Ambient Water and Sediment Quality of Galveston Bay: Present Status and Historical Trends

Galveston Bay
National Estuary Program

GBNEP-22
August 1992

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Volume I

Final Report

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The Galveston Bay National Estuary Program

Publication GBNEP-22

August, 1992

This project has been funded in part by the United States Environmental Protection Agency under assistance agreement # CE-006550 to the Texas Water Commission. The contents of this document do not necessarily represent the views of the United States Environmental Protection Agency or the Texas Water Commission, nor do the contents of this document necessarily constitute the views or policy of the Galveston Bay National Estuary Program Management Conference. The information presented is intended to provide background information for Management Conference deliberations in drafting of official policy in the Comprehensive Conservation and Management Plan (CCMP). The mention of trade names or commercial products does not in any way constitute an endorsement or recommendation for use.

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AMBIENT WATER AND SEDIMENT QUALITY OF GALVESTON BAY:

PRESENT STATUS AND HISTORICAL TRENDS

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EXECUTIVE SUMMARY

For many years, data relating to the quality of water and sediment have been collected in the Galveston Bay system by a variety of organizations and individuals. The purpose of this project was to compile these data, and to perform a quantitative assessment of water and sediment quality of Galveston Bay and its evolution over time. There were three key objectives:

(1) compilation of a comprehensive data base in machine-manipulable format;
(2) analysis of space and time variation (i.e, "trends") in water and sediment quality parameters;
(3) identification of probable causal mechanisms to explicate the observed variations.

Their accomplishment provides a foundation for further scientific study of Galveston Bay, and for a general understanding of the controls and responses of its water quality, which must underlie rational management of the resources of the system.

This study focused on the following categories of parameters: temperature, salinity and related parameters, suspended sediments and turbidity, pH, dissolved oxygen, nutrients as measured by nitrogen, phosphorous and organic carbon, organics as measured by oil & grease, volatile solids and biochemical oxygen demand, chlorophyll-a, coliforms, metals (total and dissolved), and trace organics, including pesticides, herbicides, PAH's, PCB's, and priority pollutants.

While status-and-trends analyses were carried out for each of the Texas Water Commission (TWC) Water Quality Segments, to secure the objectives of this project it was necessary to perform analyses on a finer spatial scale than possible with the TWC segments. Therefore, a system of "Hydrographic Segmentation" was devised for Galveston Bay, based upon present knowledge of the bay and rational physical criteria, e.g., regions of homogeneity and zones of gradients, the former corresponding to the interior regions of segments and the latter to boundaries between segments. All statistical analyses were performed for *both* segmentations.

Some parameters, while technically distinct, are related so that one may be converted from one to another, allowing a much denser and longer-duration data set to be compiled. Such "proxy" relationships were employed relating salinity to conductivity, density, and chlorinity, total suspended solids to Secchi depth and turbidity, five-day biochemical oxygen demand (BOD) to other durations and nitrification-suppressed BOD's, and DDT to concentrations of the primary isomer. Dissolved oxygen was analyzed both as total concentration and as deficit below saturation, the latter removing the complicating effects of temperature and salinity dependence of solubility.

This project compiled data from 26 separate data collection programs, including the three major state programs, *viz.* the TWC Statewide Monitoring Network (SMN), the Coastal Fisheries surveys of Texas Parks and Wildlife Department (TPWD), and the Shellfish Sanitation program of Texas Department of Health (TDH). This project benefited from the recovery of lost major data sets accomplished in the preceding GBNEP Data Inventory project (Ward and Armstrong, 1991), including that of the Galveston Bay Project. The TWC SMN, TDH water-quality data, the TPWD hydrographic data, and the coastal data file of the Texas Water Development Board were obtained in digital form from the respective agencies. Most of the other data sets were keyboarded as a part of this project.

One of the principles observed in the construction of the Galveston Bay data base was the maintenance of integrity of the individual surveys. The *source* data base was differentiated from *derivative* data bases. The source data base codifies the original measurements as reported by the originating agency, and contains exactly the information in the original, even the original units of measurement. For various analytical purposes, these data must be modified, for instance converted to common units, averaged in space or time, aggregated, or screened by some criterion. The data set so processed is a *derivative* data base. The basic approach in this project was to first create the source data base for a given parameter through the data compilation effort. Then various derivative data bases were created according to analytical needs.

With each measurement in this data compilation there is included an estimate of its uncertainty, as affected by differing analytical methodologies and field procedures. In this project, we estimate the uncertainty as the standard deviation about the mean of the measurements under idealized conditions. With this uncertainty so quantified, a data user has the basic information necessary to retain or reject the data, and to further determine how the uncertainty is affected by whatever processing to which the data may be subject, e.g., aggregation, units conversions, proxy transformations, and averaging.

For each of 73 water-quality parameters and 50 sediment-quality parameters, there is created a Master Derivative Data file, coded in a uniform ASCII format for ease of dissemination and use by other researchers. Each measurement record includes the date, sample depth, latitude and longitude of the sample station, measured variable, estimated uncertainty of measurement expressed as a standard deviation, and a code identifying the origin of the data. The set of master derivative files is regarded to be our principal data resource product from this study. All told, the digital compilation is the most extensive and detailed long-term record of water and sediment quality ever assembled for Galveston Bay.

The derivative files were used to examine the general magnitudes and spatial distribution of water and sediment quality parameters in Galveston Bay. Time trend analysis was approached by a linear regression of the measurements versus time. Measurements reported as below detection limits (BDL) of the methodology were treated in three different ways. First, the measurements BDL were ignored, as providing essentially no quantitative information. Second, the BDL values were replaced with zero in the analyses, on the argument that for practical purposes the parameter is not present. Third, the BDL values were replaced with the value of the detection limit, on the argument that the potential concentration of the variate is the detection limit of the methodology. In our view, the choice is dependent upon the purpose at hand, therefore all three results are presented.

Adequacy of a data base is judged relative to its ability to resolve the various scales of variation, and in this respect Galveston Bay is undersampled. Despite the hundreds of thousands of separate measurements compiled in this study, when these data are subdivided by specific parameters, aggregated by region of the bay, and distributed over time, the data record is seen to be rather sparse. Continuity in space is undermined by too few stations, and by inconsistency between data-collection programs in the suite of measurements at different stations. Continuity in time is undermined by infrequent sampling, and the replacement of one parameter by another without sufficient paired measurements to establish a relation. Past and present sampling practice does not permit analysis of time scales of variation shorter than a few days.

Ability to resolve long-term trends in the face of high intrinsic variability requires data over an extended period. The extant period of record for Galveston Bay, with adequate continuity for trends analysis, extends back only to about 1965, except for some traditional parameters and for certain areas of the bay, for which the record can be extended back to the late 1950's. As salinity and temperature are the most easily measured variables, they represent the densest and longest data record. For metals and for complex organics, the period of record may extend back only a decade or so. Many of these measurements are below detection limits. For sediment, the data base is even more limited, amounting to one sample per 5 square miles per year, and is much less for some metals and organic pollutants.

The principal external controls on bay quality are hydrography, hydrology, and loadings. Hydrographic factors include tides, meteorology, and density currents. Tides are the most direct effect of the sea, are maximal at the inlets to the system and decline in amplitude rather quickly into the interior of the bay, especially in traversing the inlets and the mid-bay constriction at Redfish Bar. The bay is most responsive to meteorological forcing, which is manifested as windwaves, internal circulations, and wind setup and setdown. Windwaves contribute to the vertical near-homogeneity of the bay and its high mechanical aeration. Setup and setdown are the responses of the water surface to changing wind regimes, especially dramatic during frontal passages, when as much as half of the volume of the bay can be evacuated through the inlets. Density currents are the primary mechanism for salinity intrusion, and are especially prominent in the deeper areas of the bay, notably the dredged channels.

The normal pattern of Trinity River flow, which dominates Galveston Bay hydrology, is composed of an annual "flood," the spring freshet, and an annual "drought," the summer low-flow season. There is, however, considerable interannual variability in the river flow. Some years exhibit a pronounced and extended freshet, while in others the spring freshet may be totally absent. The gauged flow of the Trinity was analyzed to quantify the time signal of hydrology. The 3-month "freshet" was determined to comprise about *half* of the annual flow of the river, and to have an interannual spread of over two orders-of-magnitude in volume. A Fourier analysis of the 65-year time signal of freshet volume disclosed significant spectral peaks at 3.5-4 years and 13-14 years. The four-month (July-October) summer "drought" period comprises less than 15% of the annual discharge of the river, with strong spectral peaks at periodicities of about 5 and 7-8 years, as well as wider bands of 3.8-4.8 and 14-18 years. No statistically significant trend in total inflow volume over the period of record was apparent.

The influx of conventional pollutants as a mass load from both point source discharges and inflows peaked in the 1960's and has declined since. One prominent reason is the implementation of advanced waste treatment. A 20-fold reduction in BOD loading has occurred since about 1970. The nitrogen load has declined as well, though not so greatly. Reductions in industrial nitrogen loads began to be implemented in the early 1970's, somewhat sooner than for municipal discharges, and the reductions probably are much greater proportionately than those of domestic discharges. At present, the industrial nitrogen load is estimated to be about one-third the domestic load. In addition there has been a decline in mass loading from the river and stream inflows due to a combination of improved waste treatment, altered land use, and impoundments on the principal rivers and the concomitant entrapment of fine-grain sediments. As many nutrients and contaminants are associated with these finer particulates, these reservoirs are therefore also considered to represent an effective sink of these constituents in the inflows. Reliable data for estimating this effect are limited, however, because the reservoirs antedate the period of intensive data collection.

Salinity acts as a conservative property of Galveston Bay waters whose concentration is primarily determined by boundary fluxes at the inflow points and at the inlets to the sea, and internal transport and mixing. Substantial gradients across the bay are a normal feature of salinity structure, declining on average from values about 30 ppt at the inlets to the bay to about 3 ppt out from the principal points of inflow, such as the Trinity River. Variability about these mean values is high, however, with a standard deviation of 5-6 ppt throughout the bay. Salinities in the open-bay reach of the Houston Ship Channel are higher, on the order of 2 ppt, than those of the adjacent waters. Vertical stratification of bay waters is slight, by estuarine standards, generally averaging less than 0.6 ppt/m, and averaging less than 0.3 ppt/m over about half of the bay area, with no correlation with water depth. While freshwater inflow is the ultimate control on salinity, inflow proves to be a poor statistical predictor of salinity, achieving only about 50% explained variance in the data even with long-term processing of the inflow. There has been a general decline in salinity over the three-decade period of record, of about 0.1-0.2 ppt per year, not clearly associated with freshwater inflow. Our favored hypotheses (whose testing exceeded the scope of this study) are variations in the time signal of inflow events and the associated salinity response, reduced salinities in the adjacent Gulf of Mexico, or reduced intensity of interaction between estuary and Gulf waters.

The parameter pH is rather uniform, with its higher values, on the order of 8, in the more saline regions of the bay, an expression of the high buffering capacity of sea water.

Temperature in Galveston Bay is primarily controlled by surface fluxes, especially the seasonal heat budget, and much less--if at all--by boundary fluxes and internal transports. The horizontal gradient across the bay ranges 1-2°C, with the higher values in winter, with little systematic stratification, though on average a slight stratification on the order of 0.2°C/m emerges from the data, probably due to near-surface heat absorption rather than density effects. The seasonal signal is the principal source of variation in water temperature. Over the three-decade period of record, water temperature, especially in the summer, has declined in Galveston Bay at a nominal rate of 0.05°C/yr. Hypotheses for this decline include an alteration in climate (e.g., air temperature, wind, cloud cover), and altered interaction with the Gulf of Mexico, though these could not be tested within the scope of this project.

Dissolved oxygen is generally high throughout Galveston Bay, averaging near saturation through large areas of the bay, with frequent occurrence of supersaturation. Exceptions to this are in poorly flushed tributaries subjected to inflow and waste discharges, most notorious of which is the Houston Ship Channel. These near-saturated conditions are a manifestation of the intense vertical mixing processes in Galveston Bay, which produce mechanical surface aeration, as well as a manifestation of photosynthetic productivity. In the open, well-aerated areas of the bay, vertical stratification is on the order of 0.4 ppm/m. This stratification is much greater than the practically negligible stratification in solubility, and is considered to be the result of DO influx near the surface in concert with water-column and sediment biochemical oxygen consumption.

In Galveston Bay, BOD ranges 2-3 ppm throughout the lower bay segments, and increases inland to 4-5 ppm in the upper bay along the north and west shores, and to values greater than 5 ppm in Clear Lake and the Houston Ship Channel. Within the upper HSC, the reach above the San Jacinto confluence, the DO deficit has been reduced about 4 ppm in the past 20 years, no doubt in response to the substantial reduction of waste loads.

Like all of the Texas bays, Galveston is turbid, with long-term average total suspended solids (TSS) ranging 30-40 ppm throughout most of the bay, somewhat higher in the upper bay than in the lower bay, and 40-60 ppm within the tributaries and adjacent open-water segments. Stratification in TSS is noisy, but on the order of 5 ppm/m declining upward, consistent with settling of larger particles to the bottom as well as a near-bottom source of particulates from scour of the bed sediments. TSS in Galveston Bay has declined throughout the system over the past three decades, an average reduction of about 2 ppm/yr to current levels on the order of 20 ppm. We favor the hypothesis of a general reduction of TSS loading to the bay (in contrast to one of decreased sources within the bay itself, e.g., resuspension), due to one or a combination of TSS reduction by advanced waste treatment, TSS entrapment within reservoirs, and reduced TSS in runoff because of changing land use.

Nitrogen and phosphorus nutrients in Galveston Bay exhibit the same general spatial distributions as BOD and TSS, *viz.* elevated concentrations in tributaries and regions adjacent to inflow points, declining to lower concentrations at the inlets. Because these nutrients have an affinity for fine-grain particulates, their association with TSS is more than coincidental. The levels of concentration of total inorganic nitrogen range up to about 0.2 ppm in the lower bay, 0.2-0.5 in the upper bay, and as much as an order of magnitude greater in the upper Houston Ship Channel. These nutrients exhibit declines in concentration throughout the bay over the past two decades, total ammonia N on the order of 0.1 ppm/yr, total nitrate on the order of 0.01 ppm/yr and total phosphorus on the order of 0.05 ppm/yr. We favor the hypothesis that these reductions in nitrogen and phosphorus are a consequence of decreased wasteloads, due to advanced waste treatment, and decreased loadings in the inflows, perhaps due to reservoir entrapment or altered land uses.

Total organic carbon since 1988 has averaged about 3-5 ppm in the open bay and about 8 ppm in the Houston Ship Channel. TOC exhibits baywide declining trends similar to nitrogen and phosphorus, except in West Bay, on the order of 0.5 ppm/yr. Present levels are about one-third of the concentrations of the mid-1970's. This decline could be a direct result of reduced carbon loading, or an indirect effect of the general decline in nutrients on decreased productivity. Some credence is given the latter possibility by decreases in chlorophyll-a in the open bay, to levels about one-half of those a decade ago.

Contaminants such as oil & grease, coliforms, metals and trace organics show elevated levels in regions of runoff and waste discharge, with generally the highest values in the upper Houston Ship Channel, and generally low values in the open bay waters. Most of the metals are declining in areas of maximal concentrations. While this may well be an artifact of changing analytical techniques, we favor the hypothesis that this general decline in metals is closely related to the decline in suspended solids.

The conventional organic measures and metals in Galveston Bay sediments appear to follow the same general spatial distribution as most of the water quality parameters, *viz.* elevated concentrations in regions of runoff, inflow and waste discharges, and lower, more-or-less uniform concentrations in the open bay, with the Houston Ship Channel generally the focus of maximal concentrations in the system. The available data for conventional organic measures are sparse, with large areas of the bay unsampled, and generally too noisy for reliable detection of trends. A glaring deficiency is the almost total lack of paired chemical and texture analyses. Without basic grain-size information, it is impossible to sort out much of the variability in sediment quality.

Where trends in the sparse, noisy data for sediment metals are statistically discernible, they tend to be declining, especially in the upper Houston Ship Channel. In the Channel, the rates of decline in sediment concentrations per decade are for chromium, mercury and zinc a factor of two, for copper and nickel a factor of three, and for arsenic, cadmium and lead an order of magnitude.

These data were examined for indications of problem areas. In summary, the geographical problem areas of Galveston Bay hold no real surprises; they are where we expect them to be: in regions of intense human activity, including urban areas, points of surface runoff, waste discharges, and shipping. The analyses of this study yield a quantification of the water and sediment quality in these problem area. Perhaps unexpectedly, the quality of the bay is generally good, and where it is degraded there is a trend of improvement, in many cases substantial. The greatest problem of concern to these investigators is the systematic decline in nutrients, suspended solids and chlorophyll.

Recommendations deriving from this project fall into two categories: data collection and additional studies. With respect to data collection, we re-emphasize the observation that Galveston Bay is inadequately sampled with respect to almost all variables examined in this project. Few programs can afford the investment of long-term, comprehensive, intensive data collection in a system such as Galveston Bay. To address scientific and management questions that require such massive data bases, we must depend upon the use of data collected by different agencies for perhaps different purposes. In this sense, data collection should be regarded as a collective enterprise, and its design should reflect a certain degree of scientific altruism, to ensure maximal utility of the data. Specific recommendations include the following:

(1) A greater sensitivity is recommended to the investment in putting a sampling crew on a specific station. The incremental cost in acquiring additional measurements, perhaps peripheral to the principal objective of the sampling, must be weighed against the much greater cost of occupying the station. We suggest that short lists be formulated for guidance, giving "recommended" parameters for suites of measurements of various classes.

(2) The same principle of incremental cost versus benefits should be considered in specifying laboratory analyses. Many procedures are cost-loaded in sample preparation, and can admit additional parameters or greater resolution with minor incremental cost.

(3) Necessity for both continuity in time and continuity in space must be recognized, as well as the need for maintenance of a long period of sampling. In particular, when a new parameter replaces another, there should be a continued acquisition of the older variable together with the new, to at least establish an empirical relation.

(4) The intratidal diurnal scale of variability is virtually unsampled in Galveston Bay. The use of electrometric sensing and automatic data logging is recommended, especially for dissolved oxygen, temperature and salinity. Such data acquisition should not replace routine sampling, since routine sampling provides far better spatial continuity than is practical to achieve with automatic monitors.

(5) A great deal of information loss presently occurs due to incomplete field notes, laboratory analysis and transcription errors, and data entry errors. Any data collection program should include procedures of *timely* data screening and data-entry verification, from the original lab sheets to the digital data file. It may be useful for GBNEP to develop a standard list of data recording and verification procedures as guidance.

(6) Data entry error is not the only means of losing information from data collection. Replacing a series of raw measurements over time or space by an average, failing to preserve information on sampling time, position or conditions, or intermixing actual measurements with "estimated" values without any means of separation, all represent losses of information. We recommend adherence to the same principle of preservation of data integrity observed in this project, in which the raw data is preserved as a separate record from its combination with other data or its further processing.

(7) Some measure of suspended solids should be included in routine monitoring. For nutrients, metals, organic pesticides, PAH's or similar constituents that have an affinity for particulates, suspended solids *per se* should be routinely determined as part of the suite of measurements. Further, the analysis should include grain-size distribution or at least sequential filtration to determine partitioning of clays-and-finer and silts-and-finer.

(8) A ubiquitous deficiency of the sediment data base is the lack of paired measurements of chemistry and sediment texture (i.e., grain-size distribution). It is recommended that texture analysis be instituted as a routine aspect of any chemical analysis of a sediment sample.

(9) Because of the future potential rôle sediment organic carbon may play in evaluating sediment chemistry with respect to a standard, presuming the EPA Equilibrium Partitioning approach is adopted, we recommend that organic carbon be instituted as a routine aspect of any chemical analysis of sediment involving non-ionic organic contaminants, especially organohalogens.

Recommendations addressing further analyses and studies are as follows:

(1) Detailed mass-budgeting studies are recommended to determine the probable cause of the apparent declines in particulates and nutrients, perhaps in concert with hydrographic analyses or deterministic models, using the data base compiled in this project. Event-scenario analysis as well as time-series studies could both provide insight.

(2) Additional analysis of chlorophyll-a and related measurements from Galveston Bay, in association with *in situ* productivity studies are needed. These studies should include detailed examination of phytoplankton dynamics in Galveston Bay, and its dependence on water quality. Analysis of the time-response behavior of selected higher organisms might also be useful.

(3) More and better measurements of metals and trace organics are necessary to assess and monitor this suite of variables. Yet, the investment in complex chemical analyses does not seem highly critical to the management of Galveston Bay, apart from the present agency activity in wasteload regulation. While monitoring should continue, we do not believe that merely intensifying that monitoring will yield information in proportion to investment. We recommend a research focus on:

(a) improved measurement methodology, including relations with and among older methods, for interpretation of historical data, and better determination of precision and accuracy,
(b) bioaccumulation of metals and trace organics,
(c) detailed studies on kinetics and fluxes in carefully selected regions of the bay subject to identifiable and quantifiable controls,
(d) exploration of suitable tracers and their measurement, such as aluminum, to separate natural and anthropogenic sources of metals.

(4) In an estuary as turbid as Galveston Bay, the rôle of sediments in suspension and in the bed is quintessential. Yet every element of the sediment transport process is inadequately understood. Sediment dynamics should be the focus of a renewed research effort in the bay, ranging from more detailed observation on grain-size spectrum and its effects, to biokinetic processes operating within the sediment itself.

(5) The observed decline in temperature is probably not a serious concern from the water-quality management standpoint, but examination of its cause, especially if of climatological origin, may provide additional insight into other processes, such as the decline of chlorophyll-a and the kinetics of dissolved oxygen.

(6) The salinity data base assembled in this project is the most comprehensive available for Galveston Bay and will support analytical studies of salinity response heretofore not possible. It is recommended that salinity variability in Galveston Bay be examined using sophisticated methods of time-series and response analysis to better delineate the rôle of inflow and other hydrographic factors on salinity.

(7) The significant observed decline in salinity underscores the gaps in our understanding of even as fundamental (and conservative) a parameter as this. We recommend additional studies of the external controls on salinity. Again, we believe event-scenario and time-series analysis to be most promising.

1. INTRODUCTION

The quality of the Galveston Bay system has been of concern to citizens of the region and of Texas for at least 150 years. In 1841, the City of Houston passed an ordinance prohibiting the accumulation of sawdust on the shoreline of Buffalo Bayou, from lumber milling operations, due to the sawdust being washed into the stream (Sibley, 1968). This was an obvious cause-and-effect link to pollution of the watercourse. As the periphery and the watershed of Galveston Bay have developed, the effects of man's activities have become much more subtle and difficult to identify.

The vacillations of the fishery have long been associated with the perception of pollution, or perhaps *vice versa*. In 1928, the annual report of the Texas Game, Fish & Oyster Commission (TGFOC) states, quoting a *Houston Post-Dispatch* article comparing Galveston Bay around 1920 with its current state, "Fishing in the ship channel was ruined, and most of the marine life had been driven from the upper portions of the bay. Bathers often received generous coatings of oil. ...Today the ship channel is virtually free of oil pollution, and the bay once more teems with aquatic life. The 1928 fishing season in salt water areas below Houston has been the best season of the past ten years." (TGFOC, 1928.) In the very next year, the TGFOC (1929) commented, "It is a common thing for fishermen on the coast to remark that times are not what they used to be when phenomenal catches were made." In 1935 (TGFOC, 1935), "Refineries on the Ship Channel discharge their effluents into the channel, but it is usually clean. The oil is trapped and the acids treated. Fishing up the channel from Galveston is said to be improving." The late 1930's and early 40's received a sequence of natural catastrophes, from floods (1935-36) and hurricanes (1942) to extreme freezes (1939-40) and drought (1943-45). The annual TGFOC report of 1946 notes a sharp decline in the fishery and states (TFGOC, 1946), "The total catch from the Galveston area is an insignificant per cent of the total production in Texas waters and can be expected to remain so until the heavy industrial pollution of that region is abated."

While occasionally other types and sources of pollution were identified in the first half of the century, such as an outbreak of shellfish poisoning in 1944 due to sewage contamination of the lower reefs (Wise et al., 1944, 1948) and extensive bayshore contamination in 1950 by sanitary discharges in the upper bay (Metyko, 1952), the focus was (appropriately) on the Houston Ship Channel, and specifically the discharge of oil. Again, most of the surviving information is anecdotal. TGFOC (1928) reported on a clean-up campaign in the Channel area to reduce waste oil, which posed "a grave fire hazard" and the same *Houston Post-Dispatch* article noted that around 1910 "the Houston ship channel was smeared with oil and other destructive ingredients, from the foot of Main street to Morgan's Point, while oil covered large portions of the bay." Interestingly, even this early in the century, the idea had been floated to give up the Channel to the "uses of commerce" (TGFOC, 1928), a suggestion that has continued to emerge to the present day due to the difficulty of reconciling water quality goals with the intensive industrial-municipal activities. While the problem of Ship Channel pollution may have been reduced by 1928, it certainly had not been eliminated. In 1933, it was noted that (TGFOC, 1933), "The oil refineries on the ship channel are making an honest effort to take care of their waste and are usually very clean.... Complaints reach the department at intervals about oil on the bay at Galveston, but it appears that this pollution is from inbound ships rather than from refineries and oil fields inland." To the present, the Houston Ship Channel has continued to be a major concern in Galveston Bay. Since 1970, it has been described as "the most-polluted body of water in the U.S." (e.g. Eckhardt, 1971) and a "water-quality success story" (EPA, 1980).

There may have been other physico-chemical alterations in Galveston Bay throughout the century as well, but again the bulk of the information is anecdotal and the rôle of man's activities is unclear. While interesting from a historical viewpoint, this type of information does not contribute to answering the questions of whether significant problems in water quality presently exist in Galveston Bay and whether there is (or has been) a long-term alteration in water quality. Two elements are needed in order to appraise variation in water quality and to identify its cause. First is a quantitative measure, i.e. identification and analysis of parameters indicative of water quality, which in principle can provide time-space continuity. Reports of fish kills and bathers coated in oil are dramatic evidence of something, but offer little basis for scientific evaluation. The second is an extensive data base on the parameter with sufficient spatial and temporal resolution, and extending over a sufficient time period to separate trends from natural variability. This latter, of course, is the real obstacle.

Several notable attempts to establish the level of water quality and the existence of trends in Galveston Bay exist in the literature. Gloyna and Malina (1964) conducted a comprehensive survey of water quality throughout the system by compiling all data available to them. They emphasized the spatial variation of quality within the season, and short-term fluctuations rather than long-term trends. At the close of the Texas State Department of Health (TSDH) Galveston Bay Project, TSDH (1968) summarized the status of the bay according to coliform and BOD levels as follows:

Area	*Rating (MPN)*	*Rating (BOD)*
Houston Ship Channel	Polluted	Polluted
Clear Lake	Poor	Poor
Trinity Bay	Excellent	Good
Upper Galveston Bay	Excellent	Good
Central Galveston Bay	Excellent	Good
Lower Galveston Bay	Excellent	Good
East Bay	Excellent	Excellent
West Bay	Excellent	Excellent

in which "excellent" means coliform MPN $< 50/100$mL and BOD < 2.5 mg/L, "good" means BOD < 5.0, "poor" means MPN < 1000 and BOD < 7.5, and "polluted" means MPN > 1000 and BOD > 7.5. Further, trend lines through these data showed a positive slope throughout the bay, evidencing a "continued degradation." This analysis covered the period 1963-67. In a report of very limited circulation, Texas Environmental Research Corporation (1968) presented a trends analysis of Trinity Bay based upon the U.S. Bureau of Commercial Fisheries (USBCF) and TSDH data, *which was inconclusive.*

In 1968, The Texas Water Quality Board initiated its ("The") Galveston Bay Project (GBP) and midway through the program performed its own trends analysis (Espey et al., 1971b) of the main sections of the bay (i.e., exclusive of the Houston Ship Channel). This analysis extended the record for all of the TSDH stations which corresponded to GBP stations, to cover the period 1963-70. (Espey et al., 1971b, noted that the TSDH trends analysis used only two or three stations from each bay section, despite a much larger number of stations available, and intimated that the selection might have been deliberate to display a trend of degradation.) The increase in coliforms in lower Galveston Bay was confirmed. There were also increases in the Chocolate Bay area and in the eastern portion of West Bay, which were offset by decreases in middle West Bay. Otherwise, no significant change in coliforms or BOD was detected.

The most recent trends analysis is due to Stanley (1989), who combined data from four long-term data bases: TSDH, U.S. Bureau of Commercial Fisheries, Texas Water Commission and Galveston Bay Project. He compiled a time series of data back to the 1960's, and examined a different suite of parameters than those of the studies cited above, but, in order to keep the scope of his study manageable, limited the analysis to a few representative stations from the major segments of the bay. He examined temporal plots at these stations by eye for trends in nitrogen, phosphorus, and trace contaminants such as heavy metals. He noted an apparent decrease in nitrogen species, which he believes is more likely an artifact due to noncomparability of the measurements in different (non-overlapping) programs rather than a real decline. Substantial declines in all of these parameters in the Houston Ship Channel were noted.

The above-cited trends studies all suffered from the same difficulty of attempting a statistical summary with a set of data that lacked either sufficient temporal or sufficient spatial scope to permit statistically meaningful inferences about existing water quality and temporal trends. Generally, any single data-collection program lacks the resources and longevity to develop a data base sufficiently comprehensive for analysis of water quality levels and trends in a system such as Galveston Bay. This is due to the extreme natural variability of water-quality parameters. The best prospect for a definitive study is to begin with a synthesis of data from a number of programs, using the entire spatial and temporal scope of each program.

For many years, data relating to the quality of water and sediment have been collected in the Galveston Bay system by a variety of organizations and individuals. The objectives of data collection have been equally varied, including the movement and properties of water, the biology of the bay, waste discharges and their impacts, navigation, geology and coastal processes, and fisheries. While the specific purposes of the individual data collection projects have limited each project in time and space, the data have great potential value to the

Galveston Bay National Estuary Program (GBNEP) if they can be combined into a comprehensive data base yielding a historical depiction of the quality of the bay environment.

The purpose of this project was to compile and evaluate these data, and to employ these data in a quantitative assessment of water and sediment quality of Galveston Bay and its evolution over time. There were three key objectives, *viz.*:

(1) compilation of a comprehensive data base in machine-manipulable format,

(2) analysis of time and space variation (including "trends") in quality parameters,

(3) identification of possible causal mechanisms to explicate the observed variations.

Securing these objectives will provide a foundation for further scientific study of Galveston Bay, for identifying and prioritizing specific problems affecting the quality of the Bay, for formulation and specification of future monitoring programs for the Bay, and for a general understanding of the controls and responses of Bay water quality, which must underlie rational management of the resources of the system.

This project sought data from various sources, relating to the general categories of parameters listed in Table 1-1, and created a computer-manipulable data base. This project relied upon and built from the work accomplished in the previous GBNEP Data Inventory Project. The Data Inventory Project was extremely useful in having identified major historical programs and probable locations of surviving data. The task of recovering historical data sets from oblivion was continued in the present program, and one major product of this project is consistent, digital forms of the major water/sediment programs from the Bay. Many of the data sets employed in this study exist only in a limited number of hard copies (frequently only one). A major part of the effort of this project was invested in keyboarding this data to create a digital data base. The problems of acquiring such data sets would be a formidable obstacle to any future researchers' compiling an adequate data base for Galveston Bay. Therefore, we regard the synthesized digital data base as a major product of the project as it allows future researchers much greater scope in analysis than could be afforded by the data sets normally available to individual scientists.

Procedures of data processing are summarized in Chapter 2, the analyzed water and sediment quality data are presented in Chapter 3, the possible cause-and-effect processes suggested by associations in the data are discussed in Chapter 4, and a summary of conclusions and list of recommendations are given in Chapter 5. These are all abridged from the Extended Technical Report (Ward and Armstrong, 1992a), which should be consulted for technical details. The core of

TABLE 1-1

General categories of water/sediment quality parameters addressed in project (See Chapter 2 for detailed parameter listings)

Indicator variables (bacteriological and chemical)
Nutrients (carbon, phosphorus and nitrogen)
Heavy metals
Pesticides
Priority pollutants
Organics
Suspended matter
Physical indicators, including density and dissolved solids

the project results is considered to be the analyzed water and sediment quality data, summarized here in Chapter 3. Our philosophy is to differentiate the *facts* of the data, as presented in Chapter 3, from the *interpretation* of the data, reserved for Chapter 4. The interpretations postulate conceptual models and may be biased by the predilections of these investigators. Certainly, they will be subject to revision upon additional data collection or more sophisticated analyses. However, the results of the data presentation should stand as *facts*, circumscribed only by the statistical measures selected, criteria for rejection or weighting, and the assumed proxy relationships.

4. CONTROLS AND CORRELATES

Following the compilation of a comprehensive long-term data base for key water quality parameters, and the statistical analysis of that data base to characterize the spatio-temporal variation in water quality of the Galveston Bay system, the next logical step is to attempt to infer cause-and-effect relations, either between the quality variables or between a given variable and external controls on the system. A thorough exploration of cause-and-effect hypotheses would exceed the resources of this project. Indeed, the prime objective of this project is to complete the data compilation, which will support such cause-and-effect studies by future researchers. Nevertheless, several straightforward evaluations are possible and useful in interpreting the results of the preceding chapters.

Generally, the processes affecting a water quality indicator may be categorized as kinetics and transport. Kinetics refers to the complex of processes that directly affect the concentration of the parameter at a point in space, including physico-chemical reactions and biological interactions, sometimes referred to as "source-sink" processes. Transport refers to the complex of processes that affect point concentration by the movement of water masses. Transport includes the various mechanisms of circulation and dispersion responsible for the intermixing of estuary and Gulf waters (the so-called "flushing" of the estuary).

Any waterborne property, including the water-quality indicators of this study, is affected by transport; the concern is the additional effect of kinetics and its relative magnitude compared to transport. A relative evaluation is based upon the rate coefficients governing the kinetics to which the property is subjected, and the proximity and significance of any boundary feature which creates a gradient in concentration within the system. Table 4-1 summarizes typical magnitudes for kinetic processes affecting important water-quality variables. The higher the kinetic rate, the more important kinetic processes are inclined to be, relative to transport processes. On the other hand, in the vicinity of a steep concentration gradient--e.g., in proximity to an outfall containing high concentrations of the parameter of concern--transport processes can become locally dominant. In the present context, the emphasis is on large-scale variations in the Galveston Bay complex, not the small-scale neighborhoods of point sources.

From Table 4-1, it is apparent that salinity, mercury, and PCB's are virtually conservative, while DO, temperature, coliforms, PAH's and Aldrin are very reactive. (These nominal values, it should be noted, are with respect to the vertical-mean concentration. For such averaging, true conservative parameters, such as salinity and suspended sediment, and nearly conservative parameters, such as temperature, exhibit an *effective* reaction due to vertical transport processes, as characterized by the indicated rate coefficient.) Therefore, we would expect that the horizontal gradients of salinity and metals would be governed by boundary fluxes and internal transports, while DO, temperature, coliforms, etc., are more influenced by point processes and much less by boundary fluxes. This indeed is the case. Salinity, for example, is determined by the interplay of

TABLE 4-1

Typical rate coefficients for representative water quality parameters

parameter	*process*	*rate coefficient* (day^{-1})
salinity	increase by evaporation	0.002
temperature	radiation	0.3
dissolved oxygen	aeration	0.5
ammonia-nitrogen	nitrification	0.1
suspended particulates	settling	
fine sand, 100 µm		300
fine silt, 10 µm		5
medium clay, 1 µm		0.05
coliforms	die-off in open water	1
mercury	aquatic metabolism	0.001
PAH's	volatilization	1
DDT		
	volatilization	0.1
	hydrolysis	0.01
Aldrin	volatilization	1
PCB's	photolysis	0.01

boundary fluxes--freshwater inflow and the Gulf of Mexico salinity regime--and the various mechanisms of internal hydrographic transport. Temperature and DO, on the other hand, are dominated by seasonal meteorology--winds, air temperature, etc.--and much less by the effect of inflow and exchange with the Gulf of Mexico.

4.1 Hydrographic Controls

Hydrography of the Galveston Bay system is principally governed by four physical factors: tides, meteorology, density currents and freshwater inflow. Each of these are highly variable in time and the character of the bay depends upon their relative predominance. Thus, the hydrography of the bay varies from season to season and year to year, and frequently on even abrupt time scales. The hydrography of Galveston Bay is surveyed in Ward (1980), TDWR (1981), and Ward (1991) and references therein.

The most obvious marine influence is the tide whose variability is governed chiefly by the declination of the moon. At great declination, the tide is predominantly diurnal and of maximum range, while at small declination, the diurnal component disappears so that the tide becomes semi-diurnal and of minimum range. Tidal range on the Gulf of Mexico shoreface in the vicinity of Galveston Bay is typically on the order of 1 m during the diurnal mode of the tide. As the tide propagates into Galveston Bay it is lagged in phase and attenuated in amplitude. During the cycle of lunar declination, there is also a storage and depletion of water within the system, with higher mean water levels during the semidiurnal phase.

While the tide is the most obvious marine influence on Galveston Bay, the most obvious freshwater influence is the inflows of the principal rivers. The predominant source of freshwater inflow to Galveston Bay is the Trinity River, comprising on average about 50-60% of the inflow to the system. The freshwater inflow is responsible for the estuarine character of Galveston Bay, in diluting ocean water and establishing a gradient in salinity across the system. Inflow has a twofold importance to this study, in that it is a primary control on transport and mixing, and in that there is an extended detailed time record of measurements available for the system, which can be combined with the water quality data of this project. The analysis and behavior of inflow are therefore treated in more detail in Section 4.2 below.

In addition to tides and inflows, the atmosphere has a significant influence on Galveston Bay. Due to the broad, shallow physiography of the bay, as well as the dynamic meteorological regimes of the area, the bay is very responsive to meteorological forcing. This response is manifested in three general ways: the development of windwaves, the generation of internal wind-driven circulations, and the excursions in water level. Indeed, in Galveston Bay, it is meteorology, not the tide, which is the dominant factor governing the excursion in water level. Part of this is the general response of the northwestern Gulf of Mexico to the imposed windstress, which is communicated through the inlets of Galveston Bay.

Within the bay, meteorological systems affect the water level variation even more, mainly due to constrictions of land boundaries. Strong onshore flow can "setup" water levels sometimes several feet in the upper bay. North winds, especially following vigorous frontal passages, can induce dramatic "setdown", and are capable of evacuating as much as half the bay volume in a few hours (Ward, 1980, 1991). Even modest weather systems significantly perturb water levels to the point that the astronomical tide is obliterated. This is especially true in the inland reaches of the bays, such as upper Trinity Bay.

The horizontal gradient in salinity in concert with variations in depth produces the fourth important component of bay circulation, the density current. This is one of the prime mechanisms for salinity intrusion into the system, and is especially prominent in the Houston Ship Channel. Density currents are exhibited in two different forms: vertical shear in the horizontal current, and large-scale horizontal circulations. The vertical shearing density current is particularly prominent in deep channels that are laterally confined, such as the Houston Ship Channel above Morgans Point, and the Galveston Harbor channels between the jetties. Usually this kind of current is exposed by averaging vertical profiles of current velocity over a tidal cycle. The resultant circulation is a tidal-mean influx from the sea into the estuary in the lower layer, and a return flow from the estuary to the sea in the upper layer. The second kind of density current results from the absence of laterally confining boundaries, so that the return flow is completed in the horizontal plane, rather than in the vertical. This circulation is induced by the presence of the Houston Ship Channel in the open waters of Galveston Bay, behaving as a deep slot in the shallow bay. In this case, the vertical-mean current is directed up (into) the estuary along the axis of the Channel, and the return flow to sea takes place in the shallow open bay to either side. Examples of the presence of density currents from measurements of current velocity in the bay are given in Ward (1991).

This description of density currents did not refer to vertical stratification. Indeed, either kind of density current can take place even when the water-column salinity is homogeneous, because the driving force for density currents is the *horizontal* gradient. The confined density current, especially, will tend to develop salinity stratification, but if the vertical mixing processes are sufficiently intense, as they typically are in Galveston Bay, the salinity can still be maintained nearly homogeneous in the vertical.

4.2 Freshwater inflow

The principal inflows to the Galveston Bay system are the Trinity River and the San Jacinto River. In addition, there are numerous minor tributaries which drain the watershed of the bay and can be locally important as fresh water sources. These include Chocolate Bayou, Clear Creek, Dickinson Bayou, and several bayous conflowing with the confined reach of the Houston Ship Channel, such as Carpenters Bayou, Greens Bayou and Brays Bayou.

As noted above, the flow of the Trinity River dominates the hydrography of Galveston Bay, and the variation of this inflow is central to the effect of inflow on the bay system (see TDWR, 1981, and Ward, 1991). Inflow into Galveston Bay is highly variable, but it is a variability with definite patterns. River flow is governed by surface runoff from storm systems, and therefore in the Texas climate this means the rivers are "flashy", exhibiting large, sudden excursions in flow: the daily flow of the Trinity spans four orders of magnitude.

The normal pattern of Trinity River flow exhibits an annual "flood" and an annual "drought." The flood is the spring freshet, the period of maximum river flow, typically April and May, and the drought is the summer low-flow season extending from July through October. There is, however, considerable interannual variability in the river flow. The watersheds in the periphery of Galveston Bay can exhibit a fall maximum in rainfall as well as the spring, due to the interaction of midlatitude frontal systems with Gulf moisture during this season and due to occasional tropical systems making landfall on the upper coast. While the runoff is intense locally, its cumulative volume--except in rare instances--is still subordinate to that of the Trinity.

The most important aspect of the year-to-year variation in annual discharge is how that is manifested in the spring flood and the summer drought. Some years exhibit a pronounced and extended freshet, while in other years the spring freshet may be totally absent. Correspondingly, in some years the summer drought may be shortened or even eliminated by unusual runoff, and in other years may be prolonged while the flows dwindle to nothing. To exhibit quantitatively the hydrologic behavior of river flow, the gauged flow of the Trinity was analyzed in several ways. The record of monthly flows from 1925-1990 was first analyzed for the annual maximum three-month period beginning January through June. The volume of flow during this period was defined to be the spring "freshet" for that year. The variation in volume for the period of record is shown in Fig. 4-1 superposed on the time history of the total annual flow volume. Also shown are the increments in reservoir storage capacity for the years in which deliberate impoundment began. Lake Livingston, with conservation capacity 1.63 million acre-feet (maf), began deliberate impoundment in summer 1969. Several observations are noted from these analyses:

(1) The 3-month "freshet" (as defined here) comprises just over *half* of the annual flow of the river (precisely, 51% with a standard deviation of ±13.9%).

(2) The annual flow is highly correlated (r=0.89) with the spring "freshet," not unexpected given (1).

(3) There is a interannual spread of over two orders-of-magnitude in the freshet volume ranging from 0.02 km^3 in 1971 to 8.9 km^3 in 1957.

(4) A Fourier analysis of the 65-year time signal of annual flow (Fig. 4-1) disclosed significant spectral peaks at periodicities of 3.5-4 years (leap-years seem especially drought-prone, for whatever one wants to make of that) and 13-14 years.

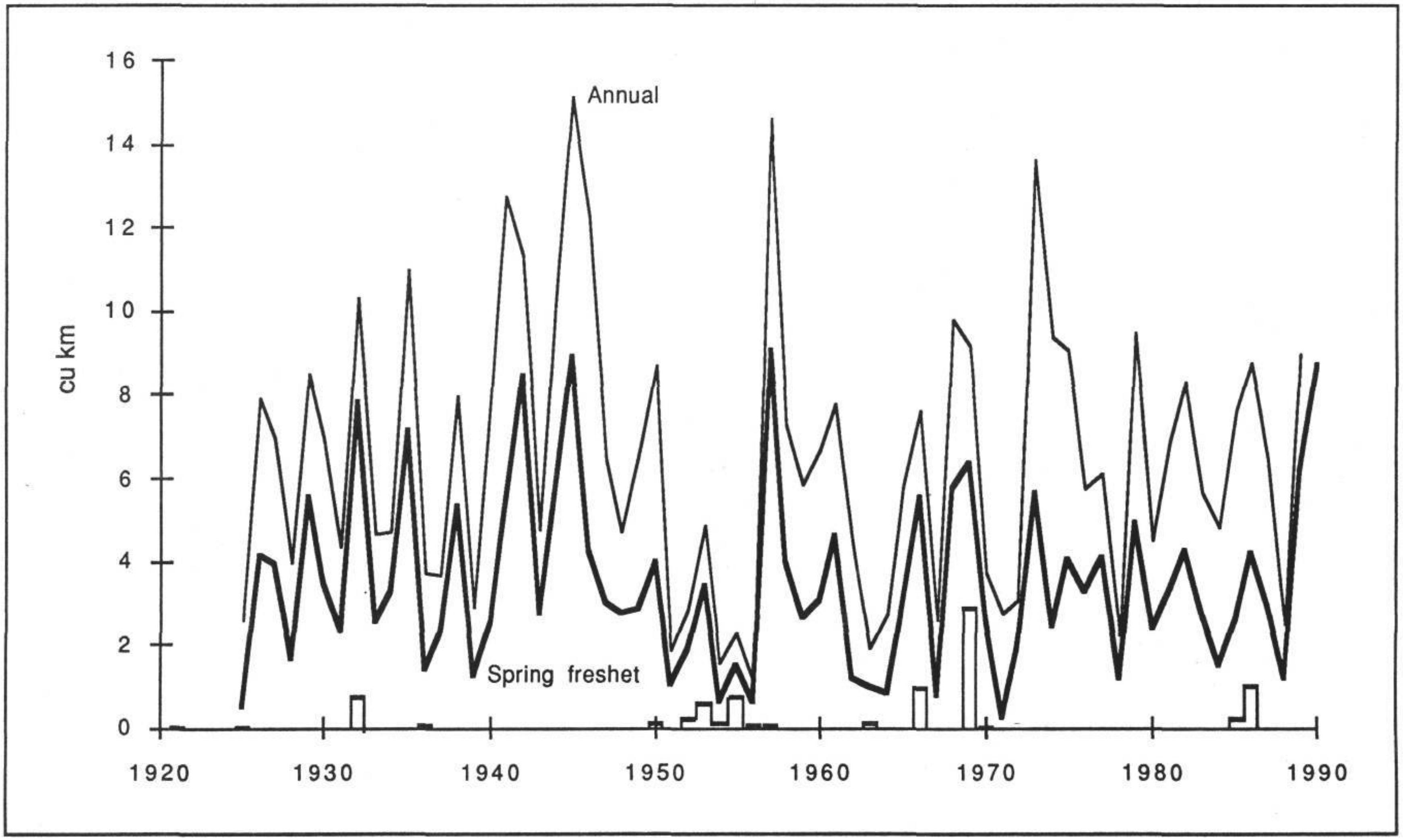


Figure 4-1. Annual flow volume of Trinity River (at Romayor) and volume of 3-month spring freshet. New reservoir capacity per year shown as bars.

(5) The first month of the 3-month period of maximum discharge is most commonly April, next January, penultimately May (14%) and lastly June (0), which emphasizes both the variability in the onset of the freshet as well as its concentration in the spring months.

(6) The four-month "drought" period comprises less than 15% of the annual discharge of the river (precisely, 13.2% with a standard deviation of ± 7.8%).

(7) Because large freshets include a hydrograph that extends into the summer, there is some correlation (r=0.55) between summer flows and freshet volumes.

(8) A Fourier analysis of the 65-year time signal of summer low flows indicated strong spectral peaks at periodicities of about 5 and 7-8 years, as well as wider bands of 3.8-4.8 and 14-18 years; the latter are generally consistent with the freshet signal and may be driven by the correlation between the two, but the former appear to be independent.

4.3 Loadings

A detailed analysis of organic, nutrient, and contaminant loading to the Galveston Bay system is presented in Armstrong and Ward (1992). In summary, the influx of conventional pollutants as a mass load from both point source discharges and inflows peaked in the early 1960's and has declined since. The former is a consequence of implementation of advanced waste treatment of both industrial and municipal dischargers, in which Operation Clean Sweep of the Texas Water Quality Board, initiated in 1969, played an early key rôle. On the other hand, with the growth of population and industry in the Galveston Bay region, there has been a steady increase in return flows.

The focus of waste loading in the Galveston Bay system is, of course, the Houston Ship Channel. The decrease in BOD loading to the Houston Ship Channel over the past several decades is indicated by the following estimates:

Date	Domestic		Industrial		Total	
(appx)	Flow (MGD)	BOD load (lbs/day)	Flow (MGD)	BOD load (lbs/day)	Flow (MGD)	BOD load (lbs/day)
1950		23,000				
1960 (permitted)	103	35,000	210	237,000	313	272,000
1970		143,000		317,000		460,000
1980	315	46,800	140	14,000	455	60,000
1990					837	19,700

(see Metyko 1952, to which we applied a factor of 0.25 lbs/day untreated BOD per capita, Gloyna and Malina, 1964, Kirkpatrick, 1986, and Armstrong and Ward, 1992b). Associated with the reduction in BOD loading has been reduction in TSS loading and advanced waste treatment for ammonia reduction. Similar reductions in waste loadings have taken place throughout the Galveston Bay system and within its watershed (notably the Dallas-Fort Worth metroplex on the Trinity).

There is less reliable data on long-term variation in nitrogen loads from waste discharges, one prominent exception being the excellent data-collection program on the City of Houston wastewater plants. Data from this program (Jensen et al., 1991) indicate that for the period 1972-90 the cumulative City of Houston wastewater load of total nitrogen has remained around 25,000 lbs/day (1.1 $x10^4$ kg/d), varying from a low of 20,000 in 1972 and 1980, to a high of 30,000 in 1979. During this same period the proportion of nitrates in the load has increased from 3% to nearly 90%, as a consequence of advanced waste treatment. Additional domestic nitrogen loads to Galveston Bay are roughly 40-60% of that of the City of Houston, and probably experienced a net decline with advanced waste treatment. Reductions in industrial nitrogen loads began to be implemented in the early 1970's, somewhat sooner than municipal discharges, and these reductions probably are much greater proportionately than domestic discharges. At present, the total industrial nitrogen load is probably about one-third the domestic load (Jensen et al., 1991, Pacheco et al., 1990).

The decline in mass loading from the river and stream inflows is a consequence of improved waste treatment as well, but also is considered to be due to impoundments on the principal rivers and the concomitant entrapment of fine-grain sediments. As many nutrients and contaminants are associated with these finer particulates, these reservoirs are therefore also considered to represent an effective sink of these constituents in the inflows. Unfortunately, the construction of most reservoirs, including Livingston on the Trinity, antedate the period of adequate data record of riverborne chemical constituents, so the quantitative effect of these reservoirs on chemical loadings cannot be directly evaluated.

Some indication of the potential nutrient-trapping capacity of Livingston is shown by the historical silt load and flow-weighted TSS concentrations in Fig. 4-2. Following the closure of Livingston about 1970, both annual load and mean concentration of suspended sediments at Romayor have fallen to one-third of their pre-lake level. Further, the variance in both of these quantities has reduced considerably since closure of the dam. While the imposition of Livingston is certainly an appealing explanation for this reduction, we must note that the TSS concentration exhibited a declining trend over the 1937-1975 period. Without the external knowledge of the creation of Livingston, one would instead seek a cause for a gradual decrease in TSS (rather than a quantum decline).

We do not have available a sufficiently long record of nutrient measurements in the Trinity prior to the closure of the dam. However, dissolved nitrates were monitored by USGS at Romayor for about 5 years prior to closure, and total nitrates for about 10 years following closure, which together give some indication of the effects of the reservoir. There is clearly a reduction in both the mean concentration and the variance with Livingston on-line, that would be even more

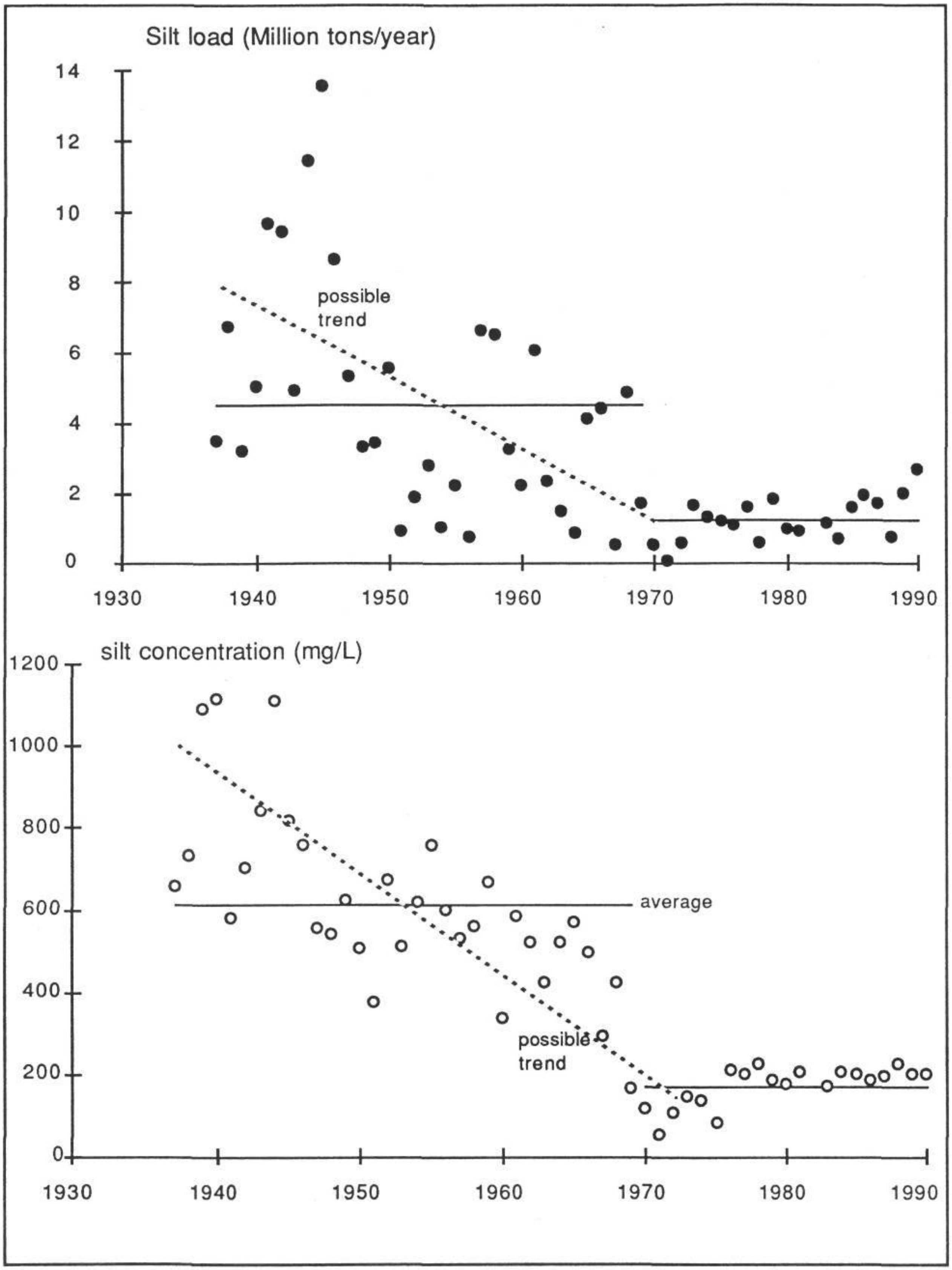


Figure 4-2. Historical variation of silt load of Trinity River at Romayor

pronounced as the ratio of dissolved nitrate in the total decreases. (As there is no paired data, we have no information on this ratio.) At the same time, we note that in the river data at Romayor there is *no* significant statistical association between suspended solids and any of the nutrients: total ammonia (143 measurements, r=0.17), total nitrates (88 measurements, r=0.077), or total phosphorus (145 measurements, r=0.17).

Jensen et al., (1991) estimated a three-to-four-fold decrease in nitrogen loading of the Trinity due to Livingston, based upon total nitrogen concentrations in the river at Crockett (upstream from Livingston) versus those at Romayor. They also estimate an increase in nitrogen loads of about the same ratio in the Trinity from the turn of the century, due to altering land use patterns and increasing waste discharges from the Dallas-Fort Worth area. Relative to this "natural" nitrogen load, the imposition of Livingston is to reduce the nitrogen load back to turn-of-the-century levels.

4.4 Water and Sediment Quality Responses

4.4.1 Temperature and Salinity

Temperature in Galveston Bay is governed primarily by surface heat exchange, which imposes a strong seasonal signal. Stratification effects are nil, and horizontal spatial structure is virtually absent. The former is an indicator of the vigorous vertical mixing which operates in Galveston Bay and renders many variables vertically near-homogeneous. The latter is consistent with the domination of surface heat fluxes, so that lateral boundary fluxes become much less important.

The most significant observation from the analyses of Chapter 3 is the long-period decline in water temperatures, primarily a result of declines in summer temperatures. Over the three-decade period of record, the net decline is on the order of 2°C. Hypotheses possibly explaining this observed decline are the following:

(1) Long-term alterations in climatology, e.g. declines in air temperature or increases in wind speed;

(2) Long-term alterations in water temperature of the Gulf of Mexico;

(3) Alterations in the intensity of interaction of Galveston Bay with the adjacent Gulf of Mexico;

(4) Sampling bias toward the earlier months of summer in more recent years.

Hypothesis (2) is rendered more plausible by the fact the the bulk of the decline is in summer temperatures, the season in which Gulf of Mexico influence on Galveston Bay waters is maximal. On the other hand, the lack of spatial structure, with gradients in temperature toward the sea, makes this hypothesis dubious. The others could not be tested within the scope of this project.

