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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 Corpus Christi 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 accomplish 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 is the complex of processes that directly affect the concentration of the parameter at a point in space, also referred to as “source-sink” processes, including physicochemical reactions and biological inter-actions. Transport, in contrast, affects point concentration by the movement of water masses, and includes the various mechanisms of circulation and dispersion responsible for the intermixing of estuary and Gulf waters (the so-called “flushing” of the estuary). A relative evaluation of the two is based upon the rate coefficients governing the kinetics to which a waterborne 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 or representative water-quality parameters. 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 Corpus Christi 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. 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 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. (These nominal reaction rates, 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

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TABLE 4-1
Typical rate coefficients for representative water quality parameters,
from Ward and Armstrong (1992a)

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.l
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

effective reaction due to vertical transport processes, as characterized by the indicated rate coefficient. For example, evaporation, a volume flux of water from the upper boundary, acts as an effective source of vertical-mean salinity.)

Kinetics and transport processes may be termed “internal controls” on water/ sediment concentrations, in that they operate within the interior of the estuary fluid volume. In contrast, “external controls” are those physicochemical factors that are applied around the periphery of the estuary, creating internal responses that are manifested as distributions of water/sediment indicators. Interpretation of the behavior of a water/sediment constituent in any watercourse requires knowledge of both internal controls and external controls. For an estuary, Corpus Christi Bay included, the transitional nature of the system makes external controls especially important.

4.1 External Controls

4.1.1 Overview

The two most important classes of external controls are hydrography and loadings. The former refers to the hydrodynamic forcing of the estuary. (For convenience, we include climatological forcing in this category.) The latter refers to influxes of constituents that are indicators of water/sediment quality in their own right, or, through kinetic processes, have a direct influence on such indicators.

Hydrography of the Corpus Christi Bay system, like most estuaries, is principally governed by four physical factors: tides, meteorology, density currents and freshwater inflow. Each of these is 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 Gulf coast estuaries is surveyed in Ward (1980a) and Ward and Montague (1996), and references therein, and the hydrography of Corpus Christi Bay in particular is addressed in TDWR (1981) and Orlando et al. (1993).

The most obvious marine influence is the tide. In the Texas Gulf coast area, 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 Corpus Christi Bay is typically on the order of 0.8 m during the diurnal mode of the tide. As the tide propagates into Corpus Christi Bay it is lagged in phase and attenuated in amplitude. The extreme constriction of the tidal passes reduces the tidal amplitude and significantly filters the semidiurnal component. Within the even more constricted areas of the interior bays, such as the Laguna Madre, even the diurnal component is significantly filtered. 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; indeed, in the open main body of Corpus Christi Bay, the tide becomes predominantly a standing wave.

These observations are relative to variation over a tidal cycle and do not represent the total excursion in water level in Corpus Christi Bay. During the cycle of lunar declination, there is also a storage and depletion of water within the system, with higher mean water levels generally during the semidiurnal phase, producing a fortnightly periodicity. 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 dominate this pattern in the Corpus Christi region, with a net range on the order of 0.3 m, but with year-to-year variability in this range.

While the tide is the most obvious marine influence on Corpus Christi Bay, the most obvious freshwater influence is the inflows of the principal rivers. The freshwater inflow is responsible for the estuarine character of Corpus Christi 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 is also an important source of external loadings. Inflow is also important analytically, because there is an extended detailed time record of measurements available for the system, which can in principle be combined with the water quality data of this project. The analysis and behavior of inflow are therefore treated in more detail in Section 4.1.2 below.

In addition to tides and inflows, the atmosphere (in which we include insolation) has a significant influence on Corpus Christi Bay. The atmosphere governs the heat budget of the estuary waters, and thus the magnitude and seasonal progression of water temperatures. Evaporation from the surface, controlled by humidity, temperature and wind, is a significant element in the water budget and therefore (indirectly) the salt budget. From a hydrographic viewpoint, wind forcing is the most important meteorological influence. 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 wind 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. Wind-driven circulations are to be expected due to the relatively steady prevailing winds in combination with the morphology of the bay, but there is little quantitative information available concerning theses circulations in Corpus Christi Bay. For other Texas estuaries such wind-driven circulations have been documented by observations, for instance in Galveston Bay and Sabine Lake.

Perhaps the most dramatic meteorological effect is that of denivellation, i.e. meteorologically forced variations in water level. Indeed, in Corpus Christi Bay, it is more often meteorology, not the tide, which is the dominant factor governing the day-to-day excursions in water level. Part of this is the general response of the northwestern Gulf of Mexico to the imposed windstress of southeasterly winds about the Bermuda High and northerlies associated with midlatitude synoptic disturbances, which is communicated through the inlets of Corpus Christi Bay. Within the bay, meteorological systems affect the water-level variation even more, mainly due to constrictions of land boundaries. Strong onshore winds can "setup" water levels in the upper bay. North winds, especially following vigorous frontal passages, can induce dramatic "setdown," and are capable of evacuating a significant portion of the bay volume in a few hours. (For bays on the upper Texas coast, with more open inlets, as much as half of the volume of the bay can be evacuated, see Ward, 1980a, 1980b.) Even modest weather systems significantly perturb water levels to the point that the astronomical tide is obliterated. This is especially true in the inland or isolated reaches of the bays, such as Copano Bay, Baffin Bay, and the Upper Laguna Madre.

The horizontal gradient in salinity in concert with variations in depth produce the fourth important component of estuarine circulation, the density current. This is one of the prime mechanisms for salinity intrusion into an estuary system, and is especially prominent in many dredged ship channels. 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 found particularly in deep channels that are laterally confined. A well-documented example on the Texas coast is the Houston Ship Channel above Morgans Point (see Ward and Armstrong, 1992a, and references therein). 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 a deep trough in open waters of an estuary, such as a talweg or dredged channel. In this case, the vertical-mean current is directed up (into) the estuary along the axis of the trough, and the return flow to sea takes place in the shallow open bay to either side.

The above description of density currents did not refer to vertical stratification. 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 Corpus Christi Bay, the salinity can still be maintained nearly homogeneous in the vertical. More detailed information on estuarine density currents is given in Ward and Montague (1996). The potential rôle of a density current in Corpus Christi Bay is addressed in Section 4.2 below in the context of salinity intrusion.

4.1.2 Freshwater inflow

The principal direct riverine inflow to the Corpus Christi Bay Study Area system, including the upper bays of Copano and Aransas and the lower bays of Baffin and the Laguna is the Nueces River. In addition, there are several smaller rivers such as the Mission and Aransas Rivers, and numerous minor tributaries which drain the watershed of the study area and can be locally important as fresh water sources. These include Copano Creek, Oso Creek, Olmos Creek, San Fernando Creek, and Petronila Creek. The key word in the first sentence above is “direct” because an important indirect riverine inflow is the combined inflow of the San Antonio and Guadalupe Rivers, which does not enter the study area *per se,* but debouches into the next bay to the north, San Antonio Bay. There is free communication between this system and the Aransas-Copano system, through Ayres-Carlos-Mesquite Bays, and there is some indication that on a long-term basis this inflow has an effect on salinities in the upper part of the study area.

As noted above, the flow of the Nueces River is important to the hydrography of the main body of Corpus Christi Bay, and the variation of this river is central to the overall effect of inflow on the bay system (see TDWR, 1981). The Nueces is also the only riverine source for which an accurate history of gauge measurements exists. (Some of the other tributaries to the system, such as Oso Creek and the Mission River, are also gauged, but the proportion of their total watershed that is gauged is much lower than that for the Nueces.) Thus one problem in analyzing freshwater inflows to the overall system is the lack of measured streamflow.

For this study, we have utilized the work in a companion CCBNEP project, the Freshwater Inflow Status and Trends Study performed by the U.S. Geological Survey (Mosier et al., 1995). USGS subdivided the watershed of the CCBNEP study area into 17 distinct subwatersheds. For each of these, the HSPF model (essentially the Stanford Watershed Model, e.g., Singh, 1989) was applied. This is a numerical runoff computation utilizing inputs of soils, land use, precipitation, wind and air temperature to compute a complete surface water budget, from which daily streamflow in the drainage channel was calculated. USGS then combined these subwatersheds into watersheds for component bays of the study area, as follows:

Copano Bay
Redfish Bay
Upper Laguna
St. Charles Bay
Corpus Christi Bay*
Baffin Bay

* including the ungauged Nueces watershed downstream from Mathis

The simulated (“synthetic”) inflow records from these six component watersheds together with the gauged flow in the Nueces at Mathis comprise the total inflow to the CCBNEP Study Area.

Inflow into Corpus Christi Bay is highly variable, but the question is whether this variability has definite patterns. River flow in the Texas climate is governed by surface runoff from storm systems; this means the rivers are “flashy,” exhibiting large, sudden excursions in flow. The daily flow of the Nueces, as a case in point, spans four orders of magnitude. One would therefore expect a seasonal variation, correlated with the usual climatological pattern of storms. But the details of each “season,” each of which is in fact a series of quickflow spikes, will vary from year to year, and systematic variation can be extracted only by averaging over a long period of record. Flows on the upper Texas coast, e.g. the Trinity River (see Ward and Armstrong, 1992a), have a predominant pattern of an annual “flood” and an annual “drought,” the flood being the spring freshet, which typically occurs in April and May, and the drought is the summer low-flow season typically extending from July through October. With distance down the Texas coast, the spring freshet diminishes in importance, due to reduced southward penetration by midlatitude disturbances. But a fall maximum, originating from tropical processes, such as the interplay of Gulf windflow with subtropical disturbances and from landfalling tropical depressions, becomes increasingly important with distance south. This is illustrated by the pattern of inflow in the Nueces.

Figure 4-1 shows the daily flow of the Nueces at Mathis averaged over the 26-year period 1968-1993, the period of record employed by USGS, and the degree of smoothing achieved by longer averaging windows. For most of the analyses of this study, we employed a monthly averaging period. The basic bimodal character of the seasonal Nueces inflow is apparent in the late spring and early

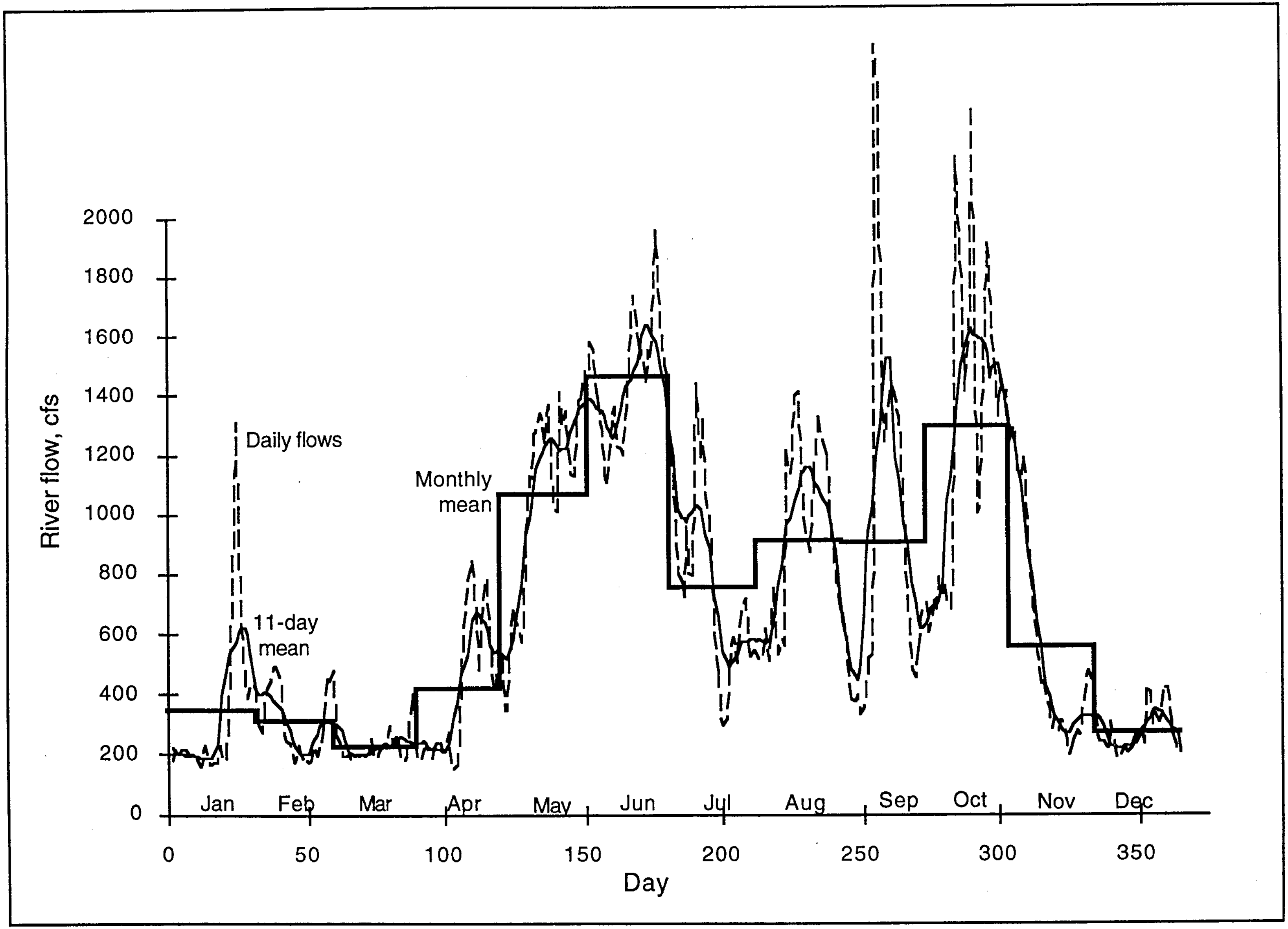


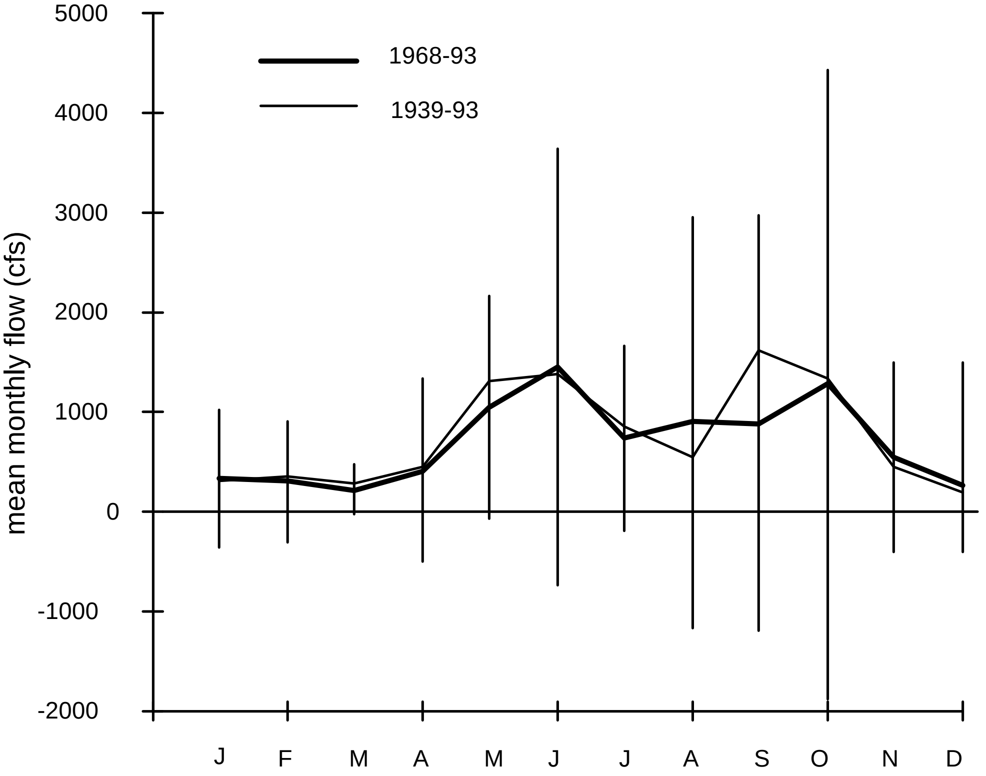
Figure 4-1. Nueces at Mathis, 1968-93, daily flow and longer-period averages

fall maxima. Additional features of the monthly averaged inflow record of the Nueces are shown in Fig. 4-2. Despite the fact that the longer gauge period of record of 1939-93 includes the 1964 drought of record and the extended drought of the 1950's, the mean annual monthly pattern is quite comparable to the 1968-93 study period. The variability of the Nueces is extreme even at a monthly averaging level, as evidenced by the standard deviation of the monthly means, shown by the vertical bars of Fig. 4-2(a). (Of course, negative values of monthly mean flow do not occur. The fact that the standard deviations extend into negative values indicates the skew in the data record toward more frequent occurrences of low monthly flows.) As the monthly flow increases, so does the variance in the data record, as demonstrated by the plot of standard deviation versus monthly mean flow of Fig. 4-2(b). This means that the coefficient of variation is fairly constant for the Nueces monthly data, and is high, about 175%. Table 4-2 presents the monthly mean and annual inflows for each of the component watersheds for the CCBNEP Study Area, including the gauged watershed of the Nueces. These same monthly flows are depicted graphically in Fig. 4-3.

