Coastal and Estuarine Research Federation

Methods for Determining Minimum Freshwater Inflow Needs of Texas Bays and Estuaries
Author(s): Gary L. Powell, Junji Matsumoto, David A. Brock
Source: *Estuaries*, Vol. 25, No. 6, Part B: Dedicated Issue: Freshwater Inflow: Science, Policy, Management: Symposium Papers from the 16th Biennial Estuarine Research Federation Conference (Dec., 2002), pp. 1262-1274
Published by: Coastal and Estuarine Research Federation
Stable URL: http://www.jstor.org/stable/1352856
Accessed: 25/11/2009 15:07

Your use of the JSTOR archive indicates your acceptance of JSTOR's Terms and Conditions of Use, available at http://www.jstor.org/page/info/about/policies/terms.jsp. JSTOR's Terms and Conditions of Use provides, in part, that unless you have obtained prior permission, you may not download an entire issue of a journal or multiple copies of articles, and you may use content in the JSTOR archive only for your personal, non-commercial use.

Please contact the publisher regarding any further use of this work. Publisher contact information may be obtained at http://www.jstor.org/action/showPublisher?publisherCode=estuarine.

Each copy of any part of a JSTOR transmission must contain the same copyright notice that appears on the screen or printed page of such transmission.

JSTOR is a not-for-profit service that helps scholars, researchers, and students discover, use, and build upon a wide range of content in a trusted digital archive. We use information technology and tools to increase productivity and facilitate new forms of scholarship. For more information about JSTOR, please contact support@jstor.org.

Coastal and Estuarine Research Federation is collaborating with JSTOR to digitize, preserve and extend access to *Estuaries.*

http://www.jstor.org

Estuaries Vol. 25, No. 6B, p. 1262–1274 December 2002

Methods for Determining Minimum Freshwater Inflow Needs of Texas Bays and Estuaries

GARY L. POWELL*, JUNJI MATSUMOTO, and DAVID A. BROCK

Texas Water Development Board, 1700 North Congress Avenue, Austin, Texas 78711-3231

ABSTRACT: In response to legislative directives beginning in 1975, the Texas Water Development Board (TWDB) and the Texas Parks and Wildlife Department (TPWD) jointly established and currently maintain a data collection and analytical study program focused on determining the effects of and needs for freshwater inflows into the state's 10 bay and estuary systems. Study elements include hydrographic surveys, hydrodynamic modeling of circulation and salinity patterns, sediment analyses, nutrient analyses, fisheries analyses, freshwater inflow optimization modeling, and verification of needs. For determining the needs, statistical regression models are developed among freshwater inflows, salinities, and coastal fisheries. Results from the models and analyses are placed into the Texas Estuarine Mathematical Programming (TxEMP) model, along with information on salinity viability limits, nutrient budgets, fishery biomass ratios, and inflow bounds. The numerical relationships are solved within the constraints and limits, and optimized to meet state management objectives for maintenance of biological productivity and overall ecological health. Solution curves from the TxEMP model are verified by TWDB's hydrodynamic simulation of estuarine circulation and salinity structure, which is evaluated against TPWD's analysis of species abundance and distribution patterns in each bay and estuary system. An adequate system-wide match initially verifies the inflow solution. Long-term monitoring is recommended in order to verify that implementation of future water management strategies maintain ecological health of the estuaries and to provide an early warning of needs for adaptive management strategies.

Introduction

The inflow of freshwater is widely recognized as an essential factor influencing the biological productivity of estuarine (tidal) areas as diverse as the Nile Delta (Ben-Tuvia 1973; Halim 1975); the Gulf of St. Lawrence (Sutcliffe 1972, 1973), and the bays and estuaries of the Gulf of Mexico (Copeland 1966; Schroeder 1978; Powell 1979). Freshwater inflow affects coastal bays and estuaries at all basic levels of interaction; that is, with physical, chemical, and biological effects. The functional roles of freshwater inflow in the ecology of estuarine environments have been scientifically reviewed by previous researchers (Hackney 1978; Cross and Williams 1981; Texas Department of Water Resources 1982; Skreslet 1986; Estevez 2002). Positive effects are noted for estuarine circulation patterns, salinity gradients, sediment transport, nutrient supplies, and the production of valuable coastal fisheries, while most negative effects are related to the associated transport of toxic compounds, pollutants, and disease organisms from adjacent land drainages.

The crucial need for freshwater inflows to Texas bays, estuaries, and their economically important fishery resources, was first recognized by Hildebrand and Gunter (1953). At that time, virtually all parts of the state were experiencing the effects of one of the most severe droughts in modern history. Beginning in 1948, the drought was finally broken by heavy rains and flooding in the spring of 1957. During 1956, the worst year of the decade-long drought, combined river discharges measured at the last streamflow gaging station on each major Texas river amounted to only 5.06×10^9 m^3, or about 14% of the average annual freshwater inflows to the state's bays and estuaries. As a result of the drought, bay oyster (*Crassostrea virginica*) production in Texas practically ceased, white shrimp (*Litopeneus setiferus*) harvests were drastically reduced, and estuarine-dependent fishes such as the black drum (*Pogonias cromis*) were blinded and exhibited body lesions from extreme high salinity stress in the state's most southern bays and lagoons (Simmons and Breuer 1962).

The first effort of the state agencies to comprehensively address the coast-wide problem of freshwater inflows in Texas began with a legislative mandate in 1975 (Texas Senate Bill 137) to perform studies on the needs of bays and estuaries. Legislative directives, policy issues, and water rights problems in Texas are described in further detail by Grubb (1981). The cooperative study program resulted in a series of reports that explored the influence of freshwater inflows on each major estuary (e.g., Texas Department of Water Resources 1981). One unique aspect of these reports was the

---

* Corresponding author; tele: 512/936-0815; fax: 512/936-0816; e-mail: gary.powell@twdb.state.tx.us.

use of a mathematical programming (optimization) approach to the problem and a recommendation to continue estuary monitoring and study in order to provide more and better data to the analysis so that the reliability of the solutions might become adequate for state water planning and permitting.

Key language added to the Texas Water Code (West Group 2000) by the state legislature in 1985 renewed the general study mandate and provided specific directives that continue to shape the Texas approach to the problem: "For permits issued within an area that is 200 river miles from the coast, to commence from the mouth of the river thence inland, the commission shall include in the permit, to the extent practicable when considering all public interests, those conditions considered necessary to maintain beneficial inflows to any affected bay or estuary system." (Texas Water Code 11.147(b)). The phrase "beneficial inflows" was defined further: "In this section, 'beneficial inflows' means a salinity, nutrient, and sediment loading regime adequate to maintain an ecologically sound environment in the receiving bay and estuary system that is necessary for the maintenance of productivity of economically important and ecologically characteristic sport or commercial fish and shellfish species and estuarine life upon which such fish and shellfish are dependent" (Texas Water Code 11.147(a)).

Subsequent agreements between the state agencies brought their staffs together with scientists from cooperating universities to work in a consensus effort to investigate each major estuary with a standard protocol for developing freshwater inflow recommendations that could be implemented in the state water planning and permitting processes. Because of potential conflicts with inland water users, where future water demands may grow an additional 9.25×10^9 m^3 by year 2050 (Texas Water Development Board 2002), there is an increasing need to incorporate results from the freshwater inflow studies into the operating rules of water impoundment and diversion projects so that they will cause the least harm to the environment while allowing the maximum beneficial use of state waters. The optimization approach provides a framework for allowing incorporation of often-conflicting goals and requirements into the decision-making process. This paper presents the method for application of the optimization approach that has evolved.

Methods for Determination of Freshwater Inflow Needs

The type of tool employed by the state agencies to bring the individual parts of the freshwater inflow study together was a mathematical programming (optimization) model. The following sections describe how the various aspects of estuarine freshwater requirements were quantified in the model. Application of the approach to Galveston Bay, Texas illustrates the methods used to solve the problem.

