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National Oceanic and Atmospheric Administration
National Marine Fisheries Service

# A Hydrographic Survey of the Galveston Bay System, Texas, 1963-66



E. J. PULLEN, W. L. TRENT, AND G. B. ADAMS

SEATTLE, WA.
October 1971

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# A Hydrographic Survey of the Galveston Bay System, Texas, 1963-66 [1]

By

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## ABSTRACT

Water temperature and salinity data, taken during 1963-66, and dissolved organic nitrogen, total phosphorus, and dissolved oxygen data taken during 1964-66 from Galveston Bay, Texas were analyzed by area and habitat (depth strata).

Temperatures ranged from 0.4° C to 36.0° C during the study and averaged slightly higher in the peripheral than the open-water or channel habitat. Between years, water temperature averages varied as much as 7°C between coldest months, and 3°C between warmest months.

Salinities ranged from 0.1 to 36.6‰ and increased from the peripheral to the channel habitats. Gradients of increasing salinities occurred from east to west and north to south in the system. Salinities decreased from 1963 to 1966 with the smallest difference between years occurring in March and April and the greatest difference between years in May and June. Minimum salinities always occurred during periods of high stream discharge in the winter and spring and maximum salinities during periods of low stream discharge in the late summer and fall.

Dissolved organic nitrogen concentrations ranged from 1 to 300 $\mu$g at /liter. Nitrogen concentrations decreased from the upper to the lower bays. Nitrogen values were similar seasonally and between years. High river flow was correlated with an increase of nitrogen in the lower bay areas.

Total phosphorus concentrations ranged from 0.1 to 47.5 $\mu$g at /liter. Phosphorus concentrations diminished from upper to lower bays, and from west to east in the system. Seasonal concentrations of phosphorus were similar from 1964 through the spring of 1966. In June 1966, concentrations increased, reaching an all years' maximum in the fall. River discharge was not correlated to phosphorus concentrations, although nitrogen and phosphorus values were positively correlated.

Dissolved oxygen concentrations ranged from 0.2 to 13.6 ml/liter. Lowest oxygen concentrations were in the channels and highest and similar concentrations were in the peripheral and open-water habitats. Oxygen values were inversely correlated with water temperatures.

## INTRODUCTION

Degradation or destruction of estuarine habitats by municipal, industrial, agricultural, and recreational expansion is a major problem in many estuaries and lagoons along the U.S. coast. Alterations caused by the construction of channels, dikes, and bulkheads; the discharge, of pollutants; and the reduction of freshwater flows change the hydrological char-

1 Contribution No. 315, National Marine Fisheries Service Biological Laboratory, Galveston, Texas 77550.

acteristics of estuaries. Evaluation of changes detrimental to estuarine biota is aided by information on the hydrological conditions existing before the alterations.

The hydrology and biology of the Galveston Bay system are being studied or have been studied by various State, Federal, and private agencies. Studies contributing significant information on the hydrology of this system include those by Reid (1955, 1956, and 1957); Chambers and Sparks (1959); Arnold, Wheeler, and Baxter (1960); Zein-Eldin (1961); Chin (1961); Odum et al. (1963); Pullen (1969); Baldauf (1970); and Copeland and Fruh (1970). Gloyna and Molina (1964), using data from State, Federal, and private agencies, compiled a report for the Texas Water Pollution Control Board on the water quality of the bay system. The observations analyzed and reported in the present paper and all hydrological data collected by personnel of the Estuarine Program, National Marine Fisheries Service, Galveston, Texas, from 1958 through 1967 were published by Pullen and Trent (1969).

The objectives of our study were to: (1) summarize bottom temperature, salinity, dissolved organic nitrogen, total phosphorus, and dissolved oxygen data in relation to three habitats and five bay areas, and (2) determine the temporal and spatial distributions and ranges of these parameters and some of the relations and mechanisms affecting their distributions.

## STUDY AREA AND METHODS

The Galveston Bay system, located on the upper Texas coast, has a water area of about 1,360 km$^2$ (Figure 1). Water is exchanged with the Gulf of Mexico through three tidal passes. About 85% of this exchange is through Bolivar Roads Tidal Pass, about 14% through San Luis Pass, and about 1% through Rollover Pass (U.S. Corps of Engineers, personal communication). Two major navigation channels—the Houston Ship Channel, connecting Houston to the Gulf of Mexico, and the Gulf Intracoastal Waterway, running southwesterly through the marsh areas of the lower bays—pass through the system. The tidal range is 0.5 m in the lower portion of the system and 0.3 m in the upper (U.S.

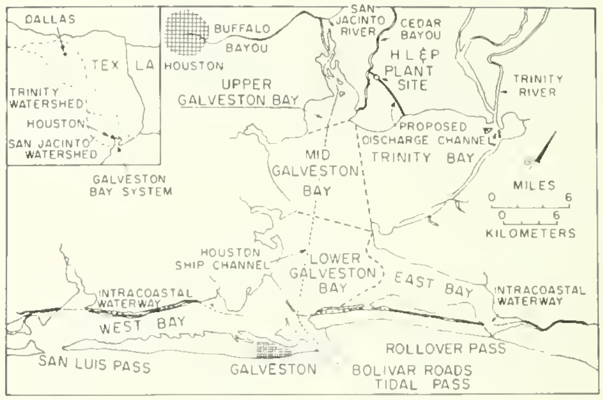


Figure 1. The Galveston Bay system and associated watersheds.

Department of Commerce, Coast and Geodetic Survey, 1969). Winds, as reported by U.S. Weather Bureau data for Galveston, Texas, are predominantly southeasterly in the summer and northerly in the winter. Thirty-seven years (1931-67) of data collected by the U.S. Weather Bureau in Galveston show the mean annual rainfall to be 113 cm and the mean air temperature 20.8° C.

Most freshwater inflow to the bay system is from the Trinity and San Jacinto watersheds (Figure 1). Stream discharge data for the Trinity and San Jacinto watersheds were obtained from the U.S. Geological Survey. Annual stream flows averaged about 7 billion m$^3$ for the Trinity and about 2 billion m$^3$ for the San Jacinto watersheds. The drainage area of the Trinity watershed is 46,540 km$^2$ and that of the San Jacinto watershed is 10,298 km$^2$. Average annual precipitatipn over the watersheds generally varies from 89 cm at Dallas to 114 cm at Houston (U.S. Bureau of Reclamation, 1964).

The bay system was divided into the following geographic areas for this study: Lower Galveston, mid-Galveston, Upper Galveston, East, and Trinity Bays (Figures 1 and 2). West Bay was not included in this study.

