Methodology for Estimating Nutrient Loads Discharged from the East Coast Canals to Biscayne Bay, Miami-Dade County, Florida

U.S. GEOLOGICAL SURVEY
Water-Resources Investigations Report 99-4094

Prepared as part of the
U.S. Geological Survey South Florida Ecosystem Program

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By A.C. LIETZ

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Methodology for Estimating Nutrient Loads Discharged from the East Coast Canals to Biscayne Bay, Miami-Dade County, Florida

By A.C. Lietz

Abstract

Biscayne Bay is an oligotrophic, subtropical estuary located along the southeastern coast of Florida that provides habitat for a variety of plant and animal life. Concern has arisen with regard to the ecological health of Biscayne Bay because of the presence of nutrient-laden discharges from the east coast canals that drain into the bay. This concern, as well as planned diversion of discharges for ecosystem restoration from the urban and agricultural corridors of Miami-Dade County to Everglades National Park, served as the impetus for a study conducted during the 1996 and 1997 water years to estimate nutrient loads discharged from the east coast canals into Biscayne Bay.

Analytical results indicated that the highest concentration of any individual nutrient sampled for in the study was 4.38 mg/L (milligrams per liter) for nitrate at one site, and the lowest concentrations determined were below the detection limits for orthophosphate at six sites and nitrite at four sites. Median concentrations for all the sites were 0.75 mg/L for total organic nitrogen, 0.10 mg/L for ammonia, 0.02 mg/L for nitrite, 0.18 mg/L for nitrate, 0.20 mg/L for nitrite plus nitrate nitrogen, 0.02 mg/L for total phosphorus, and 0.005 mg/L for orthophosphate. The maximum total phosphorus concentration of 0.31 mg/L was the only nutrient concentration to exceed U.S. Environmental Protection Agency (1986) water-quality criteria. High concentrations of total phosphorus usually reflect contamination as a result of human activities. Five sites exceeded the freshwater quality standard of 0.5 mg/L for ammonia concentration as determined by the Miami-Dade County Department of Environmental Resources Management. Median total organic nitrogen concentrations were higher in urban and forested/wetland areas than in agricultural areas; median concentrations of nitrite, nitrate, and nitrite plus nitrate nitrogen were higher in agricultural areas than in urban and forested/wetland areas; and ammonia, total phosphorus, and orthophosphate concentrations were higher in urban areas than in agricultural and forested/wetland areas. These results coincide with expected differences in nutrient concentrations based on knowledge of point and nonpoint source influences and nutrient cycling.

The Wilcoxon signed ranks test (WSRT) was used to compare differences between point (grab) samples and depth-integrated samples for total nitrogen and total phosphorus concentrations at 12 east coast canal sites. Statistically significant differences (alpha level of 0.025) in total phosphorus concentrations between point (grab) samples collected 1.0 meter deep and depth-integrated samples were detected at three sites. One site also showed statistically significant differences in total phosphorus concentrations between point (grab) samples collected 0.5 meter deep and depth-integrated samples. There were no statistically significant differences in total nitrogen and total phosphorus concentrations between point (grab) samples collected 0.5 meter deep and 1.0 meter deep for all the sites. Results of the line of organic correlation, a fitting procedure used to compare

point (grab) and depth-integrated samples where statistically significant differences exist as defined by the WSRT, indicated that point (grab) samples underestimate total phosphorus concentrations when compared to depth-integrated samples. This underestimation probably can be attributed to the reduced suspended-sediment concentrations near the surface during periods of flow as compared to those near the streambed.

Predictive models were developed to estimate total nitrogen and total phosphorus loads by means of an ordinary least-squares regression technique. Instantaneous discharge was used as the independent variable, and total phosphorus load or total nitrogen load represented the dependent variable. A software program called Estimator was used to develop the regression models and to compute total nitrogen and total phosphorus loads at site S-26 along Miami Canal. The coefficients of determination (R^2) were adjusted to conform with the number of degrees of freedom in the model. The adjusted R^2 for total nitrogen load models ranged from 0.69 to 0.99, and the adjusted R^2 for total phosphorus load models ranged from 0.23 to 0.99. The average adjusted R^2 for total nitrogen load models and the average adjusted R^2 for total phosphorus load models were 0.87 and 0.76, respectively. All but two of the models were statistically significant at an alpha level of 0.05. One total phosphorus load model was statistically significant at an alpha level of 0.10 (site G-58), and the other total phosphorus load model was not statistically significant at either 0.05 or 0.10 (site S-21A).

INTRODUCTION

A major concern in many coastal areas across the Nation is the ecological health of bays and estuaries. One common problem in many of these areas is nutrient enrichment as a result of agricultural and urban activities. Nutrients are essential compounds for the growth and maintenance of all organisms and especially for the productivity of aquatic environments. Nitrogen and phosphorus compounds are especially important to seagrass, macroalgae, and phytoplankton. However, heavy nutrient loads transported to bays and estuaries can result in conditions conducive to eutrophication and the attendant problems of algal blooms and high phytoplankton productivity. Additionally, reduced light penetration in the water column because of phytoplankton blooms can adversely affect seagrasses, which many commercial and sport fish rely on for their habitat.

Biscayne Bay, a shallow subtropical estuary along the southeastern coast of Florida, provides an aquatic environment that is habitat to a diversity of plant and animal species. Increased nutrient loads in discharges from the east coast canals in southern Florida (fig. 1), as a result of agricultural and urban activities, are a potential threat to the health of Biscayne Bay. Dissolved-oxygen concentrations average about 5 mg/L (milligrams per liter) in Biscayne Bay, but hypoxic conditions along with nutrient enrichment exist in the east coast canals. Plans are being formulated by water-management officials to reestablish natural flow to Everglades National Park (ENP) by diverting water that now flows through the agricultural/urban corridor and then discharges by way of canals to Biscayne Bay.

An understanding of nutrient loading to Biscayne Bay is needed for both an assessment of the ecological health of the bay as well as an evaluation of the water-quality impact of the diverted water to ENP. The U.S. Geological Survey (USGS) began a study in April 1996 to: (1) develop methodology for the purpose of estimating nutrient loads in Biscayne Bay, and (2) determine whether point (grab) samples, historically collected at 0.5 and 1 m (meter) below the surface near the centroid of flow, accurately represent water quality in the stream cross section. The study was done as part of the South Florida Ecosystem Program, which is a collaborative effort by the USGS; various other Federal, State, and local agencies; and Indian Tribes to provide earth science information needed to resolve land-use and water issues in southern Florida.

For planning purposes, Biscayne Bay is divided into three subregions; namely, north bay, central bay, and south bay (Alleman, 1995). North bay extends from about 5 mi (miles) north of the Dade/Broward County boundary to the Miami shoreline, central bay extends from the Miami shoreline to the featherbed banks east of Model Land Canal, and south bay extends from the featherbed banks east of Model Land Canal to Barnes Sound (fig. 1). Certain areas of north bay exhibit severely degraded water quality that largely is attributed to heavy loads of nutrients and toxicants from the tributary canals, including Arch Creek, Snake Creek, Biscayne Canal, and Little River Canal. Hypoxic

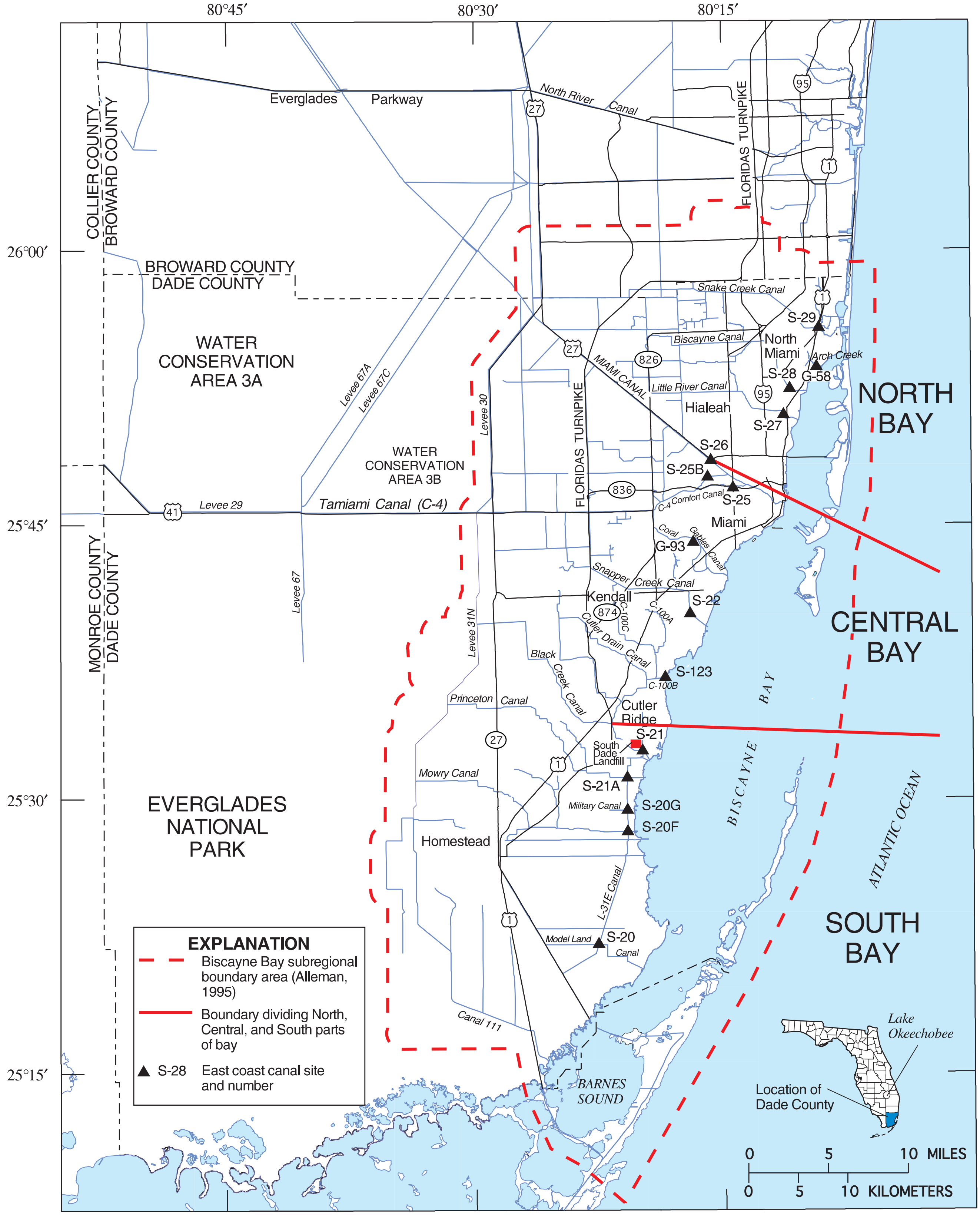

Figure 1. Location of the east coast canal sites and subregions in Miami-Dade County.

conditions exist in the canals and high concentrations of ammonia, total phosphorus, and trace elements are common. Water quality in the central bay region ranges from pristine to highly degraded. Miami Canal, flowing through a highly urbanized area, contributes heavy discharges of pollutants to Biscayne Bay. Tributary or coastal canals that drain into central bay, such as Miami Canal, Coral Gables Canal, and Snapper Creek Canal, tend to be nutrient enriched and contribute toxicants to Biscayne Bay. Canals draining into south bay receive nutrient enrichment from agricultural activities. Black Creek Canal contains high levels of ammonia as a result of leachate from the south Miami-Dade landfill.

Purpose and Scope

The purpose of this report is to present methodology that can be used to estimate nutrient loads discharged from the east coast canals into Biscayne Bay in southeastern Florida. Graphical summaries have been created to compare medians and evaluate the distribution of nutrient concentrations in the east coast canal system based on land-use categories in the Biscayne Bay watershed. Vertical depth profiles of dissolved-oxygen, total phosphorus, and total nitrogen concentrations have been constructed to document horizontal and vertical variability within the canal system. A statistical approach is used to compare differences between point (grab) and depth-integrated samples (from the east coast canal sites) for total nitrogen and total phosphorus concentrations. A modeling technique is used for developing equations through simple linear regression analyses in order to estimate nutrient loads based on discharge. The nitrogen and phosphorus species described in this report include total organic nitrogen, ammonia, nitrite, nitrate, nitrite plus nitrate nitrogen, total phosphorus, and orthophosphate. Most of the data presented in this report were collected from the east coast canal sites during the 1996 and 1997 water years. Data from one site (S-26 along Miami Canal) were collected from 1966 to 1996.

Background on Nutrients

The ecological health of Biscayne Bay is dependent on nutrient loads. An understanding of the processes that control nutrient loads to the bay is needed to properly develop restoration efforts in southern Florida. Nutrients fall into three categories – macronutrients, micronutrients, and trace nutrients. The macronutrients (generally represented as nitrogen, phosphorus, and carbon species) are required in the greatest amounts and are major components in the cells of all organisms. Nitrogen and phosphorus compounds are important to free-floating type plants, such as algae (Hem, 1985, p.128). Micronutrients consist of trace elements such as manganese, copper, and zinc.

Nitrogen, phosphorus, and carbon species can exist in both organic and inorganic forms. The most common inorganic forms of nitrogen are ammonia, nitrite, and nitrate. Total organic nitrogen can exist as particulate or nonparticulate organic nitrogen. Most of the nitrogen compounds in surface-water bodies exist in an oxidized form as nitrate and nitrite. The U.S. Environmental Protection Agency (1986) has established water-quality standards or guidelines for nitrate, nitrite, nitrite plus nitrate nitrogen, and ammonia. Nitrate, nitrite, and ammonia in concentrations above established standards or guidelines can be detrimental to the health of humans, and ammonia is toxic to aquatic organisms.

Phosphorus exists inorganically as soluble reactive phosphorus and in the particulate inorganic and nonparticulate inorganic states. Soluble reactive phosphorus is commonly referred to as orthophosphate. Particulate inorganic phosphorus consists mostly of phosphate minerals, such as apatite. Nonparticulate inorganic phosphorus includes condensed phosphates, such as those found in detergents. Phosphorus exists organically as particulate organic and nonparticulate organic phosphorus. Particulate organic phosphorus exists in plants, animals, and organic detritus. Nonparticulate organic phosphorus comprises mainly dissolved or colloidal organic compounds (Chapra, 1997, p. 523).

Nutrients exist in water bodies as a result of both natural and anthropogenic (manmade) sources, although contributions from natural sources are minimal. Anthropogenic contributions might be significant, however, and can result from agricultural activities, domestic and animal waste, municipal wastewater, and byproducts of manufacturing processes. Phosphorus generally is lower in concentration than other nutrients because it does not naturally occur in the atmosphere nor is it abundant in the earth’s crust. Phosphorus also tends to strongly adsorb to sediments and fine-grained particles, causing its removal from the water column. Nitrogen differs from phosphorus in that it naturally occurs in the atmosphere and does not adsorb as strongly to particulate matter. Additionally, denitrification acts as a removal mechanism for nitrogen under anaerobic conditions.

The nitrogen cycle principally is a series of oxidation and reduction reactions catalyzed by bacteria, mostly the *Nitrobacter* and *Nitrosomonas* species (Lawrence, 1996, p. 9). Under aerobic and anaerobic conditions, total organic nitrogen catalyzed by bacteria is decomposed to amine groups in a process called deamination. This reaction continues under aerobic conditions to produce ammonia (ammonification) as well as nitrite and nitrate (nitrification). The process is expressed below:

Total organic nitrogen ⇒Amines ⇒ Ammonia ⇒
Nitrite ⇒ Nitrate

Furthermore, the microbes use nitrogen under aerobic conditions by consuming electrons in the oxygen molecule. However, during reducing conditions (usually when dissolved-oxygen concentration is below 1.0 mg/L), the microbes use electrons from oxygen in the nitrate molecule. With this process, the nitrate ion is depleted of oxygen (denitrification), resulting in the formation of nitrous oxide or gaseous nitrogen (Lawrence, 1996, p. 10). The nitrogen atom eventually is reduced by reacting with hydrogen ions to form ammonia in a process called nitrate reduction. The process is expressed below:

Nitrous oxides or nitrogen gas ⇐ Nitrate ⇒
Nitrite ⇒ Ammonia

Most nitrogen compounds in surface-water bodies exist as nitrate because of prevailing aerobic conditions.

Eutrophication is defined as a natural or artificial addition of nutrients to a water body (Hackney and others, 1992, p. 693) and is the principal threat to lakes, estuaries, or streams that receive excessive total nitrogen and total phosphorus loads. Nutrient enrichment can result in inordinate algal production, known as cultural eutrophication, and produces an undesirable taste and odor problems to a water supply. Many other undesirable chemical effects also could be attributed to eutrophication. Algal dieoffs result in an increase in the amount of organic matter available for consumption by bacteria, resulting in oxygen depletion. If oxygen is depleted faster than it is replenished by photosynthesis or absorption from the atmosphere, hypoxic or anoxic conditions can ensue, thus adversely affecting aquatic species and ultimately resulting in fish kills. The consequences of oxygen depletion include changes in redox states, especially as they apply to certain trace elements. Sulfate reduction and methanogenesis can occur, iron sulfides can form in the sediments, and soluble iron can be transferred to the water column. Additionally, the release of phosphate to the water column from iron/phosphate complexes (because of changes in iron/sulfur oxidation states) could further accelerate the eutrophication process.