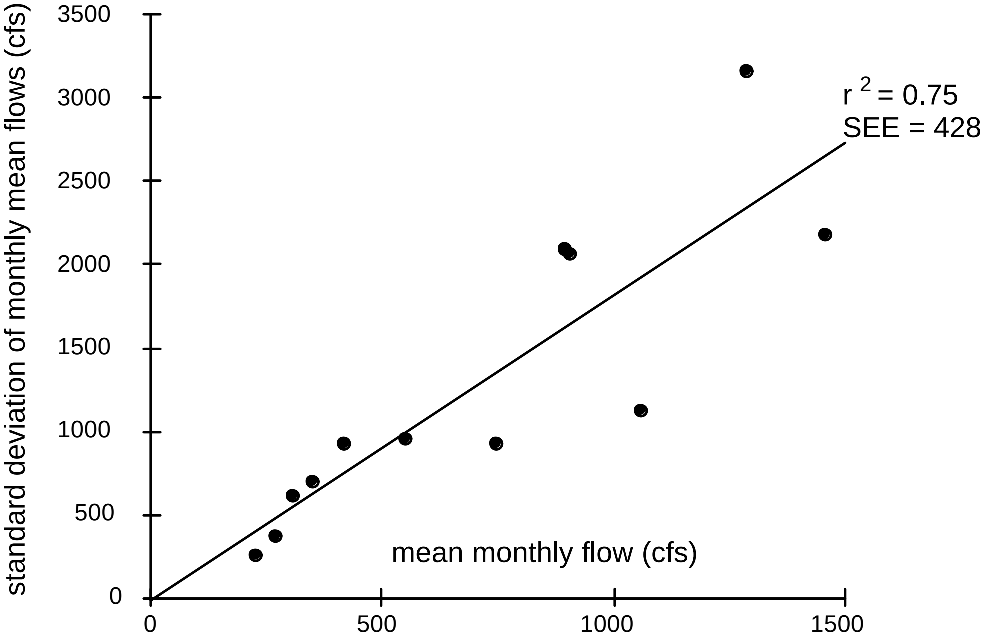
There is considerable year-to-year variation in inflow, as shown by the annual-mean flows for each of the component watersheds from the USGS simulations and the gauged flow of the Nueces in Table 4-3. The most important aspect of the

Table 4-2
Mean flows (1968-93) for principal component watersheds in CCBNEP study area
(cubic feet per second)

	Baffin	*Upper Laguna*	*Corpus Christi*	*Nueces River*	*Redfish*	*Copano*	*St. Charles*	*Total*
				-Monthly means-				
J	141	4	340	347	15	791	113	1751
F	193	6	345	308	14	905	171	1942
M	46	4	232	227	9	441	66	1025
A	29	2	301	419	9	279	29	1068
M	73	5	731	1061	18	695	69	2652
J	242	12	1120	1459	18	1513	97	4461
J	114	5	660	749	14	992	100	2634
A	108	6	653	905	13	479	40	2204
S	296	9	984	895	33	1988	224	4429
O	371	11	927	1288	21	1475	98	4191
N	76	4	448	551	13	690	118	1900
D	71	3	266	268	13	741	128	1490
				-Annual means-				
	147	6	584	706	16	916	104	2479
				-Fraction (percent) of total inflow to Study Area-				
	6	0	24	28	1	37	4	100



(a) Monthly flows, mean and standard deviation of mean



(b) Standard deviation of monthly mean flows versus mean flows

Figure 4-2. Nueces at Mathis, monthly mean flows

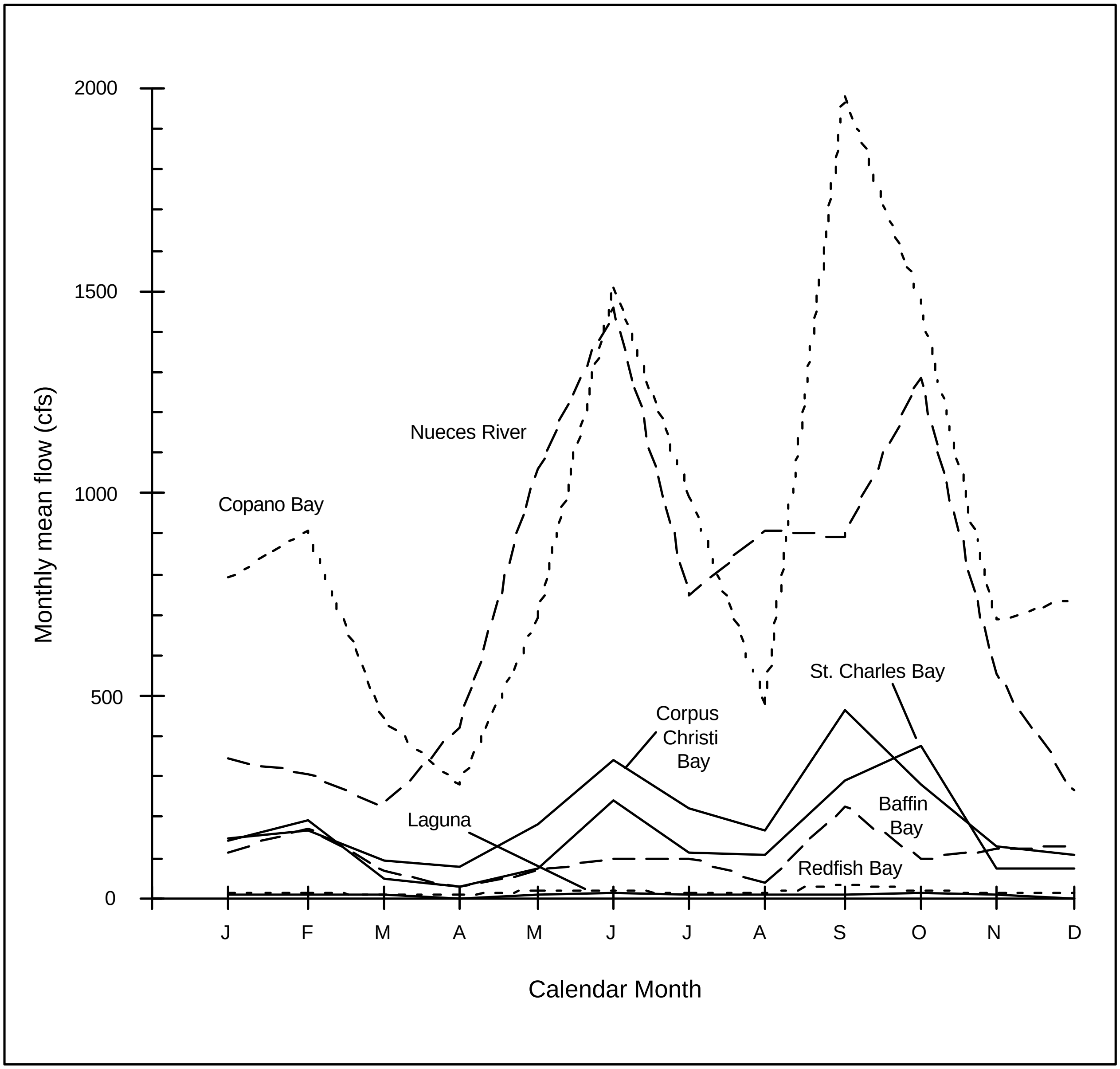


Figure 4-3. Monthly mean inflows (1968-93) for principal watersheds draining into Corpus Christi Bay Study Area

Table 4-3
Annual inflow measures by component watershed, 1968-93, in cfs

	St Charles				*Copano*				*Redfish*			
year	*mean*	*freshet mean*	*first month*	*ratio*	*mean*	*freshet mean*	*first month*	*ratio*	*mean*	*freshet mean*	*first month*	*ratio*
68	1.2	7.1	4	1.00	1123	4118	5	0.61	19.7	45.7	5	0.39
69	0.1	0.5	11	1.00	827	2090	11	0.42	13.5	28.1	11	0.35
70	0.0	0.0	11	-	708	2377	9	0.56	18.3	66.0	9	0.60
71	226.8	597.0	11	0.44	2413	12558	9	0.87	31.7	120.5	9	0.63
72	63.3	195.1	4	0.51	895	2958	5	0.55	19.5	42.3	5	0.36
73	99.5	381.4	9	0.64	1625	4618	9	0.47	14.8	33.0	9	0.37
74	192.2	890.2	11	0.77	443	1255	9	0.47	13.6	31.3	5	0.38
75	26.9	127.4	8	0.79	240	813	9	0.57	10.1	20.5	8	0.34
76	148.0	515.7	11	0.58	1160	3159	11	0.45	22.1	40.7	11	0.31
77	51.8	149.6	5	0.48	230	813	1	0.59	9.9	16.0	4	0.27
78	115.5	532.2	9	0.77	562	2347	8	0.70	12.7	32.6	9	0.43
79	332.3	1189.2	8	0.60	1332	3617	8	0.45	27.8	71.2	8	0.43
80	29.1	130.5	8	0.75	705	2635	8	0.62	11.3	32.2	8	0.47
81	189.1	743.8	5	0.66	1687	3455	10	0.34	20.7	30.8	10	0.25
82	45.3	175.7	2	0.65	217	1129	2	0.87	6.1	13.6	2	0.37
83	85.2	250.3	9	0.49	1507	4984	9	0.55	19.4	44.0	6	0.38
84	52.3	225.7	10	0.72	671	2047	1	0.51	7.5	16.5	9	0.37
85	16.8	61.1	3	0.61	508	974	3	0.32	13.1	21.5	9	0.27
86	129.3	549.0	10	0.71	983	3038	10	0.51	12.4	23.2	9	0.31
87	96.1	219.4	6	0.38	742	1946	6	0.44	14.1	22.8	6	0.27
88	0.4	1.0	6	0.40	63	128	9	0.34	8.5	15.9	8	0.31
89	103.0	347.0	1	0.56	92	266	6	0.48	7.4	15.0	6	0.34
90	63.5	191.5	7	0.50	571	2051	7	0.60	10.1	15.5	2	0.26
91	175.9	435.4	11	0.41	927	2578	11	0.46	21.8	42.2	11	0.32
92	198.3	646.0	1	0.54	2001	6984	1	0.58	27.9	103.1	1	0.62
93	274.7	1297.7	2	0.79	1587	5412	5	0.57	15.3	35.9	2	0.39
mean	104.5	379.2	11*	0.63	916	3013	9*	0.54	15.7	37.7	9*	0.38

* Most frequent month

Table 4-3
(continued)

	Nueces River				*Corpus Christi*				*Baffin*			
year	*mean*	*freshet mean*	*first month*	*ratio*	*mean*	*freshet mean*	*first month*	*ratio*	*mean*	*freshet mean*	*first month*	*ratio*
68	920	2502	5	0.45	700.9	2015.3	5	0.48	62.8	208.4	5	0.55
69	344	1167	10	0.57	347.9	946.1	11	0.45	45.4	95.7	8	0.35
70	496	2103	5	0.71	441.1	1403.7	5	0.53	38.8	73.4	5	0.31
71	3487	12887	9	0.62	2309.3	9225.9	9	0.67	770.8	4218.6	9	0.91
72	409	1406	5	0.57	368.3	1010.8	5	0.46	45.2	94.5	5	0.35
73	1431	4405	9	0.51	1109.6	3255.2	9	0.49	537.8	2333.4	9	0.72
74	540	2021	8	0.62	371.1	1132.7	8	0.51	37.3	60.4	2	0.27
75	516	1795	5	0.58	366.3	1021.4	6	0.46	33.2	75.0	7	0.38
76	1276	3545	10	0.46	970.6	2214.4	10	0.38	173.6	433.9	11	0.42
77	735	3008	4	0.68	480.8	1691.4	4	0.59	33.9	62.1	5	0.31
78	308	940	8	0.51	415.7	1091.0	8	0.44	37.5	80.9	9	0.36
79	505	1995	5	0.66	644.3	1665.8	8	0.43	147.2	563.5	9	0.64
80	767	2760	8	0.60	634.7	2518.5	8	0.66	187.3	808.8	8	0.72
81	1458	5148	5	0.59	1005.8	3129.7	6	0.52	206.4	927.6	6	0.75
82	287	947	5	0.55	315.5	759.6	2	0.40	46.1	156.2	2	0.56
83	148	176	5	0.20	336.8	844.4	6	0.42	43.9	73.4	6	0.28
84	129	178	4	0.23	240.4	537.2	10	0.37	81.3	341.6	10	0.70
85	646	1620	10	0.42	535.1	1086.3	10	0.34	102.8	317.4	10	0.51
86	175	387	11	0.37	232.0	476.4	11	0.34	48.4	119.8	11	0.41
87	1053	5010	6	0.79	774.3	3124.2	6	0.67	194.9	521.1	5	0.45
88	158	197	7	0.21	156.1	256.5	9	0.27	28.0	60.0	9	0.36
89	166	199	7	0.20	155.1	199.0	8	0.21	21.7	40.7	8	0.31
90	481	1562	7	0.54	339.8	859.0	7	0.42	30.3	54.5	3	0.30
91	252	487	5	0.32	387.0	615.8	11	0.27	94.9	356.5	11	0.63
92	1283	3094	5	0.40	1069.2	2548.0	1	0.40	576.9	3144.0	1	0.91
93	296				471.9	1696.7	5	0.60	190.1	1009.0	6	0.88
mean	703	2382	5*	0.49	583.8	1743.3	8*	0.45	146.8	624.3	5,9*	0.51

* Most frequent month

year-to-year variation in annual discharge is how that is manifested in the occurrences of high flows. That is, the freshet is the central feature of the annual hydrograph. As an approximate index to freshet behavior, it was postulated that a two-month sequence would capture the freshet in each of the watersheds, so for each year the highest two-month inflow was determined. This two-month average is also tabulated in Table 4-3, as "freshet mean." The proportion of total annual flow represented by this two month period is shown as "ratio." It is remarkable that for most of the inflow to the Study Area, these two months average half of the annual inflow.