The bay areas were further divided into peripheral, open-water, and channel habitats (Figure 2). Station numbers and locations indicated in Figure 2 are those reported by Pullen and Trent (1969). The peripheral habitat was in water depths less than 1.2 m; the open-water habitat was in depths of 1.2 to 3.0 m; and the channel habitat was in depths

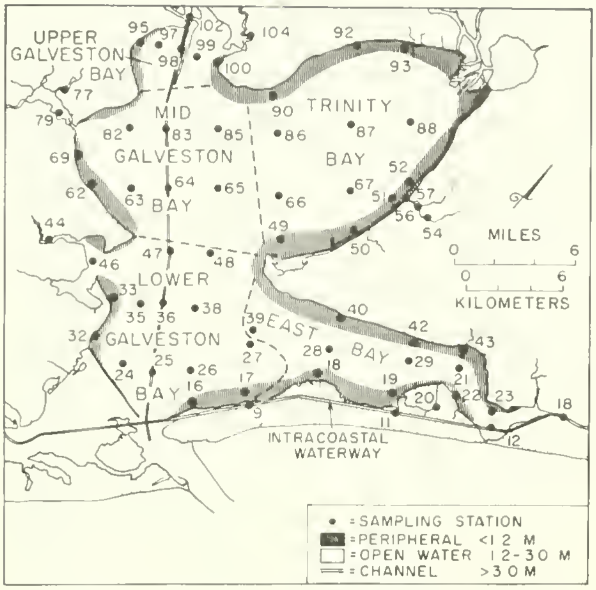


Figure 2. Study areas of the Galveston Bay system showing bay areas, habitats, and locations of sampling stations.

greater than 3 m. Habitat depths (mean low water) were determined from the U.S. Coast and Geodetic Survey Nautical Chart No. 1282.

Sampling frequency and the number of sampling stations in each habitat and bay area varied from year to year, and frequency also varied within each year except 1963 (Table 1). During a collection period, samples were taken at all stations within a 2- or 3-day interval except when adverse weather interrupted sampling. All sampling was in daylight hours.

Water samples or *in situ* measurements were taken from the lower 0.3 m of the water column to determine temperature, salinity, dissolved organic nitrogen, total phosphorus and dissolved oxygen. The techniques for measuring each parameter are described by Pullen and Trent (1969).

## ANALYSIS AND PRESENTATION OF DATA

Data for each parameter were independently related to habitat and bay area within each year and are presented in statistical and/or graphical form. Paired-comparison $t$-tests or two-way analyses of variance were used for all comparisons between habitats or bay areas. Bay areas or habitats served as treatments and dates of sampling as blocks. Mean values of a given variable determined by combining data from all stations within a particular habitat and bay area for each collection were used as observations for the statistical comparisons.

## WATER TEMPERATURE

Water temperatures during this 4-year survey ranged from 0.4° C to 36.0° C. The smallest annual range was 23.4° C (9.0° C to 32.4° C) in 1965 and the largest was 33.6° C (0.4° C to 34.0° C) in 1963.

### Comparison Between Habitats

Comparisons of temperatures by habitat within bay areas are shown in Table 2. Average

Table 1.—Sampling frequency, type of information obtained, and the number of samples taken by habitat and year in the Galveston Bay system, 1963-66.

| Year | Habitat | Number of stations | Sampling frequency: Weekly | Semi-monthly | Monthly | Type of information obtained: Temperature | Salinity | Organic nitrogen | Total phosphorus | Dissolved oxygen |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | Number of observations | | | | |
| 1963 | Peripheral | 28 | | X | | 624 | 749 | 0 | 0 | 0 |
| | Open water | 22 | | X | | 519 | 519 | 0 | 0 | [illegible] |
| | Channel | 8 | | X | | 191 | 191 | 0 | 0 | 0 |
| 1964 | Peripheral | 27 | | X | X | 506 | 505 | 137 | 50 | [illegible] |
| | Open water | 22 | | X | X | 308 | 308 | 148 | 143 | 57 |
| | Channel | 9 | | X | X | 121 | 121 | 47 | 43 | 67 |
| 1965 | Peripheral | 15 | X | X | X | 452 | 462 | 424 | 418 | 39 |
| | Open water | 16 | X | X | X | 466 | 473 | 288 | 292 | 235 |
| | Channel | 5 | X | X | X | 149 | 149 | 97 | 107 | 75 |
| 1966 | Peripheral | 17 | X | X | | 397 | 401 | 316 | 293 | 286 |
| | Open water | 17 | X | X | | 466 | 447 | 144 | 140 | 143 |
| | Channel | 6 | X | X | | 157 | 159 | 0 | 0 | 0 |

Table 2.—Comparisons of annual mean bottom water temperatures between habitats within each bay area in the Galveston Bay system, 1963-66.

| Bay area | Year | Habitats compared and mean temperatures: Peripheral | Open water | Channel | Degrees of freedom | Test value: F | t |
|---|---|---|---|---|---|---|---|
| | | ° C. | | | | | |
| East | 1963 | 22.7 | 22.3 | 22.3 | 2, 46 | 3.95* | |
| | 1964 | 20.9 | 20.7 | 20.7 | 2, 26 | 0.52 | |
| | 1965 | 23.3 | 22.9 | 22.9 | 2, 54 | 4.23* | |
| | 1966 | 23.1 | 23.2 | 23.1 | 2, 52 | 0.32 | |
| Trinity | 1963 | 22.2 | 21.8 | - | 22 | | 1.59 |
| | 1964 | 20.6 | 19.9 | - | 13 | | 1.96 |
| | 1965 | 22.7 | 22.2 | - | 31 | | 4.67** |
| | 1966 | 22.0 | 22.2 | - | 26 | | 1.61 |
| Upper Galveston | 1963 | 23.2 | 23.0 | 23.1 | 2, 42 | 0.34 | |
| | 1964 | 21.1 | 20.8 | 20.0 | 2, 26 | 2.50 | |
| | 1965 | 22.5 | 22.4 | 22.1 | 2, 38 | 2.37 | |
| | 1966 | 23.6 | 23.7 | 23.6 | 2, 50 | 0.27 | |
| Mid-Galveston | 1963 | 22.1 | 22.0 | 22.1 | 2, 46 | 0.13 | |
| | 1964 | 21.4 | 19.9 | 19.9 | 2, 26 | 7.33** | |
| | 1965 | 23.9 | 22.9 | 22.8 | 2, 58 | 16.65** | |
| | 1966 | 23.8 | 22.8 | 22.8 | 2, 48 | 10.26** | |
| Lower Galveston | 1963 | 21.6 | 21.8 | 22.0 | 2, 46 | 1.04 | |
| | 1964 | 20.4 | 20.2 | 19.8 | 2, 26 | 0.56 | |
| | 1965 | 22.5 | 22.3 | 22.5 | 2, 60 | 0.50 | |
| | 1966 | 23.4 | 23.3 | 23.4 | 2, 52 | 0.10 | |

* Significance level = 5%.

** Significance level = 1%.

\- No data.

temperatures were usually highest in the peripheral habitat and similar in open-water and channel habitats. The differences in average temperatures between habitats were, however, usually less than 1° C. Although the differences were small, they were statistically significant in 6 of 20 comparisons. The differences were highly significant in mid-Galveston Bay in 3 of the 4 years; the temperatures in the peripheral habitat were distinctly higher than in the other two habitats.

We had expected larger temperature differences between the shallower open-water habitat and the deeper ship-channel habitat than were observed. The lack of large differences could not be attributed to the method used to combine our data because similar results were apparent throughout each year when the temperatures were plotted by date. It is likely that large ocean-going vessels passing through the channel caused substantial mixing of the surface and bottom water, thus causing water temperatures in the channel to remain similar to those of the adjacent open water.

