FINAL TECHNICAL REPORT

PHYSICAL FEATURES OF THE INDIAN RIVER LAGOON

INDIAN RIVER LAGOON NATIONAL ESTUARY PROGRAM MELBOURNE, FLORIDA

Prepared By:
Woodward-Clyde Consultants
Marshall McCully & Associates, Inc.
Natural Systems Analysts, Inc.

Prepared For:
Indian River Lagoon National Estuary Program
1900 South Harbor City Boulevard - Suite 109
Melbourne, Florida 32901-4749
December 1994

Woodward-Clyde

Woodward-Clyde Consultants
3676 Hartsfield Road
Tallahassee, Florida 32303

Project Number: 92F274C

TABLE OF CONTENTS

TABLE OF CONTENTS, Continued

TABLE OF CONTENTS, Continued

SECTION			PAGE

TABLE OF CONTENTS, Continued

LIST OF TABLES

LIST OF TABLES, Continued

LIST OF FIGURES

LIST OF FIGURES, Continued

LIST OF FIGURES, Continued

LIST OF FIGURES, Continued

INTERNATIONAL SYSTEM (SI METRIC)/
U.S. CUSTOMARY CONVERSION TABLES

TO CONVERT FROM	TO	MUTLIPLY BY
LENGTH		
centimeters	inches	0.3937
inches	centimeters	2.5400
feet	meters	0.3048
meters	feet	3.2808
kilometers	meters feet miles	1.0×10^3 $3.280\ 84 \times 10^3$ 0.621 37
miles	kilometers	1.609 34
AREA		
acres	hectares square feet square kilometers (km^2) square miles	0.404 69 4.356×10^4 .00404 .00156
hectares	square meters acres	1.0×10^4 2.471
square kilometers	hectares acres square miles (mi^2)	100.0 274.105 38 0.3861
square miles	hectares square kilometers (km^2) square feet acres	258.998 81 2.589 99 $2.787\ 84 \times 10^7$ 640.0
VOLUME		
liters	cubic feet gallons	0.035 31 0.264 17
gallons	liters cubic feet	3.785 41 0.133 68
cubic feet	cubic meters (m^3) gallons (gal) acre-feet (acre-ft)	$28.316\ 85 \times 10^{-3}$ 7.480 52 $22.956\ 84 \times 10^{-6}$
cubic yards	cubic meters cubic feet	0.764 55 27.0

INTERNATIONAL SYSTEM (SI METRIC)/ U.S. CUSTOMARY CONVERSION TABLES, Continued

TO CONVERT FROM	TO	MUTLIPLY BY
VOLUME		
cubic meters	gallons cubic feet cubic yards acre-feet	264.1721 35.314 67 1.307 95 8.107×10^{-4}
acre-feet	cubic feet gallons	43.560×10^{3} 325.8514×10^{3}
TEMPERATURE		
	degrees Celsius (C) (t_c)	$t_c = (t_f-32)/1.8 =$ $t_k - 273.15$
	degrees Fahrenheit (F)	$t_f = t_c/1.8 + 32$
VELOCITY		
kilometers per hour	meters per second miles per hour	0.277 78 0.621 47
miles per hour	kilometers per hour meters per second	1.609 34 0.447 04
FORCE		
kilograms	pounds (lbs)	2.2046
MASS		
pounds (avdp)	kilograms	0.453 59
VOLUME PER UNIT TIME FLOW		
cubic feet per second	cubic meters per second (m^3/s) gallons per minute (gal/min) acre-feet per day (acre-ft/d) cubic feet per minute (ft^3/min)	0.028 32 448.831 17 1.983 47 60.0
gallons per minute	cubic meters per second cubic feet per second (ft^3/s) acre-feet per day	0.631×10^{-4} 2.228×10^{-3} 4.4192×10^{-3}
acre-feet per day	cubic meters per second cubic feet per second	0.014 28 0.504 17

1.0 GENERAL INFORMATION

1.1 INTRODUCTION

The Physical Features Summary is a compilation of existing information concerning the physical characteristics of the Indian River Lagoon system. The physical features define the Lagoon and regulate the ecosystem. These features determine the extent of the ecosystem, provide the fundamental biological habitats, define the sources and transport of pollution loading, and control or modify human population impacts. In this report the estuary system includes the Indian River Lagoon (from Turnbull Hammock in the north to Jupiter Inlet in the south), the Banana River, and the Mosquito Lagoon.

For more than a century, many large and small projects have been carried out throughout the Indian River Lagoon system to aid navigation, drain flood waters, control mosquitos, provide access to the barrier islands, and stabilize tidal inlets. These projects have substantially changed the physical features of the Lagoon, including the infiltration, runoff, shallow-aquifer storage, and land drainage capacities and rates of the watershed. They have also greatly enlarged the dimensions of the watershed and interconnected it with the adjoining South Florida/Everglades watershed and the St. Johns River Watershed. Many of these changes have degraded the natural functions of the Indian River Lagoon system.

This is one of eight volumes of Technical Reports prepared to support the Indian River Lagoon Characterization for the Indian River Lagoon National Estuary Program (IRLNEP). Overall, these volumes, which can be obtained from IRLNEP, include:

- Physical Features
- Biological Resources
- Uses of the Indian River Lagoon
- Historical Imagery Inventory and Seagrass Assessment
- Non-Governmental and Governmental Programs
- Water and Sediment Quality Assessment
- Point and Non-point Source Loads Assessment
- Status and Trends Assessment

The subjects that are discussed in this summary include a general description of the physiography, climate and weather, hydrology, hydrogeology, and hydrodynamics of the Lagoon. Most of these subjects were also covered in the Indian River Lagoon Joint Reconnaissance Report (Steward and VanArman, 1987) hereafter referred to simply as the Recon Report. The Recon Report was produced jointly by the St. Johns River Water Management District (SJRWMD) and the South Florida Water Management District (SFWMD). These subjects were further developed in the unpublished document, the Indian River Lagoon Estuarine Monograph (Marine Resources Council, 1988), hereinafter simply designated as the Monograph. The information presented herein builds upon and updates information provided by those two documents. This Technical Report includes information sources current and readily available as of June, 1993.

1.2 DEFINITION OF THE INDIAN RIVER LAGOON SYSTEM

This report is produced for the Indian River Lagoon National Estuary Program (IRLNEP). This program uses the term Indian River Lagoon to include the whole estuarine region of Florida's east coast from Ponce de Leon Inlet near New Smyrna Beach to Jupiter Inlet in Palm Beach County. This area is actually comprised of several water bodies which have natural or man-made connections. In this report, the terms "Lagoon", "Indian River Lagoon Complex", and "IRL" are used interchangeably to refer to the aggregate of these water bodies including the Indian River Lagoon proper, Banana River, Mosquito Lagoon, and Hobe Sound. The term Indian River Lagoon is used because the use of the term "Indian River" mistakenly conveys the notion that the lagoon is a river. When the word "Lagoon" is used alone it means the whole Indian River Lagoon. The term "Indian River Lagoon system" includes the Lagoon and the entire watershed emptying into the Banana and Indian Rivers, Mosquito Lagoon, and Hobe Sound.

1.3 THE INDIAN RIVER LAGOON SYSTEM

A lagoon is an area of shallow water that is separated from the ocean by a barrier island. An estuary is a partially enclosed area of water that opens to the ocean and has freshwater inflows (Pritchard, 1967). The Indian River Lagoon estuary system is shallow, has freshwater inflows, is connected to the Atlantic Ocean, and is separated from the ocean by a barrier island. Therefore, it is both a lagoon and an example of a "bar-built" estuary.

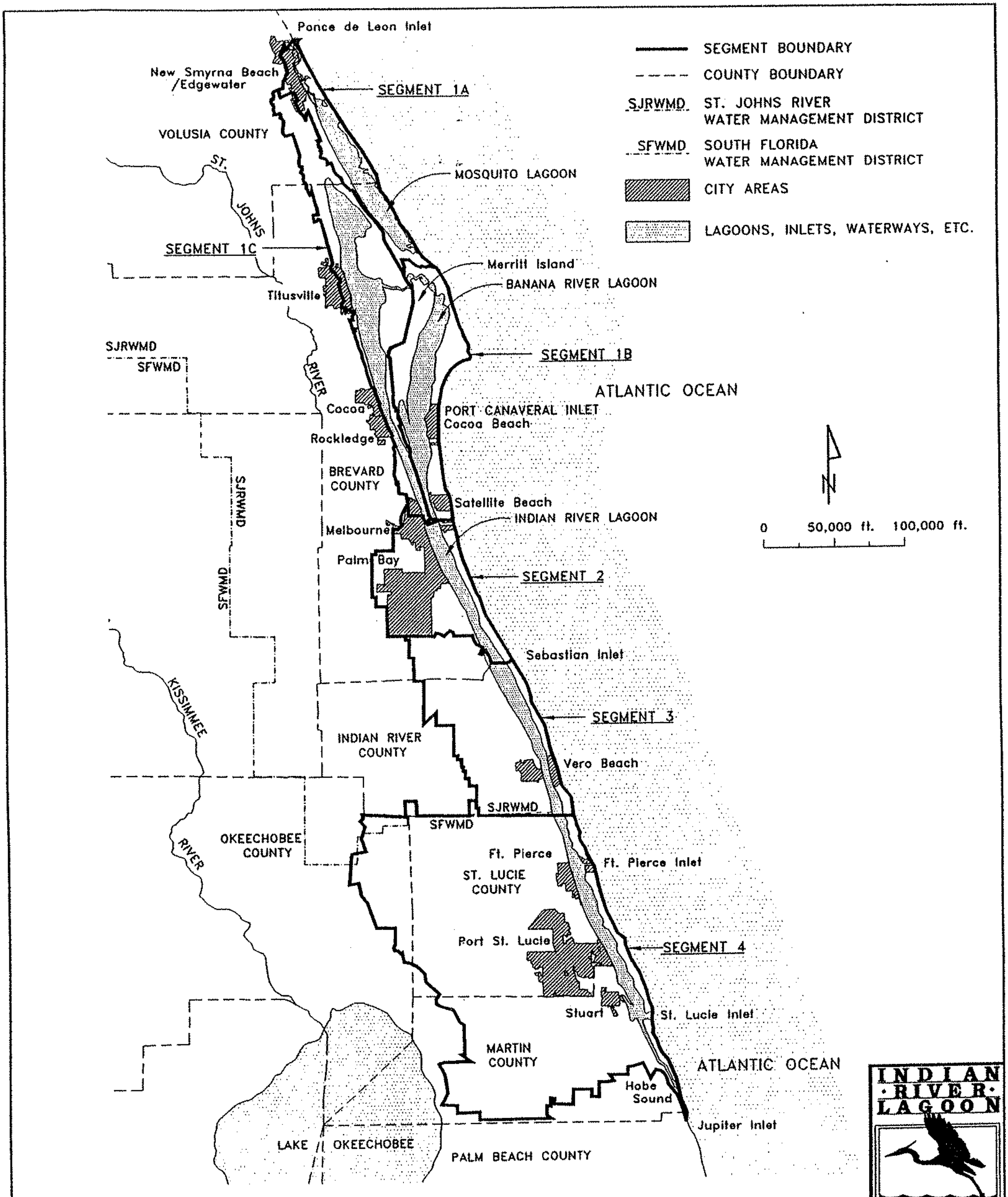
Saltwater and freshwater come into contact in an estuary. The degree of mixing depends on temperature, chemical composition, volumes of tide and freshwater inflow, and particularly on the energy provided for mixing. Evaporation can play an important part in estuary or lagoon processes. Because estuaries are smaller and shallower than the open ocean, they are strongly influenced by activities that occur on the adjacent land. The Indian River Lagoon complex is unique among Florida estuaries because of its long, narrow configuration and separation from the ocean by a barrier island chain with few breaks or inlets. However, this barrier island has always been a dynamic feature undergoing many changes over time due to changes in water level and hydrology, hurricane occurrences and other factors. As a result, the estuarine system has been extremely dynamic, with variation in water depth, salinity, and circulation.

Anthropogenic influences to the Indian River Lagoon system include point sources (treatment plants), non-point sources (primarily stormwater runoff) and enhanced drainage, all of which increase freshwater flows and contribute nutrients and pollutant loadings to the Lagoon. Plants and animals that inhabit this natural estuarine transition zone must be capable of tolerating substantial variations in osmotic equilibrium due to occasional rapid salinity and temperature changes, as well as adjusting to exposure from growth stimulating or inhibiting substances.

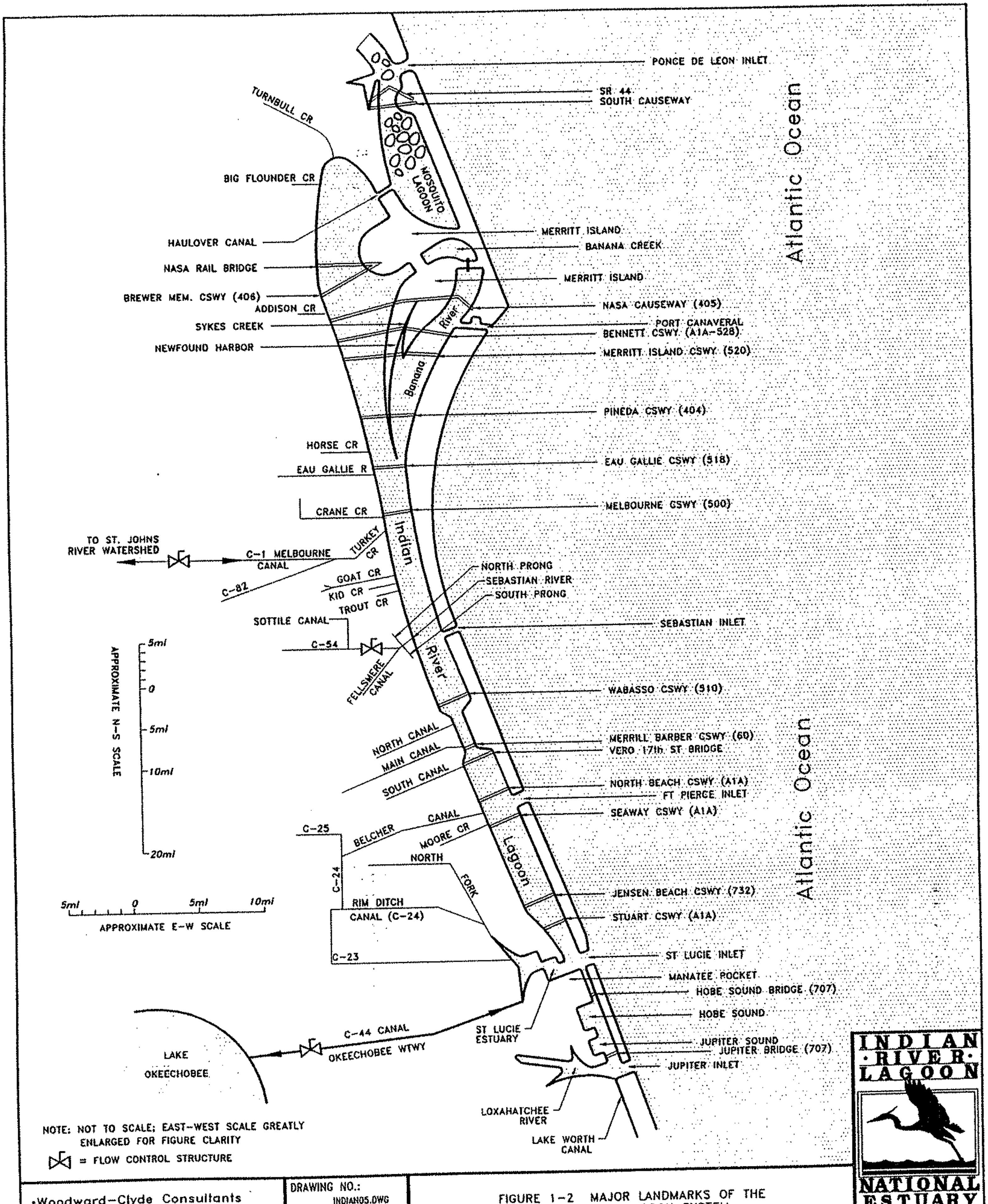
The Indian River Lagoon system lies on the east coast of Florida approximately between latitudes 26°57'N and 29°03'N, and longitudes 80°05'W and 80°55'W. The northern boundary of the system is Ponce de Leon Inlet in Volusia County. The southern boundary of the system is 155 mi to the south in Palm Beach County at Jupiter Inlet. The watershed of the system is bounded on the east by the crown of the dune on the barrier island. The existing western limit is not as easily defined. In places it is the crest of the coastal ridge, which is the natural upland limit of the drainage watershed. However, in many places in the watershed, drainage basins have been expanded to divert man-made drainage to the Lagoon from areas formerly linked to other watersheds such as the St. Johns River.

For study purposes, the Indian River Lagoon and its watershed has been divided hydrologically into six segments. These segment divisions are based on hydrologic basins defined by the SJRWMD and SFWMD and on study segments first defined by Clapp (1987) in the Recon Report. The segments utilized in the present report are slightly different from the divisions presented in the Recon Report and the Monograph, both of which divided the Lagoon primarily according to geographical and political boundary criteria. The segments and their changes are described in Section 2.1.

The segments of the Indian River Lagoon system are illustrated in Figure 1-1. Cities, water bodies, and inlets are shown as a reference for locations described in this report.
Figure 1-2 is a general location map of the Indian River Lagoon system, showing major landmarks including the many water courses.



•Woodward-Clyde Consultants •Marshall McCully & Associates •Natural Systems Analysts	DRAWING NO.: INDIAN10.DWG DATE: 7-5-94	FIGURE 1-1 MAP OF INDIAN RIVER LAGOON SYSTEM AND WATERSHED SHOWING SEGMENTS



•Woodward-Clyde Consultants •Marshall McCully & Associates •Natural Systems Analysts	DRAWING NO.: INDIAN05.DWG DATE: 7-5-94	FIGURE 1-2 MAJOR LANDMARKS OF THE INDIAN RIVER LAGOON SYSTEM

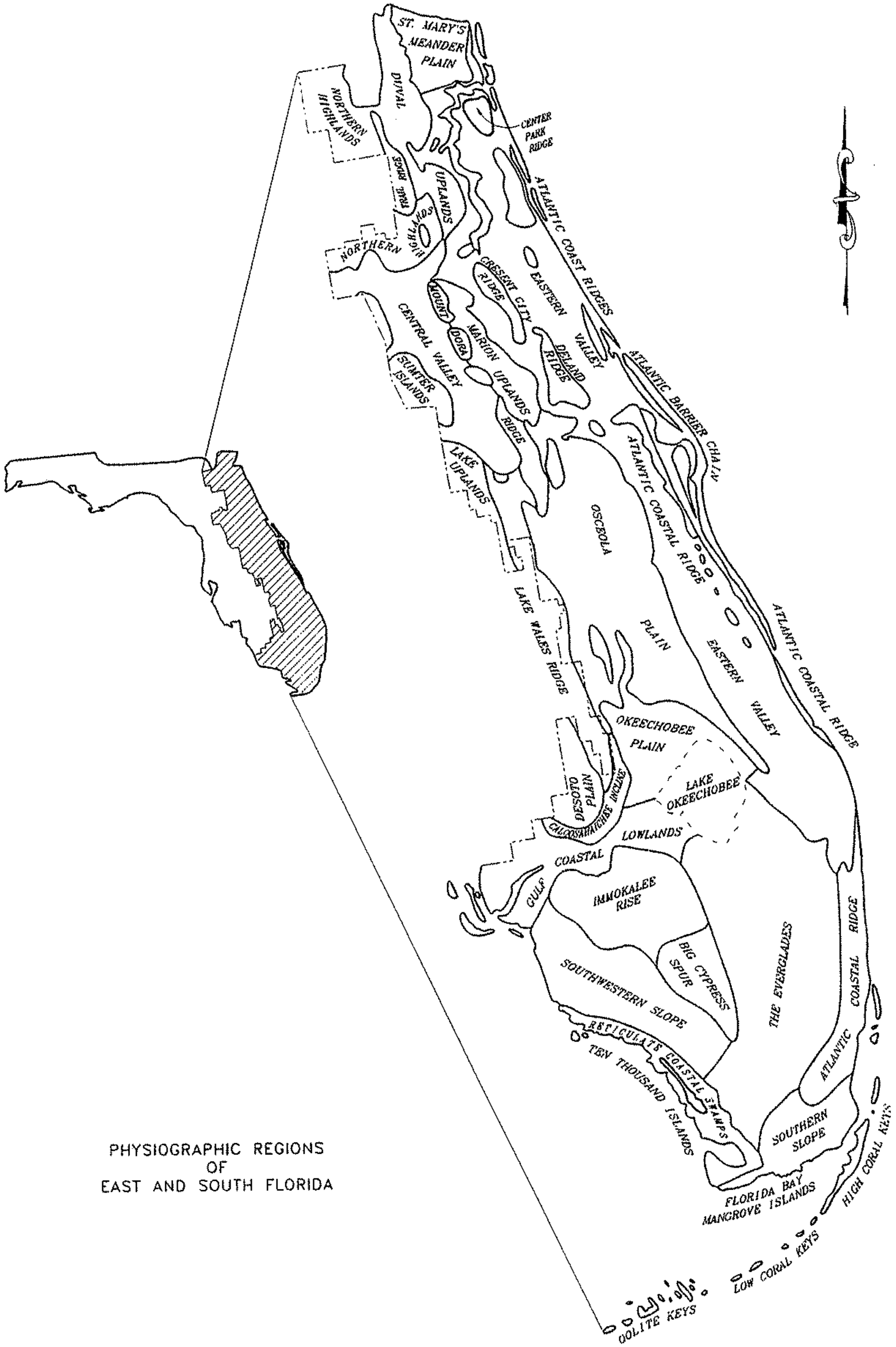
2.0
PHYSIOGRAPHY

2.1 REGIONAL FEATURES AND SEGMENTS

The physiography of the Indian River Lagoon system includes its topography, geomorphology, surface waters, inlets, soils, drainage patterns, and watershed boundaries. Generally, there is sufficient data supporting the descriptions. However, the state of the knowledge regarding the watershed basin and sub-basin boundaries is not consistent. Several drainage basins and sub-basins in the northern part of the area are still poorly defined.

A physiographic map of east and south Florida is presented as Figure 2-1. The Indian River system drains a narrow section of the east coast of Florida which lies east of the major water drainage systems of South Florida (Kissimmee River-Lake Okeechobee-Everglades) and of northeast Florida (the St. Johns River). It is generally separated from these systems by the Atlantic Coastal Ridge. However, canals and control structures have been built as part of the South Florida Water Management District that connect Lake Okeechobee and its drainage to the Lagoon. Interconnections and Interbasin diversions have also been constructed between the St. Johns River and the Lagoon.

Table 2-1 presents a cross-reference between the segments defined for this study and the segment designations used in the Recon Report and Monograph. The sub-basin boundary and name designations correspond with the schemes presently being utilized by SJRWMD and SFWMD for the areas within their jurisdictions. The numbering scheme is new because there was no prior numbering scheme for the SFWMD sub-basins and because the scheme used by SJRWMD covered the entire SJRWMD region but not the SFWMD area. The sub-basin designation conventions for this project, shown in Table 2-1, were created to provide a unified system specifically for the entire Indian River Lagoon system that is independent of schemes used for the separate Water Management Districts.



PHYSIOGRAPHIC REGIONS
OF
EAST AND SOUTH FLORIDA

•Woodward-Clyde Consultants •Marshall McCully & Associates •Natural Systems Analysts	DRAWING NO.: INDIAN03.DWG DATE: 7-5-94	FIGURE 2-1 PHYSIOGRAPHIC REGIONS OF EAST AND SOUTH FLORIDA

INDIAN RIVER LAGOON NATIONAL ESTUARY PROGRAM

TABLE 2-1

CROSS-REFERENCE FOR SUB-BASIN DESIGNATIONS

SEGMENT	SUB-BASIN DESIGNATION	WATER MANAGEMENT DISTRICT DESIGNATION	RECONNAISSANCE REPORT/ MONOGRAPH DESIGNATION
1A - Mosquito Lagoon Basin	1A-01	10A-01	I.A
	1A-02	10A-02	I.A
1B - Banana River Basin	1B-01	10B-01	I.C.2
	1B-02	10B-02	I.C.3
1C - North Indian River Lagoon Basin	1C-01	10C-01	I.B.1
	1C-02	10C-02	I.B.1
	1C-03	10C-03	I.B.2
	1C-04	10C-04	I.C.1
	IC-05	10C-05	I.C.1
	1C-06	10C-06	I.B.2 and I.C.1
2 - North Central Indian River Lagoon Basin	2-01	10D-01	II.A
	2-02	10D-02	II.A
	2-03	10D-03	II.B and II.C
	2-04	10D-04	II.D.1
	2-05	10D-05	II.D.1 and II.I
	2-06	10D-06	II.C and II.D.2
	2-07	10D-07	II.D.1
	2-08	10D-08	II.D.1
	2-09	10D-09	II.C and II.D.1

TABLE 2-1

CROSS-REFERENCE FOR SUB-BASIN DESIGNATIONS, Continued

SEGMENT	SUB-BASIN DESIGNATION	WATER MANAGEMENT DISTRICT DESIGNATION	RECONNAISSANCE REPORT/ MONOGRAPH DESIGNATION
2 - North Central Indian River Lagoon Basin, Continued	2-10	10D-10	II.D.1
	2-11	10D-11	II.D.1 and II.I
	2-12	10D-12	II.D.1 and II.E
	2-13	10D-13	II.F
	2-14	10D-14	II.I
	2-15	10D-15	II.G
	2-16	10D-16	II.I
	2-17	10D-17	II.I
	2-18	10D-18	II.1
	2-19	10D-19	II.I
	2-20	6D-04	II.D.3
3 - South Central Indian River Lagoon Basin	3-01	10E-01	III.A.2
	3-02	10E-02	III.A.2
	3-03	10E-03	III.A.1
	3-04	10E-04	III.A.1
	3-05	10E-05	III.A.1A.2
	3-06	10E-06	III.A.1
	3-07	10E-07	III.A.1
	3-08	10E-08	III.A.1

TABLE 2-1

CROSS-REFERENCE FOR SUB-BASIN DESIGNATIONS, Continued

SEGMENT	SUB-BASIN DESIGNATION	WATER MANAGEMENT DISTRICT DESIGNATION	RECONNAISSANCE REPORT/ MONOGRAPH DESIGNATION
3 - South Central Indian River Lagoon Basin, Continued	3-09	10E-09	III.A.1
	3-10	10E-10	III.A.1
	3-11	10E-11	III.A.1
	3-12	10E-12	III.A.1 and II.H.1
	3-13	10E-13	II.H.4
	3-14	10E-14	III.A.3
	3-15	10E-15	II.G, II.H.1, and II.H.4
	3-16	10E-16	III.A.1
	3-17	10E-17	II.H.1
	3-18	10E-18	III.B
	3-19	10E-19	III.B
	3-20	10E-20	III.B
	3-21	10E-22	III.D
	3-22	6D-01	III.A.4
	3-23	6D-02	II.H.3
	3-24	6D-03	II.H.2
4 - South Indian River Lagoon Basin	4-01	Joe Gore Slough	Not included in Recon Report
	4-02	St. Johns Marsh	IV.A
	4-03	Belcher Canal	III.C

TABLE 2-1

CROSS-REFERENCE FOR SUB-BASIN DESIGNATIONS, Continued

SEGMENT	SUB-BASIN DESIGNATION	WATER MANAGEMENT* DISTRICT DESIGNATION	RECONNAISSANCE REPORT/ MONOGRAPH DESIGNATION
4 - South Indian River Lagoon Basin, Continued	4-04	Moore's Creek	Part of III.C and III.D
	4-05	C-24	IV.C
	4-06	North St. Lucie	IV.B.1
	4-07	C-23	IV.C
	4-08	North Coastal	III.D
	4-09	Middle Coastal	IV.B.2
	4-10	South Coastal	IV.E.7
	4-11	Basin 4	IV.E.1
	4-12	Basin 5	IV.E.2
	4-13	Basin 6	IV.E.4
	4-14	C-44	IV.F
	4-15	Tidal St. Lucie	IV.E.4
	4-16	Basin 2	IV.E.5
	4-17	Intracoastal	Part of IV.E.7
	4-18	Unnamed	Not included in Recon Report

Sources: Clapp, 1987
SJRWMD, 1993

The six major Lagoon segments and their associated drainage basins are defined as Segments 1A, 1B, 1C, 2, 3, and 4. Areas within the six basins have been further subdivided into sub-basins. In the primary segmentation level used in this report, the northern-most basin (1A) is the Mosquito Lagoon basin. The Banana River and Sykes Creek drainage areas are Basin 1B. The North Indian River Lagoon from the southern tip of Merritt Island to Turnbull Hammock and the adjoining watershed area are designated as 1C.

Segments 1B and 1C have been altered from the corresponding basins presented in the Recon Report. In the Recon Report, Segment I.B covered Indian River Lagoon north of Bennett Causeway (SR 528), while Segment I.C combined all of Banana River (I.C.2) and Sykes Creek (I.C.3) with the Indian River Lagoon from Bennett Causeway to the southern tip of Merritt Island (I.C.1). For the Characterization study, the Indian River Lagoon segments (IB and I.C.1) have been combined into Segment 1C. The Banana River/Sykes Creek segments (I.C.2 and I.C.3) have been separated into Segment 1B since they are hydrologically distinct from the Indian River Lagoon proper.

The North Central Indian River Lagoon (Segment 2) and associated basin has been revised from the Recon Report by moving the drainage sub-basins (II.G and II.H.1 to II.H.4) of the north prong of the Sebastian River from this segment into the South Central Segment (Segment 3) and renumbering them accordingly (3-12, 3-13, 3-15, and 3-17). This was done to combine the drainages that discharge to the Lagoon through the mouth of the Sebastian River since hydrologic basins are normally defined upstream from the discharge point, and since the waters from these sub-basins are indistinguishable when they enter the Lagoon.

The South Central Indian River Lagoon segment has been revised by the addition of the north prong of the Sebastian River drainage sub-basins as described above and by the moving the Ft. Pierce Farms Water Control District sub-basin (III.C) and the North Coastal sub-basin (III.D.) to Segment 4 (now sub-basin 4-01) . The primary reason for this change is that these were the only sub-basins in Segment 3 that were within the SFWMD rather than the SJRWMD. An additional change has been the elimination of a portion of sub-basin III.A.5 (Fellsmere Water Control District). This change reflects the current efforts of SJRWMD and other agencies to eliminate discharge from this sub-basin into the Lagoon drainage system.

The Ft. Pierce Farms Water Control District sub-basin (4-01, also known as Taylor Creek) and the North Coastal drainage area (4-08) have been added to the South Indian River Lagoon - Segment 4. Segment 4 and its basin now includes all of the area that is located within the SFWMD boundary. Segments 1A, 1B, 1C, 2, and 3 are located within the limits of the St. Johns River Water Management District. Each segment and drainage basin is described in more detail in Section 2.6 and segment/basin maps are provided.

2.2 GEOMORPHOLOGY

2.2.1 General

Both the land and water features of the Indian River Lagoon system are determined by, and have been formed by, the changing level of the sea (Head, 1981). The prominent land features of the Indian River Lagoon system are the southern barrier islands, the Cape Canaveral cuspate foreland formation, the mainland ridges that naturally form the western boundary of the watershed, and the valleys or sloughs between the ridges. The prominent water features are the three interconnected lagoons, the inlets, the natural creeks and streams, and the man-made water management systems (canals and ditches).
The entire state of Florida is located on the Floridian Plateau (Head, 1981). The plateau is approximately 500 miles (mi) in length and between 250-400 miles in width. The Floridian Plateau includes the subaerial land mass as well as the submerged continental shelf. This plateau has existed for millions of years and has been alternately covered by water and exposed as dry land many times. These alternating periods created areas of marine and terrestrial deposits, one on top of the other. The area has also undergone a general uplift created by tectonic forces (Head, 1981).

2.2.2 Topography

The current topography of Florida, and particularly eastern Florida, is formed largely by eroded relict dune lines and broad marine terraces, as well as the present barrier islands and Lagoon system. Terraces were formed during high still-stands which allowed erosion by waves and currents to form flat plains that emerged as flatlands when the sea level subsided (Brooks, 1982; Glatzel, 1986).

The terraces in the watershed include the Talbot, the Pamlico, and the Silver Bluff in descending elevation. As sea level receded, dune ridges formed on these terraces (Schnable and Goodell, 1968). The Atlantic Coastal Ridges formed on the Silver Bluff Terrace, the Ten Mile and Green Ridges formed on the Pamlico Terrace, and the Orlando Ridge formed on the Talbot Terrace (Brooks, 1972).

2.2.3 Physiography

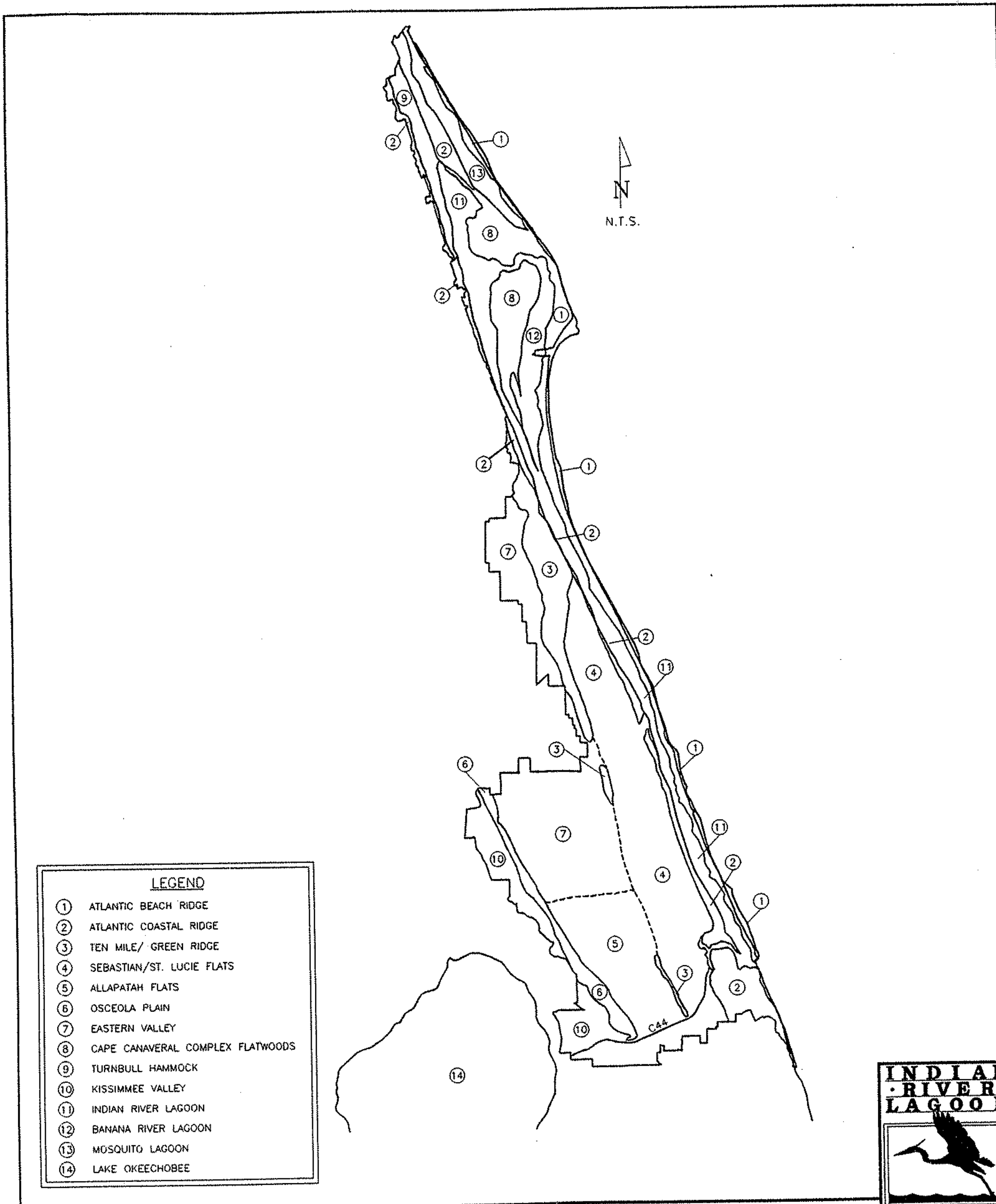
The physiography of this region has been described by White (1970), Clapp (1987) Glatzel and Da Costa (1988a, 1988b), Stauble (1988), and Nealon, et al. (1987). Figure 2-1 shows the regional physiographic setting, and Figure 2-2 presents the features of the Indian River Lagoon system. The ridge on the existing barrier islands has been termed the Atlantic Beach Ridge. The mainland ridge nearest to the coast is called the Atlantic Coastal Ridge. Between the two are the Atlantic Coastal Lagoons which form the present-day Indian River Lagoon system.

From Indian River County north, the flatlands west of the Atlantic Coastal Ridge make up the Eastern Valley. From central Brevard County north, the Atlantic Coastal Ridge forms the natural western boundary of the Indian River Lagoon system drainage basin. In south Brevard and north Indian River counties, the natural drainage basin is bounded by the Ten Mile Ridge. South of Brevard County, a portion of the Eastern Valley between the Ten Mile Ridge and the Atlantic Coastal Ridge, called the Sebastian-St. Lucie Flats, drains into the Sebastian River.

The Ten Mile Ridge disappears in southern Indian River County, but re-emerges in south St. Lucie County as the Green Ridge, to define the St. Lucie River watershed.

This small ridge may be an eroded relict part of the Ten Mile Ridge. In St. Lucie County the Eastern Valley grades into the Allapattah Flats, and the Orlando Ridge grades into the Osceola Plain in western Martin County.

Natural streams drain the flatlands to the Lagoon in several locations in south Brevard, north Indian River, south St. Lucie, and north Martin counties, except in those locations where the natural Atlantic Coastal Ridge watershed boundary blocks interior drainage and limits the



•Woodward–Clyde Consultants •Marshall McCully & Associates •Natural Systems Analysts	DRAWING NO.: INDIAN09.DWG DATE: 7-5-94	FIGURE 2–2 PHYSIOGRAPHIC FEATURES OF THE INDIAN RIVER LAGOON

INDIAN RIVER LAGOON NATIONAL ESTUARY PROGRAM

basin to a narrow strip along the Lagoon. In south Brevard, Indian River, Okeechobee, St. Lucie, and Martin counties, the watershed boundary of the Indian River Lagoon also has been extended westward through this ridge into the Eastern Valley and the Allapattah Flats by artificial drainage.

A predominant physiographic land feature of the barrier island system is Cape Canaveral. Cape Canaveral was described by Stauble (1988) as a "cuspate foreland" similar to Cape Hatteras in North Carolina, in which a sandy cape has developed where offshore currents have met.

The moderate wave climate, small tidal range, and the accumulation of sand in the flood tide delta of the inlets led Stauble (1988) to note that the Hayes (1975) model of barrier island types fit the Indian River Lagoon barrier island system. These characteristics are associated with an elongated lagoon, widely spaced inlets and low relief on the islands. The southern barrier islands have developed largely from longshore sand transport from the Cape Canaveral foreland (Glatzel and Da Costa, 1988).

2.2.4 Hydrologic Sub-basins

Stauble (1988) divided the geomorphological features of the Indian River Lagoon system into six sub-divisions. These sub-divisions generally correspond to the primary basin divisions (segments) that have been made in this report based on watershed hydrology. The northern sub-division includes Mosquito Lagoon which was created by the cuspate foreland of Cape Canaveral. Mosquito Lagoon is a shallow [<6 feet (ft)], wide water body. It consists of a northern area dominated by the flood tide delta of a migrating Ponce de Leon Inlet (before stabilization) and a second inlet, now closed, that was located in the vicinity of Bethune Beach in Volusia County (Stauble, 1988). The southern two thirds is a broad open waterbody with very little tide but relatively strong wind-driven circulation.

The next sub-division to the south is the Cape Lagoon Complex which includes Cape Canaveral, the northern extent of the Indian River Lagoon (including Turnbull Hammock) and the Banana River. South of the Cape Lagoon Complex is the Central Lagoon sub-division which stretches from just north of the Eau Gallie River to Sebastian Inlet and the Sebastian River. This area has many small creeks and rivers that extend westward through the Atlantic Coastal Ridge. Sebastian Inlet is a man-made inlet located where a natural inlet had opened and closed many times. The Sebastian River, probably following the location of a former inlet through the Atlantic Coastal Ridge (Stauble, 1988), provides natural drainage from the area west of the Atlantic Coastal Ridge and east of the Ten Mile Ridge (Sebastian-St. Lucie Flats). This river also drains areas of artificially extended watershed in Brevard and Indian River counties.

South of the Central Lagoon sub-division is the Indian River Narrows sub-division, as defined by Stauble, 1988. The Narrows sub-division, extending from approximately Wabasso Causeway to the Main Canal at Vero Beach, separates the more open water of northern Indian River from the Southern Lagoon system. Over a period of hundreds of years, Sebastian Inlet has undergone several cycles of opening and closing. In each cycle, it has probably formed opposite Sebastian River and then naturally migrated south almost to Ft. Pierce before closing again. As a result, the Narrows was most likely formed over time from a sequence of flood tide deltas formed by the migrating Inlet (Stauble, 1988).

The Southern Lagoon sub-division includes a very shallow portion of the Lagoon as well as Jupiter and St. Lucie Inlets. The portion of the Indian River Lagoon south of St. Lucie Inlet is known as Jupiter Narrows. This area consists of small open water areas connected by the Intracoastal Waterway channel, separating Hobe Sound and Jupiter Inlet from the rest of the Lagoon complex.

2.2.5 Anthromorphic Features

Infrastructure, navigation, and agricultural developments have strongly modified the natural system. These anthromorphic (human-caused) activities have included dredging of the Intracoastal Waterway and Haulover Canal, stabilization of inlets, construction of causeways, filling of low areas subject to flooding, installation of mosquito control drainage ditches and dikes, and very extensive channelizing of the watersheds to drain fields in the wet season and provide irrigation in the dry season. Canals and control structures now connect the Lagoon with the Lake Okeechobee and St. Johns River drainage systems. Water management and pumping over wide areas control much of the discharge to the Lagoon.

The Intracoastal Waterway (ICWW) was dredged to create a safe passage for water-based commerce from Maine to Key West. In the Indian River Lagoon system, the ICWW created a deep water channel [maintenance depth of 12 ft in an otherwise shallow system (typical depths are 3-6 ft with large areas less than 3 ft)]. The ICWW altered the natural system by becoming a sediment trap and forming a conduit for denser ocean water to penetrate into the Lagoon from the inlets (Evink, 1980; Smith, 1988). In many places dredge spoil from the ICWW channel was dumped directly onto salt marshes, mangroves, and submerged seagrass areas. This created uplands with little beneficial transitional fringe and eliminated productive wetland habitat. The dredging of the ICWW also created a hydraulic link between Mosquito Lagoon and north Indian River Lagoon by cutting through the Cape Canaveral Complex Ridge at Haulover Canal.

The need for access from the mainland to the barrier island for vehicular traffic led to the building of bridges over the Lagoon. The first bridges were wooden structures built on pilings (Evink, 1980). Because of the open spaces between pilings, these bridges probably had minor effects on water circulation in the Lagoon. The original wooden bridges, which replaced boats and ferries, were themselves replaced with causeways constructed of fill materials. These causeways were solid barriers stretching across most of the Lagoon except for narrow openings which could be spanned by drawbridges. The causeways split and compartmentalized the Lagoon into sections with little hydrodynamic connection between sections (Evink, 1980).

When the drawbridges across the ICWW began to be replaced by fixed, high-rise bridge spans some correction of the compartmentalization occurred. Several of the central openings were widened. In addition, some relief bridges were constructed in some of the causeways (Evink, 1980). Relief bridges are low bridges constructed near the landward ends of the causeways, creating gaps that allow water to pass from compartment to compartment. These relief bridges, when properly maintained, somewhat alleviate the reduced circulation problem, but in most cases still have not restored the natural circulation pattern (Evink, 1980). From north to south, the following causeways and bridges are currently present (more information, including date of construction is found in the Uses of the Lagoon Technical Report):

- New Smyrna Beach North Causeway/State Road (SR) 44
- New Smyrna Beach South Causeway/SR AIA
- NASA Railroad (FEC) Causeway
- Titusville/Brewer Memorial Causeway/SR 406
- Kennedy Space Center (NASA) Causeway/SR 405
- Bennett Causeway/Cape Canaveral Parkway/SR 528
- Merritt Island/Cocoa Beach Causeway/SR 520
- Pineda Causeway/SR 404
- Eau Gallie Causeway/SR 518
- Melbourne Causeway/US 192/SR 500
- Wabasso Causeway/SR 510
- Merrill Barber Causeway/SR 60
- Vero Beach 17th Street Bridge
- Ft. Pierce North Beach Causeway/SR AIA
- Ft. Pierce South (Seaway) Causeway/SR AIA
- Jensen Beach Causeway/SR 732
- Stuart Causeway/SR A1A
- Bridge Road Bridge (Hobe Sound)/SR A1A
- Jupiter Island Bridge (Jupiter)/SR A1A

Several inlets also have been created or stabilized by man. The northern limit of the Indian River Lagoon system is at Ponce de Leon (Ponce) Inlet, a natural inlet which has been artificially stabilized. Port Canaveral (Canaveral) Inlet is a man-made and stabilized inlet with a system of locks that largely isolate the Banana River from the ocean's influence by limiting the exchange of water. Sebastian and Ft. Pierce Inlets are both naturally unstable inlets that have opened and closed many times over geological time (Stauble, 1988) and they are now stabilized. In the process of opening and closing, they have migrated along the coast. Both are presently artificially stabilized in their present locations in an attempt to prevent migration and shoaling, and to provide access to the ocean. Most recently, a natural inlet existed about 4 miles north of the existing Ft. Pierce Inlet. When St. Lucie Inlet was dug in its present location and stabilized to keep it open, the natural Ft. Pierce inlet shoaled and closed, later being re-constructed in its present location in the 1920's (Stauble, 1988).

St. Lucie Inlet is also a natural inlet that has been stabilized. Jupiter Inlet is a natural inlet at the south end of the Indian River Lagoon that has been stabilized to eliminate migration. Additional inlets have opened and closed in the Pecks Lake area between Jupiter and St. Lucie Inlets. The most recent openings and subsequent closings were in 1943 and 1962. The 1962 opening was artificially closed because it caused shoaling problems at St. Lucie Inlet (Thurlow, 1992).

These inlets are important in controlling the flushing rates of the Lagoon segments and the transport of materials through the Lagoon. These transport and flushing processes have presumably varied considerably over time as the number and arrangement of inlets changed. As inlet stabilization has occurred, the degree of variation in the system has been lowered, although even today dredging and other modifications of the inlets have effects on the water quality of the Lagoon.

The physiographic features of the Indian River Lagoon and its watershed have established a natural structure around which the hydrology of the estuary and its watershed are defined. Many civil works have been directed at improving drainage, reducing mosquitos, enhancing navigation and vehicle access, mitigating flooding, and increasing irrigation. Little, if any attention was directed to alteration of the natural structure and the unintended impacts that these projects had on the water quality and ecology of the Indian River Lagoon.

2.3 THE SURFACE WATERS

According to the definition used by the National Estuary Program, the Indian River Lagoon complex consists of three interconnected lagoons: Mosquito Lagoon, Banana River, and the long linear Indian River Lagoon proper.

Mosquito Lagoon is located mostly in Volusia County, with the southern-most reaches in Brevard County. The Banana River is located entirely in Brevard County. The Indian River Lagoon spans six counties - Volusia, Brevard, Indian River, St. Lucie, Martin and Palm Beach. The full length of the Indian River Lagoon system, from Ponce de Leon Inlet to Jupiter Inlet is approximately 155 mi.

The surface area of Mosquito Lagoon (Segment 1A) is 37,853 acres (ac). The surface area of the Banana River (Segment 1B), including Sykes Creek, is 47,762 ac. The Indian River Lagoon proper has a surface area of 142,123 ac (Clapp, 1987). Average water depths in different parts of the Lagoon are between 3 and 6 ft, but depths of greater than 13 ft are present in some dredged channels (NOAA, 1991, 1992).

2.3.1 Mosquito Lagoon

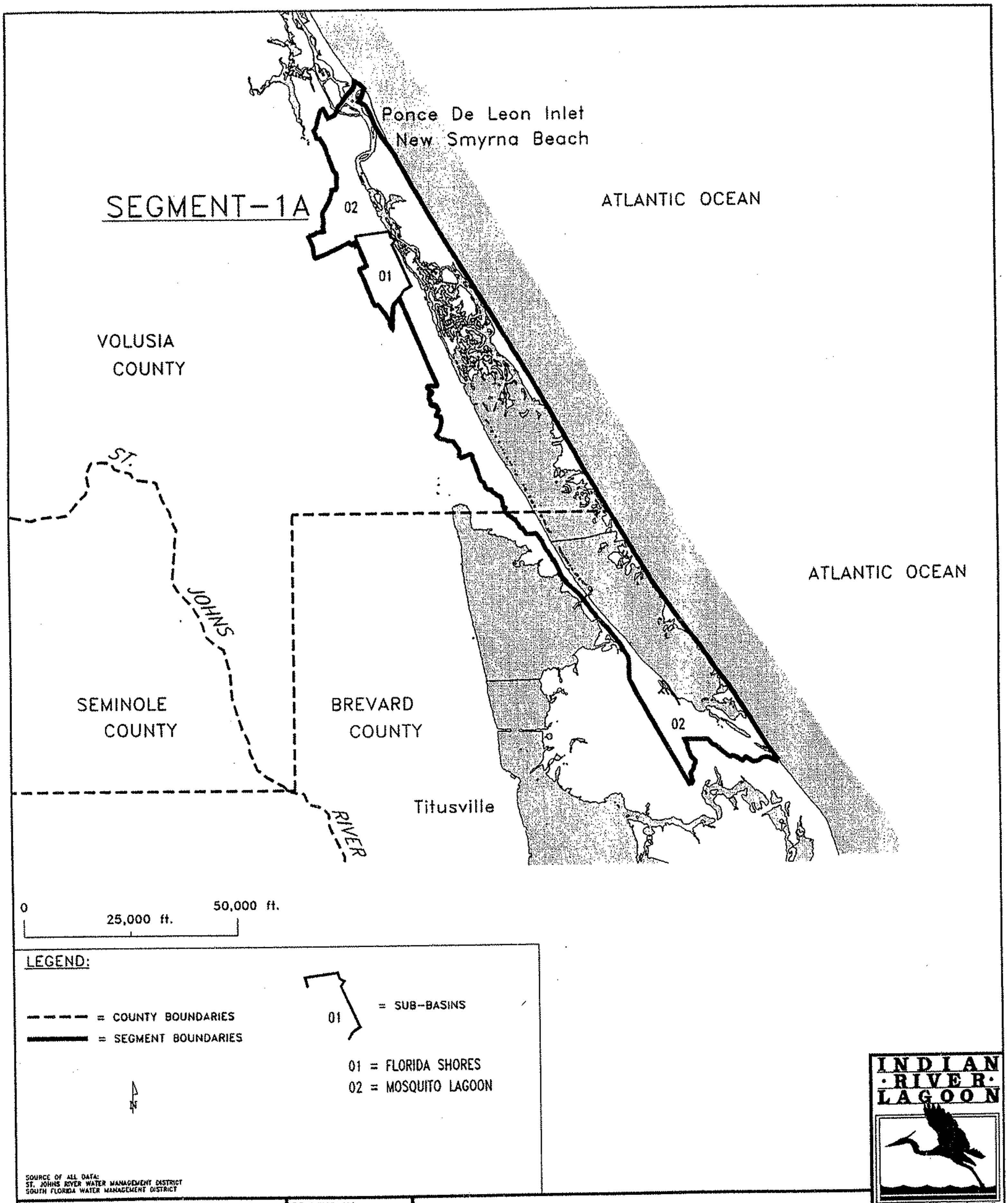
Ponce de Leon Inlet, the only existing inlet on Mosquito Lagoon, is located at the northern end of Mosquito Lagoon (and the defined north end of the Indian River Lagoon system). Hydraulically, Mosquito Lagoon is connected to the Indian River Lagoon by way of man-made Haulover Canal. Historically, Mosquito Lagoon may have been connected to the Atlantic Ocean by additional inlets and to the rest of the Lagoon system to the south by channels north and west of Cape Canaveral (Mehta and Brooks, 1973; Almasi, 1983).