HYDROLOGIC DATA

Hydrological data referred to below and used in the analyses were compiled from U.S. Geological Survey (USGS) gaged flows measured at the last nontidally affected streamgaging station in each contributing river basin, ungaged flows of river and coastal drainage basins that contribute freshwater to each estuarine system, and records of permitted water diversions from and wastewater discharges into the ungaged watersheds. The ungaged inflows were estimated using the TxRR model (Matsumoto 1992) to simulate rainfall runoff. The sum of all these surface discharges is referred to below as the combined inflow to the estuary. Direct precipitation on and evaporation from the bay surface was also calculated and used in some aspects of the analysis, such as the salinity modeling and the estimation of atmospheric deposition of nitrogen.

UPPER AND LOWER INFLOW BOUNDS

Three different sets of flow bounds were defined to constrain the optimization solution. Monthly flow bounds limited modeled flow in any monthly period. Seasonal bounds, based on 2-mo intervals, corresponded with the bimonthly periods used in fishery harvest equations. Annual bounds were used to limit modeled flows on an annual basis. Because stream flows to Texas bays and estuaries are typically episodic and exhibit kurtotic distributions, median inflows were most often chosen over mean average inflows as the central tendency value of the upper bounds. In this way, the upper bounds more reliably reflect the amount and frequency of normal flows to the systems. Lower bounds were based on the 10th percentile of inflows to avoid the potential problem of producing solutions requiring severe drought conditions. Between the 10th and 50th percentiles lies a zone within which water management strategies in Texas can be most effective in protecting estuaries. Developing solutions that require droughts or floods to meet an estuary's needs for normal flow were considered undesirable by the state agencies. All bounds were based on combined inflow statistics for the 54-yr period 1941 to 1994.

SALINITY AND INFLOW RELATIONSHIPS

Perhaps the most direct and measurable effect of freshwater inflow is on an estuary's salinity gra-

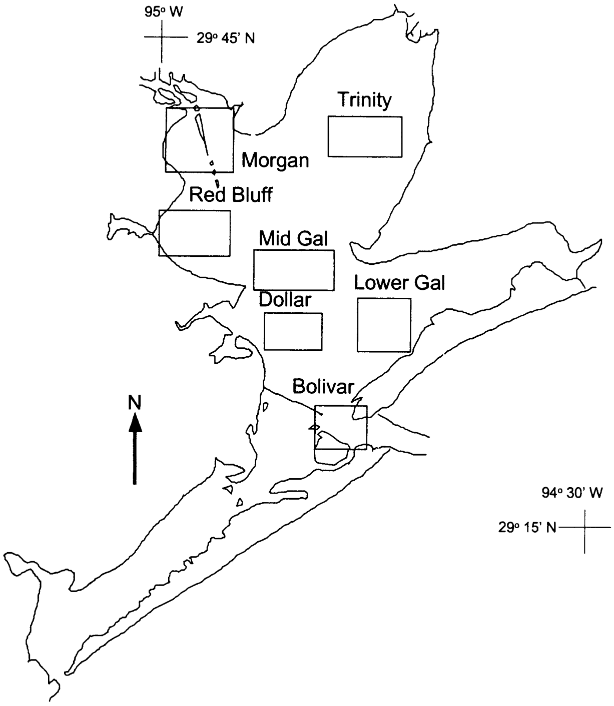

Fig. 1. Location of salinity areas within Galveston Bay for which salinity bounds and salinity-inflow regressions were computed.

TABLE 1. Lower and upper salinity bounds (psu) for Galveston Bay index stations.

	Dollar Point		Red Bluff		Trinity Bay	
Month	Lower	Upper	Lower	Upper	Lower	Upper
January	10	30	5	20	5	20
February	10	30	5	20	5	20
March	10	25	5	20	5	15
April	10	25	5	20	5	15
May	10	20	5	20	1	15
June	10	20	2	15	1	15
July	10	25	5	15	1	15
August	10	30	5	20	5	15
September	10	30	5	25	5	20
October	10	30	5	25	5	20
November	10	30	5	20	5	20
December	10	30	5	20	5	20

dient. The goal here is to identify a salinity gradient that is characteristic of that system and its associated flora and fauna. Most Texas bays are vertically well mixed, at least outside the deep navigation channels. This, together with their broad shallow morphometry, means that spatial salinity gradients, rather than vertical salinity profiles, show freshwater-saltwater interaction (Solis and Powell 1999). For development of freshwater inflow recommendations, an efficient representation of salinity variation and its dependence on the inflow regime was needed. In bay areas with adequate amounts of salinity data available, temporal salinity frequency distributions were examined in order to determine what salinity ranges are characteristic of each area. Salinity-inflow regressions were used to quantitatively relate freshwater inflow to salinities at key sites. A high-resolution hydrodynamic and conservative mass (salinity) transport model was also used in later stages of the analysis.

In the Galveston Bay example, seven areas with a substantial amount of salinity data available were used to define the salinity gradient (Fig. 1). From these, three were selected to represent the longitudinal salinity gradient from the river inflow points to the Gulf of Mexico: Trinity Bay, Red Bluff-Clear Lake, and Dollar Point. Salinity data from the past three decades were taken from the ambient water, fish, and seafood sanitation monitoring programs of the Texas Water Development Board, Texas Parks and Wildlife Department, Texas Commission on Environmental Quality, and the Texas Department of Health. All data before December 1986, and some data after that date, came from single point measurements made at various times throughout the year. Beginning in late 1986, ambient water quality data at several sites also were collected in situ by automated instruments (Hydrolab Datasondes) recording at 1-h or 2-h intervals. To keep Datasonde data from overly influencing the less-frequently collected single point measurements, data from the near continuously-recording instruments were reduced to single points by averaging over 7-d periods.

SALINITY BOUNDS

One way to incorporate the desired salinity gradient into the optimization approach is through specification of upper and lower salinity bounds for each salinity zone. In practice, this is a two-part process. The 25th and 75th percentile salinities are first calculated from the historical salinity distributions of each area of interest. These salinities are then evaluated with respect to the salinity tolerances and preferences of characteristic indicator species of plants and animals in each area, such as emergent marsh vegetation, seagrass beds, and reef communities of fish and shellfish (Copeland and Bechtel 1974; Longley 1994; Estevez 2000). Salinity limits are evaluated monthly in order to also take into account the needs of migratory species which enter the estuary, often as larvae, at various times during the annual cycle (Rounsefell 1975; Sheridan and Livingston 1979). Because Texas estuaries can have remarkable salinity variations from near fresh to hypersaline levels as a result of episodic floods and droughts (Collier and Hedgpeth 1950), the upper and lower salinity bounds are broadly set (Table 1).

TABLE 2. Salinity-inflow equations for index sites in Galveston Bay. Q_1 is sum of previous 30-day inflow. Q_2 is summed inflow for the 30 days preceding Q_1.

	Equation	n	SE	F	Adj-r^2
Trinity Bay	$S = 49.109 - 3.221 \times \ln(Q_1) - 3.039 \times \ln(Q_2)$	226	3.25	338.3	0.72
Red Bluff	$S = 42.438 - 3.567 \times \ln(Q_1) - 1.179 \times \ln(Q_2)$	260	3.70	141.7	0.52
Dollar Point	$S = 48.803 - 4.316 \times \ln(Q_1) - 0.757 \times \ln(Q_2)$	277	4.29	156.8	0.53

SALINITY-INFLOW EQUATIONS

Salinity data for the period 1977 through 1990 were used in developing the salinity-inflow equations for Galveston Bay and the Trinity-San Jacinto estuary (Table 2). Salinity was treated simply as a function of two values, the total inflows in the previous 30-d period before the salinity measurement (Q_1) and the total inflows of the antecedent period 30 to 60 d before the salinity measurement (Q_2). Regression of salinity on inflow is problematical in that hysteresis effects (Whitfield and Schreier 1981) and offshore salinity variations influenced by the Mississippi River plume (Wiseman and Kelly 1994) both introduce noise, but satisfactory equations were generated using logarithmic transformations of inflows.