Historical Surface-Water-Quality Data

A considerable amount of historical surface-water-quality data exists from the east coast canal system in southern Florida, much of it having been collected intermittently for many years by the USGS for determination of concentrations of nutrients and major inorganic constituents. Since 1940, a voluminous amount of salinity monitoring data has been collected from the east coast canal sites. In 1974, the USGS began a program called the National Stream Quality Accounting Network (NASQAN), which was designed to determine long-term water-quality trends associated with major drainage basins throughout the Nation. Concentrations of major inorganic constituents and physical characteristics, nutrients, trace elements, suspended sediment, selected organic compounds, and bacteriological and biological constituents were determined at one NASQAN east coast canal site (S-26 along Miami Canal). Water samples from this site were collected monthly from October 1974 to September 1981 and quarterly from October 1981 to September 1994. Data that were collected under other programs since 1966 also exist. The Miami-Dade County Department of Environmental Resources Management (DERM) has collected surface-water-quality data from the east coast canals since 1979. Much of the same data, as determined under the NASQAN program, also were collected by DERM under a variety of programs. Most of the DERM data were collected as part of the Biscayne Bay Monitoring Program, General Canal Monitoring Program, or Intensive Canal Monitoring Program.

Previous Studies

Previous studies involving the development of models based upon linear regression techniques are numerous. Smith and others (1982) studied trends in total phosphorus measurements at NASQAN stations based upon concentration/discharge models. Cohn and others (1989) studied the problem of retransformation bias, which can result when log-linear regression models are used to estimate constituent loads. Gilroy and others (1990) studied mean square errors of regression-based constituent transport estimates. Cohn and others (1992) evaluated the validity of a minimum variance unbiased estimator (MVUE) to estimate fluvial constituent loads. Watts (1993) and Ries (1994) used regression models to estimate monthly water-level changes in the Closed Basin Division of the San Luis Valley in Colorado and low-flow deviation discharges in Massachusetts, respectively. Belval and others (1994) estimated loads of water-quality constituents in the James and Rappahonnock Rivers in Virginia based upon multiple-regression techniques. Stoker and others (1995) used an ordinary least-squares technique to describe loading characteristics of McKay Bay, Delaney Creek, and East Bay in Tampa, Fla.

Acknowledgments

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DESCRIPTION OF STUDY AREA

Miami-Dade County, located on the southeastern tip of peninsular Florida (fig. 1), encompasses an area of about 2,000 mi^2 (square miles). The county is bounded by the Atlantic Ocean on the east, Broward County on the north, Collier and Monroe Counties on the west, and the Florida Keys (Monroe County) on the south. The area is characterized as a subtropical, marine environment with long, hot, wet summers and mild, dry winters. Seasonal variation in rainfall is pronounced; about 75 percent of areal rainfall occurs during the 5-month wet season from June through October. Long-term records (1966-95) indicate that average annual rainfall in Miami is about 59 in. (inches), ranging from as low as 39 in. in 1975 to as high as 83 in. in 1968 (fig. 2).

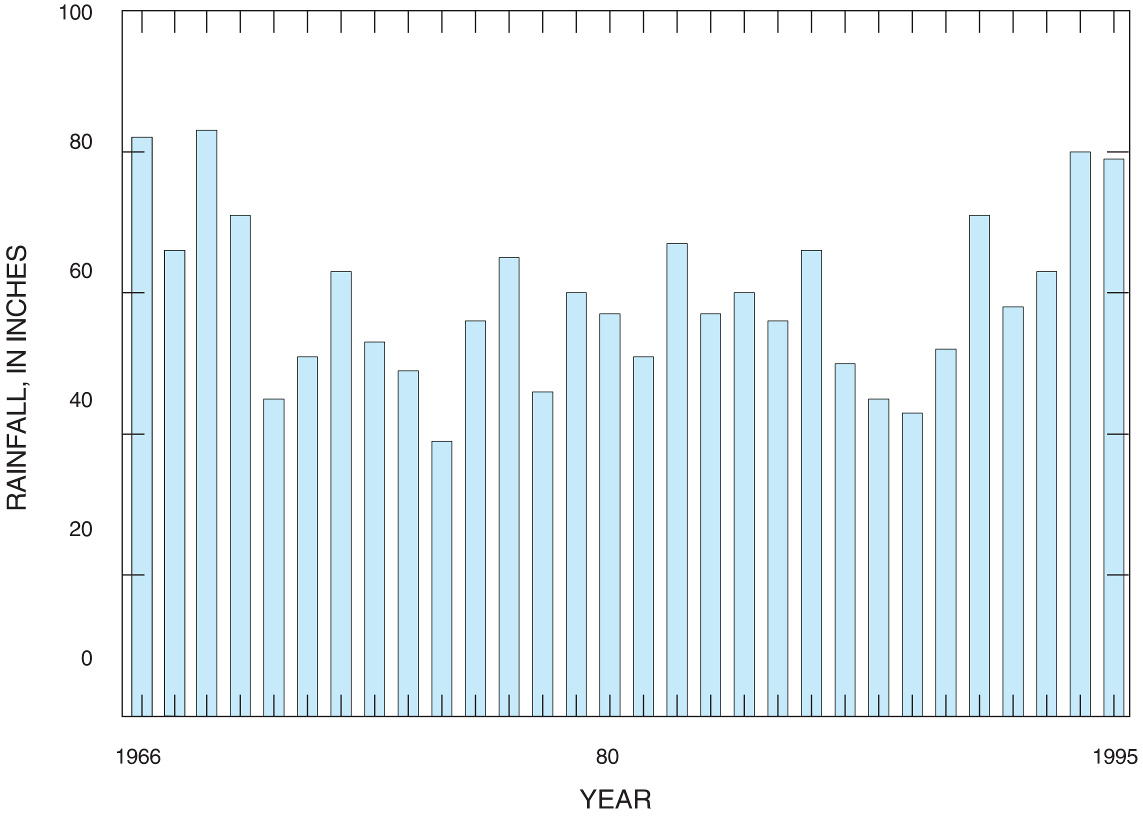

Figure 2. Average annual rainfall in Miami, 1966-95.

A total of 15 east coast canal sites in Miami-Dade County (fig. 1) were selected for the study; 13 sites are gated spillways and 2 sites are gated culverts. All east coast canal sites that have automatic gate operation contain an overriding mechanism that closes the gates to prevent saltwater intrusion when the headwater and tailwater differential reaches a certain level. The operational description of the 15 east coast canal sites in table 1 is condensed from recently published reports by the U.S. Army Corps of Engineers (1995) and by Swain and others (1997).

Environmental Setting

Physiographic features (fig. 3) have significantly controlled the environment, drainage, and ultimately the land use in Miami-Dade County (Fish and Stewart, 1991, p. 4). The Atlantic Coastal Ridge, 2 to 10 mi in width, forms the highest ground in the county. Elevations along the ridge range from about 8 to 15 ft (feet) above sea level, but are 20 ft above sea level or greater in some places. West of Homestead, elevations of the Atlantic Coastal ridge are from 5 to 8 ft above sea level. The Atlantic Coastal Ridge is a natural barrier to drainage of the interior, except where it is breached by shallow sloughs or rivers.

Table 1. Operational description of the east coast canal sites in Miami-Dade County

[High and low ranges in stage, as indicated at specific sites, depend on field conditions and agricultural needs. Operational purpose: 1, control flooding; 2, prevent saltwater intrusion. Type of control: 4B-CMPC, four-barrel, corrugated metal-pipe culverts; RCGS, reinforced-concrete gated spillway; 1B-CMPC, single-barrel, corrugated metal-pipe culvert. Other notes: N/A, not applicable]

Site No.	Local identification number	Operational purpose	Type of control	Number and type of gates	Stage, in feet above sea level		
					Level at which gates automatically open	Level at which gates become stationary	Level at which gates automatically close
G-58	255406080094600	1	4B-CMPC	Four flap gates	N/A	N/A	N/A
G-93	02290560	2	RCGS	Two vertical lift gates	N/A	N/A	N/A
S-20	252129080223500	2	RCGS	One vertical lift gate	1.4	1.2	1.0
S-20F	02290725	2	RCGS	Three vertical lift gates	1.4 or 2.2	1.2 or 2.0	1.0 or 1.8
S-20G	252922080204800	2	RCGS	One vertical lift gate	1.4 or 2.2	1.2 or 2.0	1.0 or 1.8
S-21	02290711	2	RCGS	Three vertical lift gates	2.0 or 2.4	1.5 or 1.9	1.0 or 1.5
S-21A	253110080204700	2	RCGS	Two vertical lift gates	1.4 or 2.2	1.2 or 2.0	1.0 or 1.8
S-22	02290700	2	RCGS	Two vertical lift gates	3.5	2.9	2.5
S-25	02290520	2	1B-CMPC	One circular sluice gate	2.2	2.0	1.8
S-25B	254735080154800	2	RCGS	Two vertical lift gates	3.0	2.8	2.0
S-26	02288600	2	RCGS	Two vertical lift gates	2.8	2.5	2.3
S-27	02286380	2	RCGS	Two vertical lift gates	1.9	1.7	1.6
S-28	02286340	2	RCGS	Two vertical lift gates	2.1	1.8	1.5
S-29	02286300	2	RCGS	Four vertical lift gates	2.5	2.0	1.5
S-123	02290704	2	RCGS	Two vertical lift gates	2.4 or 3.5	2.0 or 3.0	1.6 or 2.5

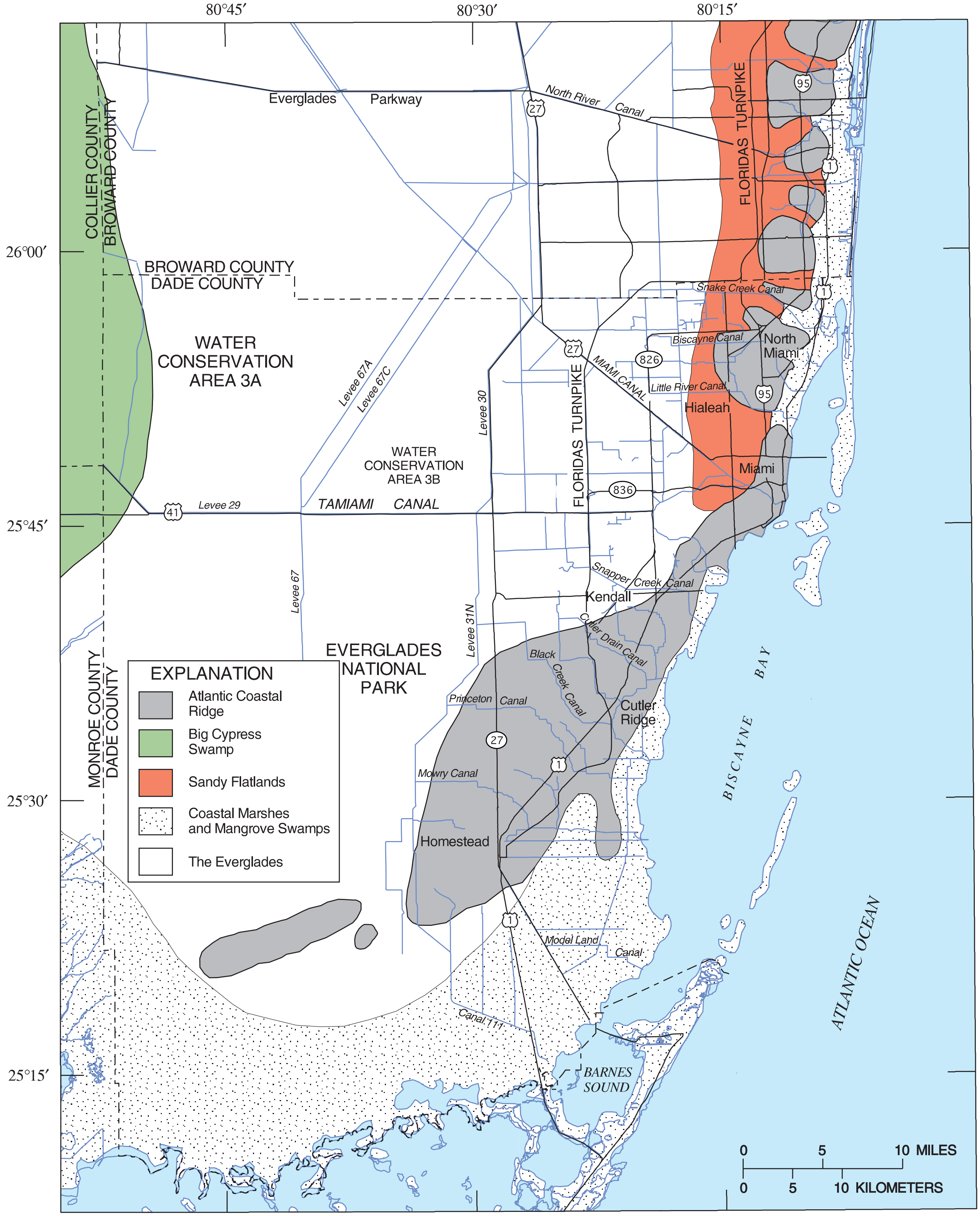

Figure 3. Physiographic features of Miami-Dade County.

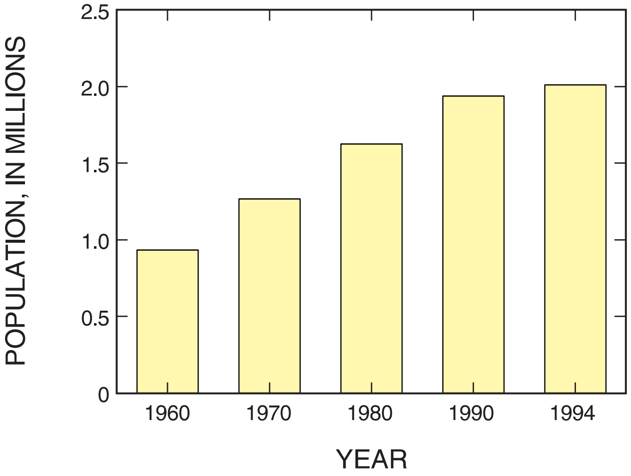

Figure 4. Population of Miami-Dade County, 1960-94.

The Sandy Flatlands in northeastern Miami-Dade County is lower in elevation (6-18 ft above sea level) than the Atlantic Coastal Ridge, and prior to development was poorly drained. The Everglades, by far the largest feature, is slightly lower than the Sandy Flatlands, and before development, was wet in most years and subject to seasonal flooding. Drainage was slow and generally to the south and southwest, channeled behind the higher Atlantic Coastal Ridge. The Everglades forms a natural trough in north-central, central, and southwestern Miami-Dade County. Elevations range from about 9 ft above sea level in the northwestern corner to about 3 ft above sea level in southwestern Miami-Dade County, except for tree islands or hammocks which may be a few feet higher than the surrounding land. Most of the eastern part of the Everglades within the county is used for agriculture, rock quarrying, or urban development.

A small part of the Big Cypress Swamp occupies northwestern Miami-Dade County where elevations range from 7 to 10 ft above sea level. Coastward from the Everglades and the Atlantic Coastal Ridge lie coastal marshes and mangrove swamps at elevations that generally range from 0 to 3 ft above sea level. This description of the physiographic features in Miami-Dade County was taken from a published report by Fish and Stewart (1991, p. 4).

One of the principal factors influencing the development of southern Florida water control is the rapid population growth along the lower east coast. According to the 1990 census, the population in Miami-Dade County doubled every 10 years between 1910 and 1960 (Metropolitan Dade County, 1995, p. I-79). Although the rate of population slowed over the next two decades, there still was a significant growth in population, with about 1.3 and 1.7 million people in 1970 and 1980, respectively (fig. 4). Immigration accounted for 78 percent of the population growth from 1960 to 1990; as of 1994, Miami-Dade County had attained a population of about 2.0 million people.

As of 1985, about 205,827 (16.5 percent) and 1,045,162 acres (83.5 percent) of total land area in Miami-Dade County was classified as developed and undeveloped land, respectively (Metropolitan Dade County, 1988, p. 39). The major land-use categories in the developed area include residential, transportation, parks and recreation, industrial, and commercial and institutional (fig. 5). The residential category comprises the highest percentage of land use in the developed area of Miami-Dade County. The undeveloped land area in Miami-Dade County includes agriculture, barren/urban open land, and forested/wetland.

Hydrologic Setting

A rapidly expanding population in the urban and agricultural areas of southern Florida has resulted in an extensive water-management system that has evolved over the years. This system of canals, levees, pump stations, and gated water-control structures was constructed over the last century, initially for the purpose of draining the wetlands and for flood control. The earliest attempt at water management occurred in 1905 with the Florida Legislature’s creation of the Everglades Drainage District. This resulted in the construction of North

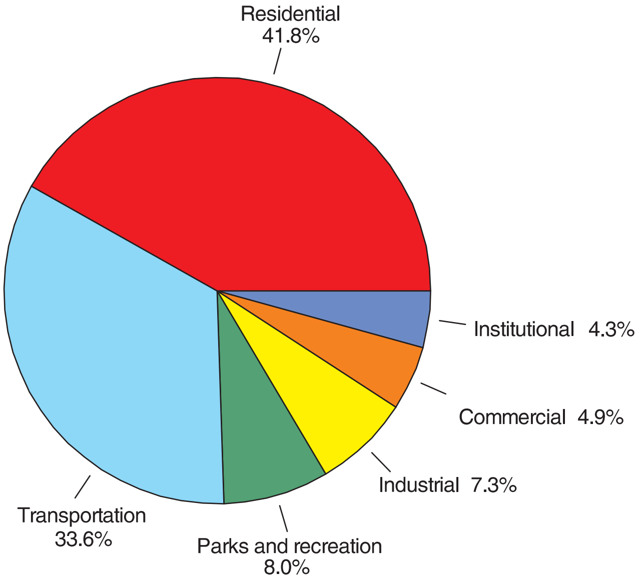

Figure 5. Approximate land-use percentages in the developed area of Miami-Dade County.