In Mosquito Lagoon the natural watershed boundaries are much the same as those that existed prior to the permanent arrival of Europeans in the 1700's. Mosquito Lagoon and its watershed are entirely located within Volusia and Brevard counties (Figure 2-3). New Smyrna Beach, Edgewater, Oak Hill, and unincorporated Silver Sands/Bethune Beach are located along Mosquito Lagoon. The natural streams or creeks are very short (several thousand ft) and drain into a hardwood slough just behind the Atlantic Coastal Ridge. There are several minor man-made drainage ditches that discharge into the Mosquito Lagoon. The limits of these natural and artificial watersheds have not been mapped. Therefore, information concerning the relative effects of each watershed on the Lagoon is lacking and the influence of specific drainages cannot presently be assessed.

2.3.2 Banana River

The Banana River is hydraulically connected to the Indian River Lagoon at the south end of Merritt Island. The Banana River was naturally connected at its north end to the north Indian River Lagoon by Banana Creek until construction of the crawler road to the vehicle assembly building (VAB) severed the connection. The Banana River is hydraulically connected to the Atlantic Ocean through the locks of Port Canaveral Inlet. However, the locks restrict water exchange to a negligible amount.

Much of the northern drainage basin of the Banana River is within the Kennedy Space Center and is relatively undeveloped. The Banana River also receives drainage from the heavily developed Sykes Creek basin by way of Newfound Harbor. The urban areas of Cape Canaveral, Cocoa Beach, Satellite Beach, Indian Harbor Beach, and unincorporated Merritt



•Woodward-Clyde Consultants
•Marshall McCully & Associates
•Natural Systems Analysts

DRAWING NO.: SUBSEG1A.DWG

DATE: 7-5-94

FIGURE 2-3 DRAINAGE SUB-BASINS OF THE MOSQUITO LAGOON WATERSHED (SEGMENT 1A)

Island exist on the banks of the Banana River. Four causeways have been constructed across the Banana River and Port Canaveral has been created from dredge spoil at Port Canaveral Inlet (Figure 2-4). Large areas of fill also have been placed in the Banana River for such uses as Kennedy Space Center facilities, Cape Canaveral Hospital and the Cocoa Beach Golf Course.

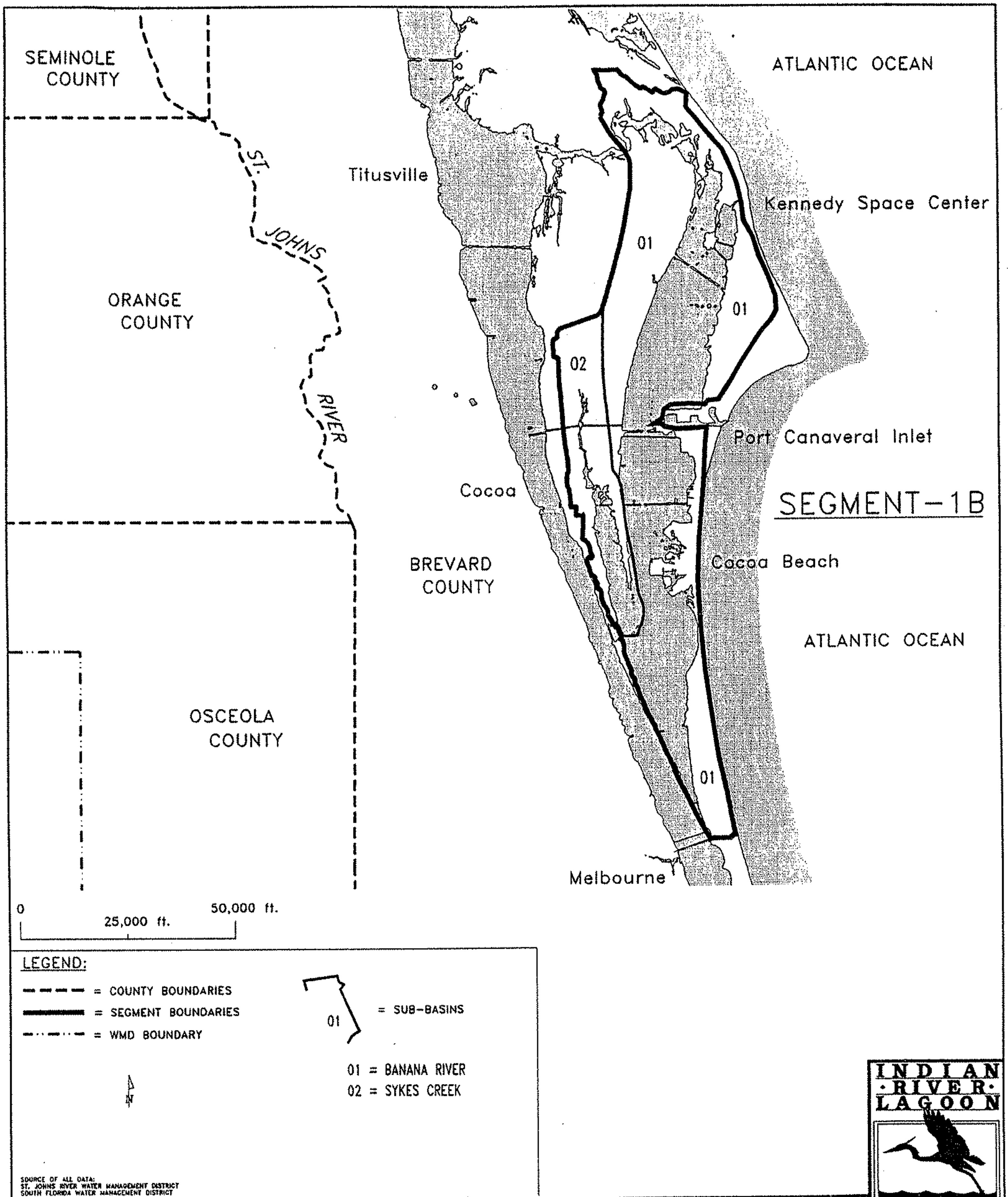
2.3.3 Indian River Lagoon

The Indian River Lagoon proper receives drainage from local overland flow, creeks, streams and drainage canals, some of which extend beyond the Atlantic Coastal Ridge. Most of the naturally occurring streams or creeks have had their flow characteristics altered by channelization and the extension of the headwaters into areas west of the natural watershed boundaries. An exception is Turnbull Creek at the extreme north end, which has been altered only slightly. There are also man-made canal and ditch systems that discharge directly into the Indian River Lagoon. Fourteen causeways have been constructed across the Indian River Lagoon and Banana River (Figure 1-2). Figures 2-5 through 2-8 show the principal segments and drainage features of the Indian River Lagoon.

2.3.4 Indian River Lagoon System

The shoreline of the Indian River Lagoon system has been drastically altered by dredge, fill, and impoundment activities. Impoundment of salt marsh areas has essentially removed 39,016 ac from communication with the open surface water area. Sixty-nine percent of that area is located within the Merritt Island National Wildlife Refuge (MINWR) in Brevard County. Impounded areas in the remainder of the Indian River Lagoon system include 478 ac in Volusia County; 3,527 ac in Brevard County outside of MINWR; 2,769 ac in Indian River County; 4,694 ac in St. Lucie County; and 625 ac in Martin County (Rey and Kain, 1989).

As a receiving water, the Indian River Lagoon system accepts inputs of salt water from the ocean through the inlets and freshwater from direct precipitation, ground water seepage, surface runoff, creeks and streams, drainage systems, and point sources such as wastewater treatment plants. The tidal forces of the inlets add to the wind driven forces that cause circulation. Only in the vicinity of the inlets does the effect of tide exceed the effect of



•Woodward-Clyde Consultants •Marshall McCully & Associates •Natural Systems Analysts	DRAWING NO.: SUBSEG1B.DWG DATE: 7-5-94	FIGURE 2-4 DRAINAGE SUB-BASINS OF THE BANANA RIVER WATERSHED (SEGMENT 1B)

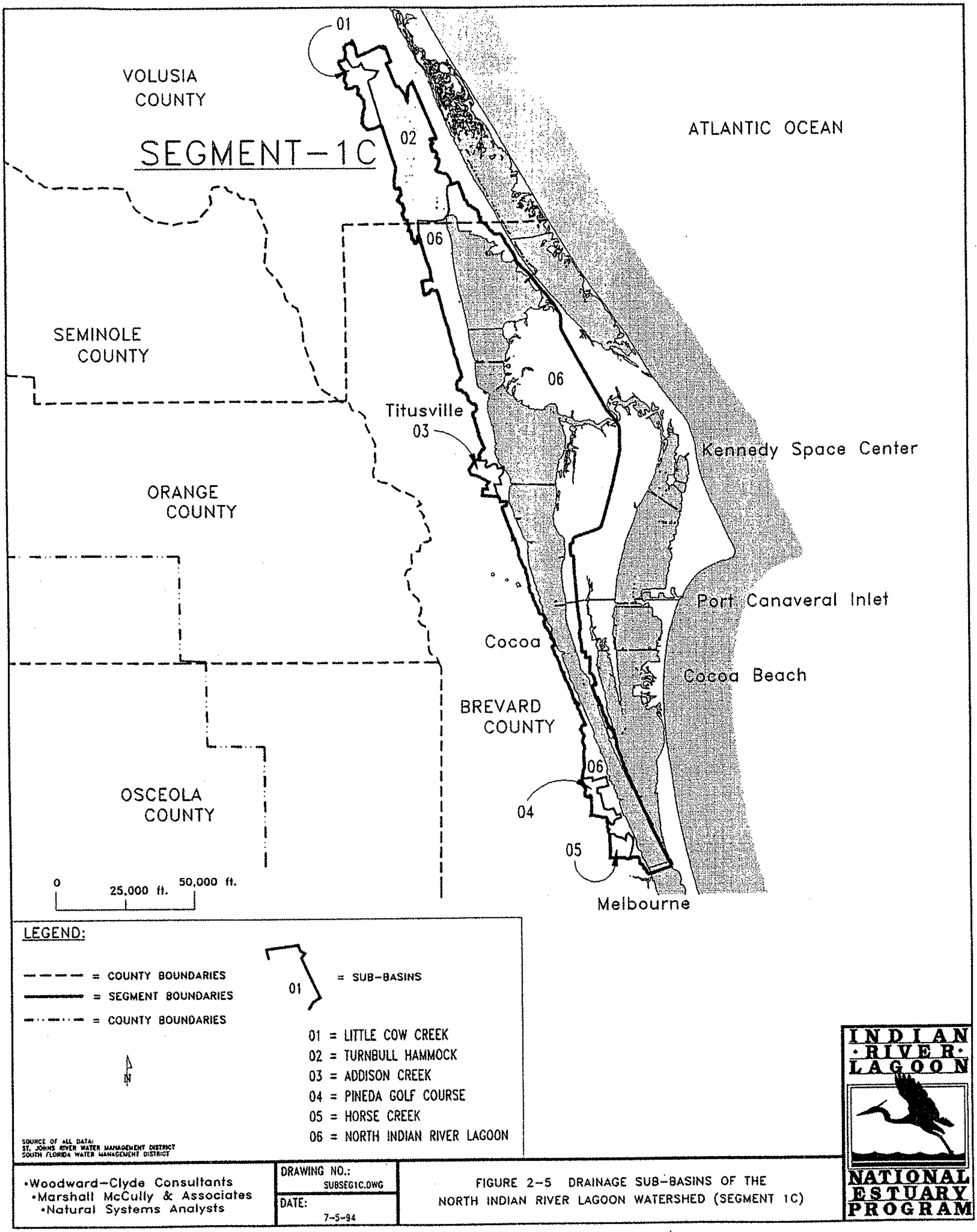
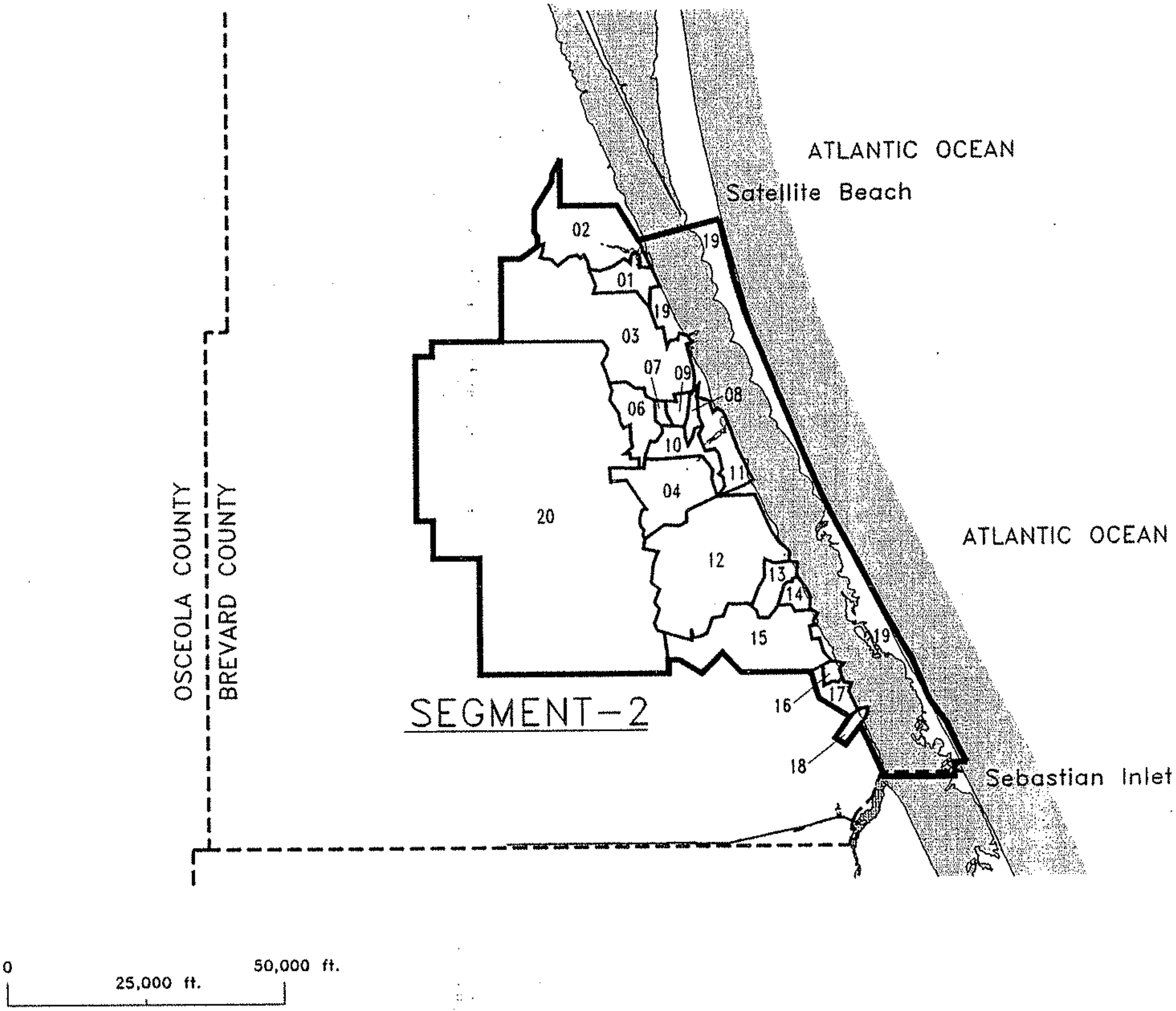


FIGURE 2-5 DRAINAGE SUB-BASINS OF THE NORTH INDIAN RIVER LAGOON WATERSHED (SEGMENT 1C)



LEGEND:

01 = SUB-BASINS

= COUNTY BOUNDARIES

= SEGMENT BOUNDARIES

01-02 = ELBOW CREEK/EAU GALLIE RIVER
03 = CRANE CREEK
04-11 = TURKEY CREEK
12 = GOAT CREEK
13 = KID CREEK
14 = UNNAMED COASTAL
15 = TROUT CREEK
16 = UNNAMED COASTAL
17 = UNNAMED COASTAL
18 = UNNAMED COASTAL
19 = NORTH CENTRAL INDIAN RIVER LAGOON
20 = WATER CONTROL DISTRICT OF SOUTH BREVARD

N

SOURCE OF ALL DATA:
ST. JOHNS RIVER WATER MANAGEMENT DISTRICT
SOUTH FLORIDA WATER MANAGEMENT DISTRICT

•Woodward-Clyde Consultants •Marshall McCully & Associates •Natural Systems Analysts	DRAWING NO.: SUBSEG2.DWG DATE: 7-5-94	FIGURE 2-6 DRAINAGE SUB-BASINS OF THE NORTH CENTRAL INDIAN RIVER LAGOON WATERSHED (SEGMENT 2)

INDIAN RIVER LAGOON NATIONAL ESTUARY PROGRAM

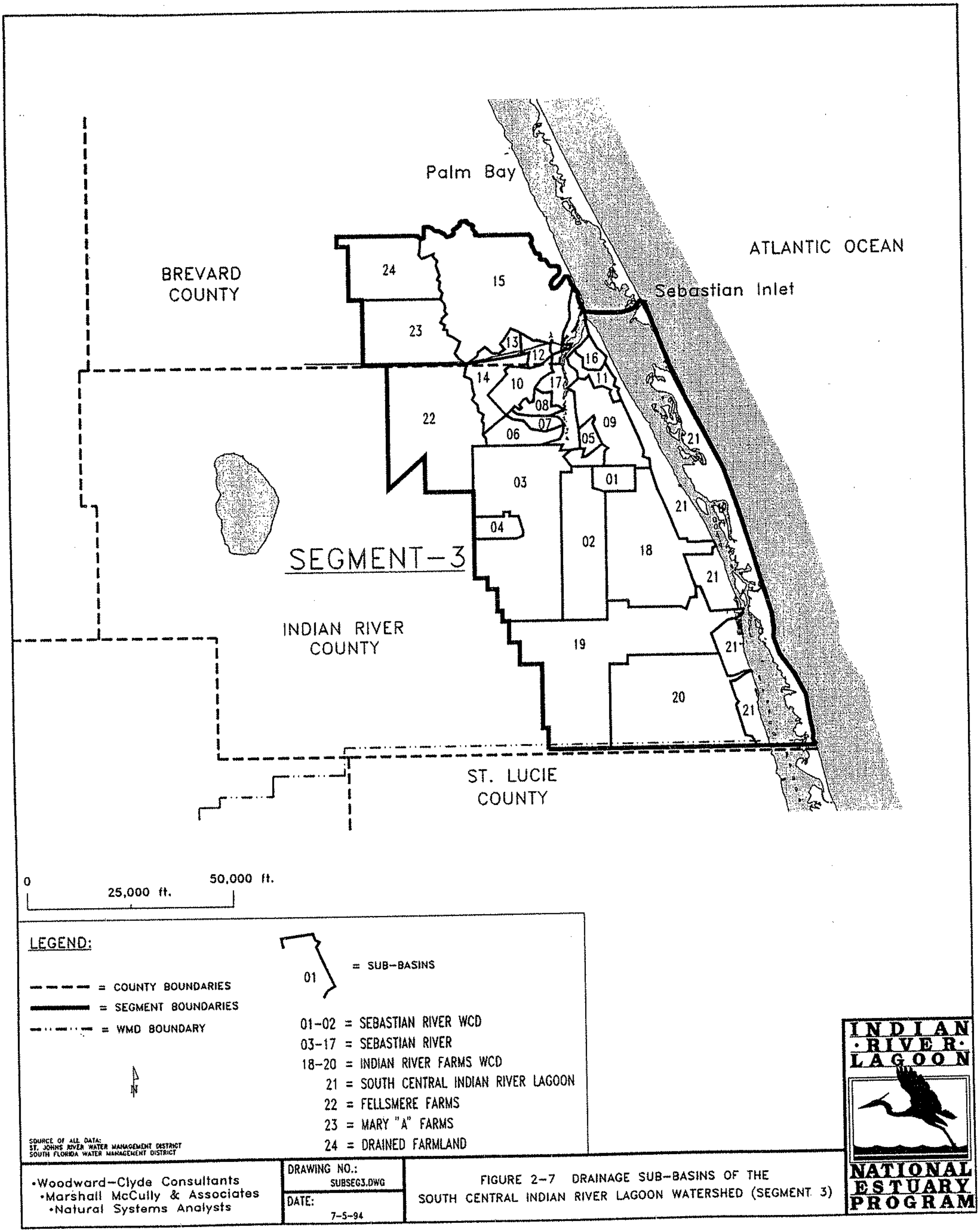


FIGURE 2-7 DRAINAGE SUB-BASINS OF THE SOUTH CENTRAL INDIAN RIVER LAGOON WATERSHED (SEGMENT 3)

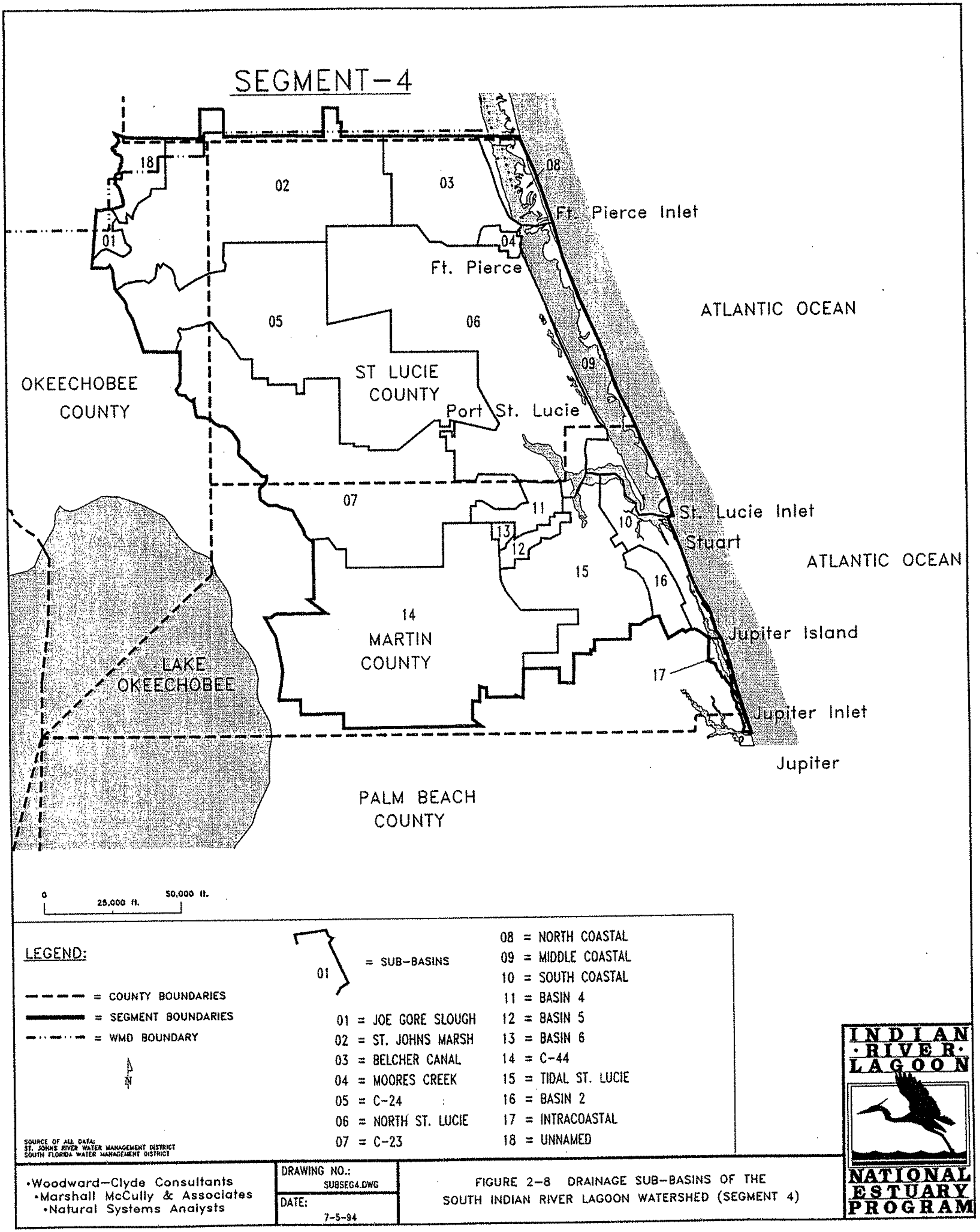


FIGURE 2-8 DRAINAGE SUB-BASINS OF THE SOUTH INDIAN RIVER LAGOON WATERSHED (SEGMENT 4)

wind-driven currents within the Lagoon. This area in which the intertidal volume (tidal prism) is dominant may vary from about 1 to 2 mi at Sebastian Inlet to about 6 mi at Ft. Pierce Inlet (Smith, 1988).

The drainage of freshwater from the land into the Indian River Lagoon system is partially a function of soil type. The characteristics of the soil determine soil storage of water which affects the volume of stormwater runoff. The soil type also determines whether or not the soil is easily drained by ditch and canal systems. Therefore, drainage patterns and the extent of the watershed depend on land use, soil type, and the ground surface elevation or the elevation of a defined drainage flowway.

Because the Indian River Lagoon system has been affected by the construction and stabilization of inlets and the construction of extensive drainage systems that extended the watershed, inlets and drainage basins will be discussed separately below. A discussion of the soils of the region is also included to supplement the drainage discussion.

2.4 INLETS

Natural tidal inlets allow tidal exchange between the Lagoon and the ocean. The volume of the flow is determined by the difference between the Lagoon volumes at high and low tides. This is called the tidal prism and it can be noticeably augmented by river and ground water inputs to the Lagoon. The strong tidal currents at an inlet act to keep it clear of sediment build-up. Waves and longshore currents on the ocean side of the barrier islands tend to move sand along the beaches and into the inlets. Although the longshore current processes tend to balance inlet shoaling and the tidal currents that keep them open, natural inlets are often shallow and nearly choked by shifting shoals. Changes in sand transport may close an inlet or a new inlet may be driven through the barrier island during a major storm, replacing the function of a prior inlet.

When inlets form, sand accumulates seaward of the inlet, in a lunate shoal called the ebb-tidal delta, and also on the lagoon side of the inlet, called the flood-tidal delta. The predominance of either the ebb- or flood-tidal delta is a result of the dynamic balance between wave action, tidal currents, and longshore sediment drift (Hayes, 1975). If an inlet remains open, it is usually because the tidal flow is strong enough to overcome the longshore sediment depositional drift and resulting sedimentation inside the inlet. After an inlet closes, the flood-tidal (lagoon side) delta becomes vegetated by seagrass and marsh vegetation because energy has been reduced. These inlet closure features are seen as broad protrusions extending into the Lagoon from the barrier island. Examples on the Indian River Lagoon system include eastern shore of the Mosquito Lagoon, the Indian River (Vero) Narrows, and the Jupiter Narrows. The old location of Ft. Pierce Inlet, about three miles north of the present inlet, is an example of revegetation.

According to Stauble (1988), and Stauble and Da Costa (1988), the trend for longshore sand transport in this region of the Atlantic Ocean is that of a seasonally reversing longshore pattern with long-term net transport to the south in most areas. Superimposed nodal points of changing longshore direction in the area of Bethune Beach in Volusia County and also in several areas of Brevard County have also been identified.

Offshore bathymetric features identified by Jensen (1983) may create conditions that tend to cause overwash and may eventually lead to inlet development or closing. Evidence of abandoned flood tide shoals shows that inlets have been present in several locations in the Indian River Lagoon system at some time in the past and have since closed (Mehta and Brooks, 1973). For example, it is known that an inlet existed and then closed near the Bethune Beach area in Volusia County in about 500 A.D. (Mehta and Brooks 1973). An inlet was also found by Spanish explorers about 3 miles north of the present location of the Ft. Pierce Inlet. Walton (1974) attributed its final closure to the construction of St. Lucie Inlet to the south in 1892. The opening of the new inlet decreased the tidal flow of the old inlet to the point where the longshore depositional drift clogged the inlet.

The locations of the existing inlets in the Indian River Lagoon system are shown on Figure 1-1 and Figures 2-3 through 2-8. From north to south the inlets are Ponce de Leon Inlet in Volusia County, Port Canaveral Inlet in Brevard County, Sebastian Inlet on the Brevard/Indian River County line, Ft. Pierce Inlet in St. Lucie County, St. Lucie Inlet in Martin County, and Jupiter Inlet in Palm Beach County. Projects to construct jetties at all six of these inlets have been undertaken in an attempt to halt migration and increase tidal current velocities to eliminate shoaling. None have been completely successful. These jetties have interfered with the natural longshore drift on the ocean side of the barrier islands. Each of the inlets has a strong influence on circulation and sediment deposition in the Lagoon near the inlet (Stauble, 1988).

2.4.1 Ponce de Leon Inlet

Ponce de Leon Inlet first appeared on a map in the 1500's as Mosquito Inlet. Because of the dynamic behavior of the shoreline on both sides of the inlet and the shoaling of the mouth, a stabilization project was conducted between 1968 and 1972. Studies by Stapor and May (1983) and Stauble and Da Costa (1988) indicate a seasonally reversing but predominately northerly longshore drift. Evidence of such a predominance of the northerly longshore drift includes erosion of sand on the north side and sediment accumulation on the south side of the inlet, a relatively large ebb-tidal delta, and a nodal point of changing longshore current direction south of Ponce de Leon Inlet (Hull, et al., 1990). However, Taylor, et al. (1990) produced a model of the inlet indicating that it may have an erosion/deposition pattern similar to that of the inlets south of the Cape, a condition that shows evidence of a net southerly longshore drift. Thus the drift patterns around this inlet may be changeable and do not appear to be well understood.

2.4.2 Port Canaveral Inlet

The Port Canaveral Inlet is a completely man-made inlet which was constructed between 1950 and 1954 in an area already known to shipping interests to be a safe anchorage from storms due to protection by the Cape. The effect of jetties on the net southerly longshore drift has caused with loss of sand on the south side and an accumulation on the north side. Several beach renourishment projects have taken place on the south side in an attempt to remedy the erosional loss impacts. The harbor within the inlet is relatively small. A system of locks keeps the flow of seawater out of the brackish Banana River and also eliminates any tidal influences on the Banana River.

2.4.3 Sebastian Inlet

Sebastian Inlet is a man-made inlet that was first opened in 1886 at the site of a former natural inlet. It closed and was reopened several times, and is now relatively stable with jetties on both north and south shores. An erosion/deposition pattern has developed with sand accumulating north of the inlet and eroding to the south. The flood-tidal delta is quite large and would cover a larger area except that dredging projects have removed sand from the flood-tide delta and placed it on the sand-starved south ocean shoreline (Coastal Technology Corp., 1988).

2.4.4 Ft. Pierce Inlet

Ft. Pierce Inlet is also man-made and is located about 3 miles south of the location of the former natural inlet that closed when the St. Lucie Inlet was opened. Construction of jetties at this inlet began in the 1920's, but numerous problems with shoaling occurred during the early periods of the inlet's construction. Outcroppings of the Anastasia Formation that became exposed during the cutting of the barrier island have become inhabited by sabellariid worms, creating a reef that constricts the throat opening today. Again, erosional patterns have developed which has required renourishment of the beach on the south side of the inlet (U.S. Army Corps of Engineers, 1992; Coastal Planning and Engineering, 1993).

2.4.5 St. Lucie Inlet

St. Lucie Inlet was originally cut in its present location in 1892. Its construction resulted in the closing of the natural inlet to the north of the current Ft. Pierce Inlet. Jetties were first constructed in 1929. In 1962, a new inlet formed at Pecks Lake about 4 miles south of St. Lucie Inlet during a severe "northeaster" storm. Significant shoaling of the ICWW resulted, causing the U.S. Army Corps of Engineers (COE) to close this new Pecks Lake inlet in 1963. St. Lucie Inlet also that has required numerous beach renourishment projects on the south shoreline (Applied Technology and Management, Inc., 1993).

2.4.6 Jupiter Inlet

Jupiter Inlet is the southernmost inlet of the Indian River Lagoon system and is a natural inlet. South of Jupiter Inlet, the ICWW is cut through a former headland. Jetties have been constructed on both shores. This inlet also has experienced numerous dredging projects that have been needed to maintain the required depth and to renourish the starved ocean shoreline on the south side.

2.4.7 Summary

The construction and stabilization of inlets has had a profound effect on the hydrodynamics and circulation of the Indian River Lagoon system. The natural process of occasional overwash with inlet formation followed by shoaling and closing strengthens the genetic pool of sea life in the region, among other benefits. Inlet stabilization has interfered with that process. Because inlet stabilization has not eliminated shoaling at any location, money must be spent to bypass and dredge inlets so that they remain navigable. In some locations (Port Canaveral, Ft. Pierce, and St. Lucie Inlets), the commerce that is created is considered to more than offset the expenditure. At other inlets (Ponce de Leon, Sebastian, and Jupiter Inlets) the primary economic gain is recreational fishing, and the cost/benefit ratio may be limited.

2.5 DRAINAGE PATTERNS AND WATERSHED BOUNDARIES

2.5.1 System-Wide Patterns

Under natural conditions, soil type, vegetation type, and ground surface elevation are the primary factors that determine drainage patterns and the extent of drainage basin that drains into a surface water body. In much of the Indian River Lagoon system watershed, however, watershed limits have been greatly increased by artificial drainage systems. The first man-made drainage system was constructed by Andrew Turnbull before 1800 in New Smyrna Beach. Today, constructed drainage systems are abundant in South Brevard, Indian River, St. Lucie, and Martin counties.

According to the Recon Report, the Indian River Lagoon system watershed including the surface waters and the drainage basin encompassed a total area of 1,460,905 ac in 1987. Since 1987 approximately 28,946 ac have been removed from the watershed, by redirecting drainage to the St. Johns River resulting in a current total watershed area of 1,431,959 ac based on computation of current watershed boundaries. Based on reports of Glatzel and Da Costa (1988b), it appears that 61 percent (%) of the currently existing Indian River Lagoon system watershed is comprised of artificially extended watershed. The natural watershed of the Lagoon system would thus have encompassed 558,464 ac. Based on this, the area of the extended watershed at the current time is 873,495 ac.

The first chapter of this report describes how the Indian River Lagoon system may be divided into six surface water segments with their associated drainage basins. Each segment is a distinct hydrologic basin, although the division of the barrier island area is somewhat arbitrary. Table 2-2 presents each segment/basin and the sub-basins within each basin. This table was constructed from GIS data files provided by the SJRWMD, the SFWMD, and the Recon Report.

Basins and sub-basins are described below. In some areas, sub-basins have been sub-divided again into smaller areas as part of a project undertaken by one of the water management districts or by a local government agency. The Turkey Creek area near Melbourne is a good example of this. In other areas such as Mosquito Lagoon, sub-basins are known to exist but have not yet been defined. This does not reduce the accuracy of any description in this report. It simply paints a broader picture in these areas and helps to identify areas with study needs.

2.5.2 Segment 1A - Mosquito Lagoon

The Mosquito Lagoon is at the northern end of the Indian River Lagoon system (Figure 2-3). Mosquito Lagoon has the following distribution of lagoon and watershed areas:

LAGOON AREA		WATERSHED AREA		TOTAL	
km^2	acre	km^2	acre	km^2	acre
159	37,853	168	41,569	327	79,422

The Mosquito Lagoon basin includes areas within both Volusia and Brevard counties. Three municipalities exist within this basin, the Cities of New Smyrna Beach, Edgewater, and Oak Hill. The western basin boundary passes through New Smyrna Beach and Edgewater, but includes all of Oak Hill.

Ponce de Leon Inlet is the northern connection of the Indian River Lagoon system with the ocean and is also the north end of Mosquito Lagoon (Figure 2-3). The hydraulic link between Mosquito Lagoon and north Indian River Lagoon is Haulover Canal, which is a

TABLE 2-2

WATERSHED AND SURFACE WATER AREA BY SEGMENT AND SUB-BASIN

SEGMENT	SUB-BASIN DESIGNATION	WMD DESIGNATION	BASIN NAME	LAGOON AREA KM^2	LAGOON AREA ACRE	WATERSHED AREA KM^2	WATERSHED AREA ACRE
1A-Mosquito Lagoon	1A-01	10A-01	Florida Shores	0	0	13.7	3,386.5
	1A-02	10A-02	Mosquito Lagoon	158.8	37,853.4	154.6	38,182.3
1B-Banana River	1B-01	10B-01	Banana River	179.2	44,393.6	196.6	48,552.6
	1B-02	10B-02	Sykes Creek	13.6	3,369.2	51.7	12,773.1
1C-North Indian River Lagoon	1C-01	10C-01	Little Cow Creek	0	0	14.3	3,542.1
	1C-02	10C-02	Turnbull Hammock	0	0	97.2	24,012.8
	1C-03	10C-03	Addison Creek	0	0	8.1	2,001.4
	1C-04	10C-04	Pineda Golf Course	0	0	11.0	2,709.9
	1C-05	10C-05	Horse Creek	0	0	7.1	1,753.1
	1C-06	10C-06	North Indian River Lagoon	286.4	70,727.6	316.5	78,176.8
2-North Central Indian River Lagoon	2-01	10D-01	Elbow Creek	0	0	6.4	1,582.7
	2-02	10D-02	Eau Gallie River	0	0	18.7	4,617.4
	2-03	10D-03	Crane Creek	0	0	47.3	11,684.1
	2-04	10D-04	Little Turkey Creek	0	0	11.9	2,929.7
	2-05	10D-05	South Ditch	0	0	1.6	396.5
	2-06	10D-06	---	0	0	1.4	1,819.7
	2-07	10D-07	---	0	0	0.3	69.3
	2-08	10D-08	Radiation Ditch	0	0	1.7	430.2

TABLE 2-2

WATERSHED AND SURFACE WATER AREA BY SEGMENT AND SUB-BASIN, Continued

SEGMENT	SUB-BASIN DESIGNATION	WMD DESIGNATION	BASIN NAME	LAGOON AREA		WATERSHED AREA	
				KM^2	ACRE	KM^2	ACRE
2-North Central Indian River Lagoon, Continued	2-09	10D-09	—	0	0	2.0	502.1
	2-10	10D-10	North Ditch	0	0	4.6	1,137.1
	2-11	10D-11	Turkey Creek	0	0	11.9	2,934.0
	2-12	10D-12	Goat Creek	0	0	41.5	10,252.0
	2-13	10D-13	Kid Creek	0	0	4.7	1,161.5
	2-14	10D-14	—	0	0	1.9	466.7
	2-15	10D-15	Trout Creek	0	0	22.0	5,436.1
	2-16	10D-16	—	0	0	1.4	335.5
	2-17	10D-17	—	0	0	2.6	634.2
	2-18	10D-18	—	0	0	1.0	252.5
	2-19	10D-19	North Central Indian River Lagoon	93.2	23,088.7	38.0	9,385.6
	2-20	6D-04	—	0	0	201.8	49,839.2
3-South Central Indian River Lagoon	3-01	10E-01	—	0	0	6.3	1,562.4
	3-02	10E-02	Sebastian River WCD	0	0	35.6	8,805.8
	3-03	10E-03	—	0	0	77.2	19,066.2
	3-04	10E-04	—	0	0	5.4	1,341.3

TABLE 2-2

WATERSHED AND SURFACE WATER AREA BY SEGMENT AND SUB-BASIN, Continued

SEGMENT	SUB-BASIN DESIGNATION	WMD DESIGNATION	BASIN NAME	LAGOON AREA KM²	LAGOON AREA ACRE	WATERSHED AREA KM²	WATERSHED AREA ACRE
3-South Central Indian River Lagoon, Continued	3-05	10E-05	---	0	0	2.6	639.0
	3-06	10E-06	---	0	0	9.9	2,446.4
	3-07	10E-07	---	0	0	1.8	453.1
	3-08	10E-08	---	0	0	4.2	1,041.1
	3-09	10E-09	---	0	0	20.5	5,065.4
	3-10	10E-10	---	0	0	10.0	2,468.2
	3-11	10E-11	---	0	0	4.9	1,220.3
	3-12	10E-12	C-54 Canal	0	0	3.8	931.7
	3-13	10E-13	C-54 Above Control	0	0	4.7	1,151.1
	3-14	10E-14	Fellsmere Canal	0	0	10.5	2,604.7
	3-15	10E-15	North Sebastian River	0	0	73.3	18,094.0
	3-16	10E-16	---	0	0	3.1	765.8
	3-17	10E-17	Sebastian River	0	0	21.7	5,363.5
	3-18	10E=18	North Canal	0	0	53.0	13,096.6
	3-19	10E-19	Main Canal	0	0	87.9	21,720.0
	3-20	10E-20	South Canal	0	0	67.1	16,582.3
	3-21	10E-22	South Central Indian River Lagoon	70.8	17,486.1	72.1	17,807.2

TABLE 2-2

WATERSHED AND SURFACE WATER AREA BY SEGMENT AND SUB-BASIN, Continued

SEGMENT	SUB-BASIN DESIGNATION	WMD DESIGNATION	BASIN NAME	LAGOON AREA KM^2	LAGOON AREA ACRE	WATERSHED AREA KM^2	WATERSHED AREA ACRE
3-South Central Indian River Lagoon, Continued	3-22	6D-01	Fellsmere Farms	0	0	59.7	14,748.1
	3-23	6D-02	Mary "A" Farms	0	0	56.6	13,980.8
	3-24	6D-03	Sottile Farms	0	0	32.4	7,992.5
4-South Indian River Lagoon	4-01	Joe Gore Slough	Joe Gore Slough	0	0	16.7	4,131.7
	4-02	St. Johns Marsh	St. Johns Marsh	0	0	379.1	93,617.7
	4-03	Belcher Canal	Belcher Canal	0	0	108.5	26,797.2
	4-04	Moore's Creek	Moore's Creek	0	0	61.4	15,171.0
	4-05	C-24	C-24	0	0	429.2	106,011.9
	4-06	North St.Lucie	North St. Lucie	0	0	485.8	119,978.6
	4-07	C-23	C-23	0	0	431.8	106,638.7
	4-08	North Coastal	North Coastal	18.8	4,638.1	71.9	17,751.1
	4-09	Middle Coastal	Middle Coastal	91.2	22,521.7	59.5	14,683.4
	4-10	South Coastal	South Coastal	14.8	3,659.8	47.1	11,630.1
	4-11	Basin 4	Basin 4	0	0	32.5	8,016.7
	4-12	Basin 5	Basin 5	0	0	3.9	959.2
	4-13	Basin 6	Basin 6	0	0	18.7	4,612.8
	4-14	C-44	C-44	0	0	491.4	121,376.9
	4-15	Tidal St. Lucie	Tidal St. Lucie	0	0	181.4	44,811.0

TABLE 2-2

WATERSHED AND SURFACE WATER AREA BY SEGMENT AND SUB-BASIN, Continued

SEGMENT	SUB-BASIN DESIGNATION	WMD DESIGNATION	BASIN NAME	LAGOON AREA KM^2	LAGOON AREA ACRE	WATERSHED AREA KM^2	WATERSHED AREA ACRE
4-South Indian River Lagoon, Continued	4-16	Basin 2	Basin 2	0	0	36.4	8,994.0
	4-17	Intracoastal	Intracoastal	3.0	733.6	8.8	2,163.3
	4-18	Unnamed	Unnamed	0	0	38.5	9,500.1

man-made canal constructed to replace an overland system of transporting boats. Boats have been using the Haulover Canal area as part of the waterway trading route since the early 1800's. Haulover Canal was excavated in 1854 (Hutchinson, 1987).

The Mosquito Lagoon basin consists of two sub-basins, the largest of which is called the Mosquito Lagoon sub-basin (1A-02). It includes the area draining to the Lagoon by direct overland flow, sub-surface flow, or conveyed by drainage ditches. Watershed (upland) area within the Mosquito Lagoon sub-basin is 41,569 ac. The smaller basin is a well-defined area called the Florida Shores sub-basin (1A-01) within the City of Edgewater that is drained by a single drainage canal. The Florida Shores sub-basin covers an area of 3,386 ac. Watershed (land) area within the Mosquito Lagoon sub-basin is 41,569 ac.

The drainage pattern in the Mosquito Lagoon basin is a combination of natural and altered waterways. The natural pattern on the mainland is largely direct surface runoff from the coastal ridge, which is directly adjacent to the Lagoon in most areas. Surface runoff occurs when the sandy soils become saturated. The surficial aquifer contributes sub-surface flow into the Lagoon. In some areas small creeks extend west of the coastal ridge. There are storm sewers in the cities of New Smyrna Beach and Edgewater that direct runoff into the Lagoon instead of allowing infiltration. On the barrier island (except from the impermeable areas within the developed areas), the soils are so permeable that natural runoff is practically non-existent.

There are numerous small ditches that drain small slough areas parallel to the shoreline into the Mosquito Lagoon sub-basin that have not yet been mapped. Much of the area south of the City of Oak Hill is undeveloped. This area is owned and managed by the National Aeronautics and Space Administration (NASA), and the Department of the Interior. Some of NASA lands are managed by the U.S. Fish and Wildlife Service. Lands within the Canaveral National Seashore are managed by the National Park Service.

Two wastewater treatment plants serve the cities of New Smyrna Beach and Edgewater and discharge to Mosquito Lagoon. Both cities are in the process of implementing reuse plans to eliminate flows to Mosquito Lagoon.

2.5.3 Segment 1B - Banana River

The Banana River segment is located entirely within Brevard County and includes all of the Banana River, Sykes Creek, and Newfound Harbor (See Figure 2-4). Banana Creek, at the northern end, was once connected to north Indian River Lagoon. Construction of the VAB crawler road severed that connection. The lagoon area (including Sykes Creek/Newfound Harbor) and the watershed area for this segment are:

LAGOON AREA		WATERSHED AREA		TOTAL	
km^2	acre	km^2	acre	km^2	acre
193	47,763	248	61,326	441	109,089

The Banana River sub-basin (1B-01) has an upland area of 48,553 ac and open water area of 44,394 ac (Table 2-2). Most of the northern part of the Banana River basin is occupied by the Kennedy Space Center and the Cape Canaveral Air Force Station. The cities of Cape Canaveral, Cocoa Beach, Satellite Beach, and Indian Harbor Beach are also located within this sub-basin, as well as Patrick Air Force Base. Within this sub-basin there are four causeway/bridge transportation links from the mainland to the barrier island. Some of the area located at the eastern tip of Cape Canaveral and adjacent to the ocean is internally drained or drains to the Atlantic Ocean. Other areas have been disconnected the surrounding watershed by the construction of the Port Canaveral facilities.

This basin contains highly developed land on Merritt Island in an unincorporated part of Brevard County, particularly in the Sykes Creek sub-basin. Most of the area on Merritt Island and within the cities was developed prior to the adoption of stormwater management regulations. Large urban areas along the shoreline have impervious areas that drain directly to the Lagoon.

In the less developed portions of the sub-basin, there has been extensive ditching through the flatwoods and sloughs in an attempt to lower the ground water table for control of flooding and mosquito hatching. Sykes Creek has been extensively ditched, thereby increasing base flows to this stream.

The remaining hydraulic connection to the Indian River Lagoon system is a very small opening (500 ft wide) at the south end of Merritt Island. Water exchange through this opening is minimal. The distance of the basin from Sebastian Inlet means that tidal mixing in Banana River is virtually non-existent. During the late spring/summer, when Indian River stormwater loads are the highest, Banana River can act as a "negative" estuary (evaporation exceeding freshwater inflows), actually receiving water from the Indian River Lagoon proper due to wind driven flows and excess evaporation (Glatzel and Da Costa, 1988a, 1988b).

The Sykes Creek (Including Newfound Harbor) sub-basin (1B-02) has an upland area of 12,773 ac and an open water area of 3,369 ac. Sykes Creek was a well-published example of point source pollution during the early 1980's when many small, overloaded wastewater treatment plants (WWTP) discharged to Sykes Creek. At the time the Recon Report was written, flows from the smaller plants had been combined into more effective larger treatment plants and treatment had improved, but the discharge of high levels of suspended solids and nutrients continued. All of these older plants have now been decommissioned, and a single regional WWTP has been constructed on Merritt Island. All discharges are now disposed of by deep well injection and thus there is no discharge to Sykes Creek. (FDER, 1991).

Overall, seven wastewater treatment plants discharging to the Banana River basin have closed, and five new discharging plants have been constructed. Two of these plants replace closed plants at Kennedy Space Center. The other three new plants are seafood processing plants in Port Canaveral (FDER, 1991). These three seafood plants operate intermittently and their discharge is actually into the port and into the Atlantic Ocean rather than to Banana River.

2.5.4 Segment 1C - North Indian River Lagoon

The North Indian River Lagoon basin includes lands and surface waters located within both Volusia and Brevard counties (Figure 2-5). The north end of the Indian River Lagoon watershed is located in Volusia County north of Turnbull Creek in Turnbull Hammock. Little Cow Creek drains some land west of I-95 in Volusia County into the north end of Turnbull Hammock.

The lagoon area and watershed area for this segment are:

LAGOON AREA		WATERSHED AREA		TOTAL	
km^2	acre	km^2	acre	km^2	acre
286	70,728	454	112,197	740	182,925

This shows that the land area is very small, accounting for only 35% of the whole basin area.

There has been very little artificial expansion of the watershed in this segment. In the southern half of the segment there are several distinct drainage areas including Addison Creek (1C-03), the Pineda Golf Course (1C-04), and Horse Creek (1C-05). There are several small ditch systems in the Scottsmoor area whose drainages have not been completely mapped as of late 1993, although stormwater master plan studies are currently underway by Brevard County and a stormwater management needs assessments has been prepared for Volusia County. There are also several ditch systems on west Merritt Island in the Kennedy Space Center. Non-point source discharges in this basin are primarily from the urban areas adjacent to the Lagoon from Titusville South. To the north of Titusville, the main non-point source discharge is from citrus groves in the Flounder Creek basin/Scottsmoor areas and in scattered areas on the east shore of the Lagoon. Along much of this basin, U.S. Highway No. 1 is located adjacent to the west shore, contributing highway runoff directly to the Lagoon. Municipalities located within the north Indian River Lagoon segment are Titusville, Cocoa, Rockledge, Palm Shores and part of Indian Harbor Beach. The west side of unincorporated but highly developed Merritt Island is also located within this segment. Seven causeway/bridge systems cross the Lagoon in this segment/basin. Additionally, there are seven wastewater treatment plants that discharge to the North Indian River Lagoon as well as two power plants with thermal effluent.