FRESHWATER INFLOW AND NUTRIENTS

Since freshwater inflow is the major supplier of nutrients to the bays and estuaries of Texas, a desirable approach to its assessment included the evaluation of estuarine nutrient status (i.e., potential eutrophication) and the balance between estuarine mechanisms of nutrient gain and loss. The volume of flows is tied not only to the rate of nutrient input, but also to the rate of nutrient export through flushing, and to the amount of time nutrients are exposed to biogeochemical cycling in the estuary (Dettmann 2001). The approach tried in Texas was to develop nutrient budgets for annual periods that link gains and losses to the internal pool to freshwater inflow volumes. Budgets of total nitrogen were developed using the method described in Brock (2001). There was insufficient data on the inflow relationship of a major loss term, denitrification, despite several studies that contributed valuable data (Zimmerman and Benner 1994; Joye and An 1999). This greatly hindered the effort to develop a nutrient constraint for direct inclusion in the optimization approach. Uncertainty in the budget components was also a limiting factor. The nutrient constraint for Galveston Bay was developed based mostly on assumptions concerning pre-development input levels. The loading of nitrogen into Galveston Bay under premodern conditions was based on median stream flows with concentrations of 1.2 mg L^{-1} N (Jensen et al. 1991), although lower estimates were suggested in early data compiled by Omernik (1976). If the median historical flow (12.5×10^9 m^3) is used to represent pre-modern flows, then the nutrient concentration times the median inflow rate gives a mass loading of 14.94×10^9 g N yr^{-1}. This pre-development median streamflow loading is proposed as a minimal bay nitrogen requirement under current conditions. A nitrogen-based lower bound on required freshwater inflows can be calculated from this loading information. Since current stream concentrations have a median value of 2.49 mg L^{-1}, it would take a target median annual inflow of 6.00×10^9 m^3 to deliver 14.94×10^9 g N yr^{-1}. This constraint was used as a general external check on the feasible solutions, rather than applied internally to the optimization model for Galveston Bay.

SEDIMENT CONSTRAINT

Historical data on suspended sediment concentrations in Texas rivers was collected by the USGS as part of their streamgaging activity, but it did not include the bed load fraction that is also important in building and maintaining river deltas. For Galveston Bay, there was the additional uncertainty concerning how much sediment the river would carry below upstream reservoirs. A sediment requirement based on maintaining the salt marshes of the Trinity River delta was considered. Studies were undertaken to relate the rate of deposition of sediments in the delta to flood flows of the Trinity River. Sediment cores were taken at 10 sites in the delta and strata were dated using naturally occurring lead isotopes (White and Morton 1993). Amounts of sediment deposited were compared with cumulative river flows for each period in which the flood deposition occurred. Various volumetric thresholds were used to try to focus the analysis on flood flows large enough to overbank the river and reach the sample sites in the deltaic marshes. Only one site immediately adjacent to the river's natural levee showed a weak correlation between flood flows and deposition. None of the other sites showed any positive relationship between flood flows and sediment deposition. Attempts to relate deposition with sediment load from the river were also unproductive. Consequently, a sediment constraint for the analysis could not be defined in terms of freshwater inflow. This was probably because the river only inundates the delta 2–3 times

TABLE 3. Sources of data for fisheries harvests in Texas.

Fisheries	Years Covered	Source
Fish and shellfish	1962 through 1968	Texas Landings, Farley 1963–1969, U.S. Department of the Interior
	1969 through 1976	Texas Landings, Farley 1970–1978, U.S. Department of Commerce
Fish and shellfish	1977 through 1987	Quast et al. 1988
Shrimp	1959 through 1968	Gulf Coast Shrimp Data, U.S. Department of the Interior
	1969 through 1976	Gulf Coast Shrimp Data, U.S. Department of Commerce

per year on average, while tidal inundation occurs more than two dozen times per year (Texas Department of Water Resources 1981). This suggests that sediments carried by the river into upper Trinity Bay are being resuspended by wind and storm tides and transported back into the delta's wetlands. Since geological compaction, anaerobic fermentation, and other forms of subsidence can reduce the surface elevation of these wetlands, the fact that the delta continues to be more or less stable indicates that sediment inputs under current conditions appear adequate to maintain the delta, providing no barrier to these tidal flows is erected as part of a water management strategy.

QUANTIFYING THE INFLOW AND FISHERIES RELATIONSHIPS

Harvest data on red drum (*Sciaenops ocellatus*), black drum (*Pogonias cromis*), spotted seatrout (*Cynoscion nebulosus*), southern flounder (*Paralichthys lethostigma*), blue crab (*Callinectes sapidus*), eastern oyster (*Crassostrea virginica*), brown shrimp (*Farfantepenaeus aztecus*), and white shrimp (*Litopeneus setiferus*), were used to quantify the relationship between inflows and fisheries. Annual catch data were obtained from several sources because of periodic changes in governmental methods, coverage, and publications (Table 3).

All harvest weights are given as whole animal weights except for shrimp and oysters. Heads-on shrimp weights were calculated by multiplying the heads-off weights by 1.54 (white shrimp) or 1.61 (brown shrimp). Oyster weights are given only as shucked meat weights.

Although there are several environmental variables that could be related to coastal fisheries in Texas, such as minimum water temperatures, red tides, or amount of intertidal marsh, the focus of this analysis was on the effect of freshwater inflows on fisheries harvest.

Because some of the target fisheries species, such as the red drum, are long-lived, while others like the shrimp species can be considered annual crops in Texas waters, the harvest of most species was not simply related to the corresponding inflows during the year. The harvest of brown and white shrimp is related in the analysis to inflows during the past year in which they matured, while the harvest of oysters and blue crabs is related to inflows over the past two years because of their slightly longer life-cycle to maturity. Lagging inflows one, two, or more years has proven effective in developing relationships with catch metrics (Hildebrand and Gunter 1953; Sutcliffe 1972, 1973; Powell 1979; Stevens 1979). In consideration of their life histories, and with some trial and error, the harvest of marine fishes like the red drum and spotted seatrout in any year were related to inflows over the previous three years to produce the best harvest equations. This procedure recognizes that environmental effects on the survival and growth of the young may not be expressed until the affected age-class matures and enters the commercially exploited adult population sometime later (Hjort 1914; Gulland 1965; May 1974).

STATISTICAL METHODS

The fisheries-inflow relationship was quantified through statistical regression of seasonal inflows on annual harvests. Because of potential problems with covariance among the monthly inflows and the relatively limited number of years with harvest data ($n < 30$), the desire to include each of the twelve monthly flows in the harvest equations could not be accomplished without compromising the statistical analysis. A reduction in the number of independent variables was required. Sorting the data into bimonthly intervals reduced the number of inflow variables from twelve to six. A further reduction to four using quarterly inflow variables was considered but proved unnecessary in developing statistically significant equations. The bimonthly flow variables were defined as Q_{JF} = January + February, Q_{MA} = March + April, etc. Multiple regression equations of the following form were estimated to relate the fishery harvests (H_k) to seasonal inflows:

$$H_k = a_0 + \sum_{s=1}^{6} a_s \cdot \ln(Q_s)$$

where a_0, a_s are the regression constants, s is the index for seasons, and Q_s is the total seasonal inflow.

Analysis of the time series records of the dependent variable (fishery harvest) and the independent predictor variables (bimonthly freshwater inflows and fishing effort, where available) was accomplished using the All Possible Subsets Regression (9R) computer program contained in the BMDP statistical package (Dixon et al. 1988). The statistical procedure allows the ten best subsets of predictor variables to be identified using the Mallows' C_p criterion. Mallows' C_p has a built-in penalty to guard against overfitting the model, as may happen when the selection criterion is based solely on maximization of r^2. Evaluations based on how equation variables meshed with the months or seasons when the migratory species were using the estuary also guided selection of final equations used in the optimization approach.

