Tidal-Flow, Circulation, and Flushing Changes Caused by Dredge and Fill in Hillsborough Bay, Florida

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Prepared in cooperation with the U.S. Army Corps of Engineers

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METRIC CONVERSION FACTORS

For readers who wish to convert measurements from the inch-pound system of units to the metric system of units, the conversion factors are listed below:

Multiply inch-pound unit	By	To obtain metric unit
inch (in)	25.4	millimeter (mm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
square mile (mi^2)	2.590	square kilometer (km^2)
square mile foot (mi^2ft)	0.7894	square kilometer meter (km^2m)
cubic foot (ft^3)	0.02832	cubic meter (m^3)
cubic yard (yd^3)	0.7646	cubic meter (m^3)
foot per second (ft/s)	0.3048	meter per second (m/s)
knots, nautical miles per hour (nmi/hr)	1.853	kilometer per hour (km/h)
square foot per second (ft^2/s)	0.09290	square meter per second (m^2/s)
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)
foot per square second (ft/s^2)	0.3048	meter per square second (m/s^2)

ALTITUDE DATUM

Sea level: In this report "sea level" refers to the National Geodetic Vertical Datum of 1929 (NGVD of 1929)—a geodetic datum derived from a general adjustment of the first-order level nets of both the United States and Canada, formerly called Sea Level Datum of 1929.

GLOSSARY

Gyre.—An area of rotational water flow that is characterized by little or no motion near its center and generally circular or elliptical motion elsewhere.

Mean lower low water.—A tidal datum computed as the average of the lowest low-water altitude of each tidal day observed over a given period of time, generally an 18.6-year tidal epoch.

Tidal prism.—The volume of water that enters or leaves a tidal water body between high slack water and low slack water. This is approximately equal to the surface area of the water body multiplied by the tidal range between high tide and low tide.

Tide-induced circulation.—In general, the tidally averaged, long-term water motion that occurs because of the existence of alternating flood and ebb (inward and outward) movement of the tide over an irregularly shaped bottom. More specifically, the tidally averaged rate of inward-flowing water defined at any cross section within a tidal water body, expressed in volume per unit time. Owing to continuity, this is also equal to the tidally averaged rate of outward-flowing water minus average tributary streamflow.

Transit time.—The average time for suspended or dissolved material to move from the head to the mouth of an estuary.

Water transport.—The rate and direction of movement of a quantity of water, expressed in volume per unit time.

Tidal-Flow, Circulation, and Flushing Changes Caused by Dredge and Fill in Hillsborough Bay, Florida

By Carl R. Goodwin

Abstract

Hillsborough Bay, Florida, underwent extensive physical changes between 1880 and 1972 because of the construction of islands, channels, and shoreline fills. These changes resulted in a progressive reduction in the quantity of tidal water that enters and leaves the bay. Dredging and filling also changed the magnitude and direction of tidal flow in most of the bay.

A two-dimensional, finite-difference hydrodynamic model was used to simulate flood, ebb, and residual water transport for physical conditions in Hillsborough Bay and the northeastern part of Middle Tampa Bay during 1880, 1972, and 1985. The calibrated and verified model was used to evaluate cumulative water-transport changes resulting from construction in the study area between 1880 and 1972. The model also was used to evaluate water-transport changes as a result of a major Federal dredging project completed in 1985.

The model indicates that transport changes resulting from the Federal dredging project are much less areally extensive than the corresponding transport changes resulting from construction between 1880 and 1972. Dredging-caused changes of more than 50 percent in flood and ebb water transport were computed to occur over only about 8 square miles of the 65-square-mile study area between 1972 and 1985. Model results indicate that construction between 1880 and 1972 caused changes of similar magnitude over about 23 square miles. Dredging-caused changes of more than 50 percent in residual water transport were computed to occur over only 17 square miles between 1972 and 1985. Between 1880 and 1972, changes of similar magnitude were computed to occur over an area of 45 square miles.

Model results also reveal historical tide-induced circulation patterns. The patterns consist of a series of about 8 interconnected circulatory features in 1880 and as many as 15 in 1985. Dredging- and construction-caused changes in number, size, position, shape, and intensity of the circulatory features increase tide-induced circulation throughout the bay.

Circulation patterns for 1880, 1972, and 1985 levels of development differ in many details, but all exhibit residual landward flow of water in the deep, central part of the bay and residual seaward flow in the shallows along the bay margins. This general residual flow pattern is confirmed by both computed transport of a hypothetical constituent and long-term salinity observations in Hillsborough Bay. The concept has been used to estimate the average time it takes a particle to move from the head to the mouth of the bay. The mean transit time was computed to be 58 days in 1880 and 29 days in 1972 and 1985.

This increase in circulation and decrease in transit time since 1880 is estimated to have caused an increase in average salinity of Hillsborough Bay of about 2 parts per thousand. Dredge and fill construction is concluded to have significantly increased circulation and flushing between 1880 and 1972. Little circulation or flushing change is attributed to dredging activity since 1972.

INTRODUCTION

Dredge, fill, and other construction activities have created many physical features in Hillsborough Bay that were not present before about 1880. Most construction occurred between 1880 and 1972, with peak activity in the 1950's and 1960's. The extent to which these features (ship channels, islands, submerged dredged-material disposal sites, and several large shoreline landfills) have changed tidal flow, circulation, and flushing in the bay has not been adequately determined. The cumulative impacts of these features on movement of water and waterborne constituents in the bay have been previously investigated by Goodwin (1987) as part of a modeling study of Tampa Bay as a whole. This investigation extended the earlier work by evaluating the impact of physical changes in Hillsborough Bay in greater detail.

A Federal dredging project to widen and deepen the main ship channel in Hillsborough Bay was started in 1977. By 1985, approximately 20 million yd^3 (cubic yards) of bay bottom (U.S. Army Corps of Engineers, 1974, p. 12) had

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been moved and deposited as two large islands along the 8-mi (mile)-long main ship channel. Before dredging began, the magnitude of the project and the lack of information about possible changes in tidal flow, circulation, and flushing caused considerable concern regarding potential adverse environmental effects. A need for predictive and comparative information on flow, circulation, and flushing was recognized.

Changes in water circulation and flushing can have an effect on the overall health and ecological stability of estuaries. In general, increases in estuarine circulation result in more rapid net movement of dissolved and suspended constituents from regions of high concentration to regions of low concentration. Changes in circulation and flushing in an estuary, therefore, can cause changes in the distribution and concentration levels of all waterborne material. These changes, in turn, may induce ecological shifts that could destroy natural intrinsic checks and balances that have evolved over many hundreds or thousands of years. The need to assess the effect of dredge and fill projects on water circulation and flushing, as an aid in forecasting the ecological shifts that might result, led to this study. The study was undertaken by the U.S. Geological Survey in cooperation with the U.S. Army Corps of Engineers. We are grateful to the Tampa Port Authority, particularly Delmar Drawdy, for initiation and cooperative financing from 1971 to 1973 of work that led to this study. We are also grateful to the U.S. Army Corps of Engineers, Jacksonville District, for continuation of the study and financial support through 1985.

Purpose and Scope

Tidal flow, circulation, and flushing in estuaries can be influenced by physical alterations created by construction of channels, islands, and shoreline dredge and fill areas. Computer-simulation techniques can be used to investigate the nature and extent of this influence. This report presents results of such an investigation, including

1. Tidal-flow, circulation, and flushing changes resulting from the cumulative effect of dredge and fill construction in Hillsborough Bay from 1880 to 1972 (before a large Federal dredging project to widen and deepen the main ship channel in Hillsborough Bay);
2. Tidal-flow, circulation, and flushing changes between 1972 and 1985 resulting from the Federal dredging project; and
3. Comparison and evaluation of tidal-flow, circulation, and flushing changes that occurred during these periods.

A detailed hydrodynamic simulation model of water motion was applied to three levels of development in Hillsborough Bay. The levels represent (1) conditions that existed in 1880 before any significant alterations had been made, (2) conditions that existed in 1972 before start of ship-channel dredging, and (3) conditions in 1985 after completion of ship-channel dredging. Data used for model development include measured tidal stages at three sites, tidal currents at two sites, average freshwater inflows, windspeed and direction, pumping rates for powerplant cooling water, and bay bottom configuration.

The study area includes all of Hillsborough Bay proper (approximate surface area of 43 mi^2 (square miles) in 1880) and an adjacent 22-mi^2 part of Middle Tampa Bay (fig. 1). For the purposes of this report, the term "Hillsborough Bay" refers to the larger area of about 65 mi^2. The term "Hillsborough Bay proper" refers to the smaller, 43-mi^2 area.

Methodology

A two-dimensional, vertically integrated, finite-difference, numerical simulation model described by Leendertse and Gritton (1971) was used in this study to compute tidal flow and circulation patterns for the 1880, 1972, and 1985 physical configurations of Hillsborough Bay. Model results were analyzed and compared using vector maps, vector-change maps, and longitudinal summary diagrams to determine the nature and degree of changes in tidal flow and circulation between the various configurations.

The terms "tidal flow" and "circulation" are primarily descriptive in nature. The former connotes the alternating landward and seaward movement of coastal waters associated with the daily rise and fall of the tide; the latter implies a longer term motion that is superimposed on the daily pattern and slowly moves water from place to place in a loosely structured pattern. In general, tidal flow is visually observable, circulation is not. These terms are useful for many purposes, but their definitions are not sufficiently precise to allow their application to analysis and interpretation of model results.

In this report, the term "transport" and several appropriate modifiers are used to provide the precision needed to unambiguously define the various types of water motion investigated. Transport is defined as a directional rate of mass or volume movement, such as pounds per second or cubic feet per second. Modifiers, such as water or constituent, are used to identify the material being transported. Additional modifiers, such as ebb (seaward), flood (landward), and residual (tidally averaged), are used to further identify a particular type of motion. Both ebb water transport and flood water transport are associated with the general term "tidal flow." Residual water transport is associated with the term "circulation."

Changes in flushing due to dredge and fill construction were evaluated by comparing mean transit times computed for each level of development in Hillsborough Bay. Mean transit time is a measure of the average time it takes dissolved or suspended particles to transit from the

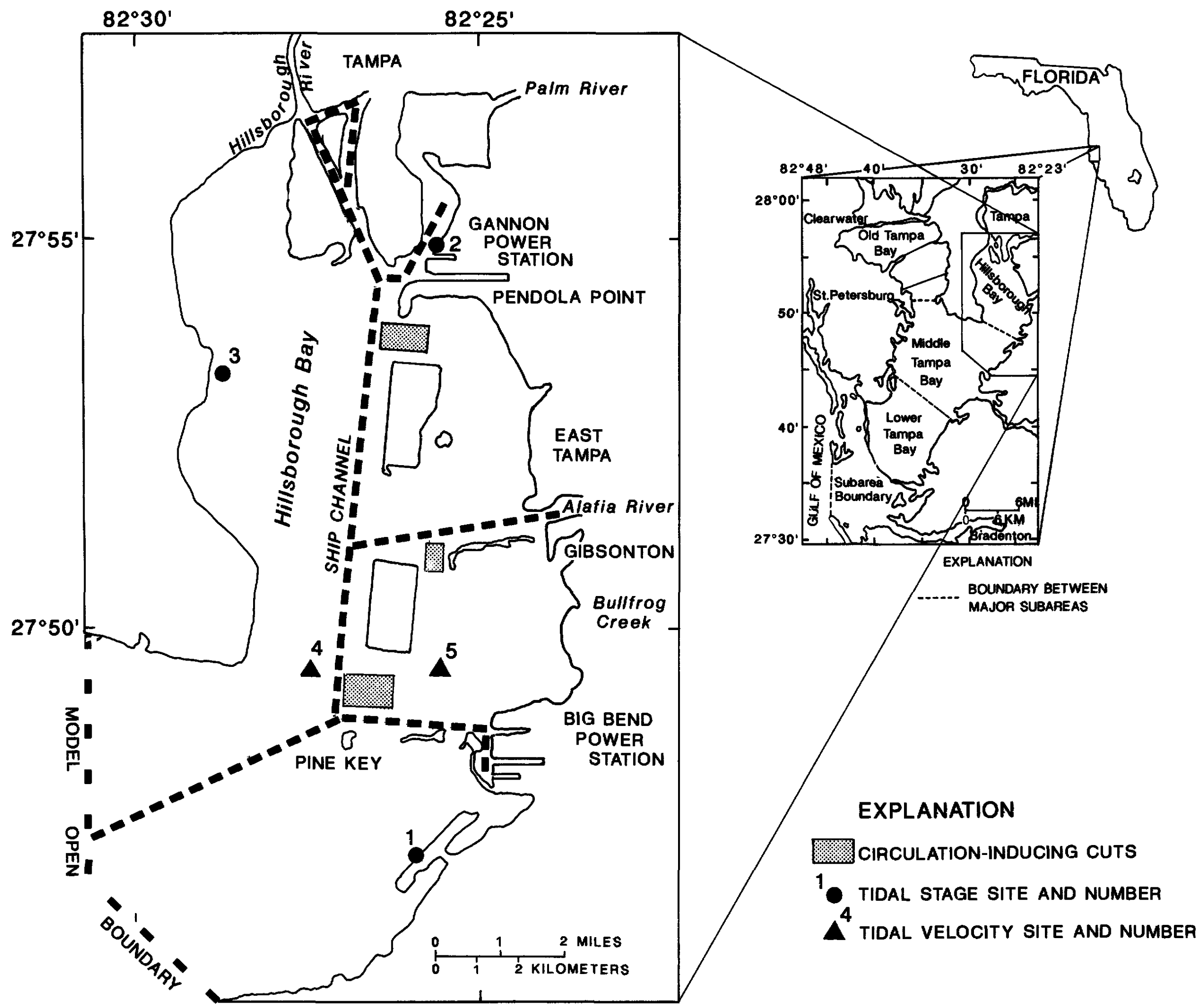

Figure 1. Location of Tampa Bay and Hillsborough Bay, Florida.

head to the mouth of the bay. Computation of mean transit time is based on a generalization of the bay's circulation pattern and the separation of computed circulation into two parts, one that primarily contributes to intertidal dispersion and another that contributes to intertidal convection.

Description of Study Area

Hillsborough Bay proper is a named part of Tampa Bay, a shallow Y-shaped embayment along the west-central coast of peninsular Florida (fig. 1), in the midst of one of the most rapidly growing regions of the State. Hillsborough Bay proper is bordered by the city of Tampa to the north and west and by the communities of East Tampa and Gibsonton to the east.

After completion of dredging in 1985, Hillsborough Bay proper attained a total surface area of about 37 mi^2 and an average depth of about 10 ft (feet) (Goodwin, 1987, p. 8). Maximum natural depths of about 20 ft occur in a small area in the south-central part of the bay. The main ship channel is maintained to a depth of about 43 ft.

The west-central area of peninsular Florida has a subtropical climate that is characterized by warm, humid summers and mild winters. Total rainfall averages about 53 in/yr (inches per year) (Heath and Conover, 1981, p. 43). More than half the rainfall, primarily from thunderstorms, occurs from June through September.

Tributary inflow to Hillsborough Bay proper, mainly from the Hillsborough and Alafia Rivers, averages about 1,200 ft^3/s (cubic feet per second) (Goodwin, 1987, p. 17). Tributary inflow, municipal and industrial discharge, and runoff from adjacent urban and agricultural basins into the bay contain a variety of dissolved and suspended organic and inorganic constituents. Many constituents settle to the bottom of the bay, where they are subject to benthic processes. Some constituents, however, remain dissolved and are distributed throughout the bay by water circulation. The dissolved constituents undergo various chemical and

Table 1. Physical characteristics of Hillsborough Bay proper for 1880, 1972, and 1985 levels of development

Physical characteristics	1880 actual	Level of development[1] based on sea level			Percent change		
		1880	1972	1985	1880 to 1972	1972 to 1985	1880 to 1985
Surface area, in square miles	41.6	42.7	38.8	36.9	−9.1	−4.9	−13.6
Water volume, in square miles-feet	327	352	373	388	+6.0	+4.0	+10.2
Average depth, in feet	7.9	8.2	9.6	10.5	+17.1	+9.4	+28.0
Tidal prism, in square miles-feet	96	99	95	93	−4.0	−2.1	−6.1

[1]To investigate changes due to dredge and fill and to avoid interferences introduced by a rising sea level trend, the physical characteristics of each bay configuration are based on the same reference water level, equal to sea level. Actual 1880 characteristics are given for a water level 0.6 foot below sea level, based on an average rate of sea level rise along the Gulf Coast of 0.006 foot/year (Hicks and others, 1983).

biological processes before being flushed into Middle Tampa Bay and eventually into the Gulf of Mexico (fig. 1).

Seasonal variations in freshwater runoff cause measurable changes in the concentration and distribution of salinity and other constituents in bay water (Goetz and Goodwin, 1980, p. 20). However, tide and wind action combine to inhibit formation of salinity differences of more than 1 or 2 ppt (parts per thousand) from top to bottom under most conditions (Cardinale and Boler, 1984, p. 220). The bay is predominantly well mixed vertically and has little density stratification.

Water motion is dominated by tides that typically convey about 3 billion ft^3 (cubic feet) of water during each flood and ebb cycle at the mouth of Hillsborough Bay proper. The magnitudes of water-level fluctuations that are attributable to the effects of the sun (diurnal)—one high and one low tide per day—and the moon (semidiurnal)—two equal high and low tides per day—are approximately equal. The result is a highly variable tide that exhibits predominantly diurnal characteristics on some days and semidiurnal characteristics on others. Most of the time, the tides are a mixture of both and result in two unequal high tides and two unequal low tides each day (Goodwin and Michaelis, 1976, p. 11), with an average diurnal range of 2.8 ft (U.S. Department of Commerce, 1982b, p. 228) and an average diurnal high of about 1.8 ft above sea level. The tide in Hillsborough Bay exhibits standing wave properties, with flow reversals occurring very near the times of high and low tides.

The physical dimensions of Hillsborough Bay have been altered many times since the late 1800's. Most changes have resulted from man's desire to develop and expand port and other commercial facilities, to improve navigation, to allow entry of deeper draft vessels, to build waterfront residences, to construct power-generating stations, and to develop recreational areas. Locations and descriptions of areas in Tampa Bay that were physically changed from 1880 to 1985 have been presented by Goodwin (1987, p. 4). A summary of the physical characteristics of Hillsborough Bay proper for 1880, 1972, and 1985 levels of development, along with associated percentage changes (Goodwin, 1987, p. 8), are given in table 1.

The physical characteristics described in the table are approximate water-surface area, volume, average depth, and tidal prism. To allow direct comparison of physical changes due to dredge and fill, a water-level reference for each configuration was chosen to be equal to sea level. All subsequent computations in this report are based on this comparability between configuration characteristics. Table 1 also gives actual physical characteristics in 1880 for a water level 0.6 ft below sea level, based on an average rate of sea level rise along the Gulf Coast of 0.006 ft/yr (foot per year) identified by Hicks and others (1983, p. 22). The percentage change in each physical characteristic from 1880 to 1972, from 1972 to 1985, and from 1880 to 1985 also are given. Greater physical changes to the bay due to dredge and fill occurred between 1880 and 1972 than between 1972 and 1985.

Decreases in surface area (see table 1) reflect construction of islands and other fills. Increases in water volume have occurred because (1) the source of material for most fill construction was the bay bottom and (2) only part of the dredged material was redeposited in the bay. The remaining dredged material became new emergent upland and is equivalent to the net gain in water volume of the bay. Under these conditions, the average depth also must increase.

Dredging and filling from 1880 to 1985 reduced the surface area of Hillsborough Bay proper by 13.6 percent. Water volume increased by 10.2 percent, and the average depth increased by 28.0 percent.

Changes in the physical characteristics of Hillsborough Bay proper influence the quantity of water that enters and leaves the bay during every tidal cycle. This quantity, called the tidal prism, is defined as the volume of water that enters or leaves a tidal water body between high slack water and low slack water. Tidal prism is approximately equal to the surface area times a representative tidal range of the water body. Even though the total volume of water in the bay has increased substantially because of dredging activity, the tidal prism has decreased (see table 1). This apparent anomaly is explained by the reduced surface area of the bay due to filling within the intertidal zone (between the limits of high tide and low tide). Additional discussion of the tidal-prism concept has been given by Goodwin (1987, p. 8).

Tidal-prism reduction from 1880 to 1985 is computed to be 6.1 percent for Hillsborough Bay proper. A logical consequence of this reduced tidal exchange would be proportionate reductions in tidal mixing and flushing. Modeling results by Goodwin (1987, p. 62) have shown, however, that dredge and fill construction actually results in substantial mixing and flushing increases.

The circulation mechanism described in this report is a tidal pumping action caused by interaction between tidal flow and the irregular bottom configuration (Fischer and others, 1979, p. 237). After a tidal cycle, a water parcel will return to the same position it occupied at the start of the cycle if tidal inflow (flood) and outflow (ebb) patterns and volumes in an estuary are identical, providing other flow-inducing mechanisms are not effective. If flood and ebb conditions differ, the water parcel will not return to its initial position. The net displacement of every water parcel over successive tidal cycles is a result of circulation caused by tidal pumping. Different flood and ebb conditions typically are caused by the irregular physical features of an estuary. These features include the estuary's general shape and bottom configuration and the size and shape of islands, peninsulas, channels, shoals, and marshes.

Previous Studies

This report follows a series of previous investigations that were either directly or indirectly concerned with tidal effects in Tampa and Hillsborough Bays. As background and reference information, many of these studies are briefly described and discussed in Goodwin (1987).

This report extends preliminary results for circulation from a detailed hydrodynamic model of Hillsborough Bay (Goodwin, 1980) which (1) showed complex residual tidal currents that previously had not been detected and (2) compared simulated tidal-flow and circulation patterns for conditions both before and after the Federal dredging project that began in 1977. Also in this report, analytical techniques used by Goodwin (1987) for Tampa Bay were applied to a spatially more detailed simulation of Hillsborough Bay. Goodwin (1987) reported changes in tidal flow, circulation, and flushing caused by dredge and fill construction in Tampa Bay. He concluded that circulation and flushing increased in most parts of Tampa Bay by 10 to 80 percent owing to physical changes from 1880 to 1985. In part of Hillsborough Bay, however, the increase in circulation and flushing was more than 250 percent.

Acknowledgments

Initial model calibration by Jan Leendertse of the Rand Corporation and by Robert Baltzer of the U.S. Geological Survey research staff on a precursor of the model described in this report is gratefully acknowledged.

DESCRIPTION OF COMPUTER SIMULATION SYSTEM

The model used in this study can simulate water and constituent motion in well-mixed estuaries, embayments, and other coastal areas. Equations that describe the physical laws governing water and constituent motion in two dimensions are employed. The governing partial-differential equations describe general relations among the many phenomena that control water motion. Because the equations cannot be solved analytically for most real-world conditions, procedures have been devised that provide approximate solutions by using computers to rapidly perform an enormous number of numerical computations. These equations are solved at successive small time steps to provide a close approximation of the time history of water level, water transport, and constituent transport throughout the water body.

Water motion in estuaries is governed by the physical laws of mass and momentum conservation. The two-dimensional model (SIM2D) used in this study solves vertically integrated forms of the partial-differential equations that describe conservation of mass and momentum, as given by Leendertse and Gritton (1971, p. 8). These equations assume that water density is constant both horizontally and vertically. The model is limited in application to water bodies that are vertically and horizontally well mixed. However, this type of model has been successfully applied to water bodies having gradually varying horizontal density gradients. A more detailed description of the governing equations used in SIM2D can be found in Goodwin (1987, p. 10).

