7. 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). The more prominent of these are reviewed in the first section below, with specific attention given freshwater inflow and density variation as controls.

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 7-1 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 7-1, 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.,

TABLE 7-1

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

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 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.

7.1 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. The principal astronomical determinant for tidal variability is 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. The mid-bay constriction at Redfish Reef reduces the tidal amplitude to about 1 ft and significantly filters the semidiurnal component. Ward (1991) examined dense synchronous tide records from the late 1930's and observed:

(1) The tide loses 30-40% of its range just in traversing the inlet, i.e. from the ocean tide at the south jetty to the tide at Bolivar Point.

(2) Within the scour region of the main inlet, as indicated by the range at Texas City Dike, the tide is attenuated to less than 40% of that of the Gulf.

(3) From the mid-bay constriction at Redfish Bar north, i.e. the upper bay and Trinity Bay, the range is less than 40% of that at the Gulf, and at the end of the enclosed basin of East Bay the range is 45% of that at the Gulf. All of these values are somewhat amplified by the effects of enclosed physiography.

(4) Behind the flood bar of San Luis Pass, the Gulf tide is attenuated a factor of three.

(5) The tide at Karankawa Reef in mid-West Bay is greater than that inside San Luis Pass, suggesting an importance of the tidal propagation

Bolivar Roads at least equal to that from San Luis Pass, and perhaps some co-oscillation as well.

The tide is manifested in the inlets and lower segments of the bay as a progressive long wave. Within the bay, the effects of constraining physiography introduces a standing-wave component, and above the mid-bay constriction at Redfish Reef, the tide becomes predominantly a standing wave. An analysis of current and stage measurements is presented in Ward (1991) to demonstrate the progressive character of the tidal wave in the lower bay, for which synchrony is diagnostic.

These observations are relative to variation over a tidal cycle and do not represent the total excursion in water level in Galveston Bay. 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. In the Gulf there is a longer-term secular rise and fall in water levels, partly astronomical in origin, but mainly climatological. The seasonal meteorology leads to a characteristic annual variation in water levels along the nearshore Gulf of Mexico, bimodal along the Texas coast with maxima in spring and fall, and minima in winter and summer. The winter minimum and fall maximum predominate this pattern, with a net range on the order of 0.3 m (Ward, 1991). The long-term mean range in the *monthly mean* tide record at Galveston is from -2.8 to +1.8 ft NGVD (Harris, 1981), which includes both astronomical and meteorological effects. Further, meteorological systems can induce shorter term fluctuations in Gulf water levels, so-called "wind tides" described further below.

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 7.2 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. Windwaves are important from the standpoint of creating intense vertical mixing, and thus vertical near-homogeneity of waterborne constituents, especially in the shallow portions of the system. Windwaves also aerate the water column. There is little quantitative information available concerning the wind-driven circulations, but the existence of these large-scale circulations is predicted by dynamical models, and has been documented in several areas of the bay. One notable example is the general clockwise circulation developed in Trinity Bay by wind from the southeasterly quadrant, as evidenced by preferential salinity intrusion along the north shore.

Perhaps the most dramatic meteorological effect is that of denivellation, i.e. meteorologically forced variations 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 produce 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. This is the classical estuarine density current observed in these types of systems since the nineteenth century, whose mechanics is that of denser water underflowing and displacing lighter water. 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. In a broad estuary with a natural bathymetry of deeper water near the center and shallower near the side, a combined circulation results with both horizontal and vertical shear, and with secondary circulations in a plane inclined intermediate between the vertical and the horizontal. In Galveston Bay, we have both extremes, the confined rectilinear channel with nearly pure vertical circulation, and the deep slot in a broad shallow bay, with very nearly horizontal circulation. Examples of the presence of density currents from measurements of current velocity in the bay are given in Ward (1991).

The above 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.

7.2 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 (in contradistinction to the Trinity which extends well into North Texas) 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 principal USGS streamflow gauge on the lower reach of the Trinity is at Romayor. (The drainage area below the Romayor gauge contributes an additional flow of about 5%.) The record of monthly flows at Romayor 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. 7-1 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 maf (million acre-feet), began deliberate impoundment in summer 1969. In Fig. 7-2 is shown the variation in flows of the summer "drought" period, defined here as July-October, for the same period of record. Several observations are noted from these analyses (not all inferred from Figs. 7-1 and 7-2):

(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 Fig. 7-1 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.

(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 Fig. 7-2 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.

Analysis of the summer low-flow behavior of the Trinity based upon the gauge at Romayor as an index to inflow into the bay must be couched with the fact that there are withdrawals from the river below Romayor, principally for irrigation during May-September. During the summer drought, the diversions for irrigation can impose a significant decrease in the river flow reaching the bay, and even consume the entirety of the river flow under conditions of prolonged drought. Since the operation of Livingston was begun (about 1970), the river channel is used for delivery of water released from Livingston for downstream withdrawals, which is reflected in the gauge record at Romayor. Moreover,