River Canal and Miami Canal by 1913, and the construction of Hillsboro Canal and West Palm Beach Canals (north of the study area) shortly thereafter. By 1921, all four canals had hurricane gates at the Lake Okeechobee end. Many of the canals along the east coast of southern Florida were completed by the 1930's for the purpose of flood protection, but were uncontrolled and did not impede saltwater intrusion.

During 1943-45, saltwater intrusion became a serious threat to the water supplies of southern Florida because of severe drought conditions. The need for a system of gated control structures on the primary east coast canals was realized and came to fruition with the creation in 1948 of the Central and Southern Florida Flood Control Project, designed by the U.S. Army Corps of Engineers (USACE). Operational control of this project came under the direction of the Central and Southern Flood Control District, now known as the SFWMD, which was created in 1949 by the Florida Legislature. An extensive series of levees was constructed, eventually resulting in the formation of major water-conservation areas used to supply water for ENP and to store water for recharging the Biscayne aquifer. Most of these water-conservation areas were completed by the early 1960's. As a result of this highly managed system, the hydrology of southern Florida has been altered. Recent plans have focused on "replumbing" the water-management system to restore more natural flow to ENP.

The water-management system provides flood protection during the wet season (June-October) by storing excess water in the water-conservation areas and by discharging water through the east coast canals when flood events occur. During the dry season (November-May), replenishment of ground-water supplies along the east coast is accomplished by conveying water through the primary canals from the water-conservation areas. All of the major tributary canals along the east coast contain gated control structures that are opened during flood situations to permit discharge of excess water, and are closed during dry periods to maintain high freshwater heads, recharge ground water, and retard saltwater intrusion.

A key element in the operation of the water-management system is the communications and control system, which is a sophisticated electronic system that relies on remote acquisition and control units to operate control structures and to record hydrologic and meteorological data. These data are transmitted by way of telemetry to the operations control center in West Palm Beach, Fla. (north of Broward County), where decisions are made regarding water-management needs.

The close hydraulic connection that exists between ground and surface water in southern Florida is due to the highly transmissive nature of the Biscayne aquifer, the sole source of drinking water for residents of Miami-Dade County. Depending on the relation of the canal stages to the surrounding water table, water is exchanged from surface water to ground water or vice versa, and canals can be classified as either "gaining" or "losing" (fig. 6). At the east coast canal sites, the gates are opened during the wet season to discharge excess water to the Atlantic Ocean and are closed during the dry season to prevent saltwater intrusion. When the gates are opened during the wet season, canal stages generally become lower than the surrounding water table, inducing ground-water flow to the canals (gaining) and eventual discharge to tide. During the dry season, the gated control structures are closed to prevent saltwater intrusion; however, the ground-water hydraulic gradient is generally seaward, and the inland reaches of the coastal canals continue to collect ground water and transport it downstream to the coastal controls. The stages at the gated control structures are generally higher than the surrounding ground-water levels, and the canals (losing) recharge the aquifer and retard saltwater intrusion.

Canal-aquifer relations can also affect water quality. During dry periods when there is no flow, the canals tend to be chemically and physically stratified, resembling long lakes. During periods of flow, mixing occurs in the canals and ground-water seepage contributes highly mineralized water devoid of oxygen to the canals. Recharge to the tributary canals can be the result of rainfall, surface runoff, inflow from secondary canals, seepage through levees, and in some cases, releases from water-conservation areas or from Lake Okeechobee (by way of Miami Canal), all of which provide water of varying quality. The canals also provide a permanent surface for evaporation.

DATA-COLLECTION METHODS AND PROCEDURES

During periods of flow, water samples were collected for the determination of nitrogen and phosphorus species that truly represent the stream cross section. This was accomplished by collecting depth-

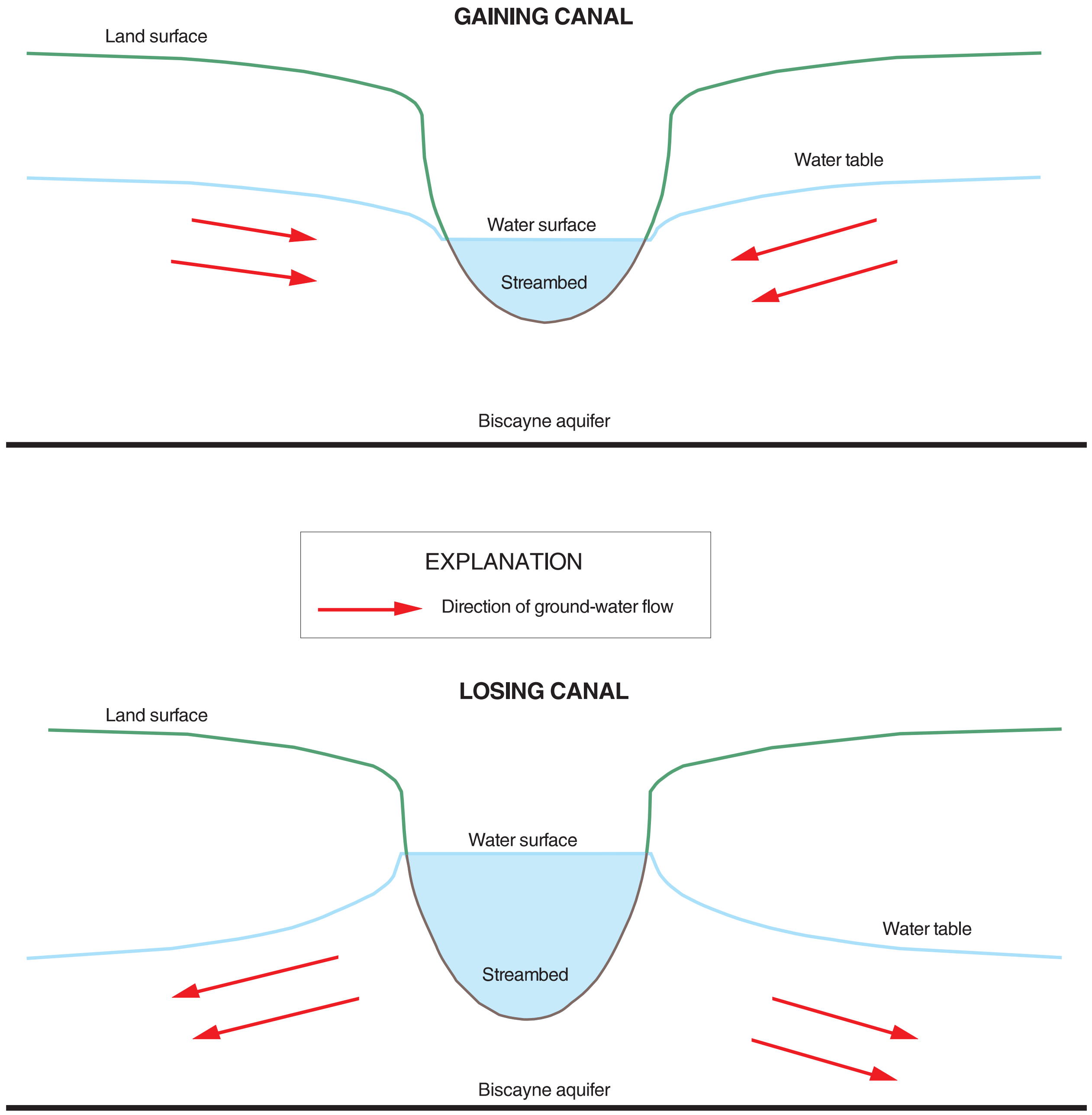

Figure 6. Hydraulic connection between gaining and losing canals.

integrated samples and point (grab) samples from midstream at 0.5- and 1.0-m depths for comparison. These samples were collected mostly upstream of the gated control structures at locations where most of the historical data were collected. Additionally, hydrologic data were collected concurrent with each sampling event for use in the determination of instantaneous discharge. Based on these data, statistical comparisons were made between point (grab) and depth-integrated samples, and models were developed to estimate total nitrogen and total phosphorus loads.

Sample Collection and Processing

Depth-integrated and point (grab) samples for nutrients were collected from the gated control structures at the east coast canal sites in Miami-Dade County during periods of flow. Most of the samples were collected near low tide when the gates at the sites usually are open. Depth-integrated samples were collected by means of the equal-width-increment method (fig. 7), which commonly is used when a discharge measurement is not made before sampling. In this

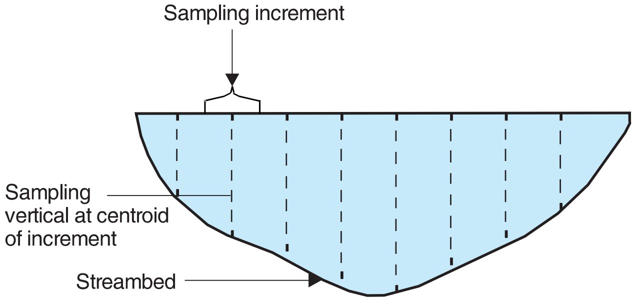

Figure 7. Depth-integrated sample collected by use of the equal-width-increment method.

method, the width of the stream is subdivided into equal-width intervals with a sampling vertical associated with each interval.

In each cross section for the study, 8 to 10 verticals were used. The first vertical selected was half the distance of the first interval from the edge of the stream bank, and the other verticals were equally spaced apart across the stream from the first vertical. Because flow velocities of the east coast canals in Miami-Dade County are nearly always less than 2 ft/s (feet per second), the weighted-bottle method was used to collect each sample. The weighted bottle does not sample isokinetically (nozzle velocity equal to stream velocity); however, it can be used during low flows and when differences in water quality across the stream are believed to be insignificant (Shelton, 1994, p. 11). In the initial step, the vertical with the greatest velocity is selected; the weighted bottle is then lowered and raised at a constant rate so that it is not overfilled when returned to the surface. For each specific site, this transit rate was maintained throughout for all the verticals in the cross section, and a sample from each vertical was composited in a churn splitter for processing. The transit rate as well as the nozzle size was varied for each specific site in order to prevent overfilling of the bottle.

During sample processing, the water in the churn was stirred by the churn disc at a rate of about 9 in/s (inches per second) to minimize error, with care being exercised to prevent the churn disc from breaking the surface. A total of 125 mL (milliliters) of this composite sample was siphoned off into an amber polyethylene bottle, chilled immediately, and within 48 hours was shipped to the USGS Water Quality Service Unit in Ocala, Fla., for analysis according to the procedures described by Fishman and Friedman (1989). The constituents determined were total organic nitrogen, ammonia, nitrite, nitrate, nitrite plus nitrate nitrogen, total phosphorus, and orthophosphate.

A point (grab) sample was collected concurrently with each depth-integrated sample. Point (grab) samples, depending on the site, were collected at 0.5 or 1.0 m below the surface near the centroid of flow by using a Niskin bottle. This bottle is spring loaded so that a messenger can trip it shut at the appropriate depth. After collection of the point (grab) sample, 125 mL of the sample was transferred from the Niskin bottle into an amber polyethylene bottle, chilled, and shipped for analysis according to protocol (Fishman and Friedman, 1989).

Before each sampling trip, the Niskin bottle, weighted bottle, and churn splitter were cleaned with a dilute nonphosphate detergent and then rinsed with tap water followed by deionized water. Two rinses with native water were required for the samplers before sample collection at each east coast canal site. Between sampling sites, the samplers were rinsed with deionized water before being rinsed with native water.

Quality Assurance Samples

To ensure the integrity of the field data collected for the study, quality assurance samples (equipment blanks, field blanks, and split samples) were used extensively in the data-collection phase. Blank solutions essentially are samples free of the analytes being determined in the environmental samples. An equipment blank is a blank solution that is processed through all of the equipment used in the collection and processing of the environmental samples. Field blanks are actually equipment blanks done in the field and are subject to all aspects of the data-collection efforts as the environmental samples, including processing, preservation, transport, and laboratory handling. Two types of field and equipment blanks were used: one for the Niskin bottle and the other for the weighted bottle and churn splitter. These two field blank solutions consisted of inorganic blank water prepared at the USGS Water Quality Service Unit and were processed and analyzed according to protocol. Analytical results from the equipment blanks and field blanks indicated that most of the concentrations for the individual nitrogen and phosphorus species were below the detection limits for the analytical methods.

Split samples were collected concurrently by the USGS and DERM to verify interlaboratory accuracy. The sampling data consisted of point (grab) samples that were collected from the same Niskin bottle by both agencies. The samples were sent to the USGS Water Quality Service Unit and to the DERM laboratory for analysis.

Determination of Instantaneous Discharge

During 1960-61, the USACE performed a study on a 1:16 scale physical model of a typical SFWMD gated east coast canal site (U.S. Army Corps of Engineers, 1963). Test results indicated that four possible flow regimes exist: submerged orifice flow, submerged weir flow, free orifice flow, and free weir flow. The USACE developed theoretical flow equations for the stage-discharge relations for the gated spillway east coast canal sites under these regimes. In their laboratory analyses, the USACE determined experimental values for the discharge coefficients for the equations under these flow regimes, relating the coefficients and pertinent variables in plots (U.S. Arms Corps of Engineers, 1963). Since then, the SFWMD has applied the USACE equations and calibrated them for each east coast canal site (Otero, 1994).

Because only experimental discharge coefficients existed for gated spillways and culverts for the various flow regimes, a study was conducted to develop discharge-coefficient ratings based on actual field conditions (Swain and others, 1997). The discharge-coefficient ratings were determined from field measurements made by an Acoustic Doppler Current Profiler (ADCP). The ADCP uses the Doppler shift in reflected acoustic signals to determine the velocity of moving water (RD Instruments, 1989). A discharge measurement can be made rapidly at low, irregular flow conditions, which often exist for the east coast canal sites. The discharge-coefficient ratings developed by this methodology were used in the determination of instantaneous discharge for each sampling event. The upstream and downstream stages and gate readings were recorded before and after each sampling event. The gates were held stationary during the sampling periods. Discharge-related data collected during each sampling event were used in the following equations to compute discharge for the submerged orifice and weir flow regimes.

Submerged orifice flow for gated spillways is expressed by the equation (Collins, 1977):

$$Q = C_{gs} L h \sqrt{2g(H-h)} \ , \tag{1}$$

where Q is discharge, in cubic feet per second; C_{gs} is the discharge coefficient relative to the function of a gate opening and submergence; L is length of gate sill, in feet; g is acceleration of gravity, in feet per square second; H, is headwater height above sill, in feet; and h is tailwater height above sill, in feet. C_{gs} can be derived from field measurements by rearranging equation 1 as:

$$C_{gs} = \frac{Q}{Lh\sqrt{2g(H-h)}} \ . \tag{2}$$

Submerged weir flow for gated spillways is expressed by the equation (U.S. Army Corps of Engineers, 1963):

$$Q = C_{ws} L h \sqrt{2g(H-h)} \ , \tag{3}$$

which can be rearranged in the form:

$$\frac{Q}{Lh\sqrt{2g}} = C_{ws}\sqrt{H-h} \ , \tag{4}$$

where C_{ws} is a discharge coefficient for submerged weir flow. C_{gs} should approach C_{ws} as the gate opening approaches submerged weir flow conditions.

Ratings for gated culverts include multiple flow conditions depending on submergence of the upstream and downstream ends. The standard rating equation for a submerged culvert used in southern Florida originates from the orifice-flow equation:

$$H - h = K\frac{v^2}{2g} , \tag{5}$$

where K is a flow coefficient which accounts for the entrance, friction, and exit losses; $v = Q/A$, the mean flow velocity; and A is the open area of the gate. With some manipulation, equation 5 becomes (Swain and others, 1997, p. 7):

$$Q = AC_c\sqrt{2g(H-h)} \,, \qquad (6)$$

where C_c is a submerged culvert coefficient. C_{gs}, C_{ws}, and C_c are the discharge coefficients determined under actual field conditions for submerged orifice flow (gated spillways), submerged weir flow (gated spillways), and submerged culvert flow, respectively.

ESTIMATION OF NUTRIENT LOADS AND WATER-QUALITY ANALYSES

Water samples were collected from the gated control structures at the east coast canal sites in Miami-Dade County (fig. 1) for the purpose of developing models that could be used to estimate nitrogen and phosphorus loads. Box plots were constructed (shown later) to show differences in the median concentration of the individual nutrient species at each site. Additionally, field measurements of selected water-quality constituents (specific conductance, pH, water temperature, and dissolved oxygen) were made at specific intervals to describe vertical and horizontal variability of an east coast canal site (S-22). Plots have been constructed for site S-22 (shown later) to determine whether total nitrogen and total phosphorus concentrations increase with depth.

Statistical comparisons also are made to determine differences between point (grab) samples collected at 0.5 and 1.0 m deep and depth-integrated samples collected from the east coast canal sites. Finally, a least-squares regression analysis technique is used to determine the relation between nutrient loads and instantaneous discharge. By use of this technique, the total number of samples required to attain a certain level of precision in load estimates is reduced and error in load estimates is minimized because models are based on complete data sets and not daily observations, which are subject to sampling errors of a single observation.

The constituent load at any given time can be determined if the constituent concentration and the discharge at the time of sampling is known. The load is computed as follows:

$$L = C \times Q \times 0.002697 \,, \qquad (7)$$

where L is the constituent load, in short tons per day; C is the constituent concentration, in milligrams per liter; Q is discharge at time of sampling, in cubic feet per second; and 0.002697 is a conversion factor to short tons per day.