The numerical procedure used in SIM2D is briefly described below and has been presented in detail by Leendertse and Gritton (1971, p. 15). In the basic computation procedure, each governing partial-differential equation is approximated over a region in time and space by a large number of difference equations. Each difference equation is similar in form to the parent differential equation and contains discretizations of spatial and temporal gradients that relate individual points to each other. Such a finite-difference approximation is valuable because, by using the approximation, a partial-differential equation is reduced to multiple interrelated algebraic equations involving quantities at defined locations. Each of the difference equations contains known and unknown quantities. As long as the number of such equations equals the number of

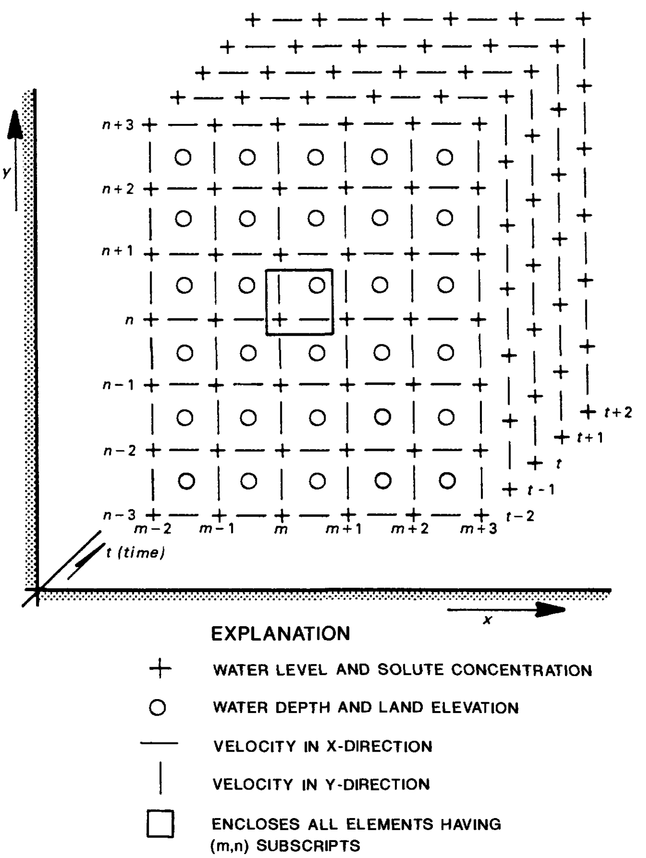

Figure 2. Finite-difference scheme for computer simulation model. (Modified from Leendertse and Gritton, 1971.)

unknown quantities, the entire system of equations is solvable. The method of solution for the unknown quantities involves a repeating, two-step procedure that incorporates previously computed values and input data as additional information.

A space-staggered grid (fig. 2), upon which the finite-difference equations are developed, is used in the SIM2D model. Water levels (z) are defined at integer values of m and n. Reference water depths (h) are defined at points midway between integer values of both m and n. Velocities in the x direction (U) are defined at points midway between integer values of m and at integer values of n. Velocities in the y direction (V) are defined at points midway between integer values of n and at integer values of m.

The rectangular grid encompasses the entire area of the water body to be modeled. On land areas, reference water depths (h) are replaced by land elevations ($-h$). Water velocities are computed in a grid cell only during times when its governing water level exceeds the defined land elevation for the cell. Time (t) is advanced in a stepwise manner, with various computational elements alternately defined at full and half time-step intervals.

Leendertse and Gritton (1971, p. 11) have given a complete description of how each partial-differential equation is structured at each (x, y, t) point and how the unknowns are determined in each equation. An overview of the solution scheme also has been given by Cheng and Casulli (1982, p. 1655).

Three categories of input data must be defined in order to implement SIM2D:

1. Fixed conditions;
2. Initial conditions; and
3. Boundary conditions.

The first category includes bay bottom depths, land elevations, and Manning's friction factors, as well as water density in each cell. The second category includes starting water-surface elevations and starting water velocities. The third category of input data includes information that can be entered as a function of time. Tidal fluctuations are defined at the open boundary. Speed and direction of the wind are defined at the water surface. The rates of water inflow are defined at appropriate locations to simulate tributary river inflow as well as powerplant cooling-water intake and discharge.

SIM2D is the primary component of several interrelated programs that constitute the SIMSYS2D modeling system:

1. The principal components of the SIMSYS2D system have four main functions. The Input Data Processor (IDP) scans the user-prepared input data file (often several thousand card images in size) and checks for any potential format and logic error. IDP also creates a file containing the size of all dimensioned variables for each model application.
2. The file created in step 1 is combined with the FORTRAN source code of the general SIM2D model by the MIXER program. Compilation and linkage-editing steps produce an executable load module that is tailored to the particular water body being modeled. SIM2D is the load module that is produced by MIXER.
3. During computation, water elevations, velocities, and other quantities are computed and stored by the model at user-selected time intervals.
4. The stored data serve as a source of information for plotting routines contained in the POST PROCESSOR section. Programs in this section produce graphs and maps of model results.

A more detailed explanation of the SIMSYS2D system has been given by Goodwin (1987, p. 13).

MODEL DEVELOPMENT AND APPLICATION

Model development is the process by which a general estuarine simulation system is structured and adjusted to represent a particular estuary, embayment, or other coastal area. The objective of the process is to achieve as close

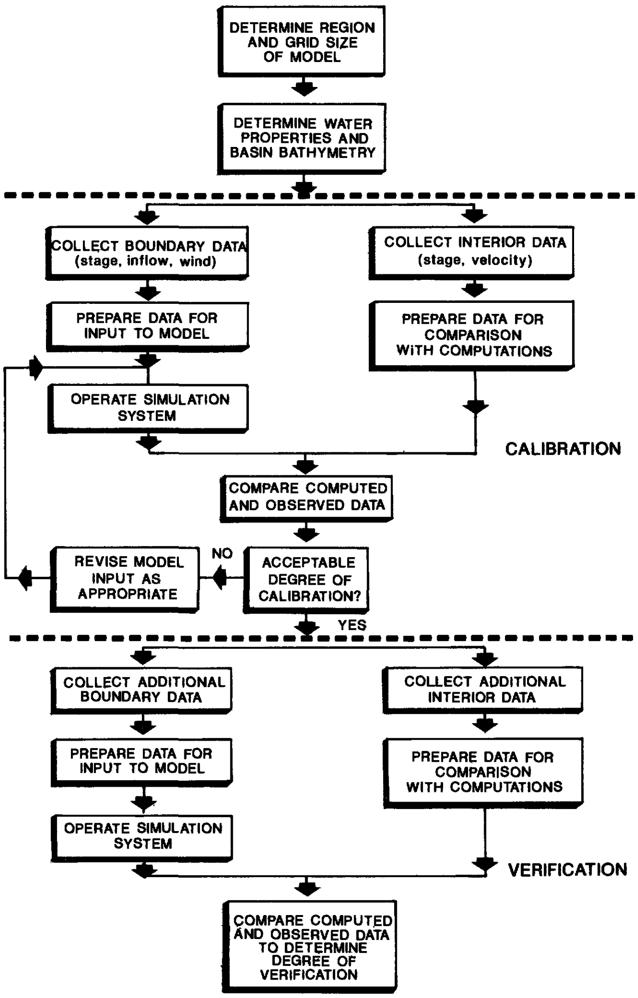

Figure 3. Calibration and verification steps in model development.

agreement as possible and practicable between simulated and observed values of tidal stage, tidal currents, and other measurable properties. The closer the agreement, the more confident model users can be that the results of subsequent numerical experiments accurately reflect real conditions.

The development procedure comprises two basic steps, calibration and verification (fig. 3). Both steps involve comparison of computed and observed data. The calibration step has a feedback loop that is not present in the verification step. Feedback allows adjustments to imprecisely known input data to improve the match between observed and simulated data. Verification is conducted for one or more data sets that were not used during calibration. During verification, further adjustments are not allowed. The degree of agreement between observed and simulated data achieved during the verification step is a measure of model accuracy and reliability.

If verification results are not acceptable, it is important that the reason or reasons for the discrepancy be determined and corrected before using the model. Reasons can include such things as

1. Inaccurate field data requiring additional data collection;
2. Improper model schematization or data input; and
3. Lack of sufficient match between conditions in the water body and primary model assumptions.

Close attention to these items, particularly reason 3, can often lead to new understandings of either the water body itself or the numerical simulation process.

The following sections describe how the bottom configuration, boundary conditions, and initial conditions were determined and give the results of calibration and verification comparisons for development of the Hillsborough Bay hydrodynamic model.

Bottom Configuration

The area of Hillsborough Bay and the part of Middle Tampa Bay modeled are shown in figure 1. The total modeled area is 102 mi^2, approximately 36 percent of which is land that has elevations higher than mean high water. The modeled area is defined by an 80- by 142-cell grid system. Each cell in the system is 500 ft on a side, adequate to define most major physical features with little distortion. A time step of 5 min (minutes) was determined to provide numerical stability as well as tidal flow and circulation accuracy. This time step was used for each model run during the study.

The most important aspect of model development is accurate representation of the bottom configuration, as defined by water depths in each grid cell. These depths define bottom-shape characteristics that largely control how water is numerically distributed by the model.

A combination of available and new data was employed to determine the depths to be used in the Hillsborough Bay model development. Detailed depth information was obtained from the National Ocean Service (NOS) for surveys made in 1957 and 1958. Survey results were in the form of maps annotated with numbers representing the depth of water referenced to mean lower low water datum. The maps were compiled at a scale of 1:10,000. The density of coverage averaged about 1,000 depth observations per square mile. For this study, all depths were adjusted to sea level.

Resurveys of selected areas were made by the U.S. Geological Survey in 1971 and 1973 by using automatic positioning equipment and a digital fathometer. The objectives were to (1) determine whether any significant, areally extensive bottom changes had occurred since the NOS surveys and (2) define dredged channels and dredged-material disposal sites constructed since the NOS surveys. Direct stereo compilation of bottom configuration also was conducted wherever low-level aerial photography could sufficiently penetrate the water column to define bottom

Table 2. Average annual freshwater inflow to, and power-generation station cooling-water pumpage in, Hillsborough Bay

[Location of streams and stations shown in fig. 1. ft^3/s, cubic feet per second]

Stream or power station	Modeled flow rate (ft^3/s)
Alafia River	465
Hillsborough River	642
Bullfrog Creek	32
Palm River	42
Gannon Station	[1]1,960
Big Bend Station	[1]1,960

[1]See Goodwin (1987).

relief. A description of fathometric and photogrammetric approaches is given in Rosenshein and others (1977, p. 695). No extensive changes were detected in areas where the bottom had not been dredged.

Depth assignments were made by using a combination of automated and manual techniques. The automated procedure (Schaffranek and Baltzer, 1975) involved compiling, editing, combining, and gridding data from the various sources. Thousands of quasi-random depth observations were fitted to a polynomial surface from which a representative depth for each cell was computed. The cell depths were then compared with bathymetric charts and manually revised if necessary. Revisions were sometimes needed near shorelines and channels and in areas of sparse data.

Land elevations for cells that were higher than mean high water were assigned a default value of 2.5 ft. This value limited the model to investigation of tides that reached maximum elevations of less than 2.5 ft. This limitation was not a constraint for this study.

Boundary Conditions

Boundaries of the Hillsborough Bay model, including the bay bottom, the shoreline, tributary streams, and the water surface, are in all respects the same as those used in the two-dimensional model of Tampa Bay described by Goodwin (1987, p. 16). A Manning's friction factor of 0.0235 was used to approximate the resistance to water flow by the bay bottom.

The shoreline was defined as a no-flow boundary except where tributary streams enter the bay. A flooding and drying feature of the model simulated landward or seaward movement of the shoreline with changes in tidal stage. Values of average annual freshwater inflow of streams tributary to Hillsborough Bay and cooling-water inflow and outflow of power-generation stations (fig. 1) that were used in this study are given in table 2.

Tidal stages, the primary forcing function causing time-dependent water motion, were used to define conditions at 11 points along the seaward boundary of the model. These input data were extracted, with some minor smoothing, from computed results of a two-dimensional model of Tampa Bay reported by Goodwin (1987). The seaward-boundary location was chosen to be many cells distant from the southern boundary of Hillsborough Bay proper. This was done to avoid possible contamination of computed results by simplified finite-difference approximations that are needed at the open-water boundary. These assumptions have been discussed by Leendertse (1967, p. 67).

Tide conditions during the calibration period were mainly diurnal, with a tidal range of 3.6 ft. The verification period had mixed tide characteristics with large semidiurnal inequalities; the diurnal tidal range was 3.0 ft.

Wind was also treated as a forcing function during model development. Windspeed and direction applied during the Hillsborough Bay calibration and verification periods were the same as those applied in the Tampa Bay model simulations (Goodwin, 1987, p. 19). The computed wind field was assumed to be variable with time but spatially uniform over the modeled area. Wind during the calibration period averaged about 6 knots. The direction changed at a uniform rate in a clockwise manner starting from the east-southeast, through north, and around to north a second time. Wind during the verification period began as calm, then averaged about 7 knots from the south-southwest.

Initial Conditions

Initial conditions are necessary to define two time-varying parameters, tidal stage and tidal current, at the start of each model run. A level water surface was assumed throughout the bay at an elevation equal to the starting water level at the seaward boundary. Correspondingly, all tidal currents at the start of each model run were zero.

Operationally, about 12 hours of real time must be simulated before the effects of assumed initial conditions disappear from the solution and model computations accurately represent valid stage and current conditions. Tests using repeating tides have demonstrated that circulation computations are more sensitive and require simulation of about 24 hours of real time before the effects of initial conditions disappear.

Calibration and Verification

Observations of tidal stage and tidal currents for model calibration and verification were made in 1972. The following table shows starting and ending times for the calibration and verification periods.

Period	Start		End		Duration (hours)
	Day	Hour	Day	Hour	
Calibration	Jan. 27	1205	Jan. 28	2400	36
Verification	Jan. 30	0005	Jan. 31	1200	36

Table 3. Summary of tidal stage and current sites in Hillsborough Bay

Site (fig. 1)	USGS downstream order number	North latitude	West longitude	Type
1	02300560	27°46′57″	82°25′53″	Stage
2	02301761	27°54′54″	82°25′25″	Stage
3	02306032	27°53′22″	82°28′47″	Stage
4	—	27°49′20″	82°27′25″	Current
5	—	27°49′16″	82°25′44″	Current

Tidal stage and current data for the calibration and verification periods were measured at five sites, shown in figure 1. Table 3 gives number and position information for each site. Instrumentation at each site has been described by Goodwin (1987, p. 22).

Graphical comparisons between observed and computed tidal stage and currents for each site are shown in figures 4 and 5. From the graphs, it can be seen that about 12 hours of real time must be simulated before the effects of assumed initial conditions disappear and model computations reflect real stage and current conditions.

Standard errors between computed and observed tidal stages and currents for the last 24 hours of each comparison shown in figures 4 and 5 are given in table 4. Standard errors for stage ranged from 0.03 to 0.05 ft, with averages of 0.037 ft for the calibration period and 0.040 ft for the verification period. Standard errors for current speed ranged from 0.05 to 0.08 ft/s (foot per second), with an average of 0.065 ft/s for both the calibration and verification periods. Standard errors for current direction ranged from 14 to 26 degrees, with averages of 22.5 degrees for the calibration period and 20.0 degrees for the verification period. That the standard errors are about the same for both periods is evidence of the model's capability to simulate real conditions consistently.

Some of the larger deviations between computed and observed tidal currents (fig. 5) may indicate either imprecise field data or model bias. At site 4, for instance, the difference in speed during ebbtide between hours 28 and 33 of the verification period cannot be explained with available information. It should be pointed out that currents computed by the model represent averages over the area of each cell and, as such, are sometimes difficult to compare with discrete readings from a velocity meter. Very localized conditions not represented by the model can significantly affect the field data. Deviations between observed and computed current directions at both sites often increase during times of very slow current speeds. This is an unavoidable characteristic of the instruments used. In spite of these few inconsistencies, the values for tidal stage and current are sufficiently similar to justify use of the model in this study.

Application to 1880, 1972, and 1985 Levels of Development

Subsequent to calibration and verification, the model was applied to determine flow and circulation characteristics of Hillsborough Bay for historical (1880), predredging (1972), and postdredging (1985) levels of development. The bottom configurations for these conditions are shown in figure 6. In 1880 (fig. 6*A*), bottom depths varied gradually, did not exceed 37 ft, and were deepest in the south-central part of the bay. From 1880 to 1972 (fig. 6*B*), extensive areas were filled in the northern and southeastern parts of the bay, mostly for residential- and port-development purposes. Ship channels were constructed to depths of 36 ft, and emergent dredged-material disposal areas (islands) and submerged disposal areas were created alongside the channels. From 1972 to 1985, deepening (to 43 ft) and widening (from 400 to 500 ft) of the ship channels required creation of two large dredged-material disposal islands (see Goodwin and Michaelis, 1984, p. 48). Three localized areas of the bay were deepened in an attempt to avoid constrictions to tidal flow that might impede tide-induced circulation. These circulation-inducing cuts (fig. 6*C*) were proposed by an environmental advisory committee, as reported by Goodwin (1977, p. 168). The overall changes to some important physical characteristics of the bay are summarized in table 1.

Also shown in figure 6 is a line starting near the open boundary of the model and ending at the northern end of the study area that is graduated in miles. This line, called the longitudinal summary line, defines the distance scale used for the abscissa in later figures in this report.

Input data at the open boundary of the Hillsborough Bay model were derived from tidal stage information computed for the appropriate level of development by an earlier Tampa Bay model having a 24-hour, repeating tidal stage input at the open boundary, as given by Goodwin (1987, p. 32). Computed stage data for 11 cells were extracted, smoothed, and applied to the ends of 10 equally spaced sections in the Hillsborough Bay model to closely approximate the time and spatial water-level variations at the open-water boundary. The 11 repeating boundary tides are not presented in this report but are visually approximated by the site 1 verification tide, shown in figure 4, from 10 to 34 hours.

A condition of zero wind was used, and freshwater inflow was held constant, for each model application at the average annual discharges listed in table 2. Cooling-water flow rates used by power-generating stations for 1972 and 1985 levels of development, as shown in table 2, also were held constant. There were no power-generating stations on Hillsborough Bay in 1880.

Tidal currents throughout the modeled area were assumed to be zero at the start of each model simulation.

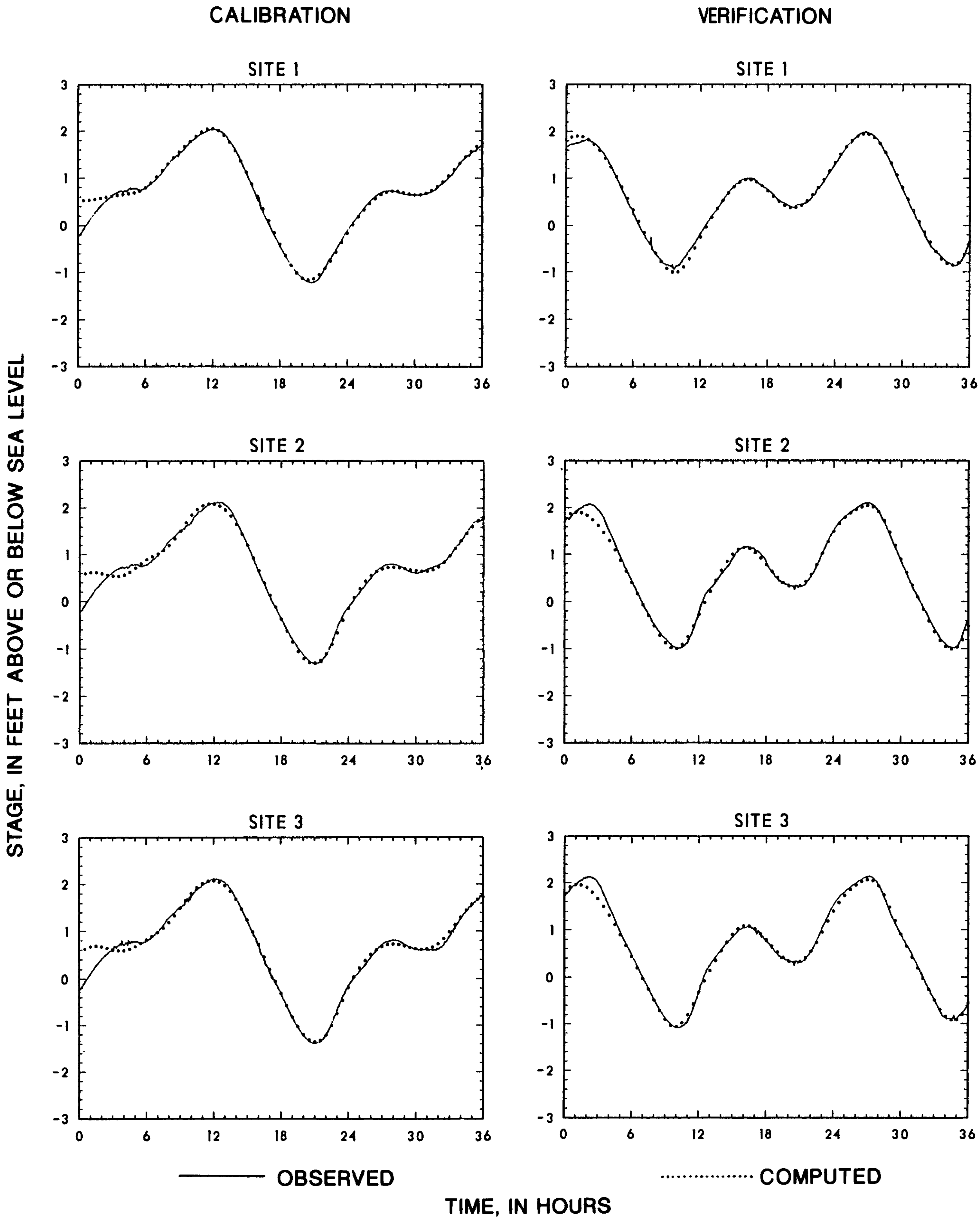

Figure 4. Observed and computed tidal stage during calibration and verification periods. (Location of tidal stage sites shown in fig. 1.)

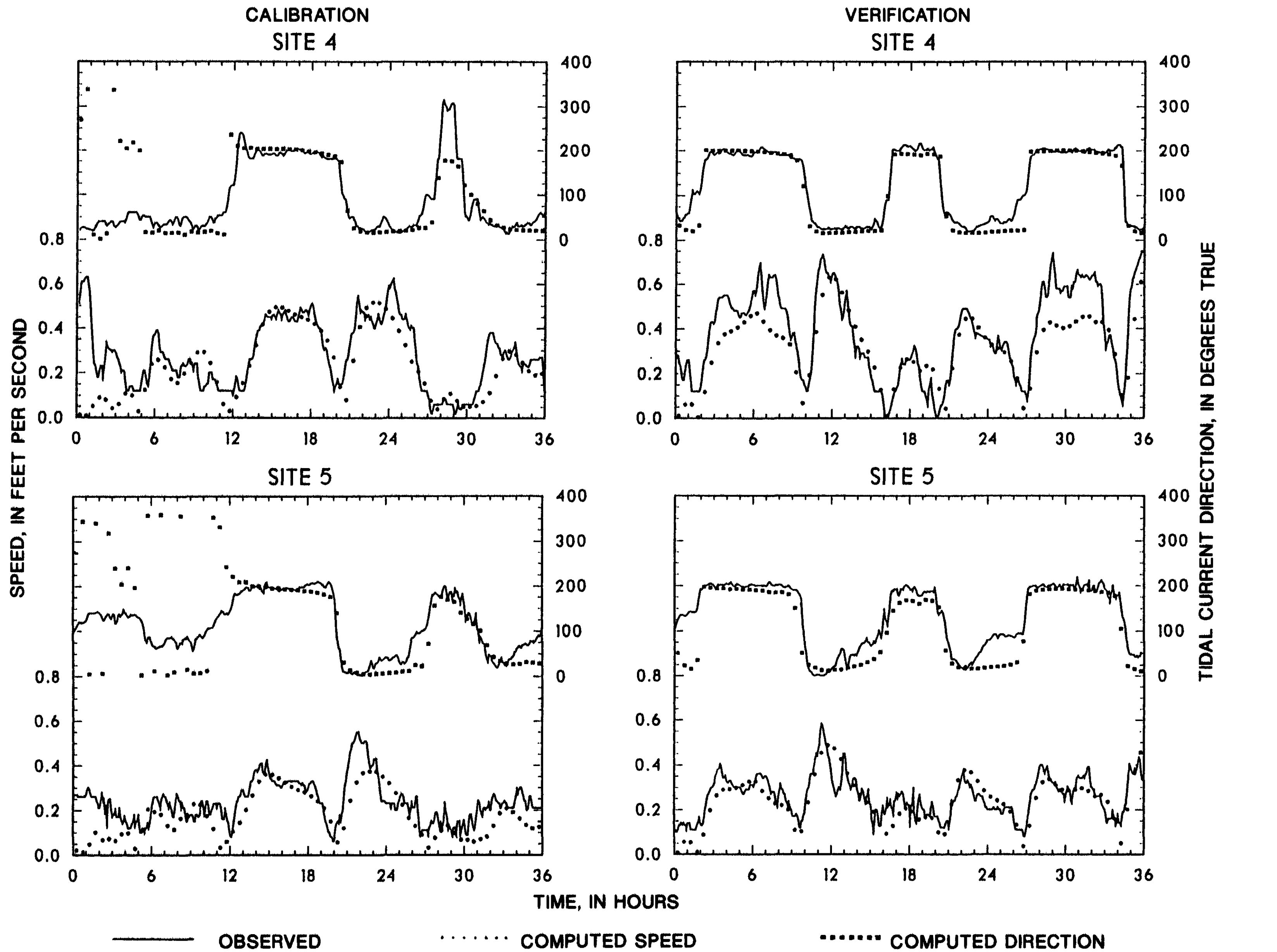

Figure 5. Observed and computed tidal current speed and direction during calibration and verification periods. (Location of tidal velocity sites shown in fig. 1.)