Nonlinear and curvilinear relationships among the variable were transformed to linearity most successfully with natural logarithms (ln) in the analysis. Regression analyses were performed with both transformed and non-transformed data. The unexplained variation (residuals) from the regression analyses were also statistically examined using the Runs test for serial correlation and the Durbin-Watson test for autocorrelation to guard against acceptance of equations with collinearity. Statistical errors were generally homoscedastic because inflows are randomly distributed about the regression line.

Detection and removal of outliers were accomplished where necessary by identifying the case(s) with maximum values for Cook's Distance, Mahalanobis Distance, and the standardized residual. When potential outliers were identified, the regression analysis was repeated with the outlier case(s) removed sequentially, usually producing an improved harvest equation. Outliers never exceeded 10% of the years in any of the fishery records analyzed here.

The regression analysis produced statistically significant relationships for the eight target species from the Galveston Bay system (Table 4). Although most species related negatively to winter (January + February) inflows and positively to fall (November + December) inflows, there is a substantial amount of variability among the fishery species to inflows in the other months or seasons. For example, the oyster, red drum, and white shrimp are negatively related to summer (July + August) inflows, while the black drum, brown shrimp, and flounder are positively related to inflows in this same season. The fishery species may have conflicting relationships to inflows or they may reinforce each other's needs, depending upon the season being considered.

FISHERIES CONSTRAINTS: HARVEST TARGETS AND HISTORICAL VALUES

Harvest targets were computed for use as constraints in the optimization modeling to represent

TABLE 4. Fisheries inflow regression equations for Galveston Bay.

Species	Equation	R^2	Adj-r^2	SE	N Used	N Deleted
Blue crab	$H = 751.23 - 0.2756Q_{JF} + 0.8464Q_{MA} - 0.1839Q_{MJ} - 0.4747Q_{SO} + 0.6001Q_{ND}$	0.82	0.76	413.29	23	3
Eastern oyster	$H = 4169.8 - 0.9397Q_{JF} + 0.2838Q_{MJ} - 0.9445Q_{JA}$	0.53	0.46	914.01	25	1
Red drum	$\ln(H) = 3.1548 + 0.000393Q_{MJ} - 0.002043Q_{JA} + 0.0006981Q_{SO}$	0.66	0.59	0.536	19	1
Black drum	$H = 50.225 - 0.02985Q_{JF} + 0.1040Q_{JA} - 0.06391Q_{SO} + 0.03292Q_{ND}$	0.51	0.41	42.12	25	1
Spotted seatrout	$\ln(H) = 8.2764 - 1.8241 \times \ln(Q_{JF}) + 1.4248 \times \ln(Q_{ND})$	0.57	0.52	0.494	20	0
Brown shrimp	$H = 1019.8 - 0.5779Q_{JF} + 0.4192Q_{JA} + 0.4060Q_{SO} + 0.3533Q_{ND}$	0.57	0.49	582.75	27	2
White shrimp	$H = 3212 - 0.6905Q_{JF} + 0.2734Q_{MA} - 0.3254Q_{JA} + 0.5046Q_{ND}$	0.64	0.57	584.3	27	2
Flounder	$H = -12.12 - 0.03094Q_{JF} + 0.05408Q_{JA} + 0.0494Q_{ND}$	0.60	0.54	42.49	25	1

TABLE 5. Galveston Bay selected fisheries harvests (10^3 kg yr^{-1}) and harvest targets for optimization.

Species	Minimum	Maximum	Mean	Target (80% of Mean)
Blue crab	141.21	1,369.24	770.94	616.76
Eastern oyster	19.55	3,160.28	1,195.87	956.69
Red drum	0.59	44.23	14.11	11.29
Black drum	3.58	122.02	30.48	24.40
Spotted seatrout	7.71	156.13	75.93	60.74
Brown shrimp	3.90	1,479.37	597.53	478.00
White shrimp	445.44	2,132.24	1,314.26	1,051.40
Flounder	1.91	101.02	25.95	20.77

TABLE 6. Galveston fisheries harvest proportions and harvest ratio bounds for selected species.

Species	% of Harvest	Harvest Ratio Lower Bound	Harvest Ratio Upper Bound
Blue crab	19.0	0.116	0.266
Eastern oyster	27.9	0.095	0.462
Red drum	0.4	0.000	0.007
Black drum	0.7	0.002	0.012
Spotted seatrout	2.0	0.007	0.033
Brown shrimp	14.1	0.066	0.217
White shrimp	35.5	0.233	0.478
Flounder	0.3	0.001	0.005

desired levels of productivity of the system (Table 5). Oyster harvest is given as shucked meats only and, for blue crabs, the meats were estimated to be 15% of the whole animal weight reported in the harvest records. The fishery harvest targets used in the optimization model were more or less arbitrarily set to no less than 80% of the mean historical harvest of each species in the analysis to allow for good production from each sector of the commercial fishery. This has the added benefit of providing the optimization model more mathematical space in which to find feasible solutions. If the targets were set at the average harvest of each species, then there would be no feasible solution because all species can not be at their average harvest level at the same time, unless they all have the same response to the monthly or seasonal inflows.

FISHERIES CONSTRAINTS: HARVEST RATIOS

In its original form, the optimization model permitted harvest equations to be weighted for individual species in the calculation of the objective function (i.e., the freshwater inflow need). The purpose of this weighting was to allow control of the relative importance of individual species in the optimization procedure. If the weight of a regression equation were set to zero, that equation would not help drive the model's solution. The optimization results would be independent of that species' relationships to inflows, although the model will calculate the estimated harvest of that species under the optimized inflow conditions dictated by the other species in the model. The harvest equation of a species could be weighted so it contributed more to the solution of the objective function than the equation of another species. This was considered to be a convenient way to allow different management options to be tried. The nonlinear nature of the equations frequently resulted in calculated harvests for some species greater than that observed historically. To remedy this unrealistic tendency, a constraint was added as a refinement to the optimization routine. This constraint was referred to as the harvest or biomass ratio and was based upon historical harvest or biomass data from the estuary. For Galveston Bay, the only years that included commercial harvests from all of the fishery species were 1962–1981, because the red drum and spotted seatrout were declared to be recreational species after that period (Table 6). The constraint guaranteed that the relative harvests of species from the optimization model remained within ranges that have been observed for the estuary (e.g., the Galveston Bay inflow solutions produce about 10 kg of white shrimp for every 1.0 kg of spotted seatrout). The constraint avoids the problem of the model calculating a solution that provides exceptionally abundant harvest for one or two species to the detriment of all others.

Setting the model's bounds on the harvest ratios was more difficult. A variety of methods were considered in defining the upper and lower bounds including use of observed minimum and maximum ratios over the period of record or selection of a statistical ratio. Consideration was initially given to using the mean ratio plus or minus three standard errors. The attraction of the standard error was that its statistical characteristics are well known. However, the range of values for the bounds was deemed too narrow so several other bounding conditions were tried. The condition that worked well and allowed feasible solutions to be computed by the optimization model was plus or minus 1.15 standard deviations about the mean. This bounding condition includes approximately 75% of the harvests during the period of record, since 1.15 standard deviations includes 75% of the area under a normal distribution curve.

TEXAS ESTUARINE MATHEMATICAL PROGRAMMING (TxEMP) MODEL

The optimization approach selected here has one major advantage, it results in objective recommendations for inflow requirements that are not dependent upon the professional judgement of the scientists and engineers involved to pick the right number. This approach has removed potentially stifling negotiations on technical points from

TABLE 7. Form of constraints and objectives used in the TxEMP optimization model.