Distribution of Nutrient Concentrations

More than 200 depth-integrated samples were collected for this study during a range of flow conditions to determine nutrient concentrations in the east coast canal waters of Miami-Dade County. The individual nitrogen and phosphorus species (depth-integrated samples) that were analyzed for the study are summarized in table 2. The box plots presented and discussed herein show concentrations of nutrients among three land-use categories: forested/wetland, agricultural, and urban. Forested/wetland areas are considered to be the land-use category with the lowest level of human activities whereas the agricultural and urban areas are the highest (Ham and Hatzell, 1996, p. 12). The results coincide with expected differences in nutrient concentrations based on knowledge of point and nonpoint source influences and nutrient cycling.

The median total organic nitrogen concentration for all the east coast canal sites was 0.75 mg/L, which represents the highest median concentration of any nutrients sampled for in this study. The box plot in figure 8 indicates that median total organic nitrogen concentrations generally were higher in forested/wetland and urban areas than in agricultural areas. The minimum total organic nitrogen concentration of 0.20 mg/L was detected at site S-21A along Princeton Canal, and the maximum total organic nitrogen concentration of 1.7 mg/L was detected at site S-26 along Miami Canal. Miami Canal is one of five canals that distributes water from Lake Okeechobee to the highly urbanized southeastern coast of Florida. The entire reach of the canal traverses forested/wetland, agricultural, and urban areas. Agricultural and urban runoff and sewage effluent discharges contribute to the water-quality degradation in Miami Canal.

Table 2. Summary of nutrient concentrations determined at the east canal sites in Miami-Dade County

[All units in milligrams per liter as nitrogen or as phosphorus]

Category	Total organic nitrogen	Ammonia	Nitrite	Nitrate	Total nitrite plus nitrate	Total nitrogen	Total phosphorus	Orthophosphate
Site G-58								
Mean	0.55	1.27	0.020	0.090	0.11	1.92	0.23	0.17
Median	.55	1.20	.020	.080	.10	1.95	.24	.17
Maximum	.60	1.50	.047	.154	.20	2.10	.31	.26
Minimum	.50	1.10	<.001	.020	.02	1.70	.13	.09
No. of samples	6	6	6	6	6	6	4	6
Site G-93								
Mean	.58	.39	.036	.360	.39	1.37	.05	.02
Median	.52	.25	.035	.300	.35	1.30	.05	.02
Maximum	1.00	.80	.081	.570	.60	2.20	.08	.04
Minimum	.40	.05	.003	.017	.02	.61	.04	.01
No. of samples	10	10	10	10	10	10	10	10
Site S-20								
Mean	1.05	.06	.003	.004	.007	1.12	.007	.002
Median	1.10	.05	.003	.004	.008	1.10	.007	.001
Maximum	1.20	.10	.006	.007	.010	1.30	.010	.010
Minimum	.83	.04	.002	.002	.002	.88	.006	<.001
No. of samples	11	11	11	11	11	11	11	11
Site S-20F								
Mean	.32	.04	.016	1.21	1.23	1.58	.010	.004
Median	.32	.04	.016	1.19	1.20	1.50	.010	.002
Maximum	.47	.10	.020	1.38	1.40	1.90	.020	.010
Minimum	.21	.03	.014	.99	1.00	1.40	.007	<.001
No. of samples	10	10	10	10	10	10	10	10
Site S-20G								
Mean	.40	.06	.017	.780	.79	1.21	.025	.008
Median	.40	.06	.019	.930	.95	1.30	.02	.006
Maximum	.50	.10	.028	1.180	1.20	1.70	.08	.020
Minimum	.23	.02	.004	.056	.06	.51	.01	<.001
No. of samples	7	8	8	8	8	7	8	8
Site S-21								
Mean	0.58	0.19	0.019	0.37	0.39	1.16	0.012	0.006
Median	.56	.20	.022	.46	.50	1.20	.010	.004
Maximum	.75	.30	.037	.69	.70	1.70	.030	.020
Minimum	.41	.10	<.001	.07	.07	.62	.007	<.001
No. of samples	17	17	17	17	17	17	17	17
Site S-21A								
Mean	.30	.03	.021	3.69	3.7	4.04	.006	.002
Median	.30	.03	.020	3.69	3.7	4.10	.005	.001
Maximum	.42	.07	.028	4.38	4.4	4.70	.010	.004
Minimum	.20	.01	.014	2.88	2.9	3.30	.004	<.001
No. of samples	7	7	7	7	7	7	7	7

Table 2. Summary of nutrient concentrations determined at the east canal sites in Miami-Dade County--(Continued)

[All units in milligrams per liter as nitrogen or as phosphorus]

Category	Total organic nitrogen	Ammonia	Nitrite	Nitrate	Total nitrite plus nitrate	Total nitrogen	Total phosphorus	Ortho-phosphate
Site S-22								
Mean	.78	.08	.010	.12	.12	.97	.010	.004
Median	.75	.09	.009	.11	.12	.97	.010	.004
Maximum	1.10	.20	.024	.19	.20	1.20	.020	.008
Minimum	.55	.01	.004	.07	.08	.75	.006	.002
No. of samples	21	21	21	21	21	21	21	21
Site S-25								
Mean	.76	.21	.015	.13	.14	1.10	.049	.023
Median	.75	.10	.013	.08	.09	1.00	.045	.014
Maximum	1.10	.50	.037	.28	.30	1.50	.100	.060
Minimum	.50	.06	.006	.07	.08	.81	.030	.004
No. of samples	14	14	14	14	14	14	14	14
Site S-25B								
Mean	.79	.07	.022	.35	.37	1.20	.02	.007
Median	.79	.07	.020	.29	.32	1.20	.02	.004
Maximum	1.00	.20	.056	.59	.60	1.40	.03	.040
Minimum	.55	.01	.001	.24	.25	.89	.01	.001
No. of samples	20	20	20	20	20	20	20	20
Site S-26								
Mean	1.05	0.60	0.032	0.170	0.20	1.8	0.020	0.004
Median	1.00	.61	.020	.110	.15	1.7	.020	.003
Maximum	1.70	1.10	.100	.460	.56	2.8	.050	.020
Minimum	.70	.03	.006	.002	.01	1.3	.008	.001
No. of samples	19	19	19	19	19	19	19	19
Site S-27								
Mean	.79	.64	.028	.190	.22	1.6	.04	.02
Median	.70	.65	.030	.180	.21	1.7	.04	.02
Maximum	1.10	.96	.040	.300	.33	1.9	.05	.03
Minimum	.55	.41	.010	.060	.07	1.4	.03	.01
No. of samples	17	17	17	17	17	17	16	17
Site S-28								
Mean	.86	.16	.011	.110	.110	1.10	.04	.014
Median	.86	.15	.009	.070	.080	1.10	.03	.010
Maximum	1.20	.47	.036	.260	.300	1.50	.07	.020
Minimum	.66	.02	.002	.001	.002	.83	.03	.008
No. of samples	18	18	18	17	18	18	18	18

Table 2. Summary of nutrient concentrations determined at the east canal sites in Miami-Dade County--(Continued)

[All units in milligrams per liter as nitrogen or as phosphorus]

Category	Total organic nitrogen	Ammonia	Nitrite	Nitrate	Total nitrite plus nitrate	Total nitrogen	Total phosphorus	Orthophosphate
Site S-29								
Mean	1.02	.29	.021	.19	.22	1.51	.020	.003
Median	1.00	.30	.020	.18	.20	1.51	.020	.002
Maximum	1.30	.50	.064	.48	.50	2.10	.030	.007
Minimum	.85	.03	<.001	.06	.06	1.60	.008	<.001
No. of samples	17	17	17	17	17	17	17	17
Site S-123								
Mean	.37	.16	.004	.13	.13	.58	.03	.014
Median	.39	.09	.005	.08	.09	.56	.02	.004
Maximum	.47	.70	.01	.40	.40	.87	.12	.07
Minimum	.26	.03	<.001	.01	.01	.31	.02	.002
No. of samples	7	8	8	8	8	7	8	8

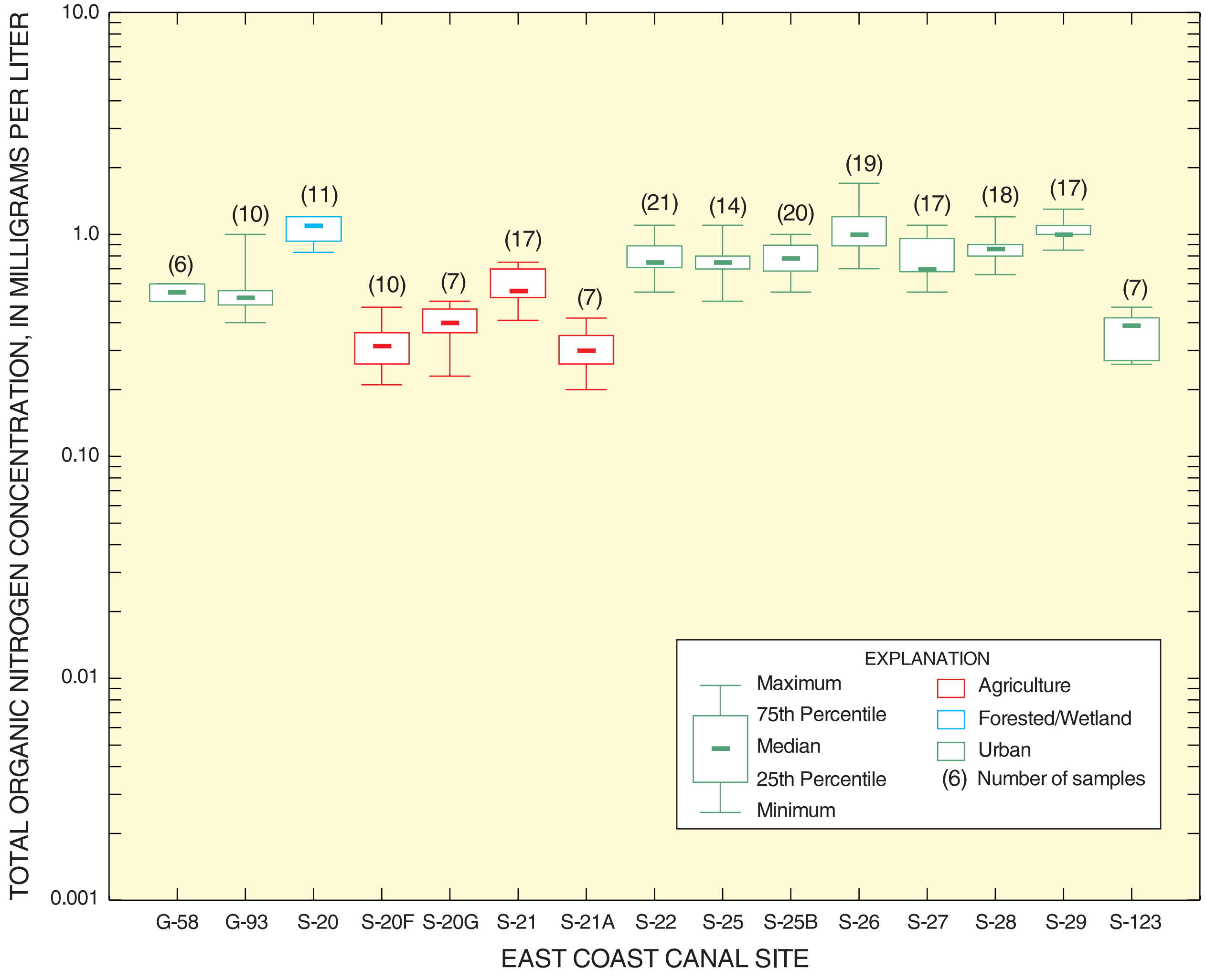

Figure 8. Total organic nitrogen concentrations among land-use categories.

Total organic nitrogen is transformed by the process of ammonification to ammonia. The median ammonia concentration for all the east coast canal sites was 0.10 mg/L. The box plot in figure 9 indicates that median ammonia concentrations tend to be higher in urban areas than in agricultural and forested/wetland areas. The minimum ammonia concentration of 0.01 mg/L was detected at sites S-21A, S-22, and S-25B. The maximum ammonia concentration of 1.5 mg/L was detected at site G-58 along Arch Creek. The upper Arch Creek watershed is highly contaminated as a result of possible landfill leachate and industrial waste (Alleman, 1995, p. 20). The highest ammonia concentration detected was well below the U.S. Environmental Protection Agency (USEPA) maximum concentration of 2.1 mg/L for chronic exposure to aquatic organisms (U.S. Environmental Protection Agency, 1986). However, five sites (G-58, G-93, S-26, S-27, and S-123) had concentrations that exceeded the Miami-Dade County DERM water-quality freshwater standard of 0.5 mg/L for ammonia.

Nitrite is an intermediate species in the nitrification process by which ammonia is transformed into nitrate under aerobic conditions which exist in most canals. The median nitrite concentration for all the east coast canal sites was 0.02 mg/L, which is below USEPA maximum contaminant level of 1.0 mg/L (U.S. Environmental Protection Agency, 1986). The maximum contaminant level is the maximum permissible level of a contaminant in water which is delivered to any user of a public water system. Median nitrite concentrations tend to be higher in agricultural areas than in urban and wetland areas. The minimum nitrite concentration of less than 0.001 mg/L was

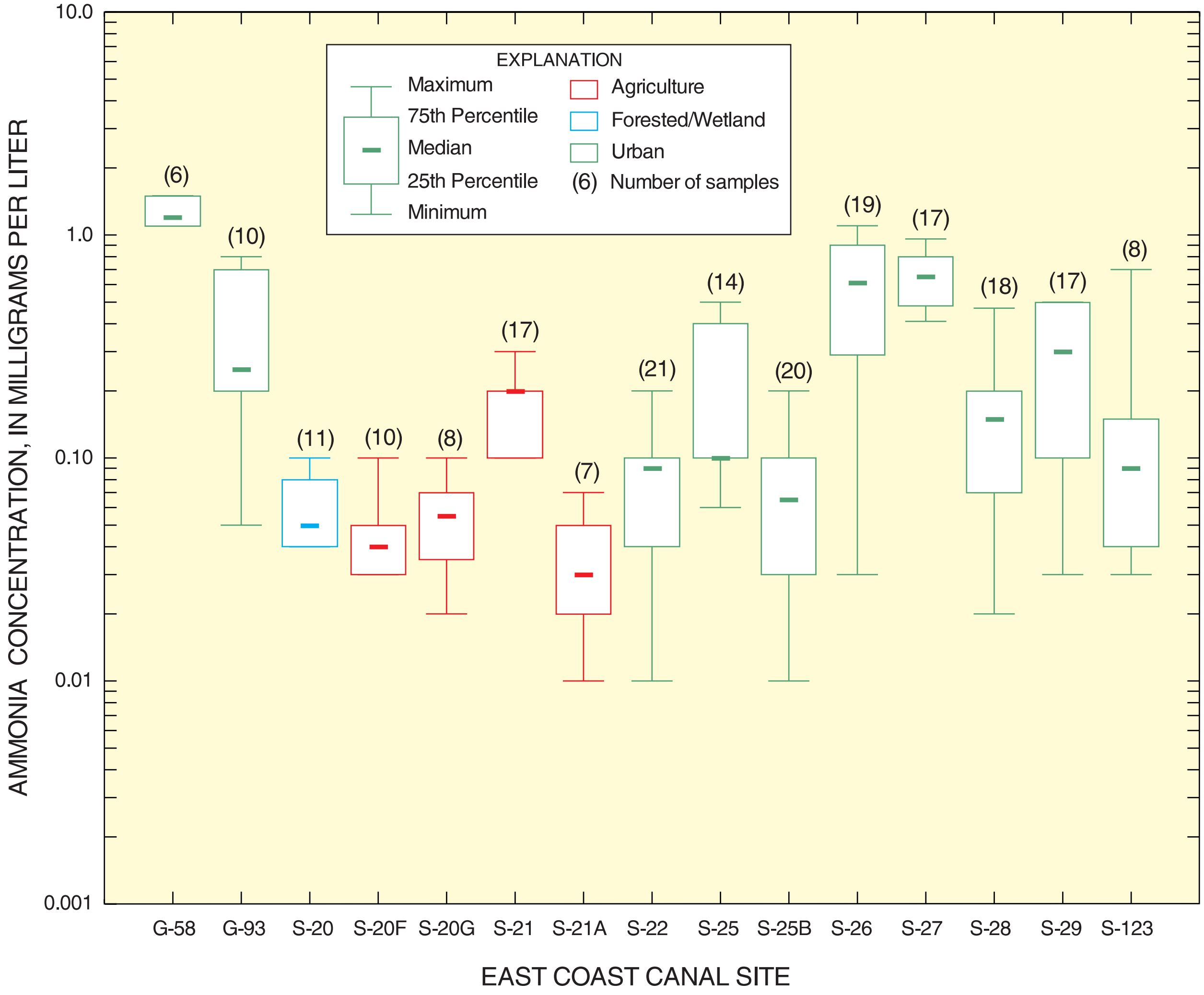

Figure 9. Total ammonia concentrations among land-use categories.

detected at sites G-58, S-21, S-29, and S-123, and the maximum nitrite concentration of 0.10 mg/L was detected at site S-26 (table 2).

Nitrate represents the end product of the nitrification process. The median nitrate concentration for all the east coast canal sites was 0.18 mg/L. The box plot in figure 10 indicates that median nitrate concentrations tend to be higher in agricultural areas than in forested/wetland and urban areas. The minimum nitrate concentration of 0.001 mg/L was detected at site S-28; the maximum nitrate concentration of 4.38 mg/L was detected at site S-21A (table 2), which is well below the maximum contaminant level of 10.0 mg/L (U.S. Environmental Protection Agency, 1986). The maximum nitrate concentration, which was the highest maximum concentration of any nutrients sampled for in this study, was probably the result of agricultural runoff.

