8. The Everglades

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Introduction

The Everglades is one of the more extensive freshwater wetland ecosystems in the world. Although it is not a river in the classic sense, there is heuristic value in using a river paradigm as a way of understanding the Everglades, especially those intriguing aspects of its ecology that may illuminate the workings of other slow-flowing systems. The hydrology of the Everglades, even called the "River of Grass" by Douglas in 1947, is dominated by rainfall and by the resulting downgradient flow of surface water, just as in any flowing water system. Variation in this surface water flow, and therefore variation in water depth and hydroperiod, has shaped the physical form of the Everglades basin and dominates the ecological relationships of plant and animal populations that occur there. Flowing water therefore affects the Everglades in ways that are homologous to those of more classic lotic ecosystems. The hydraulic control exercised by water movement is militated by its slow velocity and low load-carrying capacity.

The natural Everglades drainage system is rather complicated, encompassing more than 77,000 km^2 of uplands, wetlands, rivers, and lakes. It is composed of three quite distinct sub-basins: the Kissimmee River Valley, Lake Okeechobee, and the Everglades, covering several physiographic provinces (Figures. 8.1, 8.2, and 8.3). Because of the distinctiveness of these units, the Everglades may be thought of as heading either at the Kissimmee chain of lakes or at the south shore of Lake Okeechobee. There are good arguments for, and utility in, using either interpretation.

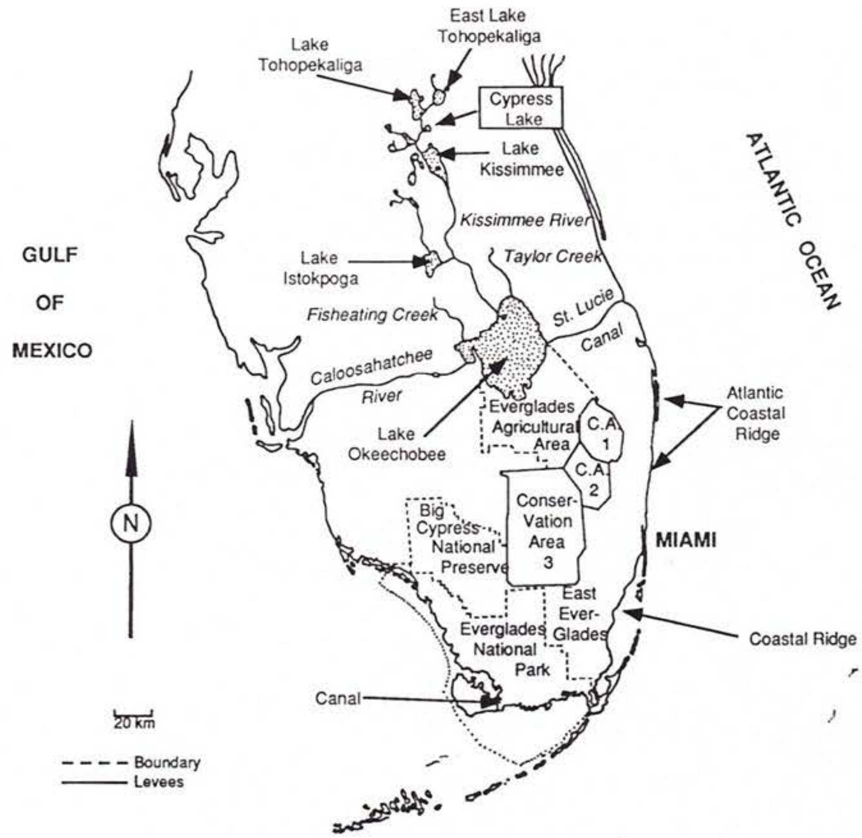

Figure 8.1. Map of south Florida showing the Everglades system, including the Kissimmee River, Lake Okeechobee, and the Everglades.