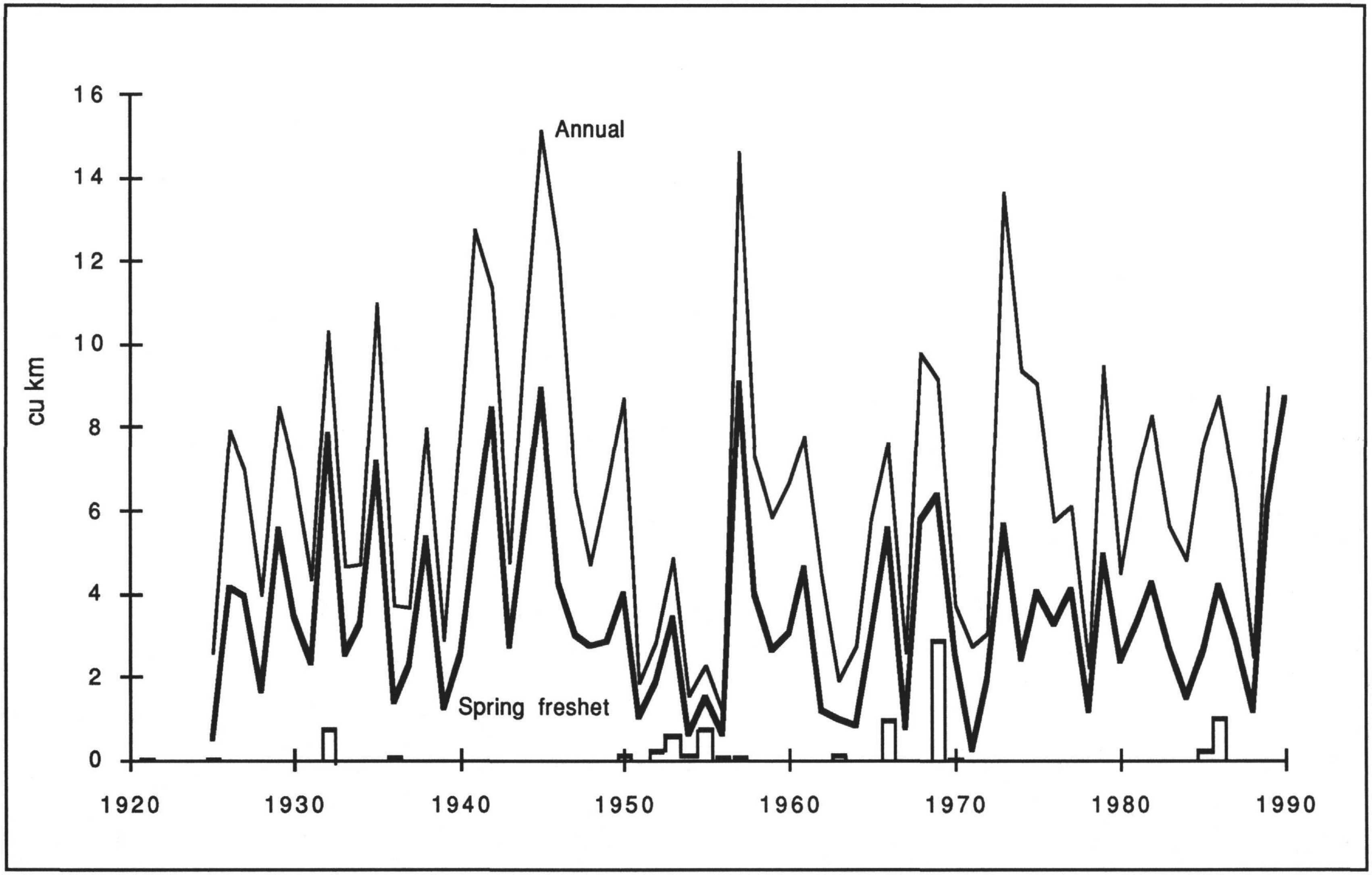

Fig. 7-1 Annual flow volume of Trinity River (at Romayor) and volume of 3-month spring freshet. New reservoir capacity per year shown as bars.

