SPATIAL AND TEMPORAL DYNAMICS IN THE EVERGLADES ECOSYSTEM WITH IMPLICATIONS FOR WATER DELIVERIES TO EVERGLADES NATIONAL PARK

By

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Dedicated to Gene, Dorothy and Sara Gunderson

My immediate links with the past and the future

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NATIONAL PARK

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The Everglades is a unique wetland ecosystem. During this century, the ecosystem has been partitioned for disparate uses of human habitation, agriculture, water conservation and ecosystem conservation in a national park. The sustainability of Everglades National Park is dependent upon upstream water sources. Water management in the Everglades and water deliveries to the Park are linked to human perceptions of ecosystem dynamics.

One line of inquiry used expansion of a state-of-the-art computer model to examine the upstream area that once contributed water to the Park. Linkages between vegetation and hydrology were added as vegetation mediation of evapotranspiration and flow and hydrologically induced vegetation changes, but neither addition appreciably improve understanding of hydrodynamics in the Everglades system at the scale of the model. Prior to management, the entire system, south of Lake Okeechobee, contributed flow to Everglades Park except

during dry years. Since the onset of intensive water management, an equivalent area of only about one-third of the historic drainage basin has supplied water into the Park. But these conclusions are dependent upon the assumptions made to represent the system at a specific spatial-temporal scale in a model. At other scales the conclusions could well be different. That led to the second major topic of this thesis; that of cross-scale structure and dynamics.

A cross-scale mode of inquiry suggests that ecosystems exhibit discontinuities in spatial structures and temporal patterns across time and space due to the interaction of key processes operating over different scale ranges. Spatial patterns in the topography, vegetation and fire data sets exhibited scale regions of self-similarity separated by distinct breaks. Temporal patterns of rainfall, stage, flow, evaporation and sea-level exhibited multiple cycles. These analyses support the theory that ecosystems are structured around a few keystone variables of mixed spatial and temporal dimensions. Dramatic discontinuities appear in patterns as a result of the interactions of processes operating at different space and time domains. This emerging viewpoint of ecosystem structure and dynamics will hopefully provide a basis for new understanding and hence improved management of this unique ecosystem.

CHAPTER 1.
INTRODUCTION TO THE EVERGLADES ECOSYSTEM

There are no other Everglades in the world.

-Marjory Stoneman Douglas

The Everglades is a wetland ecosystem unlike any other on Earth. Situated in the subtropics of southern Florida, the unique combination of physiography and biota blend into a landscape whose name is internationally recognized. Undoubtedly some of the values and distinctions that the area now holds are due to attributes of the natural system. During the twentieth century, the human population in and around the Everglades ecosystem has increased dramatically, resulting in a myriad of demands on and uses of a unique ecosystem. Many of the current management problems are associated with the historical spatial partitioning of resources within a once contiguous ecosystem. The pattern unfolding throughout the past century is one of a transition of land uses, from a pristine wetland with negligible human use to one dominated by a variety of human uses each with characteristic spatial and temporal domain. These varied land uses range from intensive agriculture in the northern Everglades to Everglades National Park in the south.

The primary purpose of this work is to improve understanding of the critical processes and factors in the Everglades ecosystem that influence water deliveries to Everglades National Park. The issues surrounding water deliveries to the park cannot be described from a single moment in history nor from a spatial perspective of the current border of the park. Indeed, the water problems of the park are woven throughout a rich tapestry extending back thousands of years and covering the southern half of peninsular Florida. In order to make the problem tractable, the dissertation is divided into five chapters. The introductory chapter contains descriptions of the natural and human histories in the system that lead to a conclusion that water management is fundamentally linked to concepts of ecosystem dynamics. The second chapter in this work compares and contrasts alternative concepts of ecosystem dynamics from which the hypotheses and objectives of the dissertation are derived. The third chapter presents the results of an attempt to invalidate the hypothesis that the entire Everglades drainage basin contributed water to the park. The "upstream area" hypothesis was tested using a state-of-the-art ecosystem model that couples vegetation and hydrologic dynamics. The fourth chapter contains the results of analyses of a series of data sets that are used to test the second hypothesis, based on an alternative concept, and seeks to understand system dynamics based upon a recognition of the role of discontinuities in both structure and processes . The final chapter contains a summary that compares and contrasts the understanding of system dynamics and water deliveries that were developed in chapters three and four and presents implications of these results on water management and policy.

This introductory chapter is devoted to describing both the natural and human components in the Everglades ecosystem. First, the components and processes of the pristine or natural Everglades ecosystem are described. The next three sections are historical accounts, documenting the increasing human involvement with the system. These historical accounts include a brief history of relevant human activities, a review of how water management developed in southern Florida, and finally, how the understanding and policies of water deliveries to Everglades Park have changed. This chapter concludes with a description of the linkages between management, policy and understanding of system dynamics, and how these relationships have evolved in this complex wetland system.

The Everglades Ecosystem

The Everglades is a distinct physiographic region located in southern Florida, and its natural features have been described for over 100 years (Heilpren 1887, Willoughby 1898, Harshberger 1914, Harper 1927, Davis 1943, Craighead 1971, Gunderson and Loftus In Press). Prior to intervention by man, the Everglades encompassed approximately 10,500 km^2 of freshwater marshes, sloughs and hardwood tree islands (Davis 1943). The system was approximately 210 km along the north-south axis, bordered by Lake Okeechobee on the north and Florida Bay on the south. The widest east-west dimension was 77 km, from the higher Atlantic coastal ridge on the east to the Big Cypress Swamp on the west (Figure 1).

The wetland complex is a result of a large arcuate trough in the underlying limestone bedrock. Three surficial formations are recognized, and all were formed by shallow marine accumulations during the Pleistocene Era, primarily the Sangamon interglacial stage (Parker and Cooke 1944). The Fort Thompson formation underlies the northern Everglades, and is comprised of marine and freshwater marls beds interleaved with limestone and sandstone. The Anastasia formation is found in the northeastern Everglades, and is characterized by sandy limestone, calcareous sandstone. The surficial feature of the southern Everglades is Miami limestone, comprised of oolitic and bryozoan facies (Hoffmeister 1974).

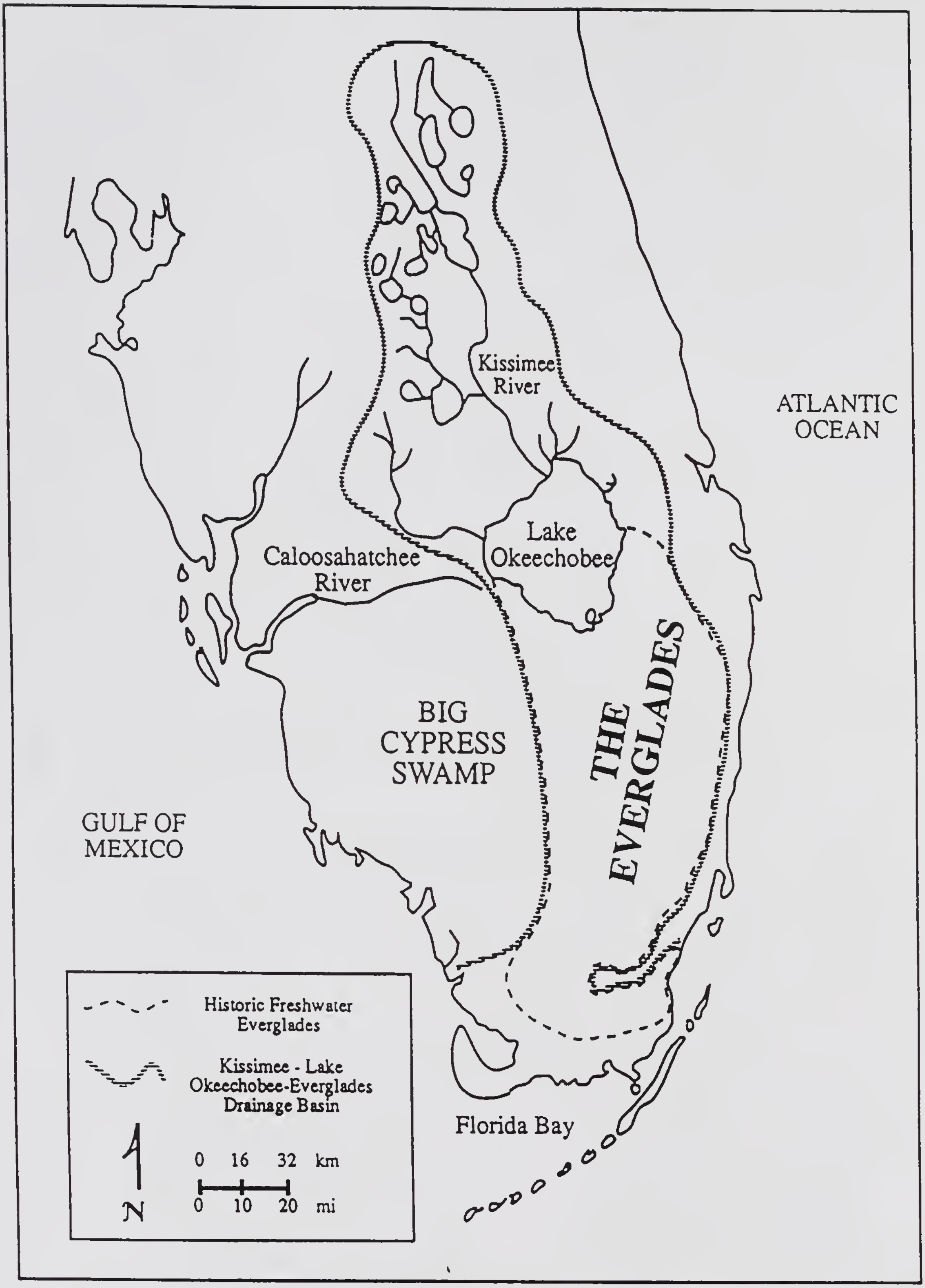

Figure 1. Location of the Kissimmee River, Lake Okeechobee and Everglades Drainage Basin in Southern Florida.

The wetland soils of the Everglades are Holocene sediments, categorized as peats, mucks and marls, and are biogenic. The oldest soils in the Everglades are approximately 5500 years old (Gleason et al. 1984), dating back to an approximately 3 m transgression of sea level (Robbin 1984). Peats and mucks are histosols, named by the dominant recognizable plant remains from which the soils are derived, and accumulate under extended periods of inundation. The marls are a calcitic mud, produced by reprecipitation of calcium carbonate from saturated water during photosynthesis by blue-green algae (Gleason 1972).

The topography of both the bedrock and the soil surface is flat, characterized by almost no relief with extremely low gradients. The maximum elevations in the northern Everglades are approximately 5.3 m above the national geodetic vertical datum (NGVD), and now occur in the Arthur R. Marshall National Wildlife Refuge (Figure 2). The elevational gradient is mostly north to south, with an average slope of 2.8 cm/km (Parker et al. 1955). The variation in elevation is attributed to the underlying bedrock structure and accumulations of organic sediments. The microtopographic variation is caused by and contributes to differences in vegetation cover and type.

The vegetation of the Everglades region is a complex of gramineous and woody wetland associations. The spatially dominant communities are sawgrass marshes, wet prairies, and hardwood swamp forests (Davis 1943, Craighead 1971, Olmsted et al. 1980, Gunderson and Loftus In Press). Sawgrass marshes, monotypic stands of sawgrass, *Cladium jamaicense* found over peat and marl, are the ubiquitous, characteristic association of the Everglades. Wet prairies over peat are sparsely vegetated, generally dominated by either spikerush *Eleocharis cellulosa*, or maidencane, *Panicum hemitomon*. Wet prairies on marl are diverse association, dominated by sawgrass and muhly grass, *Muh-lenbergia filipes*, and contain over a hundred other species (Olmsted et al. 1980).

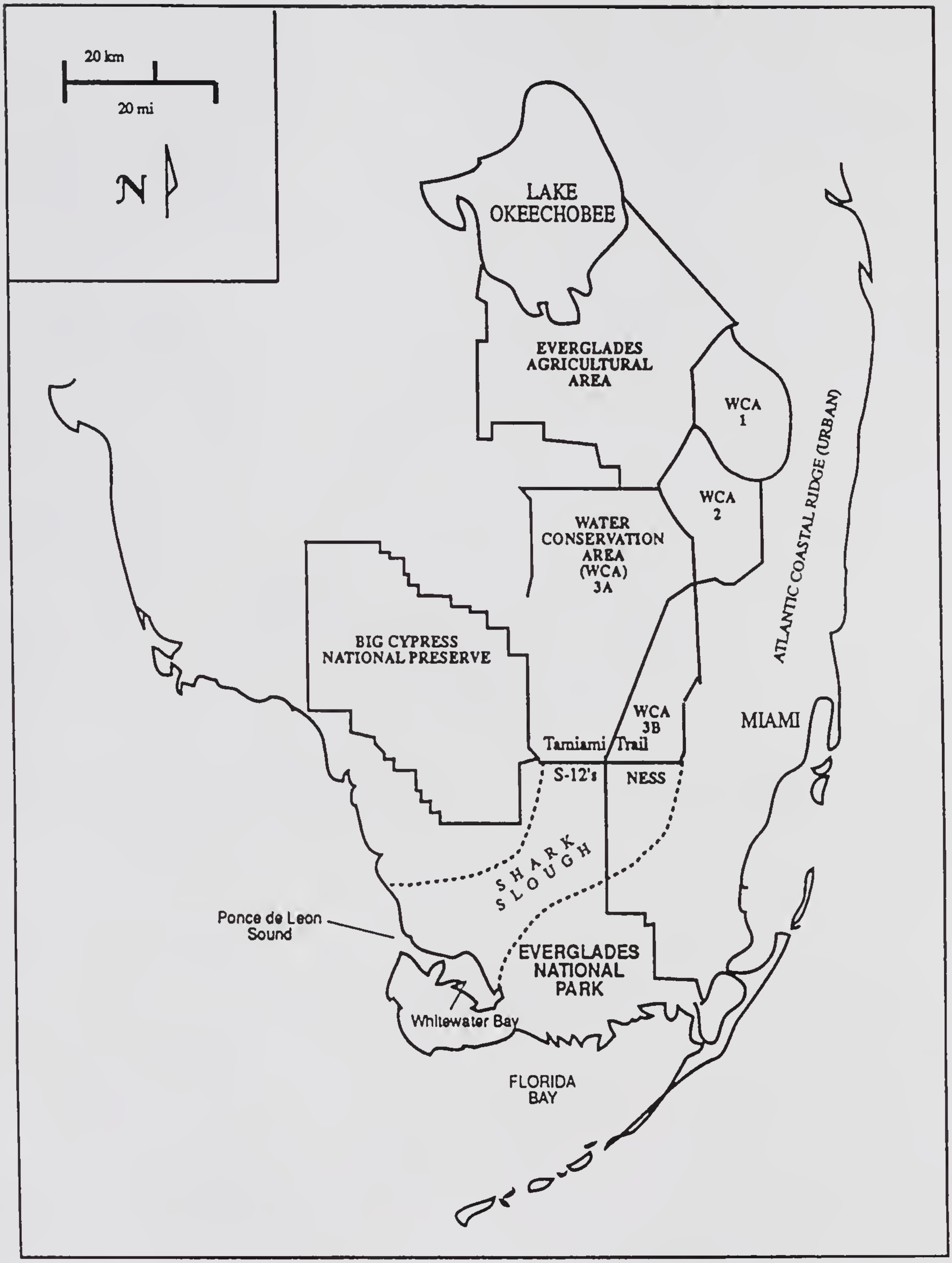

Figure 2. Current broad scale land-use designations in the historic freshwater Everglades drainage basin.

The hardwood swamp forests of the Everglades are called tree islands, descriptive of the isolated clumps of trees surrounded by the lower stature wetland grass communities. Dominant species in the tree islands are mostly bay trees; swamp bay, *Magnolia virginiana*, red bay, *Persea palustris*, dahoon holly, *Ilex cassine*, wax myrtle, *Myrica cerifera*.

The Everglades is a unique wetland due in part to the spatial and temporal patterns of the components of the hydrologic regime. Year to year variation in the hydrologic cycle results in oscillating periods of flood and drought. The intra-annual variation is also great, characterized by wet summers and dry winters. Rainfall and overland flow are the principal inputs, yet the relative contribution of each to the hydrologic budget is debated. The magnitude of direct rainfall contribution to the hydrologic regime of the Everglades distinguishes it from other large freshwater wetland systems such as the Llanos in Venezuela, the Okavango in Botswana or the Pantenal in Brazil where most of the marsh water originates from rivers.

The climate of southern Florida is subtropical, classified by Hela (1952) as a tropical savanna, with insufficient rainfall during the summer months to compensate for a winter dry season. The area has also been classified as subtropical moist forest type (Dohrenwend 1977, Greller 1980) due to the high annual rainfall and moderate annual biotemperatures.

Rainfall over the Everglades exhibits both spatial and temporal variability. Annual rainfall over the system averages 130 cm (Thomas 1970, Bradley 1972, MacVicar and Lin 1984). Annual rainfall extremes for the period of record 1940 through 1980 range from low of 95 cm in 1961 to a high of 270 cm in 1947 (MacVicar and Lin 1984). Thomas (1970), using spectral analysis, found about a seven year pattern within the record, indicative of a cyclical pattern with this return interval. Rainfall patterns exhibit distinct seasonality; approximately 85%

of the annual average rain falls between May and October. Thomas (1970) found that rain totals during the wet season were bimodally distributed, with peaks in June and September. Spatial analysis of rainfall records indicate that the coastal region receives on the average 30 to 35 cm more than the interior marshes. The northern Everglades and southern Everglades receive more rainfall than the central regions (MacVicar and Lin 1984).

The rainfall patterns can be related to different processes which influence the timing and amount of precipitation. The summer rainy season is attributed to convective thunderstorms, which are linked to mesoscale land-sea breeze patterns. During the summer, insolation results in differential heating of the air over the land mass compared to air over the water. The heated air over the land rises, creating low pressure and establishing a pressure gradient along which maritime air flows toward the center of the Florida peninsula. The moisture-laden air rises, cools adiabatically, condenses, and forms convective thundershowers. This process has been described as the 'rain machine' (Pardue 1982, Yates 1982). Some authors suspect that rainfall totals have decreased because drainage and development have altered the net radiation budget (increased reflectance due to a higher albedo of developed areas) which in turn decrease the rate of convection (Gannon 1978, Pardue 1982). Statistically higher rain amounts measured during September have been explained by the greater incidence of tropical cyclones during this month. Rain during the winter dry season is associated with the passage of cold fronts that pass on the average every seven days. Annual variations in frontal passage have been linked to jet stream location.

Historically, surficial flow left the Everglades system through a number of pathways. In the northeast, water moved through the cypress-dominated Hungryland and Loxahatchee Sloughs. Major rivers that carried Everglades waters through the coastal ridge include the New River, Little River and Miami River. Surface water moved through the higher coastal ridge in a series of transverse glades. Water flow in the southern Everglades occurred in the broad shallow depressions of Taylor and Shark Sloughs, named for the rivers that received the bulk of the flow.

Although the Everglades are recognized as a distinct physiographic region, it is part of a much larger drainage system, containing a number of river systems and Lake Okeechobee to the north (Figure 1). Prior to development, hydrologic connections were traceable to central Florida where the Kissimmee River originates. The Kissimmee is the largest of the rivers and other smaller creeks and sloughs which empty water into Lake Okeechobee. Surface water entered the Everglades from the southern boundary of the lake at two points when stages exceeded 4.5 m NGVD, and a 52 km long spillway when stages exceeded 5.6 m NGVD (Parker 1984). The entire system has been referred to as the Kissimmee-Lake Okeechobee-Everglades (KLOE) system.

The hydrology of the historic Everglades ecosystem can be summarized as follows. The system is a wide, shallow flat basin, with an overall small topographic gradient. The primary hydrologic input is rainfall, and although averages 1.3 m/yr, is characterized by wide spatial and temporal variability. Other inputs occurred as surface and subsurface flow from Lake Okeechobee and from wide sloughs in the Big Cypress Swamp. Evapotranspiration is the primary avenue of water loss, estimated to be 80% of rainfall. Remaining water in the system flows slowly to the south either to the east recharging the surficial aquifer of the coastal ridge or the southwest entering the estuarine mangrove zone prior to reaching Florida Bay. The seasonal patterns of rainfall and evapotranspiration interact to yield distinct annual wet and dry periods as well as variations in overland flow.

History of Human Use

Evidence of human inhabitance in southern Florida dates to well over 10,000 years. B.P. (Carr and Beriault 1984), prior to the existence of the vast wetland ecosystem. Written accounts, which date back almost 500 years, describe native humans using the resources of the wetland ecosystem. Nunez de Cabeza (1514) relays descriptions of the fierce native Indian tribes that inhabited the coastal portions of southern Florida and the peaceful Mayami tribes which colonized the edge of Lake Okeechobee. These early Americans probably burned the Everglades (Robertson 1954), and used the area for hunting and fishing purposes.

The name Everglades first appeared on British maps in the early 1800s (Vignoles 1823) probably a contraction of "Never a glade," descriptive of the large treeless expanses. With the expansion of European derived settlers throughout the southeastern coastal plain, native Americans translocated from the Carolinas to southern Florida. The term "Seminole," which is the name for the major tribes of current native populations that persist today, means "runaway." The Seminole term for the area is "Pa-hay-okee", which loosely translates into "grassy lake", again, descriptive of a non-forested wetland system. These native Americans used the elevated tree islands for homesites and cultivation of crops, as well as hunted and fished throughout the system. The United States fought a series of wars with the Seminoles during the mid 1800s, restricting their territory to a few reservations through south Florida. One remains within the Everglades proper, where the Miccosukee Indians still retain land use rights.

The latter part of the nineteenth century marked the first influx of white settlement and attempts at "reclamation" of the wasteland known as the Everglades. Soon after Florida became a state in 1845, early settlers and their governments embarked on programs to drain the Everglades for habitation and agriculture. Buckingham Smith was commissioned by the U.S. Senate to reconnoiter the Everglades for development potential (Smith 1848). In 1850, under the Swamp and Overflowed Lands Act, the federal government deeded 7500 mi^2 to the state, including the Everglades. The Florida legislature established the Internal Improvement Fund, whose board was to sell and improve these swamp lands through drainage. Attempts at manipulation of the water were ineffective in the 1800s, as the magnitudes of the variations in hydrology were far greater than the minor control structures could handle.

By 1900, initial colonization of the coastal regions east of the Everglades was underway. The population of Palm Beach, Broward and Dade counties in southern Florida in 1900 was 28,000 (U. S. Dept. of Commerce 1990). By 1920, the major land uses now found in southern Florida had started. Urban development was occurring along the railroad line down the east coast. Agriculture was developing in the peat lands south of Lake Okeechobee. Conservation of the natural resources had begun with the formation of Royal Palm State Park in 1917 in the southern Everglades.

During the period 1920 through 1990, the spatial extent of these land uses grew, in large around these three general loci. In the 1940s, 283,000 ha of the northern Everglades was designated as the Everglades Agricultural Area (EAA). By the mid 1940s Water Conservation areas were designated in the central regions of the glades to manage water resources for multiple purposes. Conservationists work started during the 1920s came to fruition in 1935 with the establishment of Everglades National Park in the southern Everglades, although the park was not formally dedicated until 1947. The park area was increased in 1989 from 1.4 million to 1.6 million acres by the addition of Northeast Shark Slough. Urban development along the east coast has followed the exponential increase in population, and resulted in the drainage and colonization of former wetland areas. As of 1990, 5.1 million people live within the confines of the historic drainage basin (U. S. Dept of Commerce 1990). The current configuration of the Everglades ecosystem depicting agricultural areas in the north, water conservation areas in the central areas and Everglades National Park in the south is shown in Figure 2.

Through the past century, the spatial extent of the historic Everglades ecosystem has been slowly whittled away, to the degree that perhaps one-half of the original system has been irrevocably converted to specific land uses. As of 1985 the historic Everglades ecosystem as defined by Davis (1943), was partitioned into at least five major use types. Gunderson and Loftus (In Press), estimate that 32% of the historic Everglades is in areas designated for water management, 27% in agriculture, 17% for preservation of natural resources, 12% has been developed for urban purposes, and 12% remains as drained, undeveloped lands. Davis et al. (In Press), estimate that only half of the original land area of the Everglades is still in native vegetation types, and that certain landscape types, including a large pondapple forest in the north as well as marshes and cypress forests in the east, are gone. The remaining natural areas have probably been hydrologically altered, and their future viability is largely dependent upon water management actions.

Water Management

Water management within the Everglades is accomplished by physical structures and operational criteria. The physical structures consist of levees or dikes, canals, water control gates (mainly weirs), and pumps. The operational criteria are constructed around the multiple objectives of the system. The two primary objectives are flood protection and water supply, having evolved with the changes in land use within the system and the nature of the historical ecosystem. The history of water management appears to be one where natural events or crises precipitated plans and activities that resulted in more infrastructure and attempts to control the variation in the natural system. Reactions to natural crisis have resulted in changes and development of two components of water management; the physical structures of water manipulation (Table 1) and the policies and programs by which water is managed (Table 2).

Canal construction typified the earliest period of water management in the Everglades. The first large canal in the system was completed in 1882, when dredges excavated a channel between Lake Okeechobee and the Caloosahatchee River. Water levels in the Lake were reported to have declined approximately 50 cm (Johnson 1958). During the next 45 years, canal construction proceeded sporadically as a result of intermittent funding. By 1917, four major canals, the Miami, North New River, Hillsboro and West Palm Beach had penetrated the interior of the Everglades, probably resulting in some drainage of the wetland system.

Hurricanes during the 1920s devastated human developments along the east coast and south of Lake Okeechobee. Earthen dams which had been constructed to exclude waters of the Lake were breached during the hurricane of 1928, resulting in extensive flooding and a loss of about 2400 lives (Blake 1980). In response, the federal government funded the construction of the Hoover Dike around the Lake, which was completed by 1938, in order to contain floodwaters.

During the 1940s, federal and state laws established the system of water management as it now exists. Rainfall during this decade varied wildly, creating

Table 1. History of major water management structures in the Everglades ecosystem that influenced water deliveries to Everglades National Park.

YEAR	STRUCTURE	RESULT
1917	Construction of Miami, North New River, Hillsboro and Palm Beach Canals	Drainage of coastal areas and interior Everglades wetlands
1924	Construction of Caloosahatchee Canal	Lowering of water level in Lake Okeechobee
 1926 -- 1938 --	Lake Okeechobee levees Muck levee constructed Hoover dike constructed	Impound water in Lake Okeechobee, control water movement to south
1928	Construction of Tamiami Trail	Alteration of flow patterns channel through culverts
1959	Everglades Agricultural Area levees completed	Control of water movement in northern Everglades
1962	Water Conservation Areas 1, 2, and 3 enclosed by levees	Control of water movement in middle Everglades
1962	S-12 structures complete	Flow spatially constricted to four flowways
1967	L-67 canal and levee	Canal to deliver water into center of Shark Slough

Table 2. History of major water management policies that influenced water deliveries to southern Everglades and ENP. (Blake 1980, Wagner and Rosendahl 1985).

YEAR	POLICY	PURPOSE
1907	Everglades Drainage District	To drain Everglades for agricultural and development
1948	Flood Control Act PL 80-858	Ameliorate flood effects by construction of conservation areas, levees
1962 -- 1966	Deliver water from WCA 3A, based upon stages	Store water in WCA 3A, park to receive after storage requirements met
1966 -- 1970	Deliver water based upon stage in Lake Okeechobee	Increase flow to park during hurricane season, restrict flow during drought
1970 -- 1982	Minimum delivery schedule (PL 91-282 guarantee park a amount of water)	To assure ENP 260,000 acre-feet/year, and share in certain drought adversity
1982 -- 1985	Flow through plan (PL 98-181 allowed for experimental deliveries)	Allow S-12 structures to remain open, no regulation schedule
1985 -- present	Rainfall plan	Deliver water based upon upstream climatic conditions

conditions which prompted action. The early 1940s were extremely dry,resulting in saline intrusion into the freshwater aquifers of the coast and subsequent salt dam construction. Extensive flooding occurred during 1947, following an extremely wet summer and the passage of two cyclonic storms. Over 105 inches (270 cm) of rain was reported to have fallen (MacVicar and Lin 1984) during 1947. This flood resulted in the passage of the federal Flood Control Act in June 1948 (PL 80-853). The act authorized the U.S. Army Corps of Engineers to develop a plan known as the Central and Southern Florida Project for Flood Control and Other Purposes, which would address the water management needs of the area. The plan contained three basic elements: 1) designation of the EAA, 2) construction of water conservation areas in the central Everglades and 3) construction of an eastern levee. The purposes of the water conservation areas were to protect the east coast and agricultural areas from flooding, recharge regional aquifers and prevent salt water intrusion. In 1949, the state legislature created the Central and Southern Florida Flood Control District (FCD) to act as local sponsors for the federal project. The FCD was renamed in 1977 as the South Florida Water Management District, at which time an additional objective, enhancing environmental resources, was added to the above mentioned purposes.

Construction of the physical structures of the project began in the early 1950s and continues to be modified to date. Three water conservation areas (WCA) were surrounded by levees (Figure 2). Water conservation area 1, was also given designation as the Loxahatchee National Wildlife Refuge in 1951. (In 1984, the area was renamed the Arthur R. Marshall National Wildlife Refuge in honor of an eminent ecologist). Water Conservation Areas 2 and 3 were divided into subunits A and B, primarily to decrease infiltration losses in the southeastern portions of these areas. By 1962, the conservation areas were closed in and functionally intact. Canal construction to date has resulted in approximately 1400 miles of canals.

Operational criteria for water management in the southern Everglades revolves around the stated regulation schedules for the water conservation areas. The schedules are target stages which vary over the year, which tend to revolve around two objectives: 1) minimizing flood risk during the hurricane season (June-October) and 2) maximizing storage during the dry season (November-May). When levels are below regulation schedule, water outflow is minimized to allow stages to increase to the regulation level. When the schedule is exceeded, water is released to lower levels. Modifications to these schedules have been made during recent years. The schedule for WCA 3A has been modified to allow zones around a certain stage value, within these zones water input and outflow are moderated so that rapid movement of water is negated. The regulation schedule of WCA 2 has been modified to allow periodic drydown (Worth 1987). Currently, the schedule for the Marshall NWR (WCA1), is being evaluated for changes that would improve wildlife habitat.

The water conservation areas are not only spatially central, but functionally central to water management in the Everglades. These areas are designed to be used for many purposes, primarily flood control and water supply. These areas act as surge tanks in receiving water during flood periods. Runoff from agricultural areas to the north is placed in these areas. Water in the WCA's is also kept from flowing into areas to the east, in order to lessen flood impacts. During dry periods, water is also stored in order to meet demands along the coast and to the south, especially Everglades Park.

Water Deliveries to Everglades National Park

Estimates of pre-drainage water flow into the area now in Everglades park are tenuous due to at least two reasons. No measurements of flow were made prior to 1940 and by 1940 many upstream canals were in place and may have siphoned upstream waters to the coast. The Miami Canal was cut through the ridge as of 1917 (Blake 1980) thereby removing water from the area immediately north and east of the park. Historic (pre-drainage) average annual flows to the area of the park were calculated to be 2 to 2.5 million acre feet. (Parker 1984). The U.S. Army Corps of Engineers (1968) calculated a smaller mean value, approximately 1.25 million acre feet. These flows were estimated to be the amount of overland flow into the southern Everglades. Smith et al. (1989) using a correlation between freshwater flow and the annual band width of a coral in Florida Bay, estimated that during the period 1881-1939 annual flow averaged 1.15 million acre feet (1.4 billion cubic meters), whereas flow during 1940-1986 was estimated to be 0.47 million acre feet (0.5 billion cubic meters). Dynamic flow models (Walters et al. 1992) driven by actual rainfall during the period 1960-1987, predict flow to have varied between 0.5 and 2.5 million acre feet (0.62 and 3.1 billion cubic meters), depending upon rainfall.

Overland flow has entered the area now in northern Everglades Park (primarily Shark Slough) through man-made structures since about 1928 when a series of round and square culverts were placed beneath the roadbed of Tamiami Trail (US Highway 41). Most of these culverts are still in place and deliver water to northeast Shark River slough. As part of the plan to enclose southern WCA 3A, a levee (named L-29) was constructed on the border between WCA 3A and ENP. This effectively altered the distribution of flow through the western half of the historic Shark Slough. Four sets of gates (designated S12A through S12D) were placed in Levee-29 to allow water movement between the conservation area and the park. Each of the four gates is comprised of six 25 foot wide vertical lift gates. Each set of gates is designed for a maximum flow of 8000 cfs (226 m^3/sec), with a maximum headwater stage of 12.4 ft. and maximum tailwater stage of 11.9 ft. (U.S. Army COE 1968). The L-29 borrow canal provides the headwater to the gates. Other structures that were constructed for various reasons to direct flow in the Shark Slough, but no longer used, include the L-67 extension canal, S-12-E, S-12-F and S-14 (Wagner and Rosendahl 1982). The alignment of park boundary also bisects the other main drainage basin (Taylor Slough) from its headwater. The physical structures that deliver water at the boundary into Taylor Slough include a pump station (S-175) that delivers water out of canal L-31 W .

There have been at least eight different time periods each with varying hydrologic regimes under which water has flowed into the Shark Slough area of the park. Prior to initiation of construction of L-29 and the S-12 structures, water flow into the park was unregulated in the sense that water across the boundary was dependent upon hydraulic gradients within the upstream marshes and only restricted by the capacity of the culverts. Starting in 1961, overland flow was entirely cut off to Shark Slough while construction was underway, marking the second flow regime. From December of 1963 through March of 1965, water was moved from WCA 3A only after regulation schedule was met, that is, the park only received excess water after upstream storages were met (Wagner and Rosendahl 1985). During 1965 and 1966, three zones within WCA 3A were used to deliver a monthly amount of water. From the period of March 1966 through September 1970, the stage in Lake Okeechobee was used to determine water deliveries to the park, with totals scaled from no delivery if the stage was below 12.5 ft, 150 cfs if the stage was above 12.5 and below 13.5, and 1000 cfs if the stage was greater than 13.5 ft. (Wagner and Rosendahl 1985).

During the 1960s the park experienced low rainfall years and was concerned about the quantity of water it received in context of increasing urban demands. Two studies defined the water needs of the park using existing flow and stage data. Dunn (1960) analyzed data for the period 1947-1952 and found that the median annual flow into the Shark Slough area was 273,000 acre feet (3.36×10^8 m^3), a value that he recommended be adopted as the minimum flow requirement. Hartwell et al. (1964) developed stage-duration curves for station P-33 in the park and stage-discharge correlation between P-33 and flow into the park, and used these relationships to determine an annual discharge requirement of 243,000 ac. ft. (2.97×10^8 m^3). A crude average of these two figures was incorporated into a congressional act in 1970 (PL 91-282) which guaranteed the park an annual minimum delivery of 315,000 ac. ft. (3.85×10^8 m^3) or 16% of the water in the system. These annual deliveries were to be partitioned into the three flow sections into the park. Shark Slough was to receive a minimum of 260,000 ac. ft (3.18×10^8 m^3) annually, 37,000 ac. ft.(0.45×10^8 m^3) were to be delivered into Taylor Slough, and 18,000 ac. ft. (0.22×10^8 m^3) into the eastern panhandle area of the park (Wagner and Rosendahl 1985). This law established the legal right of the park to a minimum amount of water and to share adversity associated with periods of drought. During the 1970s the minimum delivery concept was altered from a minimum threshold to one of a static portion of water allocated to the park each year. The annual flows through the S-12s were regulated tightly, and during the years 1970 through 1982, met minimum delivery requirements, but tended to release water over the schedule during summer months.

In 1983, following a wet year and changes in the operating criteria for backpumping into Lake Okeechobee, the park service requested alterations to the "minimum" delivery schedule. Fearing too much water would come into the park, a number of alterations to the structures of the system were requested, along with changes to methods of delivery. In order to remove water from eastern and southern WCA 3A through pathways other than into the park, culverts were placed in Levee 28 in order to allow water to flow into the Big Cypress. Other outlets for WCA 3A were requested but not implemented. Water was to be diverted into WCA 3B. In response to these requests, Congress passed a law (PL 98-181) that allowed for experimental water deliveries to the park. For the next two years (1983-1985), the S-12 structures were left entirely open, so that water would enter the park as a function of hydraulic gradients between WCA 3A and the park. Although the flow-through plan may have achieved objectives of restoring the natural timing of flow, the situation of leaving the gates open did not bode well with water managers faced with the necessity of storing as much water as possible in WCA 3A for meeting other needs on the coast.

The latest act in the unfolding play of water deliveries to the park was the Rainfall plan developed by Tom MacVicar of the SFWMD and staff of the COE. They analyzed rainfall-runoff data from the period 1940 through 1952, and developed a statistical model which predicted weekly flow based upon net rainfall (rainfall minus evapotranspiration) over WCA 3A from the previous ten week period and the previous weeks' discharge. The model achieved two objectives; the timing and quantities of deliveries were linked to upstream weather conditions, and the flow would be re-distributed spatially as it was prior to the construction of the water conservation area. The regulation schedule was also modified to allow for variation in water level conditions within WCA 3A in order to avoid the rapid releases of water into the park (MacVicar and VanLent 1984, MacVicar 1985, Neidrauer and Cooper 1988). In essence, the rainfall plan limits the source basin of the park to WCA 3A by directly timing delivery to rainfall over the area. Buried in this delivery plan is the unknown contribution of other areas in the Everglades (and Lake Okeechobee) to water in WCA 3A and eventually to the park. This is manifest in the supplemental deliveries, by which more water than the rainfall formula predicts is delivered. The supplemental deliveries are linked to a modified regulation schedule. The key elements of the rainfall plan are 1) to link timing and quantity of baseline deliveries to upstream rainfall, 2) to increase quantity of flow during periods of high water, 3) to decrease quantity of insured deliveries during dry periods, and 4) to supplement the baseline quantity of water depending upon a wider range of water depths (regulation schedule) within WCA 3A.

Major determinants to the constantly changing methods and policies of water delivery to the park have been the observed degradation of biological resources in the southern Everglades and Everglades National Park. Dry years and accompanying fires during 1962 and 1971 prompted the appeal for more guaranteed water. Increased mortality of alligator young (Kushlan and Kushlan 1980) was attributed to rapid water level rises associated with regulatory releases during the early dry season. Browder (1985) developed relationships between flow into the estuary of Florida Bay and shrimp production. The most attention has been drawn to a dramatic decline in the number of wading birds; nesting success of wading birds has decreased by 95% of levels in 1930s (Robertson and Kushlan 1984). Reasons for the declines have been intimately linked with decreases in flow through the park (Ogden 1978, Ogden 1987, Powell et al. 1989, Walters et al. 1992). Other authors believe that too much water in the Everglades has contributed to the population decreases (Kushlan 1987) and that the park should receive less water.

The preceding review of the Everglades ecosystem has followed two separate paths: one recounts the natural history and the other the human history. These histories intertwine, and are linked by the ways in which humans perceive, understand and react to nature, the subject of the next section.

Managing Ecological Systems

One interpretation of the history of water management in the Everglades is that it appears to follow a pattern of crisis and reconfiguration (Light et al, In press). The crises arise from dramatically unexpected system behavior, such as floods, droughts and fires. Crises in the past have appeared suddenly, as surprises, and the subsequent responses have dramatically changed the way the system has been managed (Table 1). The central reconfiguration occurred following the flood of 1947, when the Central and Southern Florida Project was spawned. Since then, other crises have occurred with subsequent changes in the policy and practice of delivering water to the park. The reaction by humans to these surprises takes the form of policies and management actions. The responses are shaped by perceptions and interpretations of how nature operates.

At least two concepts are involved in the interpretation of nature that create the basis of policy and management formulations. The first concept relates to various views of system stability. The second concept deals with the assumed or perceived uncertainties associated with either system understanding or impacts of management actions. At least three views of system stability have been abstracted: equilibrium, dynamic and evolutionary (Holling 1987). An equilibrium view is defined as one dominated by the assumption that key response variables always return to a point or set of points. The dynamic perspective recognizes that system variation occurs within and between a range of stability regions so that system behavior appears at times constant, other times continuously changing, and at times jumping abruptly into another stability regime. In the evolutionary view, the stability landscape can change, implying fundamental structural and organizational changes in the system. Dealing with the inherent and fundamental uncertainty associated with shifts within and among these stability domains is at the heart of adaptive management (Holling 1978, Walters 1986). During the last decade both the policy and management philosophy in the Everglades crossed thresholds involving both changes in views of stability domains, and in strategies of management.

Policy in the Everglades is still largely rooted in the equilibrium-centered perspective, although the dynamic view has been recognized and partially incorporated into management schemes in the mid 1980s. Water movement is largely determined by regulation schedules in the different components of the system (Lake Okeechobee and the water conservation areas). These regulation stages reflect an equilibrium view of water management, that is, it always returns to an ideal stage within a retention pool. The modifications to WCA 3A schedule associated with the rainfall delivery plan, however, indicate a shift to a dynamic viewpoint, allowing variability in the managed system.

Water management in the southern Everglades during the last decade has developed more attributes of adaptive environmental management (Holling 1978, Walters 1986). Within the last decade, programs such as the iterative testing plan (Light et al. 1989) have been applied using the concept that water management necessarily has some experimental attributes. This has even been codified, by the adoption of PL 98-181 which allows for experimental deliveries to the park. The rainfall plan can be classified as a passive adaptive technique (Walters 1986), whereby historical data are used to construct a model that guides management plans. Two problems with this technique are that 1) environmental and management effects are confounded, and 2) little opportunity exists for improving the model or testing new models (Walters 1986, Walters and Holling 1990).

Summary

In this chapter, the key pieces of the interplay between the natural and human dimensions of the Everglades are described. The undisturbed Everglades ecosystem can be characterized as an oligotrophic, sub-tropical wetland system with high temporal variability in rainfall input. The landscape is flat, yet supports a complex spatial mosaic of marsh and woody vegetation plant associations. Humans have interacted with the system for as long as it has been a wetland. Dramatic changes have occurred during this century, within which time about half of the land area has been converted to agriculture and urban development. Over the past 50 years, Everglades National Park has been established, as has one of the largest water management infrastructures in the world. Water management and deliveries to Everglades Park have undergone dramatic, non-linear changes resulting from recurrent crises and surprises. The foundations for policy and management development during these periods of reconfiguration are intimately linked to and dependent upon our understanding of ecosystem dynamics. Understanding ecosystem dynamics and the different paradigms regarding system organization is the point at which the first chapter ends and the second chapter begins.

CHAPTER 2.
POSING THE QUESTIONS

Using all the weapons of our logical, mathematical and technical armoury we try to prove that our anticipations were false--in order to put forward, in their stead, new unjustified and unjustifiable anticipations, new 'rash and premature prejudices' as Bacon derisively called them

-K.R. Popper

As indicated in the preceding sections, the problem of water deliveries to Everglades Park has many dimensions, including how ecosystems vary over different time spans, and the subsequent reactions and adaptations of people to these fluctuations in the system. Resource policy and management is fundamentally related to how humans perceive and attempt to comprehend the vagaries of nature. Even though institutional and human dynamics of the system are important, they are fundamentally rooted in basic paradigms about how ecosystems function. The study of ecosystems can be particularly difficult because of the variety of components, processes and variables. Attempting to incorporate all variables makes the problem overwhelmingly complex (Gallopin 1991). Simplifying assumptions allow for these studies to become tractable. The remainder of this chapter will outline and contrast three existing approaches to simplify understanding of ecosystem dynamics and a description of a new emerging paradigm. Hopefully, this theoretical background will lay the framework from which hypotheses and objectives of this work are derived in the concluding sections of this chapter.

Views of Ecosystem Structure and Function

Understanding and interpreting ecosystem structure and function are based upon underlying methodological assumptions and paradigms held by the observer. At least three such concepts are recognized, while a new one is emerging to account for the paradoxes that emerge from applying the first three. These viewpoints can be characterized and contrasted by two components of the paradigms: 1) the factors or variables that are important in the system and, more fundamentally, 2) the manner in which these variables interact. The first assumption is that variables interact in such a way that the strength or significance of the interaction can be tested against a null model that is random. The second paradigm is based upon a view that the world is structured in a hierarchical manner, with distinct levels of causation defined by the observer. The third view of ecosystem science is rooted in mathematical modeling, and concentrates on system dynamics across a limited range of scales. The newest belief, emerging because of limitations in the other views, is cross-scalar in scope and implies a world of lumps and discontinuities in which a small number of key processes determine function, each over its own range of scales. None of these views are wrong; indeed, all represent partial truths and continue to thrive because they are useful. Following a brief characterization of each existing assumption and their limitations, the emergence of a new view will be presented.

Ecosystem science as practiced by the 'Stochastics' is characterized by multi-variate statistical approaches. The implicit assumption is that the variables are operating within similar domains in space and time and therefore have correspondingly similar ranges of variation. Explicit assumptions include that the variables are essentially derived from continuous distributions and therefore have certain properties that can be estimated from sampling. In the extreme, variation in response variables is partitioned to either the variation of other variables or to a random error term. In all cases, the null hypothesis is a random one; relationships can only be inferred by rejection of the null. Examples of work in the Everglades ecosystem of this type include analyses by Smith et al. (1989) and Browder (1985) in correlating freshwater flow in the system with biotic responses in Florida Bay. Indeed, the current rainfall formula developed by MacVicar (1985) is a statistical approach, whereby flow through the southern Everglades is regressed against rainfall and stage. This approach is powerful, because the tools are readily available, and only a statistically significant number of samples are necessary for application.

The hierarchical view of ecosystems, on the other hand, while a powerful concept, is still struggling for widespread application after being introduced at least 50 years ago. The basic framework offered by hierarchists is one of partitioning variables and interactions into distinct levels or "holons" (Allen and Starr 1982). Variables that operate at similar scale ranges occupy the same level within a hierarchy and interact more than with variables between levels. One feature of hierarchies is dubbed as asymmetry, where the variables at slow levels constrain the variables at fast levels. The underlying assumptions of variability are similar to the random approach, in that the variables are assumed to have continuous distributions and that these distributions are predictable. Another common belief of hierarchists is that hierarchies are relatively stable, static and operate near equilibrium. The most current view of hierarchists is that the world should be partitioned into the appropriate hierarchical level such as landscape, ecosystem, population, organism for study, analysis and understanding (Allen and Hoekstra 1992). To my knowledge, no applications of this theory has been applied to studies of the Everglades.

A tremendously rich understanding of ecosystem structure and function has been achieved by modellers who apply the third aproach to explanation.

Although inductive, the approach can improve understanding by testing dynamic interactions among variables. Assumptions regarding variables and interactions can be clearly stated by mathematical formulae translated into computer code. The utility or power of modeling also carries related costs. Empirical rules such as "parsimony in the selection of variables" (Clark et al. 1979), the "power of two" (Walters 1986) or the optimum trade-off between articulation and predictability (Costanza and Sklar 1985) all attest to constraints on modeling.

The limitations imposed on each of these views has to do with issues of scaling. All of these approaches to explanation treat both variables and interactions as scale invariant. Scale invariant means that the behavior of variables and the rules or properties of interaction do not change within the scale limits imposed by the observer. The power of these approaches comes from the knowledge of a rule set, and how far (over what range of scales) the rules apply. Limitations related to scale are a result of underlying assumptions (stochastics), theoretical frameworks (hierarchists) and of practical experience (modellers). For variables to be analyzed, compared or contrasted using the available statistical approaches, they must change within a similar manner. If there are dramatic differences in the space or time dynamics of variables, then statistical methods either give erroneous conclusions or, flat out, don't work. An example of this is the rainfall formulation (MacVicar 1985) mentioned above, where the regression analysis indicated that no statistical relationship existed between rainfall and flow!

Similar problems of the mismatch between variable spatial or temporal domain arise in hierarchical theories and in the application of modeling techniques. The hierarchists (Allen and Starr 1982, O'Neill et al. 1986) recognize that "slower" variables constrain "intermediate" variables while "faster" variables are essentially meaningless, or noise. Little progress has been made with linking these variables together other than in a conceptual or qualitative sense.

Modellers have come to essentially similar conclusions, as expressed in the practical "Rule of Two". The empirical rule states that the best models never extend more than two orders of magnitude in either space or time. The basic approach of scaling in modeling, is to treat "slower" variables as constants, and to treat "faster" variables as random or stochastic events. Existing space-time models of hydrodynamics in the Everglades fall within this guideline and will be described later in the modeling section. The result of limitations imposed by these various approaches is the breakdown of understanding, as evidenced by inherently unpredictable system behavior (Holling 1986). These limitations and inevitable surprises helped prompt the development of a theory that attempts to embrace the cross-scale dynamics of ecosystems.

This emerging cross-scale theory has roots in both the hierarchical and modellers perspective and can be traced to a review and synthesis of the dynamics of a number of ecosystems. Holling (1986) compared the dynamics of 23 ecosystems, and concluded that the essential behavior of the system could be traced to three or four sets of variables, each of which operated at distinctly different rates. The sample ecosystems were categorized into one of four classes of systems: forest insects, forest fires, grazing in savannas and aquatic harvesting. Models of the reviewed ecosystems all generated complex behavior in space and time that qualitatively correlated with observations of the actual systems. The essential dynamics of the systems could be attributed to a small number of keystone variables. The speeds of each keystone variable differed from each other by as much as an order of magnitude, so that the time constants were discontinuous in distribution (the hierarchists would consider each keystone variable as a part of different levels or holons) or as a small number of nested cycles. The results of the review led to the hypothesis that ecosystem dynamics are organized around the operation of a few key variables, each operating at distinct speeds.

The next critical step in development of theory was the proposed hypothesis that the system should be structured in such a way that the keystone variables entrain other variables. The entrainment should occur in both spatial and temporal dimensions creating structural features that exhibit distinct gaps and lumps and temporal processes that exhibit distinct periodicities. An overt manifestation of a lumpy, discontinuous world should be expressed by attributes of the animals that live in these systems. This hypothesis was challenged by a series of tests using data from three biomes (Holling 1992). The tests using adult body mass of birds and mammals from the boreal forests, prairies and pelagic ecosystems, indicated the presence of discrete gaps that defined groups (Holling op cit.). Alternative hypotheses using developmental, historic or trophic explanations for the groupings were all invalidated, leaving only the strong inference that ecosystems (abiotic and biotic components) were similarly organized (Holling op cit.) into discreet lumps.

Hypotheses

Two hypotheses are posed in this work and arise from two of the approaches mentioned above. Both are aimed at improving understanding of the structure and function of the Everglades ecosystem that specifically relates to system dynamics and flow to Everglades Park. The first hypothesis derives from the approaches that understanding complex system behavior can be induced from modeling non-linear interactions among continuous keystone variables within a constrained range of scales. The second hypothesis is developed from the cross-scale arguments, and attempts to invalidate the lumpy, discontinuous view of the world.

Water Deliveries to Everglades National Park - The First Hypothesis Set

A dynamic water budget approach is a powerful conceptual tool for evaluation of the factors influencing deliveries to Everglades Park. The amount of water in the southern Everglades at any time is a net result of changes between inputs (rainfall and inflow), and outputs (outflow, evapotranspiration, and groundwater infiltration). Theoretically, the rates of flow and evapotranspiration are related to vegetation type and structure. Since Everglades National Park is situated at the downstream end of the historic ecosystem, it is dependent upon water from upstream sources. The water that enters the park comes from two sources: rainfall over the park and overland flow from the north. Assuming that local rainfall contributions to the park water budget are relatively unchanged, the first hypothesis deals with the contribution of upstream sources to the water requirements of the park.

Hypothesis: The effective drainage basin that supplied water to Everglades Park was the entire Kissimmee, Lake Okeechobee and historical Everglades ecosystem. Implicit in this hypothesis is that overland flow is a dominant pathway of water movement, and that hydrologic continuity throughout the historic system is crucial to maintaining water supply to the park.

Corollary: In an area as flat as the Everglades, the vegetation and hydrology are intimately coupled. The structure and type of vegetation affect both evapotranspiration rates and resistance to overland flow.

Vegetation type and structure are in turn, affected by water depths and hydroperiod. The coupling between hydrology and vegetation determines the relationship between the amount of water that flows through the system and the amount that evapotranspires to the atmosphere.

Null: The effective drainage basin was a much smaller geographic area. Overland flow into the park system originates from an effectively smaller drainage basin. This is because evapotranspirative losses are high relative to rainfall, therefore water would evaporate before moving very far downstream. Other users in the system can remove water without major disruption of the flow that entered the park historically.

Cross-Scale Patterns In The Everglades Ecosystem - The Second Hypothesis Set

The processes that influence flow to the southern Everglades cover a wide range of space and time scales. Rainfall results from atmospheric processes, ranging from meso-scale (Florida peninsula) to global dynamics. Vegetation structure can be identified at scale ranges from parts of individual plants (stems, leaves) to the organization of plant associations in the landscape. The combined processes of evaporation and transpiration occur from the level of leaf stomata to entire ecosystems. Other processes have similarly wide ranges of variation in space and time.

In order to attempt to invalidate the first hypothesis, the methodology requires that the world of the Everglades be "squeezed" into a framework of fixed spatial and temporal domains. The second hypothesis is based upon the emerging theory which suggests that across scale ranges, ecosystems are organized in such a way so that clumps and gaps appear in structural features while a small number of cycles and harmonics occur in temporal features.

Hypothesis: The Everglades ecosystem is structured by a small number of processes, of which hydrology and vegetation are one set of keystone variables. Over a range of scales, patterns produced by vegetative and hydrologic processes should have a few characteristic domains in space or time that are separated by discontinuities. Within the time domain, a few dominant frequencies or cycles should emerge in the hydrologic processes of rainfall, water level, flow and evapotranspiration. Within the spatial domain, a few groupings of object size (such as vegetation patches), or texture will emerge that correspond to levels in a spatial hierarchical structure. Other ecosystem level processes, such as topography and fire, will exhibit similar patterns.

Null: Over a range of scales, the temporal patterns of hydrology and spatial patterns of vegetation in the Everglades will exhibit structures that correspond to underlying continuous distributions . No dominant or nested cycles will appear in the time patterns of hydrologic processes such as rainfall, water level, flow or evapotranspiration. No breaks or discontinuities in the spatial patterns will be found, and patterns will be self-similar over a wide range of scales.

Objectives

The aim of this work is to develop new understanding of ecosystem dynamics by testing hypotheses regarding water and vegetation dynamics that are rooted in two different viewpoints. There are two main objectives: 1) use "scale-bound" modeling techniques to help understand factors influencing water deliveries to Everglades Park, and 2) apply cross-scale analyses to Everglades data sets to test for breaks or discontinuities in patterns.

The first objective will involve the construction of a spatially and temporally explicit model to capture the dynamics of the system in order to test the first hypothesis. The model will couple dynamics of hydrology and vegetation within a spatial domain of two orders of magnitude and a temporal domain of almost three orders of magnitude. The model will be used to attempt invalidation of the proposal that the entire basin contributed water to the southern Everglades. This objective is the focus of Chapter 3.

The second objective will be to develop, test and apply a variety of cross-scale methods to identify patterns in keystone variables in the Everglades ecosystem. Since the theory of cross-scale interactions is just emerging, a great deal of this work has been devoted to the development of new methods and methodology. Fortunately, this work was able to reap the benefit of data sets of many variables that have been collected over the years on different portions of the Everglades system. The methodology, and results of the cross-scale analyses are the subject of Chapter 4.

CHAPTER 3.
MODELING THE "RIVER OF GRASS"

When your only tool is a hammer, the answer to every problem is a nail.

-R. Yorque

Almost 50 years ago, Marjory Stoneman Douglas created a dramatic image when she described the Everglades as a "River of Grass" (Douglas 1947). Technically, neither of these terms are appropriate. The system is hardly a river because there is no defined water course and water flows very slowly, only about 60 kilometers a year. The "grass" in the title refers to sawgrass, which is properly classified as a sedge. However, the metaphor is still appropriate because it can be interpreted to depict the coupling of the vegetation and hydrology in this ecosystem that at one time, was a united ecosystem.

In this chapter, the test of the first hypothesis that the entire Everglades system provided water to Everglades National Park and test of the corollary hypothesis regarding the coupling of vegetation and hydrology, are presented. These hypotheses were tested with a model that incorporates coupled vegetation and hydrologic dynamics over time within an explicit spatial array. Hydrologic models of the Everglades system have been used to evaluate management options within the current system configuration (MacVicar 1985) or to create views of the system prior to human intervention (Walters et al. 1992, Perkins and MacVicar In prep.). Such models provide a robust methodology from which the contributions of upstream areas to flow into the southern Everglades can be evaluated. Key uncertainties in these models include information about overland flow resistance and evapotranspiration and infiltration to groundwater.

In a system as flat as the Everglades, vegetation influences surficial hydropatterns by mediating resistance to flow and controlling evapotranspiration. Hydrologic regimes also influence the vegetation pattern (Davis 1943, Craighead 1971, Gunderson 1989). The corollary hypothesis posits that the interactions between hydropatterns and vegetation patterns are coupled and create feedback loops. None of the previously developed hydrologic models of the Everglades incorporate complete feedbacks between hydrology and vegetation. The SFWMD models (MacVicar 1985, Perkins and MacVicar, In prep.) vary flow and evapotranspiration by land cover types, but the land cover types do not change as a function of hydrology. The model of Walters et al. (1992) changes vegetation types as a function of hydrology and other factors, but has spatially fixed flow and evapotranspiration rates. The approach in this work, therefore, is to couple vegetation and hydrologic feedback dynamics in the framework of existing models to test hypothesis about upstream area contributions to the park.

This chapter is divided into four sections: background, model development, results and summary. A fair portion of this chapter is devoted to improving understanding of the interactions among evapotranspiration, flow and vegetation since they are key uncertainties in the model. The background section will develop a theoretical base for understanding these processes and the results of studies that compares evapotranspiration rates among vegetation communities of the Everglades in order provide a foundation for the linkages in the model. Following the background section, the model is described including components and their interactions. The section following the model description presents the results of testing the upstream area hypothesis and the corollary hypothesis regarding the coupling of vegetation and hydrologic processes. This chapter is concluded with a summary of modeling the "River of Grass" and implications of the results to policy and management.

Background

Evapotranspiration in Wetlands

Evapotranspiration is the combined processes of water flux into the atmosphere by evaporation from water or soil surface and transpiration from vegetation. In an area such as the Everglades, both processes are in effect, as there are areas of relatively sparse vegetation (open water marshes), grassy wetlands and forested wetland communities. In addition to the interaction between evapotranspiration and vegetation, other physical variables influence the rate of water flux. All of these variables, and measures of evapotranspiration, appear to vary across scales of interest. Previous studies on evapotranspiration in the Everglades have been made at different scales, and will be reviewed below in relation to spatial and temporal groupings, but first a review of theoretical background.

Evapotranspiration is a component of the energy budget. A general formulation for steady state system at a specific location is shown in equation (1), modified from Brutsaert (1984), and Viessman et al. (1989). The amount of net solar radiation (ambient minus reflected) determines the amount of energy available for other processes. The energy can be used to increase the temperatures (sensible heat) of both the atmosphere and the soil substrate. Some of the energy is used in photosynthesis, and some may be moved by advection (wind) to other areas. The other energy is used for the phase transition of water from liquid to vapor. Since the evaporative process requires energy for the phase transition, the energy is not measurable or latent. The latent heat of evaporation times the rate of evaporation describes the evaporation term in the energy budget equation.

(1) $R_n = L_eE + H + G + P + A$

R_n	=	specific flux of incoming net radiation
L_e	=	latent heat of evaporation
E	=	rate of evaporation
H	=	specific flux of sensible heat into the atmosphere
G	=	specific flux of sensible heat into the ground
P	=	rate of energy used in photosynthesis
A	=	rate of lateral advection of energy

Due to difficulties in measurement of the latent heat of evaporation and the confounding effects of vegetation influences on the processes, a number of techniques have been developed to measure evapotranspiration. The techniques fall into two categories, those that derive from energy budget, with certain simplifying assumptions and those that are empirical. Penman (1948) derived a formula that includes a wind (advection) term with assumptions of constant Bowen ratio (ratio between sensible and latent heat) that allows for measurement at one level. Other techniques derive from the Dalton formulation that estimates a vapor gradient between the surface and the atmosphere. Empirical methods include formulations by Blaney-Criddle (1950) who related evapotranspiration with average temperature; Holdridge (1967) who related vegetation form to temperature and potential evaporation and simple techniques such as pan evaporation or lysimetry.

Evapotranspiration is influenced by a mixture of processes that occur at different scales in space and time. Solar insolation at a spot on the earth fluctuates on daily, annual and multiple year cycles. The solar radiation is also influenced by fast (on the scale of minutes) fluctuations in processes, such as cloud cover. Vegetation both directly and indirectly influences the evapotranspirative processes. The fastest controls vegetation occur at the level of the stomata, where water flux is linked to photosynthesis (Jarvis and McNaughton 1986). Individual plant species' genetic composition and adaptations influence the size and density of stoma, leaf orientation, responses to various changes in insolation, wind, humidity and temperature (Jarvis and McNaughton 1986). The composite architecture of the canopy in wetlands can influence the reflectance of both short and long wave radiation, with implications to net energy and water use (Odum 1984, McClanahan and Odum 1991). At the landscape or regional level, the vegetation cover type influences the reflectance or albedo.

The preceding paragraphs gave a brief review of evapotranspiration theory to provide a basis for understanding the various approaches and techniques for measurement of this complex process. The following section will present the results of previous investigations and present published measurements of rates of evapotranspiration at different spatial and temporal scales.

Measurements of Evapotranspiration in southern Florida

Measures of evapotranspiration in southern Florida have also been made at different scales ranging from local up to the entire peninsula. For convenience, these can be grouped for discussion into broad-scale measures that include the region and basins, medium scale measures (less than 10 m on a side) typified by lysimeters, and evaporation pans and small scale measures that examine losses from leaf surfaces.

For the region, Dohrenwend (1977) used an empirical formula developed by Holdridge (1967) that related evaporation and mean annual biotemperature to calculate an annual evapotranspiration of about 1000 mm. Input-output analyses of basins in and around the Everglades calculate a range of values of evapotranspiration that are similar. Allen et al. (1982) estimated annual evapotranspirative losses from 890 to 1040 mm from Taylor Creek basin north of Lake Okeechobee. Leach et al. (1971) estimated evapotranspiration from the Water Conservation Areas at 965 mm/yr. Shih et al. (1983) estimated water losses from the Everglades Agricultural area at 1018 mm/yr using a water budget approach and also compared a number of other techniques and found annual means ranging from 1018 to 1035 mm.

Most of the smaller scale investigations involve the use of lysimeters (tanks with planted vegetation), evaporation pans or shallow wells to derive monthly and annual estimates of evapotranspiration. Clayton et al. (1949) planted sawgrass in lysimeters and found monthly ranges of 78 to 208 mm and mean annual losses of 1735 mm. Parker et al. (1955) estimated evapotranspiration from pan evaporation and reported annual values from 1016 to 1143 mm. The Army Corps of Engineers (1968) reported monthly values from 63 to 135 mm. Shih (1981) compared average monthly and annual evapotranspiration among sugarcane, alfalfa, and bahiagrass plants planted in lysimeters with data from Clayton (1949). Shih (1981) found a range of monthly values from 35 mm to 212 mm for sugarcane. Other crops were within these monthly averages, and had lower annual totals. Carter et al. (1973) derived annual estimates of 1100 mm for the Big Cypress Swamp area, immediately west of the Everglades.

A number of studies attempted to develop relationships between evapotranspiration (from lysimeters) and climatological data. Most assume constant Bowen ratio; that is, a constant proportion between the sensible heat flux and the evapotranspiration. Stephens and Stewart (1963) found that best approximation to lysimeter values of potential evapotranspiration were based upon a fraction of ambient radiation. Shih (1981) found good correlation between lysimeter losses and monthly temperature corrected for cloudy days, a modification of the Blaney-Criddle technique. Stewart and Mills (1967) and Shih (1983) both measured decreasing evapotranspiration rates with declining, subsurface water levels.

Perhaps the fewest studies have been done at the level of the individual or on a daily basis. Brown (1981) studied pondcypress in southern Florida, and measured average daily losses at 1.3 mm/day. Dolan et al. (1984) working to the north measured daily marsh evapotranspiration from 0.5 to 10 mm/day. One small scale study (Alexander et al. 1976) compared evapotranspiration rates of potted seedlings of sawgrass and *Melaleuca*..

Different variables operating at different space and time scales have been shown to influence evapotranspiration. Some variables, such as radiation are spatially global; that is, they remain the important input to the process across all scales. Other variables, such as leaf stomata, dictate fine scale (leaf level) control, but cease to be important at the regional scale (Jarvis and McNaughton 1986). More work has been done on scaling measures of evapotranspiration over the time domain by increasing the extent or window (day to month to year). Authors working in southern Florida (Stephens and Stewart 1963, Shih 1981, and Carter et al. 1971) all recognized a decrease in variation as the time unit is increased.