## Comparison Between Years

Differences in temperature between years in the whole system were compared by combining habitat area data and plotting the average and range by date and year (Figure 3). Average temperature varied as much as 7° C between years in the winter months, and only about 3° C in the summer months. Year-to-year variations occurred in the seasonal cycles of water temperature. For example, if an arbitrary value of 20° C is selected, temperatures averaged above 20° C for about 7.5 months in 1963 and only about 5.5 months in 1966.

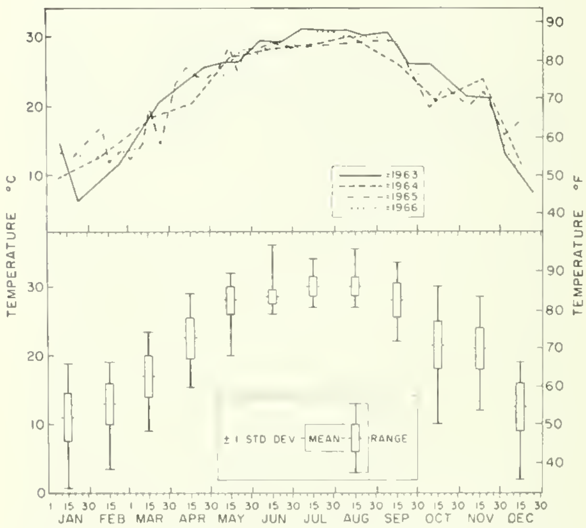


Figure 3. Average water temperature by date and year and the monthly mean, standard deviation, and range of temperatures in the Galveston Bay system for all years combined, 1963-66.

## Four-Year Average

All temperature observations taken during the 4-year period were averaged by month to show the average seasonal trend (Figure 3). Bottom water temperatures were lowest in January with a mean of 11° C and a range of 18° C. Average monthly temperatures increased from January to July with the most rapid increase from March to May. Mean temperature in July was 30° C with a monthly temperature range of only 7° C. Values decreased rapidly from September to October, were about the same in October and November, and then decreased sharply again from November to December. Temperatures fluctuated over a greater range in the fall and winter than in the spring and summer, probably because cold fronts frequently move over the system during fall and winter.

## SALINITY

Salinities in the Galveston Bay system ranged from 36.6‰ in the Houston Ship Channel in Lower Galveston Bay during 1963 to 0.1‰ in Trinity Bay in 1965 and 1966. The lowest and highest salinities observed over the entire area for each year were 0.4 and 36.6‰ in 1963, 0.3 and 33.3‰ in 1964, 0.1 and 36.0‰ in 1965, and 0.1 and 34.3‰ in 1966.

### Comparison Between Habitats

In most bay areas and during most years, mean salinity was slightly higher in the open water than in the peripheral habitat and considerably higher in the channel than in the other two habitats (Table 3, Figure 4). These differences in salinity between habitats were highly significant except for East Bay in 1965. The greatest difference between habitats was in the three western bay areas, which are under the direct influence of the Houston Ship Channel.

Table 3.—Comparisons of annual mean bottom salinities between habitats within each bay area in the Galveston Bay system, 1963-66.

| Bay area | Year | Habitats compared and mean salinities: Peripheral | Open water | Channel | Degrees of freedom | Test value: F | t |
|---|---|---|---|---|---|---|---|
| | | ‰ | ‰ | | | | |
| East | 1963 | 17.7 | 19.0 | 22.9 | 2, 46 | 60.30** | |
| | 1964 | 16.4 | 18.5 | 23.0 | 2, 26 | 36.85** | |
| | 1965 | 16.6 | 16.5 | 15.3 | 2, 56 | 2.82 | |
| | 1966 | 10.7 | 10.5 | 16.8 | 2, 52 | 83.26** | |
| Trinity | 1963 | 13.3 | 15.4 | - | 23 | | 6.33** |
| | 1964 | 12.6 | 15.7 | - | 13 | | 5.85** |
| | 1965 | 7.8 | 9.2 | - | 31 | | 4.58 |
| | 1966 | 5.5 | 7.3 | - | 26 | | 5.11** |
| Upper Galveston | 1963 | 18.2 | 18.8 | 24.7 | 2, 42 | 31.48** | |
| | 1964 | 17.9 | 19.5 | 24.1 | 2, 26 | 26.34** | |
| | 1965 | 17.6 | 14.6 | 21.5 | 2, 30 | 7.78** | |
| | 1966 | 11.5 | 11.6 | 20.2 | 2, 50 | 15.31** | |
| Mid-Galveston | 1963 | 17.7 | 20.0 | 27.0 | 2, 46 | 68.70 | |
| | 1964 | 18.2 | 19.9 | 26.0 | 2, 26 | 35.78** | |
| | 1965 | 15.3 | 15.9 | 21.2 | 2, 58 | [illegible] | |
| | 1966 | 9.5 | 12.1 | 22.6 | 2, 50 | 18.37 | |
| Lower Galveston | 1963 | 22.9 | 24.8 | 29.1 | 2, 46 | 35.46 | |
| | 1964 | 21.4 | 24.8 | 28.8 | 2, 26 | 39.48** | |
| | 1965 | 15.7 | 21.1 | 23.7 | 2, 58 | 56.93** | |
| | 1966 | 12.7 | 18.9 | 25.8 | 2, 50 | 144.63** | |

** Significance level = 1%.
- No data.

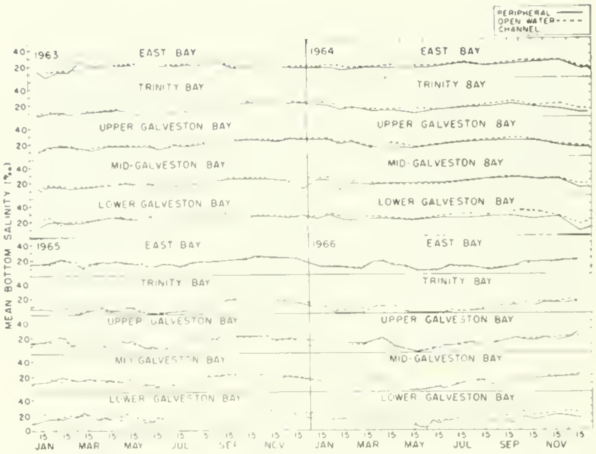


Figure 4. Mean bottom salinity by date and habitat within each bay area of the Galveston Bay system, 1963-66.