2.5.5 Segment 2 - North Central Indian River Lagoon

The North Central Indian River Lagoon basin represents the northernmost portion of the watershed in which the watershed boundary has been extensively extended by artificial drainage systems (See Figure 2-6). This segment/basin is one of the most intensely studied areas of the Indian River Lagoon and, as such, there are many sub-basins with well-delineated drainage areas. Total lagoon area and watershed area of the North Central Indian River Lagoon basin is presented below.

LAGOON AREA		WATERSHED AREA		TOTAL	
km^2	acre	km^2	acre	km^2	acre
93	23,089	429	105,866	522	128,955

Creeks and streams that are located within this basin include Elbow Creek, Eau Gallie River, Crane Creek, Little Turkey Creek, Turkey Creek, Goat Creek, Kid Creek, and Trout Creek. Each of these watercourses and its basin has been extended by construction of drainage canals.

One of the extended watershed sub-basins (2-20) within this basin is referred to as an "interbasin diversion area". An interbasin diversion area is an area that was once located in another watershed but now has been artificially drained into the Indian River Lagoon. Historically, this area west and south of Melbourne was hydrologically connected to the St. Johns River. However, a drainage system was constructed which now discharges into the Indian River Lagoon through Turkey Creek. Originally called the Melbourne-Tillman Drainage District, it was a Chapter 298 District, formed in 1922 (Adkins and Yan, 1993). A Chapter 298 Drainage District is an area that has been established under the provisions of Chapter 298 Florida Statutes, for purposes of removing surface and ground water to control flooding. The drainage system of the District was completed, but other system improvements were never completed. Some improvements, such as a discharge control structure into Turkey Creek, were not completed until the 1970's (SJRWMD and SFWMD, 1993). This drainage district is now called the Water Control District of South Brevard. A plan is presently under development by SJRWMD to remove approximately 20% of the contributing drainage area to use for construction of a detention basin to attenuate peak runoff flows during storm events (Adkins and Yan, 1993).

Municipalities located within the North Central Indian River Lagoon basin include Melbourne, Melbourne Village, West Melbourne, Melbourne Beach, Indialantic, Palm Bay, and Malabar. Extensive impervious areas exist that are directly connected to the Indian

River Lagoon through storm sewer systems. U.S. Highway No. 1, located directly adjacent to the Lagoon along much of this basin, contributes highway runoff. Two wastewater treatment plants in this basin discharge to a canal which is a direct tributary to this Lagoon segment.

2.5.6 Segment 3 - South Central Indian River Lagoon

The South Central Indian River Lagoon basin is located within southern Brevard and Indian River counties (Figure 2-7). It includes large areas that have been drained by man-made drainage systems. The Sebastian River is located at the northern end of this segment. A large drainage canal, C-54, can divert flood waters from the St. Johns River flood plain and water management areas into the Sebastian River. Total lagoon area and watershed area for the South Central Indian River Lagoon basin are presented below:

LAGOON AREA		WATERSHED AREA		TOTAL	
km^2	acre	km^2	acre	km^2	acre
71	17,486	724	178,947	795	196,433

There are 23 sub-basins within this basin. Three of these areas are interbasin diversion areas. These are Sottile Farms (3-24), Mary "A" Farms (3-23), and Fellsmere Farms (3-22). Three Chapter 298 districts exist within this basin. They are Fellsmere Farms Water Control District, Sebastian River Water Control District, and Indian River Farms Water Control District. These three districts are varied in land use and drainage system characteristics.

The Fellsmere Farms Water Control District (FFWCD) drainage system construction began in 1919, with original plans for 300 miles of canals. Within the FFWCD only a portion (sub-basin 3-14) of the area discharges directly to the Sebastian River. Currently, all of the remainder of the FFWCD area, approximately 13,196 ac, flows under gravity to the Fellsmere Main Relief Canal, which then drains to the Sebastian River (Harper and Marshall, 1993). There is no control structure on the Fellsmere Main Relief Canal except for a salinity weir near the discharge point. There are an additional 1,552 ac with drainage ditches that can be pumped if necessary into the FFWCD canal system to discharge into the Lagoon.

The Sebastian River Water Control District (SRWCD) began canal construction in 1927 to drain approximately 10,500 ac into the south prong of the Sebastian River (sub-basin 3-01 and 3-02). Citrus production occurs in 90% of the area. The two main lateral canals, which have flow control structures, discharge by gravity to a slough of the South Prong of the Sebastian River (Harper and Marshall, 1993).

The Indian River Farms Water Control District (IRFWCD) began construction of a drainage system in 1920. Total area drained by this system (sub-basins 3-18, 3-19, and 3-20) is 50,210 ac, with citrus production on 41% of the area of IRFWCD. A substantial area (47%) of IRFWCD is used for non-agricultural uses, primarily urban development. A series of levees separates the IRFWCD from the surrounding area. Three primary discharge canals connect to a grid of secondary and tertiary ditches which discharge directly to the Indian River Lagoon. There are radial gate structures for flow control on all discharge canals (Harper and Marshall, 1993).

Because these water control districts (FFWCD, SRWCD, IRFWCD) were in place before 1977, they are not subject to regulations controlling their discharge or flows. While each system was designed to remove a specific volume of runoff water in 24 hours, the systems are operated primarily for ground water control for agricultural purposes (Harper and Marshall, 1993). Only IRFWCD has an operation and maintenance staff to operate flow control structures. In SRWCD and IRFWCD, artesian wells have historically been used to irrigate crops, and runoff from this irrigation also adds to the discharge volumes.

Municipalities within the South Central Indian River Lagoon basin include Fellsmere, Sebastian, Indian River Shores, and Vero Beach. With the exception of Fellsmere, all of these cities are located adjacent to the Indian River Lagoon and all have stormwater management systems that connect directly to the Lagoon. Much of the Vero Beach area is also located along the canal system of the Indian River Farms Water Control District. As such, there are substantial urban areas that contribute stormwater runoff to the Lagoon via the discharges from this canal. Ten wastewater treatment plants, including one small power plant, discharge into the Lagoon in this basin.

2.5.7 Segment 4 - South Indian River Lagoon

The south segment and basin of the Indian River Lagoon watershed includes much of St. Lucie and Martin counties, and small parts of Palm Beach and Okeechobee counties (Figure 2-8). This basin is located entirely within the SFWMD boundaries. The natural watershed of the Lagoon has been extended far to the west in Segment 4. Agriculture is the primary land use in the extended watershed. The total lagoon area and watershed area within the South Indian River Lagoon basin are presented below:

LAGOON AREA		WATERSHED AREA		TOTAL	
km^2	acre	km^2	acre	km^2	acre
125	30,820	2,903	716,845	3,028	747,665

Municipalities within the South Indian River Lagoon basin include:

- St. Lucie Village
- Ft. Pierce
- Port St. Lucie
- Ocean Breeze Park
- Sewells Point
- Stuart
- Tequesta
- Jupiter Island
- Jupiter Inlet Colony

Untreated stormwater discharges from stormwater management systems in these urban areas discharge either directly to the Indian River Lagoon or to one of the drainage canals leading to the Lagoon. There are two large Chapter 298 drainage districts within the South Indian River Lagoon segment - North St. Lucie Water Control District and the Ft. Pierce Farms Water Control District. Two smaller Chapter 298 drainage districts are also present in Martin County - the Hobe-St. Lucie Conservancy and Troupe-Indiantown Water Control District. However, these two districts currently have no active projects underway.

North St. Lucie River Water Control District (NSLRWCD)

This district began construction of the drainage ditch system in St. Lucie County in 1917. NSLRWCD encompasses approximately 62,490 ac, and has over 200 miles of canals. The land use is 93% agricultural and 7% urban. The NSLRWCD is subdivided into 3 separate sub-basins:

1) Sub-basin 4-03 (26,797 ac) drains agricultural development into the C-25 canal which discharges into the Lagoon through Taylor Creek at Ft. Pierce.

2) Sub-basin 4-05 drains (106,012 ac) into C-24, which discharges into the North Fork of the St. Lucie River. This sub-basin land use is approximately 65% urban.

3) Sub-basin 4-06 (119,979 ac), the largest sub-basin, drains ground water and surface water by gravity into Ten Mile Creek and Five Mile Creek (USDA SCS, 1992). These creeks come together and flow by gravity into the North Fork of the St. Lucie River.

Flow control structures, including pump stations, are located on both C-24 and C-25 canals. These facilities are controlled by SFWMD operating schedules. There is one control structure (on Ten Mile Creek) for the flows from sub-basin 4-06, the largest in NSLRWCD.

Ft. Pierce Farms Water Control District (FPFWCD)

This district is part of sub-basin 4-03, and has an area of 13,790 ac, of which about 5% is urban (USDA, SCS, 1992). Three residential sub-divisions, with a total area of 15,510 ac) also drain into FPFWCD for a total sub-basin drainage area of 29,300 ac. This drainage system consists of about 50 miles of canals. The primary discharge canal flows into Taylor Creek, which discharges into the Indian River Lagoon (USDA, SCS, 1992). An irrigation storage discharge control structure is located on the primary FPFWCD canal. In addition to these Chapter 298 drainage districts, the Port St. Lucie Stormwater Utility has recently been established to provide flood control, drainage, and water quality protection to the North Fork of the St. Lucie River for the City of Port St. Lucie.

Central and South Florida Flood Control Project (CSFFCP)

The most significant ditch and canal system in this basin is part of the (CSFFCP). This extensive set of large scale primary, secondary, and tertiary drainage ditches is intended to provide flood protection in the wet season and irrigation water in the dry season. Although not directly mentioned in any of the design documents, another purpose of the extended drainage system is to lower the ground water table, making otherwise undevelopable land useful for agriculture and urban development (SJRMD & SFWMD, 1993).

The federally sponsored CSFFCP flood control project, which was initiated after the 1947 floods in south Florida, encompasses a total project area of over 16,000 square miles and includes the Kissimmee River as well as the St. Johns River basin. This project has had a profound effect upon agricultural and urban development in all of south Florida and has caused extensive environmental damage to Lake Okeechobee and the Everglades. The potential impact of the massive freshwater discharges on the St. Lucie Estuary resulting from this drainage system are only now being realized (SJRMD & SFWMD, 1993).

During the 1950's the COE delineated surface water management basins in what is now designated by the SFWMD as the Upper East Coast Planning Area (Segment 4). The COE then designed and constructed canals, levees, and control structures whose primary function was to provide flood protection. There are nine sub-basins in the Upper East Coast Planning Area that are served by CSFFCP project works. There are 12 other sub-basins in the planning area that do not have any CSFFCP project works within their limits. Two of these are SLRWCD and FPFWCD, the Chapter 298 drainage basins discussed earlier.

The Eastern St. Lucie County Area of the Upper East Coast Planning Area includes the NSLRWCD and the FPFWCD, as well as the Port St. Lucie Stormwater Utility. As previously mentioned, water levels are maintained for flood control during the wet season and irrigation during the dry season.

The St. Lucie Agricultural area of the Upper East Coast Planning Area includes the C-25, C-24, and C-23 basins as well as those areas of the NSLRWCD which flow into C-25 and C-23. These improvements in this area were designed to carry 30% of the Standard Project Flood (SPF). This is equivalent to the 10-year, 72-hour storm. However, the actual operation of the control structures is dictated by an operating schedule that provides flood control in the wet season and stores water for irrigation in the dry season. When needed, water can be diverted into one or more of the primary canals (C-23, C-24, and C-25). Artesian wells add to the water supply, providing additional runoff and ground water flows to the canals, which can be discharged into the Indian River Lagoon.

The St. Lucie Canal (C-44), the primary drainage canal, was originally constructed between 1916 and 1924. Its purpose was to improve the conveyance of Lake Okeechobee flood waters. The C-23, C-24, and C-25 (Belcher Canal) canals, the other major drainage canals in the Upper East Coast planning area, were constructed to provide outlets for the two Chapter 298 drainage districts, flood protection in the western area, and irrigation water to the Allapattah Flats marshland agricultural activities during the dry season. Reports on the initial operation of the system showed that the original system was only marginally successful in controlling floods, and the 1947 South Florida flood prompted the CSFFCP project.

The St. Lucie River Area of the Upper East Coast Planning Area includes most of Martin County. It is typically divided into two sub-areas: a small coastal or tidal area consisting of Basins 4, 5 and 6 (sub-basins 4-11, 4-12, and 4-13); and a very large area consisting of C-44 sub-basin (4-14), S-153 sub-basin (FP&L reservoir), and Tidal St. Lucie sub-basin (4-15). The C-44 sub-basin (4-14) is hydrologically connected to Lake Okeechobee.

The primary CSFFCP Project Canal is the C-44 Canal. The purposes of the canal and its structures in the C-44 sub-basin (4-14) are as follows:

- Provide drainage
- Provide flood control
- Accept flows from the S-153 sub-basin (FP&L Martin County power plant cooling reservoir at Lake Okeechobee) for discharge into the Indian River Lagoon
- Discharge water from Lake Okeechobee to the Caloosahatchee River and/or the South Fork of the St. Lucie River when the lake operating criteria indicate the lake water level is too high

- Store and supply water for agricultural irrigation

- Provide a navigable waterway from the Intracoastal Waterway to Lake Okeechobee

Under certain conditions, water may backflow or be pumped from C-44 into Lake Okeechobee. Locks are provided at structures on C-44 to allow boat traffic to pass around the structures. A cooling reservoir for the Florida Power and Light generating plant is also hydraulically connected to C-44.

The functions of the CSFFCP Project canal and structures in the Tidal St. Lucie sub-basin (4-15) are as follows:

- Discharge C-44 flows to the St. Lucie River
- Provide a navigable waterway for the portion of C-44 in this basin
- Provide drainage for portions of this basin

Basins 4, 5, and 6 (sub-basins 4-11, 4-12, and 4-13) have no CSFFCP project improvements within their boundaries. These basins have inadequate flood control systems and flood often. Bessey Creek drains sub-basin 4-11 and Danforth Creek drains sub-basin 4-13 into the St. Lucie Estuary (Graves and Strom, 1992).

The operation of Lake Okeechobee as a reservoir controls the operation of all of the CSFFCP project canals and structures, including all of those in the Upper East Coast Planning Area. Lake Okeechobee operation is controlled by a "regulation schedule". When the elevation of the lake's water surface is above regulation schedule, water is pumped to C-44 and other CSFFCP Project canals, subject to some provisions. The regulation schedule was developed by the COE. The regulation schedule utilized since 1978 requires regulatory releases from the lake when the elevation of the water exceeds 15.5 ft National Geodetic Vertical Datum (NGVD).

In 1991, the regulatory release schedule was modified by implementing a schedule called Run 25. Run 25 allows for pulsed releases of water from Lake Okeechobee to the St. Lucie River subject to certain controlling factors which regulate the volume and duration of the pulsed release. Zones are established in the operation schedule to cause early pulsed releases in an attempt to avoid large scale releases later. The Run 25 pulsed release program was developed, in theory, to mimic the natural response of the upper watershed of the St. Lucie Estuary (and also the Caloosahatchee River) during and after a rain event. The intended effect is to maintain adequately high salinity levels on a long-term basis. (SJRWMD & SFWMD, 1993)

2.6 ENVIRONMENTAL SIGNIFICANCE OF THE WATERSHEDS AND DRAINAGE PATTERNS

Before Europeans arrived, the watershed of the Indian River Lagoon system was narrow and well-defined. The first attempts to artificially extend the watershed of the Lagoon occurred before 1800. Since the 1900's, the area of land draining surface runoff and ground water into the Indian River Lagoon complex has been increased drastically by canal and ditch systems. The purpose of these systems is to lower the ground water table, to allow planting of crops without water damage to roots and also provides additional soil storage for stormwater during a rain event. Unless controlled by a structure, these man-made drainage canals continue to drain ground water into the Lagoon as long as the ground water table is above the bottom of the ditch and a hydraulic gradient is present.

The potential adverse effect of the diversion of water is multi-faceted. A basic effect is the introduction of additional freshwater into a primarily saline system. Any estuary has a capacity for receiving some freshwater and responding without a loss of function of the ecosystem. Whether or not the Indian River Lagoon has been impacted adversely by too much freshwater, too little freshwater, or too large a range of salinity is being analyzed by looking at water quality, pollution loadings, biological diversity, and other areas of study.

The discharge from the extended watershed introduces nutrients, metals, pesticides, suspended solids, and organically stained waters into the Lagoon. Some of the constituents (nutrients) stimulate growth of algae; others (metals) inhibit growth for a short time. The potential magnitude of the loads is difficult to quantify, because during the dry season, water is held in the canals to be used as irrigation water. Today it is known that this type of drainage engineering is causing significant impacts to the receiving water (Wanielista and Yousef, 1993).

Approximately 20 years ago, over 170 years after the first ground water drainage projects and 50 years after initiation of large scale projects in the Indian River Lagoon system, stormwater runoff was identified as a pollutant to natural aquatic and marine systems (Wanielista and Yousef, 1993). Until that time, engineering of a drainage system consisted of determining the volume of water that would be generated, finding a receiving water that provided a hydraulic gradient, and sizing the conveyance system hydraulically. Toward that end, the drainage systems in the Indian River Lagoon system were successful. Ecological effects and impacts were not considered.

Mixing and dispersion are important factors in determining the environmental significance of anthropogenic changes to watersheds and drainage patterns of the Indian River Lagoon system. It may be necessary to determine the extent of mixing and hydrodynamic dispersion within the Lagoon in order to fully assess the effects of alterations to drainage patterns. The role played by the hydrodynamics of the Lagoon system is discussed in Section 6.0. None of these effects is easy to characterize for a particular location and situation. A need that has been identified by this analysis is to better understand whether, and to what extent, the large volume of freshwater flows and associated pollutants are mixing with the Lagoon at Sebastian, Fort Pierce, and particularly St. Lucie Inlets. Some effects may appear not in the Lagoon, but as adverse impacts to the near shore reefs and sea life habitat in the Atlantic Ocean.

2.7 SOILS

The soils comprising the Indian River Lagoon watershed are characterized by location-specific geologic, hydraulic, hydrologic, and biological factors. The upper layer soils are Holocene sedimentary deposits, which contain the surficial aquifer. Land use changes along the Lagoon have probably altered soil characteristics during the latter portion of this century. Drainage and cultivation in particular may have altered the surficial hydrologic and biologic factors that are the basis for soil characterization. Some of these changes occur very gradually and have begun manifesting themselves in recent times.

County soil surveys and general soil maps in Geographical Information System (GIS) format, obtained from the SJRWMD and SFWMD, were the primary sources of soils information for this report. Detailed soils maps in GIS format were not available for Martin and

Okeechobee counties (Martin County will be available in March, 1994). The source of all of the soil maps were soil surveys sponsored by the U.S. Department of Agriculture Soil Conservation Service (SCS). These surveys were completed at different times since 1974.

The broad categories of soils present in the Lagoon watershed are: 1) the barrier island sands; 2) soils that are characteristic of the mainland coastal ridges, knolls, and flatwoods; 3) soils that are characteristic of swamps, marshes, sloughs and hammocks; and 4) soils of the tidal or waterfront areas. Each type of soil has specific drainage characteristics. For example, barrier island and coastal ridge sands are either excessively-drained or well-drained. The knoll and flatwood soils typically have an infiltration-limiting layer (hard pan) below a relatively permeable, sandy surficial layer. This hard pan often causes perched water tables to develop on these soils. Control of high seasonal water tables by ditching systems is a common practice in this region. Swamps, marshes, sloughs, and hammocks are typically very poorly drained soils which have a high organic and clay content. They are usually located where there is no significant hydraulic gradient. Artificial drainage generally is not very successful in the swamp and marsh soils.

Sandy ridge soils are sandy throughout and contain shell fragments. The barrier island sands are found on a wide variety of slopes ranging from steep to nearly level. Soil drainage is highly variable, ranging from excessively-drained through moderately well-drained soils, including minor areas of poorly drained soils. "Excessively-drained" means the soil has a wet season water table >6 ft and is generally permeable, while "well- drained" means the soil is very permeable and the infiltration rate is high. This infiltration results in considerable soil storage of rainfall runoff and low runoff coefficients unless the area has been paved. In contrast, "Poorly drained" means soils having a wet season water table typically within 10 inches of the surface. Infiltration usually is limited and the runoff coefficient is high.

The soils of the mainland coastal ridge are also typically nearly level with steep sloping areas to a minor extent. They include excessively drained, well-drained, moderately well-drained and poorly drained soils. The soils on the eroded low ridges and knolls are level and moderately well to poorly drained. Some have a weakly cemented, sandy sub-soil, and in some places they are underlain by loamy material.

Soils of the flatwoods areas are very level, poorly drained soils that usually occur in broad areas. Most soil groupings in the flatwoods have a dark sandy sub-soil that may be weakly cemented in some places. In most areas the sub-soil is sandy in the upper part and loamy in the lower part. Many of the soils in this group have a sub-soil that is also stained by organic matter or iron. Scattered swamps exist throughout the flatwoods areas.

Soils of the swamps, marshes, sloughs, and hammock areas are typically nearly level, poorly to very poorly drained soils. Some of the soils are organic throughout, while some have stratified sand and clay. Some have a very dark, sandy sub-soil while others have a loamy sub-soil within a depth of approximately 20 inches (in.). Hammocks are typically slightly higher in elevation than swamps or sloughs but are generally saturated since they are somewhat poorly drained to very poorly drained. Soils of the tidal swamp areas are comprised of organic materials and are very poorly drained. They are generally present along either shore of the Indian River Lagoon and along the watershed drainages.

The soil categories can be further defined by general soils associations, in which several individual specific soil types are found together. Table 2-3 shows broad soil categories, the general soil associations included within these categories, and the acreage of each soil category that is present in the basin of each segment. Differences in soil association names are common between counties, based on type localities in his area. SCS is in the process of defining common names among counties, but older surveys may have different nomenclatures for similar soils. For example, the barrier island sands in Volusia County are called the Palm Beach-Paola-Canaveral association, but in the Brevard County area they are called the Canaveral-Palm Beach-Welaka association. Similarly, the coastal ridge in Volusia County is known as the Daytona-Paola-Astatula association but becomes the Paola-Pomello-Astatula association in Brevard County.

Interpretation and judgement have been necessary when assigning soil associations to system-wide categories since the lagoon-wide GIS general soils map is less detailed than the individual county soil association maps. Checks of areas with the detailed soils maps showed good agreement. A comparison of the areas shows an increase in occurrence of flatwoods, hammocks, and slough soils in the southern region of the Lagoon watershed as compared to the northern region. Part of the increase can be attributed to the natural drainage pattern where the Ten Mile/Green Ridge naturally restricts drainage in Indian River, Martin, and

TABLE 2-3

SOIL CATEGORY, SOIL ASSOCIATION, AND AREA BY SEGMENT/BASIN

SEGMENT/BASIN	LANDFORMS	SOIL ASSOCIATION	AREA
1A - Mosquito Lagoon	Barrier Island	Palm Beach-Paola-Canaveral	22 km^2 (5,350 ac)
	Coastal Ridge	Daytona-Paola-Astatula	54 km^2 (13,275 ac)
	Tidal Marsh	Hydraquents-Turnbull	66 km^2 (16,452 ac)
	Flatwoods	Pomona-Wauchula	53 km^2 (13,200 ac)
1B - Banana River	Barrier Island	Canaveral-Palm Beach-Welaka	75 km^2 (18,600 ac)
	Merritt Island Sand Ridge	Canaveral-Palm Beach-Welaka Paola-Pomello-Astatula	13 km^2 (3,275 ac)
	Tidal Marsh	Copeland-Wabasso Hydraquents-Turnbull	37 km^2 (9,050 ac)
	Flatwoods	Myakka-Eau Gallie-Immokalee	111 km^2 (27,830 ac)
1C - North Indian River Lagoon	Coastal Ridge	Palm Beach-Paola-Canaveral Paola-Pomello-Astatula	71 km^2 (17,500 ac)
	Tidal Marsh	Hydraquents-Turnbull	84 km^2 (20,850 ac)
	Flatwoods	Myakka-Smyrna-Immokalee Myakka-Eau Gallie-Immokalee	231 km^2 (57,100 ac)
	Hammock	Tuscawilla-Chobee	69 km^2 (17,100 ac)

TABLE 2-3

SOIL CATEGORY, SOIL ASSOCIATION,
AND AREA BY SEGMENT/BASIN, Continued

SEGMENT/BASIN	LANDFORMS	SOIL ASSOCIATION	AREA
2 - North Central Indian River Lagoon	Barrier Island	Canaveral-Palm Beach-Welaka	33 km^2 (8,250 ac)
	Coastal Ridge	Paola-Pomello-Astatula	47 km^2 (11,520 ac)
	Flatwoods	Myakka-Eau Gallie-Immokalee	339 km^2 (83,750 ac)
	St. Johns River Flood Plain	Felda-Floridana-Winder	7 km^2 (1,650 ac)
3 - South Central Indian River Lagoon	Barrier Island	Canaveral-Captiva-Palm Beach	22 km^2 (5,380 ac)
	Coastal Ridge	Astatula-Archbold-St. Lucie	213 km^2 (5,690 ac)
	Tidal Marsh	McKee-Quartzipsamments-St. Augustine	33 km^2 (8,115 ac)
	Flatwoods	Myakka-Immokalee Eau Gallie-Oldsmar-Wabasso Eau Gallie-Myakka-Riviera	182 km^2 (45,200 ac)
	Low Knolls and Eroded Ridges	Immokalee-Myakka-Sattelite	65 km^2 (16,150 ac)
	Hammock	Riviera-Pineda-Wabasso Winder-Riviera-Manatee	253 km^2 (62,650 ac)
4 - South Indian River Lagoon Basin	Barrier Island	Palm Beach-Canaveral Pompano-Variant-Kalioa Variant-Canaveral	34.4 km^2 (8,500 ac)
	Coastal Ridge	St. Lucie-Sattelite-Welaka Variant Bessie Variant-Terra Ceia Variant	93 km^2 (23,000 ac)
	Tidal Marsh	Pompano Variant-Kaliga Varient-Canaveral Bessie Variant-Terra Ceia Variant	38 km^2 (9,500 ac)

TABLE 2-3

SOIL CATEGORY, SOIL ASSOCIATION, AND AREA BY SEGMENT/BASIN, Continued

SEGMENT/BASIN	LANDFORMS	SOIL ASSOCIATION	AREA
4 - South Indian River Lagoon Basin, Continued	Low Knolls and Eroded Ridges	Salerno-Jonathon-Hobe Salerno-Hobe-Waveland	6 km^2 (1,413 ac)
	Flatwoods	Waveland-Longwood-Bassinger Nettles-Kona-Pepper Wabasso-Winder Bassinger-Myakka-Longwood	2,465 km^2 (609,409 ac)
	Hammock and Slough	Pineda-Wabasso-Riviera Pineda-Riviera-Boca Bassinger-Ft. Drum-Valkeria Winder-Riviera Chobee-Samsula Variant-Myakka Variant Canova Variant-Floridana Fluaquents-Terra Ceia	217 km^2 (53,714 ac)
	St. Johns River Flood Plain		24 km^2 (6,003 ac)

Source: USDA, SCS, 1974a, 1974b, 1974c, 1974d

St. Lucie counties and the natural creeks and streams (Sebastian River, St. Lucie River) break through the coastal ridge. However, most of the increase has been a result of expansion of the watershed westward into inland areas with low, poorly drained soils by means of ditching and diking low-lying areas.

3.0 CLIMATE AND WEATHER

3.1 CLIMATE

The climate of the Indian River Lagoon system is influenced by several situational facts: it is located in the northern latitudes (between 27°N and 29°N), it is part of a peninsula (the State of Florida) surrounded by large bodies of water, it is directly adjacent to the Atlantic Ocean, and it has the Gulf Stream in the Atlantic Ocean passing close offshore throughout the length of the estuary. It is a transition region between the temperate and sub-tropic climates. The summer months are very warm and humid and the winters are relatively mild, although severe cold fronts can pass through the Indian River Lagoon region in the winter causing very cold temperatures for a period of time lasting several days. These cold spells can have extensive impacts on the biota of the region, as well as the economy of the region.

In general, the east coastal region of Florida is slightly warmer in the winter and slightly cooler in the summer than the inland areas due to predominant easterly winds blowing from the ocean. Throughout the Lagoon there are typically two seasons, a rainy season from May through October and a dry season from November through April.

Information presented in this chapter is drawn from the Recon Report, the Monograph, and reports prepared by the SJRWMD and SFWMD. The period of record for the information in the Recon Report runs through 1985 and the period of record for the monograph information runs through 1987. The SJRWMD and SFWMD information begins in 1980, and runs through 1992.

3.2 TEMPERATURE

Table 3-1, taken from the Recon Report (Rao, 1987), presents information on average monthly temperatures for five coastal stations and three inland stations for a 30-year period of time. Based on these data the average annual temperature in the Indian River Lagoon is 72.6°F. The data show that average temperatures during the warm summer

TABLE 3-1

NORMAL MONTHLY AVERAGE TEMPERATURE, °F (30-YEAR AVERAGE, 1951-1980)

MONTH	TITUSVILLE	MELBOURNE	FELLSMERE*	VERO BEACH	FT. DRUM*	FT. PIERCE	STUART INLET	OKEECHOBEE*
January	60.2	61.5	61.3	61.9	62.0	62.7	64.7	61.7
February	61.0	61.8	63.2	62.6	62.4	63.1	65.0	63.2
March	66.2	66.9	68.0	67.2	67.1	67.8	69.4	67.7
April	71.4	71.3	72.0	71.7	71.1	71.9	73.2	72.8
May	76.6	75.9	77.1	76.2	75.8	76.2	77.1	76.9
June	79.9	79.4	80.3	79.4	79.5	79.4	80.1	80.1
July	81.5	81.3	81.8	81.1	81.1	81.0	81.6	81.7
August	81.5	81.4	82.4	81.4	81.3	81.4	82.1	81.8
September	80.0	80.1	80.7	80.2	79.9	80.3	81.1	81.0
October	74.1	74.8	75.4	75.2	75.0	75.7	76.5	76.0
November	67.0	68.1	68.8	68.9	68.3	69.4	70.7	69.6
December	61.6	62.9	63.1	63.4	62.9	64.3	66.0	63.3
ANNUAL	**71.7**	**72.1**	**73.0**	**72.4**	**72.1**	**72.8**	**74.0**	**72.7**

Source: Rao, 1987

* = For these stations, the data were missing for several months. The values shown are the averages based on available records for 1951-1980.

months are relatively uniform throughout the region, however, during the coldest months there is a temperature difference of approximately 4° to 5°F between the northern and southern stations. Almost all stations have recorded a maximum temperature of 100°F or greater. The lowest recorded temperatures range from 18°F at Titusville to 26°F at Stuart.

Doehring and Barile (1988) evaluated the weather patterns by dividing the data into several consecutive periods of time. Titusville and Ft. Pierce represent the north and south areas of the Lagoon in this analysis. Both of these stations have long and complete records.

In the period 1821-1915 several severe freezes are known to have occurred. A severe freeze is defined by Doehring and Barile (1988) as a period during which the temperature reached a low of 28°F or less. Snelson and Bradley (1978) presented information that showed that severe freezes occurred during this period in 1835, 1856, 1868 and 1886, even though temperature data is not available during this time. Official U.S. Government temperature measurements began late in the 19th century. Beginning shortly after the turn of the century, temperatures were recorded at Merritt Island, Titusville and Ft. Pierce. Records in Titusville beginning in 1890 show that severe freezes occurred in 1895, 1898, 1899, 1901, 1902, 1905, 1909. In Ft. Pierce severe freezes occurred in 1895, 1896, 1897, 1899, 1905, and 1910. As such, it can be seen that extremely cold weather occurred almost every year between 1895 and 1910. The most severe winter occurred in 1894-1895 when back-to-back freezes in late December 1894 and February 1895 wiped out the citrus industry as it was known at the time in the Indian River Lagoon region. During the freeze of January, 1905, Titusville recorded four days with a minimum temperature of 28°F or lower.

Doehring and Barile (1988) describe a warming trend during the period 1916 through 1950. During this 34-year period a total of 18 severe freezes were recorded in the north part of the Lagoon, but only one severe freeze was recorded in the southern half of the Lagoon. Although severe freezes occurred in the winter of 1917 and 1918, another severe freeze did not occur until the winter of 1927 and 1928. The period of 1934 through 1950 showed a recurrence of more severe freezing weather in the winter. Freezes occurred in the northern half of the region on an almost annual basis. However, during this period, no severe freezes were recorded in the southern region. The data collected during this period seem to indicate that the cold fronts stalled over the northern part of the Indian River Lagoon region. From 1951 through 1970 the freezes continued in both the north and south Lagoon regions.

During this period of 20 years a total of 26 freezes were recorded in the northern region and 13 in the southern region. In the period between 1957 and 1970, a severe freeze occurred almost annually at both north and south stations. During the freeze of December, 1962 both Titusville and Ft. Pierce had low temperatures below 28°F for four consecutive days.

During the period 1971 through 1988 (17 years), 11 severe freezes occurred in the north Lagoon and 7 severe freezes occurred in the south Lagoon regions. Beginning in the winter of 1978 the freezes got worse every year until January, 1985 when a low temperature of 19°F was recorded at Ft. Pierce and Titusville. This freeze was the most severe ever recorded over the entire Indian River Lagoon region. Damage to vegetation was heavy and resulted in the death of almost all Australian Pine trees north of Sebastian Inlet. Mangrove forests, particularly in the northern region of the Lagoon, were damaged. Sea turtles and fish were stunned, and many died during and soon after this extremely cold weather. Another equally severe freeze occurred during December 1989 (Christmas) which effectively eliminated citrus crops north of Brevard County.

3.3 PRECIPITATION

The average annual rainfall in the Indian River Lagoon basin is about 50.2 in. Variations through the Lagoon range from a low of 44.6 in. at Patrick Air Force Base to a high of 56.7 in. at Titusville for the period of 1951 through 1980. Doehring and Barile (1988) present evidence that the Cape Canaveral cuspate foreland and its associated open water bodies create this high variation over a relatively short distance [approximately 30 mi]. Titusville is just north of the Cape and Patrick Air Force Base is just south of the Cape. The Recon Report (Rao, 1987) presents normal average monthly rainfall as a mean of 17 stations located in and around the Indian River Lagoon for the period 1951 to 1980 as follows:

- January 2.18 in.
- February 2.72 in.
- March 2.92 in.
- April 2.39 in.
- May 4.35 in.
- June 6.90 in.
- July 6.59 in.
- August 6.29 in.
- September 7.16 in.

- October 5.10 in.
- November 2.12 in.
- December 2.00 in.

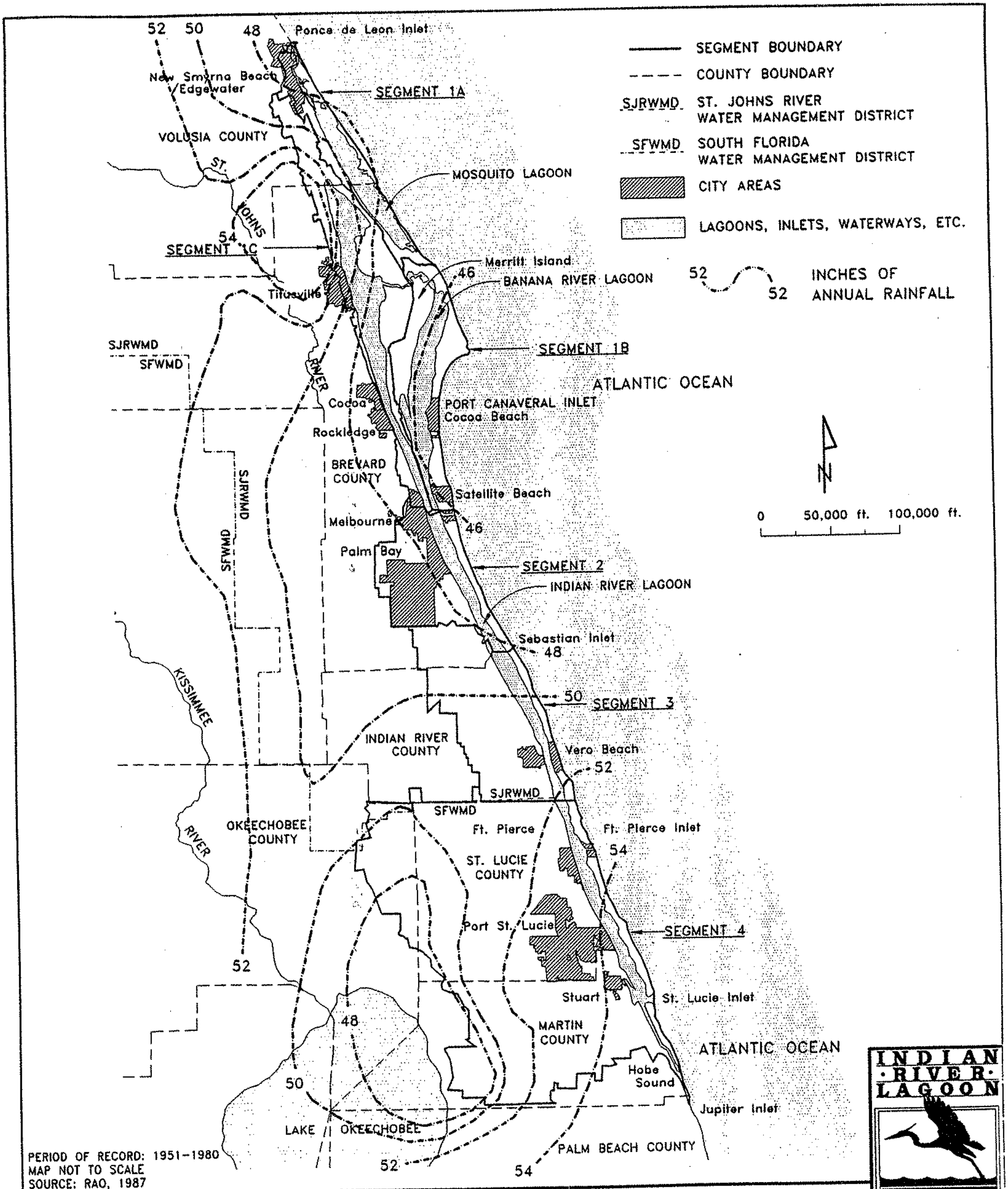
Based upon this information, it can be seen that a wet period occurs from May through October and a dry period from November through April.

Figures 3-1 through 3-5 illustrate the general patterns of rainfall, indicating higher rainfall in the extreme northern and extreme southern areas, with minimums between Port Canaveral and Sebastian Inlet. Figures 3-2 and 3-3 show that the agricultural areas in the extended watershed of western St. Lucie and Martin counties receive higher rainfall during the warm (wet) season, but less during the cold (dry) season than do the areas along the Lagoon and natural coastline. This means that these extended watershed areas contribute a disproportionately high amount of wet season rainfall runoff that is drained into the Lagoon when ground water levels are high. Therefore, climatological factors exacerbate the problems related to freshwater discharges that were described in Section 2.6.

Information in the Recon Report indicates that maximum yearly rainfall in the Lagoon region ranges from 65 in. to over 90 in. The highest annual rainfall in the Indian River Lagoon basin was recorded at St. Lucie at 92 in. During that period, the rainfall exceeded 100 in. for a consecutive 12-month period. Minimum rainfall records over any consecutive 12-month period of time show that the lowest value occurred at the Patrick Air Force Base recording station and the highest value in the Titusville area (Rao, 1987).

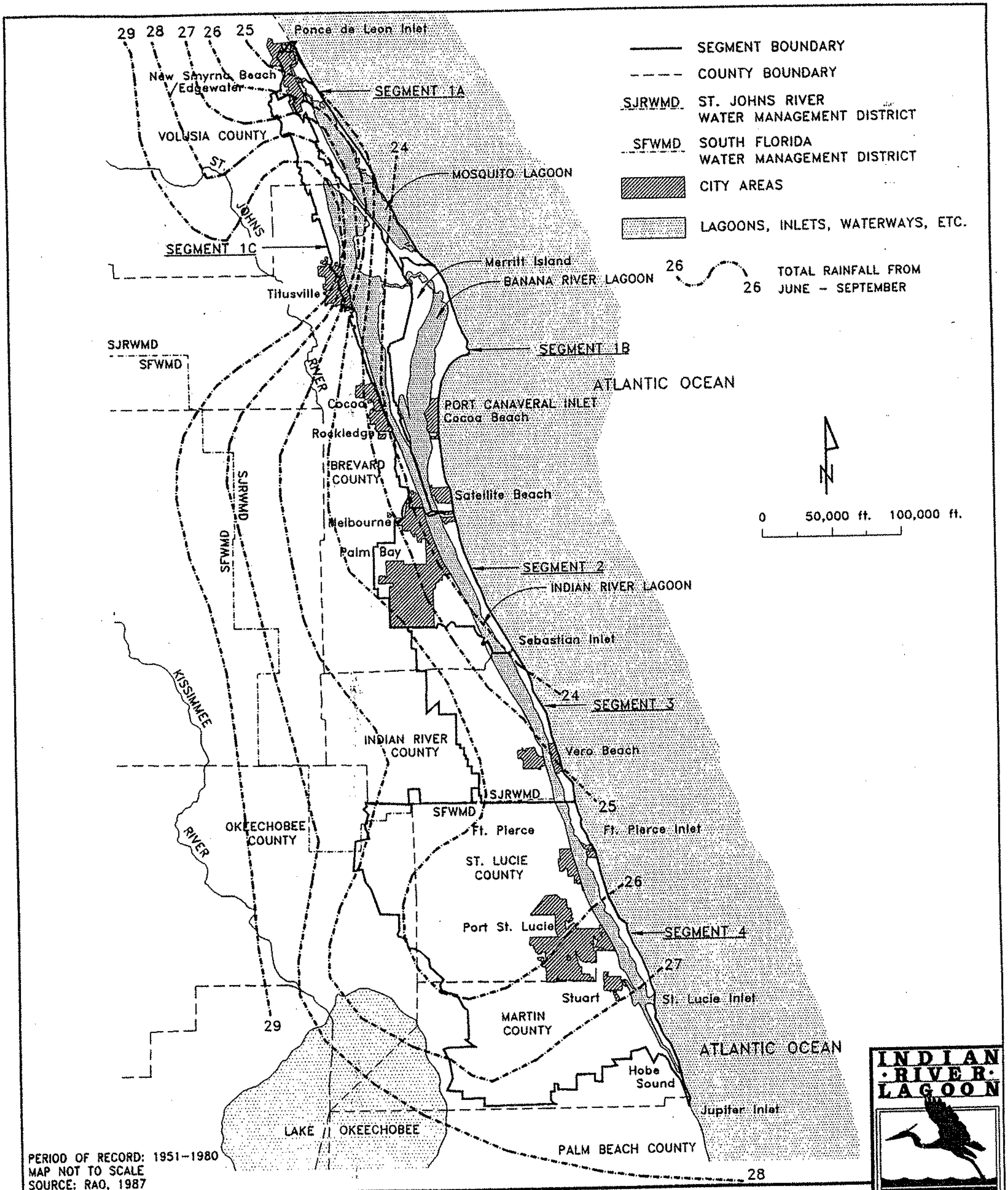
A SFWMD report (Sculley, 1986) discusses the results of an analysis of the rainfall frequency. The annual average rainfall for the district is 53 in., based on a 71-year period (the South Indian River Lagoon basin is in the extreme northeast corner of the in. A 1956 minimum of 39 in. was between the 1-in-50 and the 1-in-100 year events. District). The 1-in-10 year rainfall for a "dry" year is 44.3 in., and for a wet year is 62.5 The 77 in. of rainfall recorded in 1947 was slightly less frequent than a 1-in-200 year event. Several sub-basins have consistently recorded below average rainfalls for the previous 10-15 years.