Total nitrogen, which represents the sum of total organic nitrogen, ammonia, nitrite, and nitrate concentrations, ranged from 0.31 to 4.7 mg/L for all the east coast canal sites (table 2). The maximum total nitrogen concentration of 4.7 mg/L was detected at site S-21A in an agricultural area, with nitrate comprising 93 percent of this maximum concentration. The minimum total nitrogen concentration of 0.31 mg/L was detected at site S-123.

The median nitrite plus nitrate nitrogen concentration for all the east coast canal sites was 0.20 mg/L. The box plot in figure 11 indicates that median nitrite plus nitrate concentrations tend to be higher in agricul-

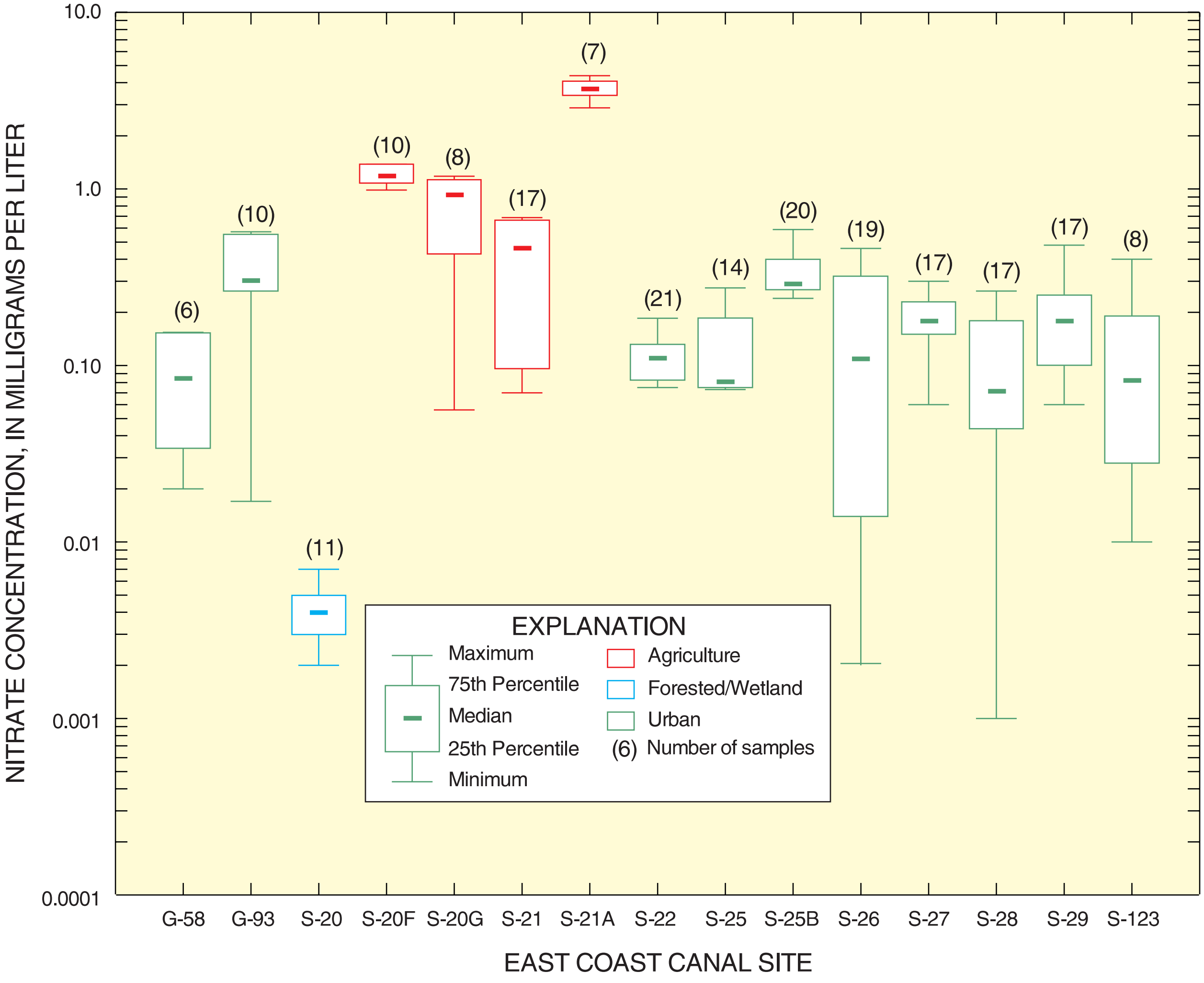

Figure 10. Total nitrate concentrations among land-use categories.

tural areas than in forested/wetland and urban areas. The minimum nitrite plus nitrate concentration of 0.002 mg/L was detected at sites S-20 and S-28; the maximum nitrite plus nitrate concentration of 4.4 mg/L was detected at site S-21A, which is below the maximum contaminant level of 10.0 mg/L (U.S. Environmental Protection Agency, 1986).

The median total phosphorus concentration for all the east coast canal sites was 0.02 mg/L. The box plot in figure 12 indicates that median total phosphorus concentrations generally were higher in urban areas than in forested/wetland and agricultural areas. The minimum total phosphorus concentration of 0.004 mg/L was detected at S-21A; the maximum total phosphorus concentration of 0.31 mg/L was detected at site G-58 (table 2), which is above the recommended upper concentration limit of 0.10 mg/L to control eutrophication (U.S. Environmental Protection Agency, 1986). Additionally, the maximum total phosphorus concentration of 0.12 mg/L at site S-123 (table 2) slightly exceeded the recommended upper concentration limit. High concentrations of total phosphorus usually reflect contamination as a result of human activities, such as from point or nonpoint source discharges.

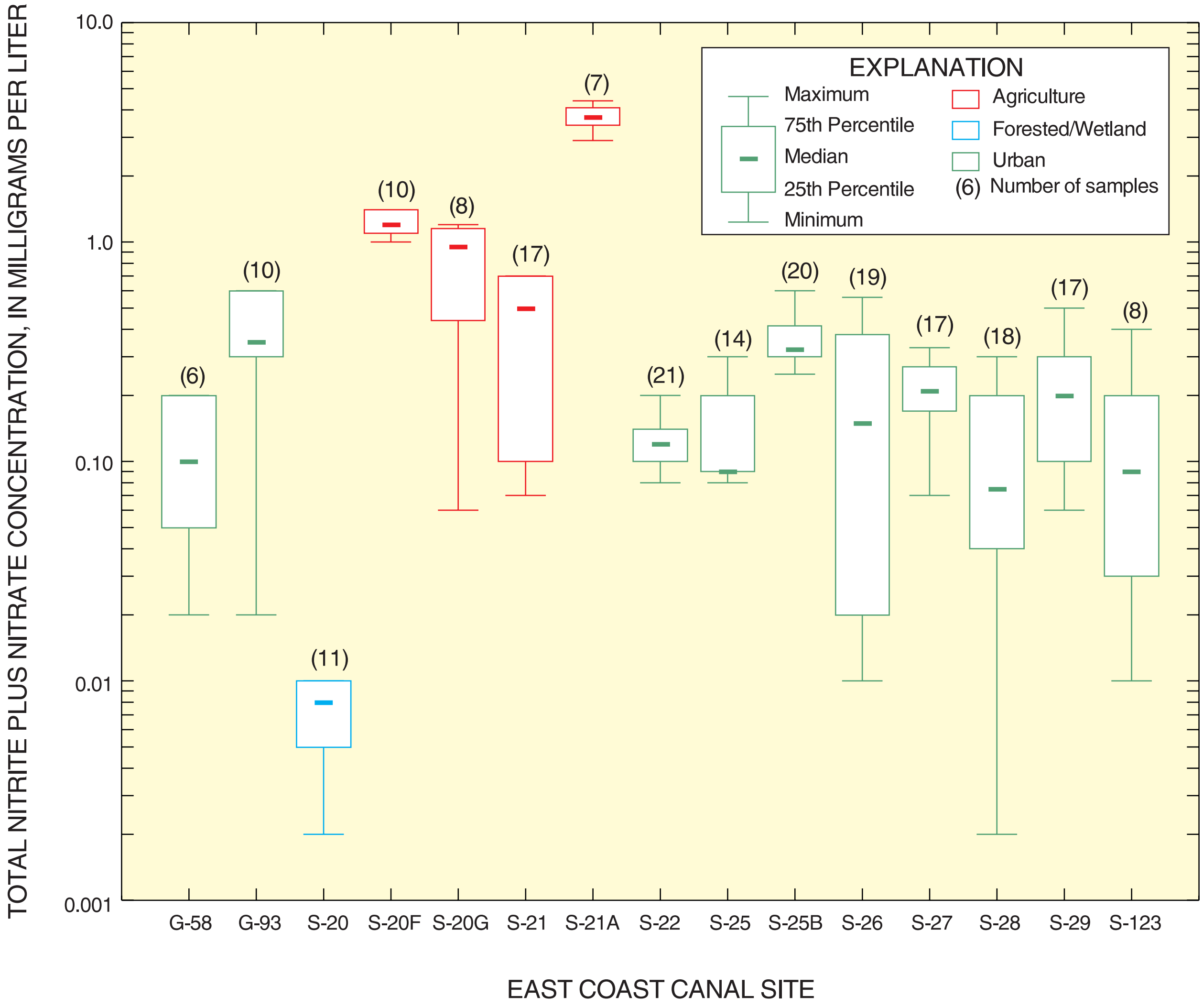

Figure 11. Total nitrite plus nitrate concentrations among land-use categories.

The median orthophosphate concentration for all the east coast canal sites was 0.005 mg/L, which is the lowest median concentration of any nutrients sampled for in this study. The box plot in figure 13 indicates that median orthophosphate concentrations generally were higher in urban areas than in forested/wetland and agricultural areas. The minimum orthophosphate concentration of less than 0.001 mg/L was detected at sites S-20, S-20F, S-20G, S-21, S-21A, and S-29, and the maximum orthophosphate concentration of 0.26 mg/L was detected at site G-58 (table 2). High concentrations of orthophosphate as well as total phosphorus are usually indicative of human activities, such as from point or nonpoint source discharges.

Water-Quality Cross-Section Surveys

Water-quality cross-section surveys for specific conductance, pH, water temperature, and dissolved oxygen were conducted to document water-quality cross-section homogeneity in the east coast canal system. On October 7, 1997, field measurements of these constituents were made (from near the surface at 1-ft intervals to the streambed) at site S-22 along Snapper Creek Canal from seven verticals about 10 ft equidistant from each other in the cross section. During the field measurements, instantaneous discharge was determined to be 414 ft^3/s (cubic feet per second). The only water-quality constituent to show any variation with depth was dissolved oxygen.

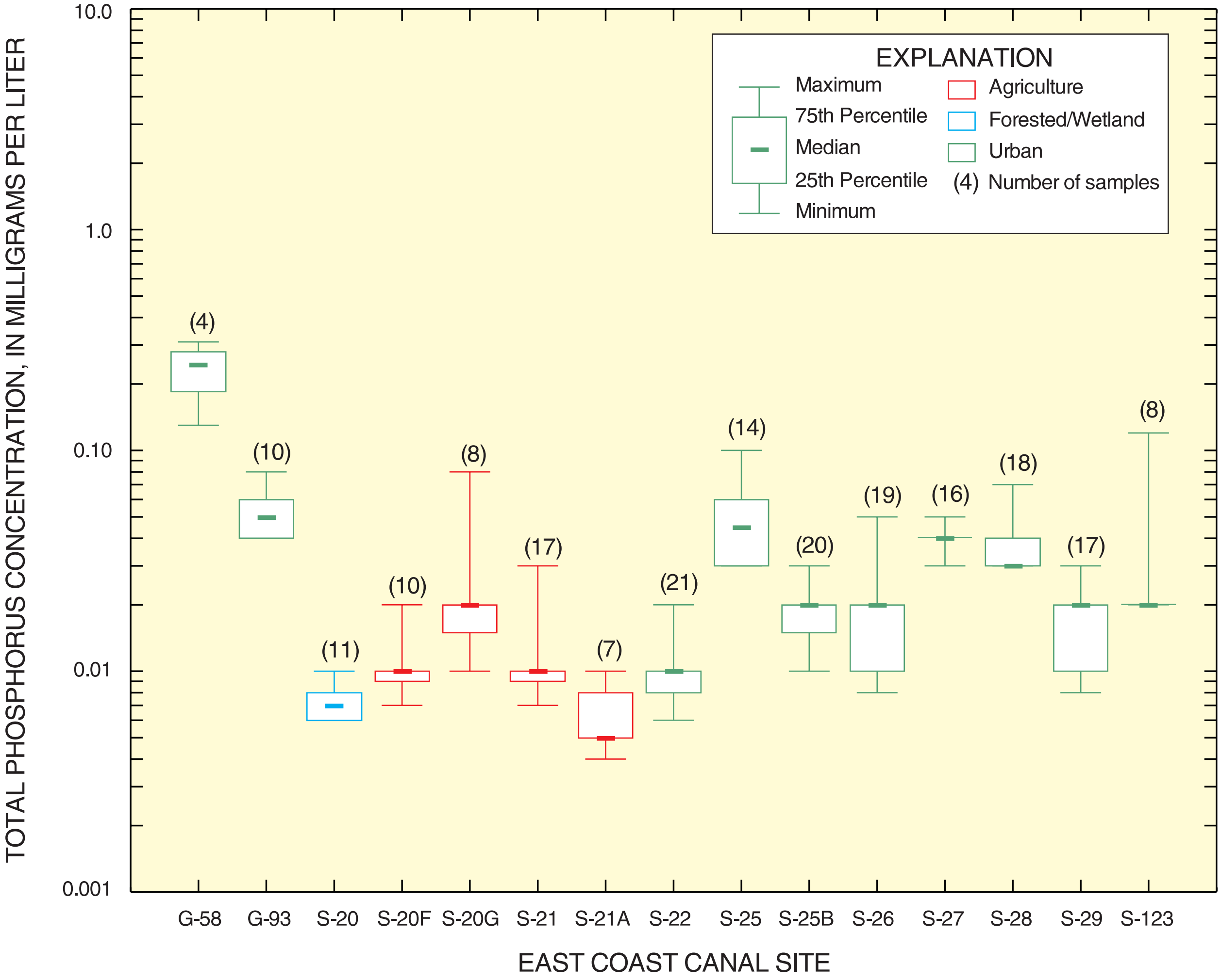

Figure 12. Total phosphorus concentrations among land-use categories.

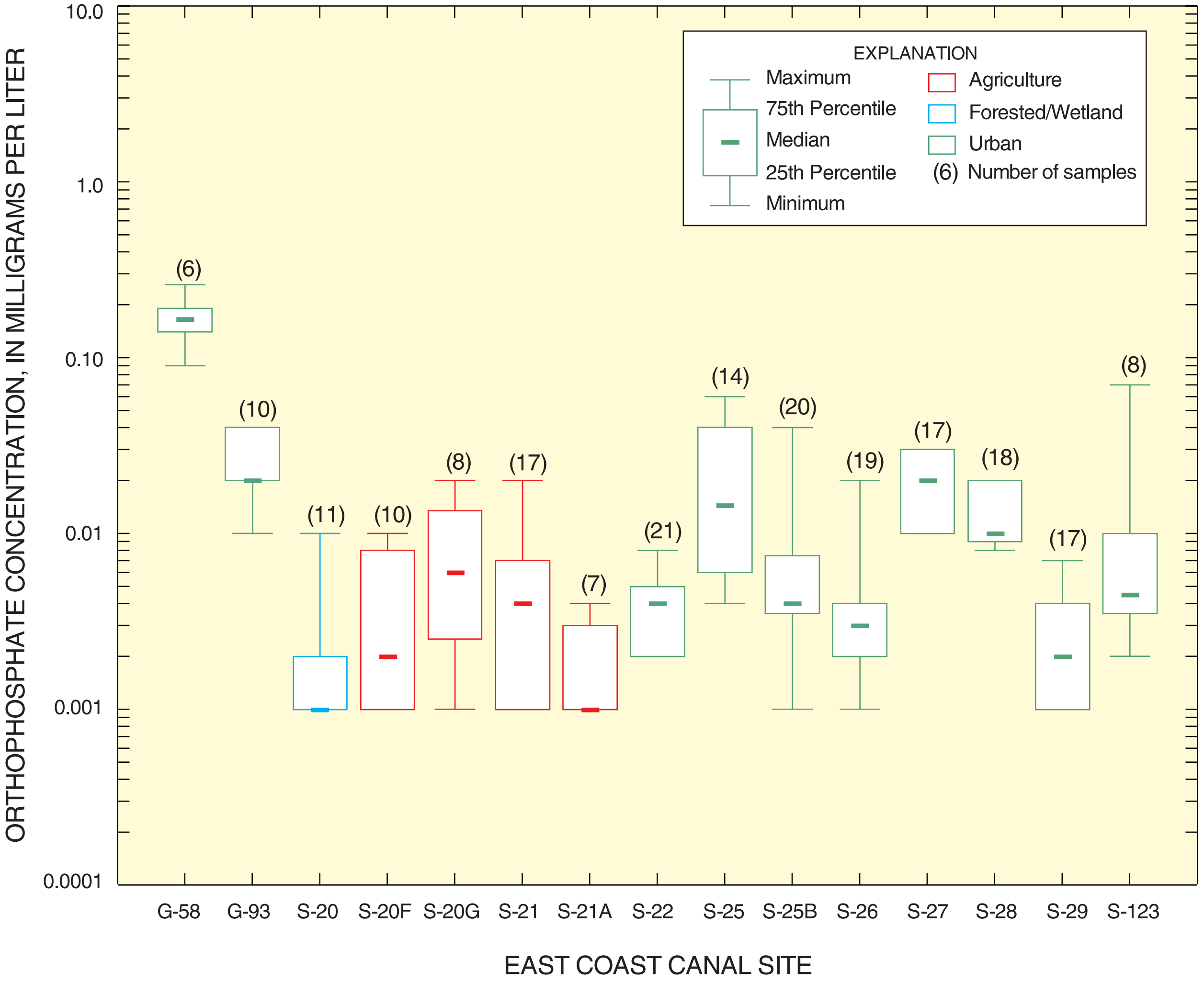

Figure 13. Orthophosphate concentrations among land-use categories.