There is probably no variable of Galveston Bay water quality that provokes as much frustration as salinity, because for this variable there is a clear, intuitive cause-and-effect association with freshwater inflow that refuses to emerge from the statistics. Many attempts have been made by past researchers to extract a salinity-inflow relationship by statistical analysis (e.g. TDWR, 1981), none of which have been satisfactory.

Salinity in Galveston Bay *is* dependent upon freshwater inflow. Without freshwater inflow to the bay, the salinities would eventually acquire oceanic values. The fallacy is to conclude from this that there is a *direct* association between a given level of inflow and the salinity at a point in the bay. The other hydrographic mechanisms, tides, meteorology, and density currents (as well as others not mentioned here), all govern the internal transports of waters of different salinities in the bay, and dictate how freshwater influences salinity. Further, the salinities present at the entrance to the bay are controlled by processes in the Gulf of Mexico, especially the effects of the freshwater plumes from river basins along the northwest coast, notably the Sabine, Neches and Mississippi.

The nature of the problem is illustrated by the salinity data of Fig. 4-3, showing the association of mid-bay salinities with gauged flow of the Trinity. While there is a discernible downward slope in the relation, as we would expect, the variance of salinity encompasses nearly the entire estuarine range, independent of the level of inflow. Put another way, for virtually any level of inflow, one can encounter in the data a disquietingly wide range of salinity. This high variance is a quantitative demonstration of the complexity of the response of salinity in the bay to many factors, only one of which is freshwater inflow. First, there is a lag between the freshwater signal as measured at an inflow gauge and its effect on the bay. In addition to this lag, salinity in the bay responds more as an integrator of freshwater inflow, i.e. with a longer time scale of variation than that of the inflow itself. Moreover, the response of salinity is affected by the operative physical processes, e.g. tidal excursion, antecedent salinity gradients, semi-permanent circulation patterns. Salinity intrusion takes place by mixing by tidal currents and advection by density currents, and intrusion into the upper bay generally requires a long time, on the order of weeks to months. Salinity extrusion, especially in Trinity Bay and upper Galveston Bay, on the other hand, is basically a mechanism of displacement by freshwater, and occurs rather rapidly when forced by seasonal floods.

The response of salinity as an integrator of the freshwater inflow signal can be accommodated to some degree by using a long-period average of inflow as the independent variable. While the explained variance can be more than doubled (in some regions of the bay) by this device, the optimal averaging still accomplishes little more than 50% explained variance, at best. Further, the standard error of the regression is still more than 4 ppt, which means the regression predicts salinity at a 95% certainty within a 16 ppt range, i.e. about half the normal range

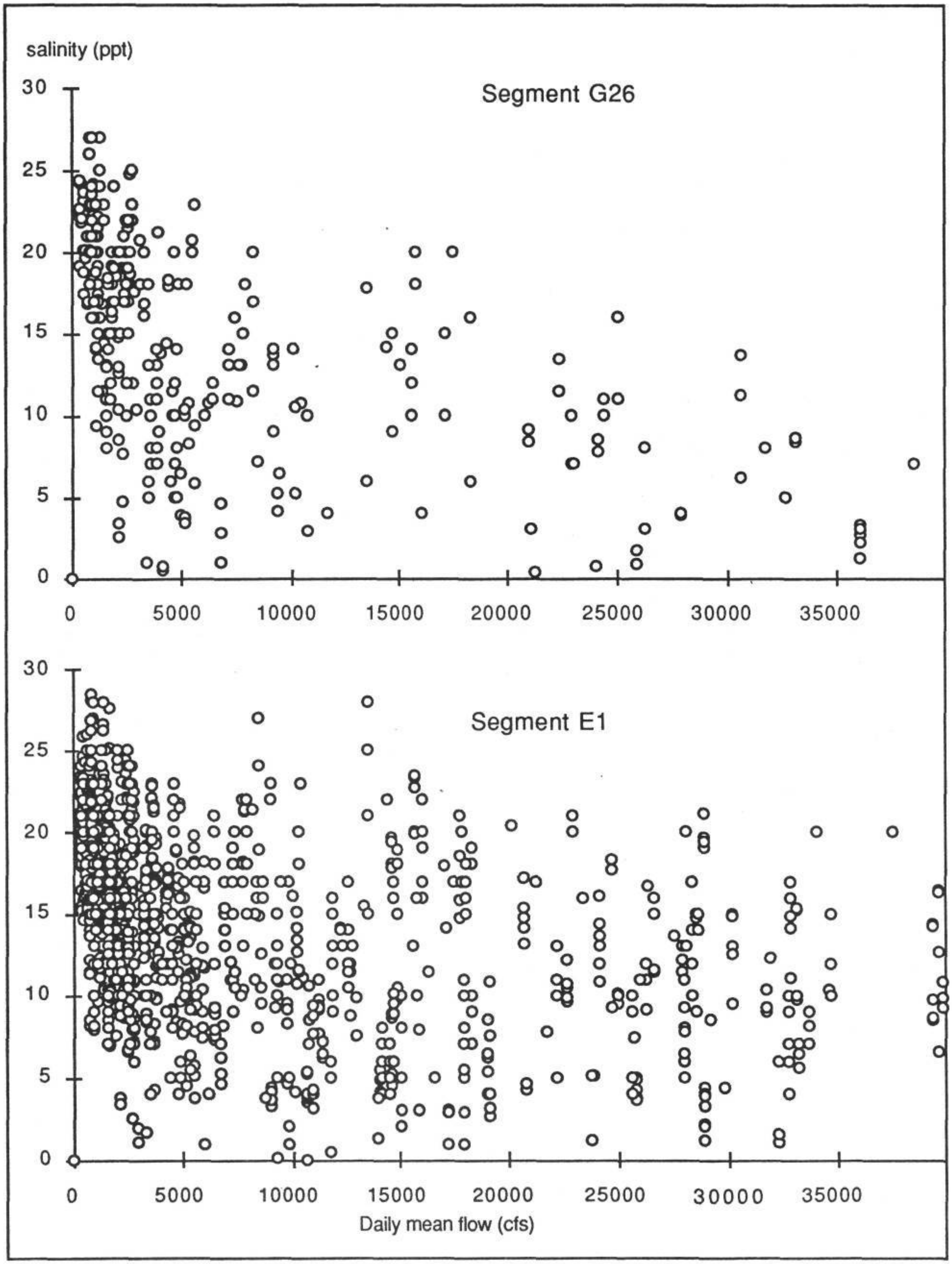


Figure 4-3. Salinity (upper 1.5 m) in mid-bay segments versus Trinity River flow

from fresh to oceanic. Moreover, in areas of the lower bay, the explained variance and standard error are even worse.

The mean spatial structure of salinity presented in Chapter 3 reflects the zones of salinity intrusion (the main inlets and the Houston Ship Channel) and extrusion (the river plume of the Trinity). A widespread systematic decline in salinity was disclosed by the trends analysis of that chapter. The declining trend in salinity (Figs. 3-29 and 3-30) is most prominent in the lower bay, especially East Bay, and those regions most influenced by intrusion, e.g. the regions west of the Houston Ship Channel. This decline is not trivial: in a two-decade period, the net decline is on the order of 4 ppt. Several non-exclusive hypotheses are proffered:

(1) Decreased salinities in the adjacent Gulf of Mexico;

(2) Increased peripheral inflow from local precipitation;

(3) Decreased interaction with the Gulf of Mexico;

(4) Altered volume and timing of freshwater inflow events to augment salinity extrusion;

(5) Increased sampling bias toward higher inflow conditions;

(6) Increased return flows.

The most obvious potential cause is, of course, an increase in freshwater inflow. If this is operating, it is too subtle to be discriminated by simple linear statistics. The variation of mean inflow (as well as summer and freshet volumes) over the past three decades are too variable to allow any confidence in extraction of a linear trend. The computed linear trend proves to be extremely sensitive to the period of record, and at the 95% confidence level not even the sign is certain. The salinities, however, do not evidence the same sensitivity to period of record. This suggests that if a freshwater inflow variation is the cause, it is not so much an alteration in mean inflow as it is in the time signal of the hydrograph and the response of salinity. This will require much more complex analysis to sort out than possible within the scope of the present study.

At least one of the principal state programs, that of the Texas State Department of Health, has altered its sampling strategy to emphasize those conditions conducive to coliform violations, which implies that salinity data would be taken during or immediately after inflow events. Over the years, this could entail a bias to lower salinities. Whether other programs may have inadvertently introduced similar biases as well is thought unlikely, but is certainly worthy of examination, hence hypothesis (5). The last hypothesis is extremely unlikely as an explanation, since the volume of return flows, even including irrigation, is far below that which would effect the observed decline in salinity. These hypotheses could not be tested within the scope and resources of the project. We note that hypothesis (3) would conflict with the observed *decline* in summer water temperatures (at least to the extent that interaction with the Gulf has any effect on bay temperatures) so it cannot be offered as a common cause for declines in both salinity and temperature. Both (1) and (3) are strengthened by the spatial distribution of the salinity decline, i.e. its prominence in proximity to the Gulf and in the saline intrusion regions.

4.4.2 Dissolved oxygen

In the open bay, dissolved oxygen, like temperature, is most strongly affected by surface processes. A high degree of aeration is implied by the saturated conditions, which is consistent with surface-wave overtopping and vigorous vertical mixing. Some oxygen consumption in the water column and in the bottom sediments is consistent with the tendency to positive stratification.

The most significant exception to the general elevated DO in Galveston Bay is, of course, the Houston Ship Channel above Morgans Point. Here there has been a notable decrease in DO deficit (e.g., an improvemnt in DO) of about 4 ppm since 1960. This decline has been gradual (Fig. 3-32), not quantum, and is almost certainly a direct function of the decrease in organic loading due to advanced waste treatment. We also note an increase in DO deficit in certain open bay regions: in the outflow plume of the Trinity River, out from Clear Lake, and in upper Galveston Bay around Atkinson Island (Fig. 3-31). The latter two, it should be noted, lie in the open bay out from those regions with marked improvement in DO deficit due to waste treatment, *viz*. Clear Creek and the Houston Ship Channel, resp., and are on the order of 1-2 ppm over two decades. Hypotheses to account for these increases in DO deficit include:

(1) Introduction or stimulation of oxygen-demanding constituents in the inflow sources, either as new contaminants or as a by-product of advanced waste treatment;

(2) Reduction in aeration;

(3) Reduction in photosynthesis, associated with advanced waste treatment or with inflows from these same sources.

The first two seem implausible. Such oxygen-demanding constituents would have much longer time constants than CBOD and NBOD, and if present in wastewater, should have been present in the waste streams all along. The local reduction in aeration would have to be due to surface interference, e.g. oil, and should have received notice. The third is most plausible of the three, and is addressed further in 4.4.4 below.

4.4.3 Suspended Solids and Turbidity

Suspended solids in Galveston Bay have a close association with points of inflow and regions of shipping. The former is due to the riverine inflow and waste discharges as sources of TSS. The latter is due to resuspension by dredging activity and--especially--by ship traffic. Because the particulates are subject to gravitational settling, there is an expected vertical stratification in TSS.

One of the surprising findings of this study is the general decline in suspended solids throughout the bay. The rate of decline over the past two decades has resulted in roughly *halving* the TSS concentrations. Hypotheses that could account for this decline are:

(1) Reductions in TSS loading due to advanced waste treatment;

(2) Reductions in TSS loading due to declines in riverine transport, in turn a consequence of

(a) reservoir construction

(b) better land-use practices on the watersheds

(c) natural modifications to watershed solids runoff;

(3) Reductions in TSS loading of peripheral runoff, due to alterations in land use around the bay;

(4) Declines in the mechanical resuspension of particulates within the bay;

(5) A laboratory artifact due to improved methods of filtration and analysis.

Among most workers (1) and (2a) would be considered the frontrunners by a considerable margin. In our view, the only one which lacks plausibility is (4). Note was made earlier of the fact that, while mean TSS concentrations are lower by a factor of three after closure of Livingston than before, TSS had been exhibiting a definite decline for the 30-year period before Livingston impoundment began, so it is not clear that the reservoir is the causal agent. Testing of these hypotheses lies far beyond the scope of the present study, and would entail a research effort in its own right. Hypothesis (5) might present an explanation for some of the nutrient declines, but is less likely for TSS since the data prior to 1980 were obtained by the Texas Water Development Board using gravimetric methods: only those after 1980 are from USGS, based upon filtration. Since the gravimetric method assumes a specific gravity of 1.102 for the suspended sediments, a decline in sediment density could account for the observed trend. We believe this to be unlikely.

4.4.4 Nutrients and chlorophyll

A finding as equally remarkable as the TSS decline is that the principal nutrients in Galveston Bay are generally declining as well. Ammonia, nitrates, total phosphorus and total organic carbon all exhibit declining trends widespread throughout Galveston Bay. The affinity of the nutrients for particulates, and their correlative responses to chemical and physical processes, including waste treatment, lead us to expect a high degree of interassociation. (Statistically, of course, these parameters will be correlated in time, since any two variates with a linear trend are correlated. Therefore, we cannot look to simple linear statistics to provide insight into causality.) Thus, hypotheses parallel to those for TSS can be offered for these declines as well:

(1) Reductions in nutrient loading due to advanced waste treatment;

(2) Reductions in nutrient loading due to declines in riverine transport, in turn a consequence of:

(a) reservoir construction

(b) better land-use practices on the watersheds

(3) A laboratory artifact due to improved methods of filtration and/or analysis.

The first two increase in plausibility due to the common behavior of all of the named nutrients, and reinforce the corresponding hypotheses for TSS. The last seems decreasingly plausible as a general explication, but still may be a factor in the decline of specific parameters. (NB, the lack of correlation between TSS and each of nitrates, ammonia and total phosphorus in the Trinity River.)

A prominent exception to the general decline in nutrient concentrations is the increasing trend in nitrate concentrations in the Houston Ship Channel. This is shown in Fig. 4-4 for example segments in the Upper HSC (i.e., above the San Jacinto confluence). This is almost certainly a result of increased nitrification of the ammonia. Two hypotheses for the seat of this increased nitrification are:

(1) Increased nitrification in the waste treatment process, thus decreasing the ammonia load and increasing the nitrate load;

(2) Increased nitrification in the waters of the Houston Ship Channel *per se*, resulting in a conversion of ammonia to nitrate with transport down the Channel, in turn a result of a

(a) a more stable, viable community of nitrifiers, due to

(i) more frequent aerobic conditions, due to the improvement of dissolved oxygen (see 7.4.2 above),

(ii) reductions in toxics and other compounds that suppress nitrifiers,

(b) longer hydrodynamic detention, due to

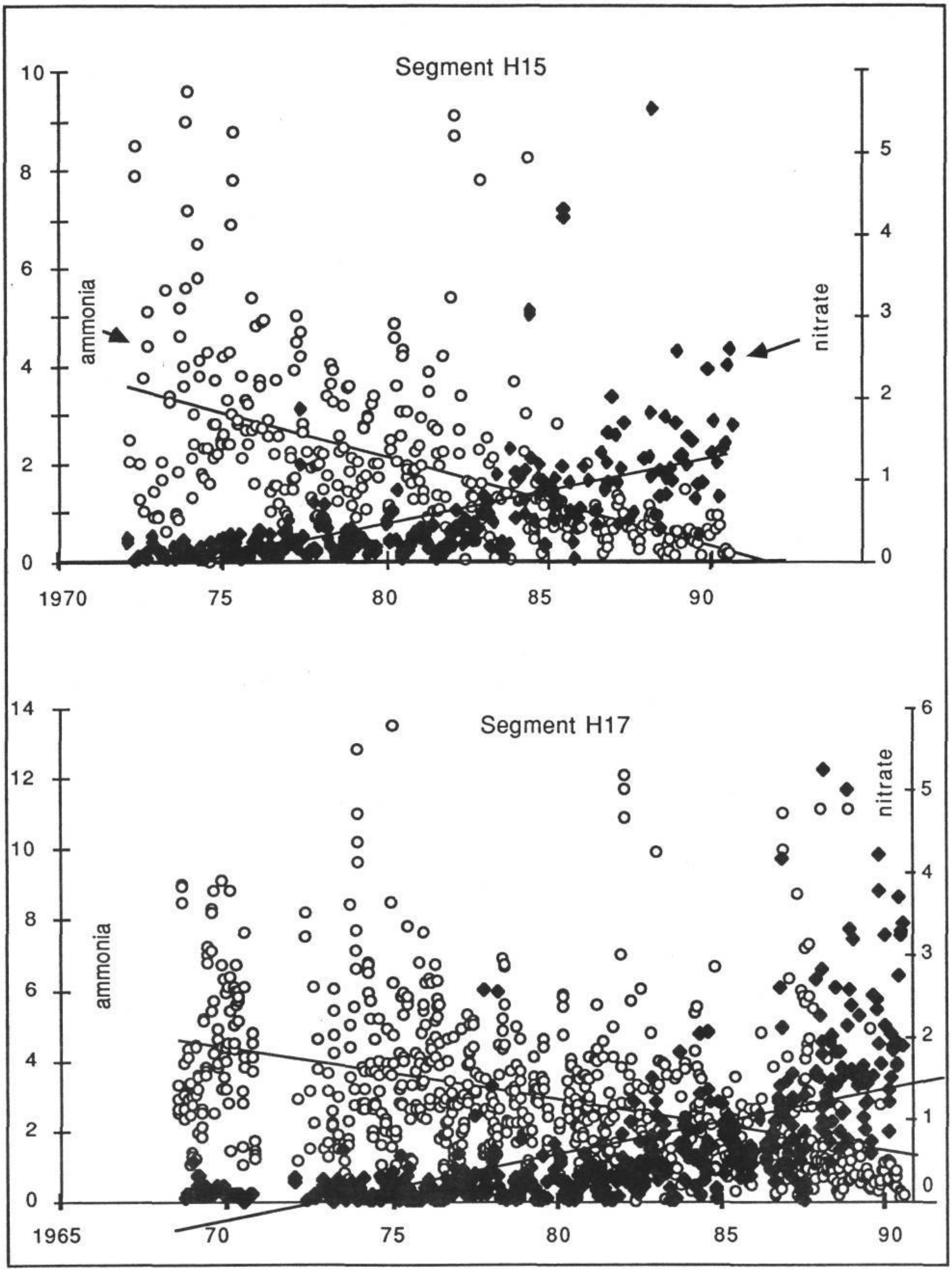


Figure 4-4. Ammonia and nitrate trends in Upper Houston Ship Channel

(i) decreased frequency of flood events which flush the Channel,

(ii) increased Channel dimensions relative to the throughflow volume,

(iii) decreased interaction with the Gulf of Mexico, through tides or meteorological flushing,

(iv) decreased density current circulation due to a reduced longitudinal salinity gradient.

There is obviously no shortage of plausible hypotheses for increased nitrification, but their testing will require detailed nitrogen budgeting on the Houston Ship Channel, as well as analysis of hydrographic processes. Hypothesis (1) is certainly consistent with the data on increasing proportion of nitrate in the total nigrogen load from the City of Houston domestic discharges. We note that the hypothesis of a decreased density current circulation is consistent with the declining trend of salinity in the open bay segments out from the Houston Ship Channel, which would reduce the longitudinal salinity gradient. This, in turn, may be itself a result of (iii), decreased interaction with the Gulf of Mexico. It should also be noted that the nitrate increase is smaller than the ammonia reduction (e.g. Fig. 4-4), so there is still a net decline of nitrogen in the Houston Ship Channel, despite the increase in nitrates. Therefore, the systemic reduction in nitrogen applies in this region also.

Finally, the trends analysis of Chapter 3 disclosed a declining trend in chlorophyll-a. The typical chlorophyll concentrations have been roughly *halved* due to this decline, over typically a decade of period of record. Assuming that chlorophyll is an indicator for photosynthetic phytoplankton biomass, this would suggest a halving in productivity. Hypotheses accounting for this decline are as follows:

(1) Decreased phytoplankton growth, due to:

(a) declining inorganic nutrient supply,

(b) increased toxicity or adverse environmental conditions, e.g. changed climate,

(c) increased phytoplankton predation,

(2) Altered species distribution with decreases in the chlorophyll-a dominated organisms;

(3) Laboratory artifact, due to alterations in methodology, especially improved correction for pheophytin.

The association of this decline with the above declines in inorganic nutrients is highly suggestive of a biological response to decreased nutrient supply. This is therefore a most pregnant hypothesis for the observed decline in chlorophyll, but the others should be considered plausible candidates as well. This might also offer an explanation for the increased DO deficits noted in several open-bay segments, provided the phytoplankton productivity and aeration together balance bacterial and sediment sinks, in which case reduction of the first would alter the water-column oxygen balance. Since generally the oxygen sources more than compensate for sinks, hence the near-saturated oxygen climate, this effect of reduced photosynthesis would be effective only where there is substantial water-column oxygen demands. We would expect this to be in the regions lying out from points of inflow, and this is precisely where the increasing trends in DO deficit are noted: out from the Houston Ship Channel, Clear Lake and the Trinity River.

The last hypothesis (3) is of particular concern because of the mix of trichromatic and spectrophotometric chlorophyll-a measurements in the data base. However, we note that the latter are the most numerous and that there is no systematic preference for one or the other as a function of time, i.e. the (uncorrected) trichromatic data are distributed throughout the period of record. Therefore the mix of the two methods would not result in the observed decline, though certainly it contributes to a high level of noise in the data. There may be, of course, other anomalies in laboratory procedures contributing to the apparent decline.

4.4.5 Contaminants

The association of BOD concentration with waste discharge sources is evident in two respects: the geographical distribution of BOD, with higher concentrations in regions affected by inflows and waste discharges, and the decline in BOD concentrations over time in the same regions. For this parameter, therefore, we do not need to look far for a causal hypothesis explicating its observed behavior in Galveston Bay: it is clearly a direct measure of organic loads, both from waste discharges and from peripheral runoff (including inflows).

Oil & grease is an alternative indicator of organic contaminants. In Galveston Bay, the highest oil & grease concentrations are found in the waters around the main inlet, with the Houston Ship Channel a distant second. Three hypotheses are offered:

(1) The Texas City area is the primary source of contaminants to which the oil & grease test respond, and their dispersal is facilitated by the intense currents in this region;

(2) The oil & grease test responds to some substance in seawater, so maximum values are detected in the trajectories of the flooding current.

(3) The oil & grease measure is elevated by shipping activities.

Unfortunately, the geographical distribution of oil & grease data is so sparse that no judgement can be offered on the plausibility of these. It is interesting that a similar elevation is indicated in sediment oil & grease around the inlet, with a local maximum in the dredged channel. There are, however, other regions of the bay, notably the Houston Ship Channel, with higher oil & grease concentrations in the sediments. Both (2) and (3) are consistent with frequency of oil-spill events, and both would suggest a rôle of boundary fluxes in establishing oil & grease concentrations within the bay analogous to that for salinity, which would imply that the available data base is too sparse to draw any quantitative conclusions.

Both total and fecal coliforms exhibit lower concentrations in open-bay areas and higher concentrations in areas affected by inflow, runoff, and waste discharges, both in arithmetic and geometric statistics. As the Houston Ship Channel is a confined, poorly flushed watercourse with strong influence by all three factors, inflow, runoff and waste discharges, the maximal concentrations in the bay system are found there. Further, there are declines in both indicators in the Channel, doubtless a result of improved waste treatment. However, apart from geographical similarity of high and declining concentrations in the Channel and north of Galveston, coliforms are inconsistent elsewhere in the bay. Total coliforms are increasing in Clear Lake and near Redfish Reef, while fecal coliforms are decreasing. Total coliforms are declining in the mid- and lower-segments of the bay, while fecals are increasing. There is a systemic increase of fecals in West Bay and a decrease in Trinity Bay, where the totals show no coherent trend. Certainly, the noisy character of these measures erode the statistical coherence in their behavior, and many of the apparent trends may be statistical artifacts. The observed trends are statistically best defined where the concentrations are greatest, *viz.* the Houston Ship Channel, so we can assert with some assurance that the decline of coliforms in that area is real and significant. Apart from this area, it is not clear what either indicator in fact indicates, and whether water quality improvement is indicated or not.

Metals, in general, behave in a quasi-conservative manner (cf. Table 4-1) and their variability in Galveston Bay would be expected to be analogous to that of salinity. Therefore, the relatively sparse data set translates to a high degree of uncertainty. It is clear, however, that the region around the Texas City Dike and the upper Houston Ship Channel exhibit consistently high metals in the water. The analog of metals concentrations to oil & grease in the lower bay area, and especially the maxima in lead and zinc in the segment over the inlet scour region should be especially noted. Sediment metals are elevated in this general region of the lower bay, as well, though the baywide maxima are consistently found in the upper Houston Ship Channel. The Houston Ship Channel waters display a consistent and substantive decline in metals concentrations (Fig. 3-42) as do the sediments (Figs. 3-43, 3-44, 3-45). Further, there is a coherent decline in sediment metals in upper Galveston Bay adjacent to the Channel. Elsewhere in the bay, trends in sediment concentrations are inconsistent geographically and from metal to metal, so without further detailed analysis, it is difficult to determine possible causes. The following hypotheses are proffered:

(1) The pathway of metals is to the sediments due to settling of solids and then to the overlying water by resuspension and reworking; that is, metals in the water column are driven principally by concentrations in the sediments and continual scour and resuspension;

(2) The pathway of metals is to the water column first, followed by transport with the main currents and settling with solids; that is, concentrations in the sediments are driven by the TSS-precipitated metals in the overlying water and zones of relative stagnation where settling is enhanced;

(3) The principal sources of metals in Galveston Bay are in the Houston Ship Channel and Texas City areas, in turn originating from

(a) runoff from highly industrialized areas

(b) waste discharges

(c) shipping activity;

(4) The decline in metals concentrations in water and sediment results from advances in waste treatment, in turn from

(a) reductions in TSS and the associated affinity of metals for fine-grained solids

(b) assimilation and/or bonding during high-detention secondary treatment

(5) The decline in metals concentrations in water and sediment results from better runoff controls in the watershed;

(6) The decline in sediment metals is due to increased dredging, removing contaminated sediments from the bay system to upland or offshore sites; if the pathway is from sediments to water, this would imply a reduced concentration in the water column, as well.

We emphasize here, as before, that these hypotheses are not mutually exclusive. Clearly, the observed decline in suspended solids and in many metals is considered to be more than just a statistical association, because there is a well-established physical relation in the affinity of metals for fine-grained solids. Therefore, any insight into the cause of the reduction in TSS would yield information on the dynamics of metals. The alternative pathways of (1) and (2) would be mooted if the reduction in metals were tied to waste-treatment or runoff control, since the net effect of either pathway would ultimately be the same. On the other hand, (1) would imply maximum concentrations in areas of strong currents and intense shipping, offering an explanation for the higher concentrations in the inlet-scour region.

The sparse data base and rarity of measurements above detection levels prevent any statements about coherent behavior of pesticides, PAH's and PCB's in Galveston Bay, other than a proclivity for higher concentrations in regions of increased urban activity.

2. DATA SETS AND DATA PROCESSING

The quantification of the quality of water and sediment in an estuary is accomplished by determination of a suite of parameters, some of which are indicator variables, such as coliforms and BOD, some of which are constituents which *per se* have major rôles in biochemical processes, such as nitrogen and phosphorus species and pesticides, and some of which serve in both capacities, such as salinity.

Temperature, salinity and pH have been routinely measured in the field for some time, therefore for point measurements, the data base is most extensive for these variables. Temperature and salinity, moreover, exhibit considerable variability, temperature due to the local heat-exchange processes at the surface, and salinity due to watermass movement within the estuary in conjunction with high spatial gradients. Generally, pH exhibits less variability, due to the high buffering capacity of seawater, but for this reason departures from the range 7-9 are especially significant. Dissolved oxygen (DO) is the traditional and ubiquitous indicator of aquatic health. Biochemical oxygen demand (BOD), oil & grease, volatile solids, and coliforms are indicator tests, and while their merit as water-pollutant parameters continues to be debated, the fact is that these parameters enjoy the longest period of record. Trace metals and pesticides are more recent arrivals, whose utility continues to be vexed by uncertain analytical procedures.

2.1 Data collection in Galveston Bay

The data analyzed in this project were drawn from numerous past and present programs in Galveston Bay. These programs are summarized in Table 2-1. Each of these comprises measurement of some of the water or sediment quality variables within a part of Galveston Bay for some definite sampling interval and period. Apart from this general feature, the programs differ in objectives and procedures.

Of central importance to Galveston Bay are the existing monitoring programs, since these are the vehicles for continued, routine acquisition of data, and therefore form the backbone for determining the present water quality and any time trends. There are four major monitoring programs presently under way which contribute information on water and sediment quality of the bay, operated by the following agencies:

Texas Water Commission
Texas Parks & Wildlife Department
Texas Department of Health
U.S. Geological Survey

The Texas Water Commission Statewide Monitoring Network (SMN) is a principal continuing source of a broad spectrum of data. The SMN sampling program is a program of sampling at fixed stations at regular intervals, usually carried out by headquarters, field and/or District offices of the Texas Water

TABLE 2-1

Sampling programs in Galveston Bay
used in GBNEP Status and Trends analysis

Abbreviation	Agency or source	Project or Program	Source of Data	Project Code	Format of source	Comments
SMN	Texas Water Commission	Statewide Monitoring Network	TWC USGS others	1	mag tape line image of report forms	40 M tape down- by special purpose mainframe codes
CDS	Texas Water Development Board	Coastal Data System	TWDB USGS contractors	2	ASCII files	different format from SMN. Line/site stations
TPWD	Texas Parks & Wildlife Dept.	Coastal Fisheries Hydrographic obs	TPWD field labs	3	ASCII	location by lat/long
GBP	Texas Water Quality Board	Galveston Bay Project 1968-72	archival tape of Espey, Huston, Inc.	5	BCD card images	Re-built file during GBNEP Data Inventory; original tape lost
TSDH EST	Texas State Department of Health	Estuarine Data File	TSDH Shellfish Sanitation	6	ASCII	Includes most of data from TSDH Project of 63-67
USCE7	Corps of Engineers Galveston District	Operations & Maintenance Div. 1970s data	USCE O&M	8	hard-copy tabulations	Keyboarded by this project
USCE8	Corps of Engineers Galveston District	Operations & Maintenance Div. 1980s data	USCE O&M	9	hard-copy, some LOTUS	Keyboarded by this project

TABLE 2-1
(continued)

Abbreviation	Agency or source	Project or Program	Source of Data	Project Code	Format of source	Comments
USCE9	Corps of Engineers Galveston District	Operations & Maintenance Div. 1989 data	USCE O&M	10	LOTUS spreadsheets	
USBCF	Bureau of Commercial Fisheries	Hydrography & water quality program 57-66 of Trent & Pullen	old tape	11	BCD or hard-copy printout	Half of file re-built by GBNEP Data Inv. The Rest keyboarded
BEG	Bureau of Economic Geology, UT	Submerged Lands Study sponsored by GLO	BEG project	12	hard copy tables & maps	Keyboarded by this project
UTD DMRP	University of Texas at Dallas	USCE Dredged Materials Research Project	DMRP reports	13	hard copy tables	Keyboarded by this project
TAMU ESP	Texas A&M Univ. Civil Engr.	Estuarine Systems Project Sediment Study	ESP reports	14	hard copy tables	Keyboarded by this project
USCE WAL	Corps of Engineers Galveston District	Trinity Marsh Biological & Hydrological/ Wallisville project	USCE warehouse	15	field sheets & tables	Keyboarded by this project
TAMU METS	Texas A&M Univ. Oceanogr.	Metals survey of Davis (68)	Ph.D. thesis	16	tabular	Keyboarded by this project
POG	Galveston Wharves (Port of Galveston)	Environmental Study for Pelican Is. Terminal	Project Reports	17	tabular	Keyboarded by this project
NOS	National Ocean Service of NOAA	National Status & Trends Project	Project reports	18	tabular	Keyboarded by this project

TABLE 2-1
(continued)

Abbreviation	Agency or source	Project or Program	Source of Data	Project Code	Format of source	Comments
EHWES	Espey, Huston & Assoc., Inc.	West Bay Env. Studies contract to USCE/Galv	Project reports	19	tabular	Keyboarded by this project
TSDH50	Texas State Dept of Health	50-52 Surveys of Galv. Bay w/ Galveston Cnty	Project reports	20	tabular/ field sheets	Keyboarded by this project
TSDH58	Texas State Dept of Health	58 Survey of Galveston Bay w/ Galveston Cnty	Project report	21	tabular	Keyboarded by this project
CEMI	Coastal Ecosystem Management, Inc.	Trinity Bay surveys, contract USCE/Ft.Worth	Project reports	22	tabular	Keyboarded by this project
HUMB	Humble Oil & Refining Co.	Hydrographic & ecological study of HSC	Project reports	23	tabular	Keyboarded by this project
HSCAERN	Espey, Huston & Assoc., Inc.	Aeration Study of HSC contract from GCWDA	Project report	24	tabular	Keyboarded by this project
HSCNIT	Espey, Huston & Assoc., Inc.	Nitrogen budget study of HSC, TDWR contract	Project report	25	tabular	Keyboarded by this project
CLCND	Chambers, Liberty Cnty Navign Distr	Salinity monitoring in Trinity Bay	USCE files	26	tabular	Keyboarded by this project
TWRI TRIN	Texas A&M Univ.	Hydrological & biological study of Trinity marsh	TWRI report	27	tabular	Keyboarded by this project
PHR NTAK	Texas A&M Univ.	Intake studies at P.H. Robinson SES	M.S. theses	28	tabular	Keyboarded by this project

Commission (TWC). Generally, field parameters are obtained *in situ*, by means of electrometric probes or portable analytical kits, and water/sediment samples are shipped to the laboratories of the Texas Department of Health for analysis. Parameters have been expanded from conventional variables in the early 1970's to trace constituents, pesticides and priority pollutants in recent years. The term Statewide (a.k.a. Stream) Monitoring Network also refers to a data management system. The SMN data base is a digitized comprehensive data management program implemented on the TWC mainframe computer and operated in coordination with the Texas Natural Resources Information System of the Texas Water Development Board. The SMN data base includes all sampling activities of the Statewide Monitoring Network, as well as special studies (including microbiology and benthos) and Intensive Surveys. It also includes selected data from other agencies, notably Texas Water Development Board and the U.S. Geological Survey. There are over 1200 separate variables with entries in the SMN data base, including water and sediment parameters, and biological parameters.

The Texas Parks & Wildlife Department and its predecessor agencies, the Texas Game and Fish Commission and the Texas Game, Fish and Oyster Commission, have monitored the fishery resources of the system for many years, and in association with this obtains a limited suite of water-quality variables. These tend to focus on estuarine habitat characteristics, e.g. salinity, dissolved oxygen, turbidity and temperature. While the range of variables is obviously much more limited than that of the SMN, the temporal intensity of the program is much greater. The TPWD program obtains data somewhere in the system on virtually a daily basis, in contrast to the sampling interval of the SMN of one to several months. Further the spatial intensity is also greater. On the other hand, the TPWD samples a random network of stations, so there is no time continuity at a fixed point in the bay. The data is now entered into a digital data base at TPWD headquarters for detailed statistical analyses.

In order to regulate the harvesting of oysters in Galveston Bay, the Division of Shellfish Sanitation Control of the Texas Department of Health (TDH) samples the bay at regular stations at varying temporal intensity, depending upon the season of year and upon the antecedent hydrological conditions. For the purpose of this program, the sampling is now limited to coliforms and a few associated hydrographic variables, salinity, temperature and pH. Like the TPWD, this program samples more intensely in space and time than the SMN and has accumulated data from many years from Galveston Bay. The collected data is maintained in a digital data base at TDH headquarters in Austin.

The activities of the U.S. Geological Survey (USGS) emphasize the inflows to the bay, though the Houston office has and does perform sampling within the estuary itself to help meet the needs of other federal and state agencies. The routine programs are described thoroughly in the publications of USGS (e.g., USGS, 1991). This data is published annually and is maintained in a digital data base, the National Water Data Storage and Retrieval System WATSTORE. Data collected in support of other agencies, e.g., Texas Water Development Board, may be managed differently, depending upon the nature of the data and the preferences of the sponsoring agency.

In addition, there are important recent or ongoing data collection programs in Galveston, as listed in Table 2-1, however these are not *monitoring* programs because they do not exhibit the regularity and time continuity implied by that term. One of the more important of these is the sampling performed by Galveston District Corps of Engineers in association with its Operations and Maintenance Program on navigation projects. This is intense sampling emphasizing sediment quality, performed in association with dredging activities. The sampling interval is therefore dictated by the condition of the channel, i.e. sediment accumulation, and may be as long as several years. The Corps data program has been subdivided in Table 2-1 according to the suite of parameters obtained. Generally, there has been an evolution from an emphasis on conventional chemistry and metals to specific hydrocarbons.

Of the historical programs available, there are several which are noteworthy. Most important is the Galveston Bay Project (GBP), a comprehensive study of the system conducted by the Texas Water Quality Board. The GBP routine monitoring program involved monthly sampling at a network of fixed stations, and was conducted in two phases. The first extended from July 1968 through October 1970. After a hiatus, sampling resumed in March 1971 and continued through August 1972. The first phase involved sampling multiple depths at 35 stations. The second phase was considerably reduced, 15 stations being occupied, only in the main bay (i.e., not in the upper Houston Ship Channel) and sampled at mid-depth for most stations, surface and 2/3 depth for the deep channel stations. One of the important accomplishments of the Galveston Bay National Estuary Program is the recovery of the digital data file from this signal program, a data file that had been lost for years. (In addition, there was a "high-frequency" component of the program, for which no record, hard-copy or otherwise, had survived. The digital data set for this program was also recovered by the GBNEP, though not employed in the present analysis.)

Another noteworthy program is the Submerged Lands Study of the University of Texas Bureau of Economic Geology, sponsored by the Texas General Land Office. This program, which focused entirely upon sediment, falls into the category of a survey, because it involved one-time only sampling. However, it is the only data set extant which samples the *entirety* of Galveston Bay at a uniform station distribution (1-mile), irrespective of the location of shoals, channels, navigation aids and reefs (which tend to spatially bias most measurements from the system).

Older studies performed by the Texas State Department of Health (TSDH, now TDH) entailed a broader suite of samples and more widely distributed sampling stations than is the case for the current program. Especially for the period 1963-67, TSDH carried out intensive sampling throughout the system. Even earlier, the TSDH in cooperation with local county agencies performed sampling of coliforms, salinity, temperature, BOD and pH in the system, providing data records back to as early as 1952.

In the period 1958-1967 the U.S. Bureau of Commercial Fisheries undertook an extended and intensive sampling of the Galveston Bay system, primarily directed at biological sampling, especially shrimp, but also including limited hydrographic and water quality data, *viz.* temperature, dissolved oxygen, salinity, phosphorus and organic nitrogen. The sampling interval ranged from weekly to monthly, usually at least twice monthly. This is one of the most intensive continuous, consistent hydrographic surveys ever performed on the Galveston Bay system as a whole. It is also the first to employ large-scale digital data manipulation as an intrinsic part of the program. All data were entered onto punched cards. Although several copies of the card deck were disseminated, as both cards and tapes, *all* are now lost. Only a few copies of the printout for water quality data exist. The loss of this valuable data set is discussed in detail in Ward and Armstrong (1991). During the present project, about half of the digital data was located in an archive tape of a consulting company, and the rest of the file was re-keyboarded from a copy of the printout (see Ward and Armstrong, 1992b). A few "patently obvious" typographical errors in the original publication (Pullen & Trent, 1969) were discovered in this process and corrected.

The data programs of Table 2-1 formed the basis for the present analysis. Most of these programs, it will be noted, are small-scale research activities, though most of the data is dominated by the few large-scale programs summarized above. The approach of this project is to combine and merge these programs to synthesize a more comprehensive data base for the system. Details on the data sets of these individual programs are given in the companion data base report (Ward and Armstrong, 1992b), along with any problems encountered in the data and how those problems were resolved (or reconciled). Particular note should be made of the programs which were keyboarded into a digital format for this project. As noted earlier, this digital data set, which is capable of much more analysis than it is subjected to here, is considered one of the chief products of this project.

2.2 Parameter relationships

In estuarine water quality, there are several classes of parameters that measure (or can be interpreted to measure) the same essential property. For example, salinity can be estimated from measurements of: chlorides concentration, total dissolved solids, density, conductivity, and light refraction. Different data collection programs in the Bay may employ different measures, depending upon objective, convenience and tradition. The relations between parameters are considered here, for two purposes. First, from an analytical viewpoint, one parameter may have conceptual advantages over another, e.g. DO deficit may be more indicative of oxygen conditions than the concentration of dissolved oxygen itself. Second, while related parameters are technically distinct, the fact that they can be associated and may be converted from one to another means that a much denser and longer-duration data set can be compiled by converting these to a common parameter. These are referred to as "proxy" relationships, and the creation of proxy data sets is treated here as an element of data processing.

2.2.1 Salinity

Salinity is one of the quintessential quality elements of estuarine waters, being determined fundamentally by the intermixing of fresh and oceanic waters. As a virtually conservative parameter, easily measured, and ubiquitous, it is an excellent watermass tracer. It is also a key ecological indicator, as it affects the suitability of habitat relative to varying osmoregulation capabilities of organisms. Since there are large spatial gradients in salinity and it exhibits high temporal variability, a lower degree of precision in salinity determination can be accepted for work in estuaries than the case either in totally fresh or oceanic systems.

Salinity originally measured the dissolved solids in seawater, which are dominated by halogen salts. A simpler measure was to determine the salts of a single halogen, *viz.* chlorine, and employ the empirical law of constant proportions (Forchhammer's Law). This gives salinity as a linear function of chlorinity and provides the means to convert from one to another (Defant, 1961, Wallace, 1974). We regard density (and specific gravity) as an alternative measure of salinity and converted using the relationship of density to salinity and temperature, the equation of state for seawater (UNESCO, 1981). One of the most common methods of salinity measurement is conductivity. This is a particularly convenient methodology for field determination. One additional measure of salinity is the refractive index of water. The field instrument used for this purpose is a portable refractometer that is calibrated for direct read-out of salinity (the Goldberg refractometer).

Generally, in the field data from Galveston Bay, one of the above measures is employed for determination of salinity, so the only decision available in analyzing the data is the proper conversion. On occasion, more than one method is used so there is a choice. This provides an opportunity to determine consistency and probable errors in measurement. Laboratory titrations and conductivity determinations from the Galveston Bay Project were evaluated in this manner, and a significant variation in lab performance was disclosed. This information was used to determine a preferential order by which GBP salinity measures were used in the data base. Similarly, in the TWC SMN data, both field and laboratory conductivity measurements may be available for a given sample, and occasionally there may be a laboratory determination of chlorides as well. To clarify the variability and relation among these different parameters, we analyzed those data records in which all three variables were measured. Widespread discrepancy was found, partly due to degraded accuracy in the laboratory determinations, and partly to the fact that a significant proportion of the reported laboratory values are not really measurements, but are "substitute data," apparently resulting from "rules-of-thumb" data entries instead of actual measurements. To summarize a detailed evaluation, the order of (decreasing) reliability was determined to be: field conductivity, laboratory chlorides and (lastly) laboratory conductivity. With respect to the last, all laboratory conductivity data before 1973 were determined to be completely unreliable and expunged from the data base; those after 1973 were used only when other measures were unavailable (about 50 measurements in all). Similar problems were encountered with the Texas Department of Health data base. Details are given in Ward and Armstrong (1992b).

This experience with salinity data exemplifies two major points concerning data collection. First, we rarely have the luxury of simultaneous determinations of two related variables, by which we can evaluate the consistency and probable error of the data. What then of the many programs in which only a single measure of salinity was made, and there is no means of cross-checking the data? Any data point should be regarded with suspicion, and the cross-comparison with other nearby, contemporaneous measurements, even from different programs, should be an indispensable guide to weighing the reality of a measurement. Second, the precision of the methodology notwithstanding, it is the procedures and technique of the field crew, the laboratory and the data entry personnel that are controlling in the level of accuracy attained, especially the laboratory. Even for as straightforward and commonplace a measurement as reading a conductivity meter or titrating for chlorides, the potential for error is substantial, as shown here. What then can be expected of more complex and demanding analyses of trace metals or organics?

2.2.2 Dissolved oxygen

As noted above, dissolved oxygen (DO) is one of the fundamental indicators of aquatic health, since it determines the ability of aerobic organisms to survive. With the development of electrometric probes for DO--a welcome technology for anyone who has ever performed Winklers in a pitching boat--field measurements of DO have increased geometrically, and are now a routine component of most *in situ* monitoring. The data base for DO is therefore approaching that for temperature and salinity, especially in the last two decades, though the data from the 1950's and 1960's are principally laboratory determinations on water samples.

DO is introduced into the water column principally through reaeration, the mechanical process of surface transport from the atmosphere, and through photosynthesis. Therefore DO can serve as an indicator of both mechanical aeration and the intensity of primary production. The primary depletion of DO is due to biochemical stabilization of organics, through the respiratory processes of the biological community (see Section 2.2.4 below), and low DO's are traditionally linked to the presence of oxygen-demanding pollutants.

One of the key controls on the concentration of DO is its solubility, which is a strong function of temperature and salinity and therefore varies substantially over the year. As temperatures range from perhaps 5° to 35°C and chlorinity from 0 to in excess of 20‰, the total excursion in solubility is from 6 to 14 mg/L. This high range of natural variability can mask variations in DO of importance in diagnosing water-quality problems. Accordingly, an associated parameter is defined, the oxygen *deficit*

$$D = C_S - C$$

where C is DO concentration and C_S is the solubility concentration, both in mg/L. The use of deficit effectively removes the influence of varying temperature and salinity, and allows a more direct interpretation of the (transformed) DO measurements in terms of water quality. Interpretation of the DO "climate" requires both parameters. Deficit, by itself, cannot be interpreted biologically: a deficit of a given magnitude may be biologically limiting in summer and biologically unimportant in winter.

2.2.3 Suspended solids and turbidity

Turbidity refers to the interference with the passage of light by suspended matter in the water, and is therefore an indirect indicator of the concentration of such suspended matter. Further, there are methods of making turbidity-related observations in the field. While turbidity has value in itself as a water-quality indicator, our present interest is in its use as a surrogate measure of suspended solids.

Laboratory turbidity measures are calibrated by standard silica suspensions, so as to eliminate the source of variation due to suspended particles of different constituency and geometry. The traditional method of viewing a candle flame through a vertical tube containing the water sample motivated the definition of the Jackson Turbidity Unit (JTU), see APHA (1985). Modern electrometric optics offer an alternative to the traditional Jackson turbidimeter (e.g., Lamont, 1981, Kirk, 1983, APHA, 1985). Nephelometers measure light scattering at 90° and the measurement is reported in Nephelometric Turbidity Units, which are defined to be numerically about the same as JTU's. This numerical equivalence holds only for the calibration compound. For different types and distributions of suspended matter, NTU's and JTU's depart. Further, each is an index and does not *per se* correspond to a physical property of the water. When the reference suspension in the nepholometric procedure is the formazin polymer, the results are often reported as FTU; for present purposes, we regard these as equivalent to NTU.

The depth of the Secchi disc has for many years been the limnologist's and oceanographer's standard means for field measurement of turbidity (Hutchinson, 1957). Unfortunately, the relation between Secchi depth and conventional measures of turbidity is murky, and their relationship is based upon a complex of theory and empiricism, see Preisendorfer (1986) and Effler (1988). Further, Secchi depth becomes decreasingly sensitive to turbidity as turbidity increases into the range typical of coastal estuaries. From scattering theory and various empirical results, turbidity is found to be roughly proportional to suspended solids (Jones and Willis, 1956, Di Toro, 1978). All of these relations were combined and calibrated with data from Galveston Bay using paired measurements of Secchi depth, turbidity and TSS from the TWC SMN data base. Each is a noisy measurement, and their interrelation is an additional source of uncertainty. Nonetheless, these relationships provide a vehicle for constructing a long-term data base on suspended solids from a variety of turbidity and physical measurements.

2.2.4 Biochemical Oxygen Demand

Since the classical work of Phelps and Streeter the biochemical oxygen demand (BOD) has become one of the fundamental parameters for estimating the presence of oxygen-demanding organics in a water sample (either from a sewage effluent or from a natural watercourse) and is one of the central parameters in the mathematical modeling of dissolved oxygen in the watercourse. Despite this long history of use, which can be traced back to the 19th Century, the BOD test is still controversial and is a continuous source of debate regarding the correct laboratory procedures and interpretation of results.

Fundamentally, the BOD is the amount of dissolved oxygen consumed in a sample of water during some period of time. The basic concept of BOD was to measure the potential oxygen depletion in a natural stream due to an injected waste. Since then the concept has evolved in two separate directions, both of which are referred to as BOD, to compound the confusion. The first is the oxygen consumed within the watercourse by the degradation of organic wasteloads, for which the ultimate BOD is the crucial quantity. The second is the evolution of the BOD bottle test as a measure of the organic wasteload of an effluent, and therefore, as a direct monitor of the operation of a waste-treatment facility and the key design parameter for treatment processes.

The amount of oxygen consumed as consequence of aerobic biochemical processes in a water parcel, whether it be a laboratory BOD bottle on a shelf or a moving parcel of water embedded within the flow of a natural watercourse, is directly dependent upon a number of variables, as follows:

(1) Types of bacteria present in the water;
(2) Initial quantities of each type of bacteria present;
(3) Multiplication or growth rates for each type of bacteria present;
(4) Chemical characteristics of the substrate, i.e., the oxidizable organic constituents within the water;
(5) The quantity, or concentration, of the oxidizable constituents;
(6) Constituents which act as an inhibitor or a stimulant for the bacterial metabolism;
(7) Environmental parameters, most notably pH and temperature;
(8) Other aerobic organisms in the water, notably phytoplankton.

It is apparent that there is quite a multiplicity of factors that can affect the BOD in the water parcel.

There are two broad categories of bacteria contributing to oxidation within the water parcel, the heterotrophs and the chemautotrophs. The former is dominated by, and therefore practically synonymous with carbonaceous. The chemautotrophs of particular concern are the nitrifiers, *Nitrosomonas* spp. and *Nitrobacter* spp, which are the principal organisms responsible for the oxidation of ammonia to nitrate. The identification and separation of the carbonaceous stage of oxidation from the nitrogenous in the BOD measurement has been a matter of considerable study. Much has been made of the use of nitrification "inhibitor" constituents, and these have become an optional step in the laboratory procedure.

There is a variety of data from Galveston Bay, all labeled "BOD". The measurements include dilution-series 5-day BOD with cultured seed, dilution-series 20-day BOD with cultured seed, aerated BOD, dilution-series 5-day BOD with natural seed, dilution-series 20-day BOD with natural seed, nitrogen-suppressed 5-day BOD and nitrogen-suppressed 20-day BOD. Further, there is no meaningful way to interconvert from one to the other. The choice of which of these to employ therefore was based upon two criteria: (1) the parameter most utilitarian for the purposes of the study, (2) the parameter affording the greatest data record. With respect to the latter, the greatest amount of data, both in spatial coverage and period of record, is for dilution-series 5-day BOD. With respect to the former criterion, it is the prime objective of this study to establish long-term trends in BOD as a measure of organic loading and labile carbon sources. For this purpose, the 5-day BOD will serve as a suitable index. (Were this a modeling study, for which the BOD would be used as a sink term in a DO budget, then much more stringent requirements would be necessary on the measurement to ensure that it bore some relation to a real physical process. But that is not our purpose here.) Accordingly, this study focused on the 5-day BOD. For consistency, it would be preferable to limit this to BOD_5 without nitrification suppression, since most of the historical data is of this type. Most of the N-suppressed BOD data has been obtained by TWC, generally since about 1980. The TWC SMN data base contains both types, but unfortunately there are no paired measurements of "total" and "carbonaceous" BOD_5 . We therefore assume that for a 5-day duration the two will generally be equivalent, and use both in the BOD_5 data base.

One ubiquitous source of error of a BOD test is in the dilution itself. In many studies employing BOD, the phenomenon has been encountered of increasing BOD (per unit volume) as the sample is subjected to greater dilutions. This problem has been found in Galveston Bay data. The increase of BOD with dilution has been attributed to toxicity in the sample water, inhibiting the metabolism of the bacteria (e.g., Espey et al., 1971a). A possible alternative explanation for the phenomenon lies in the Monod equation for bacterial growth (e.g., Monod, 1949), giving the growth rate as a function of substrate concentration. This implies the rate constant for BOD exertion is a nonlinear function of the dilution factor, which contradicts the basic assumption underlying the dilution approach. For present purposes, when dilution is reported, we use data from the smallest dilution sample available. Generally, however, the BOD is reported without any further information on dilution, so we must regard the dilution factor as a (considerable) source of uncertainty in the measurement.

2.2.5 DDT

Analysis of chlorinated organic pesticides, and trace organic chemicals in general, is a relative newcomer to water and sediment quality monitoring. Protocols and procedures are still evolving, and this is reflected in a confusion of data acquisition. Some of the problem originates in the multiple forms a specific organic can assume: various isomers, analogs and metabolites. Further, the nomenclature for many of these is nonstandard and contributes to the confusion, particularly in data reporting. Most of these problems were mooted in this project because the amount of data available was so limited that little meaningful analysis could be performed. One exception was the insecticide DDT, which is certainly the most prominent of the chlorohydrocarbons and for which the available data base is greatest.

Dichlorodiphenyltrichloroethane (DDT) as a technical product is comprised of as many as 14 analogs and isomers. By far the most important are p,p'-DDT and o,p'-DDT. The relative proportion of the two is a function of the proportion in the initial source and of the relative kinetics and metabolism in the receiving water. Neither of these is particularly well-defined, though the former is probably better established than the latter, to be about 70% p,p'-DDT and 20% o,p'-DDT in technical grade DDT (Buechel, 1983). This is roughly consistent with the rule-of-thumb of a 3:1 ratio of p,p'-DDT to o,p'-DDT that seems to be current now. Both forms are hygroscopic and sorb readily to fine particulates, both sediments and phytoplankton (Crompton, 1985). Treatments of the kinetics (including volatilization) of DDT make no differentiation between the isomers (e.g., Moore and Ramamoorthy, 1984) so we assume that their ratios will be preserved in the receiving water. While this appears to be a workable proxy relation, and was employed as such, we have no reported paired measurements by which we can test it.

2.2.6 Coliforms

The reader has no doubt noticed that this section has addressed water quality parameters in general order of increasing uncertainty. Therefore, it should be no surprise that coliforms are treated last. The specification of two basic classes of bacterial growth-response referred to as "total coliforms" and "fecal coliforms" is a controversial, low-precision measure, originally intended to provide an index to the extent of contamination by pathogens of enteric origin. There is, due to the extensive oyster industry, a considerable data set for Galveston Bay. Sometimes, total coliforms are measured, sometimes fecal, occasionally both. The question was examined of whether there is a stable relationship between the two that will allow us to proxy a data set for one or the other.

To the extent that both are dominated by an origin in discharge of sewage, the answer would be anticipated to be affirmative. However, both--especially total coliforms--are the result of a large, varied community of microorganisms with various non-sewage, non-anthropogenic, and even non-mammalian sources. (This, in fact, is the nub of the controversy surrounding the efficacy of coliforms as an indicator organism.) There is a rule-of-thumb about, that fecal coliforms are approximately one-fifth of total coliforms (e.g., Kenner, 1978) but there seems to be little published support. In the Galveston Bay Project data set, there are 1779 paired 5-tube MPN's of total and fecal coliforms with a wide range of dilutions performed throughout the bay over a five-year period, which allowed us to determine whether this or any other proportion is appropriate. In summary, the scatter in the data was too large to attach any significance to the mean of the fecal:total ratio. In fact, for practical purposes, the ratio approximates a uniform random distribution over the range 0 to 1. Consequently, we conclude that there is no useful ratio by which fecal and total coliform may be related, and the two should be treated as independent measures.

2.3 Segmentation of Galveston Bay

Segmentation refers to the subdivision of an estuary into regions, and represents a compromise between the resolution of physical detail in the natural system, and the expediency of dealing with a small number of geographical units. There are two broad objectives for imposing a segmentation system on an estuary: administrative and analytical. The former refers to administration of laws and regulations. The latter refers to the aggregation and analysis of data of some sort from subregions of the bay, related to the nature of the data (or, equivalently, the objective of the analysis). Economic or demographic analyses will require different spatial aggregation, hence different segmentations, than, say, geological or climatological analyses. It must be emphasized that the imposition of a system of segmentation is a compromise between some minimum level of spatial resolution (which carries with it a statistical level of confidence) and a minimum number of spatial units for analysis.

The General Land Office, and several other state agencies, employ the state tract system for segmentation. This is an example of a segmentation system that is purely administrative, and in which the constraints of operational surveying completely determine segment boundaries. The Texas Department of Health employs a rather gross segmentation of the bays for monitoring and regulating shellfish harvesting. The segments generally correspond to large geographical subdivisions of the bay (e.g., Clear Lake and Trinity Bay) and have little correspondence to hydrographic or water quality features of the system. Again, it is a system devised for its administrative and operational benefits, rather than analysis of water quality.

One of the earliest, and therefore best-known, approaches to segmentation of an estuary for the purpose of water-quality analysis that of Ketchum (1951a,b), who subdivided an estuary into segments of length equal to the tidal excursion. His segmentation is hydrographic in principle, based upon two fundamental postulates: (i) advection by the tidal current is the dominating transport, (ii) mixing is complete over each segment during each tidal cycle. (On closer consideration, it will be seen that these two postulates conflict, in that to the extent that one is satisfied the other is violated.) Of course, Ketchum's segmentation was devised to support *computational* analysis, which frequently imposes some rather strong requirements on the segmentation. Urban (1966) applied the Ketchum method to Galveston Bay, and devised a computational segmentation suitable for large-scale physical exchange analysis. The most prominent example of segmentation for computational purposes is the gridding of a numerical model, such as the finite-difference model of the TWC (Texas Department of Water Resources, 1981).