Table 3-2 shows maximum recorded rainfall for several durations of time in the Indian River Lagoon region and the surrounding area. Again, it can be seen that high rainfall occurs at

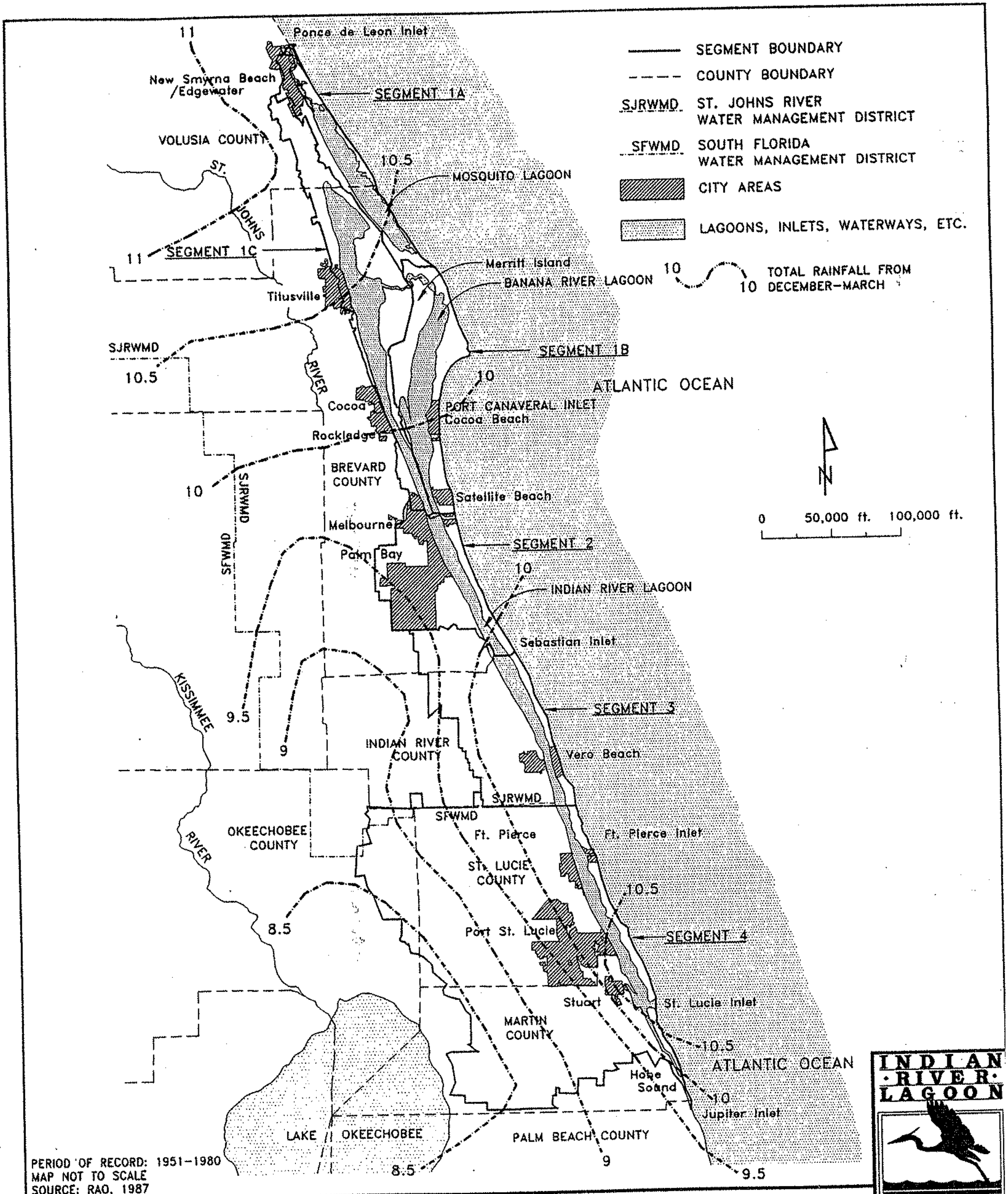


•Woodward-Clyde Consultants •Marshall McCully & Associates •Natural Systems Analysts	DRAWING NO.: RAIN01.DWG DATE: 7-5-94	FIGURE 3-1 ANNUAL RAINFALL WITHIN THE INDIAN RIVER LAGOON REGION

INDIAN RIVER LAGOON NATIONAL ESTUARY PROGRAM



•Woodward-Clyde Consultants •Marshall McCully & Associates •Natural Systems Analysts	DRAWING NO.: RAIN02.DWG DATE: 7-5-94	FIGURE 3-2 WET SEASON (JUNE-SEPTEMBER) RAINFALL WITHIN THE INDIAN RIVER LAGOON REGION



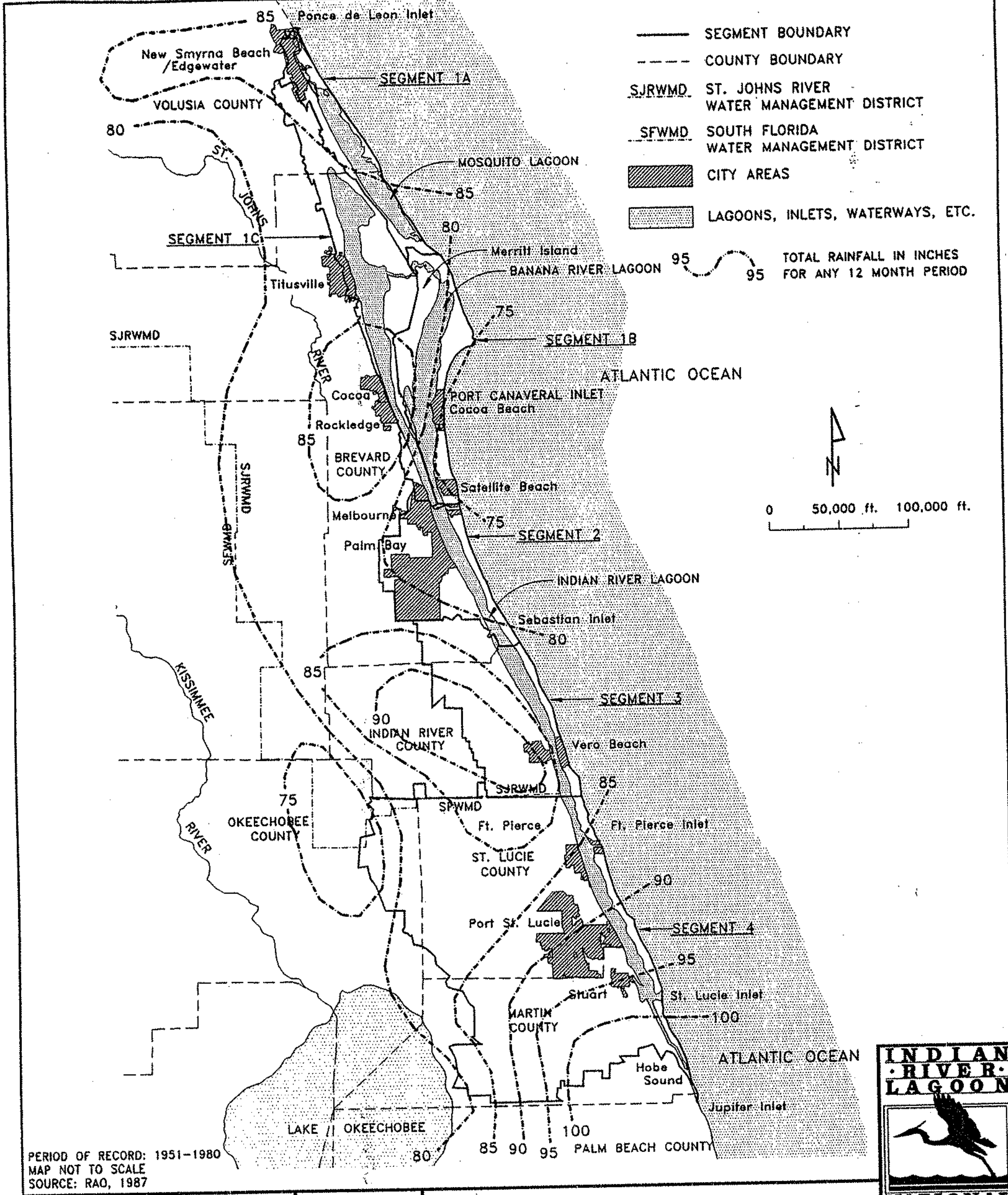
•Woodward–Clyde Consultants
•Marshall McCully & Associates
•Natural Systems Analysts

DRAWING NO.: RAIN03.DWG

DATE: 7-5-94

FIGURE 3-3 DRY SEASON (DECEMBER–MARCH) RAINFALL WITHIN THE INDIAN RIVER LAGOON REGION

INDIAN RIVER LAGOON NATIONAL ESTUARY PROGRAM



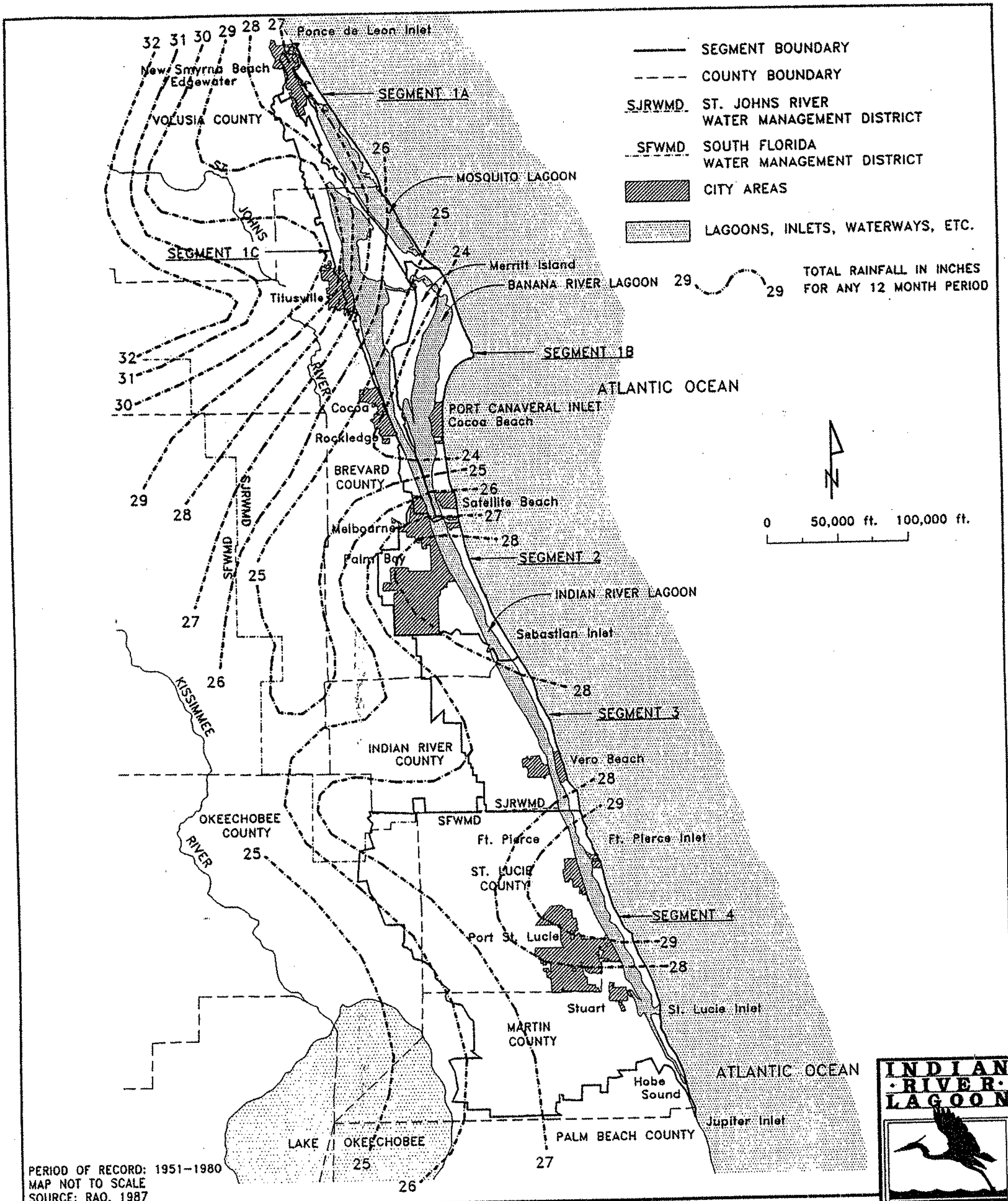
•Woodward-Clyde Consultants
•Marshall McCully & Associates
•Natural Systems Analysts

DRAWING NO.: RAIN04.DWG

DATE: 7-5-94

FIGURE 3-4 MAXIMUM RAINFALL OVER ANY 12 CONSECUTIVE MONTHS WITHIN THE INDIAN RIVER LAGOON REGION

INDIAN RIVER LAGOON NATIONAL ESTUARY PROGRAM



•Woodward–Clyde Consultants •Marshall McCully & Associates •Natural Systems Analysts	DRAWING NO.: RAIN05.DWG DATE: 7-5-94	FIGURE 3-5 MINIMUM RAINFALL OVER ANY 12 CONSECUTIVE MONTHS WITHIN THE INDIAN RIVER LAGOON REGION

TABLE 3-2

MAXIMUM RECORDED RAINFALL (INCHES) FOR STATIONS IN THE INDIAN RIVER LAGOON REGION AND THE SURROUNDING AREA

RAINFALL STATION AND COUNTY	NOAA STATION NUMBER	RAINFALL DURATION					
		24 HR	48 HR	72 HR	96 HR	5 DAY	10 DAY
Bithlo (Orange)	0758	12.05	12.81	13.45	13.54	13.54	15.36
Canal Point (Palm Beach)	1276	7.75	8.66	9.68	9.73	10.55	12.79
Daytona Beach Airport (Volusia)	2158	14.18	15.57	16.33	17.46	18.02	20.94
DeLand (Volusia)	2229	9.25	11.89	13.49	14.92	15.74	19.04
Fellsmere (Indian River)	2936	12.83	14.66	14.78	14.98	15.45	16.74
Ft. Drum (Okeechobee)	3137	9.85	11.69	13.82	14.75	15.34	16.11
Ft. Pierce (St. Lucie)	3207	10.16	10.42	10.60	12.06	12.76	14.51
Hart Lake (Orange)	3840	10.58	11.28	12.95	14.60	14.65	15.45
Melbourne (Brevard)	5612	8.28	10.99	12.24	12.84	13.04	13.34
Merritt Island (Brevard)	5643	12.15	13.31	14.05	14.35	14.56	14.85
New Smyrna Beach (Volusia)	6210	21.98	23.53	23.80	26.50	29.33	36.45
Nittaw (Osceola)	6251	12.72	13.60	13.67	13.67	13.67	16.52
Okeechobee (Okeechobee)	6485	9.55	10.11	11.28	11.95	12.03	12.77
Port Maya Ca (Martin)	---	7.46	8.50	10.31	12.78	12.95	14.02
St. Lucie (Martin)	7859	9.34	10.56	12.27	13.03	13.61	15.34
Sanford Exp. Station (Seminole)	7982	9.12	9.52	9.82	10.00	11.58	13.37

TABLE 3-2

MAXIMUM RECORDED RAINFALL (INCHES) FOR STATIONS IN THE INDIAN RIVER LAGOON REGION AND THE SURROUNDING AREA, Continued

RAINFALL STATION AND COUNTY	NOAA STATION NUMBER	RAINFALL DURATION					
		24 HR	48 HR	72 HR	96 HR	5 DAY	10 DAY
Stuart Inlet (Martin)	8620	12.92	15.47	15.53	15.57	15.57	15.57
Titusville (Brevard)	8942	11.99	13.30	14.35	15.05	15.46	16.36
Vero Beach (Indian River)	9219	9.45	10.83	11.55	12.14	12.23	15.26

Source: Roa, 1987
NOAA = National Oceanographic and Atmospheric Administration

the extreme north end of the Lagoon (i.e. Volusia County stations) and low rainfall occurs in the area around Patrick Air Force Base in the central Lagoon area (Merritt Island and Melbourne stations). In fact, the 24-hour maximum in New Smyrna Beach is almost twice the 24-hour maximum for Titusville, which is only 30 miles to the south.

A statistical analysis was performed of 1- and 3-day maximum rainfalls for the South Indian River Lagoon basin by Trimble (1990). The one day maximum rainfall for the return period is shown below:

ONE-DAY MAXIMUM RAINFALL (INCHES)			
RETURN PERIOD (years)	FT. PIERCE	STUART	JUPITER
3	4.60	5.00	6.00
5	4.75	6.00	7.25
10	6.00	7.00	9.00
25	7.00	9.00	10.25
100	9.00	12.00	14.25

Compared to the data in Table 3-2, the maximum one day rainfall for Ft. Pierce (10.16 in.) and Stuart (12.92) exceeded the 100-year return period rainfall.

The three day maximum rainfall for the return period is as follows:

THREE-DAY MAXIMUM RAINFALL (INCHES)			
RETURN PERIOD (years)	FT. PIERCE	STUART	JUPITER
10	8.50	10.00	11.50
25	9.50	13.00	13.25
100	11.50	16.00	16.50

Periodic rainfall trends were investigated by Doehring and Barile (1988). Their analysis of the period from 1916 to 1950 showed that the wettest month at Merritt Island occurred in July, 1926 with 22.78 in., and the wettest year was 1928 with a total of 85.72 in. The driest year throughout the Lagoon during this period was 1917 with an average of about 32 in. of rainfall throughout the Lagoon. Between January and April of 1917 less than 2 in. of rainfall was recorded at Merritt Island.

During the period 1951 through 1987 the wettest month occurred in June 1968 at Titusville with a monthly rainfall of 20.75 in. During this period the highest annual total rainfall occurred in 1953 with 81.74 in. at Titusville. The driest period occurred between March and May 1967 with less than 2 in. of rainfall throughout the Lagoon. The lowest annual rainfall during this period occurred at Patrick Air Force Base in 1965 with a total annual rainfall of only 29.70 in. (MacVicar, 1983).

The longest dry period took place from November, 1975 to March 1976 when only slightly more than 3 in. of rainfall occurred at Titusville. During the same period less than 3 in. occurred at Patrick Air Force Base. The annual rainfall averages throughout the Lagoon for the period 1971 to 1980 shows that this decade was the driest since 1901 - 1910 in the north Lagoon and 1911 - 1920 in the south Lagoon. Barile (1976) indicates that the data seems to show a 60 to 70 year drying cycle. Doehring and Barile (1988) indicate that a wet cycle began around the turn of the century and peaked around 1950, which was followed by a gradual decrease in annual precipitation. The 1961-1970 decade had almost 5 in. less average annual rainfall than the decade from 1951 through 1960.

Information presented in the Monograph comparing Titusville, Ft. Pierce, and Fellsmere stations show that the wet period was wetter and the dry period was drier at the Fellsmere station. According to Doehring and Barile (1988), the effect on the Lagoon may have been significant from these extremes in the extended watershed.

3.4 EVAPORATION

Evaporation rates are a function of temperature, relative humidity, wind movement, and cloud cover. Several reference stations have collected pan evaporation data from which potential evaporation can be estimated. The Recon Report (Rao, 1987) presents information from a station that was located at Vero Beach airport for thirteen years before being relocated four miles west and operating for an additional twenty years. A significant difference exists between the two stations. The airport station measured an annual average pan evaporation of 74.74 in. The western station measured 62.80 in. Pan evaporation at Ft. Pierce measured an annual average of 69.68 in.

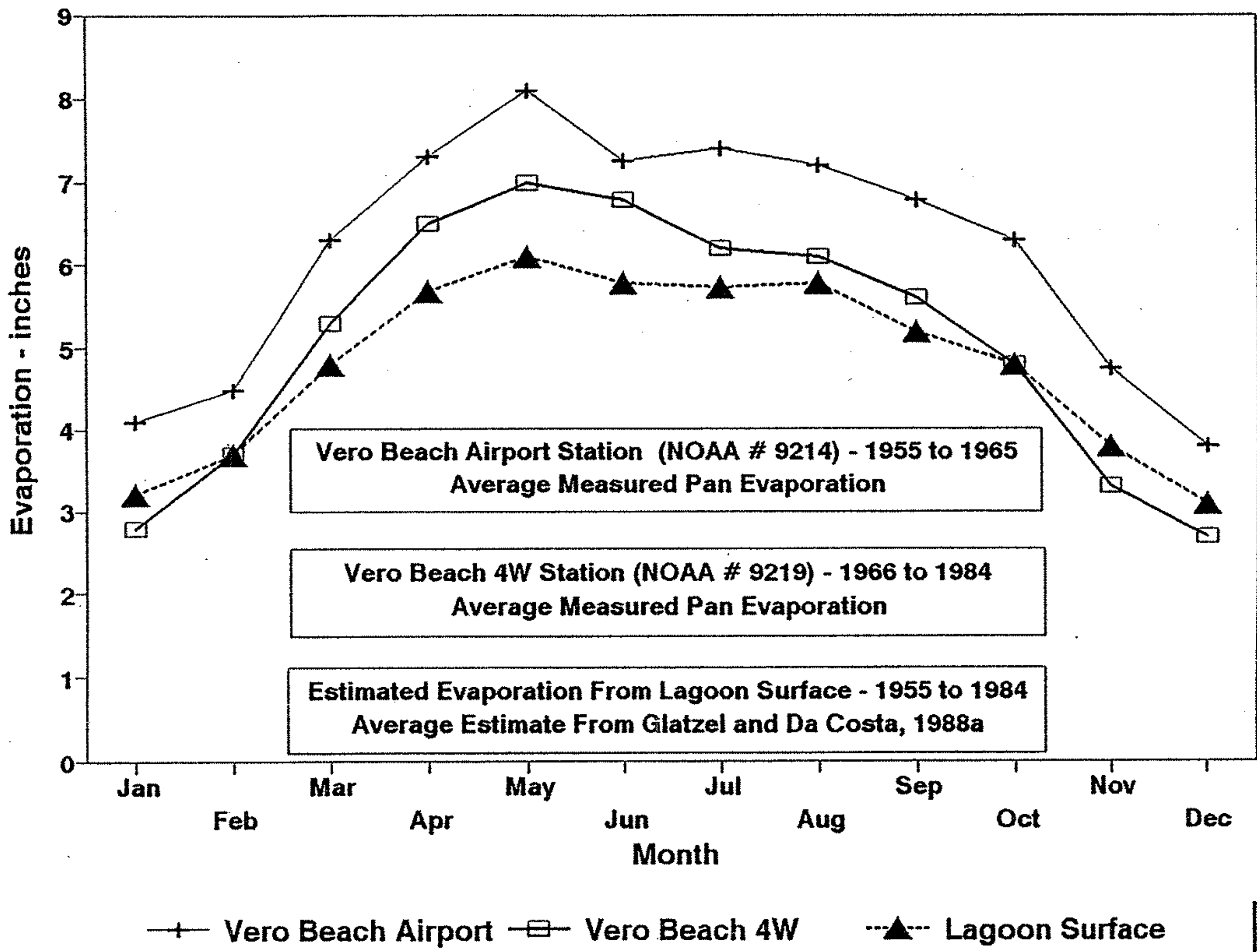
Data presented by Clapp and Wilkening (1983) showed that annual rainfall at a location in Indian River County totalled 50.64 and 48.60 in. for a two-year study. During one year, dry season pan evaporation exceeded the wet season total but this was reversed during the next year. Lin, et al. (1984) presented pan evaporation data from six stations. Average annual evaporation totalled 55.84 in. with a high value of 6.47 in. in May and a low value of 2.81 in. in December.

Pan evaporation is typically combined with the transfer of water by plants from the root zone through the leaves and into the atmospheres called transpiration, to be categorized as evapotranspiration in a water budget. Glatzel and Da Costa (1988b) estimated monthly corrected potential evapotranspiration (CPET) for the Indian River Lagoon region using the Vero Beach data set (Figure 3-6). CPET varied through the year from a low of about 1.5 in. in January to a high of about 6 in. in July. The transpiration component increases as plant growth peaks in late summer, causing the evapotranspiration peak to occur after the pan evaporation peak. The data in Clapp and Wilkening (1983) also show this behavior.

Pan evaporation rates generally overestimate actual evaporation for a region and therefore these rates are often multiplied by a pan coefficient factor to arrive at estimates of potential evaporation. Estimates of the open-water coefficient on pan evaporation in this region have included the values 0.865 (Lin, et al., 1984); 0.78 (Rao, 1987); and 0.80 (Glatzel and Da Costa, 1988a).

3.5 WIND

Wind strength and direction are seasonal in the Indian River Lagoon region. During the winter (dry) season, wind direction is predominantly north and north-northwest. During the summer (wet) season, wind direction is predominately east and southeast. For the overall year the highest relative strength and direction is east-northeast to south-southeast (Evink,



Sources: Rao, 1987
Glatzel and Da Costa, 1988a.

• Woodward–Clyde Consultants
• Marshall McCully & Associates
• Natural Systems Analysis

DRAWING NO.:

DATE:

FIGURE 3-6 MEAN MONTHLY PAN EVAPORATION AND ESTIMATED LAGOON EVAPORATION FOR THE INDIAN RIVER LAGOON REGION

INDIAN RIVER LAGOON NATIONAL ESTUARY PROGRAM

1980). A relative direction/strength wind rose for the period 1967-1976 is presented as Figure 3-7, after Glatzel (1986).

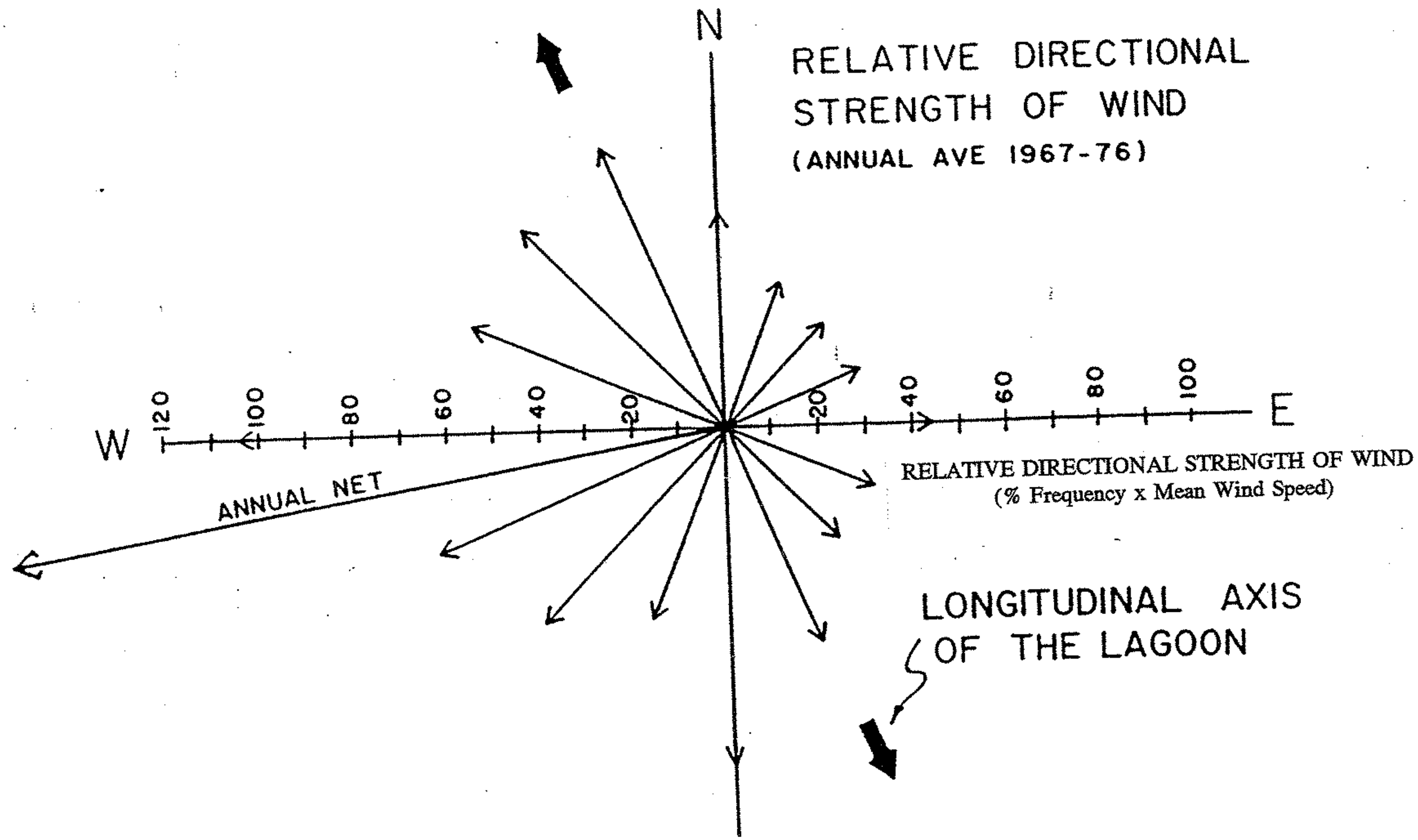
The effect of wind on circulation patterns was investigated by Evink (1980), as well as the effect of road causeways that have been constructed across the Lagoon in the North and North Central Indian River Lagoon regions. This is discussed further in Section 6.0, Hydrodynamics. Generally, it can be said that summer winds move Lagoon waters to the north through the shallow portions of the Lagoon, with a southerly return through the Intracoastal Waterway. In the winter, water moves south through the shallow portions of the Lagoon and returns to the north via the Intracoastal Waterway. The causeways cause a "compression of larger cellular water movements" (Evink, 1980).

3.6 STORMS

Both tropical and extra-tropical types of storms occur in the Indian River Lagoon region. Severe storms of temperate origin are termed northeasters and usually occur in the Winter and Spring. Summer and Fall storms are usually tropical depressions, tropical storms or hurricanes. Figure 3-8 shows track of hurricanes and tropical storms that have approached the Indian River Lagoon region since 1931 (Doehring, et al., 1993). The effects of the different types of storms are different. Northeasters typically cause heavy erosion on the barrier island with heavy rains and gale force winds. Tropical depressions and tropical storms cause flooding due to heavy rainfall during the wet season. Hurricanes have high winds, high tides, large waves, and may also be accompanied by large volumes of rainfall. A tropical storm has winds greater than or equal to 39 miles per hour (mph) and a hurricane has winds greater than or equal to 74 mph.

The National Weather Service began recording tropical storms and hurricanes in this region in 1871. The occurrences and effects of northeasters are also recorded. The occurrence of tropical storms and hurricanes is presented below based on information presented by Doehring and Barile (1988), and Doehring, et al. (1993).

Since 1871, there have been 56 tropical storms or hurricanes that passed over or within 60 mi of the Indian River Lagoon (Doehring and Barile, 1988; Doehring, et al., 1993). Prior to 1876 the intensity of the storms was not recorded. Therefore, the difference between a



Source: Glatzel, 1986

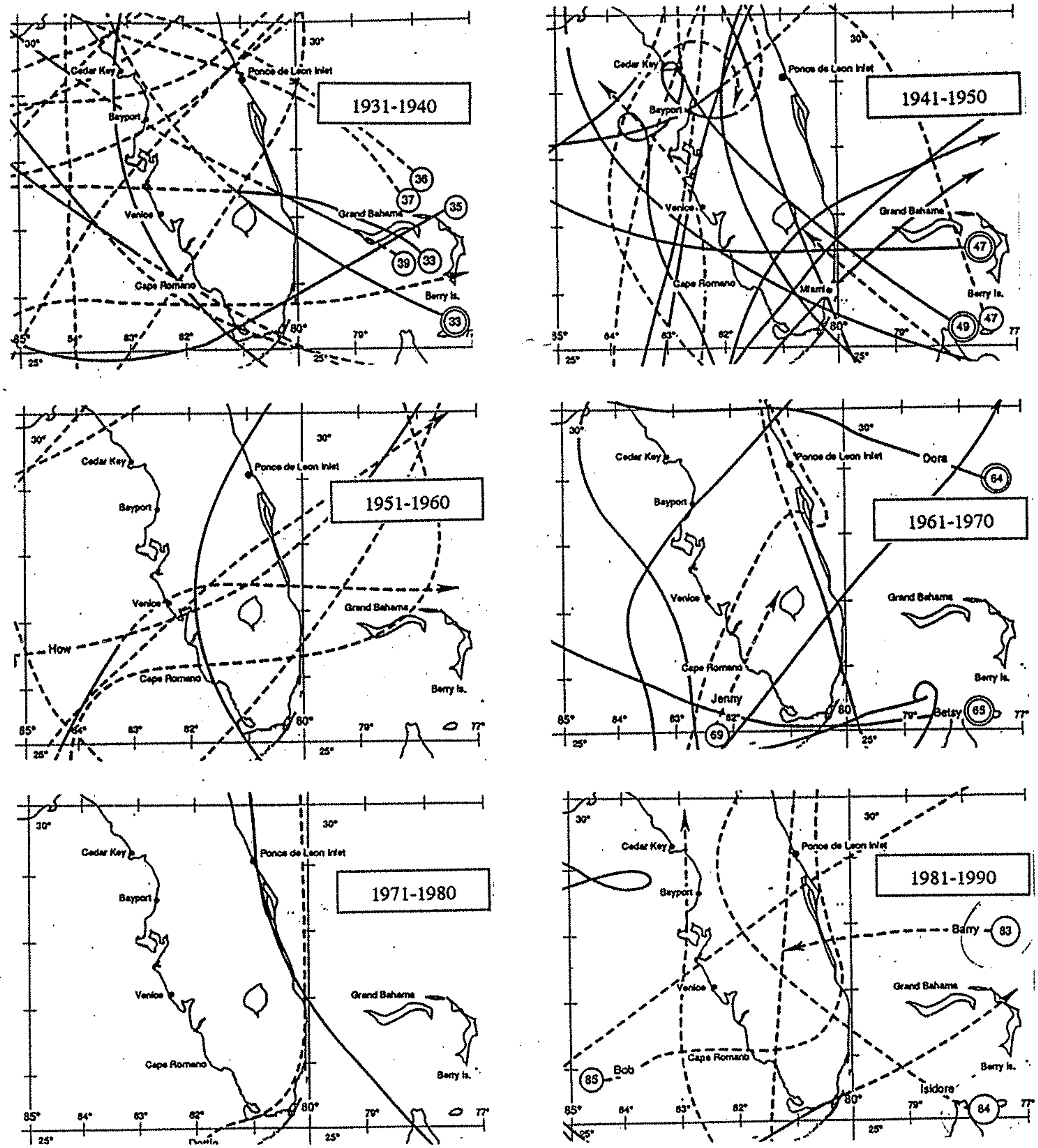
• Woodward–Clyde Consultants
• Marshall McCully & Associates
• Natural Systems Analysis

DRAWING NO.:

DATE:

FIGURE 3-7 WIND ROSE FOR THE INDIAN RIVER LAGOON REGION

INDIAN · RIVER · LAGOON NATIONAL ESTUARY PROGRAM



——— Hurricanes

- - - - - - - Tropical Storms

73 Year of Occurrence

Source: Doehring, et. al., 1993.

• Woodward–Clyde Consultants • Marshall McCully & Associates • Natural Systems Analysts	DRAWING NO.: DATE:	FIGURE 3-8	HURRICANES AND TROPICAL STORMS THAT HAVE APPROACHED THE INDIAN RIVER LAGOON REGION SINCE 1931

INDIAN • RIVER • LAGOON
NATIONAL ESTUARY PROGRAM

tropical storm and a hurricane cannot be ascertained for years prior to 1876 because of the lack of wind speed measurements. From 1876 through 1987, 20 of these storms were hurricanes and 27 were tropical storms.

Of 56 tropical storms and hurricanes that impacted the Lagoon between 1871 and 1987, one tropical storm or hurricane has occurred in May, 4 in June, 3 in July, 18 in August, 14 in September, 14 in October, and one in November (Doehring, et al., 1993). No storms occurred during the year for 58 of the years, many times with consecutive years passed without a storm. Two events occurred in each of the years in 1876, 1892, 1898, 1928, and 1968. In 1909, 3 tropical storms occurred. In 1928, both of the storms that occurred were hurricanes (Doehring, et al., 1993).

Storm activity appears to happen in cycles of various lengths. This means that several years may pass without any storm activity followed by several years during which more than one event per year occurs. The longest continuous stormy period of time during is from 1944 through 1953 during which a hurricane or tropical storm passed through the region every year except 1946 and 1952. In 1947, 1948, 1949, and 1950 a hurricane passed through the region each year.

Extreme storms not only affect the Lagoon in terms of disruptive physical forces to the ecosystem during the storm event, but also in terms of the lasting impact from large volumes of freshwater that are discharged from the drainage systems. These storms are also a major cause of natural opening and closing of inlets such as that in Pecks Lake in 1960.

3.7 TRENDS IN WEATHER

Doehring and Barile (1988) indicate that several trends are noticeable in the data from 1871 through 1987. A cool period, indicated by lower than normal mean monthly temperatures and marked by multiple freeze events occurred from 1894 through 1910 and from 1957 through 1986. The 45-year period from between 1911 to 1956 had only 16 years with extreme freezes.

The years prior to 1930 have mean monthly temperatures approximately 2° to 3°F lower compared to the warmer periods of 1931-1950. During recent periods very few freezes have occurred in the month of February, whereas, in earlier decades freezes occurred routinely during that month.

Doehring and Barile (1988) indicate that a period of high rainfall lasted from 1941 to 1960. A distinctly dry period was experienced between 1901 and 1920 and again in 1971 through 1981. The difference in average annual rainfall for these wet versus dry periods was 10-15 in. During the dry periods rainfall typically dropped below 49 in. per year and during the wet periods rainfall was about 60 in. per year. It is likely that much of the rainfall variation may be attributed to the prevalence of tropical storms and hurricanes (Section 3.6) during these periods.

3.8 EFFECTS OF WEATHER

Extreme short term or prolonged weather patterns can have significant effects on the environment while being quickly forgotten or unnoticed by people. Prior to the present development of the Indian River Lagoon region, the diversity of plant and animal species allowed the system to adapt to extreme weather patterns. Once urbanization and development occurred, the environment was altered in ways that reduced the capability of the system as a whole, and the ecosystem that depends on the system, to adapt to changes.

The direct effects of severe freezing temperatures may include killing or stunting of fish (Provancha, et al., 1992), wildlife (sea turtles and manatees in particular), and vegetation. Less direct effects include higher than normal discharges of cooling water into the Lagoon from the operation of power plants. Coal and natural gas powered plants also introduce higher air pollution loads at these times. Non-native species of plants are typically impacted to a greater degree than the naturally occurring species because the naturally occurring species have adapted over years to periodic extreme freezes. Prolonged periods of cooler weather also reduce evapotranspiration rates and slow biological activity.

In contrast, prolonged periods of warm weather and increased solar radiation raise the Lagoon water temperature. These higher temperature periods suppress dissolved oxygen concentrations. Accelerated bacterial activity in the sediments, in combination with lower dissolved oxygen concentrations in the water column, increases the return of nutrients from the sediments to the water column when the sediments become anoxic or anaerobic (Windsor, 1988).

High winds can cause waves and currents which increase turbidity by entraining flocculent bottom sediments. High turbidity adversely impacts shellfish, seagrass, and other biological resources. Wind-driven currents also may increase the dispersion of nutrients and contaminants throughout the Lagoon. Although nutrients and contaminants may thus be present in a more widespread area of the Lagoon, the net effect of dispersion may be beneficial because the concentrations are substantially diluted. Circulation may also increase productivity by allowing phytoplankton access to dissolved nutrients over a layer area of the Lagoon (Windsor, 1988).

During periods of heavy rainfall the discharge of freshwater into the Lagoon increases dramatically. Salinity in the surface waters can become reduced particularly around the location of the discharge. During periods of drought, however, evaporation increases salinity (Fan, 1985; Windsor, 1988).

Only recently have both the short- and long-term effects of extreme weather events been examined. Creation of water management districts (1972) helped to focus efforts on the impact of extreme event storms on the drainage systems that they own and operate, and those that they regulate.

During the May 22-31, 1984 Memorial Day holiday period, five days of rainfall, virtually non-stop, were experienced over South Florida including the extreme south end of the Indian River system. This event, characterized as unusual but within the normal annual range of storms (SFWMD, 1984), caused extensive flooding because of the generally wet antecedent conditions. Lin (1984) summarized the 1983-84 dry season hydrologic conditions that preceded this storm as "wet overall, but dry in January". Flood damage resulted when the West Palm Beach Canal overflowed its banks. Total rainfall over the region varied from over 4 in. to over 14 in. Pumping stations operated at maximum rates; however, no specific information on duration or total volume of releases to the St. Lucie Canal and Indian River Lagoon are available. The June 29, 1984 operation report did show an average discharge of 900 cubic feet per second (cfs) to the St. Lucie Estuary on that day (Lin, 1984).

For the entire SFWMD area, dry season rainfall during the 1983-1984 period was 130% of normal. As a result, unusual pumping discharges to the St. Lucie Estuary at Stuart and to the Indian River Lagoon at Ft. Pierce were needed throughout the 1983-1984 dry season. From November 1983 through May 1984, the discharges from S-97 in Belcher Canal varied from 3,000 to 10,500 acre-ft each month. At S-80, discharges to C-44 and the St. Lucie Estuary varied from 13,000 acre-ft to 25,000 acre-ft each month. Total volume of water discharged from the system during this "wet" dry season was approximately 1.16×10^6 acre-ft of freshwater (3.78×10^{11} gallons).

A preliminary report on a storm from November 21-26, 1984 is another good example of the spatial variability of intense storm effects. During this period, the highest rainfall of 19 in. was reported near Jupiter, while Indian River County experienced only 4-6 in. and Miami just over 1.0 in. Rainfall onto Lake Okeechobee was only about 2 in. (SFWMD, 1984).

A storm event that occurred January 15-17, 1991 is a good example of the water quality effects of an extreme event (SFWMD, 1991a). Rainfall was most severe around West Palm Beach but Ft. Pierce received over 2 in. and Stuart received over 3 in. during the period. The storm was intensely focused and required pumping of water into Lake Okeechobee from surrounding areas. The effect of pumping the nutrient rich water, particularly the phosphorous loads, resulted in an algae bloom and a fish kill in the lake. Since water is periodically discharged from Lake Okeechobee to the St. Lucie Estuary and Indian River Lagoon, there may be a potential for similar impacts to these estuarine systems from future events of this magnitude.

A report on the June 23-30, 1992 rain storm (SFWMD, 1992) showed that precipitation during the entire month of June was one of the highest in recorded history. One station reported rain on 25 days during the month, six of which had over 1 in. per day. Because of these generally wet antecedent conditions prior to the June 23-30 storm, the ground water was saturated and no soil percolation was possible. The frequency estimation of this storm, resulting in about 8.0 in. of rainfall on the south segment of the Indian River Lagoon system, was between one-in-25 years and one-in-50 years (SFWMD, 1992). High rates of discharges to the Indian River Lagoon system (as well as other receiving waters) were required "to minimize flooding of lands and environmental impacts" (SFWMD, 1992). The environmental impacts were not described. The SFWMD canal system had to operate at or near capacity through July 28, 1992 (approximately one month after the storm) to discharge the runoff from this storm and other smaller events that occurred thereafter (SFWMD, 1992).

The effect of this prolonged wet period and storm event on the St. Lucie Estuary was reported as "reduced salinities and impacted fauna and flora" (SJRWMD, 1992). Flows as high as 2,400 cfs were discharged to the St. Lucie Estuary from the S-80 structure during this storm. The salinity of this estuary dropped from 15 parts per thousand (ppt) to almost zero over a one day period (Haunert, 1988). Freshwater conditions were sustained in the St. Lucie Estuary for nearly three months.

Historical information indicates that this water body once supported extensive oyster reefs (SFWMD, 1993). It is indicated that the altering of salinity levels since construction of the drainage system to control flooding and provide irrigation water has severely impacted the natural ecosystem in the St. Lucie Estuary (Phillips, 1961; Haunert and Startzman, 1985).

The SFWMD has analyzed the data from rainfall events and drought periods that have affected the operation of their water management system. In Technical Publication 84-7, Lin, et al. (1984) discuss the 1980-1982 drought, and compare it to the droughts of 1955-56, 1961-62, 1967-68, 1970-71, and 1973-74. Lake Okeechobee dropped from 17.5 ft above mean sea level (msl) in January 1980 to 9.75 ft msl in July 1981. This drop was attributed to below normal rainfall and above normal evaporation. Statistical analysis showed the 1970-1971 drought had a return period over the area that varied between one-in-eight to one-in-fifteen years, while the 1980-1981 drought had a return period over one-in-100 years.

Because of the increase in demand for irrigation water and the lack of rainfall during the 1980-1981 period, water was pumped from Lake Okeechobee into the St. Lucie Canal (C-44). During this 21 month period, 196,832 acre-ft (6.4×10^{10} gallons) of water was required to be pumped into the St. Lucie Canal to meet withdrawals permitted by SFWMD (Fan, 1985). Ironically, at times there is too much water for the system to handle and at other times there is not enough water to meet existing commitments.

Another drought period extended from September 1988 through August 1989 (Marban, et al., 1989). Approximately 40 in. of rain fell over the SFWMD region. The drought recurrence interval was rated as greater than one-in-50 years to one-in-100 years across the Indian River Lagoon area. This rainfall deficiency caused an increase in water demand from irrigation withdrawals, and resulted in water from Lake Okeechobee being pumped into the canal system. The St. Lucie Canal (C-44) received 51,000 acre-ft for water supply and 79,000 acre-ft for salinity control. This is a total infusion of 130,000 acre-ft (4.24×10^{10} gallons) of high nutrient, low dissolved oxygen Lake Okeechobee water.

It is apparent that the effects of climate and weather are quite varied within the Indian River Lagoon Region and can be extreme. The overall mild weather conditions have encouraged residential and agricultural development in many of these areas that are best used as buffers to allow the hydrologic system the ability to react in a flexible manner when extreme conditions are present. Extreme events, however, have more potential to cause ecological impacts because of alterations to the natural drainage system.

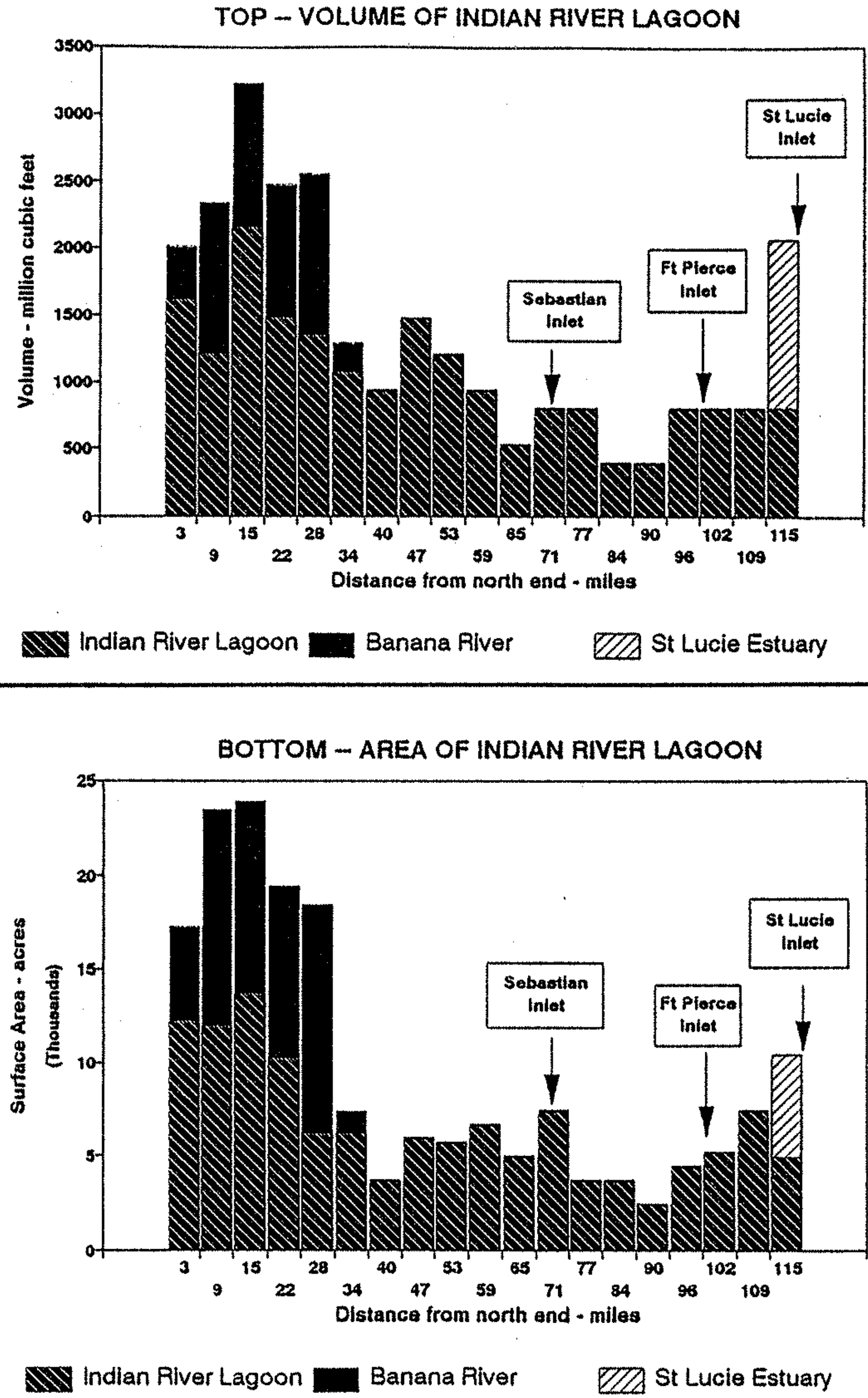
4.0 HYDROLOGY

4.1 VOLUME OF THE INDIAN RIVER LAGOON COMPLEX

Figure 4-1 shows the estimated volume and surface area of the Indian River Lagoon and Banana River (Glatzel and Da Costa, 1988a). These parameters are important in determining the water budgets of the complex as well as the chemical and water quality effects of changes in the water budget and hydrologic cycle. Figure 4-1 shows the north end of the Lagoon on the left of the figure. It is readily apparent that the north end of the complex has a much greater surface area than the central or south portions. This relationship implies that direct precipitation on the Lagoon surface and evaporation from the surface are more important parameters of the hydrologic cycle in the north end than in other portions. However, the volume of water in the Lagoon complex is also greater in the north, indicating greater potential for mixing and dilution.

4.2 HYDROLOGIC CYCLE

The balance of fresh and salt waters in the estuary is a result of the hydrologic cycle and the balance of freshwater entering and leaving the estuary. Water circulates between various compartments (e.g., ground water, atmosphere, surface water) and states (liquid versus gas). Water circulates from the ocean into the atmosphere to the land, and over and under the land surface back to the ocean in what is called the Hydrologic Cycle (Parker, 1986). A water budget analysis is a tool that can account for the movement of water within the hydrologic cycle and can evaluate sources and sinks of freshwater in the Lagoon. The water budget analysis also can be extended to examine conditions that existed before the watersheds of the Lagoon were extensively modified by drainage projects.



Note: All Values at Mean Low Water

Sources: Glatzel and Da Costa, 1988a.

• Woodward-Clyde Consultants • Marshall McCully & Associates • Natural Systems Analysis	DRAWING NO.: DATE:	FIGURE 4-1	VOLUME AND SURFACE AREA OF THE LAGOON IN 10-KM SECTIONS OF THE INDIAN RIVER LAGOON AND BANANA RIVER

INDIAN RIVER LAGOON NATIONAL ESTUARY PROGRAM

In the Indian River Lagoon, the principal compartments of the hydrologic cycle are the:

- Atmosphere
- Terrestrial watershed including the land surface and the sub-surface aquifer
- Receiving water bodies (Mosquito, Banana River, and Indian River lagoons)
- Atlantic Ocean

Each one of these components may be thought of as a compartment which can serve as a source, or a sink, a temporary storage element for water. Water moves between these compartments in certain fashions, and movements of water can be considered as either inputs or outputs to the system. The functional role of each compartment and movement may change with time and location. Therefore, water budgets can be complex.

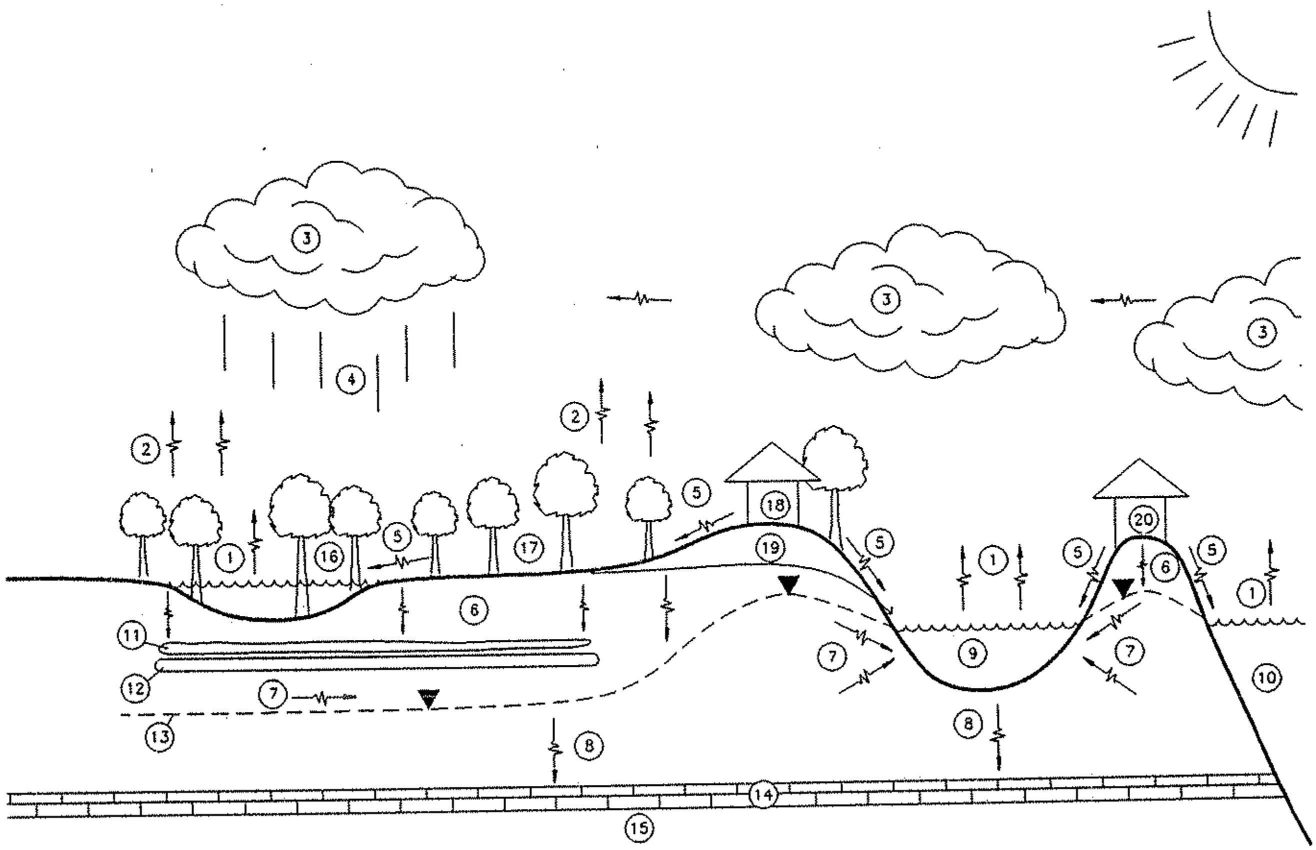
All water budgets are governed by the basic equation:

$$\mathit{Inputs} - \mathit{Outputs} \pm \mathit{Accumulation} = 0$$

in which accumulation equals the storage in the system.

Figure 4-2 is a schematic diagram showing the elements of the Indian River Lagoon system hydrologic cycle that are used in a water budget. The Floridan aquifer can be both a sink and a seepage source for water from the terrestrial watershed, the Lagoon, and the ocean (Pandit and El-Khazen, 1990). The significance of this aquifer as a source is discussed in Section 5.0, Hydrogeology.

Glatzel (1986) and Glatzel and Da Costa (1988a; 1988b) quantified the various elements of a water budget on a monthly basis for the Indian River Lagoon, using the Lagoon as the control volume. They divided the Indian River Lagoon surface water system into five separate areas. The Banana River and Sykes Creek (Segment 1B) were subdivided from North Indian River Lagoon (Segment IC). Mosquito Lagoon (Segment 1A) was not included in their analysis. However, the hydrology of the Mosquito Lagoon has not been substantially altered so a comparison of present and past budgets is of minor importance.



Source: Marshall McCully & Associates. 1993

•Woodward–Clyde Consultants •Marshall McCully & Associates •Natural Systems Analysts	DRAWING NO.: INDIAN08.DWG DATE: 7-5-94	FIGURE 4–2 TYPICAL HYDROLOGIC CYCLE FOR THE INDIAN RIVER LAGOON REGION

INDIAN RIVER LAGOON NATIONAL ESTUARY PROGRAM

If the water inputs and outputs don't balance, there must be either a change in the volume of water within the Lagoon or the water must move into or out of the compartment through other pathways not shown in the equation. For Indian River Lagoon, one primary pathway is exchange to the ocean through the inlets.

Inputs in the water budget include:

- Precipitation (rainfall) on the Lagoon
- Controlled or measured streamflow discharges to the Lagoon
- Non-point source runoff from the watershed
- Domestic and industrial treatment plant effluent discharge
- Ground water seepage

Outputs include:

- Evaporation
- Consumption for potable water and irrigation
- Ground water recharge

A more sophisticated presentation (Glatzel and Da Costa, 1988b) of the water budget equation is:

$$dQ + dV = I(i) - O(j) \quad i,j = 1,2,3,\ldots n$$

where

dQ	=	*net flow into or out of the lagoon*
dV	=	*change in volume of the lagoon*
$I(i)$	=	*inputs of water, 1 through n*
$O(j)$	=	*outputs of water, 1 through n*

Glatzel and Da Costa (1988b) considered consumptive use and ground water recharge to be negligible, based on prior work by Glatzel (1986). The precipitation element includes only rainfall directly on the surface of the Lagoon. Rainfall that falls on other parts of the watershed is considered to be either non-point source runoff or streamflow discharge.