The Everglades itself is a rather recent feature-a fact to be appreciated in understanding its history of change. It formed about 5000 years ago as sea level rise slowed sufficiently to allow the establishment of a coastwise levee, which formed under mangrove swamps, impounding an inland freshwater wetland. Throughout its existence, the Everglades has continually changed in response to peat and marl deposition, plant succession, animal invasions, long-term rainfall cycles and patterns, fire frequency and severity, and sea level rises. Through natural trends and anthropogenous causes, the present Everglades drainage system is highly altered from that occurring 100 to 150 years ago, when documentation of its appearance is first available. Flood control, reclamation, and water management have retarded, redirected, and enhanced Everglades water flow for more than a century. The hydrological patterns now extant in nearly all parts of the greater Everglades basin differ substantially, in most cases fundamentally, from those that occurred previously.

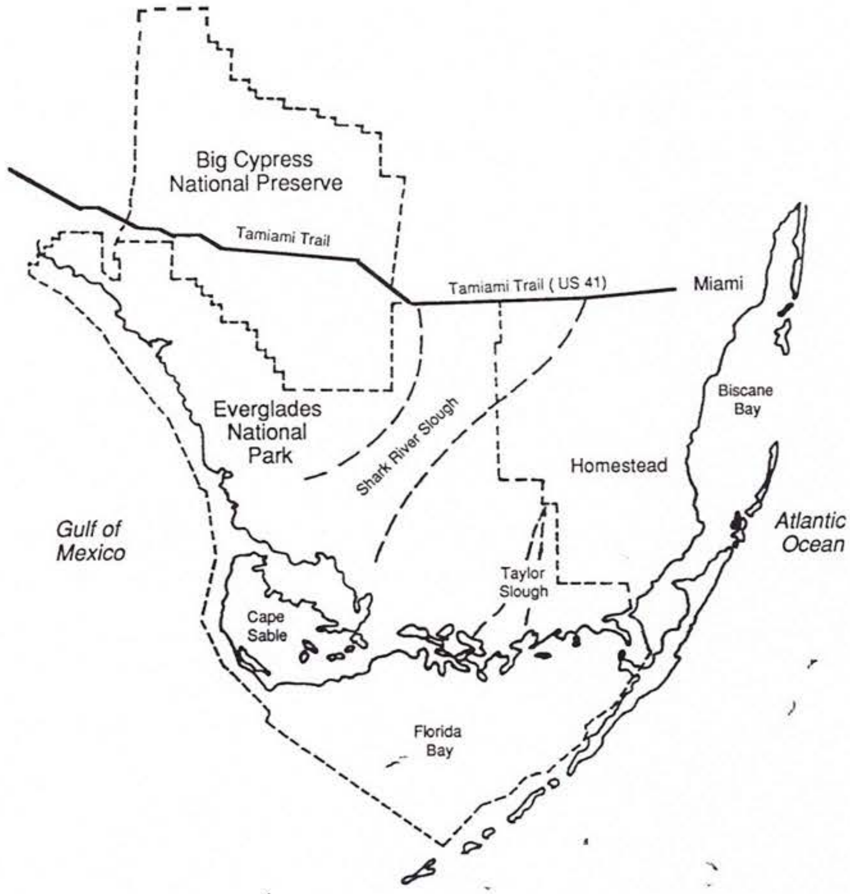

Figure 8.2. Map showing the features of the southern Everglades, Florida.

Although the three sub-basins can still interact hydrologically, there remains no resemblance of a unitary hydrologic system. Nonetheless, much remains of ecological and economic value in the remnant Everglades system. The fundamental questions we can ask about Everglades ecology are: How does it work? and How can it be managed best to conserve its ecological function and economic value? These questions are so closely tied as to be inextricable. The question of management requires an understanding of ecology and encompasses fundamental considerations regarding the need and efficacy of managing complex wetlands. Neither an understanding of ecology of the Everglades nor its need for management can be ignored if the Everglades is to persist.