Several observations are noted from these analyses:

(1) The three most prolific sources of inflow are Copano Bay, Nueces River and Corpus Christi Bay, in that order. However, there is considerable year-to-year variation in the magnitude and order of the annual inflow. The highest inflow of the 1968-93 period occurred in 1971.

(2) According to the results of the USGS HSPF simulation, the gauged flow of the Nueces comprises on average about 55% of the total flow to Corpus Christi Bay *per se*. This appears to be substantially lower than some ratios that have been promulgated recently (e.g., Copeland et al., 1994). Especially during drought periods, the Nueces proportion falls considerably below 50%, see Table 4-3.

(3) The small watershed of Redfish Bay and the Upper Laguna render their inflows of negligible importance.

(4) The low runoff from the Baffin Bay watershed is evidence of the high aridity of this region of the Study Area.

(5) The fact that a two-month period is sufficient to "capture" the annual freshet demonstrates the flashy character of the inflows to the Corpus Christi Bay Study Area.

(6) The annual flow is highly correlated with the spring "freshet," r=0.91 for Copano, r=0.98 for Nueces and r=0.97 for Corpus Christi. High correlation is not unexpected given (5), but to be this high is unexpected and further reinforces the domination of the annual hydrograph by the freshet.

(7) For the main contributors (Copano, Nueces and Corpus Christi) there is a interannual spread of nearly two orders-of-magnitude in the freshet volume.

(8) The first month of the 2-month freshet period is most commonly late summer (August or September). The exception is the Nueces, whose freshet most commonly begins in the late spring. This emphasizes the fact that the hydroclimatology of the Nueces watershed is fundamentally different from that of the coastal plain, and tracks more closely that of the upper Texas coast.

4.1.3 Loadings

A detailed analysis of organic, nutrient, and contaminant loading to the Corpus Christi Bay system is now underway in a separate project for the CCBNEP. Therefore, we do not have the advantage of quantitative results from this project for the present analyses. However, the qualitative variation in loadings over the past two to three decades is well known and suffices to anticipate responses of water and sediment quality.

Generally, loadings fall into two broad categories. Those with geographically focused sources of large magnitude are referred to as point sources. These typically originate as wastewater returns from industrial facilities or municipal sewage treatment plants. These are subject to direct regulation and are capable of being captured and "treated" by a combination of diversion, detention, filtration, and biochemical or chemical processing. In contrast, loadings whose points of origin are diffuse in space, perhaps continuous, are referred to as nonpoint sources. Typically, these involve complex interactions between the ultimate origin of the constituent and environmental flow paths, especially runoff processes in the aquatic phase or boundary layer flows in the atmosphere. The nonpoint source loadings of greatest concern in the Texas coastal environment are those transporting mobilized constituents from the watershed by storm runoff into the periphery of an estuary. Rivers hold an ambiguous position in this categorization. As high-volume, geographically focused influx points, they would appear to be a point source. But because the loaded constituents originate from diffuse upstream sources, and because the river load is amenable neither to regulation nor to capture and treatment, from an administrative viewpoint it is usually considered a nonpoint source.

The magnitude of point source loadings has been reduced in recent years, due to advanced waste treatment, driven by state and federal regulation. In the Texas coastal zone, as a general rule, improvements in waste treatment have progressed in time from the industrial sector to the municipal sector, and from the upper Texas coast to the lower. While passage of the 1972 Federal Water Pollution Control Act Amendments (PL 92-500) is usually taken to mark the beginning of this process, in Texas this was preceded by the state initiative Operation Clean Sweep of the Texas Water Quality Board, implemented in 1969. In the Houston area, where industrial and municipal dischargers are numerous, there has been accomplished a substantial reduction in total loadings, by an order of magnitude, as summarized by EPA (1980) and Powelson (1978). In the Corpus Christi Bay area a similar proportional reduction of loadings could be anticipated in the industrial wastewater discharges, and would be most evident in the regions of concentrated wastewater returns, e.g. the Inner Harbor and La Quinta Channel. Many of the point-source loads have high organic content, especially nitrogen. In the municipal sector, while wastewater treatment has improved in the Coastal Bend within the last two decades, the level of treatment is still below that achieved in the municipalities on the upper coast. With the growth of population and industry in the coastal zone, there has been a steady increase in the volume of return flows. In the Coastal Bend area, this is most evident in the municipal sector.

In those cases when data analysis has been performed of the loading of major Texas rivers, there has been found a general decline in mass loading of sediments and organics, considered to be a consequence of improved waste treatment, of improved land-management practices on the watershed, and of upstream impoundments. Reservoirs are considered to represent an effective sink of nutrients and contaminants in the inflows, because of entrapment of fine-grain sediments to which many of the constituents sorb. Unfortunately, the construction of most reservoirs, including Lake Corpus Christi on the Nueces, antedate the period of adequate record of riverborne chemical constituents, so the quantitative effect of reservoirs on chemical loadings cannot be directly evaluated with a high level of reliability. For the CCBNEP Study Area, there are relatively few results in the literature to draw upon. White and Calnan (1990) determined that the riverine suspended sediment load for the Nueces is much smaller for the period 1961-80 than for 1942-57, which they attributed to the construction of Wesley Seale Dam in 1958. Longley et al. (1994) compared nutrient and sediment loading from the watersheds into five major Texas bay systems, two of which, Aransas-Copano and Nueces-Corpus Christi are in the study area, finding that these two are lowest of the five in nitrogen, phosphorus and organic carbon loading, and among the lowest in sediment yield. The exception was the sediment yield from the Nueces watershed downstream from Mathis which was the highest of the watersheds analyzed (see Table 4.4.5 of Longley et al., 1994). No trends in these loadings are given.

4.2 Water and Sediment Quality Responses

4.2.1 Temperature

Temperature in Corpus Christi Bay exhibits a strong seasonal signal, as shown in Fig. 3-65. Because of its smaller depths and limited exchange with the Gulf, the bays lead the Gulf by about a month in their response to seasonal heating and cooling. Therefore, in the spring to early summer, the bays are about 2-3 C warmer than the adjacent Gulf, then this relation is reversed in the fall. Stratification effects are nil, amounting on average to a fraction of a degree per meter positive upward (see Table 3-13), an indicator of the vigorous vertical mixing which operates in Corpus Christi Bay and renders many variables vertically homogeneous. Horizontal spatial structure is virtually absent except for a minor increase with distance south across the study area. The strong seasonal variation and the lack of significant spatial structure are consistent with the domination of surface heat fluxes (so that boundary fluxes become much less important).

The one important exception to the lack of spatial structure in temperature is in Upper Nueces Bay, see Fig. 3-8. Segment NB7 (see Fig. 2-3) receives the cooling water discharge from the Central Power and Light Nueces Generating Station. This is a once-through fossil-fired steam-electric plant, which intakes cooling water from the adjacent Inner Harbor, Segment IH7. Presently, this SES is rated at 515 MW generating capacity and is permitted for a 21.9 m^3s^{-1} (775 cfs, 500 MGD) circulating flow (Mierschin, 1992). The actual generation and circulating flow is variable, depending upon the number of units in operation, load demand, and efficiency; a typical circulating flow is 18.4 m^3s^{-1} (650 cfs, 420 MGD). Ward (1982) compiled data on the heat rejection of this plant and the resulting thermal plume in Nueces Bay. The condenser temperature rise ranges nominally 4-10 C, and the resulting plume at 1 C (temperature rise over ambient) is about 200 ha (500 acres), ranging a factor of two about this value depending upon meteorology, especially wind direction. The effect of this heated water return is quite evident in the higher water temperatures in the south sections of Nueces Bay, Fig. 3-8.

One other major power plant of CP&L operates in the Corpus Christi Bay system, namely the Barney Davis Generating Station. Like the Nueces SES, Barney Davis is a fossil-fired steam-electric station with once-through cooling. Cooling water is drawn from the Upper Laguna Madre near Pita Island (Segment UL03) and discharged into Oso Bay (Segment OS3), at a circulating flow rate of nominally 19 m^3s^{-1} (670 cfs). Unlike the Nueces SES, the Barney Davis discharge is first detained in a shallow cooling pond of area $4.5x10^6$ m^2 (1.77 sq mi), the net effect of which is to reduce the temperature rise upon discharge into Oso Bay to less than 1 C. Therefore, there is no elevation of mean temperature in upper Oso Bay that can be attributed to this power station.

The most significant result from the statistical analyses of temperature is the long-period decline in water temperatures, especially within the open waters of Corpus Christi and Nueces Bays, and to a lesser extent within the upper bays of Copano and Aransas, see Figs. 3-47 through 3-49. Over the three-decade period of record, the net decline for those segments with a statistically probable trend is on the order of 2 C. It is noteworthy that a similar decline in water temperature, at about the same rate, was discovered in Galveston Bay (Ward and Armstrong, 1992a). The same hypotheses offered as possible explanations apply as well to Corpus Christi Bay:

(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 Corpus Christi Bay with the adjacent Gulf of Mexico;
(4) Sampling bias toward the earlier months of summer in more recent years.

These cannot be tested within the scope of this project. We note that a cursory examination of the sampling dates in this Corpus Christi period of record indicates little support for (4). With respect to (2) it is interesting to observe that the nearshore waters of the Gulf evidence a probable *increasing* trend. Since the waters of the Gulf are systematically cooler than those of the estuary, and since the nearshore waters are probably more influenced by thermodynamics of the surf zone, this observation does not eliminate (3), but certainly renders it more doubtful. Hypothesis (1) is considered the most probable. Recently Kim and North (1995) employed surface air temperatures compiled by Jones et al. (1986) by 5 x5 zones to examine trends in air temperature. Kim

(1996) notes that one of these 5 x5 boxes representing the Texas coastal zone shows a negative trend (but does not provide any quantitative detail).

4.2.2 Salinity

Of all of the conventional water-quality indicators, salinity has probably been more in the public view in the Corpus Christi Bay system than in any of the other estuaries of Texas. This is due to its perceived link to freshwater inflow and the intense local concern with the supply of inflow to the bay. From a broader analytical standpoint, there is probably no variable 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, Longley, 1994), none of which have been satisfactory.

Salinity in Corpus Christi Bay *is* dependent upon freshwater inflow. Without freshwater inflow to the bay, the salinities would eventually acquire or exceed 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 nature of the problem is illustrated by the salinity data of Fig. 4-4, showing the association of salinities with gauged flow of the Nueces. The locations, NB5 in lower Nueces Bay and CCC7 in the Corpus Christi Ship Channel just out from the Inner Harbor (Fig. 2-3), are characteristic of open-bay areas but still presumably close enough to the mouth of the Nueces to respond to its inflow. While there is a discernible downward slope in the relation, as we would expect, the range of salinity encompasses a significant portion of the entire estuarine range, independent of the level of inflow. Put another way, for virtually any level of inflow (the exception being for the rare extremely high flow events) one encounters in the data a disquietingly wide range of salinity. Moreover, the relation of salinity with inflow displayed in this figure, such as it is, is eroded even more with distance from the Nueces.

This high variance in salinity versus inflow 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 other hydrographic mechanisms, such as tides, meteorology, and density currents, all of which govern the internal transports of waters of different salinities in the bay, and dictate how freshwater influences salinity. In addition, evaporation plays a major rôle in the salt budget of the Corpus Christi Bay system.

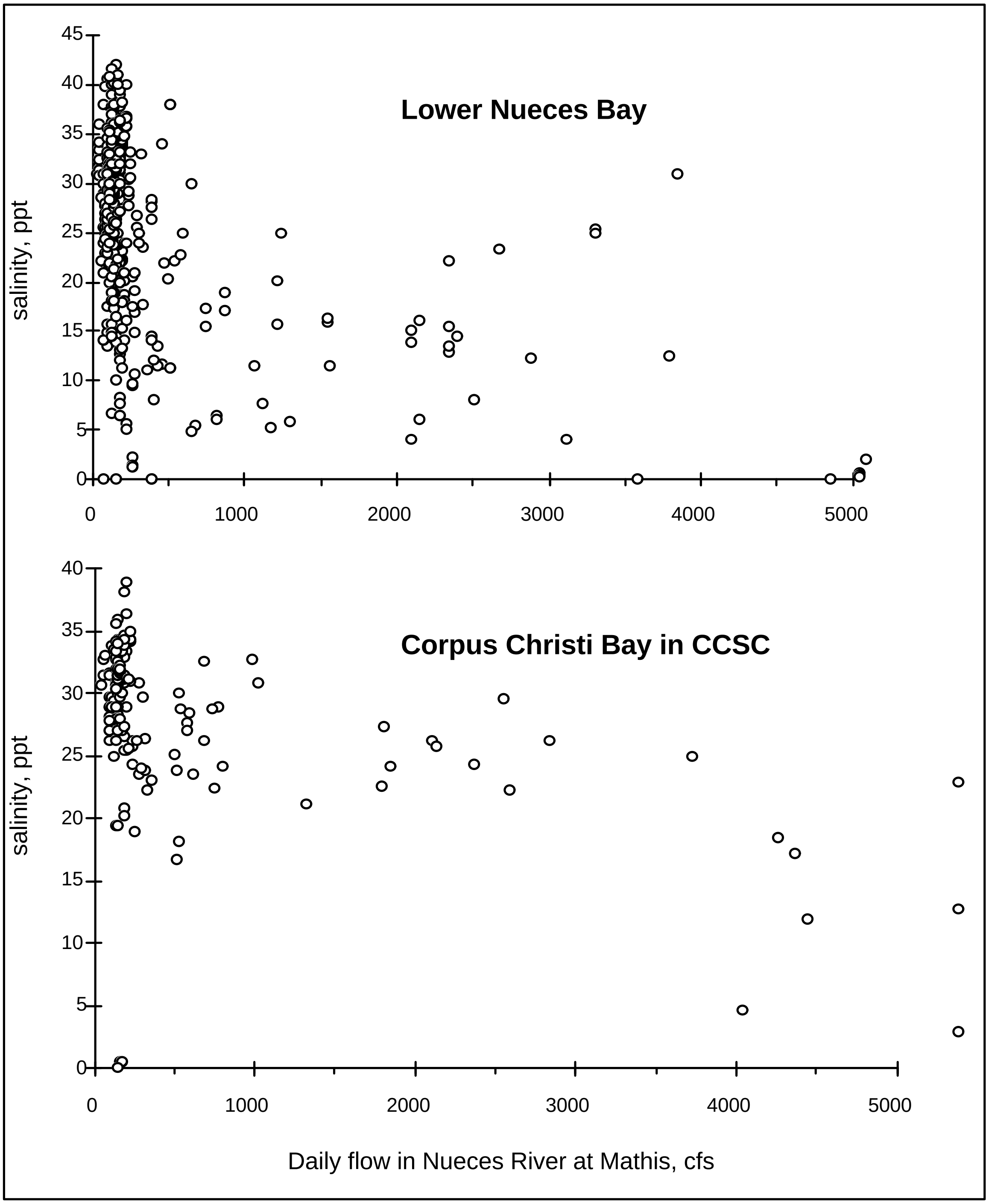


Figure 4-4. Salinity versus daily flow in two hydrographic segments, NB5 and CCC7. (Flows greater than 5000 cfs not shown.)