Rainfall that infiltrates the ground surface is included under runoff (Glatzel and Da Costa (1988a, 1988b). Based on these simplifications, a water budget equation becomes:

$$dQ + dV = P + D + R - E$$

where

P	=	*Precipitation (rainfall)*
D	=	*Discharges to the Lagoon*
R	=	*Runoff*
E	=	*Evapotranspiration*

Each of the input and output components of the Indian River Lagoon water budget is discussed in more detail in Sections 4.3 to 4.7. Table 4-1 shows the estimated magnitudes of each input and output based on estimates by Glatzel and Da Costa (1988a, 1988b). Wastewater treatment plant discharges were taken from Glatzel and Da Costa (1988a), while all other elements were taken from Glatzel and Da Costa (1988b).

4.3 PRECIPITATION INPUT

The variation of precipitation (P in the water budget equation) throughout the Lagoon was discussed previously in the climate section of this report. Glatzel and Da Costa (1988a) used an average rainfall for the Lagoon region based on the monthly mean rainfall from the Titusville, Melbourne, Vero Beach, Stuart, and Ft. Pierce stations. Figure 4-3 shows the monthly rainfall values from the five stations that were used. This element includes only rainfall on the Lagoon itself.

4.4 DISCHARGE INPUTS TO THE LAGOON

4.4.1 Streamflow

Rainfall in the non-lagoon or upland parts of the watershed may infiltrate to the surficial aquifer or runoff the surface of the ground. In much of the watershed, the runoff along the surface and surficial discharge enters streams and ditches that then unite into larger canals or rivers before discharging into the Lagoon through well defined discharge points. When flow from these discharge points has been measured, the data provide a measure of the total

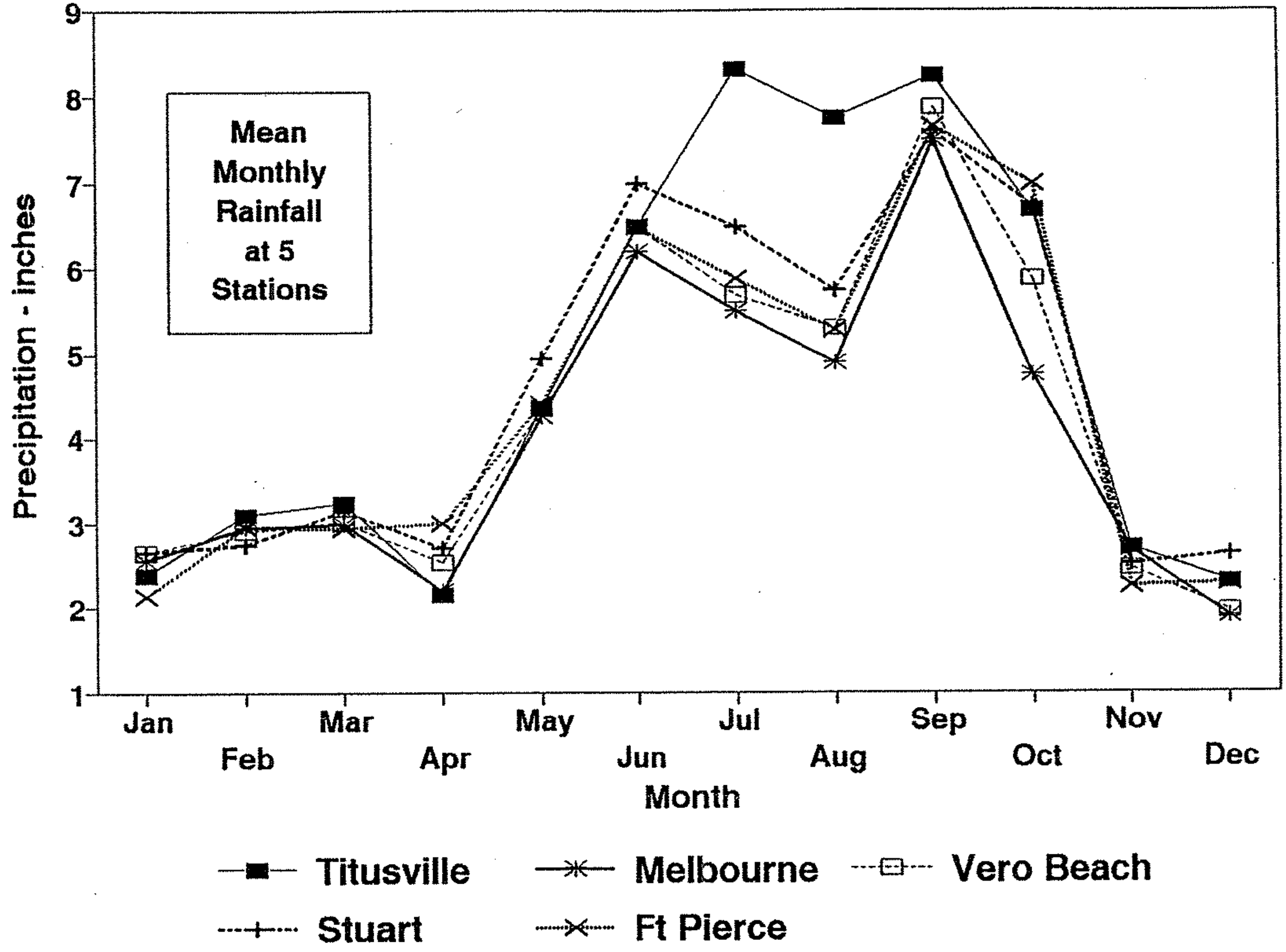
TABLE 4-1

ESTIMATED NORMAL WATER BUDGET COMPONENTS FOR EACH OF THE SEGMENTS OF THE BANANA RIVER AND INDIAN RIVER LAGOON REGION (VALUES IN MILLION CUBIC METERS PER YEAR)

SEGMENT	INPUTS					OUTPUTS	NET
	(A) RAINFALL	(B) RUNOFF	(C) STREAMFLOW	(D) WWTPs	(E) TOTAL INPUTS (A-D)	(F) EVAPORATION	(G) dQ + dV (E-F)
1B - Banana River	186.14	16.94	0.00	19.90	222.98	(243.19)	(20.21)
1C - North Indian River Lagoon	391.05	104.87	0.00	13.63	509.55	(414.59)	94.96
2 - North Central Indian River Lagoon	93.50	173.94	318.24	14.01	599.69	(111.34)	488.35
3 - South Central Indian River Lagoon	98.48	121.93	321.03	7.69	549.13	(109.88)	439.25
4 - South Indian River Lagoon	155.93	214.83	750.79	18.00	1,139.55	(167.01)	972.54
TOTAL BANANA AND INDIAN RIVER LAGOONS	**925.10**	**632.51**	**1,390.06**	**73.23**	**3,020.90**	**(1,046.01)**	**1,974.89**

Source: Glatzel and Da Costa (1988b)

( ) = negative numbers



Source: Glatzel and Da Costa, 1988b.

• Woodward-Clyde Consultants
• Marshall McCully & Associates
• Natural Systems Analysis

DRAWING NO.:

DATE:

FIGURE 4-3

MONTHLY MEAN RAINFALL AT FIVE RECORDING STATIONS ALONG THE INDIAN RIVER LAGOON

INDIAN RIVER LAGOON NATIONAL ESTUARY PROGRAM

runoff discharge from the watershed at that point. Discharges from measured or gaged streams are included in the budget as streamflow discharge.

Discharge input to the Lagoon from drainage ditches, flood control canals, and natural streams is the most variable component of the Lagoon water budget when compared by sub-basin or segment. Fortunately, the major streams have had gages to record flows for 15-20 years. The discharge varies from year to year, depending on weather events. The peak monthly flows from these canals generally occurs in September. According to Glatzel and Da Costa (1988b), total streamflow discharges to the Lagoon are on the order of 1,391 million cubic meters each year (Table 4-1). By contrast, non-gaged runoff is estimated on the order of 352 million cubic meters annually.

Table 4-2 summarizes measured streamflow discharges from gaged streams and canals for various periods of record between 1950 and 1984. These data indicate that actual gaged streamflow data is higher than Glatzel and Da Costa's estimate, and is about equal to their combined streamflow and runoff volumes. The additional gaged streamflow may represent other sources such as irrigation or ground water.

In the Lagoon north of Melbourne (Segments 1A, 1B, 1C) there are few natural streams and drainage canals that have significant gaged flows. As a result of the scarcity of large streams, there is little streamflow discharge of freshwater to the Lagoon in the north (Segments 1A, 1B, 1C). However, drainage within the North Central, South Central, and South Indian River Lagoon segments (Segments 2, 3, 4) has been altered greatly by artificial drainage canals, thus greatly increasing the input volume of the gaged streamflow discharge.

Assuming that there is virtually no streamflow drainage discharge north of Melbourne (Table 4-1), 23% of the streamflow discharge to the Lagoon occurs between Melbourne and Sebastian Inlet (Segment 2), 23% between Sebastian and Ft. Pierce inlets (Segment 3), and 54% of the total streamflow discharge occurs in the South Indian River Lagoon basin (Segment 4). The importance of this component of the hydrologic cycle is discussed further in Section 4.8, Water Budget.

TABLE 4-2

SUMMARY OF GAGED FRESHWATER DISCHARGES TO THE INDIAN RIVER LAGOON (VALUES IN CFS)

DISCHARGE POINT	SEGMENT	ANNUAL MEAN DISCHARGE[1]	MAXIMUM RECORDED (AVERAGE) DISCHARGE	
			30-DAY	1-DAY
Crane Creek	2	16	102	437
Turkey Creek	2	152	1,120	2,500
C-54 Canal	3	62	2,460	3,590
Fellsmere Canal	3	133	908	2,030
North Canal	3	31	293	1,580
Main Canal	3	78	465	1,790
South Canal	3	39	292	1,780
C-25 Canal	4	153	520	1,890
C-24 Canal	4	139	1,240	2,880
C-23 Canal	4	126	1,030	3,190
C-44 Canal	4	853	9,560	11,490

Source: Rao, 1987

1 = Various periods of record between 1950 and 1984

4.4.2 Wastewater Treatment Plant Flows

In addition to sources that are categorized as non-point sources such as stormwater runoff and discharges from drainage ditches and natural streams, there are point source loadings into the Indian River Lagoon system from wastewater treatment plants (WWTPs) and power plants. Within the SJRWMD area of the Indian River Lagoon system there were 25 wastewater treatment plants discharging to the Lagoon at the time of the Glatzel and Da Costa (1988b) water budget study. This total point source effluent discharge input into the Lagoon at that time was about 73 million cubic meters annually (Table 4-1).

Since 1987, this volume has decreased because several WWTPs have ceased surface water discharge. The volume is expected to decline to near zero in most segments of the Lagoon by 1996 because Chapter 90-262, Florida Statutes mandates that domestic WWTPs cease discharge to the Indian River Lagoon.

Table 4-1 shows that the freshwater streamflow from the drainage canals was well over an order of magnitude higher in volume than the total WWTP flow. As such, WWTP flows do not greatly affect the water balance for most of the Lagoon. However, in the North Indian River Lagoon (Segment 1C) and Banana River (Segment 1B), where there are few drainage ditch systems and very little flushing, the WWTP flows can be a significant source of freshwater and nutrients to the Lagoon on a local basis.

4.5 RUNOFF INPUTS

Terrestrial runoff and ungaged stream flow comprise the non-point source component of the water budget. This represents the rainfall that does not discharge through specific streams or canals with gaged or measured flow. Both runoff and streamflow are functions of land use, soil type, and climate. In the watershed framework used by Glatzel and Da Costa (1988b), important factors influencing runoff include rainfall, evapotranspiration, and the capability of the soil to store water. Therefore, runoff is a function of climate and weather, and is very sensitive to land use changes. Glatzel and Da Costa (1988a) showed that, on average, the maximum runoff period for the Lagoon occurs in October. Minimum values of runoff are observed in June and July, indicative of the increased evapotranspiration in that period.

An interesting observation by Glatzel and Da Costa (1988a) is that the calculated volume of runoff for some gaged sub-basins was about 3 times smaller than the volume actually measured at a control structure. While Glatzel and Da Costa (1988a) suggest agricultural irrigation as a possible cause of the higher than expected flow, other sources such as discharge from aquifer storage may also contribute to the flow. Aquifer discharge is not always a result of surface runoff in the watershed.

4.6 EVAPOTRANSPIRATION OUTPUT

Evaporation from an open waterbody has been found to be approximately proportional to land-measured pan evaporation. Glatzel and Da Costa (1988b) used pan evaporation data from a Vero Beach Station as the basis for their evapotranspiration values. This evaporation station was located at the Vero Beach Airport for 13 years and then was moved 4 miles west, where it has operated for the last 23 years. A significant difference exists in the values of evaporation at the two locations. However, the annual evaporation patterns are identical for the two stations. Therefore, the data were averaged and utilized as a data set for land-based evaporation.

Glatzel and Da Costa (1988a) considered that the Lagoon evaporation component equaled 78% of the land-based evaporation. Additional information on evaporation from Lin, et al. (1984) was compared with the above data and was not found to be significantly different. Therefore, the evaporation data (see Figure 3-6) used by Glatzel and Da Costa (1988a) appears to be reasonable.

Transpiration is the transfer of water by plants from the root zone into the atmosphere through the leaves. Transpiration is a function of available ground water, temperature and atmospheric humidity. Because transpiration is difficult to adequately quantify for use in the water budget, it has been ignored in the water budget of Glatzel and Da Costa (1988b). However, transpiration contributes significantly to the high humidity conditions that are experienced during the wet season. The replacement of natural vegetation with impervious areas may reduce the role of transpiration in the water cycle. The effect of such changes on weather has been suggested but never substantiated with scientific research.

4.7 EXCHANGE WITH THE OCEAN

One of the primary features of an estuary is the mixing of fresh and salt waters. The typical salinity regime is dependent on the size, shape, and depth of the estuary, the degree of connection to the ocean, and the discharge and timing of stream flows to the estuary. Although this regime may have a characteristic range of normal salinity values, it may also have a high salinity variability and stratification. The biota of the estuary is adapted to this salinity regime. Any conditions outside these limits may cause the biota and ecosystem to be negatively impacted.

The exchange of water between the Indian River Lagoon and the Atlantic Ocean through the inlets is a very complex phenomenon. Glatzel and Da Costa (1988a, 1988b) considered the ocean exchange component to be negligible and did not include it as a specific item in their water budget. However, salinities in the southern half of the Lagoon typically approach ocean values, indicating that most of the Lagoon volume must be composed of ocean water from the inlets. Since evaporation cannot account for the difference in freshwater, this salinity concentration indicates that exchange through the inlets may be a more important factor than Glatzel and Da Costa believed. In the water budget presented in the following sections, the exchange with the ocean is included under the volume difference and unaccounted flows part of the equation.

In spite of this difficulty in resolving saltwater exchanges, the water budget analyses of Glatzel and Da Costa (1988a, 1988b) is valuable in comparing the relative magnitudes of the different freshwater inputs to the Lagoon.

4.8 WATER BUDGET

4.8.1 Water Budgets for Lagoon Segments

Sections of the Indian River Lagoon have special hydrodynamic characteristics that make understanding their water budgets especially important. Most estuaries and lagoons have substantial river inputs and large exchanges of ocean water. In the Indian River Lagoon segments north of Sebastian Inlet this is not true. Exchange of ocean water becomes more limited with increasing distance from the inlet because of the small range of the astronomical tide. Riverine input is also very limited. Under these circumstances the relationship of evaporation outputs to direct precipitation and other water inputs controls the time-averaged circulation of the Lagoon.

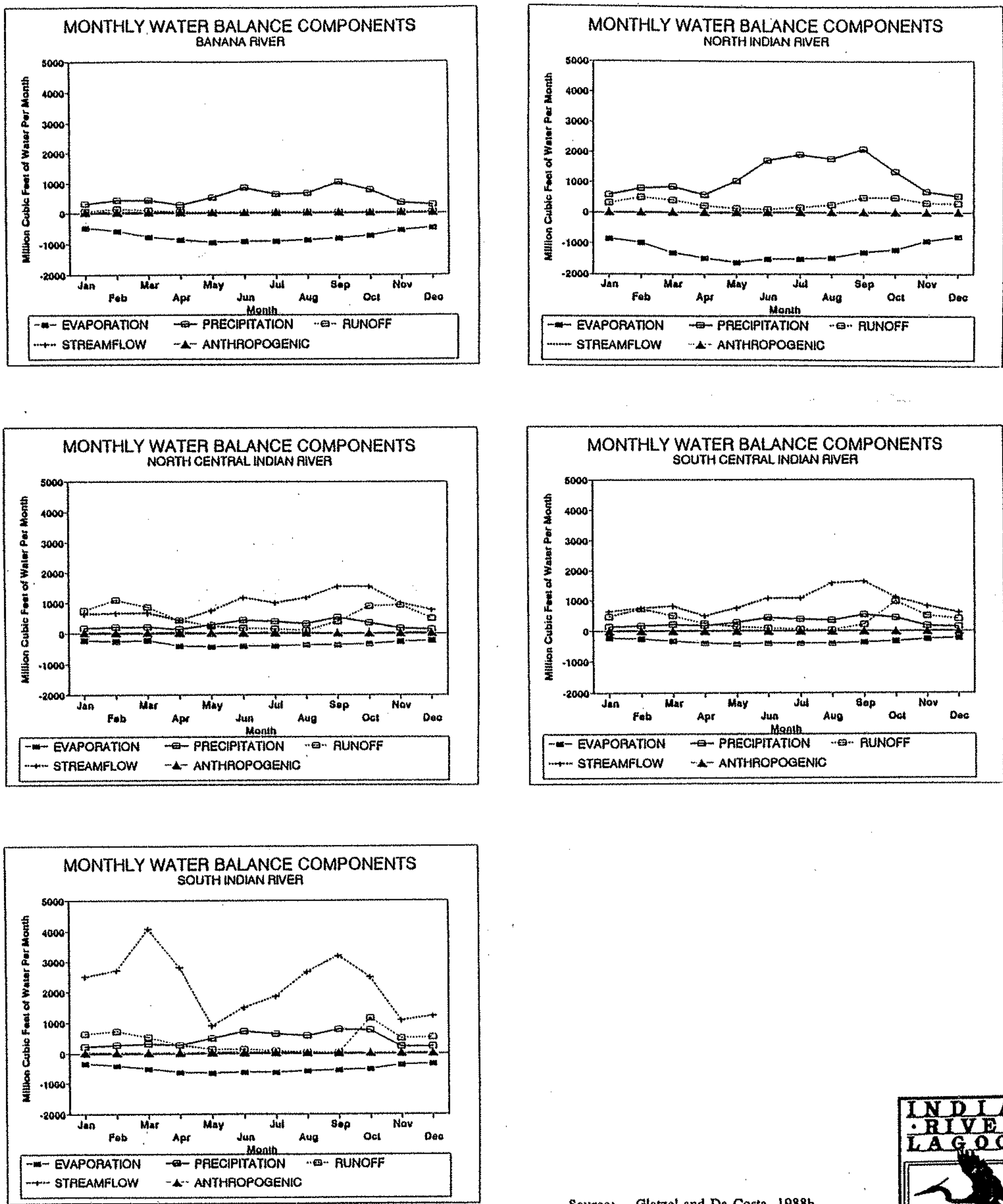
Glatzel and Da Costa (1988a, 1988b) have provided data on the water budgets for all of the segments except Mosquito Lagoon (Segment 1A). These data, on Figure 4-4, show the freshwater inputs for each section from direct precipitation, streamflow discharges, runoff, and the anthropogenic industrial and wastewater discharges. Computed evaporation values are also presented.

Figure 4-5 shows the sum of these sources and sinks for the Banana River (Segment 1B), the north section of Indian River Lagoon (Segment 1C), and the South section of Indian River Lagoon (Segment 4). It is clear that evaporation exceeds freshwater inputs in the Banana River throughout most of the year. In fact, the freshwater inputs dominate only in September, October and February. Evaporation also exceeds freshwater inputs in the Segment 1C during April and May, which is also representative of the low streamflow regime of the northern Lagoon region. The graph for Segment 4 in Figure 4-5, by contrast, shows the positive input characteristic of parts of the Lagoon with large freshwater inputs.

It is important to note that the data shown on Figures 4-4 and 4-5 are monthly averaged values for a 30-year period. The short term (i.e. daily) and long term (i.e. yearly) variability of precipitation and runoff is very high (Glatzel and Da Costa, 1988b) meaning that the periods when evaporation exceeds freshwater inputs in these lagoon sections will be different each year. The water budgets for each segment of the Lagoon are discussed below, with the exception of Mosquito Lagoon (Segment 1A) which was not included in the water budgets constructed by Glatzel (1986) and Glatzel and Da Costa (1988b).

<u>Banana River - Segment 1B</u>

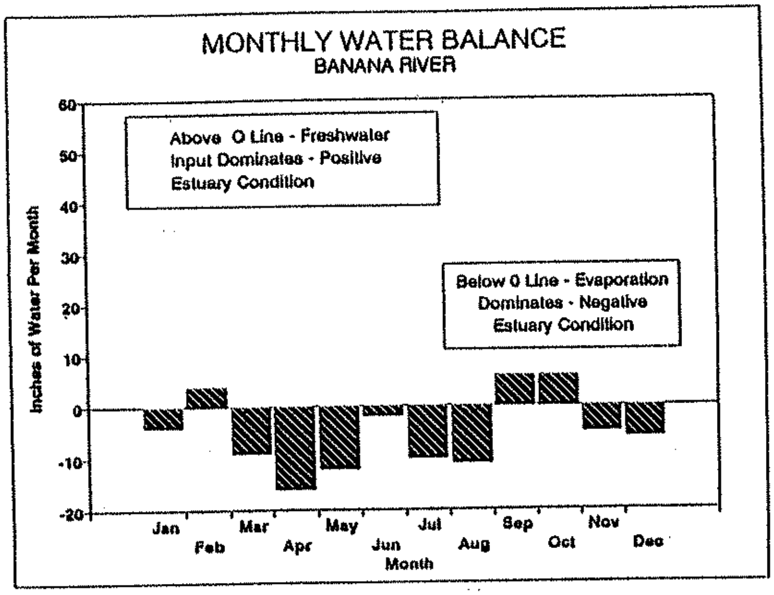
In the Banana River, the water budget input is controlled by direct precipitation which is 84% of the total input. Streamflow discharge inputs in this segment are negligible and runoff input values are small compared to the direct precipitation (Table 4-1). However, evaporation loss is greater than the total input. To offset the net loss from evaporation, the

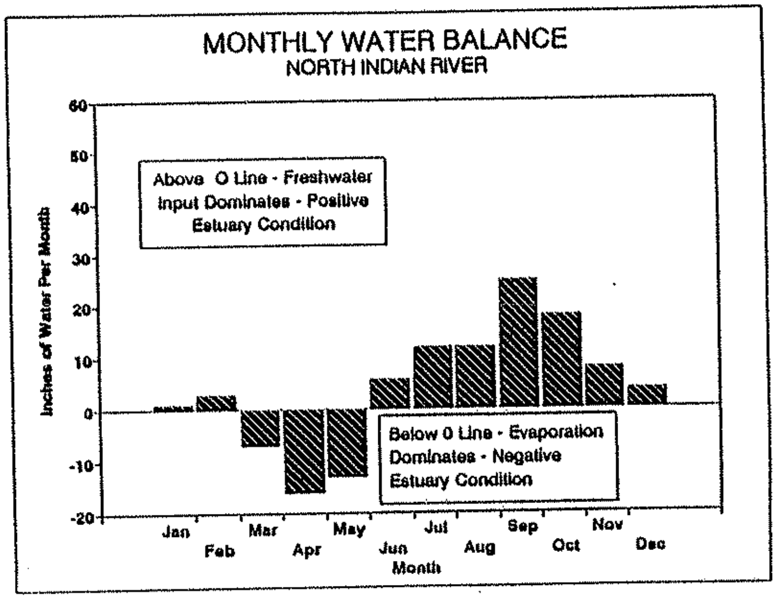


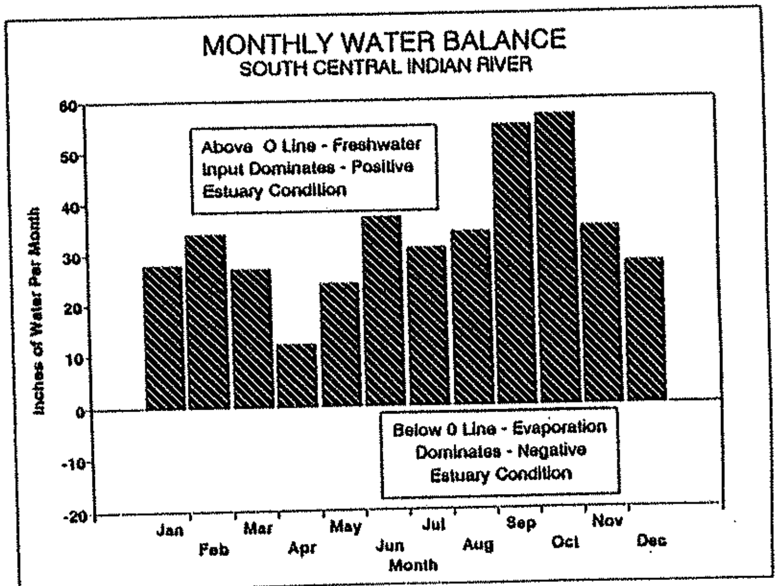
Source: Glatzel and Da Costa, 1988b.

• Woodward–Clyde Consultants • Marshall McCully & Associates • Natural Systems Analysts	DRAWING NO.: DATE:	FIGURE 4-4	APPROXIMATE MONTHLY VALUES FOR WATER BUDGET INPUTS AND OUTPUTS FOR SEGMENTS OF THE INDIAN RIVER LAGOON

INDIAN RIVER LAGOON NATIONAL ESTUARY PROGRAM







Source: Glatzel and Da Costa, 1988b.

• Woodward-Clyde Consultants • Marshall McCully & Associates • Natural Systems Analysis	DRAWING NO.: DATE:	FIGURE 4-5	THREE SEASONAL PATTERNS OF FRESHWATER INFLOW OR OUTFLOW PREDOMINANCE AS ILLUSTRATED BY SEGMENTS 1B, 1C, AND 3

INDIAN RIVER LAGOON NATIONAL ESTUARY PROGRAM

Banana River needs to receive approximately 20 million cubic meters of water from the Indian River Lagoon each year. This makeup water enters the Banana River at its south end.

This analysis presents the water budget as of 1986. At that time, effluent discharges from WWTPs provided approximately 20 million cubic meters of input annually. Effluent discharges are projected to have ceased by 1996 in order to meet the "no discharge" law, meaning that the current or future inflow needed from the south part of the Lagoon to offset these losses may actually be 40 million cubic meters of water annually instead of the 20 million projected by Glatzel and Da Costa. The 40 million cubic meters represents about 20% of the total volume of the Banana River. The effect of this shift in the water budget on aspects such as salinity has not been determined.

A major significance of evaporation exceeding freshwater input into the Banana River and the northern Lagoon section is that the Lagoon may operate like a negative estuary during the periods of net evaporative loss (Figure 4-5). That is, a net flow of ocean water into the Lagoon equalizes the water budget balance. This has major effects on the circulation, flushing rates, and capability of the Lagoon to cope with chemical and nutrient loads. These effects are described more fully in Section 6.0, Hydrodynamics.

North Indian River Lagoon - Segment 1C

In the northern part of the Indian River Lagoon (Segment 1C), evaporation is greater than in the Banana River segment (414 versus 243 million cubic meters per year) because of the larger surface area of the Lagoon. Precipitation input is also higher in the North Indian River Lagoon (391 versus 186 million cubic meters per year), as is runoff (104 versus 16 million cubic meters per year). The differences in rainfall and runoff, discussed in Section 3.0, are to some extent due to the fairly large differences in annual rainfall patterns that occur in the fairly short distance between Titusville and Patrick Air Force Base.

Gaged streamflow discharge input to the North Indian River Lagoon is negligible (Table 4-2) as it is in the Banana River, due to the small watershed area and the small flow regimes of the streams and canals.

North Central Indian River Lagoon - Segment 2

The boundaries of Segment 2 used by Glatzel and Da Costa (1988a, 1988b) do not exactly coincide with the boundaries more recently defined in this study. However, the water budget presented by Glatzel and Da Costa is believed to accurately mirror existing conditions in Section 2.0 as defined in the Characterization study.

In the segment (Segment 2) between the Melbourne Causeway and Sebastian Inlet, the effect of increased drainage from canals becomes evident in the increase in streamflow discharge input. The Fellsmere Canal and C-1 and C-54 canals are located in this segment. It is important to note that flows in the C-54 canal have been reduced considerably in the period since this water budget was developed. However, even with reduced C-54 flows, the input from streams and other drainage ditches is greater than precipitation (318 versus 93 million cubic meters) and runoff inputs (174 million cubic meters per year). Peak discharge from drainage canals most often occurs during the period from June to October (Glatzel and Da Costa, 1988a) because of increased discharge requirements for flood control, although large discharges may occur in other periods due to heavy storms, heavy irrigation use, or other factors.

South Central Indian River Lagoon - Segment 3

In Segment 3 from Sebastian Inlet to Ft. Pierce Inlet, a similar pattern exists in which total annual input (549 million cubic meters) is dominated by input from streams and drainage canals (321 million cubic meters). Ungaged non-point source runoff is relatively insignificant compared to runoff discharges through drainage canals. In fact, ungaged runoff is larger in the North Central Indian River Lagoon segment's basin than in this segment (174 versus 122 million cubic meters per year). Discharges from streams and drainage canals represent approximately 71% of the total input into this segment of the Lagoon. Segments 2 and 3 both show greatly reduced precipitation inputs and evaporative outputs compared to Segments 1B and 1C due to the substantially reduced Lagoon surface area.

South Indian River Lagoon - Segment 4

In the southernmost segment of the Lagoon from Ft. Pierce Inlet to Jupiter Inlet, there is an overwhelming dominance of drainage canal discharge flows (751 million cubic meters per year). However, in this segment there is also a relatively large input from ungaged non-point source runoff (215 million cubic meters per year). Because the watershed is large in area, streamflow and runoff are more significant compared to other segments. Even so, the discharge from drainage canals is three times as great as ungaged runoff. It was theorized by Glatzel and Da Costa (1988a) that the management of flows from Lake Okeechobee dictate the drainage canal inputs to the Lagoon. The results of their water budget calculations indicate that the discharge from drainage canals in the South Indian River Lagoon segment is equal to the discharge of drainage canals of all other segments combined.

4.8.2 Summary of Lagoon Segments

An overall analysis of the water budgets indicates that the Lagoon hydrologic inputs are highly variable over the length of the Lagoon (Table 4-1). The southern segments of the Lagoon are dominated by the flow from drainage canals. In particular, the surface water from Lake Okeechobee and the infiltrated runoff from a widely expanded watershed have increased this element. By contrast, the northern segments are affected primarily by direct precipitation on the Lagoon and by the large amount of evaporation that occurs.

4.8.3 Relationship of Water Budget to Salinity and Water Quality

The potential adverse effect of extended watershed drainage canal discharge is illustrated by water budget calculations. Based on the data presented in Table 4-1, Glatzel and Da Costa (1988a) theorized that the inputs to the southern portion of the Lagoon (Segment 4) from drainage canals should have transformed that portion of the Indian River Lagoon complex into a freshwater ecosystem which is no longer controlled by elevated salinity. However, an examination of water quality and seagrass coverage information seems to temper that conclusion. The St. Lucie River may possibly be directly connected hydrodynamically to the Atlantic Ocean through the St. Lucie Inlet and only an appreciably small volume of discharge actually may mix with the Indian River Lagoon at St. Lucie Inlet. The net outflow into the Atlantic of 972 million cubic meters per year may consist primarily of low salinity freshwater flow that has not mixed with the Lagoon prior to outflow through the inlet. As such, long-term reduced salinity impacts in the Lagoon may be less than would occur if the discharges occurred further from the inlet. The impact of the low salinity water discharge on near-shore worm reefs and other ocean littoral zone ecosystems may still be significant. Therefore, it may be important to consider the effects of freshwater quantity and resultant salinity in terms of both inflows and outflows from the Lagoon.

In contrast, the dominance of evaporative outputs over freshwater inputs in the Banana River indicate that this segment should retain high salinity levels. Such a conclusion appears to be borne out by the salinity data presented in other reports of this series. In particular the northern Banana River appears to maintain very high salinity levels as a representative of the "negative estuary" condition.

Impacts from discharges on water quality are most noticeable in the North Central and South Central Segments (Segments 2 and 3). In these areas, seasonal effects and variations in freshwater inputs lead to wide variations in salinity in these segments. The high levels of net freshwater inflow in these segments, coupled with poor connection to inlet outflow points implies that salinities should be lower and concentrations of pollutants higher in these segments, and the assessment of water quality in the Water and Sediment Quality Technical Report supports this hypothesis.

By necessity, an annual water budget analysis is a "macro" analysis and does not consider "micro" factors. The effect of one micro factor (directly connected impervious area) is important because more of the rainfall becomes runoff when the area is impervious. Increased runoff can produce a very significant impact because few of the areas with significant impervious surfaces have stormwater treatment systems. Much of the impervious area is located where it is directly connected to the Lagoon or the tributaries, and the types of pollutants transported therein have been shown to adversely impact estuarine ecosystems (Graves and Strom, 1992). The impact of directly connected impervious area runoff may be as significant as drainage canal flows in certain areas. In certain areas of the Indian River Lagoon basin such as Melbourne and Titusville, not only are stream and drainage flows high but impervious area is relatively extensive and located directly adjacent to the Lagoon.

Under urban conditions infiltration decreases, runoff increases in rate and volume, transpiration and evaporation decrease, and temporary surficial aquifer storage and flow are reduced compared to undeveloped areas. Agricultural development in artificially drained land may increase infiltration but removes sub-surface ground water flow (Harper and Marshall, 1993). Several effects of agricultural development include the increased stormwater runoff and streamflow loads of nutrients, metals, suspended solids, and pesticides and herbicides to the receiving water (Rao, 1987). The reduced volume of water entering the surficial aquifer reduces the pressure on the saltwater/freshwater interface beneath, leading to increased saltwater intrusion, reduction of the lateral flow into the Lagoon, and reduction of transpiration by plants because less water is accessible to their roots (Clapp and Wilkening, 1983; Harper and Marshall, 1993).

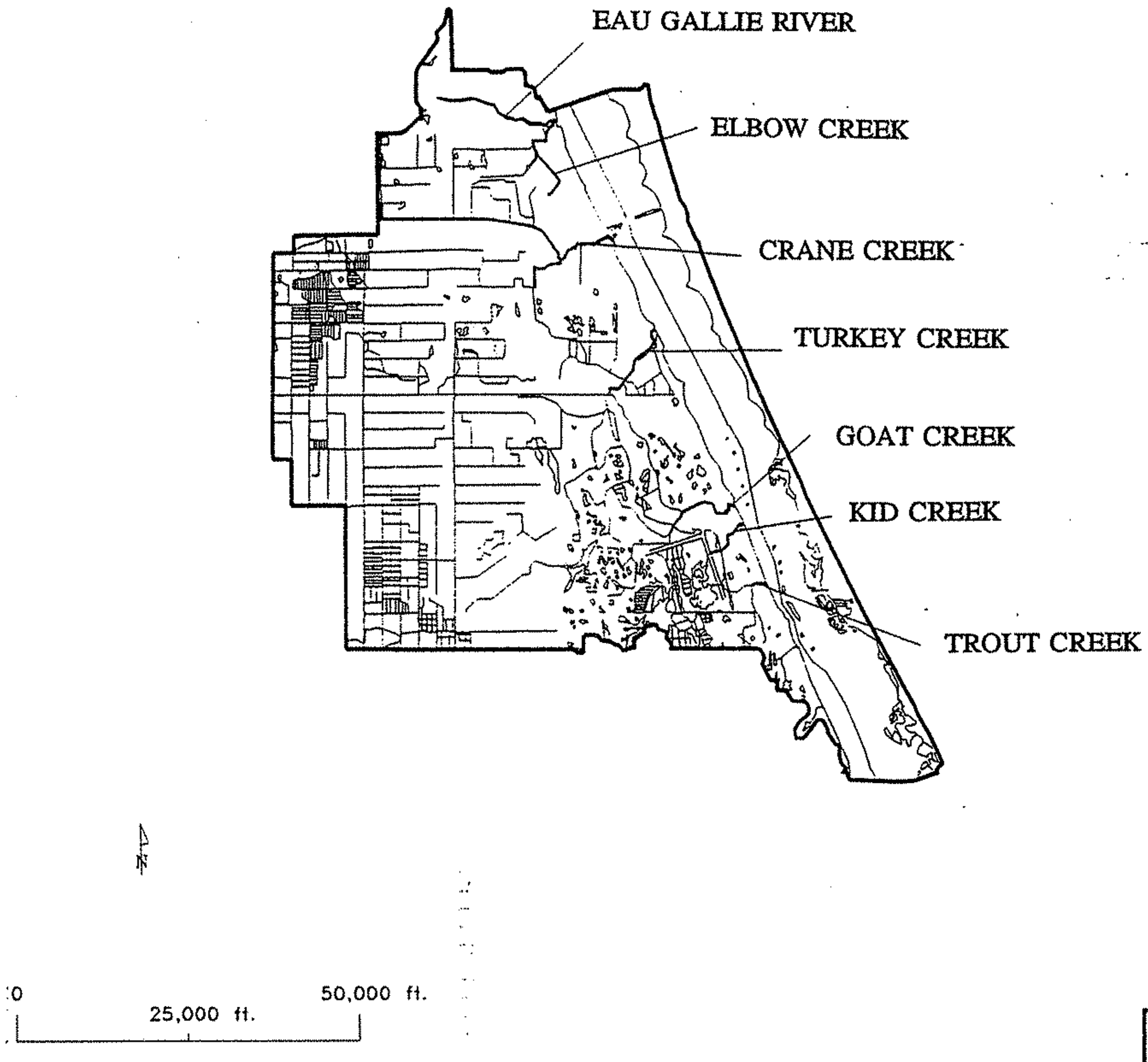
In parts of the Indian River Lagoon region, wetlands and uplands with a high water table were altered by digging drainage ditches in the sandy soil and providing a positive outfall to the Indian River Lagoon. These drainage ditches drain away water that infiltrates into the surficial aquifer above the bottom of the ditch. Additionally, any surface runoff that is channeled directly into the ditch is discharged into the Lagoon or into one of the creeks or streams that then discharge into the Lagoon.

4.9 DRAINAGE BASIN EXTENSIONS

The effects of extended drainage basins have already been mentioned several times. Extended basins are those in which the natural watershed of the Lagoon has been increased by extension of its borders to the west. This has been accomplished by construction of drainage canals that divert surface water from its natural westerly pattern of flow to a new flow direction toward the Lagoon. The segments in which there has been the largest additions to the watershed are also the segments in which there is the greatest density of drainage canals and ditches throughout the segment.

Figures 4-6 through 4-8 show the extent of drainage canals in the three most extended segments (Segments 2, 3, and 4). The density of drainage canals is extremely high in relation to the more natural drainage features observed in Figure 4-9 (Segment 1C - North Indian River).

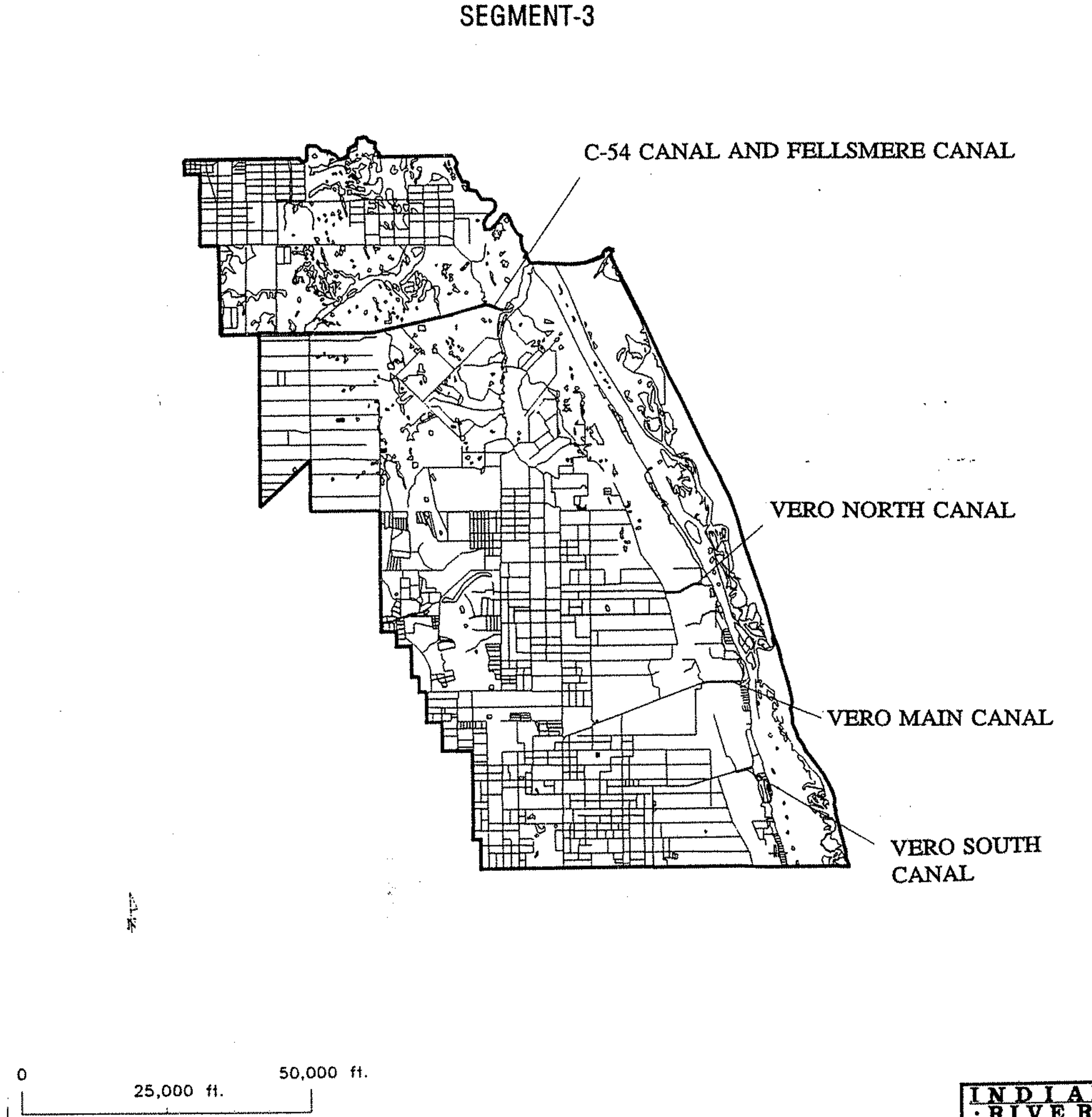
SEGMENT-2



Source: SJRWMD, 1993.

•Woodward-Clyde Consultants •Marshall McCully & Associates •Natural Systems Analysts	DRAWING NO.: DATE: 6-19-94	FIGURE 4-6	STREAMS AND DRAINAGE CANALS IN THE NORTH CENTRAL INDIAN RIVER LAGOON (SEGMENT 2)

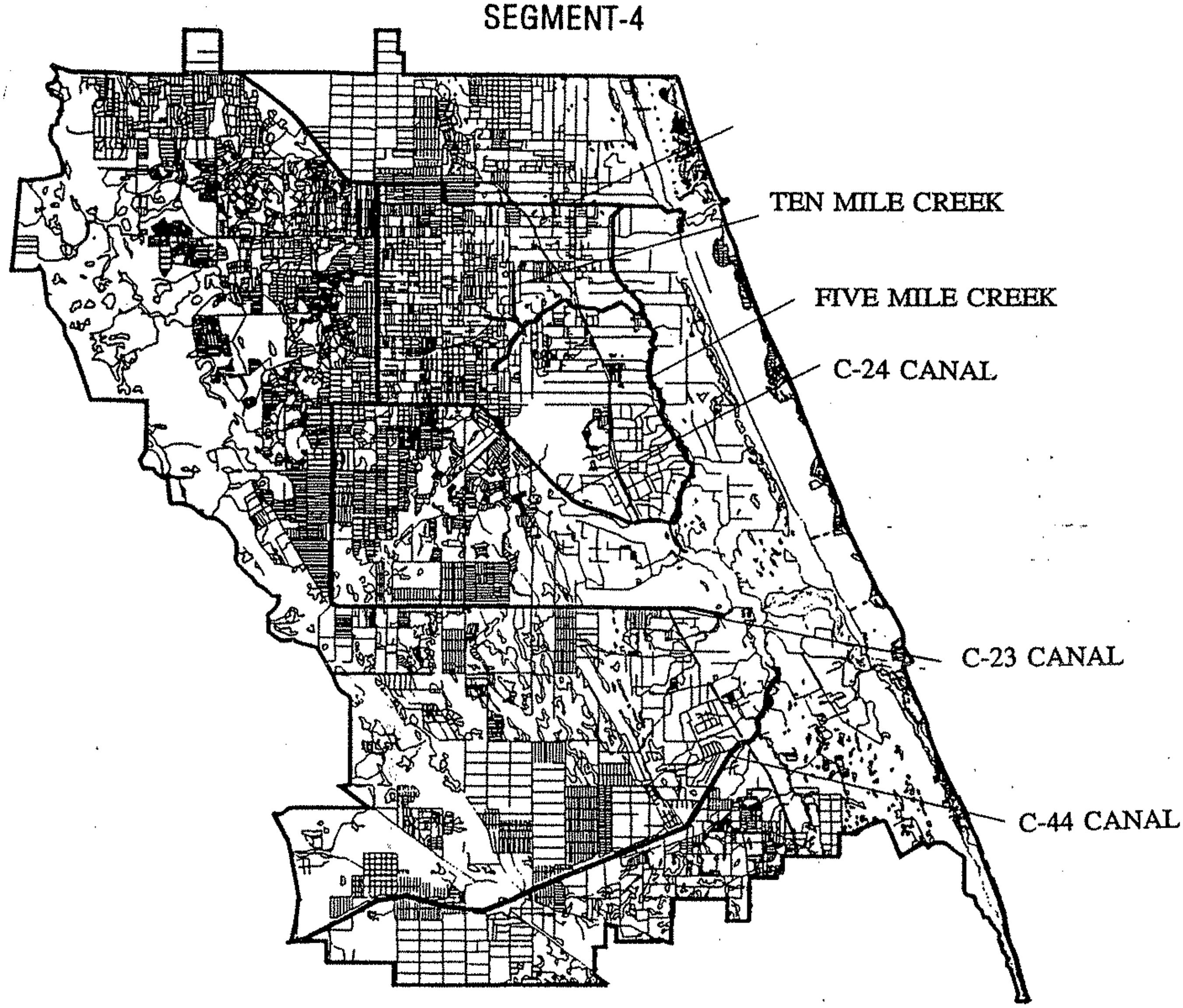
INDIAN RIVER LAGOON NATIONAL ESTUARY PROGRAM



Source: SJRWMD, 1993.

•Woodward-Clyde Consultants •Marshall McCully & Associates •Natural Systems Analysts	DRAWING NO.: DATE: 6-19-94	FIGURE 4-7	STREAMS AND DRAINAGE CANALS IN THE SOUTH CENTRAL INDIAN RIVER LAGOON (SEGMENT 3)

INDIAN RIVER LAGOON NATIONAL ESTUARY PROGRAM



Source: SJRWMD, 1993.

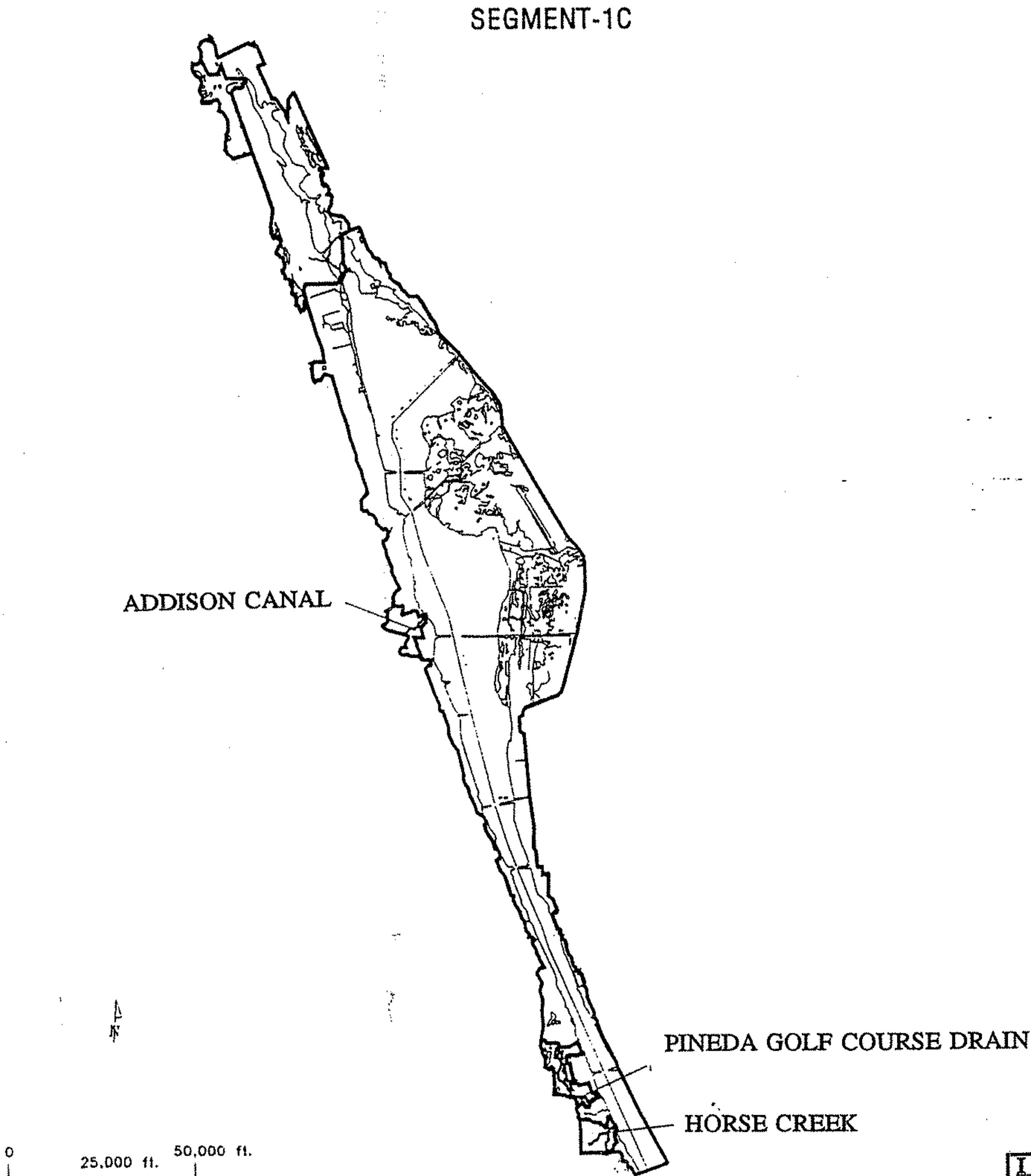
•Woodward–Clyde Consultants
•Marshall McCully & Associates
•Natural Systems Analysts

DRAWING NO.:

DATE: 6-19-94

FIGURE 4-8 STREAMS AND DRAINAGE CANALS IN THE SOUTH INDIAN RIVER LAGOON (SEGMENT 4)

INDIAN RIVER LAGOON NATIONAL ESTUARY PROGRAM



Source: SJRWMD, 1993.