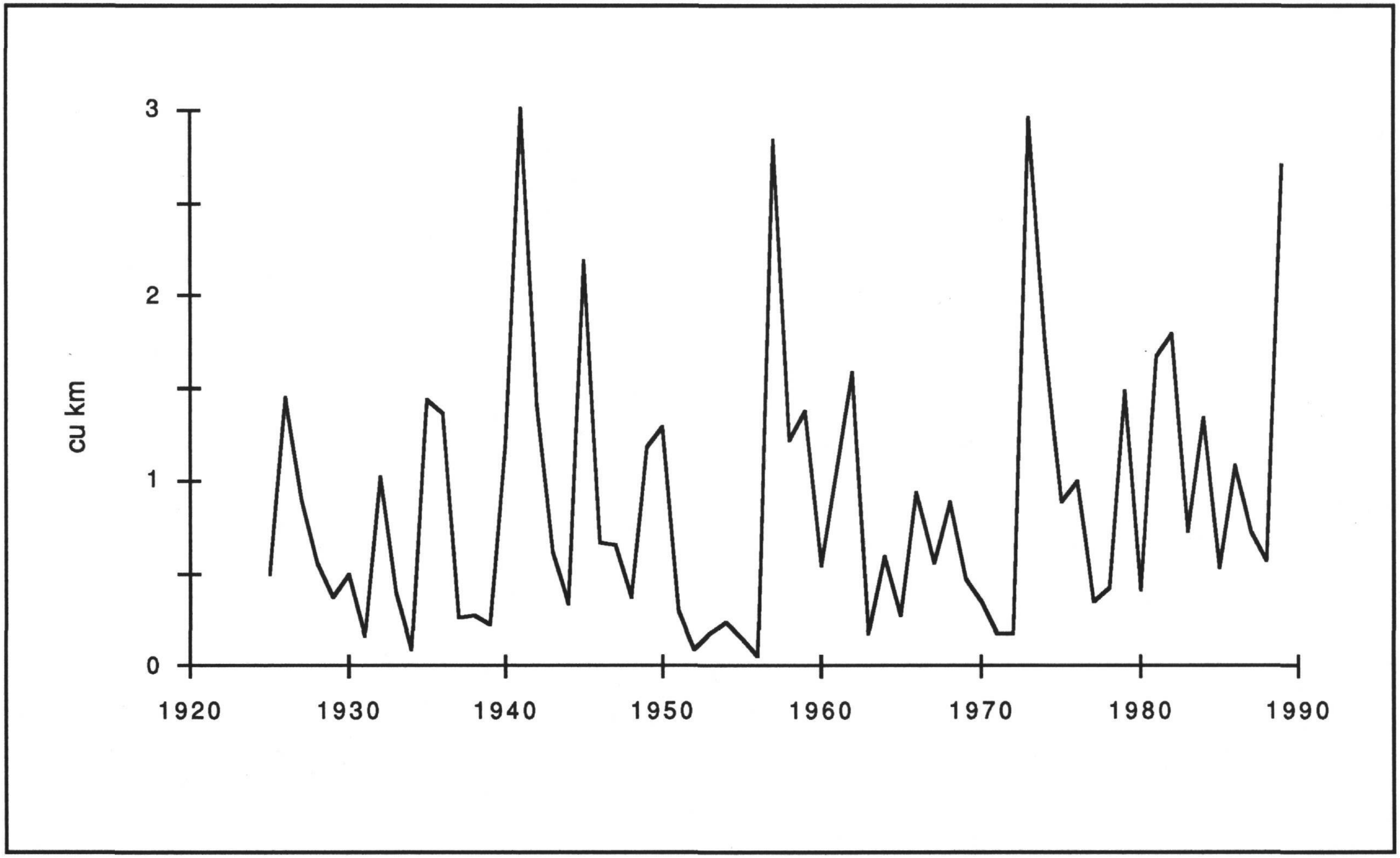

Fig. 7-2 Summer "drought" flows (JASO) of Trinity River

Livingston for saltwater extrusion in the river channel, which are included in the Romayor record as well. (Pending construction of a salt barrier in the Trinity River, a release of 1000 cfs from Livingston in *excess* of downstream water rights was agreed to be made during irrigation season, on an as-needed basis.)

7.3 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. The recent history of wasteload reductions in the Houston area, especially to the Houston Ship Channel, is recounted by EPA (1980) and Powelson (1978), and summarized in Armstrong and Ward (1992). 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:

	Domestic		*Industrial*		*Total*	
Date (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, 1992). 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 complex 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 (1.1×10^4 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 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. 7-3. 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, Fig. 7-4. (The nitrate loads in this figure are single measurements of concentration and flow. The loads in Fig. 7-3 are true annual loads, based upon many individual measurements per year, estimation of missing data by TSS vs. flow relationships and integration over the year.) There is clearly a reduction in both the mean concentration and the variance with Livingston on-line, that would be even more 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, $r=.077$), or total phosphorus (145 measurements, $r= 0.17$).

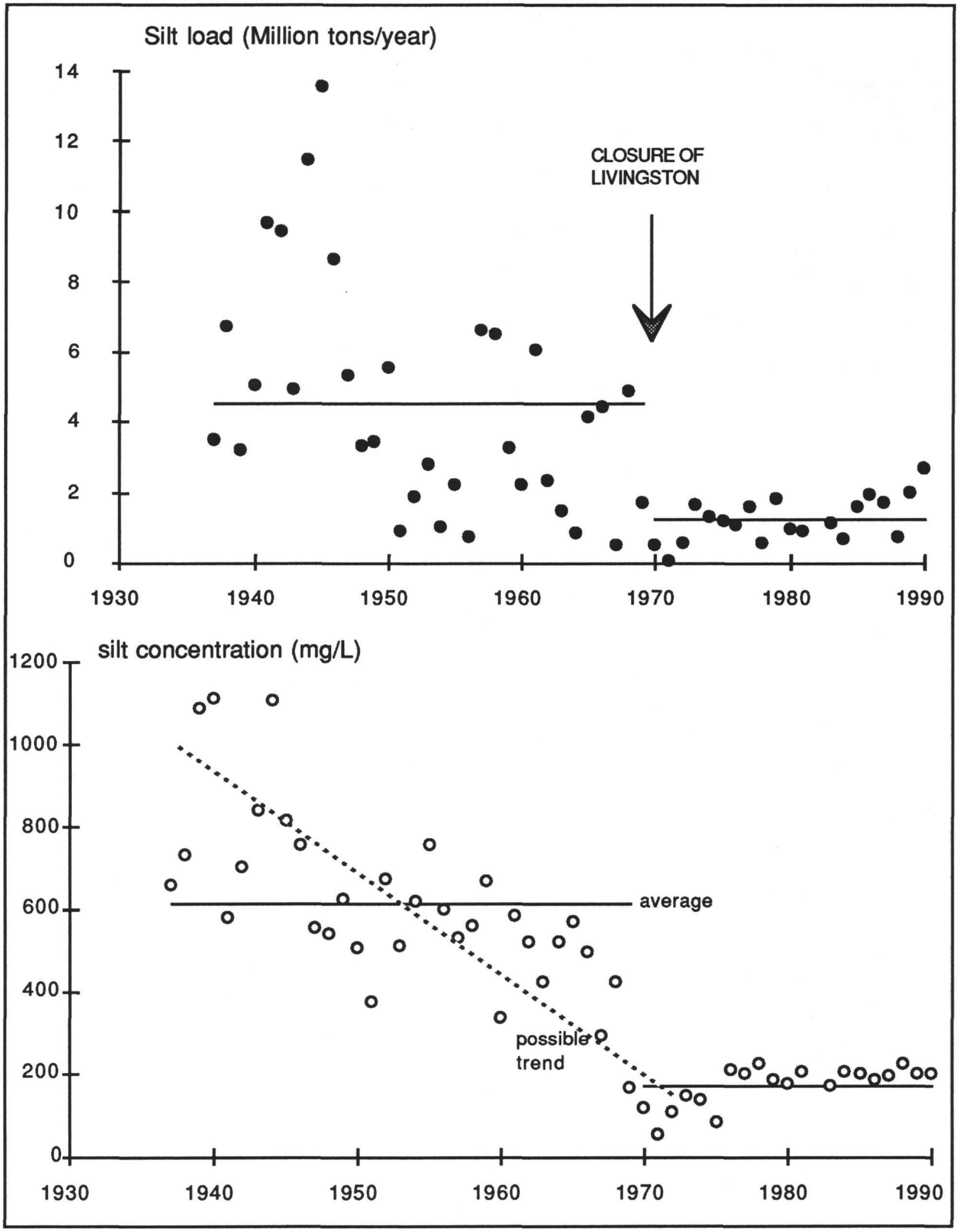

Fig. 7-3 Historical variation of silt load of Trinity River at Romayor, from data of Bloodgood & Meador (1945), Board of Water Engineers (1955), Stout et al. (1961), Adey & Cook (1964), Cook (1967, 1970), Mirabal (1974)

