spotted sea trout, white shrimp, and blue crabs are each required to be at least as great as their 1962–1976 historical average levels. Salinity limits and marsh inundation needs are also to be observed. To satisfy these criteria, it is estimated that an annual freshwater inflow of 0.92 × 10^9 m^3 (with 44% from ungaged areas) is needed. This annual inflow volume is 75% of the average inflow (1941–1976).

Under alternative III (finfish harvest enhancement) the Nueces and Mission-Aransas estuaries have an annual estimated freshwater need of approximately 1.24 × 10^9 m^3 (41% from ungaged areas), distributed in a seasonally unique manner, to achieve the objective of maximizing the total annual predicted commercial bay harvest of finfish from both estuaries. The estimated water need to these estuaries equals the arbitrary maximum annual inflow set at the 1941-1976 average level. This limit was imposed to allow comparison of estuarine conditions, particularly harvest levels, when the entire average annual flow was assumed to be available. The annual finfish harvest, using the harvest regression equations with the calculated monthly inflow needs, is estimated to be 91% greater than the 1962–1976 average annual harvest. Of course, this estimate is only valid under the economic and regulatory conditions prevalent during the years 1962–1976.

Interpretation of Estimated Freshwater Inflow Needs

Texas estuarine ecosystems are dynamic and have historically received a wide range of freshwater inflows from drought to wet or hurricane years. In fact, it is generally believed that a constant rate of freshwater inflows would be detrimental to the estuarine organisms which have adapted to the prevailing dynamic annual and seasonal cycles. For this reason, the estimates of freshwater inflow needs in this report should be regarded as statistical long-term central tendencies (such as the average) of inflows needed to sustain the estuarine systems. Major events, such as hurricanes and uncontrolled floods, will continue to provide freshwater inflows that may greatly exceed the estimated needs.

Freshwater inflows needed to maintain an estuarine ecosystem can be provided from a combination of unregulated and regulated sources. In these analyses it has been assumed for computation purposes that the estuarine inflow from local uncontrolled drainages in adjacent coastal basins will continue in the future at historical levels. Inflows from the major contributing river basins, however, will in many cases be subject to significant alteration due to man's activities. In addition to freshwater entering an estuary in the needed volume and at the appropriate time it is also necessary that the inflows be relatively free of toxic pollutants and contain sufficient nutrient materials to insure continued reproduction and growth of estuarine organisms.

By law, surface water in Texas belongs to the state. Water is allocated, generally, by the Prior Appropriation Doctrine, which recognizes priority for beneficial use based upon the time of initial water use. Water rights to use and store surface waters are granted by the Texas Water Commission. The implementation of actions to meet any estuarine freshwater inflow requirements is subject to the decisions of the Texas Water Commission, through the existing state water management program. Such actions could most easily be accomplished by evaluating future applications for the appropriation of state waters on the basis of their estimated effect on the inflows to the estuaries during a specified base historical hydrologic period. Should a requested permit result in an estimated significant depletion of inflows, either on a monthly or an annual basis, to the estuary below the volume and frequency desired, then the permit might be modified to comply with any estimated estuarine freshwater inflow needs.

The use of freshwater for municipal, industrial, agricultural, and other activities is often in direct conflict with estuarine freshwater inflow needs. This conflict has generated a major public policy controversy in Texas over the past several decades [*Shelley et al.*, 1986]. Presently, Texas law does not mandate specific freshwater inflow needs. However, 5% of the firm yield of any reservoir within 200 river miles of the coast that is constructed with state financial involvement, is appropriated to instream uses and estuarine inflow releases. Further, for water use permits within 200 river miles of the coast the Texas Water Commission must include conditions for maintaining beneficial estuarine inflows, to the extent practicable when all public interests are considered.

Limitation and Extensions

The analysis described herein is considered by the author to be only a first step in quantifying the importance of freshwater inflows to Texas estuaries. The mathematical programming model as well as the analyses used to develop the statistical relationships used in the model are subject to limitations. The model is deterministic, while the physical and biological processes have significant random components. Generally, the statistical equations in the model accounted for more than 60% of the variation in the salinity and fisheries harvest data. Thus the model accounts for the major interactions on the average. A stochastic programming model would provide some measure of the uncertainties in the impacts of freshwater inflows. Further, the statistical salinity and fisheries harvest relationships used in the model often contain substantial standard errors which reflect additional causal factors besides freshwater inflows which should be included as data become available.

The results of the model are fixed monthly inflow need estimates reflecting the long-term needs of an estuary. They cannot be directly compared with historical average monthly inflows to evaluate the impact of a water development project upon an estuary. To perform such an evaluation, the monthly variation in inflows with the project in operation must be calculated over an extended historical period of many years. Such a period should cover both wet and dry years.

The process described above has been applied to determine the approximate impact of meeting several of freshwater inflow need levels upon the firm yield of a major reservoir [*Burnitt et al.*, 1983]. The firm yield was calculated based upon passing through the reservoir all inflows necessary to meet the fixed monthly and seasonal needs. The reservoir firm yield was reduced over 50%, for one of the inflow need alternatives, from the firm yield without any releases for bays and estuaries.

Further Studies

The 1985 Texas Legislature mandated that additional estuarine data collection and analysis programs be conducted by several state agencies, including TWDB, to provide information for water resources planning and management. These studies are to be completed by December 31, 1989. It is anticipated that the studies will include updating all data through at least 1985 and significantly revising all relationships developed as part of the previous studies. Further, detailed methods will be developed to analyze the impact of future major surface water resources projects upon estuaries' environmental conditions. Also, these procedures will assess alternative management plans for such projects which could reduce or eliminate some adverse impacts.

CONCLUSIONS

A mathematical programming model is presented for determining the monthly freshwater inflow needs for an estuary. The model is based upon relating freshwater inflows to key indicators of estuarine environmental conditions. The model is solved to determine the optimal freshwater inflow needs for each of the alternative management policies in six of the seven major estuarine systems in Texas. In the remaining estuary, freshwater inflows for only one of the management alternatives could be solved.

The limitations of the mathematical model are discussed, as well as extensions needed to answer questions concerning the impact of individual water resources development projects on estuarine ecosystems and productivity.

NOTATION

a constant coefficient.
b constant exponent.
c constant exponent.
E_k annual harvest effort.
f monthly average salinity.
F objective function.
H_k annual commercial harvest function.
$HMIN_k$ minimum allowable annual commercial harvest.
i month index.
j river basin index.
k fisheries harvest group index.
$L(m)$ beginning month of season m.
m season index.
$MQMAX_{ij}$ maximum monthly inflow allowed.

$MQMIN_{ij}$ minimum monthly inflow allowed.
$\mathbf{Q}$ array of all monthly inflows Q_{ij}.
Q_{ij} monthly inflow to estuary.
$QIND_{ij}$ minimum monthly inflow for inundation purposes.
QT_j maximum annual inflow.
QS_{mj} average monthly inflow in season.
S_{ij} monthly average salinity.
$SMAX_{ij}$ maximum monthly average salinity allowed.
$SMIN_{ij}$ minimum monthly average salinity allowed.
$SQMAX_{jm}$ maximum seasonal inflow allowed.
$SQMIN_{jm}$ minimum seasonal inflow allowed.

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