Generally, the salinity at a point in the bay is better correlated with the average flow over the preceding several weeks. However, there is a limit to the improve-ment in statistical association achieved by time-averaging the river flow. Even with the optimal averaging, not even 50% of the variance is explained by the relation to inflow. Further, the standard error of the regression is still more than 7-8 ppt, which means the regression predicts salinity at a 95% certainty within a 32 ppt range, i.e. about the normal range from fresh to oceanic. Moreover, in most areas of the open bay, the explained variance and standard error are even worse.

As observed above, the fallacy with this entire approach is the implicit assumption that there is a direct relation between salinity and inflow, which therefore can be extracted by the usual regression methods. 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 or silicon, and many metals.

As noted in Chapter 3, the average salinity distribution in the Study Area is predominantly a north-to-south gradient of increasing salinity. This is undoubtedly the result of the diminishing freshwater inflow from Copano in the north to Baffin in the south, reinforced by increasing evaporation. The effect of evaporation on the salt budget is amplified by the lack of exchange of the entire system with the ocean, especially for the lower bays of Baffin and the Upper Laguna, which do not exchange well even with the larger body of Corpus Christi Bay.

As remarkable as this north-to-south salinity gradient is, equally remarkable is the lack of a prominent gradient in salinity in those regions most affected by freshwater inflow. In Copano Bay, Fig. 3-1, which receives the greatest quantity of inflow, the average gradient in only about 4 ppt from the causeway to the mouths of the rivers. In Nueces Bay, even more surprisingly, the gradient from the mouth of the bay to the delta is flat, only a couple of ppt, Fig. 3-2. This is clear evidence that the effect of freshets in depressing salinity is relatively infrequent and short-lived. Another noteworthy feature of the mean salinity patterns is the absence of systematically higher salinities in the channel segments. This would suggest that, on average, the deepdraft ship channel has little additional effect on salinity intrusion. This is in direct contrast to the Houston Ship Channel in the Galveston system (Ward and Armstrong, 1992a). The reason for this is also rooted in the relative infrequency of freshets in the Corpus Christi Bay system. For a density current in a deep channel to develop, there must be a horizontal gradient in salinity. This gradient is regularly present in Galveston Bay, due to the inflow from the Trinity and San Jacinto Rivers. In Corpus Christi Bay, as shown by Fig. 3-2, the average gradient in the open bay is flat. Without such a gradient, density currents cannot develop, and the deep channel cannot become a favored pathway for salinity intrusion. When large freshets do occur, such gradients are developed and the density current becomes important in salinity intrusion, but such events are apparently so rare that they do not affect the long-term statistics.

Time trends in salinity are obscured because there is such relative constancy in salinity in the system, which makes the parameter susceptible to random variations. Despite this, regions of the study area exhibit defined trends, notably Copano Bay, St. Charles Bay, Nueces Bay and most of the open areas of Corpus Christi Bay, all of which show increasing salinities with time, see Figs. 3-44 and 3-45. The average rates of increase over those segments with a probable trend are: Copano, 0.081 ppt/yr; St. Charles, 0.26; Nueces, 0.25 ppt/yr; Corpus Christi, 0.047 ppt/yr. These are not trivial increases. Over two decades (say), these would translate to increases in average salinity of: Copano Bay, 1.6 ppt; Corpus Christi Bay, 1 ppt; and Nueces Bay, 5 ppt.

In seeking a possible explanation for these trends, the obvious control to examine is freshwater inflow. With respect to the gauged flow of the Nueces, a linear decreasing trend in the monthly mean flows over the period of 1968-93 is indeed disclosed, with rate 29 cfs per year. Inspection of the monthly flow data over this period, Fig. 4-5, indicates that the greatest contributor to the declining trend is the reduced frequency of occurrence of high-inflow events. Similar trend analyses were carried out for the synthetic flows, developed by USGS (see Section 4.1.2 above), for Copano and Corpus Christi Bay watersheds, averaged by month. (Recall that Corpus Christi Bay watershed is defined to be all of its peripheral drainage area, including the Nueces watershed downstream from the gauge at Mathis.) For Copano a barely resolvable declining trend emerged, of 5.1 cfs/yr, and for Corpus Christi Bay a declining trend of 16 cfs/yr.

To determine whether such a declining trend in inflow could be responsible for the increasing trend in salinity would require a detailed salt budget for the system, manifestly beyond the scope of the present study. Some judgements can be proffered based on magnitudes, however. By comparison of these inflow trends to their initial values in 1968, the respective reduction in annual mean inflow over the 1968-93 period would be about 14% for Copano Bay, 53% for Corpus Christi Bay, and 69% for the Nueces River (at Mathis). This is substantial.

While the decline in inflow is likely to be the explanation for the increasing trends in salinity, we note that there are other hypotheses which could be contributors as well:

(1) Increased salinities in the adjacent Gulf of Mexico;
(2) Altered interaction with the Gulf of Mexico;
(3) Altered volume and timing of freshwater inflow events in such a way as to augment salinity intrusion;
(4) Sampling bias due to changing seasonality, geographical distribution or vertical profiling over time;

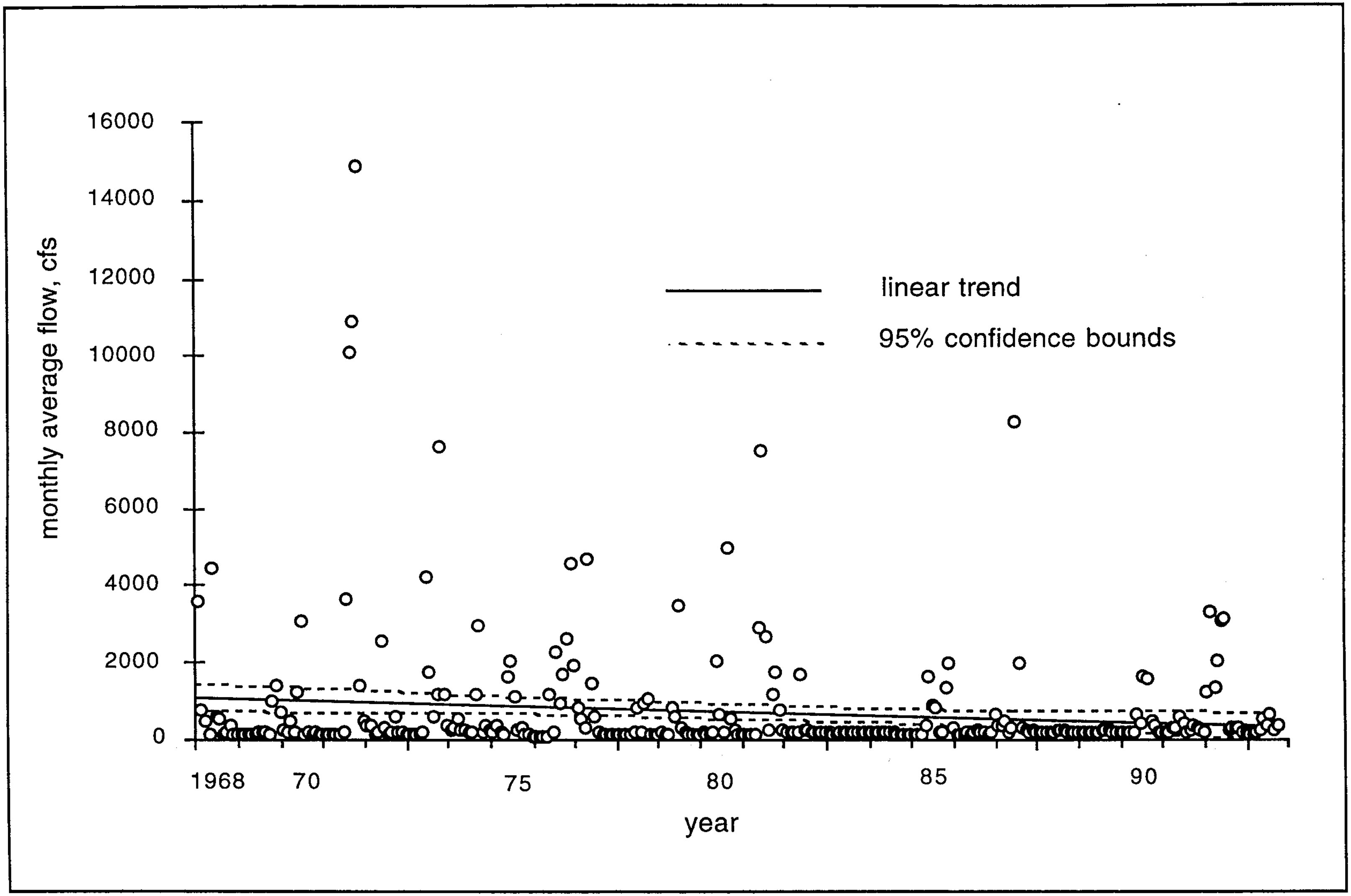


Figure 4-5. Monthly mean flow of Nueces at Mathis and linear trend line

(5) Increased diversions and/or decreased return flows.

Some of these may be locally important, even if not important on a bay-wide or system-wide scale. There is no evidence of (1) based upon the trends analyses of this project (see Fig. 3-46). The volumes of diversion and return flow in Corpus Christi Bay are smaller by an order of magnitude than the trends in inflow, so (5) appears unlikely, except, again, in some specific localities. A cursory inspection of the sampling intensity does not reveal any obvious bias in the more recent data compared to those of the 1970's, so (4) does not seem likely, at least on a baywide basis. Both (2) and (3) appear to be viable, warranting additional study.

4.2.3 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. A relatively slight stratification in DO increasing upward, equivalently a stratification in DO deficit decreasing upward (Table 3-14), is consistent with oxygen consumption in the water column and in the bottom sediments, in conjunction with the influx of oxygen through the surface. There is no apparent correlation with depth in stratification through the system, though deeper water will evidence a greater top-to-bottom DO difference, since the gradient is multiplied by a greater depth. Even at this, the Inner Harbor, the greatest focus of oxygen-demanding waste loads in the system, averages only about 3 ppm top-to-bottom difference in DO.

Since the system is so near saturation, systematic trends are difficult to discern. This is reflected in the statistical results, e.g. Figs. 3-50 and 3-51, which are mixed. One prominent exception is the outer bays, Copano, Aransas and Baffin, that show a systematic trend of declining DO deficit (i.e., increasing DO). One hypothesis for this trend could be as the result of improvements in waste treatment implemented by the communities on the shore of these bays. Other hypotheses include diminishing oxygen-demanding loads in runoff and altered kinetics within the bay waters themselves.

One aspect of DO behavior that is obscured by long-term statistical analyses is the occurrence of low-DO events, i.e. hypoxia. The potential impact of these events on the ecosystem may be far greater than their relative infrequency might suggest. For this reason, special attention was given to the occurrence of such depressed events by separately analyzing the data for concentrations below 2 ppm. The relative frequency of occurrence of such low-oxygen events in the data record, as a percent of all measurements, is summarized in Table 4-4 by component bay (see Table 3-4 for definitions). The majority of hydrographic-area segments in the system have never logged an occurrence of DO below 2 ppm. The greatest systematic occurrence is in those areas affected by high organic loading and poor flushing, notably the Inner Harbor, LaQuinta Channel, Upper Laguna, especially along the King Ranch reach and near the

JFK Causeway, Redfish Bay near Ingleside, and the nearshore of Corpus Christi Bay along the urbanized south shore. Low DO events are much more a phenomenon of summer and occur primarily in the measurements at depth, although in the 1960's and 1970's occasional profiles of DO in the Inner Harbor show depleted DO throughout the depth.

An even more serious circumstance is DO that is virtually zero. The occurrence of near-zero DO events as a fraction (percent) of the hypoxic events, where we define "near-zero" to be a DO concentration 0.5 ppm, is summarized in Table 4-5 by *hydrographic segment*. To better focus this table, we include only those segments in which there are at least three measurements that are hypoxic (so that the relative frequency of those that are near-zero has some meaning), and at least one near-zero occurrence is logged in the period of record. Again, the Inner Harbor is the predominant low-DO environment in the system.

What emerges from these tables is that hypoxia (DO 2) is relatively rare in the system, and there are geographical regions of consistent occurrence. Near-zero events (DO 0.5) are rarer yet, being primarily confined to the Inner Harbor and Nueces River. In the time domain, most of the occurrences of hypoxia in the Corpus Christi Bay main body were logged in the 1960's and 1970's, especially in the Inner Harbor. In the outer bays of Copano, Aransas, the Upper Laguna and Baffin, most of the occurrences have been in the late 1980's and early 1990's.

Table 4-4
Monthly and total frequency of occurrence of dissolved oxygen values 2 ppm
as percent (%) of measurements of DO by principal component bay

segment	*J*	*F*	*M*	*A*	*M*	*J*	*J*	*A*	*S*	*O*	*N*	*D*	*all*
Aransas Bay	0.4	0	2.9	0	0	0.6	0	1.0	0.5	0.3	0	0	0.6
Copano Bay	0	0	0	0	0.3	0.4	0	0	0.5	0.2	0	0	0.1
St Charles	0	0	0	0	0.7	0	1.3	0	0	0	0	0	0.2
Mesquite	0	0	0	0	0	0	0	0	0	0	0	0	0
Redfish	0	2.5	0	0	0	0	0.5	1.7	1.0	1.1	0.7	0	0.6
Corpus Christi	0	0	0	0	0	0.1	0.8	1.7	0.1	1.2	0.1	0.1	0.4
CCSC (bay)	0	0	0	0	0	1.0	1.0	5.0	1.3	1.7	0	0	0.7
Inner Harbor	0	0.5	5.8	4.6	2.6	25.8	27.5	10.4	26.7	13.8	2.8	7.6	8.5
Nueces Bay	0	0	0	0	0	0	0.4	0	0.5	0	0	0	0.1
Aransas Pass	0	0	0	0	0.7	0.3	0.4	0	0	0	0	0	0.1
Causeway N	0	0	0	0.6	0	0	0	0	0	0	0	0	0.1
Causeway S	0	0	3.1	0	0	0	0	0	1.1	0	0	0	0.3
Laguna (King)	0	0	5.2	0	0.5	1.0	0.8	1.7	1.3	1.0	0.2	0	1.0
Laguna (Baffin)	0	0	0	0	0	2.6	0	2.6	0	0	0	0	0.9
Baffin Bay	0	0.5	0.7	0	1.4	1.3	1.0	3.3	0.4	1.9	0	0	0.9
GOM inlet	0	0	0.5	0.5	0	1.2	0	0	0	0	0	0	0.2

Table 4-5
Monthly and total frequency of occurrence
of dissolved oxygen (WQDO) values 0.5 ppm
as percent (%) of the occurrence of hypoxic values
by hydrographic-area segment

segment	*J*	*F*	*M*	*A*	*M*	*J*	*J*	*A*	*S*	*O*	*N*	*D*	*all*
C15							0	14					7
CCC3								100		0			60
CCC7						50		83	100	0			69
IH1					100	50	35	41	50	58	100	100	52
IH3				17		50	100			83			57
IH5				0	50	29	46	33	38	25			35
IH6				67		25	20	29	29	50	0		33
IH7			67		0	0	23	46	50	22	0		30
NR1			80							0			57
NR3			100	50	67					33	80		65
UL03									100	0			38

Recently, the occurrence of near-bottom near-zero DO has been reported in the region north of the JFK Causeway (Montagna, pers. comm., 1996), Hydrographic Segment C14 (Fig. 2-2). These measurements are not included in the present compilation because they were received too late in the data-compilation process. However, by comparison with the rest of the data, this region evidences no proclivity for the occurrence of hypoxia, so we must regard this recent occurrence as probably localized and transient.