Table 4. Standard errors between computed and observed tidal stage, tidal current speed, and tidal current direction
[ft, feet; ft/s, feet per second]

Site	Calibration			Verification		
	Tidal stage (ft)	Tidal current		Tidal stage (ft)	Tidal current	
		Speed (ft/s)	Direction (degrees)		Speed (ft/s)	Direction (degrees)
1	0.03			0.03		
2	.04			.05		
3	.04			.04		
4		0.06	22		0.08	14
5		.07	23		.05	26

Tidal stages throughout the modeled area were initially constant at a level consistent with that of the open boundary.

TIDAL FLOW, CIRCULATION, AND FLUSHING

The results of model computations presented in this section are largely dependent on use of vector maps that visually represent the tidal flow and circulation patterns of water movement computed by the hydrodynamic model. In this report, the flood (landward moving) and ebb (seaward moving) components of tidal flow are represented by the terms "flood water transport" and "ebb water transport," respectively. Transport is defined as a directional, volumetric flux, in cubic feet per second, and can be visually displayed as vector symbols (arrows) oriented to show the flux direction and magnitude of water transport in each cell of the modeled area. When viewed in map form, these transport vectors reveal computed tidal (flood and ebb) flow patterns. Similarly, map displays of tidally averaged (residual) water-transport vectors reveal computed circulation patterns.

Analytical methods to discern differences in tidal flow and circulation patterns between 1880, 1972, and 1985 levels of development are dependent on some concepts of vector arithmetic that have been described by Goodwin (1987, p. 35). These concepts are used for (1) preparation of vector maps showing the computed magnitude and direction of flood, ebb, and residual water transport in the modeled region, (2) preparation of maps showing the areal distribution of vector changes in flood, ebb, and residual water transport resulting from physical changes to the bay, and (3) development of a method to graphically summarize some of the information inherent in vector maps as a function of longitudinal distance from the open boundary.

The longitudinal technique summarizes computed flood, ebb, and residual water transport along a series of cross sections within the bay. Each cross section extends from bank to bank and is approximately perpendicular to the predominant direction of tidal flow. The series of cross sections extends from the model boundary in Middle Tampa Bay to the head of Hillsborough Bay proper along the longitudinal summary line identified in figure 6. Information extracted from the model for each level of development normal to each cross section includes

1. Total water transport during a typical floodtide;
2. Total water transport during a typical ebbtide; and
3. Total landward-flowing residual water transport. This quantity is equivalent to the total seaward-flowing residual water transport less any tributary inflow landward of each cross section. It can also be thought of as the residual water transport that exists because of tidal influences. For the purposes of this report, the total landward-flowing component of residual water transport computed in this manner at each cross section is defined as tide-induced circulation.

Tidal Flow

Tidal flow (flood and ebb water transport) is computed at water-depth locations of the finite-difference grid (fig. 2) by using the cell dimension (500 ft), the depth value, and the four velocity values and four water-level values on the sides and at the corners of the surrounding square. The total water depth for the entire cell is defined as the depth value at the center of the square plus the arithmetic average of the water levels at the four corners of the square. The north-south and east-west cross-sectional areas are equivalent, and are equal to the total water depth times the cell width. Each pair of velocity values on opposite sides of the square are arithmetically averaged to produce square-centered, north-south, and east-west velocity components. North-south and east-west water-transport components in each cell are computed as the appropriate velocity component times the cell cross-sectional area. Each of these components can then be combined and plotted in resultant form (magnitude and direction) to show flood and ebb tidal flow patterns for the entire modeled region.

Flood and ebb water transports presented in this report represent typical conditions computed to exist during selected half-hour time segments within strength-of-flood and strength-of-ebb periods of the tidal cycle.

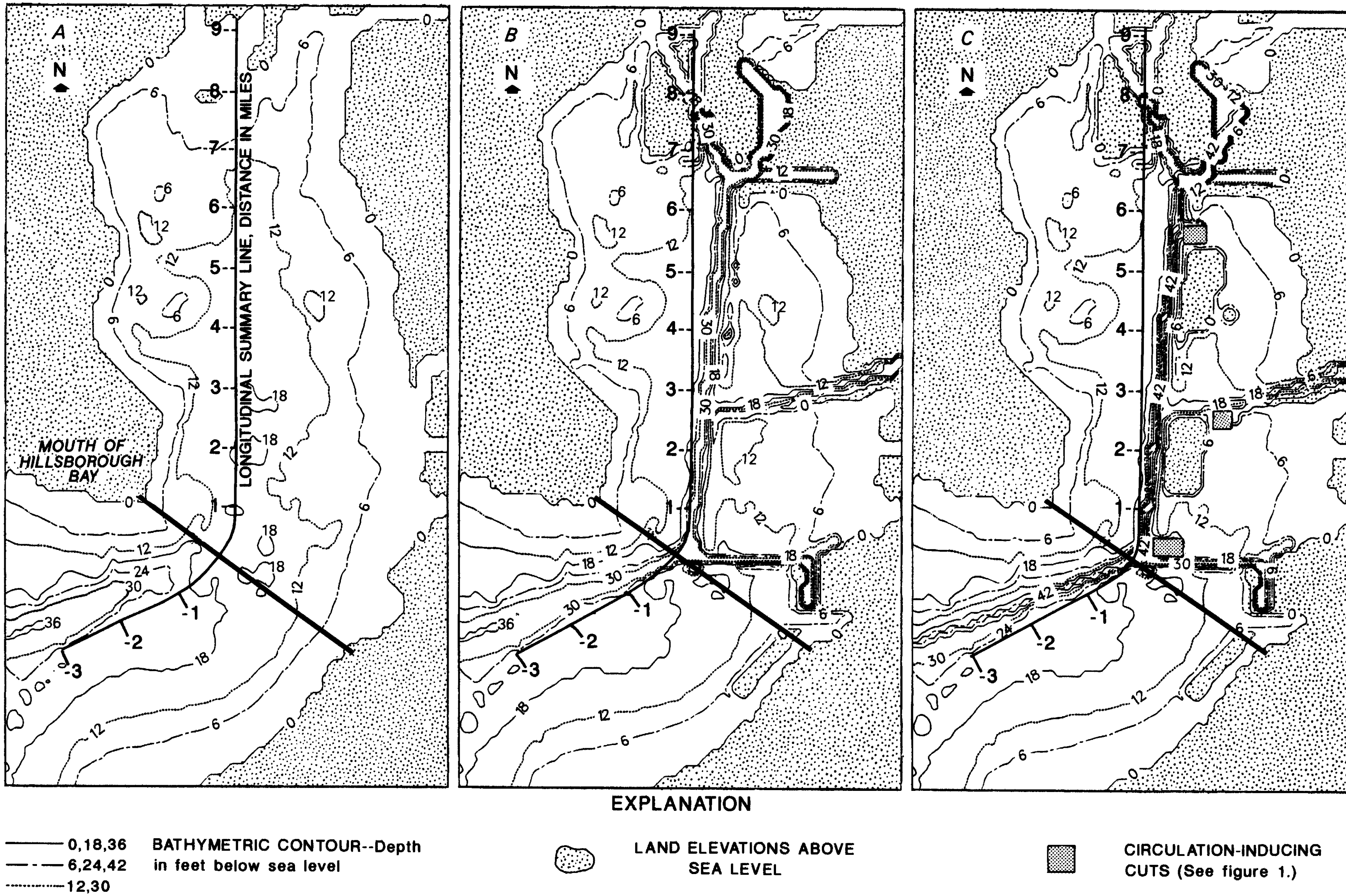

Figure 6. Hillsborough Bay bottom configurations for 1880 (*A*), 1972 (*B*), and 1985 (*C*) levels of development, with longitudinal summary lines showing distance from mouth.

Flood and Ebb Water Transport

Typical flood and ebb water-transport patterns during floodtide for 1880, 1972, and 1985 levels of development are shown in figures 7, 8, and 9, respectively. Lines of equal vector magnitude, in cubic feet per second, are shown to help reveal some of the major features of each pattern. The transport-vector maps for 1972 and 1985 show many similarities, but both differ in some obvious ways from the pattern computed for 1880. For one thing, tidal water cannot flow where islands and shoreline fills have been constructed since 1880. Moreover, water flow near these islands, fills, and submerged dredged-material disposal sites is in many cases much different than at the same location in 1880. The manmade features either block or impede the free flow of water sufficiently to cause significant flow diversions around the obstructions and flow reductions in their wakes. The diversions and flow reductions can be seen by visually comparing the locations of computed flow vectors and lines of equal vector magnitudes near islands in figures 8 and 9 with the same locations in figure 7.

Changes in floodflow patterns since 1880 resulting from construction and enlargement of ship channels are less visually obvious than are changes resulting from construction of islands and fills. Channel alignments are usually designed to occupy the naturally deep parts of existing waterways. The overall effect, therefore, is to induce more water to flow where large flows occur naturally. This is illustrated by successively greater areas of large transport rates in the deeper parts of Hillsborough Bay from 1880 through 1985.

Typical water-transport patterns and lines of equal transport magnitude during ebbtide for 1880, 1972, and 1985 levels of development are shown in figures 10, 11, and 12, respectively. Overall ebb-transport patterns, although opposite in direction, are similar to flood-transport patterns shown in figures 7, 8, and 9.

One noticeable difference between flood and ebb patterns for each level of development is that typical ebb transports are substantially greater than typical flood transports throughout the bay. This difference is caused by faster rates of water-level change for falling tide than for rising tide. The faster rate is balanced by a shorter duration of ebbflow.

Similarities between 1880 flood- and ebb-transport patterns are striking. The changes in flow magnitude and direction from place to place in the bay are very gradual for both flow conditions, and the differences that do exist can be detected only by very close scrutiny of figures 7 and 10. Differences between flood- and ebb-transport patterns for 1972 (figs. 8, 11) and 1985 (figs. 9, 12) levels of development are more visible than those for 1880. Flow diversions around obstructions tend to occur in similar ways, but the actual flow patterns at such diversions are in many places visibly different between floodtide and ebbtide. This is perhaps most noticeable along east-west-trending channels leading to the mouth of the Alafia River and to the Big Bend area (see fig. 1). The ebbflow patterns in these areas seem to be more influenced by the existence of a ship channel to the north of the islands than do the floodflow patterns.

During floodflow, sections of the east-west channels are in the wake of adjacent dredged-material disposal islands, and water-surface gradients in the direction of channel alignments are low. Under these conditions, water transported by the east-west channels is also low. During ebbflow, however, these same channels are in an ideal position to help convey diverted water at least part of the way around island obstacles. The greater magnitude of ebbflow and the ease of conveyance by the channel interact to produce much different flow angles than those during floodflow. The most obvious occurrence of this is in the vicinity of Pine Key (see fig. 1), at the entrance to Hillsborough Bay proper, where the effect of a discernible jet of diverted water can be seen in 1972 and 1985 ebbflows (figs. 11, 12) trending toward the southwest. In short, both floodflow and ebbflow patterns become more visually complex from 1880 to 1985 owing to manmade physical changes, and the visible differences between flood and ebb patterns at successive levels of development become more obvious.

Flood and Ebb Water-Transport Differences Between 1880, 1972, and 1985

Differences in floodflow and ebbflow patterns between the three levels of development can be represented directly by computation of the difference vector for each cell. For floodflow, the distribution of water-transport changes is shown by four percentage groupings for 1880 to 1972, 1972 to 1985, and 1880 to 1985 in figures 13, 14, and 15, respectively. Ebbflow changes are shown in figures 16, 17, and 18. Details of the vector computation have been given by Goodwin (1987, p. 35).

Computed floodflow and ebbflow differences between the same levels of development show similar areal distribution patterns. Compare, for instance, figures 13 and 16, which show the areas of transport differences from 1880 to 1972 for floodflow and ebbflow, respectively. As deduced in the previous section, places of largest change include sites at and near filled areas, along and near ship channels, and near power-generating stations. Figures 15 and 18 are included to show the computed, overall, cumulative effects that manmade physical changes have had on tidal water transport in the bay between 1880 and 1985.

The number of square miles of modeled surface area that are contained within each percentage grouping of water-transport change and between each level of development for floodflow and ebbflow are shown in tables 5 and 6, respectively. The values confirm that more of Hillsborough Bay sustained greater areas of large transport

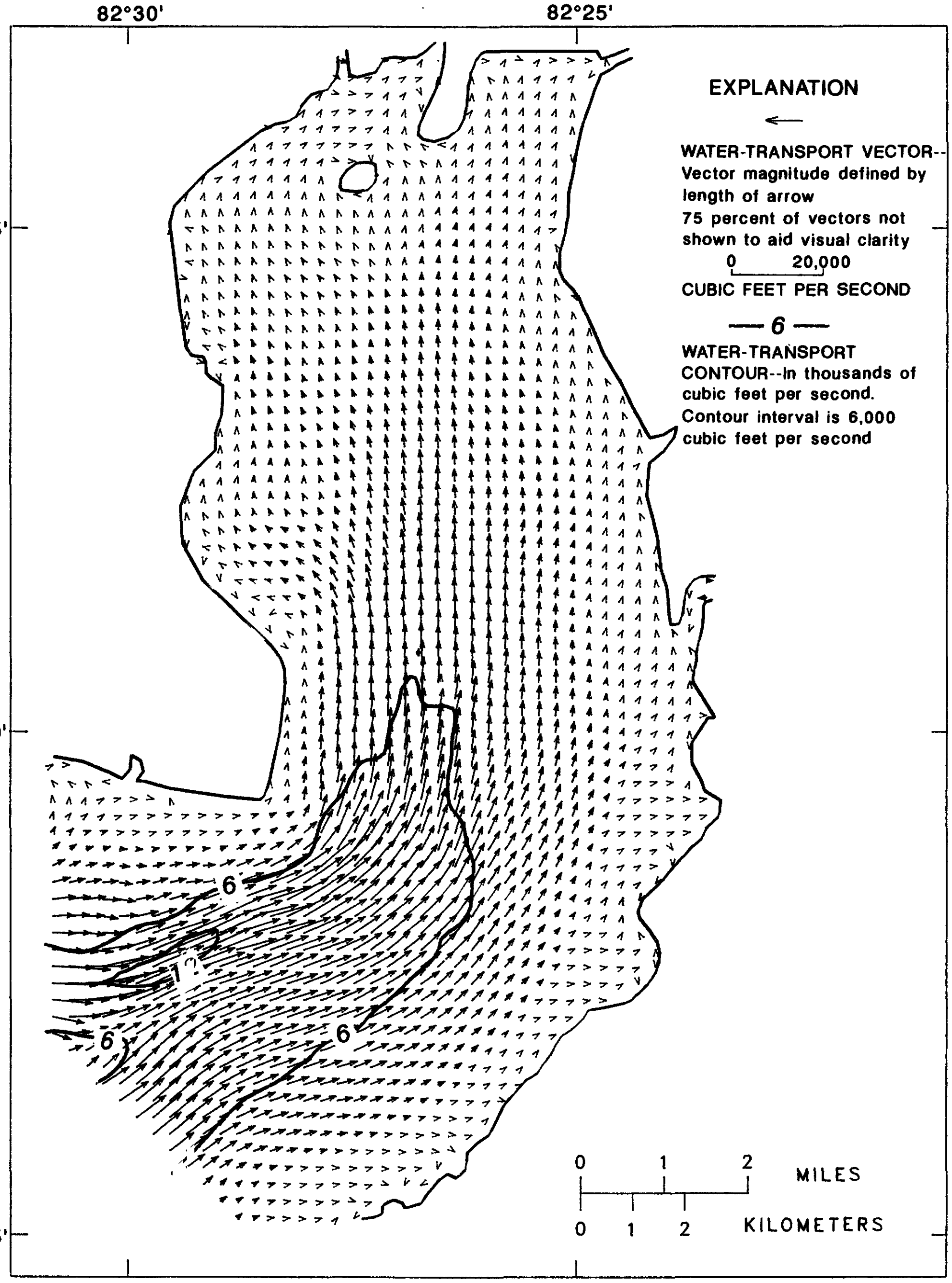

Figure 7. Water-transport pattern during typical floodtide for 1880 level of development.

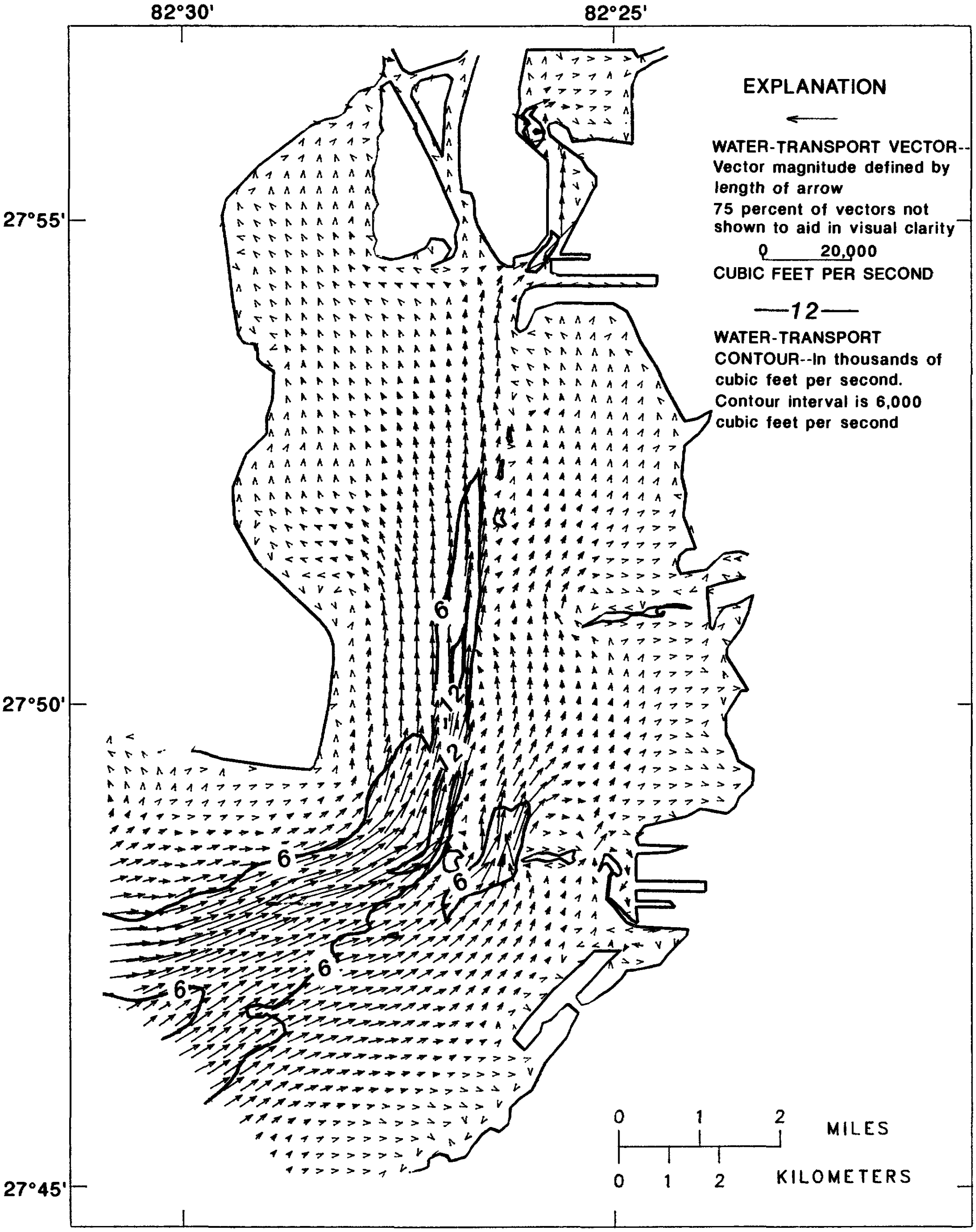

Figure 8. Water-transport pattern during typical floodtide for 1972 level of development.

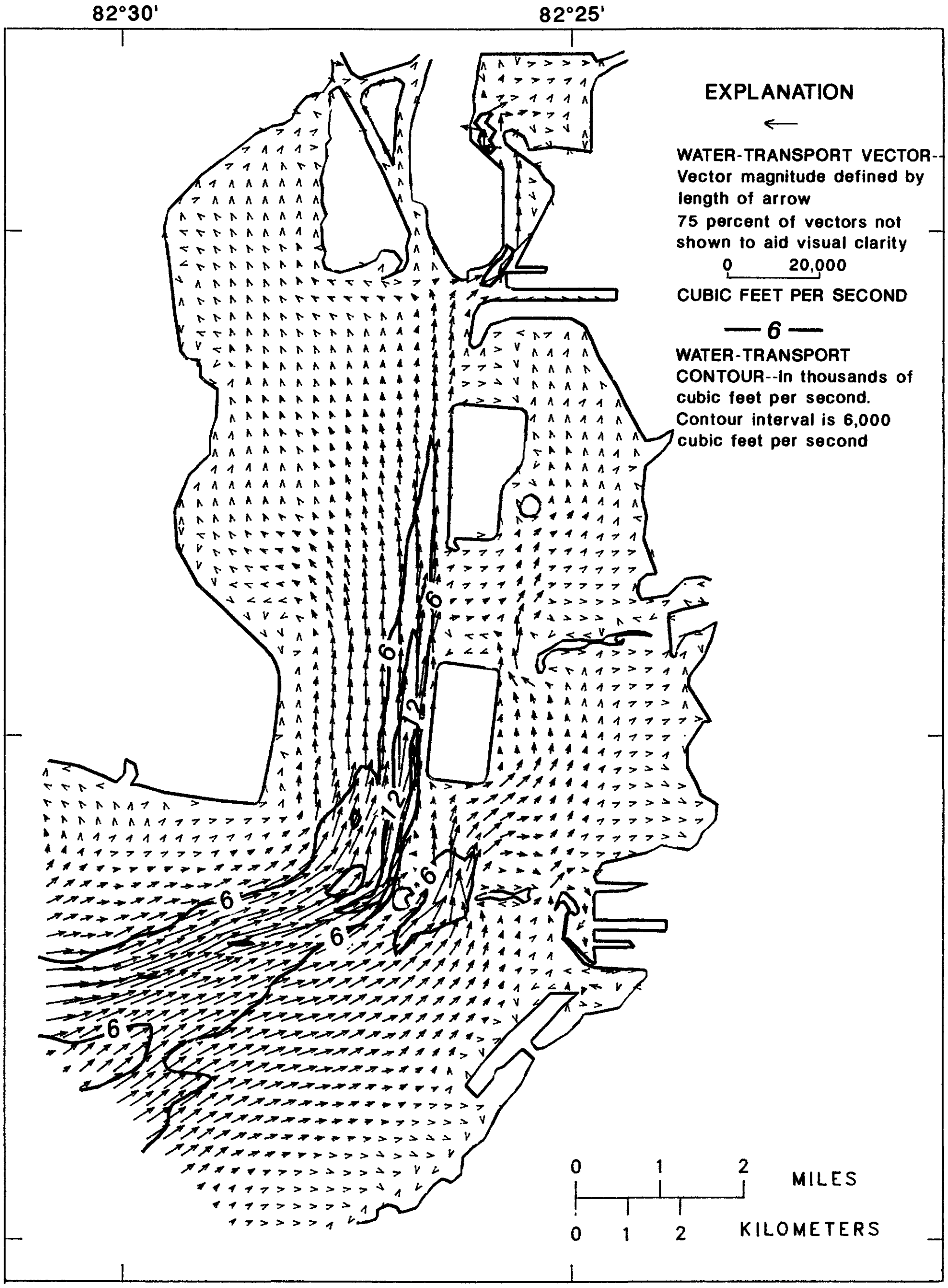

Figure 9. Water-transport pattern during typical floodtide for 1985 level of development.