### Comparison Between Bay Areas

Salinities were significantly different between bay areas within each habitat during each year (Table 4). Salinities were lowest in Trinity Bay and highest in Lower Galveston Bay. A progressive increase in salinity from the upper bays to the Gulf was evident in all habitats each year, with the exception of East

Table 4.—Comparisons of annual mean bottom salinities between bay areas within each habitat in the Galveston Bay system, 1963-66

| Habitat | Year | Bay areas compared and mean salinity: East | Trinity | Upper Galveston | Mid-Galveston | Lower Galveston | Degrees of freedom | F value |
|---|---|---|---|---|---|---|---|---|
| | | ‰ | ‰ | ‰ | ‰ | ‰ | | |
| Peripheral | 1963 | 17.9 | 13.0 | 18.1 | 17.9 | 22.7 | 4, 92 | 29.8** |
| | 1964 | 16.4 | 12.6 | 17.9 | 18.2 | 21.4 | 4, 52 | 19.2** |
| | 1965 | 16.7 | 7.9 | 15.5 | 15.4 | 16.7 | 4, 112 | 63.5** |
| | 1966 | 10.5 | 5.4 | 10.9 | 9.8 | 12.5 | 4, 96 | 38.0** |
| Open water | 1963 | 19.4 | 15.3 | 18.8 | 19.9 | 24.9 | 4, 84 | 35.5** |
| | 1964 | 18.5 | 15.7 | 19.5 | 19.9 | 24.8 | 4, 52 | 34.1** |
| | 1965 | 17.5 | 11.8 | 13.9 | 17.8 | 23.5 | 4, 60 | 39.9** |
| | 1966 | 10.5 | 7.3 | 11.6 | 12.5 | 18.7 | 4, 104 | 78.1** |
| Channel | 1963 | 22.9 | - | 25.0 | 27.0 | 29.4 | 3, 69 | 25.4** |
| | 1964 | 23.0 | - | 24.1 | 26.0 | 28.8 | 3, 39 | 8.6** |
| | 1965 | 15.9 | - | 19.0 | 21.7 | 23.6 | 3, 72 | 15.0** |
| | 1966 | 16.9 | - | 20.2 | 22.8 | 25.8 | 3, 75 | 32.9** |

** Significance level 1%. - No data.

Bay. Salinities in the peripheral and open-water habitats of East Bay were similar to those in mid-Galveston and Upper Galveston Bays, whereas salinities in the Intracoastal Waterway (channel habitat) were lower than those in the Houston Ship Channel. This anomalous situation in East Bay is probably related to drainage of a large marsh adjacent to the Intracoastal Waterway and to reduced saltwater intrusion in the waterway as compared with the Ship Channel.

### Comparison Between Years

For between-year comparisons, salinity data for all bay areas were combined by habitat and by year and plotted by date for the bay system (Figure 5). The data indicated a general decrease in salinity in all habitats from 1963 to 1966. The smallest difference in salinity be-

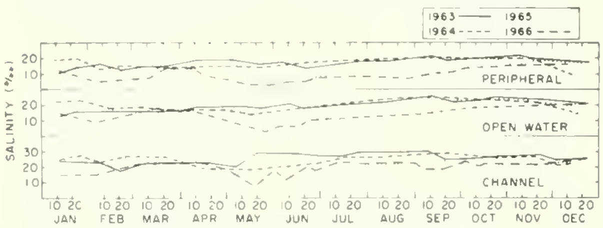


Figure 5. Mean values of bottom salinity by date, habitat and year in the Galveston Bay system, 1963-66.

tween years (about 4‰) was in March and April, and the greatest difference between years (about 20‰) was in May and June. Differences of 10‰ or greater between years were observed from May to September in the peripheral and open-water habitats. The channel habitat, which generally had the least salinity variation between years, had differences of 10‰ or greater from May through June.

Seasonal trends varied between years in all habitats, although minimum salinities always occurred during the winter and spring and maximum salinities always occurred during the late summer and fall.

### Relation to River Discharge

The relation between river flow and maximum, minimum, and mean salinity in the bay system is shown in Figure 6. The Trinity and San Jacinto watersheds discharged between 2.5

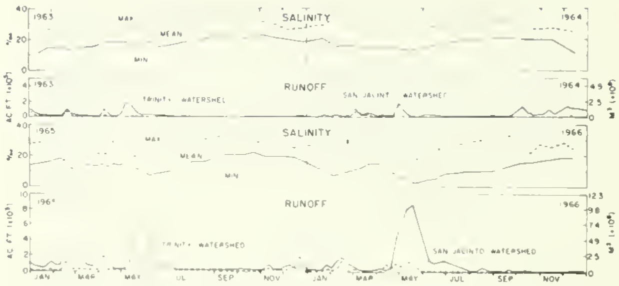


Figure 6. Maximum, minimum, and mean salinity compared with stream flow in the Galveston Bay system, Texas, 1963-66.

billion $m^3$ of water in 1963 and 10.1 billion $m^3$ in 1966. Of the yearly totals, the Trinity watershed contributed 75% or more of the total discharge each year. Salinities were inversely correlated with stream discharge ($r$ = -0.60, *d.f.* = 96 for the Trinity and $r$ = -0.37, *d.f.* = 96 for the San Jacinto watersheds) with the upper bay areas responding quickly to changes in stream flow (Figures 4 and 6).

The maximum water discharge during the 4 years occurred in 1966, initiating a marked reduction in salinities in the peripheral and open-water habitat of all bay areas (Figures 4 and 5). Salinities in the channel habitat are primarily controlled by tidal waters from the Gulf and, thus, were less affected by freshwater inflow than those in the other habitats.

### Salinity Isopleths

Annual isohalines for the bay system, and an isohaline constructed from the 4 years of data, are shown in Figure 7. Average salinities of 10‰ or greater were recorded near the Trinity River in 1963-64, whereas the 10‰ isohaline shifted westward toward Upper Galveston Bay in 1965 with increased freshwater inflow. In 1966, salinities averaged below 10‰ in Trinity Bay. Lower Galveston Bay, which is adjacent to the Gulf, averaged 25‰ or greater in 1963-64, but not in 1965-66. In general, the system changed from a high-salinity regime brought on by a drought period in 1963-64 to a low-salinity regime in 1965-66 as a result of high rainfall and river discharge.

The areal distribution of average salinities for the 4-year period showed that salinities increased from east to west and north to south in the system. The configuration of the isohalines

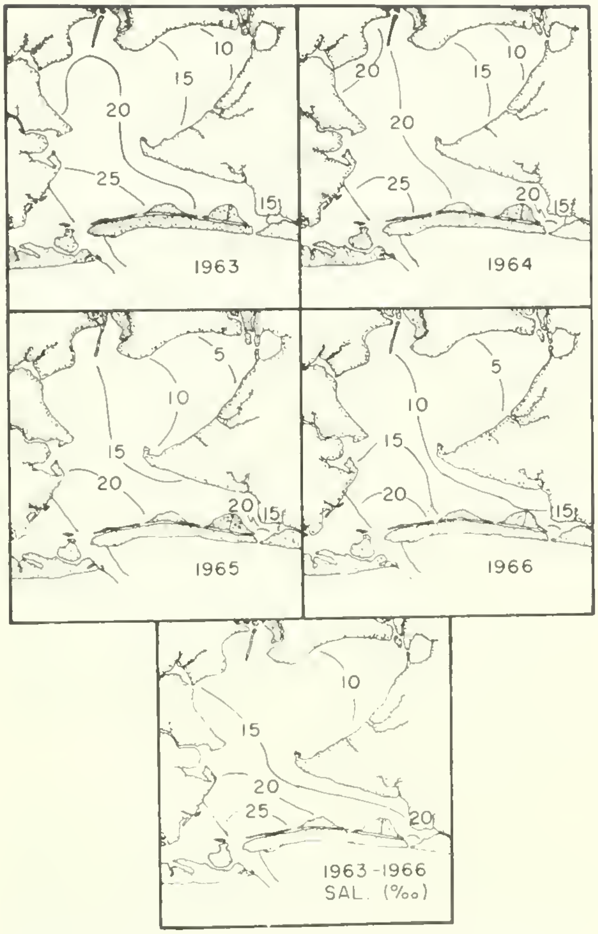


Figure 7. Annual isohalines and the average isohaline based on 4 years of data, 1963-66.

in the western portion of the system emphasized the importance of Bolivar Roads Tidal Pass and the Houston Ship Channel as an exchange mechanism for bay and Gulf waters. Rollover Pass had little influence on the system, except in East Bay in the immediate vicinity of the pass.