In reviewing the available literature, few measurements of evaporation or transpiration from the native plant communities in the Everglades have been published. In order to incorporate community level measures into the model, a series of studies were done to develop measures of water loss by community type. The studies were important for two reasons, 1) to establish that evapotranspiration rates varied among the major vegetation communities, and 2) to estimate the magnitude of any differences. If there was no difference among the vegetation types, then evapotranspiration could be modeled by a variable that only changed in time and not over space. If there was a difference in water loss rates among the vegetation communities, then maps of vegetation communities could be used to develop spatial patterns of evapotranspiration.

The next section of this chapter reports on the summary of two studies using two different methods to calculate rates of evapotranspiration among the dominant native plant communities. The first study uses transpiration rates reported in Herndon and Gunderson (1989), and, with a few assumptions, attempts to aggregate from the leaf level to the community. The second study uses data reported by Gunderson and Stenberg (1990) on evapotranspiration from two wet prairie sites. The measures reported in these two studies will be summarized for use in the model.

Transpiration from Three Everglades Plant Communities

The rates of water flux from the leaves of dominant species in three community types; sawgrass, tree island and marl prairie. (wet prairies had no macrophytes) were measured. The measurements of leaf transpiration were multiplied by the leaf area per vegetation type to yield community estimates. Water flux rates (millimoles/cm^2/sec) from the leaf surfaces were measured using a steady state porometer (Li-Cor Model 1600). During the period from

December 1984 through February 1986, measures were made at 10 am, 12 pm and 2 pm local time during one day every other month. At each sample period a total of thirty measurements were made at random locations within the community. The thirty measurements were combined to give an average flux for each period. The rates of water loss were integrated over the day in order to yield a water loss per day. To translate or scale these measures to a community level, estimates of leaf surface area were made for each community type. All leaves within a one meter square area were counted and leaf areas measured to yield a leaf area/ m^2.

Transpiration rates did not vary much among the vegetation types sampled. Mean and range of water fluxes (transpiration) from the leaf surface were determined from the field measures. Sawgrass transpiration ranged from a low of 0.9 $mmol \cdot m^2 \cdot sec^{-1}$ during December 1985 to a high of 3.2 $mmol \cdot m^2 \cdot sec^{-1}$ in July of 1985 (Table 3). Muhly grass, *Muhlenbergia filipes*, the co-dominant species in the marl prairie, had similar rates, ranging from 1.6 to 2.4 $mmol \cdot m^2 \cdot sec^{-1}$ (Table 3). The swamp forest species showed similar transpiration, with values ranging from 1.8 to 3.0 $mmol \cdot m^2 \cdot sec^{-1}$ (Table 3). A one-way analysis of variance was performed, and indicated no significant difference in daily transpiration among vegetation type. A second analysis of covariance that removed the seasonal trend in the data, also indicated no significant difference in transpiration rates among the species monitored.

Daily water losses per community type were estimated by first calculating daily transpiration and multiplying by leaf area per community type. Daily transpiration was calculated by multiplying a six hour day length times the leaf transpiration rates. A six hour day was thought to reflect an average period of daily metabolic activity through out the year and probably underestimates daily transpiration in the summer and overestimates wintertime values. Estimates of

Table 3. Daily transpiration rates for three vegetation types in the Everglades.

VEGETATION TYPE	DATE	TRANSPIRATION RATE Mean	High	Low	DAY LENGTH (sec/day)	DAILY TRANSPIRATION Mean	High	Low	LEAF AREA m2 LA/ m2 g	WATER LOSS Mean	High	Low
		mmol/m2 LA/sec				cc/m2LA/day				cm/day	cm/day	cm/day
Sawgrass	Jan-85	1.4	1.5	0.8	21600	544	583	311	2.44	0.13	0.14	0.08
	Mar-85	2.1	2.4	1.9	21600	816	933	739	2.44	0.20	0.23	0.18
	May-85	2.4	2.8	1.9	21600	933	1089	739	2.44	0.23	0.27	0.18
	Aug-85	2.0	2.1	1.7	21600	778	816	661	2.44	0.19	0.20	0.16
	Oct-85	1.7	1.7	1.2	21600	661	661	467	2.44	0.16	0.16	0.11
	Dec-85	0.9	1.2	0.2	21600	350	467	78	2.44	0.09	0.11	0.02
Sawgrass	Dec-84	1.9	2.1	1.1	21600	739	816	428	0.67	0.05	0.05	0.03
	Feb-85	1.1	1.2	1.0	21600	428	467	389	0.67	0.03	0.03	0.03
	Apr-85	2.0	2.2	1.9	21600	778	855	739	0.67	0.05	0.06	0.05
	Jul-85	3.2	4.0	2.2	21600	1244	1555	855	0.67	0.08	0.10	0.06
	Sep-85	1.7	2.1	1.5	21600	661	816	583	0.67	0.04	0.05	0.04
	Dec-85	1.0	1.8	0.2	21600	389	700	78	0.67	0.03	0.05	0.01
Marl Prairie	Feb-85	1.8	2.4	1.4	21600	700	933	544	0.22	0.02	0.02	0.01
(muhly grass)	Apr-85	2.4	2.6	1.2	21600	933	1011	467	0.22	0.02	0.02	0.01
	Jul-85	2.0	2.1	1.9	21600	778	816	739	0.22	0.02	0.02	0.02
	Sep-85	1.6	1.9	1.0	21600	622	739	389	0.22	0.01	0.02	0.01
	Dec-85	1.6	2.1	0.6	21600	622	816	233	0.22	0.01	0.02	0.01
Swamp Forest	Jan-85	1.8	3.2	1.5	21600	700	1244	583	5.00	0.35	0.62	0.29
	Mar-85	2.5	3.2	1.2	21600	972	1244	467	5.00	0.49	0.62	0.23
	Jun-85	3.0	4.8	1.5	21600	1166	1866	583	5.00	0.58	0.93	0.29
	Jul-85	2.8	3.5	1.8	21600	1089	1361	700	5.00	0.54	0.68	0.35
	Oct-85	2.0	2.5	1.5	21600	778	972	583	5.00	0.39	0.49	0.29
	Jan-86	1.8	2.2	1.4	21600	700	855	544	5.00	0.35	0.43	0.27

leaf area per m^2 of ground area were multiplied times the daily transpiration to yield a community water loss.

Seasonal trends in community transpiration among the three types were most evident in the swamp forest (Figure 3), and less evident in the marl prairie. Transpiration was measured from all three vegetation types throughout the year, indicating year round metabolic activity and no dormant period.

Analyses indicated a significant difference in water loss among the vegetation types, due to differences in leaf area. A one-way analysis of variance and one-way analysis of covariance (removing seasonal trend) both indicated a significant difference in daily water loss among the three vegetation types. Water loss rates from the marl prairie vegetation was the lowest, with an annual mean of 0.016 cm/day. Average loss from the sawgrass marsh was 0.16 cm/day and from the swamp forest 0.45 cm/day. *Posteriori* contrasts indicated that these three types were significantly different.

In summary, estimates of water loss using the technique of scaling from small scale transpiration to community values are dependent upon the vegetation structure more than the flux rates. The water flux from the leaf surfaces tend to vary seasonally, and do not exhibit differences among vegetation type. Significant differences in water loss do appear to exist among community types and appear to be related to the amount of leaf area present.

Measurements of community evapotranspiration

Other estimates of community evapotranspiration were made using recorded tracings of water levels in shallow wells at two sites in Everglades National Park. One well is designated P33 and is surrounded by wet prairie on peat vegetation type. The other well is designated P37 and is situated in a wet prairie on marl.

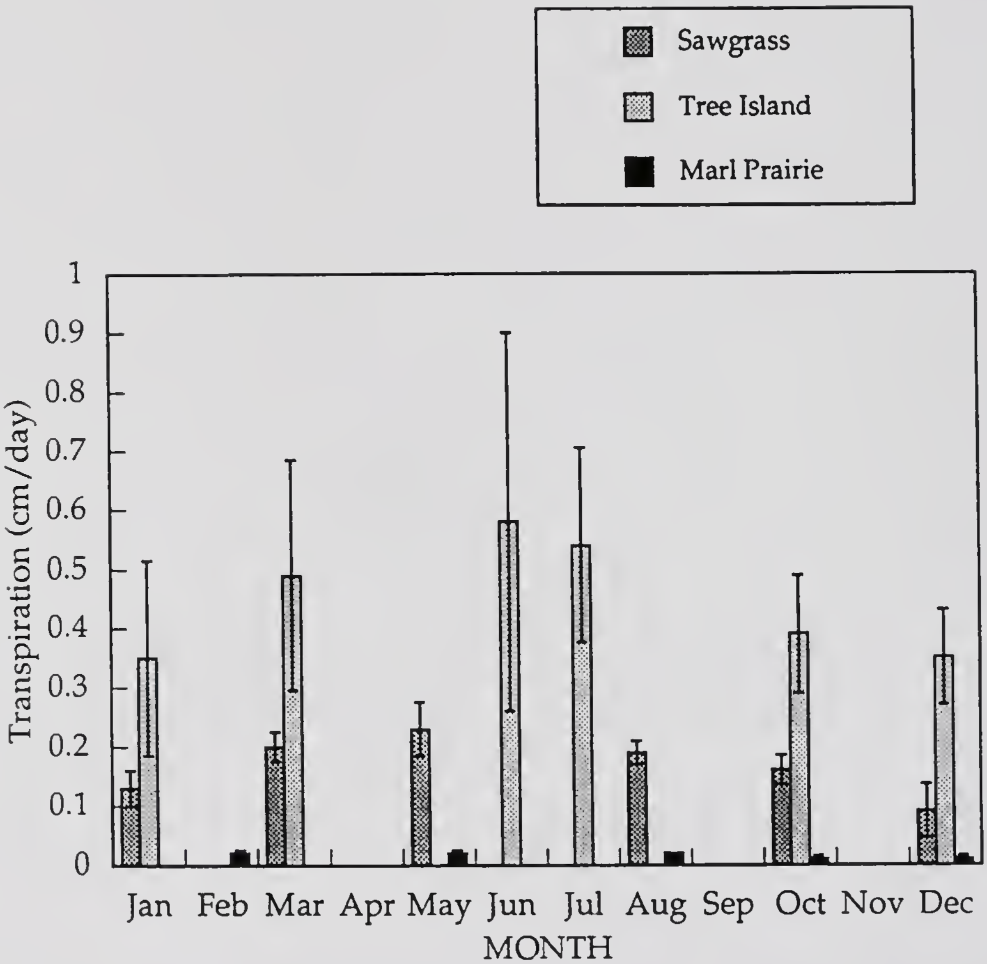

Figure 3. Mean daily transpiration rates from sawgrass, tree island and marl prairie plant communities.

Evapotranspiration was estimated by comparing nighttime water losses with daytime water losses, similar to the technique reported by Dolan et al, (1984). The method is based upon the assumption that the only difference between daytime and nighttime recession rates is due to evapotranspiration. The technique is not useful on days with rain.

Rates of community evapotranspiration were different between the wet prairie on peat and marl prairie sites. Mean daily water loss rates from the marl prairie, calculated for each month of available data, ranged from a low of 0.10 cm/day during December to a high of 0.28 cm/day during June (Figure 4). This translates to a mean annual total water loss of about 77 cm at the marl prairie site. Daily rates were higher at the peat site. Anomalously high rates were observed during June 1985, when the mean daily rate was 1.15 cm/day. This occurred during a period of high temperatures, little rainfall and low ambient water levels. Annual water loss at the peat wet prairie site was about 114 cm. The mean difference between sites was 0.10 cm/day, (significant at $P = 0.001$), indicating dramatically higher water loss rates at the peat site than at the marl prairie site.

Mean daily evapotranspiration rates at the marl prairie (P37) followed a smooth sinuous pattern over the time course of a year (Figure 4), whereas the peat prairie site had dramatic anomalies during the early part of the summer. The variation over time was summarized as percentages of annual water loss for each month for use in the modeling section.

Summarization of Evapotranspiration Studies

The transpiration studies indicate that a difference in community transpiration exists among the types studied, that comprise a hierarchy of water

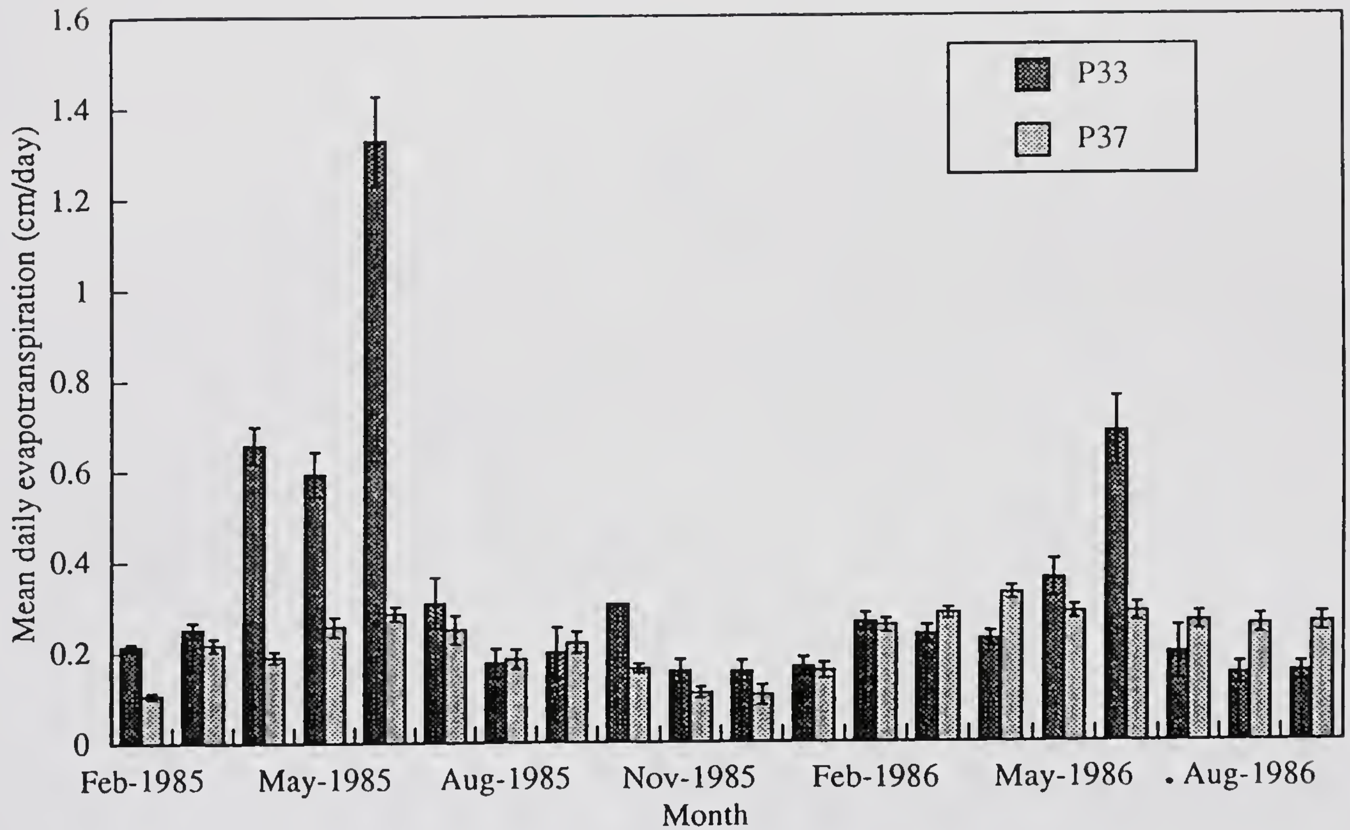

Figure 4. Time course of mean daily evapotranspiration (cm/day) at study sites P33 and P37 from February 1985 through September 1986.

use in the landscape. The variation in community rates is due to dramatic differences in leaf area among the vegetation types, more than losses per leaf area. The marl prairie has low rates of transpiration, has a small total leaf area per unit ground area, and is the most oligotrophic of the sites. The sawgrass sites on peat have higher leaf area and community transpiration rates. The highest transpirative water loss is from the tree island/swamp forest community, due to higher rates and highest leaf areas. The swamp forest appears to be the most eutrophic of the sites.

The studies of community evapotranspiration, indicate that differences among types exist, the components of evaporation and transpiration vary among the types. The transpiration and community evapotranspiration data both indicate the fluctuation in rates over an annual cycle. Even though the rates fluctuate seasonally, a mean daily rate will be used as the basis of comparison among types and pathways of water loss. The P37 site is the only one of the sites to have both transpiration and community estimates. The transpiration estimates (0.02 cm/da) were about an order of magnitude lower than the community estimates (0.2 cm/day), indicating that transpiration is not a large pathway of water loss. The wet prairie on peat site (P33) had a higher daily rate (0.3 cm/day) than the marl prairie. The wet prairie rates were higher than the daily transpiration rates in the sawgrass and lower than the transpiration rates at the tree island site.

Evapotranspiration is one major pathway of water flow out of wetland ecosystems. The other major outflow is via overland flow. The theoretical and practical work studying this process will be reviewed in the next section.

Flow in Wetlands

Surface water flow in wetland ecosystems has been studied using principles of applied hydraulics. The theoretical foundations for flow arise from hydraulic principles, although there appears to be disagreement in the literature as to the fundamental nature of flow regimes. A unique functional feature of wetland systems is the periodic flooding and flow followed by periods of no flow. This periodicity involves transitions among flow regimes from no flow to laminar flow to turbulent flow. Most studies of wetland flow (Ree 1949, Petryk and Bosmajian 1975, Lin and Shih 1979, Rosendahl and Probst 1980, Rosendahl 1981, Shih and Rahi 1982) assume a turbulent flow regime and utilize Manning's formula (Manning 1890). Kadlec (1990) argues that laminar flow is dominant in wetlands due to the low energy gradients and suggests a formulation such as the one given in Equation (2) be used. Wetland flow is of the magnitude that momentum terms in flow equations are usually ignored (Kadlec 1990, Hammer and Kadlec 1992). The disagreement involving flow regimes can be partially resolved as one of parameter values, as shown in Equation (2). Equation (2) is a generalization of the Manning equation relating flow velocity as a function of hydraulic radius and hydraulic slope. The critical parameters are α and β and are assigned values of $\alpha = 0.5$ and $\beta = 0.67$ in the Manning formula. Kadlec (1990) reports values of α range from 0.4 to 1.0 and β from 2.5 to 3.75 for laminar flow in wetlands.

(2) $V = K * S^{\alpha} * R_h^{\beta}$

V = velocity

K = general resistance coefficient

S = Hydraulic slope (difference in elevation potential)

R_h = Hydraulic radius (Cross-sectional area/wetted perimeter: Note for very wide channels, Rh is approximated by water depth)

α = slope exponent

β = hydraulic radius exponent

In Manning's formula, K is represented by 1/n in SI units (1.49/n in English units), and n is referred to as a roughness coefficient or as Manning's n.

Assuming turbulent regimes, most prior work on wetland flow has attempted to develop better estimates of Manning's n, and particularly how this coefficient varies with factors of water depth and vegetation density. The earliest work relates n with water depth (Ree 1949) and the product of velocity and water depth (Palmer 1945). Ree worked with flow in short grasses and found an increase in n with depths up to the height of the grass, then a decrease, similar to Palmer. Petryk and Bosmajian (1975) laid much conceptual framework, and related n as a function of vegetation characteristics (primarily vegetation density), boundary roughness and hydraulic radius. Petryk and Bosmajian (1975) thought that vegetation resistance was much greater than boundary roughness, and hence related n to vegetation density and inversely to hydraulic radius; for n to remain constant vegetation density had to decrease if depth (R_h) increased. Shih and Rahi (1982) using principles of Petryk and Bosmajian (1975), developed estimates of n from 0.16 to 0.55 for marshes in the Kissimmee basin, where n varied with seasonal changes in vegetation density.

Studies of flow in the marshes of the Everglades date back to the 1940s, with the earliest work (Parker et al. 1944) measuring decreased flow in canals resulting from infestations of water hyacinths. The U.S. Army Corps of Engineers developed estimates of Manning's n in design memoranda for the C&SF project, that averaged 0.035 and ranged inversely with water depth (U.S.

Army 1954). Leach et al. (1971) investigated data from a series of years and found maximum flow rates of 1600 ft/day (0.6 cm/sec), which translate to a cumulative annual distance of 50 miles (81 km). Rosendahl and Probst (1980) and Rosendahl and Rose (1981) measured flow rates and resistance coefficients in sawgrass and open marshes in Everglades National Park and reported greater flow rates; from 0 to 0.022 ft/sec (0.67 cm/s) in dense sawgrass strands and from 0 to 0.034 ft/sec (1.0 cm/s) in open marshes. Rosendahl (1981) calculated a range of values of Manning's n between 0.4 and 2.4, with a mean of 0.99 and found little correlation with depth.

Most of the models of water flow in the Everglades marshes use Manning's equation and with varying reports as to the sensitivity of model output to variations in the roughness coefficient. Lin and Shih (1979) used values of n between 0.4 and 1.2, with an inverse relationship between n and depth. Lin and Shih (1979) found that seasonal variation in n was necessary to achieve model calibration, with lower values in the dry season and higher values in the wet season. MacVicar et al. (1983) relate flow coefficients as a function of land cover type, with values ranging from 0.1 to 2. Perkins and MacVicar (In press) did a sensitivity analysis using very low value of n (0.05) and very high (2.0) and found more effect on flow volume than stage, recommending development of better coefficients with vegetation type. Walters et al. (1992) developed a coefficient of flow equivalent to K in equation 2, of 2, which translates to a Manning's n of 0.75.

A review of previous studies involving flow in wetland systems can be summarized as follows. Although there is still uncertainty regarding the nature of the flow regime, a generalized form of Manning's equation can be used. The equation equates flow velocity as a function of water depth, hydraulic slope, and a resistance coefficient, such as Manning's n. The flow coefficient can be estimated from vegetation density, defined as the total cross-sectional area of vegetation per unit length of flow (Petryk and Bosmajian 1975)

In the preceding sections, the processes influencing the measures of evapotranspiration in south Florida and flow relationships in wetlands were discussed in context of scale. The way in which these processes are incorporated into a landscape model is primarily a scaling issue. The details of how this scaling process was done is described below in the section on modeling methodology. A brief review of some general concepts and approaches to scaling in ecological models is included as a final piece in this background section.

Ecological Models and Scale

Most descriptive landscape or ecosystem models have explicit domains in space and time. Temporal domains are defined at the small end by the time step and at the large end by the time horizon. Similarly, spatial grain is defined by the size of grid cell and extent by the number of grid cells. Bounding the model along spatial and temporal dimensions, defines what is inside and outside the model domain in terms of scale. The empirical rule of thumb is that models cover no more than two to three orders of magnitude in either space or time. The rule is probably not related to technical constraints such as computer processing power (Costanza and Maxwell 1992). The scale restriction may be related to practical factors, such as debugging problems, validation criteria (Clark et al. 1979), or understanding the model (Costanza and Sklar 1985).

By using an ecological model with a fixed domain, decisions must be made about what to do about processes that occur at different scale ranges. The common approach in model construction is to treat processes that occur at slower speeds and over broader ranges as constants. For example, if a model is constructed to examine seasonal dynamics in sea level, then the global processes that created a dramatic sea level rise between 5 and 10 thousand years ago, are assumed to not change much over the course of a few years and therefore are treated as constant. Faster processes are generally treated as noise or random fluctuations within the system and can be averaged. Using the same example, tidal influences on sea level occur over a short term and therefore can be treated as noise over time spans of a year. The short term (daily) influences are averaged to study seasonal or annual dynamics.

Components both inside and outside model structures are dealt with by processes of aggregation and disaggregation. The simplest form of aggregation is linear scaling. Scaling is defined as the translation of units based upon a fixed relationship or ratio among metrics used in measurement. For example, temporal metrics of minutes, hours, and days have a fixed relationship, therefore one can trivially determine that one day is equal to 1440 minutes. Broadly, the issue of aggregation has been dealt with either in terms of applying standard statistical methods to derive "best" estimates and minimize error (O'Neill et al. 1986, Gardener et al. 1982), or by assuming linear aggregations among complex variable sets (Iwasa et al. 1986, 1989). Basically, aggregation works if the assumptions and rules used remain valid over the scales of translation.

Incorporation of evapotranspiration, flow and vegetation dynamics into a spatially and temporally explicit hydrologic model of the Everglades involves "fitting" these into a model with explicit bounds in time and space. The next section describes the structure and development of the model used to investigate hydrodynamics in the system.

Model Description and Development

The framework for the model was developed during a series of workshops held between 1989 and 1990. The initial objective of the model was to improve communication among scientists, engineers and practitioners in order to discuss issues related to Everglades restoration. The model resisted a series of attempts at invalidation (Walters et al. 1992, Richardson et al. 1990) and hence has become a credible tool for examination of movement of water across the landscape. The model framework depicts the time dynamics of the hydrology within approximately 800 4 x 4 km grid cells (Figure 5) that cover the historic Everglades ecosystem and surrounding areas. The model is bounded by Lake Okeechobee to the north, the Atlantic coastal ridge to the east, Florida Bay to the south and the Big Cypress National Preserve to the West (Figure 5). The basic framework reported by Walters et al. (1992) was modified to include coupling of vegetation and hydrology. The hydrology and vegetation components of the model are described in the next two sections, followed by the development of subroutines of evapotranspiration and flow that link the hydrologic and vegetation components.

Hydrologic Components

Water depths within a cell change over time due to inflow associated with rainfall, losses via evapotranspiration, net flux associated with overland runoff from adjacent cells and net flux of water into or out of canals. The model is driven by historic rainfall data, covering the period from January 1960 through December 1988. Input data are of total monthly rainfall, averaged over the entire basin area. Even though spatial gradients exist in the system (MacVicar and Lin 1984) equal amounts are added to each cell at the beginning of each simulated month. Annual rainfall during the model time period ranges from 100 to 150

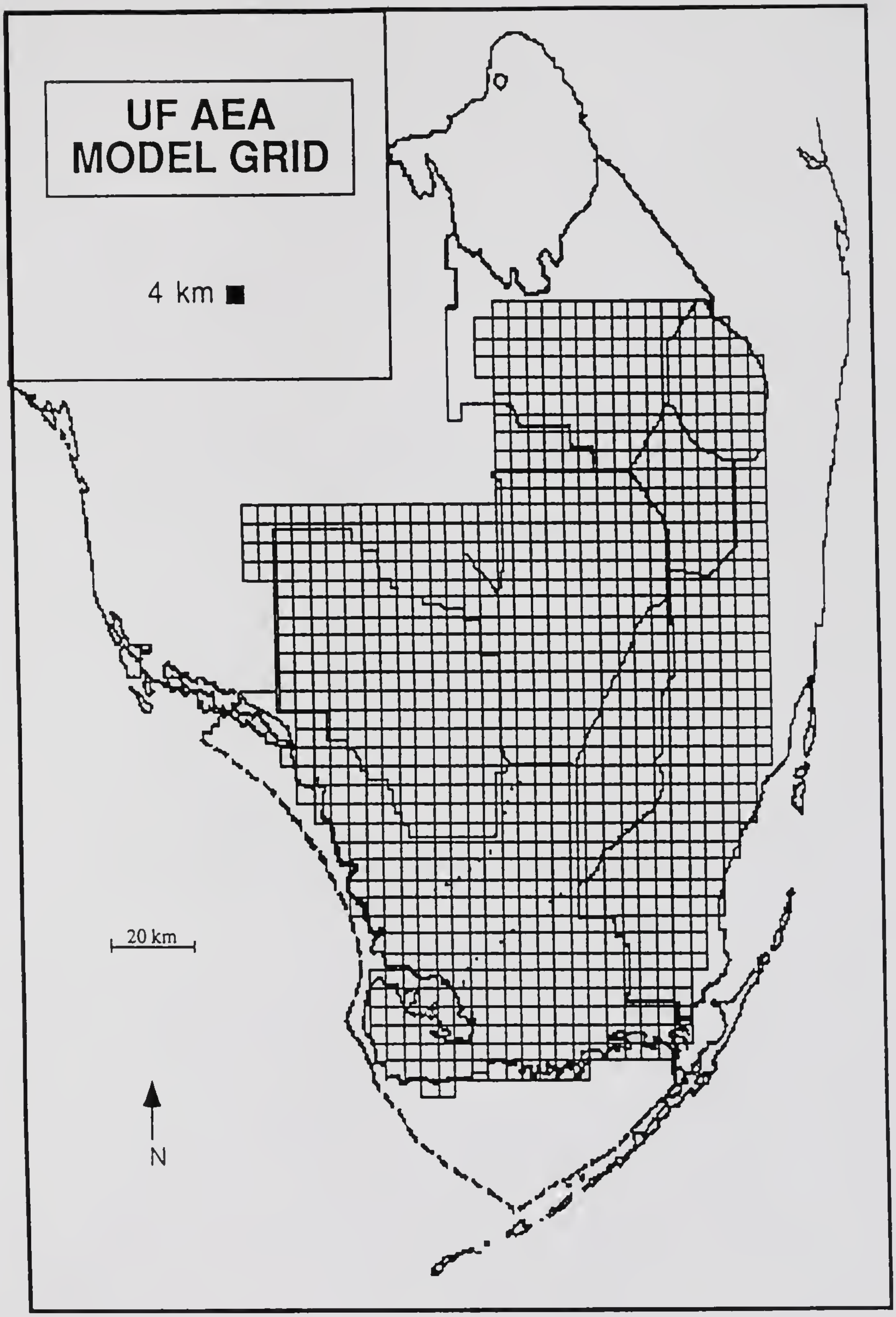

Figure 5. Model grid used to depict hydrologic and vegetation dynamics in Everglades ecosystem.

cm/yr. The input to a cell is actually as net rainfall; that is, the recorded rain total minus evapotranspiration.

Water is moved to adjacent cells based upon the Manning formula, where velocity is a function of hydraulic slope, water depth and a resistance coefficient (Equation 2). The alpha and beta values from equation 2 are 0.5 and 0.67. Hydraulic slope is determined by difference between adjacent cells in the sum of ground elevation and water depth. Levees in the model stop flow movement.

Water management is incorporated in the model by a series of water management schedules within each conservation area and rules of water movement around the schedules. If water levels at index cells are above the monthly schedule, then water is removed from certain output cells. If water levels are below scheduled levels, then water is retained. Water is diverted to coastal areas by removal from key index cells to simulate removal via canals. Target diversion rates are a function of maximum diversion (flow allowed in a canal) and water depth.

Only surface water movement is calculated; no losses to groundwater are included. In the peat areas of the system, with high infiltration resistance, this is not considered to be a major source of error. In the transitional, sandy and marl areas, movement from surface to groundwater is considerable, resulting in overestimates of water depths.

The modeled area exchanges water with the surrounding areas. Water is input from Lake Okeechobee, based upon decision rules and schedules within the Lake. The Big Cypress regions to the west receives the same rainfall inputs as areas over the Everglades proper. Water exchange with this area is only constrained by structures in the model. No exchange (other than management diversion) is made with the east, even though under historic conditions water moved through the coastal ridge through a number of rivers, sloughs and finger glades. Boundary conditions at Florida Bay vary seasonally from a low value in winter to a high value in late fall, to reflect the annual dynamics of sea level.

Information on water depth and flow over time can be output for each grid cell. Target cells that correspond to the locations of sites P33, P35, P37 and P38 (Figure 6) were used as key indicators of model results. Cumulative annual flow amounts were determined for three flow sections. One is for the set of cells that coincide with the Tamiami Trail Flow section (Figure 6). The other sections are at the boundary cells at the mouth of Shark River Slough, and at the mouth of Taylor Slough.

The preceding paragraphs summarized the hydrologic variables and interactions within the model framework. The next section deals with the structure of the vegetation component of the model.

Vegetation Components

A total of 26 cover types were created to capture the variety of vegetation patterns in the landscape of the model area (Table 4). The types were based upon combinations of plant associations, as a grid cell of four kilometers generally covers a non-homogeneous combination of plant communities. Some of the vegetation types, such as sawgrass, can be the only type within some grid cells. Other types, such as sloughs and tree islands are always smaller than the grid cells. To determine the percent cover of vegetation communities within the dominant landscape types, and how robust the measures of percent cover were with a change in scale, the following exercise was done.

Vegetation cover was measured in a series of subsamples from the two classified sixteen kilometer SPOT satellite scenes used in the vegetation map section above. A total of thirty two samples were made (sixteen from each scene), for window sizes of 500, 1000, 2000 and 4000 m. Percent cover was

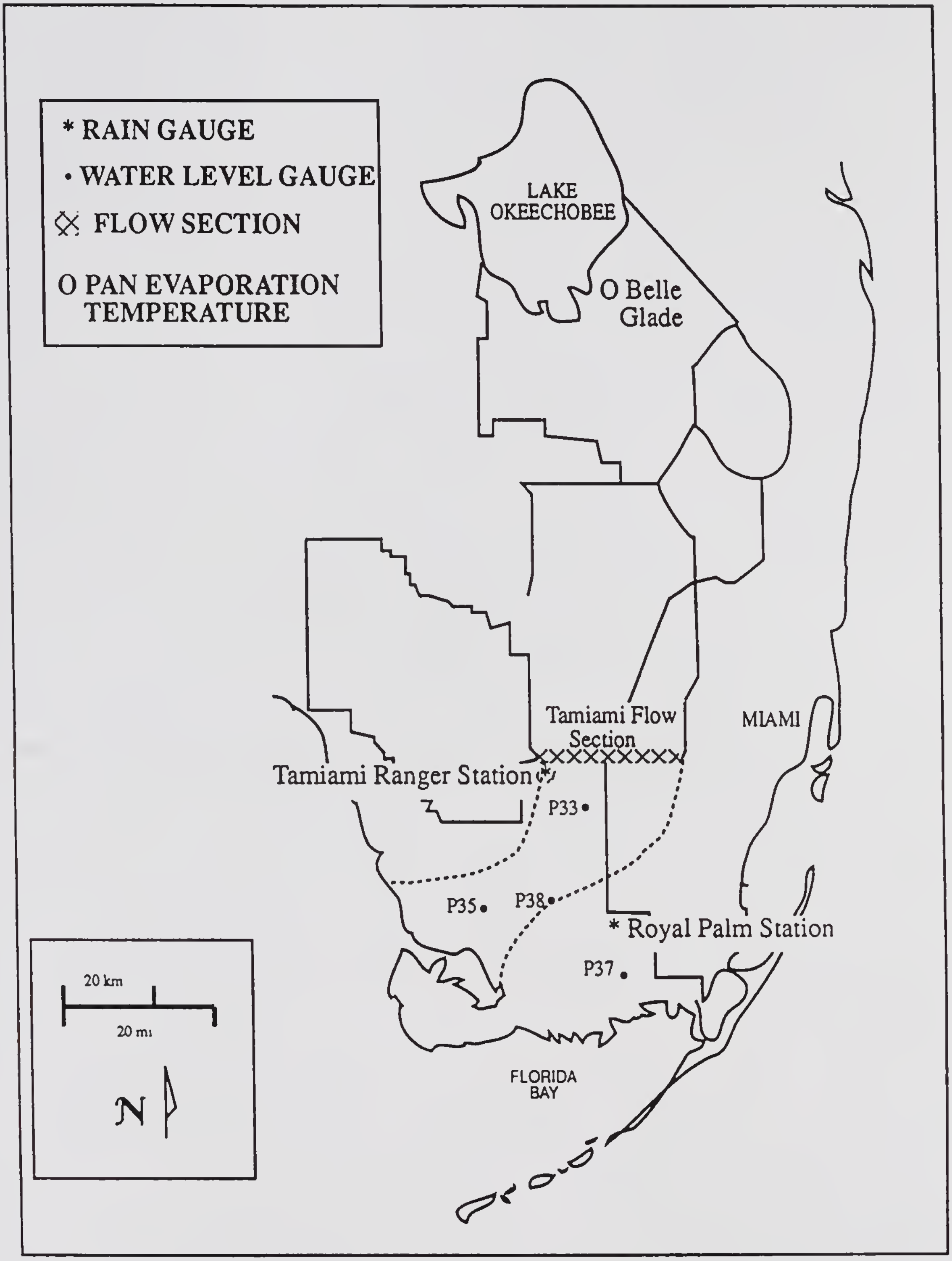

Figure 6. Location of sample rain and stage gauges, flow sections and pan evaporation sites within the Everglades region.

Table 4. Description of vegetation categories (landscape units) used in Everglades model.

Map No.	LANDSCAPE UNIT Description of Components
1	sawgrass, slough, tree island
2	sawgrass/slough
3	slough, with periphyton
4	slough, no periphyton
5	sawgrass marsh
6	sawgrass with woody invasion
7	sawgrass,cattail
8	wet prairie, on peat, tree islands
9	wet prairie, on peat, native woody plants
10	wet prairie, on peat, exotics
11	wet prairie, on marl and tree islands
12	wet prairie, on marl, muhly grass
13	wet prairie, on marl,native woody plants
14	wet prairie, on marl, exotics
15	Pine, hammock
16	Pine, hardwood
17	Pine, prairie
18	Upland hardwood scrub
19	tall mangrove forest
20	short mangrove forest
21	mangrove prairie
22	dwarf cypress
23	cypress dome
24	cypress hardwood
25	agriculture
26	no vegetation

calculated from each sample for each of the three major vegetation types; sawgrass, tree island and wet prairie. The percent cover of sawgrass, wet prairie and tree island communities in the southern Everglades did not vary over the sampled window sizes. For windows sizes from 500 through 4000 m, the cover of each of the three types was relatively constant (Figure 7). The mean cover was about 66% for sawgrass, 21% for wet prairie and 13% for tree island. A two-way analysis of variance indicated no significant difference in cover among the window sizes. Although variances tended to decrease with window size, the differences were not enough to violate assumptions of homoscedasticity. These results indicate that using the percent cover of plant communities to describe the landscape units is very robust to changes in the cell size of the landscape units.

A map editor is established in the model to allow for creating the initial or starting vegetation array within the active cells. The map editor creates an array that consists of a vegetation type code for each cell that can be addressed and updated during the simulation. The rules in the model for changing the vegetation types are the subject of the next section.

Changes in Landscape Vegetation Types

The vegetation change module of the model is set up to switch among vegetation types, based upon rules relating to hydroperiod, nutrient concentration and fire. At the end of each year of simulation, the hydroperiod (number of months per year that a site is wet) and soil nutrient concentration are calculated for each grid cell. The annual hydroperiod value is used to update a running average hydroperiod for each cell. Fire is a stochastic event, with probability related inversely to the annual hydroperiod value. If a random number is less than the assigned probability for the hydroperiod value, then a fire event is said to have burned the cell. The average hydroperiod, soil nutrient

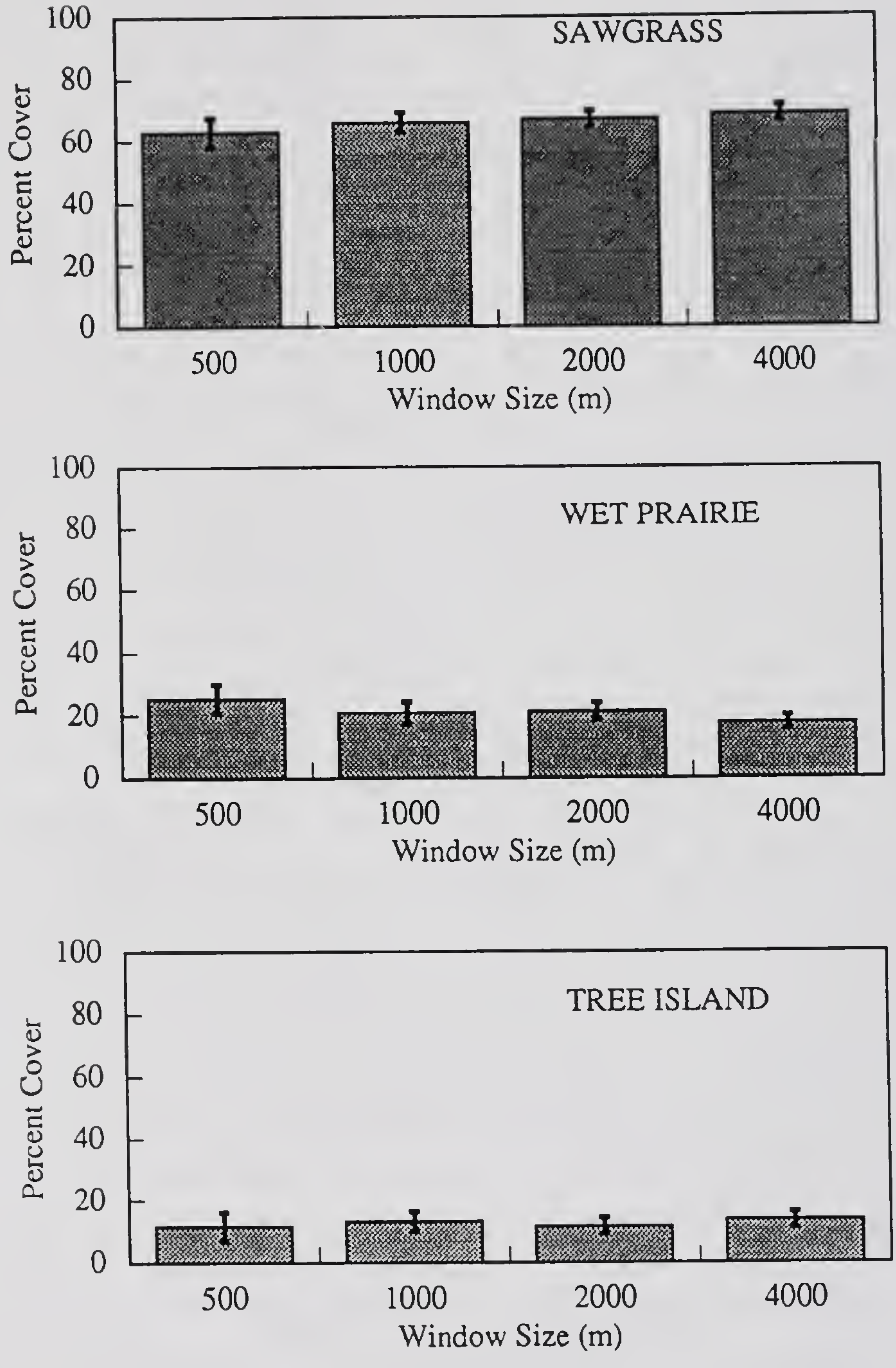

Figure 7. Percent cover of sawgrass, wet prairie, and tree island in various window sizes.

concentration and a fire event are all used as critical values to make changes among vegetation types. If average hydroperiods are wetter or drier than a certain threshold value, or if the soil nutrient concentration exceeds a critical value, or if a fire occurs in the cell, then the vegetation cover type for that cell changes. The threshold values of hydroperiods and target transition types are user defined.

The transitions among vegetation types were determined using information derived from a combination of sources, namely, literature and field experience. The transitions involve the loss or gain of certain community types within a cover type. The primary cover in the peat portions of the Everglades system is a mosaic of sawgrass, slough and tree islands, designated as type one. The hydroperiod ranges from 9 to 11 months in this type. If hydroperiods exceed 11 months, then the tree island and sawgrass types disappear, leaving only slough (Craighead 1971, Worth 1987). If hydroperiods are less than 9 months, then woody plants invade the sawgrass and slough (Craighead 1971, Gunderson and Loftus In Press) resulting in a change to type 9. The other dominant peat landscape type was a monospecific stand of sawgrass in the area now known as the EAA (Davis 1943). If the sawgrass burns or dries out, woody plants invade, (Wade 1980) resulting in type 6. The vegetation dynamics associated with a change in nutrient status include a loss of periphyton in a slough system (Swift 1984), and a transition from sawgrass to cattail (Davis 1989).

The preceding paragraphs describe the "landscape" vegetation units used in the model. These units are comprised of combinations of identifiable plant communities. The transitions among landscape types involve the addition or replacement of plant communities within each landscape unit. Since the plant communities provide the "building blocks" for each landscape unit, they will be used as the basis of relating flow and evapotranspiration.

Development of Flow Coefficients for Landscape Units

Two steps were involved in the determination of flow coefficients by landscape unit. The first step related estimates of vegetation density for each of the dominant plant communities to flow coefficients. The second step used the percent cover relationships within a landscape type to develop a spatially weighted flow coefficient.

To develop relationships between vegetation type and flow regimes, estimates of vegetation density were derived. Vegetation densities were then translated to Manning's flow coefficients using relationships developed by Petryk and Bosmajian (1975) and Shih and Rahi (1982). Vegetation density was determined for four vegetation types: sawgrass marsh, wet prairie over peat, marl prairie and tree island. The literature was surveyed for measured values of stem density for the gramineous vegetation types (marsh and prairie) and for values of basal area for the forest type (tree island). Average stem densities in the graminoid vegetation types were multiplied by the average stem size to yield an average cross sectional area per length of flow. Total basal area was divided by the stem density to yield an average tree size, then average cross sectional area was determined per unit of flow length. The values of vegetation density were then correlated to a Manning's n value based upon data compiled by Petryk and Bosmajian (1975) .

Stem density varied from a low value in the wet prairie (0.05 $/m^2$) to the highest ($42/m^2$) in the marl prairie (Table 5). Even though the marl prairie had the highest stem density, the sawgrass had the highest vegetation density. The cross-sectional area of the plants comprising the marl prairie were much smaller than sawgrass. The vegetation density reflects the total cross-sectional area (m^2) per ground area in the direction of flow (m^3), and is in units of m^{-1}. The vegetation densities were highest in the sawgrass areas (0.15 m^{-1}),

Table 5. Vegetation density and related flow coefficients as a function of depth for sawgrass, tree island, wet and marl prairie vegetation types.

Vegetation Type		Sawgrass		Wet Prairie		Tree Island		Marl Prairie	
Stem Density									
(#/m2)		28	*(1)	3	*(2)	0.6	*(3)	42	*(4)
(#/ft2)		8.5		0.9		0.2		12.8	
Stem Size (ft)		0.08		0.03		0.30		0.02	
Stem Area									
(ft2/ft2)		0.71		0.03		0.05		0.27	
	Depth (ft)								
Vegetation Density (ft2/ft3)	0.5	1.42		0.06		0.11		0.53	
	1	0.71		0.03		0.05		0.27	
	1.5	0.47		0.02		0.04		0.18	
	2	0.36		0.01		0.03		0.13	
	2.5	0.28		0.01		0.02		0.11	
	3	0.24		0.01		0.02		0.09	
	3.5	0.20		0.01		0.02		0.08	
Mannings n * *(5)	0.5	1.12		0.22		0.31		0.68	
	1	1.26		0.25		0.35		0.77	
	1.5	1.35		0.27		0.37		0.82	
	2	1.41		0.28		0.39		0.87	
	2.5	1.47		0.29		0.41		0.90	
	3	1.51		0.30		0.42		0.93	
	3.5	1.55		0.31		0.43		0.95	
Model Flow Coefficient K *(6)	0.5	1.3		6.7		4.8		2.2	
	1	1.2		5.9		4.3		1.9	
	1.5	1.1		5.5		4.0		1.8	
	2	1.1		5.3		3.8		1.7	
	2.5	1.0		5.1		3.7		1.7	
	3	1.0		4.9		3.5		1.6	
	3.5	1.0		4.8		3.5		1.6	

REFERENCES
*(1) Herndon et al. 1991
*(2) Goodrick 1984
*(3) Gunderson 1982
*(4) Olmsted et al. 1980
(5) Petryk and Bosmajian, 1975 — n = (depth)^0.67(veg density)^0.5
*(6) Walters et al., 1992 — K = 1.49/n

intermediate in the marl prairie (0.06 m^{-1}) and tree islands (0.05 m^{-1}), and lowest in the wet prairie (0.01 m^{-1}). The estimated flow coefficients for sawgrass was about twice that of tree island and wet prairie, and substantially greater than in the wet prairie.

A spatially weighted average flow coefficient was determined for each landscape unit. First, a mean flow coefficient was calculated over a range of depths for each plant community type. The percent cover of each plant community in a landscape unit was used as the weighting factor. For example, in landscape unit 1, sawgrass covers on the average 66% of a cell, wet prairie covers 22%, and tree islands cover 12%. The depth averaged flow coefficient for these three types are 1.09, 5.44 and 3.93, respectively. The flow coefficient for this landscape unit is (0.66*1.09+.22*5.44+.12*3.93) = 2.4. The spatially weighted coefficients are given in Table 6. Even though the values vary among plant community types, the spatially weighted averages are similar among the landscape units

<u>Development of Evapotranspiration Coefficients for Landscape Units</u>

A spatially weighted average evapotranspiration rate was also calculated for each landscape unit. The plant community rates were derived from average daily rates calculated from the evapotranspiration data. The values ranged from a low of 0.22 cm/day in the marl prairie to 0.4 cm/day in the swamp forest (Table 7). The values for cattail and melaleuca were estimated from other sources (Koch, unpub. data; Woodall 1980). The calculation of annual totals is extremely sensitive to the daily rates, a difference of 0.1 cm in the daily rates results in an annual difference of 36 cm. The spatially weighted mean annual evapotranspiration values ranged from 95 cm (marl prairie, type 11) to 159 cm for the unit of exotic trees on peat (Table 7). Annual totals for each landscape type

Table 6. Spatially weighted flow coefficients for each landscape unit used in the Everglades Model.

Map No.	LANDSCAPE UNIT Description of Components	Spatial % Components	Spatially Weighted Average K
1	sawgrass, slough, tree island	66-22-12	2.4
2	sawgrass/slough	78-22	2.0
3	slough, with periphyton	100	5.4
4	slough, no periphyton	100	5.4
5	sawgrass marsh	100	1.1
6	sawgrass with woody invasion	88-12	1.4
7	sawgrass,cattail	50-50	1.3
8	wet prairie, on peat, tree islands	80-20	5.1
9	wet prairie, on peat, native woody plants	60-40	4.8
10	wet prairie, on peat, exotics	20-80	4.2
11	wet prairie, on marl and tree islands	80-20	2.2
12	wet prairie, on marl, muhly grass	80-20	2.2
13	wet prairie, on marl,native woody plants	60-40	2.6
14	wet prairie, on marl, exotics	40-60	2.6
15	Pine, hammock	100	1.8
16	Pine, hardwood	100	1.8
17	Pine, prairie	100	1.8
18	Upland hardwood scrub	100	1.8
19	tall mangrove forest	100	10.0
20	short mangrove forest	100	10.0
21	mangrove prairie	100	10.0
22	dwarf cypress	100	2.0
23	cypress dome	100	2.0
24	cypress hardwood	100	2.0
25	agriculture	100	2.0
26	no vegetation	100	2.0

Table 7. Average daily and annual evapotranspiration for plant communities used to develop evapotranspiration coefficients for Everglades model.

Plant Community	Daily ET (cm)	Annual ET (cm)	Annual ET (in)
Sawgrass	0.33	120	47
Wet Prairie/Slough	0.26	95	37
Tree island	0.42	153	60
Marl Prairie	0.22	80	32
Exotic-Melaleuca	0.48	175	69

Map No.	LANDSCAPE UNIT Description of Components	% Spatial Components	Spatially Weighted Annual ET (cm)	Relative Annual Rate X/114 cm
1	sawgrass, slough, tree island	66-22-12	119	1.04
2	sawgrass/slough	78-22	115	1.01
3	slough, with periphyton	100	95	0.83
4	slough, no periphyton	100	95	0.83
5	sawgrass marsh	100	120	1.06
6	sawgrass with woody invasion	88-12	123	1.08
7	sawgrass,cattail	50-50	145	1.27
8	wet prairie, on peat, tree islands	80-20	107	0.93
9	wet prairie, on peat, native woody plants	60-40	118	1.04
10	wet prairie, on peat, exotics	20-80	159	1.40
11	wet prairie, on marl and tree islands	80-20	95	0.83
12	wet prairie, on marl, muhly grass	80-20	95	0.83
13	wet prairie, on marl,native woody plants	60-40	110	0.96
14	wet prairie, on marl, exotics	40-60	118	1.04
15	Pine, hammock	100	114	1.00
16	Pine, hardwood	100	114	1.00
17	Pine, prairie	100	114	1.00
18	Upland hardwood scrub	100	114	1.00
19	tall mangrove forest	100	114	1.00
20	short mangrove forest	100	114	1.00
21	mangrove prairie	100	114	1.00
22	dwarf cypress	100	114	1.00
23	cypress dome	100	114	1.00
24	cypress hardwood	100	114	1.00
25	agriculture	100	114	1.00
26	no vegetation	100	114	1.00

were expressed as a ratio of 114 cm/yr, the fixed coefficient for the model. As with the flow values, there appears to be some spatial convergence of averages. That is, a relatively constant percentage of plant community types within a landscape unit combined with a difference in rates among plant communities, appears to result in a global average for a grid cell.

The preceding section of this chapter described the hydrologic components, vegetation components and linkages of flow and evapotranspiration in the model. Water depths within each grid cell change monthly as a function of historic rainfall, net flow, and evapotranspiration. At the scale of the model, 26 landscape types comprised of plant communities, are used to describe vegetation patterns. Flow and evapotranspiration rates are linked to the "landscape" type. This linkage was done through two steps: first to determine coefficients for the dominant vegetation communities, then to develop a spatially weighted average coefficient for each landscape unit based upon the percent cover of vegetation types within the landscape unit. The transitions among the landscape units are a function of cumulative water depths (hydroperiod), fire and nutrient concentration. The next section of the chapter presents the results of sensitivity analyses and testing the hypotheses.

Results

The results section has three parts. The first part assesses the sensitivity of key parameters to flow calculations and compares model output with historic data. The second part presents attempts to invalidate the linkages between vegetation and hydrology. The third portion of this section reviews the tests of the upstream area hypothesis.

Sensitivity Analysis- Flow and Evapotranspiration

Tests were done to explore the sensitivity of the model output (primarily flow) to uncertainties in parameters associated with flow and evapotranspiration. The sensitivity analyses of flow coefficients were done by doubling and halving all coefficients calculated in the above paragraphs, running the model for a full 28 year scenario under natural conditions (no water control structures in the system). The sensitivity to evapotranspiration was tested by running a full 28 year natural scenario with the annual evapotranspiration rate set at 89, 102, 107, and 114 cm (35, 40, 42 and 45 inches).

Doubling and halving the flow coefficients did not appear to have an appreciable affect on flow through the Tamiami flow section (Figure 8). The largest deviations among the three sets of coefficients occurred during wet years (model simulation years 1967, 1969, 1970; Figure 8). During these periods, the flow differed by about 500 x 10^6 m^3/yr between either of the runs with adjusted coefficients and the unadjusted coefficients. This difference during wet years, between the adjusted coefficient flows and the unadjusted flow, was about 12% of the unadjusted flow. Differences during dry years were much less. There was no evidence that changes in vegetation landscape types during any of these runs altered or confounded the flow relationship among the adjusted coefficients. The flow results from the unadjusted run were always intermediate between the higher flows calculated by doubling the flow coefficients, and the lower flows associated with halving the flow coefficients.

The results of varying base evapotranspiration indicate counter-intuitive effects on rates of annual flow through the Tamiami flowsection. The results are unexpected because there is not a constant relationship between the evapotranspiration rate and amount of flow. The lower evapotranspiration rates should generate higher stages and higher flow. The simulated flow data start out

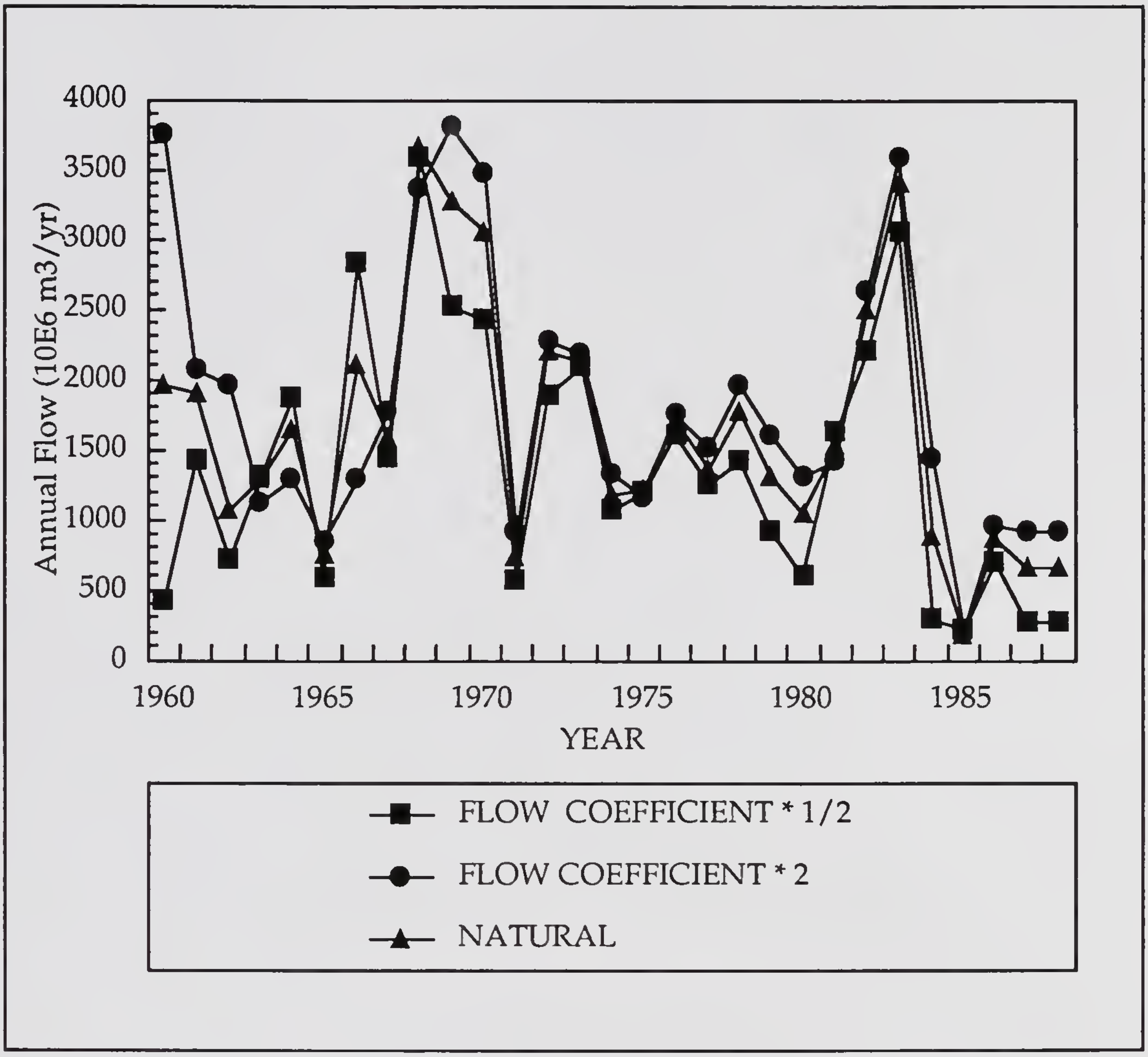

Figure 8. Effects of doubling and halving flow coefficients on simulated flow through Tamiami flow section.

with this relationship, but the relationship changes through the time course of the model run (Figure 9). These discrepancies are the result of the linkages between hydrologic conditions and the vegetation landscape conditions. If the system gets too dry, such as the scenario of higher base annual evapotranspiration (114 cm/yr), then woody species invade the landscape, increasing the evapotranspirative loss and lowering flow rates. The system appears to entrain flows at lower levels of evapotranspiration. The lower evapotranspiration maintains "wetter" landscape types that result in higher flow rates.

Even with these interesting and counter-intuitive effects of vegetation-hydrology-evapotranspiration linkages on flow, the model is apparently more sensitive to changes in evapotranspiration than to variations in flow coefficients. Changing the base transpiration rate only 25 cm/yr, results in a variation of annual flow on the order of 500×10^6 m^3/yr (Figure 9). A similar effect was achieved by doubling and halving the flow coefficients. After establishing the sensitivity of changing the base settings on flow regimes, model output using the base settings will be compared to historic data.

Agreement with Historic Data

The model output, both stage and flow, indicates periods of agreement and divergence with measured data. The actual stage at P33 and P35 and flow through Tamiami tend to be lower than the model output during the period from 1961 through 1965 (Figures 10 and 11). This is probably due to the management policy in effect during this period, when little or no flow was delivered to the park (Wagner and Rosendahl 1985, Gunderson 1989). During other years, the actual and modeled stage data tend to qualitatively agree. Since there was no groundwater component to the model, agreement was only possible with surface

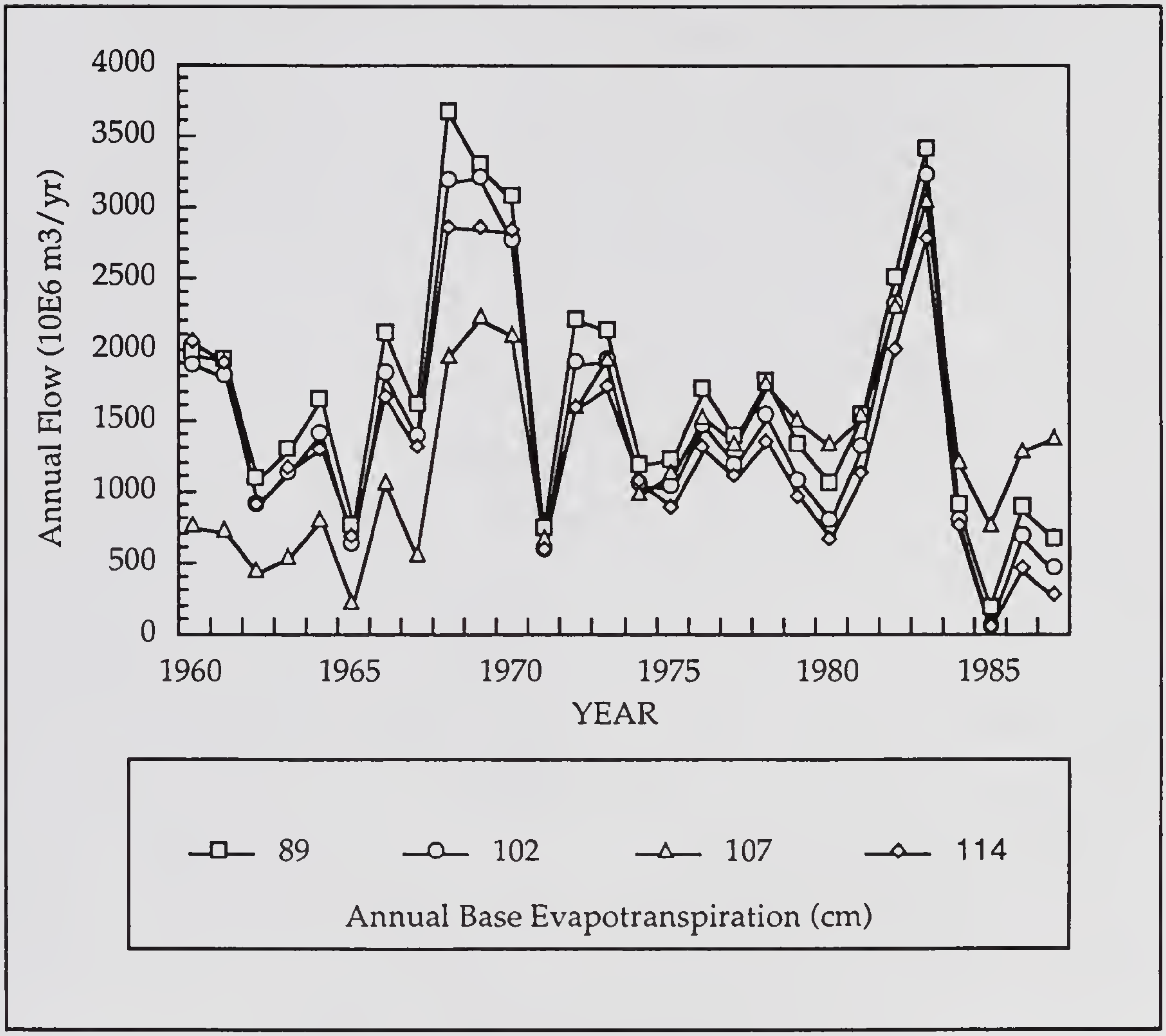

Figure 9. Effects of varying base evapotranspiration rates on simulated flow through Tamiami flow section.