Constraint or Objective	Formal Expression	Notes	No.
MinQ	$\min \sum_{j=1}^{12} Q_j$	The minimum flow which meets all demands and constraints; Q_j is inflow for month j	1
MaxQ	$\max \sum_{j=1}^{12} Q_j$	The maximum allowable flow; Q_j is inflow for month j	2
MaxH	$\max \sum_{k=1}^{K} H_k$	H_k is harvest, species k	3
MaxH species set	$\max \sum_{k=1}^{K} P_k \cdot H_k$	P_k is preference factor, species k	4
MaxSalP		Maximum probability of satisfying salinity constraints	5
MaxHarP		Maximum attainable probability of satisfying fishery harvest constraints	6
Deterministic salinity constraint	$SLB_{ij} \leq S_{ij} \leq SUB_{ij}$	SLB is lower bound, i refers to zone, j refers to month	7
Chance form of salinity constraint	$Prob\{SLB_{ij} \leq S_{ij} \leq SUB_{ij}\} \geq SalP_i$	Prob is probability of satisfying constraint	8
Lower bound salinity chance constraint	$Prob\{S_{ij} \geq SLB_{ij}\} \geq SalP_i$		9
Upper bound salinity chance constraint	$Prob\{S_{ij} \leq SUB_{ij}\} \geq SalP_i$		10
Harvest chance constraint	$Prob\{H_k \geq T_k\} \geq HarP_k$	T_k is harvest target for species k	11
Monthly inflow constraint	$QLB_j \leq Q_j \leq QUB_j$	Subscript j is month	12
Seasonal inflow constraint	$QLB_j \leq Q_j \leq QUB_j$	Subscript j is season	13
Total annual flow constraint	$TQLB \leq TQ \leq TQUB$		14
Sediment constraint	$SD \geq SDLB$		15
Nutrient constraint	$NR \geq NRLB$		16

the process, such as the comparative importance of various functional components of the estuary being analyzed.

Martin (1987) initiated the use of an optimization model to resolve the estuarine management problem in estimating the monthly freshwater inflow need to meet specified conditions. His model related freshwater inflow to key estuarine indicators of salinity, deltaic marsh inundation, and commercial fishery harvest. The problem was formulated as a linear programming problem to minimize the sum of monthly inflows subject to the monthly and seasonal inflow constraints, fishery harvest constraints, salinity constraints, and inundation constraints.

Bao et al. (1989) and Tung et al. (1990) extended Martin's formulation of the estuarine management problem by incorporating chance constraints to deal with the statistical uncertainties of the salinity and fishery regression equations, and solved the optimization problem by a nonlinear programming package, GRG2 (Lasdon and Waren 1986). This programming package contains a nonlinear, stochastic, multi-objective mathematical programming model that searches for feasible solutions that optimize system performance, such as fisheries production, for a given amount of inflows.

Matsumoto (1990) developed the Texas Estuarine Mathematical Programming (TxEMP) model used here by modifying Bao and Tung's model to treat the lower and upper salinity bounds separately. This modification made it possible to treat the chance constraint more uniformly. Another new feature of the TxEMP model is the capability to address multiple objectives (Matsumoto et al. 1994). By providing a range of possible solutions from the minimum required inflow to the maximum allowable inflow, decision makers are presented with a clear picture of system performance as a function of freshwater inflows.

COMPONENTS OF TxEMP OPTIMIZATION

The ecological relationships, constraints, and desired state management objectives must be expressed mathematically to be used as input to the TxEMP optimization model. While the ecological relationships were discussed above, the constraints and objective functions used in the analysis of Texas bays and estuaries are given formally in Table 7. Specific points about the application are discussed below, with reference to equation number in the table.

MinQ (Eq. 1 in Table 7) is the minimum inflow solution and MaxQ (Eq. 2) is the maximum inflow solution that satisfies all of the constraints and state management objectives, such as the availability of water and the needs of the ecosystem. MinQ and MaxQ solutions define the feasible range of freshwater inflows to the estuary because inflows above MaxQ or below MinQ can not meet one or more of the constraints. The objective function MaxH (Eq. 3), is defined as the maximum balanced fishery harvest resulting from the optimization analysis, which turned out to be an easily accepted definition a productive estuary among the state agencies involved in this study.

When a specific species or a set of selected species are to be optimized, the objective function can incorporate a preference factor (Eq. 4). An objective function can be specified to find the maximum attainable probability of satisfying the salinity constraint (MaxSalP, Eq. 5) or the harvest constraint (MaxHarP, Eq. 6).

The chance constraint for salinity may be stated as the probability of attaining salinity within the lower (SLB) and upper bounds (SUB) that is ≥ SalP (Eq. 8). It was found that this type of chance constraint is too strongly dependent upon the bounds, SLB and SUB, and it is difficult to treat the probability level uniformly among different locations in the estuary. To alleviate the difficulty, the chance constraint was changed to treat the lower and upper bounds separately, as in Eq. 9 and Eq. 10. With this new treatment, the deterministic case originally given in Eq. 7, now corresponds to a salinity chance constraint with 50% SalP, since the deterministic case lies on the regression line and represents the midpoint of the expected salinity distribution with a given amount of freshwater inflows. At each point along the salinity regression line, for a given amount of freshwater inflow, the resulting salinity estimate represents the 50% exceedence value of the homoscedastic distribution of salinities.

The chance constraint for fishery harvest (Eq. 11) can be selected along with the target harvest level. For Galveston Bay, the target harvest was set at 80% of the mean harvest of each of the eight species, and the harvest probability was set at 50% to match the salinity probability and avoid overconstraining the model's range of feasible solutions.

Monthly inflow bounds (Eq. 12) are important components because they force the solution into a range of reality with respect to the normal amount of inflows the rivers and tributaries are capable of discharging to the estuary. In the Galveston Bay application, the median inflow was used as the upper bound and 10th percentile was used as the lower bound. Inflow bounds are also expressed seasonally (i.e., bimonthly in this case) and annually to facilitate production of an annual performance curve composed of optimized inflow solutions (see below).

The sediment constraint (Eq. 15) and the nutrient constraint (Eq. 16) can be placed directly in the TxEMP model if desired, or they can be examined independently of the optimized solution curve, as was done in the Galveston Bay example.

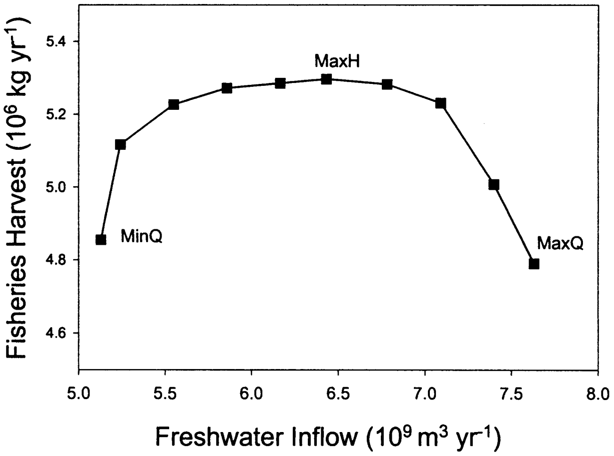

Fig. 2. TxEMP performance curve of optimal feasible solutions.

DEFINING THE MULTI-OBJECTIVE PROGRAMMING PROBLEM

The mathematical optimization problem is formulated by combining any one of the objective functions and all five types of the constraints in the model. For instance, a MinQ problem is formulated with the objective function of Eq. 1 and the constraints from Eqs. 9–13. The multi-objective programming allows the interactions among competing objectives to be investigated. One way to do this is to examine the range of optimized solutions between MinQ and MaxQ. This set of solutions is referred to as the noninferior set because each point along the performance curve represents the maximum harvest possible with that given amount of inflows. This set was generated as outlined by Cohon (1978) by solving a series of MaxH optimization problems in which the limit on the total inflow available is varied incrementally from MinQ to MaxQ. In the Galveston Bay application, this procedure produces an optimized performance curve of estuary fisheries production versus inflow (Fig. 2).