## DISSOLVED ORGANIC NITROGEN

Concentrations of dissolved organic nitrogen in the Galveston Bay system varied from 1 $\mu$g at/liter to 300 $\mu$g at/liter. Both extremes were recorded in Upper Galveston Bay. The range in values in the bay system for each year that nitrogen was sampled were 10 to 251 $\mu$g at/liter in 1964, 1 to 300 $\mu$g at/liter in 1965, and 6 to 200 $\mu$g at/liter in 1966.

### Comparison Between Habitats

Concentrations of nitrogen differed significantly between habitats in Lower Galveston, Upper Galveston, and East Bays in 1965 and in Lower Galveston Bay in 1966 (Table 5, Figure 8). The greatest concentration of nitrogen was in the channel habitat in Upper Galveston and East Bays in 1965, whereas the peripheral habitat of Lower Galveston Bay had the greatest concentration of nitrogen in 1965 and 1966.

Table 5.—Comparisons of annual mean concentrations of dissolved organic nitrogen between habitats within each bay area in the Galveston Bay system, 1964-66.

| Bay area | Year | Habitats compared and mean nitrogen values: Peripheral | Open water | Channel | Degrees of freedom | Test value: F | t |
|---|---|---|---|---|---|---|---|
| | | - - - - $\mu$g at/liter | - - - - - | | | | |
| East | 1964 | 47 | 46 | 48 | 2, 18 | 0.07 | |
| | 1965 | 37 | 31 | 65 | 2, 50 | 34.04** | |
| | 1966 | 58 | 58 | - | 28 | | 0.18 |
| Trinity | 1964 | 62 | 53 | - | 9 | | 1.71 |
| | 1965 | 37 | 38 | - | 30 | | 0.83 |
| | 1966 | 46 | 42 | - | 25 | | 1.82 |
| Upper Galveston | 1964 | 91 | - | 106 | 8 | | 0.92 |
| | 1965 | 73 | - | 129 | 24 | | 4.16** |
| | 1966 | 87 | 83 | | 24 | | 0.62 |
| Mid-Galveston | 1964 | 78 | 64 | 65 | 2, 18 | 0.87 | |
| | 1965 | 60 | 54 | 52 | 2, 40 | 0.84 | |
| | 1966 | 68 | 80 | - | 23 | | 1.86 |
| Lower Galveston | 1964 | 45 | 39 | 44 | 2, 18 | 0.55 | |
| | 1965 | 42 | 35 | 26 | 2, 38 | 6.55** | |
| | 1966 | 47 | 40 | - | 27 | | 3.23** |

** Significance level = 1%. - No data

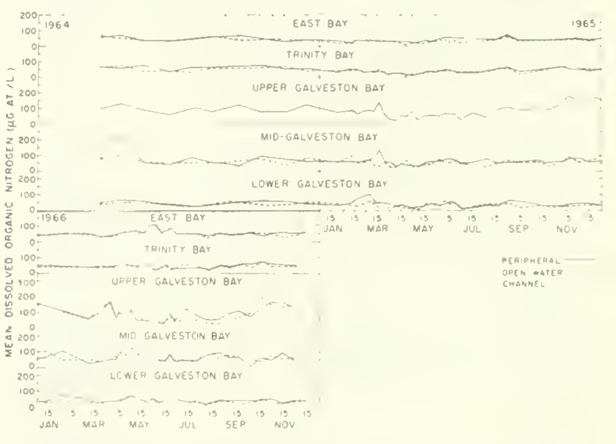


Figure 8. Mean concentrations of dissolved organic nitrogen by date and habitat within each bay area of the Galveston Bay system, 1964-66.

## Comparison Between Bay Areas

Differences in nitrogen concentration between bay areas in each habitat were highly significant (Table 6). Concentrations of nitrogen were highest in all habitats of Upper and mid-Galveston Bays except in 1965 when the concentrations in the channel habitat of East Bay exceeded that in mid-Galveston Bay.

Table 6.—Comparisons of annual mean concentrations of dissolved organic nitrogen between bay areas within each habitat in the Galveston Bay system, 1964-66.

| Habitat | Year | Bay areas compared and mean nitrogen values: East | Trinity | Upper Galveston | Mid-Galveston | Lower Galveston | Degrees of freedom | $F$ value |
|---|---|---|---|---|---|---|---|---|
| | | - - - - - - - - | μg at/liter | - - - - | - - - - | - - - - | | |
| Peripheral | 1964 | 47 | 62 | 89 | 78 | 45 | 4, 36 | 6.74** |
| | 1965 | 37 | 38 | 84 | 62 | 41 | 4, 104 | 22.04** |
| | 1966 | 59 | 44 | 90 | 66 | 47 | 4, 100 | 15.57** |
| Open water | 1964 | 46 | 53 | - | 64 | 39 | 3, 27 | 11.54** |
| | 1965 | 32 | 39 | - | 51 | 30 | 3, 27 | 18.31** |
| | 1966 | 57 | 42 | 94 | 73 | 40 | 4, 80 | 11.90** |
| Channel | 1964 | 46 | - | 106 | 63 | 40 | 3, 24 | 15.97** |
| | 1965 | 72 | - | 142 | 55 | 27 | 3, 42 | 80.14** |

** Significance level = 1%. - No data

Areal distributions of nitrogen concentration in the bay system are shown in Figure 9. An isopleth was not drawn for 1966 because nitrogen was sampled at only 16 stations. The greatest concentration of nitrogen was in the Houston Ship Channel, and concentrations decreased from Upper Galveston to Lower Galveston Bay. The second major source of nitrogen was the Intracoastal Waterway where concentrations decreased from the eastern to the western part of East Bay. The isopleths also indicate the relative contribution of nitrogen from the creeks and bayous. The influence of Gulf waters low in nitrogen was apparent in Lower Galveston and East Bays.

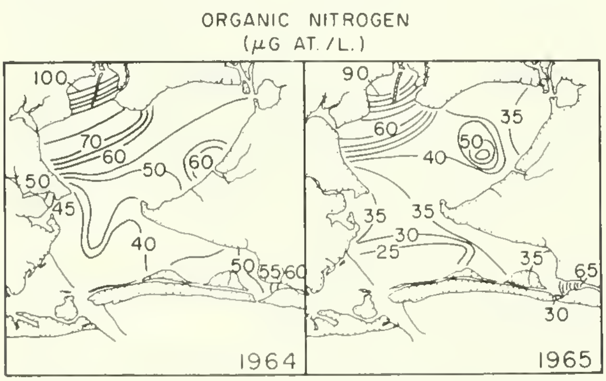


Figure 9. Isopleths (annual average) for dissolved organic nitrogen in the Galveston Bay system, 1964-65.

## Comparison Between Years

In general, nitrogen values were similar between years within each habitat of the Galveston Bay system (Figure 10). Greatest variations between years in the peripheral and open-water habitats were in the spring and fall, whereas the variations between years in the channel were erratic.