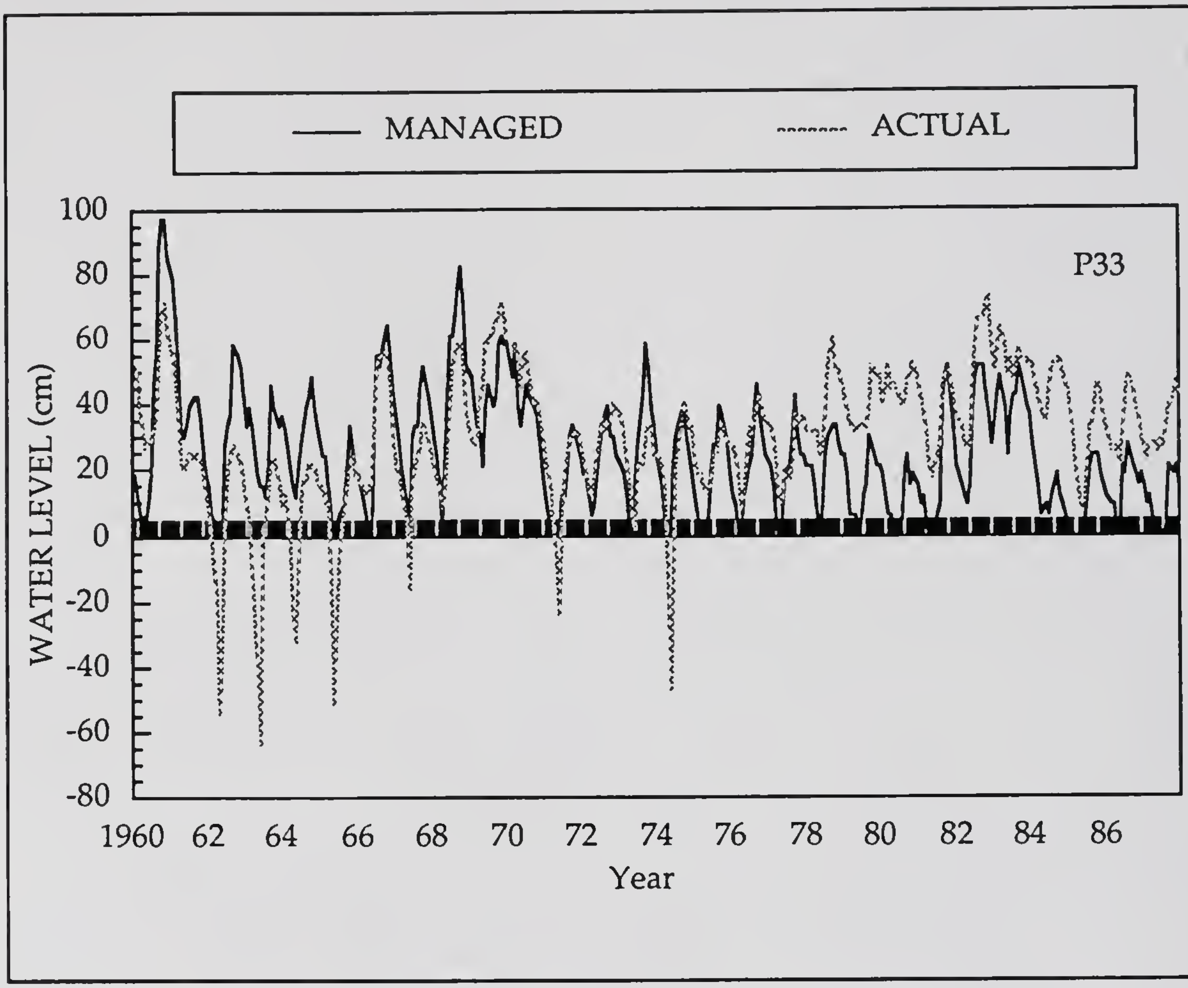

Figure 10. Time series of simulated (solid lines) and actual (dashed lines) stages at gauge P33 from 1960 to 1988.

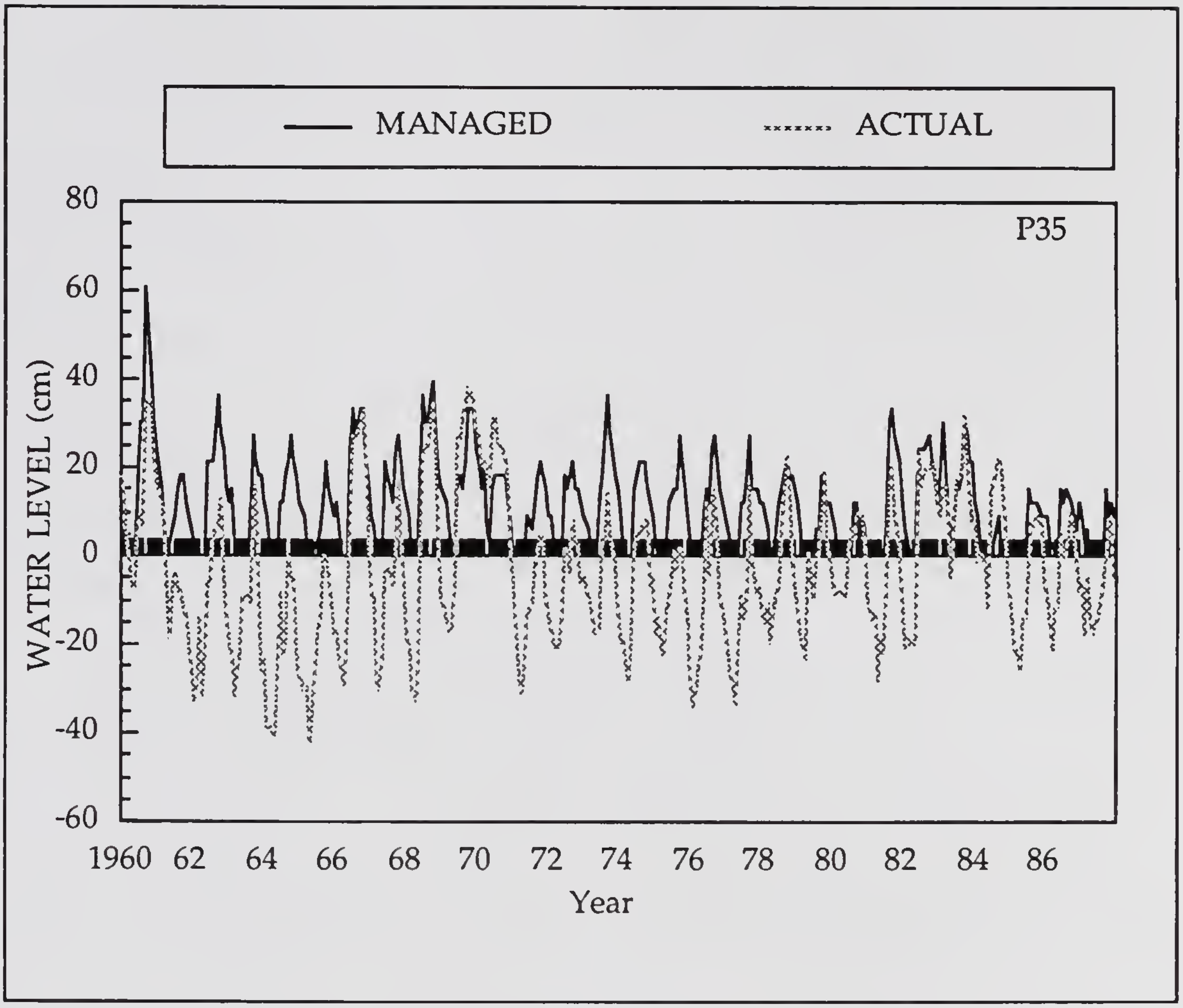

Figure 11. Time series of simulated (solid lines) and actual (dashed lines) stages at gauge P35 from 1960 to 1988.

water conditions. The modeled flow through Tamiami trail also agreed fairly well with measured flow in periods other than the early 1960s and early 1970s. The vegetation patterns at the end of the simulation period of the natural scenario appear to agree with early descriptions of vegetation in the Everglades. The initial array of landscape units in the model grid consisted of a sawgrass plain south of Lake Okeechobee, the tree island/sawgrass mosaic in the central core of the system, and marl prairies units in the south. (Figure 12). At the end of the run, the sawgrass plain and marl prairie units had persisted (Figure 13). The tree island/sawgrass mosaic had changed to a sawgrass/slough type in the area of the persistent pool described in the paragraph above. Davis (1943) and Jones (1948) observed and mapped similar patterns; the tree island/sawgrass mosaic was only mapped in the northeast and southwest portions of the central Everglades and a tree-less marsh was in the topographically lower southeast region. The tree-less sawgrass/slough vegetation type is also captured in the native Americans description of the system as "Pa-hay-okee", which loosely translates to a grassy lake (Douglas 1947).

The output from the model agrees fairly well with historic hydrologic and vegetation information. Even with uncertainties and sensitivities to understanding flow and evapotranspiration processes, the model captures key aspects of hydrologic and vegetation dynamics of the system. The next section puts the model at risk, and attempts to determine the bounds of the relationships between the hydrology and vegetation.

Linkages between hydrology and vegetation

Since the model output agreed fairly well with historic data sets, a test was developed to determine the limits of the influence of vegetation dynamics on the relationship between rainfall and runoff. The test consisted of a series of model

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Figure 12. Map codes for initial landscape vegetation types in the Everglades model. Dominant code in the Everglades proper is type 1. Cover types developed from Davis (1943). Explanation of codes is found in Table 4.

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Figure 13. Map codes of landscape vegetation types in grid cells of Everglades model at end of 28 year simulation run. Note presence of type 3 codes in right -central portion of array. See Table 4 for explanation of codes.

runs. For each run, a set amount of rain was delivered each year of a 20 year simulation. The rain varied seasonally, as modeled by composite sine waves to emulate the natural annual pattern, but remove any interannual variation. Four runs were made, ranging from a very dry year to a very wet year. The model inputs were equivalent to annual totals of 105, 118, 142 and 176 cm (36, 46, 56 and 68 inches).

The relationships between rain and runoff appears constant over a wide range of rainfall inputs, then dramatically shifts if the system becomes very wet. The flow and stages at key stations all reached a seasonally oscillating equilibrium with rainfall inputs less than 142 cm. At steady rainfall up to 142 cm, the landscape vegetation types remained constant, and hence, the relationship between rainfall and runoff was linear. At an annual input of 176 cm, a dramatic shift occurred around year 6, when the landscape units shifted to a treeless wet prairie. Without tree islands or sawgrass, the overland flow rates were greatly increased, resulting in a new equilibrium of flow coming through the Tamiami flow section (Figure 14). No such vegetation shifts occurred in the mangrove areas and hence, no dramatic change in the flow relationships in either the Shark Slough or Taylor Slough flow sections.

These results indicate that the vegetation-hydrology linkages can be invalidated at an extreme. The key point is that the vegetation array is fairly stable with constant levels of average rainfall input and the relationship between rainfall-runoff is constant. However, if the system has a prolonged (at least five year period) of surplus rainfall, then the vegetation structure is destroyed and a different equilibrium in the rainfall-runoff relationship occurs. Since the vegetation units are fairly stable with constant levels of average rainfall, the relationship between rainfall and runoff may not be dramatically influenced by the coupling of landscape vegetation dynamics with the hydrology.

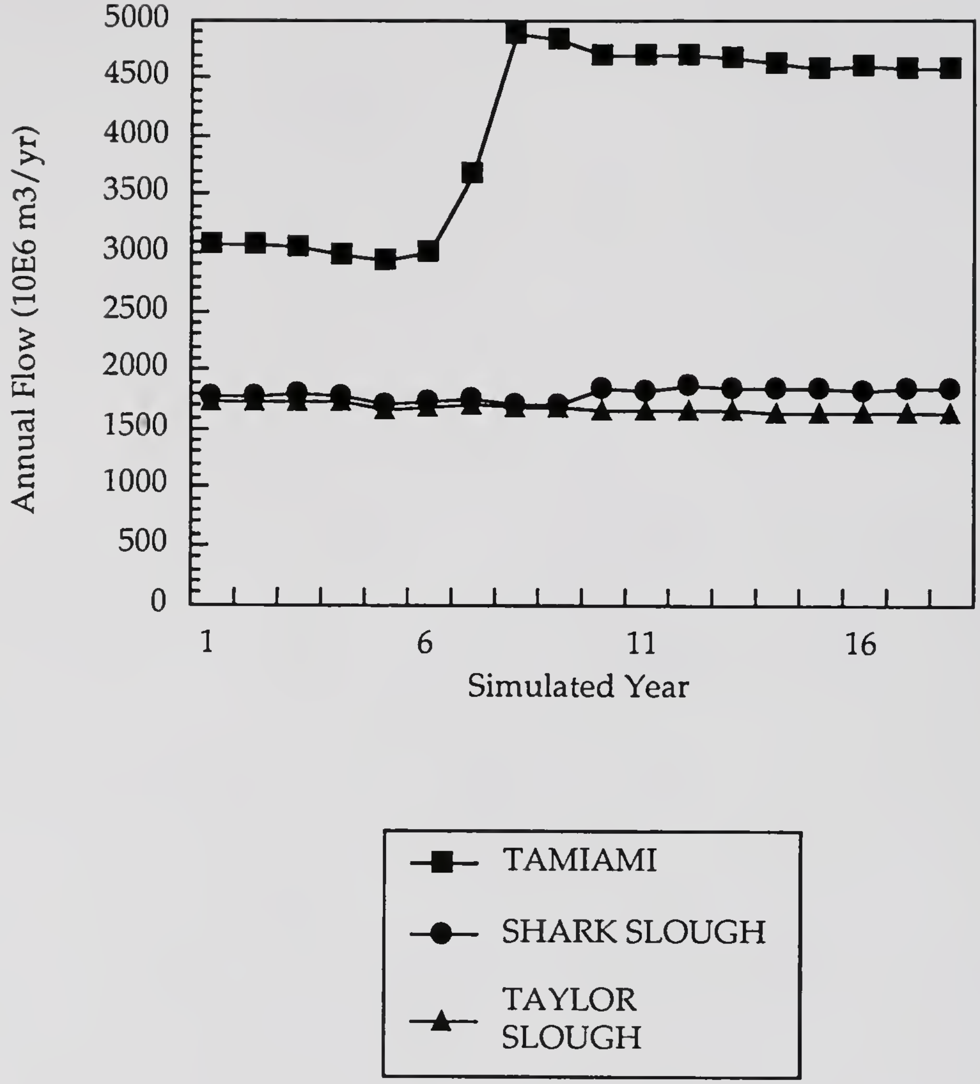


Figure 14. Results of changing vegetation patterns on simulated flow through three flowsections in the southern Everglades.

The output of two models, one with and one without coupled vegetation-hydrologic dynamics, was compared to see if addition of the linkages changed the predicted hydropatterns. The output of the model with linkages qualitatively agrees with the models without linkages (Walters et al. 1992, Perkins and MacVicar In press) All models predict a persistent pool of water north and east of Tamiami Trail in the area now known as the Pennsuco wetlands. Flow and stage results are similar between the model with and without linkages (Figure 15). Key uncertainties to these results are in assumptions about the amount of water that moved surficially and as groundwater into the coastal ridge, and contributions from Lake Okeechobee.

The results in the preceding paragraphs lead to the conclusion that the addition of the vegetation and hydrologic dynamics does not improve the models' ability to predict stage and flow. Dramatic changes in rain and runoff relationship occurs only after persistent wet conditions. Model output of flow and stage is not different between models with and without vegetation linkages. One of the reasons may be that the dominant influence on surficial hydropatterns is the rainfall. Certainly this is partially true. Other reasons are related to problems of scaling. The landscape units are composites of vegetation communities. There is good evidence for dramatic differences in evapo-transpiration rates and flow resistance coefficients among the vegetation communities. However, when composite values are calculated at the landscape levels, the differences are spatially homogenized and converge towards singular coefficients. The net result of modeling at the landscape scale is that the addition of more complexity at "smaller" scales does not dramatically improve accuracy of the model to predict surficial hydropatterns. The failure to improve model accuracy by the addition of complexity agrees with previous workers (Walters 1986, Clark et al. 1979, Costanza and Sklar 1985). In spite of these limitations, the

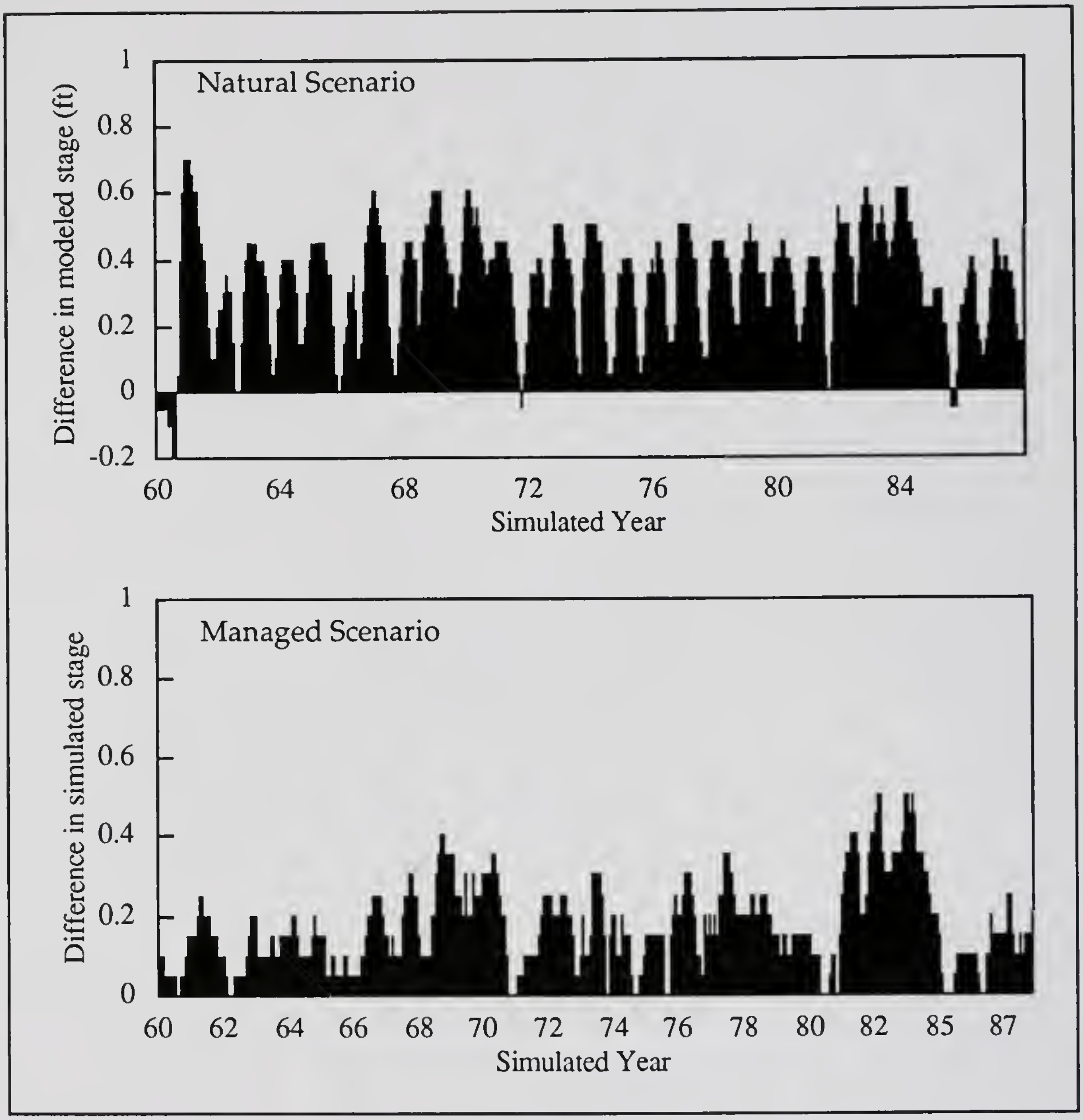


Figure 15. Difference in predicted stage between models with and without vegetation linkages of succession, evapotranspiration and flow. The model without linkages tended to predict higher stages (less than 0.5 ft) , under both the natural and managed scenario.

model can be used to test the hypothesis regarding contribution of upstream area to flow in the Park.

Flow and upstream area

The hypothesis of upstream area contributions to Everglades Park was tested with a series of simulations. All simulations were done using the same rainfall input (28 years of historic data) and none of the current control structures. Each successive scenario increased the upstream area that contributed flow to the park by creating a levee that contained and diverted flow to the north of the levee, allowing only the area south of the levee to generate flow into the park. The contributing area was systematically increased, in increments of two rows of cells across the system. Annual flow across Tamiami Trail was tallied during each scenario for comparison to annual rainfall and upstream area. For each scenario, the parameter settings represented a pristine system, with historic topographic data, an outlet at the Miami River, and no diversion of water to the coast. A schedule was developed so that Lake Okeechobee contributed water only after stages exceeded 20 ft, which is similar to values reported by Parker (1984) .

Increasing the upstream area both increases the flow at Tamiami Trail and magnifies the amount of interannual variation. The flow appears to increase in a logarithmic profile as area contributing to the flow is increased (Figure 16). The effects are variable with rainfall; wetter years generate substantially more flow per upstream area than drier years with large upstream area. Another way of stating this is that the amount of area upstream appears to amplify variations in annual rainfall.

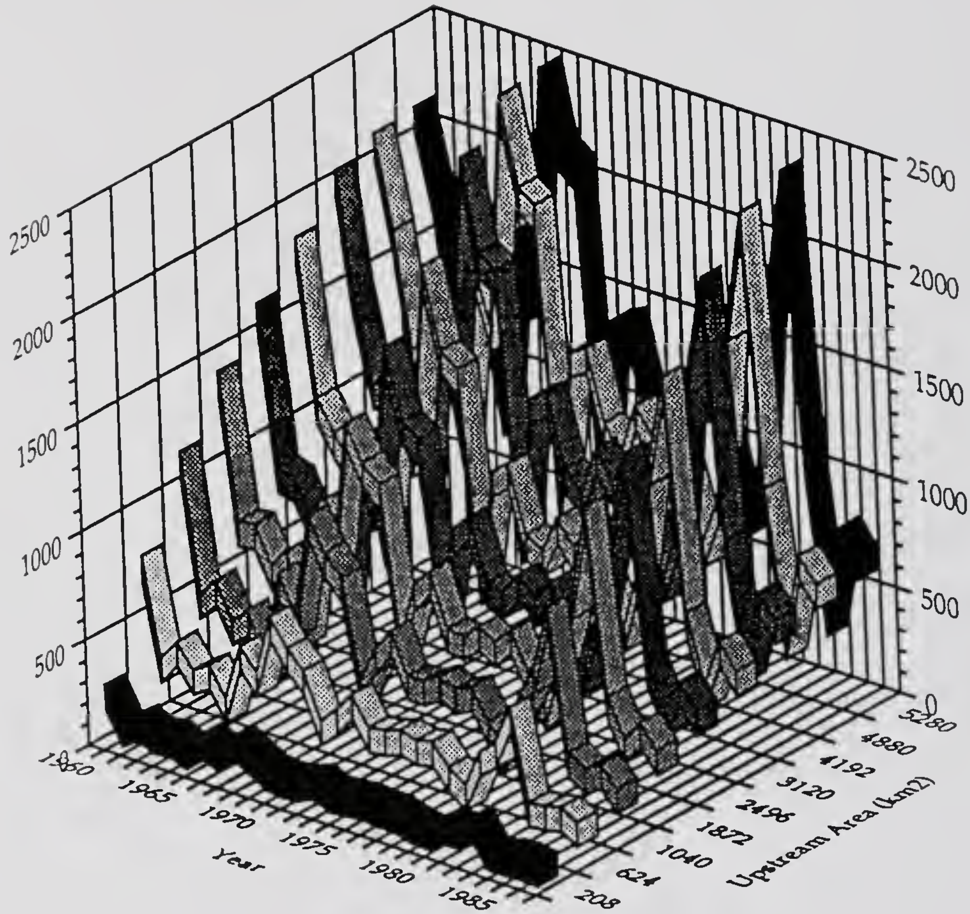


Figure 16. Three dimension plot showing increase in annual flow (z) as upstream area is increased (y) over a 28 simulated year.

The relationship between upstream area and flow has been shown empirically to follow a logarithmic profile of the form shown in equation (3) (Viessman et al. 1989). A constant exponent in the equation is evidence that a constant relationship exists between flow and upstream area. The test of constancy of the exponent was done using regression analysis of a log-log plot between upstream area and flow (Figure 17). In the log transformation, r is the slope of the regression line and K is the intercept on the dependent axis. The straight line in the log-log plot indicates that the relationship between flow and upstream area is constant. A rolling regression analysis was done and no breaks were found in the relationship.

$$Q = K * A^{r} \qquad (3)$$

$$Q = 5.2 * A^{0.63}$$

Q = annual flow

K = coefficient

A = upstream area

r = exponent

The significance of the exponential parameter in equations such as the above, is uncertain. Perhaps the parameter is just an empirical or model artifact. Some authors indicate that parameter is indicative of an underlying system property. In similar hydrologic work, Hack (1959) found a constant exponential parameter (equal to 0.6) in relating streamlength to drainage area. Mandelbrot (1983) and Feder (1988) interpret this as evidence of a fractal relationship between streamlength and drainage area. The exponent has also been described as a scaling parameter (Mandelbrot 1983, Feder 1988) and indicates a fractal or self-similar relationship between flow and area. The parameter may be related to some geomorphologic attribute of the system. If the scaling exponent has a value of one, then a linear relationship would exist between flow and upstream area. A fractal dimension between 1 and 2 is indicative of a structure that fills more surface than a line and less than a plane. A fractal dimension of less than one can be represented by "dust"; something less than a line that indicates perhaps a "patchy" relationship. One explanation then, is that as area contributing to flow increases, the flow increases in a non-linear or "spattering" manner perhaps because water has other pathways (evapotranspiration or infiltration) and does not end up as overland flow. Another possibility is that the "patchiness" in the spatial dimension may be a reflection of variation in the temporal domain. The variation of rainfall inputs may be somehow creating a non-linear variation in system flow as upstream area is increased.

The analysis so far has examined how flow varied solely as a function of upstream area. Interannual variation in rainfall appears to confound the relationship between flow and area. The variation in the plot of flow versus upstream area is due to annual variation in rainfall (Figure 17). The variation increases as the area contributing flow increases, as would be expected if area and rain are confounded. During years of low rainfall, the relationship between area and flow appears to reach a plateau (bottom points, Figure 17) indicating that increasing the upstream area does not increase flow. During dry years, smaller upstream areas contributed flow to the park. The remaining years, the relationship is not confounded and it appears that the entire freshwater system (south of the Lake) contributed flow.

Lake Okeechobee does not appear to directly contribute flow to the southern Everglades. A series of model runs were made; changing the regulation

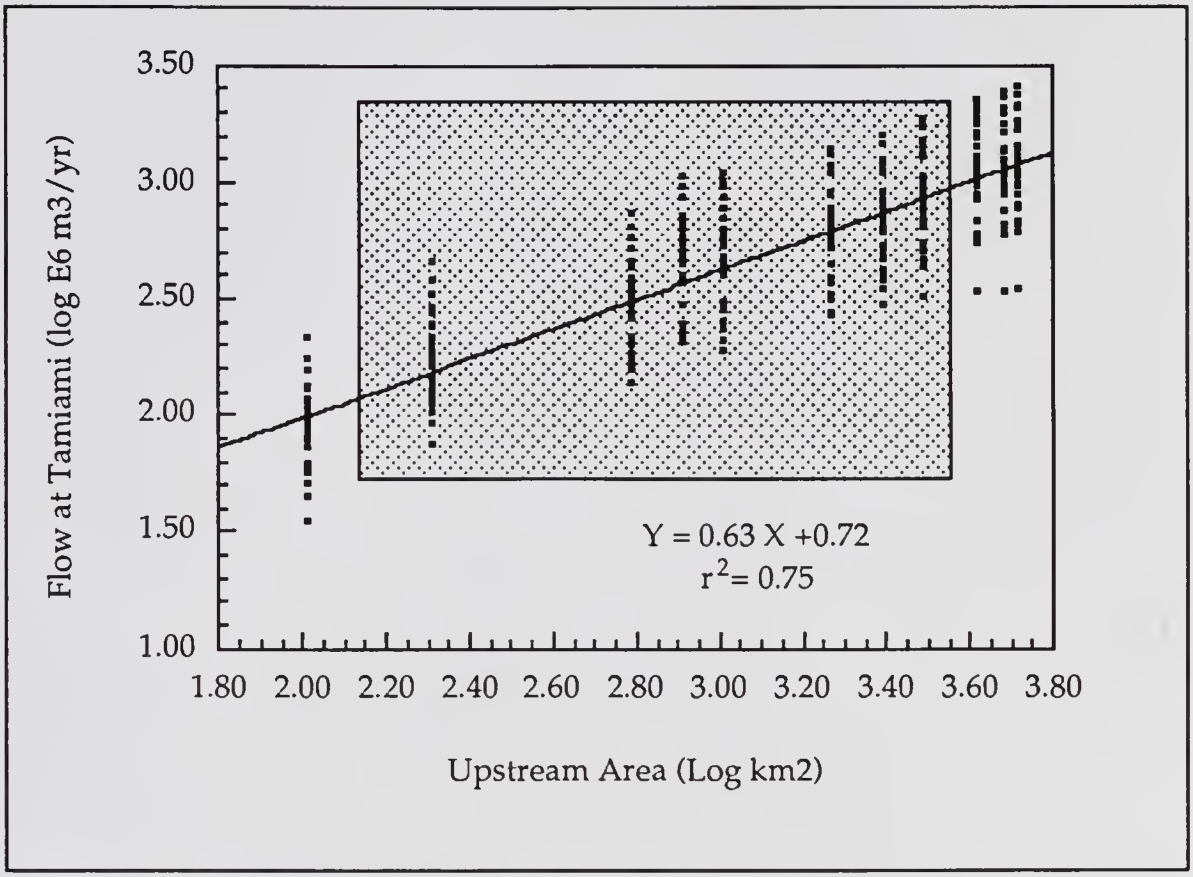


Figure 17. Log-log plot of simulated flow versus upstream area. Scatter due to differences in annual rainfall. Gray area represents bounds of actual flow and equivalent area.

schedule of the Lake and monitoring flow to the Park. The amount of flow into the southern Everglades did not significantly change with changes in Lake schedules from 20 to 22 ft. above sea level. Water from the Lake would enter the marsh system, flow south and contribute to a pool in the topographic low areas of the Pennsuco wetlands, north of the Park.

The Park is at the downstream end of the historic ecosystem. Since the early part of this century, upstream water has been diverted for other use. Even so, water continued to flow into the park. The effective upstream area that has been used to deliver water to the Park was estimated with the empirical equation (3). This was done by translating the range of actual flows into equivalent upstream area. The lowest and highest measured annual flows during the period 1960-1987 were approximately 50 and 2000 x 10^6 m^3. These flows translate into equivalent upstream areas of between 140 and 3500 km^2 (Figure 17). These results are consistent with the deliveries in the early 1960s, when the S-12 structures were closed and little upstream water was let into the park. The largest upstream equivalent area is slightly more than a third of the Everglades ecosystem, or about the size of the three water conservation areas. Since the completion of the Central and Southern Florida Flood Control Project, it appears that, at the maximum, only about one third of the historic freshwater wetland system has contributed flow to Everglades Park.

Summary

The vegetation-hydrologic interaction is an example of feedback dynamics operating at distinct spatial and temporal scales. The vegetation responds to longer term variations in hydrologic patterns (depth and flow); if water depths are too deep for long periods, the system looses the tree island and sawgrass communities (Worth 1987, Craighead 1971). If the system dries over multiple years, woody species invade and dominate the marshes. The resultant vegetation patterns appear stable for over time frames of multiple decades, if not longer,(Alexander and Crook 1975, Davis et al. In Press, Gleason 1984). The vegetation patterns set the conditions for the "faster" dynamics of stage and flow by influencing flow coefficients and evapotranspiration rates. In the context of hierarchy theory, the vegetation can be thought of as a "slow" variable, that entrains the behavior of more rapid hydrologic dynamics. The model incorporates the feedback dynamics by summarizing hydrologic conditions over periods of times that are used to change the "slower" variable of vegetation pattern.

Coupling the dynamics in the model framework does not appear to appreciably improve understanding of hydrodynamics because of two reasons. The feedback dynamics described in the above paragraph occur on a smaller spatial scale. Aggregation of these processes was done based upon spatial cover of plant communities in the landscape. The spatial averaging tended to homogenize the differences among the communities, which led to a convergence of parameter values. The second reason, is that the landscape vegetation categories appear to be relatively stable in a system without human intervention even with high variation in rainfall.

There is good evidence that the entire freshwater system, south of Lake Okeechobee, contributed water that flowed into Everglades Park except during extremely dry years. The relationship between upstream area and flow appears to be fractal or spatially self-similar. As the upstream area is changed, the flow is changed in a similar amount. The scale invariance of this relationship may be a property of hydrologic systems within a drainage basin. The management implications of these results are that since the early 1960s, when the construction of the Central and Southern Florida Flood Control Project was essentially finished, the equivalent contributing areas to flow into Everglades Park have been the Water Conservation Areas. Under pre-management conditions, the entire basin contributed to flow into the southern Everglades. The evidence that the southern Everglades received more water and hence had a greater upstream area agrees with previous work by Smith (1989), Powell (1989) and Walters et al. (1992).

The conclusions reached in this chapter are based upon the results of a model with fixed and limited scales in space and time. The model includes the interactions of variables operating across two orders of magnitude in space and three orders of magnitude in time. The spatial grain of the model is 4 km, with a spatial extent of 160 km or about two orders of magnitude. The temporal grain (time step) is about one week, and the temporal extent almost three decades or about three orders of magnitude greater. The model can be both powerful and limited. The power arises from the ability to interact across these distinct regimes, and understand system dynamics over longer time scales. The model is limited, in that longer and broader dynamics (such as sea level or climate change), are excluded. The dynamics of processes occurring at other spatial or temporal scales can be accounted for in the model as long the scaling relationships are invariant. The limitations therefore are not due to bounding the problem within a model, but in the translation across scales of important processes. Since processes occur at a variety of scales in the real world, and their translations or rules of scaling are not invariant, inevitable surprises will occur with the use of scale bound models.

Understanding of critical ecosystem processes and structures will be both advanced and limited using the precepts of scale limited modeling. An alternative theory base is emerging that recognizes fundamental discontinuities across scales and attempts to determine how processes and structures change with scale. Data sets from the Everglades will be used to test a hypothesis of ecosystem structure and function based upon this discontinuous hypothesis. The methodology and results of these tests are the subject of the next chapter.

CHAPTER 4.
A CROSS SCALE EXPLORATION OF THE EVERGLADES LANDSCAPE

Toto, I don't think we're in Kansas anymore
-Dorothy in the Wizard of Oz

The intertwined natural and management history of the Everglades ecosystem was described in the first chapter to establish a linkage between management and precepts of nature. Alternative concepts that guide modes of inquiry were set forth in the second chapter and formed the basis for two hypotheses. The first hypothesis was tested using the methods of mathematical modeling. The critical hydrologic and vegetation processes were combined in a model framework that covered about two orders of magnitude in space and time. Processes operating at different scales could be aggregated because the scaling rules were assumed to be invariant. As a consequence policy surprises are inevitable because of the unpredictable interactions of processes operating at scales outside the model domain. Whereas the method in the previous chapter involved the "compression" of variables into a bounded range of scales for analysis of keystone processes and structures, the work presented in this chapter is developed from a cross-scale paradigm.

The cross-scale exploration begins at this point. The word exploration was chosen to describe the contents of this chapter for the following reasons. The theory and tools to test the theory are in an early stage of development. One of the objectives of this dissertation is to develop and test methods further as well as to advance the theory. The work does not attempt to reject hypotheses based upon well accepted and proven methods. No single method or technique has the appropriate sensitivity and power to be robust. Therefore, the approach is to compare the results from a variety of techniques. Due to these uncertainties in the methods, therefore, this work should be viewed as more of an exploration into the emerging cross scale theory than rigorous hypothesis testing.

In spite of methodological shortcomings, a hypothesis is posed and tested in this chapter. The theory base presented in Chapter 2 infers that keystone ecological processes operate across space or time scales in a discontinuous manner. The hypothesis is posited that these discontinuous patterns of keystone variables should be manifest as breaks in structural features, and a few reasonant frequencies in temporal processes. The hypothesis is put at risk using a series of data sets from the Everglades ecosystem. Data on structural features of the system including soil surface topography, vegetation maps and fire size were analyzed. Time series data on various aspects of the hydrologic regime were analyzed for temporal patterns.

The remainder of this chapter has four sections. The first section is on methodology used in the cross-scale analyses. The data sets used to test the hypothesis are described in the second section of this chapter. The results of the cross-scale analyses are presented in the third section of the chapter. An intrepretation of the analyses comparing methods and data sets is the subject of the final section of this chapter.

Methodology

The purpose of this section is to present a suite of methods used to discern whether discontinuities and gaps exist in patterns of keystone ecosystem variables across time and space scales. No one method can be used with sufficient reliability, so a group of methods are necessary. Some methods measure discontinuities in distributions while other methods analyze patterns across scale ranges. Two mock distributions, one highly structured and one random, will be used to illustrate what can be distinguished by each method . The rationale for grouping methods is presented below, but first, terms necessary for describing aspects of scale are defined.

Scale is a term associated with measurement. One meaning of scale is the unit of measurement. For example, both a meter and a foot are scales, measures of objects are made using multiples or fractions of these units. Data sets used in cross-scale analysis require definition of two terms: grain and extent (O'Neill et al. 1986). These terms can be applied along either temporal or spatial dimensions. The grain is defined as the unit of the smallest resolution within a data set and thus is equivalent in meaning to scale as described above. In one dimensional spatial data, such as a transect, the grain is the unit of measure or step length. In two dimensional spatial data, such as a map, a pixel or grid cell size is the grain of the data set. In temporal data, the grain is usually defined as the minimum time unit, such as minute, day, or year. The extent of a data set defines the bounds in space or time. For one dimensional spatial data, the extent could be the length of a transect. For two dimensional spatial data the extent is defined as the window of the map. For temporal data, the window is the period of record used in analysis. Therefore, for the remainder of this chapter, scale is defined by two components; the grain and extent. Both components of scale can describe not only data, but also discern among types of methods.

Two groups of methods are described below; 1) methods that discern discontinuties in data sets and, 2) methods that measure patterns across a range of scales. The extent and grain of data sets is one way of distinguishing between these groups. The methods that determine discontinuities utilize data sets with a fixed grain and a fixed window. The second group of methods (fractal and

Fourier techniques) utilize a fixed window data set, but vary grain in the analysis. Before the methods aimed at detecting patterns and breaks across scale ranges are discussed, a brief review of problems derived from assumptions of underlying distributions to the interpretation of frequency histograms or rank order distributions.

Frequency histograms are frequently used to portray patterns of sampled data sets, primarily for comparison with distributions of known statistical properties. The pattern portrayed by a histogram is very dependent upon the size or width of the bin used to tally occurrences. The technique tends to mask differences between sets of points within the distribution. Hence, differences within data set that are derived from two distinct distributions, may be smoothed over in histogram analyses

Rank order plots are an alternative method of exploring the distribution of samples. They are derived by sorting a data set and plotting the magnitude of sequential observations. Three examples are presented to contrast the differences in rank order plots derived from a continuous distribution, a random distribution and a clumped distribution (Figures 18-20). The continuous example is relatively smooth, with few bumps (Figure 18). The random distribution is more jagged, with a few jumps between successive observations (Figure 19). The structured distribution (Figure 20) looks like a staircase; dramatic jumps (risers) followed by flat spots (runs). The jumps represent gaps in the distribution, and the flat spots represent clumps. A rank order plot of a data set derived from a discontinuous distribution, therefore, should exhibit a pattern of rises and runs.

A number of theories have been proposed to explain rank order distributions. Although some of these theories are derived for species abundance and niche space, the conceptual underpinnings are similar. The arguments

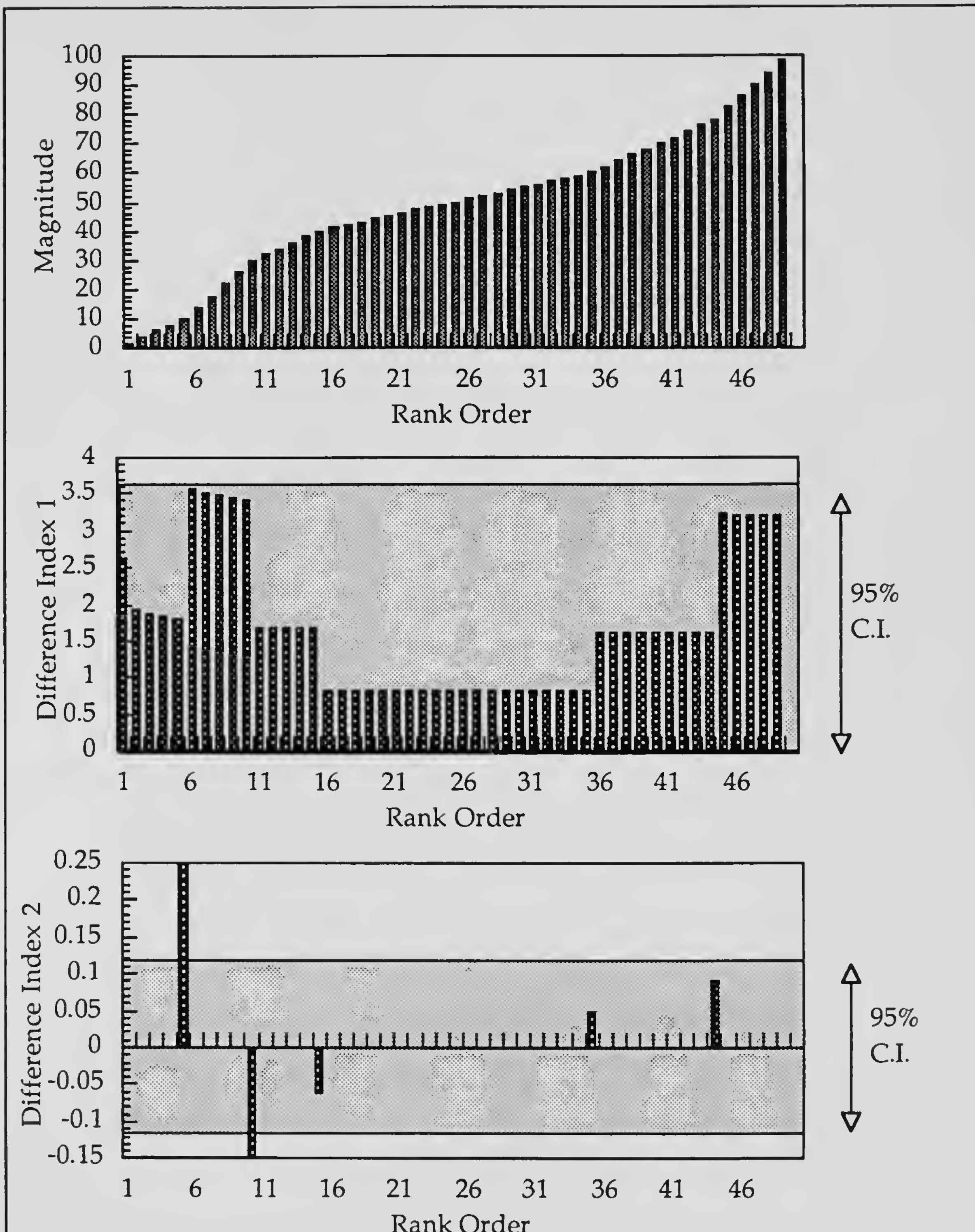


Figure 18. Rank order plot, difference indices 1 and 2 for mock data set designed to simulate continuous normal distribution. Distribution has mean of 50. For smooth curves such as this, no value of DI1 is significant. No sequential values of DI2 are significant.

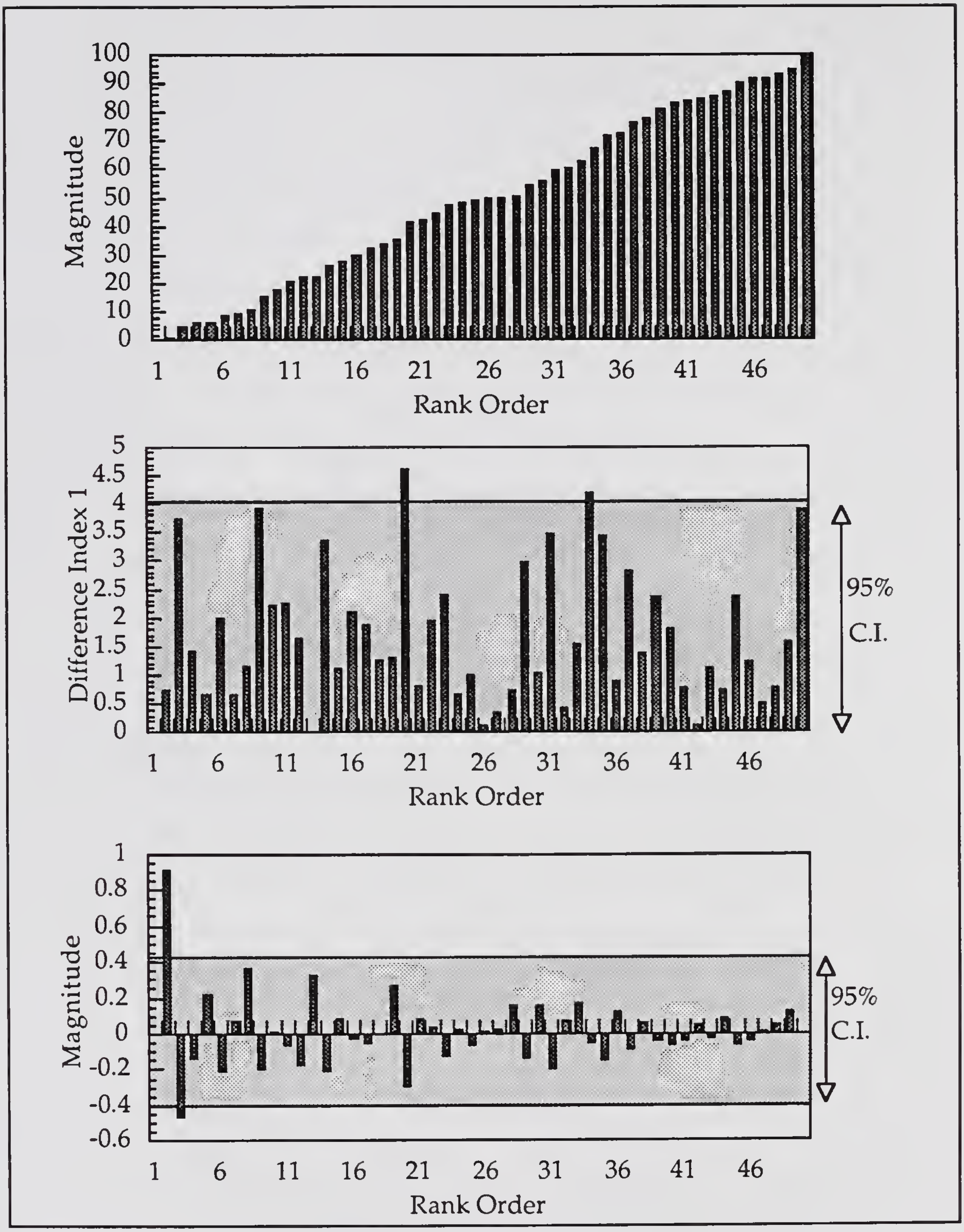


Figure 19. Rank order plot, difference indices 1 and 2 for mock data set derived from uniform random distribution. Values of both DI1 and DI2 are significant, yet values between gaps exhibit no pattern.

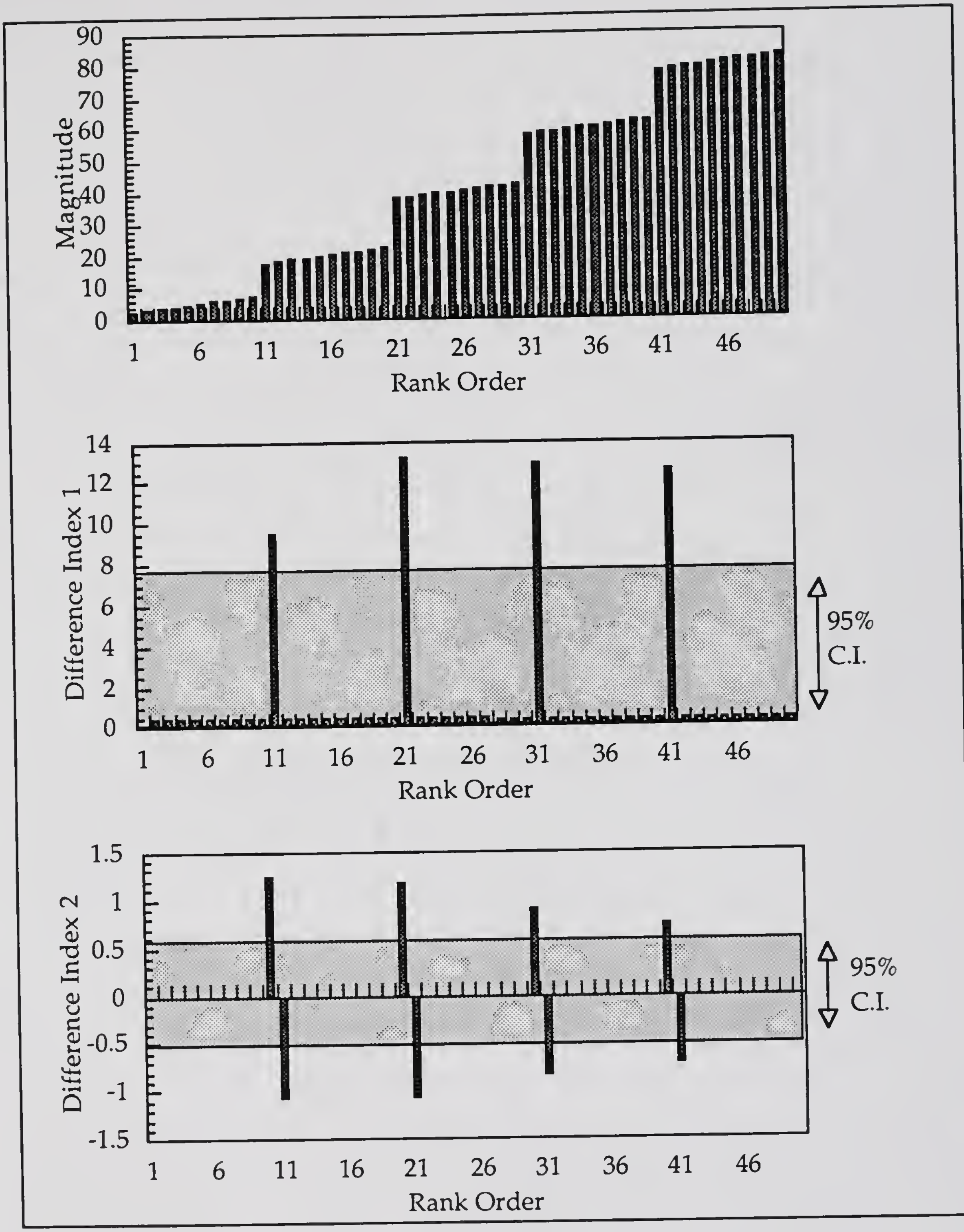


Figure 20. Rank order plot, difference indices 1 and 2 for mock data set designed to show gaps. Gaps are values of difference indices (1 and 2) outside a 95% confidence interval. Clumps are not evident, but indicated by a pattern of uniformity small groups of difference indices.

contain both random and deterministic elements. MacArthur (1957) , and Hutchinson and MacArthur (1959) proposed the "broken-stick" model to explain observed abundance distributions. The model conceptualizes that random partitioning (breaking) of resources space (stick) yields observed patterns of few large pieces, and sequentially more little pieces. Odum (1983) relates that rank order patterns are a result of the energy required to support and maintain structure. Holling (1992) building on earlier work (Holling 1986) argues that the hierarchy of structures are the result of causal variables operating at characteristically different domains in space and time.

To determine if patterns in rank order distributions are derived from underlying multiple scale processes, and hence exhibit discontinuities, the patterns are compared against a null random distribution. Both the size and patterns of gaps are compared between these two distributions. The methods or techniques to quantify gaps in distributions are the subjects of the next section.

Methods to Detect Discontinuties

Two methods have been used to measure gaps. Both methods calculate a relative distance between successive points in a rank order distribution. The magnitude of the statistic in both methods is related to the size of the gap (or rise) in the distribution.

The simpler index, called difference index one (DI1), calculates a relative difference between a point and the next highest point as shown in equation (3) and was developed by Holling (1992). A mean difference index (and variance) was calculated for each data set. A 95% confidence interval was calculated for each set of difference indices and any value greater than this was thought to represent a significant gap in the distribution.

(3) Difference Index One

$$DI1_i = (S_{i+1} - S_i)/S_i^r$$

DI	=	relative change index
S	=	value of variable
i	=	position in rank order
r	=	exponential parameter

Difference index one as given in equation (3) has a number of difficulties. One is that the index tends to emphasis differences at the low end of the value scale, that is small absolute changes can be large relative changes. For example, an increase from 0.5 to 1.0 is an absolute change of 0.5, but a relative change of 1. This is corrected by the parameter r, however, r must be estimated. This was done so that the values of the difference index at the low end of the distribution were approximately the same magnitude as those at the high end of the distribution. Another problem with this formulation is the population of index values do not have a normal distribution, and appear to follow a chi-square distribution. The non-normality may change the value of the confidence level used to determine the statistical significance of a measured gap size. Therefore, another difference index was used, and was called difference index two.

The formulation is shown in equation (4), and uses a three position or window reference frame. The difference statistic DI2, has been shown to have a mean of zero, and a normal distribution (Silverman 1986) and was developed for "bump hunting" in probability distributions.

(4) Difference Index Two

$$DI2_i = (S_{i+1} - 2S_i + S_{i-1})/((2(S_{i+1} + S_i + S_{i-1}))^{0.5})$$

Both difference indices are used in the analyses, although difference index one tends to be a little more difficult to use, in that it requires determination of the exponent parameter r. Both indices applied to the same data set indicate significant gaps in similar locations. Difference index one is always positive, difference index two is both positive and negative. The next paragraph discusses how the magnitude and pattern of these indices can be used to interpret gaps and lumps in data sets.

Each of the difference indices were calculated for the three rank order distributions presented above (Figure 18-20). No pattern was apparent from the difference indices calculated for the continuous distribution. The difference indices indicate significant gaps in the random distribution. Difference indices for the structured mock data set exhibit a pattern of high magnitude (detecting the jump or rise), followed by a sequence of low values (Figure 20).

Two criteria are important in the detection of gaps and lumps. The first is the presence of a significant gap. Significant gaps can be determined by calculating a 95% confidence interval about a mean gap size. A significant gap is any gap with a value greater than the value defined by the 95% confidence interval. The second criteria is the pattern of difference indices that define a clump. A series of gradually smaller gaps that converge to a small value and then gradually increase indicate a clump or flat spot in the rank order distribution. Both of these criteria; a significant gap followed by a clear convergence or clump, in the difference indices are necessary to detect lumpiness of a rank order distribution.

The pattern of difference indices or gap detectors can be used to determine the texture or structure of a data set. Structure can also be analyzed using a hierarchical clustering techniques.

Hierarchical cluster analyses

Hierarchical cluster analysis is a technique for identifying at structure and similarities in a data set and was used as a corollary to the rank order/gap assessment. In this work, all data sets are univariate. The technique utilizes two components, one is the calculation of distance between data points and the other is a grouping of all data points into levels of a hierarchy, based upon the calculated distances. Each observation in a data set is set into an individual cluster. Clusters are merged based upon the calculated distance between it and other clusters. The process is continued until all groups are joined into one cluster. The average linkage method was used, the mean value of a cluster is used to calculate distances to other clusters. A pseudo-t^2 distribution can be generated from the distance measures, and was used as a measure of significance of a cluster level. All data were analyzed using the CLUSTER routine in SAS/PC version 6.03 (SAS 1990).

The techniques listed above can be used to analyze pattern in data sets with a fixed extent and fixed grain. Discontinuites and clumps in a data set are based upon relationships defined by a fixed grain size. The techniques that follow take a different approach, and can be used examine how patterns or structure of the data vary by systematically changing the size the grain.

Methods to Analyze Patterns of Self-Similarity

The next set of methods are used to analyze for patterns of self-similarity across scale ranges. Self-similarity can be defined as the property of retaining similar structure or pattern with a change in grain size. Although the size of the grain changes, the grain retains a similar shape. For example, Fourier analysis is described as decomposition of a signal into a series of progressively smaller sine waves. The sine waves have similar shape, but differ in size (wavelength or frequency). These techniques incorporate an approach of analysis based upon a fixed window, then determining how patterns change with a systematic variation of grain size.

Two primary methods have been developed to examine patterns of self-similarity of data sets. Spatial patterns can be studied using techniques derived from fractal geometry (Mandelbrot 1983). Temporal patterns can be analyzed using Fourier techniques applied to time series ecological data. A more detailed description of each method is presented next, starting with fractals.

What is a fractal dimension?

Fractal geometry (Mandelbrot 1983) provides a basis for describing how structure of an object varies with spatial scale. To define a fractal dimension, first a formal method for measurement of any object is described by equation (5) following derivations presented in Mandelbrot (1983), Burrough (1981), and Morse et al. (1985). In this equation, the total measure (length, area, volume) of an object is determined by the count (K) of number of unit lengths (r), raised to a scaling parameter. The exponential parameter (D) is related to the number of dimensions to be described in space. In Euclidean geometry, the exponential parameter D is one for one dimensional objects (lines) two for two-dimensional objects (planes) and three for three dimensional objects (cubes). Mandelbrot (1983), and others realized that the scaling parameter did not have to be an integer, but indeed a fractional (abbreviated as fractal) value appeared to better describe many natural objects.

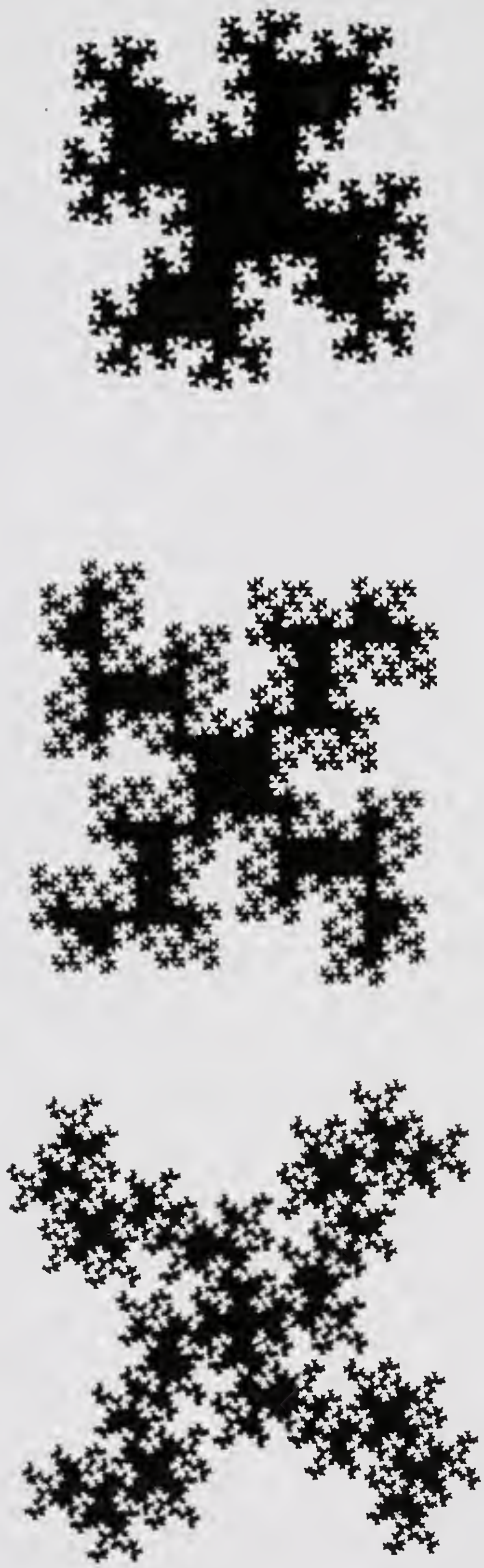
(5) $$L_{(r)} = K * r^{(D)}$$

L	=	Total object measure
r	=	unit of measure
K	=	number of units

D = exponential parameter or fractal dimension

Attempting to understand the meaning of a fractal dimension tugs at deep rooted concepts and intuition. The integer values of the exponent D, may not be recognized as such, but form the basis of learned models of perception. Traditionally, objects are measured in terms of length (D=1), area (D=2), or volume (D=3). Most measurements are done using a fixed scale (grain size or unit of measure) and assume integer values of the parameter D. This leads to a problem in the measurement of most irregular objects; total measure (length, area, etc) is dependent upon the unit used to make the measurement! Geographers (Richardson 1961) noted this in attempting to answer the question; How long is the coast of Britain? The solution proposed by Mandelbrot (1983), is that the relationship between total measure and unit of measure can be constant over wide ranges of units and measures. If this relationship is constant, then the exponent D or fractal dimension is constant and the pattern exhibits a property of self-similarity. But what does a fractal dimension of 1.2 mean and how is it different from 1.5? Irregular objects on a page have a fractal dimension between one (a line) and two (a solid plane). Generally, a fractal dimension closer to one exhibits more linearity As the fractal dimension increases between one and two an object becomes more articulated, and fills up a greater percentage of space intermediate between a line (D=1) and a solid plane (D=2). Three curves with increasing fractal dimensions between one and two are shown in Figure 21.

The fractal dimension has been used in the ecological literature to determine changes in structure or patterns with scale (both grain and window). Breaks in fractal dimension can define the scale that separates ranges where different processes affect patterns. Within the ranges that the fractal dimension is constant, a structure or object exhibits a pattern of self-similarity. For example,



D = 1.5

D= 1.61

D = 1.73

Figure 21. Sample Koch curves to show patterns of increasing fractal dimension (1.5 - 1.7), from Mandelbrot (1983).

Bradbury et al. (1983, 1984) found three regions of self-similarity on a coral reef that were defined by abrupt changes in the fractal dimension. The fractal dimension (D=1.13) at the smallest step length was attributed to the structure associated with individual corals. The next scale range had lower fractal dimensions (D=1.05) and was associated with the processes of coral colonies. The fractal dimension (D=1.17) at the largest step length was related to geologic processes. Kent and Wong (1982) measured the fractal dimension of the littoral zone of a lake in Canada, found a change in the fractal dimension at a step length of 350 m. They (op. cit.) found a higher fractal dimension (D=1.44) for longer step lengths and attributed the pattern to broad scale geologic processes and and a smaller dimension (D=1.14) at shorter step lengths which they attributed to processes of shoreline erosion such as wind and waves. Although the measures of fractal dimension are of interest, the utility appears to be in the separation of regions of scale invariance. Each of these regions of self-similarity appear to be associated with different structuring processes, that operate at characteristically different domains in space and time.

The two previous paragraphs describe the conceptual underpinnings of fractal geometry and how these concept have been interpreted by ecologists. The next section describes how a fractal dimension can be measured using one-dimensional or two-dimensional data.

Techniques of estimating fractal dimensions

A fractal dimension is estimated by repeated measures of an object using different grain sizes or units of measure within a fixed window. The fractal dimension is the relationship between changes in total object measure and the units of measure. The relationship of general measurement (equation 5) can be made linear by a log transformation, resulting in equation (6). The fractal dimension (D) can be estimated from regression analysis of the slope of a log-log plot of total object measure versus the size of the unit of measures.

(6) $\log L_{(r)} = D \log (r) + \log K$

The technique is applicable for one or two dimensions. In one-dimension (such as a topographic transect), the total object measure is total length and the unit of measure is called the step length. The fractal dimension for one dimensional data is estimated by the slope of a log-log plot of total length versus step length. For data of two-dimensions (such as maps), the total object measure is area, and the unit of measure is the box or tile size. Similarly, the fractal dimension is estimated from the slope of a log-log plot of total area versus box size (Morse et al. 1985, Milne 1988). The slope of the line is estimated using regression analysis.