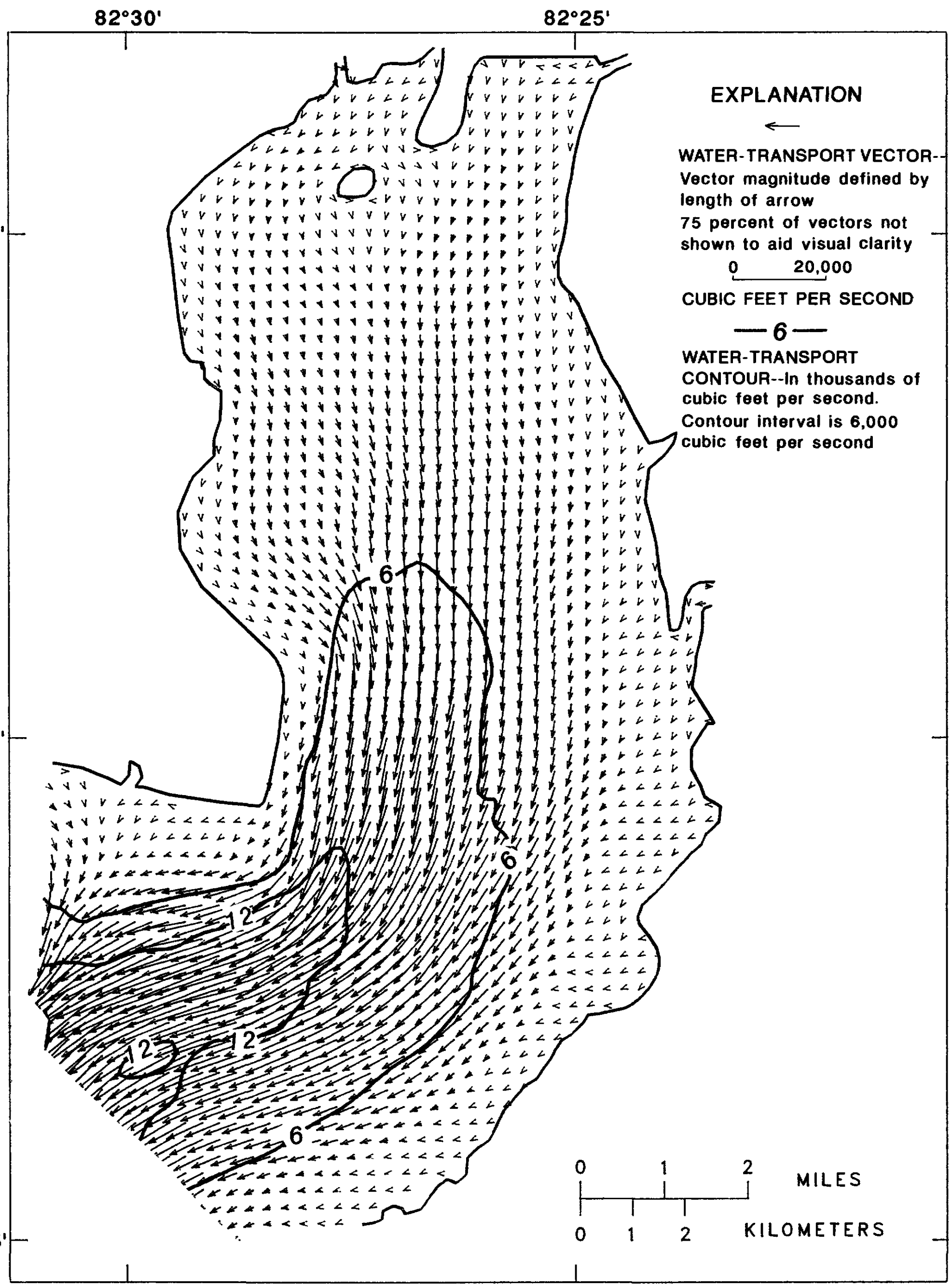

Figure 10. Water-transport pattern during typical ebbtide for 1880 level of development.

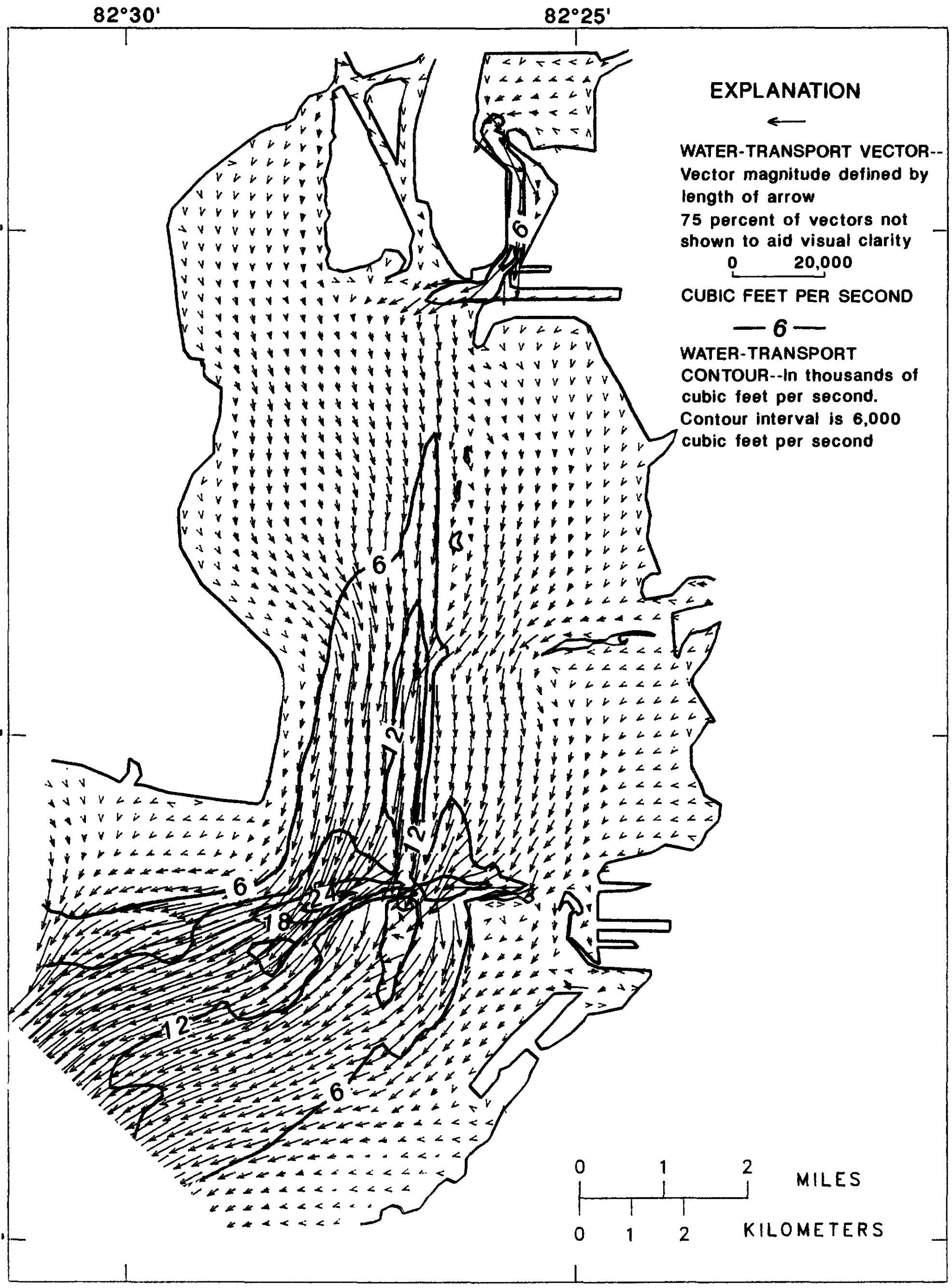

Figure 11. Water-transport pattern during typical ebbtide for 1972 level of development.

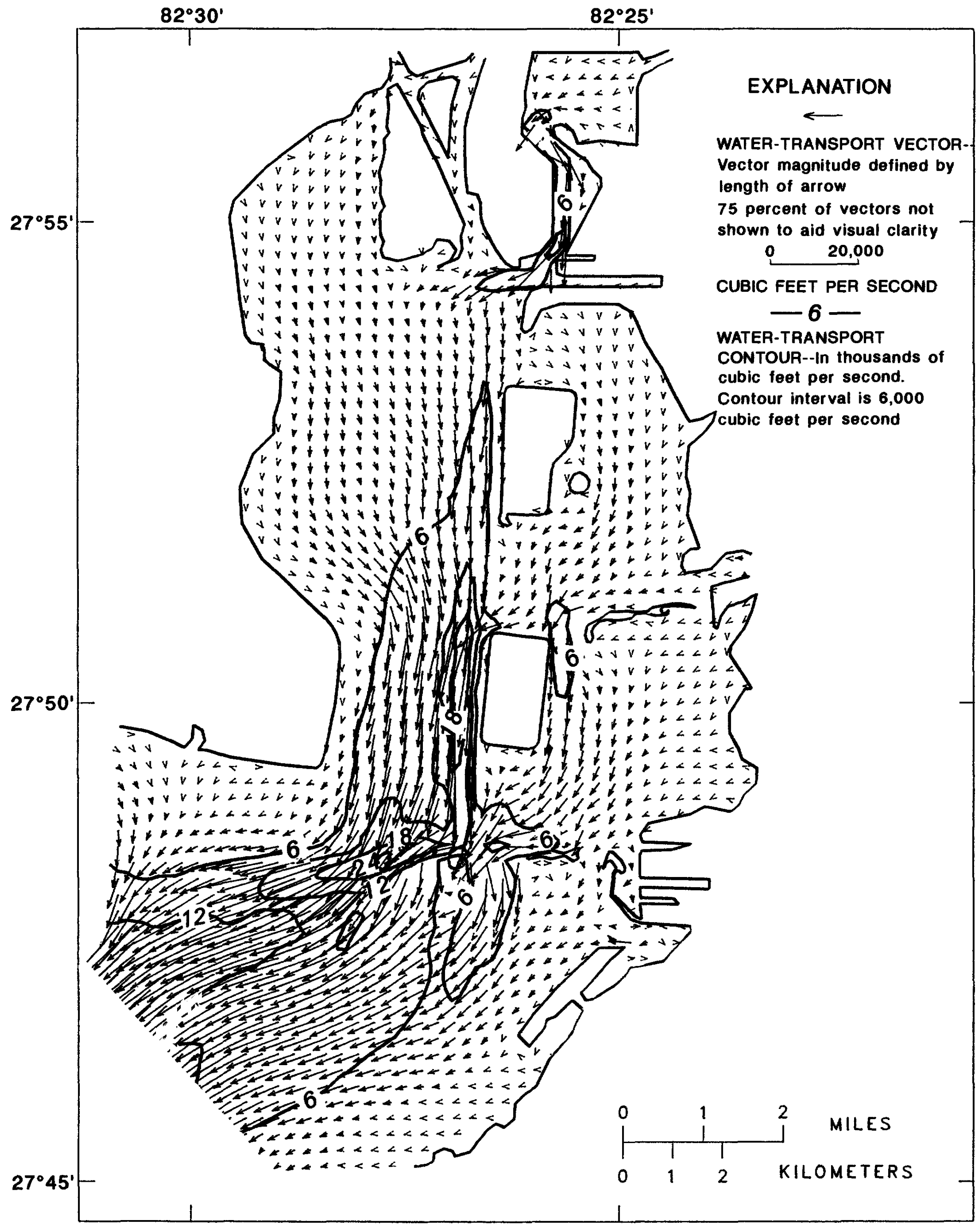

Figure 12. Water-transport pattern during typical ebbtide for 1985 level of development.

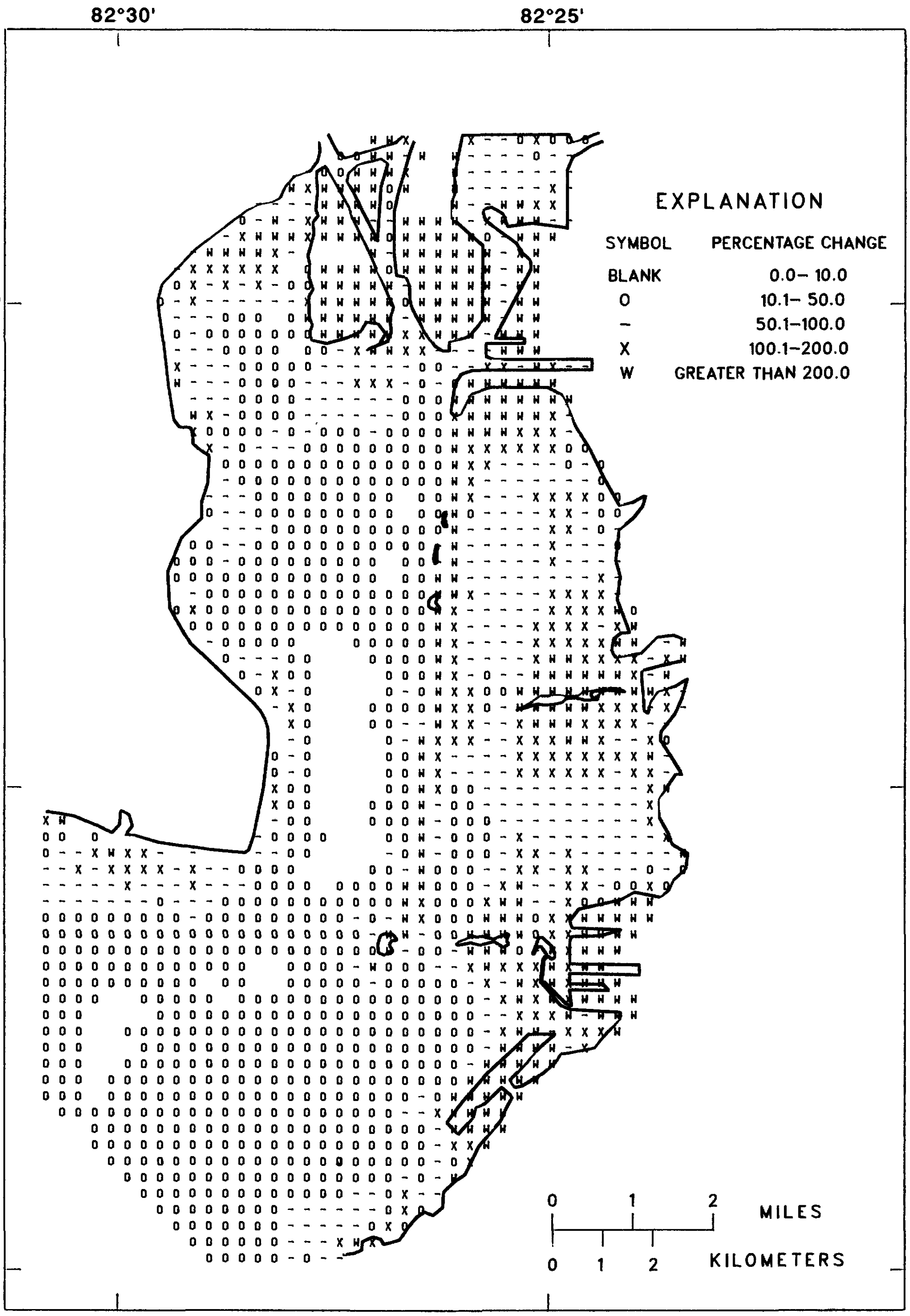

Figure 13. Change in water transport for typical floodtide between 1880 and 1972 levels of development.

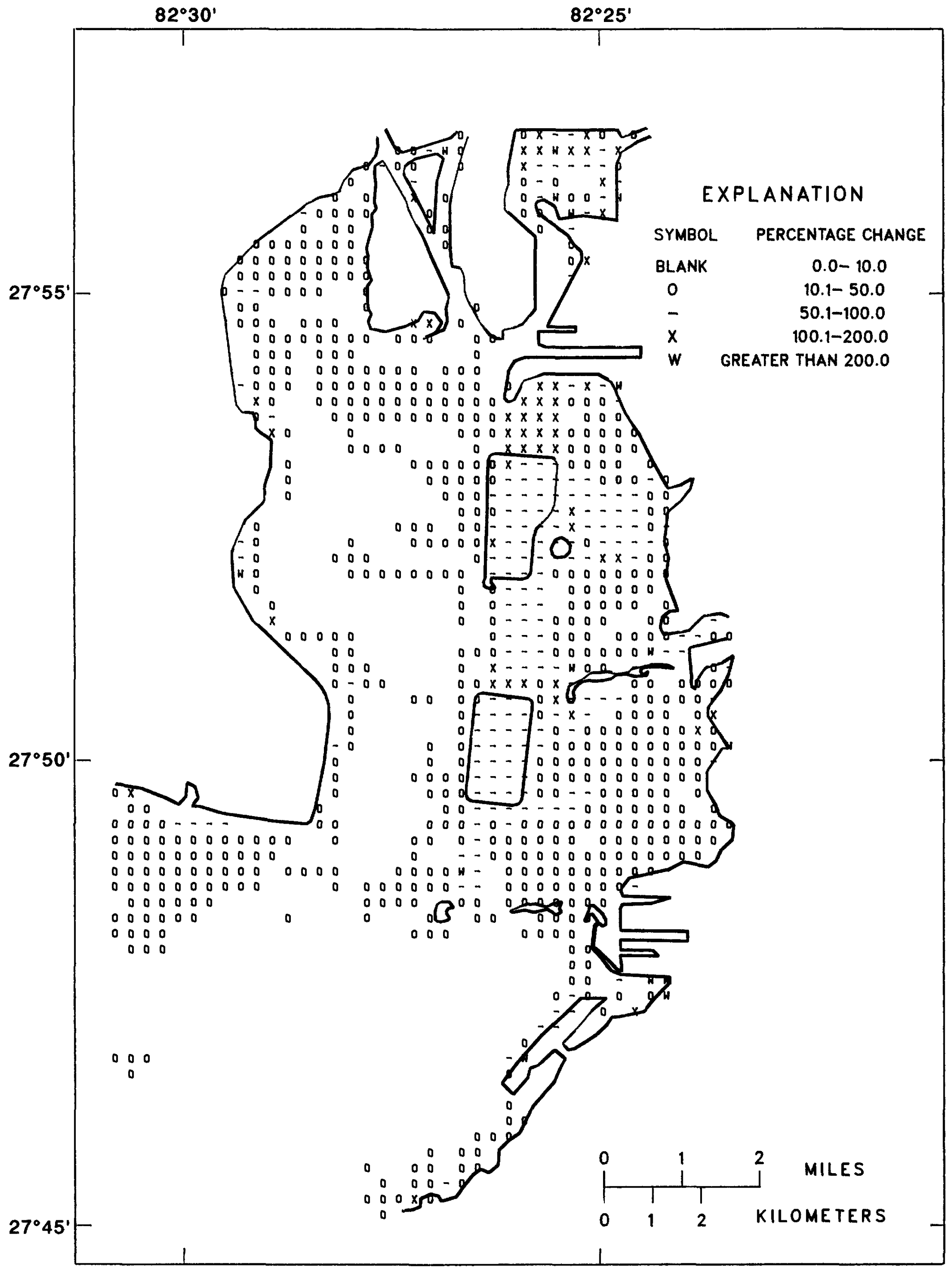

Figure 14. Change in water transport for typical floodtide between 1972 and 1985 levels of development.

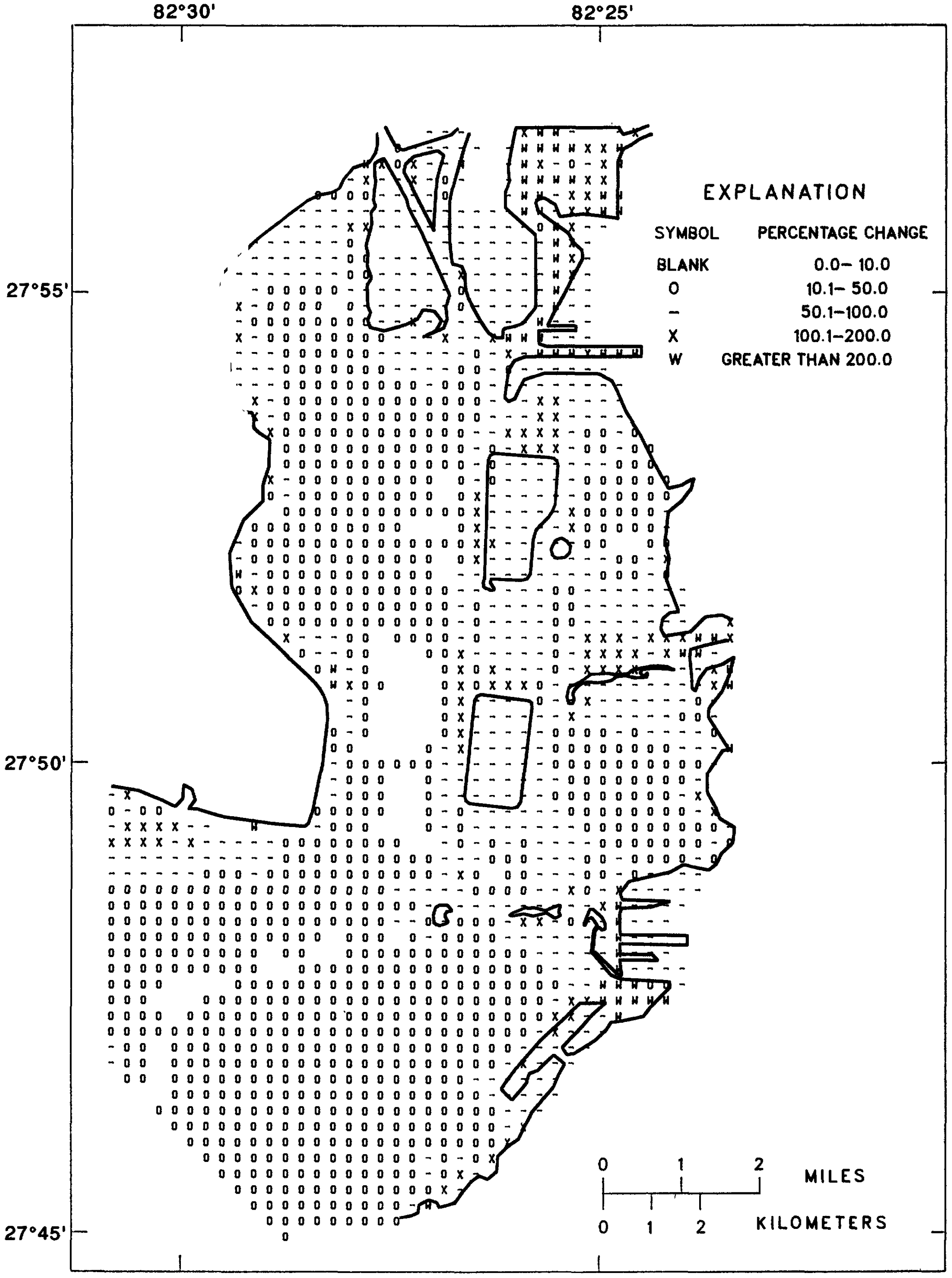

Figure 15. Change in water transport for typical floodtide between 1880 and 1985 levels of development.

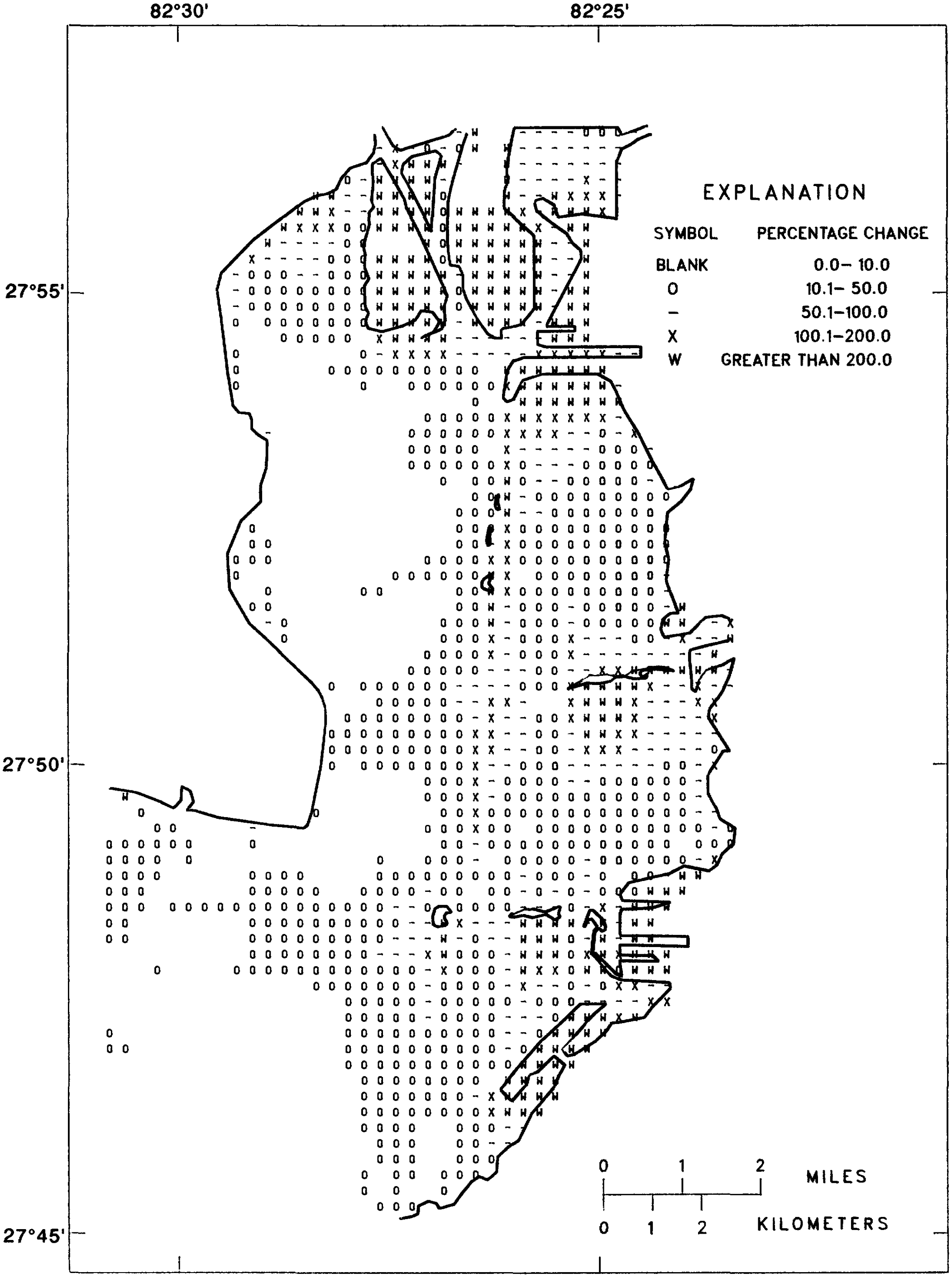

Figure 16. Change in water transport for typical ebbtide between 1880 and 1972 levels of development.