OPTIMIZATION PRODUCTS FOR MANAGEMENT DECISIONS

It has been most useful to use the TxEMP model to produce the following products for use in interagency discussions of appropriate inflow requirements: the optimized performance curve, the monthly inflow bounds, the predicted fishery harvests and biomass ratios by species, and the predicted monthly salinities at locations along the es-

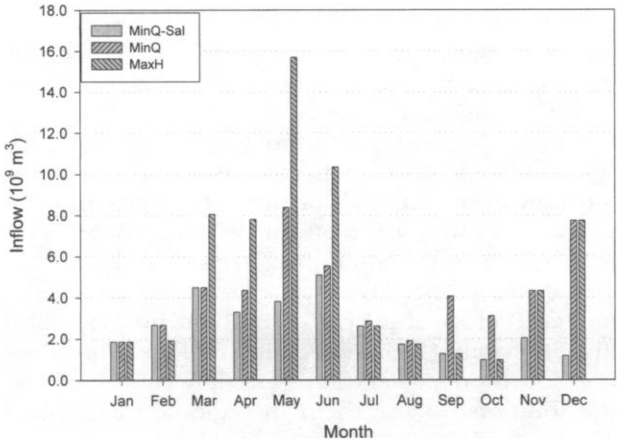

Fig. 3. Comparison of monthly inflow distributions produced by TxEMP for target inflow levels.

tuary's salinity gradient for which the salinity regressions were generated. This allows the involved parties to examine the solutions from various points of view and interest.

The feasible solutions from the TxEMP model application to Galveston Bay and the Trinity-San Jacinto estuary vary from an annual inflow of 5.13 × 10^9 m^3 (MinQ) to 7.65 × 10^9 m^3 (MaxQ), and reach a peak performance (MaxH solution) at 6.44 × 10^9 m^3 (Fig. 2). In reality, the solutions shown in Fig. 2 are computed monthly, and the monthly distribution of inflows is not uniform among the feasible solutions (Fig. 3). One additional calculation that has been commonly requested involves computing a minimum inflow that satisfies only the monthly salinity constraints. This solution is referred to as the MinQ-Sal and it is used to address minimal inflow requirements during partial drought conditions to avoid reproductive failure and loss of biodiversity. This solution is also considered incompetent because it does not meet all of the constraints and objectives established for estuary maintenance, but it should provide for basic survival, growth, and reproduction of the estuary's flora and fauna under this type of stressed condition.

Discussion

VERIFICATION OF OPTIMIZATION SOLUTIONS

For Texas bays and estuaries, the process of determining freshwater inflow requirements goes beyond the use of the optimization model to produce candidate inflows. An additional step involves verification of the recommended solution by comparing the circulation and salinity patterns produced by modeled inflows with the naturally observed patterns of species abundance and distribution in the estuary. This process is performed by the natural resource managers at Texas Parks and Wildlife Department and is outside the scope of this paper. The resulting patterns of circulation and salinity in the estuary from the optimization model's solutions are investigated using Texas Water Development Board's TxBLEND model, a high-resolution hydrodynamic and conservative mass transport model that can simulate two- and three-dimensional bay conditions expected under the various inflow solutions. The model was originally developed as FLEET by Gray (1987), expanded as BLEND, and subsequently modified by Texas Water Development Board as TxBLEND to accommodate its use in applications to Texas bays and estuaries. The finite element model employs the generalized wave continuity equation with linear triangular elements (Lynch and Gray 1979; Kolar et al. 1992). An example of the salinity gradient produced by the application of TxBLEND to Galveston Bay is shown in Fig. 4.

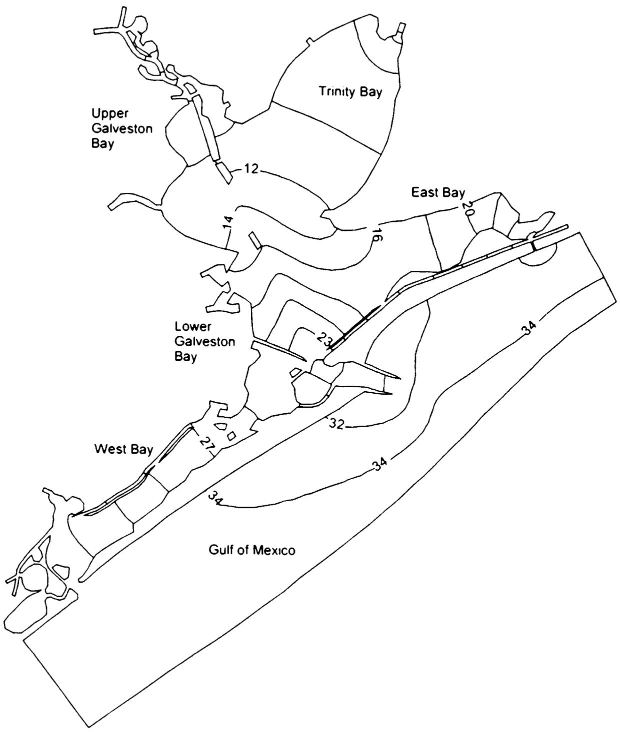

Fig. 4. Example salinity gradients produced by TxBLEND for verification of MaxH inflow recommendations for January 1988, a low flow month.

Working through the main components of the optimization approach described above has been the main effort in determination of inflow requirements. Some items have generated additional attention as applications were sought for different estuaries. There has been considerable discussion among the participants over the suitability and use of mean versus median central tendency values for inflows, annual and monthly, in the analysis. Where inflows are episodic, as in the semi-arid regions of Texas, the median flow values, which are based on the frequency of occurrence, may differ by a factor of two or three from the mean values, which are based on the volume of flow occurring. Because upstream reservoirs can alter the duration and timing of flows on most Texas rivers, the decision about which statistic is most appropriate also includes consideration of the natural versus impacted hydrology of the contributing basins.

The use of commercial harvest data to represent estuarine productivity has some conceptual problems, although it is easily understood beyond the scientific community. In particular, fishing trends over the years and abrupt changes in the amount of fishing effort caused by regulation of the fisheries has introduced complications. Measures of commercial effort, such as number of fishing trips each year, have been tested in optimization procedure, but they carry an additional degree of uncertainty into the analysis. The availability of commercial harvest data differs among the estuaries. Texas has initiated a fishery-independent monitoring program (McEachron and Green 1986; Hensley and Fuls 1998) that holds the potential of providing a better measure of fishery production than that arising from the fishery-dependent commercial harvest records. In the early years of the inflow study, there were not enough fishery monitoring data to be statistically useful in developing fishery-inflow relationships. There is now more than a decade of such monitoring data available for most estuarine areas. In testing the use of this data in the optimization model, a potential problem with the age classes represented was recognized in going from one measure of fishery production to the other. While the commercial harvest involves catches of mostly adult organisms, the monitoring database that best represents most of the fishery species of interest, except for the oyster, comes from bag seine samples that primarily catch juveniles. This brings some additional uncertainty into the analysis, because the strength of juvenile age classes may not translate directly into similar amounts of the harvestable size classes (Kimmerer et al. 2001).

One of the strengths of the optimization approach, as described above, is the production of an estuary performance curve. This allows both the scientists and the water managers to examine the shape and span of the curve of feasible solutions and to evaluate what it means for the water planning and permitting processes. For several of the estuarine systems investigated so far, it is apparent that a given amount of increased inflow to an estuary does not produce a proportional increase in the estuary's fishery harvest. As seen in the fishery regression equations, this is because a 1:1 relationship between inflows and fisheries is not present. Some suboptimal solutions may provide similar levels of expected fishery production, but they don't meet all of the constraints and objectives that were set forth in the analysis.

In general, the optimization approach has received acceptance. Because it is based on fundamental ecological information about inflows, salinities, nutrients, sediments, and biological production, decision makers have enough confidence in the solutions to use them in regional water planning and water rights permitting. Preliminary optimization results for Corpus Christi Bay and the Nueces estuary were accepted by the Corpus Christi City Council on November 19, 1991 and later used by the Texas Natural Resource Conservation Commission (now Texas Commission on Environmental Quality) in its 1995 Agreed Order, as amended, for the operation of the combined Choke Canyon Reservoir-Lake Corpus Christi water supply system. This work was subsequently subjected to the scrutiny of the City's independent consultants, who were able to identify some problems, such as the relatively weak salinity-inflow relationships with low explanatory power, but ultimately concluded that the solutions were based on the best available empirical data and sound science.