The most important administrative water-quality segmentation system is, of course, that of the Texas Water Commission. The Galveston Bay system, including the tributaries, is presently subdivided into about 40 segments. The TWC WQ Segments (also referred to as Classified Segments or Designated Segments) represent one of those instances of a segmentation system that reflects both objectives named above, i.e. it is used both for regulation and for analysis. In regulation, the Water Quality Segments are the basis for setting water quality standards, hence underlie discharge permitting, compliance enforcement, and administrative actions. In the analytical arena, the Water Quality Segments are the basis for establishing monitoring stations and determining ambient water quality. The rationale for TWC WQ segmentation is a combination of geography, tradition and politics. In this project, status-and-trends analyses were carried out for each of the Texas Water Commission Water Quality Segments presently in use in the Galveston Bay system. These results are presented in the appendices to the Extended Technical Report (Ward and Armstrong, 1992a). However, to secure the objectives of this project, it was necessary to perform analyses on a finer spatial scale than possible with the TWC segments.

A system of "hydrographic segmentation" was devised for Galveston Bay to form the basis for detailed analysis. The development of this segmentation begins with the observation that in many areas of the bay, *to within a certain level of confidence* (in the statistical sense), there is no difference between measurements taken at one position and those from another, perhaps even several kilometers removed. Moreover, it is desirable to aggregate data from several sampling stations in order to create a sufficiently extended and dense set of data to allow statistical characterization of these specific water quality regions. Aggregation of data--i.e., segmentation--should be based upon the determination of regions of homogeneity (within some statistical threshold), and zones or loci of sharp gradients in properties. The former corresponds to the interior regions of segments and the latter to boundaries between segments. This should take into account transports, bathymetry, waste sources (where appropriate), inflows, and in general the distribution of physicochemical features which will either homogenize the parameter (to define the region encompassed by a water quality segment) or create steep gradients (to define the boundary between segments). These notions were formalized and used as specific criteria of segmentation to guide the specification of analytical segments for Galveston Bay. Since water quality is a property of the fluid medium, one of the determinants of water quality is the pattern of transport within the estuary system. Therefore, specification of water quality segments must include morphology and hydrography, hence our reference to this as "hydrographic segmentation." The segmentation system adopted for these analyses is depicted in Figs. 2-1 through 2-3.

Underlying any segmentation scheme is a dominant spatial scale of analysis, which carries with it an associated level of confidence one is willing to accept in the aggregation of samples over a region of the estuary. For someone studying the variation of water quality in Galveston Bay on a scale of tens of kilometres, it is appropriate to depict Chocolate Bay as one or two segments. Another researcher with the different purpose of studying the kinetics of a constituent within

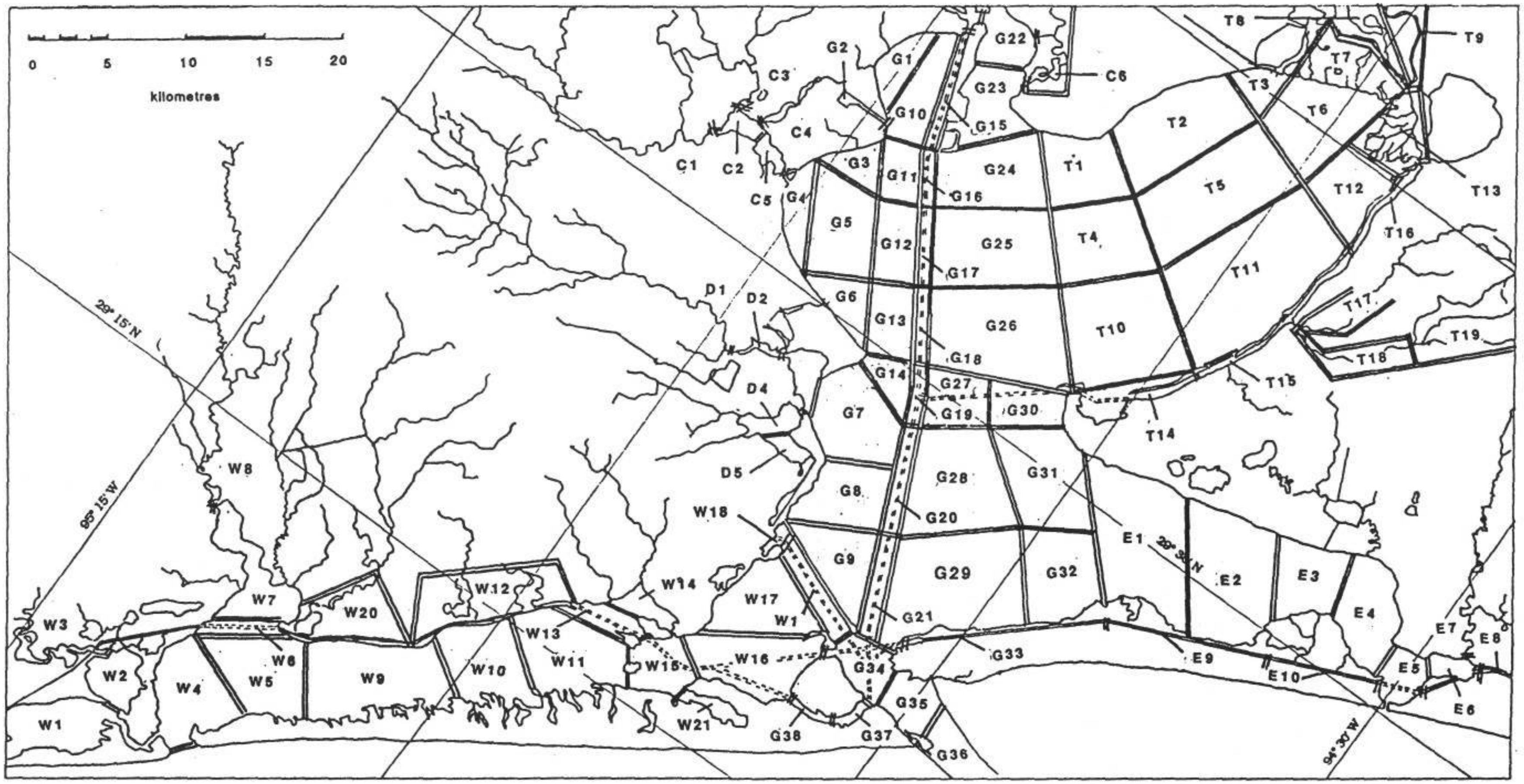


Figure 2-1. GBNEP hydrographic segmentation for Galveston Bay

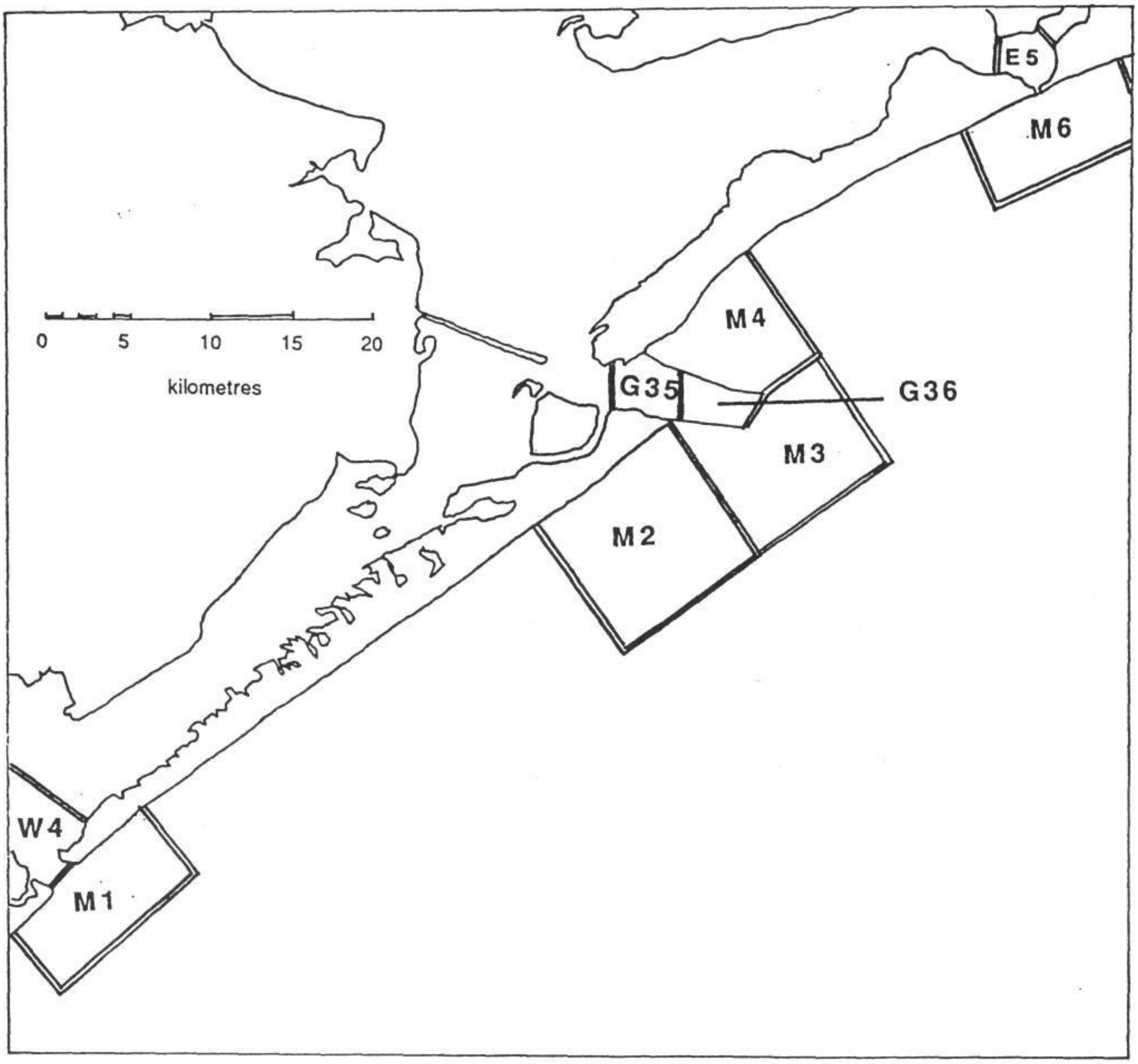


Figure 2-2. GBNEP hydrographic segmentation for Gulf of Mexico nearshore

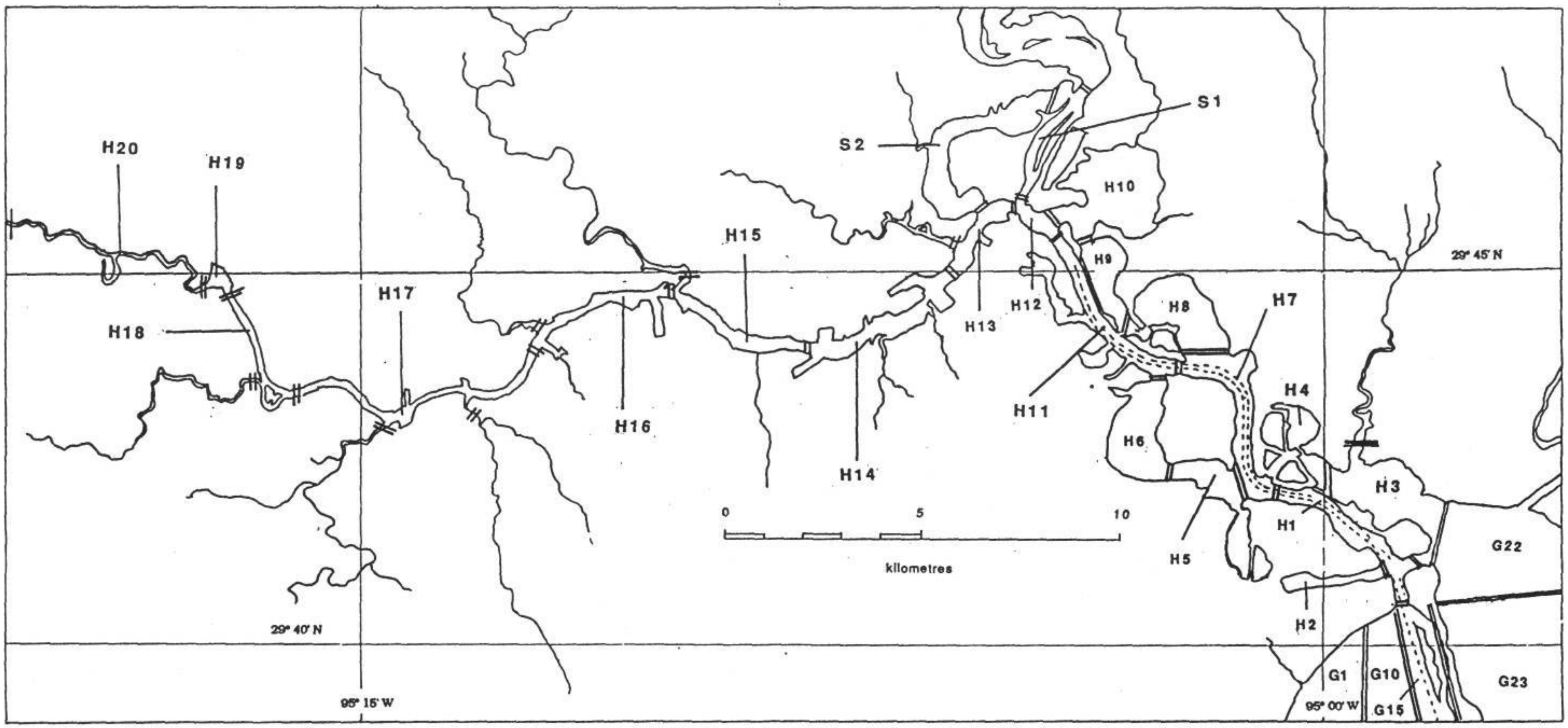


Figure 2-3. GBNEP hydrographic segmentation for Houston Ship Channel

Chocolate Bay itself would find this scale of representation much too coarse, and would employ a much more refined spatial segmentation. Either level of segmentation would be inappropriate and unworkable for the other's purpose. (Note that the specification of a network of sampling stations implicitly assumes a spatial scale, in that each sampling station is presumed to represent water quality over some extended area in which the station is located.)

For data processing purposes, each segment was defined as the union of nonoverlapping quadrilaterals encompassing the watercourse lying within that segment. The corners of each quadrilateral are given by latitude/longitude pairs. In addition to providing a quantitative mechanism for processing large data bases, the quadrilateral depiction of segments has another benefit: it is a means of precisely and quantitatively defining the boundaries of a segment. The quadrilaterals for both the Texas Water Commission Water Quality Segments and the hydrographic segments of this project are given in the appendix to the Extended Technical Report.

These hydrographic segments formed the fundamental organizational units for the water quality and sediment data in the present project. Some particular features of this segmentation warrant mention. The Houston Ship Channel in the open bay occupies its own segments, a narrow strip of approximately 1 km width centered on the dredged channel. Similarly, the Texas City Channel and prominent reaches of the GIWW are also embedded within narrow segments. This is due to the peculiar hydrodynamics of salinity intrusion and increased tidal response dictated by the deeper water, and also due to the isolating effect of dredge disposal areas on the lateral boundaries of these channels. Two rather odd-appearing segments, T3 and G6, enclose the returns from major power plants. The orientation of the segments in Trinity Bay track the typical plume of runoff from the river. The boundaries of several of the segments are dictated by reefs or other bathymetric features. For example, G32 is bounded on the east and north by Hannas Reef, W10 is bounded on the west by Karankawa Reef, and G14, G27 and G30 encompass the complicated mid-bay reef and shoal complex of Red Fish Bar. Segment T7 is the Trinity marsh below the old Wallisville levee, and T13 encompasses the active distributaries of the modern channel of the Trinity River.

The differences between the TWC and GBNEP hydrographic segmentations are:

(1) The TWC segments tend to be larger in space, especially within the open bay, and generally have arbitrary or political boundaries;

(2) The GBNEP hydrographic segments are smaller in spatial extent and are defined by principal geomorphic controls on flow and/or known predominant flow patterns;

(3) The TWC segments include tributaries of the principal inflows but exclude the Gulf of Mexico;

(4) The hydrographic segments focus upon the bay system *per se*, its immediate periphery, and the nearshore Gulf of Mexico, but do not consider the upper reaches of the tributaries;

Analysis by TWC segments has the advantages of: (a) treating a smaller number of segments, (b) corresponding to the administrative framework for Galveston Bay, and therefore allowing direct comparison with standards and past surveys. On the other hand, analysis by GBNEP hydrographic segments allows: (a) better spatial definition of variability, especially in the open bay, and (b) more realistic definition of areas that are nearly homogeneous, i.e., based upon hydrographic controls rather than political boundaries or convenience of access, therefore greater precision in the analyzed data.

2.4 Data processing

The data acquired in this project can be broadly categorized as digital format and hard-copy format. The former refers to any magnetic medium capable of manipulation on the digital computer, e.g. magnetic tape and floppy discs. The latter refers to field sheets, tabulations, and (sadly) computer printout from digital files that no longer exist. Many hard-copy data sets were keyboarded as a part of this project effort. This proved to be an extensive process, undertaken by the employ of a welter of data-entry gnomes who hammered away at the data sets over a period of months. It is probably not inaccurate to observe that the probability of marshalling this kind of data-entry effort in the future is unlikely, so certainly one of the major products of this project is the digital data base itself. The further analysis of these data requires their conversion, combination and transformation in various ways, all of which can circumscribe the interpretation of the data. The general procedures used in this project are outlined here.

2.4.1 Data Set Construction

Data-base formats were devised specific to this project. To facilitate transfer and use of the data by other workers, emphasis was placed on data structure that is manipulable via microcomputers (especially PC's), i.e. compact ASCII files. Details on the data sets themselves, the formatting of the data base, and related processing information are given in a companion report, Ward and Armstrong (1992b), which is intended to serve also as a User's Guide to the data.

One of the principles observed in the construction of the Galveston Bay data base was the maintenance of integrity of the original data. The *source* data files are distinguished from *derivative* data bases. The source data file codifies the original measurements as reported by the originating agency. It contains exactly the information in the original: nothing is lost or added. Even the original units of measurement are retained, since an apparently innocuous conversion of units can introduce a distortion. Of course, in adapting the data file to the needs of the project, the source data file may be re-formatted. This might entail re-ordering of the variables, removing unneeded or redundant fields, or re-writing in a more compact format. For various analytical purposes, the data must be modified, for instance converted to common units, averaged in the vertical, aggregated, or screened out according to some criterion. The data set so processed is a *derivative* data base. Any number of derivative data bases can be created according to the needs of a scientific investigation; it is our opinion, however, that the source data base, once established, should remain inviolate and sacrosanct.

Thus the basic approach in this project was to first create the source data base for a given parameter through the data compilation effort. Then various derivative bases were formed to selectively include certain subsets and to subject these to specific processing. There is a derivative file for each water/sediment-quality variable of concern, comprised of records of measurements at points in time and space. Each data record in the derivative files also includes coded information identifying the data source, e.g. TWC Statewide Monitoring Program, Corps of Engineers, or TWDB Bays and Estuaries program.

Establishing the position in space can be problematic. Almost all sampling programs express position by an alphanumeric station name. In order to be able to process the data spatially, this point must be expressed quantitatively. In this project, latitude/longitude coordinates were used to locate the horizontal position of the sample, and depth (i.e., distance below the water surface) to locate the vertical position. The former required precisely plotting the sampling stations from descriptions or from project maps and determining by manual measurement the coordinate positions, which were then keyboarded into the digital data base.

2.4.2 Quality assurance and reliability

The limits of resolution of measurements and the associated imprecision, and the extent of infection of a data set with errors contribute a degree of uncertainty to each entry in the data record. The need for determining the reliability of historical data and discounting measurements that are judged to be "unreliable" is clearly important. It is our conviction that such judgements must be formulated carefully, and the rejection of data be given close consideration. In data compilation and processing in this study, major concerns were the detection of errors capable of elimination and the quantification of the residual uncertainty in the data.

The GBNEP primary data bases were compiled from various original data sources, some digitally and some manually, and because a transfer of information is involved, there is the possibility of error. Therefore, specific measures were employed to minimize the occurrence of error, and maximize its detection. All data available in machine-readable form from an originating agency were obtained, manipulated and entered in that form. Further, intermedia transfers were minimized. Data-entry procedures utilized simple software with formats that mimicked the source hard copy, and were implemented to minimize factors such as fatigue.

We note that several of these procedures are significant departures from those recommended by Tetra Tech (1987) for National Estuary Programs. For example, Tetra Tech (1987) recommends that re-formatting into a uniform format, as well as conversion and/or mathematical transformation, be carried out as part of the data-entry process. We believe this strategy is seriously flawed, as it reduces efficiency and magnifies the chances of error. Moreover, we take exception to the philosophy of altering the source data, even by units conversion or rounding, as discussed above, and this is precisely what Tetra Tech (1987) recommends.

The errors introduced by the data transfer procedures of this project were the simplest to deal with, because their existence (i.e., that they were in fact errors of entry) could be confirmed by comparison with the original source, and corrections could be expediently implemented. The same screening process, i.e. testing for values within "reasonable" bounds, spatial continuity and temporal continuity, occasionally detected aberrant values in the source data files themselves. When possible, we contacted the agency source to verify the reported information. For most of the data files, however, there is no longer an authoritative source with which to compare the reported data: the original field sheets are discarded, or the principal investigator or originating agency is not accessible (or even extant). This forced us to make probability judgements. Consonant with our philosophy of leaving the source data files sacrosanct, "corrections" were introduced into these data files only when a typographical error was "patently obvious."

Latitude and longitude coordinates were also subjected to screening. This employed a "range of limits" screen to verify that the positions fell within the latitude-longitude range of Galveston Bay of 29° 00' to 29° 50', 94°30 to 95° 15 (which helped in identifying wildly incorrect points) and a comparison of station descriptions to where the station plotted. In a few instances, enough information was given on the boat tracks during sampling to allow some judgement as to the likelihood of error. Generally, finer corrections were reserved for the derivative data-base screening unless some independent information was available.

2.4.3 Uncertainty measures and data quality

The screening procedures outlined in the two preceding sections address data errors of the typographical or "blunder" variety. There remains, of course, a residual error in any set of measurements, deriving from the omnipresent sources of imprecision. In this project, data bases for specific variables were created by the combination of data sets from different sources, with differing analytical methodologies, different agency objectives, and differences in field procedures. Each entry also includes a measure of the degree of uncertainty. A data user then has the basic information to further determine how the uncertainty is affected by whatever processing of aggregation, units and proxy transformations, and averaging to which the data may be subject.

This uncertainty measure is the magnitude of the population standard deviation about a fixed value of the variate. It is estimated by the standard deviation about the mean of a series of measurements performed under controlled laboratory conditions, as reported in the literature on methodology for that parameter. The uncertainty may vary with the magnitude of the measurement, and is often generalized as a linear function. This is the format used in the most recent USGS manual (Fishman and Friedman, 1989) for dissolved analytes (see also Friedman and Erdmann, 1982). This uncertainty was quantified in this study in several ways depending upon the extent of documentation for the data set, in decreasing order of preference:

(a) review of QA/QC procedures observed by the collecting agency, as reflected in practices memos, manuals and directives;

(b) identification of the specific methodologies used and their established accuracy;

(c) statistical variation of the measurements themselves, relative to some external standard, e.g. a more accurate proxy relation or data from a contemporary, independent source;

(d) judgement of the principal investigators, based upon experience with the method or equipment, and upon the practice of workers in the field using that methodology.

The best published sources of precision data for specific analytical methods are *Standard Methods* (e.g., APHA, 1985), the American Society of Testing and Materials annuals (e.g., ASTM, 1976), and the USGS *Techniques of Water-Resources Investigations*. Generally, there is more information--and more quantitative scope--on precision in the later editions than the earlier, which raises a dilemma: when precision information changes, should we utilize the data contemporaneous with the measurements, i.e. assumed to be reflective of the technology and procedures of the time, or should we presume that the more recent data derives from a larger base of measurements, and represents an improved estimate of precision applicable to the older techniques as well? Considering that the reported precision for many trace metals and organics is *lower* (i.e., greater standard deviations) in more recent publications (e.g., Fishman and Friedman, 1989) than in the older (e.g., Skougstad et al., 1979), this is not a merely pedantic concern. No doubt there are elements of truth in either alternative, but we have elected the former. This is not an irreversible decision, as any later user of the data base has the option of employing a different measure of precision, and consequently a different data rejection procedure.

Also, we note that the precision data available are generally much more complete and accurate for the water-phase analytes than the sediment. Indeed, in the USGS manuals (Wershaw et al., 1987, Fishman and Friedman, 1989), for each of the bottom-material analyses there is simply the statement: "It is estimated that the percent relative standard deviation for [parameter name] in bottom material will be greater than that reported for dissolved [parameter name]." When precision data are presented for water-suspended sediment mixtures, we have used that preferentially over the dissolved data to estimate uncertainty for the sediment analysis.

A separate concern in data processing is the handling of anomalous values lying well beyond the expected range of the variate. Most of these are the result of human error at some point in the process from laboratory or field measurement to entry into the data base. A frequent manifestation is a decimal point mislocation, resulting in multiplying the true value by one or several orders-of-magnitude. A screening rule can be formulated to reject such points. The problem is how to assign a rejection trigger so as to exclude points certainly in error, but not to exclude points that happen to deviate widely from "normal" values, since such deviations may in fact be real and therefore significant. It has become traditional in data processing to differentiate between values that are so extreme as to be rejected as "unlikely" (including "impossible") and those that are "unusual" but within the realm of possibility, see, e.g., Bewers et al. (1975). This is the approach recommended by Tetra Tech (1987) who provide "A" and "B" values for an extensive list of estuarine variables, corresponding respectively to "unusual" and "unlikely." It must be noted that the normal strategy is to use these limits to identify anomalous points *during the data analysis and entry process*, to provide feedback to the originators of the data for verification and correction. In our present study, there is no prospect of tracing back to the originator of the data (except for verifying data entry performed during this project), so we need to determine a criterion for data rejection. We also note that any such rejection trigger was applied at the earliest to the compilation of the derivative data files, not to the source data.

The appendix to the Extended Technical Report (Tables A-1 and A-2) summarizes the measures of uncertainty and rejection criteria assigned in this study. Both the uncertainty and the rejection triggers are provided more as guidance to the future users of these data sets than as absolute bounds on data inclusion, and reflect as much our judgement of the quality of the different data programs as statistical constructs.

Data rejection can be performed based upon either the level of uncertainty of the measurement or its magnitude relative to the rejection trigger (when one is provided). Each measurement in the Derivative Data Base is accompanied by the specified level of confidence, transformed into units of the variable and scaled (when appropriate) to the magnitude of the measurement. Thereafter, any data processing can be preceded by an assignment of acceptable accuracy of measurement; any measurements failing this level would be excluded from that analysis. But these measurements would still be retained in the data base. We believe this to be a superior approach to merely deleting data, especially older data, by a sharply defined criterion of "reliability."

2.5 Data base summary

The principal steps in data processing in this study were:

(1) For each parameter of concern, sift through the Source Data Files, applying whatever screening, proxy relationships, and

units conversions are necessary, and order chronologically to create a Master Derivative File for that parameter;

(2) Sort the Master Derivative Files into TWC Water Quality or GBNEP hydrographic segments for the Galveston Bay system;

(3) For each segment of interest, carry out statistical and/or graphical analyses of the data.

We regard the Master Derivative data files to be a chief product of this project, capable of much more study and analysis than is given here.

Generally, as a matter of personal philosophy, we reject very little data in the formulation of the Derivative Files, reserving further data screening for the specific analyses to which the Derivative Data Bases are subject. Data were rejected from the Derivative Files if the date, position, or depth were obviously impossible and there were no satisfactory means of judging the correct value.

Parameter names are abbreviated for compactness here and throughout the remainder of the report; their definitions are given in Table 2-2. The data bases for water quality and for sediment quality are summarized on a baywide basis in Tables 2-3 through 2-6. It is important to note that these tables characterize the data *sets* rather than the *parameters*, because these data have not been screened by rejection triggers for bad data. Indeed, the range of each variable discloses the presence of obviously spurious entries in the data set. For example, pH ranges from 0 to 17000, and the largest measured salinity is 50000 ppt. Many of the zero values appear to be blank entries (i.e., no measurement) that in the process of agency transcription and digitization were replaced with a zero.

These tables also illustrate the dilemma of applying rejection triggers. For example, the maximum sediment volatile solids value of 98% (Table 2-6), though lying within the range of *possibility*, lies outside the range of *probability*. (Surely there would have been reports of lab technicians lacking eyebrows.) The same remark can be addressed to the values of 19% zinc and the 9.4% iron. Below this, though, the demarcation between the two is less certain: the 3.2% value for oil & grease or the 0.6% DDT may be more unlikely than unusual, but we are hesitant to dismiss them on strictly an *a priori* basis.

For many of the parameters, such as metals and pesticides, the lower range of measurement is delimited by the detection limits of the procedure, and detection limits are generally reported as part of the data set. Despite this, several of the data sets include zero values. The data in these tables have not been screened for such anomalies, either; therefore minimum values are given both for the entire data set and for only nonzero values. These tables do provide a ready index to the relative intensity with which different variables have been measured, and the extant period of record. Because of the large spatio-temporal variability in most of these parameters, the baywide means have little importance; however

TABLE 2-2

WATER AND SEDIMENT QUALITY PARAMETERS:
ABBREVIATIONS, UNITS AND NOMINAL UNCERTAINTY

abbreviation	*parameter*	*units*	*nominal stnd devn (as % of value)*
	Conventional Parameters, Water		
WQTEMP	temperature of water	deg Celsius	1
WQSAL	salinity of water, converted from various proxy measures	parts per thousand	1
WQDO	dissolved oxygen in water	mg/L	2
WQDODEF	dissolved oxygen deficit in water	mg/L	5
WQPH	pH of water	pH units	5
WQTURB	turbidity of water	NTU, JTU	10
WQSECCHI	Secchi depth of water	meters	varies
WQTSS	total suspended solids in water	mg/L	10
WQXTSS	extended total suspended solids in water, based on proxy data	mg/L	10
WQAMMN	ammonia nitrogen in water	mg/L	20
WQORGN	total organic nitrogen in water	mg/L	20
WQKJLN	total Kjeldahl nitrogen in water	mg/L	20
WQNO3N	nitrate nitrogen in water	mg/L	25
WQTOTP	total phosphorus (as P) in water	mg/L	15
WQVOLS	total volatile solids in water	mg/L	10
WQVSS	volatile suspended solids in water	mg/L	20
WQO&G	oil & grease in water	mg/L	10
WQTOC	total organic carbon in water	mg/L	10
WQBOD5	5-day biochemical oxygen demand	mg/L	20
WQCBOD5	5-day biochemical oxygen demand, nitrification-suppressed	mg/L	20
WQXBOD5	extended record of 5-day BOD, based on proxy relationships	mg/L	20
WQCHLA	chlorophyll-a in water	μg/L	20
WQTCOLI	total coliforms in water	org/100 mL	200
WQFCOLI	fecal coliforms in water	org/100 mL	200
	Metals, Water		
WQMETAST	total (unfiltered) arsenic in water	μg/L	35
WQMETASD	dissolved arsenic in water	μg/L	35
WQMETBAT	total barium in water	μg/L	15
WQMETBAD	dissolved barium in water	μg/L	25
WQMETB	total boron in water	μg/L	25

TABLE 2-2
(continued)

abbreviation	*parameter*	*units*	*nominal stnd devn (as % of value)*
WQMETCDT	total cadmium in water	µg/L	15
WQMETCDD	dissolved cadmium in water	µg/L	20
WQMETCRT	total chromium in water	µg/L	100
WQMETCRD	dissolved chromium in water	µg/L	100
WQMETCUT	total copper in water	µg/L	25
WQMETCUD	dissolved copper in water	µg/L	100
WQMETFET	total iron in water	µg/L	20
WQMETFED	dissolved iron in water	µg/L	100
WQMETPBT	total lead in water	µg/L	10
WQMETPBD	dissolved lead in water	µg/L	20
WQMETMNT	total manganese in water	µg/L	100
WQMETMND	dissolved manganese in water	µg/L	35
WQMETHGT	total mercury in water	µg/L	40
WQMETHGD	dissolved mercury in water	µg/L	40
WQMETNIT	total nickel in water	µg/L	20
WQMETNID	dissolved nickel in water	µg/L	30
WQMETSET	total selenium in water	µg/L	50
WQMETSED	dissolved selenium in water	µg/L	50
WQMETAGT	total silver in water	µg/L	50
WQMETAGD	dissolved silver in water	µg/L	50
WQMETZNT	total zinc in water	µg/L	15
WQMETZND	dissolved zinc in water	µg/L	100
	Organics, Water		
WQ-ABHC	alpha-BHC in water	µg/L	10
WQ-LIND	lindane (gamma-BHC) in water	µg/L	10
WQ-DDT	Total DDT in water	µg/L	10
WQ-DDE	Total DDE in water	µg/L	10
WQ-DDD	Total DDD in water	µg/L	10
WQ-PDDD	p,p'-DDD in water	µg/L	10
WQ-PDDE	p,p'-DDE in water	µg/L	10
WQ-PDDT	p,p'-DDT in water	µg/L	10

TABLE 2-2
(continued)

abbreviation	*parameter*	*units*	*nominal stnd devn (as % of value)*
WQ-ENDO	Endosulfan I in water	µg/L	25
WQ-ENDR	Endrin in water	µg/L	5
WQ-TOXA	Toxaphene in water	µg/L	30
WQ-HEPT	Heptachloride in water	µg/L	5
WQ-HEPX	Heptachloride epoxide in water	µg/L	5
WQ-MTHX	methoxychlor in water	µg/L	
WQ-PCB	Total PCB's in water	µg/L	25
WQ-MALA	Malathion in water	µg/L	35
WQ-PARA	Parathion in water	µg/L	10
WQ-DIAZ	Diazinon in water	µg/L	20
WQ-MTHP	methyl parathion in water	µg/L	10
WQ-24D	2,4 D in water	µg/L	10
WQ-245T	2,4,5 T in water	µg/L	10
WQ-PAH	total PAH's in water	µg/L	20
WQ-NAPT	napthalene in water	µg/L	
WQ-ACEN	acenapthene in water	µg/L	
WQ-FLRA	fluoranthene in water	µg/L	
WQ-BNZA	benzo(a)pyrene in water	µg/L	
	Conventional Parameters, Sediment		
SEDAMMN	ammonia nitrogen in sediment	mg/kg	20
SEDORGN	total organic nitrogen in sediment	mg/kg	20
SEDTOTP	total phosphorus (as P) in sediment	mg/kg	10
SEDO&G	oil & grease in sediment	mg/kg	25
SEDKJLN	total Kjeldahl nitrogen in sediment	mg/kg	20
SEDTOC	total organic carbon in sediment	mg/kg	10
SEDVOLS	volatile solids in sediment	mg/kg	25
	Metals, Sediment		
SEDMETAS	arsenic in sediment	µg/kg	20
SEDMETBA	barium in sediment	µg/kg	5
SEDMETB	boron in sediment	µg/kg	20
SEDMETCD	cadmium in sediment	µg/kg	35

TABLE 2-2
(continued)

abbreviation	*parameter*	*units*	*nominal stnd devn (as % of value)*
SEDMETCR	chromium in sediment	µg/kg	20
SEDMETCU	copper in sediment	µg/kg	25
SEDMETFE	iron in sediment	µg/kg	10
SEDMETPB	lead in sediment	µg/kg	60
SEDMETMN	manganese in sediment	µg/kg	5
SEDMETHG	mercury in sediment	µg/kg	20
SEDMETNI	nickel in sediment	µg/kg	50
SEDMETSE	selenium in sediment	µg/kg	35
SEDMETAG	silver in sediment	µg/kg	50
SEDMETSR	strontium in sediment	µg/kg	
SEDMETZN	zinc in sediment	µg/kg	10
	Organics, Sediment		
SED-ABHC	alpha-BHC in sediment	µg/kg	25
SED-LIND	lindane (gamma-BHC) in sediment	µg/kg	25
SED-DDT	Total DDT in sediment	µg/kg	25
SED-DDE	Total DDE in sediment	µg/kg	25
SED-DDD	Total DDD in sediment	µg/kg	25
SED-XDDT	Extended DDT in sediment, based on proxy relation	µg/kg	25
SED-ALDR	Aldrin in sediment	µg/kg	20
SED-CHLR	Total chlordane in sediment	µg/kg	25
SED-DIEL	Dieldrin in sediment	µg/kg	25
SED-ENDO	Endosulfan I in sediment	µg/kg	10
SED-ENDR	Endrin in sediment	µg/kg	20
SED-TOXA	Toxaphene in sediment	µg/kg	25
SED-HEPT	Heptachloride in sediment	µg/kg	25
SED-HEPX	Heptachloride epoxide in sediment	µg/kg	20
SED-MTHX	methoxychlor in sediment	µg/kg	10
SED-PCB	Total PCB's in sediment	µg/kg	25
SED-MALA	Malathion in sediment	µg/kg	35
SED-PARA	Parathion in sediment	µg/kg	10

TABLE 2-2
(continued)

abbreviation	*parameter*	*units*	*nominal stnd devn (as % of value)*
SED-DIAZ	Diazinon in sediment	µg/kg	20
SED-MTHP	methyl parathion in sediment	µg/kg	10
SED-24D	2,4 D in sediment	µg/kg	15
SED-245T	2,4,5 T in sediment	µg/kg	15
SED-PDDD	p,p'-DDD in sediment	µg/kg	25
SED-PDDE	p,p'-DDE in sediment	µg/kg	25
SED-PDDT	p,p'-DDT in sediment	µg/kg	25
SED-PAH	total PAH's in sediment	µg/kg	25
SED-NAPT	napthalene in sediment	µg/kg	25
SED-ACEN	acenapthene in sediment	µg/kg	15
SED-FLRA	fluoranthene in sediment	µg/kg	5
SED-BNZA	benzo(a)pyrene in sediment	µg/kg	10

TABLE 2-3

SUMMARY OF WATER QUALITY DATA FROM GALVESTON BAY:
CONVENTIONAL PARAMETERS
(Unscreened)

Parameter (Table 2-2)	units	No.of obs	Avg >DL	St dev	No. > DLs	% > DLs	Min >DL	date	Min >0	date	Max	date	Avg w/ BDL=0	Avg w/ BDL=DL
wqtemp	deg C	75993	22.4	8.4	75993	100	0	760108	0.1	661022	460	710930	22.4	22.4
wqsal	ppt	77376	15.5	360	77375	100	0	560810	0.00065	780307	50000	800709	15.5	15.5
wqdo	ppm	59181	7.28	6.4	59179	100	0	580224	0.01	880519	910	590512	7.28	7.28
wqph		42106	8.31	83	42106	100	0	870211	0.1	580603	17000	731210	8.31	8.31
wqturb	JTU	13815	40.5	56	13815	100	0	690528	0.9	750318	2000	500605	40.5	40.5
wqtss	ppm	8221	43.6	71	8126	98.84	0	761018	1	770110	2000	741216	43.1	43.2
wqsecchi	m	5388	0.545	0.31	5385	99.94	0.0072	761020	0.0072	761020	7.5	860915	0.544	0.552
wqammn	ppm	12713	1.18	4.3	11575	91.05	0	671001	0.001	870409	170	790511	1.08	1.1
wqorgn	ppm	6508	1.16	1.5	6482	99.6	0	680716	0.01	790612	57	770927	1.15	1.15
wqkjln	ppm	7059	2.73	14	7022	99.48	0	680716	0.01	770824	340	790511	2.72	2.72
wqno3n	ppm	12003	0.462	2.2	10555	87.94	0	700707	0.002	820427	140	730911	0.406	0.409
wqtotp	ppm	12291	0.941	1.3	12282	99.93	0	711228	0.01	690731	48	760707	0.941	0.941
wqvols	ppm	984	2990	2500	984	100	0	760419	2	750203	17000	730113	2990	2990
wqvss	ppm	10663	11.8	13	10308	96.67	0	630402	1	631015	500	730426	11.4	11.5
wqo&g	ppm	1245	5.12	8.3	596	47.87	0	750403	0.2	750709	100	860822	2.45	3.03
wqtoc	ppm	7278	12.4	11	6615	90.89	0	740212	0.13	890719	230	840507	11.2	11.8
wqbod5	ppm	9520	5.93	110	9051	95.07	0	500605	0.1	500831	10000	740710	5.64	5.75
wqcbod5	ppm	308	2.67	1.6	294	95.45	0.5	671001	0.5	671001	16	820804	2.55	2.59
wqchla	ppb	4705	18.8	25	4058	86.25	0	760831	0.2	770915	460	780322	16.2	16.4
wqtcoli	/100 ml	17061	61000	770000	16263	95.32	0	770125	0.8	710316	$8x10^7$	750219	58200	58200
wqfcoli	/100 ml	19745	12000	110000	18032	91.32	0	740515	2	680402	$3.5x10^6$	690819	11000	11000

TABLE 2-4

SUMMARY OF WATER-QUALITY DATA FROM GALVESTON BAY: METALS
All units in micrograms per liter
(Unscreened)

Parameter (Table 2-2)	No.of obs	Avg >DL	St dev	No. > DLs	% > DLs	Min >DL	date	Min >0	date	Max	date	Avg w/ BDL=0	Avg w/ BDL=DL
wqmetast	1830	17.2	48	965	52.7	0	730911	0.0029	730911	1200	800212	9.1	13.4
wqmetasd	33	4.67	1.4	5	15.2	2.4	890516	2.4	890516	6	900524	0.708	5.34
wqmetbat	396	161	130	347	87.6	0.07	880406	0.07	880406	800	741119	141	171
wqmetbad	24	84	76	24	100.	30	900815	30	900815	430	900606	84	84
wqmetb	2	300	-	2	100.	300	840925	300	840925	300	840925	300	300
wqmetcdt	1988	14.2	14	505	25.4	0	730911	0.002	730911	120	750828	3.62	10.1
wqmetcdd	65	1.36	0.64	26	40.	0.5	750412	0.5	750412	3.8	750611	0.543	1.47
wqmetcrt	1953	26.5	30	721	36.9	0	730911	0.013	730911	610	761122	9.78	22.8
wqmetcrd	48	7.56	3.5	8	16.7	2.3	750507	2.3	750507	11	750328	1.26	8.57
wqmetcut	2030	98.7	130	1297	63.9	0	730911	0.03	880406	1400	840925	63.1	68.1
wqmetcud	80	3.76	3.2	38	47.5	0.24	671015	0.24	671015	16	901008	1.78	5.73
wqmetfet	379	1430	2600	379	100.	1	760518	1	760518	28000	750930	1430	1430
wqmetfed	57	76.9	91	42	73.7	5	750328	5	750328	490	900524	56.7	58.1
wqmetpbt	2023	58.6	130	809	40.	0	730911	0.06	730911	1900	791204	23.4	51.2
wqmetpbd	80	9.03	12	31	38.8	1	750328	1	750328	64	890516	3.5	4.73
wqmetmnt	1041	124	88	926	89.	0	760907	0.065	880406	1000	750709	111	114
wqmetmnd	63	35	45	30	47.6	0.3	671015	0.3	671015	170	671215	16.7	20.3
wqmethgt	2044	1.49	7.8	882	43.2	0	750709	0.02	820428	210	740716	0.641	0.873
wqmethgd	62	0.828	3.4	44	71.	0.003	750920	0.003	750920	23	900719	0.588	0.653
wqmetnit	1726	72.9	100	894	51.8	0	730911	0.045	880406	2000	760609	37.8	46.8
wqmetnid	70	12.8	9.4	33	47.1	1.5	671215	1.5	671215	40	900222	6.02	9.84
wqmetset	344	21.4	23	72	20.9	2	730711	2	730711	100	880223	4.48	6.83
wqmetsed	35	-	-	0	0.	-	-	-	-	-	-	0	5
wqmetagt	441	16.1	13	215	48.8	0	730911	0.006	730911	130	730911	7.83	13.9
wqmetagd	35	16	-	1	2.9	16	900606	16	900606	16	900606	0.457	18.7
wqmetznt	1818	145	270	1345	74.	0	730911	0.061	730911	4600	750227	107	113
wqmetznd	78	20.6	23	71	91.	1.3	750611	1.3	750611	140	900402	18.8	19.3

TABLE 2-5

SUMMARY OF WATER-QUALITY DATA FROM GALVESTON BAY: ORGANICS
All units in micrograms per liter
(Unscreened)

Parameter (Table 2-2)	No.of obs	Avg >DL	St dev	No. > DLs	% > DLs	Min >DL	date	Min >0	date	Max	date	Avg w/ BDL=0	Avg w/ BDL=DL
wq-abhc	24	-	-	0	0	-	-	-	-	-	-	0	0.0267
wq-lind	235	0.032	0.004	5	2.1	0.03	850716	0.03	850716	0.04	850716	0.000681	0.183
wq-ddd	81	-	-	0	0	-	-	-	-	-	-	0	0.106
wq-dde	81	3.01	3	2	2.4	0.024	750715	0.024	750715	6	740521	0.0744	0.153
wq-ddt	81	5.41	7.3	3	3.7	0.092	731011	0.092	731011	16	740521	0.2	0.311
wq-pdde	278	0.014	0.0049	5	1.8	0.01	800619	0.01	800619	0.02	800619	0.000252	0.023
wq-pddt	461	0.0811	0.094	9	1.9	0	851003	0.03	800619	0.3	891115	0.00158	0.0248
wq-xddt	542	1.44	4.3	12	2.2	0	851003	0.042	800619	16	740521	0.0318	0.0759
wq-aldr	338	1.08	2.7	8	2.4	0.018	750715	0.018	750715	8.3	740521	0.0256	0.0478
wq-chlr	437	0.1	-	1	0.2	0.1	851018	0.1	851018	0.1	851018	0.000229	0.594
wq-diel	339	0.16	0.3	9	2.6	0.04	800619	0.04	800619	1	710628	0.00425	0.0403
wq-endo	124	0.01	0	5	4.0	0.01	800619	0.01	800619	0.01	800619	0.000403	0.0242
wq-endr	82	0.504	0.5	2	2.4	0.007	750522	0.007	750522	1	710628	0.0123	0.115
wq-toxa	427	-	-	-	-	-	-	-	-	-	-	0	0.966
wq-hept	279	0.0458	0.1	6	2.2	0	740507	0.005	750520	0.27	780815	0.000986	0.0207
wq-hepx	97	0	0	4	4.1	0	740507	-	-	-	-	0	0.0377
wq-mthx	95	0.1	0.2	5	5.3	0	740507	0.5	810805	0.5	810805	0.00526	0.345
wq-pcb	533	2.43	2.7	25	4.7	0	740425	0.03	751023	10	860325	0.114	0.696
wq-mala	65	0	-	2	3.1	0	760803	-	-	-	-	0	0.459
wq-para	65	0	-	2	3.1	0	760803	-	-	-	-	0	0.235
wq-diaz	56	1.04	0.98	6	10.7	0.24	860911	0.24	860911	3.2	860711	0.112	0.468
wq-mthp	51	0	-	-	-	-	-	-	-	-	-	0	0.262
wq-24d	58	0	-	2	3.4	0	760803	-	-	-	-	0	19
wq-245t	58	0.02	0.028	3	5.2	0	760803	0.06	860806	0.06	860806	0.00103	4.57
wq-pah	238	12.5	9.8	22	9.2	1.6	870825	1.6	870825	41	851003	1.16	5.09
wq-napt	180	0	0	48	26.7	0	890615	-	-	-	-	0	1.47
wq-acen	180	0	0	48	26.7	0	890615	-	-	-	-	0	1.47
wq-flra	180	92.9	81	2	1.1	12	870909	12	870909	170	861001	1.03	1.93
wq-bnza	180	9.08	65	53	29.4	0	890615	0.2	870825	480	861001	2.67	3.03

TABLE 2-6

SUMMARY OF SEDIMENT DATA FROM GALVESTON BAY
(Unscreened)

Parameter (Table 2-2)	units	No.of obs	Avg >DL	St dev	No. > DLs	% > DLs	Min >DL	date	Min >0	date	Max	date	Avg w/ BDL=0	Avg w/ BDL=DL
sedorgn	mg/kg	457	1100	4400	446	97.6	0.8	731011	0.8	731011	56000	780907	1080	1080
sedtotp	mg/kg	401	577	550	400	99.8	1.5	750520	1.5	750520	5200	870929	575	575
sedo&g	mg/kg	1233	1250	2600	1184	96.0	0	750220	0.049	731024	32000	751106	1200	1200
sedkjln	mg/kg	724	1080	1200	714	98.6	3	801211	3	801211	10000	770524	1060	1060
sedtoc	mg/kg	895	8.6	9.1	895	100.0	0.1	720410	0.1	720410	200	761003	8.6	8.6
sedvols	mg/kg	889	57100	84000	889	100.0	80	760712	80	760712	980000	740515	57100	57100
sedmetas	ug/kg	1407	4.73	4.5	1251	88.9	0	740703	0.1	780418	50	800825	4.21	4.32
sedmetba	ug/kg	616	225	170	616	100.0	1	751112	1	751112	1600	761003	225	225
sedmetb	ug/kg	239	54.8	28	236	98.7	3.3	760912	3.3	760912	120	761003	54.1	54.2
sedmetcd	ug/kg	1531	1.71	2.8	727	47.5	0	840731	0.01	750520	41	750412	0.81	1.18
sedmetcr	ug/kg	1705	30.3	36	1614	94.7	0.02	750520	0.02	750520	650	750328	28.7	28.9
sedmetcu	ug/kg	1783	19.6	37	1692	94.9	0.01	750520	0.01	750520	830	671215	18.6	18.8
sedmetfe	ug/kg	364	15900	11000	364	100.0	800	720410	800	720410	94000	750412	15900	15900
sedmetpb	ug/kg	1790	36.9	70	1584	88.5	0.05	750520	0.05	750520	2000	771115	32.6	33.8
sedmetmn	ug/kg	826	390	320	826	100.0	21	740703	21	740703	4700	750328	390	390
sedmethg	ug/kg	1526	0.329	1.2	755	49.5	0	740703	0.004	720410	19	780815	0.163	0.223
sedmetni	ug/kg	1641	17.2	22	1542	94.0	0	750711	0.5	780414	720	750328	16.1	16.5
sedmetse	ug/kg	404	0.827	0.89	89	22.0	0	840731	0.08	821206	3.8	830105	0.182	0.897
sedmetag	ug/kg	63	1.01	2.5	47	74.6	0	840731	0.049	840731	12	720123	0.755	1.14
sedmetsr	ug/kg	250	156	200	250	100.0	13	760911	13	760911	1400	761003	156	156
sedmetzn	ug/kg	1785	202	4700	1704	95.5	1.9	870909	1.9	870909	190000	790802	193	194
sed-abhc	ug/kg	68	0.761	1.1	19	27.9	0.01	719994	0.01	719994	3.3	719994	0.213	0.717
sed-lind	ug/kg	505	4.7	13	65	12.9	0	731024	0.02	719994	100	760915	0.604	1.73
sed-ddt	ug/kg	211	435	1400	39	18.5	0	731024	0.15	780525	6100	740515	80.3	84.4
sed-dde	ug/kg	210	190	610	38	18.1	0	731024	0.29	780525	2300	740515	34.4	37.2
sed-ddd	ug/kg	190	43.3	89	17	9.0	0	731024	1.9	780515	300	760915	3.88	7.89
sed-aldr	ug/kg	527	356	1500	51	9.7	0	731024	0.04	711228	7300	740515	34.5	35.5
sed-chlr	ug/kg	617	164	360	47	7.6	0.06	711228	0.06	711228	2000	760915	12.5	14.3
sed-diel	ug/kg	527	10.1	38	66	12.5	0	731024	0.06	711228	300	760915	1.27	2.7
sed-endo	ug/kg	55	0.606	0.3	2	3.6	0.3	780525	0.3	780525	0.91	780525	0.022	7.09
sed-endr	ug/kg	231	18.6	70	17	7.4	0	731024	0.12	720713	300	760915	1.37	5.01

Table 2-6
(continued)

Parameter (Table 2-2	units	No.of obs	Avg >DL	St dev	No. > DLs	% > DLs	Min >DL	date	Min >0	date	Max	date	Avg w/ BDL=0	Avg w/ BDL=DL
sed-toxa	ug/kg	632	561	1600	9	1.4	0	731024	50	760916	5000	760915	7.99	25.6
sed-hept	ug/kg	443	3.29	16	36	8.1	0	731024	0.02	720411	100	760915	0.268	1.35
sed-hepx	ug/kg	251	5.51	20	25	10.0	0	731024	0.06	711228	100	760915	0.549	1.27
sed-mthx	ug/kg	190	184	570	11	5.8	0	731024	20	760916	2000	760915	10.6	19.7
sed-pcb	ug/kg	282	442	1100	49	17.4	0	731024	7.8	770915	6400	800124	76.8	91.1
sed-mala	ug/kg	121	-	-	0	0.0	-	-	-	-	-	-	0	5.55
sed-para	ug/kg	152	253	250	2	1.3	5	760916	5	760916	500	760915	3.32	6.47
sed-diaz	ug/kg	141	68.9	150	9	6.4	1.4	860930	1.4	860930	500	760915	4.39	9.93
sed-mthp	ug/kg	147	110	200	5	3.4	5	760916	5	760916	500	760915	3.73	6.94
sed-24d	ug/kg	52	2.58	0	1	1.9	2.6	870917	2.6	870917	2.6	870917	0.0496	33.7
sed-245t	ug/kg	52	-	-	0	0.0	-	-	-	-	-	-	0	6.8
sed-pddd	ug/kg	249	6.05	13	37	14.9	0.21	870731	0.21	870731	71	840106	0.899	1.26
sed-pdde	ug/kg	361	5.2	9.2	45	12.5	0.04	721229	0.04	721229	51	810805	0.649	1.1
sed-pddt	ug/kg	542	13.2	25	31	5.7	0	890615	0.24	711228	120	880727	0.753	1.2
sed-pah	ug/kg	261	5.21	14	99	37.9	0.1	880328	0.1	880328	130	870420	1.98	7.61
sed-napt	ug/kg	230	31.6	49	14	6.1	1.2	870718	1.2	870718	150	870825	1.92	43.2
sed-acen	ug/kg	232	18.1	21	13	5.6	5.9	870825	5.9	870825	83	870825	1.02	42.2
sed-flra	ug/kg	232	123	320	85	36.6	1	870226	1	870226	1900	870825	45.2	51.4
sed-bnza	ug/kg	232	132	380	74	31.9	1	870226	1	870226	2400	870825	42	48.5

they are useful in typifying the magnitudes of the different variables (provided the spurious values do not seriously corrupt the mean).

It should be noted that most of the EPA priority pollutants do not appear in Tables 2-3 *et seq*. Very few measurements have been made in Galveston Bay of most of the priority pollutants. In some instances, there may be a scattering of measurements, but not enough to use in any meaningful way in a status-and-trends analysis. For example, there were two measurements of water-phase Endosulfan-I from the entire Galveston Bay system. Similarly, most of the individual PAH's were represented only by a handful of data. Those variables for which the sample base is totally lacking or inadequate are excluded from these tables. For those parameters for which there is at least a minimum analyzable data base, most of those measurements are below detection limits (BDL), as indicated in these tables.

The treatment of detection limits in analysis of water quality is particularly vexing. There are three logical alternatives, each of which has a rational basis. First, the measurements BDL can be simply ignored, as providing essentially no quantitative information. Second, the BDL values can be replaced with zero in the analyses, on the argument that for practical purposes the parameter is not present. This is probably the most commonly elected alternative. It is, for example, the approach adopted by the National Ocean Service in its National Status & Trends Program (NOS, 1991). Third, the BDL values can be taken to be the reported detection limits, on the basis that the actual concentration could be as high as the detection limit.

In our view, the selection is dependent upon the purpose at hand. The non-BDL statistics can provide some insight into the precision and variability of the parameter, which the more constant DL values would corrupt or even mask. However, to completely ignore BDL results is to lose information, albeit non-quantitative. The fact is that a water or sediment sample was obtained (usually at great effort), a careful analysis performed, and an upper bound established on the concentration of the parameter. This information should not be dismissed cavalierly. The latter two alternatives use that information, either optimistically or pessimistically, depending upon the intent of the analyst. In this project, with typical equivocation, we decided to employ all three, i.e. to compute *appropriate* statistics with only above-DL data, with the BDL values set to zero and with the BDL values set to the DL, thereby establishing a probable *range* of the statistic. The "appropriate" statistics include averages and variability for the above-DL data, but do not include calculations of variability for the latter two, since the largely invariant values of either end of the the range (i.e. either value assumed for a BDL measurement) would distort the results. Even in a trends analysis (which is variability in time), to incorporate 0 or DL values might either mask any vestige of a real trend by padding the data with zeroes or displace the real trend with a trend of measurement sensitivity. The user of these results therefore can choose among them whichever best serves the purpose of the analysis.

Figures 2-4 *et seq.* display graphically the sampling intensity throughout the bay for a few of the more important water and sediment parameters. Sampling intensity is measured by the number of observations within each hydrographic segment for the period of record. The amount of data available is strongly dependent upon the parameter. Further, what might appear to be a large number of historical samples for a given parameter on a baywide basis, from Tables 2-3 through 2-6, is shown to be quite modest--even inadequate--when related to specific areas of the bay. It is apparent at once from Figs. 2-4 *et seq.* that sampling intensity is highly heterogeneous in space, some areas of the bay having been subjected to relatively frequent sampling, and some rarely sampled. There is a particular bias, as might be expected, for the main channels and for those areas with historical pollution problems. The period of record generally ranges over many years (see Tables 2-3 *et seq.*) so the number of samples *per year* is a considerably smaller number. There is roughly an order of magnitude less sediment data from Galveston Bay than water quality data. On the other hand, sediment transport processes and kinetics are thought to vary on time scales longer than that of the overlying water, so relative to the time and space scales of natural variability less data would be necessary for sediment chemistry than water chemistry (though probably not an order of magnitude).