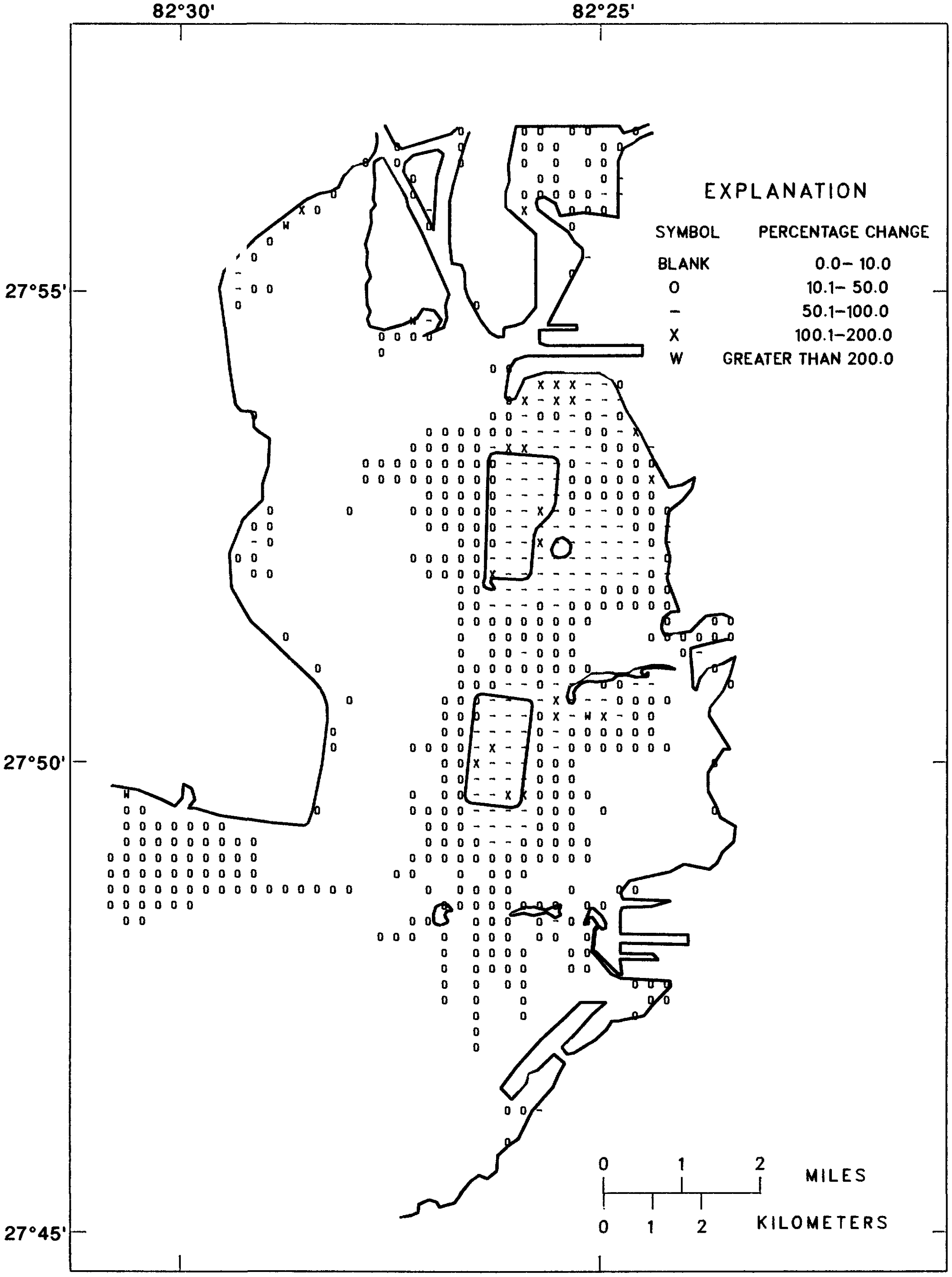

Figure 17. Change in water transport for typical ebbtide between 1972 and 1985 levels of development.

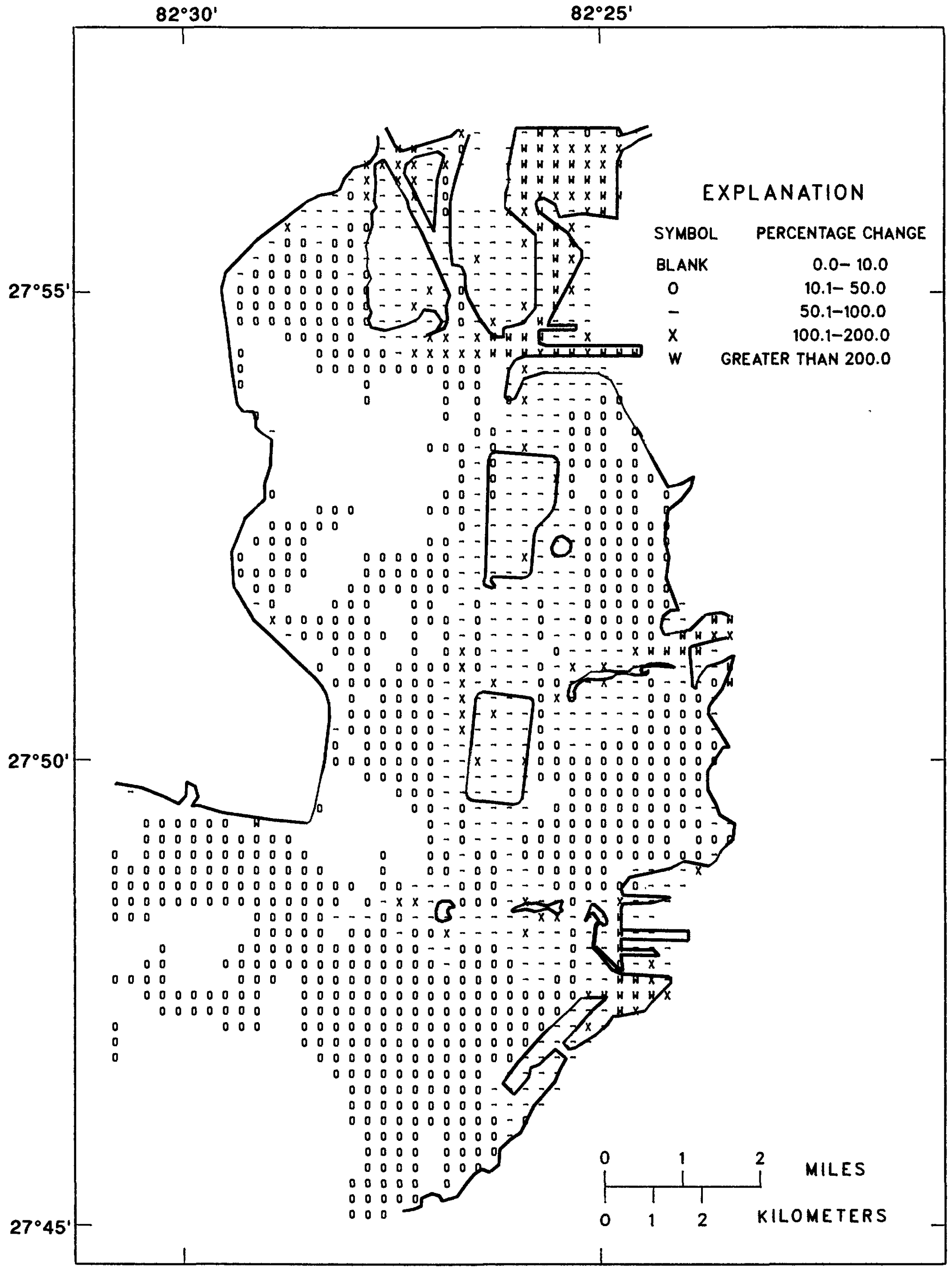

Figure 18. Change in water transport for typical ebbtide between 1880 and 1985 levels of development.

Table 5. Summary of flood water-transport changes affecting Hillsborough Bay between 1880, 1972, and 1985 levels of development

Percentage change in transport	Affected surface area (square miles)		
	1880 to 1972	1972 to 1985	1880 to 1985
0.0–10.0	3.6	27.3	2.8
10.1–50.0	35.1	23.3	33.8
50.1–100.0	21.0	6.5	21.9
100.1–200.0	3.4	1.8	4.4
>200.0	2.0	.7	2.2

Table 6. Summary of ebb water-transport changes affecting Hillsborough Bay between 1880, 1972, and 1985 levels of development

Percentage change in transport	Affected surface area (square miles)		
	1880 to 1972	1972 to 1985	1880 to 1985
0.0–10.0	13.6	37.2	13.9
10.0–50.0	29.7	16.1	28.9
50.1–100.0	16.6	5.4	16.7
100.1–200.0	2.8	.7	3.2
>200.0	2.4	.2	2.4

changes and lesser areas of small transport changes between 1880 and 1972 than between 1972 and 1985. The cumulative transport changes from 1880 to 1985 reflect the dominance of the changes that occurred between 1880 and 1972. Between 1880 and 1985, an average of 25 mi^2 of the modeled area sustained at least a 50-percent change in flood and ebb water transport.

Typical floodflows and ebbflows (see figs. 7 through 12), determined for each cross section along the longitudinal summary line (see fig. 6) for 1880, 1972, and 1985 levels of development, are shown in figure 19. Progressive flow reduction throughout the bay over time is a reflection of reduced bay surface area and tidal prism caused by dredge construction (see table 1). Typical flood and ebb

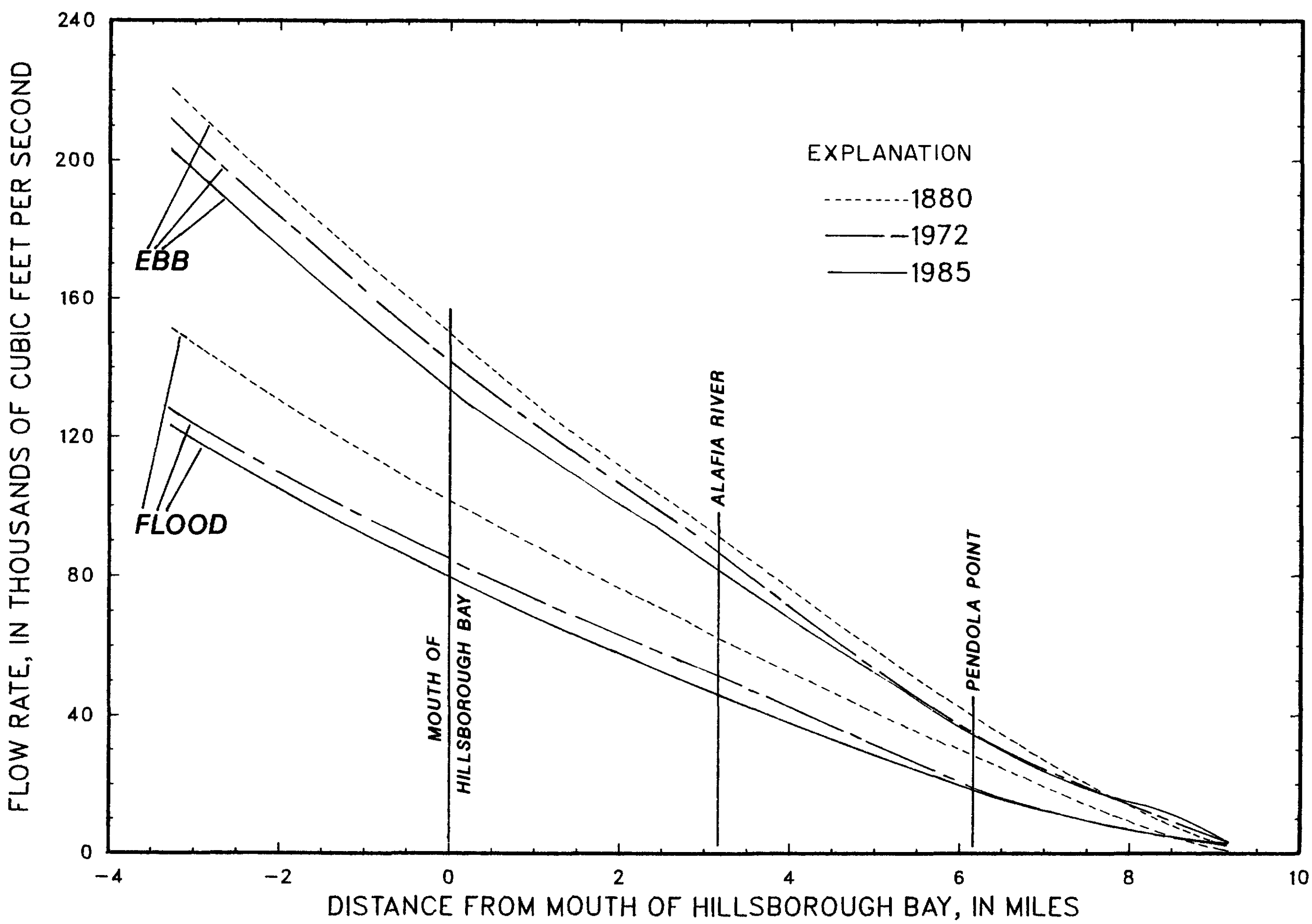

Figure 19. Water transport in Hillsborough Bay proper during typical floodtides and ebbtides for 1880, 1972, and 1985 levels of development.

water transport at the mouth of Hillsborough Bay proper (see fig. 1) decreased an average of 12 percent from 1880 to 1972 and 5 percent from 1972 to 1985. Flow reductions to that part of the bay north of the Alafia River (see fig. 1) averaged 14 percent from 1880 to 1972 and 7 percent from 1972 to 1985. North of Pendola Point, average flow reductions were 28 percent from 1880 to 1972; no appreciable change occurred from 1972 to 1985.

It is apparent that physical changes to Hillsborough Bay have lessened the overall volumetric movement of water throughout the bay. The largest percentage reductions occurred between 1880 and 1972 near the head of the bay. Without other influences, this reduced overall water movement suggests a reduced potential for tidal mixing and flushing caused by dredge and fill construction in Hillsborough Bay. Analysis of residual water transport in the following sections, however, indicates the opposite.

Circulation

Circulation patterns in the study area are revealed in a manner that is completely analogous to that used to reveal tidal flow patterns. The only difference is that tidal-flow (flood and ebb water-transport) determinations are based on computed water depth and velocity parameters averaged over selected half-hour periods, whereas circulation is based on the same parameters averaged over a repeating tidal cycle of 24 hours. Tidally averaged or residual water transport, in cubic feet per second, is computed and plotted for each model cell in the same manner as described in the section on "Tidal Flow." The quantity is also known as Eulerian residual water transport.

Residual Water Transport

Computed residual water-transport patterns (circulation patterns) for 1880, 1972, and 1985 levels of development are shown in figures 20, 21, and 22, respectively. Each vector map shows a series of circulatory features, or gyres, that range in diameter from about 0.5 to 2 mi. These features define tide-induced water-circulation patterns for a mixed tide and average freshwater inflow in the absence of water-density and wind effects.

Circulation patterns computed within about 2 mi of the open boundary of the model differ little in appearance between 1880, 1972, and 1985. The pattern in this region is similar to the results of Goodwin (1987, p. 54–56).

The circulation pattern computed for 1880 (fig. 20) is visually much different than for either the 1972 or 1985 levels of development (figs. 21 and 22, respectively). Annotations on each figure are meant to highlight the circulation features that can be identified using the residual-transport-vector method. For 1880, four primary gyres (circlelike features) are noted in figure 20 as *A*, *B*, *C*, and *D*. Non-gyre, but seemingly persistent, circulation-related features are indicated by flow paths labeled a, b_1, b_2, b_3, e, f_1, and f_2. The lowercase letters are indicators of non-gyre features as well as hypothesized associations with parent gyres (if any), which are labeled with corresponding uppercase letters. For example, small deviations from the indicated path for gyre *B* (fig. 20) could produce many different paths, such as those shown by b_1, b_2, and b_3. A similar argument can be made for path a from gyre *A*.

Unlabeled gyres and paths are indicated as dashed arrows to show circulation features of lower intensity than the labeled features. Paths e, f_1, and f_2 (fig. 20) are of low intensity but have characteristics different from those of other circulation features. All are more linear than circular, are continuous for long distances, and occur in depths of less than about 6 ft. Path e starts in the northwestern part of the bay and extends southward along the western shore until it merges with gyres *A* and *B* at the mouth of Hillsborough Bay proper. Water following path e probably is split in some proportion to follow paths similar to paths a, b_1, b_2, and b_3. Paths f_1 and f_2 could be parts of the same path, but strict adherence to vector direction indicates a separation in the vicinity of the mouth of the Alafia River. The net river flow seems to partly induce formation of path f_2. Adjacent to path e along the western side of the bay is a series of computed gyres, including *B*, *C*, and *D*, that all rotate counterclockwise. A corresponding series of less intense, clockwise-rotating gyres exists on the eastern side of the bay. The overall effect of these individual features is a circulation system that tends to slowly move water northward in the central part of the bay and southward along both margins of the bay. Complex gyre interaction causes considerable side-to-side motion and mixing superimposed on the overall system.

This description is undoubtedly a simplification of the circulation process that existed in 1880, because water-density and wind effects are not included in the analysis and because computed circulation patterns are based on an idealized, repeating tide and constant river inflow. These assumptions were made to make it possible to reveal general tendencies in Hillsborough Bay circulation that could serve as a basis for comparison with circulation patterns computed for later stages of development. Actual bay circulation may have been similar to the computed patterns if averaged over a sufficiently long time period, but considerable variation from the computed pattern probably occurred on a day-to-day basis.

The circulation pattern computed for 1972 (fig. 21) has several features similar to those computed for 1880 (fig. 20). These include gyres *A*, *B*, *C*, and *D* and paths a, e, and f_1. Path f_2 in figure 20 is, in figure 21, divided into two segments, f_2 and f_3, owing to the existence of a flowthrough, north-to-south, cooling-water pumping system for a power-generating station in the Big Bend area (see fig. 1). Other similarities can also be seen in some of the

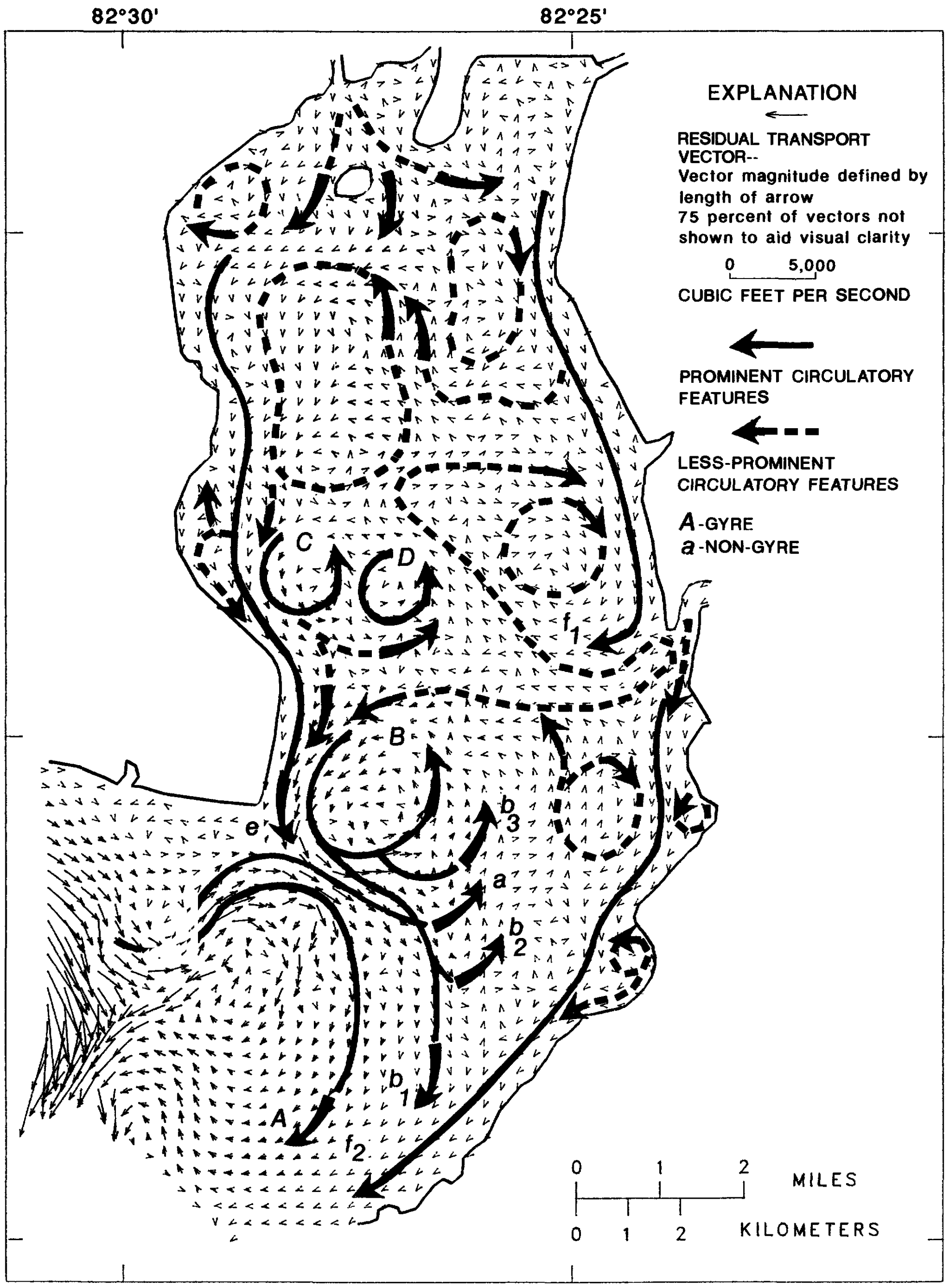

Figure 20. Residual water-transport pattern for 1880 level of development. Significance of letters and numbers explained in text.