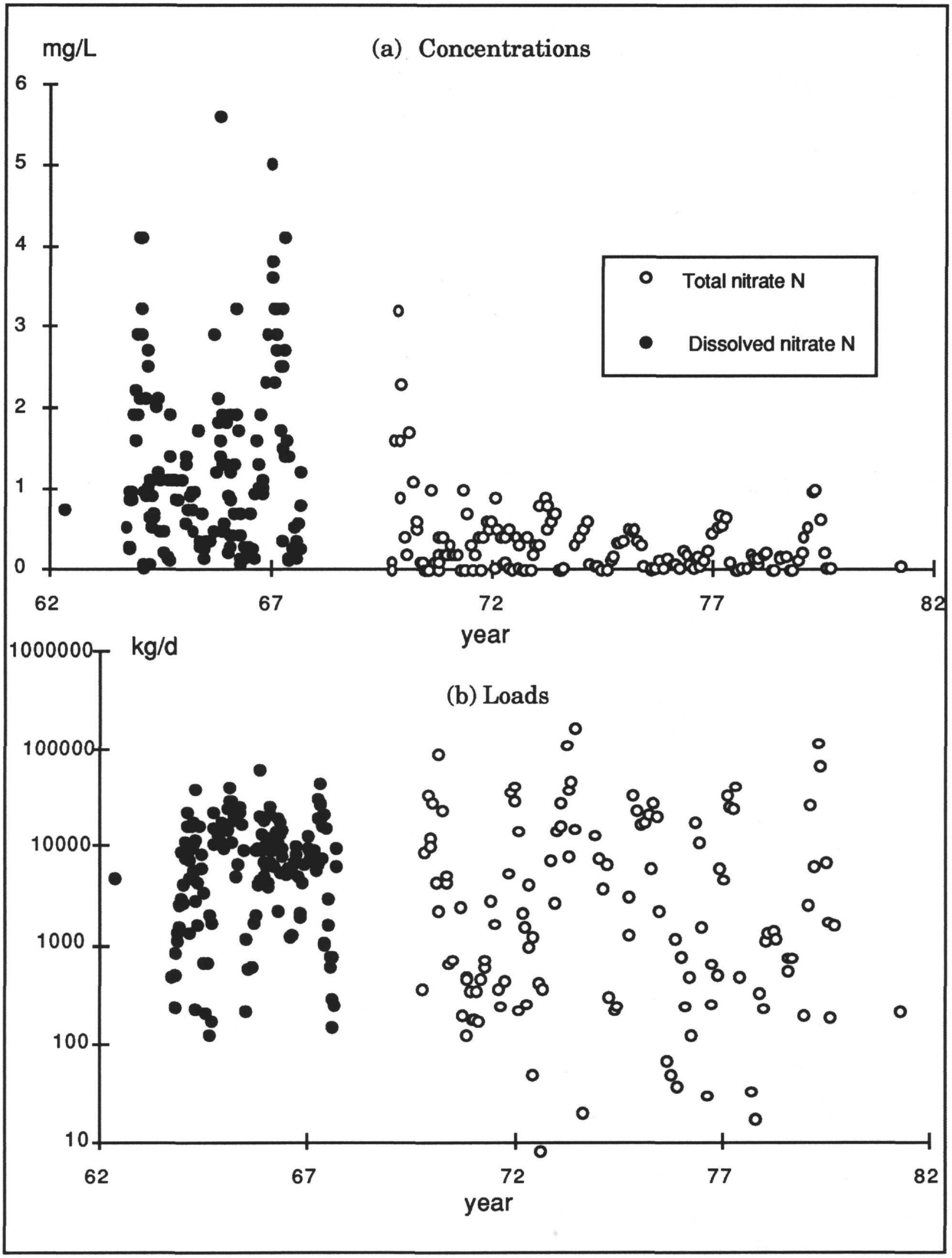

Fig. 7-4 Time history of nitrate in Trinity River at Romayor

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.

7.4 Water and Sediment Quality Responses

7.4.1 Temperature and Salinity

Temperature in Galveston Bay is governed primarily by surface heat exchange, which imposes a strong seasonal signal. As noted in Chapter 5, 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 homogeneous. The latter is consistent with the domination of surface heat fluxes, so that boundary fluxes become much less important.

The most significant observation from the analyses of Chapter 5 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 that 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. 7-5, 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. Generally, the salinity at a point in the bay is better correlated with the average flow over the preceding several weeks. In Fig. 7-6 is shown the improvement in statistical association achieved by time averaging the river flow, for a range of averaging periods, at segments in the middle regions of Galveston Bay. The corresponding salinity versus river flow scatterplots are shown in Fig. 7-7. While the explained variance can be more than doubled (in this region of the bay) by this device, the optimal averaging still accomplishes little more than 50% explained variance. 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 from fresh to