Plots of dissolved-oxygen concentration for the seven vertical profiles at site S-22 along Snapper Creek Canal (from the left bank looking downstream) were constructed and are shown in figure 14. Dissolved-oxygen concentration decreased with increasing depth for all but one vertical. The vertical 46.2 ft from the left bank showed no variation with depth, which probably can be attributed to complete mixing in the vertical. In June and July 1996, preliminary water-quality surveys at three verticals in the cross section were performed at sites S-22, S-25B, S-26, and S-28. Results were similar to those for the water-quality survey done at site S-22 in October 1997, with dissolved-oxygen concentration decreasing with depth.

During the same October 1997 period when a water-quality cross-section survey was made at site S-22, total nitrogen and total phosphorus concentrations also were determined at the same location. Water samples were collected midstream at a depth of 1 ft below the surface and at 2-ft intervals thereafter, until near the streambed at a depth of 15 ft. The plots in figure 15 indicate that both total nitrogen and total phosphorus concentrations increased with depth. Additionally, point (grab) samples at 1.0 m deep near midstream and depth-integrated samples were collected for analysis of suspended-sediment concentration. Significant differences in suspended-sediment concentration were detected between the point (grab) and depth-integrated samples (1.0 and 3.0 mg/L, respectively). This is plausible because suspended-sediment concentrations usually are higher near the streambed during periods of flow than near the surface and would not be “captured” by a point (grab) sample.

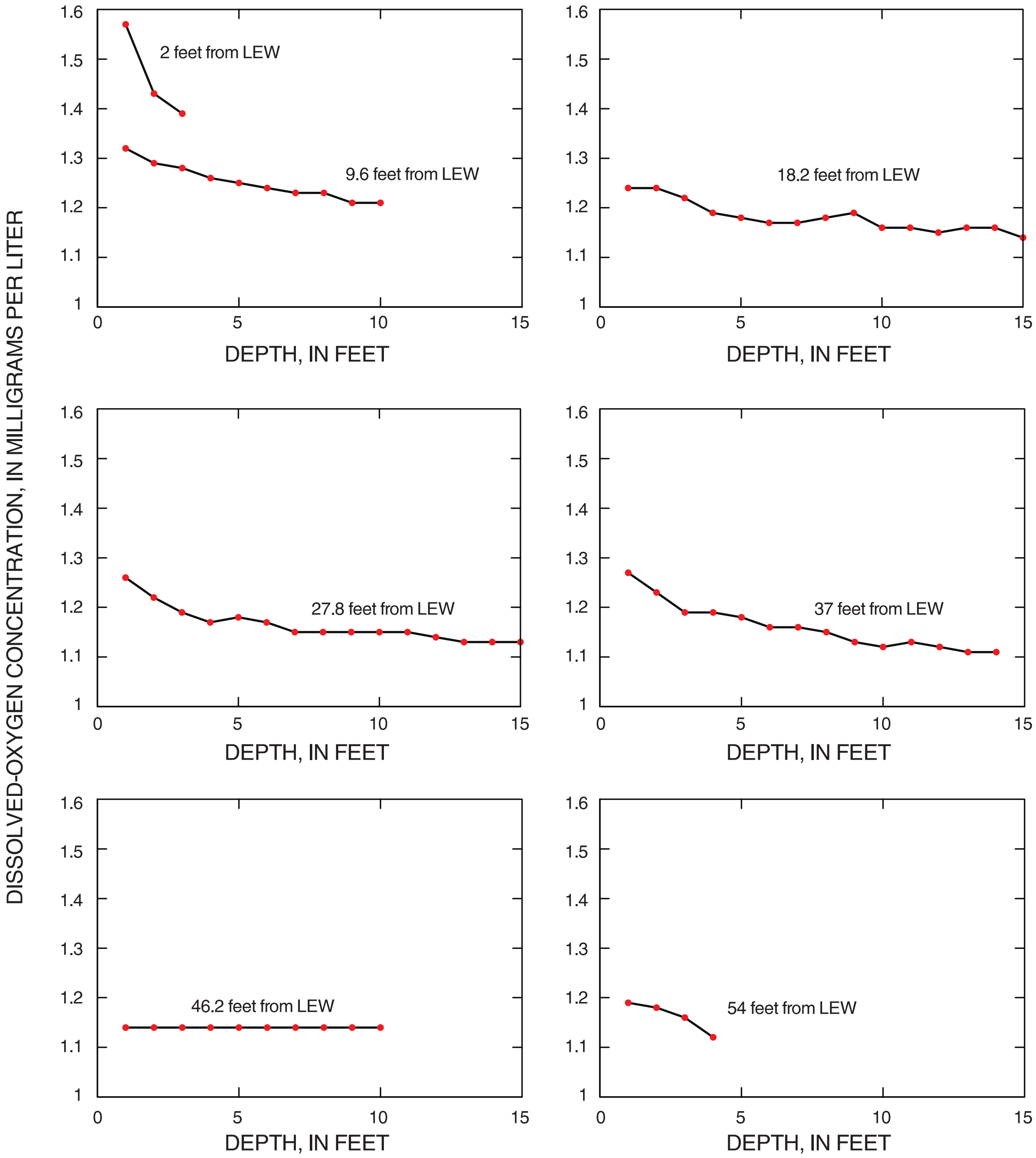

Figure 14. Vertical profiles of dissolved-oxygen concentration in Snapper Creek Canal at site S-22 at various distances from left bank looking downstream (LEW). Instantaneous discharge is 414 cubic feet per second. LEW represents left edge of water.

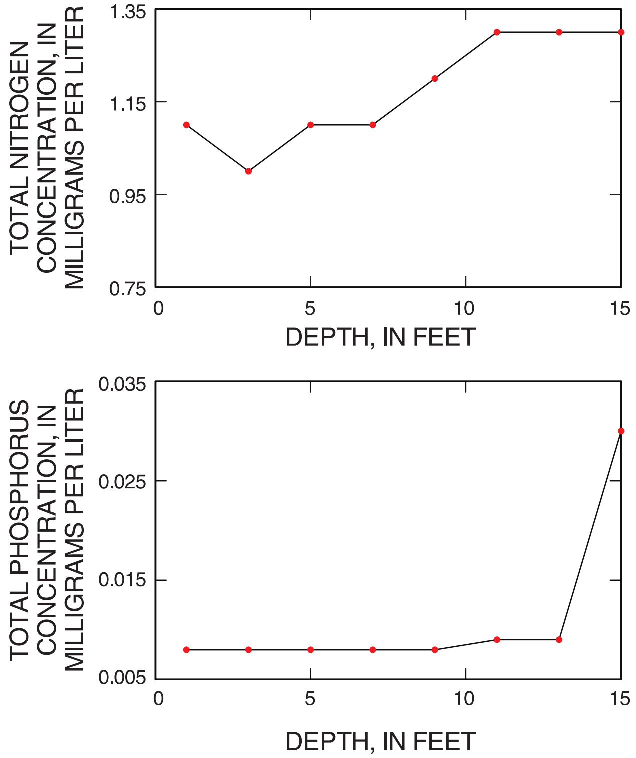

Figure 15. Depth profiles of total phosphorus and total nitrogen concentrations from midstream in Snapper Creek Canal at site S-22. Instantaneous discharge is 414 cubic feet per second.

Statistical Comparisons of Point (Grab) and Depth-Integrated Samples

Statistical tests were used in this study to compare differences between point (grab) and depth-integrated samples for total nitrogen and total phosphorus concentrations from the east coast canal sites in Miami-Dade County. A matched-pair approach using the Wilcoxon signed ranks test (WSRT), a nonparametric statistical test, was used to compute differences between sample pairs and to rank the absolute values of the nonzero differences. Each rank was assigned a negative sign if the original difference is negative and a positive sign otherwise. Because of the small sample sizes, the exact form of the test statistic (W+) was used rather than the large sample approximation (Helsel and Hirsch, 1992, p. 144). The W+ statistic is the sum of all the ranks having a positive sign. The p-value (Helsel and Hirsch, 1992, table B6) is the attained significance level and must be less than the alpha or significance level to reject the null hypothesis of no difference in medians between the data sets. The significance (or alpha level) for a one-sided WSRT is 0.05 and indicates that there is a 5 percent, or a 1 in 20, probability of incorrectly rejecting the null hypothesis when it is actually true. When a two-sided WSRT is used (x is either larger or smaller than y), the significance (or alpha level) then becomes 0.025. The WSRT was used in this study because the null hypothesis of normality is difficult to reject for small sample sizes, and water-quality data frequently assume a non-normal or asymmetric distribution.

Table 3 presents the results of the WSRT for total nitrogen and total phosphorus concentrations for 12 of the east coast canal sites by comparing: (1) differences between point (grab) samples collected at 1.0 m deep and depth-integrated samples, (2) point (grab) samples collected at 0.5 m deep and depth-integrated samples, and (3) point (grab) samples collected at 0.5 and 1.0 m depths. There were no statistically significant differences in total nitrogen concentration between point (grab) samples collected at 1.0 m deep and depth-integrated samples; however, there were statistically significant differences in total phosphorus concentration for the same comparisons at sites S-21, S-25B, and S-28. No sites showed any statistically significant differences in total nitrogen concentration between point (grab) samples collected at 0.5 m deep and depth-integrated samples, and only one site (S-21) showed statistically significant differences in total phosphorus concentration. At none of the sites were statistically significant differences detected in total nitrogen and total phosphorus concentrations between point (grab) samples collected at 0.5 m and 1.0 m depths. Based on these statistical results, depth-integrated samples probably provide a more realistic representation of total phosphorus concentrations in the stream cross section than do the point (grab) samples.

The WSRT, like all hypothesis tests, only indicates which differences are statistically significant and does not describe the relation between the variables. For this reason, differences between point (grab) and depth-integrated samples that were indicated by the WSRT were further examined by using the line of organic correlation (LOC). This fitting procedure, first proposed in hydrology by Kritskiy and Menkel (1968), is also known as the reduced major axis, unique solution, or equivalence line and is represented by the equation:

$$\hat{y} = \bar{y} + \operatorname{sgn}(r)\frac{Sy}{Sx}(x - \bar{x}) \ , \qquad (8)$$

where $\hat{y}$ is the estimated value of y, $\bar{y}$ is the average of y values, $\bar{x}$ is the average of x values, Sy is the standard deviation of y values, Sx is the standard deviation of x values, and sgn (r) is the sign of correlation coefficient (1 if r is greater than 0, 0 if $r = 0$, and -1 if r is less than 0).

The LOC is basically a geometric method as it minimizes the sum of the areas of right triangles formed by the horizontal and vertical lines from data points to the fitted line (Hirsch and Gilroy, 1984, p. 707). Unlike an ordinary least-squares regression technique, the LOC is useful in describing the relation between two variables,

Table 3. Statistical interpretation of total nitrogen and total phosphorus concentrations at the east coast canal sites in Miami-Dade County

[Significant level (a) = 0.05/2 = 0.025; P values from Helsel and Hirsch (1992, table B6); DI, depth integrated; >, greater than the value; N/A, not applicable]

Site No.	Constituent	Statistical difference between samples											
		Grab samples collected at 1.0-meter depth and DI samples				Grab samples collected at 0.5-meter depth and DI samples				Grab samples collected at 0.5-meter and 1.0-meter depths			
		No. of sample pairs	No. of nonzero differences	W+ statistic	P value	No. of samples	No. of nonzero differences	W+ statistic	P value	No. of sam-ples	No. of nonzero differences	W+ statistic	P value
G-58	Total nitrogen	6	4	3.5	>0.312	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
	Total phosphorus	6	4	4	>.312	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
G-93	Total nitrogen	10	8	15	>.191	4	3	4	.375	4	4	7.5	>0.188
	Total phosphorus	10	2	1.5	>.375	4	0	0	>.375	4	1	1	>.375
S-21	Total nitrogen	17	15	56	>.151	8	7	11	>.188	8	7	17.5	>.188
	Total phosphorus	**17**	**14**	**94**	**.003**	**8**	**7**	**25.5**	**.023**	8	4	2	>.312
S-21A	Total nitrogen	7	7	15	>.188	5	5	10	>.219	5	4	8	>.188
	Total phosphorus	7	4	8	.188	5	1	1	>.375	5	4	2	>.312
S-22	Total nitrogen	21	14	80	.045	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
	Total phosphorus	21	7	14.5	>.188	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
S-25	Total nitrogen	14	9	29	>.180	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
	Total phosphorus	14	6	14	>.219	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
S-25B	Total nitrogen	20	13	63	.122	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
	Total phosphorus	**20**	**10**	**55**	**.001**	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
S-26	Total nitrogen	18	8	10.5	>.191	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
	Total phosphorus	18	6	17	.109	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
S-27	Total nitrogen	17	7	10.5	>.188	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
	Total phosphorus	17	4	4	>.312	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
S-28	Total nitrogen	18	11	44	>.160	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
	Total phosphorus	**18**	**6**	**21**	**.016**	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
S-29	Total nitrogen	17	11	38.5	>.160	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
	Total phosphorus	17	7	18	>.188	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
S-123	Total nitrogen	7	6	19	.047	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
	Total phosphorus	7	4	10	.062	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A

STATISTICALLY SIGNIFICANT DIFFERENCES BETWEEN GRAB AND DEPTH-INTEGRATED SAMPLES

🟦 **Equation from line of organic correlation is Grab = 0.2973 DI + 0.0057. Direction of bias of grab is low.**

🟪 **Equation from line of organic correlation is Grab = 0.25 DI + 0.00625. Direction of bias of grab is low.**

🟩 **Equation from line of organic correlation is Grab = 0.8255 DI – 0.0018. Direction of bias of grab is low.**

🟦 **Equation from line of organic correlation is Grab = 1.093 DI – 0.008. Direction of bias of grab is low.**

and thus, was used in this study to describe the relation between point (grab) and depth-integrated samples. The LOC eliminates variance reduction in estimates by eliminating the correlation coefficient from the slope. The variances of the LOC estimates are then in proportion to the variances of the original data (Helsel and Hirsch, 1992, p. 278).

Statistically significant differences for total nitrogen and total phosphorus between point (grab) and depth-integrated samples collected from sites S-21, S-25B, and S-28, as defined by the LOC (the same samples and sites as defined by the WSRT in table 3), are shown in figure 16. As illustrated, point (grab) samples collected from 0.5- and 1.0-m depths underestimate total phosphorus concentrations compared to depth-integrated samples. Because of the affinity of total phosphorus to adsorb to particulate matter, underestimation of concentrations by point (grab) samples probably is due to the reduced suspended-sediment concentrations near the surface compared to concentrations near the streambed during periods of flow. The suspended-sediment concentration determined from a point (grab) sample during the October 1997 water-quality cross-section survey at site S-22 was only one-third the concentration determined from the depth-integrated sample collected concurrently. However, suspended-sediment concentrations in southern Florida canals are low; for example, the average concentration based on 108 samples collected from site S-26 along Miami Canal over a 20-year period was 6.7 mg/L.