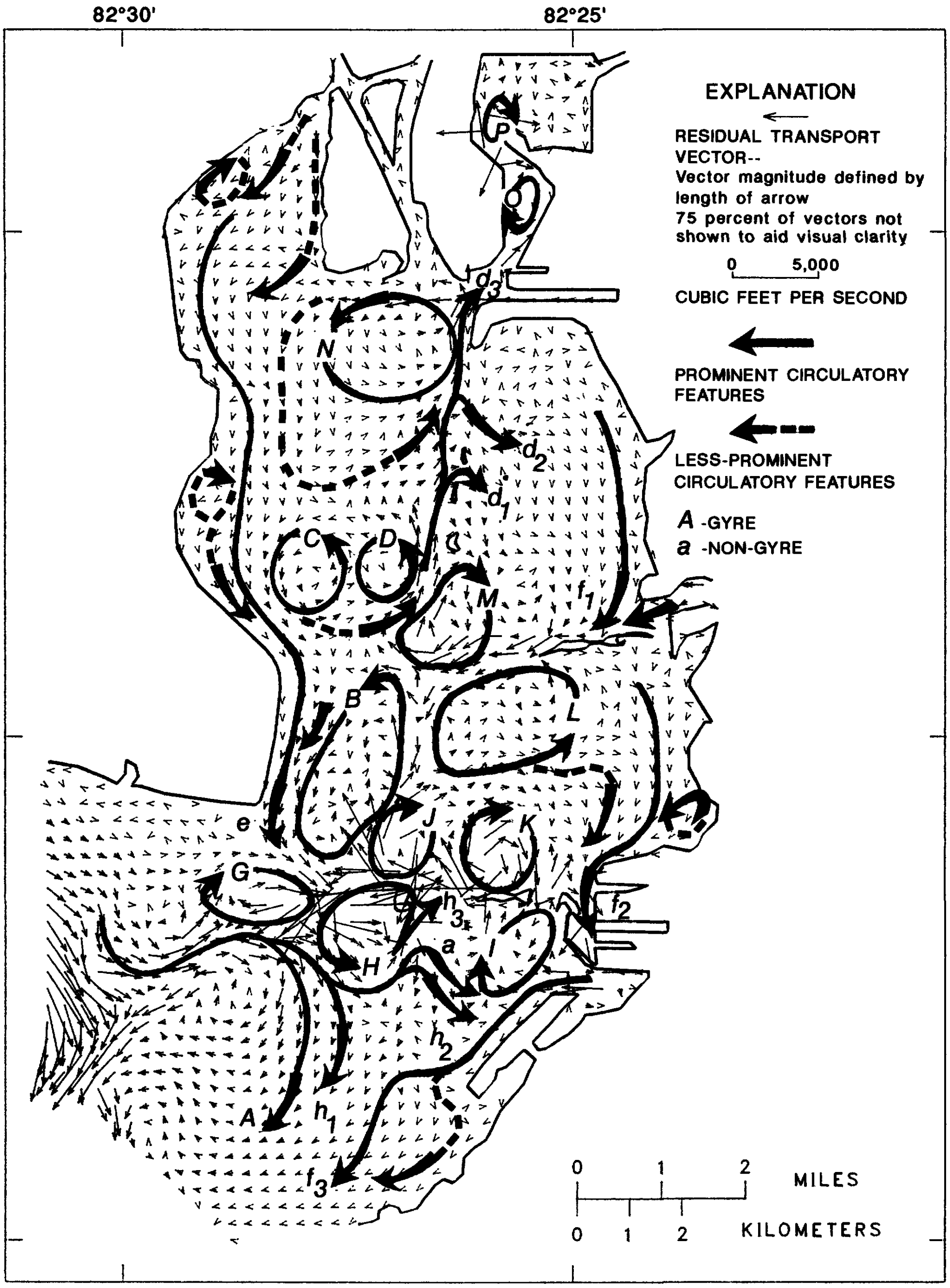

Figure 21. Residual water-transport pattern for 1972 level of development. Significance of letters and numbers explained in text.

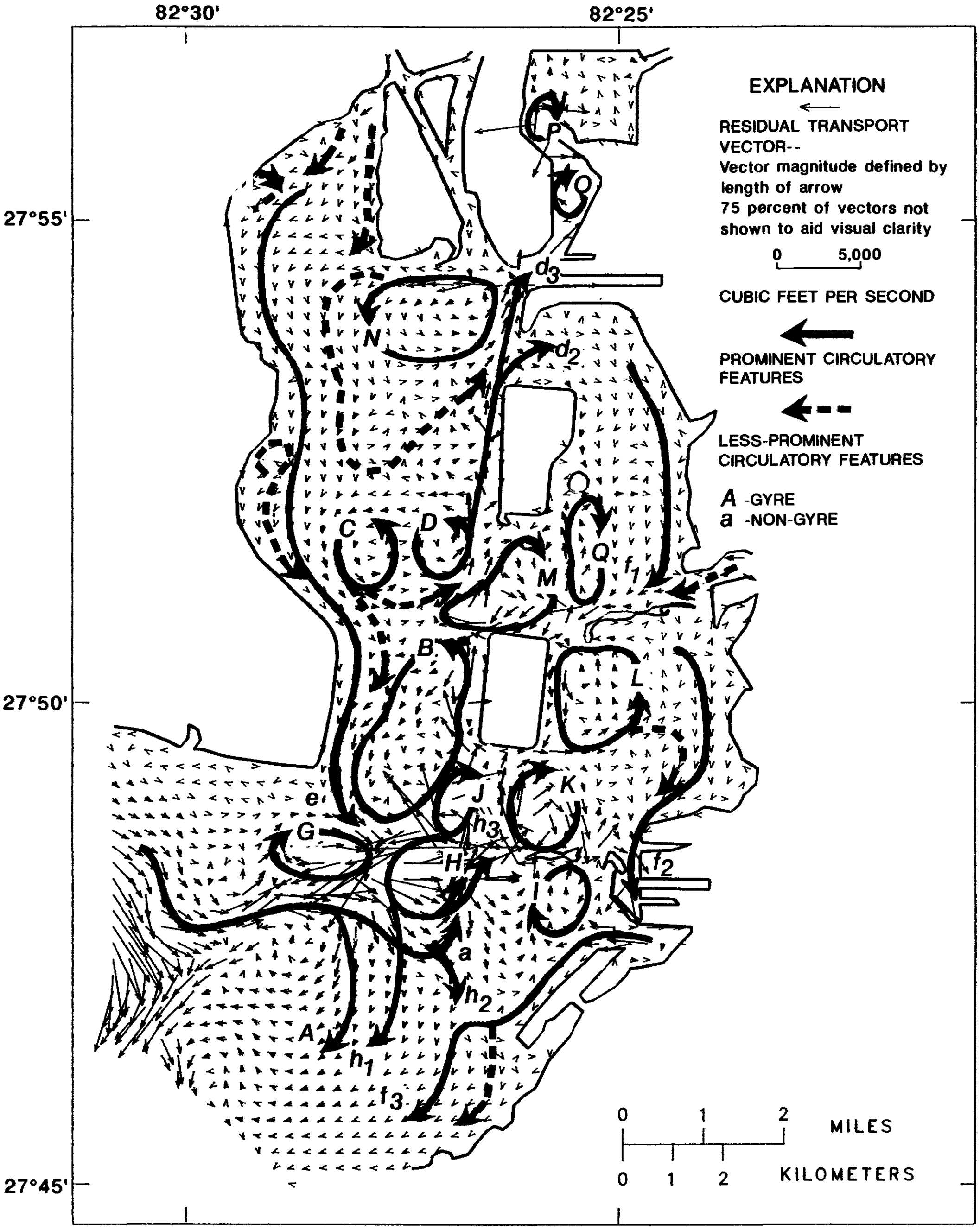

Figure 22. Residual water-transport pattern for 1985 level of development. Significance of letters and numbers explained in text.

unlabeled, less intense features, particularly along the bay margins.

Several major differences between 1880 and 1972 circulation patterns are apparent when figures 20 and 21, respectively, are compared. Gyre *A* does not extend as far northeastward in 1972 as it does in 1880 in order to accommodate gyres *G* and *H*, which are very intense features, as indicated by the length of the individual vectors that define the gyres. Gyre *H* seems to spawn paths h_1, h_2, and h_3 in a manner similar to that of gyre *B* in 1880. Gyres *I* through *O* in figure 21 represent additional strong, identifiable circulation features that have formed in response to physical changes in the bay between 1880 and 1972 (see figs. 6*A* and 6*B*, respectively, for bay bathymetry). Gyres *G, H, I, J*, and *K* (fig. 21) exist because of tidal-flow patterns near the mouth of the bay caused by dredged channels and by islands and submerged mounds created by dredged material. Gyres *L* and *M* are also associated with dredged channels near the middle of the bay. The main ship channel to the Port of Tampa, at the head of Hillsborough Bay, seems to induce much greater northward residual transport than occurred in 1880. This is particularly true in the upper part of the bay, as shown by paths d_1, d_2, and d_3. Gyre *N* seems to have formed in response to the east-to-west, jetlike discharge of power-generation cooling water. Gyres *O* and *P* (fig. 21) are within confined areas of the port; because of lack of adequate model resolution in those areas, these two gyres may be numerical artifacts rather than realistic patterns.

Another difference between computed 1880 and 1972 circulation patterns is the absence of some features in 1972 that existed in 1880. Most noticeable is the lack of three low-intensity, clockwise-rotating gyres in the eastern part of the bay.

The circulation pattern computed for 1985 (fig. 22) is very similar to the 1972 pattern in most respects. Construction of two large islands in the central part of the bay, deepening and widening of the main ship channel, and development of three circulation-inducing cuts (see fig. 6*C*) have, however, resulted in at least some localized circulation differences from 1972. For 1985, gyre *K* is visually more intense and gyre *L* is more compact than in 1972, owing to construction of the more southerly island and the most southerly circulation-inducing cut. Gyre *Q* is a new feature in 1985, a response to the circulation-inducing cut to the east of the southerly island. The path labeled d_1 in 1972 cannot exist in 1985 because of the northerly large island.

The computed circulation systems in Hillsborough Bay for 1972 and 1985 have enough features similar to the circulation system computed for 1880 that all can be considered to operate in the same general manner. Inward flow tends to occur in the central part of the bay, whereas outward flow occurs most frequently on the bay margins. The increased number and intensity of gyres in 1972 and 1985 and the disappearance of a series of gyres that existed in the eastern bay in 1880 indicate, however, that some major residual-transport changes have occurred since 1880.

Residual Water-Transport Differences Between 1880, 1972, and 1985

Areas of change in computed residual water transport between 1880, 1972, and 1985 levels of development can be shown in map form by computation of a difference vector for each cell, as previously done for figures 13 through 18. The distribution of residual water-transport changes is shown as four percentage groupings for 1880 to 1972, 1972 to 1985, and 1880 to 1985 in figures 23, 24, and 25, respectively. As with tidal water-transport differences (see figs. 13–18), the largest residual water-transport differences are associated with, and are in the vicinity of, dredged channels, dredged-material islands, shoreline residential and commercial fills, and power-generating stations. The number of square miles of bay surface area in each percentage grouping for each time period are given in table 7.

Results show that, of the total study area (65 mi^2), a large part (44.7 mi^2) sustained residual-transport changes of at least 50 percent between 1880 and 1972 (fig. 23, table 7). Much less of the bay (17.1 mi^2) sustained differences of 50 percent or more between 1972 and 1985 (fig. 24, table 7). Cumulatively, between 1880 and 1985, 45.1 mi^2 of Hillsborough Bay sustained at least a 50-percent change in residual water transport (fig. 25, table 7). This amounts to about 70 percent of the original area of the bay. The western shore sustained the least change of any part of the bay.

The areal extent of changes in residual water transport is one measure of the effects of physical change on water motion in a bay. Areal changes, however, do not provide information on how the dynamics of water motion are affected, particularly the dynamics of circulatory features such as those identified in figures 20, 21, and 22. The longitudinal summary technique described by Goodwin (1987, p. 35) is applied here as one quantitative measure of circulation dynamics at the 1880, 1972, and 1985 levels of development.

Circulation features are tide-induced residual-transport patterns that are caused by the interaction of tidal water motion and bay bottom configuration. Without the tide, there could be no incoming residual-transport vectors, all vectors would be outgoing, and the vector sum normal to each bay cross section would be equal to the total tributary inflow landward of the cross section. One feature of residual water transport is that many areas of the bay exhibit residual incoming flows. To satisfy continuity, these areas are balanced by outgoing flow in other areas. Both conceptually and by computation, the sum of all incoming and outgoing residual-flow vector components normal to a particular cross section also equals the total tributary inflow landward of the cross section.

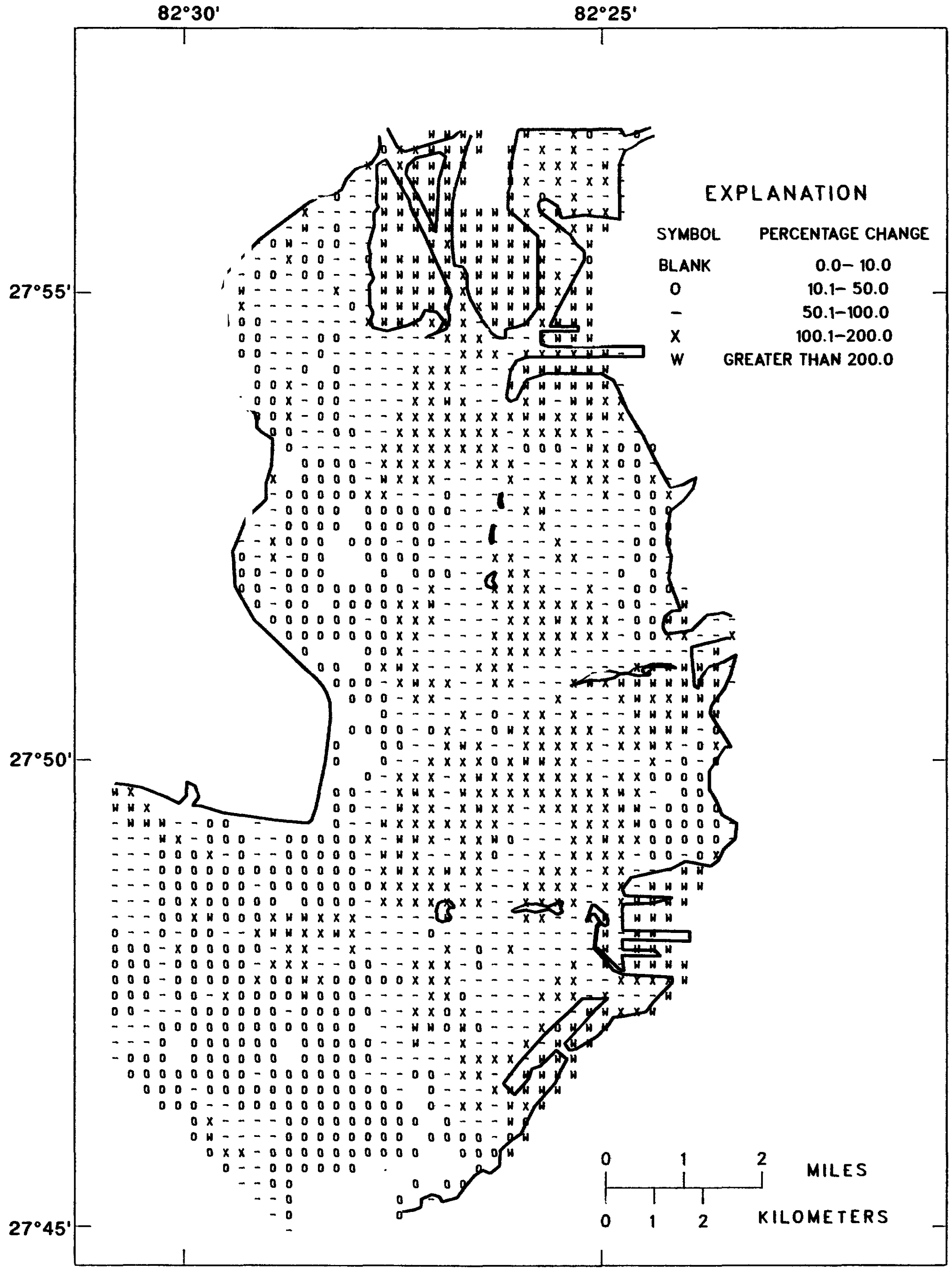

Figure 23. Change in residual water transport between 1880 and 1972 levels of development.

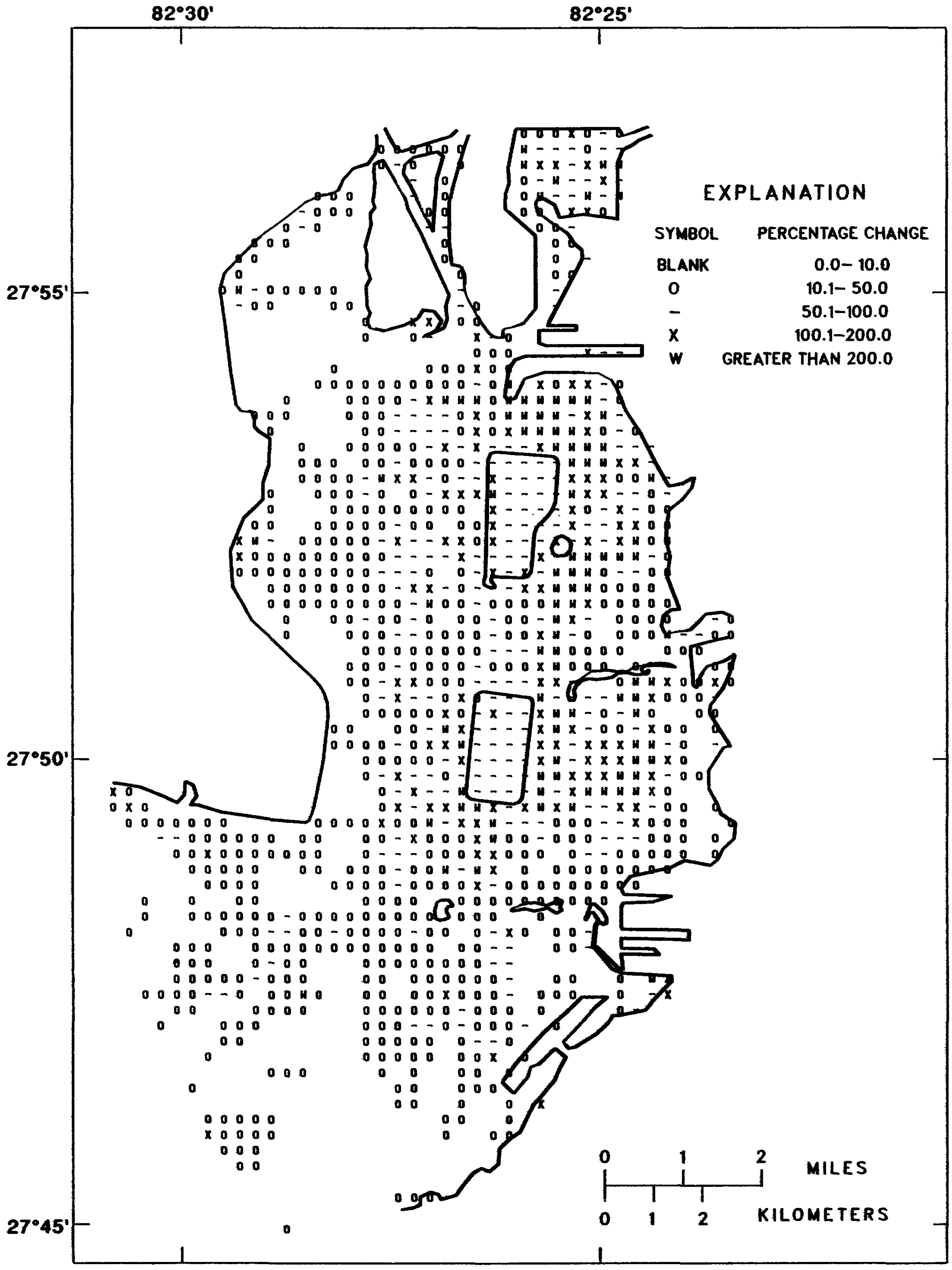

Figure 24. Change in residual water transport between 1972 and 1985 levels of development.

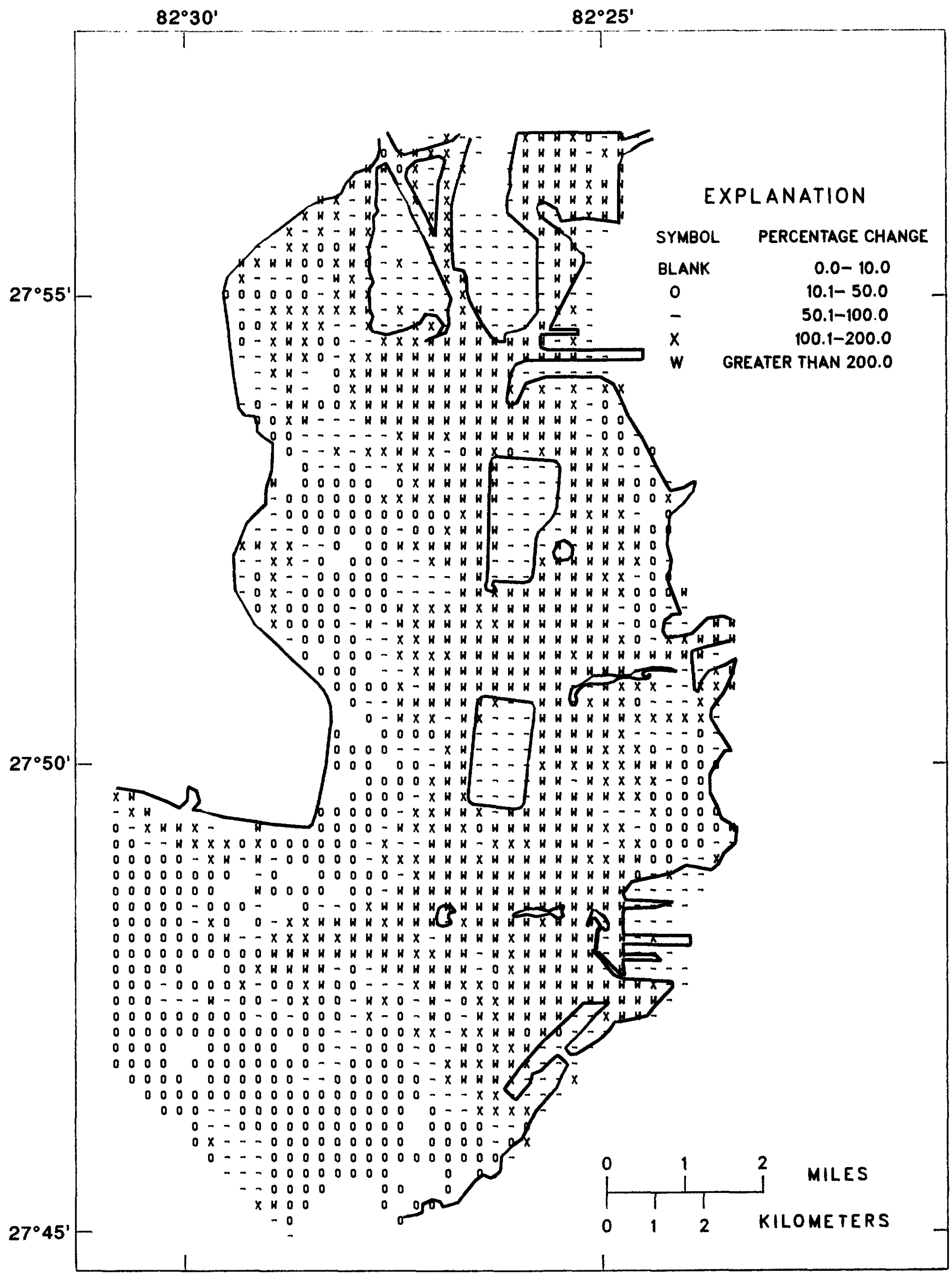

Figure 25. Change in residual water transport between 1880 and 1985 levels of development.

Table 7. Summary of residual water-transport changes affecting Hillsborough Bay between 1880, 1972, and 1985 levels of development

Percentage change in transport	Affected surface area (square miles)		
	1880 to 1972	1972 to 1985	1880 to 1985
0.0–10.0	2.8	18.5	2.3
10.1–50.0	17.6	24.0	17.7
50.1–100.0	14.2	9.1	16.2
100.1–200.0	10.6	4.6	9.4
>200.0	19.9	3.4	19.5

Because landward-flowing residual water-transport vectors are completely tide induced and because these same vectors represent the incoming part of all circulatory features (see figs. 20–22), some additional quantification of this phenomenon is warranted to aid further investigation of circulation in Hillsborough Bay. Following the analysis of Goodwin (1987, p. 62), the quantity "tide-induced circulation" is defined as a function of distance along the longitudinal summary line (see fig. 6) and represents one simple measure of the variability of circulatory intensity within the bay. This quantity is computed as the summation of all incoming residual-transport-vector components normal to a bay cross section and has units of cubic feet per second.

Tide-induced circulation plotted against distance along the longitudinal summary line for each level of development is shown in figure 26. Average annual tributary streamflow also is shown. For 1880, a circulation maximum of about 5,200 ft^3/s was computed to occur about 2.2 mi seaward of the mouth of Hillsborough Bay proper as a result of gyre *A* shown in figure 20. Circulation progressively decreased in a landward direction to a low of about 1,100 ft^3/s at about 0.6 mi seaward of the mouth before rising to a second circulation high of about 2,900 ft^3/s due to gyre *B* (see fig. 20) about 0.6 mi into the bay. A low of about 500 ft^3/s was computed prior to a third high of about 1,900 ft^3/s at mile 3.2 due to gyres *C* and *D* (fig. 20). Farther toward the head of the bay, circulation gradually decreased to nearly zero.