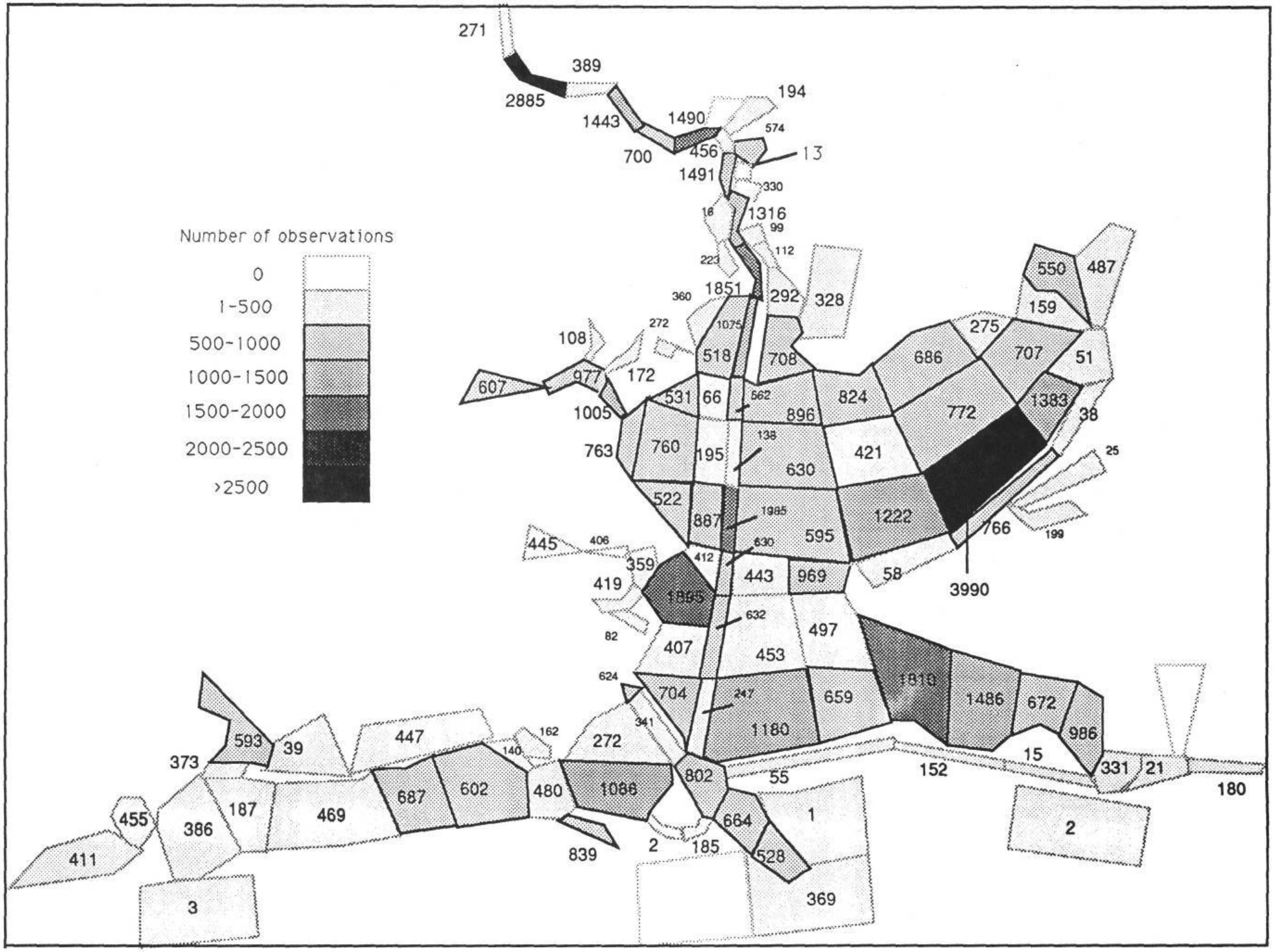


Fig. 2-4. Sampling density in Galveston Bay for WQSAL

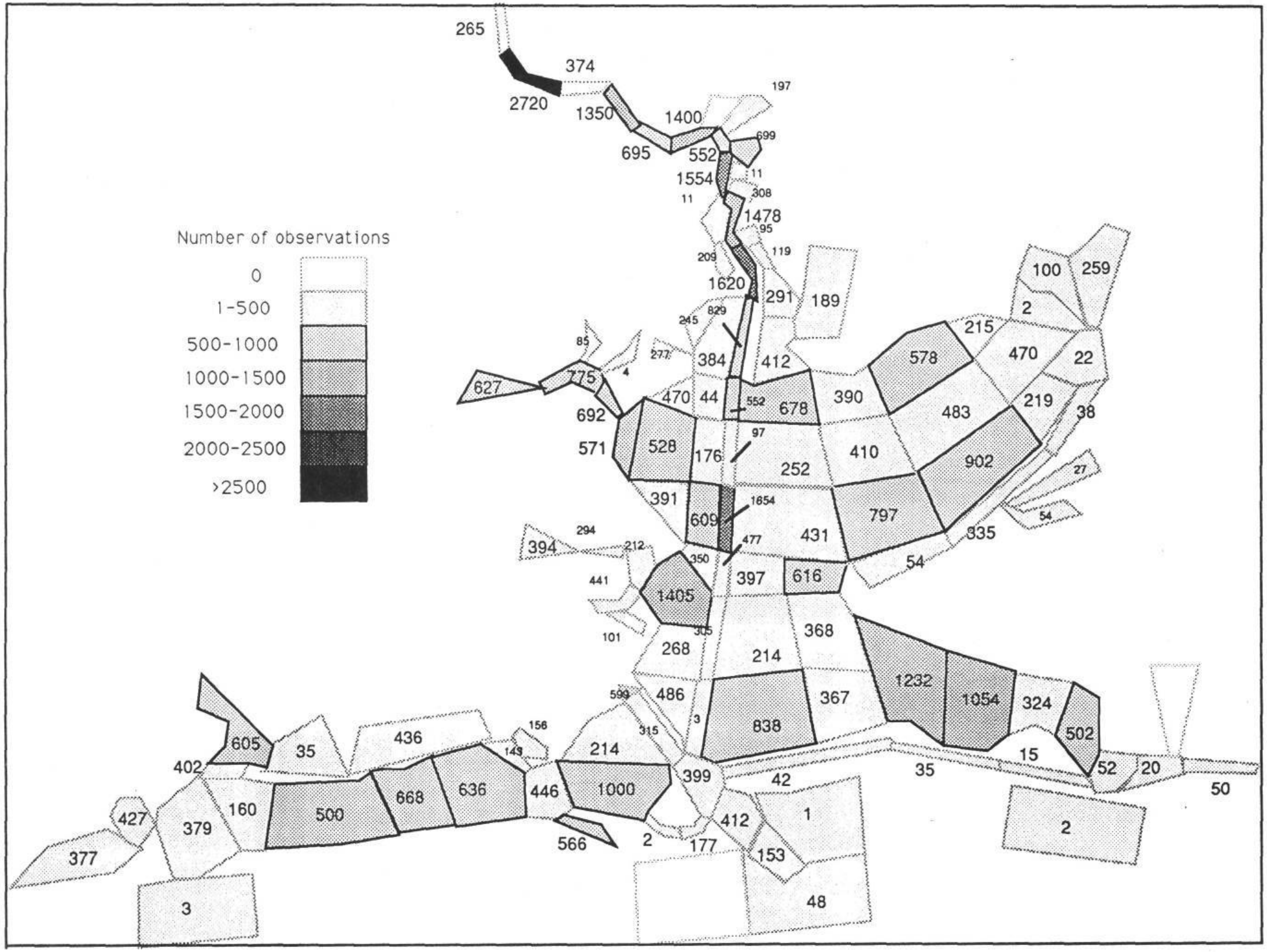


Fig. 2-5. Sampling density in Galveston Bay for WQDO

Fig. 2-6. Sampling density in Galveston Bay for WQXTSS

Fig. 2-7. Sampling density in Galveston Bay for WQO&G

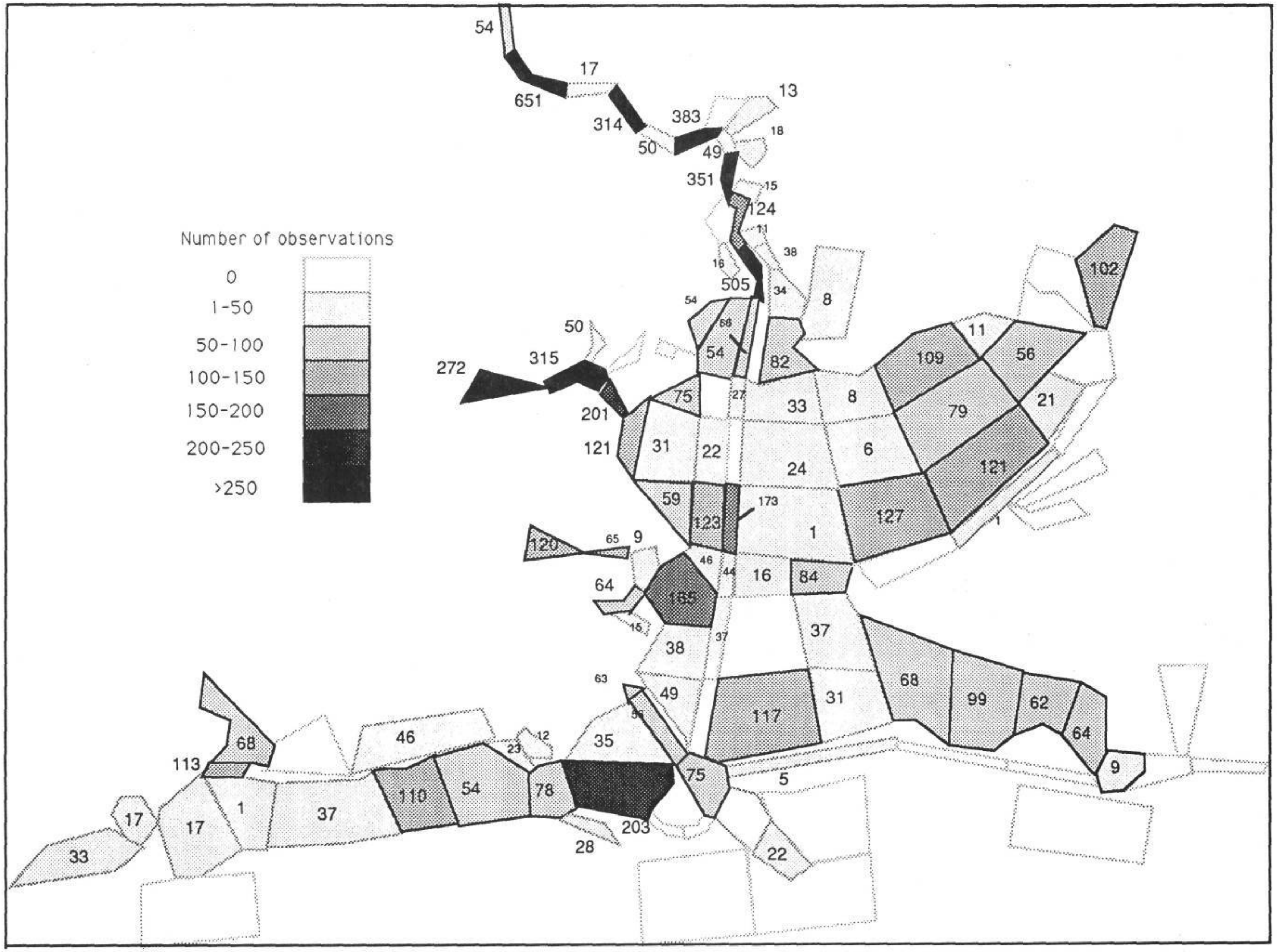


Fig. 2-8. Sampling density in Galveston Bay for WQXBOD5

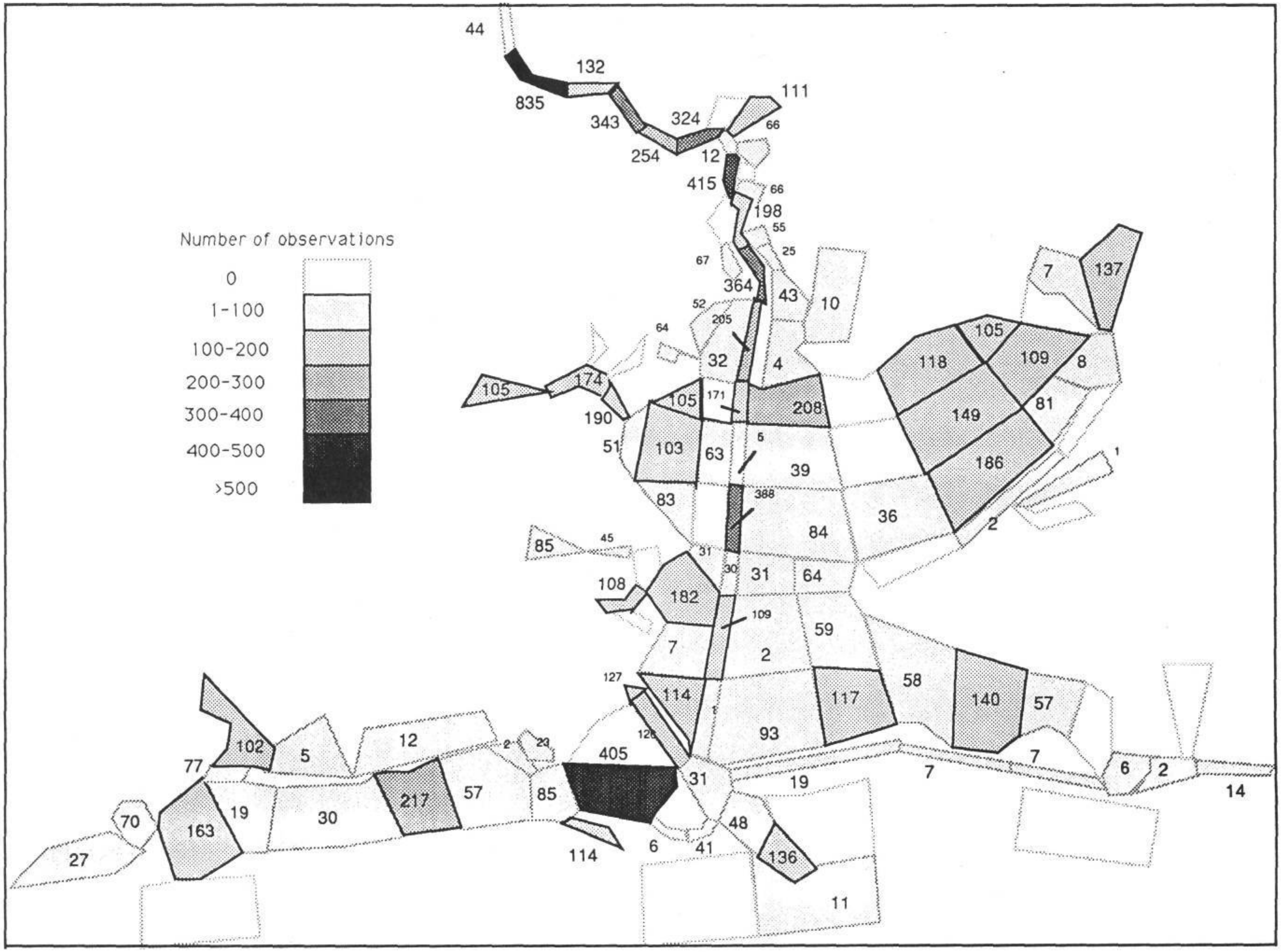


Fig. 2-9. Sampling density in Galveston Bay for WQAMMN

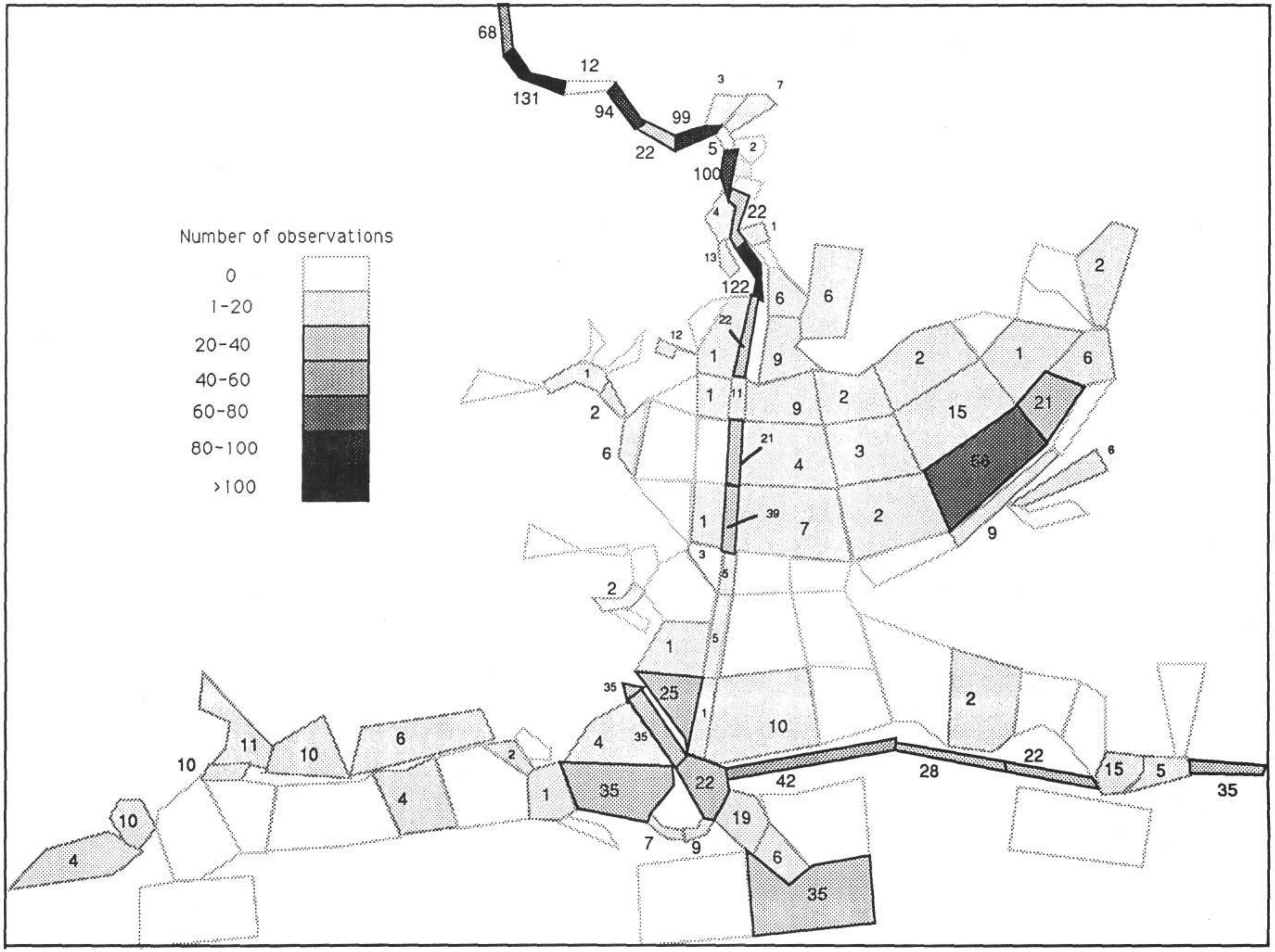


Fig. 2-10. Sampling density in Galveston Bay for WQMETHGT

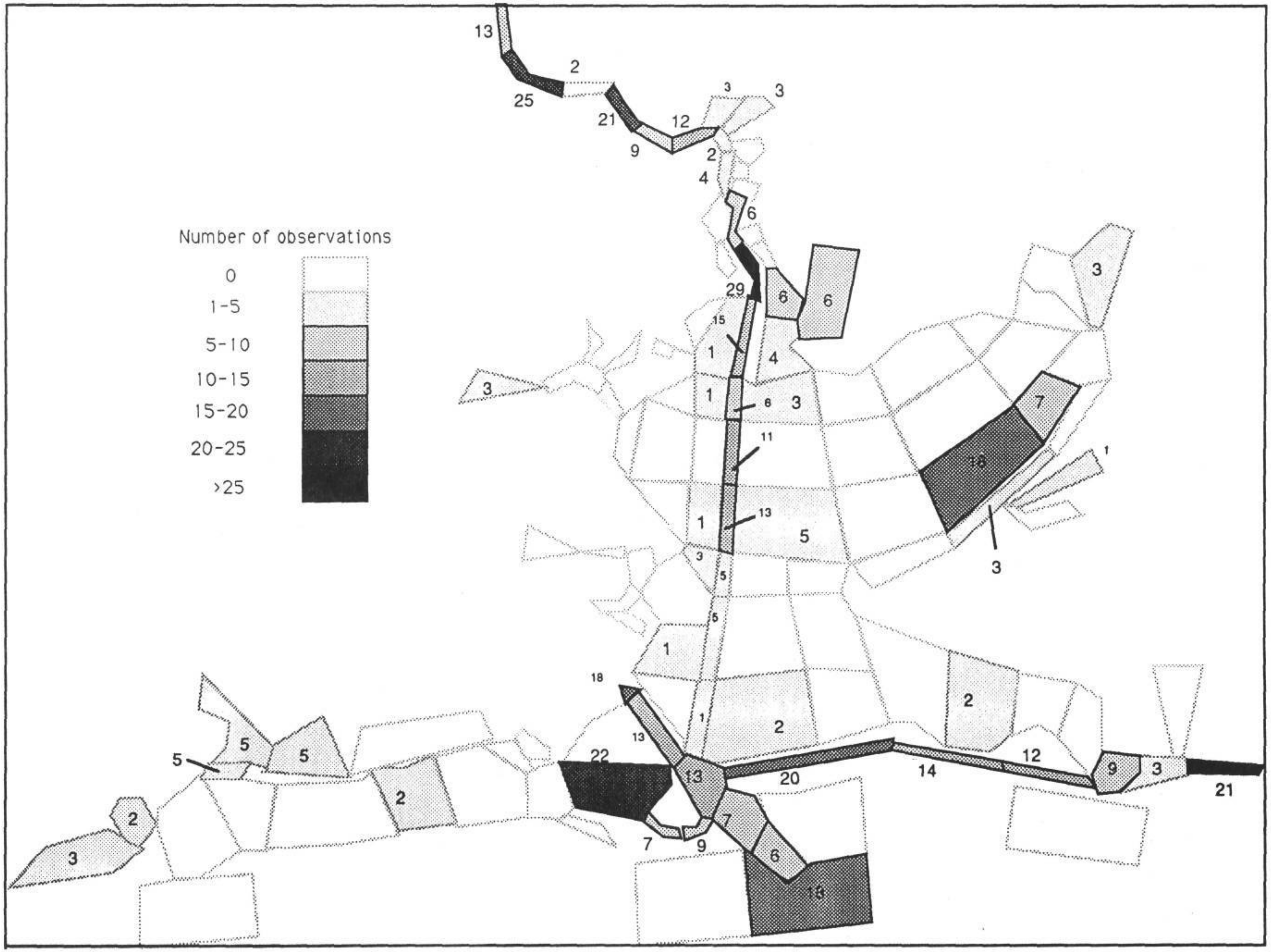


Fig. 2-11. Sampling density in Galveston Bay for WQ-XDDT

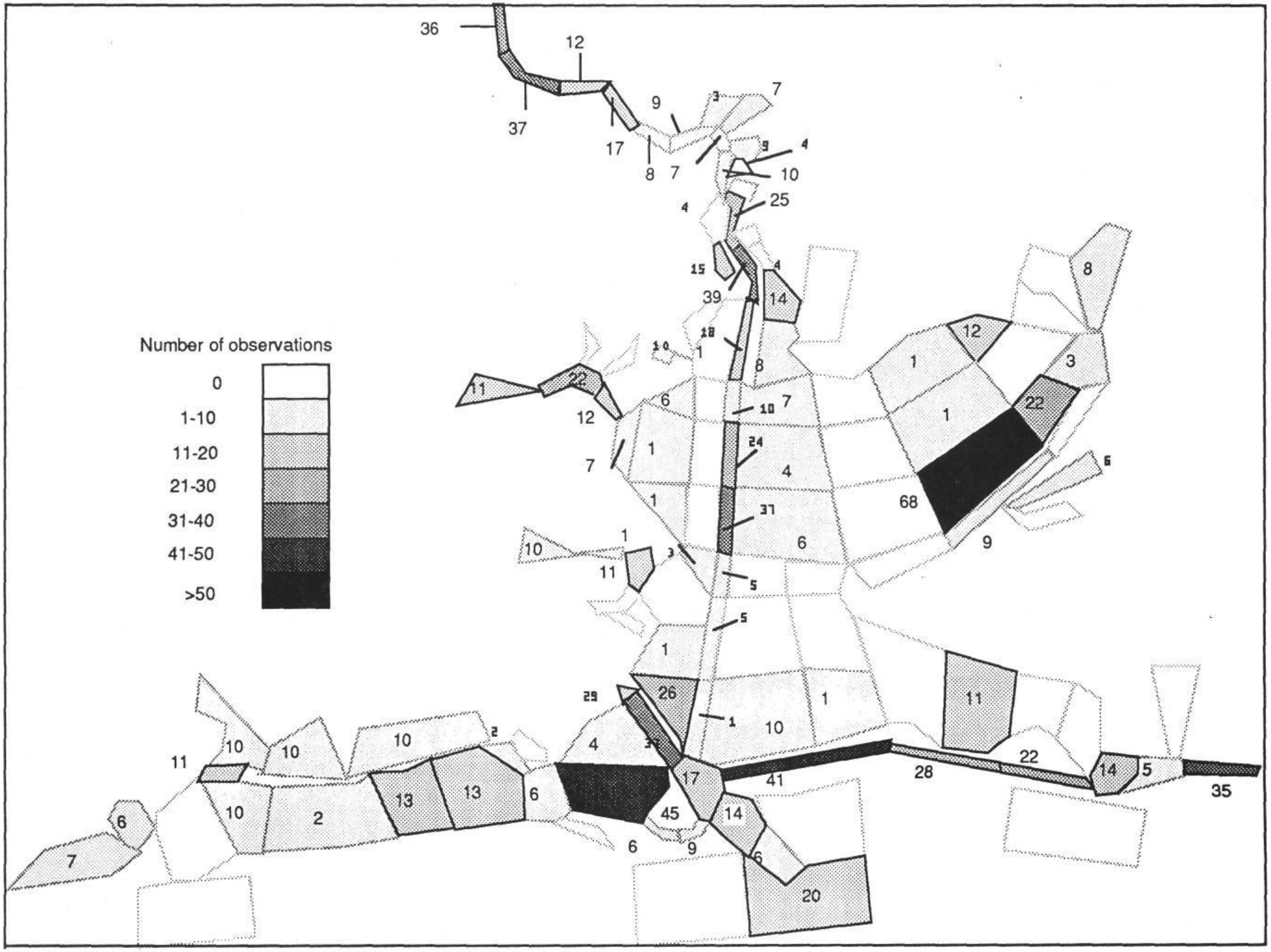


Fig. 2-12. Sampling density in Galveston Bay for SEDO&G

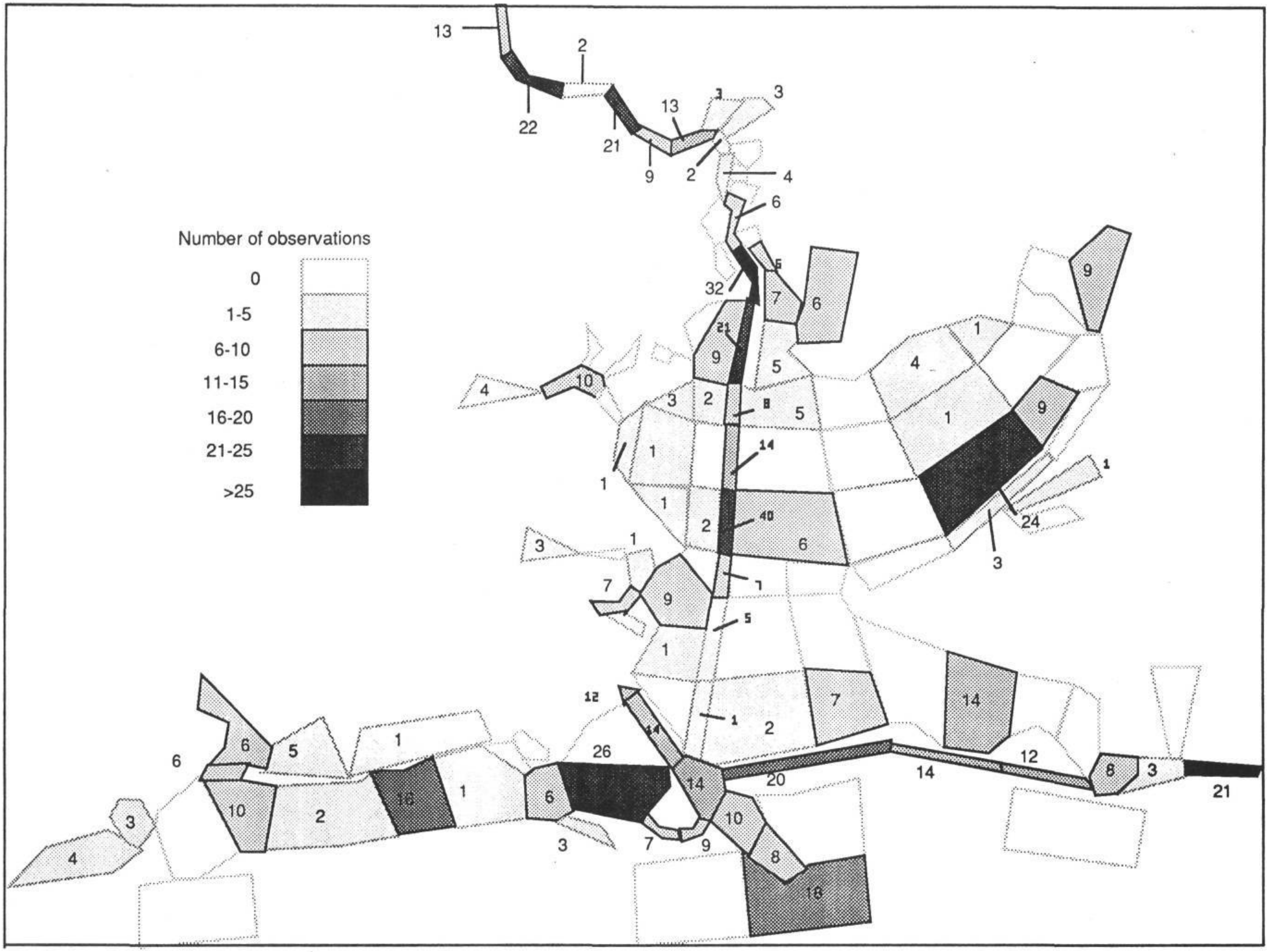


Fig. 2-13. Sampling density in Galveston Bay for SED-XDDT

3. WATER AND SEDIMENT QUALITY OF GALVESTON BAY

The Derivative Data Bases for each of the study parameters formed the basis for characterization of water quality in Galveston Bay. This characterization entails both the spatial dimension and the temporal, the latter including the analysis of trends in time. The data record for each parameter was sorted into two different segmentations of the bay: the Texas Water Commission Water Quality segments, and the GBNEP hydrographic segments developed for this project.

As discussed in Section 2.3, the philosophy of segmentation is based upon the assumption that each segment is homogeneous, within an allowable scatter in the data (i.e., within a certain statistical confidence), so that data from that segment can be considered independent measurements of the same variate. One must realize that Galveston Bay is under-sampled, relative to the time and space scales of natural variability. Therefore, any partitioning of the data in space or time involves trade-offs in statistical confidence. The more segments that are defined (i.e., the smaller their spatial extent), the fewer data points that will be placed in each segment. While spatial variability is better delineated, the statistical confidence in the values at each segment is reduced because of the fewer number of data points. To improve the number of data points by aggregating into larger segments is to introduce more "noise" in the data due to spatial variability; the ultimate extreme of this strategy is the baywide analysis given in Tables 2-3 through 2-6, in which all available data are used to compute the statistics, but the high variance renders the computed statistics practically useless. The GBNEP hydrographic segmentation developed in this study, represents our best compromise between a sufficient data record in each segment for meaningful analyses and a sufficiently small and well-defined segment domain so as to reduce the spatially-induced noise. In this report, therefore, this segmentation forms the basis for analysis of spatial variation and temporal trends. Only selected results for the GBNEP hydrographic segmentation are given in this summary report. Complete results for both systems of segmentation are presented in the Appendix to the Extended Technical Report (Ward and Armstrong, 1992a).

Along with the abbreviations for the water and sediment parameters given in Table 2-2 is a nominal estimate of the uncertainty of measurement of each (developed from the data of the appendix of the Extended Technical Report, which in turn were compiled from a study of current and historical laboratory procedural accuracy and precision data), as a coefficient of variation (based upon typical values in Galveston Bay when the standard deviation does not vary proportionately with parameter value). The associated confidence bounds for a high probability are two (95%) or three (98%) times the standard deviation, the latter corresponding to the intuitive notion of tolerance. Thus, a measurement of ammonia (WQAMMN) establishes a 98%-probable value nominally within ±60% of the measurement. This translates to an additional, and in many cases considerable, source of variation in the data.

The historical statistics for each of the study parameters, for each of the TWC segments and each of the GBNEP hydrographic segments, are presented in Appendices B and C of the Extended Technical Report. For each parameter there is a pair of tables, the first, the Period of Record Statistics, presenting basic data on magnitude and variance of the measurements, and the second, the Time Trend Analysis, presenting data on the time history dimension of the parameter's variation. These tables, and their companions on sediment quality, are the central analytical product of this study and warrant examination far beyond the comments offered here. However, because of the considerable volume of the tables and the fact that most readers will not wish to delve into the details of the analyses, these results are relegated to the appendix of the Extended Technical Report.

Tables 3-1 and 3-2 present one example of these analyses, for ammonia nitrogen. The first key entry is in the second column of the first table, *viz.* number of observations. This number obviously circumscribes the confidence of the remainder of the analyses for that segment: for many segments this number is zero, or is so small as to provide little useful information. The paucity of measurements of metals and organics is particularly notable.

It will be recalled (Section 2.5) that we have elected to treat measurements below detection limits (BDL) in three different ways. First, all such data are ignored. This is done in all computations of *variability*, including standard deviations and regressions, as well as in the first average (column three) of Tables 3-1. Second, all BDL's are assigned a value of zero, the more optimistic extreme, assuming a BDL is equivalent to nonpresence of the analyte. Third, all BDL's are assigned the value of the corresponding detection limits, the more pessimistic extreme, assuming a BDL variate is present to the maximum concentration that remains undetectable. The separate averages using these latter two strategies are given in the final two columns of the Period of Record Statistics tables (e.g., Tables 3-1). These represent upper and lower bounds on the actual mean concentration. Because many of the data records contain a high frequency of BDL values, and (worse) reported values of 0 instead of a detection limit, a census of BDL's, minimum values, and non-zero minima is also given in the Period of Record Statistics tables.

TABLE 3-1
Period of Record Statistics for Hydrographic Segments
WQAMMN

Segment	No.of obs	Avg >DL	St dev >DL	No.> DLs	% > DLs	Min	date	Min >0	date	Max	date	Avg w/ BDL=0	Avg w/ BDL=DL
C1	105	0.407	0.44	89	84.8	0.01	760916	0.01	760916	2.3	820120	0.345	0.394
C2	174	0.157	0.24	137	78.7	0	720229	0.01	750525	1.2	890329	0.124	0.126
C5	190	0.29	0.42	168	88.4	0	720127	0.01	760525	2.7	700114	0.257	0.258
C6	10	0.123	0.033	10	100.	0.08	870708	0.08	870708	0.19	880524	0.123	0.123
D1	85	0.318	0.37	74	87.1	0.01	760407	0.01	760407	1.6	740710	0.277	0.317
D2	45	0.202	0.3	25	55.6	0.01	820524	0.01	820524	1.4	750116	0.112	0.251
D4	108	0.547	1.1	84	77.8	0	711124	0.01	760714	7.3	750116	0.426	0.463
E1	58	0.0302	0.047	58	100.	0	691202	0.02	831128	0.3	700414	0.0302	0.0302
E2	140	0.11	0.25	115	82.1	0	680716	0.01	760226	1.3	890419	0.0902	0.101
E3	57	0.0549	0.064	57	100.	0	801104	0.01	781012	0.34	770202	0.0549	0.0549
E5	6	0.348	0.073	6	100.	0.27	820428	0.27	820428	0.46	840816	0.348	0.348
E6	2	0.32	0.02	2	100.	0.3	840816	0.3	840816	0.34	820428	0.32	0.32
E8	14	0.645	0.17	11	78.6	0.34	840816	0.34	840816	0.87	820428	0.507	0.518
E9	7	0.841	1	7	100.	0.32	820428	0.32	820428	3.4	820428	0.841	0.841
E10	7	0.371	0.15	7	100.	0.23	840816	0.23	840816	0.72	840816	0.371	0.371
G1	52	1	1.1	49	94.2	0	680716	0.4	690819	5.3	700210	0.943	0.948
G2	64	0.271	0.37	58	90.6	0	740221	0.01	760804	2.1	731105	0.245	0.248
G3	105	0.0934	0.16	86	81.9	0	721018	0.01	760525	1.1	890403	0.0765	0.0786
G4	51	0.0935	0.15	48	94.1	0	680716	0.1	690218	0.5	700414	0.088	0.0929
G5	103	0.196	0.38	99	96.1	0	680716	0.01	781010	2.5	700210	0.189	0.192
G6	83	0.0807	0.11	77	92.8	0	680716	0.015	841212	0.44	890403	0.0749	0.0797
G7	182	0.0954	0.22	160	87.9	0	680716	0.01	760226	1.6	740821	0.0839	0.087
G8	7	0.04	0.029	6	85.7	0.02	760719	0.02	760719	0.09	760719	0.0343	0.0414
G9	114	0.0369	0.057	108	94.7	0	680716	0.01	770824	0.29	810414	0.035	0.0385
G10	32	0.099	0.089	31	96.9	0.02	840711	0.02	840711	0.35	850227	0.0959	0.0966
G12	63	0.091	0.093	63	100.	0	801105	0.01	801105	0.52	780208	0.091	0.091
G14	31	0.088	0.088	30	96.8	0	791108	0.01	780606	0.4	810414	0.0852	0.0868
G15	205	0.785	1	200	97.6	0	680716	0.01	850430	5.7	700414	0.766	0.768
G16	171	0.251	0.41	162	94.7	0	680716	0.01	850430	1.9	700310	0.237	0.24

TABLE 3-1
(continued)
WQAMMN Period of Record Statistics

Segment	No.of obs	Avg >DL	St dev >DL	No.> DLs	% > DLs	Min	date	Min >0	date	Max	date	Avg w/ BDL=0	Avg w/ BDL=DL
G17	5	0.448	0.25	5	100.	0.24	830627	0.24	830627	0.8	800804	0.448	0.448
G18	388	0.114	0.25	328	84.5	0	680716	0.01	750525	2.1	690819	0.096	0.102
G19	30	0.00893	0.046	28	93.3	0	710316	0.25	830627	0.25	830627	0.00833	0.0117
G20	109	0.0197	0.076	88	80.7	0	680716	0.13	690114	0.4	700310	0.0159	0.0273
G21	1	0	0	0	0.	0	0	0	0	0	0	0	0.05
G22	43	0.231	0.31	40	93.	0.01	870423	0.01	870423	1.6	820126	0.215	0.215
G23	4	0.0525	0.056	4	100.	0.02	760719	0.02	760719	0.15	810524	0.0525	0.0525
G24	208	0.151	0.31	198	95.2	0	680716	0.01	800424	2.4	690218	0.144	0.145
G25	39	0.0836	0.085	39	100.	0	801105	0.01	800424	0.32	761213	0.0836	0.0836
G26	84	0.0567	0.06	84	100.	0	800424	0.01	761118	0.37	770426	0.0567	0.0567
G27	31	0.0513	0.063	31	100.	0.02	840330	0.02	840330	0.33	770426	0.0513	0.0513
G28	2	0.03	0	2	100.	0.03	760719	0.03	760719	0.03	760719	0.03	0.03
G29	93	0.0405	0.053	92	98.9	0.01	791106	0.01	791106	0.5	820526	0.0401	0.0406
G30	64	0.0586	0.25	58	90.6	0	680716	0.1	690415	1.8	700113	0.0531	0.0594
G31	59	0.0385	0.028	59	100.	0.01	761021	0.01	761021	0.11	810415	0.0385	0.0385
G32	117	0.0975	0.27	103	88.	0	680716	0.01	760226	1.3	690923	0.0858	0.09
G33	19	0.209	0.14	18	94.7	0	750425	0.01	750806	0.37	840816	0.198	0.201
G34	31	0.111	0.2	29	93.6	0.01	760721	0.01	760721	0.95	811103	0.104	0.107
G35	48	0.0528	0.055	47	97.9	0.02	750417	0.02	750417	0.27	860225	0.0517	0.0519
G36	136	0.00975	0.049	120	88.2	0	680716	0.01	750506	0.5	831116	0.0086	0.0157
G37	41	0.344	1.3	34	82.9	0.01	820427	0.01	820427	7.8	801211	0.285	0.291
G38	6	0.82	0.71	3	50.	0.16	851215	0.16	851215	1.8	801211	0.41	0.443
H1	364	0.383	0.54	310	85.2	0	720614	0.01	770214	4	741015	0.327	0.404
H2	61	0.504	0.66	58	95.1	0	730214	0.01	760818	3.4	730911	0.479	0.481
H3	25	0.955	1	23	92.	0	740214	0.03	820804	4	731115	0.878	0.881
H4	55	0.426	0.67	49	89.1	0	740214	0.01	760818	2.6	731115	0.38	0.381
H5	67	0.656	0.69	65	97.	0.017	831013	0.017	831013	3	731115	0.637	0.637
H7	198	1.35	1.4	188	95.	0	690114	0.03	840711	7.2	700707	1.29	1.29
H8	66	0.75	0.77	64	97.	0.029	830426	0.029	830426	3.7	731115	0.727	0.728

TABLE 3-1
(continued)
WQAMMN Period of Record Statistics

Segment	No.of obs	Avg >DL	St dev >DL	No.> DLs	% > DLs	Min	date	Min >0	date	Max	date	Avg w/ BDL=0	Avg w/ BDL=DL
H10	66	0.699	0.72	61	92.4	0.01	880727	0.01	880727	3	731115	0.646	0.647
H11	415	1.37	1.6	388	93.5	0	681119	0.01	860911	11	750415	1.28	1.33
H12	12	0.93	0.78	10	83.3	0.03	840711	0.03	840711	2.5	760512	0.775	0.781
H13	324	1.29	1.2	315	97.2	0.012	820519	0.012	820519	6.8	731115	1.26	1.28
H14	254	4.02	2.6	251	98.8	0	681119	0.1	681015	23	680716	3.97	3.97
H15	343	2.09	1.8	339	98.8	0	740813	0.012	820519	9.6	731210	2.07	2.08
H16	132	4.4	2.5	132	100.	0.64	840711	0.64	840711	13	690715	4.4	4.4
H17	835	2.97	2.3	831	99.5	0.01	820519	0.01	820519	22	830125	2.96	2.96
H18	44	2.46	1.6	40	90.9	0.76	770503	0.76	770503	7.9	800129	2.23	2.36
H19	494	3.34	3.1	492	99.6	0	681210	0.012	820519	39	750120	3.32	3.33
H20	420	2.09	2.5	410	97.6	0.01	760220	0.01	760220	18	811118	2.04	2.07
M3	11	0.0214	0.016	7	63.6	0.01	750610	0.01	750610	0.05	750416	0.0136	0.0282
S1	111	3.66	1.9	102	91.9	0.1	690415	0.1	690415	7.8	700210	3.36	3.36
T2	118	0.2	0.41	104	88.1	0	680820	0.01	760224	2.4	740905	0.177	0.182
T3	105	0.275	0.48	100	95.2	0	710316	0.001	870409	3.5	710817	0.262	0.262
T5	149	0.0937	0.25	129	86.6	0	680716	0.01	760224	1.1	700113	0.0812	0.0861
T6	109	0.0628	0.09	100	91.7	0	680820	0.01	761229	0.5	700210	0.0576	0.0627
T8	7	0.146	0.14	7	100.	0	760225	0.02	751015	0.4	760128	0.146	0.146
T9	137	0.163	0.22	118	86.1	0	720402	0.01	760712	1.2	740103	0.141	0.161
T10	36	0.0306	0.12	36	100.	0	691202	0.1	700210	0.7	700414	0.0306	0.0306
T11	85	0.0275	0.049	77	90.6	0	680716	0.01	761229	0.3	880816	0.0249	0.0303
T12	81	0.0891	0.15	81	100.	0	691202	0.01	760719	0.7	700113	0.0891	0.0891
T13	8	0.0675	0.044	8	100.	0.01	761118	0.01	761118	0.15	810505	0.0675	0.0675
T15	2	0:1	0	2	100.	0.1	810408	0.1	810408	0.1	810408	0.1	0.1
T17	1	0.1	0	1	100.	0.1	810408	0.1	810408	0.1	810408	0.1	0.1
W1	27	0.308	0.4	22	81.5	0	711230	0.01	760303	1	740828	0.251	0.291
W2	70	0.189	0.32	47	67.1	0.01	760303	0.01	760303	1	740828	0.127	0.132
W3	2	0.2	0	2	100.	0.2	810714	0.2	810714	0.2	810714	0.2	0.2
W4	163	0.0268	0.036	154	94.5	0	680716	0.01	770824	0.29	870129	0.0253	0.0285

TABLE 3-1
(continued)
WQAMMN Period of Record Statistics

Segment	No.of obs	Avg >DL	St dev >DL	No.> DLs	% > DLs	Min	date	Min >0	date	Max	date	Avg w/ BDL=0	Avg w/ BDL=DL
W5	19	0.584	0.54	15	79.	0.01	760226	0.01	760226	1.8	740529	0.461	0.466
W6	77	0.0757	0.21	69	89.6	0	680716	0.09	711230	1.4	700113	0.0678	0.0738
W7	102	0.159	0.27	92	90.2	0	721019	0.01	760303	1.1	840131	0.144	0.145
W8	83	0.171	0.26	62	74.7	0	730523	0.01	760819	1.5	711127	0.128	0.214
W9	30	0.0233	0.011	30	100.	0.02	831128	0.02	831128	0.08	870617	0.0233	0.0233
W10	217	0.0658	0.17	177	81.6	0	680716	0.01	760226	1	740819	0.0536	0.0635
W11	57	0.0494	0.036	57	100.	0	791107	0.01	770824	0.15	790523	0.0494	0.0494
W12	12	0.195	0.12	8	66.7	0.07	880707	0.07	880707	0.49	820111	0.13	0.133
W13	2	0.15	0	2	100.	0.15	810331	0.15	810331	0.15	810331	0.15	0.15
W14	23	0.0917	0.12	22	95.7	0.01	841218	0.01	841218	0.61	890613	0.0877	0.0886
W15	85	0.0892	0.16	59	69.4	0	711228	0.002	810909	0.91	700114	0.0619	0.0655
W16	405	0.0732	0.22	340	84.	0	680716	0.01	760204	2	740805	0.0614	0.0659
W18	127	0.501	0.63	121	95.3	0	720228	0.007	810909	4.3	690924	0.478	0.478
W19	126	0.147	0.29	109	86.5	0	680716	0.01	760824	1.4	740819	0.127	0.133
W20	5	0.18	0.024	5	100.	0.15	810331	0.15	810331	0.2	810331	0.18	0.18
W21	114	0.227	0.59	85	74.6	0	740304	0.01	760609	4.1	741104	0.169	0.173

Table 3-2
Time Trend Analysis for Hydrographic Segments:
WQAMMN

Segment	Period of record dates		Analysis period Start date	Analysis period End date	Avg obs /yr	Regression on time: slope (per yr)	Regression on time: intercept (@ start)	Regression on time: SEE	Regression on time: residual variance	95% confidence limits on slope: lower	95% confidence limits on slope: upper
C1	730919	900910	730919	900910	5.2	-0.0281	0.64	0.417	90.5%	-0.046	-0.0097
C2	720229	901210	720229	901210	7.3	-0.00543	0.21	0.239	98.7%	-0.014	0.0027
C5	690730	901210	690730	901210	7.9	-0.0267	0.56	0.388	86.9%	-0.037	-0.016
C6	810524	880526	810524	880526	1.4	0.00216	0.11	0.0328	96.1%	-0.0066	0.011
D1	671001	900710	671001	900710	3.2	-0.0158	0.55	0.365	95.6%	-0.033	0.0013
D2	700923	900710	700923	890731	1.3	-0.0185	0.35	0.285	87.2%	-0.039	0.0023
D4	701130	900815	701130	900815	4.3	-0.0537	0.88	1.05	93.%	-0.096	-0.011
E1	691202	890706	691202	890706	3	-0.000264	0.033	0.0473	99.8%	-0.0019	0.0013
E2	680716	901008	680716	900712	5.2	0.00476	0.075	0.245	98.1%	-0.0015	0.011
E3	761021	890706	761021	890706	4.5	-0.0042	0.082	0.0613	92.6%	-0.0082	-0.00023
E5	820428	840816	820428	840816	2.6	0.0565	0.28	0.0335	21.%	0.016	0.097
E6	820428	840816	820428	840816	0.87	-0.0174	0.34	0	0.%	0	0
E8	820428	840816	820428	840816	4.8	-0.139	0.76	0.0733	18.6%	-0.19	-0.089
E9	820428	820428	820428	820428	7						
E10	820428	840816	820428	840816	3	0.063	0.33	0.138	81.6%	-0.09	0.22
G1	680716	701020	680716	701020	22	0.415	0.53	1.03	93.6%	-0.045	0.87
G2	731105	900719	731105	900719	3.5	-0.0374	0.59	0.327	76.4%	-0.055	-0.02
G3	721018	900618	721018	900402	4.9	0.00223	0.07	0.155	99.5%	-0.0044	0.0089
G4	680716	701020	680716	701020	21	0.0426	0.043	0.152	96.9%	-0.026	0.11
G5	680716	890705	680716	890705	4.7	-0.0136	0.3	0.364	92.4%	-0.023	-0.0041
G6	680716	900402	680716	900402	3.5	0.00461	0.042	0.0998	85.7%	0.002	0.0072
G7	680716	901113	680716	901113	7.2	-0.000107	0.096	0.218	100.%	-0.0055	0.0052
G8	760719	840330	760719	760724	440	-0.487	0.043	0.0287	98.7%	-6.3	5.3
G9	680716	890706	680716	890706	5.1	0.00111	0.027	0.0568	98.%	-0.00039	0.0026
G10	831214	890705	831214	890705	5.6	-0.0151	0.14	0.0857	92.1%	-0.034	0.0039
G12	760719	890705	760719	890705	4.9	-0.00814	0.14	0.0857	85.3%	-0.013	-0.0032

Table 3-2
(continued)
WQAMMN Time Trend Analysis

Segment	Period of record dates		Analysis period Start date	End date	Avg obs /yr	Regression on time: slope (per yr)	intercept (@ start)	SEE	residual variance	95% confidence limits on slope: lower	upper
G14	761021	840330	761021	830627	4.5	0.00847	0.067	0.0867	96.5%	-0.0086	0.026
G15	680716	900618	680716	900402	9.2	-0.0576	1.2	0.928	81.3%	-0.075	-0.041
G16	680716	900618	680716	900402	7.5	-0.0141	0.36	0.39	91.9%	-0.021	-0.0067
G17	800804	830627	800804	830627	1.7	-0.174	0.75	0.0318	1.6%	-0.22	-0.13
G18	680716	901210	680716	901210	15	-0.00204	0.14	0.248	99.6%	-0.0054	0.0014
G19	710316	840330	710316	830627	2.3	0.0208	-0.011	0.00694	2.2%	0.02	0.022
G20	680716	840330	680716	701020	39	0.0185	-0.0029	0.0746	97.4%	-0.0058	0.043
G21	840330	840330	0	0	0						
G22	790717	900711	790717	900711	3.6	-0.0219	0.35	0.297	94.2%	-0.05	0.0064
G23	760719	810524	760719	810524	0.83	0.0268	0.02	0.00015	0.%	0.027	0.027
G24	680716	900618	680716	900402	9.1	-0.0105	0.27	0.305	94.2%	-0.017	-0.0045
G25	761021	820427	761021	820427	7.1	-0.00714	0.097	0.0842	97.8%	-0.023	0.0082
G26	760719	890705	760719	890705	6.5	-0.00472	0.082	0.0568	89.9%	-0.0078	-0.0016
G27	770426	890705	770426	890705	2.5	-0.0103	0.14	0.0514	67.%	-0.016	-0.0049
G28	760719	760724	760719	760724	150	0	0.03	0	0.%	0	0
G29	760719	890706	760719	890706	7.1	-0.00336	0.066	0.0513	93.5%	-0.006	-0.00069
G30	680716	720425	680716	720425	15	0.00823	0.045	0.246	99.9%	-0.055	0.071
G31	760719	890706	760719	890706	4.6	-0.00207	0.051	0.0266	89.8%	-0.0037	-0.00046
G32	680716	901008	680716	901008	4.6	0.000938	0.091	0.269	99.9%	-0.0062	0.008
G33	750425	840816	750425	840816	1.9	0.0354	0.023	0.0354	6.7%	0.03	0.04
G34	760719	840816	760719	831116	4	0.0613	0.05	0.149	54.9%	0.035	0.088
G35	750411	890706	750411	890706	3.3	-0.00384	0.082	0.0506	85.%	-0.0065	-0.0011
G36	680716	831116	680716	831116	7.8	0.0156	-0.026	0.0346	50.4%	0.013	0.018
G37	801211	901113	801211	901113	3.4	-0.172	1.2	1.23	86.6%	-0.32	-0.019
G38	801211	851215	801211	851215	0.6	-0.198	1.2	0.531	56.4%	-3.1	2.7
H1	720210	900711	720210	900711	17	-0.0405	0.75	0.496	85.3%	-0.052	-0.029

Table 3-2
(continued)
WQAMMN Time Trend Analysis

Segment	Period of record dates		Analysis period Start date	Analysis period End date	Avg obs /yr	Regression on time: slope (per yr)	Regression on time: intercept (@ start)	Regression on time: SEE	Regression on time: residual variance	95% confidence limits on slope: lower	95% confidence limits on slope: upper
H2	730214	900711	730214	900711	3.3	-0.0713	1.1	0.566	72.4%	-0.1	-0.041
H3	730911	850227	730911	850227	2	-0.197	1.6	0.894	72.8%	-0.34	-0.051
H4	730911	900828	730911	900828	2.9	-0.0639	0.93	0.572	73.3%	-0.094	-0.033
H5	730911	900711	730911	900711	3.9	-0.0892	1.4	0.518	57.2%	-0.11	-0.063
H7	680716	850227	680716	850227	11	-0.136	2.1	1.22	78.3%	-0.17	-0.098
H8	730911	900711	730911	900711	3.8	-0.0915	1.5	0.634	67.6%	-0.12	-0.058
H10	730911	900711	730911	900711	3.6	-0.0777	1.3	0.616	72.5%	-0.11	-0.045
H11	671001	900813	671001	900813	17	-0.143	2.8	1.23	63.%	-0.16	-0.12
H12	760512	850227	760512	850227	1.1	-0.185	1.7	0.395	25.7%	-0.27	-0.096
H13	720210	900711	720210	900711	17	-0.129	2.4	1.03	69.6%	-0.15	-0.11
H14	680716	850227	680716	850227	15	-0.212	4.5	2.5	94.3%	-0.32	-0.1
H15	720210	900813	720210	900813	18	-0.182	3.6	1.52	73.4%	-0.21	-0.15
H16	680716	850227	680716	850227	7.9	-0.237	5.1	2.24	82.8%	-0.33	-0.15
H17	680716	900813	680716	900813	38	-0.147	4.6	2.14	84.9%	-0.17	-0.12
H18	760609	850227	760609	850227	4.6	-0.0836	2.8	1.58	98.1%	-0.27	0.11
H19	680716	900711	680716	900711	22	-0.195	5.2	2.87	84.5%	-0.24	-0.15
H20	751201	900813	751201	900813	28	-0.254	3.8	2.2	75.6%	-0.3	-0.21
M3	750416	831116	750416	750610	46	-0.246	0.047	0.00571	13.5%	-0.36	-0.13
S1	680716	850227	680716	850227	6.1	-0.0979	3.8	1.89	99.1%	-0.31	0.11
T2	680820	811209	680820	811209	7.8	-0.00307	0.22	0.411	99.9%	-0.023	0.017
T3	710316	900809	710316	900809	5.2	-0.00643	0.33	0.476	99.4%	-0.023	0.011
T5	680716	900809	680716	900809	5.8	-0.000879	0.1	0.246	99.9%	-0.0072	0.0055
T6	680820	890705	680820	890705	4.8	0.00153	0.05	0.0897	98.6%	-0.001	0.0041
T8	751015	760519	751015	760519	12	0.0137	0.14	0.14	100.%	-0.84	0.86
T9	720402	900828	720402	900828	6.4	-0.0106	0.24	0.21	94.9%	-0.019	-0.0022
T10	691202	720502	691202	720502	15	-0.0294	0.059	0.115	96.2%	-0.08	0.021

Table 3-2
(continued)
WQAMMN Time Trend Analysis

Segment	Period of record dates		Analysis period Start date	Analysis period End date	Avg obs /yr	Regression on time: slope (per yr)	Regression on time: intercept (@ start)	Regression on time: SEE	Regression on time: residual variance	95% confidence limits on slope: lower	95% confidence limits on slope: upper
T11	680716	900809	680716	900809	7.6	0.0016	0.085	0.201	99.7%	-0.0028	0.006
T12	691202	831026	691202	831026	5.8	-0.00351	0.11	0.152	99.%	-0.011	0.0041
T13	761021	810505	761021	810505	1.8	0.0211	0.054	0.0304	48.9%	0.00044	0.042
T15	810408	810408	810408	810408	2						
T17	810408	810408	810408	810408	1						
W1	701218	830104	701218	810714	2.1	0.0403	0.17	0.381	92.3%	-0.025	0.11
W2	731113	900621	731113	891205	2.9	-0.0346	0.43	0.279	74.2%	-0.052	-0.017
W3	810714	810714	810714	810714	2						
W4	680716	901213	680716	901213	6.9	0.00186	0.0046	0.0327	83.8%	0.0012	0.0025
W5	731113	830104	731113	800925	2.2	-0.15	0.93	0.449	69.5%	-0.29	-0.014
W6	680716	830104	680716	810714	5.3	0.0122	0.046	0.205	96.7%	-0.0037	0.028
W7	690731	901218	690731	901218	4.3	-0.0149	0.3	0.257	90.5%	-0.025	-0.0053
W8	700929	901218	700929	901218	3.1	-0.0171	0.34	0.238	83.3%	-0.027	-0.0073
W9	831128	890706	831128	890706	5.4	0.000259	0.023	0.011	99.8%	-0.0022	0.0027
W10	680716	900919	680716	900919	8	0.000676	0.058	0.174	99.9%	-0.0028	0.0041
W11	761020	830104	761020	830104	9.2	0.000865	0.047	0.0363	99.8%	-0.0045	0.0062
W12	810331	880707	810331	880707	1.1	-0.015	0.21	0.112	90.8%	-0.062	0.032
W13	810331	810331	810331	810331	2						
W14	841218	901213	841218	901213	3.7	0.0215	0.029	0.116	89.3%	-0.0075	0.051
W15	690730	901213	690730	901213	2.8	-0.0078	0.17	0.154	88.9%	-0.014	-0.002
W16	680716	900815	680716	900815	15	0.0112	0.0093	0.208	91.1%	0.0073	0.015
W18	690730	900815	690730	900815	5.8	-0.0466	0.97	0.575	83.7%	-0.066	-0.027
W19	680716	900213	680716	900213	5.1	0.0115	0.097	0.281	97.2%	-0.0014	0.024
W20	810331	810331	810331	810331	5						
W21	740204	901213	740204	901213	5	-0.0341	0.46	0.568	92.7%	-0.06	-0.0077

3.1 Spatial Variation in Water and Sediment Quality

The general spatial variation of selected water and sediment quality parameters is depicted in Figs. 3-1 through 3-18. These are based upon the average values for each segment computed with BDL values taken as 0. Temperature, salinity, and dissolved oxygen warrant special treatment because of the nature of the external controls. To emphasize the horizontal variation in these parameters, as well as to eliminate any spurious weighting of stations where profile data were taken, these parameters were screened for near-surface values only. Further, temperature statistics were computed for winter and summer conditions, defined as December-February and July-August, respectively. For salinity, both a year-round and a late-summer period were analyzed, the latter taken as July-September, the usual low-flow season.