Similar operating rules for Lake Texana were proposed in 1991 and instituted to meet the downstream maintenance needs of Lavaca Bay, a part of the Lavaca-Colorado estuary that had been studied using the optimization approach. The Lower Colorado River Authority has also used results from the optimization analysis of the Lavaca-Colorado estuary to help guide the development of their basin-wide Water Management Plan in recent years. This plan seeks to optimize water supplies for municipal, industrial, and agricultural users, while also providing maintenance flows to the estuary. The regional water planning group established for the Houston region used the optimization results for Galveston Bay and the Trinity-San Jacinto Estuary in 2001 to help establish multistage targets for meeting environmental needs over the legislatively mandated 50-yr future planning horizon (Table 8).

It is anticipated that changes in estuarine conditions may require some estuaries to be restudied in the future so that revised estimates of the maintenance needs can be computed. First among these is the planned restudy of Matagorda Bay and the Lavaca-Colorado estuary by 2004, which is the result of the 1992 federal diversion of the Colorado River into Matagorda Bay. Data collected since

TABLE 8. Proposed inflow targets for Galveston Bay from the Houston regional water planning group. Exceedence percentage refers to amount of time the indicated levels are exceeded.

Target Amount	Historical Flow Frequency (% Exceedence)	Target Flow Frequency (% Exceedence)
Above normal conditions (maxH = 6.4×10^9 m^3 yr^{-1})	66	50
Below normal conditions (minQ = 5.2×10^9 m^3 yr^{-1})	70	60
Dry conditions (minQ-Sal = 3.1×10^9 m^3 yr^{-1})	82	75
Drought of record (historic min = 2.2×10^9 m^3 yr^{-1})	98	90

then will be used to revise the component analyses of the optimization model for this estuary.

Other approaches to determining the freshwater inflow needs of estuaries, particularly in California and Florida, have been reviewed by Estevez (2002) and their conceptual approaches compared by Alber (2002). It is apparent from this work that there are many needs for freshwater flows, but none involve more land, water, and wildlife than the needs of the bays and estuaries.

Acknowledgments

The authors would like to thank the Texas Legislature and the Texas Water Development Board for over three decades of financial support and guidance. We would also like to thank the Texas Parks and Wildlife Department, the Texas Commission on Environmental Quality and our research partners at the University of Texas, Texas A&M University, Rice University, University of Houston, Notre Dame University, and the University of Iowa that have provided scientific data and methods for this study. An expert Advisory Panel composed of Scott Nixon, Ken Tenore, Walter Boynton, Dominic DiToro, Ned Smith, and Armando de la Cruz was instrumental in getting us started on the right track. The authors want to thank Donna Tiemann and Chris Paternostro for helping prepare the manuscript. We are grateful to Peter Doering and 2 anonymous reviewers for their valuable comments on the manuscript.

Literature Cited

Alber, M. 2002. A conceptual model of estuarine inflow policy. *Estuaries* 25:1246–1261.

Bao, Y., Y.-K. Tung, L. W. Mays, and G. H. Ward. 1989. Analysis of the effect of freshwater inflows on estuary fishery resources. Technical Memorandum 89-2. Report to Texas Water Development Board. Center for Research in Water Resources, The University of Texas at Austin, Austin, Texas.

Ben-Tuvia, A. 1973. Man-made changes in the eastern Mediterranean Sea and their effects on the fishery resources. *Marine Biology* 19:197–203.

Brock, D. A. 2001. Nitrogen budget for low and high freshwater inflows, Nueces estuary, Texas. *Estuaries* 24:509–521.

Cohon, J. L. 1978. Multiobjective Programming and Planning. Academic Press, Inc., New York.

Collier, A. and J. W. Hedgpeth. 1950. An introduction to the tidal waters of Texas. *Contributions in Marine Science* 1:125–194.

Copeland, B. J. 1966. Effects of decreased river flow on estuarine ecology. *Journal Water Pollution Control Federation* 38:1831–1839.

Copeland, B. J. and T. J. Bechtel. 1974. Some environmental limits of six Gulf coast estuarine organisms. *Contributions in Marine Science* 18:169–204.

Cross, R. and D. Williams (eds.). 1981. Proceedings of the National Symposium on Freshwater Inflow to Estuaries. FWS/OBS-81/04. U.S. Fish and Wildlife Service, Office of Biological Services, Washington, D.C.

Dettmann, E. H. 2001. Effect of water residence time on annual export and denitrification of nitrogen in estuaries: A model analysis. *Estuaries* 24:481–490.

Dixon, W. J., M. B. Brown, L. Engleman, M. A. Hill, and R. I. Jennrich (eds.). 1988. BMDP Statistical Software Manual. University of California Press, Berkeley, California.

Estevez, E. D. 2000. Matching salinity metrics to estuarine seagrasses for freshwater inflow management, ch. 22. *In* S. Bortone (ed.). Seagrasses: Monitoring, Ecology, Physiology and Management. CRC Press, Boca Raton, Florida.

Estevez, E. D. 2002. Review and assessment of biotic variables and analytical methods used in estuarine inflow studies. *Estuaries* 25:1291–1303.

Farley, O. H. 1963–1969. Texas Landings: Annual summary, 1962–1968. Current Fisheries Statistics Nos. 3309, 3627 revised, 3901, 4156, 4529, 4675, and 4962. Bureau of Commercial Fisheries, U.S. Department of the Interior, and Texas Parks and Wildlife Department, Austin, Texas.

Farley, O. H. 1970–1978. Texas Landings: Annual summary, 1969–1976. Current Fisheries Statistics Nos. 5232, 5616, 5923, 6124, 6423, 6723, 6923, and 7223. National Marine Fisheries Service, U.S. Department of the Commerce, and Texas Parks and Wildlife Department, Austin, Texas.

Gray, W. G. 1987. FLEET: Fast Linear Element Explicit in Time Triangular Finite Element Models for Tidal Circulation, Users Manual. Department of Civil Engineering, University of Notre Dame, Notre Dame, Indiana.

Grubb, H. 1981. Freshwater inflow planning in Texas, p. 88–95. *In* R. Cross and D. Williams (eds.). Proceedings of the National Symposium on Freshwater Inflow to Estuaries. FWS/OBS-81/04. U.S. Fish and Wildlife Service, Office of Biological Services, Washington, D.C.

Gulland, J. A. 1965. Survival of the youngest stages of fish, and its relationship to year-class strength. *ICNAF Special Publication* 6:363–371.

Hackney, C. T. 1978. Summary of information: Relationship of freshwater inflow to estuarine productivity along the Texas coast. FWS/OBS-78/73. U.S. Fish and Wildlife Service, Biological Service Program, Washington, D.C.

Halim, Y. 1975. The Nile and the east Levantine Sea, past and present, p. 76–84. *In* R. Natarajan (ed.). Recent Researches in Estuarine Biology. Hindustan Publishing Corp., Delhi, India.

Hensley, R. A. and B. E. Fuls. 1998. Trends in relative abundance and size of selected finfishes and shellfishes along the Texas Coast: November 1975–December 1996. Management Data Series Number 159. Texas Parks and Wildlife Department, Coastal Fisheries Division, Austin, Texas.

Hildebrand, H. H. and G. Gunter. 1953. Correlation of rainfall with Texas catch of white shrimp, *Penaeus setiferus* (Linnaeus). *Transactions American Fisheries Society* 82:151–155.

Hjort, J. 1914. Fluctuations in the great fisheries of northern Europe viewed in the light of biological research. *Rapports et Procés-Verbaux des Réunions, Conseil International pour l'Exploration de la Mer* 20:1–228.

Jensen, P., S. Valentine, M. T. Garrett, Jr., and Z. Ahmad. 1991. Nitrogen loads to Galveston Bay. *In* F. S. Shipley and R. W. Kiesling (eds.). Proceedings: Galveston Bay Characterization Workshop, February 21–23, 1991. Publication GBNEP-6. Galveston Bay National Estuary Program, Webster, Texas.

JOYE, S. B. AND S. AN. 1999. Denitrification in Galveston Bay. Final Report to Texas Water Development Board. Texas A&M University, College Station, Texas.