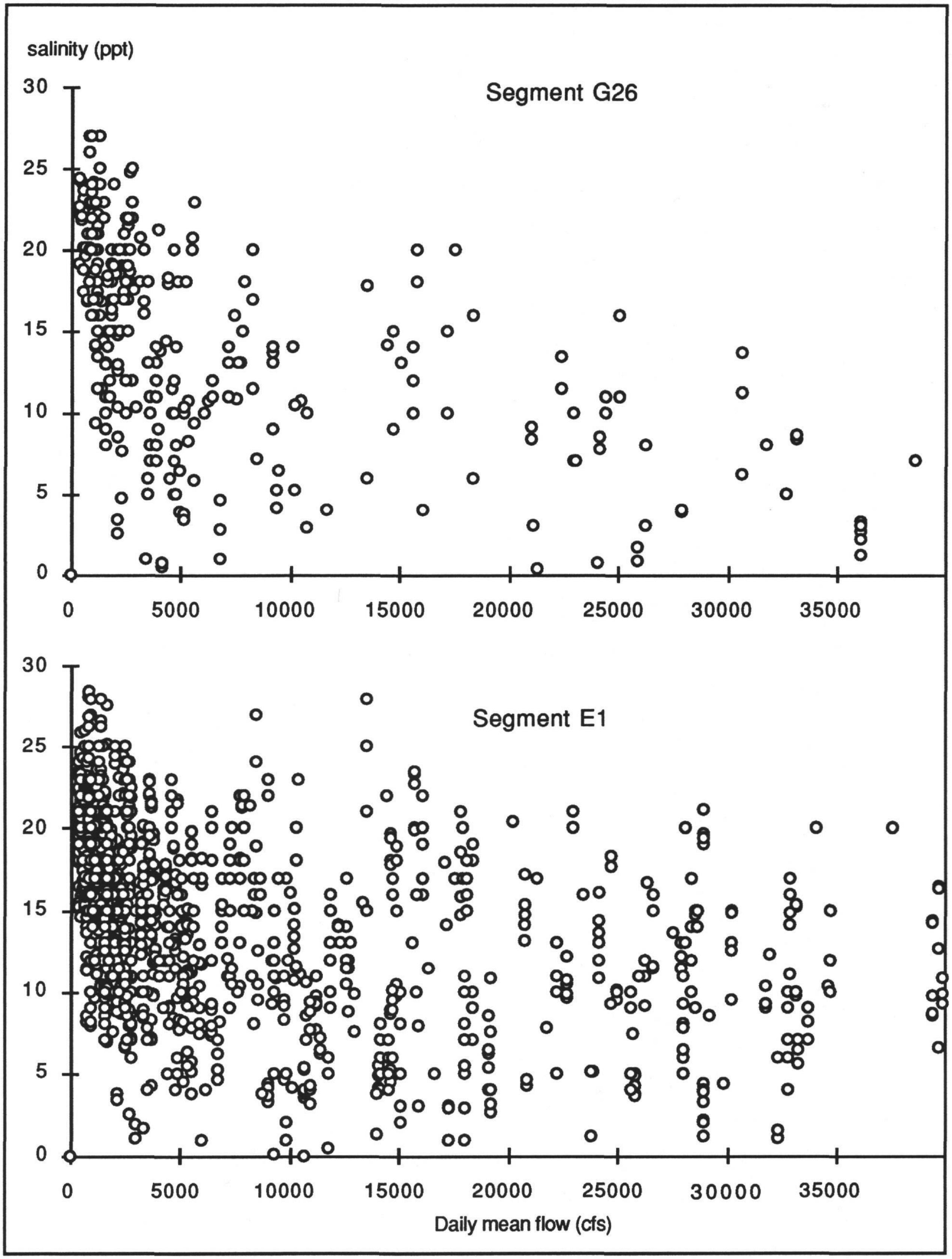

Fig. 7-5 Salinity (upper 1.5 m) in mid-bay segments versus Trinity River flow at Romayor