Coliforms present a special problem. Traditionally, coliform data have been subjected to logarithmic-transforms before analysis. The log-transform reduces the large range of variation and the extreme skewness of the raw concentrations, and therefore generally reduces the variance and improves any correlation analyses. It is inappropriate to debate here whether the processes underlying coliform behavior warrant a log-normal assumption; rather, we make both types of analysis, of both log-transformed ("geometric") and nontransformed ("raw") concentrations, available to the user. Fig. 3-13 displays the spatial variation for geometric-mean fecal coliforms.

The extent of vertical stratification in a parameter is frequently of concern in water-quality analysis. The intensity of vertical mixing in the Texas bays, and the resulting vertical homogeneity of the water column has been frequently remarked, e.g. Ward (1980). In the case of Galveston Bay, Espey et al. (1971a,b) specifically addressed the vertical structure in the Galveston Bay Project data base, and found near vertical homogeneity in the open bay, and slight-to-moderate salinity stratification in the deep channels, especially in association with freshets. With the data base assembled here, the extent of vertical stratification was analyzed for each variate for which coincident measurements at two depths were available. This was predominantly temperature, salinity and dissolved oxygen, and to a lesser extent nitrogen series, TOC, suspended solids and chlorophyll-a. Vertical stratification was computed as the vertical gradient in concentration between the two most widely separated measurements in the vertical

$$\Delta c / \Delta z$$

where Δc is the upper-to-lower difference in concentration, and Δz is the difference in elevation of the two measurements with z positive upwards. It must be emphasized that *stratification* is measured in its fluid dynamics sense, and does not imply any "layering" of the water (which entails quantum changes in parameter values at an interface, i.e. singularities in stratification). Such "layering" and associated concepts, such as the notorious "salt wedge," are rare and evanescent phenomena in Galveston Bay. The units of stratification are parameter units per unit depth, e.g. ppm per meter, and stratification is positive if concentration increases upward. Therefore, the normal density stratification implies a positive stratification in temperature and a negative stratification in salinity.

The vertical stratification in selected parameters is tabulated in Tables 3-3 through 3-7. This data is presented in two ways: the arithmetic average stratification in each segment, with the associated standard deviation, and the percentage of the data exhibiting positive stratification. The predominance of stratification is manifested by a large value of gradient compared to the normal magnitude of concentration, and/or a predominance of sign. The general negative stratification in salinity and suspended solids, and the general positive stratification in temperature and dissolved oxygen are consistent with the physical processes controlling each of these (to anticipate the discussions of Chapter 4).

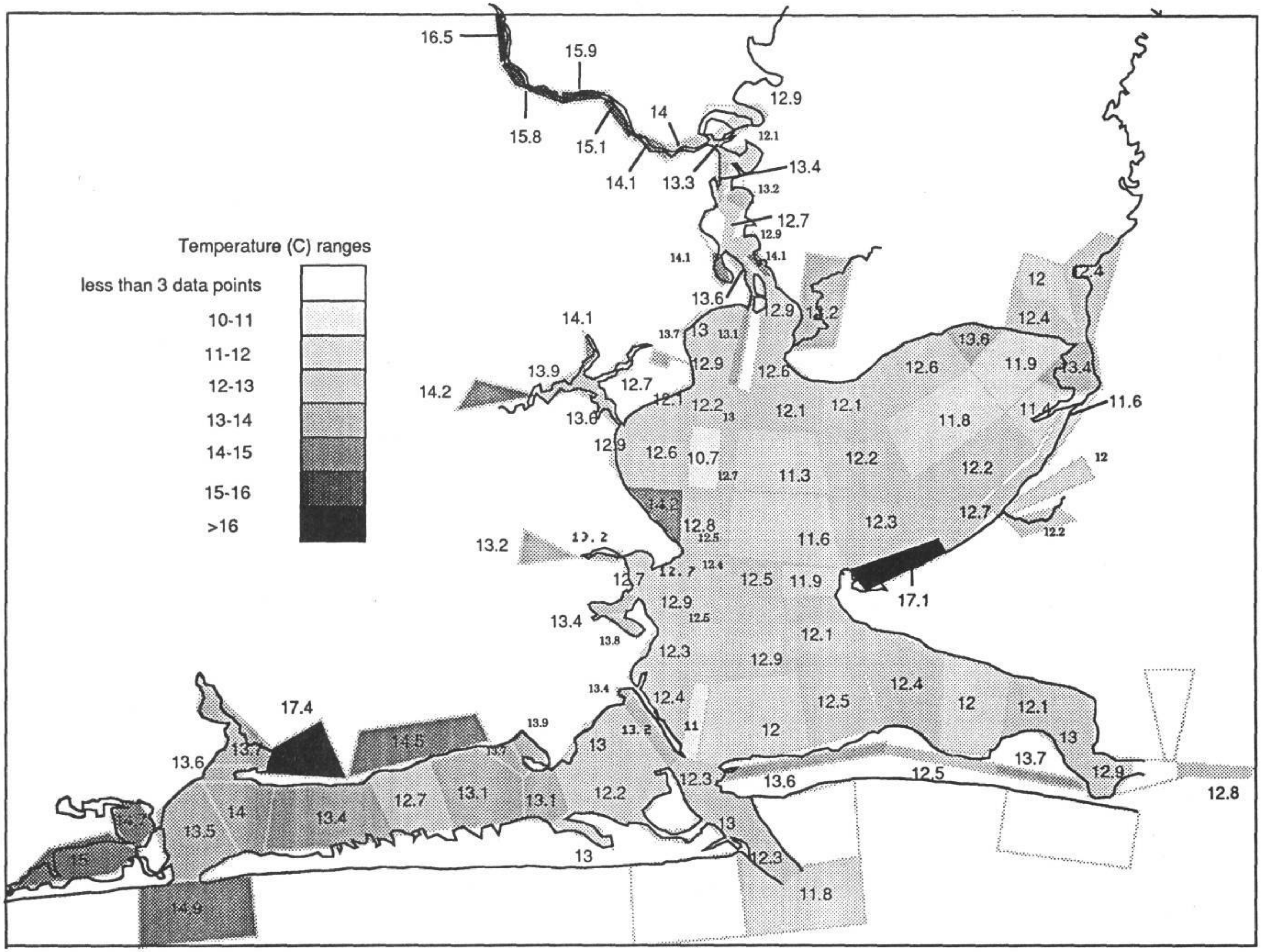


Figure 3-1. Average winter (DJF) temperatures (WQTEMP) in upper 0.5 m of Galveston Bay

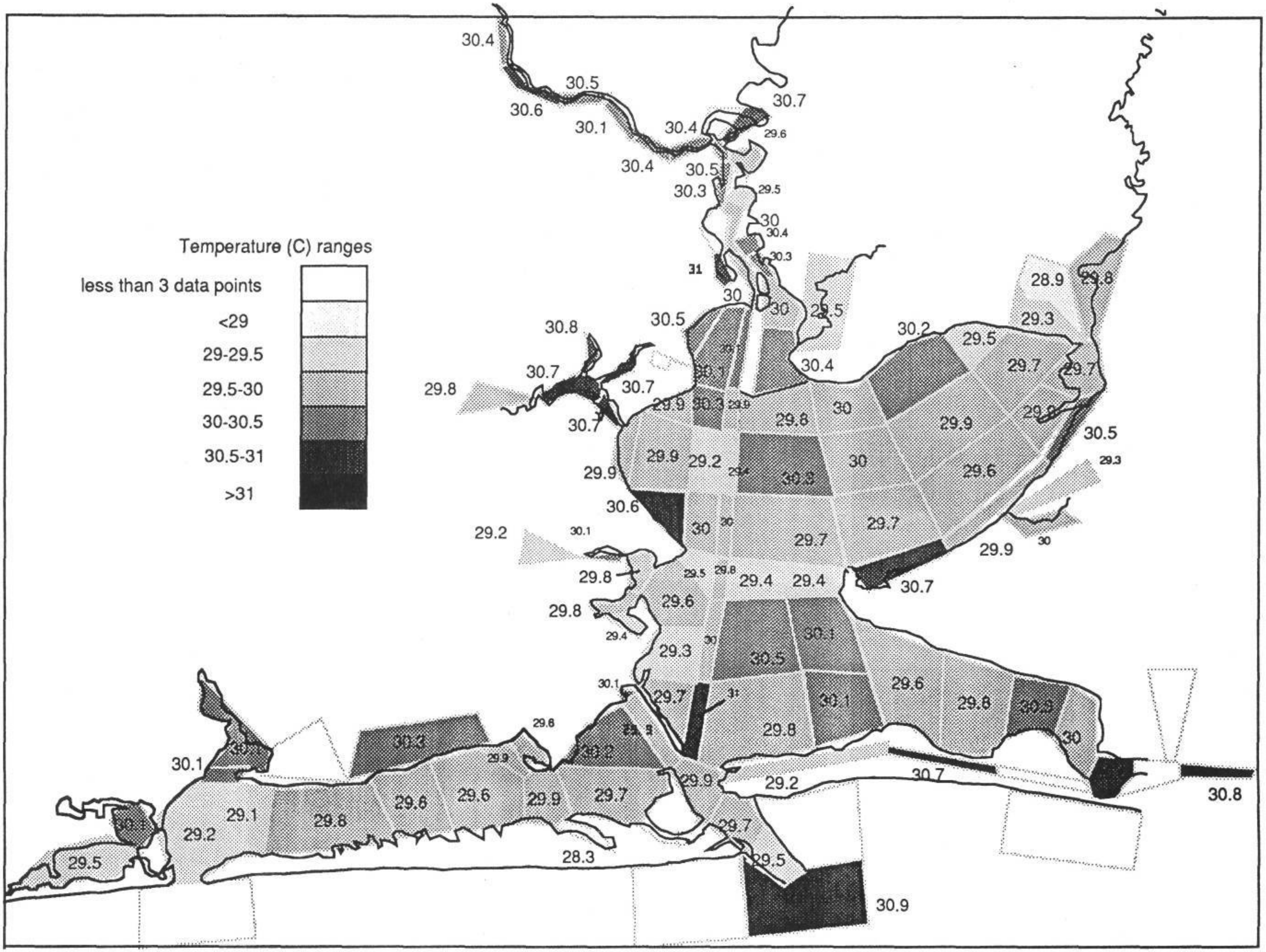


Figure 3-2. Average summer (July-August) temperature (WQTEMP) in upper 0.5 m of Galveston Bay

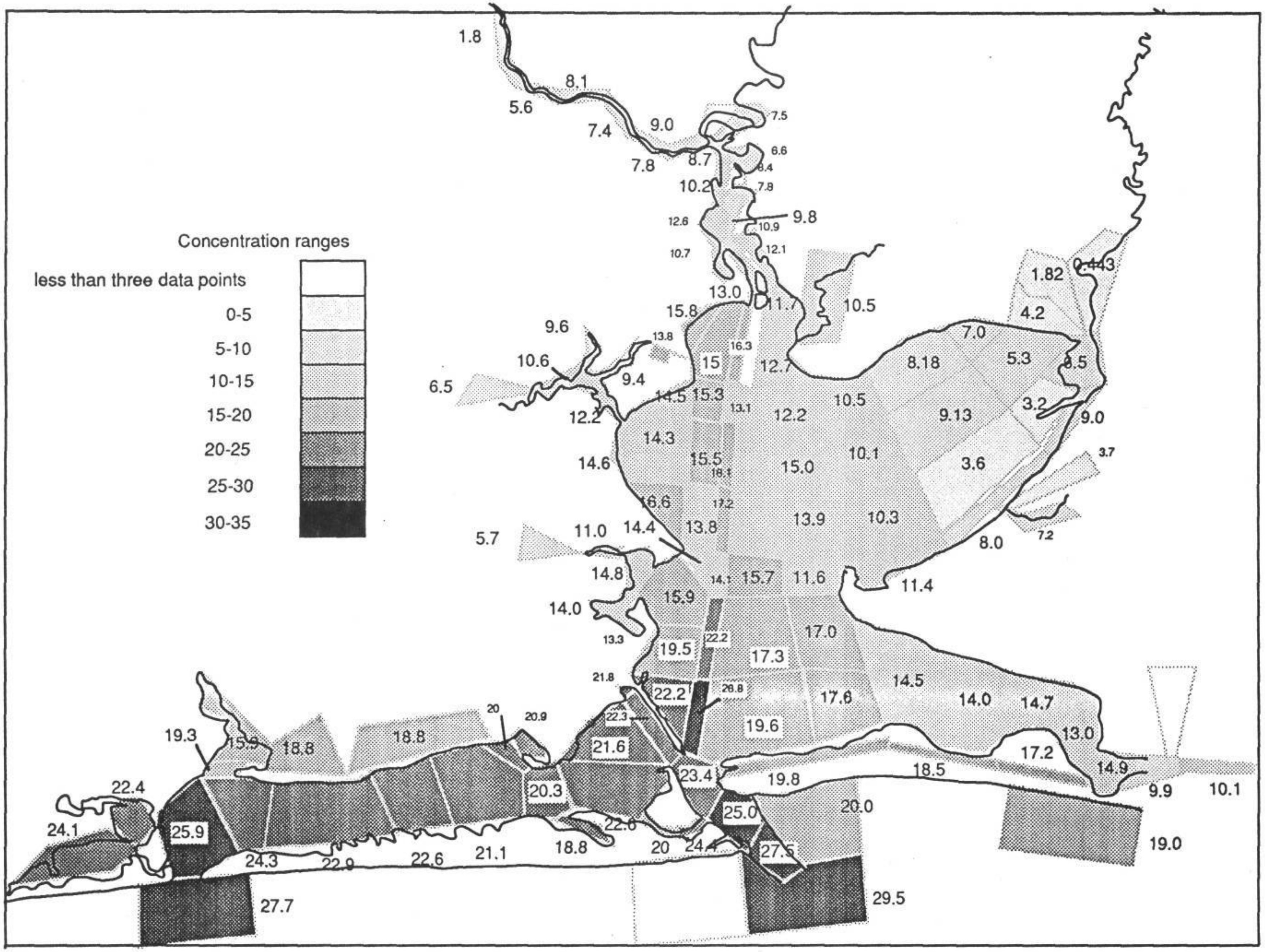


Figure 3-3. Average salinity (WQSAL) in upper 1.5 m of Galveston Bay

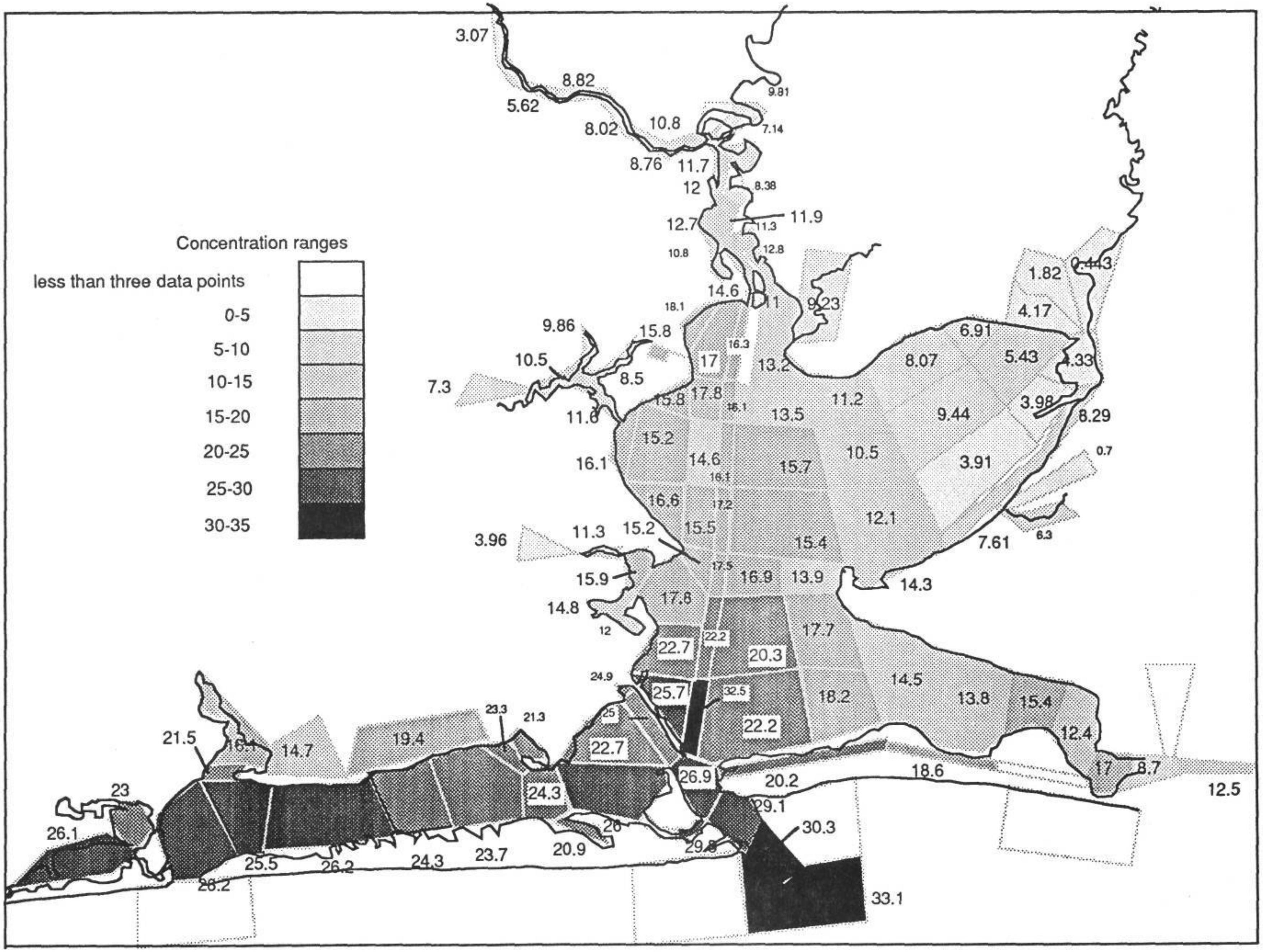


Figure 3-4. Average summer (JAS) salinity (WQSAL) in upper 1.5 m of Galveston Bay

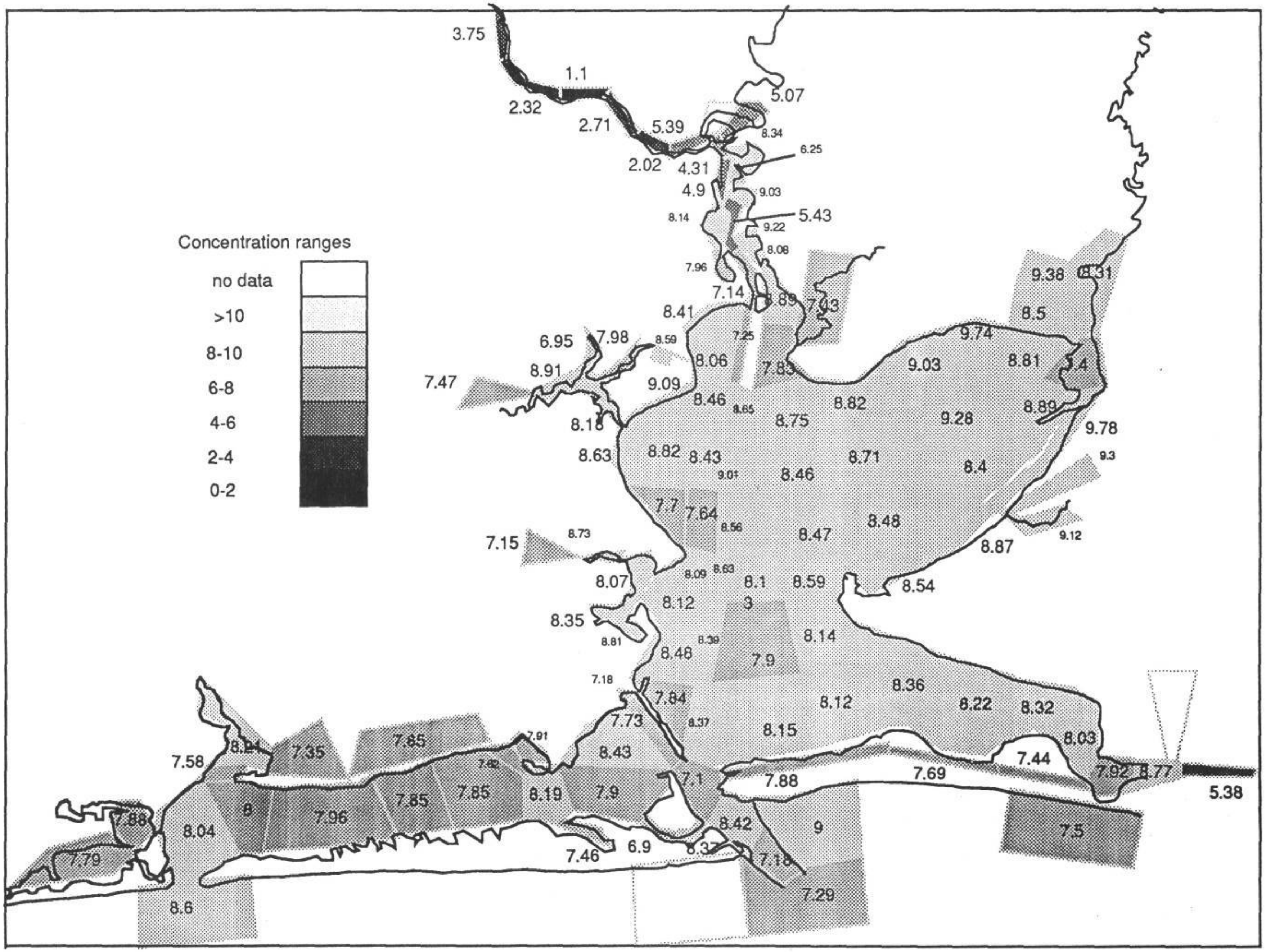


Figure 3-5. Average concentrations of dissolved oxygen (WQDO) in upper 0.5 m in Galveston Bay

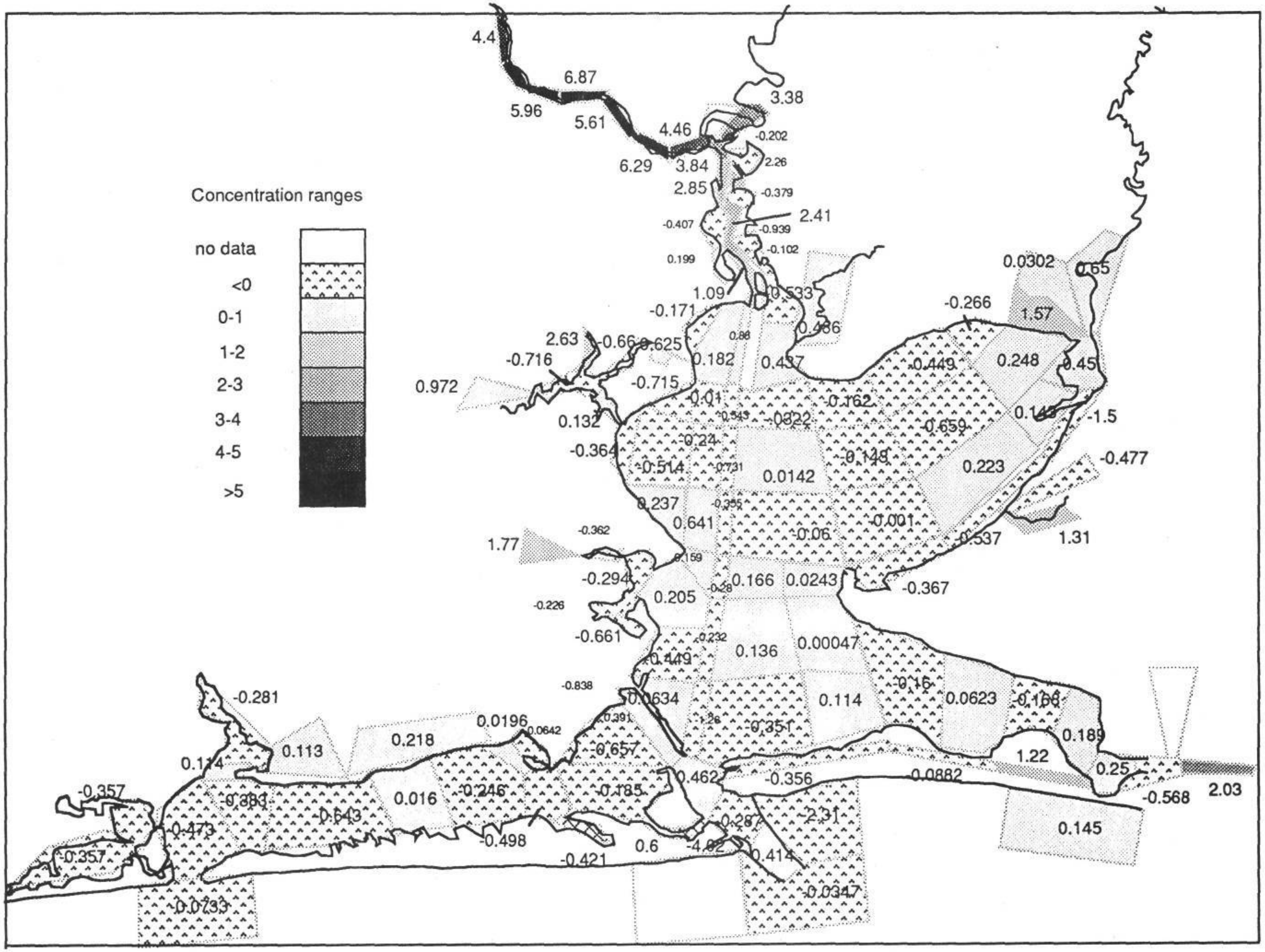


Figure 3-6. Average concentrations of DO deficit (WQDODEF) within upper 0.5 m in Galveston Bay