•Woodward–Clyde Consultants •Marshall McCully & Associates •Natural Systems Analysts	DRAWING NO.: DATE: 6-19-94	FIGURE 4-9	STREAMS AND DRAINAGE CANALS IN THE NORTH INDIAN RIVER LAGOON (SEGMENT 1C)

INDIAN RIVER LAGOON NATIONAL ESTUARY PROGRAM

Glatzel and Da Costa (1988a) also analyzed the impact of the extension of the Lagoon watershed area. They stated that 60% of the watershed (as of 1987) was area that had been added by constructing drainage extensions. This drainage extension equates to about 61% of the existing watershed as of 1993, since approximately 29,000 ac were removed from the watershed between 1987 and 1993 due to rediversion of drainage (Section 2.5.1). A water budget was constructed comparing the 1986 and past (pre-extension) configuration of the Lagoon watershed area, utilizing the existing land use. Their water budget (Glatzel and Da Costa, 1988a) showed that 67% (942 million cubic meters annually) of the 1986 streamflow volume represented the freshwater discharge increase caused by extension of drainage basins and by water management practices. The results of that analysis also indicate that the annual pre-development watershed input flows (runoff and streamflow of about 345 million cubic meters) were approximately 20% of the current combined runoff and streamflow (2,020 million cubic meters) from the watersheds. Based on this analysis, it is possible that the total annual freshwater input to the Lagoon may have increased from 1,270 to 3,021 million cubic meters (138%) in the last 200 years.

4.10 HYDROLOGY SUMMARY

In summary, water budget calculations by Glatzel and Da Costa (1988a, 1988b) have shown a large excess of freshwater inflow to the Lagoon in the southern end, particularly in Segment 4, and that this surplus declines toward the northern end of the Lagoon complex. The Banana River is actually a "negative" estuary where evaporation exceeds freshwater input and increases the salinity of the water body. Water must flow into the Banana River from Indian River Lagoon to make up for the input deficit.

A significant change in the relative importance of the input pathways occurs with progression from north to south. In the north end of the Lagoon, direct precipitation on the large surface area of the Lagoon is the primary source of input, with some input from non-point source runoff from the adjoining watershed. Preceding southward, the direct precipitation becomes a much less significant factor, decreasing from about 84% in Banana River (Segment 1B) to about 14% in the South indian River (Segment 4). Conversely streamflow and runoff from the watershed increases to the south with streamflow comprising 65% of the total input to Segment 4. These numbers indicate that freshwater inflows from drainage ditch systems have the potential for causing significant changes to Lagoon salinity and pollutant inputs.

Glatzel and Da Costa's (1988b) water budgets indicate that large surface water discharges to the Lagoon occur in North Central and South Central Segments and very large discharges occur in the South Lagoon segment. On a more detailed scale, other indicators, such as water quality sampling data, imply that drainage inputs are a potential priority problem in the North Central and South Central Segments, particularly in the Melbourne/Palm Bay area, and in the Vero Beach area. Total freshwater flow to the Lagoon may have increased by over 100% in the last 100 years, largely in the southern segments, and this increase would be expected to have significantly affected the chemistry of the Lagoon.

However, as much as 50% of this increased flow may be entering the Lagoon through the St. Lucie River in Segment 4. While the discharge through C-44 into the St. Lucie River may have severely degraded the ecosystem in the St. Lucie River and possibly near-shore Atlantic Ocean bottom ecosystems, salinity data indicate that the discharge does not appear to have had as much direct impact on the Indian River Lagoon as might be expected, possibly because the flow between the St. Lucie River estuary and St. Lucie Inlet are directly connected. Thus, because of limited mixing with the Lagoon, the impacts of the freshwater increase may not be as high as indicated by analysis of the water budget alone. Because of limited data on the ocean system and lack of spatial detail in water quality data in the Lagoon, this should not be considered as a conclusion, but instead indicates a need for further investigation.

5.0 HYDROGEOLOGY

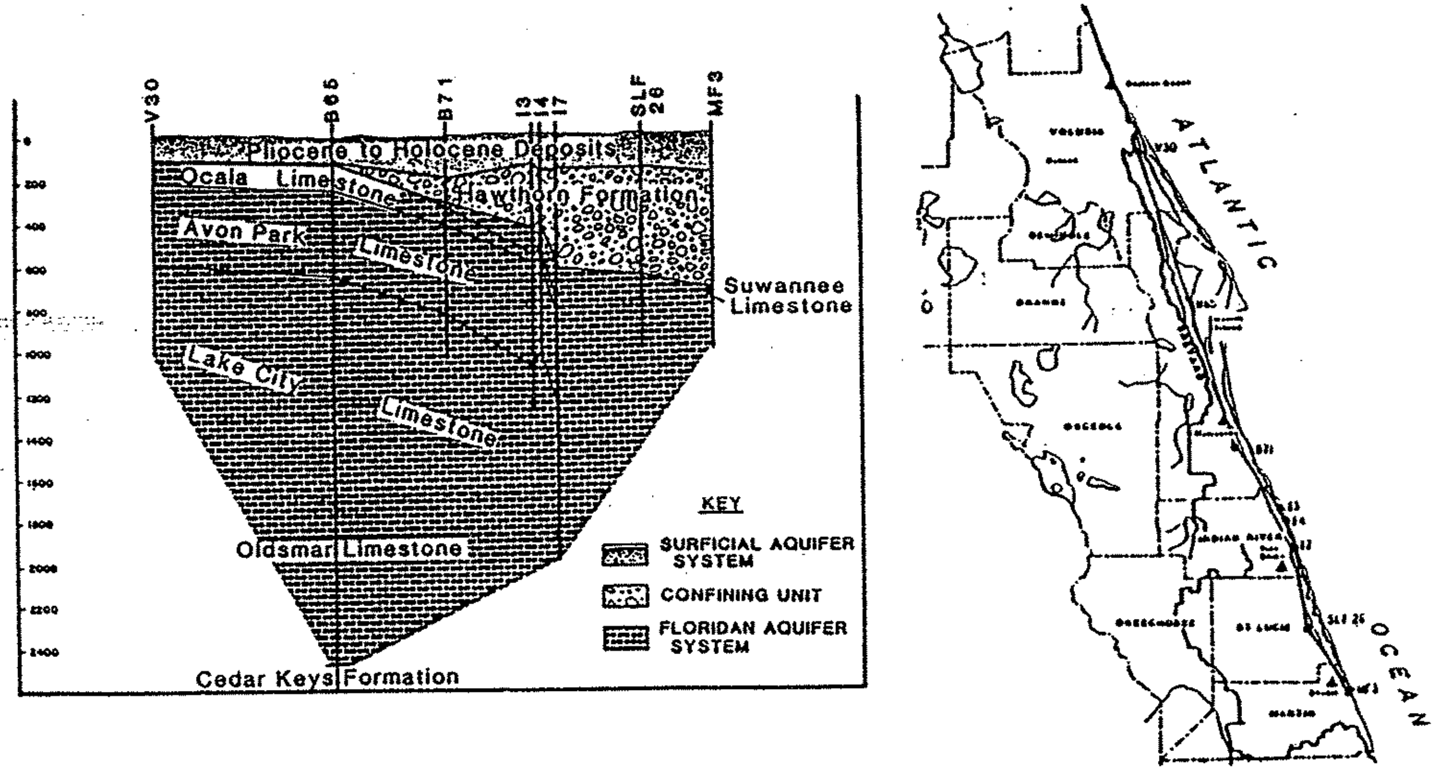
5.1 GENERAL

The hydrogeology framework underlying the Indian River Lagoon watershed includes three major units (Toth, 1987). The uppermost unit which directly interacts with the Lagoon system is the surficial aquifer in which the water table is contained. This aquifer discharges naturally to the Lagoon as well as rivers, lakes, and drainage canals (Pandit and El-Khazen, 1990). The surficial aquifer is locally recharged by rain falling within the watershed.

Underlying the surficial aquifer is the Intermediate aquifer system. The primary function of this unit is to restrict the exchange of water between the shallow and deep aquifers and thus acts as a confining unit. Although the Intermediate confining unit tends to limit downward or upward ground water movement, it may also contain minor water-bearing zones within the unit. Beneath the Intermediate aquifer system is the Floridan aquifer system which is a thick sequence of predominately carbonate rock. The Floridan aquifer is an important ground water supply in most of Florida. However, as in many coastal environments, the upper Floridan aquifer contains highly mineralized water in many locations of the Indian River Lagoon watershed and, because of artesian conditions within the aquifer, the potential exists for the migration of high chloride content water into overlying freshwater zones.

5.2 FLORIDAN AQUIFER

The Floridan aquifer is a major source of water for urban and agricultural activities in east central Florida. The top of the Floridan aquifer varies considerably from north to south along the Lagoon, which means that the overlying sediment thickness is also variable. For example, the top of the Floridan aquifer in the north Mosquito Lagoon area in Volusia County occurs at about -75 ft in reference to mean sea level [National Geodetic Vertical Datum (NGVD) of 1929]. In southern Brevard County the top of the aquifer lies at 200 ft NGVD, and near the St. Lucie Inlet the top dips to nearly -750 ft NGVD. The formations that compose the Floridan aquifer, as shown on Figure 5-1, include (from youngest to



Source: Toth, 1987.

• Woodward–Clyde Consultants • Marshall McCully & Associates • Natural Systems Analysts	DRAWING NO.: DATE:	FIGURE 5-1	GEOLOGIC FORMATIONS OF THE FLORIDAN AQUIFER IN THE INDIAN RIVER LAGOON REGION

INDIAN RIVER LAGOON NATIONAL ESTUARY PROGRAM

oldest): the Suwannee Limestone, the Ocala Limestone, the Avon Park, and the Lake City (Toth, 1987). The Suwannee Limestone is not present in north Brevard County or in Volusia County. In these areas, the Ocala Limestone marks the upper portion of the Floridan aquifer.

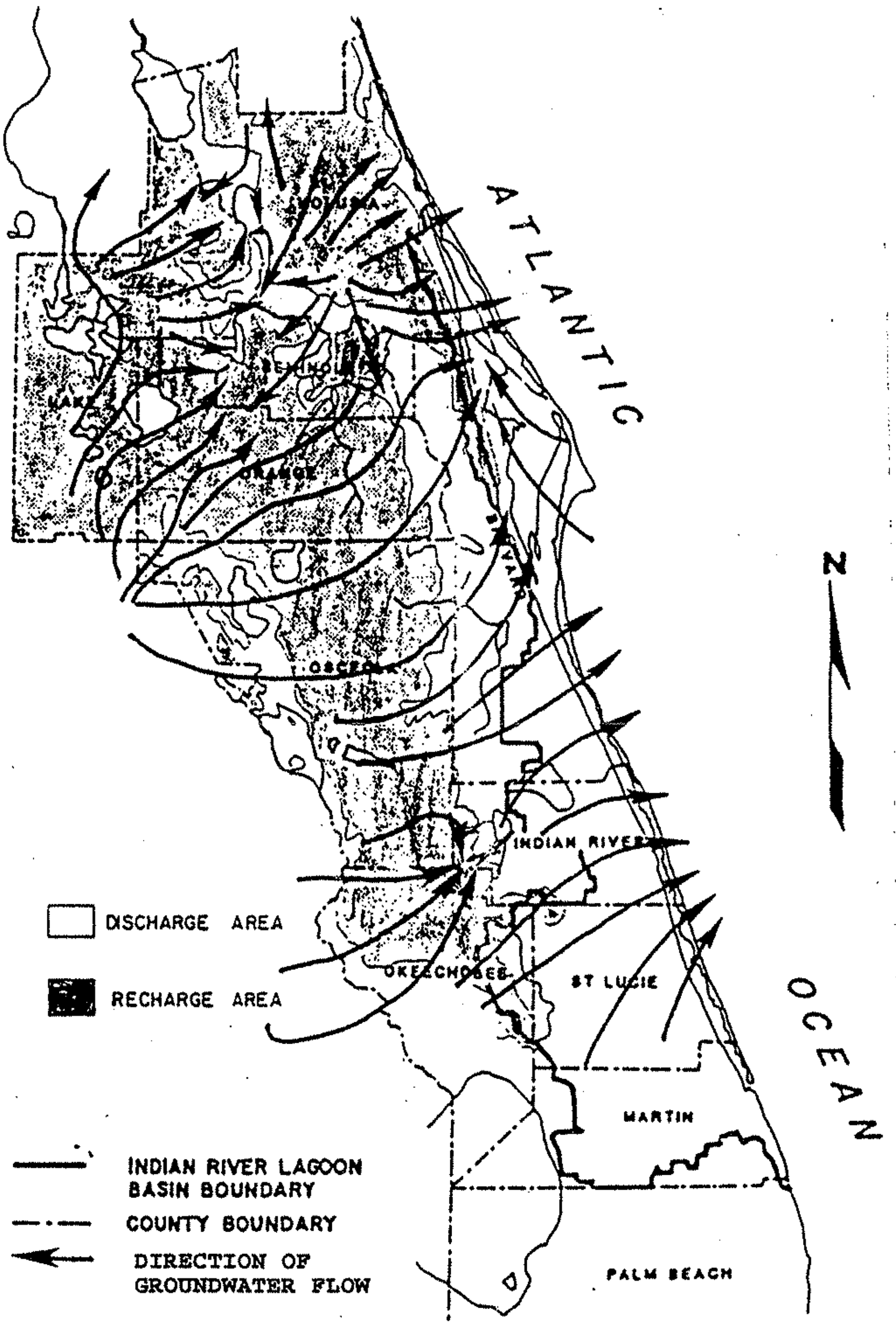
As Toth (1987) presented in the Recon Report, the direction of the ground water flow within the Floridan Aquifer system is generally to the east or northeast (Figure 5-2). West of the watershed limits in Indian River, Okeechobee, and Volusia counties, flow within the aquifer is towards the Blue Cypress Lake region in the south and toward the St. Johns River and Lake George and Lake Woodruff in Volusia County (Toth, 1987).

Recharge to the Floridan aquifer occurs primarily in the ridge areas west of the surface water divide for the Lagoon watershed. These areas include DeLand, Orlando, Lake Wales, as well as the Bombing Range ridge and the Osceola Plain. In addition, the Atlantic Coastal Ridge in Volusia County and north Brevard County probably contributes to the Floridan aquifer recharge (Bond, et al., 1993).

In the area of the Indian River Lagoon, where the Intermediate aquifer confining unit is less than 50 ft, the Floridan aquifer probably discharges to the surficial aquifer naturally due to the upward flow potential from the deeper aquifer during the dry season (Toth, 1987). During the wet season recharge may occur from the surficial aquifer to the Floridan aquifer (Toth, 1987). Turnbull Hammock in Volusia County is an example where the Floridan aquifer discharges to the surface (Wyrick, 1960).

Relict seawater exists within the Floridan Aquifer in the vicinity of the Banana River, Cape Canaveral, and Merritt Island, as well as beneath large portions of St. Lucie and Martin counties and in the extreme southeast portion of Indian River County. This relict seawater is the result of seawater being trapped within the sediments during the geologic past and freshwater recharge to the aquifer has not been sufficient to flush the seawater.

Upward leakage to the surficial aquifer from the Floridan aquifer where the deeper aquifer is highly mineralized (greater than 1,000 mg/L chloride concentrations) causes the shallow aquifer to exhibit elevated chloride concentrations (Toth, 1987). In areas near Titusville, the ground water from the upper Floridan aquifer contains chloride levels greater than 10,000



Source: Toth, 1987.

• Woodward–Clyde Consultants • Marshall McCully & Associates • Natural Systems Analysts	DRAWING NO.: DATE:	FIGURE 5-2. TYPICAL FLOW DIRECTION IN THE FLORIDAN AQUIFER (MAY, 1981)

INDIAN RIVER LAGOON NATIONAL ESTUARY PROGRAM

mg/L. The upper Floridan aquifer beneath portions of St. Lucie and Martin counties also contains mineralized water. In most other areas of the Indian River Lagoon watershed, the chloride concentration within the upper Floridan aquifer ranges between 250-1,000 mg/L. In the recharge areas of Volusia County, the upper Floridan aquifer chloride level is usually less than 250 mg/L. Toth (1987) noted the existence of freshwater lenses within the Floridan aquifer in the area of Sebastian Inlet in southeast Brevard County and northeast Indian River County.

Intrusion of saltwater into the Floridan aquifer and the replacement of freshwater with saltwater has occurred in several locations throughout the Indian River Lagoon system and its watershed. These intrusions are primarily confined to the coastal areas where the saltwater front has moved inland from municipal supply wells, as well as from irrigation and heat pump wells. Examples of locations where pumping may have caused saltwater intrusion include New Smyrna Beach, the Edgewater area, Titusville, the Satellite Beach area, the Patrick Air Force Base area, the Wabasso area, and the Vero Beach area. It can be expected that if excessive pumping from the Floridan aquifer is continued, further intrusion may result.

Several geologic faults are known to exist within the Floridan aquifer system. One fault described by Miller (1982), extends parallel to the Indian River Lagoon between Sebastian and St. Lucie Inlets. However, no apparent effect on ground water flow is attributed to the faults because the permeabilities are similar on both sides of the fault.

5.3 INTERMEDIATE AQUIFER

In south Brevard, Indian River, St. Lucie, and Martin counties, the Intermediate system between the surficial aquifer and Floridan aquifer is composed primarily of the Hawthorn Formation which forms a confining unit between the surficial and Floridan aquifer systems. The Hawthorn Formation is primarily composed of clay and limestone, with some interspersed layers of sand and shell. In places the limestone and sandy portions of the formation may be water-bearing, but overall the intermediate aquifer system provides a poor water yield in the region.

In Volusia County the confining unit becomes very thin which allows greater exchange of ground water between the Floridan and the surficial aquifers. In places, the Hawthorn Formation is absent in Volusia County (Toth, 1987). It has been speculated (Toth, 1987) that discharge from the Floridan aquifer to the surficial aquifer and possibly to the Lagoon may be occurring near the north end of the Indian River Lagoon where the Hawthorn Formation is less than 50 ft thick.

In contrast, in the southern portion of the Lagoon area, the surficial aquifer does not exchange water with the Floridan aquifer due to the significantly thicker confining unit and the artesian nature of the deeper aquifer (Toth, 1987). In parts of Martin County, the Hawthorn Formation may be as thick as 650 ft, with the base of the formation at about 750 ft below NGVD near St. Lucie Inlet (Brown and Reece, 1979).

5.4 SURFICIAL AQUIFER

The upper most units of the hydrogeologic system in the Indian River Lagoon include the surficial aquifer which consists of sand, coquina, limestone, and clay. In south Brevard County and east Indian River County, the surficial aquifer is made up of the Tamiami Limestone. The Tamiami Limestone reaches a maximum thickness of nearly 60 ft near Vero Beach (Toth, 1987). In Volusia and north Brevard counties the Intermediate aquifer system is relatively thin contributing to the more direct interchange of ground water from the Floridan aquifer to the surficial aquifer (Toth, 1987).

Due to the mineralization within the Floridan aquifer in major portions of the Indian River Lagoon watershed, the surficial aquifer serves as the principle source of potable water for the Lagoon vicinity. The surficial aquifer attains a thickness of nearly 150 ft. The upper 20 to 40 feet consist of medium to fine grained sands with increasing amounts of shell in the lower zone (Miller, 1979). A discontinuous and highly variable clay lens often may occur at depths from 30 to 40 feet (Miller, 1979).

Recharge occurs to the aquifer in the form of locally infiltrating rainfall. Additionally, some recharge may be attributed from waters infiltrating from the canal systems especially during low water table conditions. In portions of the watershed, leakage to the surficial aquifer may occur from the underlying Floridan aquifer, where an upward leakage potential exists.

Depending on the particular location, the water discharged from the Floridan aquifer may contain high total dissolved solids which includes high levels of chloride and sulfur. Other locations are also affected by high chloride concentrations especially within the surficial aquifer on the barrier island. Also in most of the area of the south Lagoon, the chloride concentrations in the surficial aquifer are above 1,000 mg/L and can exceed 5,000 mg/L.

Shallow aquifer wells in portions of Brevard and Indian River counties often exceed 250 mg/L of chloride (Toth, 1987). In the area south of Melbourne and in north Indian River County, the surficial aquifer contains ground water which has less than 250 mg/L of chloride. In the Atlantic Coastal Ridge area of north Brevard and the ridge area of Indian River counties, the chloride levels in the surficial aquifer are less than 100 mg/L.

The ground water flow within the surficial aquifer is generally laterally and moves from topographically higher areas to lower areas such as rivers, bays, creeks, ditches, and the Lagoon. Discharge from the aquifer occurs into these surface water bodies. Water is also lost from the aquifer via evapotranspiration, withdrawal by wells, and vertical leakage to underlying aquifers.

Within the natural watershed of the Indian River Lagoon, the ground water flow in the surficial aquifer is generally toward the Lagoon. However, in the south part of the Lagoon where the watershed has been extended, the flow tends to be westerly toward the St. John's River or to the Lake Okeechobee watershed.

Pandit and El-Khazen (1989, 1990) have performed analyses of the lateral seepage of the surficial aquifer and have estimated the volume of potential fresh water discharge from this aquifer to the Indian River Lagoon. Using a single-layer seepage model, Pandit and El-Khazen estimated surficial aquifer annual seepage near Port St. Lucie to have been between 1,438 and 1625 ft^3 per foot of Lagoon shoreline from the mainland side of the Lagoon and 80 ft^3 from the barrier island side in the 1976-77 period.

Assuming that similar seepage rates occur throughout the Lagoon complex, Pandit and El-Khazen's work indicates that between 40 million and 46 million cubic meters (1.2 and 1.4 billion cubic feet) of fresh water may enter the Lagoon annually through ground water seepage. Using a three-layer groundwater seepage model with various assumptions for factors such as the horizontal hydraulic conductivity, presence of the clay lens, and ground water elevation, Pandit and El-Khazen seepage estimates indicate that 110 to 300 million cubic meters (3 to 8 billion cubic feet) might potentially seep into the Lagoon annually. Other studies (SFWMD, 1987) in the St. Lucie River area have produced estimates of 60 to 600 ft^3 of seepage per foot of Lagoon shoreline. This might equal 3 to 30 million cubic meters (98 to 980 million cubic feet) of seepage for the entire Lagoon system.

Although the potential ground water seepage may be high, these seepage estimates are still at least an order of magnitude less than the approximately 3,000 million cubic meters (82 billion ft^3) of annual surface water input estimated from the water budgets of Glatzel (1986) and Glatzel and Da Costa (1988a) and flow data from Rao (1987) presented in Chapter 4.

5.5 GROUND WATER SUMMARY

In many parts of the Indian River Lagoon watershed, the volume of suitable, low chloride content ground water is exceeded by the demand from urban development. Where shortages exist other freshwater sources such as Lake Washington have been used as drinking water sources. Additionally, ground water wells are now being located in inland areas away from high demand areas and known saltwater intrusion areas. The location of wellfields in Orange, West Brevard, and Volusia counties which serve the coastal areas are examples of this inland migration. Ground water discharges directly to surface water bodies and through upward leakage to sloughs and tributaries which are natural inputs to the Indian River Lagoon. Decreases in infiltration which result in decreases in discharge due to increased runoff and ditching, as well as ground water pumping, have raised concerns about the depletion of freshwater in the aquifer systems within the Lagoon watershed.

Increased runoff and drainage thus may be increasing surface freshwater flows to the Lagoon, but the quality of discharges from the surficial and Floridan aquifers and the relationship to the Lagoon is poorly understood. Estimates of potential surficial aquifer seepage contribution to the Lagoon indicate that ground water may be a significant additional source of fresh water to the Lagoon, although this contribution is far less than that provided by either estimated current or historical surficial water inputs. Changing salinity in portions of the Floridan aquifer may result in a more saline upward leakage resulting in a more saline discharge to the Lagoon. Thus, these hydrogeologic relationships may affect the Lagoon system through the amount of freshwater or saline water discharged to the Lagoon by the aquifer systems.

6.0
HYDRODYNAMICS

6.1 HYDROGRAPHY AND HYDRODYNAMICS

6.1.1 Introduction

Hydrography is the study and measurement of the physical properties of a water body. The term "hydrography" literally means mapping water bodies or water masses. Hydrography is routinely used in two ambiguous ways to mean either the charting of the water body bottom topography by measuring its depths, or the measurement of the physical properties of the water (primarily temperature, salinity, and conductivity) to define the distribution of fresh and salt water and resultant density of the water. In a more general way, this term also covers the whole range of properties, processes, agents, forces and factors that combine to control the changing distribution of water in coastal waters. The changes in the distribution of flow and volume may also be termed the hydrodynamics of the system.

In the Indian River Lagoon system, runoff and streamflow from the land and direct precipitation are the major freshwater sources that discharge into and mix with saline ocean water in the Lagoon. The hydrodynamic processes that affect the mixing and mass exchange of saline and fresh waters and the resulting patterns of water mass dispersion and distribution within the Lagoon are described in the following sections.

6.1.2 System Components

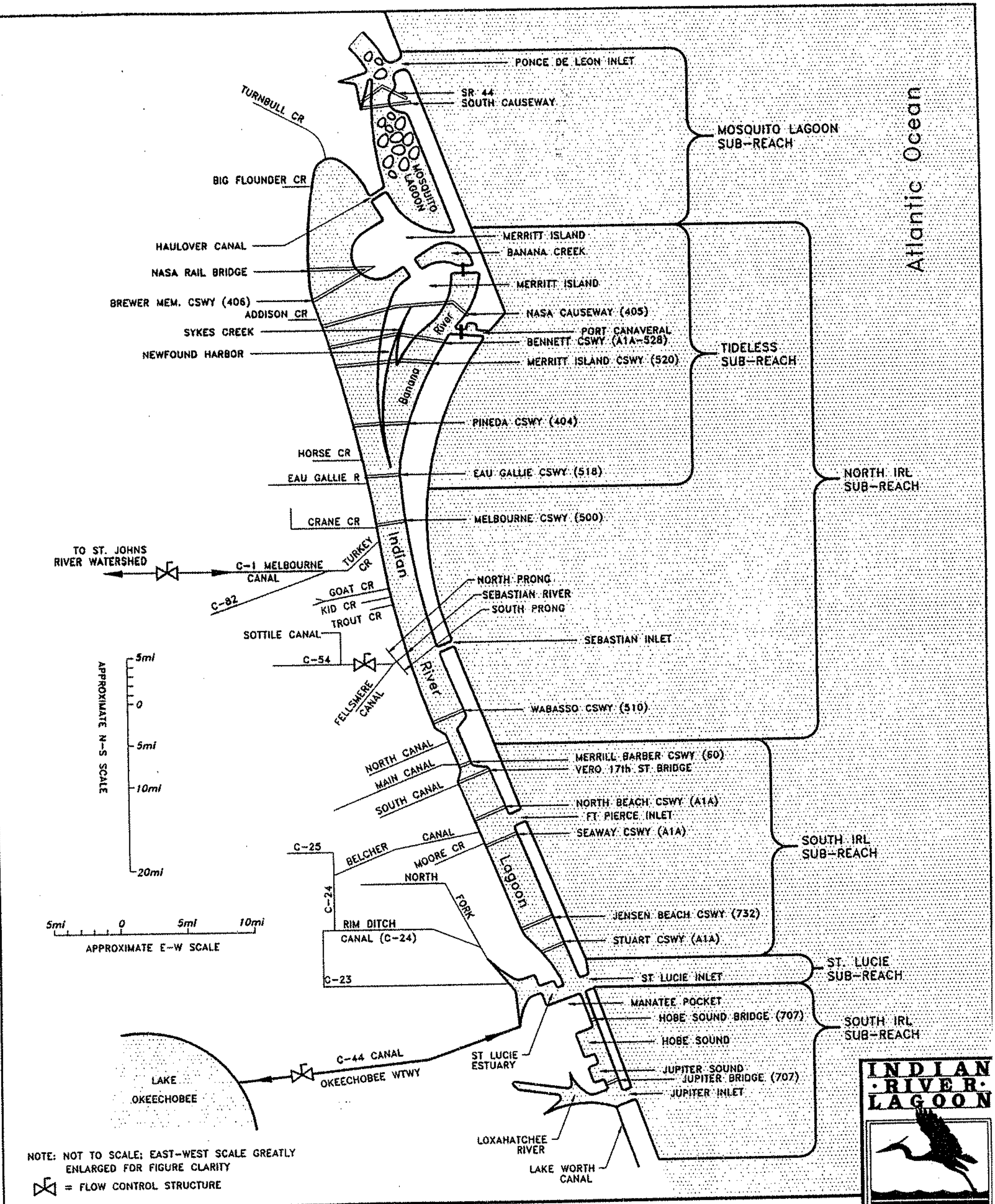
The Indian River Lagoon National Estuary Program includes the series of water bodies between Ponce de Leon Inlet and Jupiter Inlet. The major physical components of the system include the Mosquito Lagoon, the Banana River, the Indian River proper, the St. Lucie Estuary, the Jupiter Narrows, Hobe Sound and Jupiter Sound.

The various definitions of system segments that have been developed by different investigators are discussed in Section 2.2. These definitions of Lagoon segments have been influenced by the specific emphasis of the studies in which they were developed. Geographic considerations that have been applied include not only natural features such as inlets, tributaries, and watersheds, but also political boundaries (i.e., county boundaries and city locations), and districts of the state and local agencies that regulate and control water use. The segmentation system discussed previously in this report represents a modification of the system used by Stauble (1988) and Glatzel and Da Costa (1988a) which allows for greater consideration of natural watershed boundaries and less concern for political boundaries.

However, neither this segmentation scheme nor other definitions of segments of the Lagoon system are especially useful for consideration of the hydrodynamic processes and regimes. For the hydrodynamic assessment, the term "sub-reach" will be used to define physically based portions of the Indian River Lagoon complex to avoid confusion with the Lagoon segments that have been defined earlier. In several cases the sub-reaches and segments coincide, but in other cases there are differences that make description of the hydrographic features of the Lagoon more effective by following the physical definition of the sub-reaches.

The physical sub-reaches of the Indian River Lagoon complex are defined according to natural groupings of water inputs and outputs, so that contaminant, nutrient, and sediment loads can be tracked between their sources and the ocean. Each sub-reach is assumed to have similar hydrodynamic forces throughout, little mixing of waters with other sub-reaches, different tidal influences, and different inflow and outflow locations. These sub-reaches are shown on Figure 6-1. Clearly, the Mosquito Lagoon, including its watershed and the Ponce de Leon Inlet, is an independent sub-reach of the complex. The Mosquito Lagoon sub-reach corresponds to Segment 1A.

The next physical sub-reach is not so clearly isolated. However, it includes the portion of the Indian River Lagoon proper and the Banana River from their north ends at Turnbull Creek and Banana Creek south to the Indian River Narrows near Vero Beach. This sub-reach includes Segments 1B, 1C, 2, and a part of Segment 3. The flow through the navigation lock between Port Canaveral and the Banana River is so restricted as to be considered negligible in relation to the exchanges through the other inlets of the Indian River Lagoon system. The Haulover Canal is also a very restricted passage.



•Woodward-Clyde Consultants •Marshall McCully & Associates •Natural Systems Analysts	DRAWING NO.: INDIAN11.DWG DATE: 7-5-94	FIGURE: 6-1 SUBREACHES OF THE INDIAN RIVER LAGOON

Therefore, the only true ocean exit of this physical sub-reach is the Sebastian Inlet. The Vero Narrows significantly restricts but does not entirely block water exchange with areas further to the south. This portion of the Lagoon that communicates with the ocean through Sebastian Inlet will be called the North Indian River Lagoon sub-reach. It extends approximately 70 mi along the coast, and can be further subdivided into two sub-regimes because of differences in mixing characteristics.

The third sub-reach is the Southern Indian River Lagoon sub-reach. The available data on salinities and tidal circulation indicate that this physical sub-reach from the Vero Narrows to the St. Lucie Inlet also largely functions as a unit.

The St. Lucie Estuary appears to function as a surprisingly distinct entity marked by its own range of flows and salinities. Therefore the St. Lucie Estuary has been designated as a separate sub-reach (Figure 6-1). The watershed of this estuary has been greatly modified and expanded by civil works. The watershed currently has an open western boundary in that it is artificially connected with Lake Okeechobee through the C-44 Canal. This major water control artery can flow either east or west depending on water management needs.

The southern-most sub-reach includes the Jupiter Narrows and Hobe Sound/Jupiter Sound. This has been considered as a distinct physical sub-reach because the water body is of very restricted size compared to the rest of the Lagoon system and has a very small watershed. This sub-reach and its watershed are clearly tied to the forces of Jupiter Inlet and the Loxahatchee River (Figure 6-1).

6.2 HYDRODYNAMIC PROCESSES OVERVIEW

The purpose of the Indian River Lagoon Characterization Report is to define the present environmental conditions of the Lagoon and to describe trends in its quality. Hydrodynamic processes are important to these considerations. Some of these processes have been altered by civil works, often with little consideration to the environmental effects of the changes. More generally, the hydrodynamic processes of the Indian River Lagoon system are a first order control on the balance between the environmental loads introduced to the Lagoon and the natural capacity of the system to deal with them. Processes that convey water through the system (advection), disperse it throughout the system (turbulence, dispersion, and diffusion), and dilute loads with lagoon water (mixing) are of greatest importance and interest. These are governed by the behavior of tides, circulation, and water mass distributions (hydrography), which are described below.

6.2.1 Astronomical Tide

The astronomical tide is the change in water levels caused by the gravitational forces of the sun, moon, and other celestial bodies. In the Indian River Lagoon it is semi-diurnal, meaning that there are two tide cycles approximately each day. The range between the level of the high and low tide is modulated between a maximum (spring tide) range near new and full moon periods when the sun and moon are aligned and a minimum (neap tide) range at the quarter phases of the moon. Other astronomical effects cause small changes in the otherwise regular cycles of the tide but most of these are relatively unimportant. More formally, the range of the tidal oscillations at longer periods are about an order of magnitude smaller than the ranges during semi-diurnal periods, so the semi-diurnal tide components most influence the Lagoon.

Over 100 tide and water level monitoring stations have been identified within the Indian River Lagoon region (Dombrowski, et al., 1987; NOAA, 1994). These have been maintained by agencies such as NOAA, SFWMD, Indian River County Mosquito Control District, and St. Lucie County Mosquito Control District, as well as by researchers at Harbor Branch Foundation, Florida Institute of Technology, and other institutions. Dombrowski, et al. (1987) have presented station locations and details. Many of the stations have periods of record of less than 1 year.

The Indian River Lagoon is located in an area of the Florida coast where the continental shelf is so narrow that the tide range of the ocean does not increase significantly as it approaches the shore. The height of the principal semi-diurnal tide cycle was determined to be 3.3 ft by Smith (1990) based on pressure gages located 0.6 mi seaward of the Ft. Pierce and Sebastian Inlets. The astronomical tide within the Lagoon is governed ("forced") by the tide level changes at the five inlets. The spring tide ranges at the mouths of the five inlets as shown in Table 6-1, are between 3.0 and 3.6 ft.

TABLE 6-1

ASTRONOMICAL TIDE RANGES AT VARIOUS LOCATIONS OF THE INDIAN RIVER LAGOON COMPLEX

LOCATION (FROM NORTH TO SOUTH)	NOS STATION #	TIDE RANGE (FT)		MEAN TIDE LEVEL (FT)
		MEAN	SPRING	
Ponce de Leon Inlet	3553	2.3	2.7	1.4
Port Canaveral - Inlet Entrance	3559	3.6	4.3	2.0
Indian River Lagoon - Micco	3589	0.3	0.3	0.2
Sebastian Inlet - Bridge	3591	2.2	2.6	1.2
Indian River Lagoon - Sebastian	3593	0.3	0.4	0.2
Indian River Lagoon - Wabasso	3595	0.4	0.4	0.3
Indian River Lagoon - Vero Beach	3597	0.8	1.0	0.5
Indian River Lagoon - Oslo	3599	0.8	0.9	0.5
Ft. Pierce Inlet - South Jetty	3605	2.6	3.1	1.5
Ft. Pierce Inlet	3607	1.8	2.2	1.1
Indian River Lagoon - Ft. Pierce	3609	1.2	1.5	0.8
Indian River Lagoon - Ankona	3611	1.1	1.3	0.7
Indian River Lagoon - Nettles Island	3613	1.0	1.2	0.6
Indian River Lagoon - Jensen Beach	3615	1.1	1.3	0.7
St. Lucie Inlet - Great Pocket	3629	3.0	3.6	1.7
St. Lucie River - Sewall Point	3623	0.9	1.1	0.6
St. Lucie River - Manatee Pocket	3625	0.9	1.1	0.6
Indian River Lagoon - Peck Lake ICWW	3631	1.3	1.5	1.8
South Jupiter Narrows at Gomez	3633	1.3	1.6	0.8
Hobe Sound Bridge	3635	1.5	1.8	0.9
Hobe Sound at Jupiter Island	3637	1.7	2.1	1.0
Jupiter Sound at Conch Bar	3639	1.7	2.0	1.0
Jupiter Sound at South End	3641	2.0	2.4	1.2
Jupiter Inlet - US Highway 1 Bridge	3644	2.0	2.4	1.1
Jupiter Inlet - South Jetty	3643	2.5	3.0	1.4

Source: NOAA, 1993
Note: Table includes only those stations within the confines of the Indian River Lagoon complex and at the inlets of the Lagoon.

The volume change between the high and low tide level is called the intertidal volume or tidal prism. The tidal prism of the whole Lagoon can be divided into segments according to the inlets through which the water moves in each cycle of the tide. The mean tidal prism of the Indian River Lagoon proper including the Banana River has been estimated at between 103 x 10^7 ft^3 (Smith, 1988) and 137 x 10^7 ft^3 (Smith, 1992) with a range from a neap tide minimum to a spring tide maximum of between 452 x 10^6 ft^3 and 258 x 10^7 ft^3 (Smith, 1988).

Mosquito Lagoon Sub-reach

The tide in the Mosquito Lagoon is forced by the tidal water level changes at Ponce de Leon Inlet where the spring tide range is approximately 2.7 ft (NOAA, 1993). Astronomical tide effects and resulting tidal currents can be strong in the vicinity of Ponce de Leon Inlet and northern Mosquito Lagoon to points south of Edgewater. Tidal excursion from the inlet may extend as far south as Oak Hill about ten miles away (Taylor, et al., 1990). In the main channels, current and mixing forces may be strong in this area. However, as the tide travels farther south into the Lagoon it encounters shallow depths, shoals, and an intricate set of channels between islands. As a result, the range of the astronomical tide becomes very small in the open reaches of the central and southern Mosquito Lagoon from Oak Hill south. A study by Taylor, et al. (1990) indicated that the only water level variations south of the Volusia County line were due to effects of wind. The semi-diurnal characteristic tide of Florida's east coast was not seen at the south county tide station. A single daily high and a single daily low water condition with a range of only 0.5 ft were observed at this point. This diurnal tide pattern demonstrated that daily cycles in the wind dominated the hydrodynamics.

North Indian River Lagoon Sub-reach

The tide in the North Indian River Lagoon sub-reach is forced at Sebastian Inlet. The shoals and shallow depths of the lagoon cause great dissipation of energy as the tide travels north up the Lagoon. The spring tide range decreases from about 2.2 ft at the inlet mouth to about 1 ft in the Lagoon near Sebastian River to 0.2 ft in the Lagoon between the Melbourne and Eau Gallie Causeways about 17 miles north of the inlet (Evink 1980; Dombrowski, et al., 1987). The mean and spring tide ranges at Micco, about 2.5 mi north of Sebastian Inlet, are about 0.26 ft and 0.30 ft respectively (NOAA, 1993) indicating a rapid decrease of tidal amplitude within a short distance from the inlet. The high and low tides at Micco lag those at Sebastian Inlet by 2 to 3 hours (NOAA, 1993). Evink (1980) noted that there may be a time lag of nearly 6 hours between high tide at Sebastian Inlet and at the Eau Gallie Causeway. Smith (1987) noted that high and low tide may lag ocean tides by 4.4 hours at Vero Beach.

North of the Eau Gallie Causeway, the astronomical tide is effectively absent. This section of the North Indian River Lagoon sub-reach can be described as the "tideless sub-regime", although water level variations due to meteorological forcing may cause flows through Haulover Canal (Smith, 1993).

The volume of water that is exchanged with the ocean each tide cycle is equal to the volume between the high and low tide level and is referred to as the tidal prism. The astronomical tide and tidal prism become increasingly more important contributors to the mixing processes with proximity to the inlet. The North Indian River Lagoon sub-reach has an estimated tidal prism (neap tide to spring tide) of 40×10^7 ft^3 with most of the exchange occurring south of the Melbourne Causeway (SR 500) (Smith, 1992). Smith (1992) has noted that this sub-reach of the Lagoon constitutes 65% of the total surface area of Indian River Lagoon proper and Banana River, but it accounts for only 9% of the intertidal volume. This relationship is indicative of the low tidal mixing in much of this sub-reach.

In the portion of this sub-reach southward from Sebastian Inlet to the Vero Narrows, the tide becomes a more complex phenomena because it is forced not only by Sebastian Inlet, but also in part by the tide regime south of the Narrows (Liu, 1991). This interaction and the effect of the asymmetric shape of the Sebastian Inlet causes an annual net inflow predominance of the tidal currents at the inlet that is relatively small and can be over-ridden by outflow during times of large river discharge (Liu, 1992). The small net inflow at this inlet is thought to be the reason that sand moves in from the ocean and is trapped in the inlet and in the nearby flood tide shoals of the Lagoon.

South Indian River Lagoon Sub-reach

The astronomical tide in the South Indian River Lagoon sub-reach is forced at both the Ft. Pierce and St. Lucie inlets (Smith, 1987). As the tide propagates from these inlets to the interior of the south sub-reach, there is a time lag in the tidal cycle. In the most distant section, this delay is up to 5 hours, which indicates that the tide propagates with a speed of about 2.5 miles per hour (mi/hr) (Smith, 1990). Smith (1992) has estimated the tidal prism of the combined south and St. Lucie sub-reaches to be approximately 87 $x10^7$ ft^3. Smith (1992) indicates that these two sub-reaches constitute only 18% of the surface area of the Indian River Lagoon north of St. Lucie Inlet, yet they contain 63% of the Lagoon's intertidal volume. Thus mixing is strongly influenced by tidal influences in these sub-reaches.

St. Lucie Estuary Sub-reach

The tide in the St. Lucie Estuary responds primarily to forcing from St. Lucie Inlet and thus is always semi-diurnal. There is generally a diurnal inequality between the heights of the two high or two low tides in the day.

Southernmost Sub-reach

The tide range within Jupiter Narrows and Hobe Sound are reduced from the values at Jupiter inlet. Reported tide ranges are approximately 1.5 ft at Peck Lake, 1.6 ft at Gomez, 1.8 ft at the Hobe Sound Bridge, 1.9 ft in Hobe Sound, and 2.3 ft in Jupiter Sound, based upon periods of record of four months to four years from seven NOAA tide gages in this sub-reach (Dombrowski, et al., 1987; NOAA, 1993).

6.2.2 Wind-Driven Water Level Changes

Because the Indian River Lagoon is long and narrow, the wind can be very effective in causing significant water level changes. These are not the true tides of predictable periodicity like astronomical tides, but since these weather-related non-periodic water level changes are often similar in height to astronomical tides, they are often referred to as "meteorological tides". Throughout the Lagoon these wind-driven water level changes are often equal to or greater in height and volume than the astronomical tide. In the open portions of Mosquito Lagoon, Banana River, and the Indian River Lagoon proper north of Eau Gallie, the wind-driven currents and water level changes dominate the mixing of water masses.

Water level also responds to changes in atmospheric pressure. It rises as low pressure systems pass through the area. However, these effects are relatively small (<0.5 in per 1 mm of barometric pressure) compared to the direct effect of the wind and for this reason the term "meteorological tide" generally refers to water level variations caused by the wind.

The long shallow stretches of the Indian River Lagoon are especially suited for the wind stress to blow water away from the windward shore (wind set-down) and to pile it up on the lee shore (wind set-up). The Banana River provides an example. Its long dimension is 18 mi and its average depth is on the order of 4 ft. Using an analysis method developed by Bretschneider (1966) from his studies of wind set-up in Lake Okeechobee, we have calculated that, under steady state conditions, a 33 feet/second (ft/sec) wind blowing parallel to the long axis of the Banana River would cause water level to decrease by 1.1 ft along the upwind shore (wind set-down) and to increase by 1.0 ft along the downwind shore (wind set-up). Table 6-2 shows the magnitude of the resulting estimated water level changes for selected wind speeds. This table shows that such winds theoretically may cause large water level differences between the ends of Banana River.

The Mosquito Lagoon is of similar size and depth to the Banana River so the effect of the wind will also be similar. The North Indian River Lagoon sub-reach is about 70 mi long and theoretically the wind should be capable of producing proportionally larger wind set-ups. However, this portion of the Lagoon is very narrow and this reduces the response by an amount that cannot be easily quantified. Furthermore, the wind is unlikely to be uniform over this large distance. Since the response time for the set-up to come into equilibrium with a steady wind is from a quarter to a half day, it is unlikely that a strong wind will remain constant over the whole 70 mi length for that duration. Without results from a detailed analyses such as a numerical model, it may be assumed that the meteorological tide is at least as important in the North Indian River Lagoon and other sub-reaches as it is in the Banana River.

TABLE 6-2

PREDICTED WATER LEVEL CHANGES ASSOCIATED WITH WIND-DRIVEN CURRENTS AT SEVERAL WIND SPEEDS

WIND SPEED (KTS)	SET-UP[1] HEIGHT (FT)	SET-DOWN[2] HEIGHT (FT)
20	+1.0	-1.0
25	+1.7	-2.1
30	+2.1	-2.8

Source: Woodward-Clyde Consultants

1 = Set-up is the rise in water level at the downwind shore.
2 = Set-down is the fall in water level at the upwind shore.

Water level variations caused by wind and rainfall are generally not periodic like the astronomical tide. Wind data in Section 3.0 indicates that strong north winds are most frequent in January and February. These may result in set-downs of the water level in the North Indian River Lagoon sub-reach. Strong southeast and east winds may cause set-ups to develop in this sub-reach in the warm season. Winds are often related to a diurnal cycle of sea- and land-breezes so that diurnal water level variations resembling the astronomical tide can result (Smith, 1993).

6.2.3 Other Water Level Variations

The very low range of the astronomical tide means that other forms of water level variations are apparent in the Indian River Lagoon. Like the meteorological tide, these variations generally occur irregularly and over longer intervals than typical tidal periods.

One source of Lagoon water level change is high freshwater input during storms. Liu (1991) indicates that water level in the Lagoon can average many centimeters higher than the ocean during large storm events so that tidal exchange at the inlets is biased in favor of outflow.

The flow at the inlets can also be affected by rise or fall in the level of the coastal ocean outside of the inlets brought about by wind and atmospheric pressure. Also, acceleration and deceleration of the Gulf Stream leads to decreases and increases in the water level over the continental shelf (Smith, 1988). Tidal exchange can be biased toward either inflow or outflow depending on the relative levels of the lagoon and ocean. These variations usually develop and persist over periods of several days, but their effects are subtle and hard to measure directly.

One regular and very important effect on water level in the Lagoon does occur on a regular and seasonal basis. This is a seasonal increase of about 0.5 to 1.0 ft in water levels extending from about August or September through about late December, with a maximum water level in October. One reason for this water level rise appears to be an annual cycle of heating and cooling of shelf and open oceanic waters (Smith, 1986, 1987, 1988) which causes steric expansion and contraction, allowing warmer water to expand and rise into the

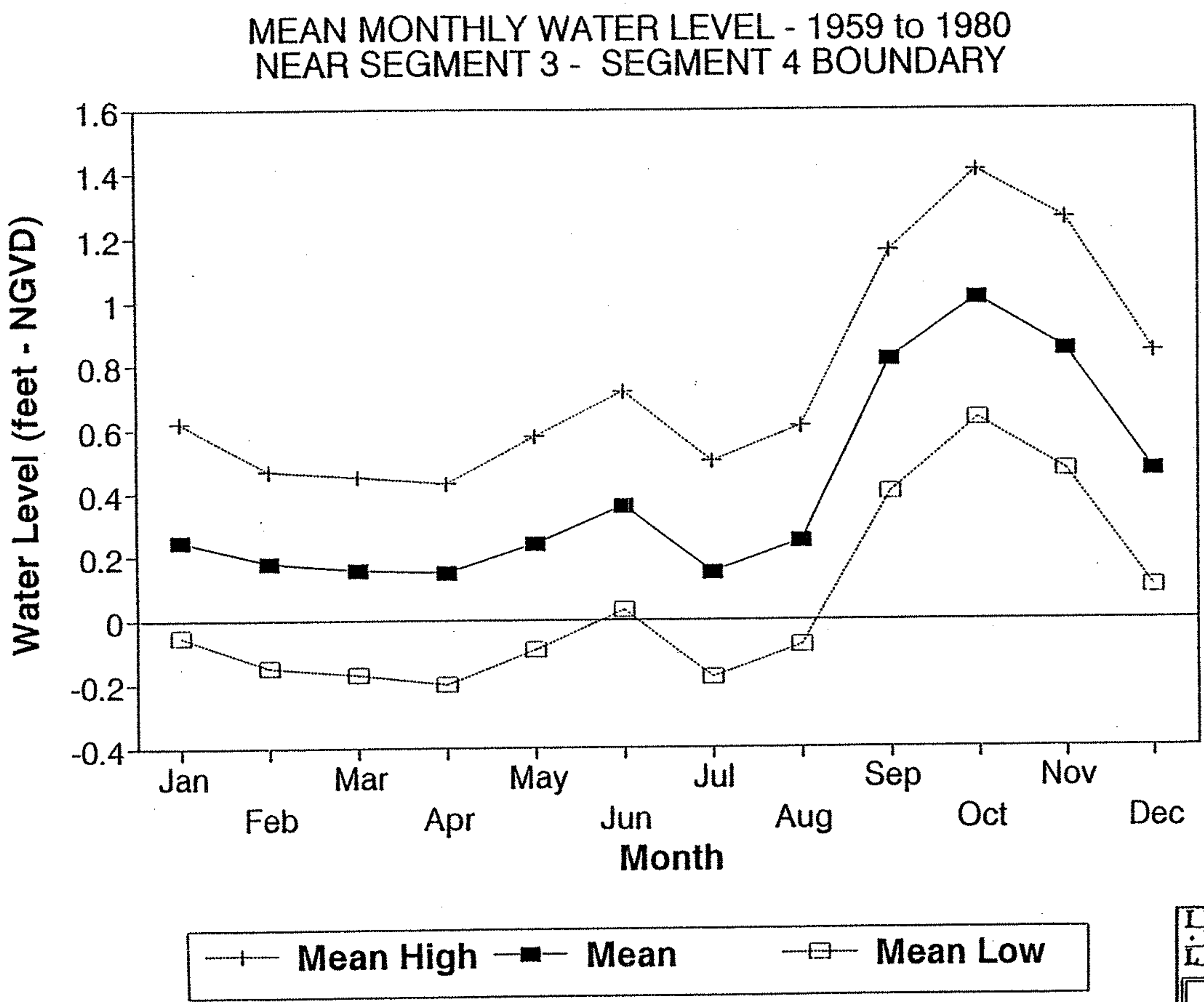
Lagoon in addition to increased seasonal runoff and perhaps changes in oceanic currents (Smith, 1988). This seasonal rise (Figure 6-2) has important effects on the function and ecology of the Lagoon. The autumn seasonal rise is the only period in which tidal height becomes sufficient to regularly inundate many of the salt marshes along the Lagoon (Provost, 1973). This factor is an important consideration for mosquito impoundment management strategies for the Lagoon.