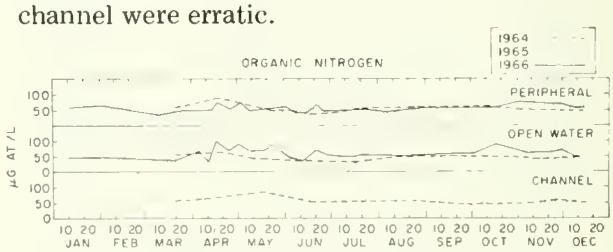


Figure 10. Mean values of dissolved organic nitrogen by date, habitat, and year in the Galveston Bay system, 1964-66.

## Relation to River Discharge

Nitrogen levels in the lower bays were more closely correlated with river discharge from the Trinity and San Jacinto watersheds than those in the upper bays (Table 7). This may be related to a rapid transport of upper bay water high in nitrogen content into the lower bays during the periods of high river flow.

Table 7.—Correlation coefficients ($r$) between average weekly stream flow and concentrations of dissolved organic nitrogen, 1964-66.

| Bay area | Nitrogen versus Trinity discharge: Peripheral | Open water | Channel | Nitrogen versus San Jacinto discharge: Peripheral | Open water | Channel |
|---|---|---|---|---|---|---|
| | - - - - - - | - - - - - - | - - - - - - | $r$ - - - - - - | - - - - - - | - - - - - - |
| East | 0.37** | 0.26* | 0.35* | 0.36** | 0.22 | 0.26 |
| d.f. | 67 | 65 | 31 | 56 | 55 | 30 |
| Trinity | -0.06 | -0.07 | - | 0.24 | 0.14 | - |
| d.f. | 68 | 65 | - | 57 | 54 | - |
| Upper Galveston | -0.29* | -0.11 | 0.27 | -0.14 | 0.33 | 0.05 |
| d.f. | 67 | 24 | 32 | 58 | 19 | 28 |
| Mid-Galveston | 0.05 | 0.35** | -0.09 | 0.09 | 0.44** | -0.12 |
| d.f. | 67 | 67 | 29 | 57 | 57 | 27 |
| Lower Galveston | 0.27* | 0.43** | 0.18 | 0.36** | 0.29* | -0.08 |
| d.f. | 67 | 64 | 30 | 57 | 53 | 27 |

* Significance level = 5%. ** Significance level = 1%. - No data.

## TOTAL PHOSPHORUS

Total phosphorus concentrations in the Galveston Bay system during 1966 varied from 0.1 μg at/liter in East Bay to 47.5 μg at/liter in Upper Galveston Bay. The lowest and highest values respectively were 0.7 and 13.7 μg at/liter in 1964, and 0.3 and 17.1 μg at/liter in 1965.

### Comparison Between Habitats

Difference in phosphorus concentrations between habitats in all bay areas except East and mid-Galveston Bays were not significant (Table 8, Figure 11). In East Bay, there was a greater concentration of phosphorus in the open water than in the other habitats in 1964 and 1965, whereas, in 1966, phosphorus concentrations were greater in the peripheral than in the open-water habitat (samples were not taken in the channel). Mid-Galveston Bay had a greater concentration of phosphorus in the open-water than in the peripheral habitat in 1966.

Table 8.—Comparisons of annual mean concentrations of total phosphorus between habitats within each bay area in the Galveston Bay system, 1964-66.

| Bay area | Year | Habitats compared and mean phosphorus values: Peripheral | Open water | Channel | Degrees of freedom | Test value: $F$ | $t$ |
|---|---|---|---|---|---|---|---|
| | | - - - - - μg at/liter - - - - - | | | | | |
| East | 1964 | 2.18 | 2.75 | 1.84 | 2, 18 | 6.73** | |
| | 1965 | 1.92 | 2.31 | 1.30 | 2, 48 | 22.71* | |
| | 1966 | 1.91 | 1.39 | - | 26 | | 2.60* |
| Trinity | 1964 | 6.60 | 7.08 | - | 9 | | 2.07 |
| | 1965 | 5.64 | 5.50 | - | 30 | | 0.78 |
| | 1966 | 7.06 | 7.49 | - | 24 | | 1.05 |
| Upper Galveston | 1964 | 10.10 | - | 10.9 | 8 | | 0.09 |
| | 1965 | 7.62 | - | 8.30 | 25 | | [illegible].11 |
| | 1966 | 14.47 | 15.04 | - | 23 | | 0.91 |
| Mid-Galveston | 1964 | 9.22 | 8.28 | 8.05 | 2, 14 | 1.71 | |
| | 1965 | 7.06 | 6.85 | 6.47 | 2, 44 | 0.67 | |
| | 1966 | 11.90 | 14.52 | - | 25 | | 5.68** |
| Lower Galveston | 1964 | 3.61 | 3.57 | 3.09 | 2, 16 | 0.77 | |
| | 1965 | 4.04 | 4.03 | 3.51 | 2, 48 | 0.95 | |
| | 1966 | 7.16 | 8.10 | - | 28 | | [illegible].94 |

* Significance level = 5%   ** Significance level = 1%.   - No data.

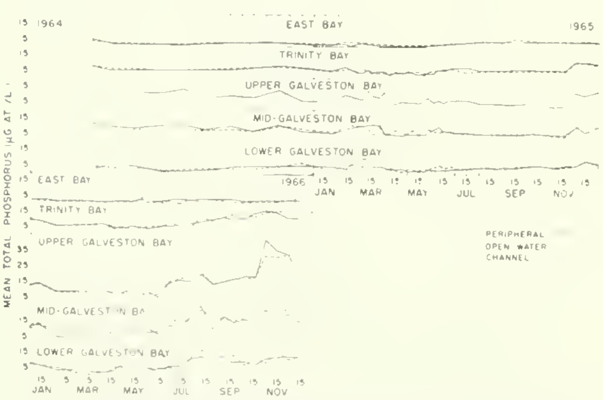


Figure 11. Mean concentrations of total phosphorus by date and habitat within each bay area of the Galveston Bay system, 1964-66.

### Comparison Between Bay Areas

Each year concentrations of phosphorus varied significantly between bay areas within each habitat (Table 9). Greatest concentrations were in Upper and mid-Galveston Bays and lowest concentrations were in East Bay. In 1964 and 1965 concentrations of phosphorus decreased from north to south and from west to east in the bay system (Figure 12).

Table 9.—Comparisons of annual mean concentrations of total phosphorus between bay areas within each habitat in the Galveston Bay system, 1964-66.

| Habitat | Year | Bay areas compared and mean phosphorus values: East | Trinity | Upper Galveston | Mid-Galveston | Lower Galveston | Degrees of freedom | $F$ value |
|---|---|---|---|---|---|---|---|---|
| | | - - - - - - - - - μg at/liter - - - - - - - - - | | | | | | |
| Peripheral | 1964 | 2.19 | 6.40 | 9.88 | 9.33 | 3.61 | 4, 32 | 47.34** |
| | 1965 | 1.95 | 5.83 | 7.27 | 6.91 | 4.22 | 4, 100 | 49.66** |
| | 1966 | 1.91 | 6.90 | 13.52 | 11.61 | 6.96 | 4, 100 | 37.01** |
| Open water | 1964 | 2.79 | 7.08 | - | 8.52 | 3.69 | 3, 27 | 128.45** |
| | 1965 | 2.29 | 5.61 | - | 6.55 | 4.18 | 3, 69 | 60.79** |
| | 1966 | 1.41 | 7.52 | 15.04 | 15.18 | 9.19 | 4, 68 | 46.38** |
| Channel | 1964 | 1.51 | - | 10.30 | 8.19 | 3.12 | 3, 18 | 43.41** |
| | 1965 | 1.21 | - | 8.66 | 6.52 | 3.46 | 3, 51 | 38.42** |

** Significance level = 1%.

- No data.