The longitudinal circulation summary computed for 1972 and 1985 levels of development (fig. 26) are very similar, and both show many features that were not present in 1880. The overall circulation increase throughout Hillsborough Bay confirms the conclusions reached by comparing both figures 20, 21, and 22 and the difference maps (figs. 23–25). For 1972 and 1985, computed circulation remains at approximately 5,000 ft^3/s from the model boundary to a point about 1.2 mi seaward of the mouth of the bay, where abrupt circulation increases to peak values of about 12,000 ft^3/s occur as a result of gyres *G* and *H*, as shown in figures 21 and 22. This zone of intense circulation extends for more than 0.5 mi inside the mouth of the bay as a result of gyres *B*, *I*, *J*, and *K* and is the most pronounced difference from computed circulation in 1880.

The presence of gyre *L* and enlongated gyre *B* (compare figs. 21 and 22 with fig. 20) in 1972 and 1985 causes circulation to be higher from 0.6 to 2.4 mi inside the bay mouth than in 1880. From 2.4 to 4.0 mi, the circulation high (about 1,900 ft^3/s) caused by gyres *C* and *D* in 1880 (fig. 20) is broader and more intense (about 4,400 ft^3/s) in 1972 owing to the addition of gyre *M* (fig. 21), and is even more intense (about 5,100 ft^3/s) in 1985 owing to the addition of gyre *Q* (fig. 22).

Circulation in the upper part of Hillsborough Bay between 4.0 and 6.4 mi from the mouth was significantly greater in 1972 and 1985 (about 1,600 ft^3/s) than in 1880 (about 500 ft^3/s), owing to flow paths d_1, d_2, and d_3 (see figs. 21, 22). The impacts of gyres *N*, *O*, and *P* (see figs. 21, 22) are shown as localized highs at mile 6.6, 7.7, and 8.4, respectively, in figure 26 for the 1972 and 1985 longitudinal summary curves. As mentioned previously, gyres *O* and *P* may be computational artifacts due to possible spatial-resolution difficulties of the model in these confined regions.

Throughout most of Hillsborough Bay proper in 1880, long-term average streamflow (fig. 26) was either greater than or equal to computed circulation. Exceptions were in the vicinity of gyres *B*, *C*, and *D* (see fig. 20). Seaward of the mouth, circulation intensity ranged from the same as to more than four times greater than average streamflow. Throughout most of the modeled area in 1972 and 1985, however, circulation was computed to range from about 2 to 10 times the average streamflow.

In 1880, residual water motion in the upper part of Hillsborough Bay was apparently dominated by nontidal streamflow effects. In the lower part of the bay, the magnitudes of both tidal and streamflow effects were about equal. In 1972 and 1985, however, tidal effects dominated Hillsborough Bay residual water motion, except in the upper reaches more than 7 mi from the mouth.

The study area of this investigation nearly coincides with the area covered by two circulation zones that were labeled zones 5 and 6 by Goodwin (1987, p. 39) using a model of larger grid size. Locations of these zones are indicated in figure 26. Table 8 gives (for both studies) a comparison of computed average circulation for each zone at each level of development. The average circulation computed using a cell size of 500 ft on a side is substantially greater for both zones for each level of development than the average circulation computed using a cell size of 1,500 ft on a side. The difference ranges from 4 to 35 percent and averages 26 percent. This indicates that fine spatial resolution, with attendant improved bathymetric and topographic definition, is an important criterion for numerically determining circulation characteristics. The finer the resolution,

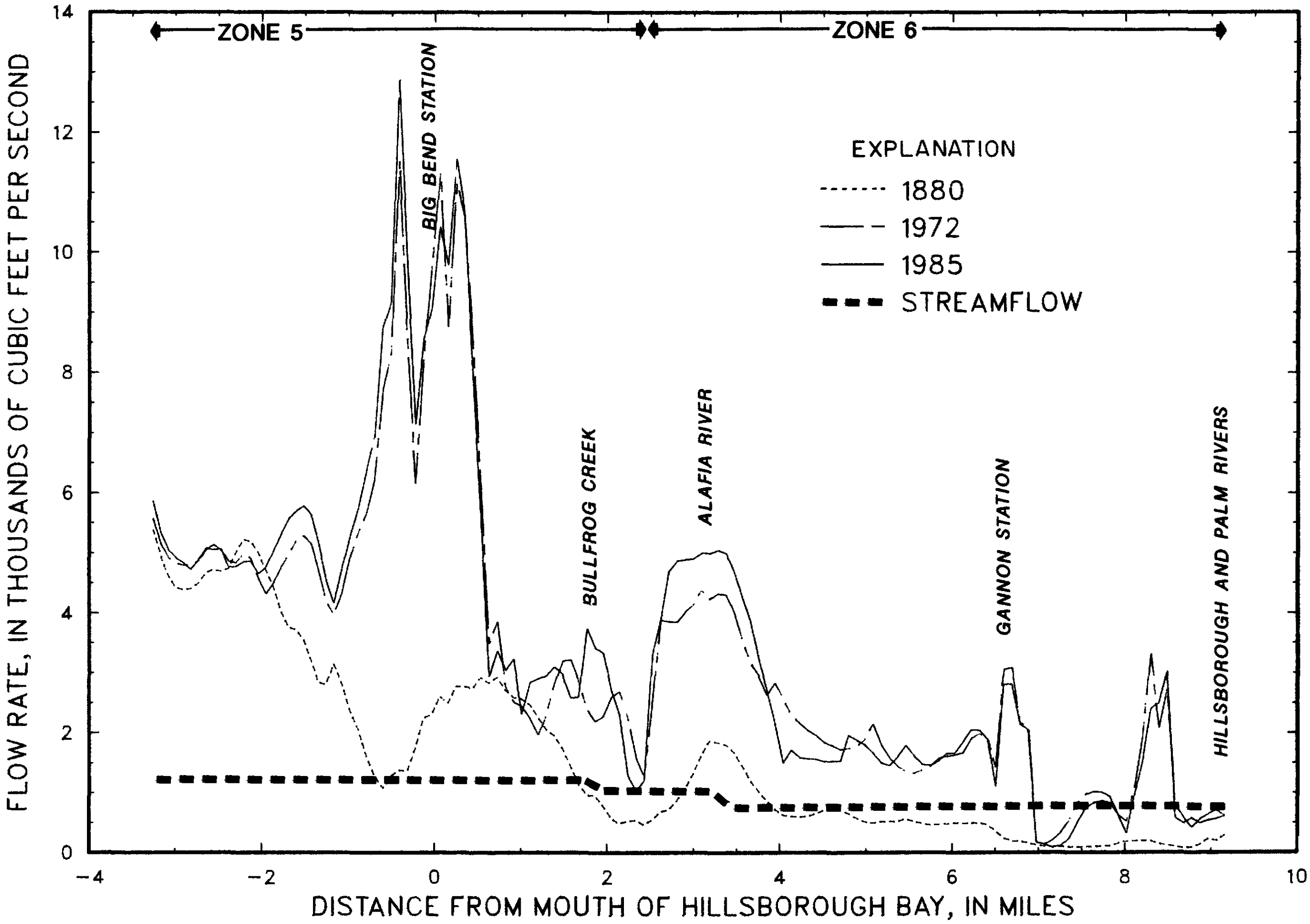

Figure 26. Tide-induced circulation for 1880, 1972, and 1985 levels of development and average tributary streamflow in Hillsborough Bay.

the more complex can be the computed residual-transport features that determine the magnitude of tide-induced circulation.

Circulation in zone 5 increased 79 percent from 1880 to 1972 and 6 percent from 1972 to 1985, for a cumulative increase of 89 percent, as derived from circulation values based on the 500-ft cell width. In zone 6, the percentage circulation increase is even greater from 1880 to 1972 (233 percent). With no significant increase from 1972 to 1985, the cumulative increase from 1880 to 1985 is also 233 percent.

Knowing how tidal flow and circulation have changed in Hillsborough Bay over the years and what parts of the bay have been most affected is important in its own right for providing a means of evaluating some of the primary effects of individual dredge and fill projects as well as the cumulative impact of many such projects. It is apparent that changes in tidal flow and circulation caused by

Table 8. Comparison of circulation in two parts of Hillsborough Bay computed by two models of different grid size

Circulation zone (fig. 26)	Distance along longitudinal summary line (miles) (fig. 26)	Average circulation (cubic feet per second)					
		1,500-foot grid[1]			500-foot grid		
		1880	1972	1985	1880	1972	1985
5	−3.2 to 2.4	2,700	3,600	3,700	2,800	5,000	5,300
6	2.4 to 9.2	400	1,300	1,500	600	2,000	2,000

[1]From Goodwin (1987).

the most recent dredging of the ship channel to the Port of Tampa are not nearly as great as the cumulative changes caused by prior dredging projects. What is not so apparent is how these changes in tidal flow and tide-induced circulation may have changed the rate at which dissolved or suspended materials are transported through, or flushed from, the bay.

Flushing

The objective of this section is to use the computed circulation information to provide a realistic estimate of the average time it takes for dissolved or suspended material to transit from the head to the mouth of Hillsborough Bay and how that time has changed as a result of physical modification to the bay. Transit times can indicate the flushing ability of the bay at each level of development and can also serve as natural timeframes against which to evaluate chemical and biological processes. It needs to be reiterated that the analyses in this section are limited to the same typical tide used throughout this report. It is likely that other types of tides, with higher or lower tidal ranges, will produce different flushing characteristics. Similarly, the effect of wind on flushing is not addressed here.

Comparison of Eulerian and Lagrangian Residual Water Transport

The principal component used to estimate transit times is the result of circulation modeling presented in this report because, as recently stated by Feng and others (1986a, p. 1623), "what determines the * * * long-term transport of dissolved or suspended matter in estuaries, coastal embayments, and shallow seas is residual current * * *." Feng and others (1986a, p. 1623) go on to point out that a Lagrangian residual is most appropriate for this purpose, and that attention must be given to determine the adequacy of results based on Eulerian techniques, such as those used in this investigation.

To this end, a direct comparison was made between computed Eulerian circulation patterns, shown in figures 20 through 22, with results of numerical experiments designed to reveal the Lagrangian motion of a hypothetical dissolved constituent in Hillsborough Bay for 1880, 1972, and 1985 levels of development. Transport of the constituent was computed in two dimensions using a finite-difference approximation to the equation of conservation of solute mass as described by Leendertse and Gritton (1971, p. 4) and as applied to Tampa Bay by Goodwin (1987, p. 11). The dispersion coefficients used in this formulation have been given by Leendertse (1970, p. 14, 54) as

$$D_x = dHUg^{0.5}C^{-1} + D_w \qquad (1)$$

and

$$D_y = dHVg^{0.5}C^{-1} + D_w , \qquad (2)$$

where

D_x=dispersion coefficient, flow in x direction, in square feet per second;
D_y=dispersion coefficient, flow in y direction, in square feet per second;
d=empirical, dimensionless constant similar to that presented by Elder (1959);
H=water depth, in feet;
U, V=vertically averaged velocities of flow in x and y directions, respectively, in feet per second;
g=acceleration of gravity, in foot per second squared;
C=Chezy roughness coefficient, in foot$^{0.5}$ per second; and
D_w=diffusion coefficient representing wave, wind, and lateral mixing effects, in square feet per second.

For the following experiments, D_w was assigned a value of 10 ft^2/s, with d equal to 25.

At the low-slack start of a 48-hour simulation period composed of two identical, repeating 24-hour tidal cycles having a range of about 3.0 ft, the concentration field was initialized as shown in figure 27. The series of six plateau-like regions of constant concentration was chosen so that subsequent plotting of iso-concentration lines, at a 0.5-unit interval, would provide a means of visually tracking the location and dispersion of each interface over time. This technique was applied to each level of development, and the results are summarized in figures 28, 29, and 30.

Each figure shows (1) the initial location of each interface, (2) one series of shaded bands showing the location of each interface at the end of the first tidal cycle, and (3) another series of differently shaded bands showing interface locations at the end of the second tidal cycle. Each band represents a concentration range of 0.5 unit. Superimposed on this Lagrangian representation of residual constituent transport is the appropriate vector summary of computed Eulerian circulation patterns given in figures 20, 21, and 22. Visual comparison of vector directions with successive local displacements of each interfacial band for each level of development indicates strong agreement between Eulerian and Lagrangian residual transport in Hillsborough Bay. At this level of analysis, the first- and second-order terms relating Eulerian and Lagrangian transport (see Feng and others, 1986a, p. 1628) appear unimportant.

Convective and Dispersive Circulation

The Lagrangian analysis, based on the deformed shape of constituent interfacial bands (figs. 28–30), agrees with the analysis given earlier in this report that residual landward transport predominates in the deep, central part of the bay, with residual seaward transport occurring primarily

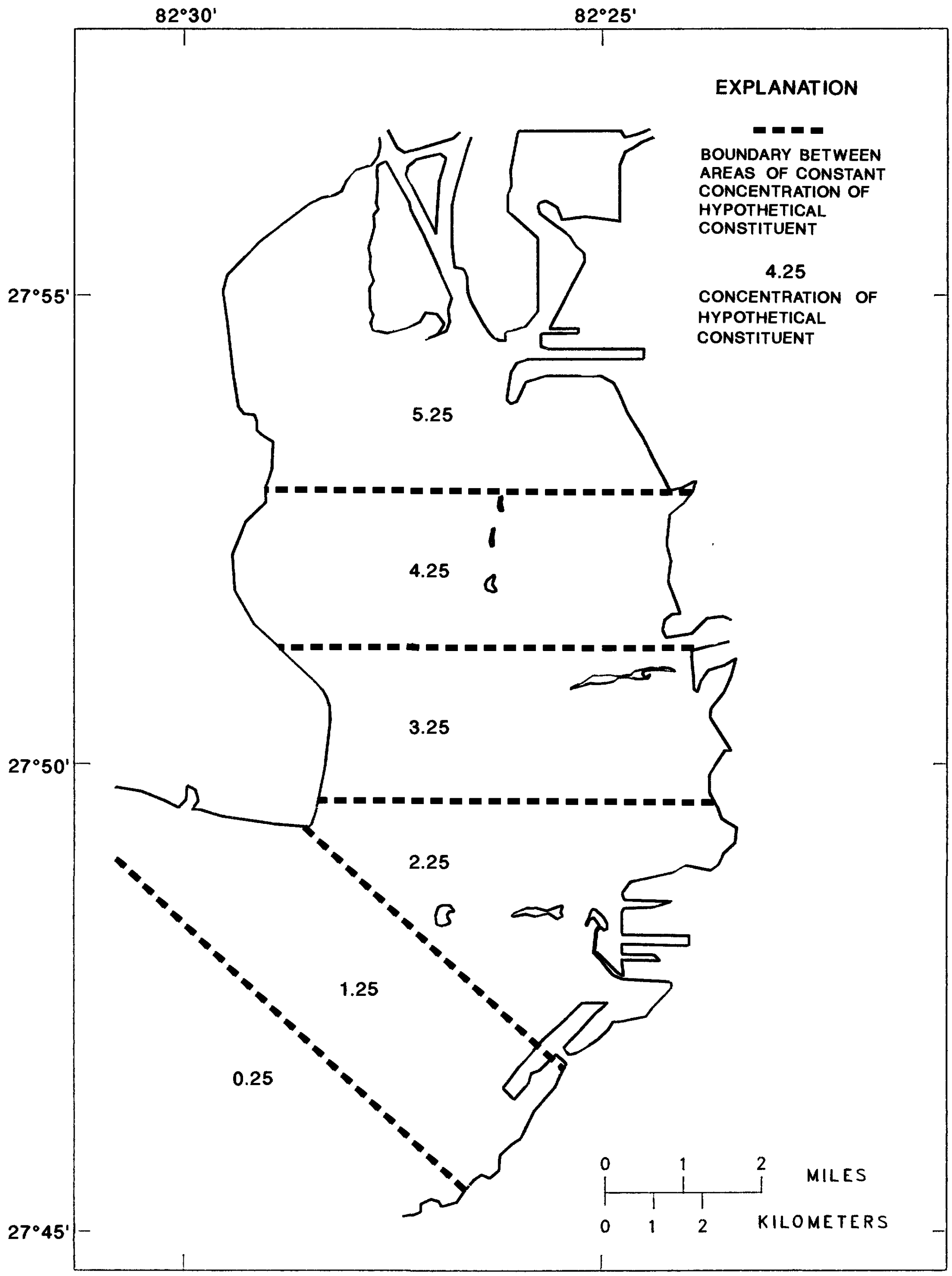

Figure 27. Initial distribution of hypothetical conservative constituent.

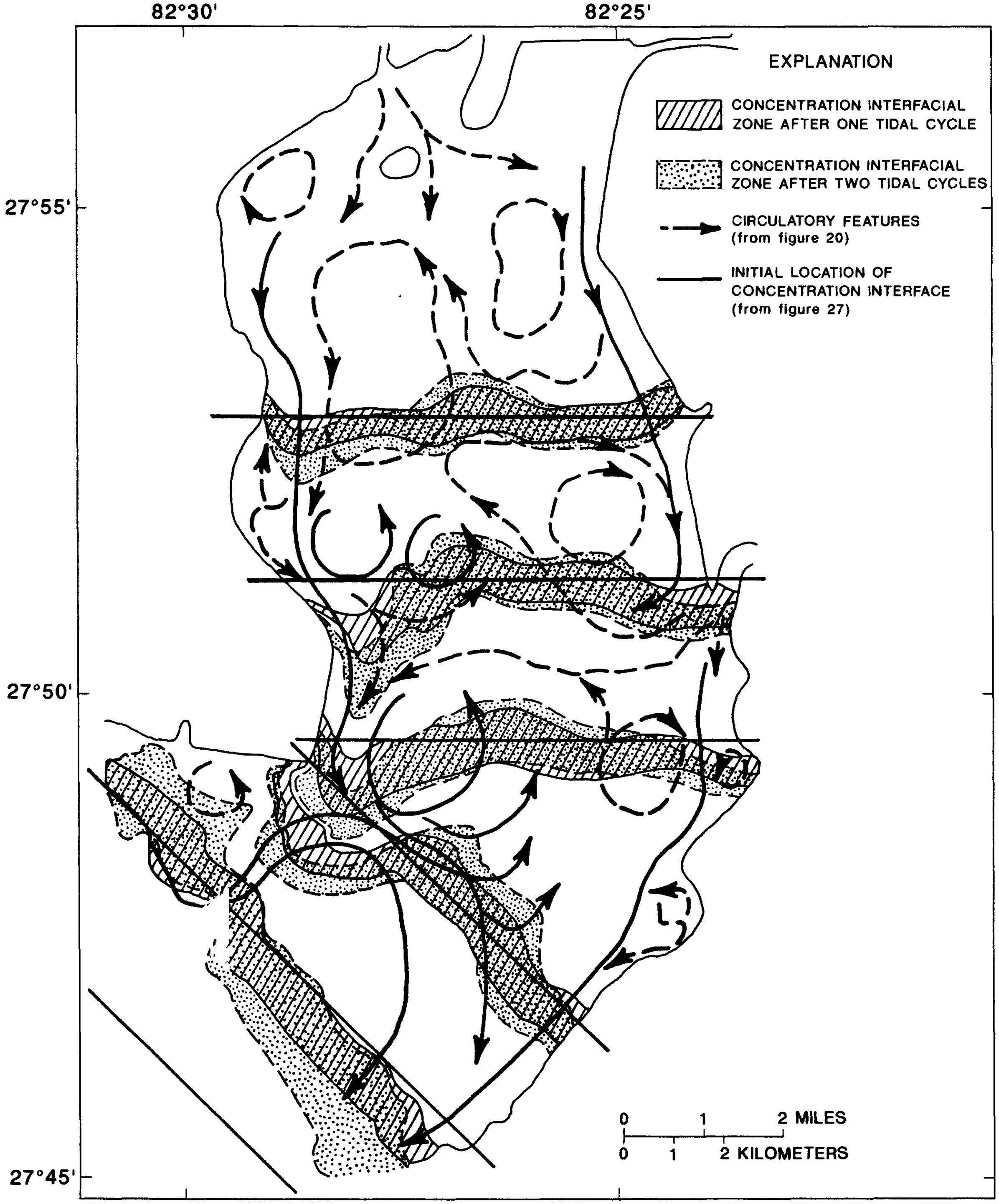

Figure 28. Computed positions of constituent interfacial bands at the end of one and two tidal cycles and computed circulatory features for 1880 level of development.

along the bay margins, as schematically represented in figure 31. This deduction, based on computational evidence, is also supported by observation. Figure 32 shows the average salinity distribution in Hillsborough Bay based on monthly observations over a 12-yr period (1974 through 1985) by the Hillsborough County Environmental

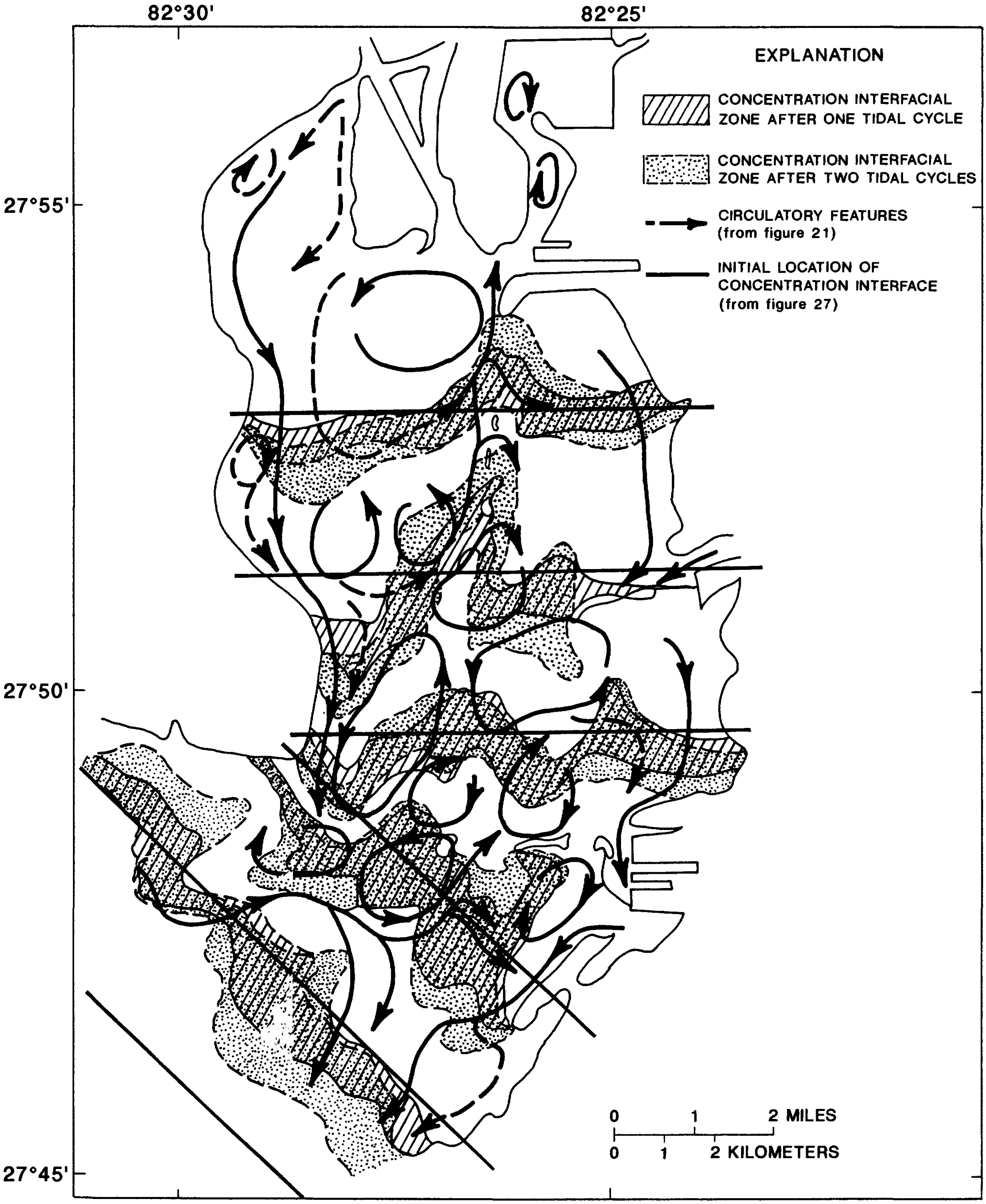

Figure 29. Computed positions of constituent interfacial bands at the end of one and two tidal cycles and computed circulatory features for 1972 level of development.

Protection Commission published in a series of reports such as Cardinale and Boler (1984).