A technique was developed to calculate the fractal dimension of spatial patterns such as vegetation maps. The maps or figures were scanned to render the patterns into a spatial array. The spatial arrays were translated into a quad-tree data format using custom software. A quad-tree format is created by successive quartering of an image in the manner of a nested hierarchy (Figure 22). The method is similar to one used in legal description of land parcels, for example, the northwest quarter of the southeast quarter of section. The recursive divisions render units (boxes or tiles) that range from the size of the map, (the tile size equals the window size) to one that has been subdivided nine times (the tile size equals the scanned pixel size). For each layer (or level in the hierarchy), all sample pixels are compared to the patterns at the finest scale, and the pixels are determined to contain either something (covering a piece of the mapped vegetation pattern) or nothing. The number of pixels which cover the

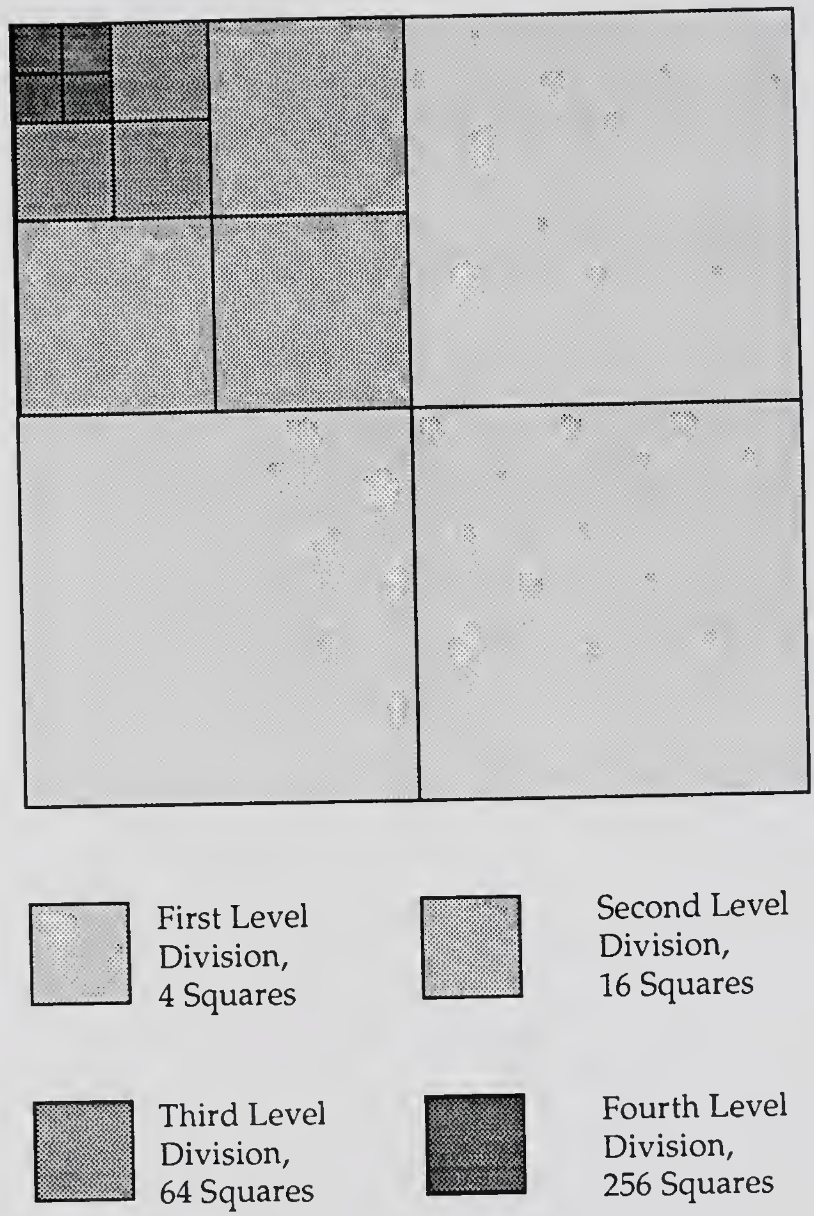


Figure 22. Example of first four levels or divisions for rendering data into a quadtree storage format.

mapped pattern for each layer are summed. The fractal dimension is determined by regressing the log of the number of pixels with something in them versus the log of the size of the sample pixels. Examples of log-log plots of box size versus number of boxes are shown in Figure 23. Although nine divisions are possible in the quad-tree, only six are used. The first three divisions of an area (total tiles = 1,4,16) do not contribute information and are not included in the plot.

The accuracy of this technique was assessed by measurement of fractal dimensions of patterns with known dimension. A group of Koch curves (Figure 21) with fractal dimensions from 1.5 to 1.76 were analyzed using the methods listed in the preceeding paragraph (Figure 23). The results indicate that the technique is accurate for curves with fractal dimensions up to 1.61, but underestimated the fractal dimension of the most intricate (highest fractal dimension) pattern.

The description of fractal methods to this point have all been based upon techniques that utilize a fixed window, variable grain approach. In order to expand the analysis across space, data from multiple, overlapping windows are analyzed. First, the patterns within each window are analyzed, then the sets of points from each window are combined to cover a broader window range. The box counts in one data sets are adjusted by the relative difference in window size between two data sets. For example, if window A is 10 x 10 m, and window B is 1000 x 1000 m, the box counts of data in window B are increased by 100 times.

The final technique used in the fractal analysis is the determination of breaks in the fractal dimension. Breaks in the fractal dimension of structural features appear to be related to a change in the processes affecting the structure. Any breaks in structural processes would fail to invalidate the hypothesis tested

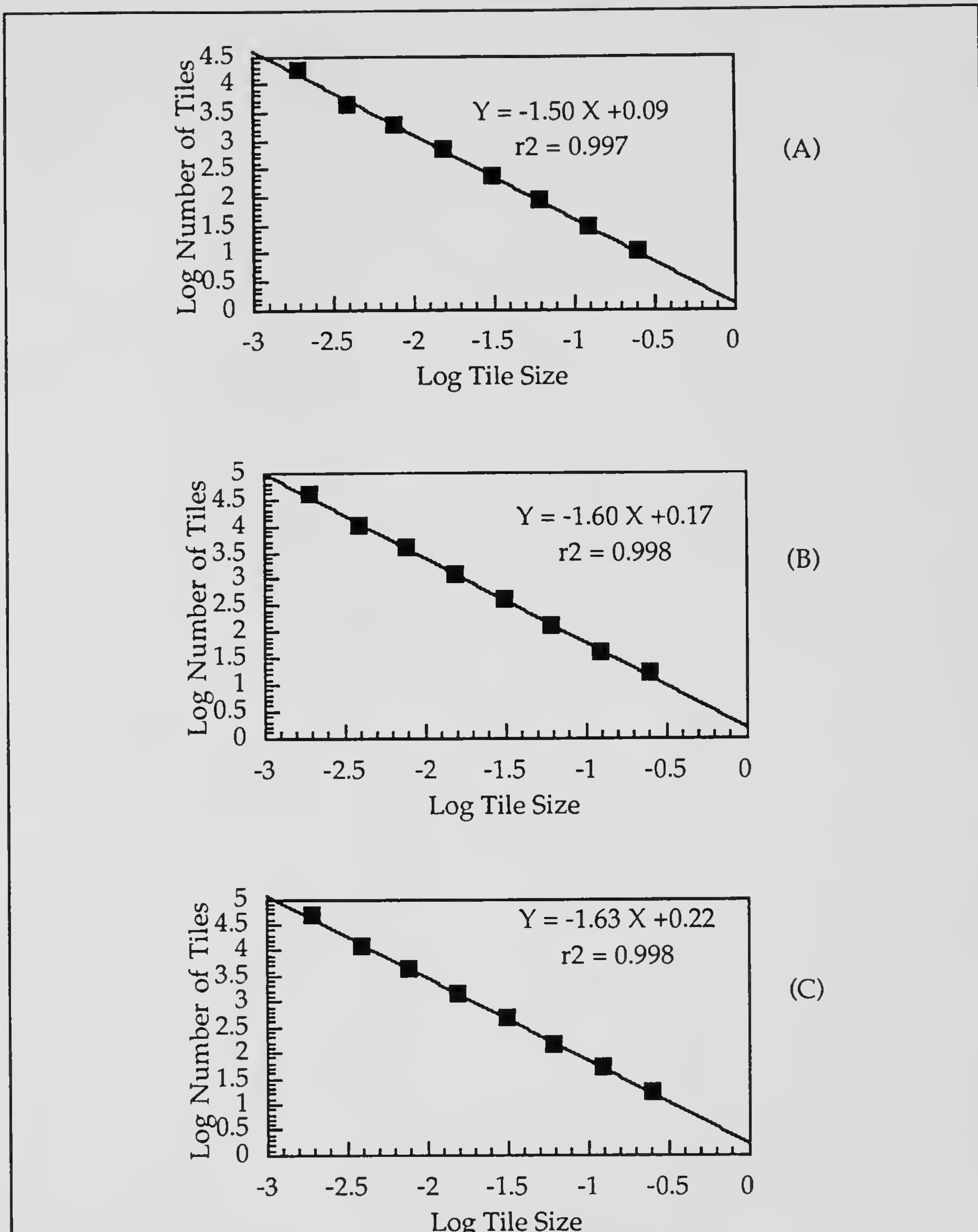


Figure 23. Log-log plots of tile size versus number of tiles for three Koch Curves of known fractal dimension. Fractal dimension is estimated by the negative slope of curves. Actual fractal dimensions (D) of curves are A) D=1.5, B) D=1.63, C) D=1.71, as shown in Figure 21.

in this chapter. Breaks or inflection points in the log-log plots were assessed using a technique named "rolling regression". The technique involves partitioning the entire data set into a smaller set of points and calculating a regression coefficient. Data points are systematically added to the analysis and a series of regression coefficients are calculated. An increase in the regression coefficient to a maximum value, followed by a decrease can be interpreted as a break in the slope or an inflection point.

Fractal geometry provides the basis for measuring techniques that quantify changes in spatial patterns across scales. The techniques examine how patterns change with respect to changing grain size. The shape of the grain size is determined by the number of dimensions in the spatial data set. For one-dimensional data, the grain shape is a line. For two-dimensional data, the grain shape is a tile or box. Similar techniques using wave-forms as the grain shape or unit of resolution have been developed to decipher patterns or signals in the time domain, and are grouped under the general heading of Fourier analysis.

Fourier analysis

Fourier analyses were developed to study harmonics or components of complex waveforms. The Fourier analysis utilizes a fixed window (extent of data in time or space) and a variable grain to discern component patterns. The technique utilizes a set of discrete values at equally spaced intervals (in time or space) and fits a series of sine waves of increasing frequency to the data. The fast Fourier technique is a modification that utilizes data sets with windows that are 2^n units. The essence of the Fourier analysis is in the transform, whereby the discrete data points are transformed from a time domain to a frequency domain. The amplitude is calculated for each frequency ranging from intervals of the entire data set (one sine wave fit to the entire set) to a frequency of one half the number of data points (wavelength every two data points). Frequencies that correlate to a large number of data points have high magnitude values. The magnitudes represent the amound of variance explained by the corresponding frequency. Statistics of mean and variance can be calculated from the magnitude values and represent the amount of noise or random behavior in the data. Dominant frequencies in the data set have high magnitude values.

The analyses were done with the fast Fourier algorithm in the SYSTAT software for the Macintosh. For each data set the mean was subtracted from every value and the data detrended, so that the values varied above and below zero with no overall change or trend in the mean. Missing data were coded at the mean value, so that they would appear at zero in the transformed data set.

Two mock data sets were developed to illustrate the techniques used to recognize dominant frequencies. Both mock data sets had 64 observations over time, and amplitude ranges from 0 to 100. The first data set was derived from a uniform random number generator and presumeably, no periodicity (Figure 24). The second mock data set was developed by adding two sine waves of different frequency, one had a wavelength of 32 time units and the other of 6 time units. The results of the analysis of structured pattern data sets is shown in Figure 25 .

Summary of Methodology

The rather lengthy description of methods presented in the section above indicates a variety of techniques can be used to analyze data for patterns across scale ranges. The three primary techniques used in the following applications are summarized below.

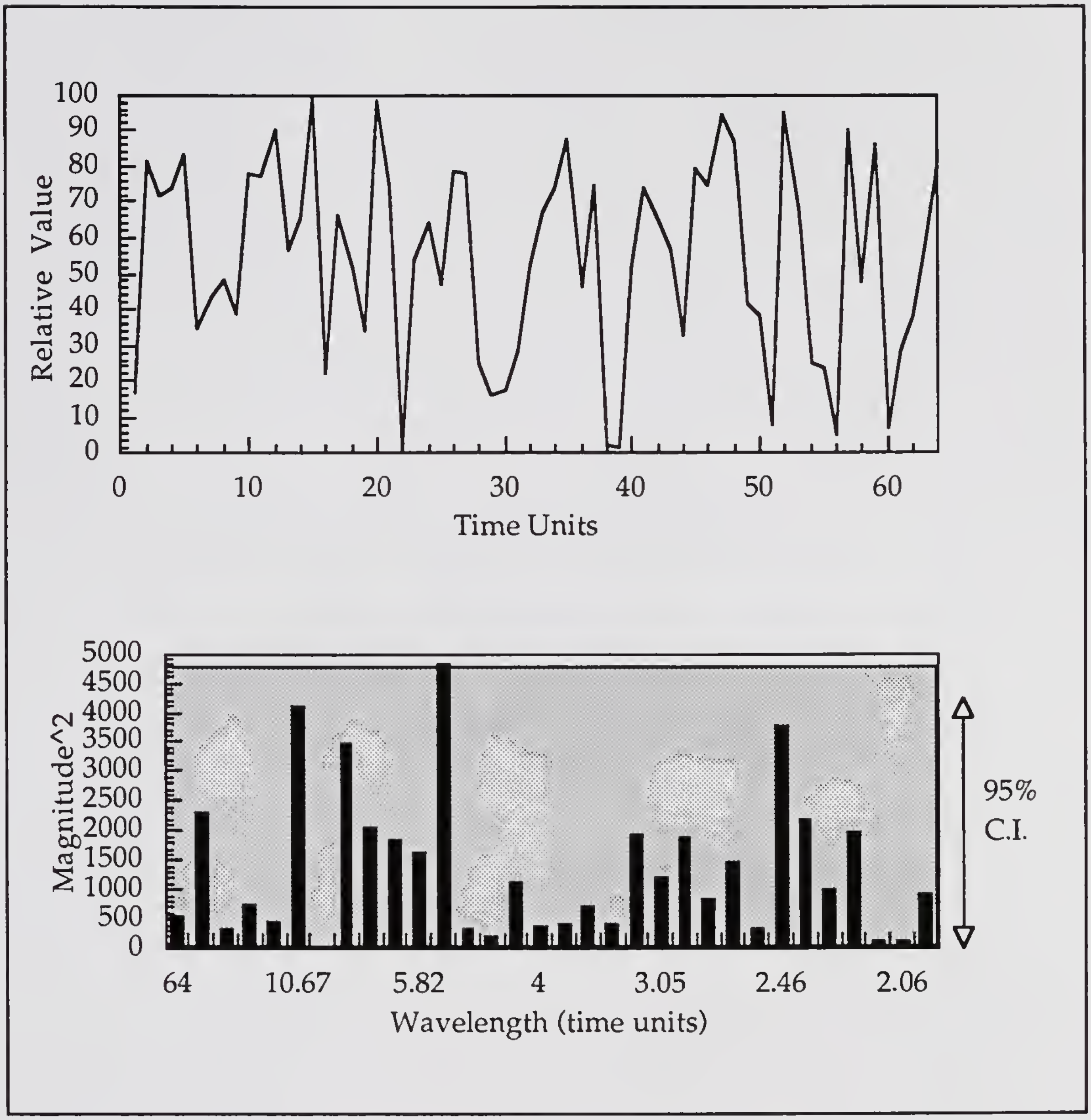


Figure 24. Fourier analysis of random mock time-series data, showing time-series plot (top) and spectral plot (bottom). This data set was created by taking 64 samples from a uniform random number distribution. No peaks are significant in the spectral plot.

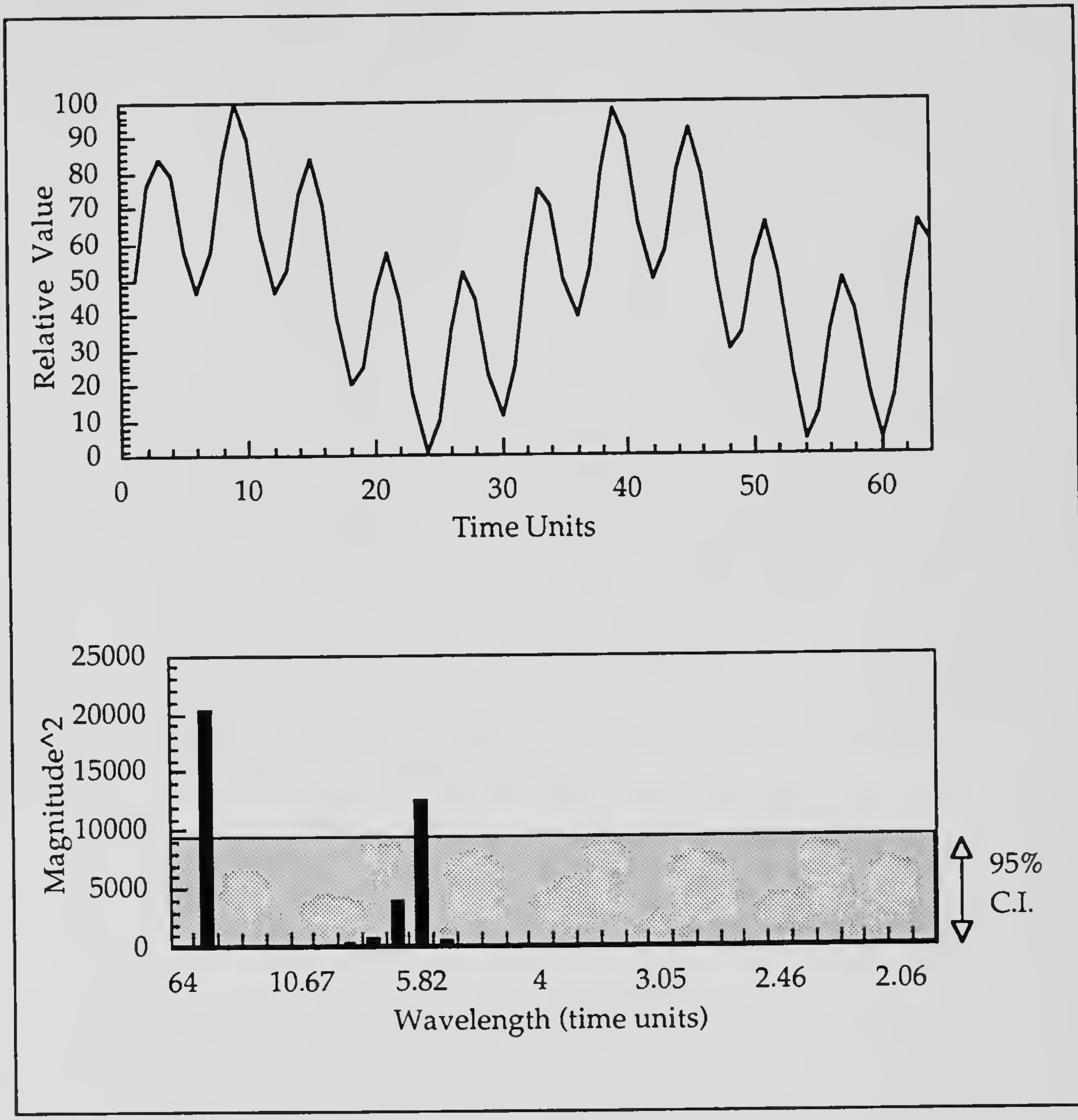


Figure 25. Fourier analysis of structured mock time series data, showing time-series plot (top) and spectral plot (bottom). This data set was created by combination of two sine waves; one 32 time units long, the other 6 time units long. Two peaks occur in the spectral plot, one at equivalent wavelengths of 32 and 6 time units.

- Discontinuites within rank order distributions can be determined by the pattern of difference indices; a signficantly large index value followed by a convergence towards a small values is indicative of a gap followed by a lump.

- Fractal dimensions can be estimated for one or two-dimensional data sets from fixed or nested window sizes. Breaks in the fractal dimension indicate changes in structural properties and can be detected by changes in the linearity of relationship between log of total measure and log of step length.

- Dominant frequencies can be determined by statistically significant peaks in spectral plots from Fourier analysis.

The next section describes the derivation of the data sets used to test for discontinuties in the spatial components and reasonanat frequencies in the temporal components of keystone features of the Everglades ecosystem.

Data Sets Used In The Cross-Scale Analyses

Two types of data were used in the cross-scale analyses; spatial and temporal. The spatial data are from key structural features of the Everglades. Some of the temporal data sets include measures of key aspects of the hydrologic regime, such as rainfall, stage, flow and evaporation. The details of the spatial data sets are presented first, followed by a description of temporal data sets.

Three data sets were analyzed to test for changes in spatial pattern across scale ranges. Two keystone features in the Everglades system are the soil surface topography and the vegetation. Ground elevation data along transects were analyzed using one-dimensional fractal methods and using Fourier techniques. Patterns from vegetation maps were analyzed using two dimensional fractal methods and for discontinuities in patch size distribution. Data on fire sizes were analyzed for discontinuities.

Seven time-series data sets were obtained. The data sets on rainfall, stage, flow, evaporation, and fire all represent a keystone process, whereas the data on air temperature and sea-level do not. All were analyzed using the Fourier technique to test for the presence of a few characteristic frequencies. Some of the temporal data sets were analyzed using the rank order/gap assessement as described above, or hierarchical cluster analyses.

Descriptions and origins of the nine data sets are presented in the following order of groups; topography, vegetation, fire, hydrology, evaporation and sea-level.

Topographic data

Elevational data from the everglades ecosystem were analyzed using two different techniques to compare topographic variation with scale. Data were obtained from Everglades National Park, and included coordinates on easting (x), northing (y) and elevation (z) from eleven surveyed east-west transects across Shark Slough (Figure 26). Elevation measures were made at approximately 100 m intervals along each east-west transect. The transects were spaced at about 2 km intervals from north to south. A program was written to estimate fractal dimension of each of the transects. The program calculated the length of the total transect by using the smallest step lengths (distance between survey points), then increased step length geometrically until the total distance of the transect equalled the step length. Slopes of the lines in a log-log plot of

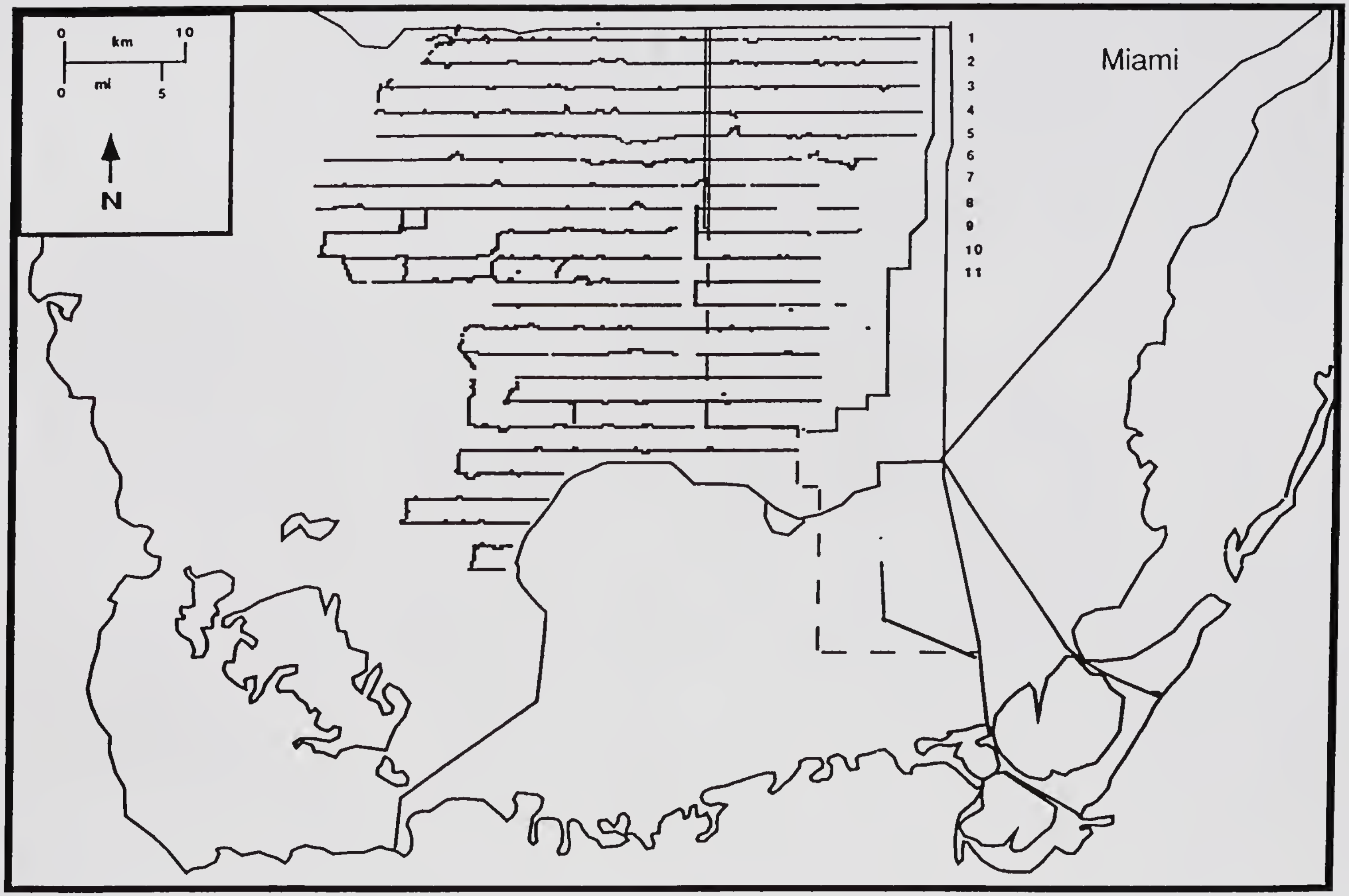


Figure 26. Location of topographic transects in the southern Everglades.

distance versus step length were used as estimates of fractal dimension (Mandelbrot 1983, Feder 1988)

Vegetation maps

Plant communities were mapped within three different windows of coverage, each an order of magnitude smaller in the linear dimension. The linear dimension of the three overlapping square windows were 16 kilometers, 1609 meters (one mile), and approximately 160 meters. The resolution of each map is defined by the size of the picture element (pixel). The relationship between pixel and window sizes were approximately constant for all three maps; the pixel size of the 16 km was 20 x 20 m; the 1609 m map was 2 x 2 m and the resolution of the 160 m map was 20 x 20 cm. The maps made in each window were derived from a different source.

The largest window and grain vegetation maps used data from the French SPOT satellite. The satellite carries a multi-spectral scanner, which measures scaled reflectance values within three wave-length bands (centered on 0.55, 0.65 and 0.80 mm). The spectral data were classified using parallel-piped clustering routing within the GRASS® software package at Everglades National Park as part of vegetation mapping activities within the park. The classification rendered a park vegetation map at the pixel resolution of 20 x 20 m, containing sixteen cover type classes. Two 16 x 16 km (800 x 800 pixels) scenes within Shark River Slough were obtained from the National Park Service. One scene included the Shark Valley Loop Road area and was designated as the Loop Road, the other scene designated as Panther Mound (Figure 27). The sixteen cover class categories were combined to create three classes of vegetation; sawgrass, wet prairie and swamp hardwood (tree islands).

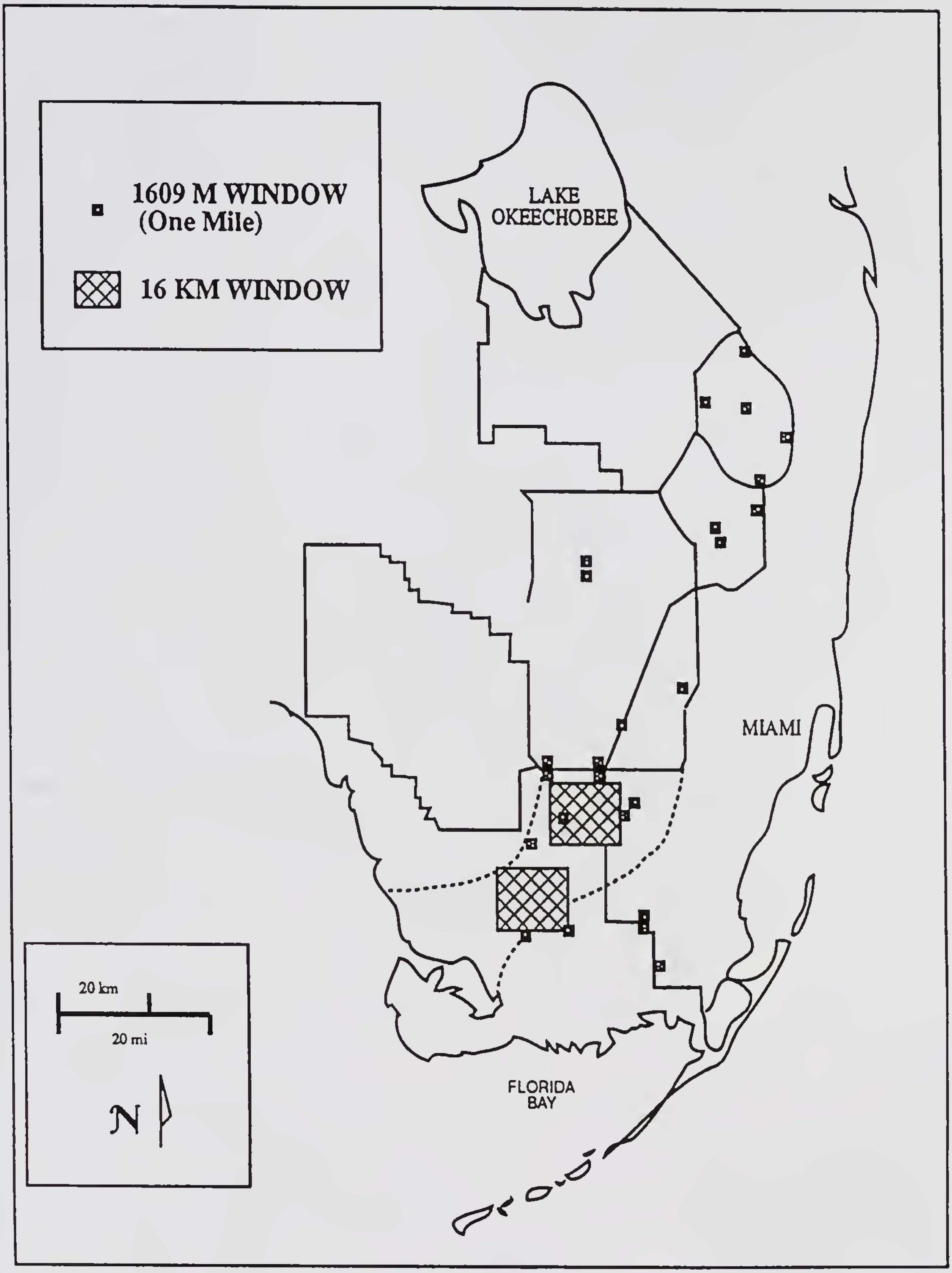


Figure 27. Location of 16 kilometer and 1609 m windows throughout the Everglades ecosystem within which vegetation communities were mapped for analyses.

The second largest vegetation maps were made within 25 square-mile windows located throughout the Everglades ecosystem (Figure 27). The maps were made by tracing vegetation patterns apparent on aerial photographs taken in 1987 onto transparent overlays. The maps used in this study were a subset of maps used to evaluate vegetation changes in the Everglades ecosystem (Davis et al, In prep). The one-square mile boundary was determined by using the scale of the imagery to calculate the appropriate box dimensions. The scale of the imagery ranged from 1:10,000 to 1:12,000, resulting in maps with dimensions of 5.4 x 5.4 in. to 6.4 x 6.4 in. Distinguishable vegetation units were outlined using a fine-tipped (00) pen. The maps were ground-truthed during the summer of 1989 using helicopter overflights. The composite vegetation maps were traced in order to produce a separate map for each vegetation type. Although many vegetation classes were mapped, only the three spatially dominant classes (sawgrass, tree island and wet prairie) categories were used in the cross windows comparisons.

The third and smallest window vegetation maps were made from 35 mm color slides taken from a helicopter during June, 1989. Attempts were made to keep the camera at right angle to the ground, in order to minimize distortion of patterns. Since the altitude was variable, the window size varied as well, from about 50 to 250 m. The photographs were made at sites in Shark Slough, Everglades Park where markers of known spacing were included in the photographs. The distance between the markers were used to calculate the window size and scale of each of the slides. The slides were projected onto a wall, where the vegetation patterns were traced onto letter size white paper. The vegetation patterns were truncated at the borders of the square plot.

The small and medium window tracings were scanned using an Apple Scanner at a resolution of 150 dots/inch. The scanned images were edited to remove irregularities introduced by the scanning process. The outlined areas were closed and filled. Typical maps of sawgrass in each window are shown in Figures 28, 29 and 30. The black and white maps are a bit map, or a raster image about 900 x 900 cells, with the bit in each cell being either on (black) or off (white). The bit map files were then transported to other programs for analyses of spatial patterns.

The sizes of each patch or clump of each vegetation type were analyzed within the two largest windows. A patch was defined as a group of pixels or cells that were isolated by a distance equal to at least one pixel. A routine from ERDAS® software was used to clump contiguous pixels at a search radius of 1.5 pixels. The output from this package rendered a pixel count for each patch. The pixel count was multiplied times the area per pixel to give the patch size in square meters. Each patch area was transformed to $\log_{10}$. The transformed series were sorted in rank order, from largest to smallest patch.

Fire data

Data on fire size were extracted from records compiled for Everglades National Park by Taylor (1979) for the time period 1948-1979, the available period of record. Fire ignition location was reported in terms of Township, Range and Section. Areas burned were tallied within a window of three townships (55-57 South) and three ranges (35-37 East) (324 mi^2 or 840 km^2 located over northern Shark Slough (Figure 31). Fire data were analyzed using the rank order/gap assessement.

A time series of fire data were analyzed for cross-scale temporal patterns. The origin of the data is described above. For the time series analysis, the time period of 256 months betweeen 1958 and 1979 was used, because the fast Fourier technique requires 2^n data points. Total area burned was tallied for each month.

Figure 28. Sample vegetation map, showing patterns of sawgrass within a 160 m window.

Figure 29. Sample vegetation map, showing pattern of sawgrass within a 1600 m sample window.

Figure 30. Sample vegetation map, showing pattern of sawgrass within a 16 km sample window.

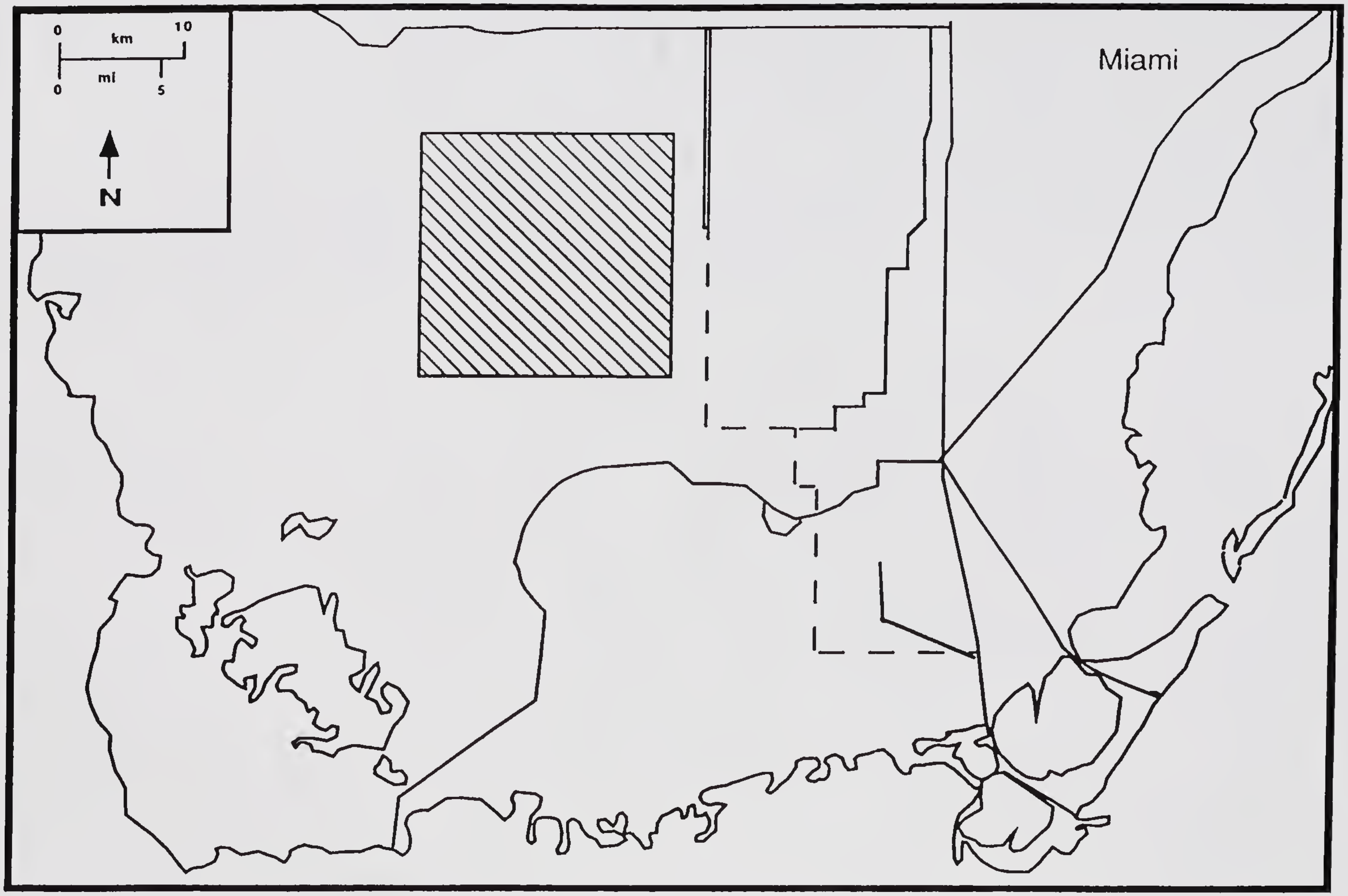


Figure 31. Location and size of sample window within which recent fire histories were analyzed for spatial and temporal patterns.

The fire sizes were log transformed (months with no fires were assigned values of zero) for Fourier and hierarchical cluster analyses.

Hydrologic data sets

Three types of hydrologic data were analyzed for temporal patterns; rainfall, stage (water level), and surface flow. For each data set, Fourier analyses were done, using the period of record (fixed window) and variable time units (days, months and years). Rank order/gap analyses and hierarchical cluster analyses were also used to determine hierarchical structure in most of the data sets.

Two data sets were used in the analysis of temporal rainfall patterns. Daily rainfall totals from May 1948 through December 1989 were obtained for Tamiami Ranger Station and Royal Palm Station (Figure 6). The daily data were totaled to yield monthly and annual amounts for the period of record.

Daily water levels were obtained from sites designated P33, P35, P37 and P38 (Figure 6). Daily and monthly summaries covering the time period January 1954 through December 1975 (256 months) were used in the Fourier analysis of stage data. Since the stations were established in 1953, these years represent the longest available set of monthly data for that is an even power of two.

Total monthly flow data from the Tamiami Trail flow section (Figure 6) were analyzed. The data span the time period October 1939 through 1983 for a total of 512 months.

Evaporation Data

Since evaporation is a large pathway of water flow in the wetlands of the Everglades, temperature and pan evaporation data sets were analyzed for temporal patterns. Temperature and pan evaporation are analogous metrics of evaporation, in that sensible heat flux is related to temperature patterns and pan evaporation is a physical model of combined factors that influences evaporation rates (Brutsaert 1984).

Monthly pan evaporation totals from sites at Tamiami Ranger Station and Belle Glade Experimental Station (Figure 6) were obtained from National Climatic Data Center for the time period 1965 through 1990. Data on mean monthly minimum and mean monthly maximum air temperature were obtained from the same source for Belle Glade (1931-1991) and Tamiami Ranger Station (1940-1991). Fourier analyses were done on each of these data sets to identify dominant time cycles.

Daily measures of pan evaporation and community evapotranspiration were obtained from work of Gunderson and Stenberg (Gunderson and Stenberg 1990). Study sites were established at P33, an Eleocharis marsh over peat in Shark Slough, and P37, a sawgrass/muhly grass marsh over marl in Taylor Slough (Figure 6). At each site, a standard Class A evaporation pan with a recorder was installed and daily pan evaporation measured between February 1985 and September 1986. During the same time period, daily estimates of community evapotranspiration were derived from daily tracings of water levels following techniques of Dolan et al. (1984), with modifications related to differences between surface and ground water conditions. Fourier analyses were done on all daily data evaporation sets.

Sea Level Data

Another variable that influences stage and flow dynamics in such a flat system as the Everglades is the height of sea level. To compare temporal patterns of the freshwater system with patterns in the surrounding saline systems, data on monthly sea level were obtained for three south Florida sites. Data from Key

West were recorded and obtained for the time period 1912 through 1991, from Miami 1932 through 1982 and at Naples from 1965 through 1991. All three data sets were detrended, to remove an obvious increase in sea level through the period of record. Fourier analyses were done on all three sets to determine dominant time cycles

A summary of the variety of data sets is presented in Table 8. The type of data (spatial or temporal), type of analyses used, grain and extent and number of replicates are presented for each of the data sets. This summary is useful as a prelude to the results of all of these data sets and the various analyses. The results of all of these analyses are the subject of the next section in this chapter.

Results Of Cross-Scale Analyses

Analyses of the data sets on the keystone structural features and processes suggest that the discontinuous hypothesis cannot be invalidated. Examination of the structual features across scales (grain and extent), imply the occurrence of breaks that separate regions of self-similarity. As the window of examination changed, regions of similar patterns would abruptly change to another region that exhibited a different pattern. Only a few frequencies were noted in the temporal fluctuations of key processes in the system. Repeated analyses that varied window and grain of the temporal data sets, still generated results with only a few reasonant frequencies.

Evidence of breaks in the structual features is shown from a summary of analyses of spatial data sets. The topographic data has two scales of variation, defined by a break in the fractal dimension at a step length of about 1.5 kilometers (Table 9). The changes in vegetation patterns over scale ranges, are suggested by the fractal analyses, but appear at more definite resolution using

Table 8. Summary of data sets used in cross-scale analyses of Everglades ecosystem.

Variable	Space/Time	Analysis	Grain	Unit	Window	Unit	Replicates
Vegetation							
Sawgrass	Space	Fractal	0.5	m	150	m	12
			2	m	1600	m	25
			10	m	16	km	2
Tree Island	Space	Fractal	0.5	m	150	m	2
			2	m	1600	m	25
			10	m	16	km	2
Wet Prairie	Space	Fractal	0.5	m	150	m	9
			2	m	1600	m	25
			10	m	16	km	2
Sawgrass	Space	Rank Order/	2	m	1600	m	25
		Gap	10	m	16	km	2
Tree Island	Space	Rank Order/	2	m	1600	m	25
		Gap	10	m	16	km	2
Wet Prairie	Space	Rank Order/	2	m	1600	m	25
		Gap	10	m	16	km	2
Topography	Space	Fourier	100	m	32	km	5
		Fractal	100	m	32	km	11
Water Flow	Time	Fourier	1	mo	44	yr	1
		Rank Order/	1	mo	44	yr	1
Rainfall	Time	Fourier	1	yr	44	yr	2
			1	mo	39	yr	2
			1	day	39	yr	2
		Rank Order/	1	yr	44	yr	2
		Gap	1	mo	39	yr	2
			1	day	39	yr	2
Water Stage	Time	Fourier	1	mo	22	yr	4
			1	mo	22	yr	4
		Rank Order/	1	mo	22	yr	4
		Gap	1	mo	22	yr	4
Fire	Time	Fourier	1	mo	22	yr	2
	Space	Rank Order/	1	mo	22	yr	2
		Gap					
Sea Level	Time	Fourier	1	mo	88	yr	3
Temperature	Time	Fourier	1	mo	22	yr	2
		Fourier	1	mo	22	yr	2
Pan Evaporation	Time	Fourier	1	mo	22	yr	2
		Fourier	1	day	22	mo	2

Table 9. Summary of cross-scale analyses of spatial data sets, indicating break points detected by fractal and gap analyses.

SPATIAL DATA SET	Type Analysis	Window SIZE (km)	Break Points Small Step Length log 10	(m)	Large Step Length log 10	(m)
Sawgrass	Fractal	16	2.2	158	-	-
Wet Prairie	Fractal	16	1.8	63	-	-
Tree Island	Fractal	16	2.4	251	-	-
Sawgrass	Gap	1.6	2.4	251	2.75	562
Wet Prairie	Gap	1.6	2.5	316	2.95	891
Tree Island	Gap	1.6	2.1	126	2.3	200
Sawgrass	Gap	16	-	-	3	1000
Wet Prairie	Gap	16	-	-	3.05	1122
Tree Island	Gap	16	-	-	3.05	1122
Topography	Fractal	30	-	-	3.2	1585
Fire	Gap	10	1.9	79	3.5	3162

Table 10. Summary of cross-scale analyses of temporal data sets, indicating dominant frequencies found in each set.

TEMPORAL DATA SET	WINDOW	GRAIN	FREQUENCIES (YEARS) Primary	Secondary	Tertiary
Rainfall	39 yr	day	1	0.25	0.3
	39 yr	month	1	0.25	0.3
	44 yr	year	6	8	11
Stage	22 yr	day	1	7	3
		month	11	1	3
Flow	44 yr	month	1	8	22
Pan Evaporation	22 yr	month	1	11	5
Sea Level	88 yr	month	1	11	0.5
Temperature	22 yr	month	1	0.5	-
Fire	22 yr	month	11	1	-

the gap detection method. Changes in the fractal dimensions of the vegetation types are suggested at step lengths of 60-250 m. Gaps in rank order distributions of patch sizes appear at a similar range(100-300 m) and again at step lengths of about 1 km. Although the measured values of breakpoints differ, all of the data sets appear to exhibit some sort of breaks in key structural features.

The dominant frequency in the temporal patterns was the annual cycle (Table 10). Other frequencies were significant in all of the analyzed data sets. Multiple year patterns of 11 years were dominant in the stage and fire data sets. Secondary frequencies of 8 to 11 years were noted in fluctuations of annual rainfall, stage, flow, pan evaporation and sea level data sets. Cycles of 3 to 6 months were noted in the rainfall and air temperature data sets. Cycles of multiple frequencies were apparent in all of the analyzed data sets, supportive of the hypotheses.

The details of the multiple analyses are presented next, grouped by the data set analyzed. The results of the spatial features of topography, vegetation maps and fires are presented first, followed by the results using the time series data on rainfall, stage, flow, fires, evaporation, air temperature and sea level. The detailed interpretations of data sets are summarized in Tables 9 and 10.

Topographic data

The topography of the soil surface in the southern Everglades appears to vary at two different spatial scales. The plots of surveyed elevation versus horizontal distance for each of the transects (Figures 32, 33 and 34: A-D), depict both the broad level changes in topography, and finer scale variation within the broader pattern.

The fractal analyses suggests the presence of two regimes of topographic variation. The plot of $\log_{10}$ transect length vs $\log_{10}$ step length (Figure 35)

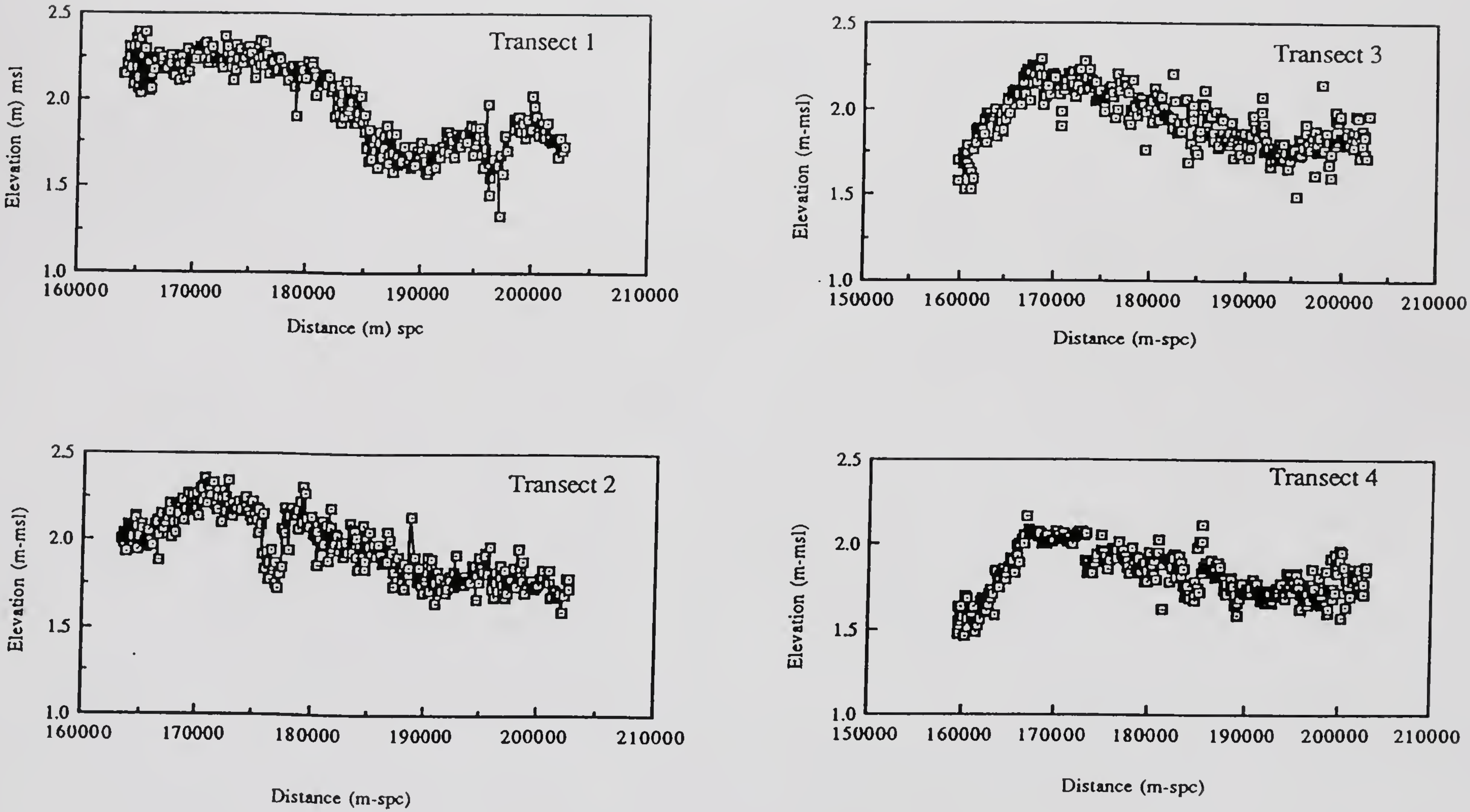


Figure 32. Topographic surveys from transects 1 through 4 (see figure 26 for locations) showing elevational variation with east west distance.

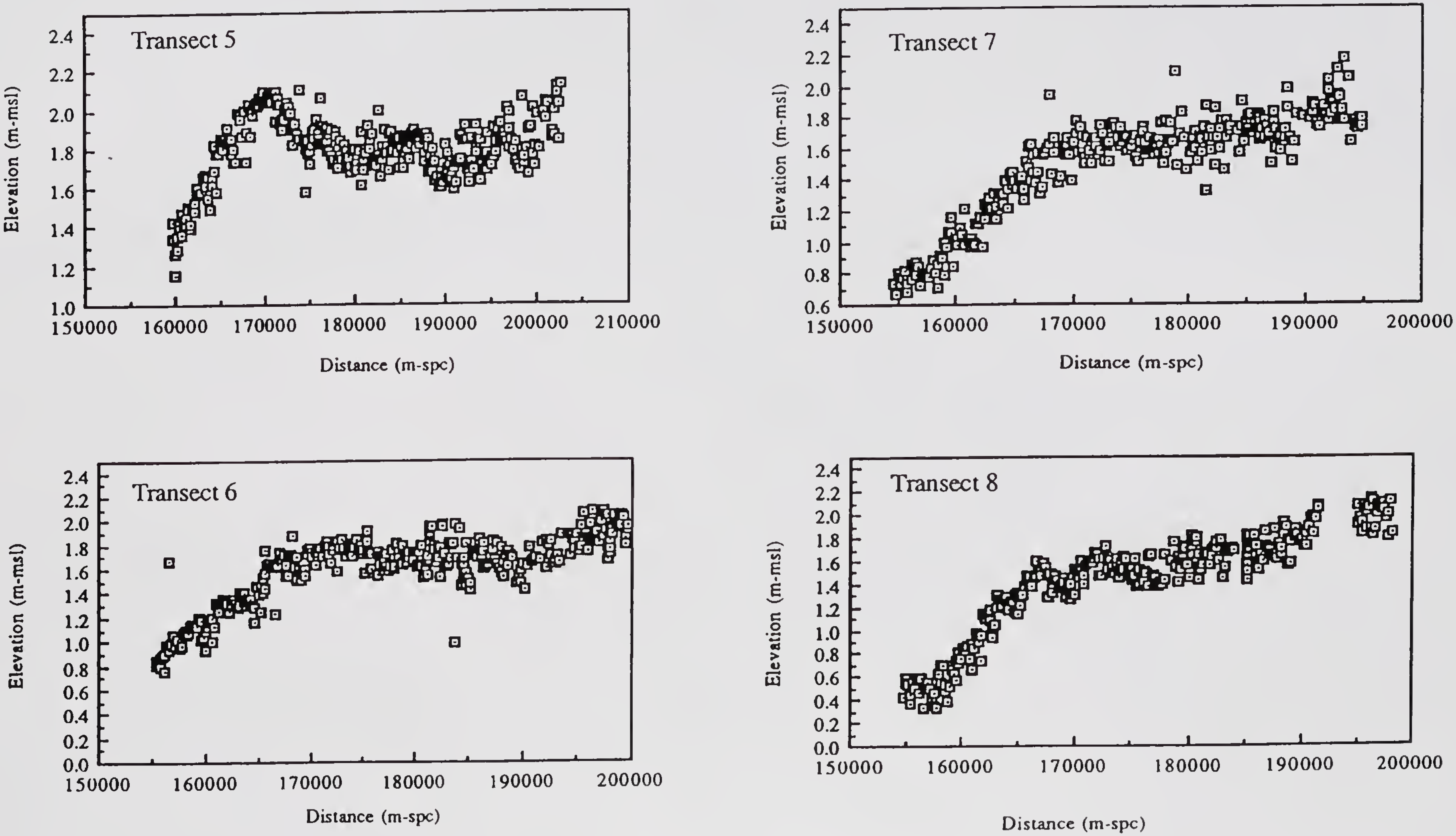


Figure 33. Topographic surveys from transects 5 through 8 (see figure 26 for locations) showing elevational variation with east west distance.

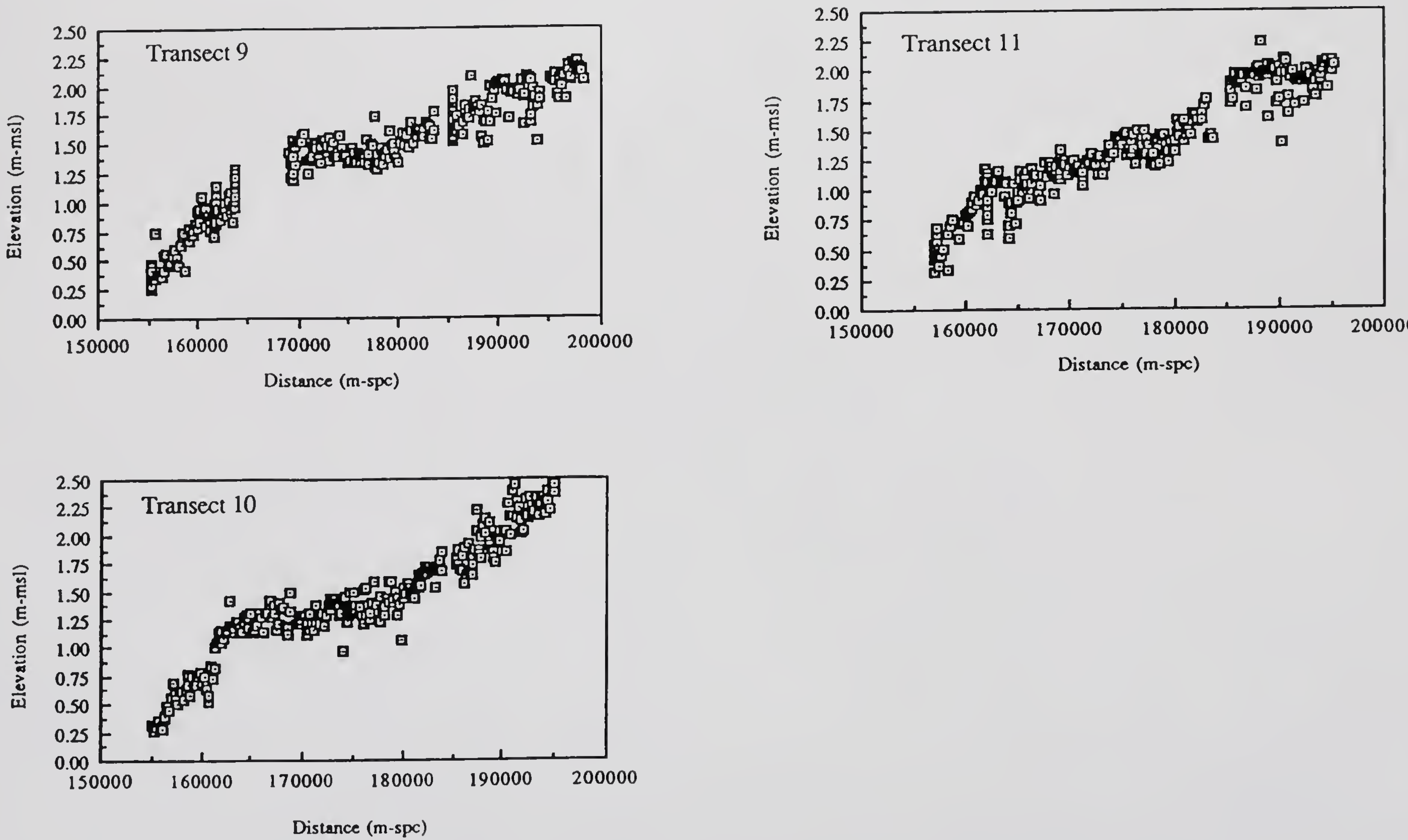


Figure 34. Topographic surveys from transects 9 through 11 (see figure 26 for locations) showing elevational variation with east west distance.

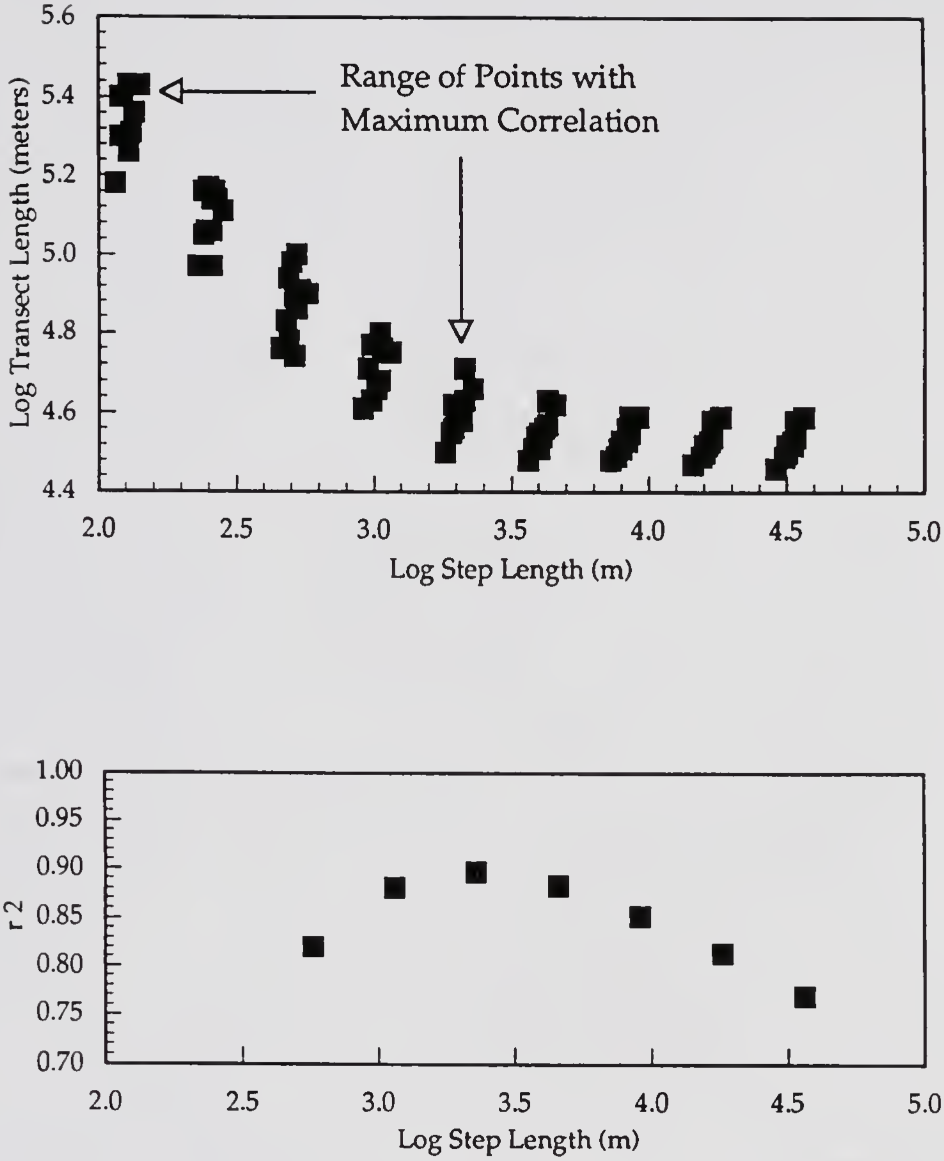


Figure 35. Log-log plot of transect length versus step length (top plot) used to estimate breaks in fractal dimension. Bottom plot shows results of rolling regressions. Break in top plot is indicated at point of maximum regression coefficient (bottom plot).

indicates a change in the slope (fractal dimension) at a horizontal step length of between 1 and 3.2 km ($\log_{10}$ 3 and 3.5). The break in the fractal dimension was further defined by using a rolling regression technique. The technique used a linear regression approach and subsequently added data points. A break in the linearity of the relationship is evident by an increase in the regression coefficient to a maximum value, then a subsequent decrease. The maximum regression coefficient was obtained using values up to $\log_{10}$ 3.25 (Figure 35). The best estimate, therefore, is that a break in the fractal dimension occurs at a step length of about 1.5 km. For smaller step lengths, the topography is reasonably self similar, with a fractal dimension of approximately 1.6. The fractal or scaling dimension can be used to estimate the length of a transect as a function of step length (between 0.1 and 1.5 km) by formula (8).

(8) $L = 6.5 * l^{1.62}$

L= transect length

l = step length

The cross-scale structure of soil surface elevation appears to change at step lengths of about a little more than a kilometer. The measure of the breakpoint is subjective and dependent upon interpretation of a pattern of two lines within a set of points. Alternative explanations may be that the relationship between length and unit of measure changes gradually, approaching some asymptotic level. In either case, the fractal analysis suggests a change in pattern with scale, and a similarity of pattern at the small step lengths. As an alternative approach, the Fourier technique was applied to five of the data sets to see if multiple "wavelengths" could be interpreted as evidence of multiple scales of variation. The Fourier analysis did indicate multiple sets of waves, but emphasized the long or broad wavelengths apparent in the data sets. Whereas the fractal analysis appear to emphasize the small scale variation, the Fourier analysis appears to emphasize the broad scale variation.