6.3 CIRCULATION

Circulation patterns in the Lagoon can be very complex and are caused by a number of factors. The primary types of currents are the tidal currents and the weather-related currents. Tidal currents are ebb and flood flows caused by tidal forces, while weather-related currents are primarily wind-driven. Current measurements can give information on the magnitude of flood and ebb currents. However, a review of literature through mid-1993 indicates that current information is lacking for many areas of the Lagoon complex, such as Mosquito Lagoon. Most of the current measurements have been taken in the ICWW.

6.3.1 Tidal Currents

Currents in coastal waters are complex because they change in speed and direction and in space and time. Currents in the Indian River Lagoon are forced by astronomical and meteorological tides, the direct effect of the wind, pressure gradients caused by a differing water levels (e.g., sloped water surfaces outward across the Lagoon originating from surge discharge of river flooding events), and pressure gradients arising from the density gradients between saline and fresh water. The current at any point represents the combined effects of these different forcing mechanisms. These currents also have different characteristic time scales or frequency ranges. Forcing mechanisms are usually considered according to the characteristic frequency ranges of the current fluctuations. These frequency ranges may be tidal, synoptic (2-5 days), or seasonal.



Sources: Smith, 1986
Smith, 1988.

• Woodward–Clyde Consultants • Marshall McCully & Associates • Natural Systems Analysis	DRAWING NO.: DATE:	FIGURE 6-2	SEASONAL WATER LEVEL VARIATION IN THE INDIAN RIVER LAGOON

INDIAN RIVER LAGOON NATIONAL ESTUARY PROGRAM

Tidal currents are driven by the astronomical tide. Smith (1990) describes the astronomical tide in terms of a long wave propagating through the inlets. As this wave moves into the Lagoon it encounters the shallow depths and the speed of propagation slows down. This results in the wave becoming steeper because the speed reduction does not change the height but reduces the wavelength. However, within a few miles of the inlet the cumulative effect of bottom friction in the shallow Lagoon causes a steady reduction in the height of the tide. Hence the currents forced by the astronomical tide are strong near the inlets and die out with distance from the inlet.

Tidal flow is primarily a factor of the tidal amplitude or height of the various tidal constituents. These constituents include diurnal (K_1, P_1, O_2), semi-diurnal (M_2, S_2, N_2), and longer term (i.e. fortnightly and monthly) components caused by various interactions with the sun and moon. Table 6-3 shows the periodicity of the diurnal and semi-diurnal constituents. Since these constituents have different periods, tidal water level and flow fluctuations do not always occur at the same time or have the same magnitude on different days.

Table 6-4 shows the approximate magnitude of the amplitude of the diurnal and semi-diurnal tidal constituents. This table shows that the M_2 semi-diurnal constituent has the greatest amplitude and is the dominating tidal factor driving tidal currents throughout the Indian River Lagoon. Because of this dominance, tidal ebb (outgoing flow) and flood (incoming flow) currents vary predominantly on a semi-diurnal (twice daily) cycle in the Indian River Lagoon.

Figure 6-3 (based on data from Smith, 1990) illustrates the tidal current amplitude based on all tidal constituents (Table 6-3) and compares it to the M_2 (principal lunar) tide height. The figure was created from a tidal harmonic analysis of current meter data taken in the ICWW along the length of the Lagoon at irregular intervals between 1976 and 1988. In general, the figure shows the average maximum RMS (root mean square) current speed along the ICWW from south of Cocoa (marker 86) to St. Lucie Inlet (marker 232) associated with the flood (or ebb) current caused by the M_2, S_2, N_2, K_1 and P_1 and O_1 tidal components.

TABLE 6-3

MAJOR TIDAL HARMONIC CONSTITUENTS OF THE ASTRONOMICAL TIDES IN THE INDIAN RIVER LAGOON COMPLEX

CONSTITUENT	SYMBOL	PERIOD (HRS)
Principal Lunar	M_2	12.42
Principal Solar	S_2	12.00
Larger Lunar Elliptic	N_2	12.66
Principal Solar	K_1	23.93
Luni-Solar	P_1	24.07
Principal Lunar	O_2	26.87

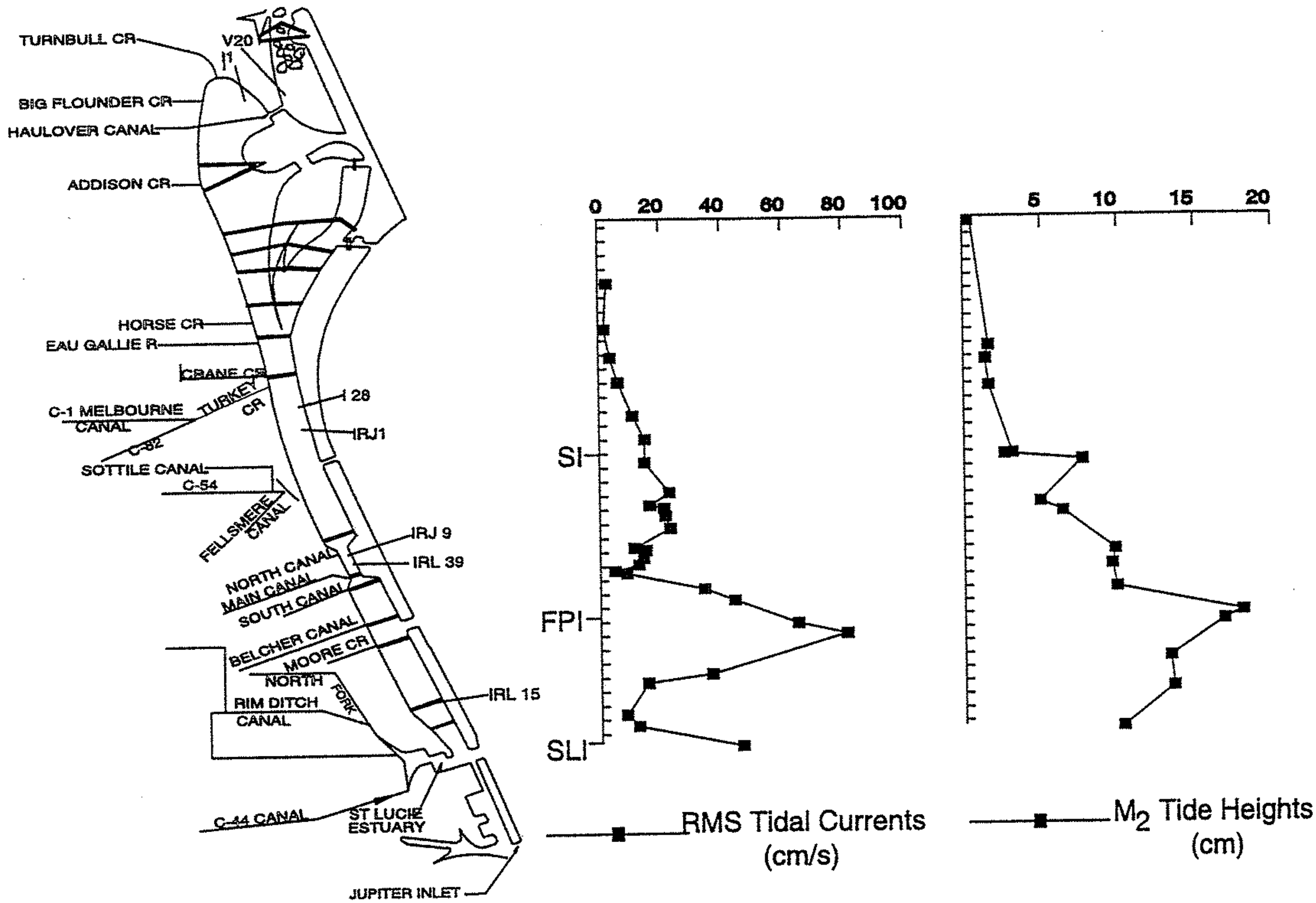
Source: Smith, 1990

TABLE 6-4

AMPLITUDES OF THE PRINCIPAL SEMI-DIURNAL AND DIURNAL TIDAL CONSTITUENTS AT VARIOUS LOCATIONS OF THE INDIAN RIVER LAGOON COMPLEX

LOCATION (FROM NORTH TO SOUTH)	LATITUDE	TIDAL CONSTITUENT (AMPLITUDES - IN)				
		M_2	S_2	N_2	K_1	O_1
Oak Hill	28° 52.0'	0.43	0.08	0.16	0.39	0.20
Scottsmoor	28° 46.0'	0.12	0.16	0.04	0.71	0.20
Haulover Canal	28° 44.0'	0.43	0.04	0.08	0.16	0.24
Titusville	28° 37.2'	0.08	0.04	0.04	0.20	0.08
Williams Point	28° 26.7'	0.16	0.08	0.00	0.35	0.20
Eau Gallie	28° 08.0'	0.63	0.08	0.16	0.59	0.20
Melbourne	28° 06.0'	0.55	0.08	0.04	0.12	0.12
Palm Bay	28° 02.5'	0.63	0.08	0.04	0.08	0.16
Micco	27° 52.4'	1.22	0.20	0.20	0.27	0.35
Miner's Marina	27° 52.3'	1.02	0.20	0.52	0.39	0.31
Sebastian Inlet	27° 51.6'	3.03	0.39	0.75	0.87	0.67
Wabasso	27° 45.3'	1.93	0.28	0.43	0.52	0.59
Jungle Trail	27° 44.0'	2.52	0.31	0.43	0.75	0.59
Vero Beach	27° 38.0'	3.86	0.47	0.75	1.14	0.90
Oslo	27° 35.6'	3.78	0.43	0.75	0.98	0.87
Link Port	27° 32.0'	3.90	0.47	0.71	1.10	1.02
Ft. Pierce Inlet	27° 28.2'	7.13	1.06	1.42	1.97	1.57
Fort Pierce Marina	27° 27.0'	6.65	0.92	1.26	1.69	1.34
Ankona	27° 21.3'	5.28	0.51	0.98	1.61	1.14
Nettles Island	27° 17.0'	5.35	0.51	1.06	1.93	1.10
Jensen Beach	27° 11.2'	4.06	0.43	0.87	1.50	1.22
St. Lucie Inlet	27° 09.3'	6.30	0.87	1.26	2.01	1.38

Source: Smith, 1987



SI, FPI and SLI represent Sebastian Inlet Ft. Pierce Inlet and St. Lucie Inlet

Source: Figure derived from data from Smith, 1987 and 1990.

• Woodward–Clyde Consultants • Marshall McCully & Associates • Natural Systems Analysts	DRAWING NO.: DATE:	FIGURE 6-3 - AMPLITUDES OF THE PRINCIPAL M_2 TIDAL COMPONENT AND TIDAL CURRENTS IN THE INDIAN RIVER LAGOON BETWEEN MELBOURNE AND ST. LUCIE INLET

INDIAN RIVER LAGOON NATIONAL ESTUARY PROGRAM

Only the amplitude of the M_2 tidal constituent is shown in Figure 6-3, because the M_2 tidal component is generally an order of magnitude greater than the other components (Smith 1990). The M_2 is the principal semi-diurnal (12.42 hr period) component, one that has two maximum flood and two maximum ebb currents each day. Figure 6-3 shows that the tidal current speeds in the Indian River Lagoon tend to follow the M_2 tidal height distribution, with highest tide heights and greatest currents occurring near the inlets. The fundamental motion is a nearly symmetrical ebb and flood. At the inlets this flow is strong with maximum currents of 4.1 feet/second (ft/sec) reported for both the Ft. Pierce and St. Lucie Inlets and 3.3 ft/sec at Sebastian Inlet (Dombrowski, et al., 1987).

Figure 6-3 is intended to illustrate the decrease in both tidal current and tidal height away from the inlets. The information is based on data from two studies (Smith, 1987 and 1990). Although tidal currents and tide heights are both results of tidal forces, the data used for the figure were measured at different stations and times. Thus the locations of the data points are not identical.

Although in reality the situation is more complicated, each tidal component can be pictured as a pure ebb and flood cycle with a maximum value (as shown for the M_2 tidal component at various locations on Figure 6-3) and a period as shown on Table 6-3. The current caused by the astronomical tide is the result of the combination of these tidal components of differing amplitude. Because the periods of the tidal components are also different (as shown in Table 6-3), the time of the maximum flood (or ebb) current due to different tidal components also differs so the maximum values are not simply additive. Only very rarely do peaks of several components coincide in time to cause a current which is the sum of the individual maximum speeds (amplitudes).

In a shallow lagoon such as the Indian River Lagoon, local effects are important and the strength and timing of the flood and ebb currents vary from place to place. Tidal currents are strongest near the inlets and decrease in magnitude as the tide moves into the Lagoon (Figure 6-3). The Ft. Pierce Inlet, dredged to a depth of about 19 ft, has the largest tidal heights and current amplitudes as well as the greatest exchange of water over the tidal cycle (Smith 1990).

Smith (1987) has shown that the combined tidal amplitude is less than 2 cm and that the tidal currents are negligible in the Indian River Lagoon north of the Melbourne-Eau Gallie area. Smith (1987) also pointed out that non-tidal, low frequency variance (meteorological forces) accounts for 92% to 99% of the fluctuation in this northern section of the Lagoon because of these low tidal amplitudes.

The minimum tidal currents occur in the broad shallow lagoon sections where the tide range is minimal. These areas occur primarily north of Turkey Creek, near the Vero Narrows, and between the Steward and Jensen Beach Causeways north of St. Lucie Inlet. In the central portion of the Lagoon, semi-diurnal and diurnal tidal constituents are lowest approximately 7.5 mi south of Sebastian Inlet (Smith, 1987). In the section between Ft. Pierce Inlet and St. Lucie Inlet, the point at which the minimum amplitude occurs is shifted well south of the midpoint between these inlets to a point just north of Jensen Beach. This may be due to the effect of the two causeways between Jensen Beach and the St. Lucie Inlet, which may impede the northward propagation of the tidal wave forms from St. Lucie Inlet (Smith, 1987), thus making tidal forcing through Ft. Pierce Inlet the dominant effect on tidal currents in this section.

Because the M_2 tidal component is the largest, it provides the best example of tidal current effects in the Lagoon. Water is moved back and forth by the flood and ebb currents. The horizontal distance that a water molecule travels on either the flood or ebb portion of the tidal cycle is called the excursion distance (Smith, 1988). The excursion distance in this back and forth motion is calculated by multiplying the tidal current amplitude (see Figure 6-3) by the tidal current component period and dividing by 3.14 (i.e., pi). This distance is on the order of 1 to 2 mi near Sebastian Inlet and 6 mi at Ft. Pierce Inlet, but can be as little as a tenth of a mile where tidal currents are least.

This means that the ocean water entering the Lagoon is not carried far into the Lagoon by the direct effect of the twice-daily (semi-diurnal) currents. However, salt water is present throughout the Lagoon so other processes must be important in controlling the rate of ocean water entrainment into the lagoon water.

One of these processes is net tidal flow within the Lagoon from one inlet to another. So far, only the back and forth movements of tidal flow have been discussed. A variety of other processes related to the wind, river discharge, and long period ocean level changes disrupt the uniform behavior of the tidal currents and cause a difference between the overall flood and ebb flows. When these flows are unequal, there is a net flow in either the flood or ebb direction depending on the particular location and circumstances. This net flow is considered to be a tidally averaged current.

6.3.2 Tidally Averaged Flows

Even when the complicating effects of river discharge, wind stress, and long period ocean level changes are removed from consideration, tidally averaged currents are present in lagoons that have more than one inlet. These residual currents have been reported (Cotter, 1974; Van de Kreeke and Chiu, 1980; Huang, et al., 1986; Liu, 1992; Liu and Aubrey, 1993) as being caused by;

1) Differences in the timing (i.e., phase) and height range (i.e., amplitude) of the ocean tide at the adjacent inlets

2) Mean sea level differences

3) Asymmetry of the channel between the inlets

Because separating these tidally averaged currents from all of the other types of currents is difficult, the knowledge of them is limited. However, such net flow is important because even the small tide of the Indian River Lagoon is very regular and the tidally averaged current is a continual component of all of the current motions of the Lagoon.
This flow is therefore important in flushing ocean water into the Lagoon and moving freshwater from the land to the ocean. The tidally averaged flow between the Sebastian, Ft. Pierce, and St. Lucie inlets is thought to be to the south on the order of 2 to 4 feet/minute (ft/min) (Smith, 1988 and 1990). Even this sluggish current will move a water molecule nearly 0.5 to 1 mi in a day. Smith calculates that the Lagoon between Ft. Pierce and St Lucie Inlets may be flushed by this action in a three week period.

6.3.3 Weather Related Flows

Weather systems may cause currents to vary over different time intervals than those due to the astronomical tide. This component is also difficult to identify from current meter records, but it can be discussed as an independent current system. The principal meteorological force is the wind, with barometric pressure and rainfall also being important.

Even a relatively ordinary wind of approximately 16 ft/sec will displace water at a rate of several ft/min, depending on the downwind length of the Lagoon. This wind stress adjustment velocity is as large or larger than the residual tidal current. In a typical case the particle excursion length due to the wind stress adjustment velocity is on the order of 1/2 mile per day. Since wind forces often change speed and direction on a daily basis, this range might be considered to be the maximum excursion length for most events.

Wind also can cause interior circulation cells within the Lagoon. These currents have not been well studied but their general behavior can be predicted through analogy with similar water bodies. Csanady (1970, 1972, 1973, 1976, 1982) has analyzed several lakes and shallow coastal water bodies and produced an overview of the patterns of wind-driven interior currents. When this analysis is applied to the Indian River Lagoon, the expected pattern is that the surface current is on the order of 3% of the wind speed so that a 5 m/sec wind results in a 1/2 ft/sec current speed. In broad open stretches of the Lagoon that are not complicated by shoals or islands, this wind-driven flow extends all the way to the bottom and moves down-wind in the shallows along the sides of the Lagoon. As the water piles up at the downwind end a return flow develops against the wind direction in the deeper middle sections. When the wind is aligned with the direction of the ICWW this return flow tends to occur in this channel (Smith, 1988). The return flow in the ICWW may be greater beneath the surface because the surface flow is retarded by the wind stress.

There is only a little data to confirm the expected patterns of wind-driven interior currents. An early study by Schneider, et al. (1974) was based on the results of tracking current drogues for periods up to 48 hours in the middle of the Lagoon opposite Melbourne. The weakly forced currents appeared to be dominantly wind-driven. Another study of circulation was conducted to establish the effect of the Melbourne and Eau Gallie causeways on circulation and water quality (Evink, 1980). Using field measurement made with drogues and a numerical model it was demonstrated the wind-driven currents followed complex paths. From these results it is clear that the actual currents have much more complex patterns than the idealized wind-driven currents discussed above. However, the current speeds are similar to those predicted by the simple cases.

Smith (1988) reported on the deployment of a current meter in the Lagoon just north of Sebastian Inlet for 224 days between summer and early winter months in 1983-84. Analyses of the current meter time series and wind records showed that the flow in the ICWW correlated well with the wind stress, but was opposite in direction. This confirms the expected pattern explained above. Smith also noted that the wind-driven currents could be grouped into two general classes. Much of the wind-driven current is a short term water response to wind stress. This is especially evident during the summer months when the cycle of daily sea- and land-breezes occurs. These variations in the wind-driven currents occur at periods that are similar to the periods of the astronomical tide.

The second class of flows are the more subtle seasonally varying patterns resulting from the north and northwest winds arising with the passage of winter weather fronts. These wind and current patterns vary over roughly 3- to 5-day cycles linked to the passage of weather fronts and systems.

Very little attention has been given to the currents that arise due to major rainfall events and the resulting increase in river drainage. Heavy rainfall events and resultant high river discharges may result in relatively strong currents at the mouths of the rivers, and have also been noted as causing offshore flows at the inlets (Liu and Aubrey, 1993).

6.3.4 Storm Surges

Extraordinary currents develop during major tropical storms and hurricanes. Extreme storms create storm surges with peak elevations greater than 10 ft. These can occur and disappear over a period of a quarter day to one full day. High storm surges can overtop the barrier islands, allowing water to rapidly enter the Lagoon as overwash across low portions of the barrier islands in addition to the inlets (Godfrey and Godfrey, 1976). As the surge reaches its peak, coastal rivers flow inland and wide areas are flooded.

The storm surge is forced by the combined effects of strong onshore wind and low atmospheric pressure in a cyclone storm. Such storms travel fast with typical forward speeds surging from 6 to 15 mi/hr. Therefore, the duration of hurricane conditions may be only a few hours. As the storm passes, the flooding drains away and strong ebb currents occur throughout the Lagoon. Hurricanes that track obliquely across the Lagoon cause strong offshore winds to occur as the storm eye passes. Sudden strong wind stress can combine with the gravity-forced storm drainage to cause very strong currents where these flows converge, such as at the inlets. Instances have been recorded at several other barrier island chains on the east coast where strong offshore flows across the flooded island have created new inlets (Godfrey & Godfrey, 1976).

6.4 HYDROGRAPHY AND MIXING

Hydrography describes the distribution of the physical features of the water masses. In coastal waters it is important to also consider the water mass distribution patterns changing through the action of the tide, meteorological forcing, and variations in the fresh water inputs. Therefore, it is better to consider the mixing processes that bring about the changes along with the hydrography of the Indian River Lagoon.

Estuaries are water bodies in which fresh water from the land and salt water from the ocean encounter each other. The difference in salinity caused by the presence of dissolved salts between freshwater and seawater is 35 ppt which creates a density difference of about 2%. Differences in density of even less than 2% are sufficient to cause pressure gradients which can cause the water to flow. On a comparative basis, the density difference caused by temperature is relatively small.

Several situations can be established due to salinity differences. In many estuaries with weak tidal forces and large volumes of freshwater discharge, a saltwater wedge can become introduced beneath an overlying wedge of freshwater. The less dense freshwater tends to flow over the surface of the saltwater. This typically creates a vertical stratification and a narrow vertical zone where the salinity change is steep. Mixing is usually relatively low where a salt water wedge occurs.

In the northernmost reaches of the Indian River Lagoon where Turnbull Creek discharges, during winter conditions of light or no wind, salt wedge conditions may develop. In the south part of the Lagoon (Segments 3 and 4) southward from Sebastian Inlet, freshwater discharges from canals can be large in volume. Salt wedges may form in these segments under heavy freshwater flow conditions that result from high rainfall events or from discharges released from flood control canals in anticipation of construction activities, hurricane season, or other events (Smith, 1986).

In one instance presented by Smith (1986) and attributed to Reichard and Lewit (1985), the effect of an unusually large release of freshwater was documented in the southern part of the Lagoon. Freshwater that had been discharged into the St. Lucie River entered the Lagoon on top of the salt water and flowed into the ocean on an ebb tide (outwardly) cycle. The ocean water that had entered the Lagoon on the preceding incoming flood tide became trapped and moved to the north to exit through the Ft. Pierce Inlet. Reichard and Lewit (1985) noted that at times of smaller volume flows, freshwater entering the Lagoon tends to mix with lagoon and ocean water more completely and salt wedges do not usually form, so that both well-mixed and stratified conditions can exist, depending upon the local conditions of tide, wind, and volume of freshwater runoff.

In partially-mixed estuaries, where tidal movement is usually appreciable, the turbulence caused by wind and the vertical motion of the tide tends to mix the water column more thoroughly than the entrainment that occurs in conditions favoring formation of a salt wedge. In order for an estuary to be well-mixed, tidal ranges must be significant, wind or current-induced turbulence must occur, or sufficient Coriolis force must be present. Coriolis force is not a significant factor in the Indian River Lagoon, and Section 6.3.1 has shown that tide range is low in some parts of the Lagoon. Thus mixing in these locations of the Lagoon is largely dependent on other turbulence sources, of which the wind is the most obvious.

There are two seasonal wind patterns in the Indian River Lagoon region, as described in Section 3. During the summer season, the predominant wind direction is south-southeast, corresponding to the setup of the sea breezes. Freshwater discharges are high in summer, and stratified conditions may become established. In the dry winter season, the wind is predominantly from the northerly direction with stronger velocity than in the summer season. Because of the stronger winds and the reduced freshwater discharges, better mixing conditions occur in winter than in summer.

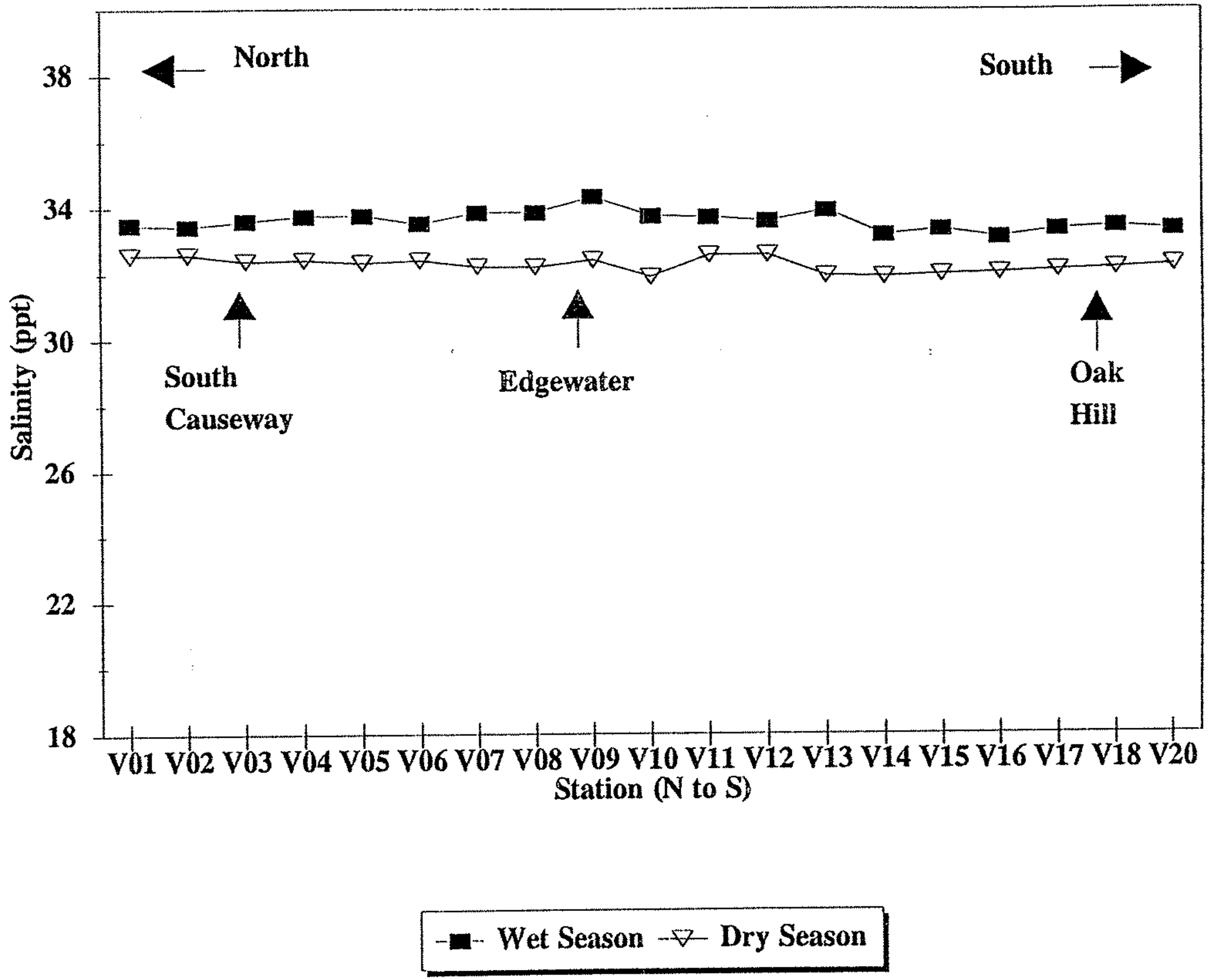
However, local conditions of tide, freshwater inflow, wind, and physical features of the bottom and shoreline determine the mixing regime at any point in time because of the wide variety of conditions that can exist in an estuary that is 155 km in length. The presence of the ICWW also has a local effect on mixing because its depth is about twice the mean depth of the Lagoon. Causeways also can affect mixing conditions by affecting wind and current patterns. To better describe these local effects, the hydrography and mixing of each sub-reach is discussed below.

6.4.1 Hydrography and Mixing in the Mosquito Lagoon Sub-reach

The water mass of Mosquito Lagoon is largely separated from the rest of the Indian River Lagoon system, although a recent study (Smith, 1993) has shown that some transfer occurs through Haulover Canal. Input to Mosquito Lagoon is in the form of runoff from a small drainage basin, direct precipitation, and ocean water inflow at the Ponce de Leon inlet. Evaporation plays a significant role in the overall water balance (Glatzel and Da Costa, 1988a). The result is that salinities are characteristic of ocean values throughout the portion of Mosquito Lagoon covered by the monitoring stations. Figure 6-4 shows the distribution of mean wet and dry season salinities in Mosquito Lagoon between 1989 and 1991. More information on the salinity data in Figures 6-4 through 6-9 (from the SWIM data set) is presented in the Water and Sediment Quality Assessment Technical Report. The effect of high evaporation on the water balance is most likely the explanation for the occurrence of higher salinities during the summer wet season as compared to the lower salinity values during the cooler dry season. The higher summer temperatures cause evaporation to exceed precipitation in spite of the greater rainfall (compared to winter) over the small basin.

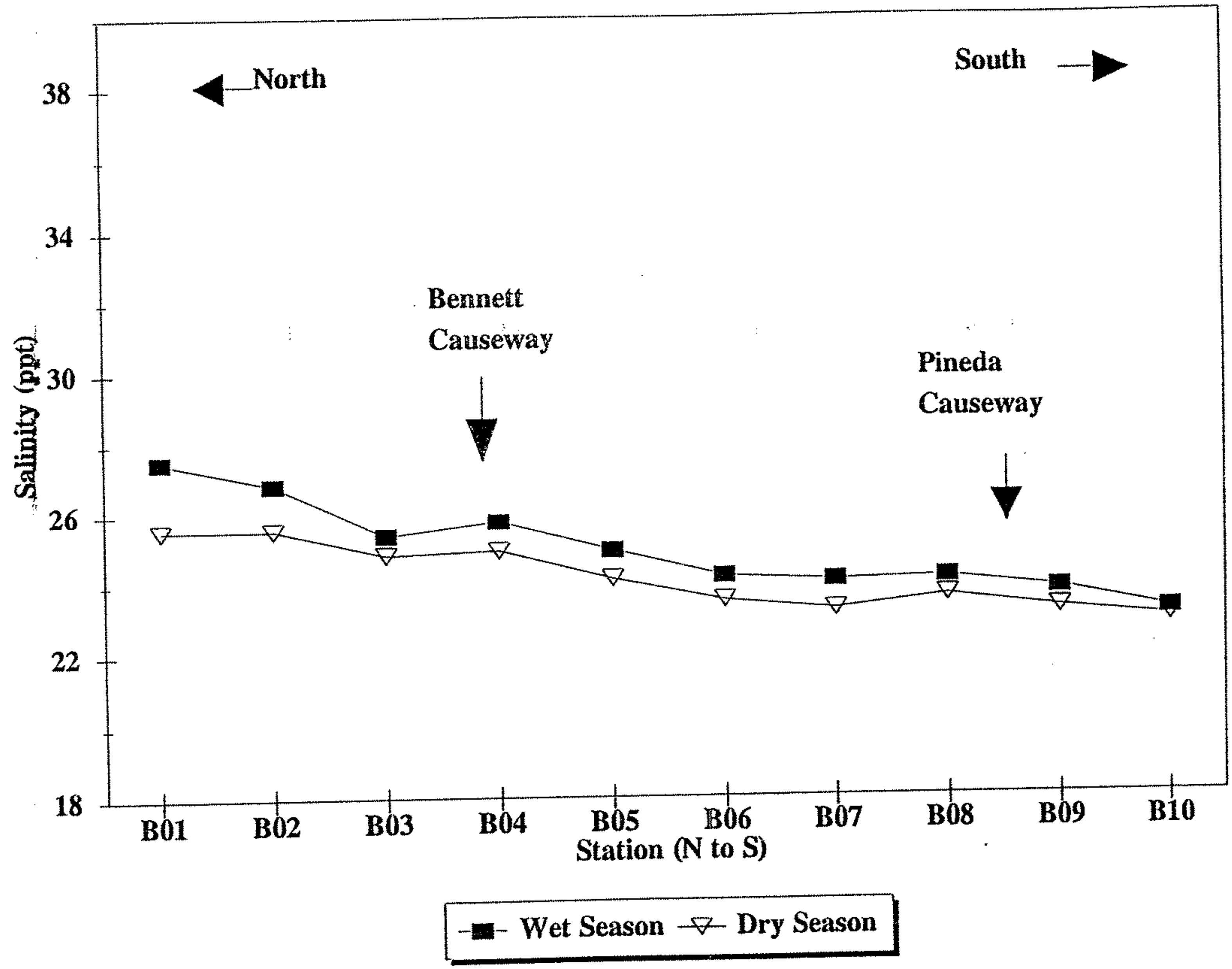
The details of circulation and mixing in the Mosquito Lagoon are poorly studied. In general, the tidal excursion length is only a few kilometers near the inlet (Hull, et al., 1990; Taylor, et al., 1990). Near the inlet, water may be replaced or mixed with ocean water in each tide cycle. However, the vast majority of Mosquito Lagoon to the south of the inlet may have little direct exchange of ocean water.

In Mosquito Lagoon there is insufficient fresh water input to cause a significant net drift to the inlet. Except for areas near Ponce Inlet, nutrient and other loads from non-point sources are capable of being mixed only by relatively weak wind-driven and density-driven currents for most of the year. Only when major weather events disrupt the system is there a short period of relatively intense mixing.



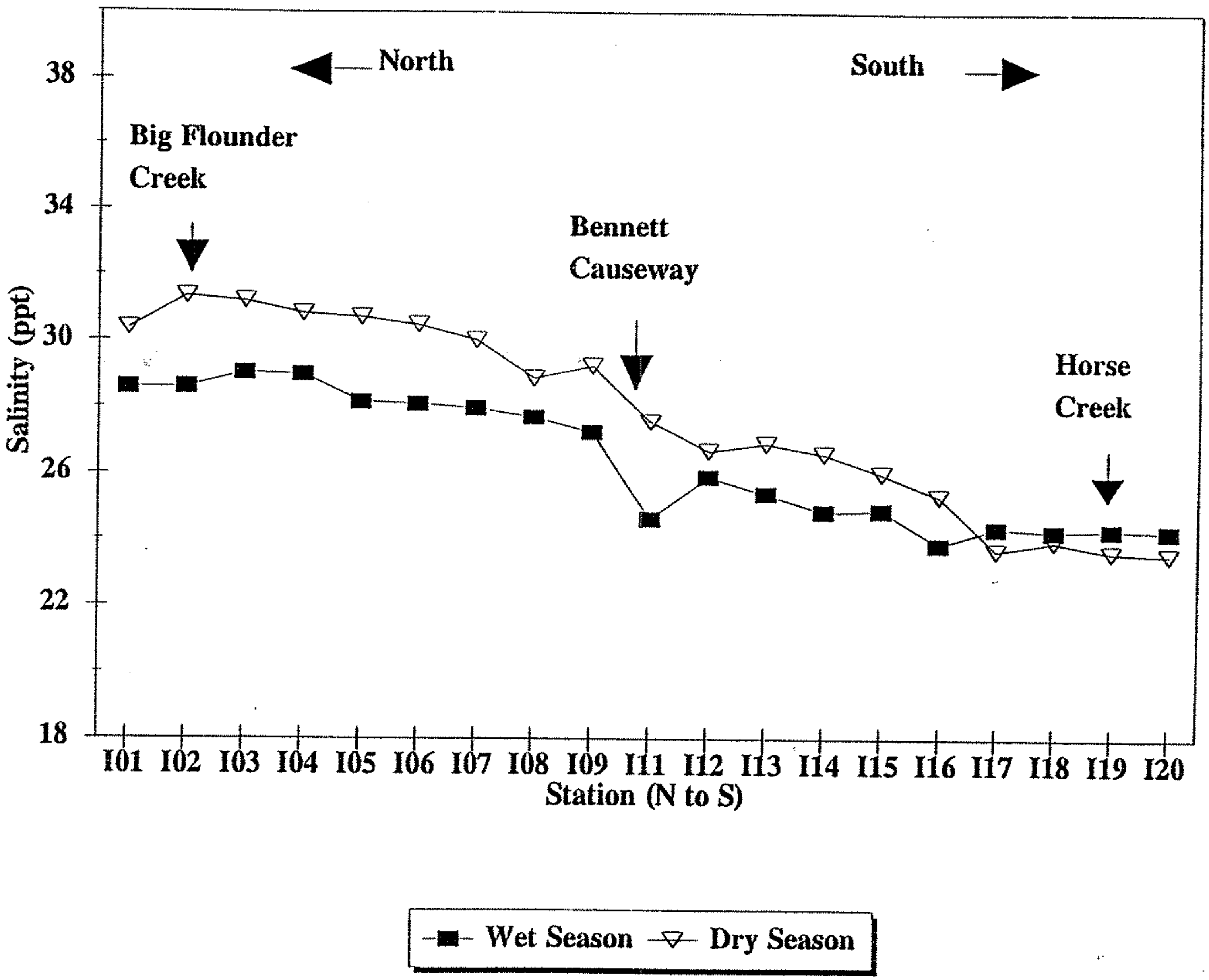
• Woodward–Clyde Consultants • Marshall McCully & Associates • Natural Systems Analysis	DRAWING NO.: DATE:	FIGURE 6-4 - SALINITY GRADIENTS IN MOSQUITO LAGOON FROM 1989-1991 (MEAN SALINITY)

INDIAN RIVER LAGOON NATIONAL ESTUARY PROGRAM



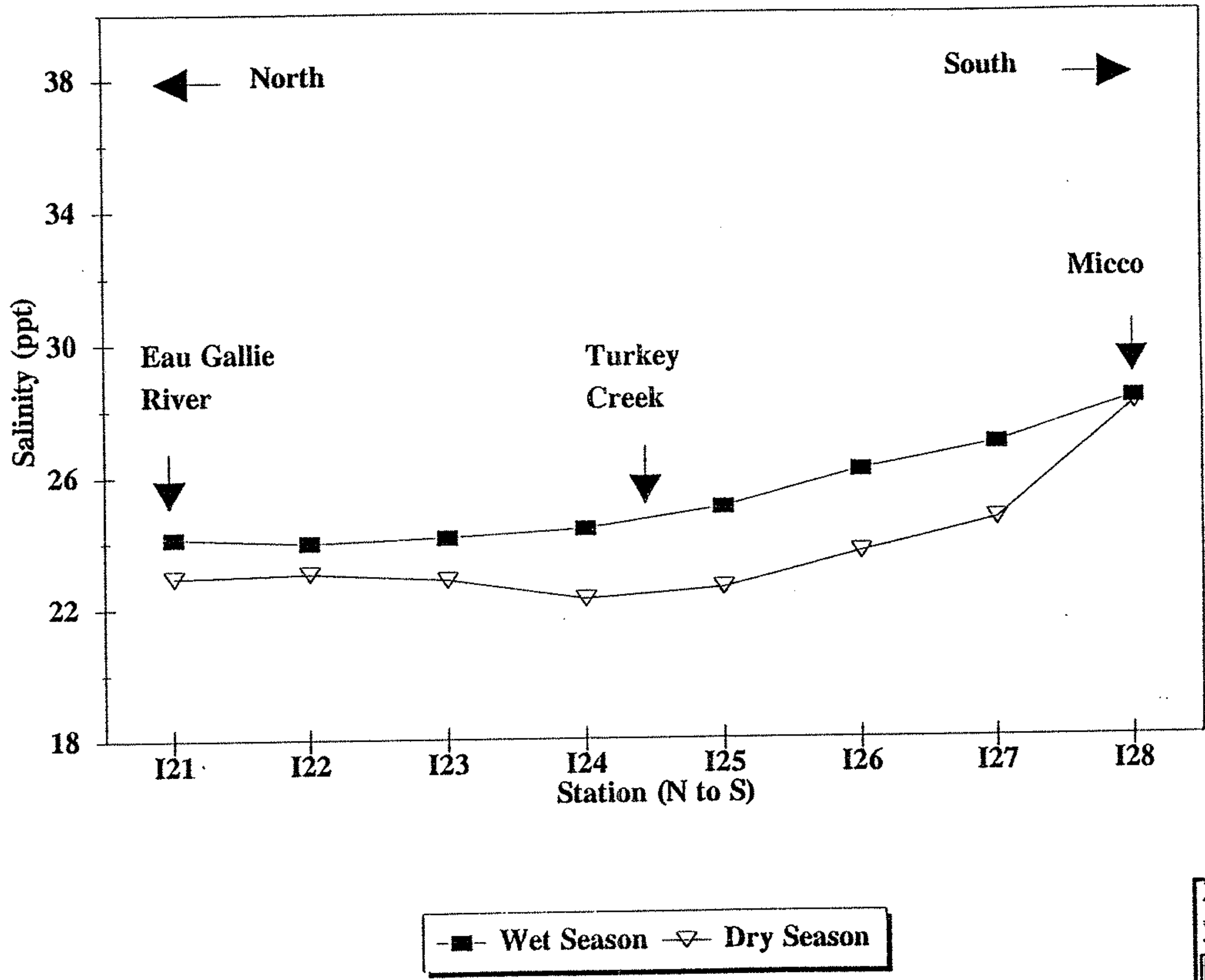
• Woodward-Clyde Consultants • Marshall McCully & Associates • Natural Systems Analysis	DRAWING NO.: DATE:	FIGURE 6-5 - SALINITY GRADIENTS IN NORTH INDIAN RIVER FROM TURNBULL CREEK TO MELBOURNE FROM 1989-1991 (MEAN SALINITY)

INDIAN RIVER LAGOON NATIONAL ESTUARY PROGRAM



• Woodward–Clyde Consultants • Marshall McCully & Associates • Natural Systems Analysis	DRAWING NO.: DATE:	FIGURE 6-6 - SALINITY GRADIENTS IN BANANA RIVER FROM 1989-1991 (MEAN SALINITY)

INDIAN RIVER LAGOON NATIONAL ESTUARY PROGRAM



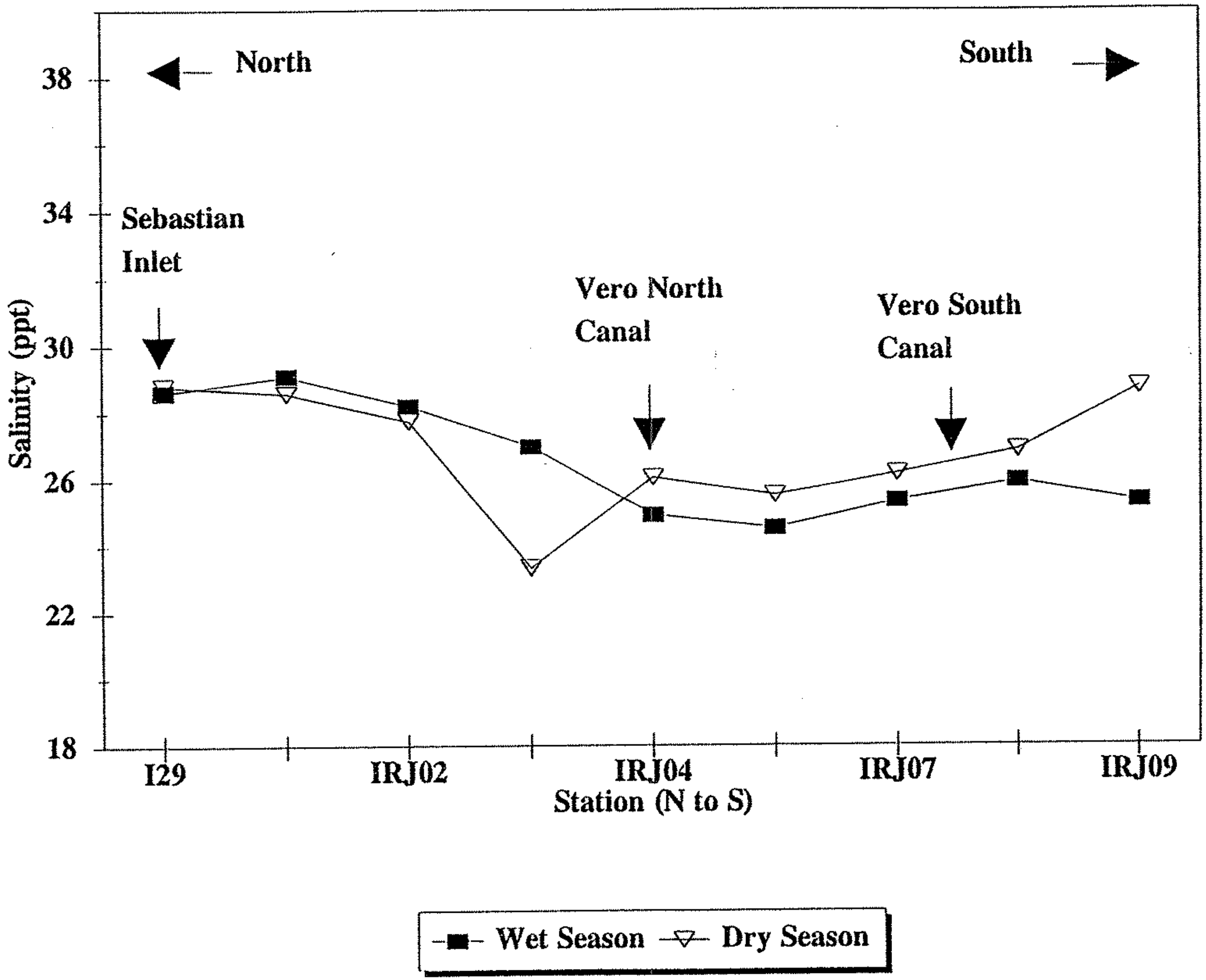
• Woodward-Clyde Consultants
• Marshall McCully & Associates
• Natural Systems Analysts

DRAWING NO.:

DATE:

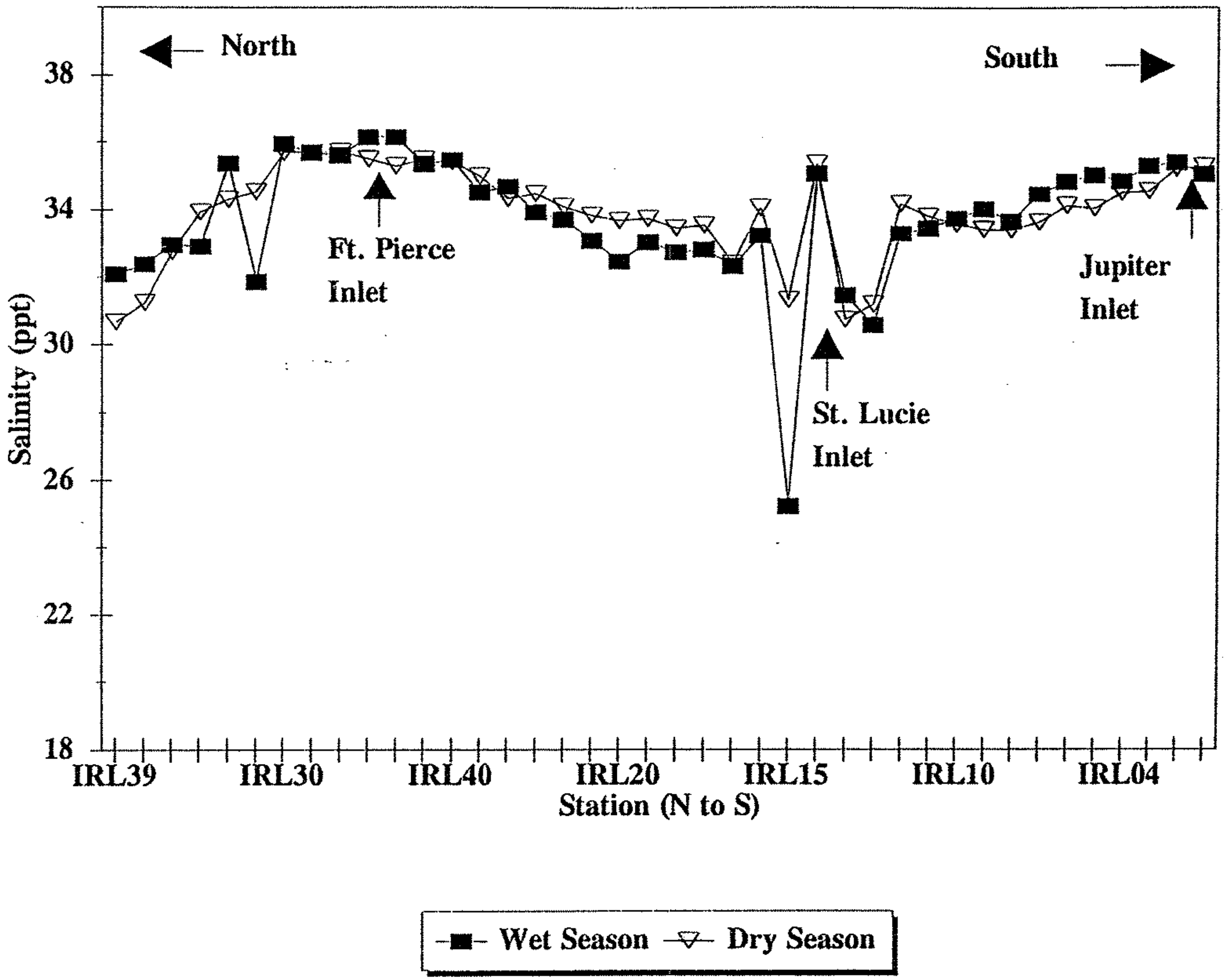
FIGURE 6-7 - SALINITY GRADIENTS IN NORTH CENTRAL INDIAN RIVER LAGOON FROM MELBOURNE TO SEBASTIAN INLET FROM 1989-1991 (MEAN SALINITY)

INDIAN RIVER LAGOON NATIONAL ESTUARY PROGRAM



• Woodward-Clyde Consultants • Marshall McCully & Associates • Natural Systems Analysis	DRAWING NO.: DATE:	FIGURE 6-8 - SALINITY GRADIENTS IN SOUTH CENTRAL INDIAN RIVER LAGOON FROM SEBASTIAN INLET TO LINK PORT FROM 1989-1991 (MEAN SALINITY)

INDIAN RIVER LAGOON NATIONAL ESTUARY PROGRAM



• Woodward–Clyde Consultants
• Marshall McCully & Associates
• Natural Systems Analysts

DRAWING NO.:

DATE:

FIGURE 6-9 - SALINITY GRADIENTS IN SOUTH INDIAN RIVER FROM LINK PORT TO JUPITER INLET FROM 1989-1991 (MEAN SALINITY)

INDIAN RIVER LAGOON NATIONAL ESTUARY PROGRAM

Taylor, et al. (1990) reported salinity at a location in Mosquito Lagoon where tidal influences are minimal. Salinity changes recorded in direct response to rainfall showed a drop from 38 ppt to about 28 ppt in a three day period during which approximately 2 in of rain fell. Additionally, a longitudinal profile presented by Taylor, et al. (1990) confirmed that salinity varied little between the south Volusia County line and Ponce Inlet, except for small reductions in a few locations where drainage ditches discharged into the Mosquito Lagoon.