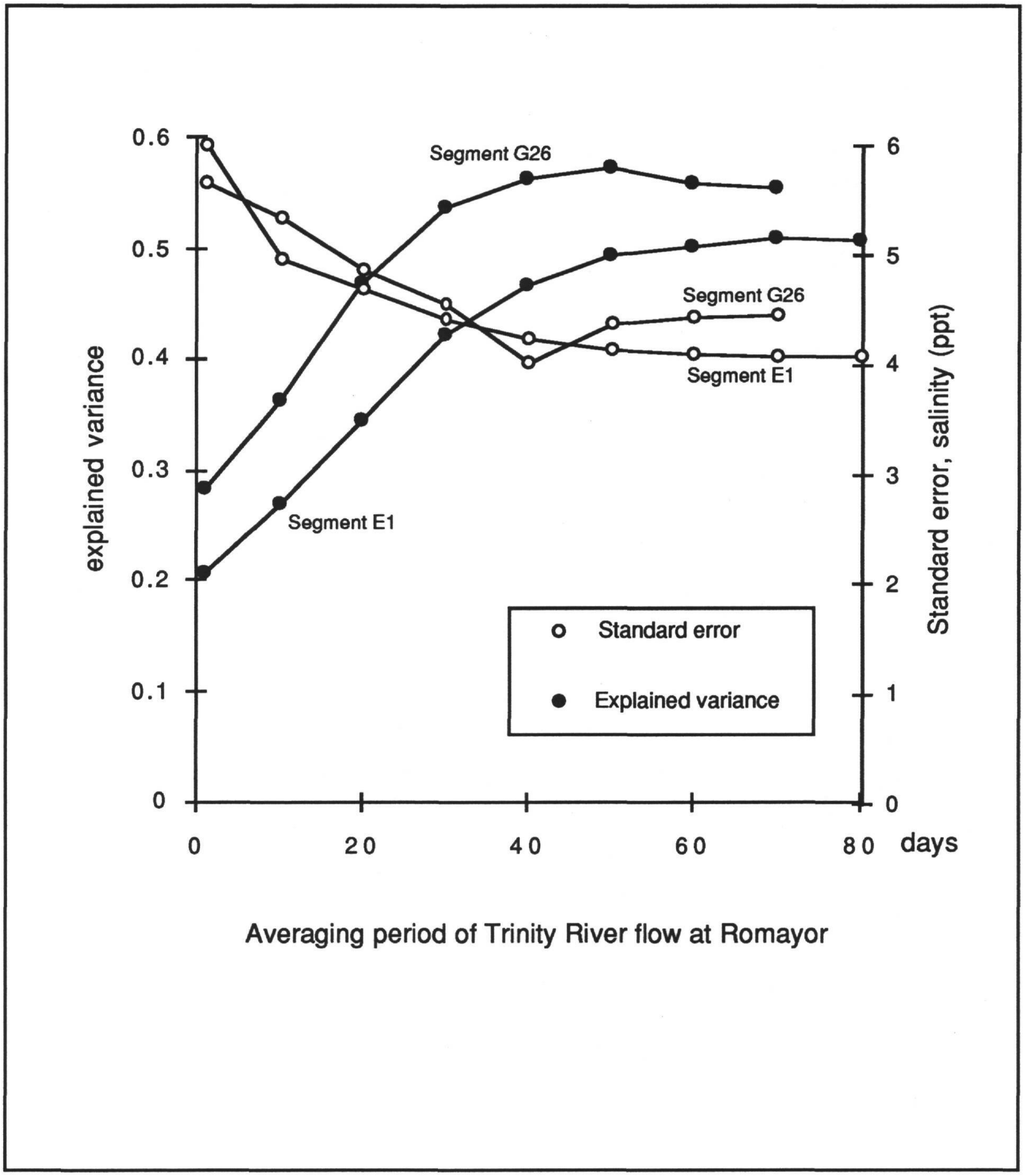

Fig.7-6 Quality of statistics as function of averaging period

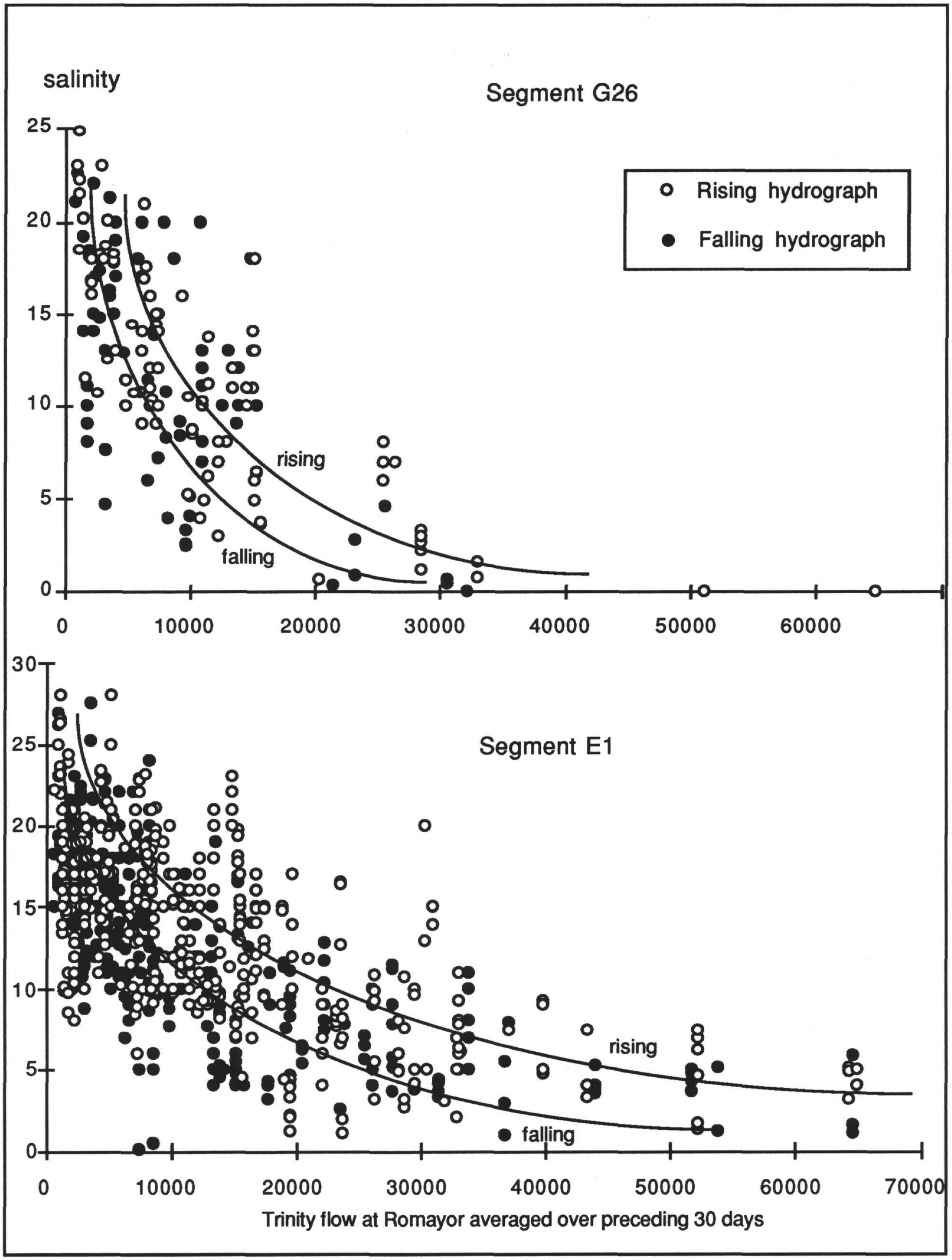

Fig. 7-7 Salinity versus flow hysteresis at mid-bay segments

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

Part of the variance is due to the differing salinity responses to the time variation in salinity, i.e. whether it is intruding or extruding, and which hydrographic processes dominates that process. For example, salinity tracking inflow can exhibit hysteresis, as shown in Fig. 7-7 in which the data are separated according to whether the (averaged) inflow hydrograph is rising (salinity extrusion) or falling (salinity intrusion). There is a proclivity for lower salinities at the same inflow level on falling than rising hydrographs. Salinity also seems to have a threshold response to inflow: for inflows less than and greater than certain threshold values, there is no longer a discernible response. For the mid-bay region, the lower threshold appears to be about 5,000 cfs, perhaps greater, and the upper threshold is about 50,000 cfs at Segment G26, somewhat higher at Segment E1 in the mouth of East Bay. The upper threshold decreases as points of inflow are approached, especially the Trinity River. The lower threshold increases as the inlet is approached.