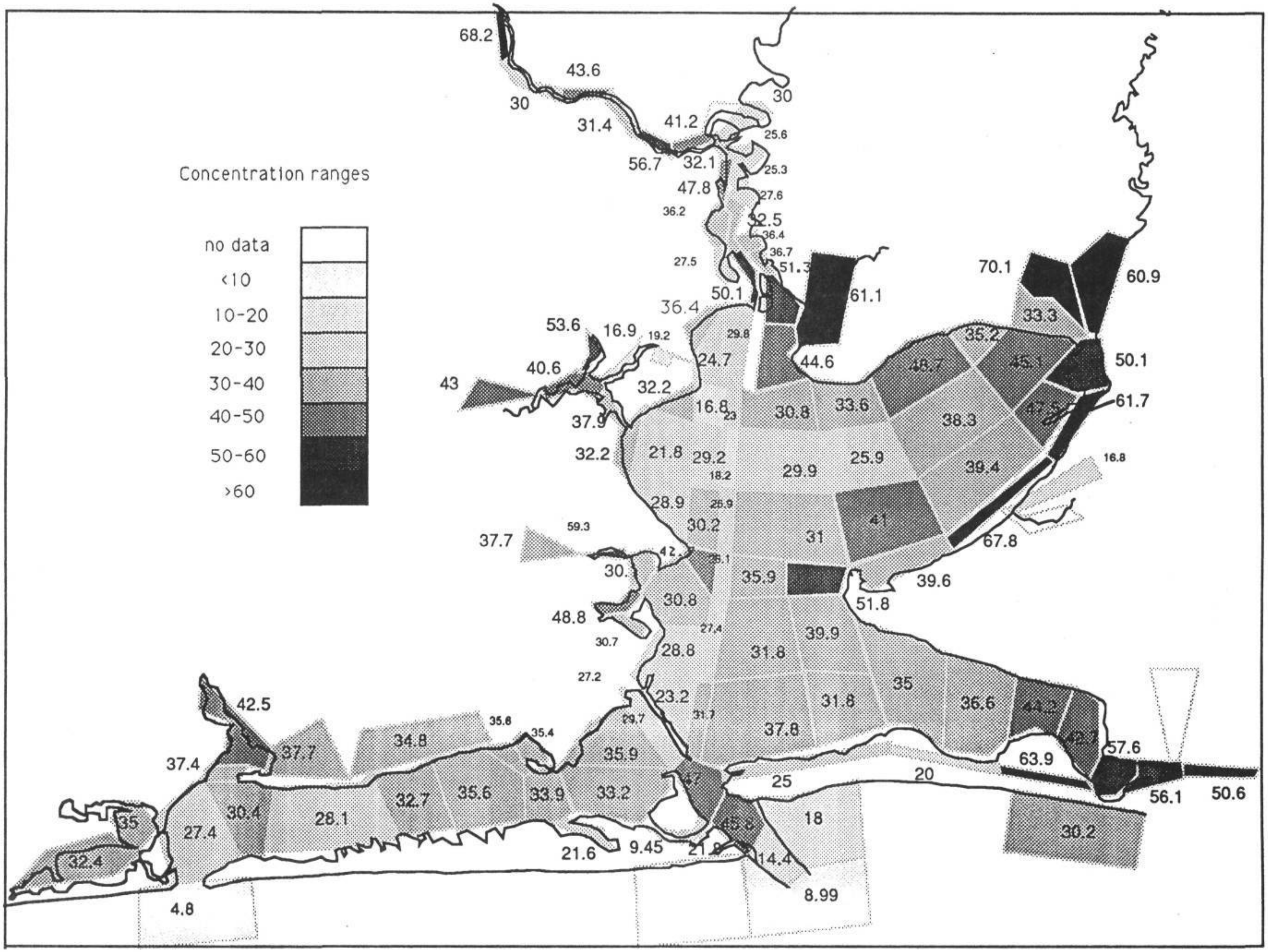


Figure 3-7. Average concentrations of WQXTSS in Galveston Bay

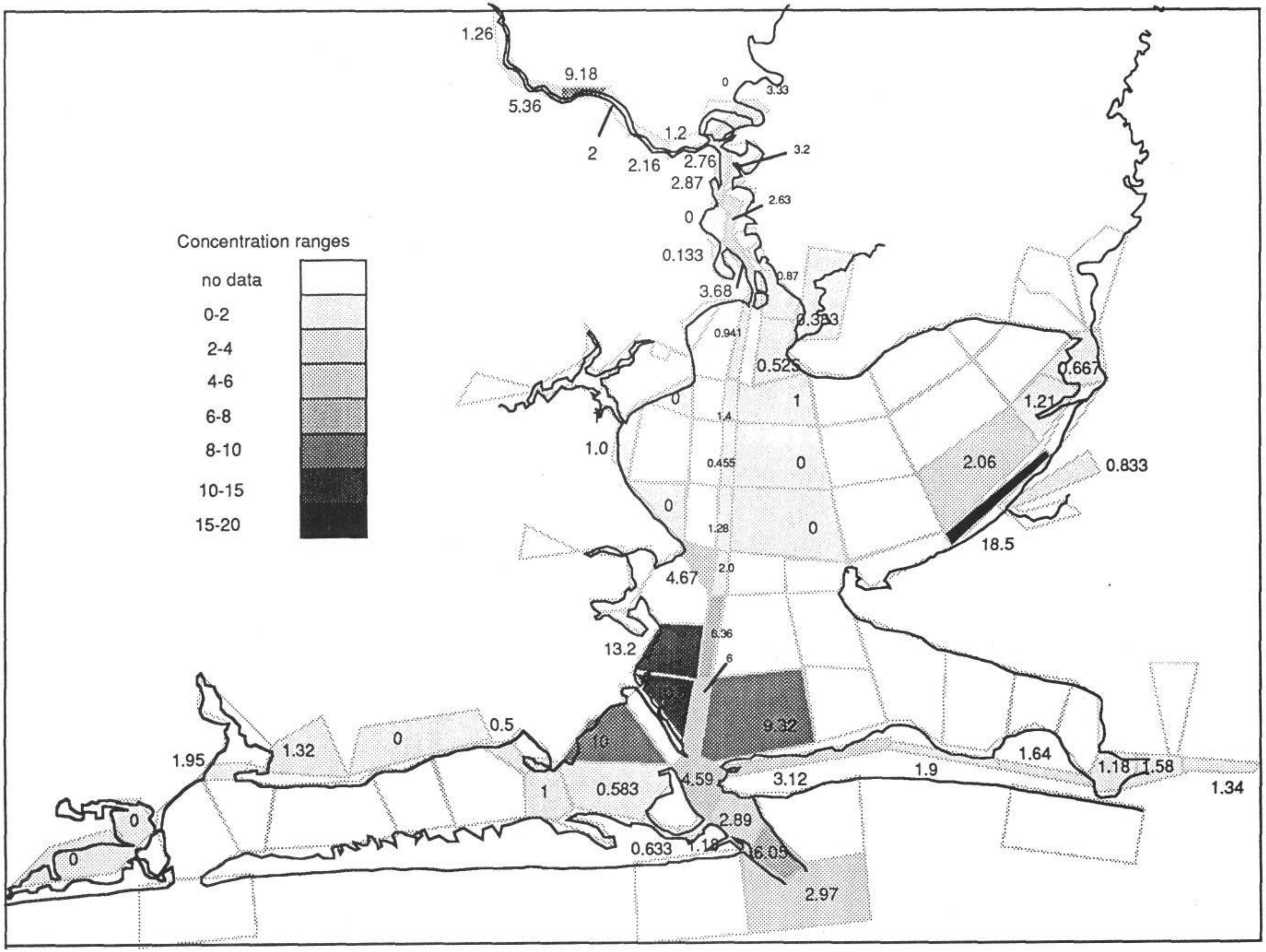


Figure 3-8. Average (with BDL = 0) concentrations of WQO&G in Galveston Bay

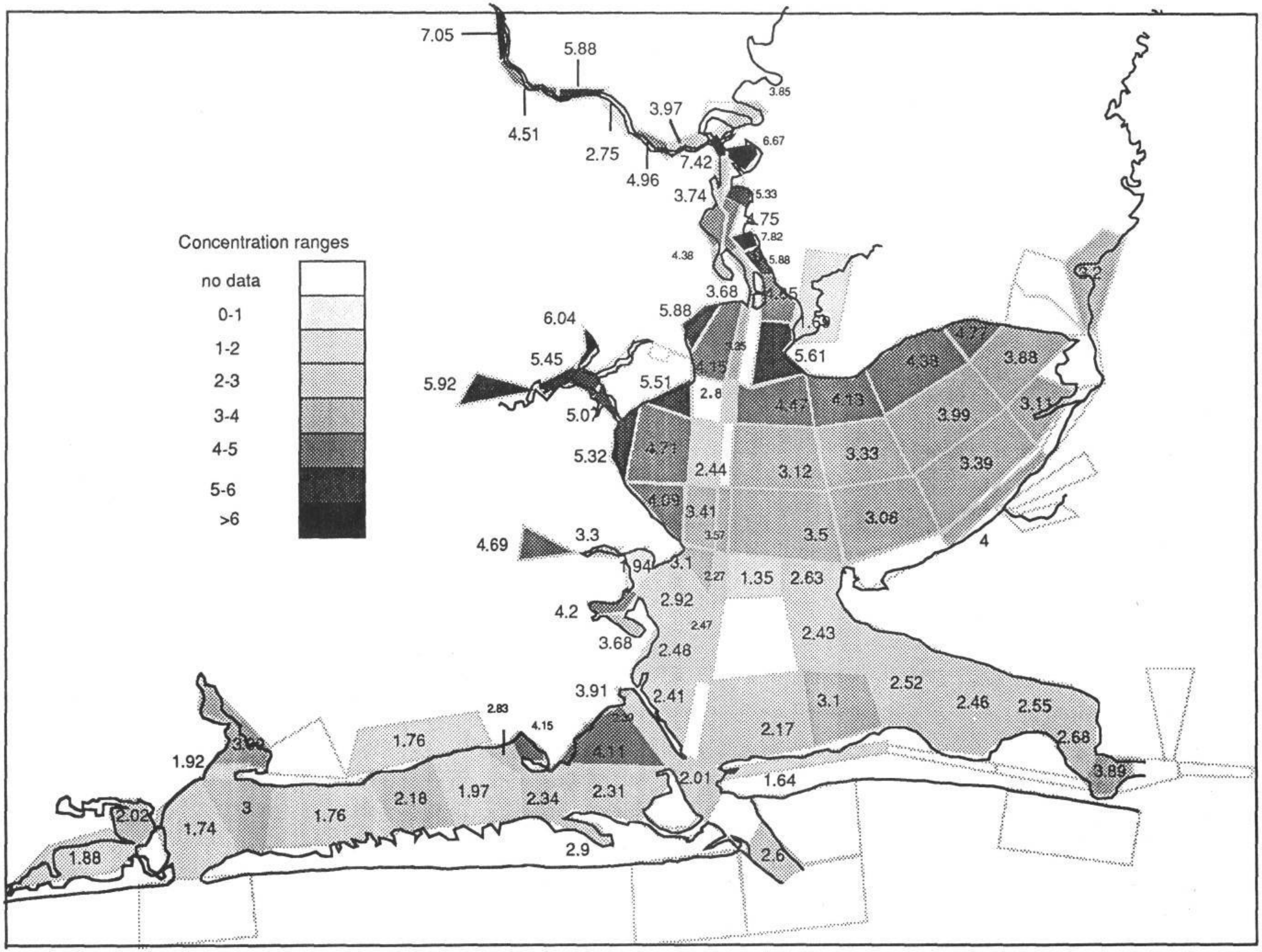


Figure 3-9. Average (with BDL = 0) concentrations of WQXBOD5 in Galveston Bay

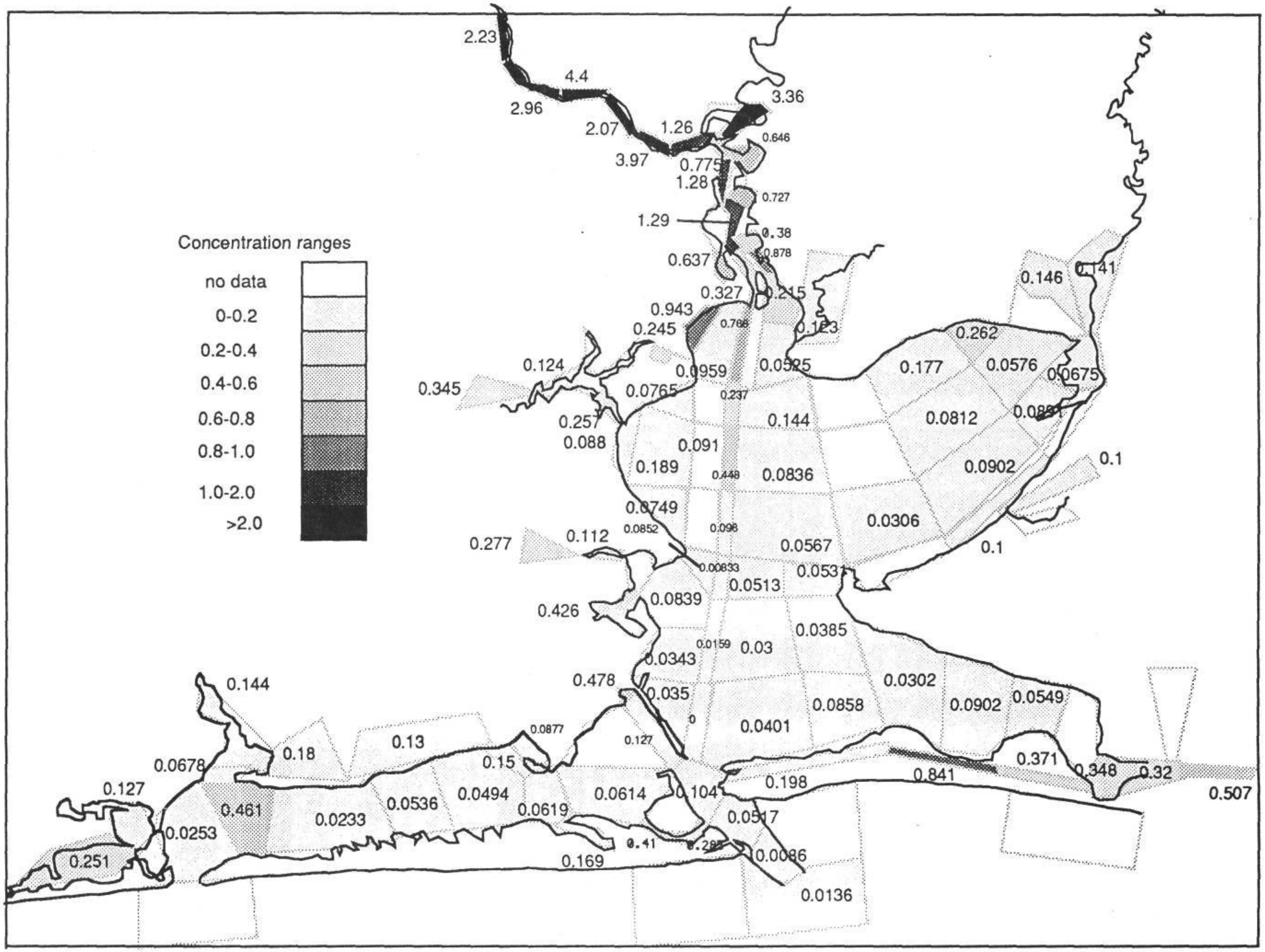


Figure 3-10. Average (with BDL = 0) concentrations of WQAMMN in Galveston Bay

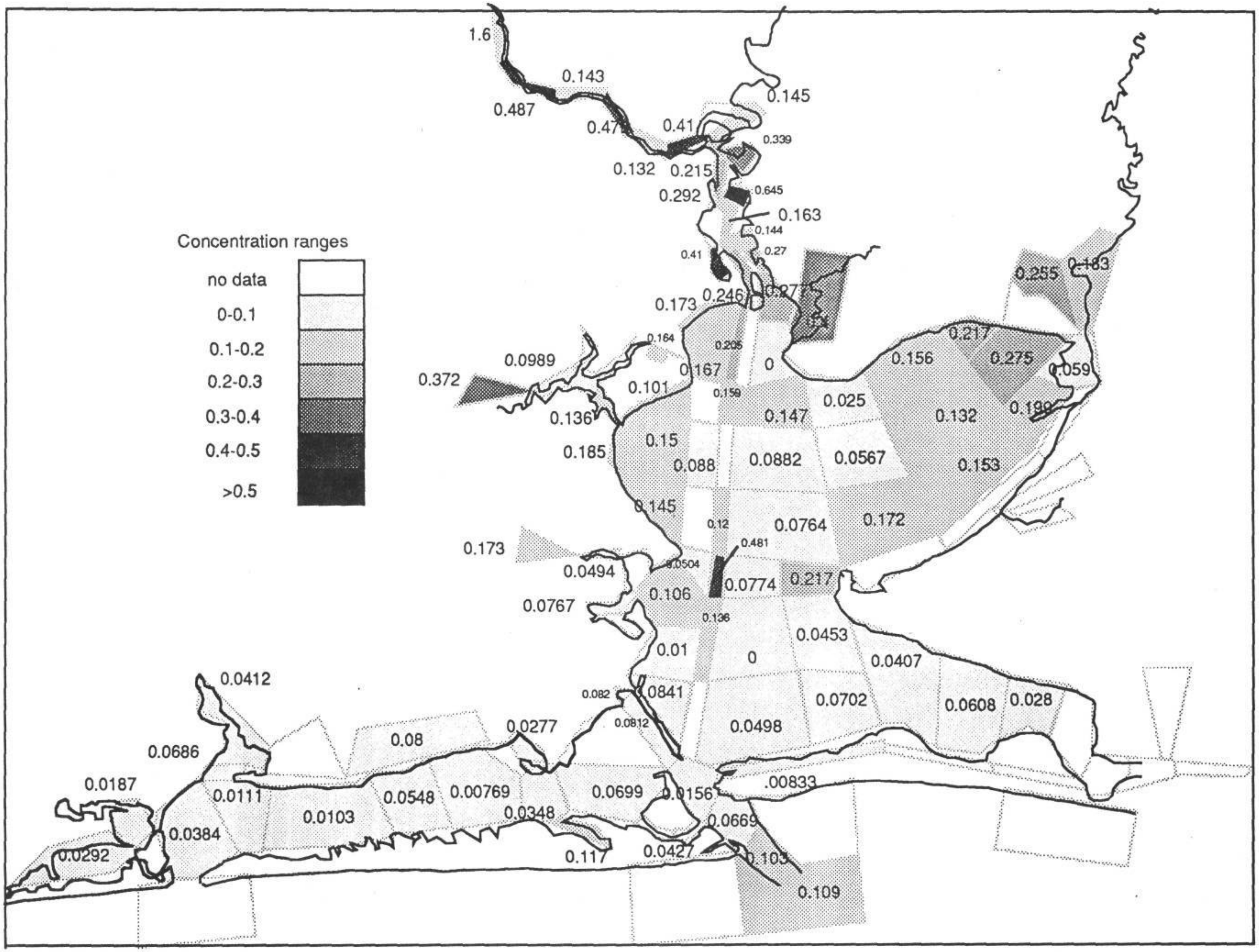


Figure 3-11. Average (with BDL = 0) concentrations of WQNO3N in Galveston Bay

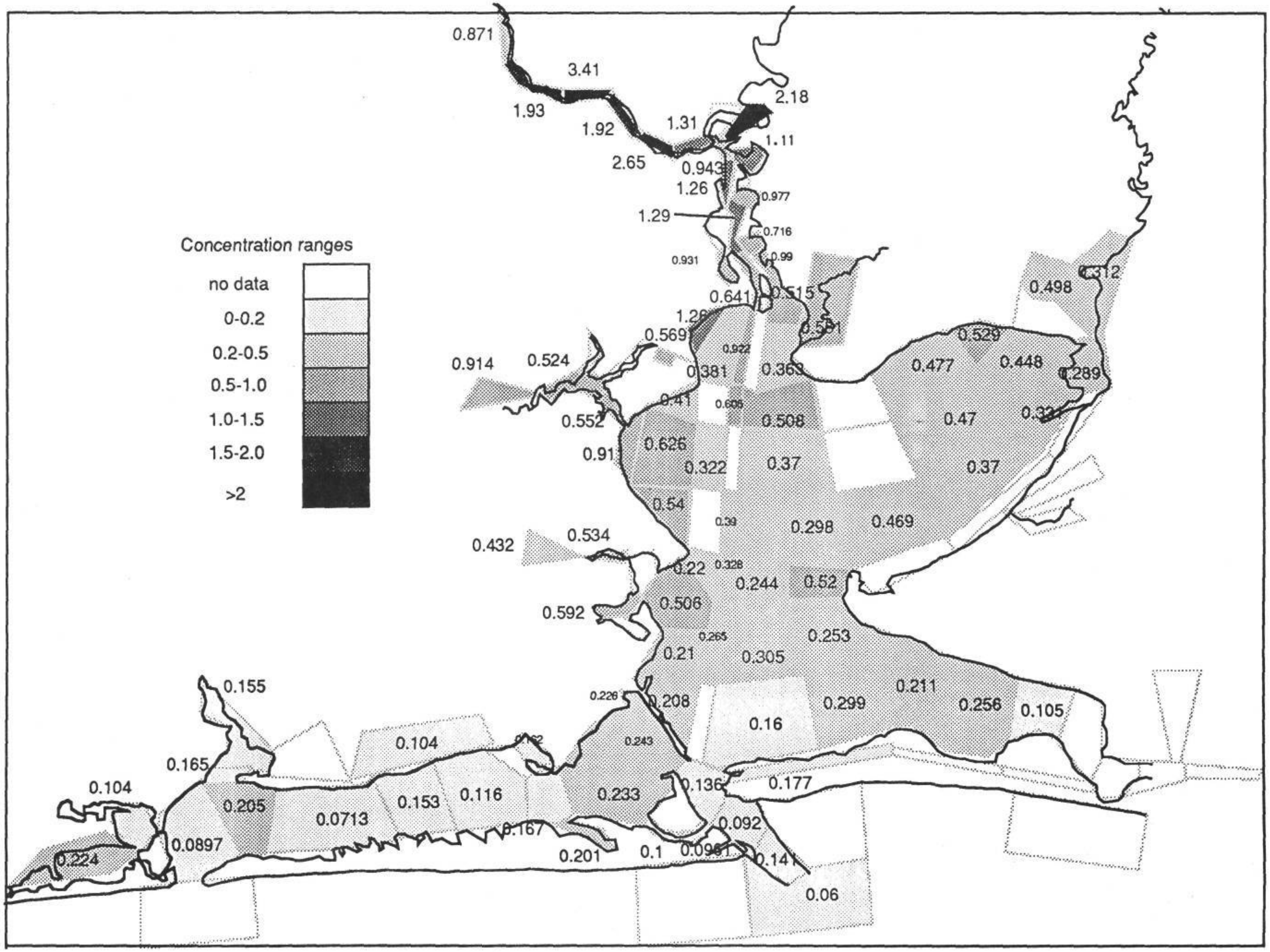


Figure 3-12. Average (with BDL = 0) concentrations of WQTOTP in Galveston Bay

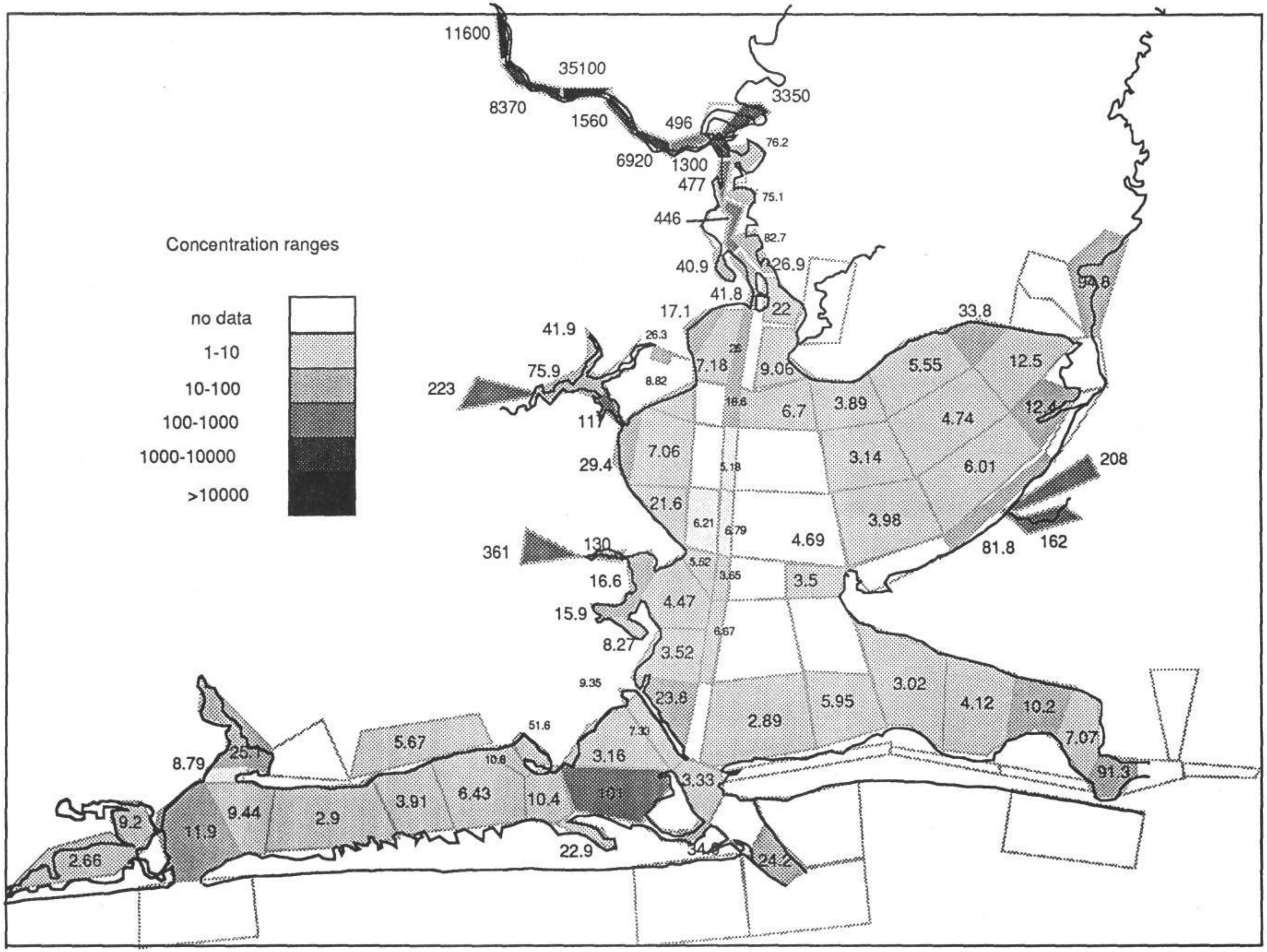


Figure 3-13. Geometric average concentrations of WQFCOLI in Galveston Bay

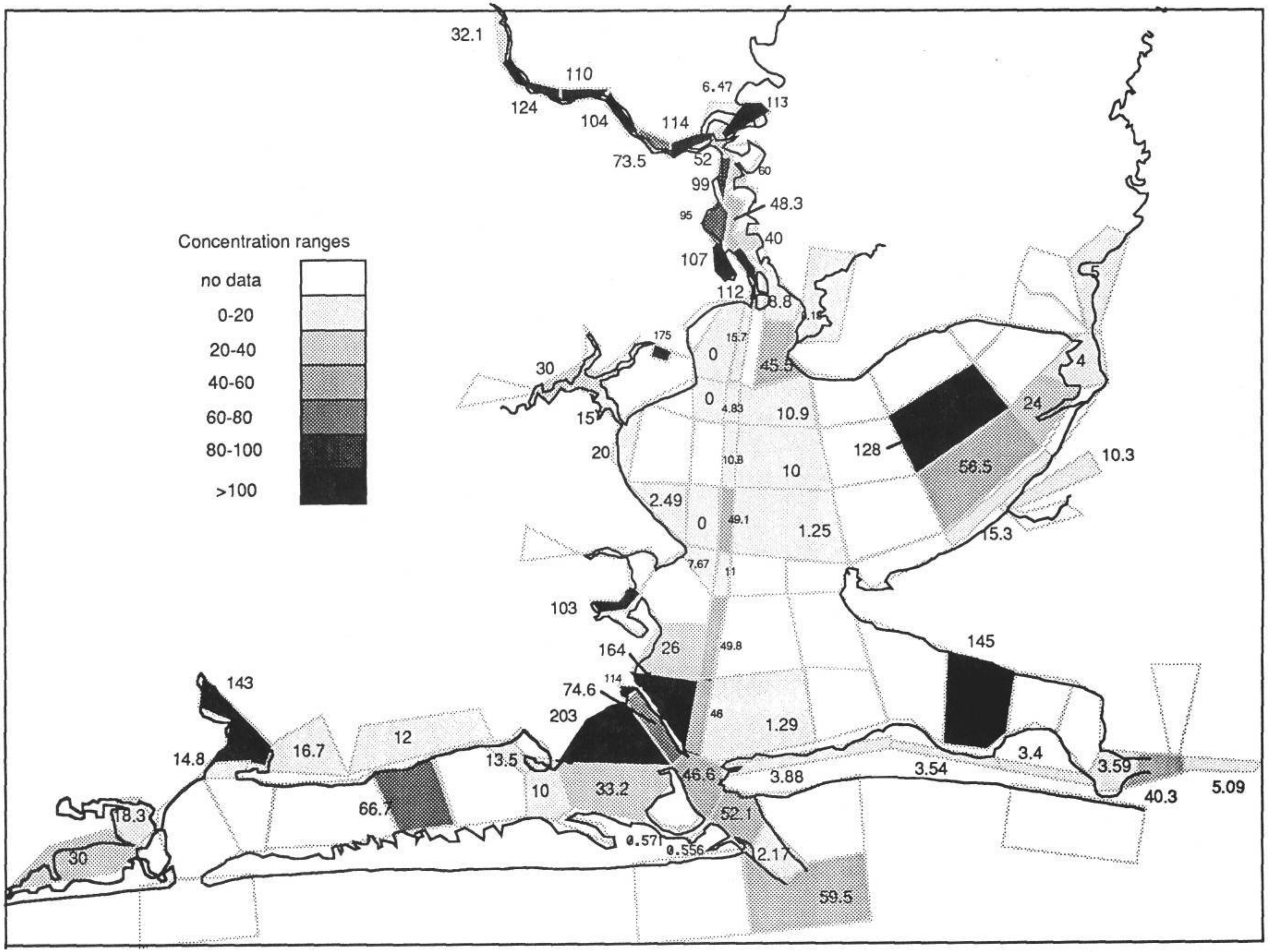


Figure 3-14. Average (with BDL = 0) concentrations of WQMETCUT in Galveston Bay

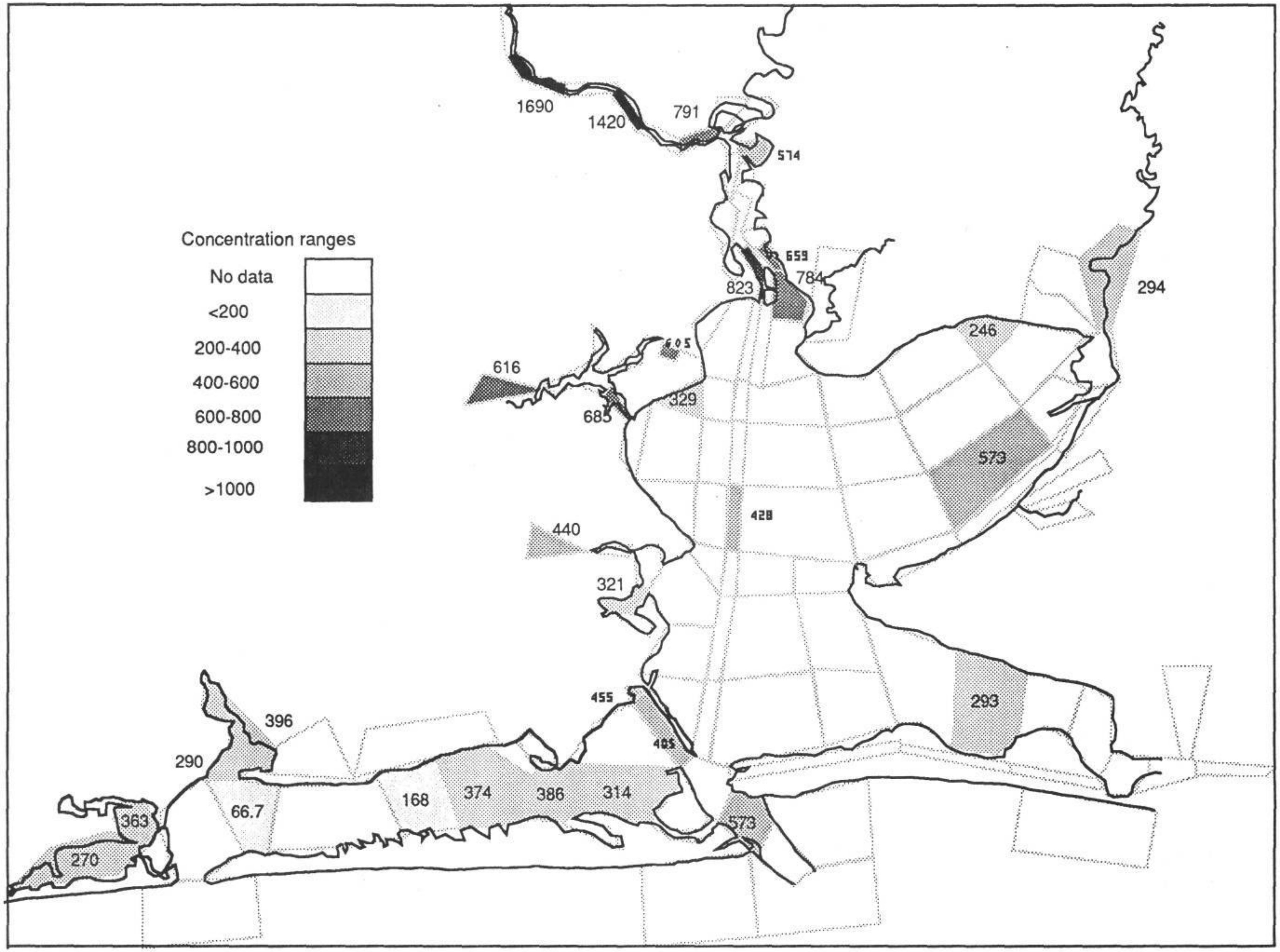


Figure 3-15. Average (with BDL = 0) concentrations of SEDTOTP in Galveston Bay

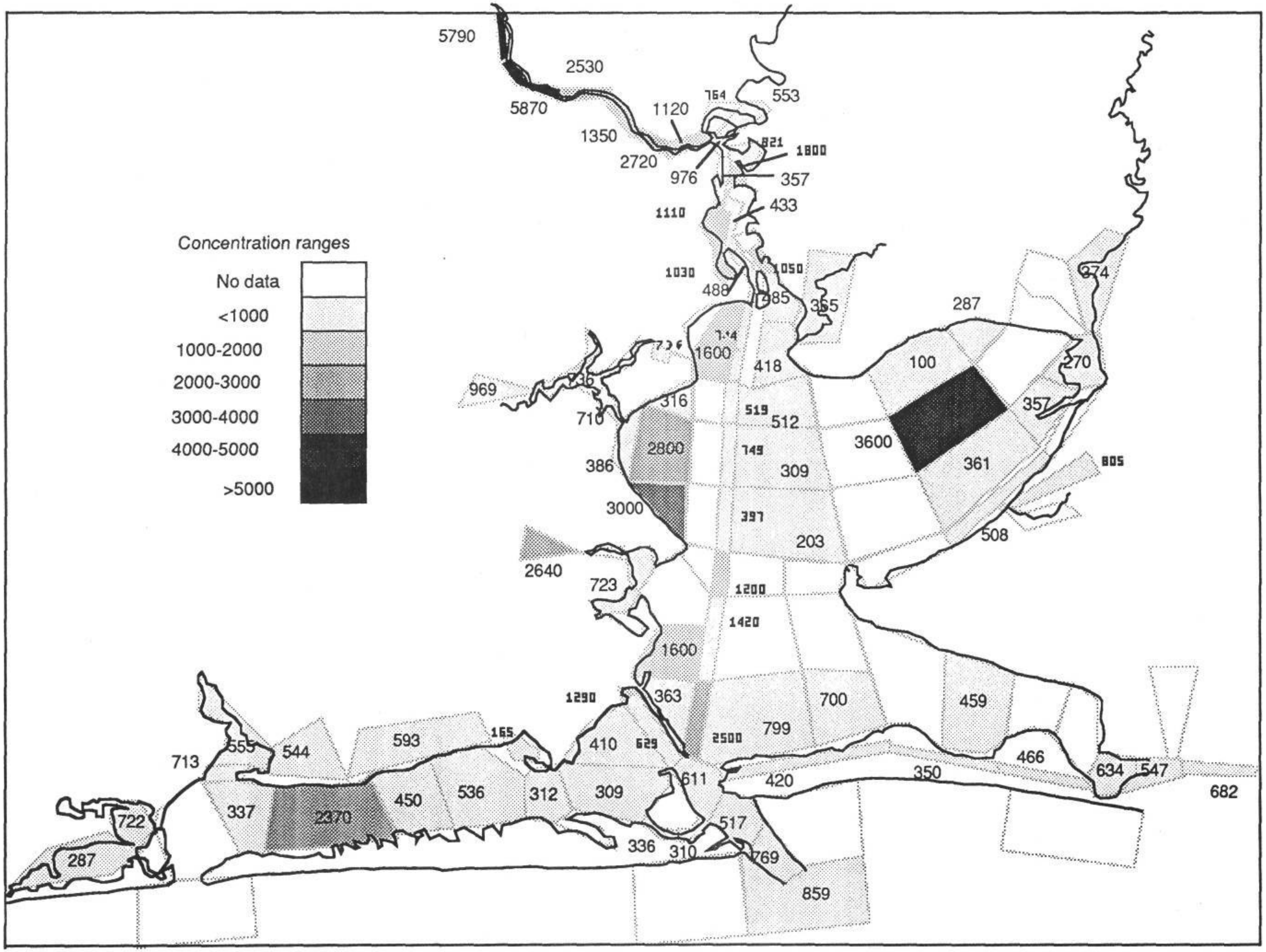


Figure 3-16. Average (with BDL = 0) concentrations of SEDO&G in Galveston Bay

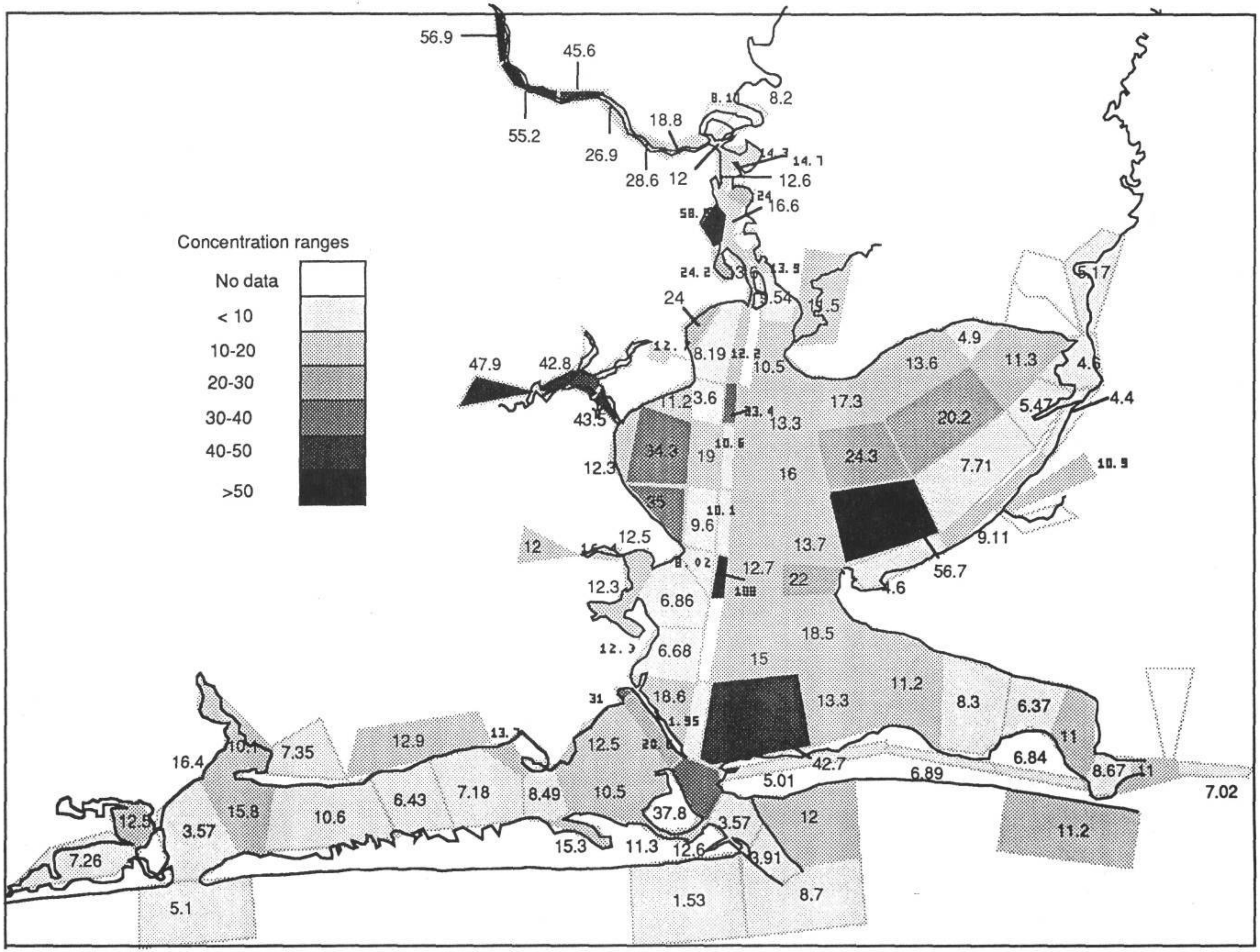


Figure 3-17. Average (with BDL = 0) concentrations of SEDMETCU in Galveston Bay

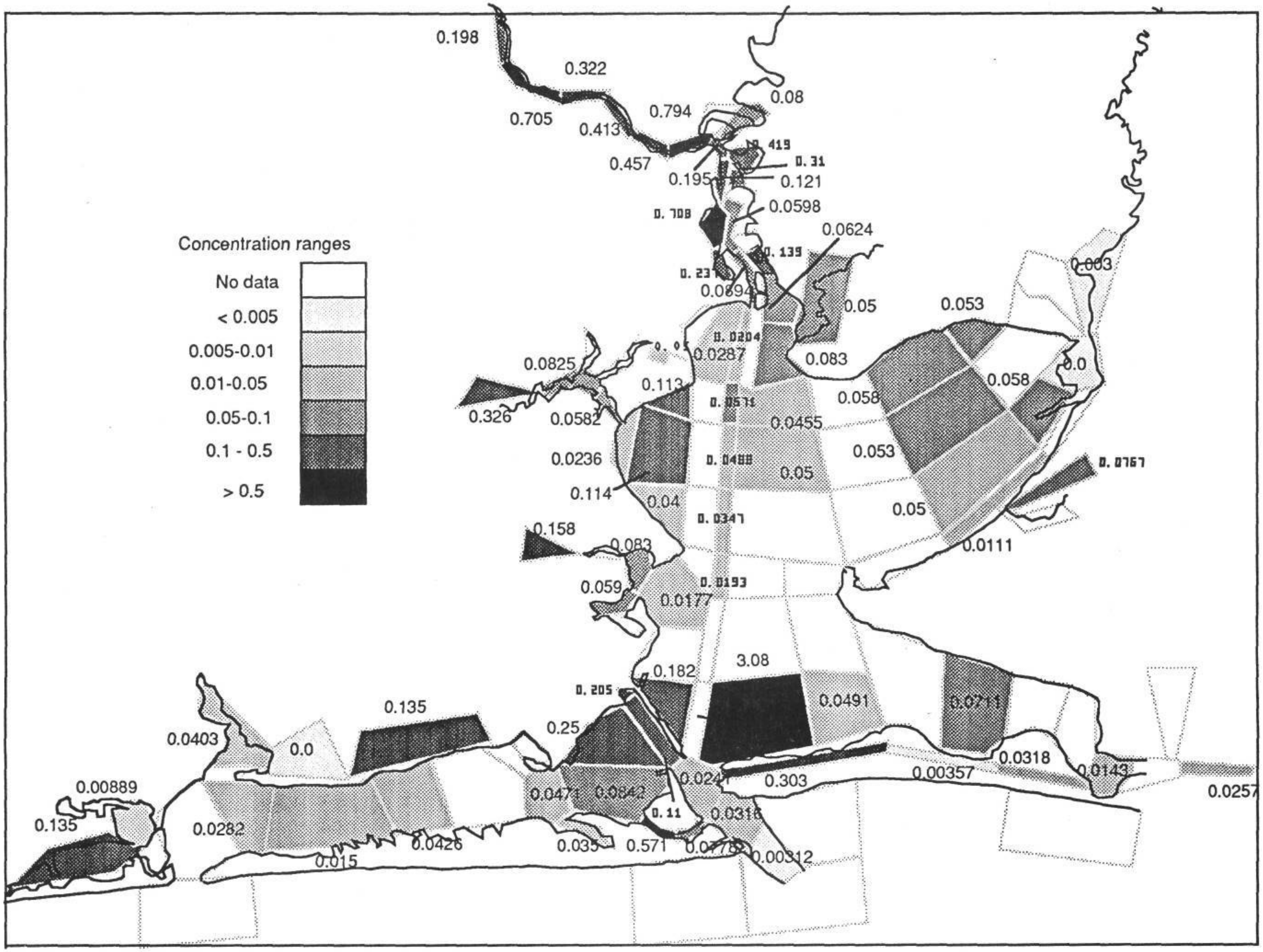


Figure 3-18. Average (with BDL = 0) concentrations of SEDMETHG in Galveston Bay

TABLE 3-3

Water temperature (WQTEMP) stratification (°C m^{-1})
Period of Record Statistics for Hydrographic Segments
with 3 or more observations

Seg-ment	No.of obs	Avg	St dev	percent positive	Seg-ment	No.of obs	Avg	St dev	percent positive
C1	69	0.007	0.330	69.57	G25	125	0.056	0.150	78.4
C2	106	0.350	0.800	84.91	G26	90	0.228	0.360	94.44
C4	27	-0.476	0.810	92.59	G27	43	0.658	2.100	93.02
C5	169	0.704	1.800	92.31	G28	94	0.289	0.430	85.11
C6	74	0.306	0.400	91.89	G29	196	0.140	0.370	88.78
D1	26	0.064	1.100	57.69	G30	120	0.029	0.200	80.83
D2	107	0.285	0.520	84.11	G31	77	0.333	0.570	92.21
D3	36	0.495	1.500	91.67	G32	121	0.097	0.350	86.78
D4	4	0.033	0.400	75	G33	6	0.060	0.085	100
E1	272	0.238	0.500	91.54	G34	133	0.036	0.085	81.2
E2	218	0.293	0.560	91.74	G35	143	0.072	0.140	86.01
E3	179	0.374	1.200	92.74	G36	109	0.054	0.100	78.9
E4	201	0.354	0.750	94.53	H1	280	0.067	0.100	89.29
E5	97	0.126	0.200	86.6	H3	11	0.799	1.100	100
E8	72	0.492	2.100	90.28	H4	16	0.261	0.460	93.75
E9	64	0.094	0.160	85.94	H5	60	0.230	0.350	85
G1	91	0.510	1.100	87.91	H7	107	0.041	0.120	76.64
G3	102	0.144	0.260	88.24	H8	77	-0.039	0.560	75.32
G4	133	0.495	2.300	86.47	H10	68	0.074	0.470	76.47
G5	164	0.323	0.720	91.46	H11	229	0.026	0.076	85.15
G6	95	0.830	2.700	84.21	H12	18	-0.019	0.100	55.56
G7	150	0.160	0.690	86.67	H13	198	0.039	0.071	83.84
G8	58	-0.007	0.500	67.24	H14	99	0.039	0.078	81.82
G9	180	0.063	0.190	83.33	H15	202	0.059	0.069	88.61
G10	102	0.280	0.410	95.1	H16	39	0.094	0.071	94.87
G12	41	0.033	0.077	73.17	H17	508	0.103	0.360	79.13
G13	93	0.130	0.380	86.02	H18	10	0.212	0.590	70
G14	20	-0.019	0.045	55	H19	229	0.041	0.120	71.18
G15	144	0.051	0.170	80.56	H20	226	0.123	0.490	79.65
G16	81	0.018	0.050	70.37	M1	3	-0.066	0.000	0
G18	167	0.025	0.098	64.07	M3	68	0.040	0.120	75
G19	55	0.120	0.390	80	S1	36	0.048	0.210	63.89
G20	121	0.033	0.089	71.07	T1	109	0.224	0.470	81.65
G21	37	0.052	0.091	75.68	T2	115	0.445	1.800	86.96
G22	39	0.017	0.110	82.05	T3	57	-0.085	0.390	59.65
G23	100	0.169	0.490	86	T4	3	0.310	0.170	100
G24	239	0.115	0.400	82.43	T5	203	0.202	0.360	86.7

(continued)

TABLE 3-3

Water temperature stratification (°C m^{-1})
(continued)

Seg-ment	No.of obs	Avg	St dev	percent positive	Seg-ment	No.of obs	Avg	St dev	percent positive
T6	170	0.482	1.300	85.88	W7	15	-0.112	0.270	80
T9	7	0.036	0.049	85.71	W8	64	0.166	0.780	79.69
T10	120	0.266	1.600	87.5	W9	41	0.214	0.700	87.8
T11	275	0.292	0.510	89.09	W10	148	0.089	0.380	89.19
T12	56	0.264	0.510	85.71	W11	31	0.075	0.370	90.32
T13	8	0.203	0.260	87.5	W14	10	0.385	0.670	100
T15	128	0.095	0.850	92.97	W15	73	0.039	0.088	84.93
T18	41	0.743	1.100	95.12	W16	100	-0.090	0.490	66
W4	105	0.129	0.410	88.57	W19	42	0.003	0.078	61.9
W5	31	0.012	0.170	83.87	W21	65	3.300	3.500	90.77
W6	38	0.069	0.340	71.05					

TABLE 3-4

Salinity (WQSAL) stratification (ppt m^{-1})
Period of Record Statistics for Hydrographic Segments
with 3 or more observations

Seg-ment	No.of obs	Avg	St dev	percent positive	Seg-ment	No.of obs	Avg	St dev	percent positive
C1	65	-0.913	2.100	10.8	G24	232	-0.500	0.590	33.6
C2	107	-0.849	1.000	17.8	G25	127	-0.556	0.590	7.1
C4	27	-0.229	0.310	48.2	G26	88	-0.251	0.300	42.1
C5	168	-0.406	2.500	40.5	G27	40	-0.504	0.520	30.
C6	73	-1.090	1.200	15.1	G28	94	-0.370	1.100	36.2
D1	25	-1.510	1.500	16.	G29	196	-0.624	0.850	33.7
D2	102	-1.310	2.700	17.7	G30	119	-0.151	0.450	42.9
D3	36	-1.040	1.100	44.4	G31	76	-0.473	0.810	40.8
D4	53	-0.407	0.670	34.	G32	164	-0.559	0.640	41.5
E1	269	-0.214	0.430	56.9	G33	7	-0.227	0.230	42.9
E2	217	-0.112	1.100	51.6	G34	136	-0.232	0.430	10.3
E3	176	-0.371	0.650	52.3	G35	143	-0.298	0.330	22.4
E4	200	-0.031	1.100	66.	G36	107	-0.225	0.260	22.4
E5	96	-1.030	1.500	7.3	G37	28	-0.341	0.340	7.1
E8	72	-0.295	0.680	43.1	H1	285	-0.446	0.490	5.6
E9	63	-0.158	0.200	30.2	H2	52	-0.447	0.000	0.
G1	92	-0.681	0.840	53.3	H3	11	-0.124	0.120	63.6
G2	57	-0.606	0.650	3.5	H4	16	-0.080	0.082	68.8
G3	98	-0.255	0.310	25.5	H5	58	-0.309	0.320	19.
G4	128	-0.050	0.850	57.8	H7	103	-0.449	0.930	4.9
G5	162	-0.319	0.440	38.9	H8	76	-0.244	0.320	43.4
G6	91	-0.313	0.770	56.	H10	79	-0.317	0.490	39.2
G7	208	-0.191	0.440	59.1	H11	234	-0.396	0.630	11.5
G8	57	-0.507	0.680	36.8	H12	18	-0.470	0.540	5.6
G9	180	-0.401	0.560	25.6	H13	204	-0.368	0.450	4.9
G10	100	-0.299	0.530	25.	H14	101	-0.486	0.510	5.9
G12	40	-0.613	0.640	7.5	H15	208	-0.352	0.410	5.8
G13	92	-0.195	0.290	38.	H16	39	-0.438	0.510	2.6
G14	20	-0.568	0.000	0.	H17	507	-0.439	0.560	7.7
G15	141	-0.466	0.490	4.3	H18	13	-0.484	0.550	7.7
G16	75	-0.593	1.100	2.7	H19	235	-0.506	0.510	5.1
G18	343	-0.595	0.640	7.3	H20	215	-0.705	0.710	31.2
G19	53	-0.414	0.440	3.8	M1	3	-1.320	0.000	0.
G20	123	-0.453	0.510	4.1	M3	69	-0.163	0.250	24.6
G21	38	-0.207	0.210	10.5	S1	36	-0.042	4.000	16.7
G22	38	-0.403	0.460	21.1	T1	109	-0.402	0.480	40.4
G23	102	-0.446	0.600	43.1	T2	116	-0.548	0.640	45.7

(continued)

TABLE 3-4

Salinity stratification (ppt m^{-1})
(continued)

Segment	No. of obs	Avg	St dev	percent positive	Segment	No. of obs	Avg	St dev	percent positive
T3	54	-1.690	1.700	24.1	W5	31	-0.480	0.520	54.8
T4	3	-0.248	0.250	33.3	W6	39	-0.761	0.850	28.2
T5	201	-0.382	0.440	34.8	W7	79	-1.110	3.200	10.1
T6	167	-0.634	3.900	37.7	W8	65	-1.040	1.100	16.9
T9	6	-0.250	0.250	66.7	W9	39	-0.311	0.400	53.9
T10	115	-0.199	2.100	47.8	W10	140	-0.188	0.940	62.1
T11	286	-0.605	0.770	36.7	W11	24	0.414	1.200	66.7
T12	56	-1.310	1.300	42.9	W14	9	-0.193	0.330	55.6
T13	8	0.189	6.200	25.	W15	71	-0.106	0.140	47.9
T15	124	-0.247	0.490	49.2	W16	159	-0.498	1.200	28.3
T18	42	-2.890	2.900	23.8	W18	97	-0.315	0.500	11.3
W1	12	-0.657	1.100	50.	W19	76	-0.426	1.100	11.8
W2	25	-0.531	0.560	44.	W21	66	-1.090	2.000	21.2
W4	98	-0.594	0.890	52.					

TABLE 3-5

WQDODEF stratification (ppm m^{-1})
Period of Record Statistics for Hydrographic Segments with >2 observations

Seg-ment	No.of obs	Avg	St dev	percent positive	Seg-ment	No.of obs	Avg	St dev	percent positive
C1	64	-0.595	2.1	18.8	H4	16	-1.00	1.7	18.8
C2	93	-0.898	1.3	15.1	H5	58	-0.488	0.54	12.1
C5	82	-0.878	1.8	14.6	H7	92	-0.0583	0.26	37.
C6	15	-0.111	0.24	26.7	H8	64	-0.687	1.3	17.2
D1	21	-1.43	2.3	19.1	H10	54	-1.18	1.8	11.1
D2	7	-0.882	1.1	14.3	H11	214	-0.0626	0.17	26.6
D4	4	-1.08	0.96	0.	H12	16	-0.179	0.26	18.8
E1	82	-0.224	0.51	25.6	H13	190	-0.0281	0.16	52.1
E2	82	-0.405	1.1	31.7	H14	96	0.0548	0.25	53.1
E3	41	-0.246	0.53	31.7	H15	196	-0.0132	0.13	41.3
G1	26	-0.591	2	46.2	H16	38	0.022	0.11	50.
G3	95	-0.497	0.62	6.3	H17	475	-0.122	0.34	29.3
G4	37	-0.288	0.52	24.3	H18	12	-0.207	0.28	16.7
G5	62	-0.632	0.85	14.5	H19	219	-0.136	0.17	23.3
G6	53	-0.0317	1.1	45.3	H20	205	-0.454	0.77	15.6
G7	28	-0.05	0.56	39.3	M1	3	-0.452	0.4	0.
G8	21	-0.101	0.12	14.3	M3	4	-0.174	0.21	0.
G9	81	-0.0125	0.24	24.7	S1	35	-0.285	0.83	14.3
G10	36	-0.305	0.37	11.1	T2	80	-0.522	1	21.3
G12	37	-0.158	0.13	2.7	T3	54	-0.348	0.82	35.2
G14	18	-0.101	0.1	5.6	T4	3	-0.804	0.067	0.
G15	100	-0.0837	0.17	27.	T5	106	-0.629	1.2	14.2
G16	76	-0.205	0.17	9.2	T6	77	-0.68	1.6	24.7
G18	123	-0.168	0.16	4.9	T9	6	-0.103	0.13	16.7
G19	15	-0.0993	0.21	20.	T10	11	-0.671	0.62	0.
G20	27	-0.0339	0.056	29.6	T11	136	-0.622	1	14.
G22	36	-0.358	0.56	25.	T12	58	-0.457	0.72	19.
G23	14	-0.488	0.52	0.	T13	8	-0.224	1.4	12.5
G24	133	-0.547	0.91	15.	W4	100	-0.138	0.57	44.
G25	32	-0.332	0.47	15.6	W5	30	-0.239	0.51	23.3
G26	49	-0.432	0.5	8.2	W6	38	-0.198	0.38	15.8
G27	40	-0.38	0.43	15.	W7	14	-0.247	0.35	14.3
G29	67	-0.176	0.3	16.4	W8	61	-0.475	0.51	14.8
G30	26	-0.14	0.4	46.2	W9	39	-0.229	0.53	30.8
G31	38	-0.359	0.49	10.5	W10	136	-0.13	0.35	27.2
G32	26	-0.0946	0.88	38.5	W11	27	-0.0692	0.17	29.6
G33	3	-0.208	0.047	0.	W14	9	-0.269	0.58	33.3
G34	6	-0.0311	0.17	50.	W15	63	-0.163	0.32	23.8
G35	29	-0.126	0.2	6.9	W16	91	0.0244	0.72	41.8
G36	38	-0.0317	0.06	29.	W19	42	-0.192	0.21	19.1
H1	210	-0.116	0.16	21.	W21	28	-0.528	0.55	7.1
H3	10	-1.93	2.4	0.					

TABLE 3-6

WQXTSS stratification (ppm m^{-1})
Period of Record Statistics for Hydrographic Segments

Seg-ment	No.of obs	Avg	St dev	percent positive	Seg-ment	No.of obs	Avg	St dev	percent positive
with 3 or more observations									
C1	3	-27.5	28	0.	H15	131	-0.676	3.7	26.
E1	4	-23.2	7.7	0.	H17	157	-1.02	5.1	39.5
G8	6	-2.75	3.3	16.7	H19	138	0.143	5.1	57.3
G9	3	-3.09	3.3	33.3	H20	16	-2.93	5.7	25.
G14	4	-22.4	32	0.	T5	3	-11.4	8.6	0.
G24	3	-11.4	12	0.	T6	6	-9.72	4.1	0.
G26	6	-25.6	18	0.	T11	7	-5.28	11	14.3
G29	4	-35.3	57	25.	T12	12	-10.8	11	16.7
G33	3	-2.2	3.5	33.3	T13	5	-13.5	14	20.
G34	5	1.07	1.2	80.	W4	4	-12.3	28	25.
G35	6	1.62	4.7	50.	W7	4	-17.9	19	25.
H1	141	-4.2	7	12.1	W9	4	-7.27	16	25.
H7	3	-0.828	1.2	33.3	W10	3	12.2	9	100.
H11	111	-4.66	8.7	15.3	W11	3	-15.7	4.9	0.
H13	133	-3.75	15	12.	W16	3	-0.617	6.8	66.7
H14	14	-3.86	7.7	7.1	W18	4	-4.76	4.9	0.
with less than 3 observations									
C2	2	-11.6	12	0.	G23	1	11.2	0	100.
C5	2	-2.24	1.2	0.	G25	2	-6.32	0.65	0.
D4	1	-0.926	0	0.	G28	2	-4.43	0.95	0.
E2	2	-3.25	4.3	50.	G31	1	-69.9	0	0.
E3	2	-48.5	19	0.	G36	1	-0.777	0	0.
E4	1	0	0	0.	G37	1	-2.53	0	0.
G3	1	2.45	0	100.	H16	1	0.084	0	100.
G4	1	-10.5	0	0.	M3	1	-1.17	0	0.
G5	2	-5.79	11	50.	M4	1	0.178	0	100.
G7	2	-2.95	5	50.	T2	2	-18.9	1.8	0.
G12	1	-32.4	0	0.	T4	1	-15	0	0.
G13	1	-3.24	0	0.	W2	1	63.9	0	100.
G15	2	-5.25	0.26	0.	W5	2	-6.25	3.1	0.
G16	2	-1.99	0.78	0.	W15	1	-0.593	0	0.
G18	1	0.378	0	100.	W17	2	-20.3	2.4	0.
G19	1	-10	0	0.	W19	1	0.546	0	100.

TABLE 3-7

WQAMMN stratification (ppm m^{-1})
Period of Record Statistics for Hydrographic Segments
with 3 or more observations

Seg-ment	No.of obs	Avg	St dev	percent positive	Seg-ment	No.of obs	Avg	St dev	percent positive
E1	14	-0.0273	0.085	0	H1	130	0.0141	0.053	55
E2	26	-0.0064	0.032	0	H7	46	0.0562	0.16	76
E3	13	0.00401	0.014	46	H11	135	0.051	0.13	69
G1	25	-0.222	0.88	20	H13	123	0.0345	0.099	71
G4	24	0.0616	0.17	17	H14	68	0.149	0.26	78
G5	29	0.0865	0.38	21	H15	129	0.0498	0.1	77
G6	26	0.0103	0.12	8	H16	31	0.166	0.15	90
G7	26	-0.0192	0.075	0	H17	164	0.0907	0.25	76
G9	41	0.00391	0.028	5	H19	162	0.0768	0.34	61
G12	16	0.00212	0.0085	38	H20	16	-0.086	0.15	13
G14	14	0.00074	0.0061	36	M3	3	0.00061	0.0009	33
G15	43	0.0732	0.067	77	S1	27	-0.0958	0.23	30
G16	28	0.0267	0.043	61	T2	34	0.0778	0.33	15
G18	27	0.0143	0.035	30	T3	8	-0.0959	0.1	0
G19	13	0	0	0	T5	33	-0.0328	0.17	3
G20	26	-0.0018	0.0073	0	T6	33	0.0187	0.085	9
G24	45	-0.0363	0.11	9	T10	11	-0.0413	0.16	9
G25	18	-0.0042	0.013	33	T11	37	-0.0191	0.085	8
G26	19	-0.0022	0.035	37	T12	24	0.00676	0.057	33
G29	14	-0.0051	0.0098	14	W4	40	-0.0008	0.0064	8
G30	25	0.077	0.39	8	W6	27	-0.015	0.097	4
G31	14	-0.0011	0.019	14	W7	12	-0.0085	0.0043	0
G32	25	0.0935	0.43	8	W10	26	0.00642	0.032	4
G33	3	-0.0036	0.0027	0	W11	15	-0.0018	0.0074	13
G34	4	0.00012	0.004	50	W16	87	0.0115	0.077	11
G35	3	0.00254	0.011	33	W19	38	-0.0043	0.034	13
G36	39	-0.0002	0.002	5					

3.2 Time Trends in Water and Sediment Quality

The second table of each pair of statistical analyses, e.g. Table 3-2, presents the Time Trend Analysis. This was approached by a linear regression of the (non-BDL) measurements versus time. The period of record, the period used for the time-trend analysis (which may differ from the former because BDL values are part of the measurement record but are excluded from the trend analysis), and the average observations per year entering the analysis all provide an indication of the validity of the trend analysis. Clearly, the shorter the period of time over which usable data are available, and the smaller the number of observations per year, the more limited the statistical validity of the trend analysis. From the water-quality analysis viewpoint, the most important regression parameter is the slope. This is the average (in the least-squares sense) rate of increase (if positive) or decrease (if negative) in the magnitude of the water quality variate, in units of the variate per year. It is the key indicator of a systematic change in that water-quality variate. The intercept is the average value (least-squares sense) of the trend at the beginning of the period of analysis. Finally, the standard error of the estimate (SEE) in units of the variate and the residual variance (per cent) provide a measure of scatter about the trend line. The larger these two indicators, the greater the scatter about the trend line. This communicates both the extent of observed variability that may be systematic in time, and the uncertainty of the computed trend.

Because of the central importance of the slope of the trend line, two additional parameters are provided in the Time Trend tables to qualify its computation, *viz.* the upper and lower 95% confidence bounds of the slope of the regression line In interpreting this analysis one must bear in mind that this assumes a 1/20 failure rate (i.e., slope judged as significant when it is not). Further, this calculation is subject to the assumption that the available data are an adequate sampling of the population. The confidence bounds measure some of this, in that the accuracy of the slope estimate degenerates, i.e., the confidence bounds become wider, as the scatter about the regression (SEE) increases, the number of data points decreases, and the spread in time decreases. But a handful of data points spuriously clustered at both ends of the period of record can yield a high confidence in the slope, which one would dismiss as fictitious based upon his external knowledge about the normal variability of the water quality variate. In this respect, the behavior of the parameter in neighboring areas of the bay, and direct inspection of the data, should be used in determining whether to accept the statistical calculation of trend. A very small value of SEE can be just as indicative of a spurious correlation, as a high value is of no relationship. We note also that this analysis does not distinguish between a statistically unresolvable trend and a trend of zero.

The most important indication is when both confidence bounds have the same sign, indicating that the real trend has that sign (with a 95% probability). In many instances, the confidence bounds have different signs, but one bound is of much greater absolute magnitude than the other, i.e. the confidence band is highly asymmetric about 0. A lower probability value would produce confidence bounds of the same sign. Therefore, as a supplement, confidence bounds corresponding to 80% probability were also computed.

Spatial structure in water quality trends in Galveston Bay is important, because the regional coherence of trends is a strong indicator of whether the trends are real or are some statistical artifact (including the 1/20 random error). In Figs. 3-19 *et seq.*, the distribution of positive and negative trends for key parameters is depicted graphically, by zones of "probable" trends, in which the 95% confidence bounds have the same sign, and "possible" trends, in which the 80% confidence bounds (i.e., a 1/5 failure rate) have the same sign. For a few, especially significant trends, the data and time regression line are plotted for selected hydrographic segments, e.g. Fig 3-20.

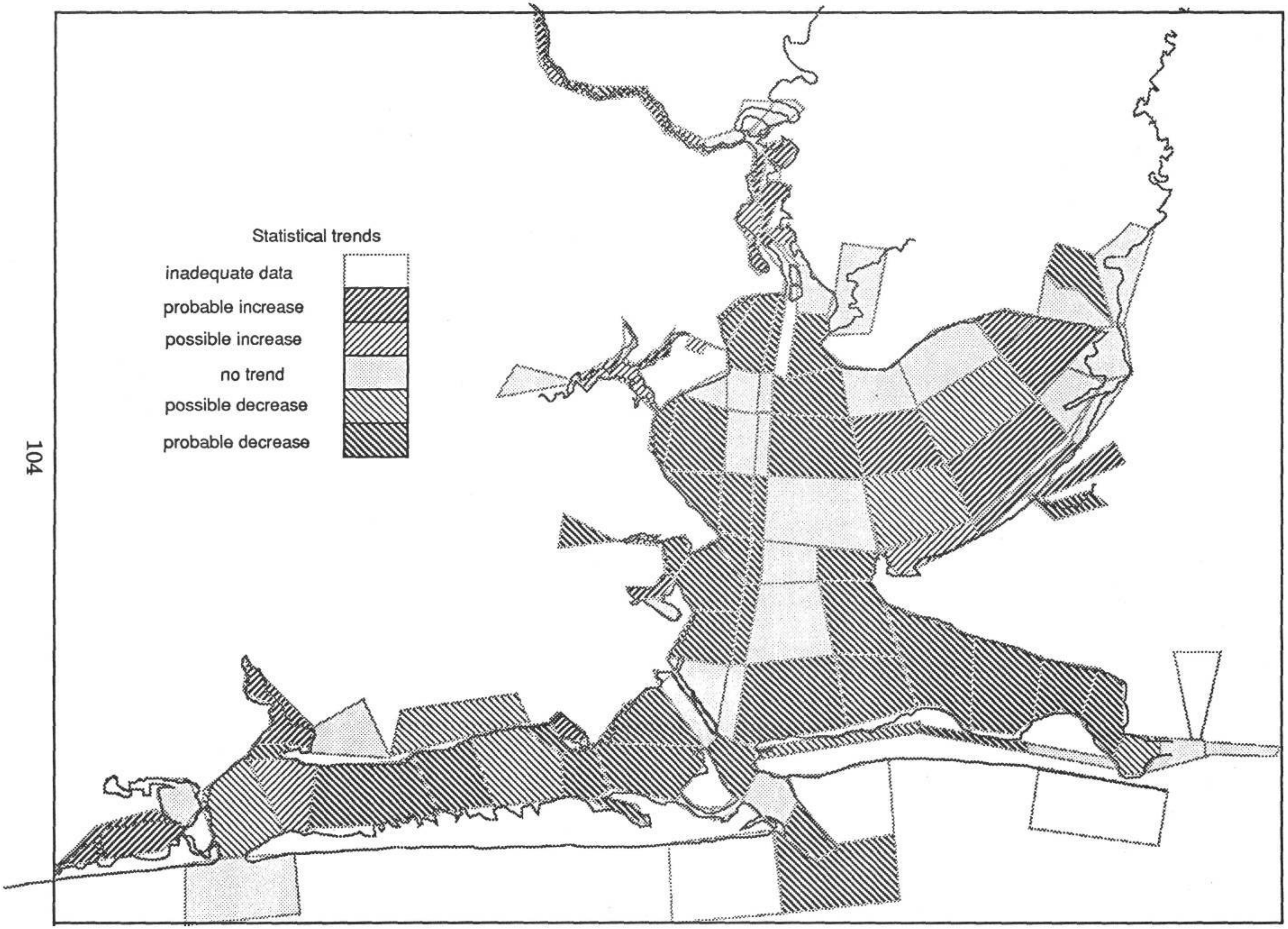


Fig. 3-19. Statistical trends of salinity (WQSAL) within upper 1.5 m in Galveston Bay

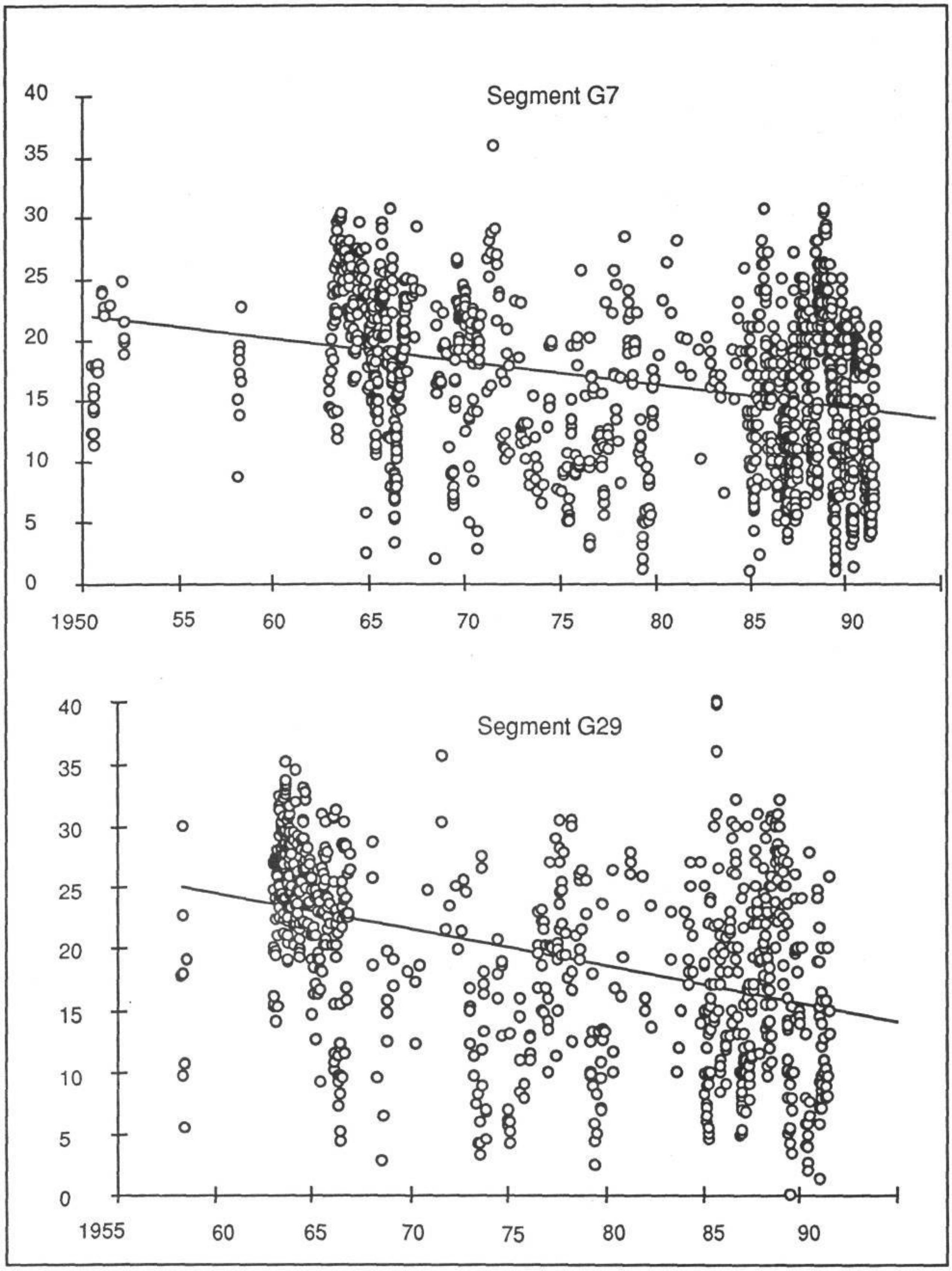


Figure 3-20. Salinity within upper 1.5 m trends at Segments G7 and G29

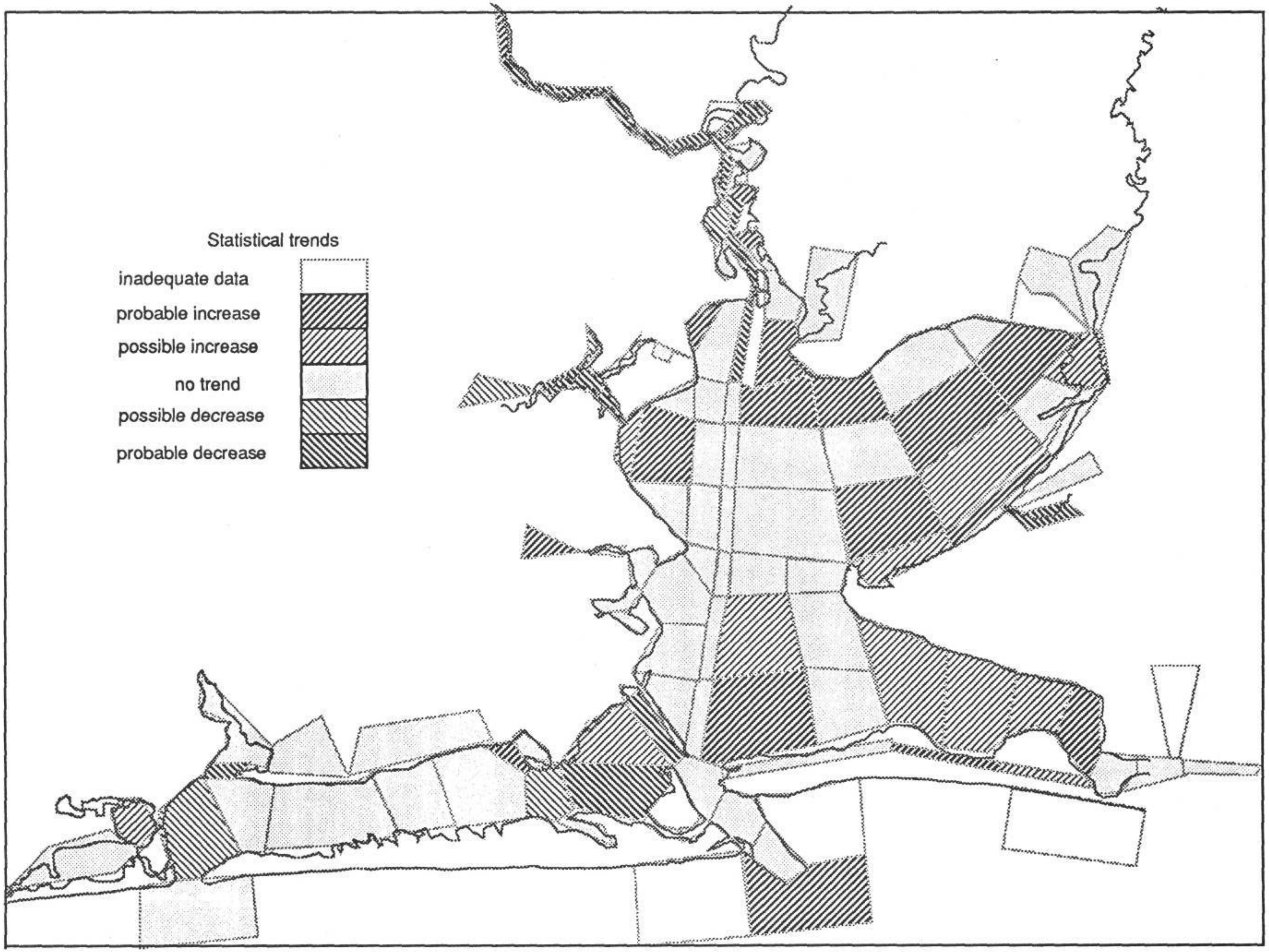


Figure 3-21. Statistical trends over period of record of WQDODEF in upper 0.5 m in Galveston Bay

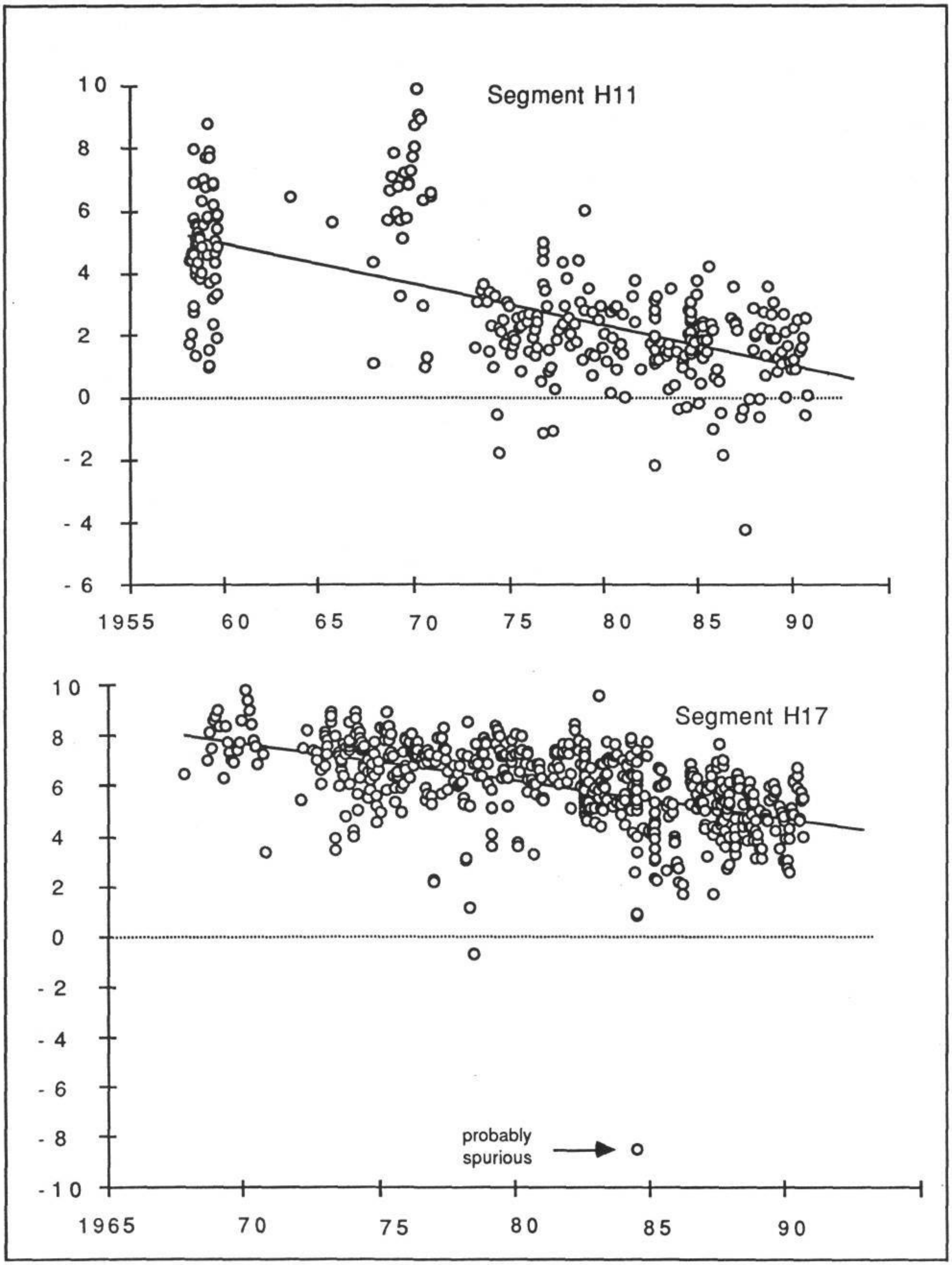


Figure 3-22. WQDODEF (upper 0.5 m) trends in confined reach of Houston Ship Channel, Segments H11 and H17