TOTAL PHOSPHORUS
(μG AT/L)

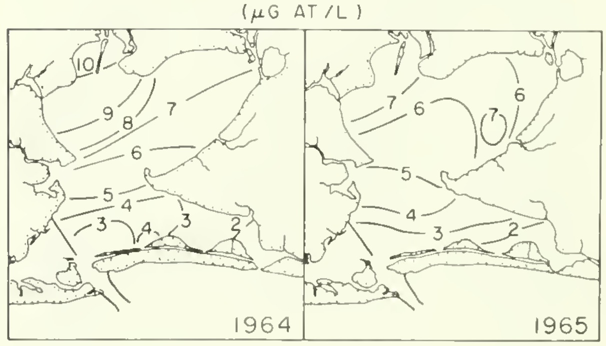


Figure 12. Isopleths (annual average)for total phosphorus in the Galveston Bay system, 1964-65.

### Comparison Between Years

Mean concentrations of phosphorus between years were similar in 1964, 1965, and during the first half of 1966 (Figure 13). Beginning in June 1966, phosphorus concentrations increased markedly from a level of about 5 $\mu$g at/liter in the habitats sampled and reached an all years' maximum of about 20 $\mu$g at/liter during the fall. Values remained above average (about 5$\mu$g at/liter) the remainder of the year.

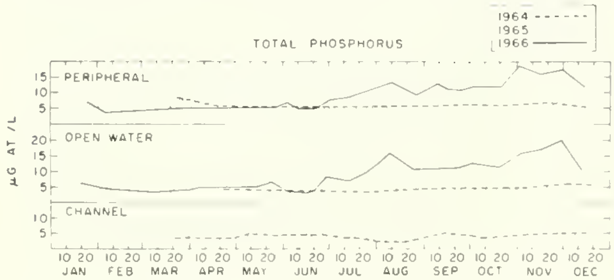


Figure 13. Mean values of total phosphorus by date, habitat, and year in the Galveston Bay system, 1964-66.

### Relation to River Discharge

River discharge from the Trinity or San Jacinto watersheds was not closely correlated with phosphorus levels in any of the habitats or bay areas (Table 10), although phosphorus concentrations in the system reached the greatest levels following the period of greatest stream flow in 1966 (Figures 6 and 11).

Table 10.—Correlation coefficients ($r$) between average weekly stream flow and concentrations of total phosphorus, 1964-66.

| Bay area | Phosphorus versus Trinity discharge | | | Phosphorus versus San Jacinto discharge | | |
|---|---|---|---|---|---|---|
| | Peripheral | Open water | Channel | Peripheral | Open water | Channel |
| | | | $r$ | | | |
| East | -0.13 | -0.26 | -0.18 | -0.10 | -0.18 | 0.19 |
| d.f. | 64 | 56 | 34 | 55 | 60 | 29 |
| Trinity | -0.41** | -0.36** | - | -0.27* | -0.24 | - |
| d.f. | 68 | 64 | - | 57 | 54 | - |
| Upper Galveston | -0.25* | -0.47* | 0.15 | -0.26* | -0.53* | 0.03 |
| d.f. | 68 | 21 | 32 | 55 | 16 | 27 |
| Mid-Galveston | -0.16 | -0.04 | 0.20 | -0.10 | 0.11 | 0.01 |
| d.f. | 65 | 66 | 29 | 55 | 55 | 26 |
| Lower Galveston | -0.07 | 0.06 | 0.28 | 0.01 | 0.16 | 0.09 |
| d.f. | 66 | 63 | 34 | 55 | 52 | 30 |

* Significance level = 5%. ** Significance level = 1% - No data

### Relation to Nitrogen

Phosphorus and nitrogen values were positively correlated each year ($r$ = 0.43, $d.f.$ = 328 in 1964; $r$ = 0.39, $d.f.$ = 757 in 1965; and $r$ = 0.36, $d.f.$ = 382 in 1966).

## DISSOLVED OXYGEN

Dissolved oxygen levels in the system varied from a minimum of 0.2 ml/liter in East Bay to a maximum of 13.6 ml/liter in Upper Galveston Bay. Annual low and high values, respectively, were 2.4 and 13.6 ml/liter in 1964, 0.9 and 13.4 ml/liter in 1965, and 0.2 and 10.8 ml/liter in 1966.

### Comparison Between Habitats

Within each bay area and year, dissolved oxygen concentrations were usually lowest in the channel and highest in the peripheral and open-water habitats (Table 11, Figure 14). The greatest variations in oxygen concentrations between habitats occurred in Upper Galveston, mid-Galveston, and East Bays.

Table 11.—Comparisons of annual mean concentrations of dissolved oxygen (ml/liter) between habitats within bay area in the Galveston Bay system, 1964-66.

| Bay area | Year | Habitats compared and mean oxygen values | | | Degrees of freedom | Test value | |
|---|---|---|---|---|---|---|---|
| | | Peripheral | Open water | Channel | | $F$ | $t$ |
| | | | ml/liter | | | | |
| East | 1964 | 5.8 | 5.7 | 5.0 | 2, 18 | 9.34** | |
| | 1965 | 6.0 | 6.0 | 4.6 | 2, 42 | 37.31** | |
| | 1966 | 5.9 | 6.2 | - | 28 | | 2.79** |
| Trinity | 1964 | 5.5 | 5.7 | - | 9 | | 1.16 |
| | 1965 | 6.3 | 6.1 | - | 29 | | 0.85 |
| | 1966 | 6.0 | 6.1 | - | 24 | | 0.29 |
| Upper Galveston | 1964 | 7.0 | - | 4.3 | 8 | | 3.03* |
| | 1965 | 6.5 | - | 4.4 | 15 | | 3.91** |
| | 1966 | 5.0 | 4.9 | - | 25 | | 0.42 |
| Mid-Galveston | 1964 | 7.3 | 5.6 | 4.7 | 2, 18 | 15.81** | |
| | 1965 | 6.4 | 5.7 | 4.9 | 2, 32 | 6.86** | |
| | 1966 | 6.4 | 5.7 | - | 24 | | 2.30 |
| Lower Galveston | 1964 | 4.9 | 5.5 | 5.2 | 2, 18 | 3.13 | |
| | 1965 | 5.9 | 5.8 | 5.6 | 2, 24 | 0.65 | |
| | 1966 | 6.2 | 6.2 | - | 26 | 0.14 | |

* Significance level = 5%.