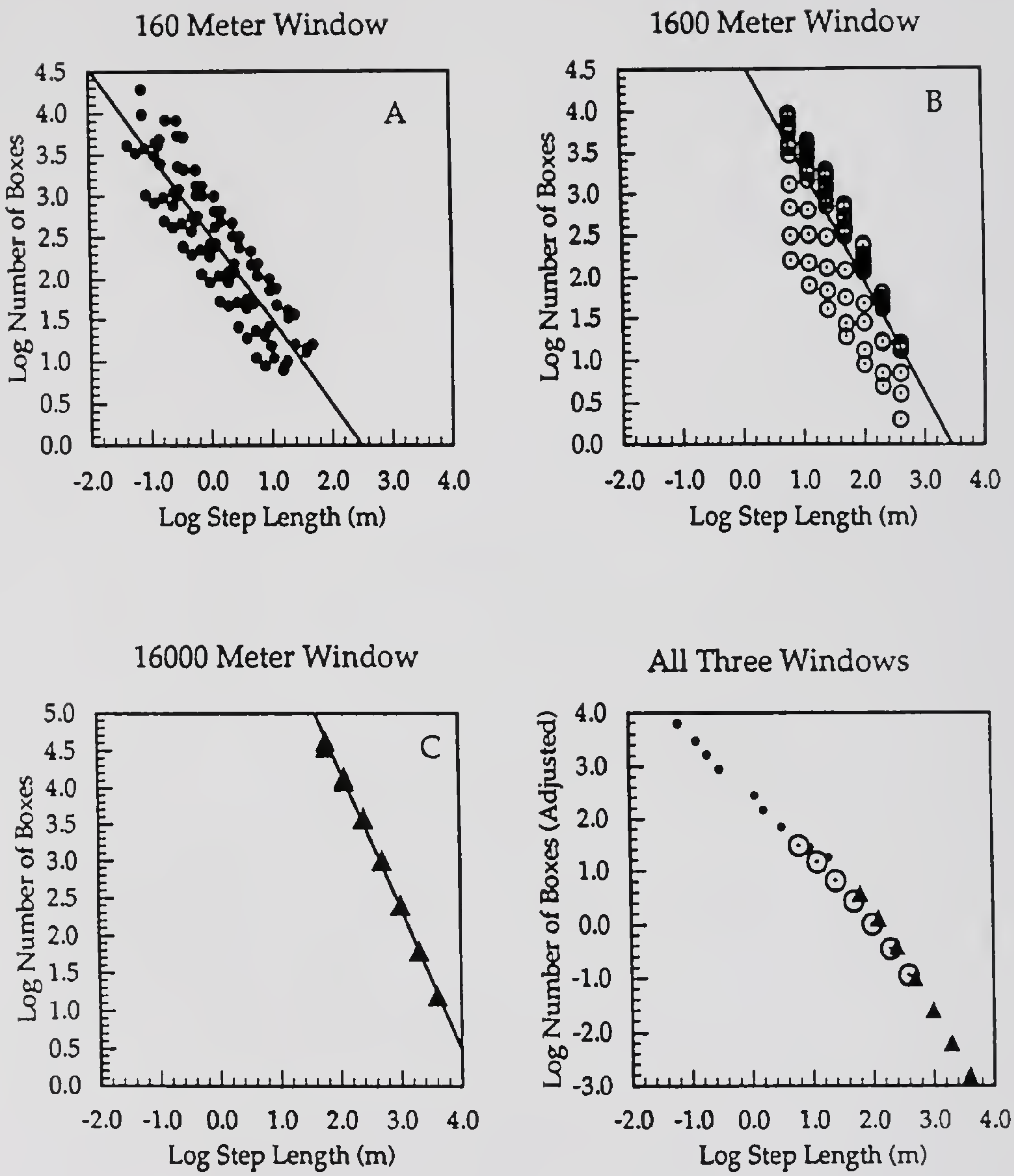
It is not the result from either, but the combined results from both techiques that indicate the presence of both a fine scale (small step length) and a broad scale (longer step length) pattern. The broad pattern reflects the basin morphometry associated with the surficial geologic features of the Everglades. At the broad scale, the elevation varies on the order of one/half meter over horizontal distances of of 20 km. The finer scale variation reflects changes of 20 cm over horizontal distances of less than 1 km. The finer scale variation reflects microtopographic processes such as dissolution of bedrock and peat accretion.

The apparent changes in scales of the topography qualitatively agree with spatial scale of processes creating the pattern. To determine if similar breaks are manifest in other ecosystem variables, the results of cross-scale analyses of vegetation patterns are presented next.

<u>Vegetation Patterns</u>

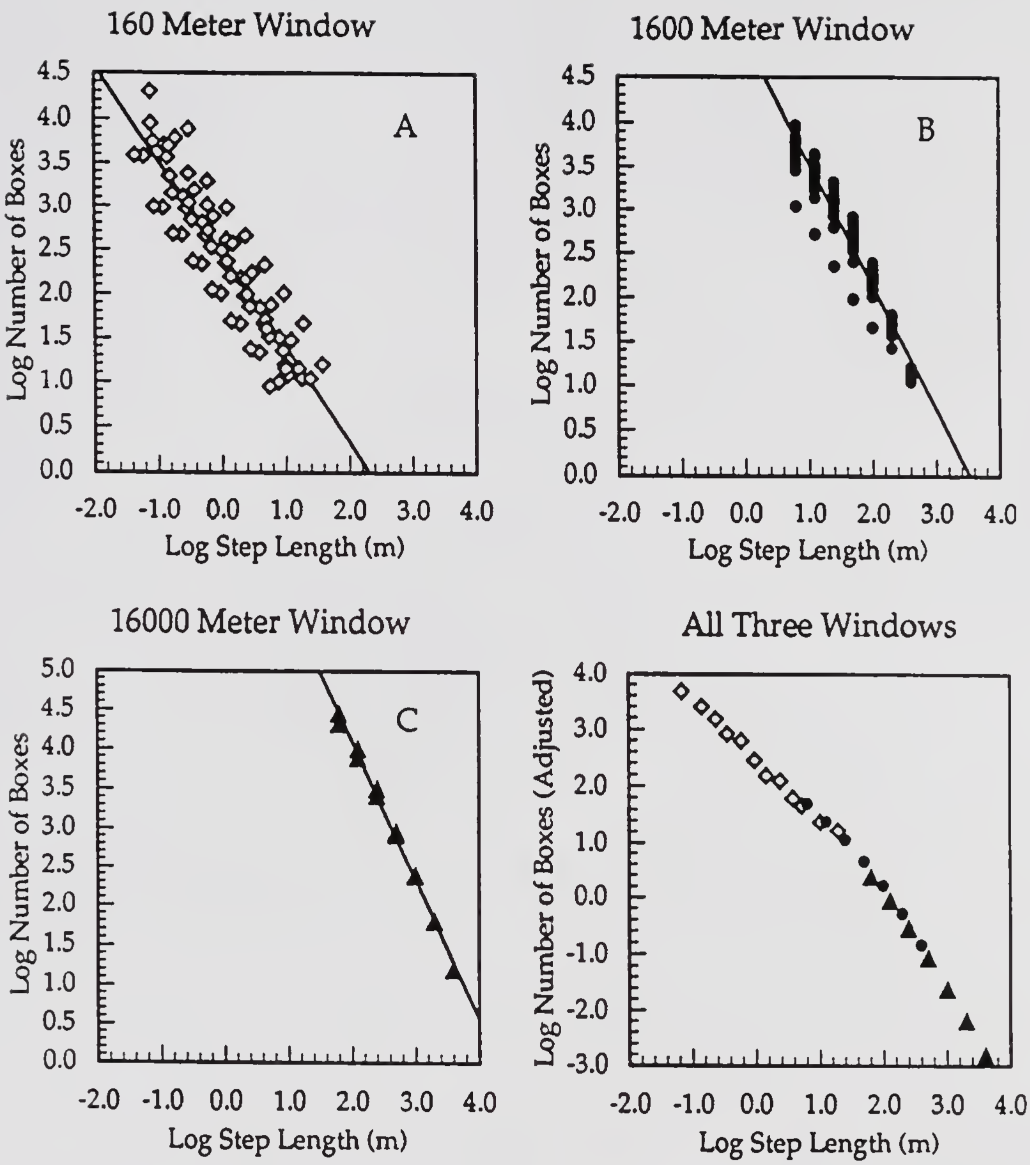
The spatial patterns of three dominant vegetation communities (sawgrass, wet prairie and tree island) appear to have breaks and discontinuities at different scale ranges. Gaps appear in the rank order plots of patch size and breaks are suggested by the fractal analysis. First, the results from the fractal analysis.

Discerning breaks in the fractal dimension proved to be problematic. The fractal dimensions of all three vegetation communities appeared to increase with the window size. The dimensions of all three vegetation types ranged from 1.01 to 1.19 in the small window, 1.23 to 1.40 in the intermediate sized window and from 1.77 to 1.89 in the large window (Figures 108-110). There is little evidence of a break or change in the fractal dimension within the single window plots. A



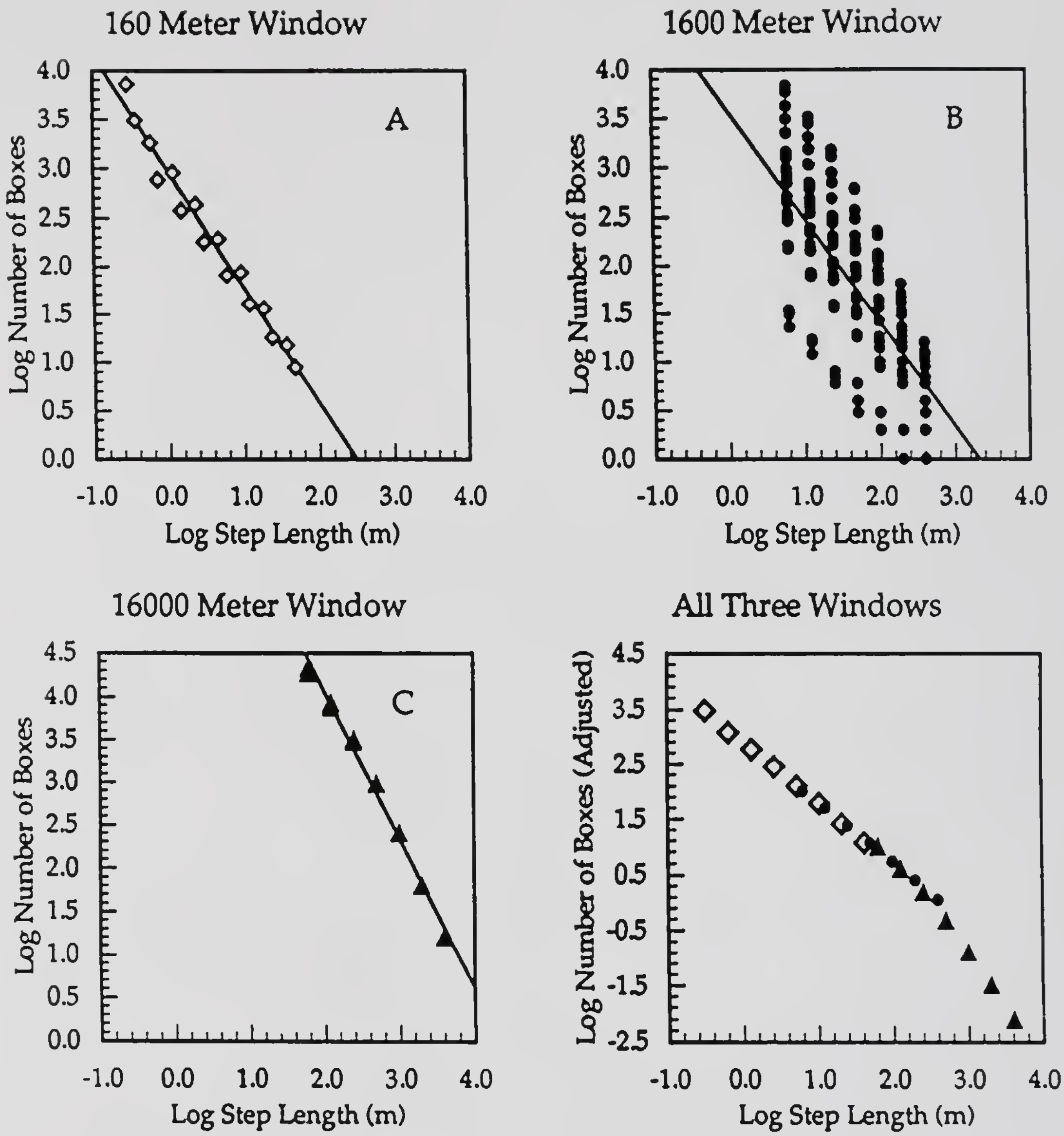
A)	Y = -1.01X + 2.51	r2 = 0.78
B)	Y = -1.36X + 2.65	r2 = 0.77
C)	Y = -1.89X + 8.07	r2 = 0.98

Figure 36. Log-log plots of box size versus box count used to estimate fractal dimensions of sawgrass vegetation within three sample windows. Estimates of fractal dimension are given by slope of regression. Data from three windows are combined in lower right plot, and suggest a break in the fractal dimension.



A	Y = -1.06 X +2.46	r2 = 0.82
B	Y = -1.40 X +4.95	r2 = 0.96
C	Y = -1.77 X +7.64	r2 = 0.99

Figure 37. Log-log plots of box size versus box count used to estimate fractal dimensions of wet prairie vegetation within three sample windows. Estimates of fractal dimension are given by slope of regression. Data from three windows are combined in lower right plot, and suggest a break in the fractal dimension.

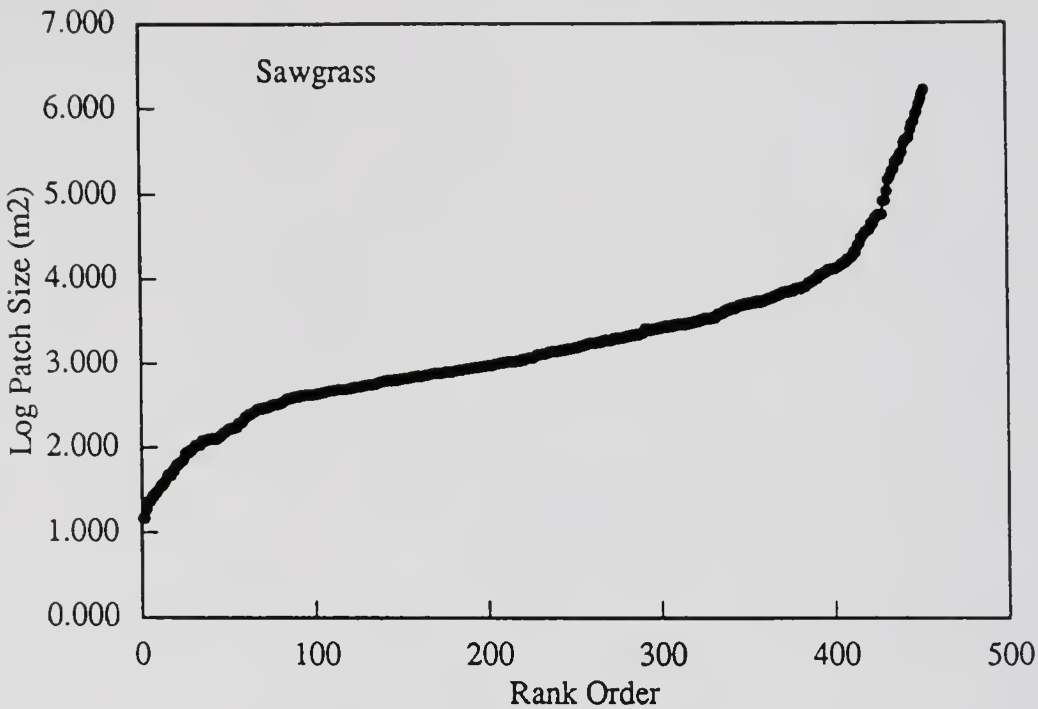


A)	Y = -1.19X + 2.97	r2 = 0.98
B)	Y = -1.23X + 3.59	r2 = 0.52
C)	Y = -1.73X + 7.54	r2 = 0.99

Figure 38. Log-log plots of box size versus box count used to estimate fractal dimensions of tree island sawgrass vegetation within three sample windows. Estimates of fractal dimension are given by slope of regression. Data from three windows are combined in lower right plot, and suggest a break in the fractal dimension.

break, if any, could be hidden by the scatter within the window. One approach examined the correlation coefficients of the individual windows. If the small and large windows had high correlation coefficients, and the intermediate window a low coefficient, then perhaps a change in the relationship would be indicated by the lower correlation coefficient. This approach proved unworkable, due to the confounding effects of different numbers of sample among the windows. As a final step, the mean number of boxes were calculated for each measured step length. The plots of average box count versus average box size suggest that a change or break in the relationships do occur (Bottom right plot-Figures 36-38). The "break" only becomes apparent when the averages from the intermediate combined with the data from smaller and larger windows. These plots suggest a change in the fractal dimension at step lengths of about $\log_{10}$ 1.8 (60 m) for wet prairie (Figure 37), $\log_{10}$ 2.2 (160 m) for sawgrass (Figure 36) and $\log_{10}$ 2.4 (250 m) for tree islands (Figure 38). In spite of these apparent breaks, the method appears insensitive when applied to the variation encountered in real data sets. Part of the insensitivity is due to the magnitudes of the parameters, within maps, the values only range from one to two. Since the methods are insensitive and the variation in the estimated parameter large, a conclusion as to presence of these changes or breaks cannot be reliably made. To determine if the "breaks" are indicative of a change in underlying process, another technique was used, the analysis of gaps in the distributions of vegetation patch sizes.

The analyses of patch sizes from the 1600 m window indicate the presence of three clumps in the sawgrass and wet prairie vegetation types and two in the tree island type. Although significant gaps occur at the beginning of all of the distribution in all vegetation types, none of these are counted. Significant gaps, followed by small index values occur in the distribution of sawgrass patch sizes



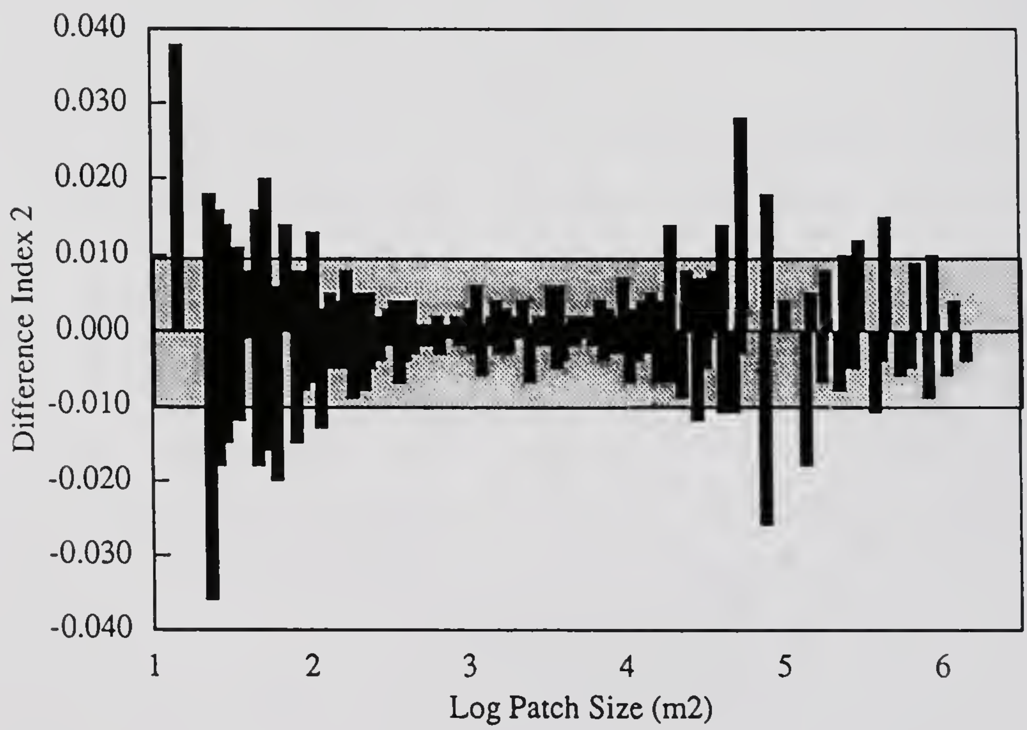


Figure 39. Rank order plot (top plot) and difference indices (bottom plot) for sawgrass patches sampled from 1600 m windows.

at two points (Figure 39). The first clump includes all patch sizes less than about $\log_{10} 4.8$ (63,000 m^2). The second clump is defined by points greater than $\log_{10}$ 4.8 and less than $\log_{10} 5.6$ (316,000 m^2). Significant gaps in the distribution of wet prairie patch sizes occur at $\log_{10}$ 5.4 and $\log_{10} 5.9$ (Figure 40). Similar gaps occur in the tree island distributions at $\log_{10} 4.2$ (Figure 41).

The analyses using data from the larger window (16 km) indicated the presence of one significant gap in rank order distributions of the three vegetation types (Figures 42-44). The gaps appeared at the upper end of the spectrum, and all occurred at patch sizes of about $\log_{10}6$, or a million square meters. These gaps appear as breaks or jumps in the rank order distributions.

Both the gap and fractal analyses indicate similar properties of the vegetation patterns displayed in maps. The gaps in the rank order distributions seem to occur at patch sizes not very different from those inferred from the fractal analyses. All three vegetation types exhibited a gap or change in the fractal dimension at step lengths between about 50 and 300 m (Table 9). Another break appears at a step length of about 1000 m (Table 9). Although none of the results alone provide irrefutable proof, together they provide evidence that supports the hypothesis that the system is structured in a series of lumps and gaps. To see if this pattern continues, the results of the analyses of the fire data are presented next.

<u>Fires</u>

During the 31 year period between 1948 and 1979, the 132 fires in Shark slough ranged in size between 300 m^2 to more than 133 km^2. At least three size classes are apparent in the data. The class with the largest fires, had two fires (122 and 133 km^2). The majority of fires (126) were between 4000 m^2 and 34

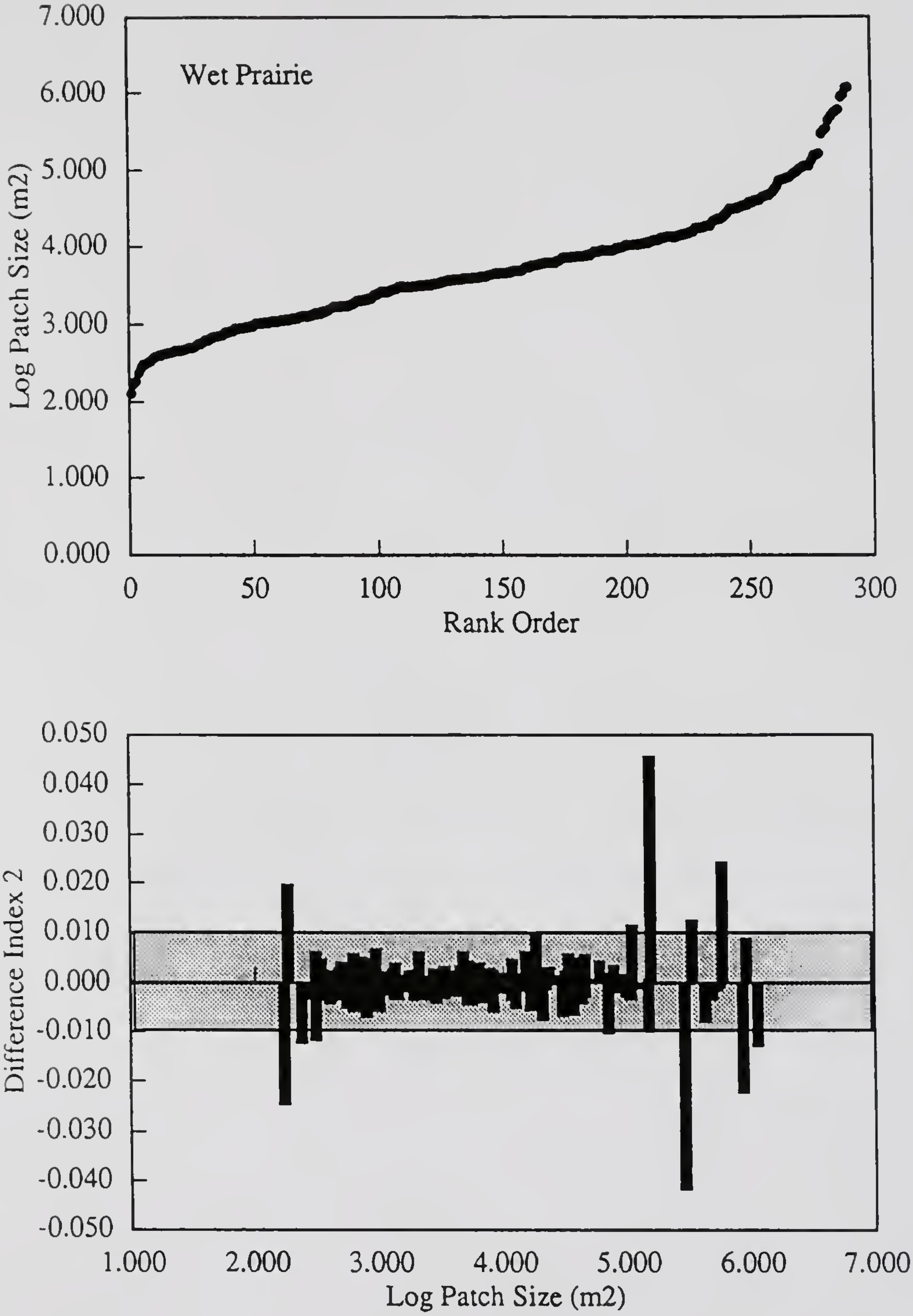
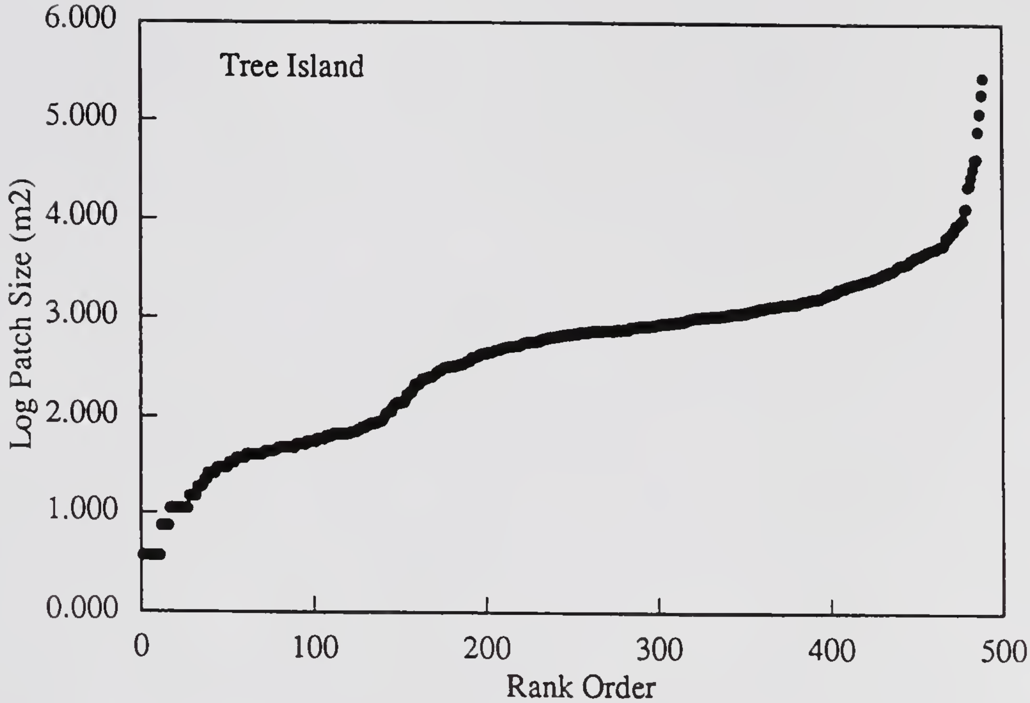


Figure 40. Rank order plot (top plot) and difference indices (bottom plot) for wet prairie patches sampled from 1609 m windows.



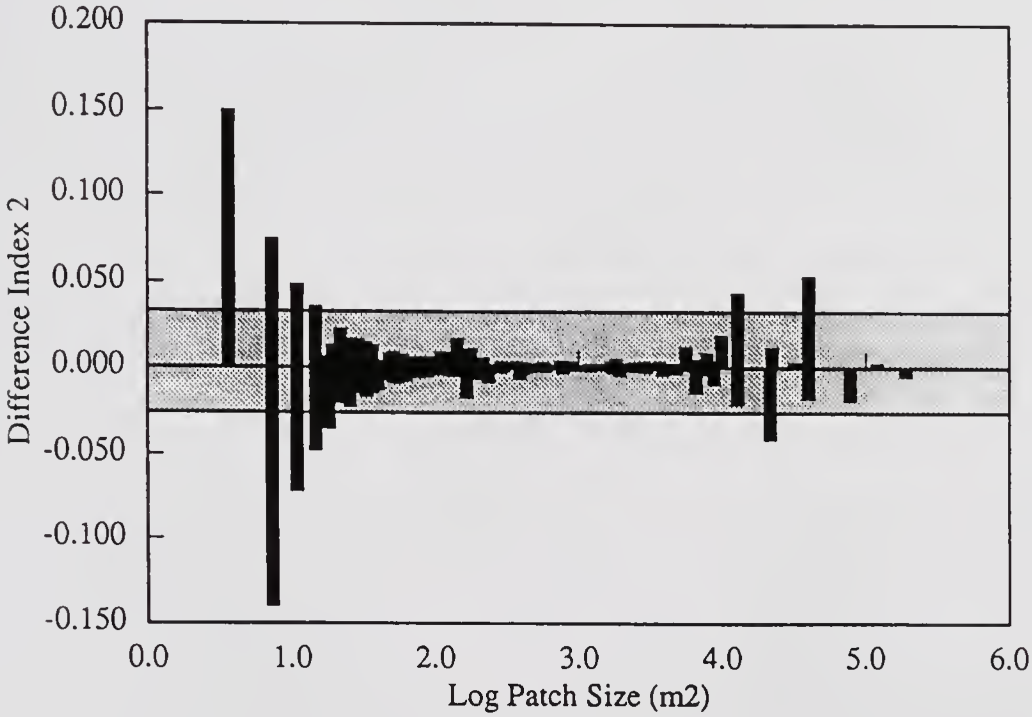


Figure 41. Rank order plot (top plot) and difference indices (bottom plot) for tree island patches sampled from 1609 m windows.

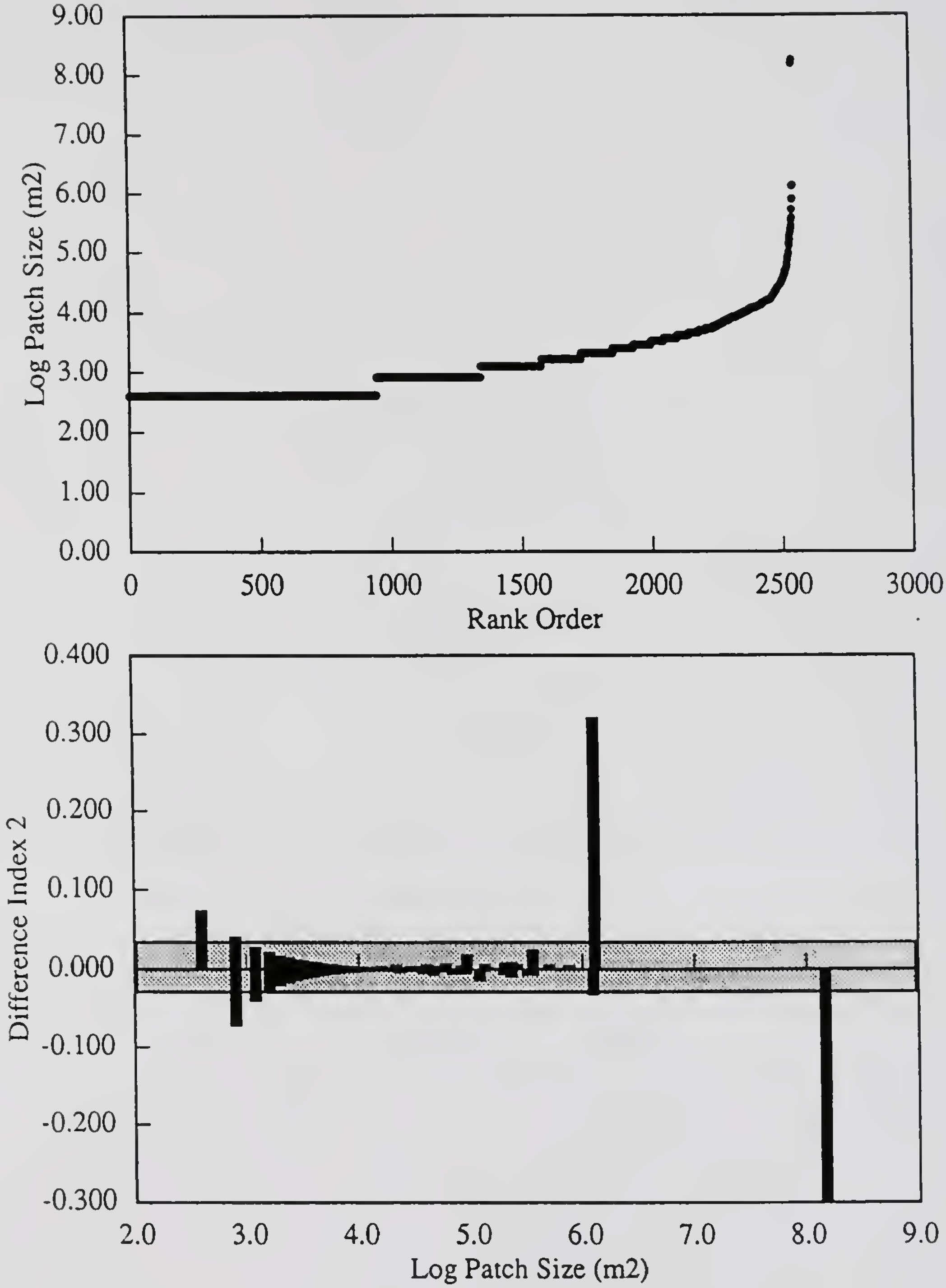


Figure 42. Rank order plot (top plot) and difference indices (bottom plot) for sawgrass patches sampled from 16 km windows.

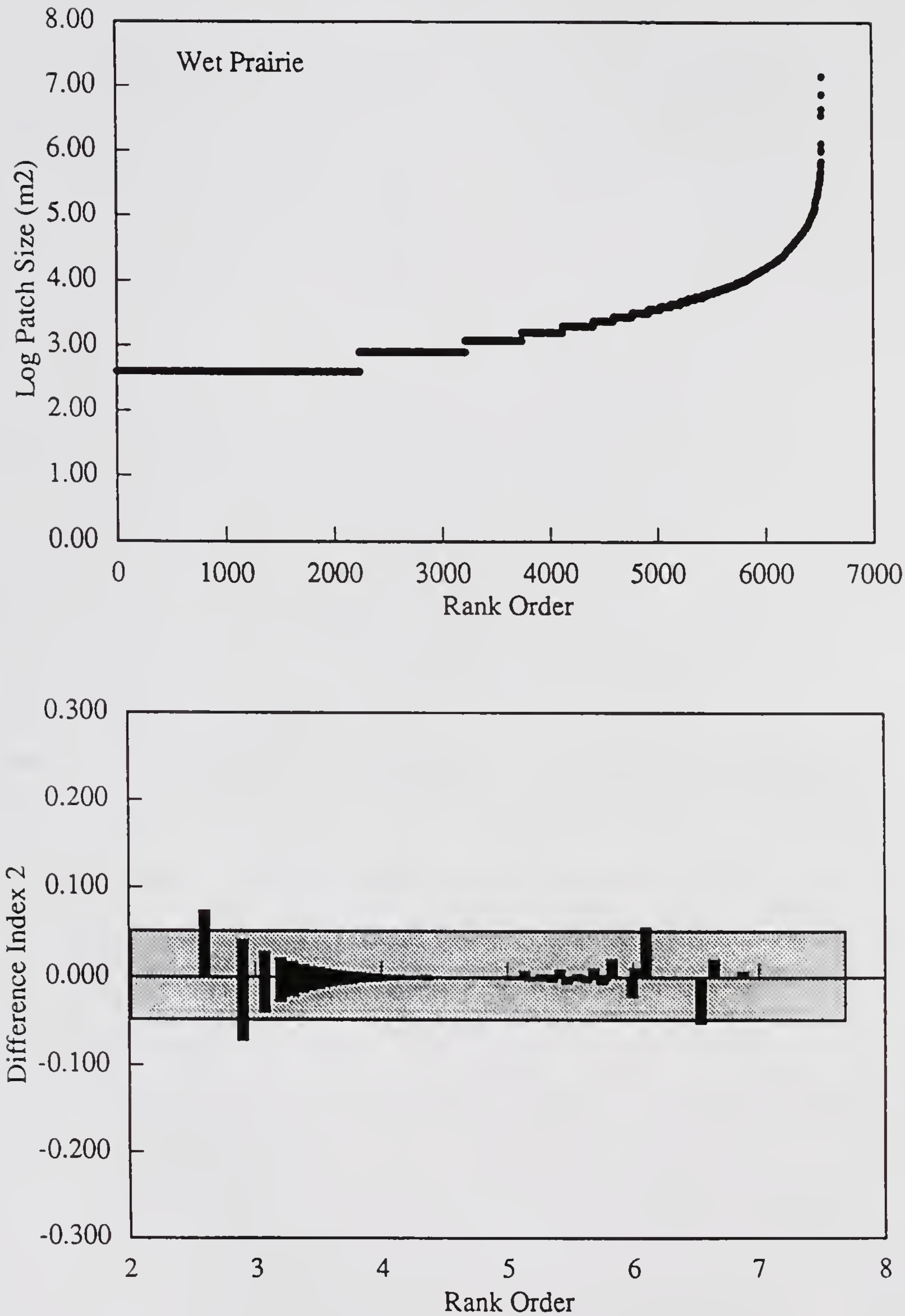
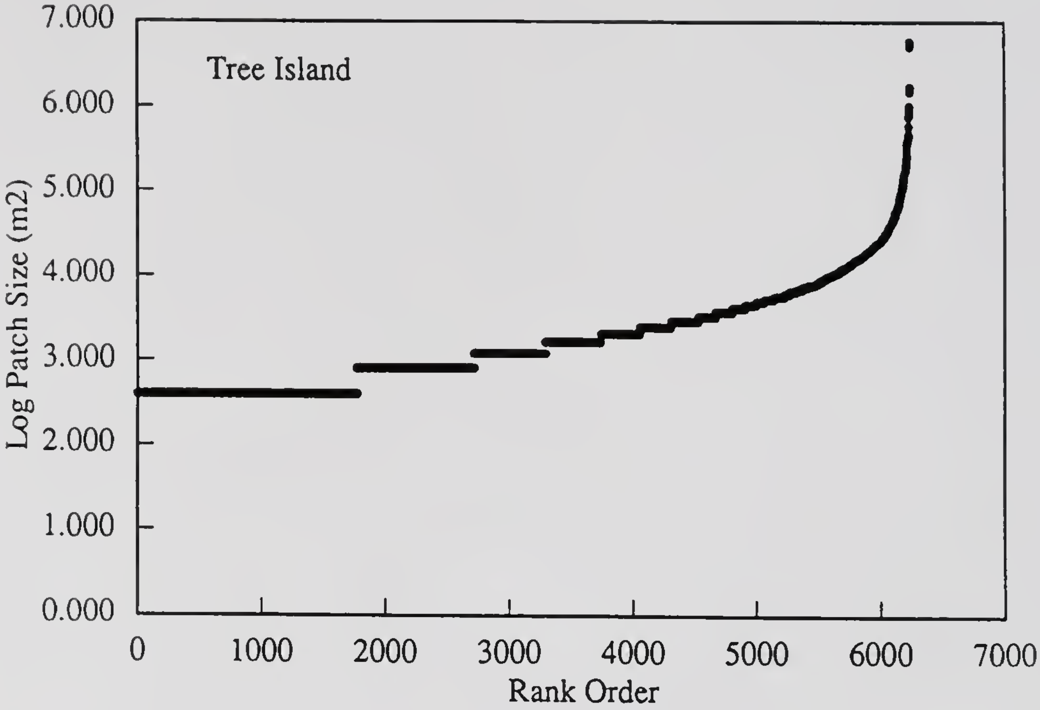


Figure 43. Rank order plot (top plot) and difference indices (bottom plot) for wet prairie patches sampled from 16 km windows.



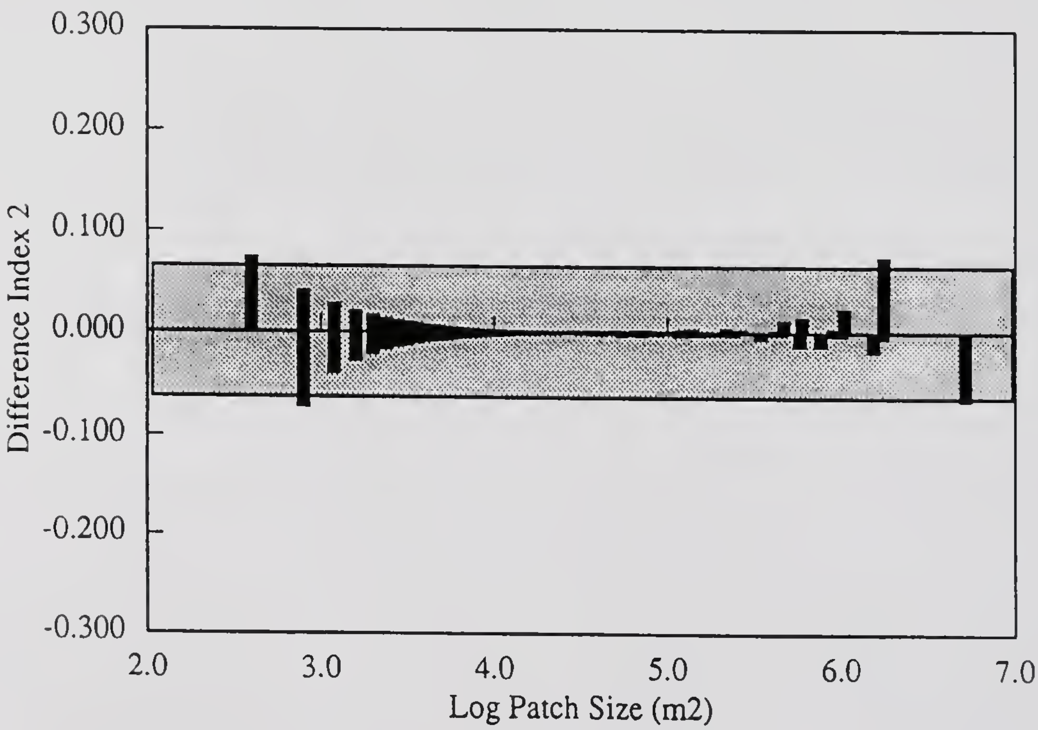


Figure 44. Rank order plot (top plot) and difference indices (bottom plot) for tree island patches sampled from 16 km windows.

km^2. The class of smallest fire sizes was defined by fires less than 2500 m^2. These classes are evident in the rank order plot (Figure 45). The two difference indices, both indicate at least two significant gaps in the rank order distribution (Figure 46). The first gap appears at fire size of 10^3 m^2, and the other significant gap occurs around $10^{7.5}$ m^2 (Figure 45).

Even though the analyses indicate three classes, the smallest group of fires is probably an artifact of the data collecting technique. During the early years of the data set, the reporting of small fires in remote areas was sporadic and done by estimating the fire sizes from airplane (Taylor 1980) The data set contains a number of observations of 100 acre fires, indicating how fire sizes were estimated. The break in the small class sizes therefore, are within the error associated with estimating fire sizes.

The larger fires sizes represent a different type of fire, one probably associated with a different set of processes that determine fire type. Once fires reach a certain size, the fire can generate conditions that produce positive feedbacks (autocatalytic) that dramatically increase fire size. Among the feedbacks include, convective circulation associated with the rapidly rising heated air, the drying of soil, and fuel near the fire. Distinctions in fire size and processes affecting size have been reported by Craighead (1971) and Wade et al, (1980) .

The analyses of the spatial data sets (topography, vegetation and fires) all indicate the presence of breaks or changes in the patterns of structure. A change in the scale of variation appears in the topographic data. Changes in the distribution of sizes of vegetation patches and fires are also noted. To see if the keystone processes in the system exhibit a few, distinct frequencies, the results of analyses of the temporal data are presented next, starting with rainfall data.

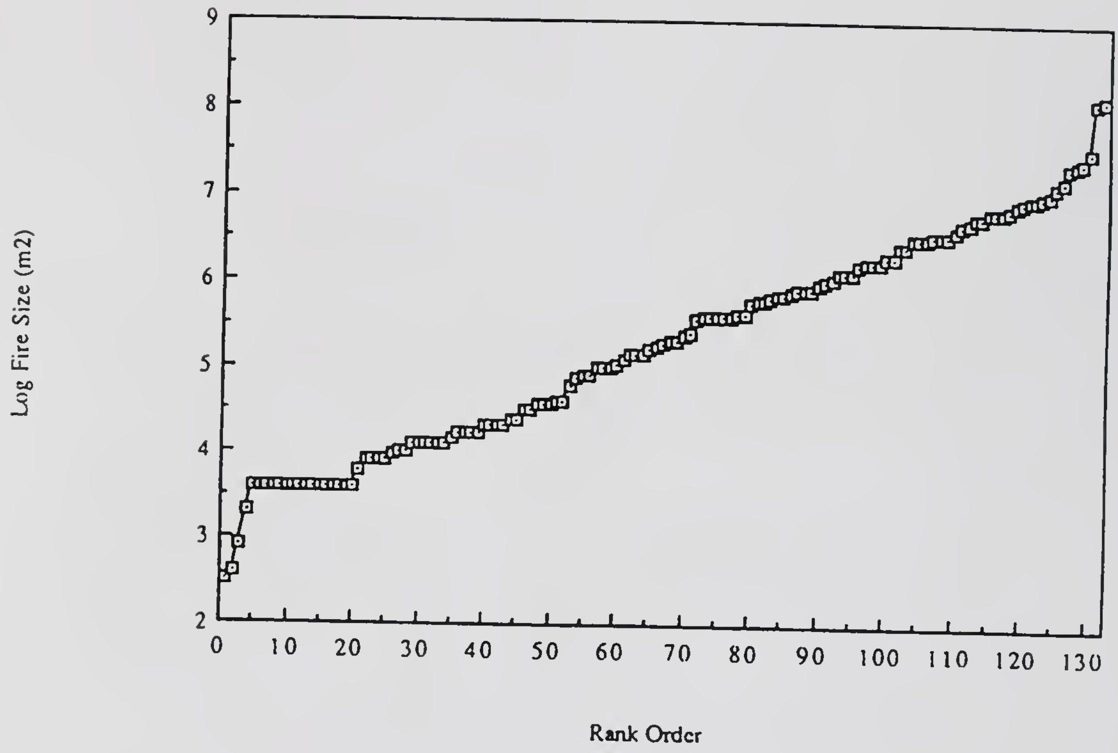


Figure 45. Rank order plot of log fire sizes from Shark River Slough, 1958-1979.

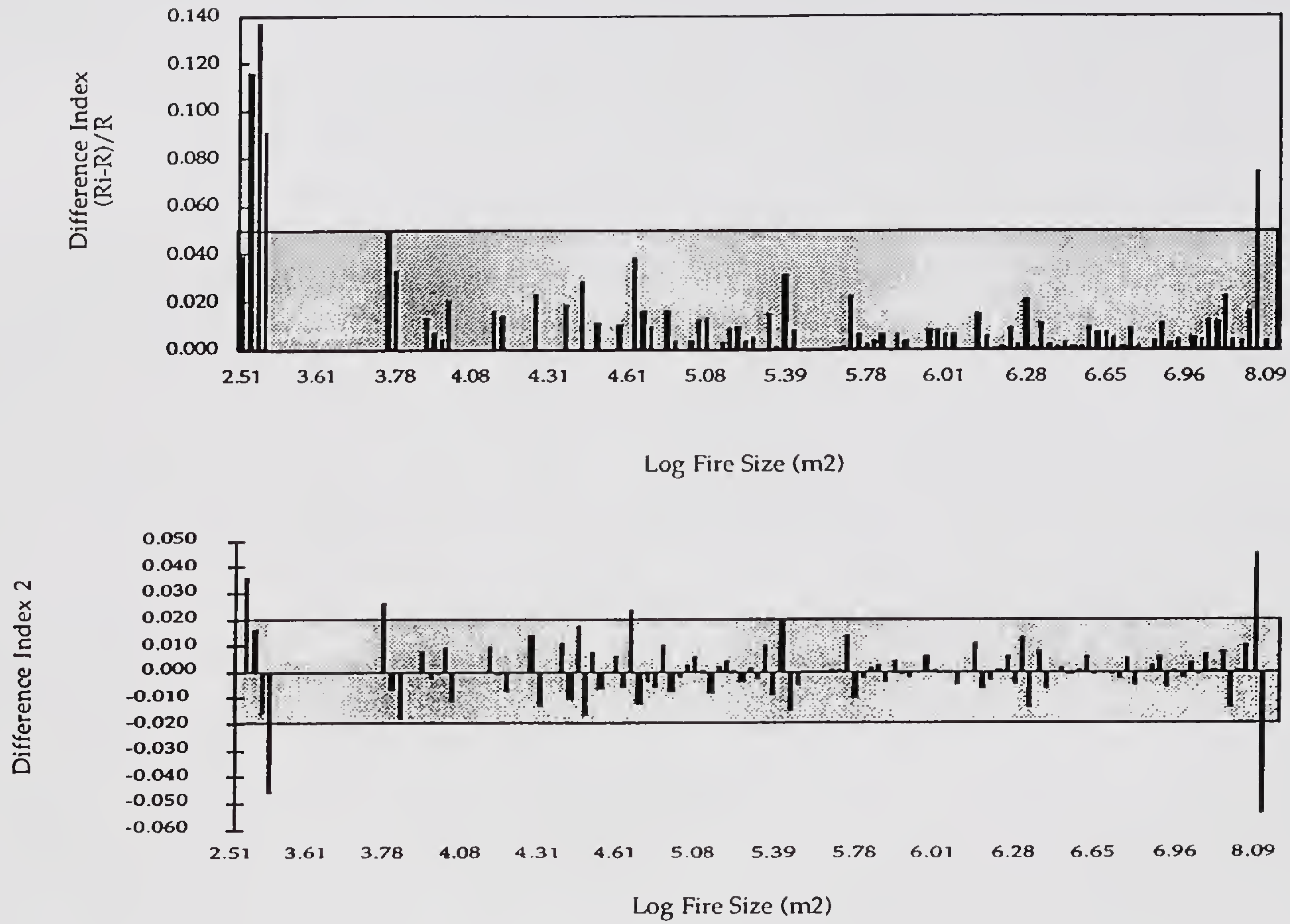


Figure 46. Difference Indices 1 and 2 used to determine gaps in fire sizes, Shark River Slough, 1958-1979.

Rainfall

Rainfall data were analyzed over the same time window (January 1949 through December 1988), using three different grain sizes; daily, monthly and annual. The monthly and annual values were derived by summing daily amounts over each of these time intervals. Two types of analyses were done on each of the three data sets; a fast Fourier transform to examine for cyclical or sinusoidal patterns and a rank order/gap analysis to test for entrainment of temporal patterns. The results are presented in the following paragraphs by examination of how patterns change with the increasing grain size, first with daily rainfall, then monthly, then annual summaries.

Daily patterns.

The temporal patterns of daily rainfall follows the typical annual cycle of a summer wet season and winter dry season (Hela 1952, Thomas 1970, MacVicar and Lin 1984). The measured daily amounts range from zero to 17 cm at Tamiami Station (Figure 47) and zero to 23 cm at Royal Palm (Figure 48). Although time series of daily rain exhibit much variation, only three significant cycles appear in the data (Figures 49, 50). The dominant cycle for data from both sites is the annual cycle, as indicated above. Significant cycling periods of three and four months were also apparent in the data. No long term (multiple year) cycles were observed from these data sets. The rank order analyses indicated a few gaps in the distribution, at the high end of the rainfall spectrum. The gaps started appearing at daily rainfall totals of 10 cm at both sites (Figure 51). The only significant gaps were among the highest totals (Figure 52). The gaps may be a function of the infrequent occurrence of high rainfall events such as tropical storms and hurricanes.

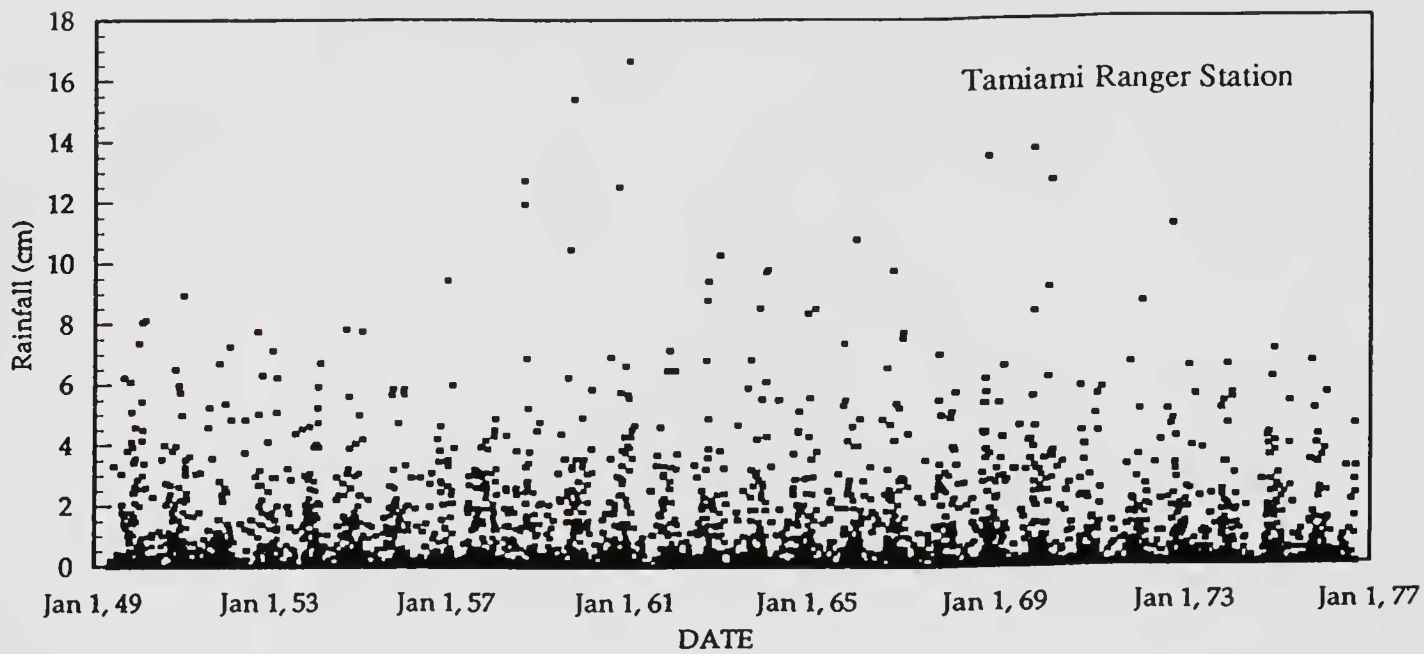


Figure 47. Time series plot of daily rainfall data from Tamiami Ranger Station, 1949 through 1977.

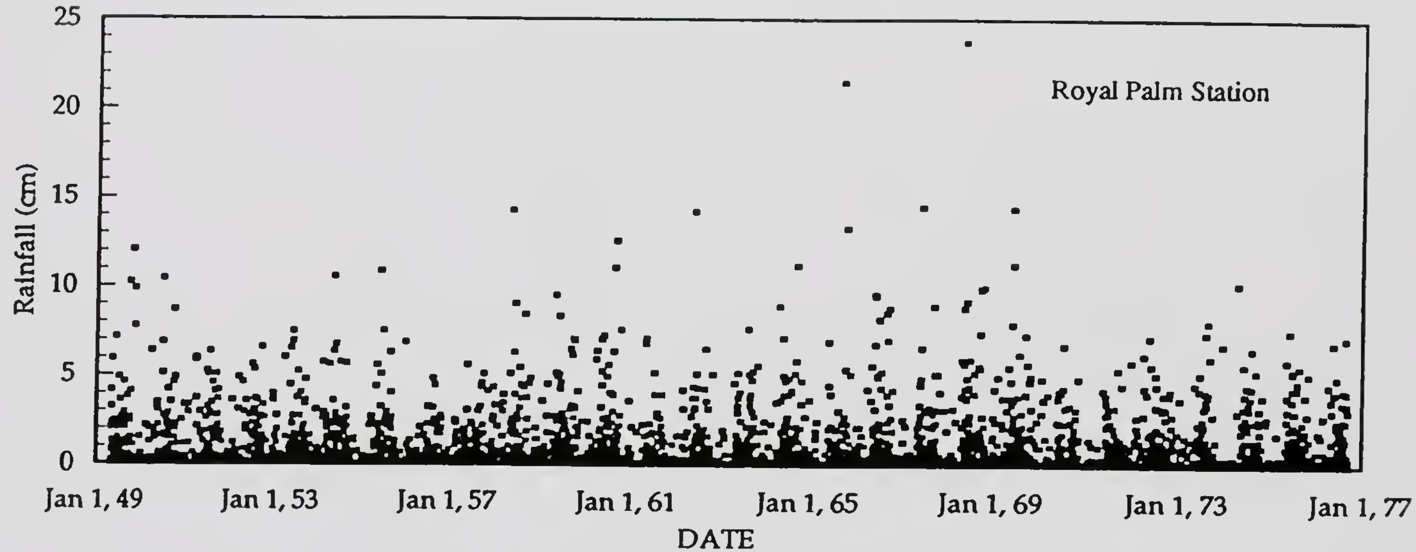
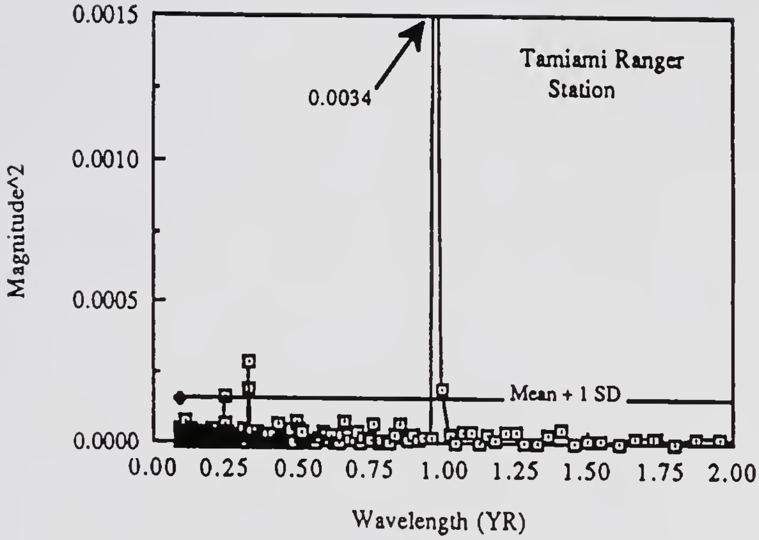


Figure 48. Time series plot of daily rainfall data from Royal Palm Station, 1949 through 1977.



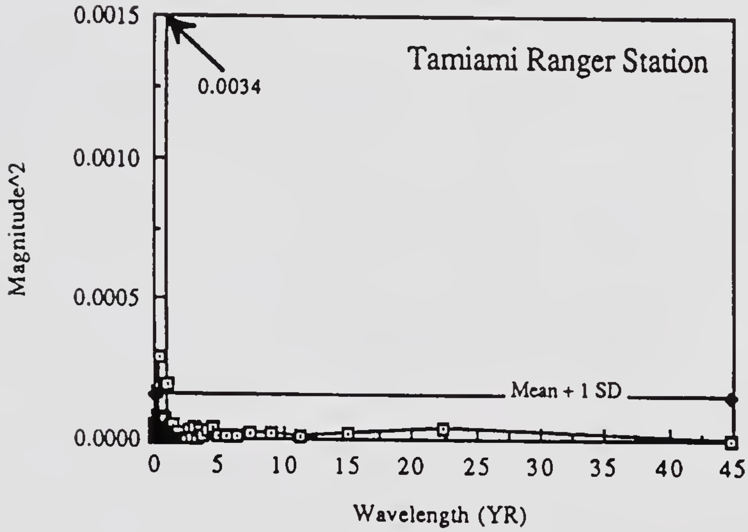


Figure 49. Spectral plots from Fourier analysis of daily rainfall from Tamiami Ranger Station, indicating dominant annual and monthly cycles.

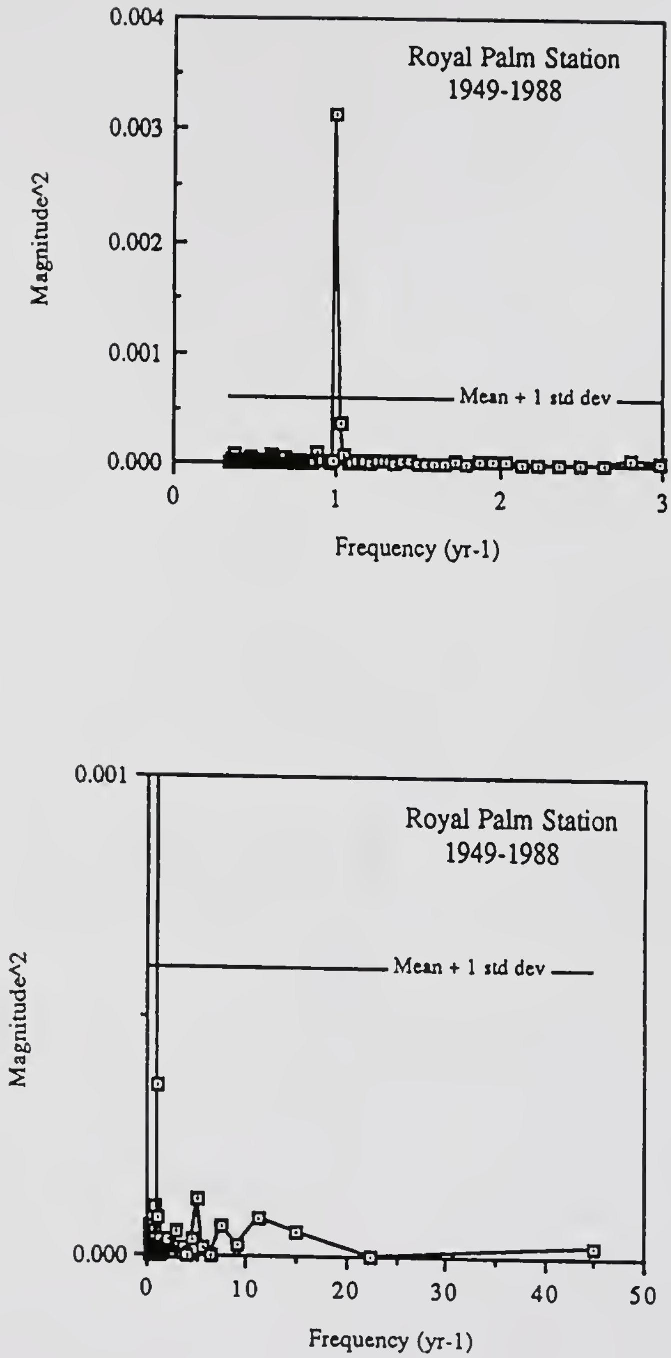


Figure 50. Spectral plots from Fourier analysis of daily rainfall from Royal Palm Station, indicating dominant annual and monthly cycles.

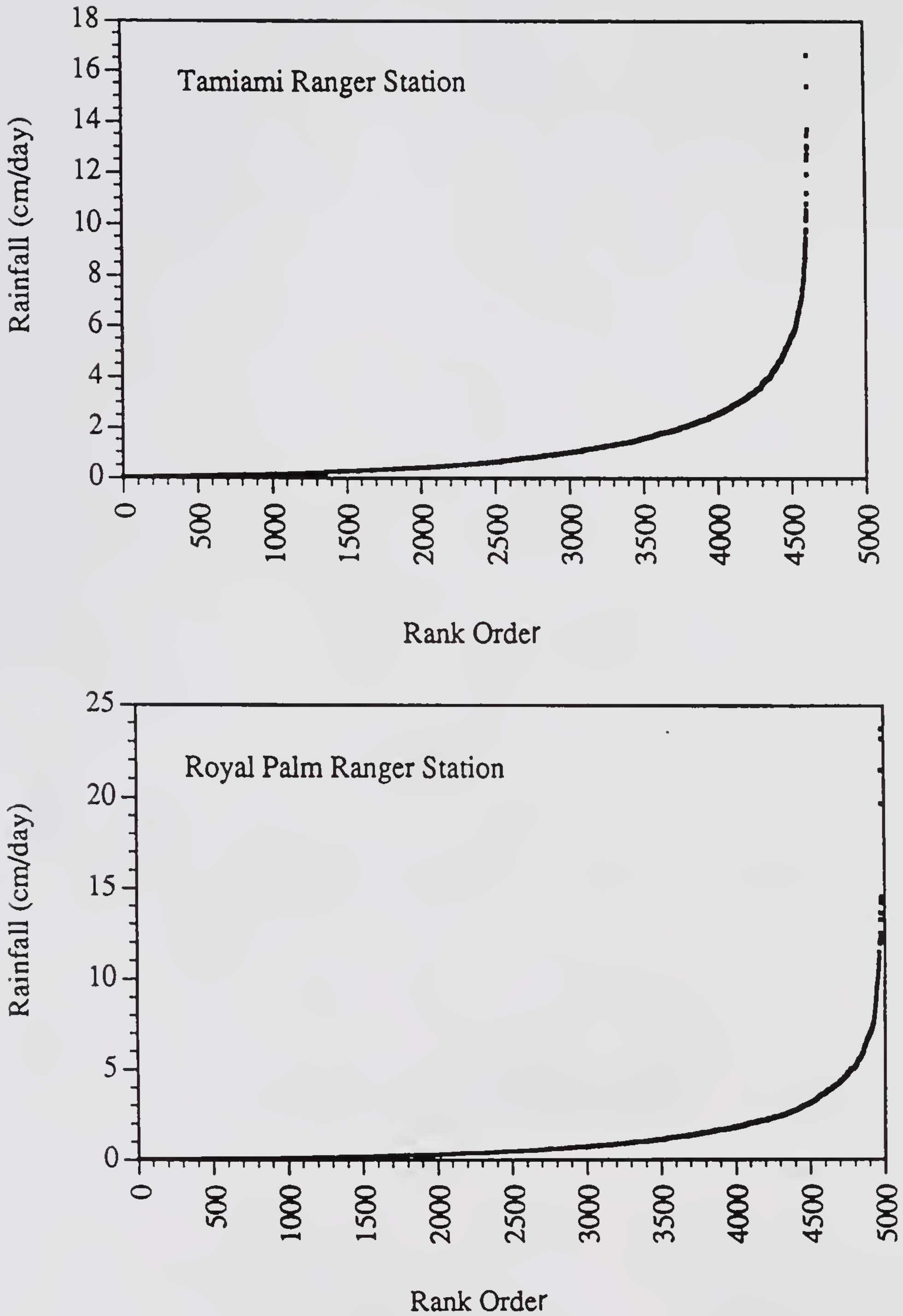


Figure 51. Rank order plots of daily rainfall data, Tamiami and Royal Palm Stations.