Generally, the salinity at any point in the bay is in a state of dynamic response to the integrated resultant of present and earlier hydrological and hydrographic factors. The complete analysis of this behavior cannot be by statistical association alone but rather must take explicit account of the time-response character of the variates. Such an analysis is beyond the scope of the present study, but could employ either of: (1) time-series and system-identification methods; (2) detailed event-response analysis, including salt-budgeting and deterministic modeling. It is probable that similar methods may be necessary for other variates whose concentration in the bay is determined by boundary fluxes and internal transports, e.g. quasi-conservative parameters such as phosphorus and many metals.

The mean spatial structure of salinity presented in Chapter 5 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. 5-27 through 5-29) 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 in recent years (or, conversely, bias toward lower inflow conditions in earlier years);

(6) Increased return flows.

The most obvious potential cause is, of course, an increase in freshwater inflow. There is no evidence of an associated increasing trend in Trinity River inflow. If this is operating, it is too subtle to be discriminated by simple linear statistics. The mean inflow (as well as summer and freshet volumes) over the past three decades or so is 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. For 1960-89, for example, the trend in Trinity River flow is increasing, averaging about 1.5 m^3s^{-1}/yr (54 cfs/yr), which amounts to a net increase since 1960 of about 25% in annual-mean flow. However, the 1957-89 trend is *decreasing* about 0.4 m^3s^{-1}/yr (13 cfs/yr), with a net *decline* of about 10%. 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. The other 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.

7.4.2 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 (i.e., an increase in DO) of about 4 ppm since 1960. This decline has been gradual (Fig. 5-32), 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. 5-30). 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 7.3.4 below.

7.4.3 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). In Section 7.3 above, note was made 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. The fifth 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 (and its previous incarnations) 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.

7.4.4 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 Figs. 7-8 and 7-9 for example segments in the Upper HSC (i.e., above the San Jacinto confluence) and in the Lower HSC (i.e., below 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 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

(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.