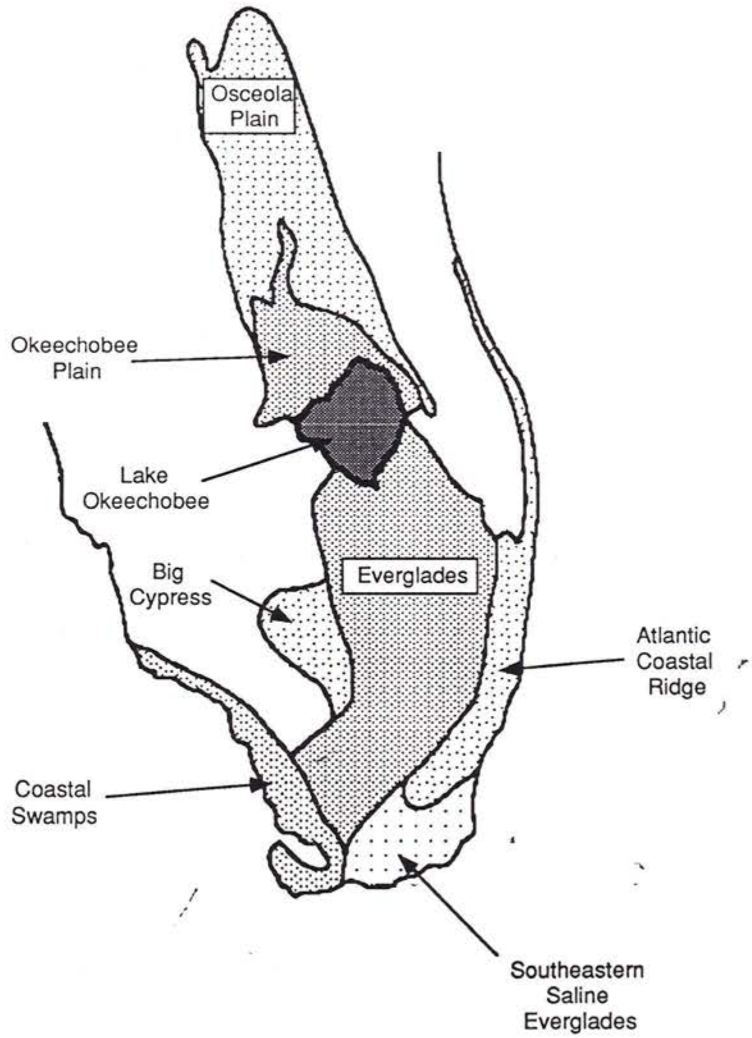

Figure 8.3. Physiographic provinces of the greater Everglades basin (redrawn from Fernald and Patton, 1984).

Natural Watershed Characteristics

Hydrological Cycle

Although, at present, the three subunits of the Everglades watershed function with a great degree of hydrological independence, the controlled and directed movement of nutrient-laden water among sub-basins can inflict substantial downstream impacts. To understand the current system, it is worthwhile to attempt to infer, from the limited evidence available, the hydrological characteristics of the natural intact watershed (Parker et al., 1955; Leach et al., 1972; Klein et al., 1975; Kushlan, 1989a, 1990).

Rainfall over the Everglades watershed is seasonal, as is the typical subtropical pattern. Throughout the system, rain falls primarily from May through October, these six months receiving 50% to 70% of the annual total. Rainfall is particularly variable at the beginning and end of the dry season, and it is variable from year to year. Winter rainfall derives from frontal systems and ocean effects; summer rainfall derives from convective thunderstorms. Hurricanes can deposit many cm of rain within a few days. The seasonality of rainfall results in marked variation in flow, and for periods of several months little or no flow occurs.

Over the basin, rainfall is greatest in the Everglades owing to a higher incidence of convective thunderstorms. Rainfall is least over Lake Okeechobee, which often remains cloud-free while the rest of the state is cloud-bound. Rainfall becomes less seasonal northward, because of the greater effect of winter storms and a drier summer.

Appreciating the inherent limitation in naturally available through-flow is essential to understanding the flow dynamics of the system. Although downgradient movement of water was the norm throughout the Everglades system, such movement was slow, had limited load capacity, and required repeated replenishment en route to maintain its hydraulic head. Rainfall has averaged about 127 cm annually, but total runoff accounts for only 19 cm of the rain that falls over the entire basin during the year (Parker et al., 1955). Thus the total runoff available for downstream movement is considerably less than total rainfall.