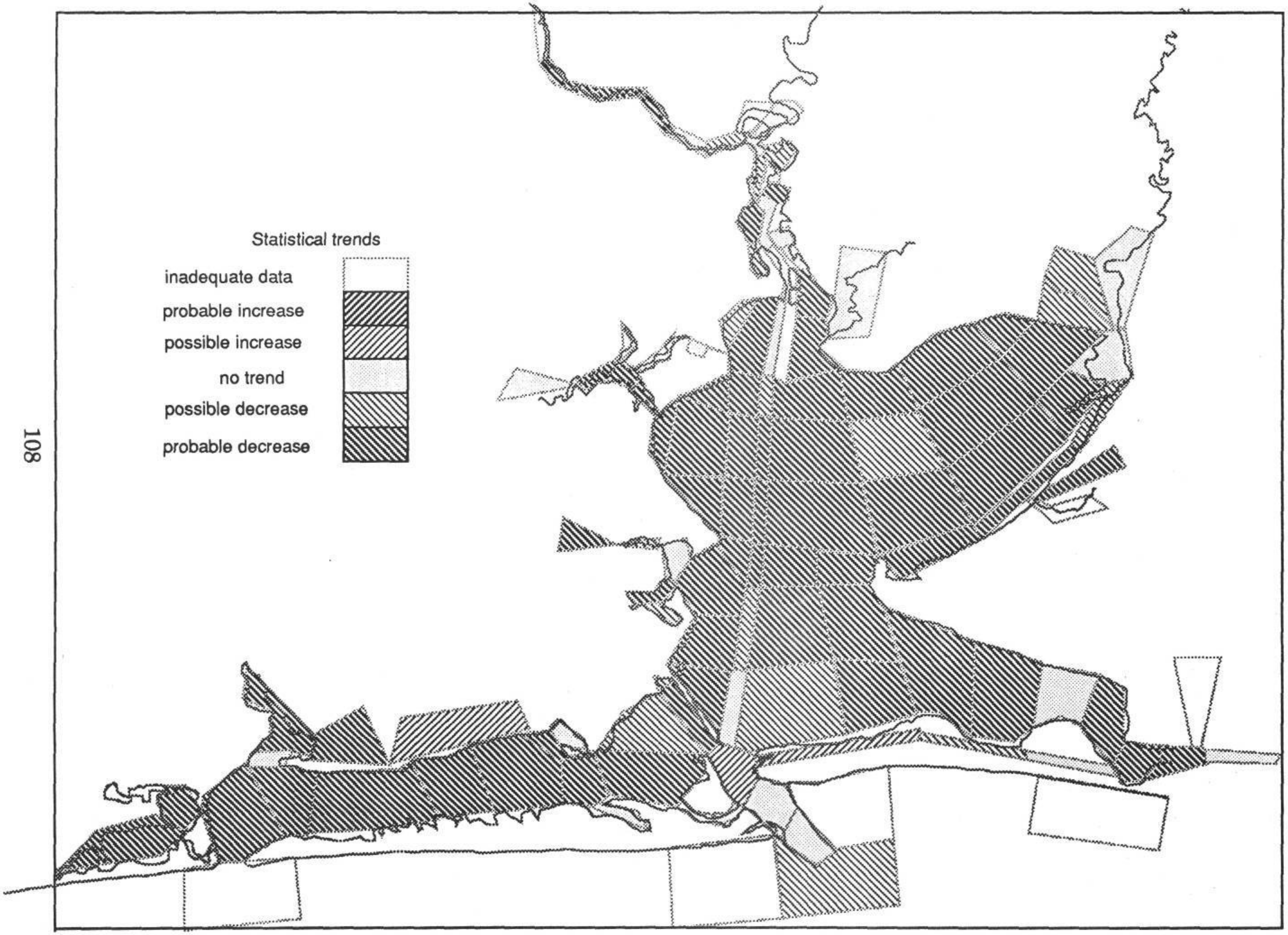


Figure 3-23. Statistical trends over period of record of WQXTSS in Galveston Bay

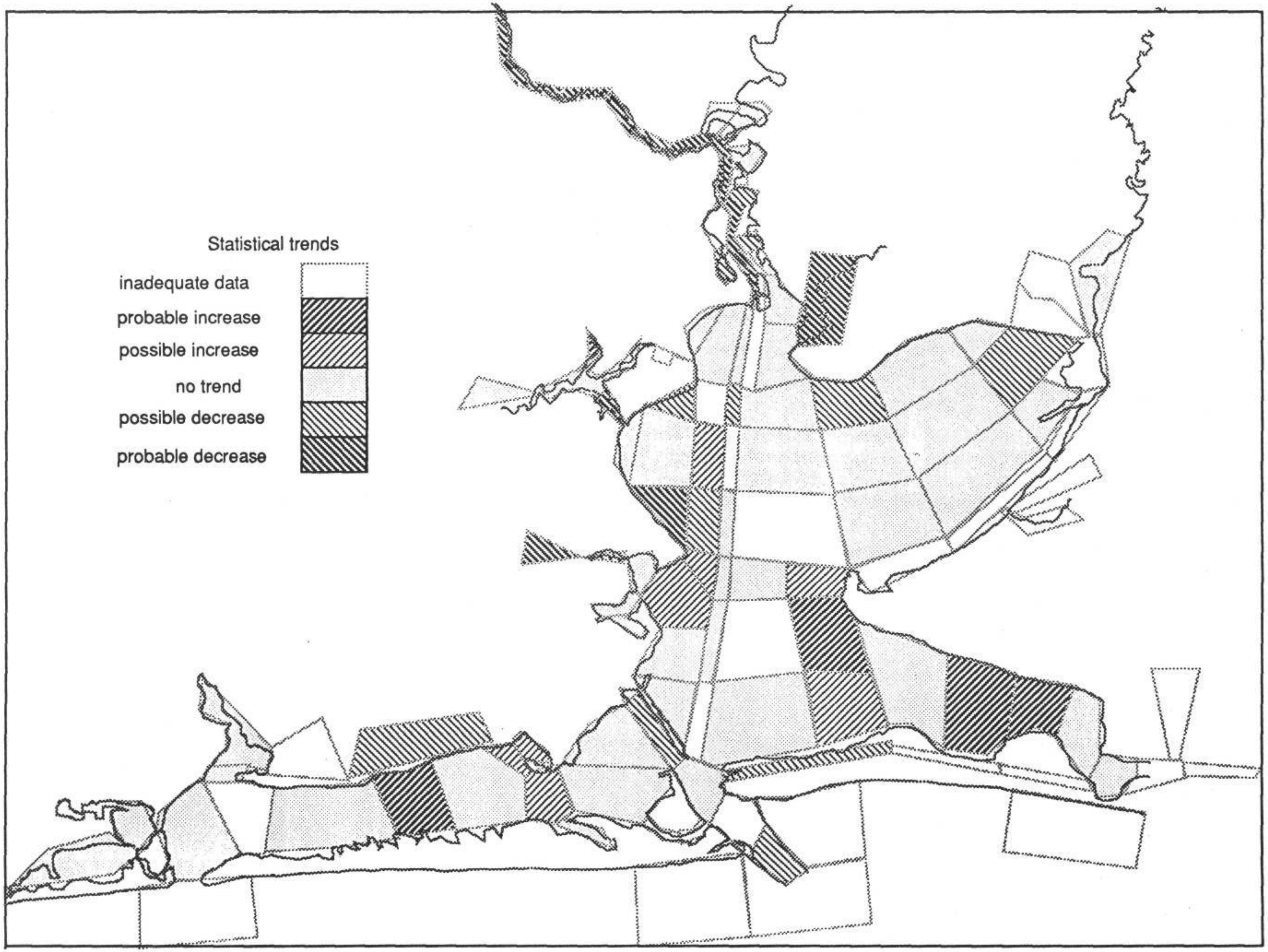


Figure 3-24. Statistical trends over period of record of WQXBOD5 in Galveston Bay

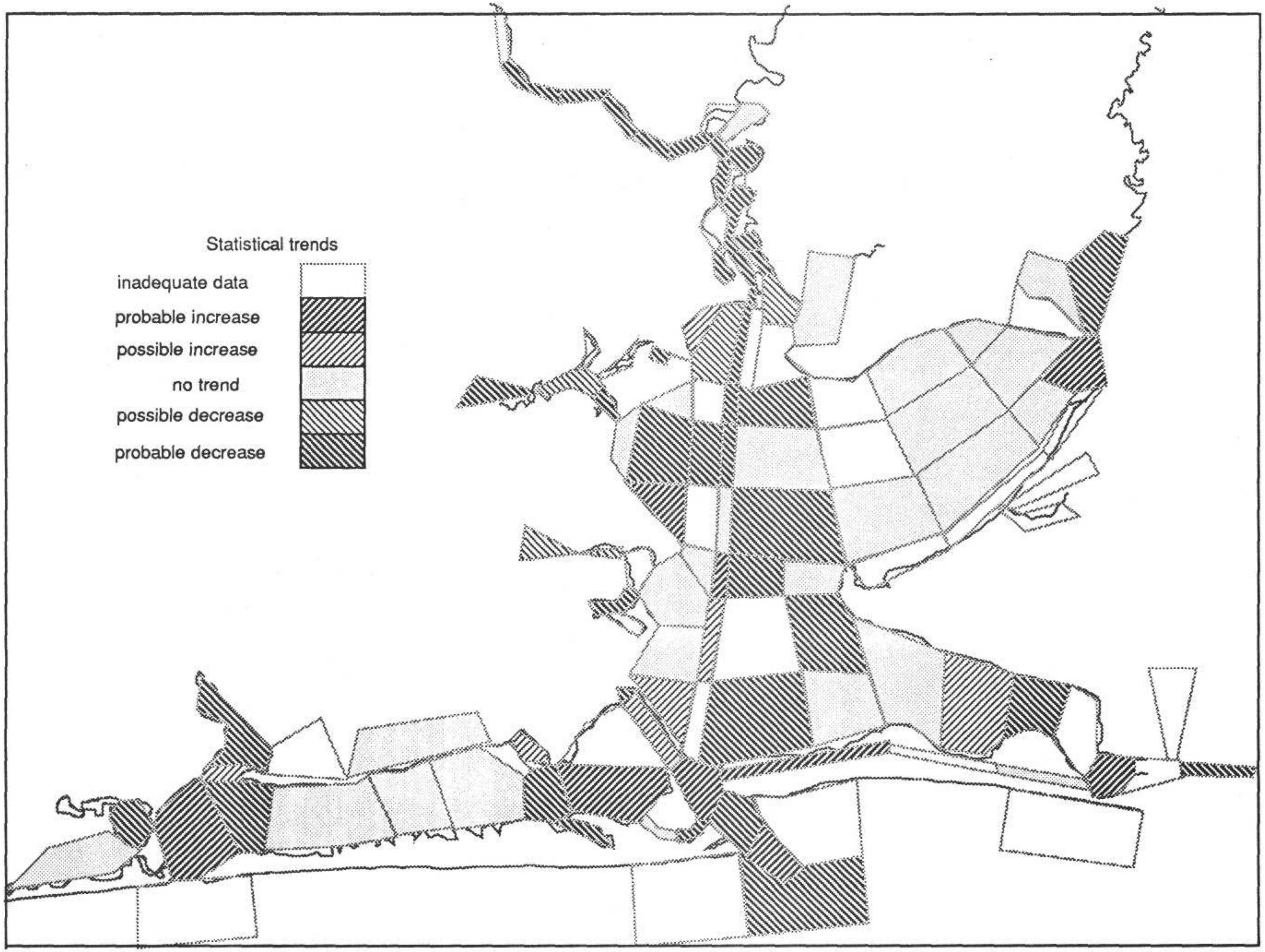


Figure 3-25. Statistical trends over period of record of WQAMMN in Galveston Bay

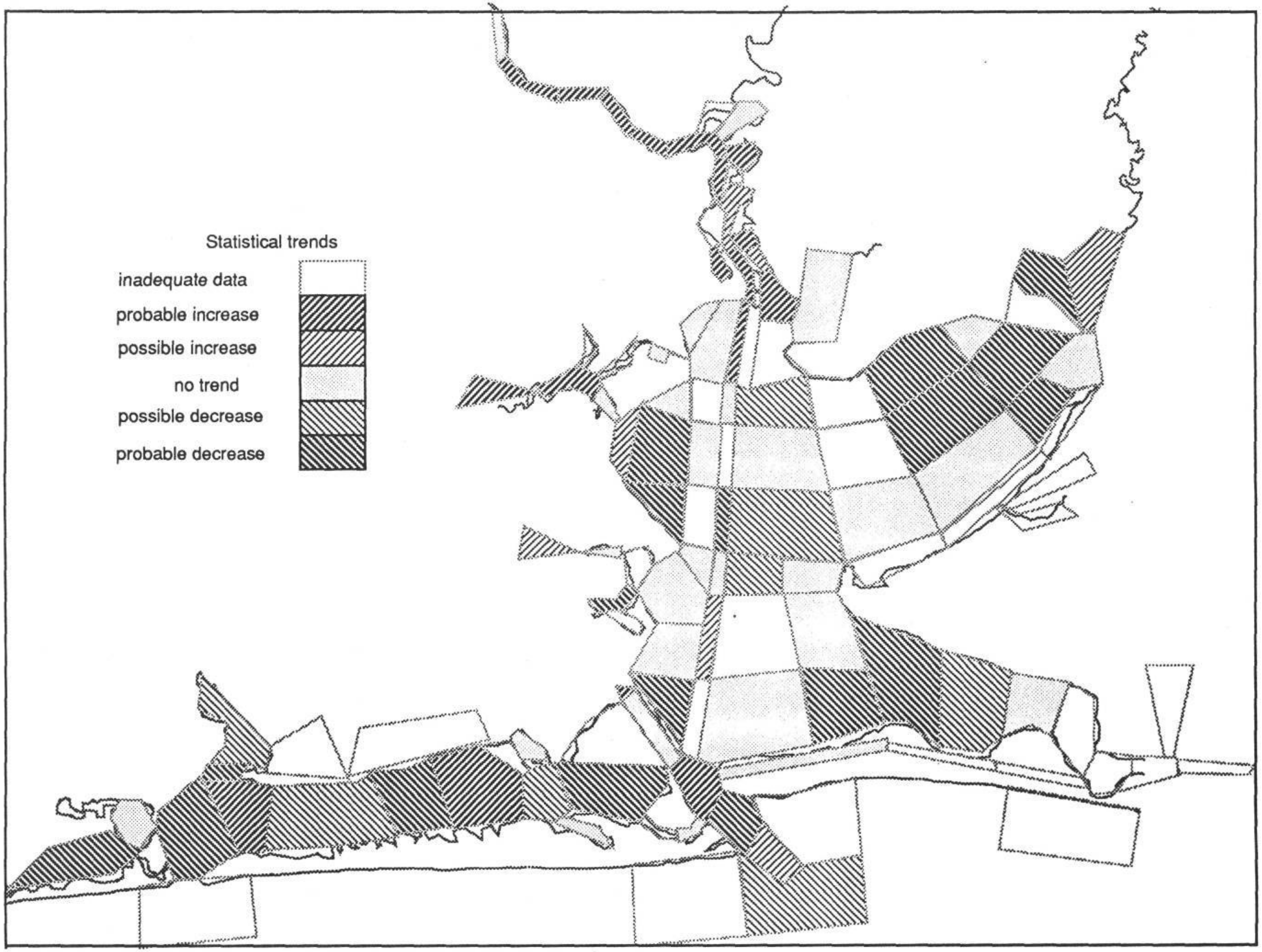


Figure 3-26. Statistical trends over period of record of WQNO3N in Galveston Bay

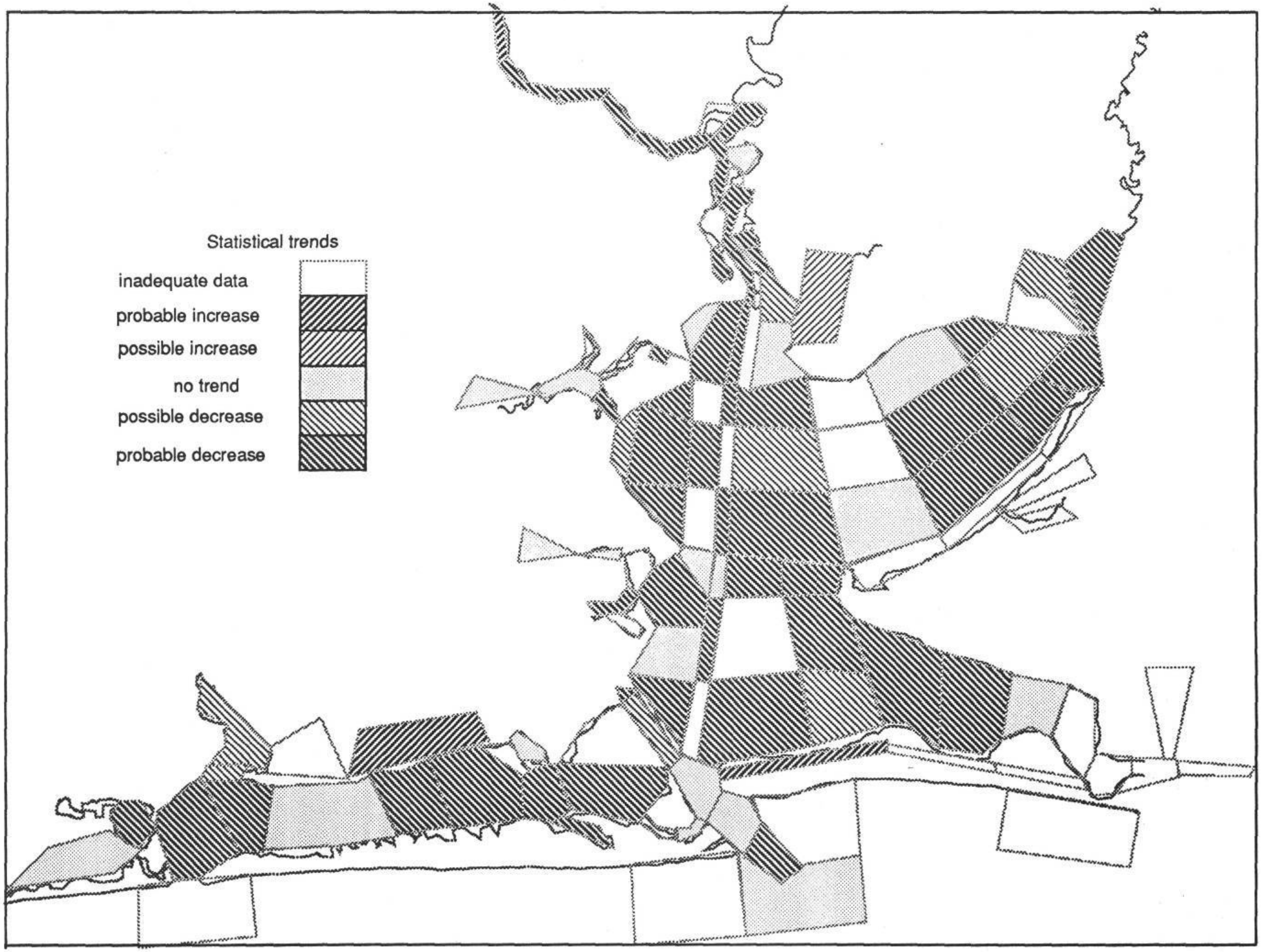


Figure 3-27. Statistical trends over period of record of WQTOTP in Galveston Bay

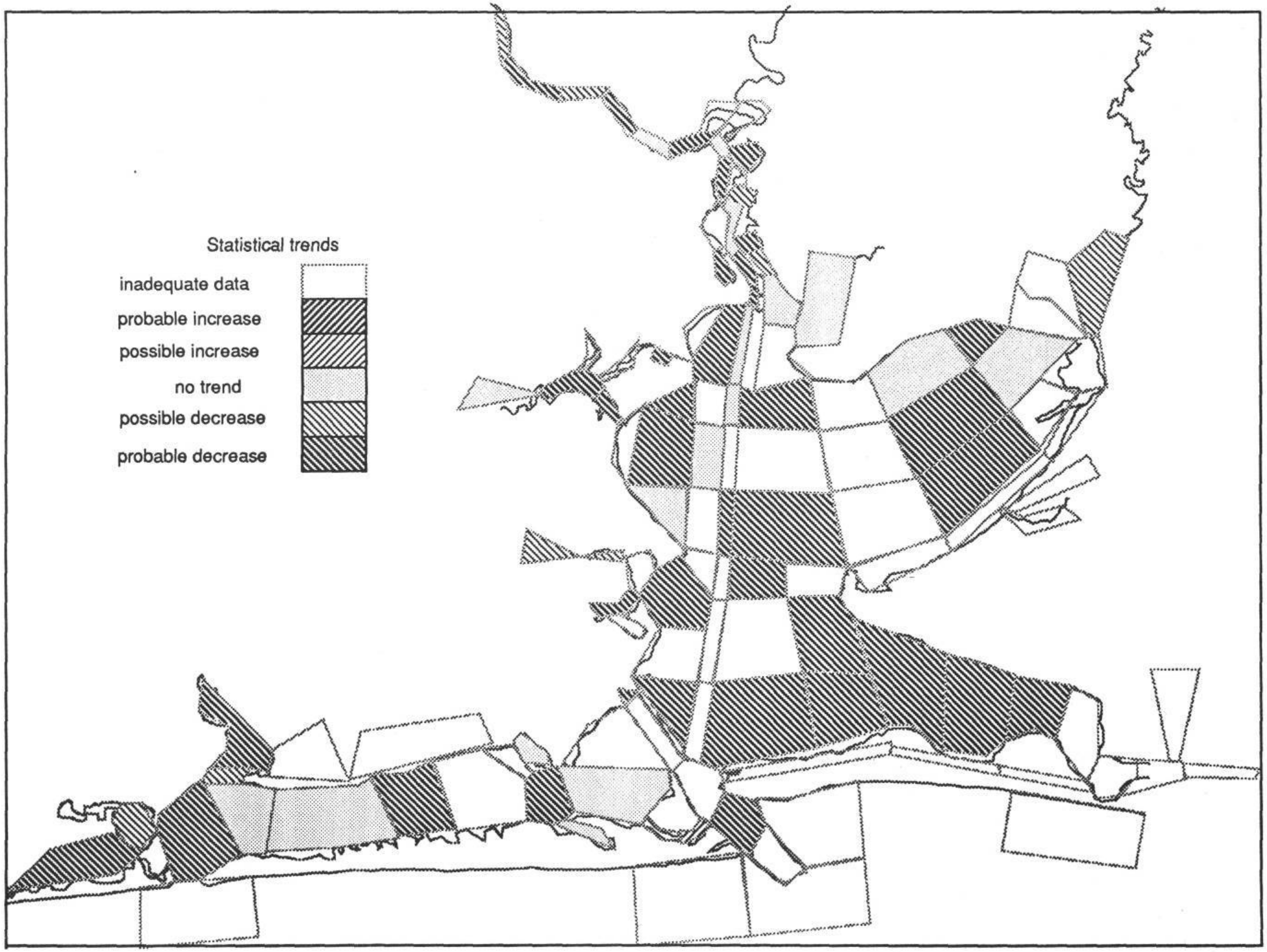


Figure 3-28. Statistical trends over period of record of WQCHLA in Galveston Bay

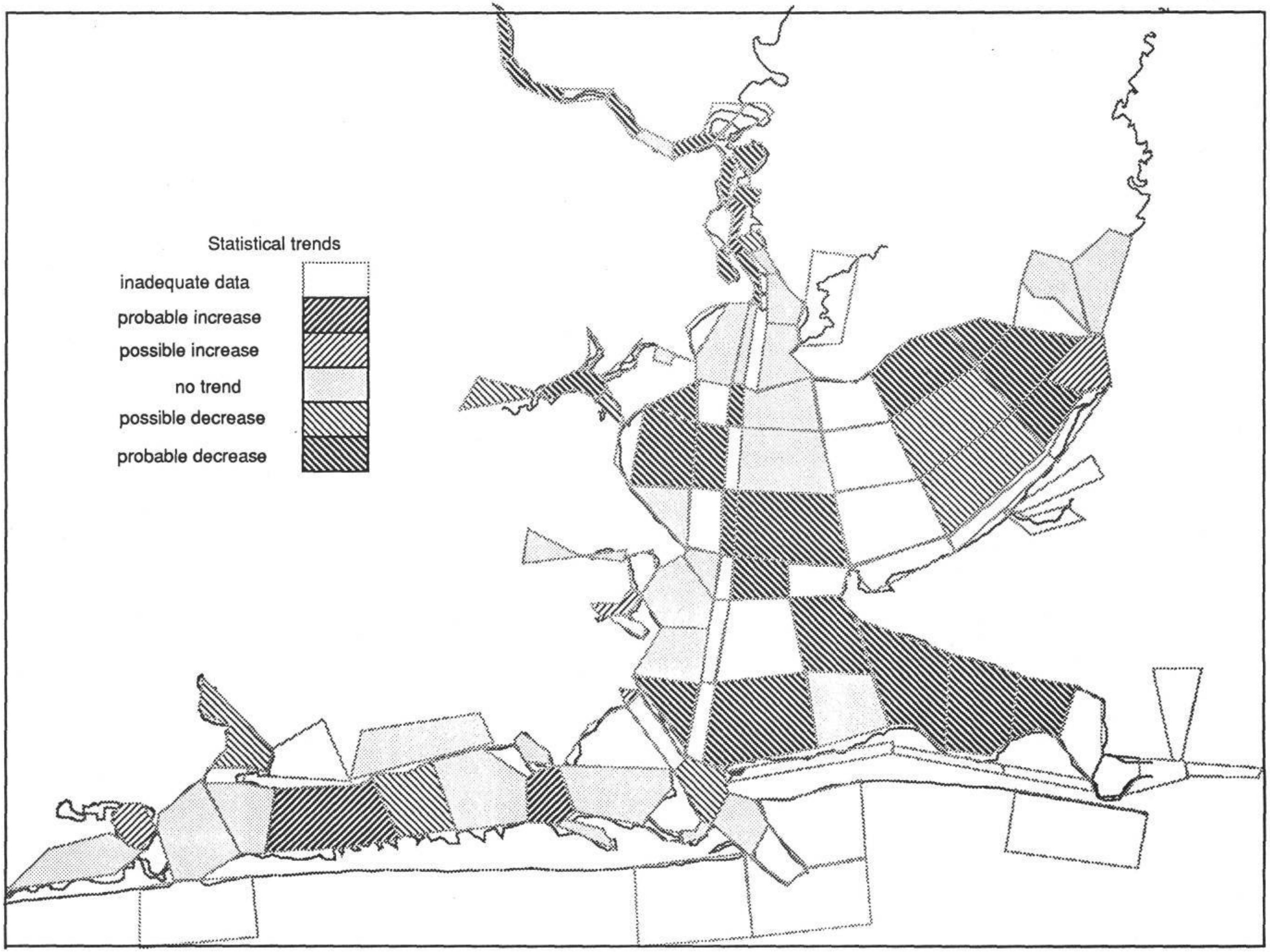


Figure 3-29. Statistical trends over period of record of WQTOC in Galveston Bay

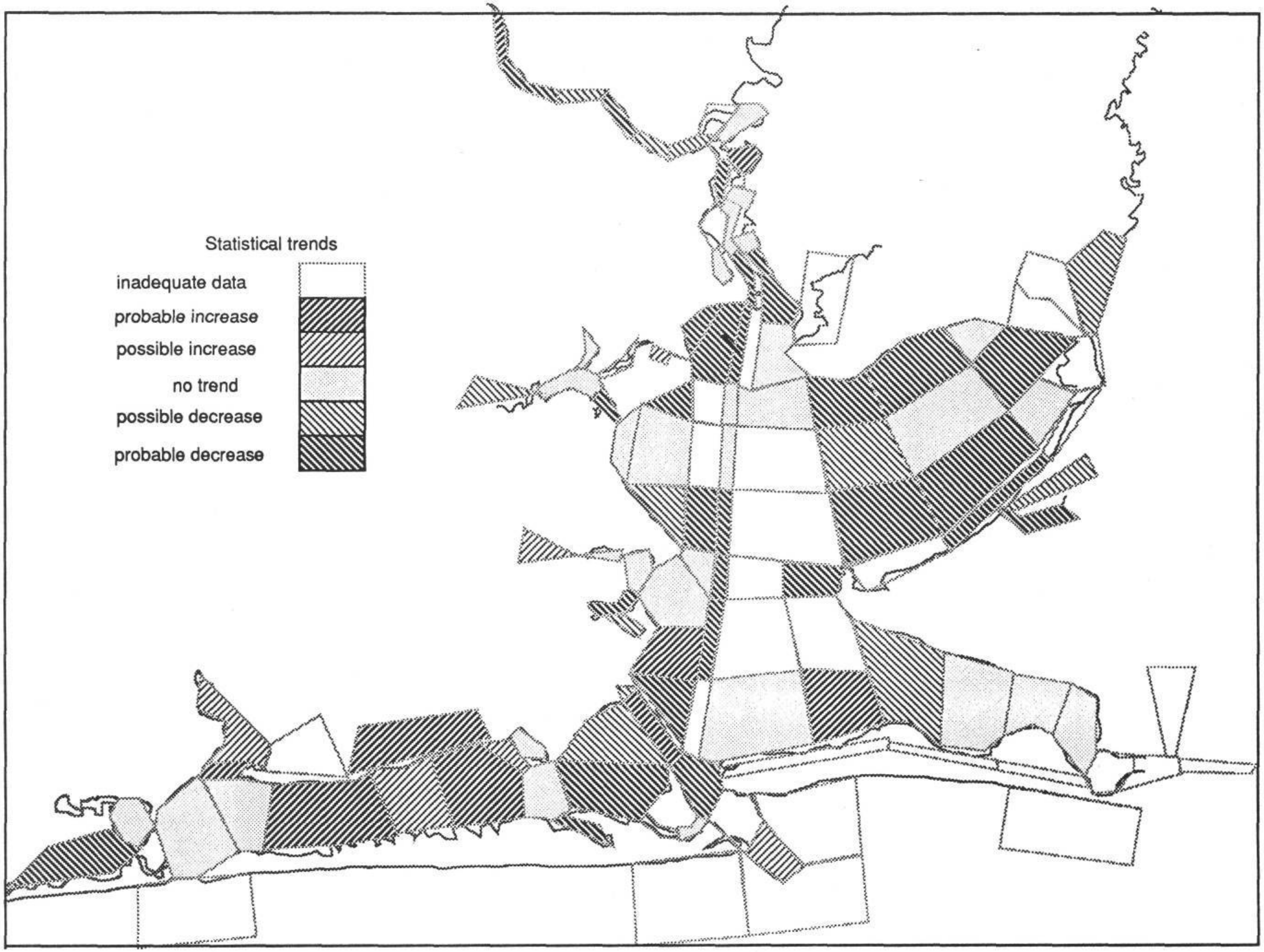


Figure 3-30. Statistical trends of base-e logarithm of WQFCOLI in Galveston Bay

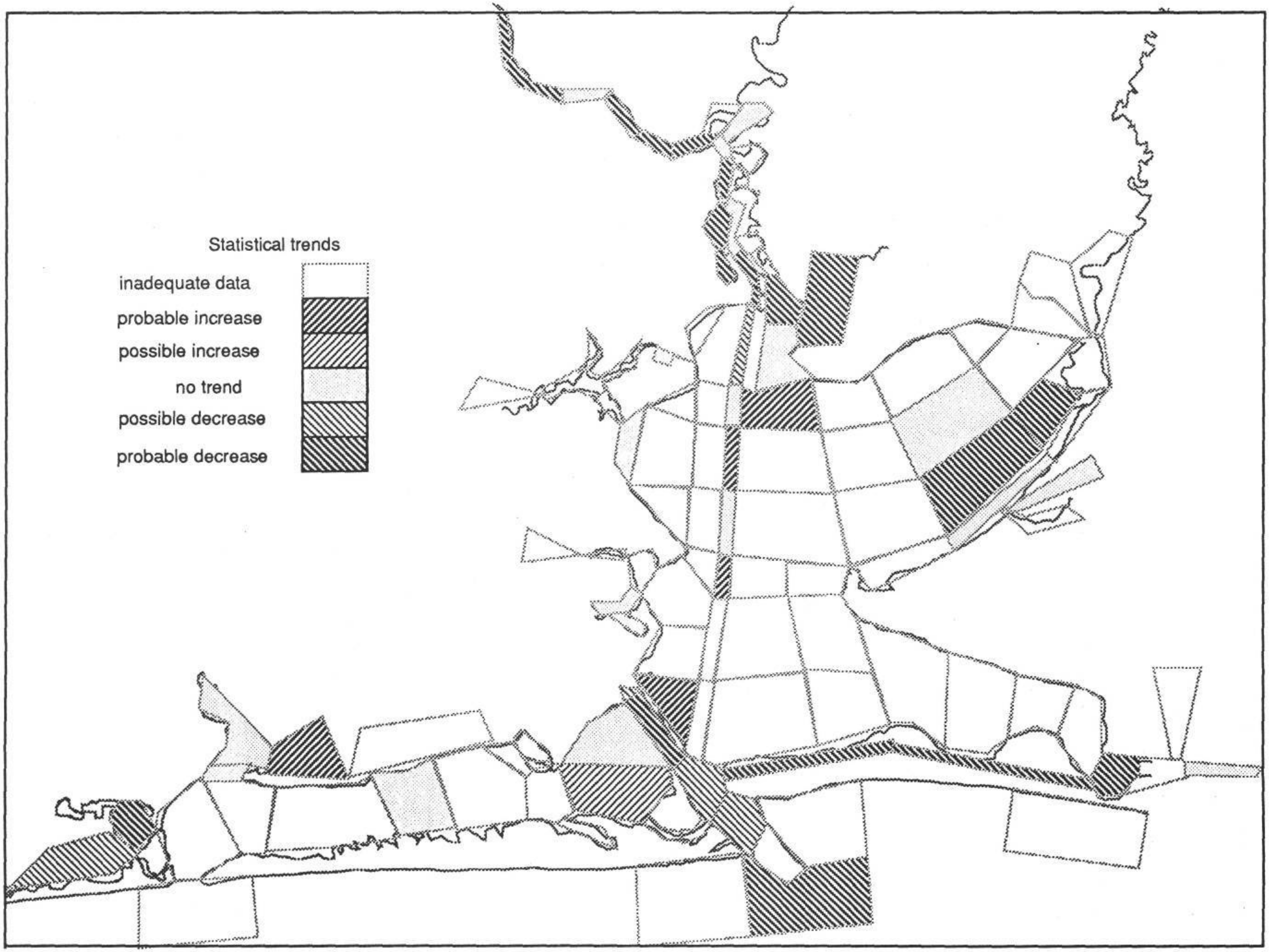


Figure 3-31. Statistical trends over period of record of WQMETCU in Galveston Bay

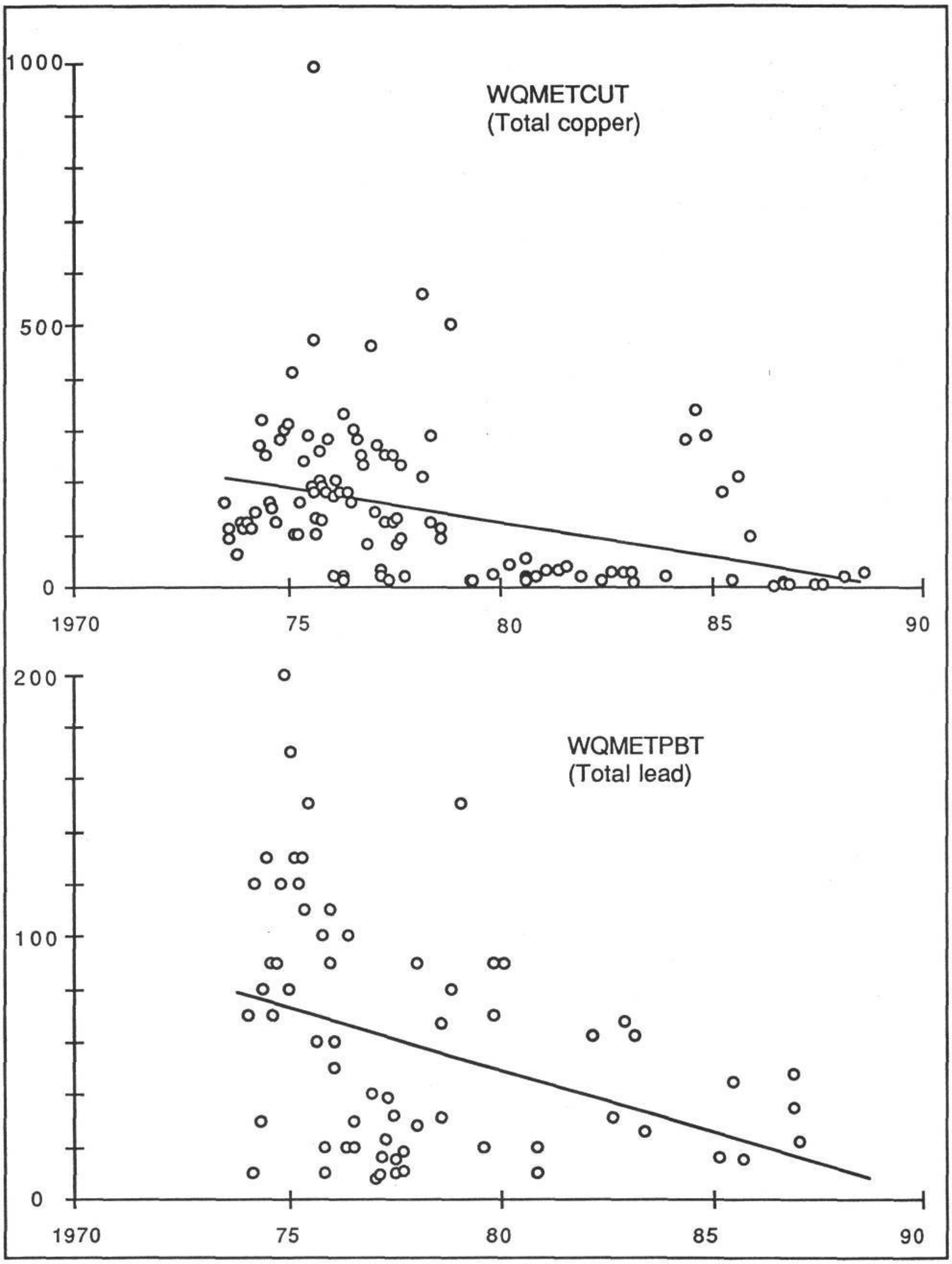
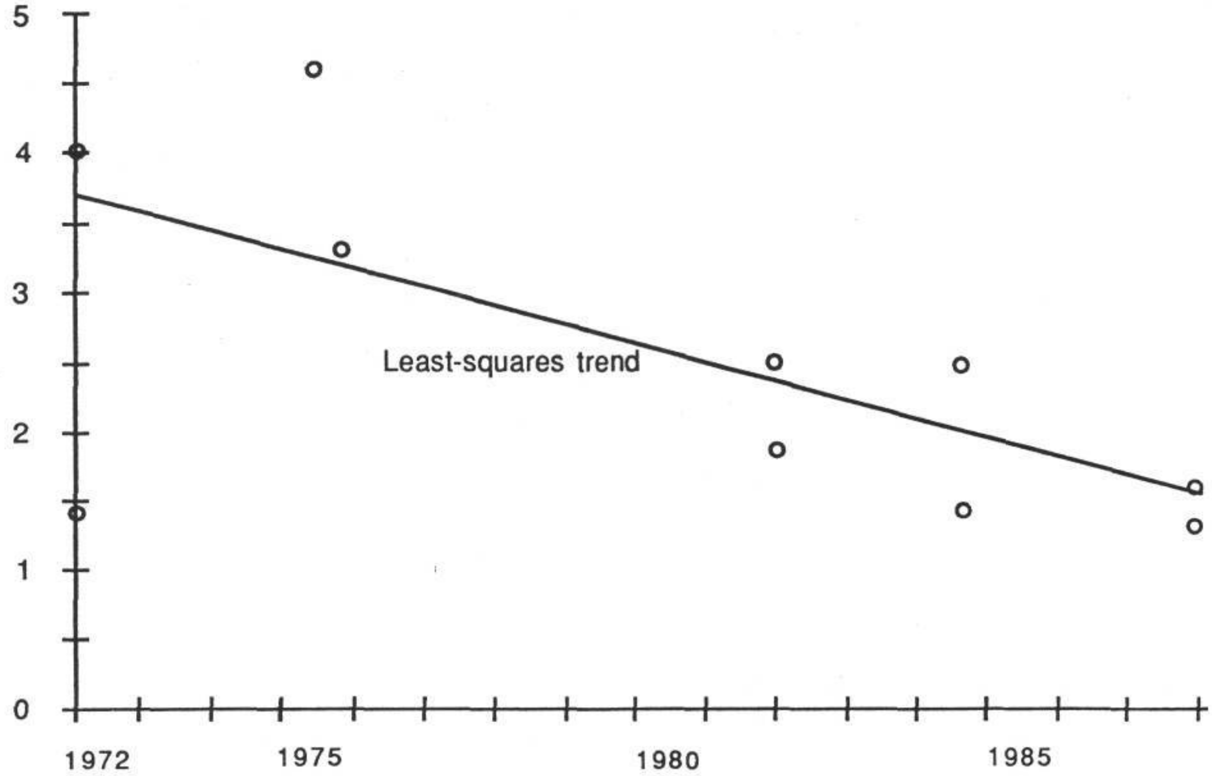
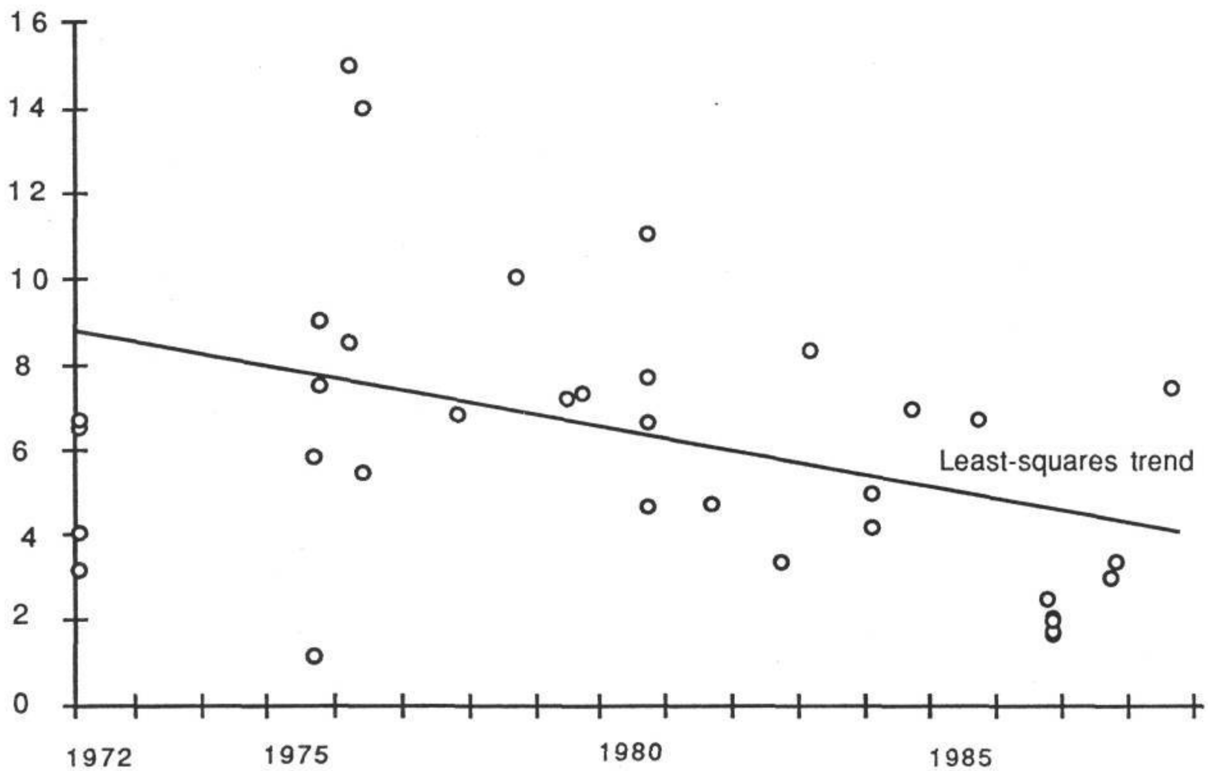


Figure 3-32. WQMETCUT and WQMETPBT trends in upper Houston Ship Channel (H17)

Figure 3-33. Statistical trends over period of record of SEDMETAS in Galveston Bay



(a) Hydrographic Segment H11



(b) Hydrographic Segment H17

Figure 3-34. Time Trend of SEDMETAS in upper Houston Ship Channel

Figure 3-35. Statistical trends over period of record of SEDMETCU in Galveston Bay

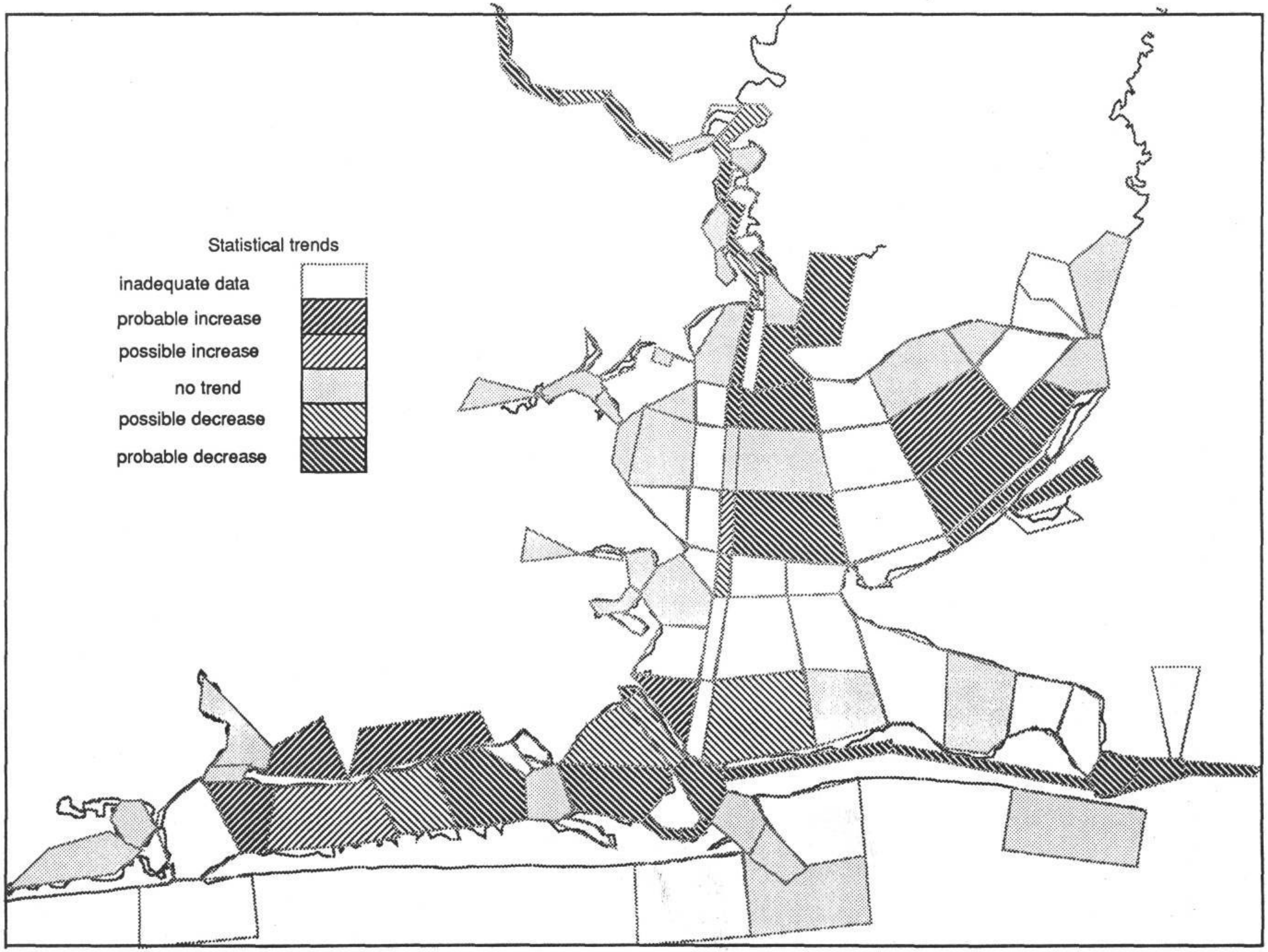


Figure 3-36. Statistical trends over period of record of SEDMETPB in Galveston Bay

3.3 Observations

Water temperature is generally homogeneous throughout the bay, varying generally less than 1°C in summer and 2°C in winter over the open bay. (The variability manifested in Figs. 3-1 and 3-2 may be as much due to varying sampling density and periods of record as to real variation.) The tributaries tend to be slightly warmer than the open bay in both winter and summer. Stratification (Table 3-3) is noisy and not well-developed, generally averaging less than 0.3 °C/m, with most open-bay and Houston Ship Channel stations less than 0.1°C/m. For the past two-three decades, there has been a general decline in water temperatures, especially in the open-bay segments, driven primarily by the warm-season temperatures. Averaged over all segments with a probable negative trend, this decline is roughly -0.06 °C/yr.

Salinity is, of course, the central hydrographic and habitat variable of Galveston Bay. Long-term average salinities exhibit a landward decline toward the sources of inflow (as expected), Figs. 3-3 and 3-4, with the largest horizontal gradient from Red Fish Bar across Trinity Bay. The Trinity plume along the south shore of Trinity Bay, the slightly higher salinities in the open (mid-bay) reach of the Houston Ship Channel, and the generally more saline conditions of West Bay are well-known features of the salinity structure that are quantified by the long-term averages of Figs. 3-3 and 3-4. Average salinity stratification (Table 3-4) is remarkably uniform through the bay, given its noisy character, and is less than 0.6 ‰/m almost everywhere except near points of freshwater inflow, and less than 0.3‰/m throughout about half of the area of the bay. There is no dependence of stratification on water depth evidenced in the long-term averages. Further, these averages are skewed by inflow events, and a high proportion of the data record in each segment evidence zero or even reversed stratification. Over the period of record, dating back in some segments to the early 1950's, there has been a declining trend in salinity, especially in the late summer values (Fig. 3-19). The mean rate of decline, averaged over those segments with a probable negative trend (e.g., Fig. 3-20), is about -0.18‰/yr.

As expected, pH varies slightly from values in excess of 8 in the open, more saline segments of the bay, to values less than 8 near points of inflow. No meaningful trends in pH were evident, in that the probable trends exhibited little spatial coherence.

Average dissolved oxygen concentrations in the open bay are uniformly high, Figs. 3-5 and 3-6. The lowest mean DO values (highest deficit values) in the system are found in the confined reach of the Houston Ship Channel (i.e., upstream from Morgans Point). Stratification is evident (Table 3-5), on the order of 0.2 ppm/m in the Houston Ship Channel (both confined and unconfined reaches) and in West Bay, and on the order of 0.4 ppm/m in the open segments Galveston Bay, including Trinity Bay. Stratification in DO deficit dominates DO stratification, that is, the vertical variation in salinity and temperature have an at-most secondary effect on vertical DO variation. The mean distribution of DO deficit, Fig. 3-6, indicates that near-saturation conditions are the rule throughout the system, except in the tributaries. Most egregious of the tributaries is the upper Houston Ship Channel, where mean deficits range almost to 7 ppm. DO deficit stratification is minimal as well in the upper Houston Ship Channel. In this area, the DO climate has been gradually improving, with a negative trend in deficit since the early 1960's, e.g. Fig. 3-22, on the order of 0.1 ppm/yr, and even higher near and downstream from the Turning Basin. In contrast, a few areas of the open bay exhibit increasing trends in deficit, Fig. 3-21. The average increase over all segments with a probable positive deficit trend is 0.12 ppm/yr.

The concentrations of total suspended solids generally increase toward points of inflow, and there are maxima also in Bolivar Roads and in East Bay near Rollover Pass, Fig. 3-7. Stratification in TSS is pronounced, with TSS decreasing upward, Table 3-6. The most remarkable feature of TSS in Galveston Bay is the declining trend throughout the bay and tributaries, with virtually all open bay segments showing either probable or possible negative trends, Fig. 3-23. WQXTSS is a proxy variable, dominated by determinations of TSS and turbidity. These components of the data were examined separately, and each found to exhibit this pattern of declining trends. The mean rate of decline, averaged over those segments with a probable negative trend, is -2.1 ppm/yr. Measurements are spottier for the volatile component of the suspended solids, but VSS appears to be fairly uniformly distributed with a declining trend, though its noisy character and sparse data render this trend less certain than that of TSS. Data on oil & grease are much more limited, with many areas of the bay unsampled. Of those regions sampled, the largest systematic concentrations are found in the vicinity of Texas City, Fig. 3-8.

The spatial variation of BOD exhibits an expected pattern of uniformity in the open areas of the bay and increases toward regions of waste discharge, Fig. 3-9. The largest mean values are in the upper Houston Ship Channel. We note the elevation in BOD along the northern shore of Trinity Bay. Generally, there is no systematic time trend in BOD in the open bay segments, but there are probable declines in BOD in Clear Lake, Dickinson Bayou, Cedar Bayou, and--especially--in the upper Houston Ship Channel (Fig. 3-24). Averaged over all segments with a probable negative trend (70% of which are in the upper Houston Ship Channel), the mean decline in BOD is -0.27 ppm/yr.

Two of the principal nutrients, nitrogen and phosphorus in their various forms, play an essential rôle in aquatic biological processes. Further, their concentrations can be significantly augmented by the activities of man, especially through point discharges of municipal and industrial wastes, and through runoff from modified watersheds. While nitrogen exists in four principal species, not all of these are routinely measured. Ammonia is fairly uniform through the open bay, generally less than 0.1 ppm, and much higher in the tributaries, especially the upper Houston Ship Channel, Fig. 3-10, and nitrate follows a similar general pattern, Fig. 3-11. Stratification in ammonia (Table 3-17) and nitrate are similar, with negative stratification (decrease of concentration from bottom to surface) in the open bay segments and positive stratification in the upper Houston Ship Channel. The magnitude of the vertical stratification, of either sign, is small. Many areas of the bay show an uncertain time trend in ammonia, but where there are trends they tend to be declining, Fig. 3-25. For the segments with a probable negative trend, the average rate is 0.11 ppm/yr. Nitrate exhibits a tendency to decrease in the open bay, but to increase in the tributaries, Fig. 3-26. Averaged over those segments with probable positive trends, the rate of increase of nitrate is 0.061 ppm/yr. This opposite trend of ammonia and nitrate should especially be noted in the upper Houston Ship Channel and Clear Lake.

The most common measures of phosphorus concentration are orthophosphates and total phosphorus. Generally, the latter is predominant in the Galveston Bay data, hence was selected as the principal measure of phosphorus for analysis. One significant source of uncertainty in this measurement is the treatment of particulate (versus dissolved) phosphorus. Phosphorus is sorptive and has an affinity for fine-grained suspended sediments. In some of the data sets, it is not clear whether the total-phosphorus analyses are restricted to the dissolved fraction (i.e., whether the sample is filtered) or includes the particulate. Total phosphorus increases from average values on the order of 0.1 ppm at the inlets of Galveston Bay to 1.0 or greater in regions of waste discharges, especially the upper Houston Ship Channel, Fig. 3-12. There is a predominant declining trend in total phosphorus in the open bay and the Houston Ship Channel, Fig. 3-27. Averaged over all segments with a probable negative trend, the rate of decline is -0.043 ppm/yr.

Although there are significant areas of the bay that are not sampled for chlorophyll-a and total organic carbon, for those where there is an adequate data base, both parameters show declining trends over the period of record, Figs. 3-28 and 3-29. Averaged over those segments with a probable negative trend, the mean decline in chlorophyll-a is -1.7 ppb/yr and in total organic carbon is -0.50 ppm/yr. TOC shows no systematic stratification, and chlorophyll-a tends to be positively stratified in the Houston Ship Channel, which is virtually the only area of the bay in which vertical sampling has been performed.

Generally, both coliform measures, both as arithmetic and geometric means, display elevated levels around the periphery of the bay, minimum values in the mid-segments of the open bay, and largest concentrations at points of inflow and waste discharge, e.g. Fig. 3-13. The highest concentrations are in the upper Houston Ship Channel, and the lowest in the midsections of Trinity Bay, Lower Galveston Bay, East Bay and West Bay. In some instances, e.g. the Trinity River and delta, an elevated level of total coliforms does not correspond to an elevated level of fecal coliforms. The time trends for the two coliform measures are different. Total coliforms show little coherency in trend, except declining trends in lower Galveston Bay, eastern West Bay, and the upper Houston Ship Channel, which are even more magnified by the logarithmic transform. Fecal coliforms, in contrast, show little coherency in the main section of Galveston Bay and in East Bay, but exhibit coherent declines in Trinity Bay and increases in the middle region of West Bay, Fig. 3-30. While fecals show some decline in the upper Channel and around Pelican Island, the extent of the areas of decline is not as great as for total coliforms. Again, these trends are magnified by the logarithmic transform.

Most areas of the Galveston Bay system have an inadequate data base for metals, and even less data for organic compounds. The general distribution of total copper is shown in Fig. 3-14. For this, as well as other metals, elevated levels are indicated in the upper Houston Ship Channel and on both sides of the Texas City Dike. High mean concentrations of copper occur in mid-Trinity Bay and mid-East Bay, while high concentrations of lead and zinc occur in lower Galveston Bay just inside the inlet. Data is even sparser on trends, Figs. 3-31 and 3-32, but where trends are indicated, they are almost everywhere negative. (The increasing trend of metals in the segment north of the Texas City Dike lacks validity because it is based upon only a few measurements in 1974-75.)

The best-monitored pesticide is DDT, and the greatest data base is that assembled by proxying the principal isomer. Even at this, most areas of the bay do not have data, and those segments which do are most often below detection limits. Where non-zero values occur, they are in areas affected by inflow and waste discharges, *viz.* the Houston Ship Channel, Clear Creek, and Texas City Turning Basin. No time trends could be computed.

The conventional organic constituents in the sediment, *viz.* total phosphorus, oil & grease, Kjeldahl nitrogen, and volatile solids, all exhibit the same general pattern as conventional water-quality parameters loaded in waste discharges and runoff: fairly consistent values in the open bay segments and higher levels in tributaries and near sources of waste discharge, e.g. Figs. 3-15 and 3-16. For all of these parameters, the upper Houston Ship Channel shows systematically elevated concentrations. Time trends are uncertain due to the paucity of data, though there appears to be a tendency for declining concentrations in the upper Houston Ship Channel.

For the metals in sediments, e.g. Figs. 3-17 and 3-18, generally the highest concentrations are found in the upper Houston Ship Channel sediments. Clear Lake, and, to a lesser extent, Dickinson Bayou also display generally elevated concentrations, especially arsenic, copper and mercury. The concentrations of all of these metals were found to be relatively low in the vicinity of the Trinity River in upper Trinity Bay. For all of these sediment metals except, perhaps, arsenic, where a trend is discernible it is generally declining, Figs. 3-31 through 3-36. This is especially the case in the upper Houston Ship Channel, including in this case, arsenic, Figs. 3-33 and 3-34. (Again, the increasing trends in the segment just north of the Texas City Dike lack validity, being based upon a few measurements in 1974-75.)

As was the case with water quality, the data base for complex organics is even more limited for sediment, with most of the measurements below detection limits. For the distribution of DDT through the bay sediments, generally the highest levels are in the Houston Ship Channel and other points of inflow, especially Cedar Bayou, Clear Creek and (NB) the Trinity River. There is also a high concentration in Offatts Bayou. Data were inadequate for a meaningful trends analysis.

5. CONCLUSIONS AND RECOMMENDATIONS

5.1 The Data Base

The principal product of this study is the compilation of a digital data base composed of water-quality and sediment-quality data from 26 data collection programs performed in Galveston Bay. This compilation included data from the three most important ongoing state monitoring programs in Galveston Bay, other major past survey programs, many of which exist in limited hardcopy and are virtually unobtainable, and research projects whose data are published only in limited technical reports or academic theses, all of which were keyboarded. All told, the digital compilation is the most extensive and detailed long-term record of water quality ever assembled for Galveston Bay. Each measurement record includes the date, sample depth, latitude and longitude of the sample station, measured variable, estimated uncertainty of measurement expressed as a standard deviation, and a project code identifying the origin of the data. Major efforts of the project were devoted to determination of latitude/longitude coordinates and to determination of accuracy based upon sample technique and historical precision information.

It is appropriate to note several deficiencies of this data set, as they relate to the interpretation of water and sediment quality, and as motivation for recommendations proffered in the concluding section.