4.2.4 Suspended Solids and Turbidity

Suspended solids in Corpus Christi Bay have a close geographical association with regions of inflow and, to a lesser extent, with regions of shipping, see Figs. 3-24 through 3-27. The former is no doubt due to the riverine inflow and waste discharges as sources of TSS, particularly very fine grained particulates that are easily maintained in suspension. The latter is probably due to resuspension by dredging activity and-especially-by ship traffic. Stratification in TSS is consistent and widespread, though not especially high, generally several ppm per m, decreasing upward, and conforms to the underlying physics. Because the particulates are subject to gravitational settling, an accumulation toward the bottom is anticipated. Also, mobilization of bottom sediments are expected to be a primary source for suspended particulates, so the resultant concentrations will be greater near the source, *viz.* near the bed.

One of the surprising findings of this study is the general declining trend in suspended solids throughout the bay, see Figures 3-57 through 3-60. In the upper bays and the main body of Corpus Christi Bay, this rate of decline is on the order of 0.5 ppm/yr, which over the past two decades has resulted in reducing TSS concentrations by approximately one-fourth. In the lower bays of the Upper Laguna and Baffin, the declining trend was even more prominent, being almost uniformly statistically probable, see Figs. 3-59 and 3-60, and at rate of decline over twice that of the upper bays. Over the period of record this has led to roughly *halving* the TSS concentrations in these bays. It is interesting to note that Ward and Armstrong (1992a) found exactly the same result in the analysis of TSS data from Galveston Bay.

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 reductions in river inflow;
(3) 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;
(4) Reductions in TSS loading of peripheral runoff, due to alterations in land use around the bay;
(5) Declines in the mechanical resuspension of particulates within the bay;
(6) A laboratory artifact due to improved methods of filtration and analysis in the more recent data.

Among most workers (1) and (3a) would be considered the frontrunners by a considerable margin. This may explain the declines in Nueces and Corpus Christi Bay, but does not account for those in the upper and lower bays. Noting that there is a general association of regions of increasing salinity and regions of declining TSS in Corpus Christi, Nueces, Aransas and Copano Bays, and the probable effect of reduced inflow on salinity (see 4.2.2 above) lend weight to (2), perhaps in concert with (3b) or (3c). Again, this does not explain the substantial decline in the lower bays. Hypothesis (5) implies a longer-term climatological change, perhaps an alteration of wind predominance or windwave production. In our view, the only one of these which lacks plausibility is (6). This is because actual TSS measurements make up a minority of the proxied data base, and the same decline is evidenced in the alternative measures of turbidity.

4.2.5 Nutrients and chlorophyll

Ammonia nitrogen is generally higher in regions affected by waste discharges, especially the Inner Harbor, while nitrate is typically highest in regions affected by runoff and inflow. Generally where these are high in concentration, they exhibit a declining trend. The exception to this statement is the occurrence of elevated nitrate in the Inner Harbor, which does not evidence a clear decline. Phosphorus is generally higher in regions affected by runoff, i.e. near the inflows of rivers and tributaries, but its distribution in the system is generally opposite to that of volume of flow, increasing in concentration from Copano in the north to Baffin in the south. Total organic carbon (TOC) is higher in the regions more influenced by inflows, namely the upper bays and Corpus Christi Bay, and in these systems the trend is toward declining concentrations. The sediments also exhibit declining trends of TOC in areas of higher concentrations.

Hypotheses explaining these observations include the following:

(1) The prominent source of ammonia is waste loads, and is declining due to improved waste treatment;

(2) Nitrate is introduced both in runoff and in waste loads, however improvements in waste treatment are not achieving a decline in nitrate in the Inner Harbor because the ammonia in the waste stream is being oxidized to nitrate;

(3) Declines in nitrate in the upper bays are due to reduced riverine loading, in turn a consequence of:
  (a) reservoir construction
  (b) better land-use practices on the watersheds

(4) TOC is declining due to reduced organic loads in the rivers;

(5) TOC is declining due to reduced biomass production in the open waters.

Whether (5) is a viable hypothesis could be judged by whether a similar trend is indicated for chlorophyll-a. Unfortunately, these data holdings are too sparse and noisy for reliable trend analysis. (In Nueces Bay, the trends are opposite, declining for TOC but increasing for chlorophyll-a.) It is noteworthy to contrast this situation with the analysis for Galveston Bay (Ward and Armstrong, 1992a), where a much more substantial data base for chlorophyll-a allowed determ-ination of a general decline in concentration throughout the system.

4.2.6 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 a tendency for decline in BOD concentrations over time in the same regions. Unfortunately, measurement of BOD seems to have gone out of fashion in recent years, so most of our knowledge about the distribution of BOD in the system applies only to the 1970's for most areas, and the early 1980's for the others. High concentrations indicated in Baffin Bay are based on data from the 1960's and 70's. Similarly, the declines in Inner Harbor values might be much more pronounced (and better defined) had we any data from the most recent decade. Thus while we do not need to look far for a causal hypothesis explicating the observed behavior of BOD in Corpus Christi Bay, since it is clearly a direct measure of organic loads, both from waste discharges and from peripheral runoff (including inflows), its association with more recent trends in the system, e.g. nutrients and increasing salinities, is unknown. Other alternative indicators of organic contaminants such as volatile suspended solids and oil & grease suffer from the same problems of limited measurements. Volatile suspended solids are high in the water and volatile solids are high in the sediment in the Inner Harbor. These are also high in Copano

Bay and Nueces Bay. For VSS, however, the data record extends to the present, and evidences a probable declining trend almost everywhere in the system (where data exist).

Fecal coliforms exhibit lower concentrations in open-bay areas and higher concentrations in areas affected by inflow, runoff, and waste discharges, Fig. 3-29 and Table 3-5. High values are found in the nearshore regions along the urbanized south shore of Corpus Christi Bay. The most widespread trend is for increasing concentrations, but this is at a low level of statistical confidence. This would seem to run counter to the above hypotheses of improved waste treatment, and diminished runoff loads. Certainly, the noisy character of this measure erodes the statistical confidence in the analysis, and many of the apparent trends may be statistical artifacts. 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. This means that apparent statistical behavior of the data base may be more a function of where and when it is sampled than in any intrinsic variation of the parameter. 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 in the water column (cf. Table 4-1) and their *variability* in Corpus Christi Bay would be expected to be high, in response to all of the factors effecting mass transport (analogous to that of salinity). The problem of inference is compounded by the relatively sparse data set and the great majority of measurements reported as “below detection limits,” all of which translates to a high degree of uncertainty. It is clear, however, that the regions in and around the Inner Harbor exhibit consistently high metals in the water. Nueces Bay is a region consistently high in metals, in both the water column and the sediment, as are Baffin Bay, Copano Bay, a region of the Upper Laguna around Pita Island, the La Quinta Channel, and Redfish Bay near Aransas Pass.

The existence of the CP&L Nueces Generating Station means there is a direct transport of water from the Inner Harbor to Nueces Bay (see 4.2.1 above), in that the plant continuously circulates a flow at a nominal rate of 18 m^3s^{-1} (650 cfs), which is approximately equal to the mean inflow of the Nueces River (Table 4-2). One hypothesis for the elevated metals in Nueces Bay, therefore, is that they are due to this influx of water (and suspended sediments) from the Inner Harbor. This hypothesis cannot, however, be the entire explanation, because there are too many parameters whose concentrations are inconsistent between Nueces Bay and the Inner Harbor, such as ammonia, suspended solids, and lead, nor are the trends consistent. A second hypothesis is that the metals are associated with oil and gas activities, a feature which Nueces Bay has in common with Copano Bay and Baffin Bay. This may also be supported by the relatively high sediment concentrations of PAH's, some of which, such as acenapthene, are not shared with the Inner Harbor. For the metals for which a reliable trend determination can be made, most are declining in the Inner Harbor. This is in general conformity to the hypothesis of improved water quality due to advanced waste treatment.

One curious exception is lead in the water phase, which shows probable increasing trends consistently in all of the segments of the Inner Harbor. This statement is not true for the sediment metals, in that no positive trends are indicated in the Inner Harbor for any of the metals.

Elsewhere in the bay, metals data for the water phase are too sparse to allow general statements. In the sediments, the open deeper waters of Corpus Christi Bay tend to be higher in concentration than the nearshore waters for most metals. This seems to be obeyed as well in the other systems, especially Baffin, but is most obvious in Corpus Christi Bay because of the high range of concentrations. On the other hand, the deepest sections of Corpus Christi Bay, namely, the Corpus Christi Ship Channel hydrographic segments, are systematically lower in metals than the sediments to either side, see Figs. 3-37, 3-39, and 3-41. This general pattern offers clear evidence of the association of metals with sediments, especially the finer grain sediments, and how they are influenced by transport, deposition and dredging. Trends in sediment concentrations are inconsistent geographically and from metal to metal, so without further detailed analysis, it is difficult to determine possible causes. We note a general probable decline in mercury in the open bay waters, and some tendency for increasing zinc, especially in the Baffin and Corpus Christi systems, but this is statistically less reliable.

Two hypotheses regarding in the interaction of water and sediment metals, and their ultimate transport and fate are:

(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-sorbed metals in the overlying water and zones of relative stagnation where settling is enhanced;

With respect to the observed distributions and probable sources, the following hypotheses are proffered:

(3) The principal sources of metals in Corpus Christi Bay are in the industrial and outer bay areas, in turn originating from
    (a) waste discharges
    (b) runoff from industrialized areas
    (c) shipping activity
    (d) oil & gas production activities

(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 in the Inner Harbor and trans-bay reach of the Corpus Christi Ship Channel is due to increased dredging, removing contaminated sediments from the bay system to upland or offshore sites, or sidecasting into areas remote from the channel; if the pathway is from sediments to water (1), this would imply a reduced concentration in the water column, as well.

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 moot 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, perhaps offering an explanation for the higher concentrations of some metals in the Port Aransas Entrance Channel regions.

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 Corpus Christi Bay, other than a proclivity for higher concentrations in regions of increased urban activity, especially the Inner Harbor.

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5. CONCLUSIONS AND RECOMMENDATIONS

5.1 The data base

A primary objective of this study was the compilation of a digital data base composed of water-quality, sediment-quality and tissue-quality data, which was assembled from 30 ongoing or historical data collection programs performed in the Corpus Christi Bay study area. This compilation, considered to be one of the principal products of this study, is the most extensive and detailed long-term record of water and sediment quality ever developed for Corpus Christi Bay. Each measurement record includes the date, latitude and longitude of the sample station, sample depth, measured variable, estimated uncertainty of measurement expressed as a standard deviation, and a project code identifying the origin of the data. (For tissue data, the sample depth field is replaced by a code identifying the organism.) The complete data base approaches half a million independent records of which water:sediment:tissue are in the approximate ratios 100:10:2, and about 43% of the water-phase data are the "field" parameters temperature/ salinity/pH/dissolved oxygen.

Spatial aggregation of the data was accomplished by two separate segmentation systems for Corpus Christi Bay, the TNRCC Water Quality Segmentation of 27 segments, and a system of 178 hydrographic segments devised by this project and designed to depict the effects of morphology and hydrography on water properties. (The 27 TNRCC segments include the original 15 specified by the Scope of Work, to which we added 5 classified segments and 7 unclassified.) Detailed statistical analyses were performed of 109 water-quality parameters and 83 sediment-quality parameters, in addition to several supplementary (e.g., DO deficit), screened (e.g., near-surface values), or transformed (e.g., proxied TSS) variables. Therefore, statistical analyses addressing water/sediment quality were performed of about 200 parameters in about 200 (exactly, 27 + 178) different segments, a total of about 40,000 independent statistical analyses, since each parameter/segment comprises an independent data set. For tissue data, an even more extensive suite of 172 analytes (including various reporting combinations of dry/wet weight and whole-organism/filet) were compiled, but the statistical analyses were confined to a subset of these analytes and to spatial aggregation by TNRCC segments only, because of the sparsity of the data base.

Adequacy of a data base is judged relative to the ability to resolve the various scales of variation, and therefore in this respect the data base for Corpus Christi Bay is sparse. When the hundreds of thousands of separate measurements compiled in this study are subdivided by specific parameters, each of which measures a different aspect of the water/sediment quality "climate," aggregated by region of the bay and distributed over time, Corpus Christi Bay is seen to be generally undersampled. This is relative to the high degree of variability of the bay. Unlike a lake or a river, which can be fairly stable in time and fairly homogeneous over large areas, Corpus Christi Bay is subject to a variety of external controls. The intermixing of fresh and oceanic waters imposes spatial gradients in both the horizontal and the vertical. The effects of tides, meteorologically driven circulations, and transient inflows all contribute to extreme variability in time. Superposed upon all of this are the time- and space-varying influences of human activities. All of these contribute to substantial variation in space and time.

Continuity in space of the data base is undermined by too few stations, and by inconsistency 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. Ability to resolve long-term trends in the face of high intrinsic variability requires data over an extended period. Data availability within the last five years has diminished because of a processing pipeline problem with several major programs, and because of reductions in intensity of data collection. The extant period of record for Corpus Christi 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 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, in a few cases back to the 1970's. Moreover, the vast majority of these measurements are reported as below detection limits. For sediment, the data base is even more limited, amounting to one sample per 50 square miles per year, and extending back in time at most to the 1970's.

Data management is generally poor. Most of the same problems encountered in the Galveston Bay Status & Trends Project (Ward and Armstrong, 1992a) were met in this one as well, though there have been conspicuous improvements in specific programs, e.g. TNRCC and the NOS Status & Trends Program. Several programs suffer data loss or data corruption from what are referred to here as data "recovery" procedures, i.e. all data manipulation procedures after the basic measurement has been documented by field sheet, laboratory report, or robot logger, including calibration or conversion, downloading, and post-processing, but especially data-entry and re-formatting. The most pressing management problem for historical data in the Corpus Christi area, as well as in other areas of the Texas coast, is preservation. Much irreplaceable and invaluable information on the Corpus Christi Bay system has been lost.

5.2 The water and sediment "climate"

Salinity acts as a water mass tracer and general habitat indicator for Corpus Christi 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. It is technically a conservative parameter, but viewed from a water-column perspective, it behaves nonconservatively much of the time because of the major rôle evaporation plays in the bay's salt budget. In contrast to the estuaries on the upper Texas coast, substantial gradients across Corpus Christi Bay from the sea to the regions of inflow are not a normal feature of salinity structure. These gradients are on average rather flat. The most significant gradient of salinity in the project Study Area is, rather, from north to south, from Copano Bay to Baffin Bay. This is clearly the combined result of diminishing inflow with distance to the south and increasing evaporation. Mean salinities often exceed seawater concentrations, sometimes by large amounts, especially in the lower bays (the Upper Laguna and Baffin Bay). Variability about the mean salinity is high, in some areas tens of parts per thousand. Vertical salinity 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 study area, with no correlation with water depth. In particular, there is no apparent correlation between mean salinities and ship channels, suggesting that density currents as a mechanism of salinity intrusion are rarely important in Corpus Christi Bay. This is consistent with the lack of horizontal salinity gradient along the ship channels.

While freshwater inflow is the ultimate control on salinity, inflow proves to be a poor statistical predictor of salinity, achieving less than 50% explained variance in those areas in proximity to sources of inflow, and even less elsewhere, even with long-term averaging of the antecedent inflow. This illustrates that the variability of salinity is influenced by factors other than simply the level of inflow.