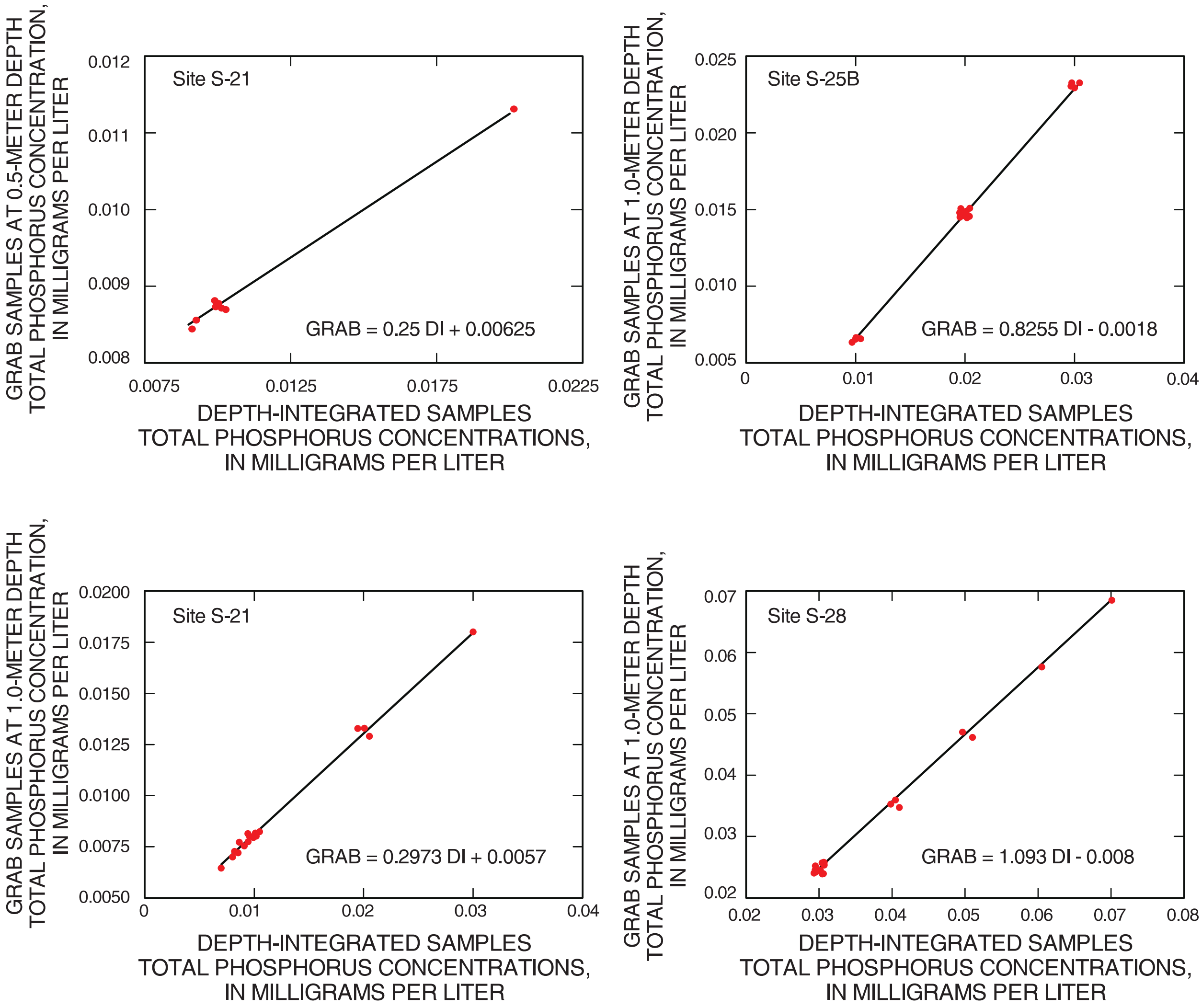

Figure 16. Comparison of grab from midstream and depth-integrated (DI) samples for total phosphorus concentrations at sites S-21, S-25B, and S-28 as defined by the line of organic correlation.

Additionally, other factors contributing to differences between sample types could be related to the degree of mixing at the sample location based upon physical characteristics of the channel, such as distance upstream or downstream from the control structures and configuration of the channel.

Model Development

An ordinary least-squares regression technique was used to develop predictive equations for the purpose of estimating total nitrogen and total phosphorus loads discharged from the east coast canals to Biscayne Bay. The predictive equations can be used to estimate the value of a dependent variable from observations on a related or independent variable. In this study, load was used as the dependent or response variable and discharge as the independent or explanatory variable. Because discharge is used in the computation of load, linearity and the best fit equation can be established or developed more easily by relating load to discharge rather than concentration to discharge.

Using more than one independent variable, such as stage, rainfall, gate opening, and discharge, multiple linear regression was attempted to improve the predictive equations. However, because discharge is computed from stage and gate openings and is based upon rainfall, collinearity between independent variables precluded this approach. A smoothing procedure, called locally weighted scatterplot smooth (LOWESS), was used by plotting load as a function of discharge to determine the degree of linearity between the two variables. When it was deemed necessary to improve the linear relation between load and discharge, transformations of the independent variable were made based upon the relation of the curve to the Mosteller and Tukey bulging rule (Helsel and Hirsch, 1992, p. 229).

Improvement in the models was based on increases in the adjusted coefficient of determination (R^2), which explains the amount of variation in the load determined by discharge and reduction in the predicted error sums of squares (PRESS) statistic. The models selected were those having the highest adjusted R^2 and the lowest PRESS statistic as well as the lowest root mean square error or standard error of the regression. The null hypothesis of no linear relation between load and discharge was rejected at the 0.05 significance level (α level) when the attained significance level (p-value) was less than 0.05.

An important part of model development is residuals analysis. Two assumptions of an ordinary least-squares regression are: (1) variance of the residuals is constant (homoscedastic) over the range of values, and (2) residuals are independent. Plots of predicted values against residuals were examined, and where nonconstant variance (heteroscedasticity) over the range of values was observed, log transformations of the response variables were made. Because of errors in comparing log space with real space, no comparisons were made with this analogy between transformed and nontransformed models based on the adjusted R^2 or PRESS statistics.

A key element in model development is regression diagnostics. Basing model adequacy solely on the adjusted R^2 may prove to be inadequate because there may be no indication as to whether the data have been well fitted. Examination of data points for leverage, influence, or outliers was required to verify model adequacy. Outliers in the x direction were determined to be significant if they exceeded $3\,p/n$ where p is the number of coefficients and n equals the number of samples (Helsel and Hirsch, 1992, p. 247). Studentized residuals were used to examine outliers in the y direction, and Cook's *D* was used to determine influence from outliers. Observations were considered to have high influence if Cook's *D* exceeded the value for the *F* distribution for $p+1, n-p$ at $\alpha = 0.1$ (Helsel and Hirsch, 1992, p. 249). Numerous data values demonstrated high leverage, but only a few data values showed both high leverage and high influence.

The ESTIMATOR Program

Because continuous discharge data are currently being computed and long-term water-quality data are available at site S-26 along Miami Canal, a software program, called ESTIMATOR, was used in the development of nitrogen and phosphorus load models and for the estimation of loads at the site. The ESTIMATOR program develops models and computes loads based on mean daily discharge and water-quality data files. This program was used at site S-26 (formerly part of the NASQAN network as previously discussed) because of the continuous discharge data available and the requirement that about 50 water samples should have been collected over at least a 2-year period. The ESTIMATOR program consists of a seven-parameter log/linear model employing the following regressors: a constant, a quadratic fit to the natural logarithm of discharge, a quadratic fit to time, and a sinusoidal first-order Fourier function to compensate for seasonality. The model is written as:

$$\ln L = \beta_0 + \beta_1 \ln Q + \beta_2 \ln^2 Q + \beta_3 T + \beta_4 T^2 + \beta_5 \sin 2\pi T + \beta_6 \cos 2\pi T , \qquad (9)$$

where ln is the natural logarithm, L is load, β_0 is the constant, β_1 to β_6 are the coefficients, Q is discharge, T is decimal time, T^2 is decimal time squared, and $\sin 2\pi T$ + $\cos 2\pi T$ are periodic functions.

The ESTIMATOR program employs a minimum variance unbiased estimator for the elimination of bias in the transformation of log space to real space. Regression models for total nitrogen and total phosphorus loads and coefficients statistically significant at the 95 percent confidence intervals for site S-26 are presented in table 4. In addition to the constant, both the logarithms of discharge and discharge squared were significant for the total nitrogen load model, whereas only the logarithm of discharge was significant for the total phosphorus load model. The program estimates monthly and annual mean daily loads. Maximum and minimum monthly mean daily and annual daily loads computed by the ESTIMATOR program at site S-26 for water years 1987 through 1996 are summarized in table 5.

Table 4. Regression models for the estimation of total nitrogen and total phosphorus loads at site S-26 developed from the ESTIMATOR program

[See equation 9 in text. The coefficients of determination (R^2) for both total nitrogen and total phoshorus models are 0.99. A total of 152 and 188 observations were used in the total nitrogen load and total phosphorus load models, respectively]

Constituent	Coefficient	Value
Total nitrogen Total phosphorus	β_0	-10.15[1] -13.81[1]
Total nitrogen Total phosphorus	β_1	1.003[1] .9995[1]
Total nitrogen Total phosphorus	β_2	.0011[1] -.0019
Total nitrogen Total phosphorus	β_3	.0034 -.0018
Total nitrogen Total phosphorus	β_4	.0005 -.0014
Total nitrogen Total phosphorus	β_5	-.0540 -.0403
Total nitrogen Total phosphorus	β_6	-.0532 -.0914

[1] Statistically significant at 95 percent confidence interval.

Table 5. Summary statistics for the estimation of total nitrogen and total phosphorus loads at site S-26 computed by the ESTIMATOR program for water years 1987-96

Water year	Constituent	Maximum monthly mean daily load (tons per day)	Minimum monthly mean daily load (tons per day)	Annual daily load (tons per year)
1987	Total nitrogen Total phosphorus	0.72 .008	0.011 1.85×10^{-4}	78.2 .70
1988	Total nitrogen Total phosphorus	1.68 .021	.004 6.32×10^{-4}	190 2.47
1989	Total nitrogen Total phosphorus	.54 .007	.00 .00	46.5 .61
1990	Total nitrogen Total phosphorus	1.01 .012	.00 .00	85.5 1.11
1991	Total nitrogen Total phosphorus	1.60 .018	.013 2.21×10^{-4}	144 1.81
1992	Total nitrogen Total phosphorus	2.63 .028	.040 6.55×10^{-4}	261 2.98
1993	Total nitrogen Total phosphorus	1.04 .012	.008 1.38×10^{-4}	188 2.18
1994	Total nitrogen Total phosphorus	.77 .008	.018 2.48×10^{-4}	127 1.45
1995	Total nitrogen Total phosphorus	2.00 .019	.00 .00	268 2.71
1996	Total nitrogen Total phosphorus	1.72 .016	.00 .00	199 2.19

Nutrient Loads Estimation Models

Measured nutrient loads were used to develop equations through simple linear regression analyses in order to estimate computed loads based on discharge. The measured data were mainly based on data collected from depth-integrated samples. The nutrient loads and/or discharge were occasionally transformed before simple linear regression techniques were employed to develop the "best fit" models used to estimate the loads. Results of the regression analyses relating load to discharge at the east coast canal sites are presented in table 6. The coefficients of determination (R^2) in table 4 were adjusted to conform with the number of degrees of freedom in the model.

Table 6. Results of regression analyses relating load to discharge at the east coast canal sites in Miami-Dade County

[Data based on depth-integrated samples, except for sites S-20, S-20F, and S-20G in which data are based on grab samples. Significant level (α) = 0.05; Annotations: ACD, adjusted coefficient of determination; N, nitrogen load, in tons per day; P, phosphorus load, in tons per day; Q, discharge, in cubic feet per second; ln, natural logarithm. Models are valid for discharges greater than zero]

Site No.	Discharge range (cubic feet per second)	Predictive equation	No. of samples	ACD (R^2)	Root mean square error	p-value	95 percent confidence intervals of the coefficient	
							Upper limit	Lower limit
G-58[1]	10 - 66	$N = 0.013 + 4.45 \times 10^{-3}Q$	6	0.99	0.01	0.00	5.07×10^{-3}	3.83×10^{-3}
		$P = -0.013 + 9.14 \times 10^{-3}\ln Q$	4	.77	.004	.08[2]	2.10×10^{-2}	-2.73×10^{-3}
G-93	30 - 237	$N = 1.5 \times 10^{-3} + 3.68 \times 10^{-3}Q$	10	.84	.113	.00	4.92×10^{-3}	2.44×10^{-3}
		$\mathrm{Ln}P = -5.69 + 1.16 \times 10^{-2}Q$	10	.81	.39	.00	1.58×10^{-2}	7.37×10^{-3}
S-20	143 - 237	$N = -0.12 + 3.76 \times 10^{-3}Q$	10	.69	.073	.00	5.64×10^{-3}	1.88×10^{-3}
		$P = 5.1 \times 10^{-4} + 9.4 \text{ x } 10^{-8}Q^2$	10	.79	.0005	.00	1.00×10^{-6}	5.80×10^{-8}
S-20F	346 - 1,080	$N = -13.8 + 2.58\ln Q$	9	.91	.26	.00	3.25	1.92
		$P = 5.08 \times 10^{-4} + 2.43 \times 10^{-5}Q$	9	.91	.001	.00	3.05×10^{-5}	1.80×10^{-5}
S-20G	286 - 429	$N = 0.225 + 9.8 \times 10^{-6}Q^2$	5	.71	.046	.046	1.93×10^{-5}	3.00×10^{-7}
		$P = 2.76 \times 10^{-4} + 5.53 \times 10^{-5}Q$	5	.97	.0005	.00	7.00×10^{-5}	4.05×10^{-5}
S-21	202 - 1,740	$N = -0.38 + 3.77 \times 10^{-3}Q$	17	.88	.45	.00	0.004	0.003
		$P = -7.38 + 10^{-4} + 4.27 \times 10^{-8}Q^2$	17	.89	.01	.00	0.004	0.003
S-21A	223 - 387	$N = 0.85 + 2.56 \times 10^{-5}Q^2$	7	.85	.33	.00	3.64×10^{-5}	1.47×10^{-5}
		$\mathrm{Ln}P = 4.72 - 1.71\ln Q$	7	.23	.24	.19[3]	1.30	-4.71
S-22	133 - 576	$\mathrm{Ln}N = -1.32 + 3.25 \times 10^{-3}Q$	21	.83	.14	.00	3.97×10^{-3}	2.54×10^{-3}
		$\mathrm{Ln}P = -6.11 + 3.81 \times 10^{-3}Q$	21	.61	.29	.00	5.52×10^{-3}	2.39×10^{-3}
S-25	21 - 82	$N = 3.61 \times 10^{-2} + 3.87 \times 10^{-5}Q^2$	14	.86	.32	.00	4.80×10^{-5}	2.94×10^{-5}
		$\mathrm{Ln}P = -6.22 + 3.18 \times 10^{-4}Q^2$	14	.78	.35	.00	4.20×10^{-4}	2.16×10^{-4}
S-25B	214 - 781	$N = 1.46 \times 10^{-2} + 3.17 \times 10^{-3}Q$	20	.82	.197	.00	3.88×10^{-3}	2.46×10^{-3}
		$P = -0.014 + 7.81 \times 10^{-5}Q$	20	.50	.01	.00	1.15×10^{-4}	4.16×10^{-5}
S-27	127 - 524	$N = -0.46 + 4.60 \times 10^{-3}Q$	17	.93	.13	.00	5.30×10^{-3}	3.91×10^{-3}
		$P = 4.05 \times 10^{-3} + 1.20 \times 10^{-4}Q$	16	.80	.006	.00	1.54×10^{-4}	8.75×10^{-5}
S-28	165 - 857	$N = -0.26 + 3.76 \times 10^{-3}Q$	18	.89	.206	.00	4.45×10^{-3}	3.07×10^{-3}
		$\mathrm{Ln}P = -4.26 + 2.40 \times 10^{-3}Q$	18	.58	.31	.00	3.43×10^{-3}	1.37×10^{-3}
S-29	333 - 1,440	$N = -17 + 3.09\ln Q$	17	.95	.35	.00	3.49	2.71
		$\mathrm{Ln}P = -4.93 + 1.87 \times 10^{-3}Q$	17	.79	.36	.00	2.38×10^{-3}	1.35×10^{-3}
S-123	514 - 1,330	$N = -1.10 + 3.11 \times 10^{-3}Q$	7	.93	.24	.00	4.01×10^{-3}	2.20×10^{-3}
		$P = 6.7 \times 10^{-4} + 5.34 \times 10^{-5}Q$	7	.99	.001	.00	5.59×10^{-5}	5.09×10^{-5}

[1] Upper and lower limits at site G-58 based on 90 percent confidence intervals of the coefficient.

[2] Statistically significant at (α) = 0.10.

[3] Not statistically significant for phosphorus load.

The adjusted R^2 for the total nitrogen load models ranged from 0.69 to 0.99 (table 4), indicating that from 69 to 99 percent of the variation in total nitrogen load is explained by discharge. The maximum adjusted R^2 of 0.99 was determined for sites G-58 (table 6) and S-26 (table 4), both in urban areas, and the minimum adjusted R^2 of 0.69 was determined for site S-20 (table 6) in a forested/wetland area. The average adjusted R^2 for all the total nitrogen load models was 0.87. Models for five sites (S-20F, S-20G, S-21A, S-25, and S-29) required transformation of the independent variable (discharge) to improve linearity, and models for one site (S-22) required log transformation of the dependent variable (total nitrogen load) due to nonconstant variance of the residuals (heteroscedasticity). All of the total nitrogen load models had p-values less than 0.05, indicating they were statistically significant at an alpha level of 0.05. Plots showing total nitrogen load as a function of discharge at the east coast canal sites are shown in figure 17.

The adjusted R^2 for the total phosphorus load models ranged from 0.23 to 0.99 (table 6), indicating from 23 to 99 percent of the variation in total phosphorus load is explained by discharge. The maximum adjusted R^2 of 0.99 was determined for sites S-123 (table 6) and S-26 (table 4) located in urban areas, and the minimum adjusted R^2 of 0.23 was determined for site S-21A in an agricultural area (table 6). The average adjusted R^2 for all the total phosphorus load models was 0.76, which is lower than that for the total nitrogen load models. Models for five sites (G-58, S-20, S-21, S-21A, and S-25) required transformation of the independent variable (discharge) to improve linearity, and models for six sites (G-93, S-21A, S-22, S-25, S-28, and S-29) required log transformation of the dependent variable (total phosphorus load) due to heteroscedasticity. Most of the total phosphorus load models had p-values less than 0.05; however, the predictive model for site G-58 had a p-value of 0.08, indicating that it is statistically significant only at an alpha level of 0.1. Thus, upper and lower limits of the slope coefficient for site G-58 represents the 90 percent confidence intervals, indicating less predictive power for the model. The total phosphorus load model for site S-21A, indicating an inverse relation between total phosphorus concentration and discharge was not statistically significant at either an alpha level of 0.05 or 0.10 and should not be used for estimating loads. Plots showing total phosphorus load as a function of discharge at the east coast canal sites are presented in figure 18.