Only 12 cm of storage remains through the usual dry season, mostly in the lakes and rivers. Thus, there is limited storage and nearly no carry-over of water from one annual hydrologic cycle to the next. Ambient conditions are almost entirely the result of seasonal variation in rainfall during that hydrologic year.

Most water in southern Florida is returned to the atmosphere via evaporation and transpiration. Unfortunately, this variable is the least understood component of the hydrological cycle. The undoubtedly large atmospheric output from the basin is the result of seasonally high temperatures, persistent sea breezes across the relatively narrow peninsula, slow flow rates and long residency time of surface water, and high surface to volume ratio of water features.

Water Quality

The water chemistry of the Everglades-Kissimmee system varies geographically, and annually. All parts of the system are highly buffered, with pH being cicumneutral to slightly basic and mineralized owing to contact with periphytic marl, limestone, calcareous sand, or fossil deposits (in Lake Okeechobee). As a result the dominant ions are calcium and bicarbonate. Dissolved solids and conductivity are high; oxygen is naturally low with stratification developing in deep open waters and within dense emergent vegetation, where water is often deoxygenated.

The water quality of Lake Okeechobee has been well studied. A significant loading of nutrients comes from rainfall, which can match concentrations in the lake itself. Joyner (1975) found that the Kissimmee River contributed about 39% of the total nitrogen and 36% of the total phosphorus to the lake.

Nutrient concentrations in the water of the core Everglades are naturally low (Waller, 1975, Waller and Earle, 1975). Phosphorus is the limiting nutrient, occurring in concentrations below 0.05 mg/l. Inorganic nitrogen is generally less than 0.1 mg/l. Waller (1975) found that 78% of the nitrogen and 90% of the phosphorus entering the northern Everglades were from rainfall. He also found that 74% and 96%, respectively, were retained in the marsh. This retention is caused by tight cycling within the plants and sediment (Steward and Ornes, 1975)

Kissimmee River

The Kissimmee River is the primary riverine subsystem of the greater Everglades Basin (Pesnell and Brown, 1977; Pierce et al., 1982; Pruitt and Gatewood, 1976; Palmer, 1986). Historically, the Kissimmee River headed at about 580 m mean sea level (MSL) and proceeded downgradient to Lake Okeechobee. Stretching 96 km from Lake Kissimmee, the river historically drained about 7000 km^2 of the Osceola and Okeechobee plains (Figure. 8.3) The river received input from headwater lakes, contiguous wetlands, surface flow off the surrounding Kissimmee prairie, and groundwater flow through the surficial aquifer. Wetlands comprised about 19% of the natural watershed.

The original Kissimmee River followed a highly meandering course over 160 km. Averaging only 1.2 m deep, the river is estimated to have flowed an average of only 3.5 months per year, but flow periods were highly variable (Montalbano et al., 1979). During the dry season, falling water tables further decreased the extent and depth of surface water in the river and nearby wetlands. During extremely wet periods, the limited flow potential caused water to impound covering the floodplain, including that north of Lake Kissimmee. It has been estimated that 2400 km^2 were flooded in 1947. Under these conditions, water level in the river rose by as much as 3.7 m over dry season levels, well beyond the usual seasonal variation of about 1 m (Perrin et al., 1982).

Lake Okeechobee

Lake Okeechobee is the second largest freshwater lake entirely within the United States, historically covering 1700 to 1900 km^2, depending on stage. It was shallow, water depth ranging from about 0.5 m below sea level at its deepest point up to 5 to 5.2 m MSL in high water. Its tributary area was about 10,900 km^2, involving input from the Kissimmee River, Taylor Creek, Fisheating Creek, and adjacent uplands, and by surface flow from adjacent wetlands (Figure.8.1).

Prior to the Kissimmee River's canalization, upstream drainage modifications appeared to have left hydrological conditions in the basin relatively unaffected, permitting Parker et al. to study the lake in 1955. They found that, during the precanal era, outflow from the Kissimmee River Basin was about 18 cm of the basin's rainfall, and accounted for 65% of the total inflow into Lake Okeechobee. Annual inflow depended on rainfall and on moisture conditions at the beginning of the wet season. However, the previous year's rainfall was unrelated to conditions in the subsequent wet season.