In the bays generally more influenced by freshwater inflow, *viz*. the Copano system, the main body of Corpus Christi Bay and Nueces Bay, there has been a general increase in salinity over the three-decade period of record, on the order of 0.1 ppt per year. During the same period there has been a declining trend in monthly-mean inflow to these same bays, over 50% in Corpus Christi and Nueces Bays, less in Copano (which also logged a smaller increase in salinity). Our favored hypothesis (whose testing would require detailed salt budgeting for the system, and exceeded the scope of this study) is that this decline in mean inflow is responsible for the increase in salinity. No clear trends in salinity emerged for the Upper Laguna or Baffin Bay.

The parameter pH is rather uniform, with its higher values, in excess of 8, in the more saline regions of the bay, an expression of the high buffering capacity of sea water. Because of its variability within a rather narrow range, no reliable trends were detectable, though in the open waters of Corpus Christi there is a proclivity to declining values. It is noteworthy that the (much smaller) data set for alkalinity shows statistically probable declining trends almost everywhere.

Temperature in Corpus Christi Bay is primarily controlled by surface fluxes, especially the seasonal heat budget, and much less-if at all-by peripheral boundary fluxes and internal transports. The horizontal gradient across the study area is from north to south, ranging 2-4 C. There is little systematic stratification, though on average a slight stratification on the order of 0.1 C/m is indicated, due to near-surface heat absorption, rather than density effects. The seasonal signal is, of course, the principal source of variation in water temperature, ranging about 14 to 30 C from winter to summer. Over the three-decade period of record, water temperature in the upper bays and main body of Corpus Christi Bay, especially in the open waters, has declined at a nominal rate of 0.05 C/yr. There are no clear trends in the open waters, has declined at a nominal rate of 0.05 C/yr. There are no clear trends in the lower bays. It is interesting to note that the same decline in temperature, at approximately the same rate, was discovered in Galveston Bay (Ward and Armstrong, 1992a). 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 consistently high throughout the CCBNEP study area, averaging near (and above) saturation through most of the system, with frequent occurrence in the data record of substantial supersaturation. Exceptions to this are in poorly flushed tributaries and areas influenced by wasteloads, especially the Inner Harbor. These near-saturated conditions are a manifestation of the intense vertical mixing processes in Corpus Christi Bay, which enhance mechanical surface aeration, as well as a manifestation of photosynthetic productivity. The most important variation in DO is due to seasonal changes of solubility. In the open, well-aerated areas of the bay, vertical stratification is slight, averaging on the order of 0.1 ppm/m and is considered to be the result of DO influx across the surface in concert with water-column and sediment biochemical oxygen consumption. The occurrence of hypoxia (which we define to be DO 2 ppm) is rare, occurring at most in several percent of the data in a minority of regions of the bay, and primarily in measurements near the bottom in deeper water. The exception is the Inner Harbor, where hypoxia has occurred more frequently, in about one-fourth of the measurements, but still primarily near-bottom.

Conventional water-phase organic contaminants as measured by BOD, oil & grease, VSS and volatile solids, are generally highest in the Inner Harbor. However, the data base is too limited for reliable trend determination. In fact, the frequency of measurement of these parameters has declined substantially in recent years. In the open waters of Corpus Christi Bay, BOD seems to be declining, and wherever adequate data for analysis exist, VSS is declining. This is probably the result of the institution of advanced waste treatment.

Like all of the Texas bays, Corpus Christi is turbid. Long-term average suspended solids range 20-100 ppm throughout most of the study area, higher in the bays influenced by freshwater inflow, i.e. Nueces, Copano and Corpus Christi Bay, as well as in Baffin. 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 highest TSS concentrations and highest stratification are found in Nueces Bay.

The remarkable feature of TSS in Corpus Christi Bay disclosed by these analyses is its decline throughout the system, increasing in significance from north to south in the study area. This is consistent with the findings for Galveston Bay (Ward and Armstrong, 1992a) but the rate of decline is about a factor of two to four smaller in Corpus Christi Bay. Still, it is sufficient to have reduced the average concentration by about 25% in the upper bays and by about 50% in the lower bays over the last two decades. This could be caused by several factors, including a general reduction of TSS loading to the bay or altered mobilization within the bay system itself. The usual hypotheses of improved waste treatment and/or TSS entrapment within __servoirs are not adequate to account for the substantial reductions in the lower bays, though they may explain the alterations in Nueces Bay.

Nitrogen and phosphorus nutrients in the water column are noisy and highly variable through the Corpus Christi Bay study area. Ammonia nitrogen is generally higher in regions affected by waste discharges, especially the Inner Harbor, while nitrate nitrogen and phosphorus are typically highest in regions affected by runoff and inflow. Generally where the nitrogen species are high in concentration, they exhibit a declining trend. No clear trends are apparent in the phosphorus data. In the sediment phase, concentrations of Kjeldahl nitrogen are elevated but not excessive in the Inner Harbor region, and the highest concen-trations in the system occur in the Upper Laguna along the King Ranch. Sediment phosphorus is relatively uniform throughout the system with no relative elevation in the Inner Harbor or in areas affected by inflow.

The levels of concentration of total inorganic nitrogen in the water are about 0.1 ppm in most sections of the system, except much higher, around 0.5 ppm in Copano and in the Inner Harbor (the latter due to high ammonia concentrations). Total phosphorus in water is about 0.05 ppm through the system, except around 0.15 ppm in regions affected by tributary inflow, notably Nueces Bay, Copano Bay and Baffin Bay. These mean concentrations are more-or-less typical of other Texas bays (e.g., Longley, 1994), though total inorganic nitrogen is about half the levels found in Galveston Bay and total phosphorus is about one-fourth (Ward and Armstrong, 1992a).

Generally water-phase TOC values are about a factor of two higher in the upper bays, decreasing from 20-30 ppm in Copano to 5-15 ppm in Baffin and the Laguna, with a seasonal peak in early summer. Much larger values (about an order of magnitude) are found in the Inner Harbor. Water-phase and sediment TOC distributions generally run counter to each other. TOC in sediments increases southward across the study area with the lowest values of sediment TOC in the Inner Harbor. Nueces Bay shows substantially depressed values of TOC in both water and sediment. There is a widespread declining trend in water-phase TOC at a rate sufficient to reduce the concentrations by about one-fourth over two decades. (The prominent exception to this is in the Inner Harbor, where average TOC is the highest in the study area, and is increasing in time.) Where sufficient sediment TOC data exist to establish a trend, this trend generally is also declining in time. Unfortunately, the data for chlorophyll-a is too sparse and noisy to determine whether any correlated time trends occur in it as well, so we cannot judge whether the decline in TOC is due to reduced primary production or to reduced loadings.

Contaminants such as coliforms, metals and trace organics show elevated levels in regions of runoff and waste discharge, with generally the highest values in the Inner Harbor, and generally low values in the open bay waters. Given this general statement, some exceptional situations should be noted. The highest average coliforms in the system occur in the nearshore segments of Corpus Christi Bay from Corpus Christi Beach to Oso Bay. Nueces Bay is a region consistently high in metals, in both the water column and the sediment, as are

Baffin Bay, Copano Bay, a region of the Upper Laguna around the Bird Islands, the La Quinta Channel, and Redfish Bay near Aransas Pass. We expect metals concentrations in both water and sediment to be closely linked to suspended sediments, which act as carriers for metals, but to also be influenced by local sources, and perhaps sources from the watersheds brought in by runoff. The only apparent commonality to all of these regions is concentrations of petroleum production facilities.

Curiously, while concentrations in the water phase of arsenic, cadmium, iron, mercury in the CCBNEP Study Area in general are substantially less than those in Galveston Bay, concentrations of copper, chromium, lead, manganese, nickel and zinc are about the same. Considering that Galveston Bay is a smaller area, is more directly influenced throughout by human activities, and is generally considered to have much higher point-source loads of metals, one would expect the Corpus Christi Bay study area to have lower concentrations. That it does not would suggest a source other than point source loadings for these metals. The metals copper, nickel and zinc, in particular, have elevated concentrations generally throughout Corpus Christi Bay where data exist (relative to the values of Moore and Ramamoorthy, 1984b). With respect to sediment metals, arsenic, cadmium, mercury, and zinc are on the same order as Galveston Bay, while copper, iron and lead are much lower (except for the Inner Harbor, which is similar to the upper Houston Ship Channel in all of these metals, save zinc, for which its sediments are an order of magnitude *higher* than those of the Houston Ship Channel).

The water-phase metals data were so sparse and noisy that reliable trends could generally not be established. For sediment metals in the principal components of the system, where a trend can be reliably established it is generally declining. It is noteworthy that Copano Bay, which shows among the highest concentrations in the study area (apart from the Inner Harbor) for chromium and nickel, also exhibits increasing probable trends for these metals, as well as for copper and zinc. Another exception to the general declining trends is sediment zinc, for which widespread *possible* increasing trends are indicated in large areas of the open waters of Corpus Christi Bay and Baffin Bay. However, the strength of these statements is blunted by the fact that metals data in the upper bays tends to be much older, with relatively little information from the most recent decade.

No definitive statements can be made about water-phase volatile organics such as pesticides and PAH's, because data is sparse, and very few measurements are uncensored, most being simply reported as below detection limits. For example, the best-monitored pesticide is DDT, for which most areas of the bay do not have data. Only four non-zero average values occur in the entire study area, two in the GIWW at Ayres Bay, one in Nueces Bay, and one in Baffin Bay. For toxaphene, only one non-zero value occurs, in Nueces Bay. The situation is similar for the other organics, with only one or a few non-zero values, and inadequate data to determine any trends or spatial variation.

The situation is a little better for sediment-phase data, but still most of the system is unsampled, and much of the data which do exist are below detection limits. The highest concentrations of the common pesticides are found in Baffin Bay and Copano Bay. Concentrations of sediment pesticides in Nueces Bay are not especially high, except for toxaphene. PCB's and PAH's follow a very different distribution, with very high concentrations (as expected) in the Inner Harbor. Elevated concentrations of PCB's also occur in Redfish Bay. There are consistent elevated concentrations of some of the PAH compounds in Nueces Bay, Copano Bay, and Mesquite Bay, but not in the Upper Laguna.

5.3 Tissue Quality

Considering the effort required to obtain, digitize and compile the tissue data for the CCBNEP study area, the information yield is disappointing. Pooling and analysis of the data are hampered by the noncomparable attributes of organism sampled, portion of organism analyzed (whole versus edible portions), and reporting convention (wet-weight versus dry-weight), in addition to the usual discriminants of analyte and geographical position. The most-sampled organism is the American oyster, with most samples from Nueces and Aransas Bays, followed by the blue crab, speckled trout, red drum and black drum. One sample each of brown shrimp and white shrimp appears in the entire data base. By far, the greatest quantity of analyses have been performed for the metals. Of the organic analytes, the greatest number of determinations have been performed for the pesticides, especially the common commercial mixtures such as chlordane and toxaphene, and for PCB's. Most of the organic analytes have never been detected in the tissues of organisms. In particular, the data base of *detected* PAH's and related hydrocarbons is negligible. For only a few, such as pyrene, have there been detects logged in the data.

For the oyster, Nueces Bay and Copano Bay exhibit systematically elevated metals in the tissue, Nueces Bay having the highest mean tissue concentrations for cadmium, copper, lead and zinc, and Copano Bay exceeding Nueces Bay slightly for mercury. This conclusion generally agrees with the relative concentrations in the sediments, if the Inner Harbor and tertiary bays are discounted. Blue crab data in Redfish Bay and Baffin Bay show elevated levels of most metals. Statistical analysis of the black drum data base was possible only for Nueces Bay, which indicated some elevated metals concentrations, especially for mercury and zinc, and where a time trend could be resolved, it is increasing. These statements notwithstanding, the limited data base in general renders any statistical judgments tenuous.

5.4 Problem Areas

With the marshalling of the data of this project, one central concern is whether there are indicated any regions of the Corpus Christi Bay study area exhibiting degraded quality or exhibiting a trend of degradation that could bode an incipient problem. As a convenient quantification, we used standards and criteria from Texas Surface Water Standards (TWC, 1991) and the EPA “Gold Book” (EPA, 1986). In the present context, we employ these as parameter levels which *may* be indicative of degraded water quality. The Texas Standards apply both to a parameter and to a segment of the bay, while the EPA criteria pertain to a parameter in the marine or estuarine environment, without regional specificity. In many cases, our use here does not conform to how the criteria are applied in regulatory practice. Thus, we flag the use of the term “violation.” Here we mean simply that the point measurement exceeds (or, in the case of DO, is less than) the numerical criterion. As our principal concern is the “present” quality of Corpus Christi Bay, we have focused on data collected since 1985.

For temperature, Table 5-1, the single instantaneous standard of 35 C (95 F) applies throughout the system. Indeed, one must recognize that the TNRCC temperature standard of 35 C is applied uniformly to the entire Texas coast, without cognizance of the natural gradient of increasing temperatures toward the south (a gradient to which the indigenous organisms would have presumably acclimated). Clearly, the shallow, poorly circulated sections of the Corpus Christi Bay system are most prone to higher temperatures, especially those in the lower bays, and violations of 35 C occur, mainly in the summer, at a low rate only a couple of percent. Only two regions have substantially higher frequencies of violation; these are in Nueces Bay and Oso Bay, both affected by return flows from power plants. From this low frequency of violation coupled with the general decline in water temperatures over time, we conclude that hyperthermality is not a problem in Corpus Christi Bay.