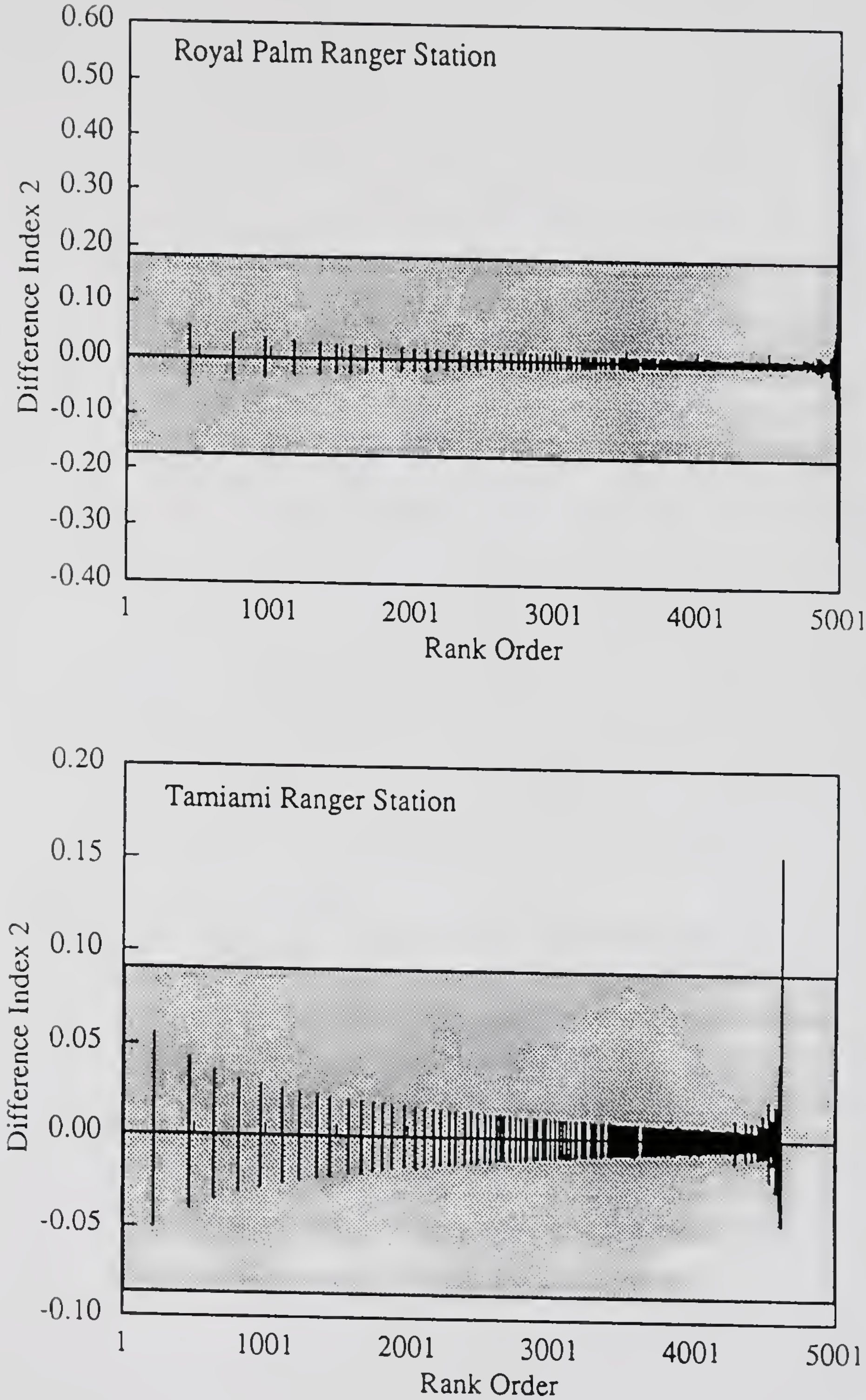


Figure 52. Difference index 2 versus rank order for daily rainfall data. Bars represent value of index, gray areas represent mean ± 95% C.I.

Monthly patterns.

As with the daily data, the monthly rainfall data sets indicate the strong annual cycle and a weaker monthly cycle. At both sites, the monthly rainfall ranged from zero to 60+ cm (Figure 53). The annual pattern of a wet summer and dry winter are visible in the time series plots of monthly rainfall (Figure 53). The dominant frequency in the signal is again the annual cycle, with significant peaks at three and four months (Figures 54 and 55). No multiple year cycle is signifcant in either data set.

Some hierarchical structure appears in the monthly rainfall data sets. The data from Tamiami exhibits at least four gaps that separate groupings of rainfall. Two gaps are at the extreme ends of the distribution, indicating low frequency events (Figure 56). Significant gaps in the rank order distribution at about 10 cm and 23 cm (Figure 56). These break points define three groups. The lowest group , with monthly rainfall values less than 10 cm, represent the winter or dry season months. The second grouping , defined by rainfall between 10 to 23 cm/month appears to reflect maximum rainfall during "drier" years. The third group, (23 to 50 cm/month rainfall) includes the maximum rainfall values in "wetter" years. Similar groupings are visible, but not significant at the Royal Palm Site, due to the high variation caused by larger individual rainfall events (Figure 57).

Annual patterns.

The annual rainfall totals for the two stations indicate the presence of longer term cycles. Both sites exhibited similar patterns, although totals were different between the sites. Annual total rainfall at Royal Palm ranged from a low of 73 cm in 1956 to a high of 217 cm in 1968 (Figure 58). Annual rainfall was

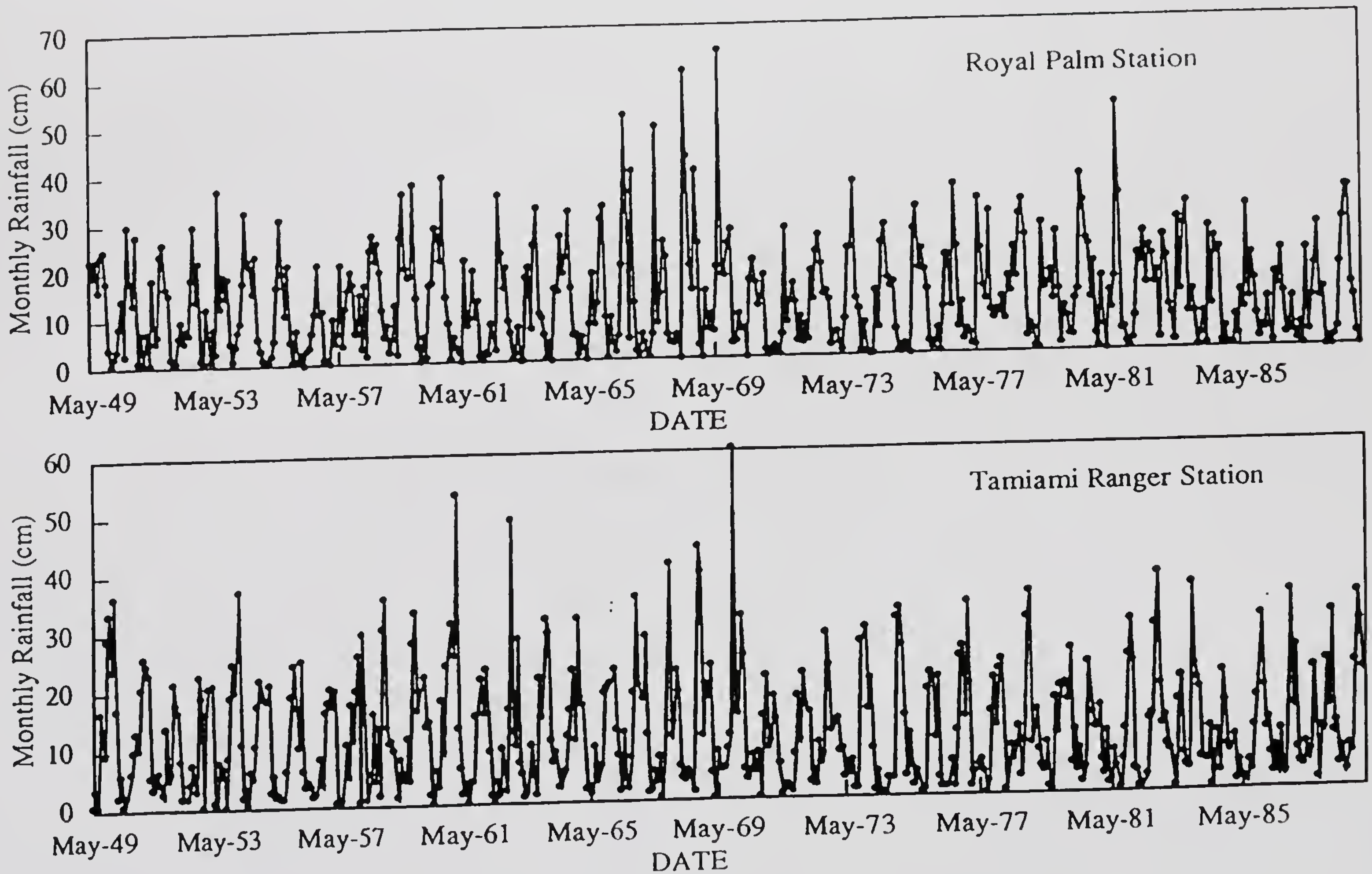


Figure 53. Time series plot of monthly rainfall data from Royal Palm and Tamiami Ranger Stations, 1949 through 1977.

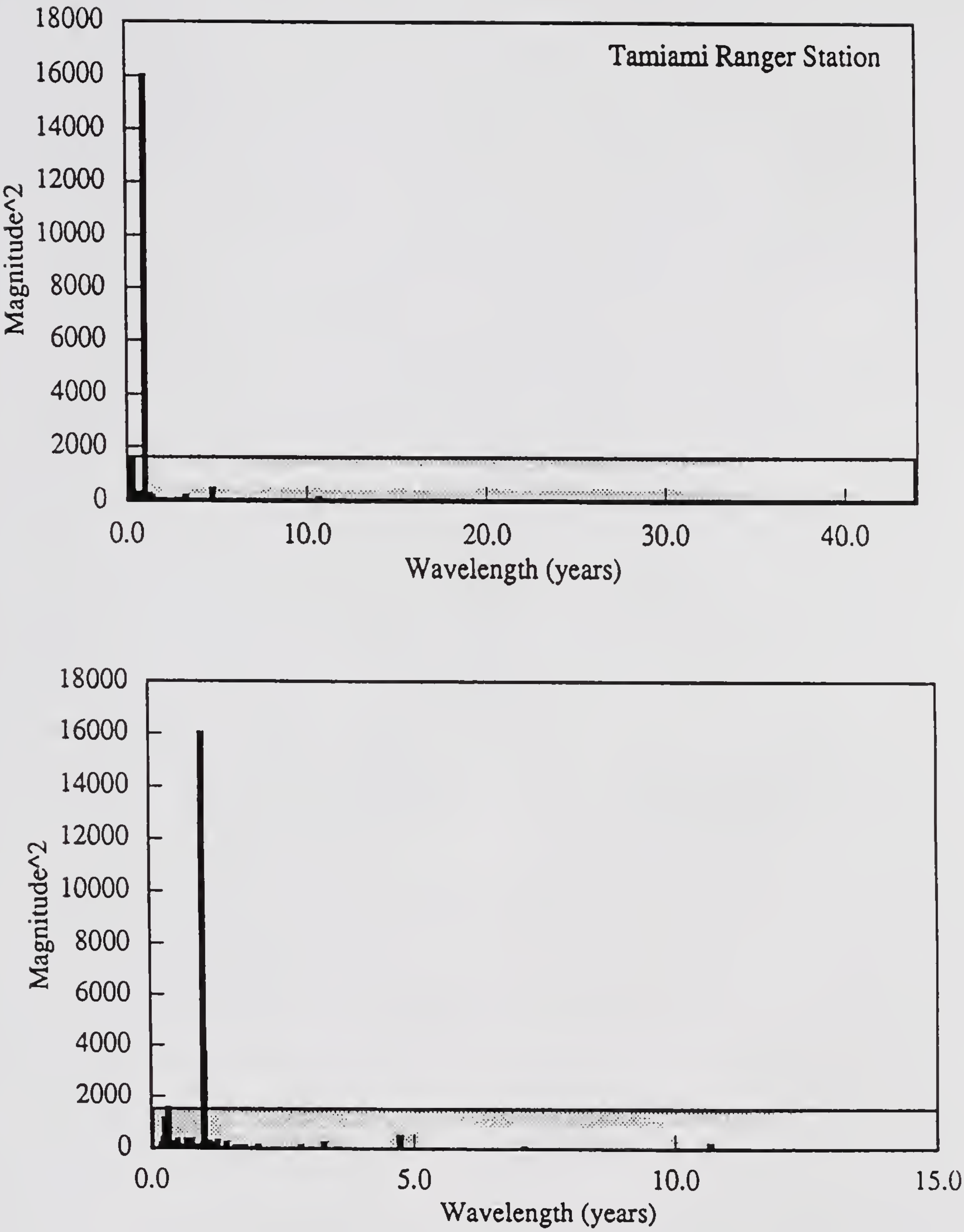
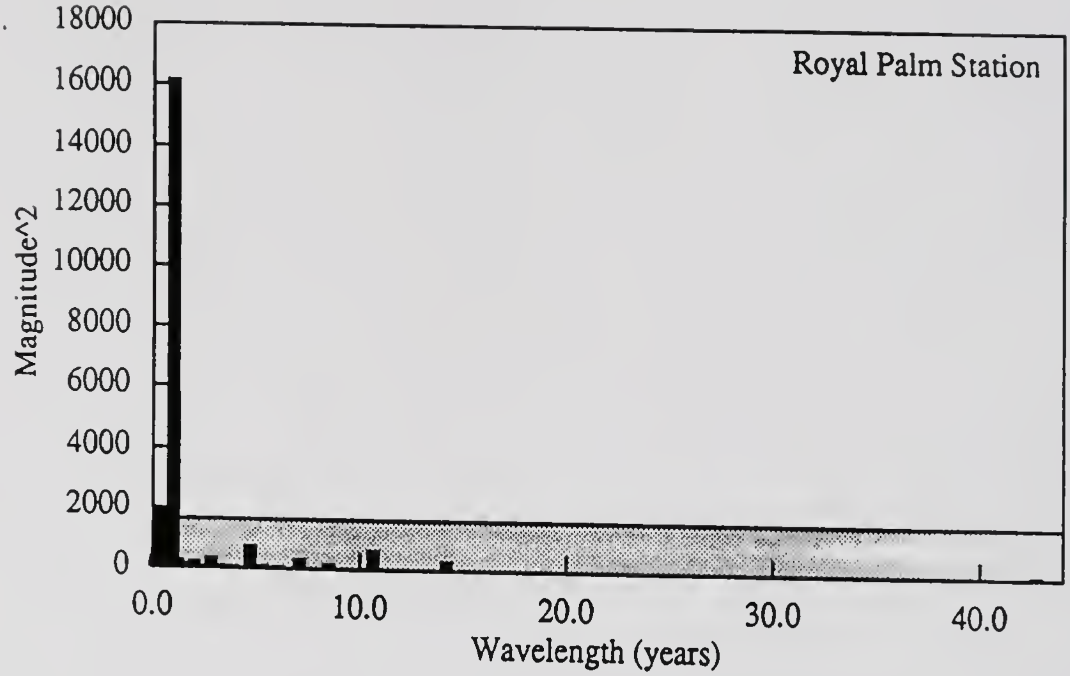


Figure 54. Spectral plots from Fourier analysis of monthly rainfall from Tamiami Station, indicating dominant annual and monthly cycles.



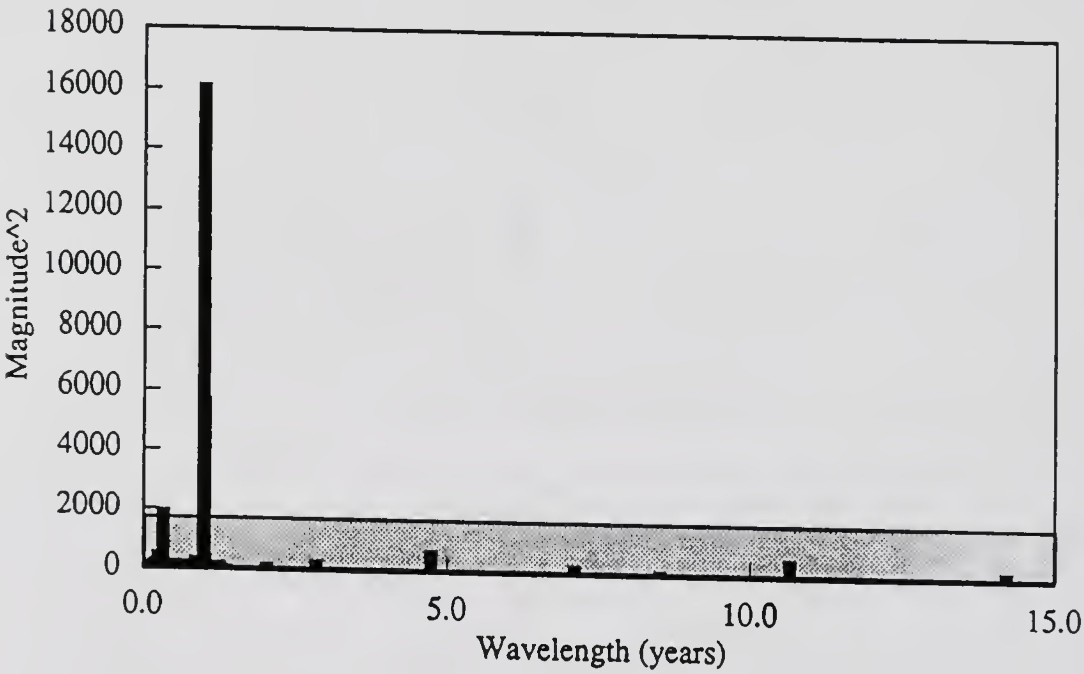


Figure 55. Spectral plots from Fourier analysis of monthly rainfall from Royal Palm Station, indicating dominant annual and monthly cycles.

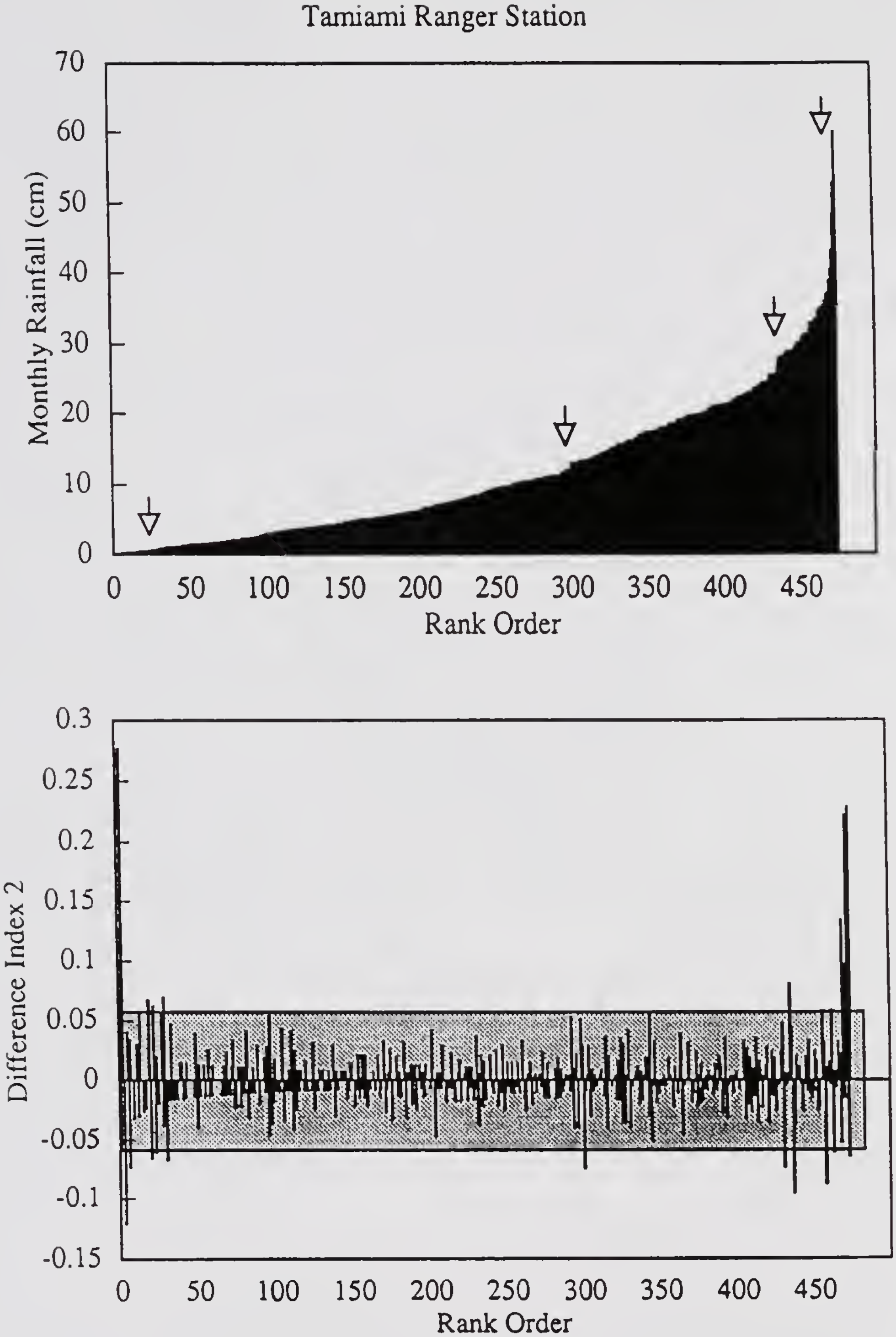


Figure 56. Rank order plot and difference index 2 for monthly rainfall data from Tamiami Ranger Station. Arrows locate significant gaps.

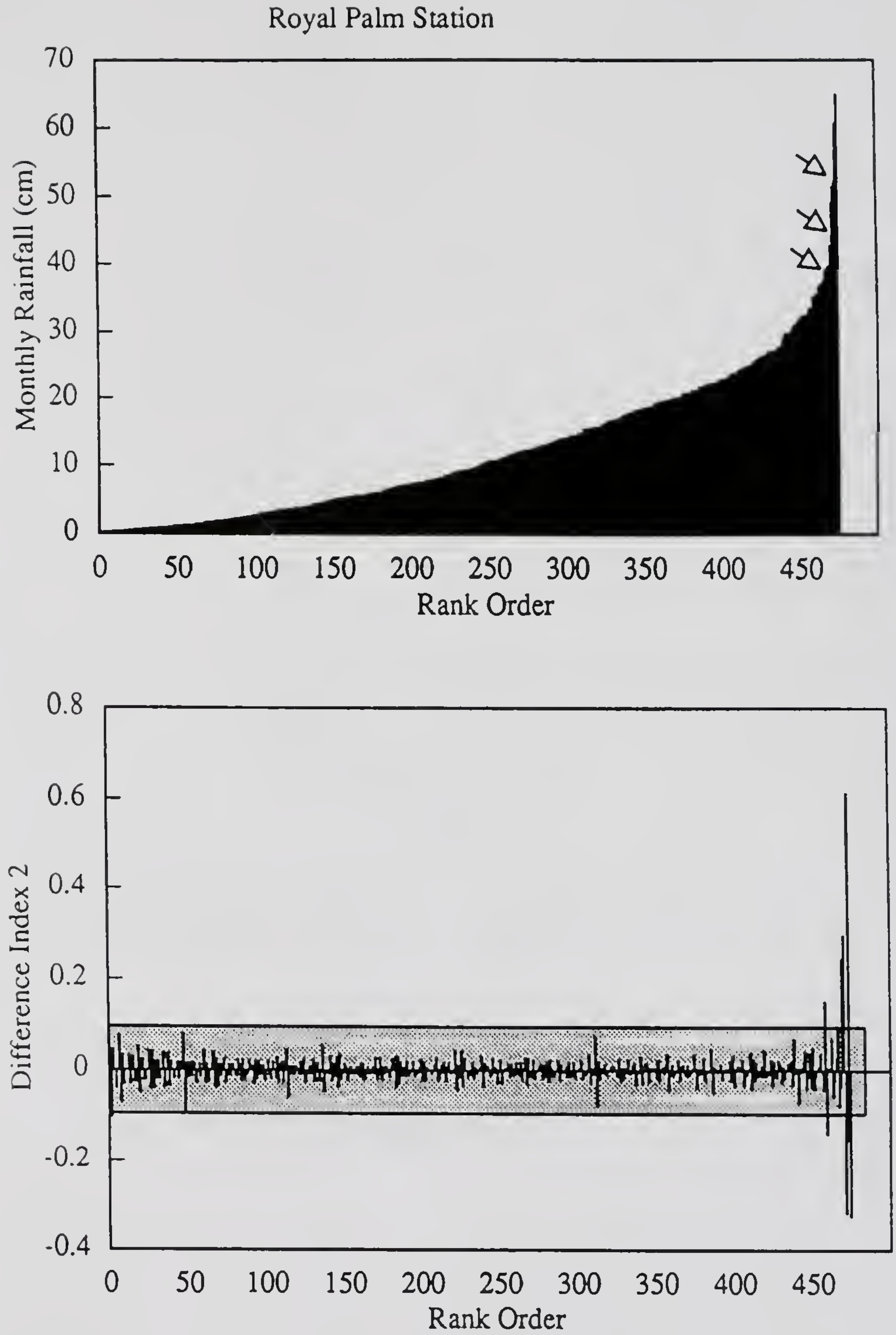
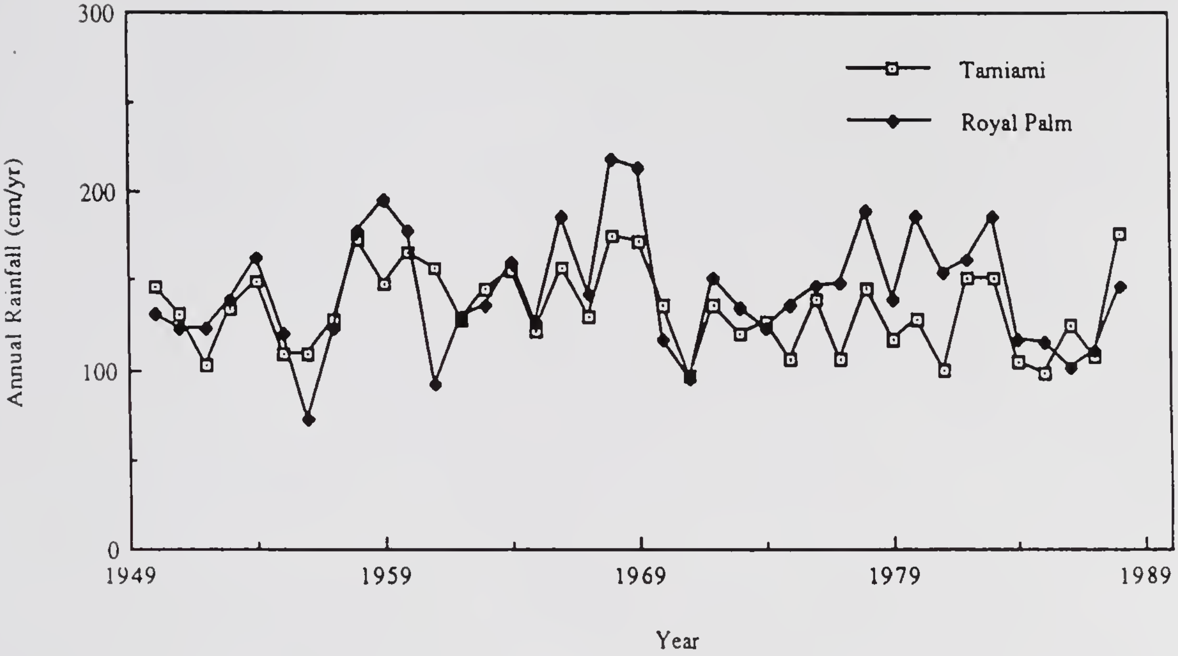


Figure 57. Rank order plot and difference index 2 for monthly rainfall data from Royal Palm Station. Arrows locate significant gaps.



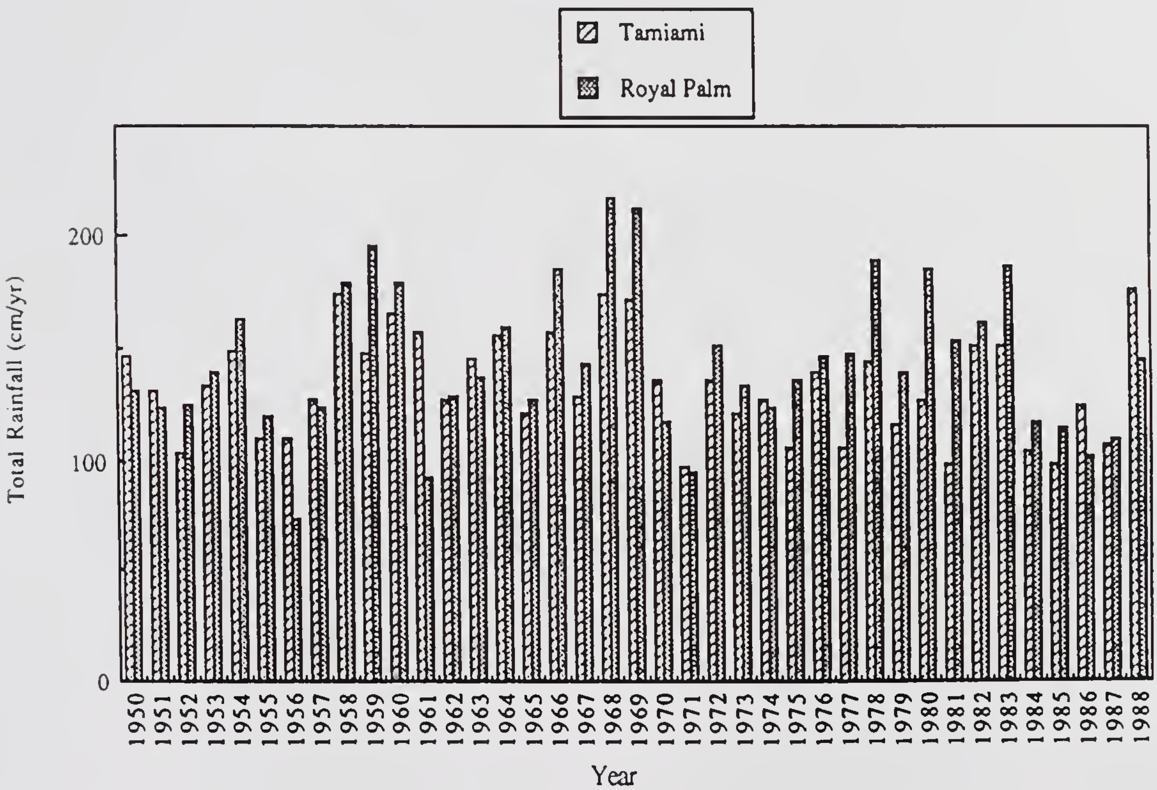
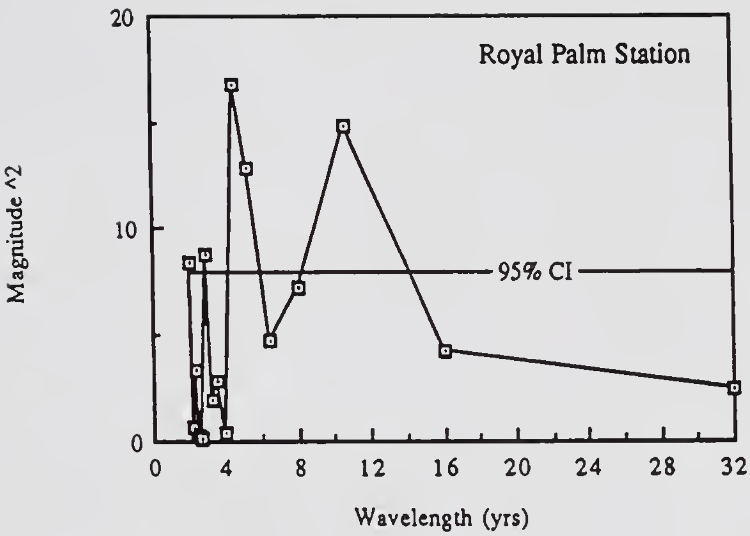


Figure 58. Time series of total annual rainfall at Tamiami and Royal Palm Stations.

less variable at Tamiami, ranging from a low of 97 cm in 1985 to a high of 177 in 1988 (Figure 58). Even though totals varied, cycling frequencies were similar between the sites. Both sites had significant peaks of approximately 11 ,5 and 3 years (Figure 59), similar to the dominant frequencies reported for south Florida by Thomas (1970)and Isaacs (1980).

Hierarchical analyses can be used to define rainfall years, as dry, intermediate or wet. Gaps or breaks in rank order plots appear in data from both sites, and define the limits of these groupings. Annual rainfall at Royal Palm shows gaps at 73 and 163 cm defined by the difference index (Figure 60). A hierarchical cluster analysis indicates similar groupings, with three groups defined by breaks at annual totals of 102 and 163 cm (Figure 61). Annual rainfall at Tamiami also exhibits three groups, but defined at different values. The rank order, difference index indicates gaps at 110 and 165 cm (Figure 62). The hierarchical cluster analysis indicated four signifcant groups with breaks at 110, 139, and 165 cm (Figure 63). The gaps and groupings at both sites are significant at the 95% confidence interval, defined by psuedo t statistics. A bootstrap simulation was done using a uniform random distribution that was scaled between 100 and 180 and from which 39 samples were drawn, indicated that three significant gaps occurred only five out of 100 times.

The analyses of the rainfall data produce different patterns at different grains. The daily and monthly data exhibit only an annual and monthly pattern. Multiple year periodicity is not evident in these data sets. The annual data sets exhibit periodicities of about 6, 8 and 11 years. It is not clear why the smaller grain data sets would not show similar patterns. Perhaps the higher variation in the smaller grain data masks the longer term patterns. Another explanation is that the summation of rainfall to yearly totals may exaggerate a pattern that is



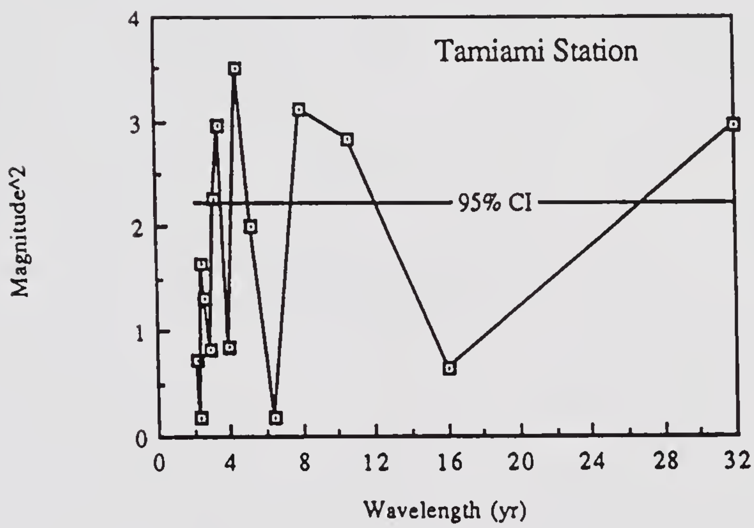


Figure 59. Spectral plots from Fourier analysis of annual rainfall data from Royal Palm and Tamiami Stations.

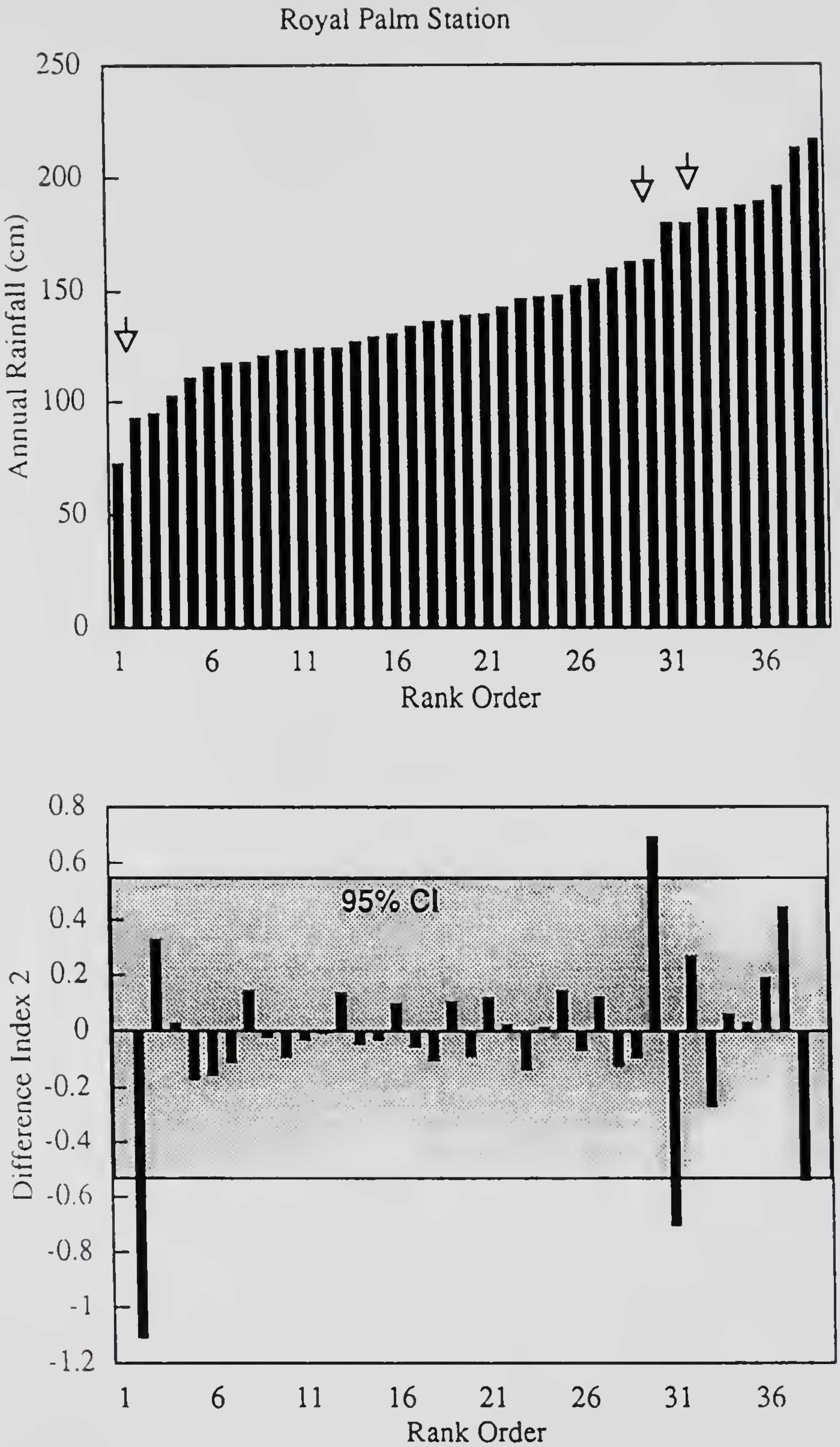


Figure 60. Rank order plot and difference index 2 for monthly rainfall data from Royal Palm Station. Arrows locate significant gaps.

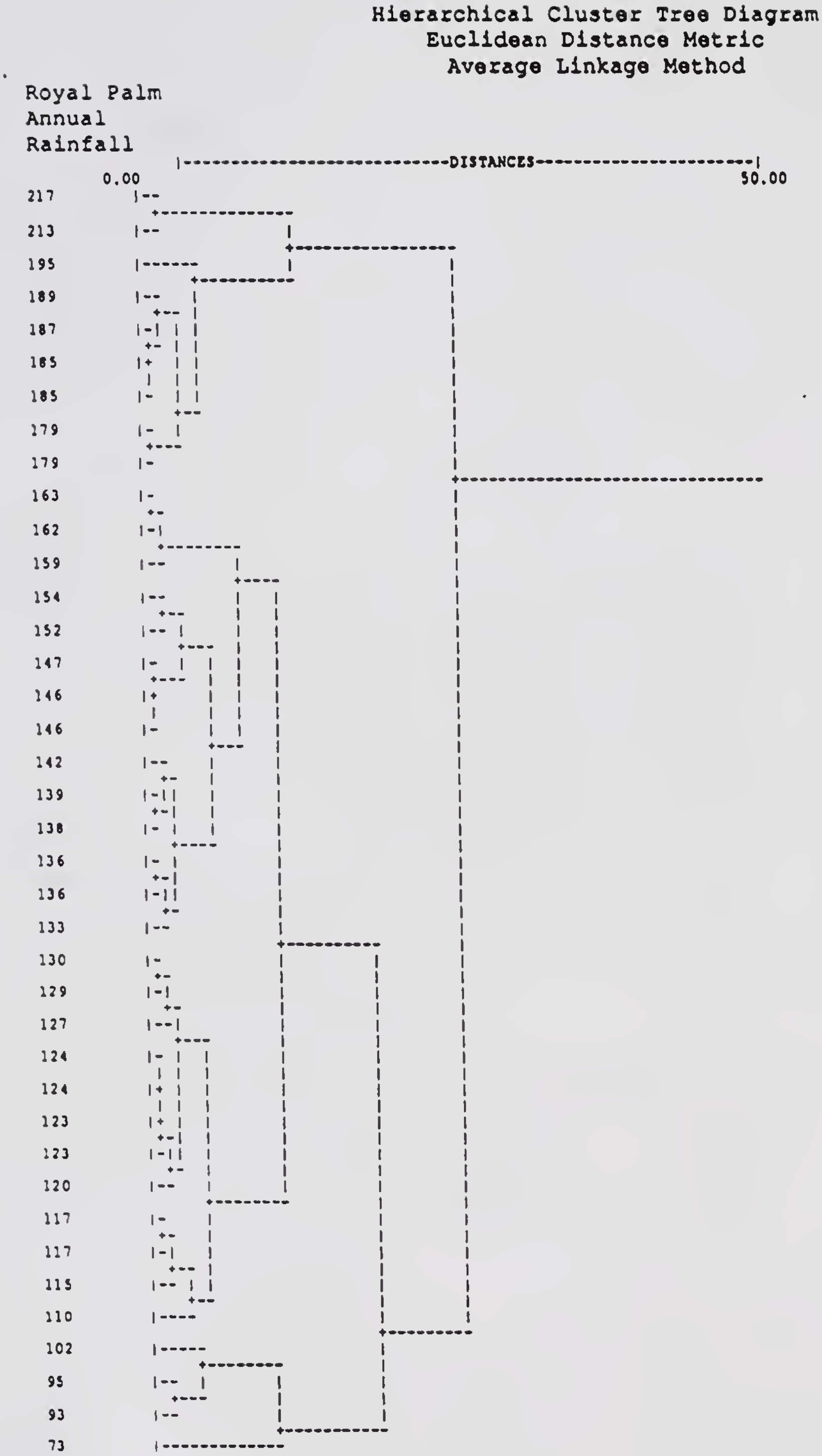


Figure 61. Hierarchical Cluster Tree for annual rainfall at Royal Palm Station.

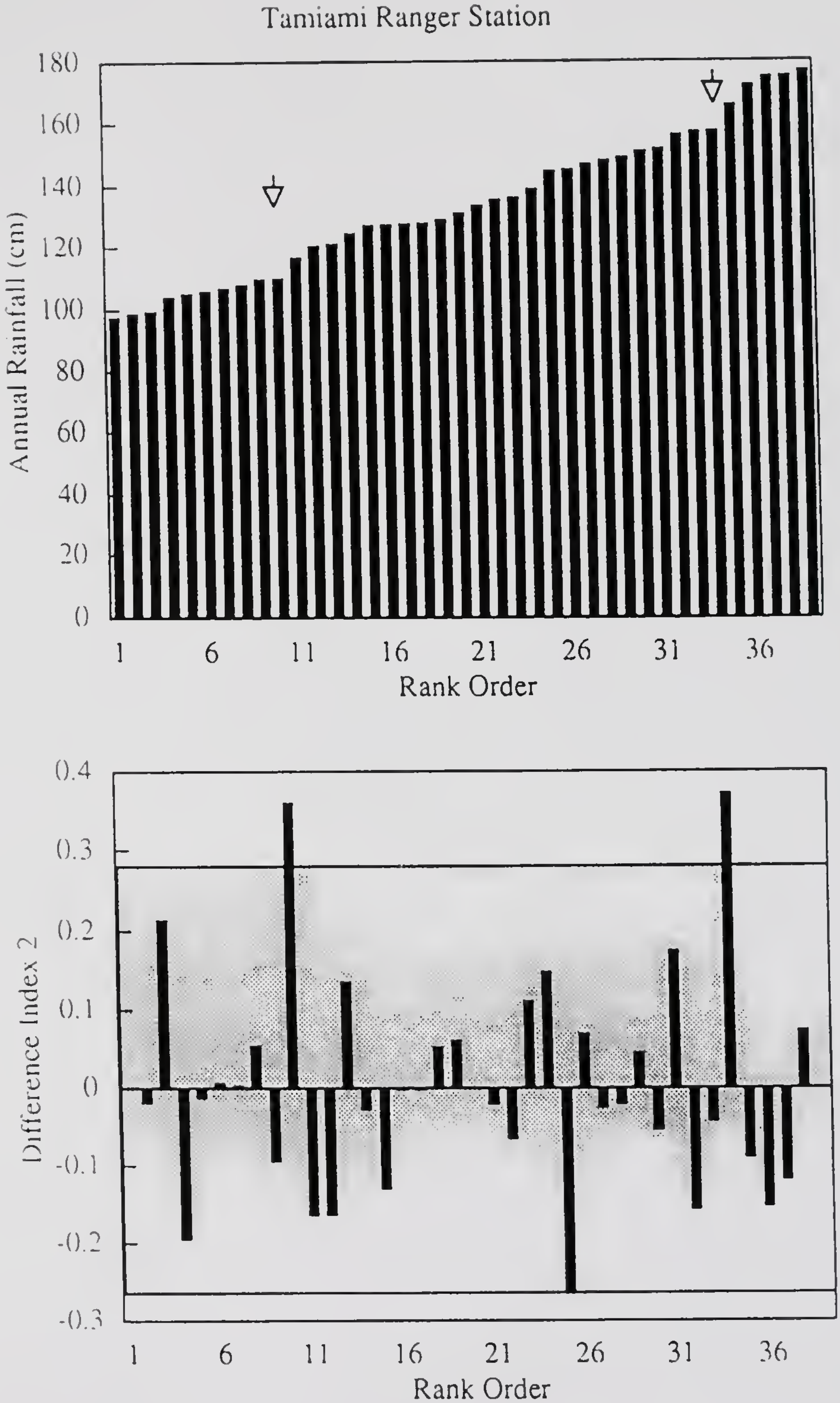


Figure 62. Rank order plot and difference index 2 for monthly rainfall data from Tamiami Ranger Station. Arrows locate significant gaps.

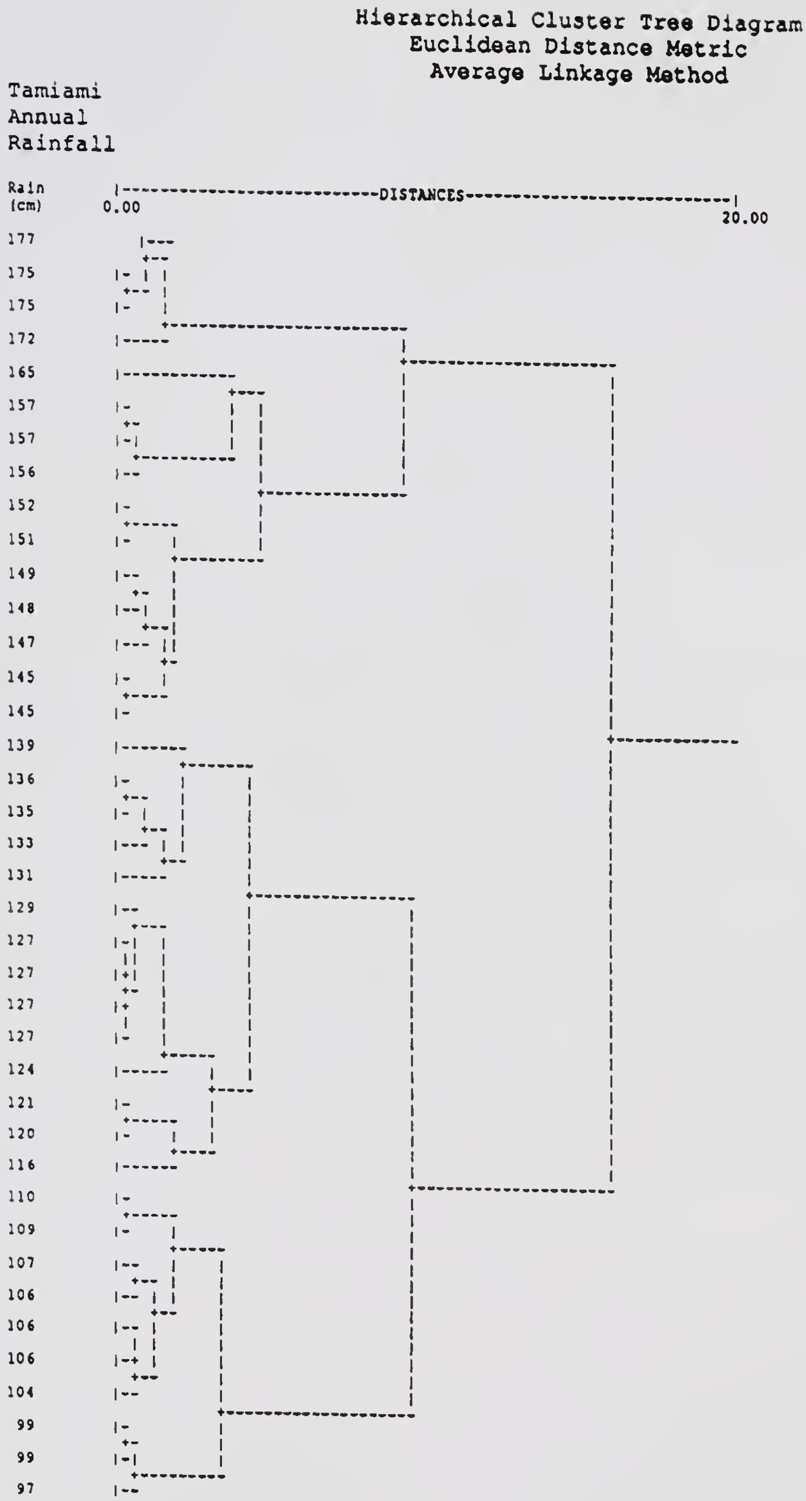


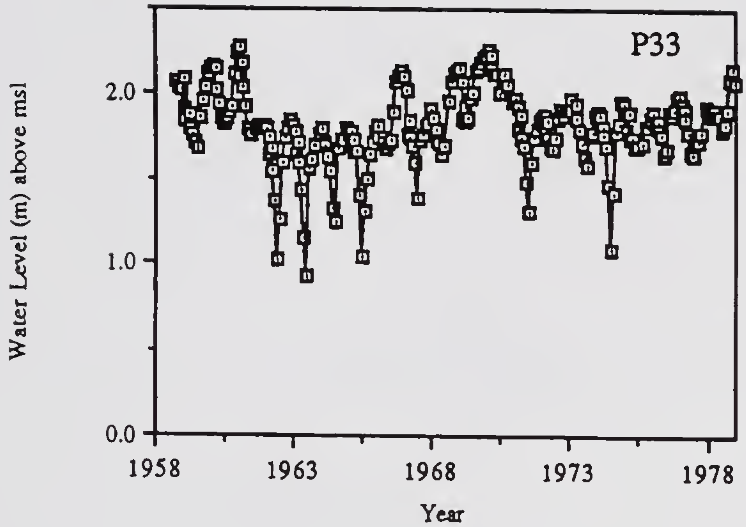
Figure 63. Hierarchical Cluster Tree for annual rainfall at Tamiami Ranger Station.

imperceptible in the other data sets. I'll revisit this anomoly later, but first the results of analyzing the stage data from the system.

Water Levels

The stage data from four stations in the southern Everglades all exhibit patterns of multiple cycles. The data were analyzed over a 22 year period, using two levels of resolution; daily and monthly. The time series plots of mean monthly stage data (Figures 64 and 65) suggest both annual variation and multi-year fluctuations. The data tend to be exaggerated when water levels go below ground, as indicated by the sharp downward spikes in Figures 64 and 65. The spectral analysis of the monthly data shows the presence of three cycles at all four sites (Figure 66). The strongest cycle is a wavelength of approximately 11 years, with other peaks at frequencies of 1 and 3 years. The daily data also exhibit three peaks in the Fourier analysis, but at slightly different wavelengths than the monthly data set. The peaks in the spectral plots using the daily data occured at wavelengths of one year, three years and 7-8 years (Figure 67).

The rank order curves of the daily data all had two deflection points (Figures 68 and 69). The lower deflection point occurs near the soil surface, where the stage readings shift from surface to ground water. This change reflects a difference in the relationships between volume of water and the vertical measure of stage. The upper deflection point in the stage data occured at about 40 to 60 cm above ground level. These fewer, higher stages correlate to infrequent flooding events that are apparent in the Fourier analyses. The monthly rank order curves (Figures 70 to 73) have similar shapes, but the averaging process appears to have smoothed the curves, removing some of the upper and lower limbs.



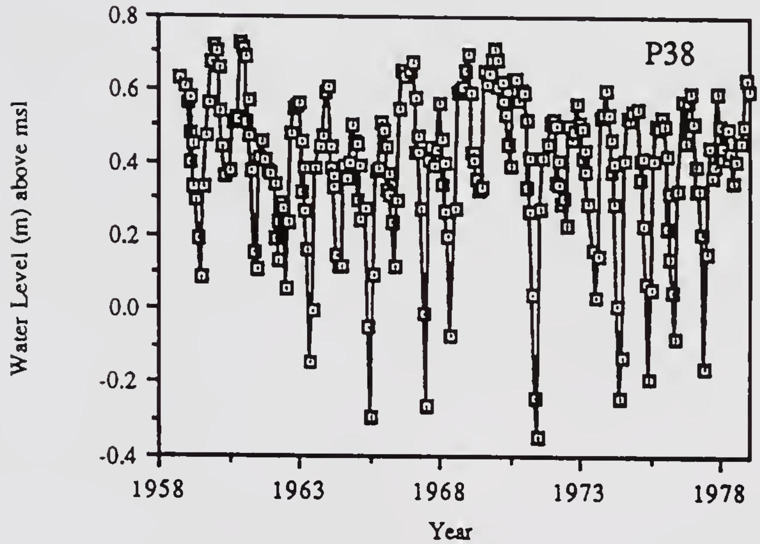
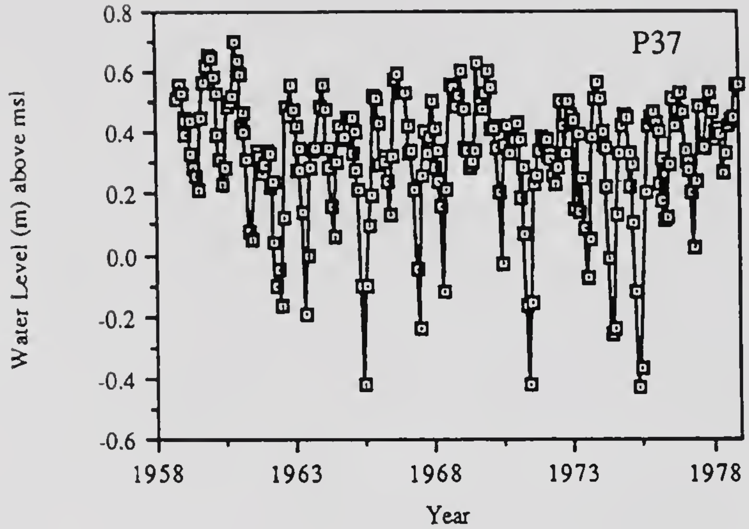


Figure 64. Time series plots of monthly water levels at gauging stations P33 and P38, from 1958-1979.



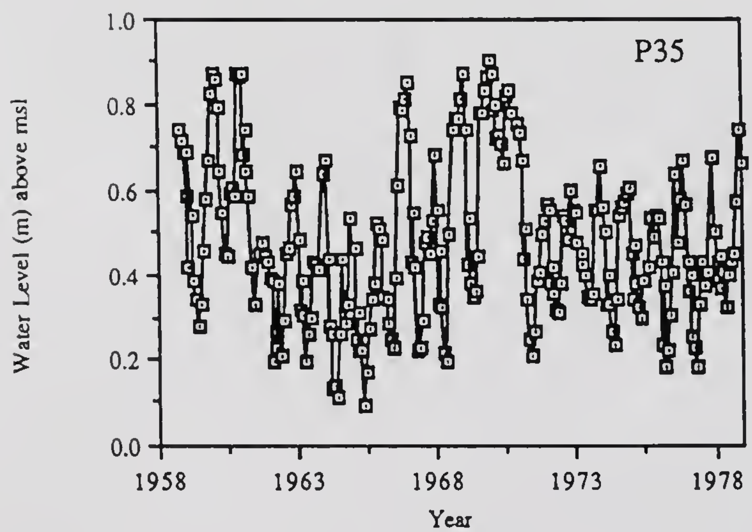


Figure 65. Time series plots of monthly water levels at gauging stations P35 and P37, from 1958-1979.

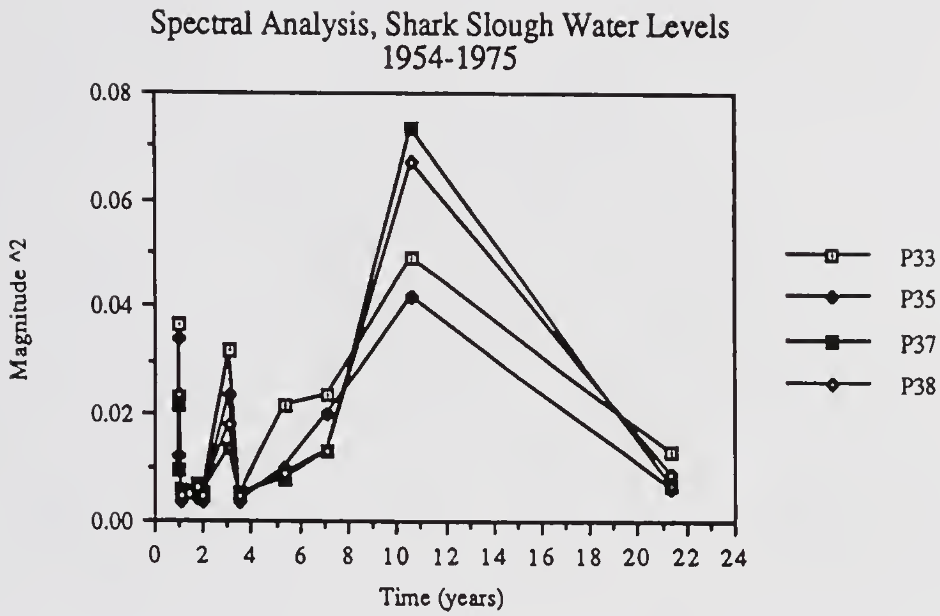
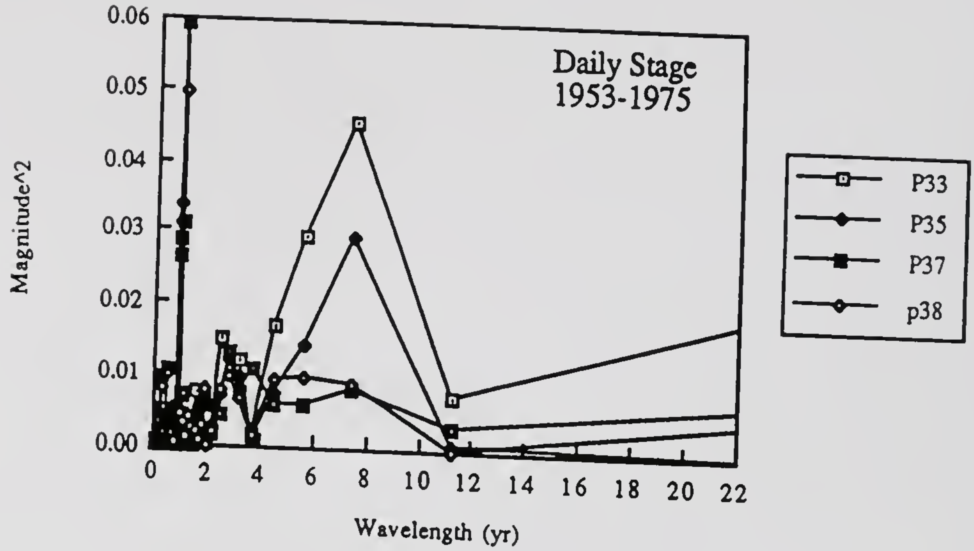


Figure 66. Spectral plots from Fourier analysis of monthly water level data from four P stations.



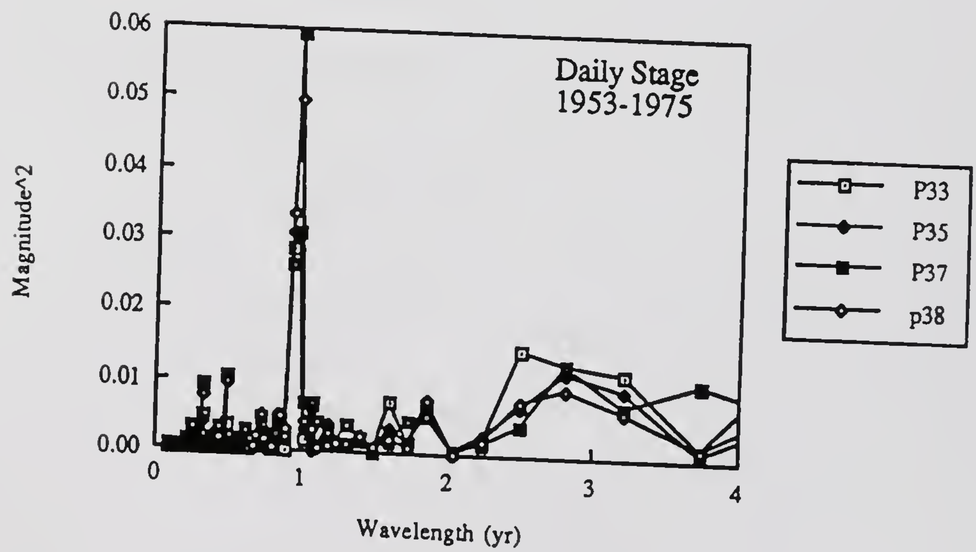
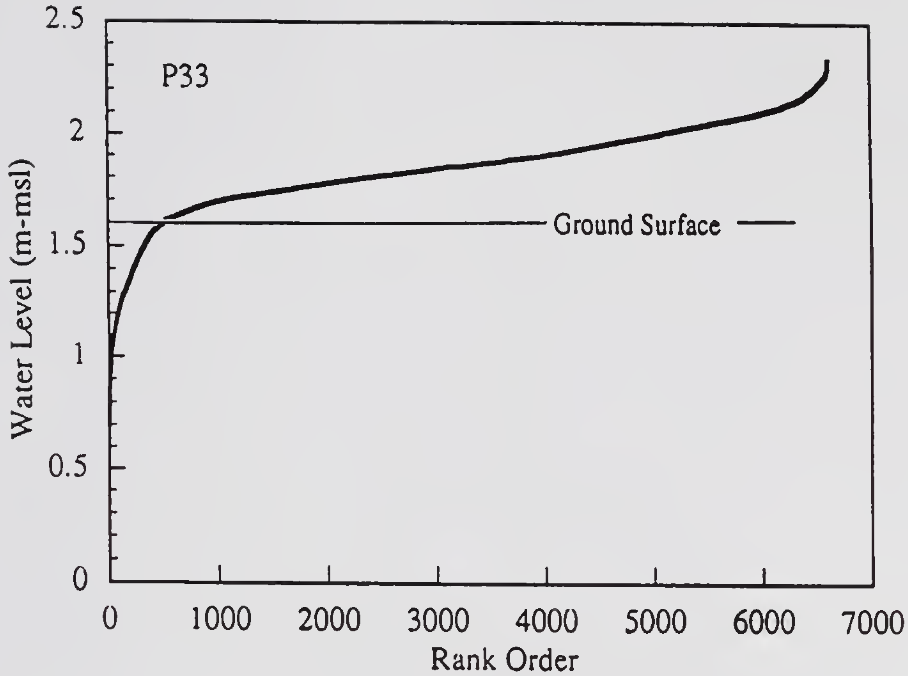


Figure 67. Spectral plots from Fourier analysis of daily water level data from four P stations.