The degree of interfacial band deformation is less for 1880 (fig. 28) than for 1972 and 1985 (figs. 29, 30). This is in general agreement with the Eulerian-based circulation summary (see fig. 26), which shows less computed circulation throughout the bay in 1880 than in 1972 and 1985. It seems paradoxical, however, that the greatest convective

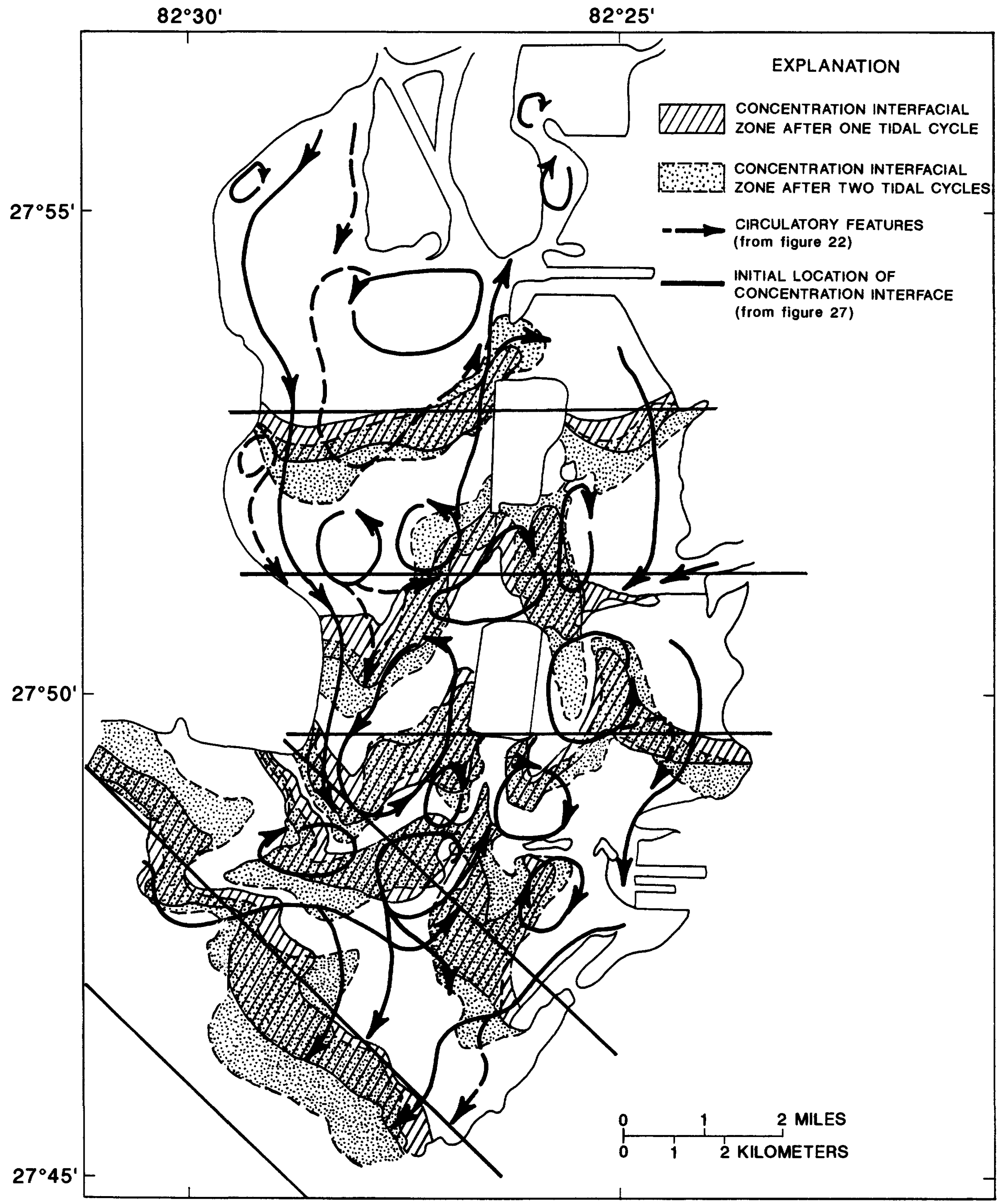

Figure 30. Computed positions of constituent interfacial bands at the end of one and two tidal cycles and computed circulatory features for 1985 level of development.

movement of interfacial bands is not associated with parts of the bay having the highest values of circulation. In 1972 and 1985, the area near the mouth of Hillsborough Bay, for instance, was computed to have four to five times the circulation that was computed for 1880 (see fig. 26). Convective movement in the same area, however, does not

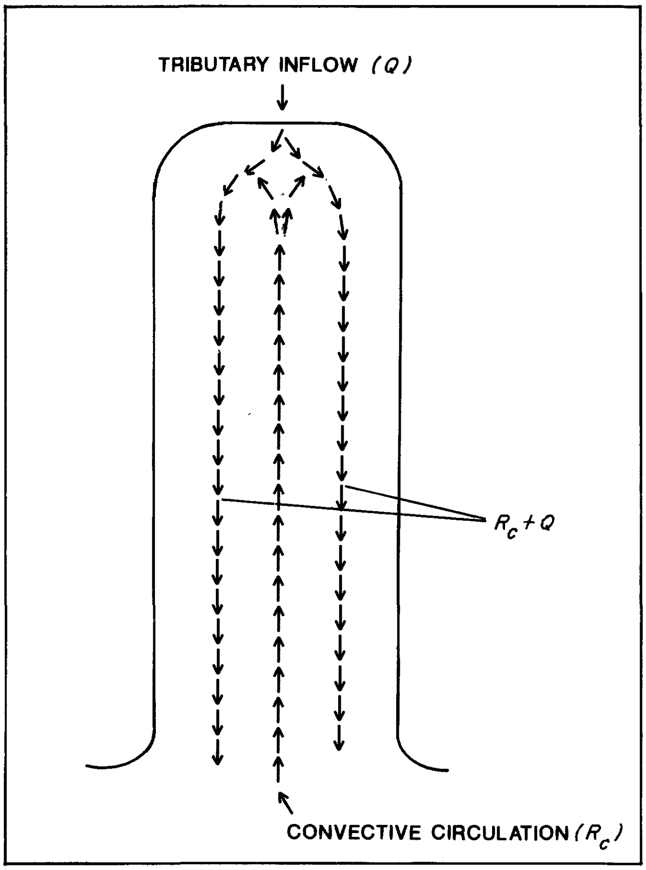

Figure 31. Conceptual, plan-view schematic of convective circulation in Hillsborough Bay.

show an increase of similar magnitude (compare fig. 28 with figs. 29 and 30). The circulatory-energy increase in this part of the bay seems to have been less directed toward convection and more directed toward dispersion, as evidenced by generally wider interfacial bands in 1972 and 1985.

Extending an argument recently proposed by Feng and others (1986b, p. 1637), the apparent increase in dispersion at the mouth of Hillsborough Bay since 1880 may be interpreted more precisely as the result of increased residual water transport, or circulation, at a length scale smaller than the local tidal excursion. The aforementioned paradox can then be explained by decomposing the total tide-induced circulation (R_T), as shown in figure 26, into two parts. It is hypothesized that dispersive circulation (R_D), at length scales smaller than the tidal excursion, primarily contributes to local dispersion, and that convective circulation (R_C), at length scales greater than the tidal excursion, mainly contributes to convection such that

$$R_T = R_C + R_D. \tag{3}$$

The maximum tidal excursion in Hillsborough Bay (fig. 33) for a tidal range of 3.0 ft varies from about 2.3 mi at the mouth to about 1.0 mi near the most northerly interfacial band shown in figures 28, 29, and 30. According to the tidal excursion criteria, few of the more intense circulation features noted in figures 20, 21, and 22 have sufficiently large diameters to contribute directly to residual convective water motion. Exceptions include gyre *A* for all three levels of development and gyres *B* and *N* for 1972 and 1985. Other circulatory features directly contributing to convective motion include most paths labeled with lower case letters and some less intense, unlabeled gyres.

To divide the total computed circulation in Hillsborough Bay for 1880, 1972, and 1885 levels of development (see fig. 26) into parts that contribute primarily to either convective or dispersive circulation, the following method was used. Cross-section locations along the longitudinal summary line (see fig. 6) were selected so as to avoid circulatory features in figures 20, 21, and 22 judged not to contribute directly to convection. In each instance where this was possible, the cross section was found to be at a point of circulation minimum in figure 26. The points of minimum circulation were then connected to provide an estimate of convective circulation (below the line) and dispersive circulation (above the line) at each bay cross section (fig. 34). The convective part (R_C) is conceived as being primarily responsible for inducing net landward and, with tributary freshwater inflow, net seaward water motion in Hillsborough Bay.

Transit Time

Initially, assuming that Q and R_C (see fig. 31) are invariant with respect to both an intertidal timeframe and distance along the estuary, an expression can be simply derived to estimate the average time (T_T) a particle will take to transit from the head to the mouth of the bay. First, the total bay volume (V_T) can be subdivided into a volume associated with landward residual transport (V_L) and a volume associated with seaward residual transport (V_S),

$$V_T = V_L + V_S\ , \tag{4}$$

with V_L and V_S having proportional equivalence to the total landward and seaward transport rates, respectively:

$$\frac{V_L}{V_S} = \frac{R_C}{R_C + Q}\ . \tag{5}$$

The bay transit time (T_T) can be computed as

$$T_T = \frac{V_S}{R_C + Q}\ , \tag{6}$$

which, with equations 4 and 5, reduces to

$$T_T = \frac{V_T}{2R_C + Q}\ . \tag{7}$$

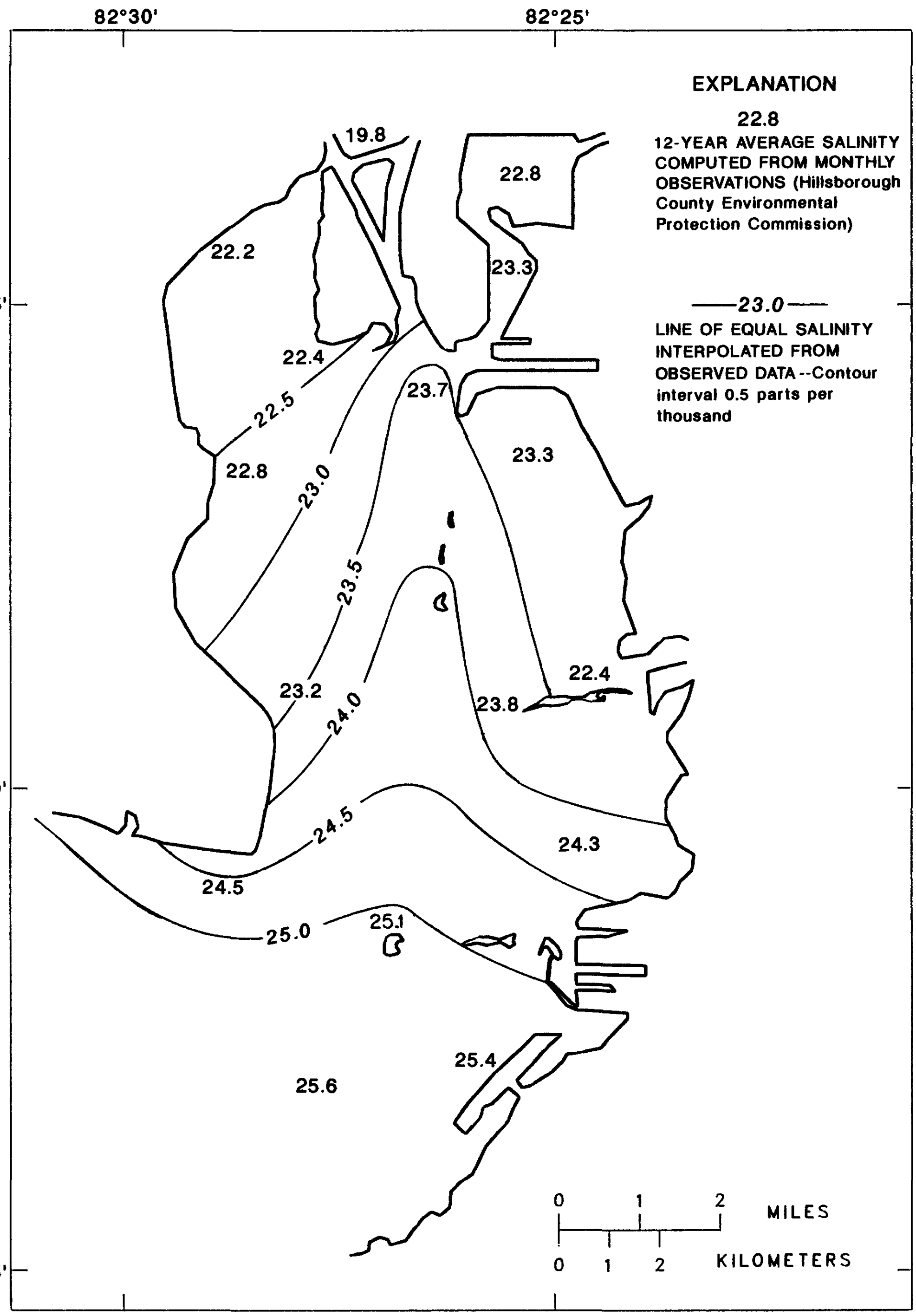

Figure 32. Mean salinity distribution in Hillsborough Bay for the period 1974 through 1985.

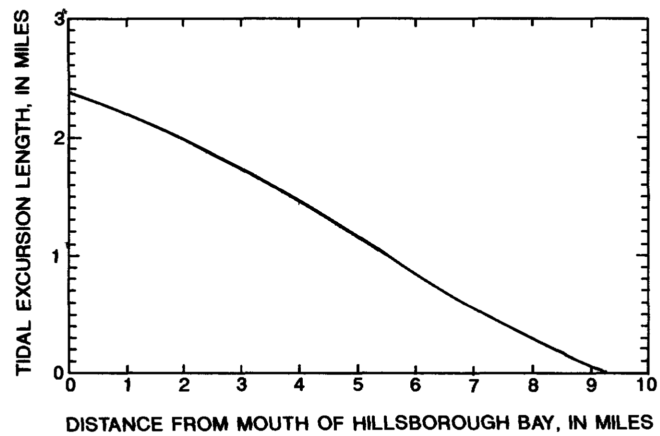

Figure 33. Approximate tidal excursion distance in Hillsborough Bay.

Because neither R_C nor Q is constant over the length of Hillsborough Bay, equation 7 must to be applied segmentally. Two segments are considered appropriate because significant changes in both tributary streamflow and convective circulation occur in the same part of the bay between about 2.4 and 3.2 mi from the mouth. Table 9 summarizes Hillsborough Bay transit times for 1880, 1972, and 1985 levels of development for the conditions and assumptions set forth in this report.

The concept of average transit time, as used here, is an incomplete measure of flushing in the bay because no provision has been made for the fact that some fraction of material exiting the bay undoubtedly returns. Because this fraction is unknown, transit times should be recognized as indicative of a somewhat faster rate of flushing than may actually occur.

Assuming that there is no reentry of material flushed from Hillsborough Bay, that average freshwater inflow in both 1972 and 1880 are equivalent to the value given in this report, and that the salinity distribution in figure 32 is representative of the 1972 level of development, it is informative to estimate how the average salinity in Hillsborough Bay may have changed from 1880 to 1972 because of greater circulation resulting from physical changes.

Because the bay could flush freshwater in 1880 at only about half the rate it could in 1972, the average volume of freshwater within the bay in 1880 (F_{1880}) was probably about twice as great as the average in 1972 (F_{1972}), or

$$F_{1880}=\frac{T_{T\,(1880)}}{T_{T\,(1972)}}\times F_{1972}\,. \tag{8}$$

By combining equation 8 with the following expression (Pilson, 1985) for the volume of freshwater (F) in an estuary in terms of a volume-weighted average bay salinity (S) and salinity at the mouth (S_o),

$$F=\left(1-\frac{S}{S_o}\right)V_T\,, \tag{9}$$

and solving for average bay salinity in 1880 gives

$$S_{1880}=S_o-\left[\frac{T_{T\,1880}}{T_{T\,1972}}\right]\left[\frac{V_{T\,1972}}{V_{T\,1880}}\right]\left[S_{1972}\right]. \tag{10}$$

Approximating S_o as 25 ppt and S as 23.5 ppt, from figure 32, and using information from tables 1 and 9, the computed average salinity in Hillsborough Bay in 1880 was approximately 21.7 ppt, or 1.8 ppt lower than in 1972. It is apparent that physical changes to Hillsborough Bay between 1880 and 1972 could have contributed to an increase in bay salinity; dredging since 1972 has not.

SUMMARY

Changes in two-dimensional tidal flow, circulation, and flushing caused by dredge and fill construction in Hillsborough Bay were determined by using finite-difference, computer-simulation techniques. Three levels of development were chosen for comparison:

1. Conditions in 1880, before any significant manmade physical changes to the bay;
2. Conditions in 1972, after construction of islands, residential and commercial shoreline fills, and a series of ship channels serving port facilities in several parts of the bay; and
3. Conditions in 1985, after completion of a Federal dredging project.

Physical changes to Hillsborough Bay since 1880 have caused a progressive decrease in the quantity of water (tidal prism) that enters and leaves the bay during each tidal cycle. Tidal-prism decreases for Hillsborough Bay proper were computed to be about 4 percent from 1880 to 1972 and about 2 percent from 1972 to 1985.

Dredged and filled areas have changed the magnitude and direction of tidal floodflows and ebbflows in large parts of the bay. Areas near islands, channels, and shoreline fills have been affected most. Tidal flow, as measured by average flood and ebb water transport, has changed by more than 50 percent over about 23 mi^2 of the bay from 1880 to 1972. Similar changes from 1972 to 1985 have occurred over only 8 mi^2.

On the basis of model results using one typical tide that occurs in Hillsborough Bay, the computed circulation pattern for the 1880 level of development shows a sequence of about eight circulatory features. These features are thought to either control or have a large influence on the intertidal motion of water and constituents both within Hillsborough Bay proper and between the bay and the adjacent part of Middle Tampa Bay. On maps of 1972 and 1985 circulation patterns, 13 to 15 gyres are identifiable. Many of these features are smaller in size and exhibit

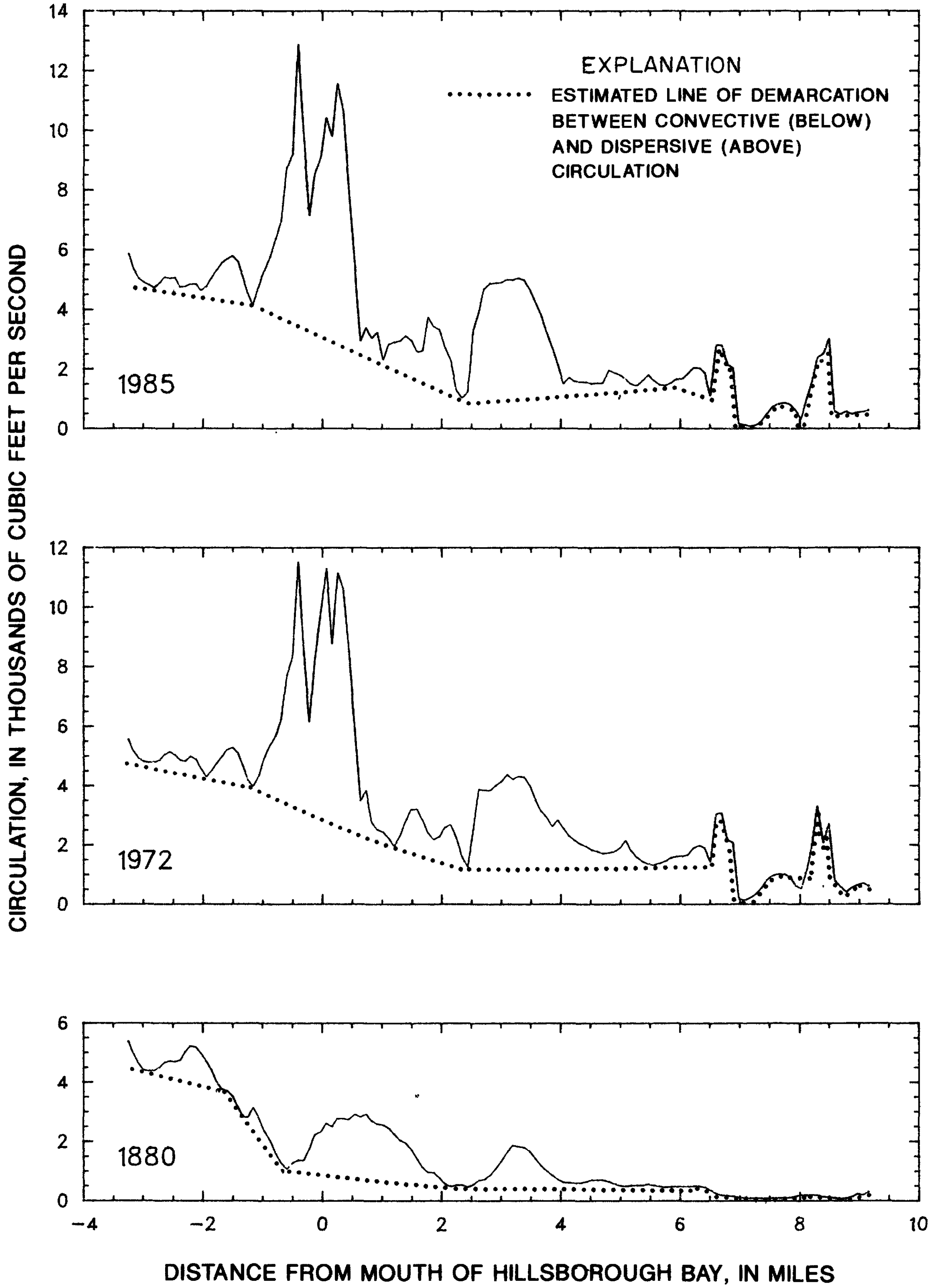

Figure 34. Estimated lines of demarcation between convective and dispersive circulation for 1880, 1972, and 1985 levels of development.

circulatory motions of greater intensity than those detected in 1880.

Areas of circulation change caused by dredge and fill, as measured by differences in residual water transport, are several times larger than areas computed for tidal-flow change. Residual water-transport changes of more than 50 percent occurred over an area of about 45 mi^2 from 1880 to 1972. About 17 mi^2 was changed by more than 50 percent

Table 9. Comparison of computed transit time in Hillsborough Bay for 1880, 1972, and 1985 levels of development
[ft^3, cubic feet; ft^3/s, cubic feet per second]

Level of development	Bay segment (fig. 26)	Segment volume (ft^3)	Freshwater inflow (ft^3/s)	Average convective circulation (ft^3/s)	Average transit time (days)
1880	mile 9.2–2.4	0.63×10^{10}	684	500	43
1880	mile 2.4–0.0	0.35×10^{10}	1,181	800	15
Total					58
1972 and 1985[1]	mile 9.2–2.4	0.67×10^{10}	685	1,500	21
1972 and 1985[1]	mile 2.4–0.0	0.37×10^{10}	1,181	2,000	8
Total					29

[1]The difference in both segment volume and computed convective circulation for these levels of development is insufficient to distinguish meaningfully different transit times.

from 1972 to 1985. Between 1880 and 1972, large residual water-transport changes occurred throughout most of Hillsborough Bay owing to dredge and fill activity. From 1972 to 1985, the bay had more localized residual changes as a result of ship-channel deepening and island construction.

In spite of significant visual and numerical differences between the less complex circulation pattern of 1880 and the more complex patterns of 1972 and 1985, some important similarities exist. In all three cases, incoming residual transport tends to occur in the deeper, central part of Hillsborough Bay, and outgoing residual transport tends to occur along the shallow margins of the bay.

Computed tide-induced circulation has increased throughout all of Hillsborough Bay in response to physical changes since 1880. The greatest circulation increase, 233 percent, occurred in the upper part of the bay from 1880 to 1972. No change was computed for that area from 1972 to 1985. In the lower part of Hillsborough Bay, increases of 79 and 6 percent occurred from 1880 to 1972 and from 1972 to 1985, respectively. Large localized increases in circulation were caused by pumping for powerplant cooling-water systems.

Comparison with prior numerical circulation computations for Hillsborough Bay by other investigators indicates that the choice of model grid size can significantly influence the result if physical features are not well represented. Differences in computed results that are based on 1,500-ft and 500-ft grid sizes indicate that the 1,500-ft grid size underestimates computed circulation by 4 to 35 percent.

The concept of residual landward-flowing water in the deep, central part of the bay and residual seaward-flowing water along the bay margins was confirmed by both Eulerian and Lagrangian computation as well as by observation that uses a 12-yr average salinity distribution. The total computed circulation also was found to be resolvable into convective and dispersive components on the basis of size of circulatory features relative to local tidal excursion length.

By use of the overall residual flow concept and the convective part of computed circulation, estimates of the time needed for dissolved or suspended matter to transit from the head to the mouth of the bay were made for one typical tide condition. The transit time was estimated to be about 58 days in 1880 and about 29 days in 1972 and 1985. The effect of increased circulation and reduced transit time in Hillsborough Bay resulting from dredge and fill construction since 1880 was estimated to be an increase in average salinity of about 2 ppt.

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