The state standard for dissolved oxygen requires special comment. Prior to 1984, standards attainment was established by comparison with a surface measure-ment of DO. With the 1984 revisions, attainment was based upon a vertical profile of DO, either depth-integrated or “under conditions of density stratification, a composite sample collected from the mixed surface layer.” Also, the state

Table 5-1
Relative frequency (per cent) of exceedance of 35 C, upper 1 m, post-1984
by hydrographic-area segment
(only segments logging violations are shown)

Seg-ment	*rel. freq. (%)*	*Seg-ment*	*rel. freq. (%)*	*Seg-ment*	*rel. freq. (%)*
A13	1.0	I8	3.3	OS5	7.1
BF3	0.3	I13	1.1	OS7	1.2
C14	0.6	NB1	0.6	UL02	1.5
C17	0.5	NB6	7.8	UL03	0.8
C25	3.5	NB7	4.2	UL05	2.9
GR2	0.5	ND4	0.3	UL07	2.0

Table 5-2
“Violations” of 5 ppm dissolved oxygen, upper 1 m, post-1984
Relative frequency (percent) by hydrographic area segment
(only segments logging violations are shown)

Segment	*rel freq*	*Segment*	*rel freq*	*Segment*	*rel freq*	*Segment*	*rel freq*	*Segment*	*rel freq*
A1	4.3	C14	3.0	I2	5.4	NB1	12.3	RB8	2.7
A5	3.4	C15	1.6	I3	7.7	NB2	9.9	SC2	5.0
A6	3.4	C17	1.4	I6	1.8	NB3	4.5	SC3	3.0
A8	6.3	C20	6.3	I7	3.3	NB4	2.5	UL01	9.1
A9	7.1	C23	8.1	I8	3.3	NB5	2.7	UL02	7.7
A10	1.7	C24	8.0	I9	15.2	NB6	8.4	UL03	37.1
A11	3.2	CB	5.2	I10	6.3	NB7	11.6	UL04	2.3
A12	2.4	CCC1	1.0	I11	1.7	NB8	4.5	UL05	2.9
A13	1.6	CCC3	0.8	I12	7.8	NB9	2.2	UL06	30.1
AL1á	1.4	CCC5	2.3	I13	11.1	ND4	7.7	UL07	3.9
AL2á	2.0	CCC6	2.7	I14	14.1	NR4	7.2	UL08	26.8
BF1á	0.5	CCC7	0.7	I15	18.8	OS1	9.5	UL09	12
BF2á	4.7	CCC8	6.6	I16	20.8	OS4	6.0	UL10	4.0
BF3á	8.1	CP01	3.7	I17	5.4	OS6	6.8	UL11	40
C01	5.3	CP02	4.5	I18	9.1	OS7	4.8	GMI1	5.6
C02	1.7	CP03	0.8	IH1áá	5.1	PB1	2.4	GMI2	9.3
C03	7.7	CP04	2.9	IH5áá	2.6	PB2	4.3	GMI3	5.5
C04	23.1	CP07	2.2	IH6áá	4.4	RB1	8.2	GMI4	10.3
C06	11.1	CP08	3.1	LS1á	7.7	RB2	4.1	GMI5	4.0
C08	5.3	EF	7.0	LS2á	2.6	RB3	2.4	GMI6	0.9
C09	3.3	GR2á	4.3	M2	6.5	RB4	3.3	GMI7	0.9
C10	1.5	HI1	4.5	MB1	1.0	RB5	4.7	GMI8	0.6
C12	1.5	HI2	3.3	MB2	2.1	RB6	1.9	GMO7	1.3

á DO standard = 4 ppm áá DO standard = 3 ppm

standards apply to 24-hour mean DO values, from which a further depression of 1 ppm in instantaneous concentration is allowable. For present purposes, we compare the instantaneous near-surface measurement to the stated standard for simplicity and uniformity of analysis. (Nor do we discriminate the data analysis by flow condition.) The relative frequencies of DO values less than the stated standard for each hydrographic-area segment logging a “violation” are shown in Table 5-2. Most areas of the bay have a violation frequency of the applicable standard of a couple of percent, almost always in the summer or early fall. There are scattered higher frequencies of violations, especially in proximity to sources of inflow and wasteloads, even higher in the shallow, poorly-circulating areas near the barrier island, and especially high in the Upper Laguna.

The apparent contradiction between the observation that the system is at or above saturation much of the time, and yet has a nonnegligible frequency of standard violation, 10-20% in some areas, is reconciled by noting that much of the year the standard is very close to the saturation concentration. Because of the high natural temperatures and salinities in these areas, saturation is only about 1 ppm above the 5 ppm "standard," and occasional excursions of DO of more than 1 ppm below saturation are not unexpected. (In fact, if one examines violations of a 4 ppm DO level instead, many of the 1-3% occurrences vanish, and most, including those in the Upper Laguna, are halved.)

The 5 ppm criterion does serve to caution that whatever the appropriate standard may be the clearance between physical saturation and the threshold level of DO entailing biological stress is small throughout much of the Corpus Christi Bay study area for a major portion of the year. These regions will therefore have a low assimilative capacity, and this should be carefully considered in any proposed waste discharges or increased wasteloading. Moreover, the time-trend analysis discloses increasing deficits in some of these same areas of low assimilative capacity, notably the Upper Laguna Madre and the open waters of Corpus Christi Bay south of the CCSC.

The state coliform standard strictly applies to a geometric mean of at least five samples "representative" of a 30-day period. The 14 col/100 mL criterion derives from the requirement for "oyster waters" (TWC, 1991, Section 307.7), which further limits the frequency in individual samples to no more than 10% over 43 col/100 mL. Our purpose here is not to strictly apply these conditions (indeed, the temporal density of most of the data will not allow computation of a 5-sample geometric mean within 30 days), but to use them as a guide. The simple frequency of exceedance of the applicable numerical value is given in Table 5-3. Those areas with a frequency of occurrence of less than about 10% would probably vanish altogether if a geometric mean of several independent measurements could be made. The areas of concern to us are those exceeding 10%. These are primarily the upper bays in proximity to sources of inflow and runoff, especially in urbanized areas, specifically: Copano Bay near the mouths of inflows, St. Charles Bay, Nueces Bay and near its entrance in Corpus Christi Bay. Corpus Christi Bay along the south shore from Corpus Christi Beach to Demit Island, Bulkhead Flats and the Upper Laguna around the JFK Causeway, Lower Oso Bay. If the raw data are screened for those sections exceeding 43 col/100 mL more than 10% of the time, these same areas emerge.

While statistical trends in data as noisy and spiky as coliforms are difficult to establish reliably, the present analysis certainly provides no indication that the coliform concentrations are declining. (At the same time, it should be noted that these concentrations are considerably smaller than the standard for contact recreation, 200 col/100 mL.) All of these areas are presently closed for shellfish harvesting (Jensen et al. 1996). To the extent that these elevated coliform levels represent a problem area, the state has already implemented appropriate action.

Table 5-3
“Violations” of fecal coliform standard (Table 10-1) post-1984
Relative frequency (percent) by hydrographic-area segment
(only segments logging violations are shown)

Seg-ment	*rel freq*	*Seg-ment*	*rel freq*	*Seg-ment*	*rel freq*
A1	2.2	CCC8	22.4	NB4	80
A2	15.2	CP02	26.5	NB5	12.5
A3	2.1	CP03	21.8	NB6	18.9
A4	6.5	CP04	7.8	NB7	23.5
A6	9.5	CP05	11.4	NB8	39.4
A8	4.7	CP06	10.5	NB9	17.6
A10	2.2	CP10	3.7	NR1á	0
A13	2.6	I4	13.6	NR4á	25.9
AR1á	0	I6	1	OS1	100
BF3	5.6	I10	52.5	OS6	42.9
C01	42.2	I12	5.9	OS7	29.4
C02	31.2	IH1á	0	PB1á	0
C03	37.9	IH5á	5.3	RB4	33.3
C12	1.4	IH6á	0	RB8	12.5
C15	25	LQ1	18.2	SC2	20.3
C17	5.6	LQ2	15.4	SC3	35.7
C19	2.8	M2	14.3	UL01	47.5
C20	2.8	MB1	11.8	UL04	5.9
CCC3	2.1	MB2	6.9	GMI6	14.3
CCC4	2.8	NB2	25.7		

á fecal coliform standard = 200 org/200 mL

The state standards for metals and pesticides are generally chronic marine criteria and strictly apply to the dissolved parameter. Because there are so few measurements of dissolved fractions from Corpus Christi Bay, and these are almost always below detection limits, the direct applicability of these standards is limited. Therefore, we have applied these criteria to the Corpus Christi Bay data base for “total” (i.e., unfiltered) metals, which will be greater in concentration than the “dissolved” metal by as much as an order of magnitude, depending upon the specific metal and the nature of suspended matter in the sample. Frequencies of “violation” of the corresponding criterion are shown in Table 5-4. Again, our purpose is to identify potential areas of concern, realizing that they may indicate a water-quality problem that does not exist. Even given the stringent limits of chronic criteria and their application to total rather than dissolved metals, it is apparent that violations are relatively infrequent. Some metals are within the criteria everywhere, namely silver, arsenic and selenium, while others are violated in only one segment in the system, namely mercury and lead. The La

Table 5-4
"Violations" of metals criteria post-1984
Relative frequency (percent) by hydrographic-area segment
(only segments shown for which metals data exist)

segment	*wqmetagt*	*wqmetast*	*wqmetcdt*	*wqmetcrt*	*wqmetcut*	*wqmethgt*	*wqmetnit*	*wqmetpbt*	*wqmetset*	*wqmetznt*
criteria:	*0.92*	*78*	*10.01*	*50*	*4.37*	*1.1*	*13.2*	*5.6*	*136*	*89*
C07	*	0	0	0	0	0	0	0	0	100.0
C08	*	0	0	0	0	0	0	0	0	100.0
C14	*	0	0	0	0	0	0	0	0	0
C18	*	0	0	0	0	0	0	0	0	100.0
C22	*	0	0	0	0	0	0	0	0	100.0
CBH	0	0	0	0	0	0	0	0	0	0
CCC2	*	0	0	0	0	0	0	0	0	0
CCC3	0	0	80.0	20.0	20.0	0	80.0	0	0	20.0
CCC4	0	0	0	0	0	0	0	0	0	0
CCC5	0	0	0	0	0	0	0	0	0	25.0
CCC6	0	0	0	0	8.7	0	0	0	0	21.7
CCC7	0	0	0	0	0	0	0	0	0	30.0
CCC8	0	0	0	0	28.6	0	16.7	0	0	16.7
HI1	0	0	0	0	0	0	0	0	0	0
I1	*	0	100.0	0	0	0	0	0	0	0
I2	*	0	100.0	0	0	0	0	0	0	0
I3	0	0	0	0	0	0	33.3	0	0	16.7
I4	0	0	6.1	0	0	0	48.5	0	0	12.1
I5	0	0	0	0	0	0	11.8	0	0	0
I6	*	0	0	0	0	0	0	0	0	0
I9	*	0	0	0	0	0	0	0	0	0
I10	*	0	0	0	0	0	0	0	0	0

(continued)

* No data

Table 5-4

Relative frequency (percent) of "violations" of metals criteria (continued)

segment	*wqmetagt*	*wqmetast*	*wqmetcdt*	*wqmetcrt*	*wqmetcut*	*wqmethgt*	*wqmetnit*	*wqmetpbt*	*wqmetset*	*wqmetznt*
criteria:	*0.92*	*78*	*10.01*	*50*	*4.37*	*1.1*	*13.2*	*5.6*	*136*	*89*
I11	*	0	0	0	0	0	0	0	0	0
I13	*	0	0	0	0	0	0	0	0	0
I14	*	0	0	0	0	0	0	0	0	0
I15	*	0	0	0	0	0	0	0	0	0
I16	*	0	0	0	0	0	0	0	0	0
I17	*	0	0	0	0	0	0	0	0	0
I18	*	0	0	0	0	0	0	0	0	0
IH1	0	0	0	0	66.7	0	0	0	0	0
IH2	0	0	0	0	0	0	0	0	0	0
IH3	0	0	0	0	0	0	0	0	0	0
IH4	0	0	0	0	0	0	0	0	0	0
IH5	0	0	0	0	50.0	0	0	0	0	0
IH6	0	0	0	0	28.6	0	25.0	0	0	0
IH7	0	0	0	0	33.3	0	33.3	0	0	0
INL	0	0	0	0	0	0	0	0	0	0
LQ1	0	0	41.7	8.3	0	0	41.7	0	0	8.3
LQ2	0	0	54.5	18.2	18.2	9.1	54.5	0	0	18.2
NB7	0	0	25.0	0	50.0	0	0	50.0	0	25.0
RB3	0	0	0	0	0	0	0	0	0	0
RB8	0	0	0	0	0	0	0	0	0	0
GMI6	*	0	0	0	0	0	0	0	0	0
GMO6	*	0	0	0	0	0	0	0	0	0

* No data

Quinta Channel and the adjacent CCSC near Ingleside (Segment CCC3) is a region of violations of several metals. The metal with the greatest frequencies of violation is zinc; these are fairly widespread within Corpus Christi Bay *per se*, especially in and around the CCSC and the La Quinta Channel.

We emphasize that dissolved metals-if we had a sufficient data base available-would exhibit lower frequencies of violations than these total-metals measurements. Even the applicability of dissolved standards such as those of Table 5-4 without taking account of the speciation of the metals is questionable. Therefore in terms of posing a threat to aquatic life, no strict conclusions can be drawn from the comparisons of Table 5-4, but it seems safe to judge that the possibility is unlikely.

Criteria appropriate for sediment are still under development, see Adams et al. (1992). Concentration ranges considered to be representative of heavy metal “pollution” in sediment compiled from the recent professional literature are tabulated in Table 5-5. These are, at very best, qualitative indicators, many being applicable strictly to freshwater rather than estuarine systems, but at least these serve as an indication of how the sediments in Corpus Christi Bay could be judged. By these criteria, copper throughout the system, and zinc in the Inner Harbor and Nueces Bay would be characterized as evidence of “heavy pollution.”

Ward and Armstrong (1992a) observed that in Galveston Bay water-phase metals 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. They added that this may be due in part to the concentration of urban activity and waste discharges in these

Table 5-5
Ranges of sediment metals (mg/kg) typifying “pollution”
from Thomas (1987), see also Baudo and Muntau (1990)

Element	*non-polluted*	*heavily polluted*
Total Hg	<1.0	>1.0
Pb	<90	>200
Zn	<90	>200
Fe	<17,000	>25,000
Cr	<25	>75
Cu	<25	>50
As	<3	>8
Cd		>6
Ni	<20	>50
Mn	<300	>500
Ba	<20	>60

same areas, but also to the fact that shipping regions are generally sampled more intensively due to dredging activity, thus allowing a greater opportunity for occasional high measurements. In the case of Corpus Christi Bay, the great majority of the water-phase metal samples have been taken from areas of ship-ping, including *all* of those since 1985, so we cannot draw any conclusions about the relative frequency of metals violations in these regions in comparison to other areas of the bay. However, the three metals with the highest frequency of violation in Table 5-4, namely zinc, copper and nickel, are also the three identified as exhibiting elevated concentrations generally throughout Corpus Christi Bay (where data exist). Recall that zinc concentrations in the sediments of the Inner Harbor are an order of magnitude larger than those in the Houston Ship Channel. This raises the speculation of whether the Inner Harbor could be the ultimate source for elevated zinc in the system. We also observe that high zinc levels have been found in some of the tissue analyses, notably oyster and black drum, especially in Nueces Bay.

With respect to pesticides and trace organics (including PAH's) in water, the data base is even sparser. Violations of the TNRCC criteria since 1985 occur for only proxied DDT and chlordane, as follows:

parameter	*criterion (ppb)*	*segment*	*violations/ measurements*
DDT (WQ-XDDT)	0.001	I1	2/2
		I2	2/2
chlordane (WQ-CHLR)	0.004	CCC6	2/20

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

From a systemic point of view, the most significant potential problems affecting the bay as a whole are related to the parameters for which there is no regulatory standard or criterion of optimality, namely, suspended particulates, nutrients and salinity. With respect to the first two, the potential problem may not be too high a concentration, but too low. The statistical analyses of TSS in Corpus Christi Bay disclosed a decline widespread throughout the system, increasing in significance from north to south. The rate of decline is sufficient to have reduced the average concentration by about 25% in the upper bays and by about 50% in the lower bays over the last two decades. Suspended sediment is an intrinsic and important aspect of the Corpus Christi Bay environment; its decline is not necessarily beneficial.

Where inorganic nitrogen is higher in the system, declining trends were found to be typical, especially in the upper bays; no clear trend in phosphorus was evident. It is interesting to compare this result with Galveston Bay, for which declining trends were much more evident in the statistics (Ward and Armstrong, 1992a). This may be due to the fact that the concentrations of these nutrients are higher in Galveston Bay, inorganic nitrogen and phosphorus levels being respectively twice and four times those of Corpus Christi Bay, but it may also be due to the fact that the data base for Galveston Bay, especially considered on a areal basis, is much greater than that available to us in Corpus Christi Bay. A widespread declining trend was, however, determined in water-phase TOC at a rate sufficient to reduce the concentrations in the Corpus Christi Bay study area by about one-fourth over two decades. It is not clear from the data whether this indicates a decline in organic loading or a decline in productivity. More importantly, whether a decline in any of these nutrients is a problem or an improvement depends upon determining the optimum levels for Corpus Christi Bay. Much more research is needed on the total ecosystem to establish these optima.