In situ rainfall, averaging about 120 cm, was also an important input to the lake's water budget. Parker et al. (1955) concluded that seepage into the lake was limited, although Brooks (1984) disagreed. Within the lake, evaporative losses were estimated to be more than 140 cm (Joyner, 1975).

Parker et al. (1955) stated that the lake itself made no contribution to water supplies farther south because the outflow was the same as the inflow from the Kissimmee River basin. The throughflow of surface water input into the lake accounted for all of the water moving downgradient out of the lake. The discharge that did occur was intermittent. In lower water, outflow was restricted by a natural levee formed by waterborne sediments. This 5 km wide dam, which supported a dense swamp forest, was breached by several short, narrow streams, 3 m deep, which ran within banks about 2/3 m above the water level (Will, 1956). Water apparently did not seep under the natural levee, and it is estimated that water overflowed when stage reached an elevation of about 4.4 m MSL.

Everglades

The Everglades proper began south of Lake Okeechobee stretching for 100 km down the central core of southern Florida, covering a drainage area of 11,500 km^2 (Figures. 8.1 and 8.2). The basin occupied an elongated trough in the underlying limestone covered by endogenous peat varying in depths from 6 m in the north to a few cm in the south (Figure 8.3). The marsh bottom had an overall gradient of 3 cm/km, or 0.3%.

The primary source of water in the Everglades was rainfall, averaging 130 cm per year. Surface inflows were restricted to the wet season, principally from Lake Okeechobee to the north and from the Big Cypress Swamp to the west. As suggested above, the extent to which flow from the lake actually contributed to the water budget of the Everglades remains unclear because only seven years of data exist prior to the construction of the southern confining dike (Parker et al., 1955). Although early explorers periodically reported high water conditions, in the period of record, the lake overflowed for only a few months of the year.

Surface water moved into the Everglades from higher ground to the west, including the Big Cypress Swamp. To the east the Everglades abutted the Atlantic Coastal Ridge, a limestone and sand sliver of higher ground adjacent to the coast (Figure. 8.3). Rather than serving as an upgradient water source for the Everglades, water movement was from the interior, flowing from the Everglades through and under the ridge into the coastal bays.

The slight land slope would result in minimal water flow under the best of circumstances. Varying naturally from zero to a few hundred m per day, flows depended on the interaction of current rainfall near a particular site, local slope, the head created by rainfall and runoff farther up-gradient, and impediments to water movement, particularly by the luxurious plant growth including emergent and floating-leaf plants, and thick periphyton mats. Historically during wet periods, surface flows would have been highest immediately south of Lake Okeechobee and near the coast, where gradients increased rapidly. There, surface flow coalesced into short streams cutting through the coastal ridge on the east and the mangrove swamps on the south.

Because of the slowness of movement and baffling effect of plants, load-carrying capacity was almost nonexistent. Dissolved nutrients, being in limited supply, were removed quickly by algae and vascular plants, and sequestered in plant biomass and detritus. Therefore, dissolved materials also were conserved within the marsh and were not transported long distances.

Loss of surface water through infiltration varied geographically. The peat substrate over much of the Everglades formed a barrier to the infiltration. In the southern reaches, surface water communicated directly with the porous Biscayne Aquifer, especially along the periphery of the Everglades. It was by this means that water passed out to sea under and through the coastal ridge, in some places forming freshwater springs offshore.

In the same way that the primary source of water in the Everglades was atmospheric, so was its output. In general, throughout the system, water moved so slowly downgradient in the wet season and evapotranspiration was so high (generally 80-90% of rainfall; Klein et al., 1975) that nearly all water was lost to the atmosphere before moving far downstream. According to Parker (1984), "It is doubtful that many drops of rain from overflow of Lake Okeechobee's southern shore could ever have survived the high evapotranspiration losses during the snailpaced flow through the Everglades." Water depths were greatest immediately south of the lake. Over the rest of the Everglades, depths were shallow, generally no more than a m or 1.5 m in the wettest seasons. Farther south, the Everglades flow-way became restricted into a trough called Shark River Slough. From just north of the present Tamiami Trail, flows moved through the slough southwestward toward Cape Sable, entering short coastal rivers before moving into the Gulf of Mexico. In extreme high water periods, water also flowed southeastward through Taylor Slough, but the extent of this flow is not yet determined. Wet season flows through west coast rivers into the Gulf of Mexico were undoubtedly substantial in the wet season, but ceased in the drying period when saline waters moved upstream.