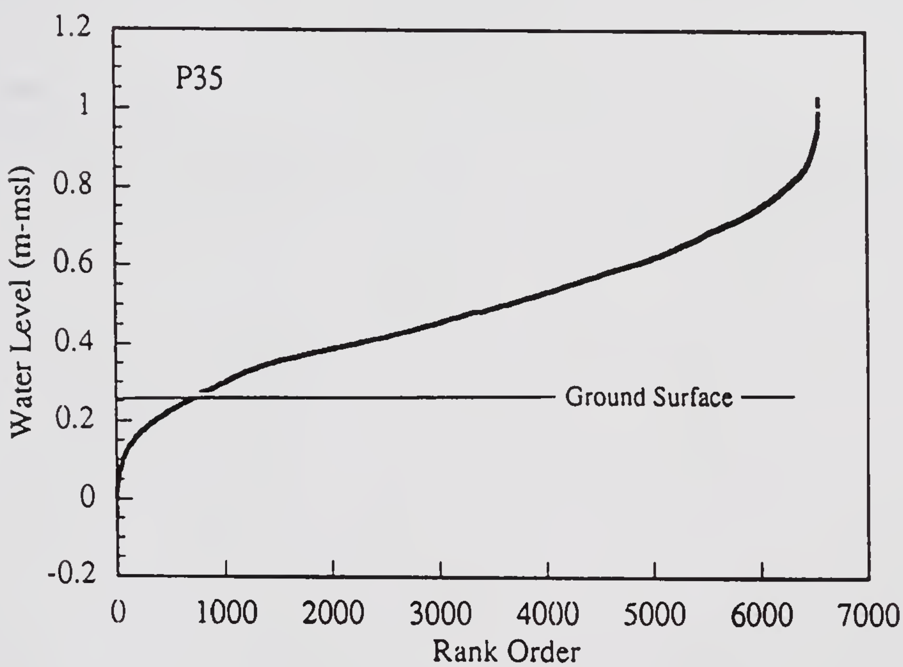


Figure 68. Rank order plots of daily water level data from stations P33 and P 35.

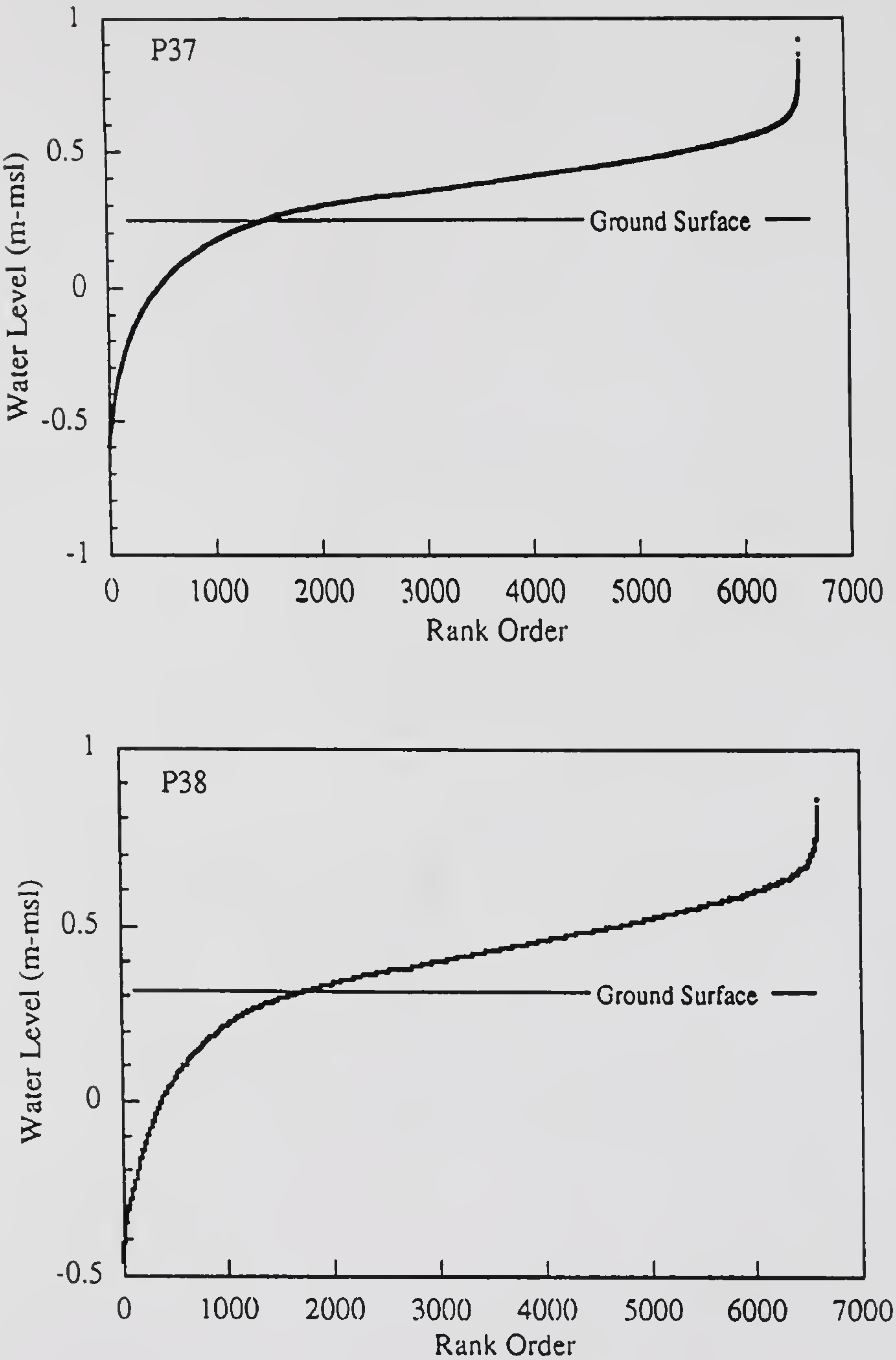
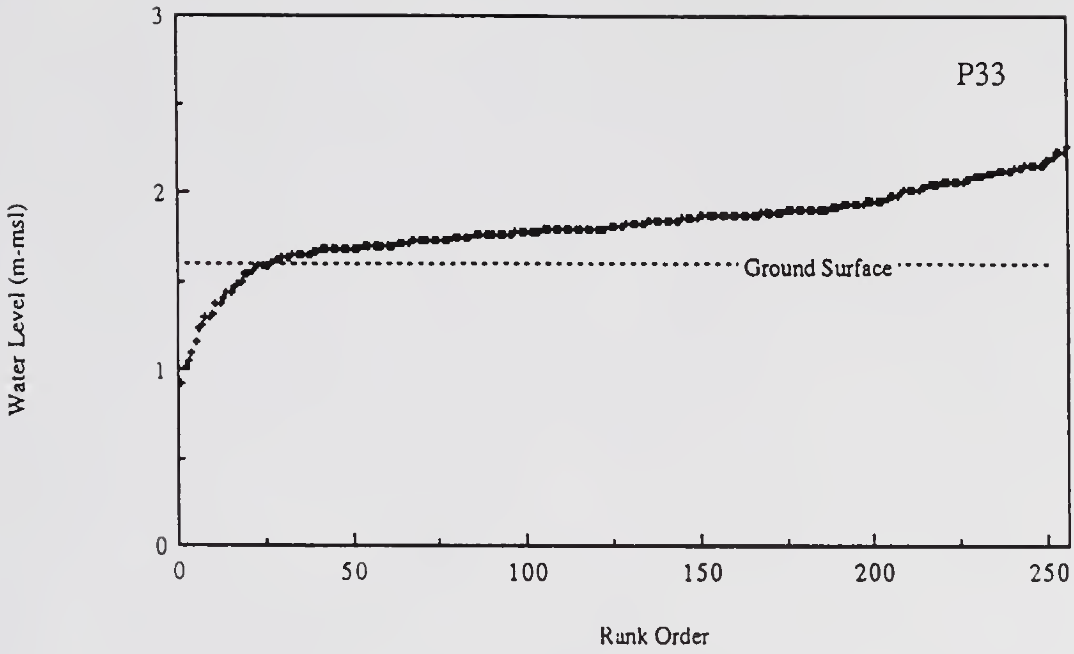


Figure 69. Rank order plots of daily water level data from stations P37 and P 38.



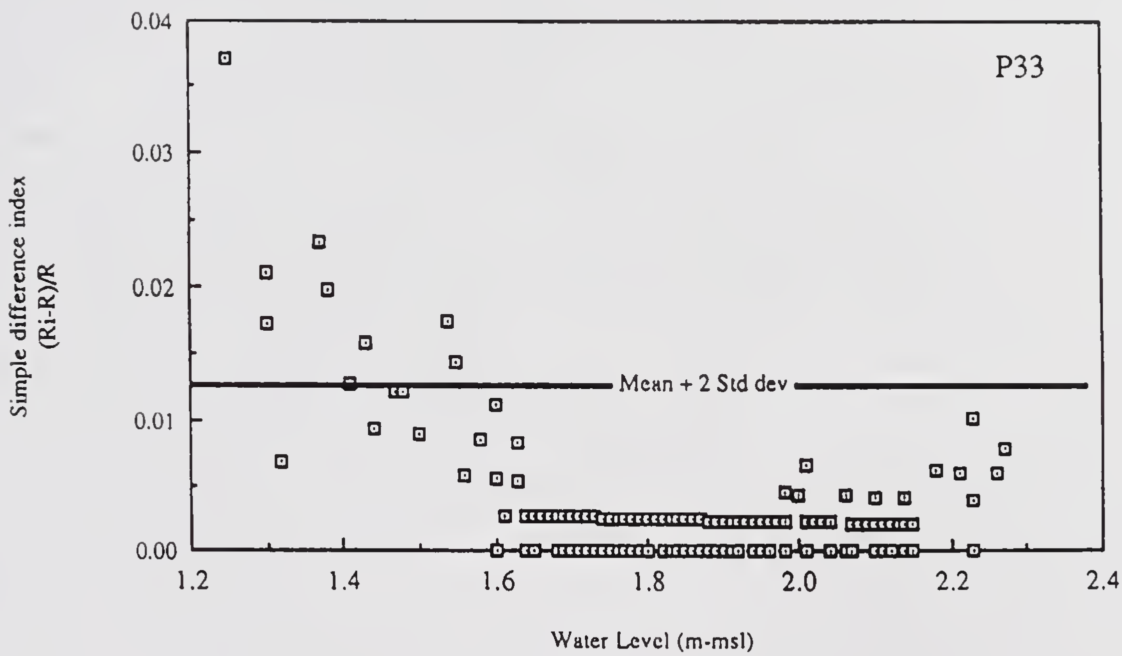
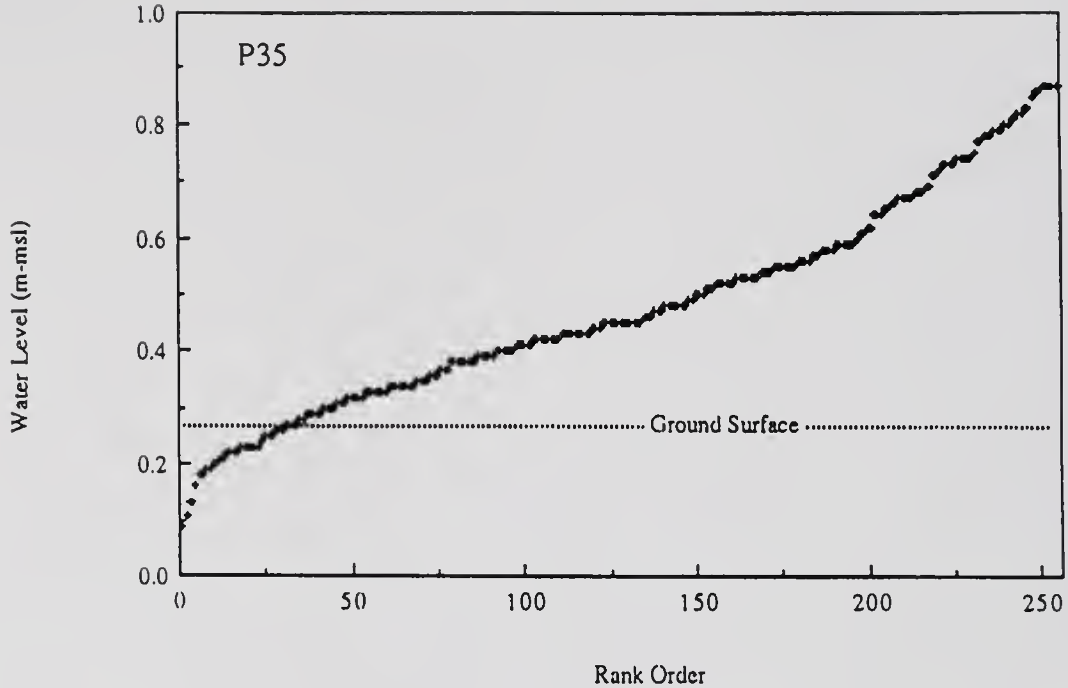


Figure 70. Rank order plot and difference index 1 for monthly water level data at station P33.



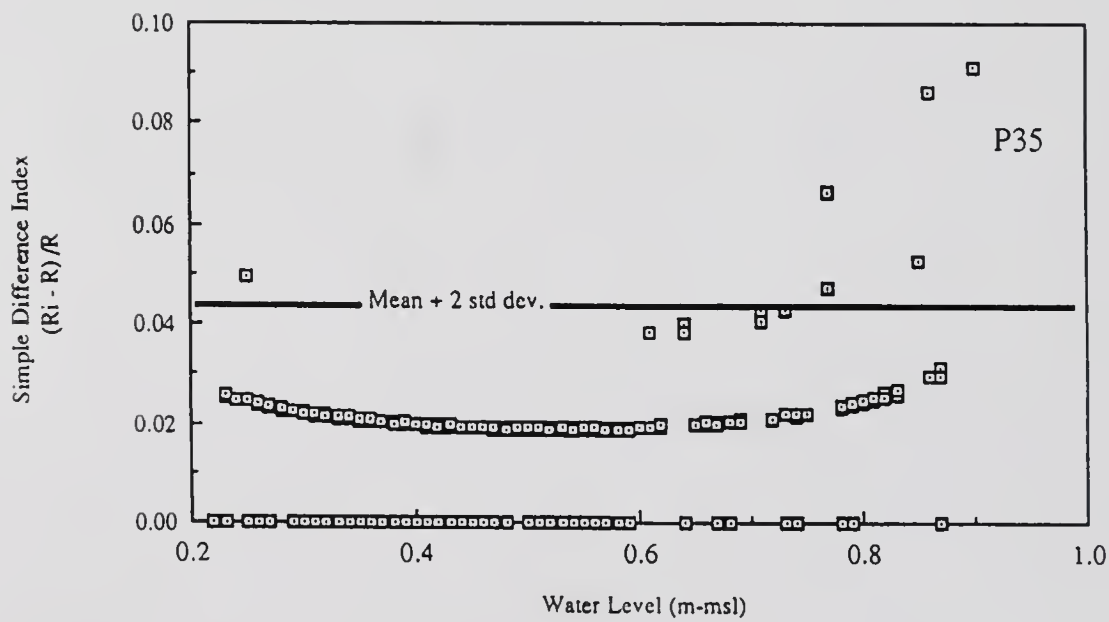
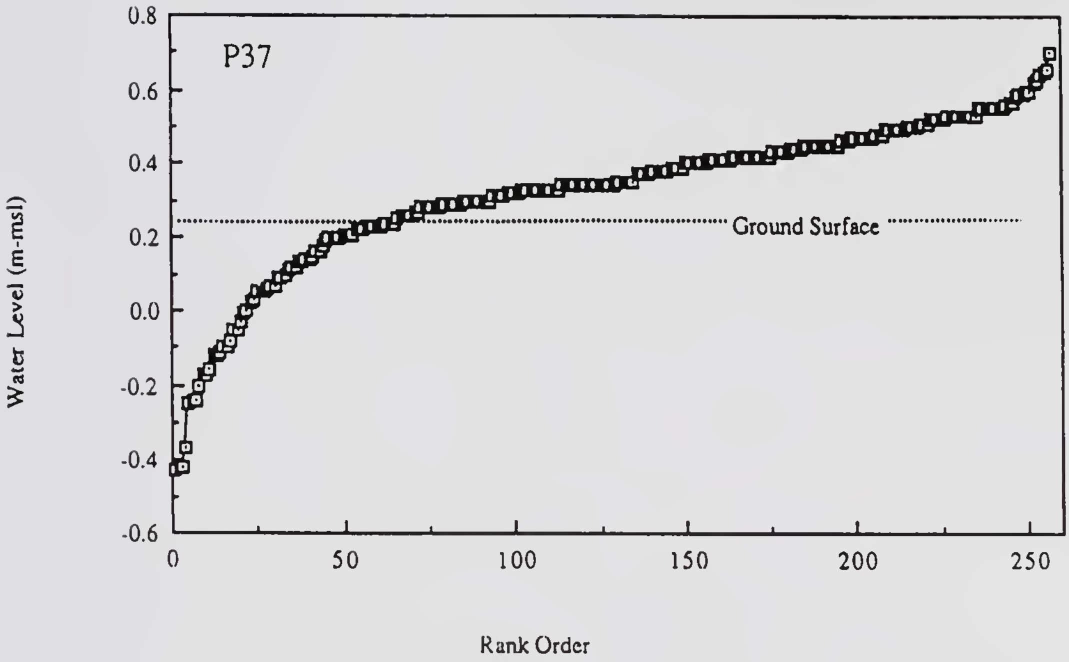


Figure 71. Rank order plot and difference index 1 for monthly water level data at station P35.



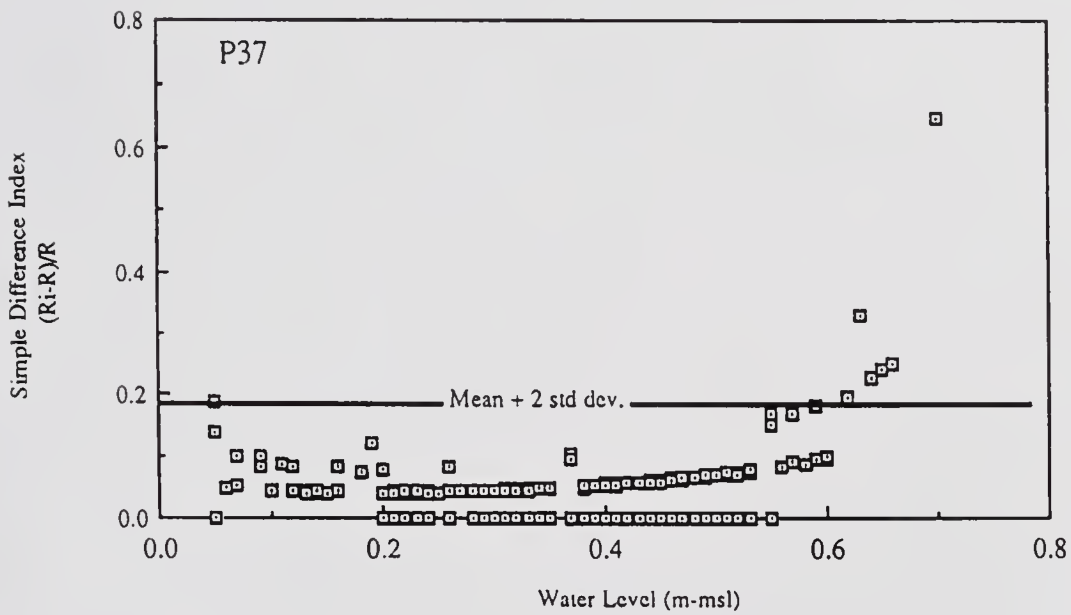
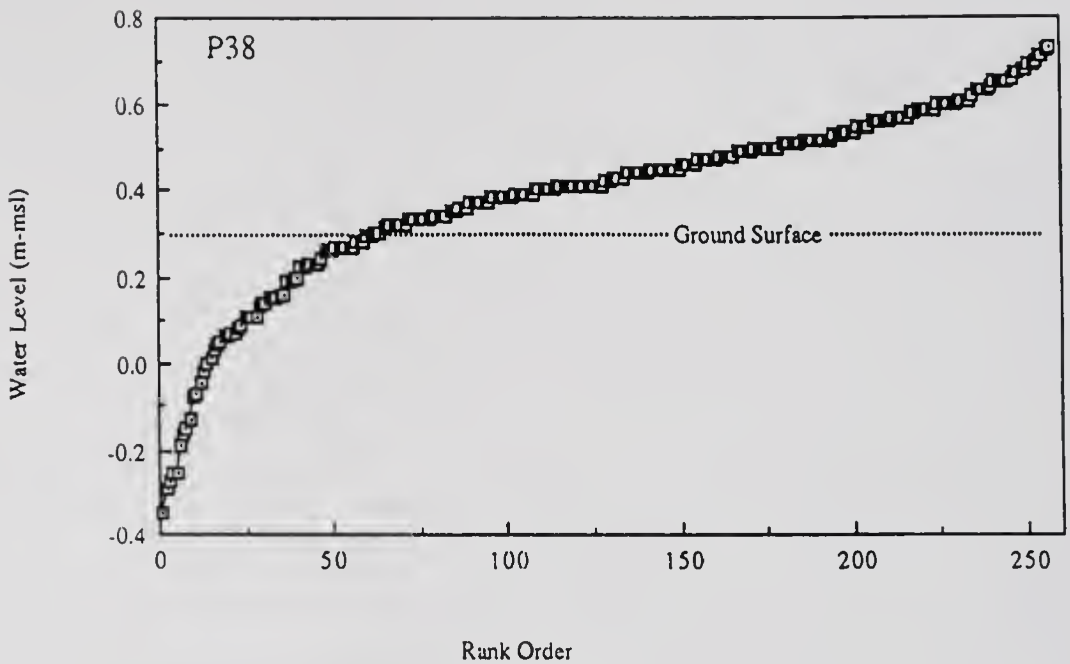


Figure 72. Rank order plot and difference index 1 for monthly water level data at station P37.



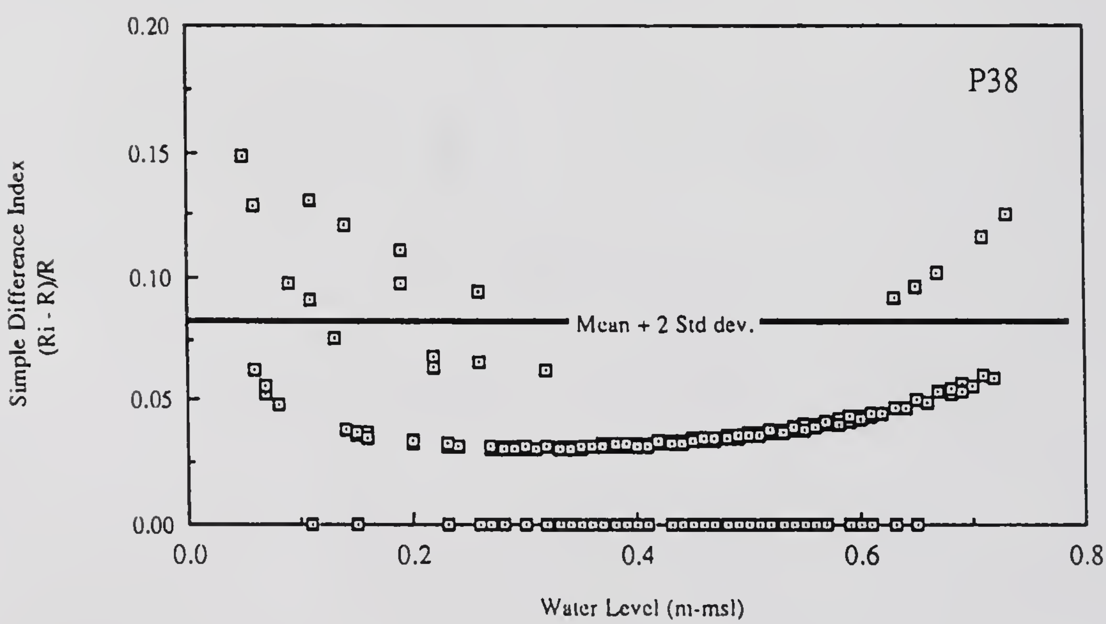


Figure 73. Rank order plot and difference index 1 for monthly water level data at station P38.

The rank order analyses of stage indicated few discontinuities in the daily data, however, a few gaps did appear in the monthly data sets. No gaps were measured in the daily data sets, due to the large number of observations.

With over 13,000 observations in each of the daily data sets, the only differences between sequentially ranked observations were those associated with the precision of measure of water level. Gaps appeared at the low and high ends of the distributions in the monthly data sets. These are probably an artifact of the averaging process, where extreme daily data points during a month were removed, creating gaps.

As with the rainfall data, the dominant frequency in the stage data is the annual cycle, although the presence of a multi-year cycle appears in both the daily and monthly stage data. To see if the pattern of annual and multiple year frequencies occur in other patterns of surface water, the results of analyses of the flow are presented next.

Water Flow

As with the water levels, the flow through the southern Everglades also exhibits multiple cycles or periodicities. The monthly flow data vary from zero flow to more than 4.2×10^8 m^3/mo which occurred during the wet year of 1947 (Figure 74). Notable peak flows occurred during 1947, 1961, 1967, and 1969-70. The spectral analysis indicated the largest frequencies of 1 and 9 years, with minor frequencies at 3, 5, and 22 years (Figure 75). The effects of water management are included in this analysis, and can be seen in Figure 74. The period in the early 1960's of extremely low flow is when the Tamiami Trail was closed while the S-12 structures were completed. The period of regularity in the 1970's through early 1980's is when the minimum flow regime was in effect.

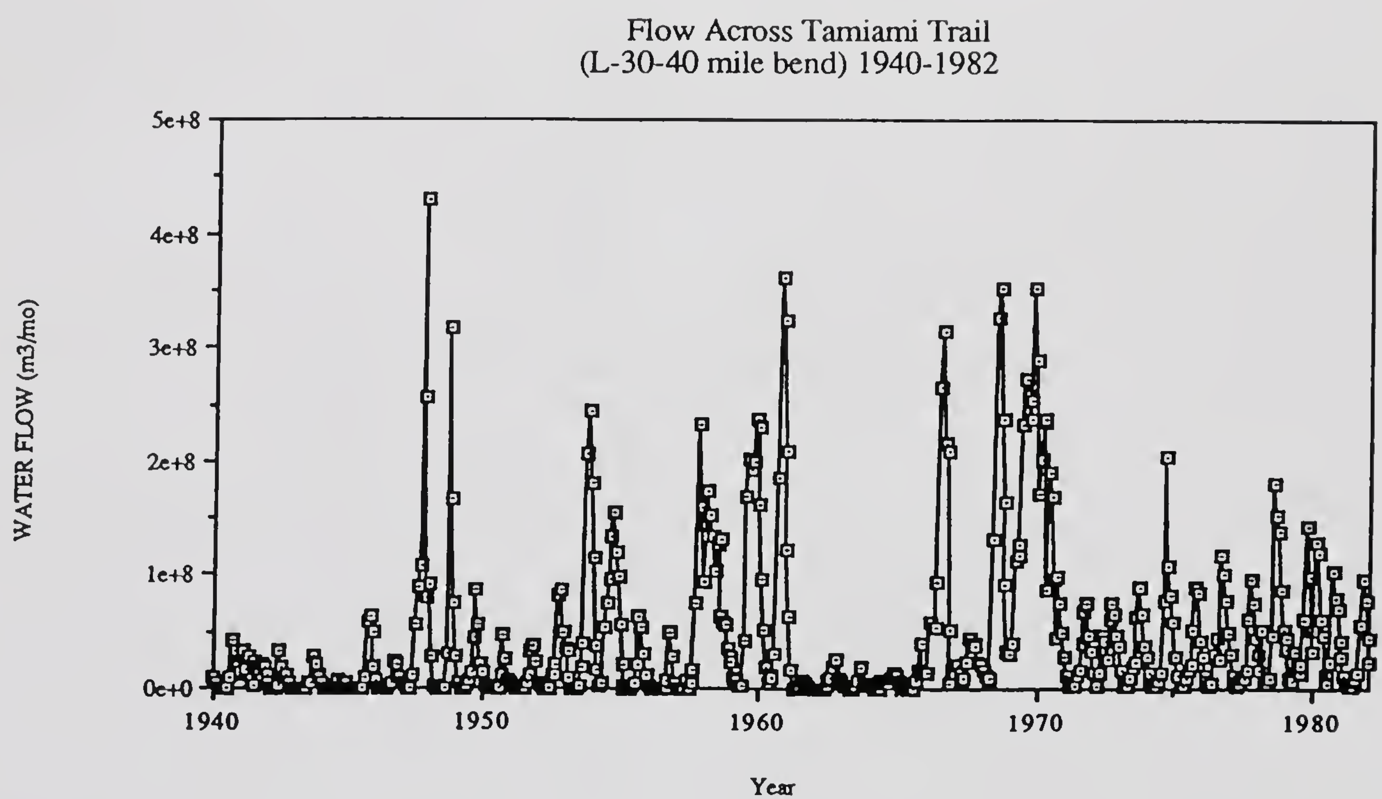
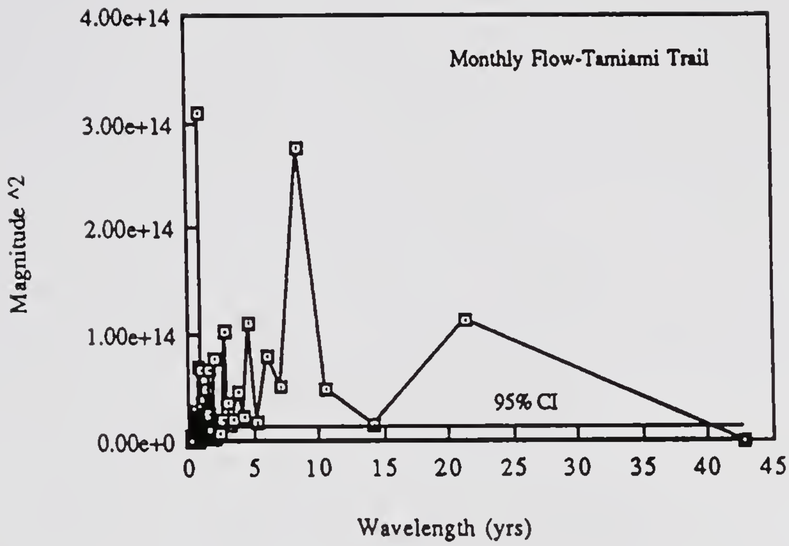


Figure 74. Time series plot of monthly water flow across Tamiami Trail flow section 1940-1982.



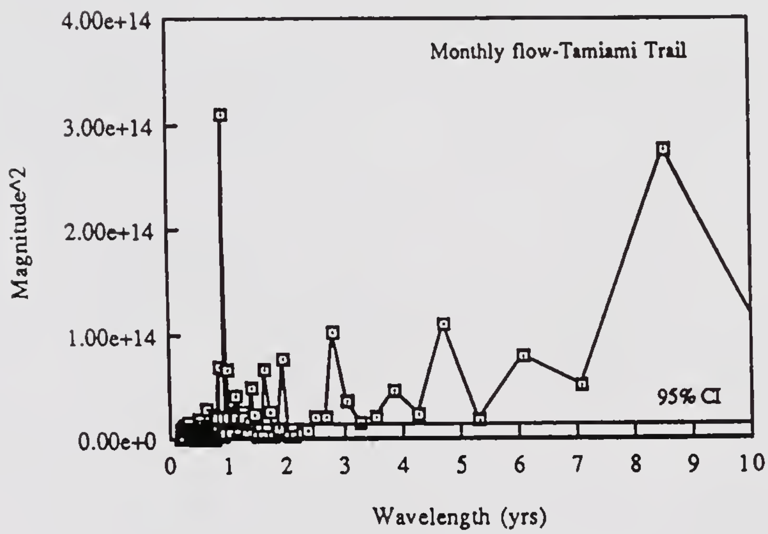


Figure 75. Spectral plots from Fourier analysis of monthly flow across Tamiami Trail flow section.

The large variation in monthly flow creates a lumps and gaps in the rank order distribution. The lumps are apparent as steps or risers in the rank order plot (Figure 76). At least five significant (> 95% confidence level) gaps occur at flows of 0.8, 1.5, 2.3, 3.2 and 3.8 x 10^8 m^3/mo. (Figure 77). The gaps can be used to define breaks among flow groupings that correlate with the periodicities listed above. Monthly flows greater than 3 x 10^8 m^3/mo occur on the long term frequencies (22+ years). The 3.2 x 10^8 m^3/mo break seems to correlate with the 9 year return interval. The 2.3 x 10^8 m^3/mo break is roughly observed on the 5 year cycle, the 1.5 x 10^8 m^3/mo the three year cycle and the smallest break seems to correlate with an annual cycle. These correlations are approximate, certainly high flows don't occur every 9-10 years. The data indicate distinct periodicities, with dramatic annual and decadal cycles, that appear to correlate with distinct volumetric groupings.

Fires

Fire size data from Shark Slough indicate similar periodicities as the water data sets. Fire sizes during the 22 year period from 1958 though 1980 ranged from 10^2 to 10^8 m^2 (Figure 46). Significant spectral peaks were measured at return intervals of 11 and 1 years with minor peaks at a 5-6 year interval (Figure 78). Although the periodicities of fires are similar to the flow and stage the phases are different. The years of high fire activitivy and size (early 1960's and early 1970's) are years of low stage and low flow.

Sea Level

Multiple cycles are apparent in all three data sets (Figure 79). The dominant cycle is the annual cycle and is probably associated with the thermal

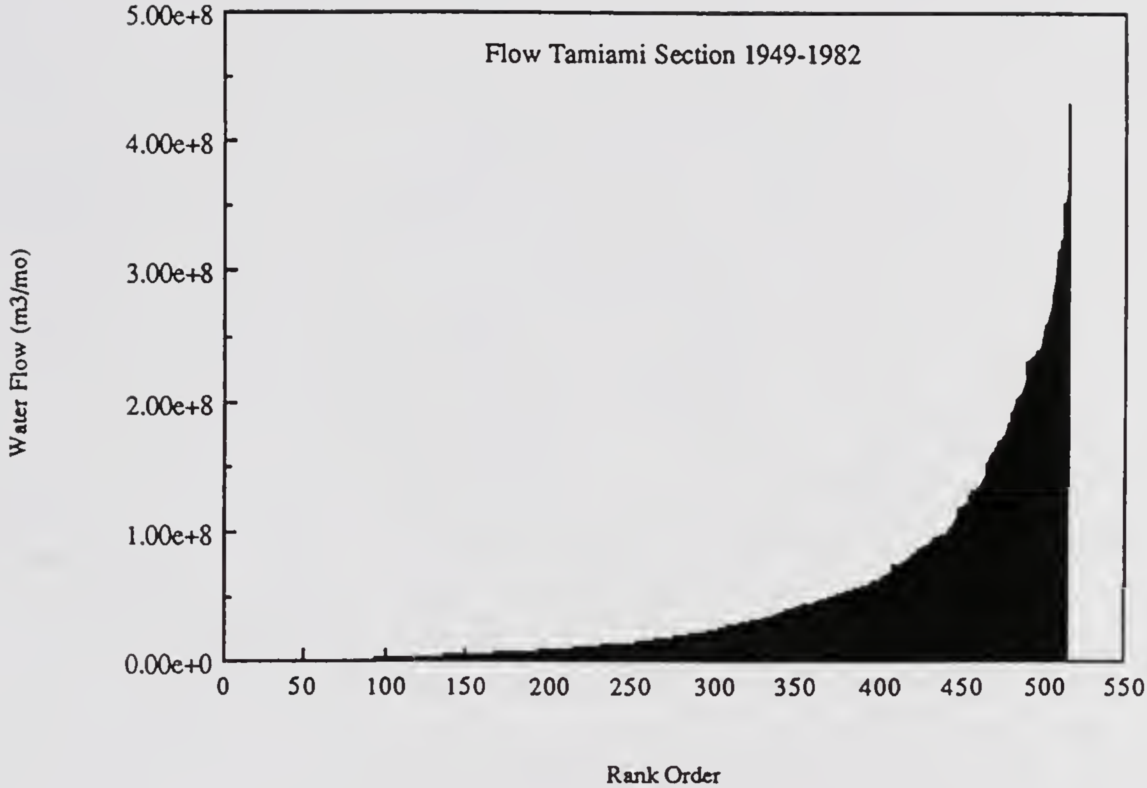


Figure 76. Rank order plot of monthly water flow across Tamiami flow section.

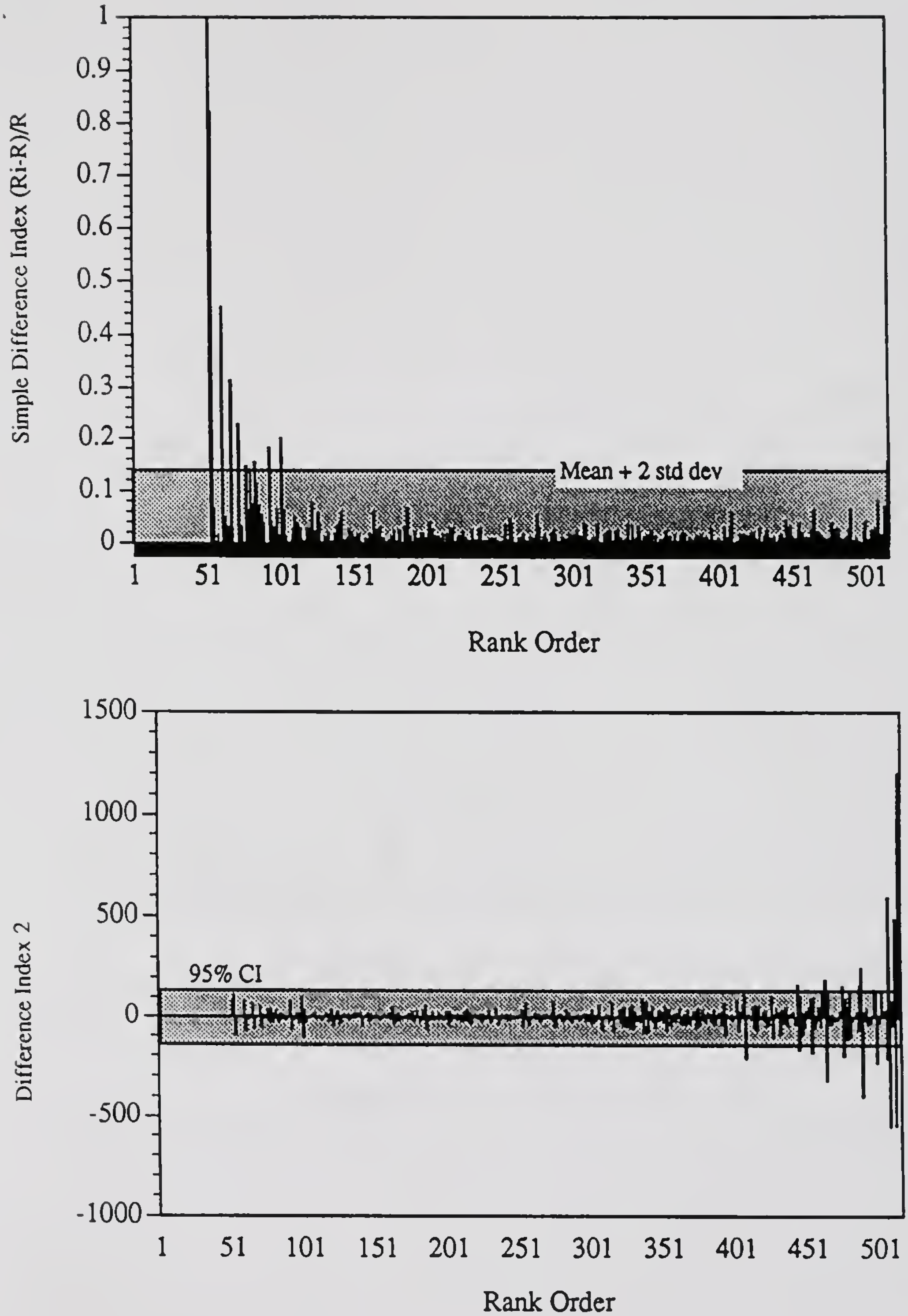
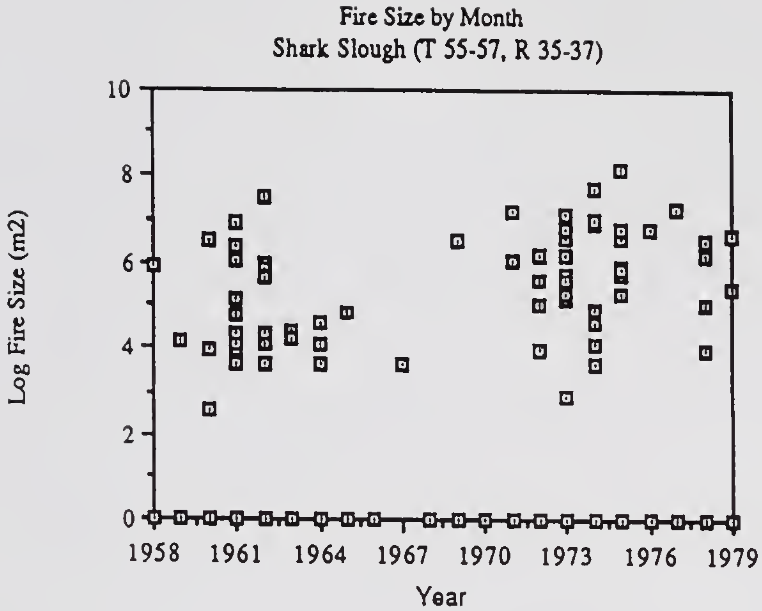


Figure 77. Difference indices 1 (top plot) and 2 (bottom plot) for monthly flow data, Tamiami flow section.



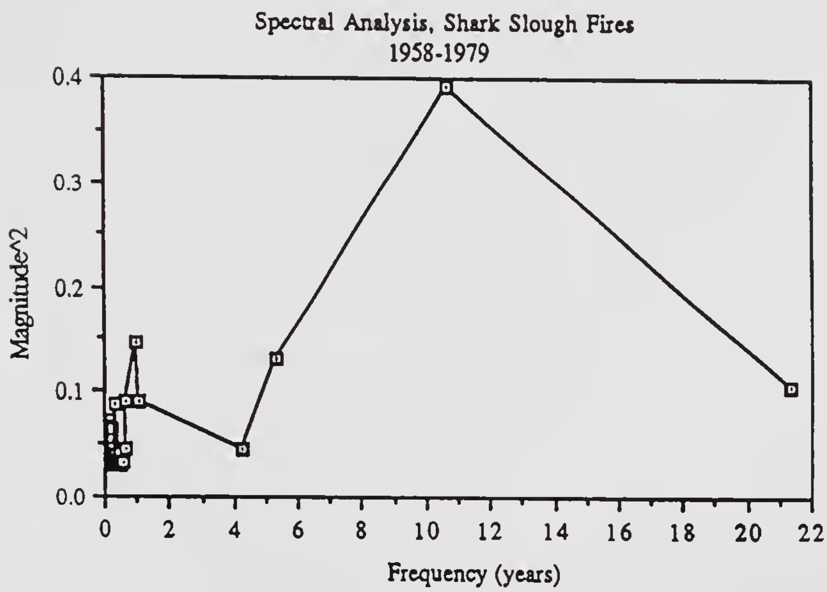


Figure 78. Time series plot of log fire sizes (top plot) from 1958-1979, and spectral analysis (bottom plot) indicating dominant cycles in fire data.

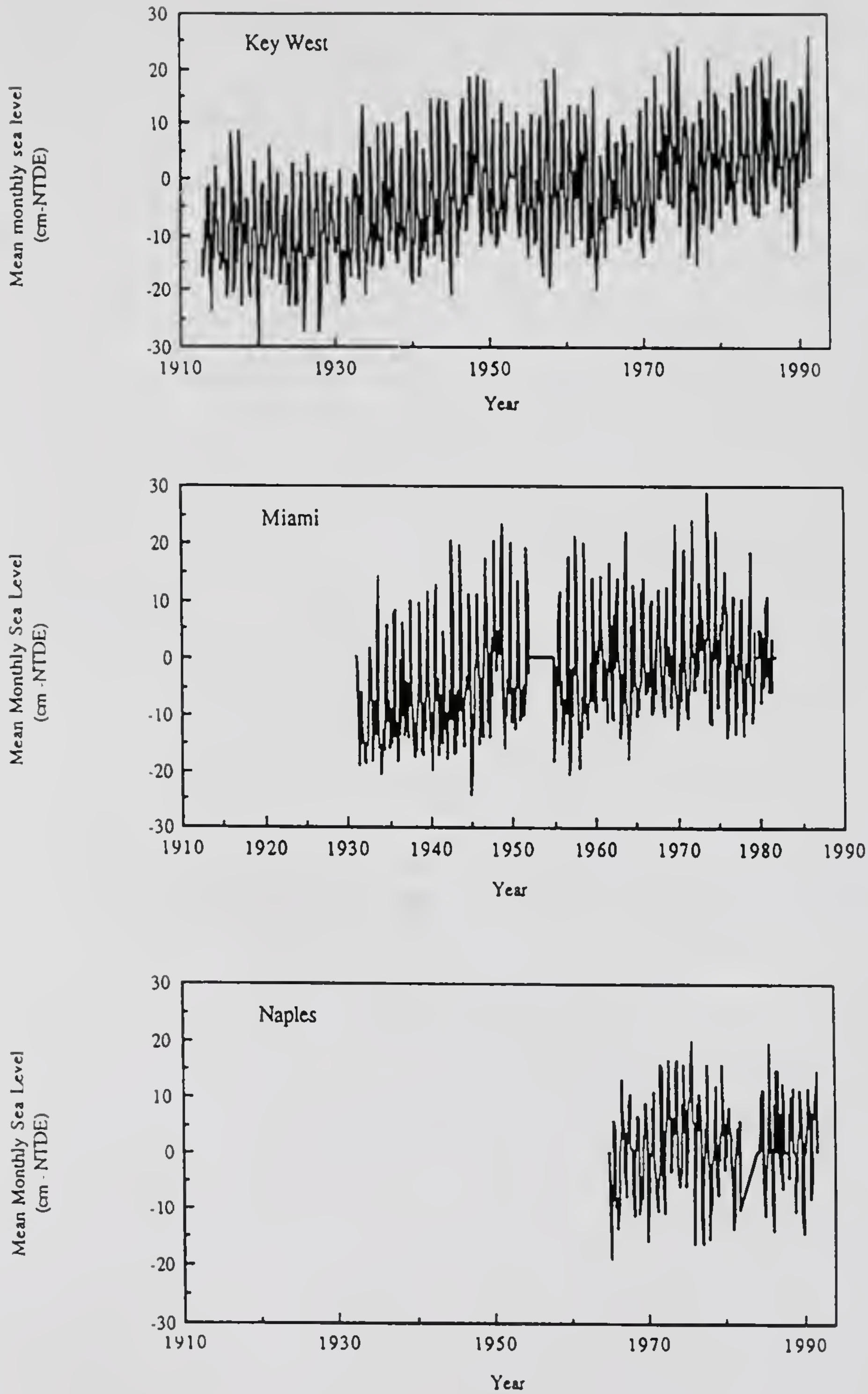


Figure 79. Time series plots of mean monthly sea level elevation at Key West, Miami, and Naples for the time period 1910 through 1990.

expansion resulting from annual variation in solar insolation. Other significant cycles occur at return intervals of 0.5 (6 months),4, 5, 6, 12 and 22 years and are most apparent in the Key West data (Figure 80). Significant cycles at Miami and Naples also occur on a six month, 5.5 year, 13 and 23 year interval (Figures 81 and 82).

Temperature and Pan Evaporation

Minimum and maximum temperatures at both sites exhibit a regular, annual cyclical pattern (Figure 83). The data tend to fluctuate more in the minimum temperatures than in the maximum temperatures. The largest cycle appears to be the the annual pattern. A significant cycle appears to be at a frequency on the order of 5-6 months in both max and minimum temperature. Only the minimum temperatures at Tamiami exhibited a multi-annual periodicity; with a cycle of about 5-6 years (Figure 84 and 85). None of the other sites or temperatures had a discernable multi-year pattern.

In contrast to the regularity of the temperature data, the pan evaporation at both sites appears to vary at multiple cycles. The monthly values appear to vary between 5 and 20 cm of water loss (Figure 86). The most significant periodicity in both data sets was the annual cycle. Signficant multi-year periods of 11 and 5.5 years were also observed in both data sets (Figure 87) although the peaks were not as significant as the annual cycle. Periods of 4-6 months also were significant. Again, just as the flow, stage, fire and sea level data, in addition to the annual cycles, all these data sets exhibit significant cycles of 8 - 11 year period and a 4-6 month period.

Daily evapotranspiration exhibits a seasonal pattern of fluctuation, with much variation in magnitude between the two sites. Daily evapotranspiration rates range from zero to almost 2 cm/day at site P33 (Figure 88). Rates at P37

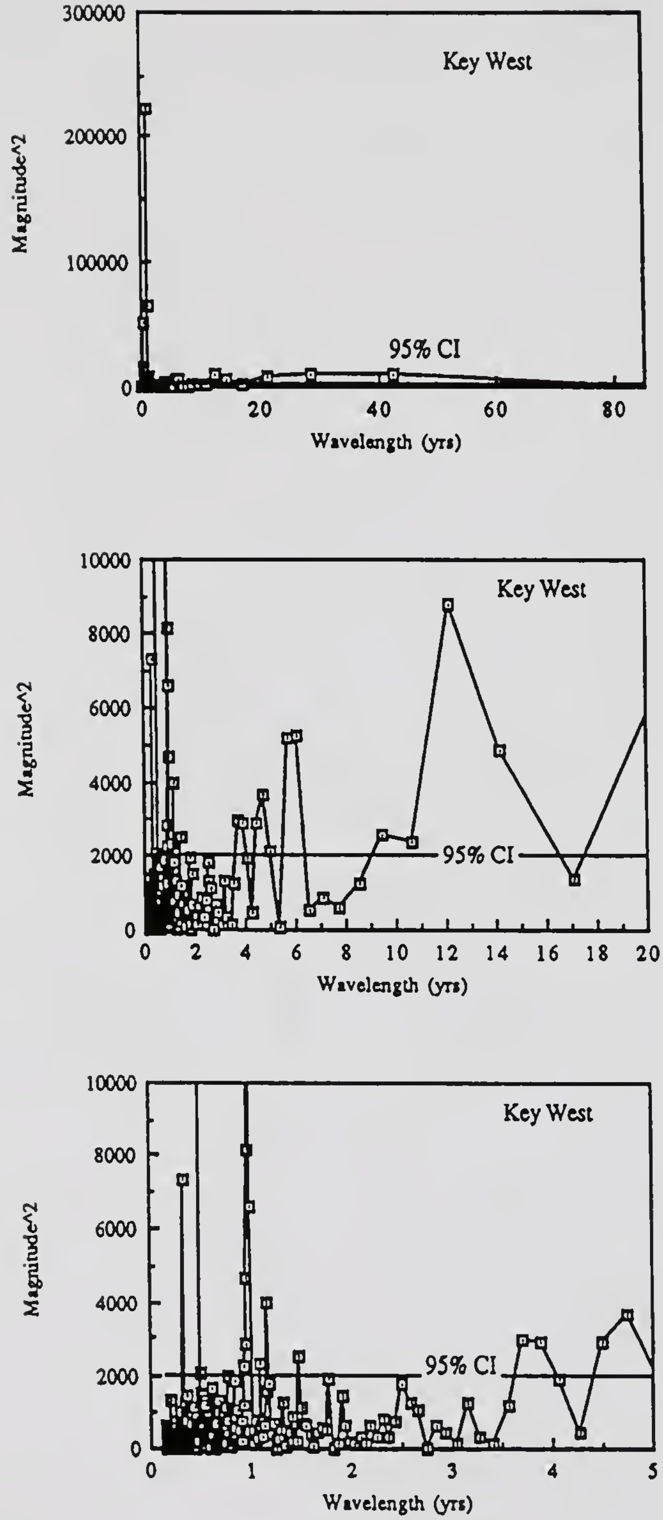
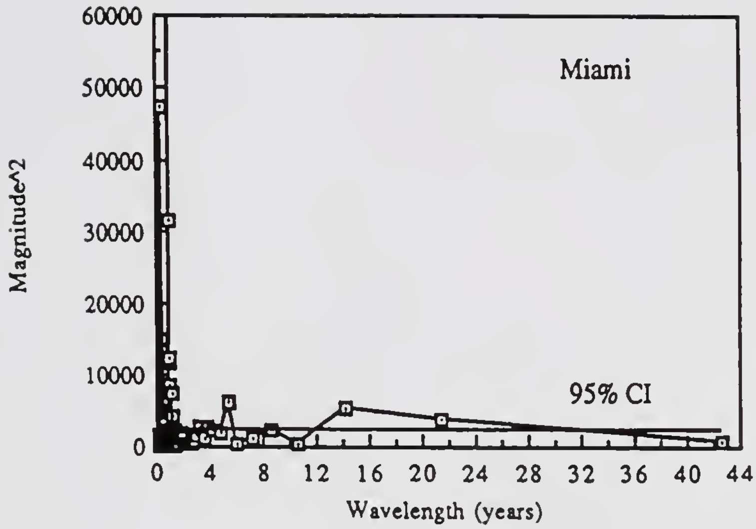


Figure 80. Spectral plots from Fourier analysis of detrended sea level data from Key West. Dominant cycle is the annual period.



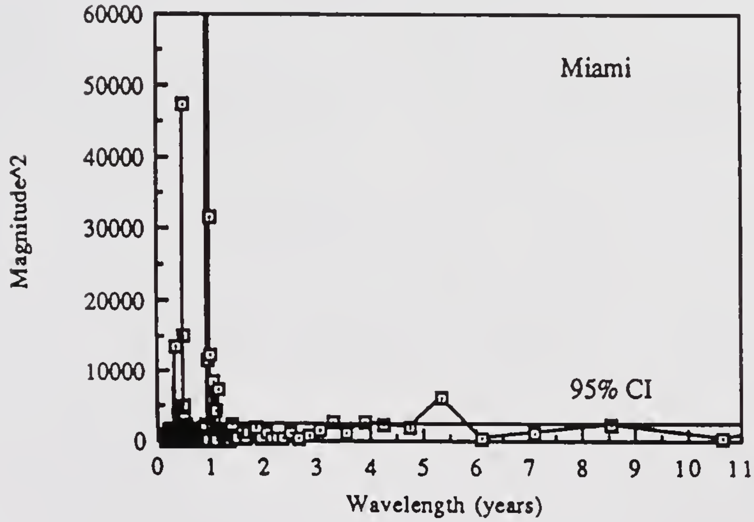
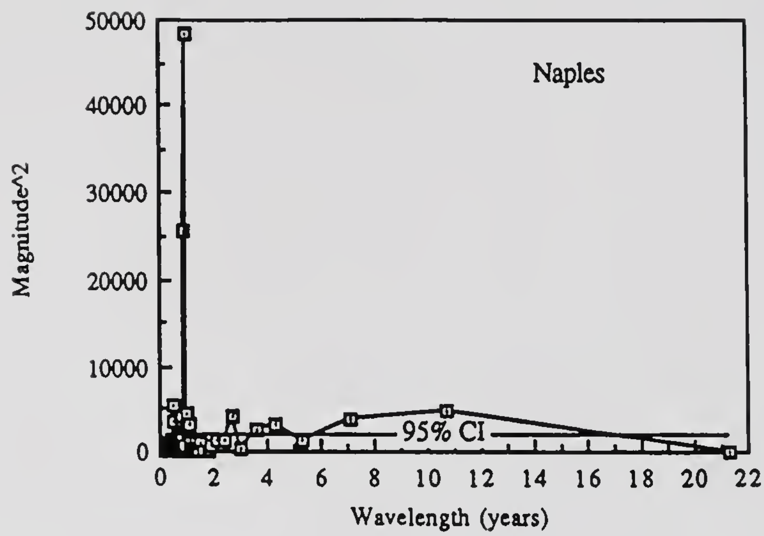


Figure 81. Spectral plots from Fourier analysis of detrended sea level data from Miami. Dominant cycle is the annual period.



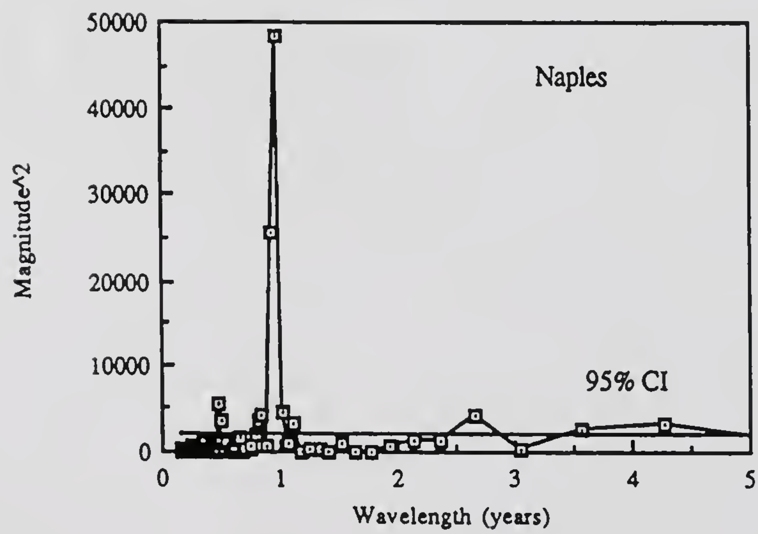


Figure 82. Spectral plots from Fourier analysis of detrended sea level data from Naples. Dominant cycle is the annual period.

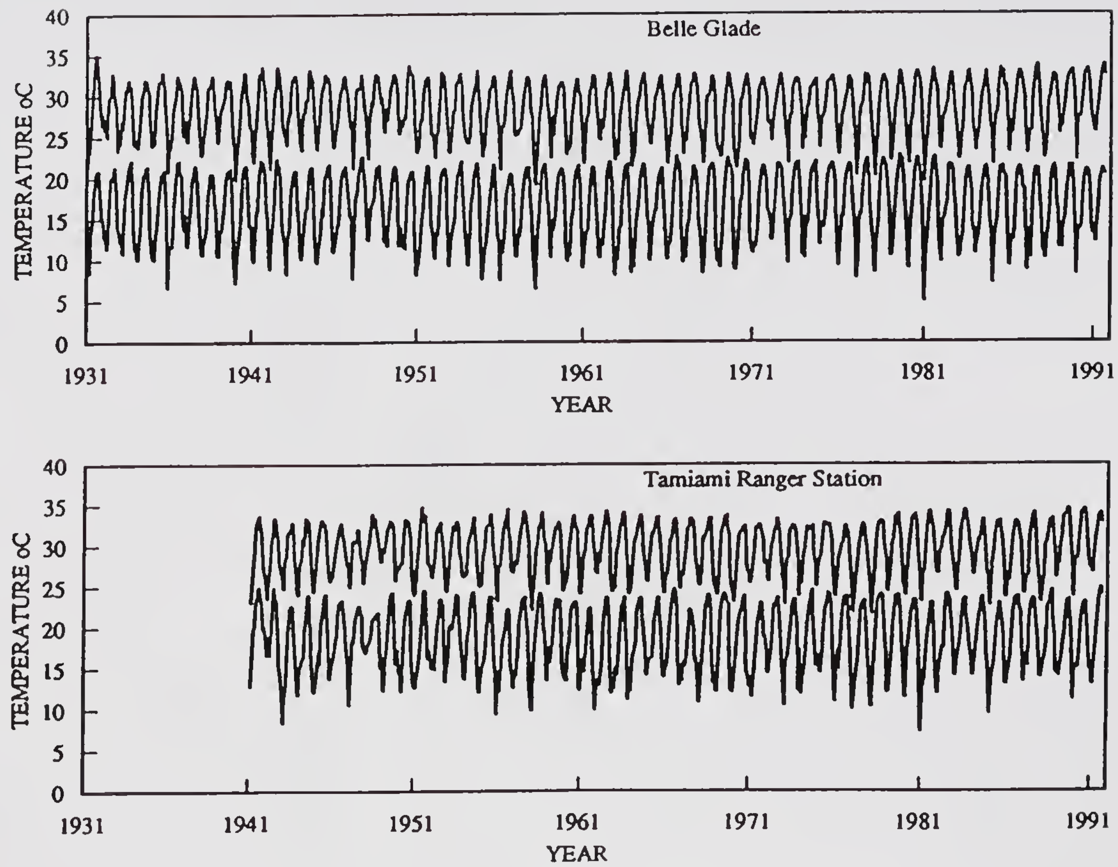


Figure 83. Time series plot of mean monthly minimum and maximum air temperatures from Belle Glade and Tamiami Ranger Stations.

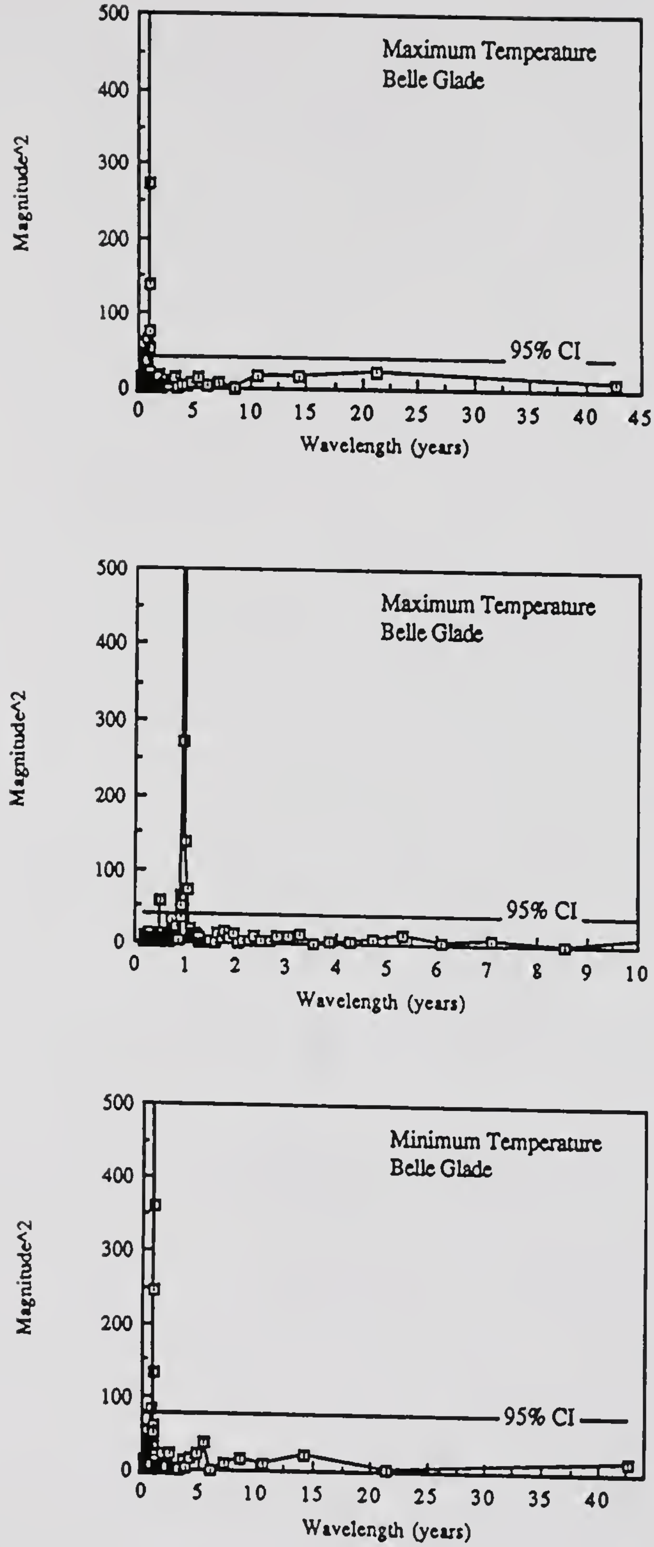


Figure 84. Spectral plots from Fourier analyses of maximum and minimum monthly temperature data from Belle Glade.