(1) Adequacy of a data base is relative to the ability to resolve the various scales of variation, and in this respect Galveston Bay is undersampled. Despite the hundreds of thousands of separate measurements compiled in this study, when these data are subdivided by specific parameters, each of which measures a different aspect of the water quality "climate," aggregated by region of the bay (segments) and distributed over time, the data record is seen to be rather sparse. Ability to resolve long-term trends in the face of high intrinsic variability requires data over an extended period. The extant period of record for Galveston Bay extends back only to about 1965. For some traditional parameters, and for certain areas of the bay, e.g., the confined reach of the Houston Ship Channel, the record can be extended back to the late 1950's. Beyond this, what data still survive are sporadic in time. For metals and for complex organics, the period of record may extend back only a decade or so.

(2) As salinity and temperature are the most easily measured variables, they represent the densest and longest data record. Even at this, past and present sampling practice does not permit analysis of time scales of variation shorter than a few days. For temperature and dissolved oxygen, especially, there is a known diurnal variability which is virtually unsampled in Galveston Bay. Moreover, the extant measurements are nearly all for daytime hours, which must be considered a source of potential bias in the data.

(3) One of the principal properties of the water of Galveston Bay is its turbidity. Suspended solids are particularly important in characterizing water quality because of the rôle particulates play in habitat quality, and in the sorption of nutrients and contaminants on the finer particulates. However, some programs do not obtain any measure of turbidity, and those few that do obtain suspended solids do not measure the grain-size distribution. The understanding of the behavior of most nutrients, metals, pesticides and priority pollutants is limited by the lack of information on suspended solids in the water column.

(4) One of the central problems in constructing a sufficiently dense and long-term data base for conventional parameters is the inconsistency in measurements and analytical methodologies from one program to another. Some programs emphasize COD and sulfides, say, while another examines phytoplankton and TOC, and a third may analyze BOD and chlorophyll-a. The net effect is limited data coverage in a specific parameter that makes spatio-temporal analysis uncertain. Even for salinity, were it not for reliable proxy relationships, our ability to synthesize a comprehensive data set would be seriously truncated.

(5) Metals data are dominated by total (unfiltered) analyses. So little measurement has been made of the dissolved phase that no characterization or trends analyses are possible. This practice is perhaps not inappropriate because of the known affinity of trace metals for particulates, but underscores the problem of not having paired measurements of suspended solids to which the total concentrations could be related. Much of the historical data for metals has been corrupted by inattention to accurate detection limits. A well-defined detection limit provides at least some information when the concentration is undetectable.

(6) Pesticides and other organic contaminants are a recent addition to the suite of measurements, and the water-quality data base is presently inadequate for any detailed analyses. The best record is the extended DDT, obtained by combining reported "total" values with those estimated from the pp'-DDT isomer. Even at this, only 12 observations are above detection limits. Interpretation of organic-contaminant data is frequently based upon normalization to organic carbon (e.g., Karickhoff, 1981, Moore and Ramamoorthy, 1984a). For Galveston Bay, there are practically no paired measurements of organic carbon and organic contaminants.

(7) Sediment data is extremely limited for the bay. This is unfortunate because the shallow nature of the bay would suggest that sediment interactions should be a signification factor in the quality of the overlying water and its habitat value, and because sediment is an integrator of bay quality, compared to the variable and evanescent nature of the overlying water. While the number of observations given in Table 2-6 might appear to be large, they reduce to about one sample per 5 square miles per year. For many metals and most organic pollutants, the data base is even smaller, and, moreover, only about 10% of the measurements are above detection limits.

(8) In recent years, there has been a shift of emphasis from older, imprecise measurements such as oil & grease, volatile solids and total PAH's, to specific,

more precise parameters. In most cases, this has involved a replacement of the old parameter with the new, so that the data record for the older parameter terminates, the data available for the new parameter is extremely limited, and there is no information as to the probable association between the two.

(9) A major deficiency of the sediment data base is that there are almost no measurements of sediment texture (i.e., grain-size distribution). As noted in (3) above, many of the parameters of concern, such as heavy metals and pesticides, are known to have an affinity for fine-grained sediment, and moreover probably enter the system through run-off, also the source for most of the fine-grain fraction of sediment. Therefore, analysis of the variability of these quality parameters in the sediment must consider the grain-size fractions. Considering that sediment texture is an inexpensive measurement, especially compared to gas-liquid chromatography and spectrometry, it is inexplicable that texture data has not been routinely obtained for sediment samples.

(10) Data management is generally poor. Reference is made to the conclusions of Ward and Armstrong (1991) concerning data management practices and data loss in general. Data management problems were encountered in the major state digital data bases, including the TWC SMN data base, which must be considered the central data repository for the Galveston Bay system. These problems are exacerbated by cumbersome and inefficient data retrieval and display routines.

5.2 The Environmental Quality "Climate"

5.2.1 Water Quality

Salinity acts as a conservative property of Galveston Bay waters whose concentration is primarily determined by boundary fluxes at the inflow points and at the inlets to the sea, and internal transport and mixing. Substantial gradients across the bay are a normal feature of salinity structure, declining on average from values about 30 ppt at the inlets to the bay to about 3 ppt out from the principal points of inflow, such as the Trinity River. Variability about these mean values is high, however, with a standard deviation of 5-6 ppt throughout the bay. Salinities in the open-bay reach of the Houston Ship Channel are higher, on the order of 2 ppt, than those of the adjacent waters. Vertical stratification of bay waters is slight, by estuarine standards, generally averaging less than 0.6 ppt/m, and averaging less than 0.3 ppt/m over about half of the bay area, with no correlation with water depth.

There has been a general decline in salinity over the three-decade period of record, of about 0.1-0.2 ppt per year, not clearly associated with freshwater inflow. Our favored hypotheses (whose testing exceeded the scope of this study) are, variations in the time signal of inflow events and the associated salinity response, reduced salinities in the adjacent Gulf of Mexico, or reduced intensity of interaction between estuary and Gulf waters.

Temperature in Galveston Bay is primarily controlled by surface fluxes, especially the seasonal heat budget, and much less--if at all--by boundary fluxes and internal transports. The horizontal gradient across the bay ranges 1-2°C, with the higher values in winter, with little systematic stratification, though on average a slight stratification on the order of 0.2°C/m emerges from the data. We believe this stratification to be due to near-surface heat absorption, rather than density effects. The seasonal signal is, of course, the principal source of variation in water temperature. Over the three-decade period of record, water temperature, especially in the summer, has declined in Galveston Bay at a nominal rate of 0.05°C/yr. Our favored hypothesis for this decline is an alteration in climate (e.g., air temperature, wind, cloud cover), though this could not be tested within the scope of this project.

Dissolved oxygen is generally high throughout Galveston Bay, averaging near saturation through large areas of the bay, with frequent occurrence of supersaturation. Exceptions to this are in poorly flushed tributaries subjected to inflow and waste discharges, most notorious of which is the Houston Ship Channel above Morgans Point (discussed further below and in the following section). In the open, well-aerated areas of the bay, vertical stratification is on the order of 0.4 ppm/m. This stratification is much greater than the practically negligible stratification in solubility, and is considered to be the result of DO influx near the surface in concert with water-column and sediment biochemical oxygen consumption.

BOD is a measure of organic oxygen-demanding constituents. In Galveston Bay, BOD ranges 2-3 ppm throughout the lower bay segments, and increases inland to 4-5 ppm in the upper bay along the north and west shores, and to values greater than 5 ppm in Clear Lake and the Houston Ship Channel. Substantial reductions in waste loads into Galveston Bay have been implemented in the last two decades. In the Houston Ship Channel, which receives the bulk of waste discharges in the system, a factor of 20 reduction in BOD loading has taken place since 1970. Within the upper HSC, the reach above the San Jacinto confluence, the DO deficit has been reduced about 4 ppm in the past 20 years.

Like all of the Texas bays, Galveston is turbid, with long-term average suspended solids ranging 30-40 ppm throughout most of the bay, somewhat higher in the upper bay and less in the lower bay, and 40-60 ppm within the tributaries and adjacent open-water segments. Stratification in TSS is noisy, but on the order of 5 ppm/m declining upward, which is consistent with settling of larger particles to the bottom as well as a near-bottom source of particulates from scour of the bed sediments. The remarkable feature of TSS is its decline throughout the system: over the past three decades, an average reduction of about 2 ppm/yr to current levels on the order of 20 ppm. We favor the hypothesis of a general reduction of TSS loading to the bay (in contrast to one of decreased sources within the bay itself, e.g., resuspension), due to one or a combination of TSS reduction by advanced waste treatment, TSS entrapment within reservoirs, and reduced TSS in runoff because of changing land use. The relative importance of these could not be tested within the scope of this study, since it would require detailed mass-budgeting. However, we note a reduction in Trinity River TSS (both load and concentration) by a factor of three since the closure of Livingston in 1970, and we estimate an order-of-magnitude reduction in TSS load from waste discharges, similar to the reduction in BOD loading.

Nitrogen and phosphorus nutrients in Galveston Bay exhibit the same general spatial distributions as BOD and TSS, *viz*. elevated concentrations in tributaries and regions adjacent to inflow points, declining to lower concentrations at the inlets. Because these nutrients have an affinity for fine-grain particulates, their association with TSS is more than coincidental. The levels of concentration of total inorganic nitrogen range up to about 0.2 ppm in the lower bay, 0.2-0.5 in the upper bay, and as much as an order of magnitude greater in the upper Houston Ship Channel. No quantitative information exists defining an "optimal" level of nitrogen and phosphorus in Galveston Bay. These concentrations in Galveston Bay are more-or-less typical of other Texas bays. Copeland and Fruh (1970), in their ecological studies in the Galveston Bay Project, determined that nitrogen was probably the limiting nutrient in Galveston Bay. The results of Armstrong and Hinson (1973) were consistent with this, though these authors found indication from *in situ* productivity measurements that light may also be limiting. These nutrients all exhibit declines in concentration throughout the bay over the past two decades, total ammonia N on the order of 0.1 ppm/yr, total nitrate on the order of 0.01 ppm/yr and total phosphorus on the order of 0.05 ppm/yr. We favor the hypothesis that these reductions in nitrogen and phosphorus are a consequence of decreased wasteloads from advanced waste treatment and decreased loadings in the inflows, perhaps due to reservoir entrapment or altered land uses. (Nitrate exhibits increasing trends in the tributaries, which is almost certainly a result of increased nitrification due to advanced waste treatment. However, the net inorganic nitrogen load is decreasing.)

Total organic carbon since 1988 has averaged about 3-5 ppm in the open bay and about 8 ppm in the Houston Ship Channel. TOC exhibits baywide declining trends similar to nitrogen and phosphorus, except in West Bay (where there is no discernible trend), on the order of 0.5 ppm/yr. The recent levels given above are about one-third of the concentrations of the mid-1970's. This decline could be a direct result of reduced carbon loading, or an indirect effect of the general decline in nutrients on decreased productivity. Some credence is given the latter possibility by the decreases in chlorophyll-a in the open bay, to levels about one-half of those a decade ago.

Contaminants such as oil & grease, coliforms, metals and trace organics (pesticides, PCB's) show elevated levels in regions of runoff and waste discharge, with generally the highest values in the upper Houston Ship Channel, and generally low values in the open bay waters. The metals cadmium, copper, nickel and zinc have elevated concentrations generally throughout Galveston Bay (relative to the values presented in Moore and Ramamoorthy, 1984b, typifying uncontaminated coastal and marine waters). Most of the metals are declining in areas of maximal concentrations. While this may well be an artifact of changing analytical techniques, we favor the hypothesis that this general decline in metals is closely related to the decline in suspended solids. Most measurements of trace organics such as pesticides are below detection limits, so we have no statistically reliable information on trends.

5.2.2 *Sediment Quality*

The conventional organic measures and metals in Galveston Bay sediments appear to follow the same general spatial distribution as most of the water quality parameters, *viz.* elevated concentrations in regions of runoff, inflow and waste discharges, and lower, more-or-less uniform concentrations in the open bay, with the Houston Ship Channel generally the focus of maximal concentrations in the system. The available data for conventional organic measures are sparse, with large areas of the bay unsampled, and generally too noisy for reliable detection of trends.

The metals chromium and lead are generally elevated in sediments throughout Galveston Bay (relative to the data compiled in Moore and Ramamoorthy, 1984b, typifying natural aquatic systems), though, again, large areas of the bay are undersampled. The metals arsenic, cadmium, mercury and nickel are generally low, *including* the Houston Ship Channel (relative to values compiled by Moore and Ramamoorthy, 1984b). Copper and zinc follow the pattern of being low in the open bay segments and elevated in the Houston Ship Channel.

Where trends in the sparse, noisy data for sediment metals are statistically discernible (i.e., at a 5% significance), they tend to be declining, especially in the upper Houston Ship Channel. In the Channel, the rates of decline are sufficient to reduce after a decade sediment concentrations of chromium, mercury and zinc by a factor of two, copper and nickel by a factor of three, and arsenic, cadmium and lead by an order of magnitude.

5.3 Water and Sediment Quality Problem Areas

With the marshalling of the data of this project, one central concern is whether there are indicated any regions of the bay exhibiting degraded quality or exhibiting a trend of degradation that could bode an incipient problem. "Quality," of course, is a relative term; here it refers to the suitability of the watercourse to sustain biological activities and a viable ecosystem, and to support quality-limited human uses typical of the nature of the watercourse, e.g. recreation but (for an estuary) not water supply. This is quantified by the most recent standards and criteria applicable to Galveston Bay (TWC, 1991, EPA, 1986). These are summarized by parameter in Table 5-1. These are used here as convenient quantifications of parameter levels which *may* be indicative of degraded water quality. As our principal concern is the present quality of Galveston Bay, we have focused on data collected since 1985.

For temperature, the only violations of the 95°F (35°C) state standard (since January 1985) occurred in the Houston Ship Channel, Segments H1 (5.3%) and H17 (6.4%). Hyperthermality is not a problem in Galveston Bay.

Table 5-1
Criteria for Water Quality
(EPA Priority Pollutants in boldface)

parameter	*State of Texas Standard*	*EPA criterion (chronic) fresh*	*marine*
	WATER QUALITY INDICATORS:		
Dissolved oxygen (mg/L)	4.0 2.0 in 1006 1.0 in 1007	4[m]	
Fecal coliforms (org/100mL)	200[a] 2000[a] in: 1006 & 1007 14[a] in: 2421,2422,2423, 2424,2432,2433, 2434,2435,2439	126(406)[c]	14[s]
Temperature (°F)	95		
	METALS (dissolved):		
Arsenic (µg/L)	78	190	36
Cadmium (µg/L)	10.01	1.1	9.3
Chromium (µg/L)		11	50
Chromium (hex) (µg/L)	50		
Copper (µg/L)	4.37	12	
Lead (µg/L)	5.6	3.2	5.6
Mercury (µg/L)	1.1	0.012	0.025
Nickel (µg/L)	13.2	96	7.1
Selenium(µg/L)	136	35	54
Silver (µg/L)	0.92	0.12	
Zinc (µg/L)	89	47	58

[m] one-day minimum
[a] 30-day geometric mean
[s] shellfish harvesting, median w/<10% exceeding 43
[c] light contact recreation, 406 single-sample max

Table 5-1
(continued)

	State of Texas Standard	*EPA criterion (chronic)* *fresh*	*marine*
PESTICIDES AND RELATED PARAMETERS:			
DDT, Total (µg/L)	0.001	0.0010 (1.1)**	0.0010 (0.13)
DDE, Total (µg/L)		0.0010 (1.1)	0.0010 (0.13)
DDD, Total (µg/L)		0.0010 (1.1)	0.0010 (0.13)
Chlordane, Total (µg/L)	0.004	0.0043 (2.4)	0.0040 (0.09)
Dieldrin (µg/L)	0.0019	0.0019	0.0019
Endosulfan (µg/L)	0.0087		
Endosulfan-I (µg/L)		0.056	0.0087
Endrin (µg/L)	0.0023	0.0023	0.0023
Toxaphene (µg/L)	0.0002	0.013	
Heptachlor (µg/L)	0.0036	0.0038	0.0036
Methoxychlor (µg/L)	0.03	0.03	0.03
PCB's, Total (µg/L)	0.03	0.014	0.030
Malathion (µg/L)	0.01	0.1	0.1
Parathion (µg/L)		0.04	0.04
2,4,5 Trichlorophenol	12		
Hexachlorobenzene (µg/L)		30	129
PAH, Total (µg/L)			300*
Napthalene (µg/L)		620	
Acenaphthene (µg/L)		520	500
Fluoranthene (µg/L)			16

* acute toxicity
** instantaneous values in parentheses

For dissolved oxygen, there are scattered violations of the 4.0 criterion throughout the bay, generally on the order of 2% of the data, and most frequently in proximity to sources of inflow and wasteloads. Chocolate Bay (W7) and the Houston Ship Channel downstream from the Monument (H11) exhibit somewhat higher frequencies of violation. Given the high degree of variability in DO (as well as many other parameters), we do not consider these to evidence any serious or systematic water quality problem. (They do argue against the wisdom of an absolute-minimum, inviolate DO standard. A statistical formulation, instead, is much better suited to real-world variability.) The particular case of the Houston Ship Channel above Morgans Point, especially Segments 1006 and 1007, is treated in Tables 5-2 and 5-3. Here, the TWC Segment is broken into its component hydrographic segments for better spatial resolution. The remarkable advance in water quality is demonstrated by comparison to the pre-1985 conditions, also shown in these tables. In 1005, all violations of the 2.0 ppm DO minimum have been eliminated (and the standard for this segment is now 4.0 ppm), and in 1006 these have been substantially reduced. While violation frequencies of 50% in 1006 are now past, there is still a substantive number of violations, in excess of 10% frequency in the upper reach of this segment. In 1007, Table 5-3, where the standard is 1.0 ppm, the rate of violation has been markedly reduced from pre-1985 conditions, and is now much less than 5% except in the Long Reach (H17).

The state coliform standard applies to a 30-day geometric mean of at least five "representative" samples. For comparative purposes, we computed monthly geometric means for each segment, for each month with at least five measurements, for which the frequency of violation was determined relative to all such monthly means for the segment, again for both pre-1985 and post-1984 data. Recent coliform measurements, Table 5-4, may be biased to higher values as a sampling artifact, since in recent years, for regulatory purposes, the sampling has been directed more to events which would be expected to cause increases in coliforms. This may also be the reason for the rather high frequency of standards violations indicated in these results. Among the bay segments, Table 5-5, the most frequent violations are logged in the segments out from Clear Lake, the Houston Ship Channel, the Trinity River, Chocolate Bayou and Galveston Channel. For both the bay and the non-bay segments where the 200 org/100mL standard applies, there is no systematic change between the earlier (pre-1985) and the recent (post-1984) data, consistent with the trends analysis of Chapter 3. In the upper Houston Ship Channel, where the standard is 2000 org/100mL, there appears to have been a substantive reduction in the violation rate since 1985, though recent frequencies are still high, Table 5-6.

The state standards for metals and pesticides apply to the dissolved parameter. Those values given in Table 5-1 are the chronic marine criteria. The direct applicability of these and the EPA criteria for metals, which are developed for "acid-soluble" metal concentrations, to the Galveston Bay data base is problematic, because there are so few measurements of dissolved fractions from Galveston Bay, and these are generally below detection limits. Therefore, we have applied these criteria to the Galveston Bay data base for "total" (i.e., unfiltered) metals, which will be greater in concentration, depending upon the specific metal and the nature of suspended matter in the sample. The values in Table 5-1 are

TABLE 5-2

Frequency of occurrence of surface dissolved oxygen (WQDO within upper 0.5 m) less than 2.0 ppm Houston Ship Channel TWC Segments 1005 and 1006

segment	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	all data
TEXAS WATER COMMISSION SEGMENT 1005													
measurements before 1 January 1985													
H1	0	0	0.0714	0.0588	0.0833	0	0.0278	0	0	0	0	0	0.0179
H7	0	0	0	0.1702	0.1633	0.0833	0.0833	0.0469	0.2353	0.0303	0.1429	0.0702	0.0903
H11	0.1538	0.0303	0.1	0.12	0.125	0.0714	0.2245	0.125	0.3143	0.3235	0.1852	0.3226	0.1795
H12	0.0769	0	0.0909	0.2	0.2143	0.375	0.1818	0.1481	0.6957	0.2083	0.3529	0.05	0.2312
measurements after 1 January 1985													
H1	0	0	0	0	0	0	0	0	0	0	0	0	0
H7	0	0	0	-	-	-	-	0	-	0	0	-	0
H11	0	0	0	0	0	0	0	0	0	0	0	0	0
H12	-	0	-	-	-	-	-	-	-	-	-	-	0
TEXAS WATER COMMISSION SEGMENT 1006													
measurements before 1 January 1985													
H13	0.2857	0.1304	0.15	0.2727	0.2414	0.6	0.425	0.7576	0.6129	0.5385	0.3462	0.4231	0.4164
H14	0.5294	0.4444	0.56	0.5217	0.7037	0.9375	0.7429	1	1	0.6471	0.4545	0.6429	0.68
H15	0	0.1538	0.4286	0.2	0.9333	0.8571	0.875	0.7143	0.8125	0.6	0.2	0.0833	0.5455
measurements after 1 January 1985													
H13	0	0	0	0	0	0.2	0	0	0	0	0	0	0.0149
H14	0	0	0	0	0	0	0	0.5	0	-	-	-	0.0455
H15	0	0	0	0	0.5	0.4	0.5	0.2	0	0	0	0	0.1194

TABLE 5-3

Frequency of occurrence
of surface dissolved oxygen (WQDO within upper 0.5 m) less than 1.0 ppm
Houston Ship Channel TWC Segment 1007

segment	month												all data
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	
						measurements before 1 January 1985							
H16	1	1	0.5	0.6667	0.8	1	0.1818	0.4286	0.75	0.6667	1	1	0.5593
H17	0.1	0.129	0.375	0.4444	0.6667	0.6	0.4146	0.4177	0.4286	0.375	0.1563	0.1333	0.3655
H18	0	0	0	0.2	0	0.4	0.5	0.56	0	0	0	0	0.2973
H19	0.3158	0.3333	0.5556	0.7059	0.6087	0.7619	0.6296	0.641	0.4783	0.55	0.6471	0.3889	0.5615
H20	0	0.0769	0.375	0.3636	0.2258	0.1538	0.1739	0.28	0.1481	0.3684	0.25	0.125	0.2066
						measurements after 1 January 1985							
H16	0	0	-	-	-	-	-	-	-	0	-	-	0
H17	0	0	0	0	0	0.2353	0.1429	0.15	0.0526	0	0	0	0.0582
H18	-	0	-	-	-	-	-	-	-	-	-	-	0
H19	0	0	0	0	0	0	0.1667	0	0	0	0	0	0.0152
H20	0	0	0	0	0	0	0	0.1333	0	0	0	0	0.0136

TABLE 5-4

Frequency of occurrence of
monthly geometric-mean fecal coliforms (WQFCOLI) above 200/100 mL,
applicable segments, measurements after 1 January 1985

segment	month												all data
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	
C1	0	1	0.75	0.5	1	0	0	0	0.6	1	1	0	0.4138
C2	0	1	0.3333	0	-	0.3333	0	0	0.3333	1	1	0	0.2609
C3	-	1	-	-	-	0	-	-	-	-	-	-	0.5
C5	0	1	0.3333	0	-	0	0	0	0	1	1	0.2	0.2174
D1	0.8333	-	-	0.8	-	-	0.6	-	-	0.6	-	-	0.7143
D2	0	-	0	-	1	-	0	-	-	0	0	-	0.125
D3	0.1667	0.4	0.25	0	0.1667	0	0	0	0	0	0.5	0.2	0.15
D4	0	-	-	0	0.5	0	0	0	0	0	0	-	0.0714
D5	0	-	-	-	-	-	-	-	-	-	-	-	0
G2	0	0	0	0	0	-	0.25	0	0	0	0	0	0.0526
G22	0.2	0	0	0	0	0	0.2	0	0	0	0	0	0.0444
H1	0.1667	0	0	0	0	0	0.1429	0	0	0	0.3333	0.1667	0.0676
H2	0.2	0	-	0	-	-	0.2	-	-	0	0	-	0.1176
H4	0.25	0	-	0	1	-	0	0	-	0.3333	0	-	0.1667
H5	0.2	0	-	0	-	-	0.2	-	-	0	0	-	0.0952
H8	0	0.5	-	0	-	-	0.2	-	-	0	0	-	0.1176
H10	0.25	0.5	-	0.3333	-	-	0.2	-	-	0	1	-	0.2941
H11	0.25	0	0.1667	0.5	0	0	0.25	0	0	0.2	0.6	0.8	0.2407
T9	0.5	0	-	0	0.3333	-	0	0.25	-	0	0	-	0.1579
T18	0	-	0	-	-	0.5	-	0	-	-	1	-	0.3333
W3	0.5	0.25	0.3333	0	-	0	0	-	-	0	0	0	0.1579
W8	-	1	0	0	-	0	0	-	0	1	-	0.3333	0.2353
W18	0	0	0	0	0.2	0	0	0	0	0	0	0	0.0333

TABLE 5-5
Frequency of occurrence of monthly geometric-mean fecal coliforms (WQFCOLI) above 14/100 mL, measurements after 1 January 1985

segment	month												all data
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	
TWC SEGMENT 2421													
G1	0.75	1	0.6667	0	0	0.6667	-	0	0	0	0.5	0.3333	0.4074
G3	0.1667	0	0.4	0	0	0	0	0	0.25	0.2	0.25	0.1667	0.1296
G4	0.7143	1	0.6667	0.25	0.25	0.3333	0	0	0.5	0.6667	0.6667	0.6	0.5217
G5	0.2857	0.3333	0.1429	0.1667	0.4	0	0	0	0	0.4	0	0.3333	0.1897
G6	0.4286	0.2	0.7143	0.3333	0.4	0.5	0	0.1667	0.6	0.5	0.6	0.5	0.4242
G10	0.5	1	0.3333	0	0	0	-	0	0	0	0.3333	0.3333	0.2188
G13	0	0.25	0	0.1429	0	0	0	0	0	0.2	0.3333	0.1667	0.0896
G23	0.6	0.3333	0.6667	0.3333	0	0	0	0.25	0	0.3333	0.4	0.6	0.3256
G24	0.1667	0.25	0	0.2857	0	0.1667	0	0	0	0	0.2	0.3333	0.1311
G26	0	-	-	-	-	-	-	-	0	-	-	-	0
TWC SEGMENT 2422													
T1	0.25	0.5	0.6667	0.5	0	0	0	0	0	0	0	0.2	0.1538
T2	0	0.5	0.3333	0	0	0	0	0.3333	0	0	0	0	0.0833
T3	0	1	-	0	0.6667	-	-	0	-	-	0.2	-	0.2941
T4	0	0.5	0.1667	0	0	0	0	0	0	0	0	0.2	0.0638
T5	0.25	0.25	0.3333	0	0	0	0	0	0	0	0	0.25	0.098
T6	0.3333	1	1	0	0	0.25	0	0	0	0	0.75	0	0.3214
T10	0.1667	0	0.1667	0	0	0	0	0	0	0.25	0	0.3333	0.0962
T11	0.25	0.25	0.2	0	0	0	0	0	0	0	0.1667	0.25	0.098
T12	-	1	1	-	-	1	-	-	-	-	0	0	0.6
T15	1	-	0	-	-	0.5	-	1	-	-	1	-	0.6667

TABLE 5-5
(continued)

segment	month												all data
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	
TWC SEGMENT 2423													
E1	0.2	0	0	0	0	0	0	0	0	0	0	0	0.0217
E2	0.2	0.3333	0.2	0	0.1667	0	0	0	0	0.25	0	0.25	0.1224
E3	0.6667	0.5	0.6667	0	0	0	0	-	-	-	0	0.3333	0.3529
E4	1	0.5	0.6667	0	0	0	0	-	-	-	0	0.3333	0.4444
TWC SEGMENT 2424													
W4	0	-	0	-	-	0.5	-	-	0	1	0	0	0.1333
W6	0.3333	0.5	0.3333	0	-	0	-	-	-	0	0	1	0.2667
W9	0	0.5	0	0	-	0	-	-	-	0	0	0	0.0625
W10	0	0.2	0	0	-	0.25	0	0	0	0	0	0	0.0426
W11	0.2	0.5	0.1667	0	-	0	-	-	-	0	0	0.25	0.1471
W12	0.25	0.4	0.1667	0	-	0	1	-	-	0	0	0.25	0.1667
W13	0.3333	0.5	0.6667	0.6667	-	0	-	-	-	0	0	0.5	0.4118
W14	-	-	0.5	0	-	0.6667	-	-	0	0	-	0.3333	0.3125
W15	0.2	0.25	0.6667	0.1667	-	0.25	-	0	0	0	0	0.1667	0.2045
W21	-	0.5	0.25	0	0	0.25	-	0	0.3333	-	0	0	0.1818
TWC SEGMENT 2432													
W7	1	-	0.3333	-	-	0	-	-	0	-	1	0.5	0.4118
TWC SEGMENT 2433													
W2	0.25	0.25	0.2	0	-	0.25	0	-	-	0	0.3333	0	0.1613

TABLE 5-5
(continued)

segment	month												all data
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	
						TWC SEGMENT 2434							
W1	0	0	0	0	-	0	0	-	-	0	0	0	0
						TWC SEGMENT 2439							
G7	0.1429	0.2857	0.1429	0	0	0	0	0	0	0	0.3333	0.3333	0.1111
G8	0.25	0.3333	-	-	0	0	-	0	-	0	-	-	0.1667
G14	0.1429	0.25	0.4286	0.1429	0	0	0	0	0	0.4	0.5	0.1667	0.1818
G15	0.6667	0.8	0.6667	0.8	0.6667	0	0.25	0	0.5	0	0.4	0.5	0.4407
G16	0	0.5	0.5	0.3333	0	0.3333	0	0	1	0.5	0.3333	0.2	0.3
G17	0.2857	0.3333	0.6	0.2	0	0.25	0	0	0.25	0.2	0	0.2	0.2157
G18	0.1429	0.2	0.1429	0.1429	0	0	0.1429	0	0	0	0	0.1667	0.0833
G19	0	0.1667	0	0.1429	0	0	0	0	0	0	0.1667	0.1667	0.0556
G20	0.1667	0.25	0.2	0.4	0	0	0	0	0	0	0.25	0.2	0.125
G29	0	0	0	0	0	0	0	0	0	0	0	0.2	0.0208
G30	0.125	0.2	0	0	0	0	0	0	0	0	0	0.1667	0.0455
G32	0	0	0	0	0	0	0.3333	0	-	0	0	0	0.0526
G34	0	0.3333	0	0	0	0	0	0	-	0	0	0	0.0357
G37	-	0.5	0	-	0.5	1	-	0.2	-	-	0	0.5	0.3333
W16	0.2	0.4	0	1	0.8	0.5	0	0.3333	-	0	0.25	0	0.3333
W17	0	0.5	0	0	0	0	0	0	-	0	0	0.5	0.1053
W19	-	0	-	-	-	-	-	-	-	-	-	-	0

TABLE 5-6

Frequency of occurrence of monthly geometric-mean fecal coliforms (WQFCOLI) above 2000/100 mL, Upper Houston Ship Channel

segment	month												all data
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	
						Measurements before 1 January 1985							
						TWC SEGMENT 1006							
H13	0.625	0.1818	0.3	0.25	0.1538	0.1111	0.5	0.1818	0.1111	0.1	0.5455	0.1	0.2542
H14	0.75	0.75	0.75	0.6667	0.6667	0.5	0.5	0.6667	0.75	0.75	1	0.6667	0.6923
H15	0.7	0.5455	0.5833	0.2727	0.4615	0.3333	0.625	0.2	0.4615	0.4167	0.6667	0.3333	0.4632
						TWC SEGMENT 1007							
H16	1	1	1	1	1	1	0.6667	0.5	1	1	1	1	0.9231
H17	0.6429	0.7692	0.7857	0.7692	0.8667	0.7143	0.9167	0.9231	0.6875	0.9333	0.6923	0.8571	0.7952
H18	0.75	0.6	1	1	0.6	0.6	0.6	0.8	0.75	1	0.6667	0.5	0.74
H19	0.6429	0.6923	0.7143	0.6364	0.7333	0.7857	0.6667	0.8571	0.75	0.8571	0.7143	0.7692	0.7378
H20	0.3333	0.625	0.5714	1	0.7778	0.5	1	1	1	0.8	0.7778	0.5	0.7375
						Measurements after 1 January 1985							
						TWC SEGMENT 1006							
H13	0.4	0	0	0	0	0	0.2	0	0	0	0.6	0.2	0.1207
H15	0.4	0.25	0.1667	0.2	0.25	0.1667	0.2	0	0.2	0.25	0.6	0.6	0.2667
						TWC SEGMENT 1007							
H17	0.6	0.5	0	0.4	0.5	0.5	0.3333	0.5	0	0.4	0.8	0.4	0.4032
H19	0.2	0.2	0	0.4	0.6	0.6	0.4	0.5	0.8	0.6	0.6	0.6	0.4483
H20	0.3333	0.25	0.2	0.5	0.25	0.6	0.4	0.8	0.5	0.5	0.8	1	0.5192

almost certainly too conservative and may indicate a water quality problem that does not in fact exist. The EPA values in Table 5-1 for mercury are especially stringent, as these are based upon final residue values for methylmercury rather than final chronic values for mercury (II), due to high biomagnification potential in certain fish and shellfish. Moreover, some of these criteria, e.g. cadmium, lead, mercury, and nickel, are less than the detection limits in the data set.

The violation frequency of a representative selection of these criteria for total metals, based on measurements since January 1985, are summarized in Table 5-7. For arsenic, cadmium, chromium and nickel, significantly more violations are indicated for the more stringent of the EPA freshwater and marine criteria, suggesting that concentrations in Galveston Bay are at the threshold of what would be satisfactory for an estuarine regime. For lead, mercury, selenium, and zinc, the frequency of violations are practically identical for fresh and marine criteria. One generalization one can infer from Table 5-7 is that concentrations in excess of the criteria are generally associated with shipping in the bay, i.e. along the Houston Ship Channel, in both its open-bay and landlocked reaches, along the GIWW, and in the turning basins. This may be due in part to the concentration of urban activity and waste discharges in these same areas, and to the fact that shipping regions are generally sampled more intensively due to dredging activity, thus allowing a greater opportunity for occasional high measurements. We emphasize that dissolved metals--if we had a sufficient data base available--would exhibit lower frequencies of violations than these total-metals measurements.

With respect to pesticides and trace organics, the data base is even sparser. Analysis of the available data from Galveston Bay indicated violations of the criteria of Table 5-1 for only DDT and PCB's, as follows:

parameter	*segment*	*violations / measurements*
DDT (extended: WQ-XDDT)	H14	1/6
	H15	1/12
PCB's	H16	2/2
	H17	4/11
	S2	2/3

Of course, virtually all measurements are below detection limits, hence the rarity of criteria violation.

For sediment, the information base for standards and criteria is not nearly so great as for water quality. At present, published criteria and standards for biological and human activities do not exist. EPA is in the process of preparing such criteria. Those available as of August 1991, are compiled in Table 5-8, and are drawn from several draft publications provided by EPA in a plain brown wrapper for use in this project, but which are prohibited from citation because of their tentative nature. It is evident that only a few pesticides and PAH's are treated; criteria for metals and other organics are still in the research and development stage.

TABLE 5-7

Frequency of occurrence of violations of metals criteria (Table 5-1), measurements after 1 January 1985

seg-	As	---Cd---		---Cr---		Cu	Pb	Hg	---Ni---		---Se---		Ag	---Zn---	
ment	mar	frsh	mar	frsh	mar	frsh	frsh	frsh	frsh	mar	frsh	mar	frsh	frsh	mar
C6	0	0	0	0	0	0	1.000	0	0	1.000	0	0	-	0	0
E5	0	0	0	0	0	0	0	0	0.333	0.667	0	0	-	0.333	0.333
E6	0	0	0	0	0	0	0	0	0	0	0	0	-	1.000	1.000
E8	0	0	0	0	0	0	0	0	0.143	0.143	0	0	-	0.571	0.571
E9	0	0	0	0	0	0	0	0	0	0	0	0	-	0.286	0.286
E10	0	0	0	0	0	0	0	0	0	0.400	0	0	-	0.600	0.600
G2	0.200	0.200	0	0	0	0.400	0.600	0.200	0.200	0.400	0	0	0.200	0.400	0.200
G10	0	0	0	0	0	0	0	0	0	0	0	0	-	0	0
G11	0	0	0	0	0	0	0	0	0	0	0	0	-	0	0
G13	0	0	0	0	0	0	0	0	0	0	0	0	-	0	0
G14	0	1.000	0	1.000	0	0	0	1.000	0	0	-	-	-	1.000	1.000
G15	0.250	0.375	0	0.375	0	0.375	0	0.375	0	0.250	0	0	-	0.125	0
G16	0	0.333	0	0.333	0	0.333	0	0.333	0	0.333	0	0	-	0	0
G17	0.167	0.500	0	0.500	0	0.500	0	0.500	0	0	0	0	-	0.167	0
G18	0.177	0.412	0	0.294	0	0.235	0.118	0.471	0.059	0.353	0.077	0	0	0.412	0.235
G19	0	0.500	0.500	0.500	0	0	0	0.500	0	0	0	0	-	0	0
G22	0	0	0	0	0	0	1.000	0	0	1.000	0	0	-	1.000	0.750
G23	0	0	0	0	0	0	0.667	0	0	0.667	0	0	-	0	0
G24	0	0.333	0	0.333	0	0.333	0	0.333	0	0.333	0	0	-	0	0
G26	0	0.750	0	0.750	0	0	0	0.750	0	0	0	0	-	0	0
G33	0	0	0	0	0	0	0	0	0	0	0	0	-	0.143	0.143
G34	0	0	0	0	0	0.143	0	0.143	0	0	0	0	-	0.143	0.143
G35	0	0	0	0	0	0	0	0	0	0	0	0	-	0.167	0.167
G36	0	0	0	0	0	0	0	0	0	0	0	0	-	0.333	0.333
G37	0	0	0	0	0	0	0	0	0	0	-	-	-	0	0
G38	0	0.250	0	0	0	0	0	0	0	0	0	0	-	0	0
H1	0.154	0.385	0.154	0.154	0	0.423	0.346	0.240	0	0.500	0.191	0.095	0.095	0.385	0.346
H7	0	0	0	0	0	0	0.500	0	0	1.000	0	0	-	0.500	0
H11	0.056	0.222	0.111	0.111	0	0.389	0.333	0.222	0	0.389	0.111	0.111	0.125	0.444	0.444

TABLE 5-7
(continued)

seg-ment	As	---Cd---		---Cr---		Cu	Pb	Hg	---Ni---		---Se---		Ag	---Zn---	
	mar	frsh	mar	frsh	mar	frsh	frsh	frsh	frsh	mar	frsh	mar	frsh	frsh	mar
H12	0	0	0	0	0	0	1.000	0	0	1.000	0	0	-	1.000	1.000
H13	0.111	0.333	0.111	0.167	0.056	0.389	0.167	0.167	0	0.667	0.222	0.056	0.111	0.667	0.611
H14	0	0	0	0	0	0.167	0	0.500	0	0	0	0	-	0	0
H15	0.083	0.208	0.125	0.042	0.042	0.333	0.125	0.292	0	0.333	0.136	0.046	0.105	0.417	0.333
H16	0	0	0	0.500	0	0	0	0	0	0	0	0	-	1.000	0.500
H17	0	0.182	0.091	0.091	0	0.273	0.273	0.227	0.046	0.273	0.046	0.046	0.294	0.727	0.682
H18	0	0	0	0	0	0.250	1.000	0	0	0.500	0	0	-	0.750	0.500
H19	0.044	0.217	0.174	0.130	0.044	0.522	0.304	0.261	0	0.474	0	0	0.091	0.435	0.391
H20	0	0	0	0.800	0	0.400	1.000	0	0	1.000	0	0	-	1.000	1.000
M3	0	0	0	0.333	0	0	0	0.333	0.133	0.333	0	0	-	0.467	0.333
S1	0	0	0	0	0	0	0	0	0	0	0	0	-	0	0
S2	0	0	0	0	0	0	0	0	0	0	0	0	-	0	0
T5	0	0.500	0	0	0	1.000	0.500	0	0	0.500	0	0	0.500	0	0
T11	0	0	0	0	0	0.333	0.200	0.467	0	0	0	0	0	0.200	0.200
T12	0	0	0	0	0	0	0.400	0.400	0	0	0	0	-	0.400	0.400
T15	0	0	0	0.333	0.333	1.000	0	1.000	0	0	0	0	-	0.333	0
T17	0	0	0	0	0	0	0	1.000	0	0	0	0	-	0	0
W2	0	0	0	0	0	0	0.333	0.667	0	1.000	0	0	0	0.667	0.667
W6	0	0	0	0.200	0	0.400	0	1.000	0	1.000	-	-	-	0.400	0.400
W7	0.111	0.778	0.111	0.111	0	0.556	0.889	0.111	0	0.778	0.111	0	0.500	0.556	0.556
W8	0.286	0.429	0	0	0	0.143	0.429	0.143	0	0.429	0.143	0.143	0.500	0.714	0.714
W16	0	0	0	0	0	0.500	0	0.900	0	0.500	-	-	-	0.500	0.500
W18	0	0.400	0	0.400	0	0.400	0.400	0.200	0	0	0	0	0	0.200	0.200
W19	0	0	0	0	0	0	0.333	0.167	0	0	0	0	-	0.333	0.333
W20	0	0	0	0	0	1.000	0	0.600	0	1.000	-	-	-	0.600	0.200

As: no violations of the freshwater criterion in the data set
Pb: one less violation of marine criterion (Segment H15) than freshwater
Hg: same frequency of violation for both fresh and marine criteria

Table 5-8

Sediment Quality Criteria (saltwater) for Study Parameters
(Compiled from unpublished EPA sources)

parameter	*concentration** *(mg/kg C)*
DDT	0.828
Dieldrin	0.130
Endrin	0.49**
Heptachlor	0.104
PCB (1254)	41.8
Fluoranthene	1883
Benzo(a)pyrene	1063

*Based on the lower of the Final Chronic Value and the Final Residue Value, if both are given.
**From Pre-draft Criterion of August 1991.

Criteria for sediment are not expressed in concentration, because the effects of contaminants in sediments are modulated by the bioavailability of the constituent, which is in turn a function of the partitioning of the constituent between the particulate and interstitial water components of the sediment, and the make-up of the sediment itself. EPA has adopted the Equilibrium Partitioning (EqP) approach to determination of sediment quality. The EqP model is a means of deriving equivalent sediment quality impacts from already-extant results for water quality, and in particular models the partitioning and bioavailability of the contaminant by its behavior with respect to sediment organic carbon. Therefore, the criteria in Table 5-8 are applicable to the contaminant concentration normalized to the concentration of organic carbon in the sediment, hence the units are contaminant mass per unit mass of organic C.

Although a general distribution of organic carbon in the bed sediments of Galveston Bay has been compiled in the present data base, the extreme heterogeneity of organic C requires that the contaminant and TOC analyses be performed on the same sample. Clearly, if sediment organic carbon was not measured on the same sample as the contaminant--unfortunately the usual case for Galveston Bay data--the criteria cannot be strictly applied. In order to determine, at least approximately, whether any of these criteria are violated in Galveston Bay, we have employed the segment average TOC distributions in such an evaluation. For only two parameters were there violations of the criteria, DDT and Dieldrin, to wit:

parameter	*segment*	*violations (%)*
DDT (extended: SED-XDDT)	H14	16
	H15	50
	H17	18
	W21	33
Dieldrin (SED-DIEL)	H17	33
	W21	33

All of these segments are in regions exposed to urban runoff.

In summary, the geographical problem areas of Galveston Bay hold no real surprises; they are where we expect them to be: in regions of intense human activity, including urban areas, points of surface runoff, waste discharges, and shipping. Perhaps unexpectedly, the quality of the bay is generally good, and where it is degraded there is a pattern of improvement.

From a systemic point of view, the most significant potential problem area affecting the bay as a whole is the general decline in particulates and nutrients. Of course, whether this is a problem or an improvement depends upon the optimum levels for Galveston Bay. Much more research is needed on the total ecosystem to establish these optima. While no definitive statement is possible, there is a discomforting chain of speculation. With the assumption that some of these nutrients, especially nitrogen, are limiting, and are at or below optimum, their decline in the last two decades should directly affect the phytoplankton of the bay. The effect would be gradual in time, because of the large mass of nutrients locked up in phytoplankton and their cycling internal to the bay. The observed decline in chlorophyll-a is consistent with such an algal response. If this trend is indicative of a large-scale decline of the base of the food chain, there should be a correlated decline in abundance of some higher organisms. This would be best manifest in those low-trophic-level organisms that are more or less permanent residents of the bay or sustain most of their growth to adulthood in the bay, examples being blue crab, mullet, and white shrimp. Trend data for these three are presented in the companion GBNEP study report on Status and Trends of Living Resources (Green et al., 1991). For blue crab, the results of Green et al. (1991) show an increasing trend in young of the year since 1983 (a function of recruitment and therefore not reflecting habitat within the bay), declining trends in juveniles and first-time spawners (by trawl, but no trend for first-time spawners by gill net), and a rather precipitious drop in larger adults, by a factor of three since 1986. Green et al. (1991) express concern at these declining patterns, and note also a decrease in mean size by over 20% since 1982. For striped mullet, the longest period of data for adults presented by Green et al. (1991) is gill-net records extending back to 1975. These show a nonlinear decline, the entirety of which is due to a reduction in catch of roughly a factor of three between 1975-77 and 1978-89. White shrimp exhibit the most dramatic decline of all. Green et al. (1991) display a steep decrease since the early 1980's, in all size classes and by all gear types. This decline is on the order of a factor of five in abundance. Certainly overharvesting is a probable culprit, as Green et al. (1991) suggest, but it may not be the only factor.

Few inferences can be more fraught with hazard than assigning causality to correlated trends. Nor do we wish to be guilty of oversimplifying a complex and dynamic system. On the other hand, the pathway from nutrient-particulate loads through receiving-water concentrations to algal uptake thence assimilation into the food chain is fundamental to the estuarine ecosystem. That a correlated trend seems to be manifest in indicators of every element of this pathway, and that this trend points toward a declining productivity for the bay, are sufficient to warrant increased attention.

5.4 Recommendations

5.4.1 Data Collection and Archiving

The primary requirement of any data collection program is to perform measurements targetted at the principal question or function which that program addresses. For research studies, the data-collection strategy is tailored to the scientific hypothesis to be tested. Many state and federal agency programs have statutorily defined missions, that in turn dictate their sampling strategies. Therefore, to the extent that any given survey is properly designed to achieve its mission, our recommendations for its performance are superfluous.

On the other hand, few programs can afford the investment of long-term, intensive data collection in a system such as Galveston Bay. To address scientific and management questions that require such massive data bases, we must depend upon the use of data collected by different agencies for perhaps different purposes. In this sense, data collection should be regarded as a collective enterprise, and its design should reflect a certain degree of scientific altruism, to ensure maximal utility of the data without unduly hampering the measurement procedures or project resources. It is in this spirit that we offer several concrete recommendations. In summary, these recommendations argue that data programs should be somewhat more careful, collect somewhat more measurements, and facilitate somewhat better their data dissemination, than strictly required for the mission at hand. These are founded on four precepts of data collection effectiveness, stated below, observation of which, we submit, will go far in achieving broader utility of collected data.

1. The density of independent measurements of a parameter should be commensurate with the space and time variability of that parameter and over the range of variation of the external factors.

2. Incremental cost relative to the total investment in effort to obtain a suite of measurements should be the governing criterion for inclusion of additional measurements.

3. Sampling design should be cognizant of the historical record of related parameters: the value of an extended historical record transcends the current utility of the parameter.

4. Data recording and archiving should minimize potential loss of information.

We re-emphasize that Galveston Bay is a highly variable environment, subject to many external factors, each of which contributes a degree of "noise" in any measured parameter. To filter this noise, and expose variations in time and space, requires that sufficient independent measurements be available over the range of variation of the external factors. For time variability, continuity of data record is an all-important property of any data base. For space variability, a high density of sampling stations repeatedly sampled is necessary. Specific recommendations, as well as some amplification of these precepts, are as follows:

(1) A greater sensitivity is recommended to the investment in putting a sampling crew (and usually a boat) on a specific station, versus the efficiency of observations once there, as expressed by *Precept 2*. The incremental cost in acquiring additional measurements (including loss of efficiency) must be weighed against the (much larger) cost of occupying the station, in specifying the suite of parameters to be obtained. Whether these additional measurements have immediate application is unimportant; they may be peripheral or irrelevant to the objective of the project, but have great value for other objectives and therefore justify the small incremental cost for their acquisition. We suggest that short lists be formulated of "recommended" parameters, to be included within suites of measurements of various classes, to provide guidance to anyone undertaking a sampling project. When the major investment of time and expense is to place a boat crew on station, a few *in situ* measurements should be standard procedure. If the crew is equipped with electrometric over-the-side probes, a vertical profile instead of a single depth should be routine. Some limited water sampling may also be simply accommodated, perhaps just surface grab samples for straightforward lab analyses. Notation should always be made of conditions, sampling location, and time and date.

(2) The same principle of incremental cost versus benefits should be considered in specifying laboratory analyses. Many procedures, e.g. mass spectrometry or grain-size by settling tube, are cost-loaded in sample preparation, and can admit additional parameters or greater resolution with minor incremental cost. A certain altruistic philosophy is necessary in the sampling agency, to acquire measurements that may be irrelevant to the immediate objective, but from which others will benefit.

(3) Necessity for both continuity in time and continuity in space must be recognized, as well as the need for maintenance of a long period of sampling. (*Precept 3.*) There are numerous examples in the data record when a parameter is suspended from further measurement. In most cases, this has involved a replacement of the old parameter with a new one. When a new, more accurate parameter is considered to replace another, there should be a continuation of data for the older variable together with the new parameter to at least establish an

empirical relation. It may be more important to continue the measurement of the older parameter, to preserve the continuity of record, even if the utility of that parameter is limited compared to the new one.

(4) We note that the intratidal-diurnal scale of variability is virtually unsampled in Galveston Bay, yet there are several parameters, such as dissolved oxygen, temperature and salinity, with significant variation on these scales. (*Precept 1.*) The use of electrometric sensing and automatic data logging now permit the recovery of nearly continuous, fine-scale time signals of several of these parameters, and should be incorporated into routine monitoring of the bay, perhaps in association with tide gauging. The Texas Water Development Board has made significant advances in the application of these techniques, though its emphasis thus far has been on the lower bays on the coast. NB, such data acquisition should not replace routine sampling, since routine sampling provides far better spatial continuity than is practical to achieve with automatic monitors.

(5) *Precept 4* above addresses the need for great sensitivity to potential loss of information. Data entry (i.e., transcription) errors are a prime cause of information loss, and any data entry procedure should include a means of verification. Any data collection program should include procedures of data screening and data-entry verification, from the original lab sheets to the digital data file. While this recommendation may seem trivially evident, the occurrence of obvious errors in all of the state data bases (to say nothing of inobvious errors) indicate that present procedures are inadequate. When the data entry is recent and the raw data sheets are still available, errors are easiest to detect and correct. Error correction at the data entry step may very well track back to the recording and/or acquisition of data. For this reason, data entry should be performed in a timely manner, not months after the event. Data-checking procedures represent the obverse face of *Precept 3*. Their implementation may be viewed as a redundant cost item in data acquisition, absorbing funds that might be better spent in a boat. Such a view is myopic, because the expense of data checking shrinks to negligibility compared to the unit cost of acquiring and analyzing a water sample. One can not afford to lose that considerable investment because of an errant keystroke. Moreover, the place that water sample potentially holds in a space or time trend may be invaluable. Data checking is an absolutely indispensable investment to preserve the information in a measurement.

(6) Data entry error is not the only means of losing information from data collection. Replacing a series of raw measurements over time or space by an average, failing to preserve information on sampling time, position or conditions, or intermixing actual measurements with "estimated" values without any means of differentiation, all represent losses of information, and are all practices that can be avoided with care and forethought. One particularly ubiquitous practice is to combine measurements from one's own data collection with data drawn from other sources, perhaps processed. This is ubiquitous because of the use of combined data bases in scientific analysis, exactly as carried out in this project. This intermixing may be compounded by further processing, e.g. averaging together. The danger lies in not maintaining a separate and uncorrupted file of the original measurements. We recommend adherence to the same principle of

preservation of data integrity observed in this project. Agencies should differentiate between the data record of observations obtained by that agency, and a compiled data record of those and other external measurements, possibly further processed.

Additional recommendations specific to data collection practices in Galveston Bay are as follows:

(7) Some measure of suspended solids (e.g. turbidity) should be included in routine monitoring. For nutrients, metals, organic pesticides, PAH's or similar constituents that have an affinity for particulates, suspended solids *per se* should be routinely determined as part of the suite of measurements. Further, the analysis should include grain-size distribution or at least a sequential filtration to determine partitioning of clays-and-finer and silts-and-coarser.

(8) A major deficiency of the sediment data base is that there are almost no paired measurements of chemistry and sediment texture (i.e., grain-size distribution). Analysis of the variability of many of the parameters of concern in environmental management, such as heavy metals and pesticides, must consider the grain-size fractions. We recommend that texture analysis be instituted as a routine aspect of any chemical analysis of a sediment sample.

(9) Because of the future potential rôle sediment organic carbon may play in evaluating sediment chemistry with respect to a standard, presuming the EPA EqP approach is adopted, we recommend that organic carbon be instituted as a routine aspect of any chemical analysis of sediment involving non-ionic organic contaminants, especially organohalogens. While it is premature to offer this as a recommendation, we draw attention to the possible rôle of acid volatile sulfide as a normalizing parameter for standards for metals in sediments, hence the desirability of instituting this parameter as a routine aspect of any chemical analysis of sediment involving heavy metals.

5.4.2 Water and sediment quality studies

On a more strategic level, regarding our understanding of water and sediment quality and information needed for effective management of the Galveston Bay resources, we recommend the following:

(1) The data base assembled in this project is capable of many more analyses. In particular, it may be useful to examine the effects of varying temporal sample density on statistical bias, to normalize the data to uniform periods of record, and to carry out more sophisticated statistical examinations than could be mounted within the scope of this project. Detailed mass-budgeting studies are needed to determine the probable cause of the apparent declines in particulates and nutrients, perhaps in concert with hydrographic analyses or deterministic models, using the data base compiled in this project. These should include detailed information on waste discharges and reservoir entrapment. Event-scenario analysis as well as time-series studies could both provide insight. This

should be extended to include numerical modeling, as an "interpolator" in space and time.

(2) Additional analysis of chlorophyll-a and related measurements from Galveston Bay, in association with *in situ* productivity studies are needed. Some special-purpose data collection activities, such as the Intensive Surveys of the Texas Water Commission and the National Marine Fisheries Service might be profitably used in a more targeted analysis. These studies should include detailed examination of phytoplankton dynamics in Galveston Bay, and its dependence on water quality.

(3) Metals and trace organics remain a major concern. The present analysis was significantly delimited by the sparsity of data and the precision of measurement. Clearly, more and better measurements are necessary to assess and monitor this suite of variables. On the other hand, the investment in complex and demanding analyses does not at the moment seem highly critical to the management of Galveston Bay, apart from the present state and federal activity in wasteload regulation. While monitoring should continue, we do not believe that merely intensifying that monitoring will yield information in proportion to investment. We recommend a research focus on:

(a) improved measurement methodology, including relations with and among older methods, for interpretation of historical data, and better determination of precision and accuracy,
(b) bioaccumulation of metals and trace organics,
(c) detailed studies on kinetics and fluxes in carefully selected regions of the bay subject to identifiable and quantifiable controls
(d) exploration of suitable tracers and their measurement, such as aluminum, to separate natural and anthropogenic sources of metals.

While information is needed on open-bay environments in general, the greater effort should be invested in those regions already manifesting a proclivity for elevated metals and pesticides, i.e. in regions of runoff, inflow, waste discharges and shipping.

(4) In an estuary as turbid as Galveston Bay, the rôle of sediments in suspension and in the bed is quintessential. Every element of the sediment transport process is imperfectly understood, as manifested in our inability for quantification, from riverine loads to exchange with the Gulf, from scour and deposition on the estuary bottom to shoreline erosion. The affinity of many key pollutants for particulates, especially metals and pesticides, and the dynamics of transport and exchange within the estuary, render an understanding of sediments absolutely indispensable to the management of water quality in general. This is compounded by the activity in Galveston Bay of dredging, shoreline alteration, and trawling, as well as the clear alterations in suspended sediments in recent years In our view, sediment dynamics should be the focus of a renewed research effort in the bay, ranging from more detailed observation on grain-size spectrum and its effects, to biokinetic processes operating within the sediment itself.

(5) The observed decline in temperature is probably not a serious concern from the water-quality management standpoint, but additional examination of its cause, especially if of climatological origin, may provide additional insight into other processes, such as the decline of chlorophyll-a and the kinetics of dissolved oxygen. We would recommend some modest examination of long-term variability in the climatological controls of the surface heat budget.

(6) The salinity data base assembled in this project is the most comprehensive available for Galveston Bay (and probably any of the Texas bays) and will support analytical studies of salinity response heretofore not possible. It is recommended that salinity variability in Galveston Bay be examined using sophisticated methods of time-series and response analysis to better delineate the rôle of inflow and other hydrographic factors on salinity. This would be valuable, not only because of the intrinsic importance of salinity as a hydrographic and ecological variable, but to yield insight into the time-response behavior of other, less intensely sampled parameters whose concentrations are dominated by internal transports.

(7) The significant observed decline in salinity underscores the gaps in our understanding of even as fundamental (and conservative) a parameter as this. We recommend additional studies of the external controls on salinity. This could probably be most usefully pursued, at least at the outset, by extending the scope of empirical analysis to include the hydrography of the nearshore Gulf of Mexico. As with nutrient and particulate loading, we believe event-scenario and time-series analysis to be most promising. There is also a place for hydrodynamic modeling, but only after the essential controls and responses of the system are much better defined.

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