In the drying season, surface water flows ceased and water depths decreased. Depending on elevation, hydroperiod in Everglades marshes was 5 to 10 months. Thus, in the dry season, water levels descended below the ground surface, although in most years the peat remained moist. Fires were usual at the end of the dry season and in the summer lightning season (Wade et al., 1980), as is evidenced by the charcoal inclusions common in the Everglades soil. It is likely that human-caused fires were a feature of the Everglades throughout its existence.

Biological Functioning

Studies have repeatedly demonstrated that the ecological functioning of the greater Everglades system is determined and driven by fluctuations in its hydrology (Kahl, 1964; McPherson, 1973; Kushlan, 1987, 1989 a,b; Perrin et al., 1982; Pesnell and Brown, 1977). Because various aspects of the hydrological characteristics of the system vary together, the best approach to understanding the system is to examine the seasonal patterns of hydrological fluctuation and their biological correlates, including vegetation and animal populations.

Hydrological Variables

Although most fundamentally, the Everglades system is rainfall driven, rainfall effects are dampened by the slow water movement and high evapotranspiration rates. Water depth, water flow, rate of change in water depth, and hydroperiod are important interacting hydrological variables that are known to affect the biological functioning of the Everglades.

Water depth is produced by an interaction of the hydraulic head of upstream flow and *in situ* rainfall. Water depth varies from 1.5 m or less to less than 0, when water retreats below ground in the dry season. Thus water depth and the extent of drying are important hydrological variables. When rain falls on site, it creates a transient mound of surface water that soon is dispersed to all sides, especially downstream. Without replenishment by local rainfall, downstream flow and evaporation result in the recession of surface water. The rate of this recession is also an important variable, especially with respect to the response of animal populations to the seasonal changes in surface water depth. Hydroperiod, the amount of time the marsh is wet, has been shown to be a primary correlate of plant occurrence and plant community development.

Vegetation

Plant distribution and therefore plant associations in the greater Everglades system vary along gradients of water depth and hydroperiod, and are also affected by the history of fire, disturbance, and colonization events (Loveless, 1959; McPherson, 1973; Pruitt and Gatewood, 1976; Pesnell and Brown, 1977; Milleson et al., 1980; Pierce et al., 1982; Kushlan, 1990). Given these multiple influences, marshes in south Florida can develop under a broad range of hydroperiods ranging from 50 to 365 days. The plant communities occupying these sites include open water, submersed marsh, water lily marsh, cattail marsh, flag marsh, sawgrass marsh, wet prairie, and swamps such as cypress and bay swamps (Kushlan, 1990)

Rooted aquatic vegetation can be lacking on permanently flooded sites, such as in canals, river channels, Lake Okeechobee, or the deep portions of reservoir pools. These sites usually have water exceeding one m deep and experience relatively high water flow and turbidities. The high turbidity of Lake Okeechobee (Secchi disk readings are often less than 0.3 m) has limited the growth of rooted submersed plants in the central portion of the lake.

In shallower or less turbid but still long hydroperiod conditions, submersed plants dominate. Along the littoral of Lake Okeechobee, these are primarily pondweed (*Potamageton*). In the Everglades, water hyssop (*Bacopa*), chara (*Chara*), and bladderwort (*Utricularia*) are common submersed plants. In slightly shallower water, floating leaf plants predominate, especially water lilies (*Nelumbo*, *Nuphar*, *Nymphaea*). Water lily marshes occur especially along the shallows of Lake Okeechobee, and in the central core of the Everglades. Both submersed stands and water lily marsh are dry for only short periods, and in some years may hold standing water year-round.