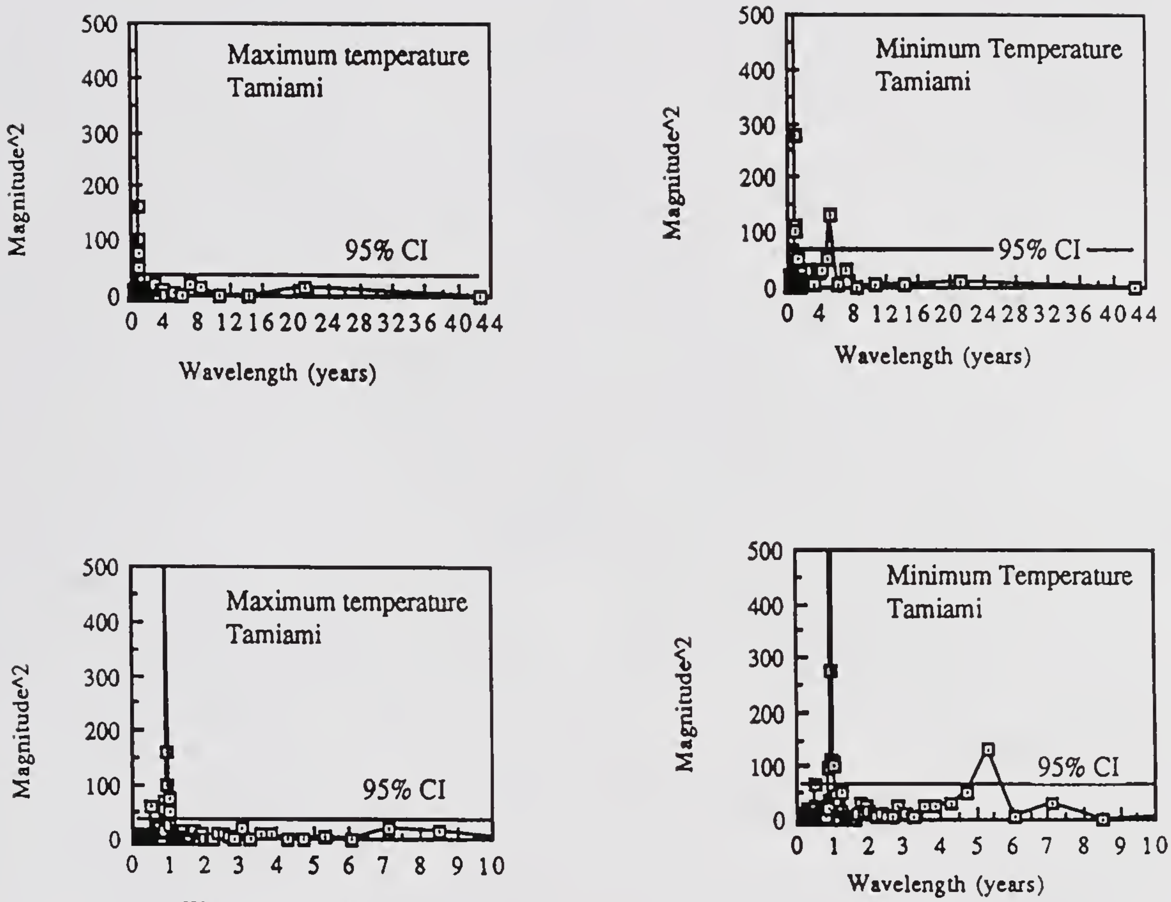


Figure 85. Spectral plots from Fourier analyses of maximum and minimum monthly temperature data from Tamiami Ranger Station.

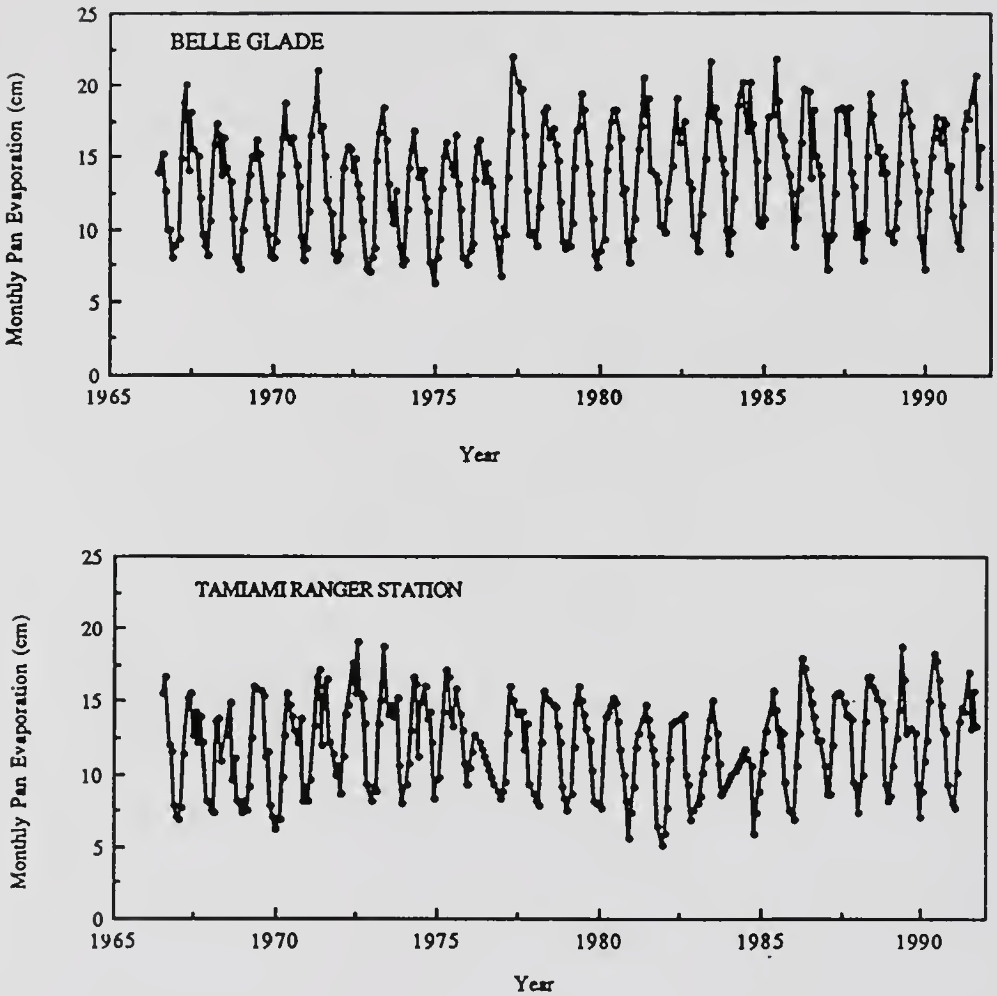
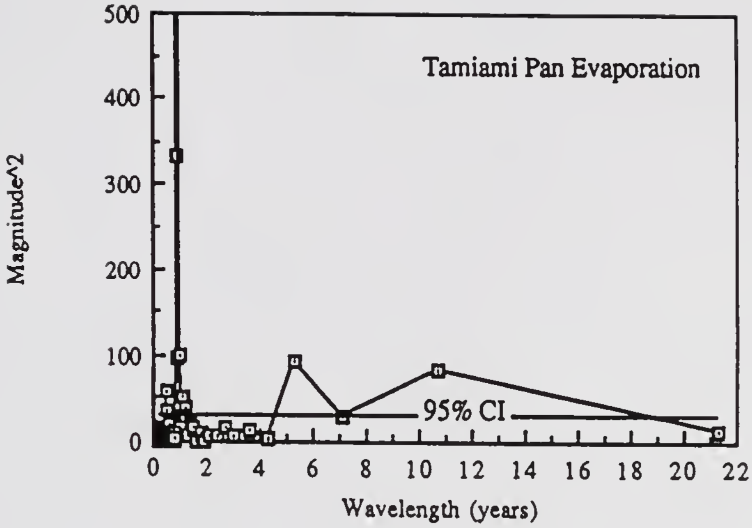


Figure 86. Time series plots of monthly pan evaporation from Belle Glade and Tamiami Ranger Stations, 1965 through 1991.



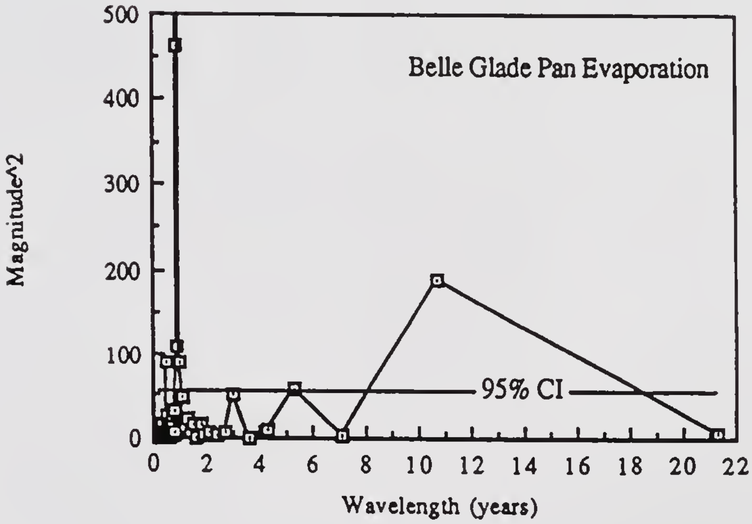


Figure 87. Spectral plots from Fourier analyses of monthly pan evaporation from Belle Glade and Tamiami Ranger Stations, 1965 through 1991.

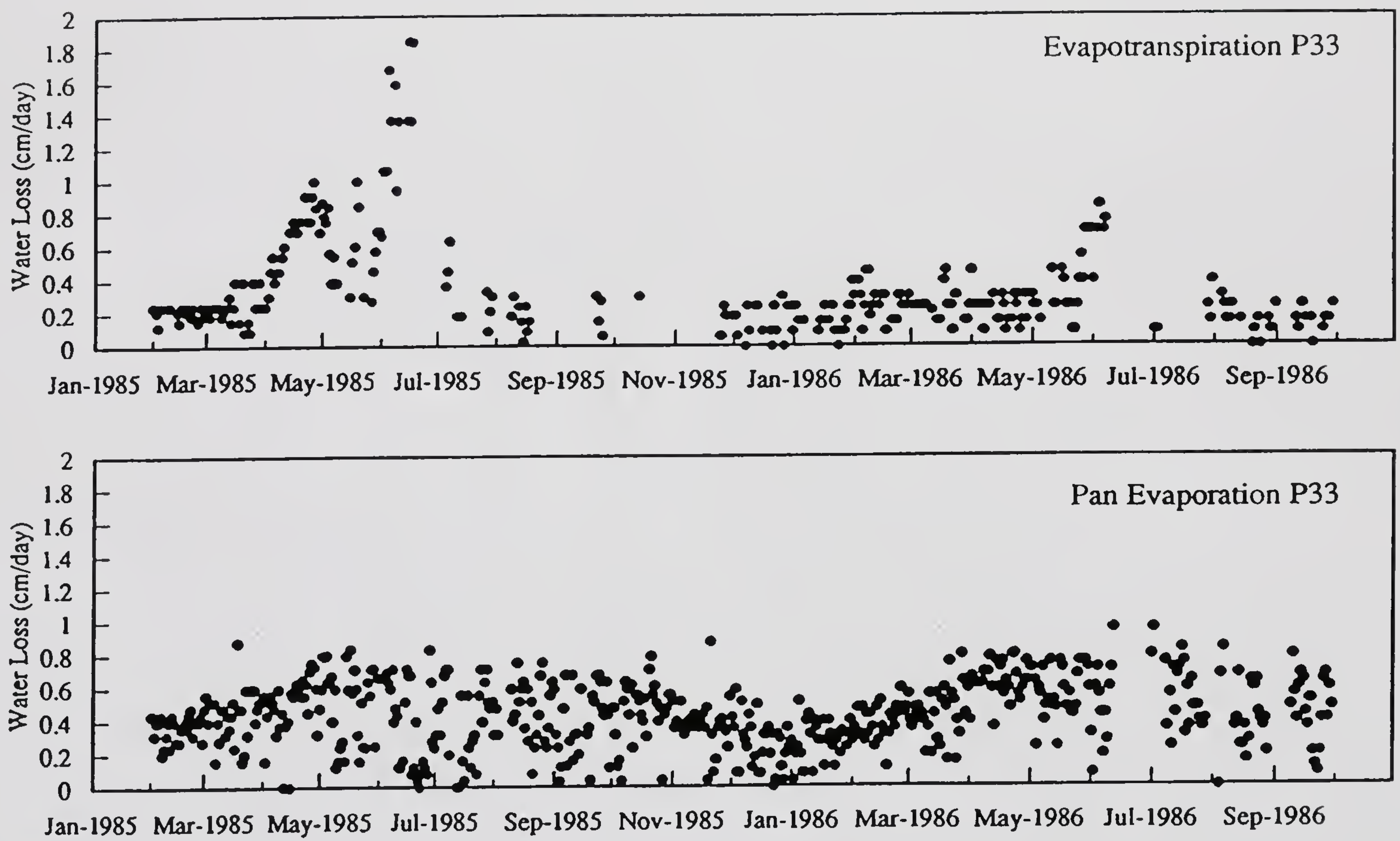


Figure 88. Time series plots of daily evapotranspiration and pan evaporation at site P33, January 1985 through October 1986.

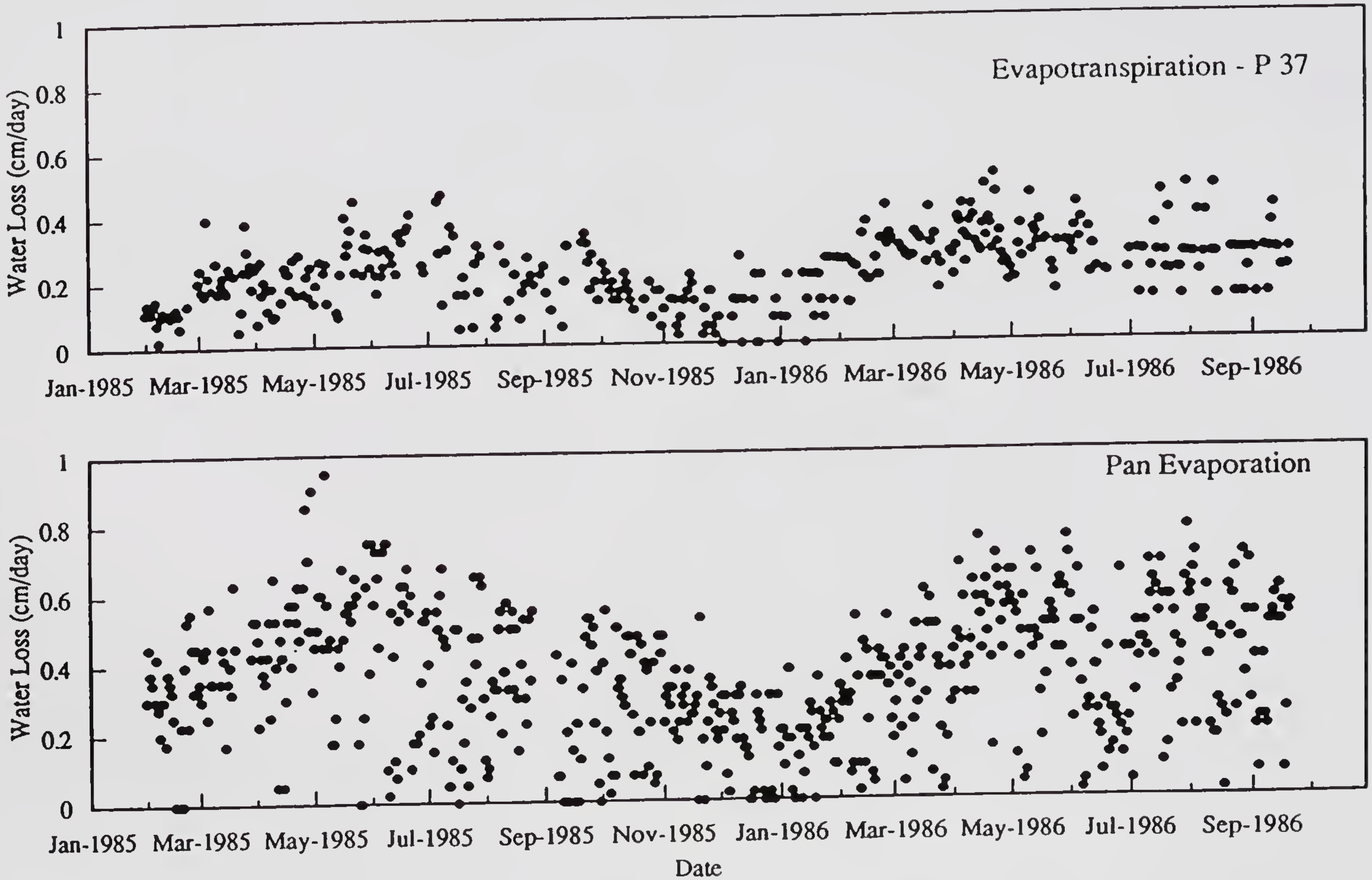


Figure 89. Time series plots of daily evapotranspiration and pan evaporation at site P37, January 1985 through October 1986.

were much lower, ranging between zero and 0.6 cm/day (Figure 89). Daily pan evaporation also varies seasonally. Both evapotranspiration and pan evaporation data exhibit sinusoidal patterns, with peak values during the period of May through July and lowest values during January and February (Figures 88 and 89).

Spectral analysis of daily evapotranspiration and pan evaporation data agree with the short term cycles found in the monthly pan evaporation data. The significant cycles for daily evapotranspiration were at return periods of 4, 6, 8 and 17 months at both sites (Figure 90). The dominant cycles in the daily pan evaporation data were at 6, 8 and 17 months (Figure 91).

All of the temporal data sets appear to exhibit multiple cycles. An annual cycle is present in all of the data sets with grains less than one year. An eleven year cycle is dominant in two of the data sets; i.e., monthly stage and the monthly fires. Monthly cycles are apparent in the rainfall data sets. An interpretation of these results is in the final section of this chapter.

Discussion of Results

Hydrology--Rainfall

The dominant cycles in the rainfall data appear to be related to fluctuations in the spatial and temporal domains of the processes that generate rainfall. The dominant cycle evident in both the daily and monthly data is the annual cycle, with peak rainfall during the summer and lower rainfall during the winter. Summer rainfall is mainly a result of convective thunderstorms associated with the daily sea and land breeze cycle (Hela 1952, Bradley 1972, MacVicar and Lin 1984). The generation of convective thunderstorms is related to the annual variation in heat budget association with the earth orbit. During the fall, winter, and spring months (November through April), rainfall is

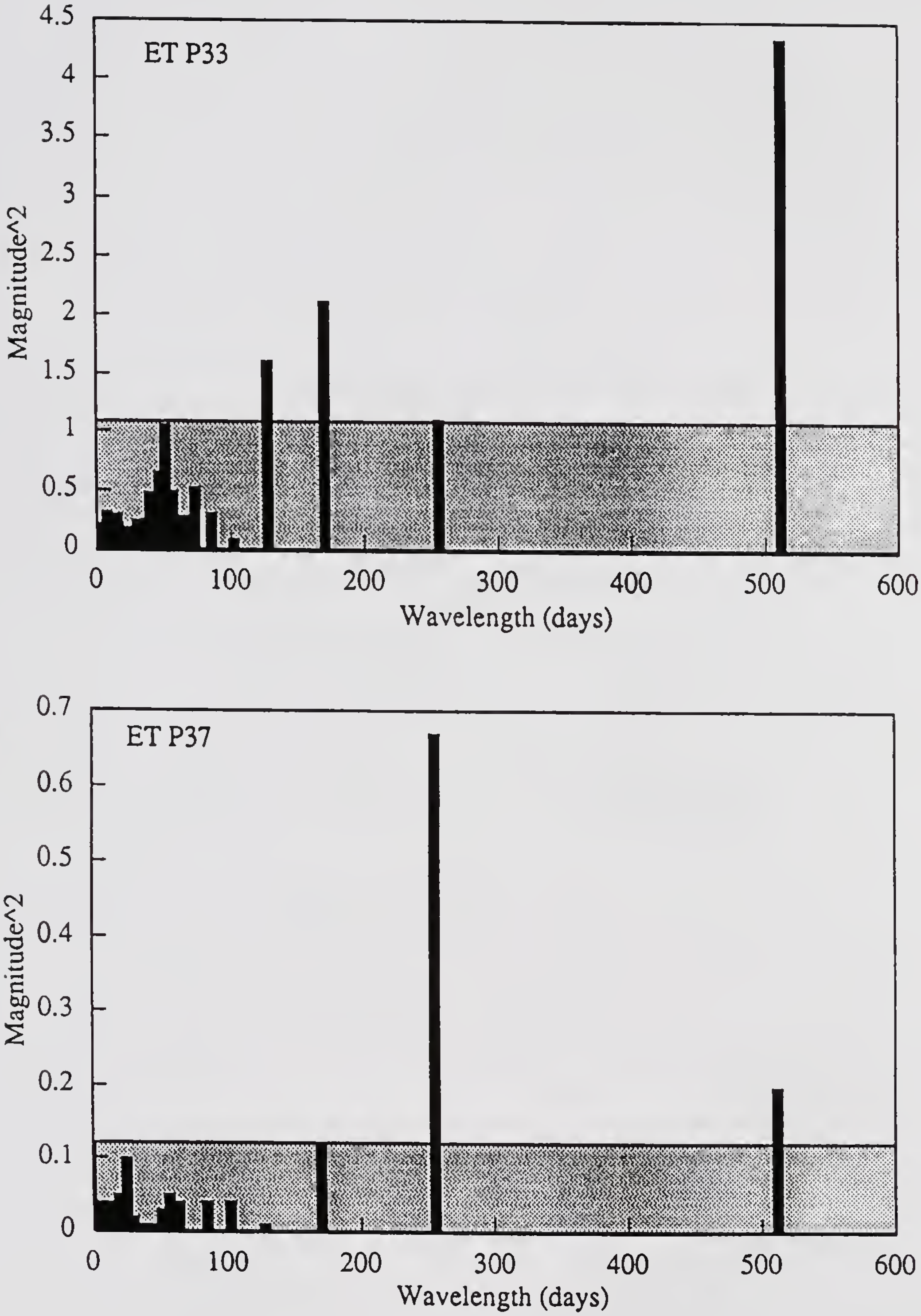
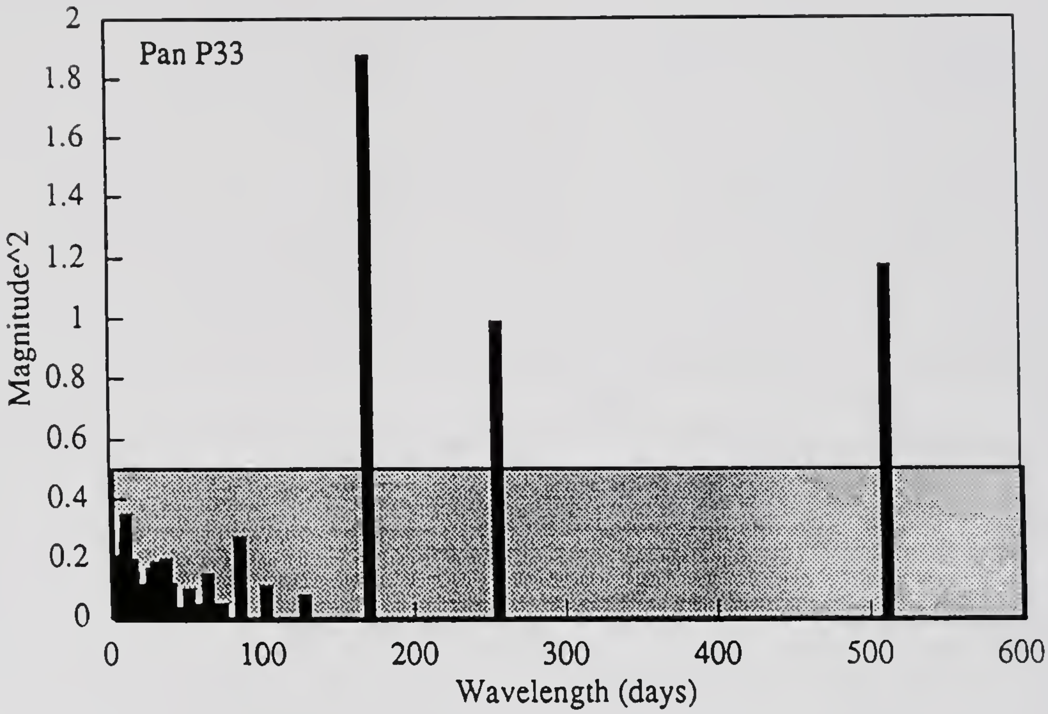


Figure 90. Spectral plots from Fourier analyses of daily evapotranspiration at sites P33 and P37. Bars represent magnitude of cycle, gray 95% C.I.



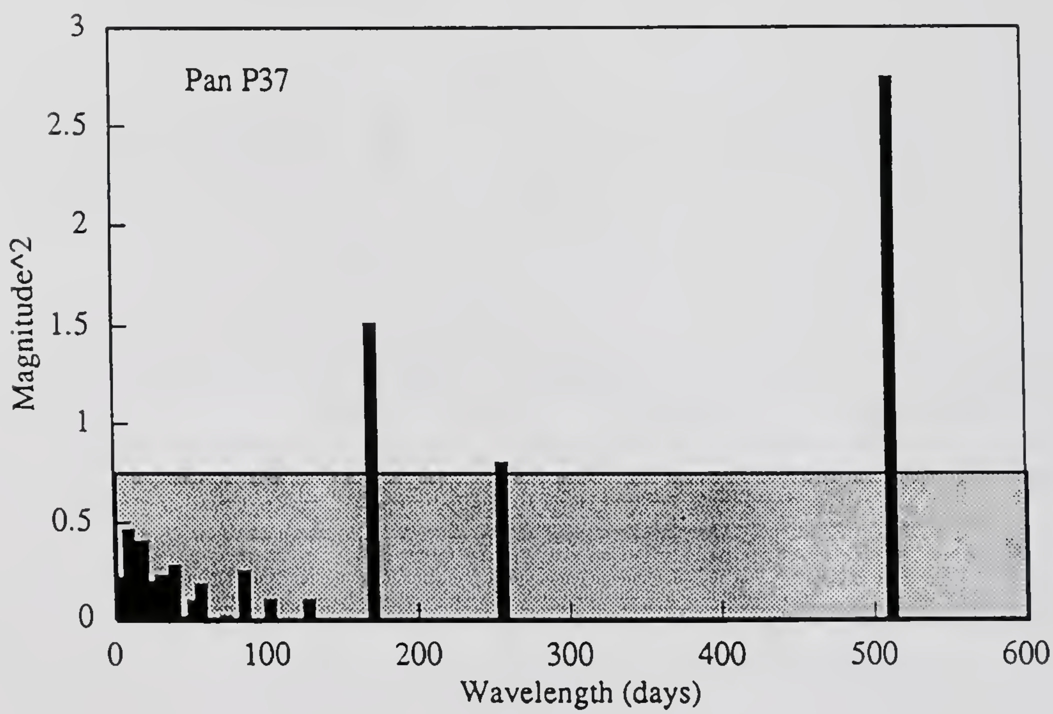


Figure 91. Spectral plots from Fourier analyses of daily pan evaporation at sites P33 and P37. Bars represent magnitude of cycle, gray 95% C.I.

associated primarily with the passage of cold fronts (Hela 1952, Bradley 1972, MacVicar and Lin 1984). The fronts pass at approximately weekly intervals and do not produce much rainfall.

The three to four month cycle evident in the data is less well understood or explained. This cycle is evident as the bimodal summer peaks of rainfall. Some authors (Thomas 1970, MacVicar 1983) attribute the summer depression to a combination of two processes. During the late summer months, convective activity may decrease or level due to feedback dynamics of changing albedo, lapse rates and heat budget after the freshwater system is full of water (Gannon 1978). The latter peak may also be a result of the increased frequency of tropical storms and hurricanes in August and September that add to rain during these months (Gentry 1984).

There is a paradox in the analyses of rainfall data as the grain or resolution changes. The dominant cycles in both the daily and monthly grain data sets are the annual and monthly frequencies. No multiple year cycle emerges from analyses using these data sets. The interannual or multiple year cycles are only significant in the Fourier analysis of annual rain totals. There are a number of explanations for these results. The first is that the multiple year cycles may be in the smaller resolution data sets, but there is so much variations that the signals are masked by all of the data. Attempts were made to mask seasonal and annual variation, and the interannual patterns were still not significant. Another explanation may be that the multiple year patterns are an artifact of the totaling process over a years time, in that they tend to exaggerate patterns. A number of authors (Thomas, 1970, Isaacs, 1980) report multiple year cycling in annual rainfall. Annual variations have been attributed to the degree of tropical storm activity (MacVicar 1983). Other phenomena such as the southern ocean oscillation (El Niño) contributes to increased rainfall over the southeast United

States (Rasmussen 1985, Ropelewski and Halpert 1987). The presence of these longer term, broader scale processes such as El Niño and tropical storm frequency, seem to account for the interannual variation in rainfall but also that these effects are probably more evident in rainfall totals summed over an annual time period.

The multiple cycles in the rainfall data appear to be related to the processes that generate rain. The next section discusses the implications of this temporal variation in input on two response variables in the system; stage and flow.

Hydrology--Stage and Flow

A significant cycle in both the stage and flow data is a multi-year (between eight and eleven) periodicity. This result was surprising, given that it is almost an order of magnitude more than the periodicity of the dominant input signal. A number of alternative explanations may account for this result.

One idea was that the basin morphometry might be creating the longer term pattern. That is, small variations in the rainfall interact with the slow flow and basin morphometry in such a way to create longer term patterns in the surface water variables. This idea was tested with the model presented in Chapter 3. The test involved inputting a regular, annually varying wave to see if a longer term wave would emerge. The input signal has a dominant annual cycle and a shorter three month cycle. The magnitude of the rainfall (mean total input) was set at one value for a 28 year simulation period at an average rainfall amount. The resulting depths and flows were analyzed using Fourier techniques, and no long term cycles were evident. These results indicate that a combination of slow flow and basin morphometry probably does not explain the longer time patterns in the surface water or flow data.

Another explanation is that the major outflow pathways, such as evapotranspiration and sea level, vary over the longer term. There is evidence to support this, since both sea level and evaporation have strong multiple year cycles on the order of the eight to eleven year cycle. To test this idea, a simple mini model was created using the ithink® modeling software. The model had one state variable (water), one input (rain), and two outflows (ET and flow). The input to the water was modeled as a sine wave with a frequency of one year. The evapotranspiration (ET) pathway was modeled as a sine wave, with a frequency of 10 years. The flow pathway was calculated as one-tenth times the amount in the water tank. The results indicate that the overlay of input and output sine waves creates both a short term (annual) and a long term (10 year) cycle in the state variable-water (Figure 92). This lends credence to the idea that the long term fluctuations in the stage and flow data in the Everglades may not be solely due to fluctuations in the input (rainfall), but can be caused by longer term cycles evident in the patterns of outflow. An anecdotal correlation is that the dominant cycles for evapo-transpiration and sea levels seem to be at the same frequency of sun-spot cycles.

The multiple-year cycles evident in the stage and flow data are probably a result of variations of both input and output operating at different time intervals. One way of depicting these cross scale interactions is the use of spatio-temporal diagrams as demonstrated by Steele (1985), Clark (1985), and Holling (1992). The diagrams are logarithmic scales over space (abscissa) and time (ordinant) that cover ranges of about six orders of magnitude. Entities within the diagram are defined by grain and window; in spatial terms grain is the smallest resolution that defines the entity and window is the extent. In temporal terms, the grain is the minimum resolution needed to define a pattern and the window is the longevity of the entity. Breaks in the fractal dimension of

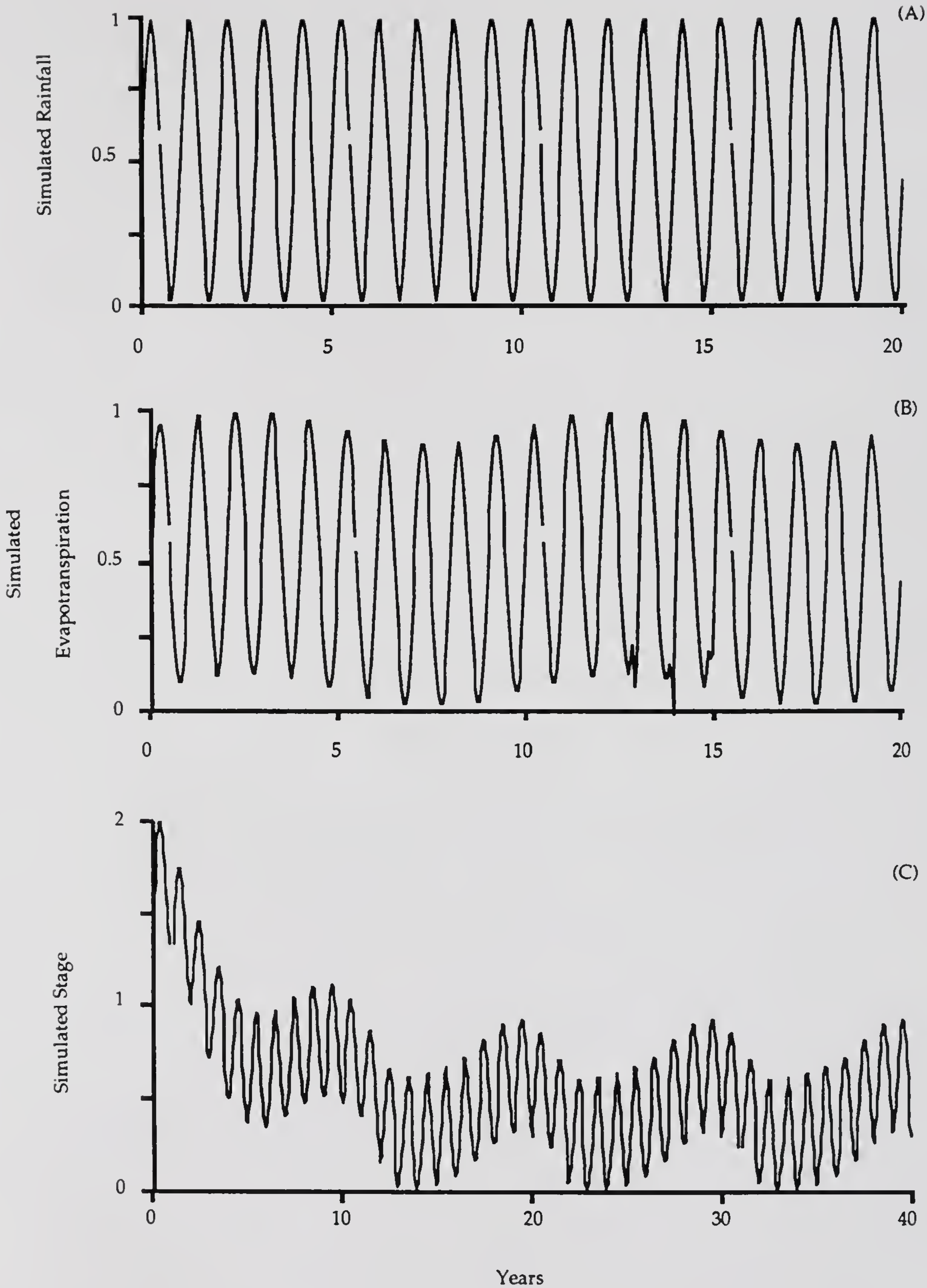


Figure 92. Results of mini-model , frequency of rain input (A), ET outflow (B), and stage fluctuations (C). Note difference in time range, stage plot covers 40 simulated years.

spatial patterns can be used to define breaks between entities in the spatial dimension. Similarly, dominant frequencies appear to differentiate temporal entities or levels. Surface water within the Everglades appears to fluctuate on at least three dominant frequencies (daily, annually and decadal), as shown in Figure 93. The daily and annual fluctuations in stage appear as a result of nested fluctuations of land/sea breeze interactions that produce convective thunderstorms on a daily and seasonal basis. The longer term fluctuations appear to coincide with long wave influencing evapotranspiration and ,to a less evident degree, decadal fluctuations in El Niño that vary rainfall. The atmospheric dynamics are all lower and to the right in the diagram, reflecting the faster dynamics over broad areas, whereas the surface water dynamics are slower and occur over smaller areas.

Fires

Fire patterns indicate at least two classes of fires occur in Shark Slough; more frequent smaller fires and less frequent large fires. The break between the small and large fires occurs at a window length of about 5600 m. Fires above this size, may be a result of many factors, including inability of humans to control or contain fires over a given size, or perhaps a less frequent combination of climatic conditions that would support the fire to burn over a broad area and longer time frame. The larger fires burn over longer time periods than the smaller ones. The periodicity of all fires exhibit the same multi year frequency (eight to eleven years) as the stage and flow data. An attempt at regression between fire size and water levels yielded no statistical correlation between these variables. Other factors such as wind speed and direction, time since last fire as influencing fuel loads and changes in ignition events all would tend to mask the relationship between fire and water levels. Even though a statistical correlation does not

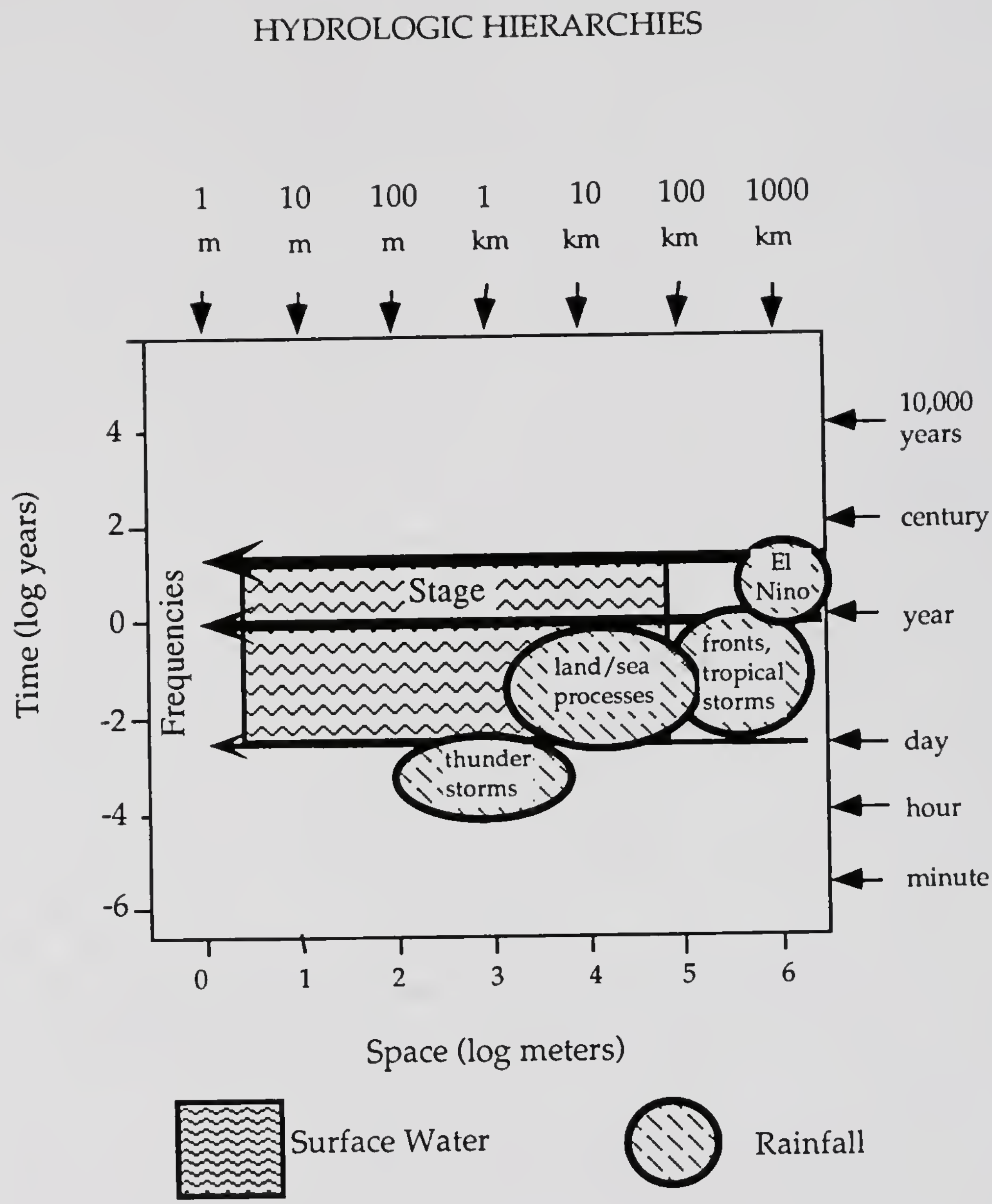


Figure 93. Hydrologic hierarchies in the Everglades ecosystem, showing scales of dominant frequencies in surface water and atmospheric variation.

exist, there appears to be some association in that the fires occur during periods of low water levels.

Topography

At least two regions of scale are evident in the topographic data and appear to correlate with the processes that create the structure. A change in the fractal dimension occurs at a step length of about 1.5 km, which defines a change between the macro and micro topographic features (Figure 94). The fine scale variations (measured by step lengths of less that the fractal break) that comprise the small scale topography are related to processes that can increase or decrease the soil surface elevation. Soil formation occurs in the areas of longer hydroperiod, as decomposition is slow, resulting in peat accretion. Organic soils can be rapidly oxidized if long-term droughts occur, or if the soil burns during severe dry periods. Marl is formed on shorter hydroperiod sites, a result of precipitation of calcium carbonate by blue green algae (Gleason 1972). Over longer term periods solution of the limestone bedrock can create small scale depressions (Hoffmeister 1974). The macro topography is associated with the geologic features of the Everglades. The geologic features are associated with broad landscape regions, defined by Jones (1948) and Davis et al. (In Press) and are the result of broad scale processes of ocean currents. Another theory (Petuch 1985, Petuch 1987) is that the gross morphometry of the Everglades basin was caused by a meteroite impact during the Eocene.

Vegetation

The observed breaks in vegetation patterns are puzzling. No plausible explanation can suitably account for the patterns. The breaks do not occur in the

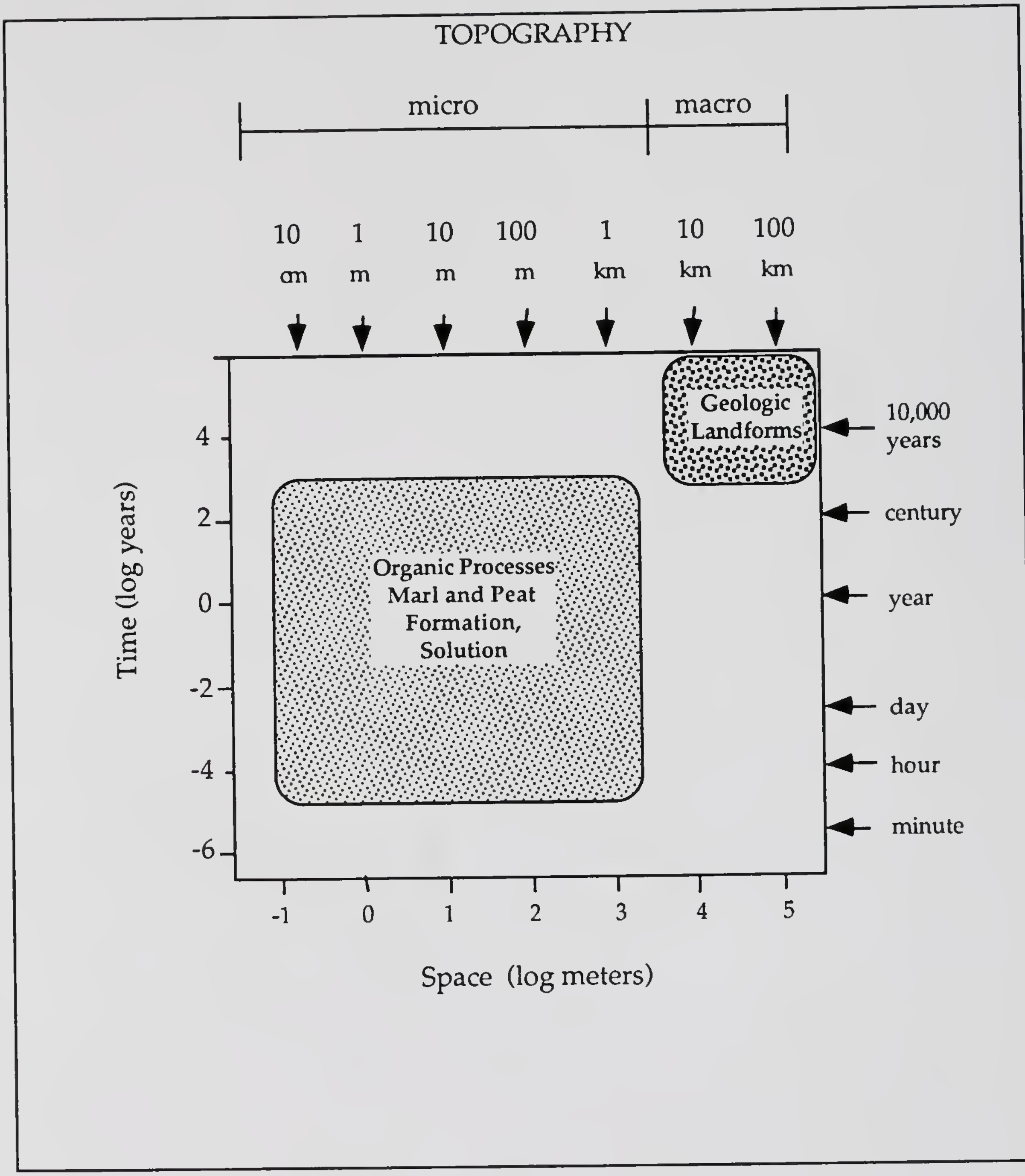


Figure 94. Topographic hierarchies in the Everglades ecosystem, indicating breaks between microtopographic and macrotopographic features and processes.

smallest windows (< 160 m), and therefore do not represent the edge profiles of communities. The breaks occur in the larger windows and appear around step lengths of 300 m and about 1 km. The break at the largest scale may be related to the topographic features, although it occurs at a smaller step length than the change in the topographic fractal dimension. The breaks appear at about the same scale grain across all three vegetation types. This suggests that perhaps some meso-scale process such as fire or water flow might be influencing the pattern rather than some biologic process such as spatial expansion of the community size. Nothing in the analysis of fire patterns appears to correspond with these scale ranges. The breaks are included in a space/time plot of vegetation features (Figure 95) even though they don't appear to correspond with any logical groupings in a vegetation hierarchy. In spite of the lack of reasons for the observed patterns, the discontinuities appear to exist in the spatial patterns of vegetation.

Summary

The analysis of existing data sets from the Everglades ecosystem fail to invalidate the hypothesis that spatial patterns should exhibit breaks and temporal patterns a few cycles. No one test is singularly convincing. Comparison of results across methods seem to corroborate findings. Spatial patterns exhibit scale regions of self-similarity separated by distinct breaks. The soil surface topography appears to vary at two distinct spatial scales, the broad scale is apparently a result of geologic features and the small scale appear related to the processes or organic soil accretion and removal. Breaks in the size of fires may be related to the approximately decadal time period between large burns. The vegetation patterns exhibit breaks between regions of self-similarity

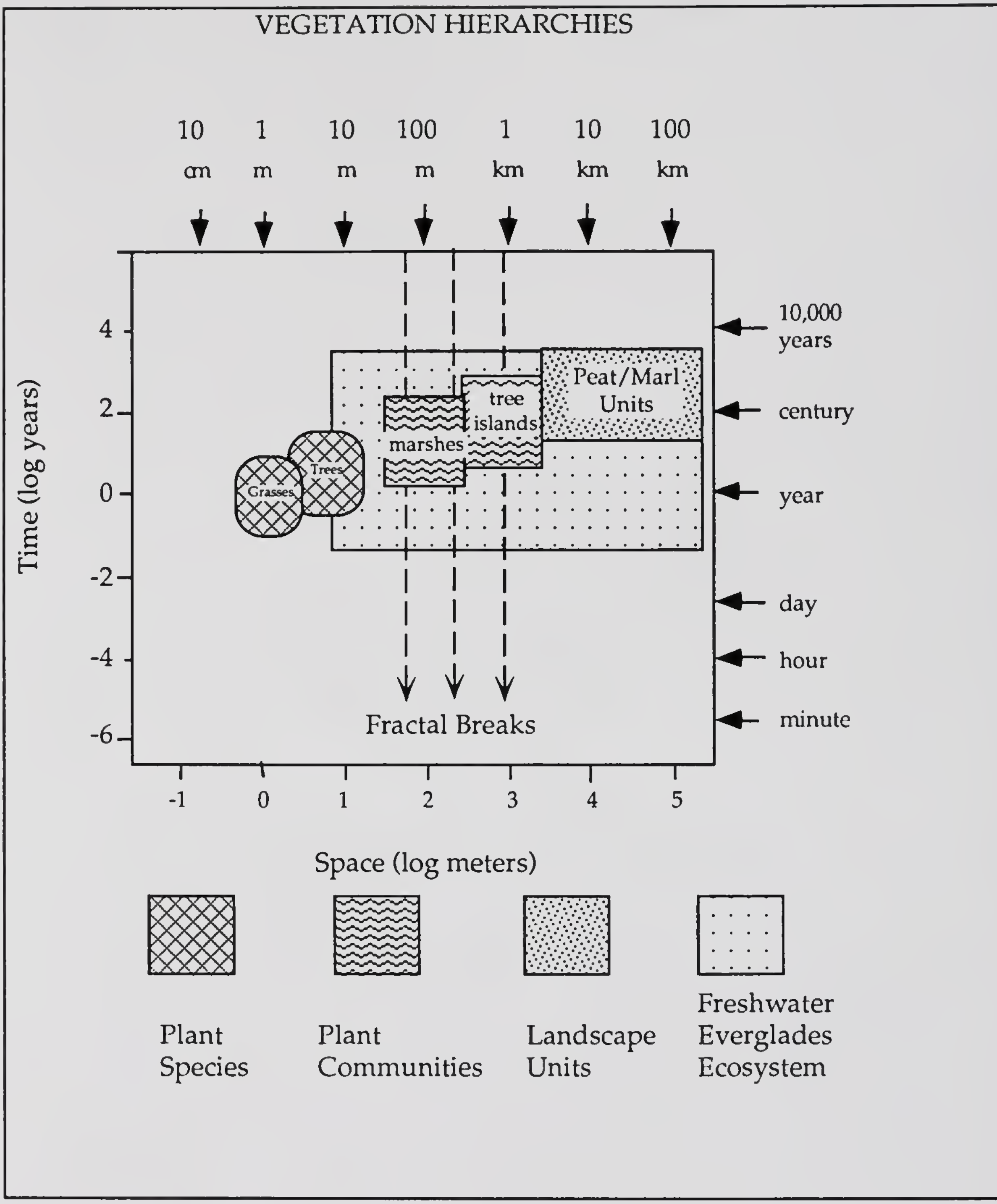


Figure 95. Vegetation hierarchies in the Everglades ecosystem, showing scales of plant species, communities, landscape units and the Everglades ecosystem as defined by breaks in the fractal dimension.

although the reasons are unclear. Temporal patterns in the stage, flow reflect dominant frequencies in the interplay between the faster dynamics of the atmopshere, the intermediate speeds of the surface water (stage and flow) and the longer term variations in vegetation, climate and sea level.

These analyses support the theory that ecosystems are structured around a few keystone variables of mixed spatial and temporal dimensions. Dramatic discontinuites patterns appear as a result of the interactions within and between hierarchical levels in space and time which in turn create non-linearities in system dynamics. The emerging viewpoint of ecosystem structure and dynamics will hopefully provide a basis for understanding and hence meeting multiple management objectives in this unique ecosystem. Failing to invalidate the cross-scale hypothesis, provides an alternative paradigm upon which ecosystem understanding and management are based. A comparison and discussion of system understanding and management based upon alternative concepts are the subjects of the next and final chapter.

CHAPTER 5.
AN END AND A BEGINNING

The only things that can be universal, in a sense, are scaling things
-Mitchell Feigenbaum

This chapter is both an end and a beginning. The dissertation ends with a summary of the first four chapters, followed by a comparison of two approaches to understanding ecosytem dynamics. The final section of the chapter casts the conclusions of this work in context of ongoing management issues of ecosystem restoration and, perhaps, a beginning of new understanding.

A Summary

The first chapter recounted the history of the Everglades, both natural and recent human experiences. The human response to environmental "crises" over the last century has determined the water management infrastructure and policies that are in place today (Light et al. In Prep) and dramatically transformed the landscape (Davis et al. In Press, Gunderson and Loftus In Press). During this century, crises have largely been the result of recurring natural phenomena, characteristic of variation in broader spatial-temporal region, but perceived as local surprises. The floods of the early 1900's coupled with the desire to cultivate the seemingly rich muck soils, prompted the creation of the Everglades Drainage District. The drainage district initiated construction of four major canals, the Miami, New River, Hillsboro and Palm Beach, that are central to the water management infrastructure today. A hurricane in 1928 caused massive human mortality, as a result of the breakage of an earthen dam around Lake Okeechobee. The response witnessed the involvement of the federal government who funded, constructed and continues to maintain the Hoover Dike around the Lake. The next crises occurred in 1947, an extremely wet year, and precipitated (sic) the Central and Southern Florida Flood Control Project. The Central and Southern Florida Flood Control Project was a joint federal and state effort that created much of the system of levees, canals and structures that are in use today. Another crises was the drought of the early 1960's, that coincided with the final phases of construction of the C&S F Project. The drought prompted the studies and political action that resulted in PL 91-282 that guaranteed Everglades National Park a piece of the water resources in the system. A drought in 1971, coincident with a growing environmental awareness, resulted in the transformation of the Flood Control District to a Water Management District. A wet year in 1983, led to a request from the Park Service seeking relief from release of flood water into the park, and for a revision in water delivery policy. The resulting adaptation was the development of the rainfall formula for calculating water deliveries to the park. This condensed history of water management in the Everglades obviously does not do justice to a rich, complex set of interacting events and people that have experienced and influenced the time course of management. However, it does support the idea that the response to crises and subsequent adaptations are strongly correlated to the way in ecosystem dynamics are perceived and understood.

Alternative concepts used to understand ecosystem structure and function were the subjects of the second chapter. Existing concepts attempt to explain the dynamics of complex systems, by either statistical approaches, mathematical representation of the interaction of variables, or hierarchical partitioning of variable interactions. A new and emerging theory provides a basis for exploring interactions across a range of spatial and temporal scales. Two hypotheses were posed from these theoretical bases. The first hypothesis was posited that the entire ecosystem, including the Kissimmee, Lake Okeechobee and historic Everglades wetlands contributed flow to Everglades Park. The other hypotheses stated that the cross-scale interaction of variables that influence ecosystem structure and function would be manifest as breaks between regions of similiarity in the spatial features and nested or reasonant frequencies in temporal processes.

A model of the space-time dynamics of the vegetation and hydrology in the Everglades was developed to test the first hypothesis. Vegetation influences on pathways of water movement were linked in the model framework; vegetation structure influenced flow resistence and vegetation type mediated evapotranspiration rates. Hydrologic influences on vegetation succession provided the link to couple these two key ecosystem components. At the scale of the model framework, differences in flow and evaptranspiration parameters among plant communities were averaged out and the vegetation types were relatively stable. Both of these factors contributed to the conclusion that the linkages between vegetation and hydrology did not substantially alter the explanation of hydrodynamics in the system, at the scale chosen for the model. At finer scales, the vegetation and hydrology clearly do interact.

The results indicate that except for extremely dry years, the entire Everglades wetlands contributed flow to Everglades Park. The relationship between flow and upstream area appeared to be "fractal" or self similar. As the upstream area is changed, the flow is changed in a similar amount. The management implications of these results are that since the early 1960's, when the construction of the Central and Southern Florida Flood Control Project was essentially finished, the equivalent contributing areas to flow into Everglades

Park have been the Water Conservation Areas. Under pre-management conditions, the entire basin (and sometimes Lake Okeechobee) contributed to flow into the southern Everglades. The evidence that the southern Everglades received more water and hence had a greater upstream area agrees with a growing body of evidence presented by Smith (1989), Powell (1989), and Walters et al. (1992).

Nine data sets representing key structures and processes in Everglades ecosystem were analyzed for cross-scale patterns using a variety of methods. The analysis failed to invalidate the proposed hypothesis. The findings were derived from a comparison of results using a variety of methods. Spatial patterns exhibit scale regions of self-similarity separated by distinct breaks. The soil surface topography appears to vary at two distinct spatial scales, the broad scale is apparently a result of geologic features and the small scale appear related to the processes or organic soil accretion and removal. Breaks in the size of fires may be related to the approximately decadal time period between large burns. The vegetation patterns exhibit breaks between regions of self-similarity although the reasons are unclear. Temporal patterns in the stage, flow reflect dominant frequencies in the interplay between the faster dynamics of the atmopshere, the intermediate speeds of the surface water (stage and flow) and the longer term variations in vegetation, climate and sea level. These analyses support the theory that ecosystems are structured around a few keystone variables of mixed spatial and temporal dimensions. Dramatic discontinuites patterns appear as a result of the interactions within and between hierarchical levels in space and time which in turn create non-linearities in system dynamics. The next section compares these cross-scale conclusions with the results of the modeling work, to provide a contrast between alternative ways of understanding the complex interactions in the "River of Grass".

Understanding Ecosystem Dynamics through Alternative Paradigms.

The surface water conditions, stage and flow, in the southern Everglades are linked to a variety of processes outside the boundaries of the Park, including rainfall and the complex factors that influence overland runoff. Some of these processes operate at numerous scales in space and time, parts of which can be captured within the framework of a model. Processes operating at scale regions outside the model cannot always be scaled into the model. The fundamental issues of scaling both empower and limit the predictability of models. Fortunately, the rules of hydrologic and atmospheric processes can be scaled to apply over a wide range of spatial and temporal domains. Part of this is due to the relatively long history that has gone into our understanding of hydrology (Viessman et al. 1989), and perhaps part is due to the nature of the medium. Unfortunately, the scaling involved with the biologic components of an ecosystem is less well understood. Scaling processes of complex components into a model is contingent upon assumptions of scale variance. In other words, the nature of the relationships can be aggregated or decomposed in a predictable manner. These scaling issues limit the ability to link hydrologic conditions in the Park with processes going on at different scale regimes. As a probe into these scaling issues, the influences of processes interacting across spatial and temporal domains on rainfall patterns are discussed next.

Rainfall over the park is influenced by processes that cover large spatial and temporal domains. The processes cover spatial scales ranging from the peninsula of Florida, to the planet. The meso-scale, land-sea breeze interaction generates rain from convective thunderstorms and has a temporal cycle of about one year. Planetary cycles, such as the southern ocean oscillation (El Niño) appears to influence rainfall at approximately 11 year periods. Less obvious linkages, such as the 'rain machine' or other hypotheses that purport feedback dynamics between land use conversion influences and rainfall, may exist, but are still largely speculative. The net result of all of these interacting processes can be captured in the model by the use of historical rainfall data that includes these periods of variation. The model does indicate that the temporal variation in the rainfall heavily influences the surface water conditions, but in a manner that may be much more subtle and complex than can be captured with our existing tools.

Although the dominant input to the Everglades system is rainfall, difficulties arise in correlations between rain and other hydrologic variables (stage and flow) perhaps because cross-scale interactions may somehow transform the relationship. Analysis of rainfall, stage and flow patterns indicate different temporal regimes. The rainfall patterns emerge at time scales of months and years; stage and flow at multiple year cycles. The implications are that the combination of little topography, vegetation influences on flow and evapotranspiration transform the "faster" rainfall inputs in such a way that "slower" stage and flow patterns emerge. This has been noted before; MacVicar (1985) in developing a statistical regression between flow at the Tamiami flowsection and net rainfall found that the rainfall term was statistically insignificant. The correlation of stage and flow is possible, because the two variables operate within similar temporal domains, wheras rainfall does not. The net result is that patterns of flow and stage emerge at distinct scale regimes. The model does such a transformation, in that the historic surface water patterns can be recreated by using the historic input data on rainfall.

Other factors at different spatial and temporal scales complicate the relationship between rainfall and flow to the Park prior to human intervention. The entire Everglades area upstream of the park, during extremely high water conditions, appears to have contributed water to the Park. During drier times, less of the system contributed water. These relationships are modified by the vegetation, although the influence appear to be related to the scale of investigation. At scales below the model grid size, the flow and evapotranspiration relationships appear to be mediated by the vegetation. At the model scale (grain of 4 km) and larger, these finer grain influences of vegetation appear less important. These are two examples of scaling issues. The relationship between upstream area and flow appears scale invariant (at least up to the Lake), while the vegetation mediation dynamics are not. The cross-scale analyses indicate the property of breaks in vegetation and topographic structure across scale-ranges. The applied techniques of aggregation don't appear to capture subtle translations across scale regimes, and hence inevitably lead to surprises in system behavior.

Most of the preceeding discussion has dealt with attempting to understand the dynamics of the relatively "natural" parts of the system. However, the system however has dramatically changed due to human intervention. Water delivered to the park is routed through canals. Water upstream of the park is diverted to urban areas to support millions of residents. Agricultural inputs are affecting water quality, in a way that causes dramatic changes in the ecosystem. Alien plant populations are expanding. All of these factors suggest that the current notion of a natural Everglades landscape may be in for a dramatic transformation. The last section of this chapter examines these possibilities in context of ecosystem restoration.

Prognosis for System Restoration

The restoration of the Everglades has been underway for over half a century. The initial survey of the biotic resources of Everglades National Park was done in the 1930's (Beard 1938). The conclusions at the time were that the park was not in good shape, but that perhaps a few decades of wise management would restore this unique system to it's previous splendor for the enjoyment of future generations. Three generations later, the restoration has not materialized. Many fine attempts have occurred at approximately decadal intervals. The floods of 1947 coincided with the formation of the national park, but spawned events that would create the massive system of levees and canals. The 1960's witnessed the park being cut-off from upstream flow, that was diverted to the coast to deal with salt-water intrusion problems. The pleas from the park were heard, and Congress assured the park it's piece of the water pie. This policy was conceptually transformed from an assurance of a minimum percentage to a consistent minimum amount. Voices such as Art Marshall and H.T. Odum, calling for ecosystem perspectives of problems and solutions, were largely ignored during the 1970's. The 1980's witnessed an onslaught of water supply, eutrophication, and flood control issues, as latent pathologies in the system design and operation became manifest. Positive signs of restoration began with the first adaptive policies in the rainfall delivery formula (Light et al. 1989). Other events such as the 1989 symposium (Davis and Ogden In Prep) provided the focus for new understandings and directions for management of which this work is an offshoot.

The state-of-the-art hydrologic models provide perhaps the best available tool for the adaptive probes into new techniques of water delivery to the park. The models provide partial truths that can combine rules across two to three orders of magnitude along space or time domains. The models also provide a framework for combining process that transform variables in ways that statistical approaches such as the rainfall formula cannot. In any case, the models should always be subjected to critical invalidation, for adaptation to changing or evolving conditions in understanding and management institutions.

An understanding appears to be emerging that ecosystems are organized and structured through a few keystone processes operating at distinct spatial and temporal scales. Data from the Everglades indicates that such patterns exist in the system. Understanding not only the obvious, but also the subtle ways in which the complex of processes affecting flow interact across space and time are necessary for system restoration. The cross-scale dimensions of the hydrologic processes, and the other portions of the Everglades ecosystem are just beginning to be unraveled through a combination of new methodologies and modeling approaches. The presence of cross-scale interactions both in natural and human systems, as documented in this work, will hopefully provide a foundation, and hence a beginning, for positive efforts towards true restoration of this unique, treasured ecosystem.

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BIOGRAPHICAL SKETCH

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I certify that I have read this study and that in my opinion it conforms to acceptable standards of scholarly presentation and is fully adequate, in scope and quality, as a dissertation for the degree of Doctor of Philosophy.

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