** Significance level = 1%.

\- No data

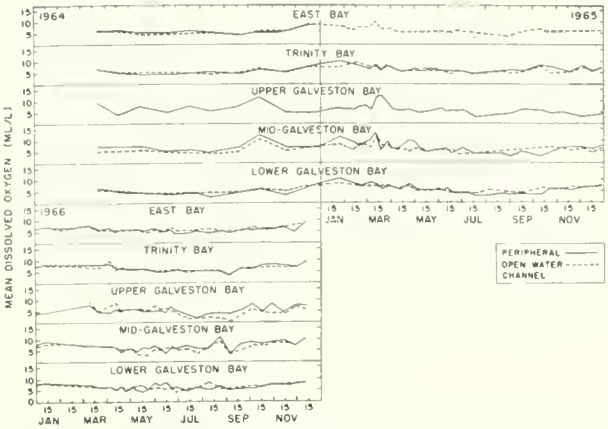


Figure 14. Mean concentrations of dissolved oxygen by date and habitat within each bay area of the Galveston Bay system, 1964-66.

## Comparison Between Bay Areas

Comparisons of dissolved oxygen values between bay areas are shown in Table 12. In the peripheral habitat, oxygen values were generally higher in mid-Galveston Bay than in the other bays. In the channel, however, oxygen values were lowest in Upper Galveston Bay and increased toward Lower Galveston Bay. Dissolved oxygen concentrations, as shown by mean values, were relatively stable throughout the open-water habitat in 1964-65 but were depressed in Upper Galveston Bay in 1966.

Table 12.—Comparisons of annual mean concentrations of dissolved oxygen (ml/liter) between bay areas within each habitat in the Galveston Bay system, 1964-66.

| Habitat | Year | Bay areas compared and mean oxygen values: East | Trinity | Upper Galveston | Mid-Galveston | Lower Galveston | Degrees of freedom | F value |
|---|---|---|---|---|---|---|---|---|
| | | - - - - - - ml/liter - - - - - - | | | | | | |
| Peripheral | 1964 | 5.8 | 5.5 | 6.9 | 7.3 | 4.9 | 4, 36 | 4.73** |
| | 1965 | 6.1 | 6.4 | 5.7 | 6.6 | 5.9 | 4, 88 | 2.05 |
| | 1966 | 5.8 | 6.0 | 5.2 | 6.6 | 6.2 | 4, 104 | 6.27** |
| Open water | 1964 | 5.7 | 5.7 | - | 5.6 | 5.5 | 3, 27 | 0.27 |
| | 1965 | 5.9 | 6.2 | - | 5.9 | 5.9 | 3, 57 | 0.88 |
| | 1966 | 6.0 | 5.8 | 4.8 | 5.5 | 5.9 | 4, 76 | 2.97** |
| Channel | 1964 | 5.1 | - | 4.3 | 4.3 | 5.3 | 3, 24 | 5.30** |
| | 1965 | 4.6 | - | 4.2 | 5.2 | 5.3 | 3, 24 | 1.59 |

* Significance level = 5%. ** Significance level = 1%. - No data

## Comparison Between Years

Seasonal trends in the concentrations of oxygen were similar between years (Figure 15). Oxygen values were maximum during the winter, decreased through the spring and attained an annual low in the summer. Oxygen levels then increased during the fall and attained an annual maximum again during the following winter. This trend was inversely correlated to temperatures as indicated by *r*-values of -0.44, *d.f.* = 343 in 1964; -0.23, *d.f.* = 686 in 1965; and -0.52, *d.f.* = 409 in 1966. The channel habitat had greatest variations in oxygen concentration between years.

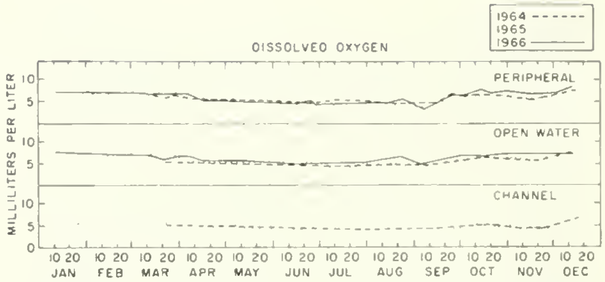


Figure 15. Mean values of dissolved oxygen by date, habitat, and year in the Galveston Bay system, 1964-66.

## DISCUSSION

Several major alterations that are expected to affect the hydrography of the Galveston Bay system are contemplated or under construction. An electric generating plant is being constructed on Cedar Bayou, which empties into Upper Galveston Bay, by the Houston Lighting and Power Company (Figure 1). A maximum of about 63.7 $m^3$/sec of water will be taken into the intake canal located 14.5 km up Cedar Bayou, warmed about 5° C, and discharged into Trinity Bay through an excavated channel. This amount of water flow is about 24% of the average annual flow from the Trinity and San Jacinto watersheds combined. The water being drawn from Upper Galveston Bay through the mouth of Cedar Bayou will flow predominantly upstream. Passage of large volumes of water through the generating plant is expected to increase temperature, salinity, dissolved organic nitrogen, and total phosphorus in some areas of Trinity Bay.

The proposed Texas Basin Project is one of many plans to develop water resources of Texas (Diener, 1964; Chapman, 1966). Reservoirs would supply water to a trans-Texas canal which would intercept tributary discharge to all coastal marshes. Anticipated water demands not related directly to the project, combined with project diversions, would reduce by one-half the average annual freshwater flow of 31.7 x $10^9$ $m^3$ now reaching Texas estuaries. Freshwater flow into the Galveston Bay system would be reduced by about one-third. Even more dramatically, Moore (1968) stated "It has been roughly computed that annual freshwater needs from the developed rivers for bays and estuaries will amount to 2.45 million acre-feet (3 x $10^9$ $m^3$) annually, while the annual Gulf water needs through new tidal inlets will amount to 33.4 million acre-feet (40.7 x $10^9$ $m^3$)." This plan, if implemented, will cause salinities in the Galveston Bay system to increase. If freshwater inflows are reduced without an increased flow of Gulf water into the bay system, we anticipate nitrogen and phosphorus concentrations to increase. If flow of Gulf water into the bay system increases, we anticipate nitrogen and phosphorus levels to decrease.

Hurricane protection levees are being built around the Galveston Bay system and tidal exchange structures for the tidal passes are being designed and planned by the U.S. Corps of Engineers. These structures are expected to reduce tidal exchange, thus affecting the normal circulation patterns in the system. Salinities would probably be reduced under the present stream flow conditions, whereas nitrogen and phosphorus levels would probably increase owing to a reduction of water exchange to the system. We would expect the large amount of nutrients that would accumulate to cause dissolved oxygen depletion of the water at times.

The quantity of industrial and domestic effluents entering the Galveston Bay system is about 1.8 million $m^3$ per day (R.A. Diener, NMFS, unpublished data). Since human populations are increasing rapidly in areas adjacent to the Galveston Bay system, we expect the domestic and industrial pollution load entering the system to increase in a similar manner for a long period of time. Nitrogen and phosphorus levels are already high in some parts of the bay system and are expected to reach much higher levels in the near future.

Various modifications to the bay system can have opposing effects on particular hydrographic variables, as indicated in the examples previously discussed. Some modifications could be planned which allow the maintenance of hydrological conditions similar to the natural state. Until more is known about the biology of estuarine animals, modifications of estuaries without maintaining present hydrological conditions involves a great risk of destroying many valuable estuarine resources.

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