Cattail marsh is found on deep soil, especially in conjunction with substrate disturbance, deep water, lack of fire, and high nutrient loads. Although not naturally dominant over substantial areas in the Everglades, cattail can form monospecific stands where appropriate conditions coincide. It appears to be able to out-compete sawgrass owing to its faster growth rate and ability to sequester nutrients. Cattails currently appear to be encroaching on sawgrass marsh near water inflow structures, along canals, following soil disturbance, and near coastal headwaters.

Flag marshes are named after some of the characteristic plants found there, such as arrowhead (*Sagitaria*) and pickerelweed (*Pontedaria*). This marsh occurs in water 0.3 to 1.0 m deep, shallower than submersed marshes. Hydroperiod is around 200 flood days per year. Depending on the soil, flag marshes may be dominated by pickerelweed (on peat) or maidencane (*Panicum*)(on sand). These marshes require seasonal drying; where flooding is prolonged, plants uproot and die. Pickerelweed persists and tends to become dominant under the longer hydroperiods. Beakrush (*Rhyncospora*), on the other hand, is intolerant of prolonged flooding and has been eliminated from parts of the northern Everglades under conditions of long-term inundation.

Sawgrass marsh (*Cladium*) is the most widespread plant association in the Everglades, once covering more than 800,000 ha. Density of the marsh depends on soil depth, hydroperiod, and history. Culm density is greatest on deep peat soil under longer hydroperiods. As hydroperiods decrease, the association becomes more complex, including increasing numbers of swamp trees.

Swamp vegetation develops on slightly higher, yet intermittently flooded, ground. When isolated stands are surrounded by different vegetation, they are often called tree islands. Cypress (*Taxodium*) and pond apple (*Annona*) forests lined the southern edge of Lake Okeechobee. Tree islands in the Everglades are generally bay (*Persea, Ilex, Cephalanthus*) or willow (*Salix*) swamps.

Where surface water flows occur, vegetation stands tend to become elongated in the direction of water movement, creating a topography of alternating swales and ridges. Slightly deeper "sloughs" in the swales alternate with slightly higher sawgrass "strands" on the ridges. In the Everglades, most strands are dominated by sawgrass. The higher ground at the head is colonized by swamp trees. Everglades strands characteristically assume a hydrodynamically determined tear-drop shape in response to water movement. In areas where historic water flow was less defined, such as in what is now Conservation Area I, vegetation stands and swamp tree islands are shaped and dispersed more irregularly. These were formed by plant colonization of floating peat.

Wet prairie has the shortest hydroperiod of Everglades marshes, 50 to 150 days per year. The hydroperiod is too short for peat production, as is characteristic of the other plant communities described above. Wet prairies are variable in composition depending on vagaries of hydroperiod, soil, and fire history. Species found there are tolerant of flooding, periodic drying, and also fire. The sparse distribution of the marsh vegetation typically permits the development of an encrustation of periphyton over the bottom and standing plant stems.

Structural changes occur in some of these plant communities as water levels recede in the dry season. The aboveground stems and leaves of emergent herbaceous species die back. Exposure of the soil permits the germination of seeds. Fire risks increase. Nearly all marsh communities can carry fire without long-term effects (Van Arman and Goodrick, 1979; Wade et al., 1980), although burning soil can alter water depth characteristics of a site, leading to vegetation changes. As noted above, it is likely that natural and human-caused fire has been a feature of the Everglades since its development.

Flooding also can bring about community changes. Because the positioning of the various plant communities is related to a gradient of water depth, fire history, hydrology, and soil type, periods of extended high water levels can cause plant communities to change markedly, and in relatively short periods of time. As noted above, some species are eliminated under continually flooded conditions, although others, such as sawgrass, pickerelweed, and willow, are persistent once established.

Animal Populations

Animal populations are also dependent on hydrological fluctuations of the Everglades during its annual cycle; and, in fact, the species that occur there are those that are particularly adapted to surviving or even taking advantage of the difficult conditions imposed by fluctuating water levels. These adaptations and accommodations have been delineated in a series of studies (Loveless, 1959; Kahl, 1964; Sykes, 1983; Kushlan, 1974, 1975, 1976a,b, 1979, 1986, 1989a,b, 1990; Kushlan and Frohring, 1986; Kushlan and Bass, 1983; Kushlan and Jacobsen, 1990; Kushlan et al., 1975; Perrin et al., 1982; Sykes, 1983; Johnson and Montalbano, 1984; Frohring and Kushlan, in preparation).