KIMMERER, W. J., J. H. COWAN, JR., L. W. MILLER, AND K. A. ROSE. 2001. Analysis of an estuarine striped bass population: Effects of environmental conditions during early life. *Estuaries* 24: 557–575.

KOLAR, R. L., W. G. GRAY, AND J. J. WESTERINK. 1992. An analysis of the mass conserving properties of the generalized wave continuity equation, p. 537–544. *In* T. F. Russell, R. E. Ewing, C. A. Brebbia, W. G. Gray, and G. F. Pinder (eds.). Computational Methods in Water Resources IX, Volume 2: Mathematical Modeling in Water Resources. Elsevier Applied Science, New York.

LASDON, L. S. AND A. D. WAREN. 1986. GRG2 User's Guide. Department of General Business, The University of Texas, Austin, Texas.

LONGLEY, W. L. (ED.). 1994. Freshwater inflows to Texas bays and estuaries: Ecological relationships and methods for determination of needs. Texas Water Development Board and Texas Parks and Wildlife Department, Austin, Texas.

LYNCH, D. R. AND W. G. GRAY. 1979. A wave equation model for finite element tidal computations. *Computers and Fluids* 7:207–228.

MARTIN, Q. 1987. Estimating freshwater inflow needs for Texas estuaries by mathematical programming. *Water Resources Research* 23:230–238.

MATSUMOTO, J., G. POWELL, AND D. BROCK. 1994. Freshwater-inflow need of estuary computed by Texas Estuary MP Model. *Journal of Water Resources Planning and Management* 120:693–714.

MAY, R. C. 1974. Larval mortality in marine fishes and the critical period concept, p. 3–19. *In* J. H. S. Blaxter (ed.). The Early Life History of Fish. Springer-Verlag, New York.

MCEACHRON, L. W. AND A. W. GREEN. 1986. Assessment of annual relative abundance and mean length of six marine fishes in Texas coastal waters. *Proceedings of the 38th Southeastern Association of Fish and Wildlife Agencies* 38:506–519.

OMERNIK, J. M. 1976. The influence of land use on stream nutrient levels. EPA-600/3-76-014. U.S. Environmental Protection Agency, Washington, D.C.

POWELL, G. L. 1979. Estuarine fishery dynamics and freshwater inflow fluctuations in the San Antonio Bay System, Texas. *Proceedings of the 31st Southeastern Association of Fish and Wildlife Agencies* 31:498–504.

POWELL, G. L. AND J. MATSUMOTO. 1994. Texas estuarine mathematical programming model: Tool for freshwater inflow management, p. 401–406. *In* K. R. Dyer and R. J. Orth (eds.). Changes in Fluxes in Estuaries: Implications from Science to Management. Olsen & Olsen, Fredensborg, Denmark.

QUAST, W. D., M. A. JOHNS, D. E. PITTS, JR., G. C. MATLOCK, AND J. E. CLARK. 1988. Texas oyster fishery management plan. Fishery Management Plan Series No. 1. Coastal Fisheries Branch, Texas Parks and Wildlife Department, Austin, Texas.

ROUNSEFELL, G. A. 1975. Ecology, Utilization, and Management of Marine Fisheries. C.V. Mosby Co., Saint Louis, Missouri.

SCHROEDER, W. W. 1978. Riverine influence on estuaries: A case study, p. 347–364. *In* M. Wiley (ed.). Estuarine Interactions. Academic Press, New York.

SHERIDAN, P. F. AND R. J. LIVINGSTON. 1979. Cyclic tropic relationships of fishes in an unpolluted, river-dominated estuary in north Florida, p. 143–162. *In* R. J. Livingston (ed.). Ecological Processes in Coastal and Marine Systems. Plenum Press, New York.

SIMMONS, E. G. AND J. P. BREUER. 1962. A study of redfish, *Sciaenops ocellata* Linnaeus and black drum, *Pogonias cromis* Linnaeus. *Contributions in Marine Science* 8:184–211.

SKRESLET, S. (ED.). 1986. The role of freshwater outflow in coastal marine ecosystems. NATO Advanced Science Institutes, Ecological Sciences Series G, Volume 7. NATO Scientific Affairs Division and Springer-Verlag, Berlin, West Germany.

SOLIS, R. S. AND G. L. POWELL. 1999. Hydrography, mixing characteristics, and residence times of Gulf of Mexico estuaries, p. 29–61. *In* T. S. Bianchi, J. R. Pennock, and R. R. Twilley (eds.). Biogeochemistry of Gulf of Mexico Estuaries. John Wiley and Sons, Inc., New York.

STEVENS, D. E. 1979. Environmental factors affecting striped bass (*Morone saxatilis*) in the Sacramento-San Joaquin estuary, p. 469–478. *In* T. J. Conomos (ed.). San Francisco Bay: The Urbanized Estuary. American Association for the Advancement of Science, Pacific Division, San Francisco, California.

SUTCLIFFE, JR., W. H. 1972. Some relations of land drainage, nutrients, particulate material, and fish catch in two eastern Canadian bays. *Journal Fisheries Research Board of Canada* 29: 357–362.

SUTCLIFFE, JR., W. H. 1973. Correlations between seasonal river discharge and local landings of American lobster (*Homarus americanus*) and Atlantic halibut (*Hippoglossus hippoglossus*) in the Gulf of St. Lawrence. *Journal Fisheries Research Board of Canada* 30:856–859.

TEXAS DEPARTMENT OF WATER RESOURCES. 1981. Trinity-San Jacinto estuary: A study of the influence of freshwater inflows. Rep. LP-113. Texas Department of Water Resources, Austin, Texas.

TEXAS DEPARTMENT OF WATER RESOURCES. 1982. The influence of freshwater inflows upon the major bay and estuaries of the Texas Gulf Coast: Executive summary. Rep. LP-115, 2nd edition. Texas Department of Water Resources, Austin, Texas.

TEXAS WATER DEVELOPMENT BOARD. 2002. Water for Texas—2002 State Water Plan. Texas Water Development Board, Austin, Texas.

TUNG, Y.-K., Y. BAO, L. W. MAYS, AND G. H. WARD. 1990. Optimization of freshwater inflow to estuaries. *Journal of Water Resources Planning and Management* 116:567–584.

WEST GROUP. 2000. Texas Water Code, Section 11.147. *In* Vernon's Texas Codes Annotated–Water. West Group, Eagan, Minnesota.

WHITE, W. A. AND R. A. MORTON. 1993. Determining recent sedimentation rates of the Trinity River, Texas. Report to the Texas Water Development Board. Bureau of Economic Geology, The University of Texas, Austin, Texas.

WHITFIELD, P. H. AND H. SCHREIER. 1981. Hysteresis in relationships between discharge and water chemistry in the Fraser River Basin, British Columbia. *Limnology and Oceanography* 26: 1179–1182.

WISEMAN, W. J. AND F. J. KELLY. 1994. Salinity variability within the Louisiana coastal current during the 1982 flood season. *Estuaries* 17:732–739.

ZIMMERMAN, A. R. AND R. BENNER. 1994. Denitrification, nutrient regeneration and carbon mineralization in sediments of Galveston Bay, Texas, USA. *Marine Ecology Progress Series* 114:275–288.

SOURCES OF UNPUBLISHED MATERIALS

MATSUMOTO, J. 1990. User's Manual for the Texas Water Development Board's Estuarine Mathematical Programming Model, TxEMP. Unpublished technical memorandum. Texas Water Development Board, Austin, Texas.

MATSUMOTO, J. 1992. User's Manual for the Texas Water Development Board's Rainfall Runoff Model, TxRR. Unpublished technical memorandum. Texas Water Development Board, Austin, Texas.

MATSUMOTO, J. 1993. User's Manual for the Texas Water Development Board's Hydrodynamic and Salinity Model, TxBLEND. Unpublished technical memorandum. Texas Water Development Board, Austin, Texas.

Received for consideration, February 18, 2002
Accepted for publication, October 15, 2002