Variation in constituent concentration relative to discharge generally is attributed to two physical processes: dilution or washoff (or a combination of both). Dilution usually occurs as constituents enter a stream or canal from a point source or because of ground-water seepage during discharge. This is reflected as an inverse relation between constituent concentration and discharge, and is common among the major ions. Washoff generally occurs as nutrients enter a stream because of surface runoff from urban or agricultural areas, and in this case, reflects an increase in constituent concentrations with discharge. Variation in phosphorus concentrations, however, is commonly the result of both the dilution and washoff processes. The low adjusted R^2 for some total phosphorus load models could be attributed to dilution and washoff occurring simultaneously, resulting in the poor linear relations between load and discharge.

Model Usage and Limitations

The models with the greatest predictive power are those with the highest adjusted R^2 and the lowest root mean square error. Because of project time constraints, data collected during this study span only 2 water years. The predictive power of the models might be enhanced if data were collected for a longer time period, such as 5 or 10 years, because a more representative range of hydrologic conditions is likely to occur over a longer time period. The small number of samples that were collected at some sites reflects the fact that the gates at the control structures rarely open, except during extreme rainfall events. Additionally, loads estimated by the models represent loads computed at the gated control structures on the canals. At some sites, such as S-25, S-25B, and S-26, the canal reaches (fig. 1) consist of several miles of ungaged sections to which both point and nonpoint source nutrient loads could be contributed before the terminus of the reaches at Biscayne Bay. This is particularly true of Miami River, downstream of S-26 along Miami Canal, which drains the urban and commercial areas of downtown Miami. Other processes, such as ground-water seepage, direct surface drainage, and precipitation, can also contribute nutrient loads to Biscayne Bay.

The upper and lower limits of the 95 percent confidence intervals of the slope coefficient for the total nitrogen and total phosphorus load models are presented in table 6. The significance of the 95 percent confidence intervals and the relation to the predictive power of the models is demonstrated by the following example. If the mean daily discharge at site S-28 along Biscayne Canal were 300 ft^3/s, the model-predicted total nitrogen load would range from 3.20 to 4.76 tons/d (tons per day) based on the lower and upper limits of the 95 percent confidence interval for the slope coefficient.

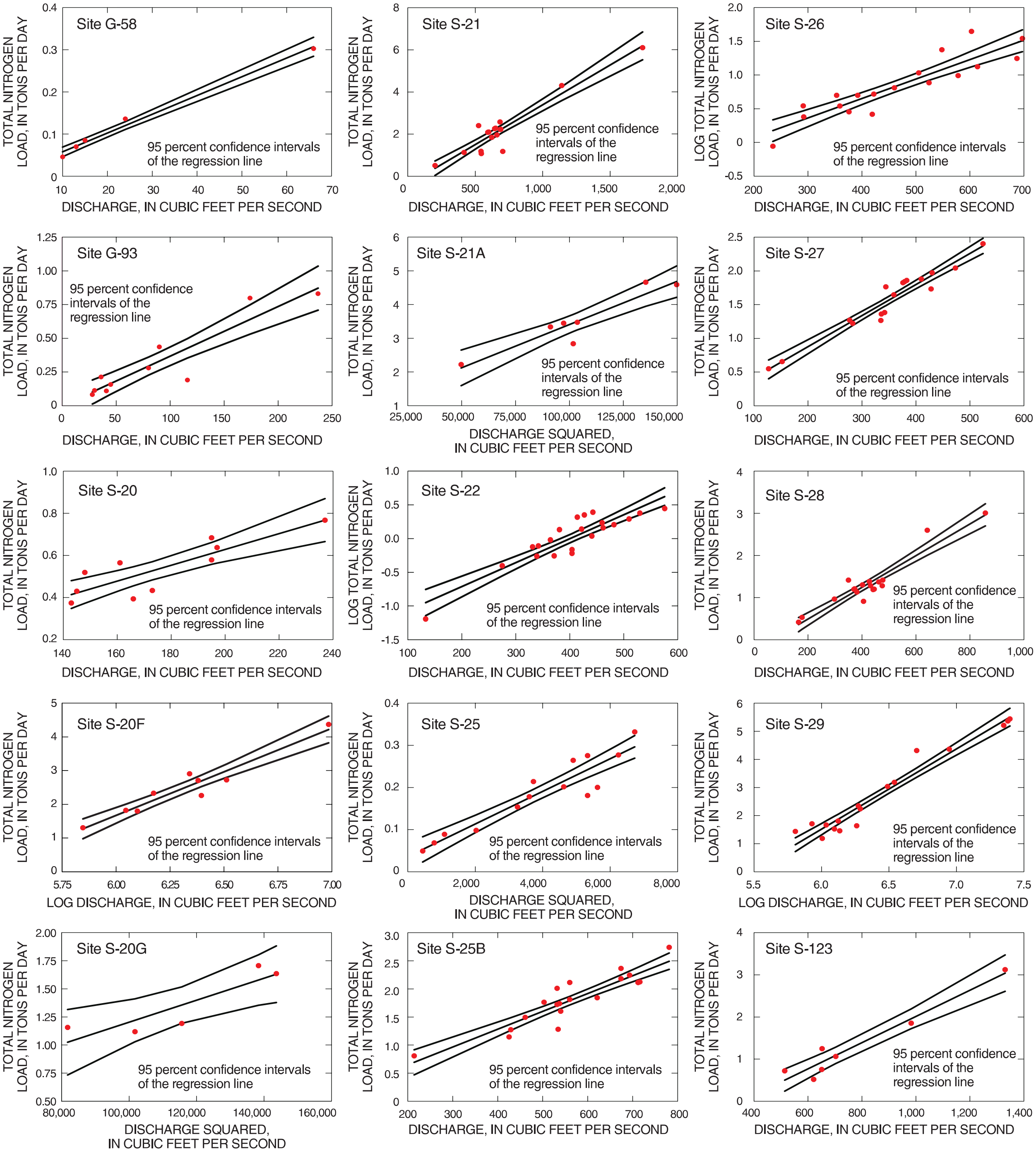

Figure 17. Total nitrogen load as a function of discharge at the east coast canal sites in Miami-Dade County.

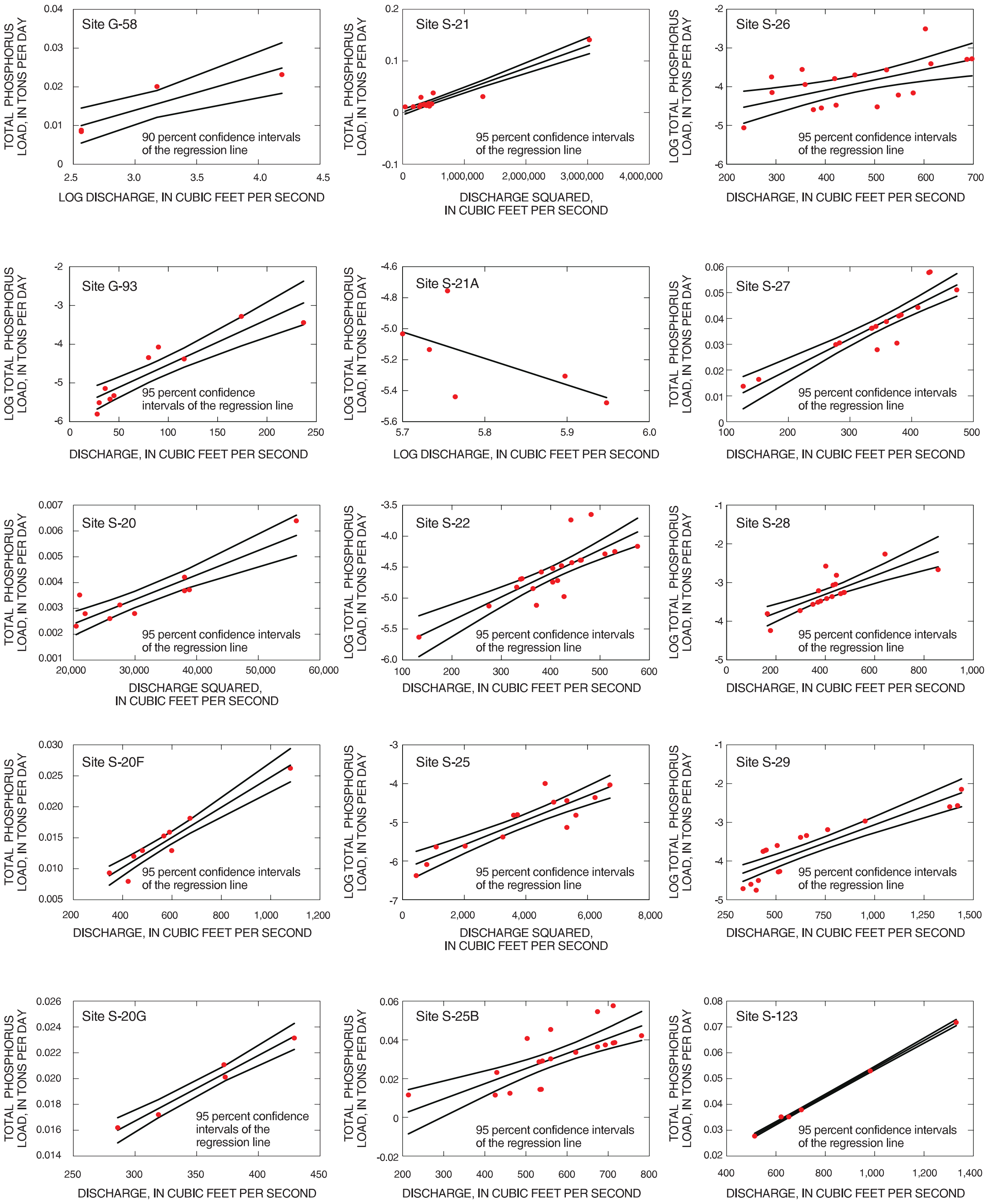

Figure 18. Total phosphorus load as a function of discharge at the east coast canal sites in Miami-Dade County.

A problem can arise with the use of log-transformed models in estimating the mean load for several time periods. If the log-transformed values are summed for a period and the mean is then transformed back into the original units, the estimates tend to be biased low and more closely resemble the median and not the mean. This can be overcome by use of the “smearing estimator” described in Helsel and Hirsch (1992) by the following equation:

$$Y_i = \frac{\sum_{i=1}^{n} f^{-1}(b_0 + b_i + X_i + e_i)}{n} , \tag{10}$$

where Y_i is the response variable; f^{-1} is the inverse of selected transformation; b_o is the intercept; b_i is the slope coefficient; X_i is the value of x for which y is to be estimated, e_i represents residuals, in original units; and n is the number of samples. Use of this equation requires that the residuals be independent and heteroscedastic. As previously mentioned, the ESTIMATOR program (used at site S-26) employs a minimum variance unbiased estimator for the elimination of bias in transforming from log space to real space.

SUMMARY AND CONCLUSIONS

Biscayne Bay, located along the southeastern coast of Florida, is an oligotrophic, shallow, subtropical estuary that provides habitat for a variety of plant and animal life. In recent years, the ecological health of Biscayne Bay has become a matter of concern due to the presence of nutrient-laden discharges from coastal canals that drain into the bay. This concern, as well as planned diversion of discharges for ecosystem restoration from the urban and agricultural corridors of Miami-Dade County to Everglades National Park, served as the impetus for a study to develop a method for estimating nutrient loads discharged from the east coast canals into Biscayne Bay. More than 200 depth-integrated samples were collected for analysis of total organic nitrogen, ammonia, nitrite, nitrate, nitrite plus nitrate nitrogen, total phosphorus, and orthophosphate concentrations during the 1996 and 1997 water years. At 15 east coast canal sites in Miami-Dade County, a comparison of nutrient concentrations by land-use category was made.

Analytical results indicated that the highest concentration of any nutrients sampled for in this study was 4.38 mg/L for nitrate (as nitrogen) at one site, and the lowest concentrations determined were below the detection limits for orthophosphate at six sites and nitrite at four sites. Total organic nitrogen concentrations ranged from 0.20 to 1.7 mg/L, with a median concentration of 0.75 mg/L for all of the east coast canal sites. The 0.75-mg/L value was the highest median concentration of any nutrients sampled for in this study. Ammonia concentrations ranged from 0.01 mg/L to 1.5 mg/L, with a median concentration of 0.10 mg/L for all the sites. Five sites had concentrations that exceeded the Miami-Dade County DERM freshwater standard of 0.5 mg/L for ammonia. Nitrite concentrations ranged from less than 0.001 mg/L to 0.10 mg/L, with a median concentration of 0.02 mg/L for all the sites. Nitrate concentrations ranged from 0.001 to 4.38 mg/L, with a median concentration of 0.18 mg/L for all the sites. Nitrite plus nitrate nitrogen concentrations ranged from 0.002 to 4.4 mg/L, with a median concentration of 0.20 mg/L for all the sites.

Total phosphorus concentrations ranged from 0.004 to 0.31 mg/L, with a median concentration of 0.02 mg/L. The maximum total phosphorus concentration of 0.31 mg/L was the only nutrient concentration to exceed water-quality standards or guidelines of 0.10 mg/L for control of eutrophication. High concentrations of total phosphorus usually reflect contamination as a result of human activities. Orthophosphate concentrations ranged from less than 0.001 mg/L to 0.26 mg/L, with a median concentration of 0.005 mg/L for all the sites. The 0.005 mg/L value was the lowest median concentration of any nutrients sampled for in this study.

Median concentrations of nitrite, nitrate, and nitrite plus nitrate nitrogen tended to be higher in agricultural areas than in forested/wetland and urban areas. Median concentrations of ammonia, total phosphorus, and orthophosphate tended to be higher in urban areas than in forested/wetland and agricultural areas. Median total organic nitrogen concentrations generally were higher in forested/wetland and urban areas than in agricultural areas. These results coincide with expected differences in nutrient concentrations based on knowledge of point and nonpoint source influences and nutrient cycling.

A water-quality cross-section survey conducted at site S-22 along Snapper Creek Canal during an instantaneous discharge of 414 ft^3/s in October 1997 indicated that dissolved-oxygen concentrations decreased with increasing depth. Water samples collected incrementally from the middle of the canal between the surface and the streambed at site S-22, demonstrated an increase in total nitrogen and total phosphorus concentrations with depth. Additionally, point (grab) samples at 1.0 m deep and depth-integrated samples were collected for analysis of suspended-sediment concentration. Significant differences in concentration were detected between point (grab) and depth-integrated samples (1.0 and 3.0 mg/L, respectively). Suspended-sediment concentrations generally were higher near the streambed during flow conditions than near the surface.

The Wilcoxon signed ranks test (WSRT) was used to compare differences between point (grab) and depth-integrated samples for total nitrogen and total phosphorus concentrations from 12 east coast canal sites. There were no statistically significant differences in total nitrogen concentration between point (grab) samples collected at 1.0 m deep and depth-integrated samples, but statistically significant differences in total phosphorus concentration between the samples were apparent at 25 percent of the sites. No sites showed any statistically significant differences in total nitrogen concentration between point (grab) samples collected at 0.5 m deep and depth-integrated samples, and only one site showed statistically significant differences in total phosphorus concentration. Statistically significant differences in total nitrogen and total phosphorus concentrations between point (grab) samples collected at 0.5- and 1.0-m depths were not detected at any sites.

A fitting procedure, referred to as the line of organic correlation (LOC), was used to compare point (grab) and depth-integrated samples where statistically significant differences exist as defined by the WSRT. Results of the LOC indicated that point (grab) samples at 0.5- and 1.0-m depths underestimate total phosphorus concentrations when compared to depth-integrated samples. Because total phosphorus tends to adsorb to particulate matter, this underestimation is attributed to the reduced suspended-sediment concentrations near the surface as compared to those near the streambed during periods of flow. The suspended-sediment concentration determined from a point (grab) sample was only one-third the concentration determined from a depth-integrated sample. Physical factors, such as distance upstream or downstream from the control structures and configuration of the sampling cross section, could influence the degree of mixing and contribute to differences between point (grab) and depth-integrated samples.

Models were developed to estimate nutrient loads in the east coast canals of Miami-Dade County. The measured loads were mainly based on data collected from depth-integrated samples. Discharge was used as the independent or explanatory variable, and total phosphorus load or total nitrogen load represented the dependent or response variable. The coefficients of determination (R^2) were adjusted to conform with the number of degrees of freedom in the model. The adjusted R^2 for total nitrogen load models ranged from 0.69 to 0.99, indicating that from 69 to 99 percent of the variation in total nitrogen load is explained by discharge. The average adjusted R^2 for all the total nitrogen load models was 0.87. The adjusted R^2 for the total phosphorus load models ranged from 0.23 to 0.99 and averaged 0.76, which was lower than that for the total nitrogen load models. All of the models, except for two total phosphorus load models, were statistically significant at an alpha level of 0.05. Some models for total nitrogen and total phosphorus loads required transformation of the independent variable (discharge) to enhance linearity, and a few models required log transformation of the dependent variable (load) due to heteroscedastic residuals. Because long-term water-quality data exist and continuous discharge is computed at site S-26 along Miami Canal, a software program, ESTIMATOR, was used to estimate total nitrogen and total phosphorus loads at that site.

Models that have the greatest predictive power are those with the highest adjusted R^2 and the lowest root mean square error or standard error of the regression. Because of time constraints, data were collected over a period of 2 consecutive water years (1996-97). Data collected over longer time periods, such as 5 to 10 years, would enhance the predictive power of the models and would more accurately represent long-term hydrologic conditions in southern Florida.

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