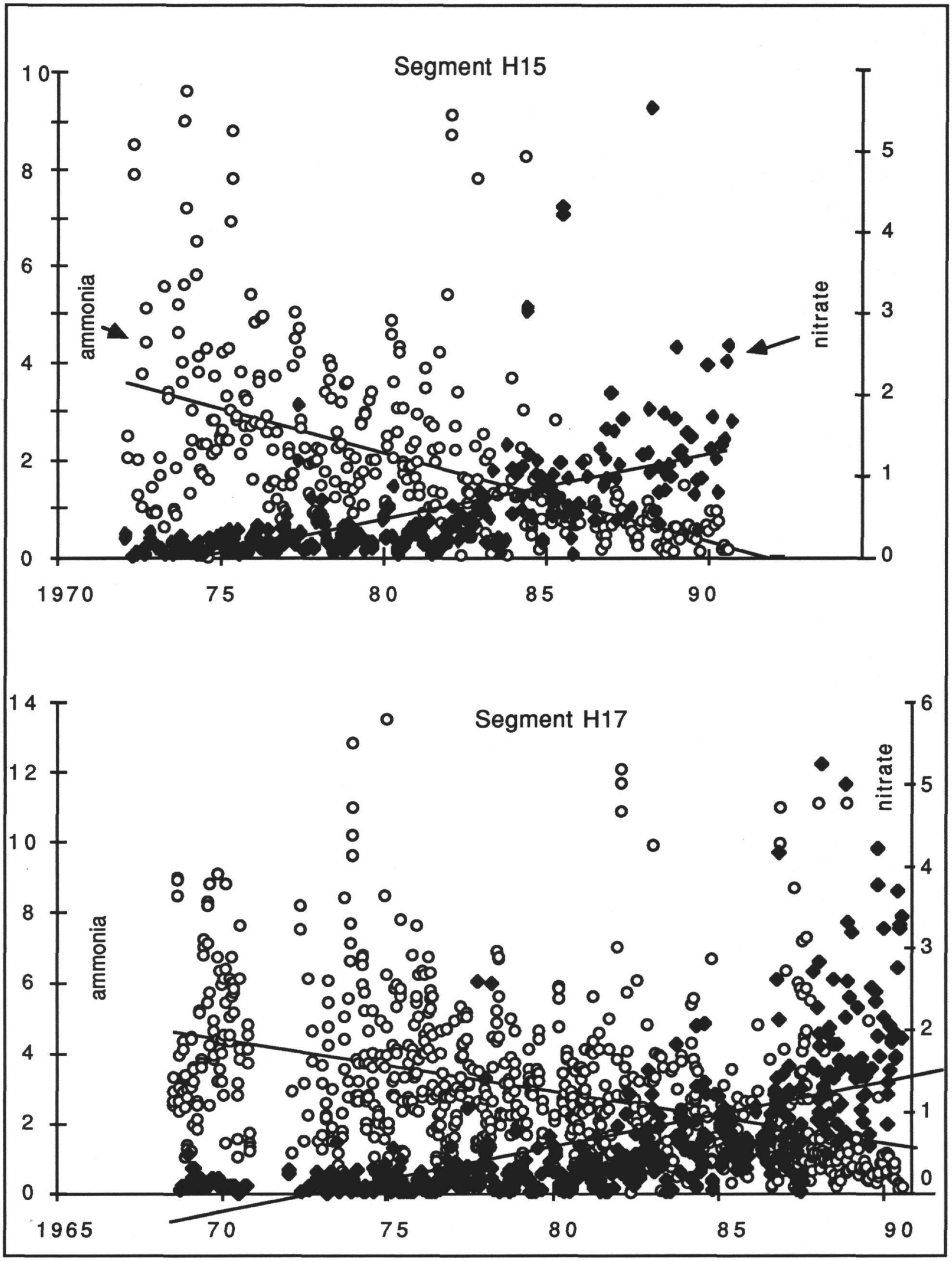

Fig. 7-8 Ammonia and nitrate trends in Upper Houston Ship Channel

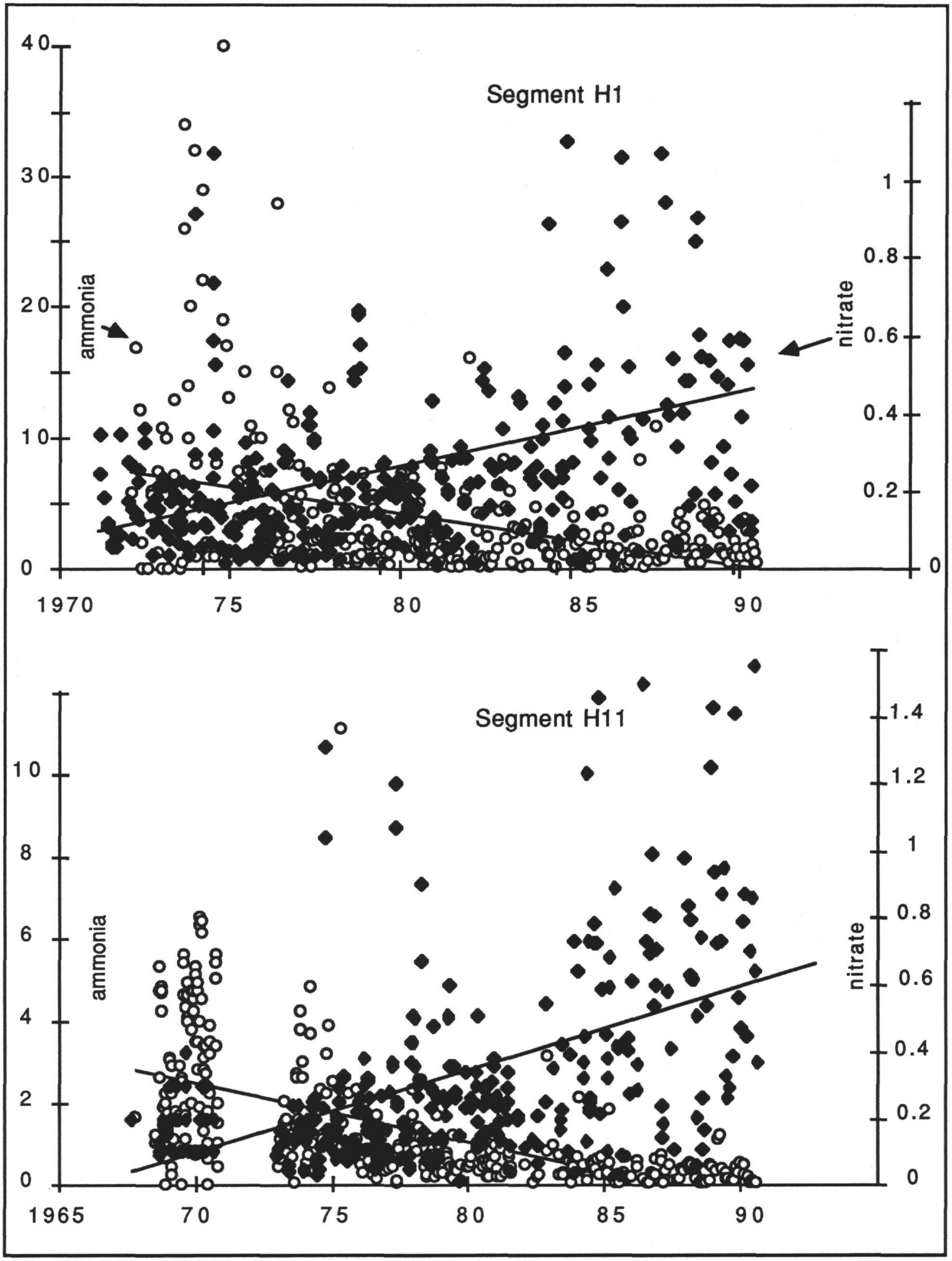

Fig. 7-9 Ammonia and nitrate trends in Lower Houston Ship Channel

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 (see Section 7.3 above). 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 (see 7.4.1 above), 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 (Figs. 7-8 and 7-9), so there is still a net decline of nitrogen in the Houston Ship Channel, despite the increase in nitrates. Therefore, the systemic reduction in nitrogens applies in this region also.

Finally, the trends analysis of Chapter 5 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 phaeophytin.

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.

7.4.5 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. The obvious hypothesis of coliform behavior is that it is a highly transient indicator responding to environmental factors that operate on much shorter time frames than implicit in a long-term data base. The fact that coliforms respond to many variables other than human enteric wastes has been remarked by many investigators, as well. The observed behavior of coliforms might profit from detailed response-type analysis including storm events, hydrographic fluctuations, and postulated attrition kinetics; such an analysis is beyond the scope of this study.

Metals, in general, behave in a quasi-conservative manner (cf., Table 7-1) 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 (Figs. 5-21 and 5-22) 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. 5-55) as do the sediments (Figs. 6-17, 6-20, 6-24). 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.