Salinity of Corpus Christi Bay has been a major source of controversy, especially within the past decade, because of its perceived value as a habitat indicator that also measures freshwater inflow. At this writing, the City of Corpus Christi water supply in the Nueces reservoirs of Choke Canyon and Lake Corpus Christi is threatened by a continuing drought, and the conflict between human water-supply requirements and the needs of the estuary ecosystem has been brought into sharp relief. One result of the present study, disclosure of increasing salinity that seems to be associated with declines in mean inflow, certainly suggests that salinity will continue to be at the center of management issues and strategies for this system, even after the current drought has abated. Certain areas of the system, notably Baffin Bay and the Upper Laguna Madre, are chronically hypersaline environments. This is the result of a combination of low freshwater inflow (as these areas are naturally arid) and poor exchange with Corpus Christi Bay and the Gulf of Mexico. Man's intervention cannot easily alter the former, but it can the latter, and, again, we can expect salinity to be a central issue in debates about physiographic alterations in this part of the study area.

5.5 Recommendations

5.5.1 Data collection recommendations

Few programs can afford the investment of long-term, intensive data collection in a system such as Corpus Christi 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, as exemplified by the present study. Each such data-collection agency must recognize that the value of its data transcends its immediate mission-specific application. In this sense, data collection should be regarded as a collective enterprise, and its design should reflect a certain degree of scientific altruism.

Ward and Armstrong (1992a) in addressing the problems of data collection in Galveston Bay proposed four precepts of data collection. They observe that it is the violation of these precepts which contribute to data deficiencies that are avoidable or correctable at little cost. These are repeated here, because they are equally applicable to the Corpus Christi Bay situation:

(I) Continuity of record in space and time should be of paramount importance.

(II) Benefit versus *incremental* cost should be a governing criterion for delineation of a suite of measurements.

(III) Basis for selection of parameters to be measured should include potential analyses the measurements will support as well as historical perspective of measurement continuity.

(IV) Recording and processing of the data (“data recovery”) as well as archiving should be performed with great sensitivity to and avoidance of potential loss of information.

The reduction in space/time density of data collection in Corpus Christi Bay within roughly the last decade has significantly diminished the utility of modern data collection at least for the types of analyses performed here. Precept I listed above emphasizes maintenance of continuity. 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.

Several data collection programs are underway simultaneously in Corpus Christi Bay. Yet these seem to be uncoordinated. The obvious reason is that each of the programs has a single, often narrow, objective, and the program is designed to meet that objective. Generally, a large investment is required to obtain the basic sample. This cost is dominated by operations: putting a sampling crew (and usually a boat) on a specific station, or installing an automatic data logger on a platform in the bay. Precept II advises that the incremental cost in acquiring additional measurements (including loss of efficiency) must be weighed against the cost of occupying the station and obtaining the water samples. Such additional parameters may be peripheral to the objective of the project, but have great value for other objectives and therefore justify the small incremental cost for their acquisition. For example, when a water sample is pulled for coliform determination, the additional cost to measure salinity is negligible. Though salinity has no bearing on the use of the data for public health purposes, it would add to the general base of information on salinity structure, perhaps from a region that is poorly sampled otherwise. A certain altruistic philosophy is necessary in the sampling agency, to acquire measurements that may be superfluous to the immediate objective, but from which others will benefit.

Not only should sample programs be coordinated among themselves to maximize the total benefit, those programs should be coordinated with historical practice, as indicated by Precept III. Extending a past data record may be sufficient to justify including a parameter, even if modern analysis and technology suggest a more useful variate. In particular, when a new parameter is inducted into an ongoing survey to replace a less satisfactory parameter, measurements of both the new and the old parameters should be performed in order to establish (or falsify) the relation between them.

One might expect Precept IV to be so patently obvious that it need not even be stated. 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 may seem straightforward, the occurrence of obvious errors in all of the state data bases (to say nothing of inobvious errors) indicate that present procedures are inadequate. We argue in Precept IV for a heightened awareness to the possibilities of data loss, even for the cultivation of agency paranoia. When the data entry is recent and the raw data sheets are still available, errors are easiest to detect and correct. This opportunity decays rapidly in time. 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 III. At present, in the culture of many of the agencies (including academic research projects) their implementation seems to be viewed as a redundant cost item in data acquisition, perhaps absorbing funds that might be better spent in a boat or diverting energies from more productive professional activities. 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.

The obvious recommendation to reduce the deficiencies identified in the Corpus Christi data base in Chapter 2 is to sample at more locations, more frequently, for more parameters. Clearly, the ability of any agency to accomplish this is dictated by available resources, and is more a matter of trade-offs to most efficiently meet that agency's mission. It seems of more immediate value to the development of a Comprehensive Management Plant for Corpus Christi Bay to present specific recommendations that will substantially improve the data base with little additional expenditures. Therefore, suggestions are offered below on alterations in monitoring procedures to assist filling data gaps or repairing data deficiencies, with emphasis on those that can be implemented with little or no cost, and that will not interfere with the objectives of the primary agency but will greatly augment the value of the data. In summary, 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.

(1) When the major investment of time and expense is to place a boat crew on station, a few *in situ* measurements should be standard procedures. Salinity should *always* be measured. If the crew is equipped with electrometric over-the-side probes, a vertical profile instead of a single depth should be routine. (Yet there are manifold examples of violation of this practice.) Some limited water sampling may also be simply accommodated, perhaps just surface grab samples for straightforward lab analyses.

(2) We suggest that short lists be formulated of “recommended” parameters, to be included within suites of measurements of various classes (e.g, *in situ* parameters, non-fixed water samples, sediment sampling for chemical analysis, etc.), to provide guidance to (and to avoid omissions by) anyone undertaking a sampling project.

(3) 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.

(4) There are numerous examples in the data record when a parameter is suspended from further measurement. In many cases, this has involved a replacement of the old parameter with a new one, e.g. JTU's replaced by NTU's, or a shift of emphasis from rather gross and imprecise measurements such as BOD, oil & grease, volatile solids and total PAH's, to specific organic and hydrocarbon parameters. While the more precise measures are welcome, the termination of the record of the others is lamentable. 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 parameters 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.

(5) We note that the intratidal-diurnal scale of variability is virtually unsampled in Corpus Christi Bay by routine monitoring programs. The use of robot data collection, based on electrometric sensing and automatic data logging, has been instituted by the TWDB and, more recently, by Conrad Blucher Institute at Texas A&M University Corpus Christi. We strongly recommend continuation of this work, but with increased attention given to Q/A procedures, data scrubbing and reconciliation, and drift control, which, as sources of error, significantly limit the utility of this data at present.

(6) 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. (Technology such as a Coulter Counter can considerably improve resolution and precision, but can be expensive.)

(7) A ubiquitous 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. As laboratory analyses go, sediment texture is a cheap measurement. This is an excellent example of how the value of the data may be enhanced by a relatively economical additional measurement.

(8) 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 (Adams et al., 1992) approach is adopted, we recom-mend that organic carbon be instituted as a routine aspect of any chemical analysis of sediment involving non-ionic organic contaminants, especially organohalogens.

(9) Too much information is sacrificed by the present practice of censoring analytical data. We recommend that chemical laboratories report both the actual instrumental determination and the computed detection limit. This will leave the decision to the user of the data of whether or how to use the instrumental value when it falls below the detection limit. Note that this recommendation requires no additional expense or action on the part of the laboratory, but rather dispenses with the last step of the reporting procedure of replacing instrumental values with the flag for "below detection limits." (With present procedures, the applicable detection limits should be reported already, independent of the magnitude of the instrumental result.)

5.5.2 Data management recommendations

(1) Data entry (i.e., transcription) errors are a prime cause of information loss, and any data-entry procedure should include a process of verification. It is perplexing that an agency will commit major funding to support field crews and state-of-the-art analytical equipment and analyses, then entrust the resulting data to unsupervised, nontechnical, and poorly trained data-entry functionaries.

(2) Any process that reduces or replaces measurements (including units conversions) may be losing data unless carefully performed. Precept IV urges a sensitivity to this potential, that seems to be largely lacking in present agency procedures. Replacing a series of raw measurements over time or space by an average, modifying the spatial position data, failing to preserve information on sampling time, position or conditions, or intermixing actual measurements with "estimated" (BOGAS) values without any means of separation, all represent losses of information, and are all practices that can be avoided with care and forethought. We recommend following the same philosophy observed here of differentiating a source data base from a derivative data base. The raw data in original units with all supporting and ancillary information should be maintained as a source data file. Any alterations, including units conversions and averaging, should be implemented in a separate derivative data base.

(3). We recommend that a clear separation be made between a data base that serves an archival function and a data base that is used for analytical purposes. One particularly ubiquitous practice is to combine measurements from one's own data collection with data drawn from other sources, perhaps subsampled or processed. At present, several agencies, e.g. TNRCC and TWDB, intermix such data in a single data base. 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.

(4) We recommend the implementation of well-structured data management procedures utilizing modern computer capabilities, including streamlined access and dissemination protocols. Even small-scale research projects can take advantage of spreadsheet software for permanent data base maintenance. It is remarkable how many data sources for this study only have hard-copy field or laboratory sheets, or (worse) keyboarded the data without retaining a magnetic copy. We recommend multiple backups of the data files, utilizing robust formats (e.g. flat-ASCII files).

5.5.3 Data preservation and archiving recommendations

Data-dissemination problems transform themselves with the passage of time into data-preservation problems. The management of historical data needs a twofold thrust: the implementation of actions to improve preservation and dissemination of current data-collection programs, and institution of actions necessary to preserve existing data. With respect to data from past programs, the primary need is preservation, which must be based upon the recognition that older data can play a central rôle in water quality management. A secondary need is to transform the data into a more utilitarian format as soon as practicable. We proffer the following specific recommendations, which we believe to lie within the purview of the National Estuary Program or its participating agencies.

(1) All sponsored research projects (including consulting contracts and interagency contracts) should include a *requirement* for preparation of a data report documenting the *raw* measurements of the project, including, if the data are digitized, a digital copy. Compliance with this requirement should be a condition for any future contracts.

(2) All projects internal to an agency, performed by an agency staff, involving observations and measurements should require preparation of a data report, including a digital copy if the data are digitized.

(3) In public agencies, the release of a data report and digital copy from both contracted projects and internal projects, should be made mandatory after a certain calendar period, e.g., six months. (If the data is still under review, it should be so marked, but being under review should not be used as a reason for delaying release.) Reimbursement for the expense of copying is appropriate, but the price should be reasonable. After all, the public has already paid for it once. Maximum advantage should be made of the Internet for dissemination.

(4) All agency files and materials should be marked with a destruction schedule by its originator. For measurements and raw data, at least, the files should be marked “permanent storage, not for destruction.” In some agencies, smaller but equivalent words may be desirable.

(5) At least one hard-copy record of every data set should be maintained. This might be raw data sheets, or might be a print-out of a digital data record. Also, even when a data set exists in a digitized data-management format (e.g., a data base management software form such as

Lotus or dBase), a separate version in general encoding format (e.g., ASCII) should be maintained.

(6) Data Inventory and Acquisition Projects should be sponsored as soon as practicable, either internal to an agency, or through external contract, to extend the present activity for Corpus Christi Bay, and to secure similar data sets for the other Texas embayments and for the Texas coast. In particular, holdings in the following agencies and sites should be retrieved, organized and, where appro-priate, digitized:

Texas Parks and Wildlife Olmeto warehouse
U.S. Corps of Engineers: Galveston District, Texas area offices and
 Waterways Experiment Station
National Marine Fisheries Service laboratories in Galveston
research universities in the Texas coastal zone
private engineering and surveying companies

(7) Some centralized, cooperative data storage and management facility is needed, one which is divorced from the separate mission-oriented state and federal agencies. The Texas Natural Resources Information System could become this entity, but it suffers from many problems, not the least of which is adequate and stable funding. This recommendation, of course, exceeds the jurisdiction of the CCBNEP agencies, but could profit from the support of these agencies. It is, however, the only long-range solution that is evident to us.

(8) Digital preservation technology has improved in recent years, and many of the long-term aging problems associated with re-writable magnetic media can now be avoided. In particular, we recommend preservation of historical data bases using CD-ROM technology, which is now sufficiently reliable and economical to be a viable alternative to tape. Again, the use of robust formats is preferable to software-specific or proprietary formats.

5.5.4 Recommendations for additional studies of water and sediment quality

On a more strategic level, regarding our understanding of water and sediment quality and information needed for effective management of the Corpus Christi 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. 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 analyses of chlorophyll-a and related measurements from Corpus Christi Bay, in association with *in situ* productivity studies, are needed. These studies should include detailed examination of phytoplankton dynamics in the study area, and its dependence on water quality.

(3) Metals 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. However, we do not believe that merely intensifying such 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 study area subject to identifiable and quantifiable controls, especially addressing the metals identified in this study as being elevated,
(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, i.e. in regions of runoff, inflow, waste discharges and shipping. We note that in the upper bays, Copano and Aransas in particular, recent data collection has been especially deficient. We recommend specific sediment and metals budgeting studies of Nueces Bay to determine the probable sources and fate of elevated metals in this system.

(4) In an estuary as turbid as Corpus Christi 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 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 Corpus Christi Bay of dredging, shoreline alteration, and trawling, as well as the declines 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 insight into other processes. We recommend some

modest examination of long-term variability in the climatological controls of the surface heat budget. Since the same trend in temperature was also discovered in Galveston Bay, this suggests that the scope of research should be extended to encompass the entire Texas coast.

(6) The salinity data base assembled in this project is the most comprehensive available for Corpus Christi Bay and will support analytical studies of salinity response heretofore not possible. In view of the mandatory releases from the Nueces River reservoirs, and the controversy surrounding the ecological value of these releases, detailed studies of the response of salinity to inflow events are highly recommended. In particular, it is recommended that salinity variability in Corpus Christi 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 increase in salinity underscores the gaps in our understanding of even as fundamental a parameter as this. While inflow has been identified as a probable causative factor, other elements of the salt budget, notably evaporative deficit and exchange with the Gulf of Mexico, could be of equal or greater importance. We recommend additional studies of the external controls on salinity. This could probably be most usefully pursued, at least at the outset, by detailed salt budgeting, combining the data base of the present study with the time-intense robot data records from TDWB and TAMU CBI. Pursuant to this we recommend that the data records at TWDB be subjected to review and correction for drift, time error, and sensor faults, so to be available as a resource for such studies. As with nutrient and particulate loading, we believe event-scenario and time-series analysis to be the most promising approaches. There is also a place for hydrodynamic modeling, but only after the essential controls and responses of the system are much better defined.

(8) There seems to be little basis for the appropriateness of the 5 ppm standard in this estuarine system, given the low saturation concentrations at high temperatures and salinities. We recommend re-evaluating the applicability of the 5 ppm average DO standard to waters with such low solubility. (We note that there is a prominent exception to the uniform application of the 5 ppm DO standard along the Texas coast-that one bay is assigned a lower open-water DO standard by TNRCC-namely the 4 ppm standard for Galveston Bay.) At the same time, these low solubilities mean a concomitantly constrained assimilative capacity for oxygen-demanding constituents. While DO does not appear to be a problem in the study area at present, we recommend renewed research on the DO requirements of organisms, methods appropriate for evaluating assimilative capacity (for evaluation of waste discharges, particularly), and the factors leading to episodes of depressed DO in the study area, especially in poorly flushed regions.

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