The water quality of the Mosquito Lagoon is relatively good simply because the pollutant loads are small. However, this system will not be able to withstand significant levels of loading because the exchange with the ocean is so limited.

6.4.2 Hydrography and Mixing in the North Indian River Lagoon Sub-reach

The tideless northern sub-reach of the Indian River Lagoon, (north of the Melbourne and Eau Gallie causeways) is also affected by net evaporation, similar to Mosquito Lagoon. Figures 6-5 and 6-6 show salinity distribution during the wet and dry seasons in the North Indian River Lagoon and the Banana River (Segments 1C and 1B). Data for Figures 6-5 through 6-9 are based on a period of record between 1989 and 1991 as obtained from the SWIM data set. This data is discussed in more detail in the Water and Sediment Quality Assessment Technical Report. These seasonally averaged salinities increase with distance away from Sebastian Inlet. Evaporation concentrates the salt and increases salinity in what is called an negative-estuary effect, probably because the surface area in the northern reaches of both the North Indian River Lagoon and Banana River is relatively large and the freshwater inflows are relatively small. However, in the southern part of this sub-reach salinity is reduced to the lowest values occurring in the Indian River Lagoon complex, as the watershed area increases and the surface area decreases.

The forces that can cause mixing on this sub-reach are not strongly influenced by the ocean tides. Even so, this sub-reach is not strictly tideless. There is a very low astronomical tide that occurs on a regular basis and a more irregular, but possibly larger, meteorological tide. The currents associated with these tide motions may be capable of causing some mixing. In addition, local wind-driven currents are also capable of introducing mixing energy to the water column. This mixing may cause a diffusive mass flux based on a horizontal concentration gradient.

Figures 6-5 and 6-6 show that there is a longitudinal gradient in the salinity concentration values. The mixing behavior can be roughly demonstrated by simple calculations. Based on the salinity gradients shown on Figures 6-5 and 6-6, this mixing gradient is equivalent to a current between 0.01 and 2.4 cm/sec carrying water with a salinity of 27.3 ppt (the section-averaged value) to the north. These estimated currents, if present, would be caused by excess evaporation, and suggest that it is possible for an advective northward flux to occur. Smith (1988) has estimated horizontal turbulent mixing coefficients within the Indian River Lagoon as between 20 m^2/sec and 4 x 10^3 m^2/sec. Further work is clearly needed before the existence of such a current is confirmed. However, if substantiated, it has considerable importance to planning and managing development and Lagoon resources because it indicates that this section of the Lagoon tends to retain nutrients and other loading constituents.

Another possible influence on circulation and hydrography in this sub-reach may be the two electric generating power plants between Rockledge and Titusville. These two plants have a combined permitted discharge rate of about 2,487 cfs (1620 mgd). If these plants discharge continuously at this rate, they would have a mean annual flow rate greater than the sum of all tributaries in the segment. This discharge water is composed of recirculated saline Lagoon water, and thus may have little effect on salinity patterns of the Lagoon. However, the mass flow and temperature differential with the receiving water may influence circulation patterns in this region. Such a phenomenon has not been studied.

Storm events may have major impacts in this tideless sub-reach of the North Indian River Lagoon and the Banana River north of the Melbourne causeway. Strong wind-driven currents in the Lagoon may cause the only substantial mixing in this part of the Indian River Lagoon complex, but it may only be an important mechanism for short time periods. Because the watershed areas are small with reduced freshwater inputs and the Lagoon is shallow, the return to pre-event conditions in the Lagoon should occur within hours to days. However, water quality impacts can also occur if sediments and associated materials are re-suspended during these events.

The Eau Gallie River, Crane Creek, and Turkey Creek enter the Lagoon in the vicinity of the Melbourne Causeway. The increased tidal range south of this causeway increases tidally forced mixing during most seasons. However, when a large storm causes high discharge from Turkey Creek, the freshwater tends to pond, float, and disperse as a distinct lens on the brackish lagoon water (Zarillo, 1993). Under these conditions, the Lagoon can be strongly stratified for a few miles around the mouth of Turkey Creek and remain that way until the action of wind and tide brings about sufficient post-event mixing. This can take several days or weeks (Zarillo, 1993). Discharges from very large storm events can cause the entire Lagoon water column to become almost fresh near the mouth of the creek.

Between Turkey Creek and the Sebastian Inlet the Lagoon functions like a more typically well-mixed estuary with sufficient freshwater input from the watershed to cause a down-estuary (southward) flux of water and sufficient tidal forces to cause mixing. Several other creeks and drainage ditches enter this reach of the Lagoon.

There is noticeably more freshwater discharge to the part of the Indian River Lagoon in the vicinities of the Sebastian Inlet and the Vero Narrows (Rao, 1987). In the vicinity of Sebastian River, large volume freshwater flows also enter the Lagoon from the C-54 and Fellsmere Canals via the Sebastian River. Although the long-term combined mean annual discharge from this drainage complex is about 28% greater than that of Turkey Creek, peak 1-day flows 125% greater than at Turkey Creek have been reported (Rao, 1987). Artificial drainage also contributes large volume flows to the South Prong which augments Sebastian River flows. The North, Main, and South Canals near Vero Beach and the Vero Narrows area of the Lagoon also contribute a mean annual discharge almost equal to that of Turkey Creek (152 cfs) and the combined peak rate is also about twice that of Turkey Creek. Flows of this magnitude have the potential for creating stratified conditions, even if the tide regime in this area is relatively large. A distinct increasing salinity gradient exists from the Narrows to the inlet (Figure 6-8). The salinity gradient, which persists in both the wet and dry seasons, may suggest that tidally forced mixing is an important mixing mechanism in this sub-reach. This may be due to the effect of both Sebastian and Ft. Pierce Inlets on the Narrows area, the small surface area and resultant lower evaporation in this area, and a reduction of wind-driven mixing forces by the many small mangrove islands at the Narrows.

6.4.3 Hydrography and Mixing in the South Indian River Lagoon Sub-reach

In the sub-reach of the Indian River Lagoon between the Vero Narrows and St. Lucie Inlet, the salinities are relatively high throughout (Figures 6-8 and 6-9). In spite of the larger inflow of freshwater, particularly from the St. Lucie River and associated canals (mean annual discharge 1,118 cfs) (Rao, 1987), this part of the Lagoon is dominated by ocean water as evidenced by the high salinities. It appears that this is a result of relatively good tidal circulation and direct transport of freshwater to the St. Lucie and Ft. Pierce Inlets from the discharge points near the inlets.

6.4.4 Hydrography and Mixing in the St. Lucie Estuary and Southernmost Indian River Lagoon Sub-reaches

The relative disjunction of the St. Lucie Estuary has been noted earlier in the discussion of currents. However, there are also periods during flood tide situations when the freshwater discharge may be forced to the area of the Lagoon north of St. Lucie Inlet. A high volume freshwater flow during a neap tide period may result in a lack of mixing and may de-couple the C-44 flow from the waters of the Indian River Lagoon. This possible phenomena needs further study. The presence of the Stuart Causeway to the north and the Jupiter Narrows to the south may also influence this condition.

During field reconnaissance for this study, visual evidence of a freshwater plume was observed from the C-44 Canal through the St. Lucie Inlet into the Atlantic Ocean with very little apparent mixing of the plume with the adjacent water of the Lagoon. A similar but less pronounced effect was seen from the C-25/Belcher Canal through Ft. Pierce Inlet on an ebb tide.

There is little information about the hydrography of the Indian River Lagoon south of St. Lucie Inlet. The salinities appear to be high during both the wet and the dry seasons as shown in Figure 6-9 indicating that there is more influence from water exchanged at the inlets, than from the small freshwater inputs.

6.5 BOAT MIXING

Mixing from boat traffic has not generally been considered to be a major component of hydrodynamics. However, on a local scale, significant mixing of Lagoon waters can be caused by boat traffic. Density gradients can restrict vertical mixing even when wind and tide forces are relatively strong. The combined effect of direct stirring by boat propellers coupled with wave action from boat wakes can mix density layers and resuspend bottom sediments. In a shallow system such as the Indian River Lagoon system, motor boat mixing is an important local effect.

Another important impact of this boat mixing is the resuspension of the bottom sediments and fine silt and organic components of the muck layers. Silt and organic particles tend to be transported and to settle from the water column in deeper water areas where wind mixing decreases. In the absence of mixing processes, particles tend to become trapped in the bottom sediments and become at least partially inactivated. However, boat mixing tends to keep these particles in suspension and can also resuspend them from the sediments. One of the effects of particle suspension in the water column is reduction of light penetration, which in turn reduces growth and survival of seagrasses (see Biological Resources Technical Report Volume). In areas of continual boat traffic, a decrease in seagrasses might be expected from boat mixing (Yousef, et al., 1978).

6.6 HYDRODYNAMIC MODELS

As the preceding sections indicate, there is a complex interaction of tides and currents affecting the hydrology of the Indian River Lagoon complex, ranging from the wind-driven circulation of the northern Indian River Lagoon and Mosquito Lagoon to the complex tide-dominated hydrodynamics between Sebastian and St. Lucie Inlets, in addition to salinity gradients and other complex situations. Hydrodynamic modeling of the entire Lagoon complex is needed to understand the relationships among the segments and the fates of materials introduced into the complex at various locations because of these diverse conditions in the Indian River Lagoon.

While hydrodynamic modeling of parts of the Indian River Lagoon has been performed in the past, a Lagoon-wide model has never been constructed to include the entire length of the complex from Ponce Inlet to Jupiter Inlet. Significant work on portions of the Lagoon has been done by Morris, Smith, Sheng, and Zarillo, as well as others. Williams (1985) performed a simulation of much of the Lagoon. Sheng, et al. (1993) discussed the issues surrounding a Lagoon-wide model for both water circulation and for water quality. Smith (1986) indicated that a one dimensional circulation model similar to the one used by Morris in 1985 and Williams in 1985 is sufficient to study the effects of hydrodynamics.

Sheng, et al. (1990) also utilized a one dimensional Lagoon-wide model to investigate tide, wind and density gradients. That model indicated that under purely tidal mixing conditions it takes approximately 30 days for ocean water and freshwater to reach a salinity equilibrium. However, with sufficient wind and tide action, only 5-10 days are needed to reach such an equilibrium. However, these results covered only a certain portion of the Lagoon complex that had relatively high tidal flushing, and different results may be found for other portions of the complex.

The SFWMD model, DYNTRAN, has been used to study the effects of freshwater discharges into the Lagoon from the St. Lucie estuary. Again, this model did not include the entire Lagoon. Taylor, et al. (1990) utilized a model called TRANQUAL to model the hydrodynamics of Ponce de Leon Inlet. TRANQUAL is a two dimensional model that was originally developed by Taylor and Dean in 1972. It is a combination of Taylor's modeling and actual measurement work that has contributed greatly to the understanding of the Mosquito Lagoon/Ponce de Leon Inlet hydrodynamics and mixing (Hull, et al., 1991).

Three dimensional modeling has been utilized as well for areas of the system other than Mosquito Lagoon. Sheng, et al. (1993) developed three dimensional circulation models for the Indian River Lagoon for the area around Melbourne Causeway and near Turkey Creek. Zarillo (1993) is developing a three dimensional model of the Turkey Creek area from Melbourne Causeway to Grant. This model is derived from an earlier model of the James River in Chesapeake Bay.

To date, no hydrodynamic models have been coupled with water quality models to ascertain and predict the effects of hydrodynamics on water quality for the entire Lagoon.

6.7 COMPARISON OF PRESENT AND PAST HYDRODYNAMIC CONDITIONS

While each of the three lagoons of the Indian River Lagoon complex are different, they can all be characterized by their long narrow shapes. Before the stabilization of Sebastian, Ft. Pierce, and St. Lucie Inlets, the only relatively stable inlets were Ponce de Leon Inlet at the far north end and Jupiter Inlet at the far south end. Washovers and breakthroughs of the barrier island created other inlets that would close over time. Obviously, the short-term hydrodynamic characteristics were affected by the existence of these temporary inlets. However, long-term hydrodynamic conditions would have been primarily a function of distance from each of the two natural inlets. It is probable that relatively little exchange between the Indian River Lagoon complex and the Atlantic Ocean occurred before the stabilization of the present inlets.

Conditions in Mosquito Lagoon have probably changed little in the last two hundred years. Ponce de Leon Inlet is currently the only Atlantic Ocean connection for Mosquito Lagoon, although there is evidence that other inlets have been present to the south. These inlets may have allowed greater exchange and a greater degree of tidal flow and flushing than is now present.

To the south, similar conditions with little tidal current occur in the North Indian River Lagoon and Banana River. It is likely that conditions in this sub-reach have not changed greatly from pre-stabilization periods. Prior to stabilization, Sebastian Inlet tended to migrate along the coastline and thus there probably have been differing current and tide patterns over time. This may have created periods in which flushing in the north Indian River and Banana River were higher than at present. A similar condition may also have occurred in the portion centered around Ft. Pierce Inlet, possibly creating periods when tidal flow and flushing were greater to the north of the inlet and less to the south.

Mixing of water masses has probably been decreased by the construction of causeways and islands in the Lagoon. These have been shown to affect local wind-driven circulation patterns and possibly create more complicated local circulation patterns than in the past (Evink, 1980).

6.8 HYDRODYNAMICS SUMMARY

For an estuarine system, hydrodynamic forces and their effects are important to understand because flushing and mixing characteristics are highly dependent on them. The fate of any freshwater mass or substance carried in the water will depend on the hydrodynamic forces acting upon the Lagoon in that location and on the time that it enters.

In the vicinity of the inlets, tidal forces are relatively high and significant tidal flows or currents are present. These tides can have a range of over 3 ft, and the resulting flows can move water at a rate of up to 1 mi/day. Such tidal flows are generally felt only within a few miles of the inlets. These flows may result in complete exchange or flushing of some portions of the Lagoon complex in periods as short as 30 days.

Farther away from the inlets, water mass movements are dominated by other forces such as wind-driven currents. Since the most prevalent winter and summer winds are generally aligned along the longitudinal axis of the lagoons, these meteorological currents can be of some importance in the complex. Calculations have shown that the elevation of the Lagoon waters may be changed as much as two feet by the action of the wind, and that water molecules may move as much as 1/2 mile per day under the influence of winds.

These meteorological currents may be the only significant currents and means of moving water in most of Mosquito Lagoon, Banana River, and the Indian River north of Melbourne Causeway. Under certain conditions, there is virtually no mass flow of water in these sections. One study in Mosquito Lagoon indicated that water particles under this condition moved no more than 300 ft in any direction. In the southern two thirds of Mosquito Lagoon, studies indicate that there is virtually no exchange with the ocean and consequently no flushing. Any materials flowing into this area will remain, indicating that Mosquito Lagoon is very sensitive to inputs and pollutant loadings. It will not be able to withstand significant loadings without degradation of water quality.

The North Indian River and Banana River are similar to Mosquito Lagoon in that they have little tidal flow and little flushing action, which means that they too are highly susceptible to increased loadings from the surrounding watershed. It appears that the small size of their watersheds and resultant small runoff volume in relation to the large surface areas of the

Lagoons has been an important element in maintaining the water quality of these sections. Flushing time for removal of materials already present in these areas is likely to be long as well.

From Melbourne Causeway south to Sebastian Inlet, the astronomical tide increases steadily, thus increasing tidal flows and potential flushing action. However, discharges from the surrounding watershed also increase, resulting in a more complicated circulation pattern that is not clearly understood and that appears to change dramatically with different meteorological conditions. Flushing and transport of materials in this section may vary substantially, but there appears to be a potential susceptibility to increased loadings, based on the hydrodynamic information on this segment. A similar condition exists in the remainder of this Sub-reach from Sebastian Inlet south to the Vero narrows.

The Southern Sub-reach between Ft. Pierce and St. Lucie Inlets appears to be forced by the actions of both inlets, with at least some tidal flow present throughout much of this Sub-reach. The tidal effect is most pronounced within about 3-5 mi of either inlet with a high rate of flushing in these zones. The zone around St. Lucie Inlet appears to be limited by Jupiter Narrows on the south and the Stuart Causeway on the north, while that of Ft. Pierce Inlet may extend about 7 mi to the south and a lesser distance to the north. Although large amounts of freshwater discharge to this sub-reach, the Lagoon appears to be capable of assimilating larger amounts than the northern sub-reaches because of the greater flushing and exchange with ocean water through the inlets.

The hydrodynamics of the Lagoon complex south of St. Lucie Inlet have not been well studied and are not well known. The main forcing factor may be Jupiter Inlet, and some tidal range and flow is present throughout this sub-reach. More information is needed to describe this sub-reach in much more detail.

Much of the knowledge of the hydrodynamics of the Lagoon complex has been gathered through the use of several different hydrodynamic models. However, none of the models takes full account of all of the forces acting within the Lagoon, and many areas of the Lagoon have not been modeled in a fashion that connects the hydrodynamic conditions throughout the Lagoon. The effects of boat traffic on the Lagoon may be significant in localized movement of water masses and more importantly in resuspension of sediments into the water column.

7.0
PRIORITY ISSUES AND RECOMMENDATIONS

The review of the status of the existing information on the physical features of the Indian River Lagoon indicates that there are several key issues that are important consideration for the management of the Indian River Lagoon. These are listed in this section, as well as relevant recommendations for addressing these issues and for management strategies for the Lagoon.

- The physical processes governing the circulation and flushing of the Indian River Lagoon are of major importance in regulating conditions that may affect chemical and biological processes in the Lagoon. In particular, these conditions are affected by the flushing and circulation effects of the inlets, the relationship between freshwater inputs and outputs from the Lagoon, and factors affecting the internal circulation.

- Inlets play a major role in maintaining flushing, controlling circulation pattern, and affecting the functions within the Lagoon. Changes in inlet characteristics may have pronounced effects, both good and bad on the Lagoon.

- The size of the drainage basins in relation to the volume of the Lagoon differ greatly within the Lagoon watershed, with very little drainage basin and potential for freshwater input to the north Indian River Lagoon, Banana River, and Mosquito Lagoon, but with a very large basin associated with the South Indian River Lagoon segment.

- Presently, there is enough known about these processes to indicate that different reaches or segments of the Lagoon system function differently and have differing physiographic, hydrodynamic and hydrological conditions which result in differing flushing characteristics and assimilative capacities that are important factors in Lagoon management in the following manner:

- Most of Mosquito Lagoon, Banana River, and the North Indian River Lagoon segments have stable salinity regimes, little inlet influence, little flushing action, and at least seasonal excesses of evaporation over freshwater inputs. This may result in a low assimilative capacity and potential for accumulation of contaminants entering the Lagoon.

- The North Central Indian River Lagoon from south of Sebastian Inlet to the south end of Merritt Island has some degree of tidal influence and flushing potential through Sebastian Inlet, but the degree of tidal influence is not strong and may vary dependent upon flows from tributaries and other factors, resulting in a potential for highly variable chemical and physical conditions in the Lagoon in this section.

- The South Central and South Indian Lagoon segments are strongly influenced by the combined tidal influences of Ft. Pierce, St. Lucie, and to some extent Jupiter Inlets, resulting in greater potential for a stable saline influence and greater flushing and removal of contaminants. This is counter-balanced by a very large drainage basin and potential for large freshwater inputs, primarily through the St. Lucie Estuary and the Belcher Canal.

- Management efforts for the Indian River Lagoon should be based on an overall Lagoon-wide understanding of the interactions among segments, but should also be sufficiently flexible to adapt different strategies to different segments based on their needs and functions.

- Although sufficient to give insight into the segmentation and overall hydrology and hydrodynamics of the Lagoon, the existing level of information and understanding is not yet sufficient to accurately predict effects of such actions as inlet modification, freshwater flow reductions, or changes to causeways on circulation and related water chemistry and deposition characteristics in the Lagoon.

- Significant refinement in hydrodynamic and water quality models may be needed before the potential effects of modifications to the drainage or circulation of the Lagoon can be accurately predicted. It is recommended that efforts be directed toward acquiring additional knowledge and accurate predictive modeling tools, with an emphasis on the reaches affected by the Sebastian, Ft. Pierce, and St. Lucie Inlets, and the interactions among these inlets in affecting functions in this region.

- Because of the apparent substantial difference in hydrology and hydrodynamics between the areas south of Merritt Island and the areas north from the island, it may be necessary to treat this area separately from the southern reach, and to develop models or predictive tools with different emphasis and sensitivities.

- Any management program should always keep in mind that the Lagoon is a dynamic, changing system, interacting with the ocean, the interior drainage basins, groundwater systems, and the atmospheric system. Lagoon management programs and urban/agricultural development throughout the region should be designed with sufficient flexibility to deal with long-term changes in these interactions.

- Drainage sub-basins vary greatly in size and detail. In many areas, such as the Mosquito Lagoon (Segment 1A) and Banana River (Segment 1B) watersheds, additional sub-basins should be defined.

8.0
SUMMARY

This report contains a synthesis of the available information concerning the physical features of the Indian River Lagoon and is a part of the Indian River Lagoon Characterization Study undertaken for the National Estuary Program. This Technical Report is the second of eight volumes of the Characterization Study. Overall, these volumes include:

- Executive Summary
- Status and Trends
- Physical Features
- Water Quality and Loading Assessments
- Biological Resources
- Uses of the Lagoon
- Historical Imagery
- Governmental and Non-Governmental Programs

The Indian River Lagoon National Estuary Program covers an extensive area from Ponce de Leon Inlet near New Symrna Beach in the north to Jupiter Inlet, 155 mi to the south. This region contains the Mosquito Lagoon, the Banana River, the Indian River Lagoon proper, the St. Lucie Estuary, and the Jupiter Narrows.

For study purposes, the Indian River Lagoon and its watershed has been divided hydrologically into the following six segments:

- Segment 1A - Mosquito Lagoon
- Segment 1B - Banana River
- Segment 1C - North Indian River Lagoon
- Segment 2 - North Central Indian River Lagoon
- Segment 3 - South Central Indian River Lagoon
- Segment 4 - South Indian River Lagoon

Barrier islands and the Cape Kennedy cuspate foreland separate the Lagoon from the ocean.

Six tidal inlets are unevenly distributed along the barrier island chain. Ponce de Leon in the north connects the Mosquito Lagoon and the ocean. This Lagoon is isolated from the rest of the system except for the narrow Haulover Canal which allows Intercostal Waterway traffic to transit the system. The inlet at Port Canaveral is man-made with limited connection to the Banana River through a channel with a lock. Sebastian, Ft. Pierce, and St. Lucie Inlets connect the main portion of the lagoon to the ocean. South of the St. Lucie Inlet the lagoon becomes narrow and ends at Jupiter Inlet.

The presence of inlets has a major effect on the hydrodynamics and circulation of the Indian River Lagoon system. Inlet migration results from the natural process of occasional overwash which causes inlet formation followed by shoaling and closing. Inlet stabilization has interfered with that process, and does not completely eliminate shoaling so inlets must be dredged to permit navigation.

The watershed of the Indian River Lagoon system has many special features. Because of the general physiography of the Central Florida east coast, the northern portions of the watershed are very narrow with their eastern limits defined by the crest of the dunes on the barrier islands and the western boundary on a coast-parallel sand ridge on the mainland. This portion of the watershed is naturally well drained and there has been relatively little modification of the natural drainage by civil works.

The central portion of the watershed, from near Melbourne to about Vero Beach, has a wider watershed on the mainland side. Natural drainage in this portion of the watershed has been extensively modified by drainage and irrigation ditches. This section, originally with poor surface drainage, has been converted into largely agricultural areas with stretches of urban development connected by a network of canals and ditches arranged in predominantly rectangular patterns. Some of these systems have been used to extend the western sections of the watershed beyond the natural inland limits.

Constructed drainage and irrigation canals are an even more prominent feature of the mainland watershed in its southern portion. Much of the land is agricultural and the canals are commonly used for both stormwater drainage and irrigation, depending on the season. The canal network has been used to extend the western limit of the watershed well inland from its natural boundary. One of these canals, designated C-44, is a major conduit connecting the St. Lucie Estuary with Lake Okeechobee. Pumps and flow control structures permit this canal to be used to drain the lake when its level rises over allowable limits. Less frequently, the flow can be reversed during dry periods when irrigation water is needed in the Lake Okeechobee area. In this way, the management of surface water resources in the

Indian River Lagoon watershed is linked to the management of water in the Okeechobee/Everglades system.

Interconnecting of major drainage systems also occurs to the north. The C-1 Canal, that extends westward from Turkey Creek, provides a bi-directional flow link with the St. Johns River watershed. A similar link to the St. Johns River watershed is the C-54 canal which connects to the Sebastian River, and has caused increased flows through the river mouth. These canals are located in the center portion of the watershed.

The Indian River Lagoon is located in a transition region between temperate and subtropical zones. The average annual temperature is 72.6°F. Summers are warm, humid, and characterized by frequent thunderstorms. Winters are characterized by alternating clear and rainy periods associated with the passage of weather fronts. In the winter the northern section are 4-5°F cooler than the southern sections while conditions are more uniform in the summer. Freezing temperatures occur in almost all years and severe freezes (<28°F) occur in nearly half of the winters. The average annual rainfall is 50.2 in. with noticeable spatial gradients varying from 56.7 in. at Titusville to 44.6 in. at Patrick Air Force Base. The wet period is May through October. The entire area is exposed to tropical cyclones that episodically bring very intense rain along with damaging wind.

The volume of suitable, low-chloride ground water is exceeded by the demand from urban development in many parts of the Indian River Lagoon watershed. Other freshwater sources are being sought, and ground water wells are being located in inland areas away from high demand areas and known saltwater intrusion areas. Ground water discharges directly to surface water bodies and through upward leakage to sloughs and tributaries which are natural inputs to the Indian River Lagoon. Decreases in infiltration which result in decreases in discharge due to increased runoff and ditching, as well as ground water pumping, have raised concerns about the depletion of freshwater in the aquifer systems within the Lagoon watershed.

Increased runoff and drainage thus may be increasing surface freshwater flows to the Lagoon, but the quality of discharges from the surficial and Floridan aquifers and the relationship to the Lagoon is poorly understood. Changing salinity in portions of the Floridan aquifer may result in a more saline upward leakage resulting in a more saline discharge to the Lagoon. Thus, these hydrogeologic relationships may affect the Lagoon system through the amount of freshwater or saline water discharged to the Lagoon by the aquifer systems.

The water budget of the Indian River Lagoon is dominated by direct precipitation, runoff and drainage, evaporation, and exchange with the ocean. In the Mosquito Lagoon, Banana River, and northern portions of the Indian River Lagoon proper evaporation dominates over runoff and direct precipitation for periods varying from the months of April and May in the north Lagoon to most of the year in other sections. As a result, these sections in summer behave as negative estuaries with a net salt water inflow, inhibiting the release of chemical and nutrient loads from the Lagoon to the ocean. Currents and net outflow are further restricted by the very small tidal range and small stream inputs to the northern portions of the system.

In the southern portion of the Lagoon the inlets are located relatively close together and there are much higher discharges of freshwater. This results in more typical estuary-like behavior of water mass distribution, circulation, and flushing than the nearly closed northern reaches. Salinities in the southern portions are usually close to ocean water values indicating that there is a good exchange of water through the inlets. Close to major freshwater discharges, this stratification can become pronounced during rain events as high volumes first enter the Lagoon. Gravitational spreading and wind can move these thin surface plumes miles from their sources before vertical mixing blurs their identity. It is speculated that low dissolved oxygen levels may result from a combination of the flushing of oxygen-depleted water from tributaries into the Lagoon and reduction in the vertical exchange of oxygen from the atmosphere because of density stratification as the plume spreads over the portion of the Lagoon adjacent to the tributary mouth. However, these conditions may occur during and shortly after episodic rainfall events and the few available data have not yet been sufficiently analyzed to evaluate how common and prevalent these conditions may be.

The portion of the Indian River Lagoon between Melbourne and the Vero Narrows appears to have different water quality and hydrodynamic characteristics than the reaches to the north or the south. This is evidenced by the greater variability between maximum and minimum salinity concentrations in this section which includes Segments 2 and 3.

Another special hydrodynamic effect appears to develop in the section of the Lagoon between the St. Lucie Estuary and the St. Lucie Inlet (Segment 4). Occasionally high discharges of freshwater from Lake Okeechobee are routed through the C-44 canal into the St. Lucie Estuary. However, there is little evidence that this freshwater mixes extensively with the high salinity water in the southern lagoon. Instead, these freshwater discharges appear to be trained right out of the inlet by a causeway to the north and the Jupiter Narrows to the south. This suggests that the expectation of substantial impact by these freshwater releases may not be realized. Again, there is only limited data available on these processes.

9.0 REFERENCES

Adkins, M. and J. Yan. 1993. Hydrologic Study of the Water Control District of South Brevard for Present Conditions and the Construction of L-74N Under the Upper St. Johns River Basin Plan. (in press). St. Johns River Water Management District. Palatka, Florida.

Applied Technology and Management, Inc. St. Lucie Inlet Management Plan. Martin County, Florida. Prepared for Florida Department of Environmental Protection Division of Beaches and Shores. Tallahassee, Florida.

Barile, D.D. 1976. "An Environmental Study of the Melbourne-Tilman Drainage District and an Evaluation of Alternative Land Use Plans for the City of Palm Bay, Florida." M.S. Thesis. Florida Institute of Technology. Melbourne, Florida.

Boniol, D., M. Williams, and D. Munch. 1993. Mapping Recharge to the Floridan Aquifer Using a Geographic Information System. Technical Publication SJ 93-5. St. Johns River Water Management District. Palatka, Florida.

Bretschneider, C.L. 1966. "Engineering Aspects of the Hurricane Surge." *in* Estuarine and Coastline Hydrodynamics. A.T. Ippen (ed). McGraw Hill Book Co. pp. 231-256.

Brooks, H.K. 1972. "Geology of cape Canaveral." *in* Space Age Geology. 16th Field Conference Proceedings. Southeastern Geology Society. Tallahassee, Florida. pp. 65-78.

Brooks, H.K. 1982. Guide to the Physiographic Divisions of Florida. Florida Cooperative Extension Service, Institute of Food and Agricultural Sciences. University of Florida. Gainesville, Florida.

Brown, M.P. and D.E. Reece. 1979. Hydrogeologic Reconnaissance of the Floridan Aquifer System Upper East Coast Planning Area. Technical Map Series # 79-1. South Florida Water Management District. West Palm Beach, Florida.

Clapp, David. 1987. "Overview of physiographic and surface drainage features." *in* J. Indian River Lagoon Reconnaissance Report. J.S. Steward and J.A. VanArman (eds). St. Johns River Water Management District and South Florida Water Management District, Palatka, Florida.

Clapp, D. and H.W. Wilkening. 1983. A Study of Crown Flood Irrigation Techniques. Technical Publication SJ 83-3. St. Johns River Water Management District. Palatka, Florida.

Coastal Planning and Engineering, Inc. 1993. Fort Pierce Inlet Management Plan. Submitted to St. Lucie County. Ft. Pierce, Florida.

Coastal Technology Corporation. 1988. Sebastian Inlet District Comprehensive Management Plan. Submitted to Sebastian Inlet District. Sebastian, Florida.

Cooper, R.M. and J. Lane. 1988. An Atlas of Eastern Palm Beach County Surface Water Management Basins. Technical Memorandum. South Florida Water Management District. West Palm Beach, Florida.

Cooper, R.M. and R. Santee. 1988. An Atlas of Martin County Surface Water Management Basins. Technical Memorandum. South Florida Water Management District. West Palm Beach, Florida.

Cooper, R.M. and T.W. Ortel. 1988. An Atlas of St. Lucie County Surface Water Management Basins. Technical Memorandum. South Florida Water Management District. West Palm Beach, Florida.

Cotter, D.C. 1974. Tide-Induced Net Discharge in Lagoon-Inlet Systems. M.S. Thesis, University of Miami. Coral Gables, Florida.

Csanady, G.T. 1970. "Dispersal of Effluents in the Great Lakes". Water Resources. Vol. 4. pp. 79-114.

Csanady, G.T. 1972. "Response of Large Stratified Lakes to Wind." Journal of Physical Oceanography. Vol. 2. pp. 3-13.

Csanady, G.T. 1973. "Wind-Induced Barotropic Motions in Long Lakes". Journal of Physical Oceanography. Vol. 3. pp. 429-438.

Csanady, G.T. 1976. "Mean Circulation in Shallow Seas." Journal of Geophysical Research. Vol. 81. pp. 5389-5399.

Csanady, G.T. 1982. Circulation in the Coastal Ocean. D. Reidel Publishing Co. Dordrecht, Holland.

Doehring, F. and D.D. Barile. 1988. "Climate of the Indian River Lagoon Basin" *in* Indian River Lagoon Estuarine Monograph. Volume II (unpublished). D. Barile (ed). The Marine Resources Council of East Central Florida. Melbourne, Florida.

Doehring, F., I. Duedall, and J. Williams. 1993. 122 Years of Florida Hurricanes and Tropical Storms, 1871-1992: An Historical Survey. (in press). Florida Institute of Technology. Melbourne, Florida.

Dombrowski, M., F.W. Morris, and R. Reichard. 1987. "Hydrodynamics". *in* Indian River Lagoon Reconnaissance Report. J.S. Steward and J.A. VanArman (eds). St. Johns River Water Management District and South Florida Water Management District. Palatka, Florida.

Evink, Gary L. 1980. Studies of Causeways in the Indian River, Florida. Report # FL-ER-7-80. Florida Department of Transportation. Tallahassee, Florida.

Fan, Andrew. 1985. Rainfall Drought Frequency and Availability of Surface Water in Martin County. South Florida Water Management District. West Palm Beach, Florida.

Florida Department of Environmental Regulation. 1991. Indian River System-Water Quality Threats from Package Wastewater Treatment Plants. Florida Department of Environmental Protection. Tallahassee, Florida.

Glatzel, Karen A. 1986. "Water Budget for the Indian River Lagoon: An Overview of Use Effects". Master's Thesis. Florida Institute of Technology. Melbourne, Florida.

Glatzel, K.A. and S.L. Da Costa. 1988a. "Hydrology of the Indian River Lagoon" *in* Indian River Lagoon Estuarine Monograph. Volume II (unpublished). D. Barile (ed). The Marine Resources Council of East Central Florida. Melbourne, Florida.

Glatzel, K.A. and S.L. Da Costa. 1988b. Variability of a Coastal Lagoon Water Balance. Presented at American Water Resources Association Symposium on Coastal Water Resources. May 22-25, 1988. Wilmington, North Carolina.

Godfrey, P.J., and M.M. Godfrey. 1976. "Barrier Island Ecology of Cape Lookout National Seashore and Vicinity, North Carolina. National Park Service Scientific Monograph Series 9.

Graves, G.A. and D.G. Strom. 1992. Bessey Creek and the Greater St. Lucie Estuary. Florida Department of Environmental Protection, Southeast District. West Palm Beach, Florida.

Harper, Harvey H. and Frank E. Marshall, III. 1993. Unpublished data.

Haunert, D.E. 1988. Sediment Characteristics and Toxic Substances in the St. Lucie Estuary, Florida. Technical Publication 88-10. South Florida Water Management District. West Palm Beach, Florida.

Haunert, D.E. and J.R. Startzman. 1985. Short-Term Effects of a Freshwater Discharge On The Biota Of St. Lucie Estuary, Florida. Technical Publication 85-1. South Florida Water Management District. West Palm Beach, Florida.

Hayes, M.O. 1975. "Morphology of Sand Accumulation in Estuaries" *in* L.E. Cronin (ed). Estuarine Research. Academic Press. New York, New York. pp. 3-22.

Head, C.M. 1981. Geologic Perspective of Florida. Unpublished report.

Hopkins, Emily. 1991. A Water Resource Analysis of the Jensen Beach Peninsula, Martin County, Florida. Technical Publication 91-03. South Florida Water Management District. West Palm Beach, Florida.

Huang, P.S., D.P. Wang, and T.O. Najarian. 1986. "Analysis of Residual Currents Using a Two-Dimensional Model." *in* Physics of Shallow Estuaries and Bays. J. Van de Kreek (ed). Springer-Verlog. New York, New York.

Hull, T.J., W.F. McFetridge, R.B. Taylor and M.A. Yanez. 1990. Engineering Evaluation of Ponce de Leon Inlet. Taylor Engineering, Inc. Jacksonville, Florida.

Hull, T.J., R.B. Taylor and M.A. Yanez. 1991. Rivers Management Program Phase II: Rivers Baseline Evaluation. Taylor Engineering, Inc. Jacksonville, Florida.

Hutchinson, J. 1987. History of Martin County. Florida Classics Library. Port Salerno, Florida.

Jensen, R.E. 1983. Atlantic Coast Hindcast, Shallow Water, Significant Wave Information. WIS Report 9. United States Army Corps of Engineers Waterways Experiment Station. Vicksburg, Mississippi.

Lin, S. 1984. Summary of 1983-1984 Dry Season Hydrologic Conditions. South Florida Water Management District. West Palm Beach, Florida.

Lin, S., J.S. Lane and J. Marban. 1984. Meteorological and Hydrological Analysis of the 1980-1982 Drought. Technical Publication 84-7. South Florida Water Management District. West Palm Beach, Florida.

Liu, J.T. 1991. "Residual Currents-The Variability of an Inlet Sediment Trapping Mechanism." *in* Coastal Sediments '91. American Society of Civil Engineers. Vol. II. pp. 1419-1433. New York, New York.

Liu, J.T. 1992. "The Influence of Episodic Weather Events on Tidal Residual Currents: A Case Study at Sebastian Inlet, Florida. " Estuaries. Vol. 15. pp. 109-121.

Liu, J.T. and D.G. Aubrey. 1993. "Tidal Residual Currents and Sediment Transport Through Multiple Tidal Inlets." *in* Formation and Evolution of Multiple Inlet Systems. D.G. Aubrey and G.S. Geise (eds). Springer-Verlog. New York, New York.

MacVicar, T.K. 1983. Rainfall Averages and Selected Extremes for Central and South Florida. Technical Publication 83-2. South Florida Water Management District. West Palm Beach, Florida.

Marban, J.A., S.P. Sculley and P.J. Trimble. 1989. Analysis of the 1988-1989 Drought. Special Report. South Florida Water Management District. West Palm Beach, Florida.

Mehta, M.J. and H.K. Books. 1973. "Mosquito Lagoon Barrier Beach Study." Shore and Beach. Vol. 41. pp. 27-34.

Miller, J.A. 1982. Geology and Configuration of the Top of the Tertiary Limestone Aquifer System, Southeastern United States. USGS Open-File report 81-1178. United States Geological Survey. Washington, D.C.

Miller, W.L. 1979. Hydrologic and Geologic Data from the Upper East Coast Planning Area, Southeast Florida. USGS Open File Report 79-1543. United States Geological Survey. Washington, D.C.

Morris, F.W. 1985. "The St. Lucie Estuary Model." *in* Proceedings of the Fifth St. Lucie Estuary Coordinating Conference. Florida Oceanographic Society. Stuart, Florida.

National Oceanic and Atmospheric Administration (NOAA). 1991. Nautical Chart # 11484. 18th ed., October, 1991. U.S. Department of Commerce. National Ocean Service. Washington, D.C.

National Oceanic and Atmospheric Administration (NOAA). 1992. Nautical Chart # 11485. 27th ed., August, 1991. U.S. Department of Commerce. National Ocean Service. Washington, D.C.

National Oceanic and Atmospheric Administration (NOAA). 1993. Tide Tables, 1994. East Coast of North and South America. U.S. Department of Commerce. National Ocean Service. Washington, D.C.

Nealon, D., G. Shih, S. Trost, S. Opalat, A. Fan and B. Adams. 1987. Martin County Water Resource Assessment. S. Trost and D. Nealon (eds). South Florida Water Management District. West Palm Beach, Florida.

Pandit, A. and C.C. El-Khazen. 1989. "Groundwater Seepage Into the Indian River Lagoon." Proceedings of the Specialty Conference on Water Resources Planning and the Management Challenge. 21-25 May. Sacramento, California. pp. 168-171.

Pandit, A. and C.C. El-Khazen. 1990. "Groundwater Seepage Into the Indian River Lagoon at Port St. Lucie." Florida Scientist. Vol. 53(3). pp. 169-179.

Parker, S.P. 1986. Encyclopedia of Ocean and Atmospheric Sciences. McGraw-Hill. New York, New York.

Phillips, R.C. 1961. "Seasonal Aspect of the Marine Algal Flora of St. Lucie Inlet and Adjacent Indian River, Florida." Quarterly Journal of Florida Academy of Science. Vol. 24(2). pp. 135-147.

Planning Department Staff, South Florida Water Management District. 1992. Water Supply Needs and Sources 1990-2010. South Florida Water Management District. West Palm Beach, Florida.

Pritchard, D.W. 1967. "What is an Estuary: Physical Viewpoint." *in* Estuaries. G. H. Lauff (ed). American Association for the Advancement of Science. Publication 83. Washington, D.C. pp. 3-5.

Provancha, J.A., C.R. Hall and D.M. Oddy. 1992. Mosquito Lagoon Environmental Resources Inventory. NASA Technical Memorandum 107548. The Bionetics Corporation. Kennedy Space Center, Florida.

Provost, M.W., 1973. "Mean High Water Mark and Use of Tidelands in Florida." Florida Scientist. Vol. 36(1). pp. 50-66.

Rao, 1987. "Surface Water Hydrology" *in* Indian River Lagoon Joint Reconnaissance Report. J.S. Steward and J.A. VanArman (eds.). St. Johns River Water Management District and South Florida Water Management District. Palatka, Florida.

Reichard, R. and S. Lewit. 1985. "Flushing of the Southern Indian River Lagoon." Abstract. Florida Scientist. Vol. 48. p. 17.

Rey, J.R. and T. Kain. 1989. A Guide to the Salt Marsh Impoundments of Florida. University of Florida-IFAS. Florida Medial Entomology Laboratory. Vero Beach, Florida.

Schnable, J.E. and H.G. Goodell. 1968. Pleistocene-Recent Stratigraphy, Evolution and Development of the Appalachicola Coast, Florida. Special paper # 112. Geological society of America.

Schneider, W., P. Dubbelday, and T. Nevin. 1974. "Measurements of Wind-Driven Currents in a Lagoon." Florida Scientist. Vol. 37. pp. 72-78.

Sculley, S.P. 1986. Frequency Analysis of South Florida Water Management District Rainfall. Technical Publication 86-6. South Florida Water Management District. West Palm Beach, Florida.

Sheng, Y.P., S. Peeve, and Y.M. Liu. 1990. "Numerical Modeling of Tidal Hydrodynamics and Salinity Transport in the Indian River Lagoon." Florida Scientist. Vol. 53. pp. 147-168.

Sheng, Y.P., S. C. McCutcheon, K.R. Reddy, N.P. Smith, and L. Motz. 1993. Water Quality and Circulation Modeling Needs of the Indian River Lagoon. Proceedings of an Indian River Lagoon Workshop. Department of Coastal and Oceanographic Engineering. University of Florida. Gainesville, Florida.

Smith, N.P. 1986. "The Rise and Fall of the Estuarine Intertidal Zone." Florida Scientist. Vol. 9. pp. 95-101.

Smith, N.P. 1987. "An introduction of the Tides of Florida's Indian River Lagoon. I Water Levels. Florida Scientist. Vol. 50., N.1. pp. 49-61.

Smith, Ned. 1988. "Indian River Lagoon Monograph Water Level Variations" *in* Indian River Lagoon Estuarine Monograph. Volume II (unpublished). D. Barile (ed). The Marine Resources Council of East Central Florida. Melbourne, Florida.

Smith, N.P. 1990. "An introduction of the Tides of Florida's Indian River Lagoon. II Current, Florida Scientist. Vol. 53., N.3. pp. 216-225.

Smith, N.P. 1992. "The Intertidal Volume of Florida's Indian River Lagoon." Florida Scientist. Vol. 55. pp. 208-215.

Smith, N.P. 1993. "Tidal and Wind-Driven Transport between Indian River and Mosquito Lagoon, Florida. Florida Scientist. Vol. 56., N.4. pp. 235-246.

Snelson, F.F. and W.K. Bradley. 1978. "Mortality of fishes due to cold on the East Coast of Florida, January 1977." Florida Scientist. Volume 41. pp. 143-164.

South Florida Water Management District. 1984. Preliminary Report of Rainfall Event November 21-26, 1984, South Florida Coastal Area. South Florida Water Management District. West Palm Beach, Florida.

South Florida Water Management District. 1985. Report of Tropical Storm Bob July 22-24, 1985. South Florida Water Management District. West Palm Beach, Florida.

South Florida Water Management District. 1991a. Storm Event of January 15-17, 1991. South Florida Water Management District. West Palm Beach, Florida.

South Florida Water Management District. 1991b. Storm Event of October 8-10, 1991. South Florida Water Management District. West Palm Beach, Florida.

South Florida Water Management District. 1992. Preliminary Report on Rainstorm of June 23-30, 1992. South Florida Water Management District. West Palm Beach, Florida.

South Florida Water Management District. 1993. Indian River Lagoon SWIM Plan. Appendix I: St. Lucie Estuary Watershed Plan (Draft). Planning Department, South Florida Water Management District. West Palm Beach, Florida.

St. Johns River Water Management District and South Florida Water Management District. 1993. Draft Surface Water Improvement and Management (SWIM) Plan for the Indian River Lagoon. Joel Steward, Robert Vernstein, Dan Haunert, and Frank Lund (eds). St. Johns River Water Management District, Palatka, Florida and South Florida Water Management District, West Palm Beach, Florida.

Stapor, F.W. and J.P. May, 1983. "The Cellular Nature of Littoral Drift Along the Northeast Florida Coast." Marine Geology. Vol. 51. pp. 217-237.

Stauble, D.K. 1988. The Geomorphology, Geologic History, Sediments and Inlet Formation of the Indian River Lagoon System. Volume I (unpublished). D. Barile (ed). The Marine Resources Council of East Central Florida. Melbourne, Florida.

Stauble, D.K. and S.L. Da Costa. 1988. "Evaluation of Backshore Protection Techniques" *in* Coastal Zone '87. American Society of Coastal Engineering. Seattle, Washington. pp. 3233-3247.

Stodghill, A.M. and M.T. Stewart. 1984. Resistivity Investigation of the Coastal Ridge Aquifer Hydrostratigraphy Martin County, Florida. Technical Publication 84-5. South Florida Water Management District. West Palm Beach, Florida.

Steward, J.S. and J.A. VanArman. 1987. "Indian River Lagoon Joint Reconnaissance Report." Final Report for Contract Nos. CM-137 and CM-138. St. Johns River Water Management District and South Florida Water Management District. palatka, Florida.

Taylor, B., M. A. Yanez, T. J. Hull and W. F. McFetridge. 1990. Engineering Evaluation of Ponce de Leon Inlet Final Phase II Report. Taylor Engineering, Inc. Jacksonville, Florida.

Taylor, R.B. and Dean R.G. 1972. Numerical Modeling of Hydromechanics of Biscayne Bay/Card Sound System Part II: Dispersive Characteristics. University of Florida, Department of Coastal and Oceanographic Engineering. Gainesville, Florida.

Thurlow, S. H. 1992. Sewell's Point, the History of a Peninsula Community in Florida's Treasure Coast. Sewell's Point Company. Stewart, Florida.

Toth, D. 1987. "Hydrogeology" *in* Indian River Lagoon Joint Reconnaissance Report. J.S. Steward and J.A. VanArman (eds.). St. Johns River Water Management District and South Florida Water Management District. Palatka, Florida.

Trimble, P. 1990. Frequency Analysis of One and Three-Day Rainfall Maxima for Central and Southern Florida. Technical Memorandum. South Florida Water Management District. West Palm Beach, Florida.

Trimble, P.J., J.A. Marban, M. Molina, and S.P. Scolley. 1990. Analyses of the 1989 - 1990 Drought - Special Report. South Florida Water Management District, West Palm Beach, Florida.

U.S. Army Corps of Engineers. 1992. Navigation Study for Ft. Pierce Harbor, Florida - 10196. General Reevaluation Report and Supplement to the Final Environmental Impact Statement. Jacksonville District. Jacksonville, Florida.

United States Department of Agriculture, Soil Conservation Service. 1992. Indian River Lagoon Agriculture Land-Use Inventory and Discharge Study. United States Department of Agriculture. Soil Conservation Service. Gainesville, Florida.

United States Department of Agriculture, Soil Conservation Service. 1974. Soil Survey of Brevard County, Florida. United States Department of Agriculture. Soil Conservation Service. Gainesville, Florida.

United States Department of Agriculture. Soil Conservation Service. 1974. Soil Survey of Indian River County, Florida. United States Department of Agriculture. Soil Conservation Service. Gainesville, Florida.

United States Department of Agriculture. Soil Conservation Service. 1974. Soil Survey of Martin County, Florida. United States Department of Agriculture. Soil Conservation Service. Gainesville, Florida.

United States Department of Agriculture. Soil Conservation Service. 1974. Soil Survey of St. Lucie County, Florida. United States Department of Agriculture. Soil Conservation Service. Gainesville, Florida.

United States Department of Agriculture. Soil Conservation Service. 1974. Soil Survey of Volusia County, Florida. United States Department of Agriculture. Soil Conservation Service. Gainesville, Florida.

Van de Kreeke, J. and S.S. Chiu. 1980. "Tide-Induced Residual Flow." *in* Mathematical Modeling of Estuarine Physics. J. Bundermann and K.P. Hotz (eds). Springer-Verlog. New York, New York.

Walton, T.L. 1974. St. Lucie Inlet, Glossary of Inlets. Report No. 1. Florida Sea Grant College. Gainesville, Florida.

Wanielista, Martin P. and Yousef A. Yousef. 1993. Stormwater Management. John Wiley and Sons, Inc. New York, New York.

White, W.A. 1970. The Geomorphology of the Florida Peninsula. Bulletin # 51. Florida Bureau of Geology, Florida Department of natural Resources. Tallahassee, Florida.

Williams, J.L. 1985. Computer Simulation of the Hydrodynamics of the Indian River Lagoon. M.S. Thesis, Florida Institute of Technology. Melbourne, Florida.

Windsor, J.G. 1988. "A Review of Water Quality and Sediment Chemistry with an Historical Perspective" *in* Indian River Lagoon Estuarine Monograph. Volume III (unpublished). D. Barile (ed). The Marine Resources Council of East Central Florida. Melbourne, Florida.

Wyrick, G.G. 1960. The Ground-Water Resources of Volusia County, Florida. USGS RI #22. U.S. Geological Survey. Tallahassee, Florida.

Yousef, Y.A., W.M. McLennon, R.H. Fagan, H.H. Zeboth, and C.R. Larrabee. 1978. Mixing Effects Due to Boating Activities in Shalow Lakes. U.S. Department of Interior, Office of Water Research and Technology. Washington, DC.

Zarillo, G. 1993. Personal Communication.