For example, the central links in the Everglades food chain are the fish and macroinvertebrates. Their populations depend entirely on the hydrological cycle (Kushlan, 1976a). During the drying season, as water levels decrease and the marshes dry, many individuals become concentrated in the remaining pools. There, they undergo population reductions through predation or catastrophic mortality. Under appropriate timing and extent of drying, they can become prey for several groups of predators, especially wading birds whose nesting season is timed to coincide with the high availability of energy in remnant pools of water (Kushlan, 1976b). Otherwise, fish kills can occur. In many instances the pools dry out completely. This annual mortality event determines the character of the remnant fish community present at the beginning of the next wet season. If water levels are stabilized by excessive dry season discharge, marshes may not dry, and fish communities may be altered as a result.

In years of normally fluctuating conditions, the Everglades aquatic community is populated by several small species of fishes and invertebrates. However, without a dry season, the community is dominated by the larger predatory fishes, populations of which would be reduced in most years. The small fishes that are most numerous in the Everglades under normal conditions have a rapid life cycle and can mature within a few months, repopulating the marsh rapidly during the wet season. Thus, the character of the fish community is directly related to the antecedent pattern of seasonal water fluctuation.

Similarly, the annual hydrological fluctuation affects other animal populations. Deer (*Odocoilus virginianus*) fawn in the dry season and are adversely affected by continuously high water levels. Wading birds, particularly the wood stork (*Mycteria americana*) and herons, depend on particular conditions caused by falling water levels for successful nesting. Wood storks nest successfully during years when water levels fall in the winter. Frohring and Kushlan (in preparation) have demonstrated that the nesting success of several species of herons is dependent on high drying rates that create dense concentrations of certain sizes and types of fishes. These are made available in the high concentrations necessary for nesting by falling water levels during the spring.

The nesting success of alligators (*Alligator mississippiensis*) is also dependent on specific patterns of water level fluctuations, in this case during the wet season. The alligator nests as water levels are rising in the summer, and its eggs are susceptible to flooding. Kushlan and Jacobsen (1990) demonstrated that the amount of egg mortality depends on the height of water during the nest building period and the following summer. It appears, in fact, that successful nesting in part depends on a predictable rise in water level during the nesting season from the point where nesting begins.

Other species, such as the snail kite (*Rostrhamus sociabilis*), depend on deep water, where its food, the apple snail (*Pomacea paludosa*), can survive the drying season (Sykes, 1983, Kushlan, 1975). Under natural conditions, the nomadic kite was able to move around the system finding localized patches of flooded wetlands that supported snails in any particular year.

Thus, many of the characteristic animal populations of the Everglades depend on water depths and the rates of water level change over the annual water cycle. What is particularly intriguing is that reproductive success and hydrological conditions are so highly correlated. It would appear that animal populations using the Everglades system depend on very specific patterns of water level fluctuations.

Anthropogenous Impacts

Human changes imposed on the Everglades ecosystem have been many and dramatic. Drainage, beginning in the last century, was the first salvo in the war against the "wastelands" of southern Florida, located in the greater Everglades basin. Over the following 50 years, reclamation was joined first by flood control and then water management as objectives for the management, use, and control of the Everglades. Because of the control now exercised on the downgradient flow of surface water in the Everglades system, this war may be considered won. Operation of the current water management system has prevented flooding during hurricanes, conserved water for the dry season, permitted the development of rich agricultural areas, stopped saltwater intrusion into the aquifer, and allowed more than two million people to settle in south Florida. In fact, for these circumscribed objectives, the water management system works extremely well. Unfortunately, along with the water management have come some rather sweeping changes in the ecological function of the remaining Everglades system.

Hydrological Impacts

The first dredges began work in the late 1880s at the Kissimmee lakes, at Lake Okeechobee, and along both coasts (Blake, 1980). These efforts had limited effects on the hydrology of most of the greater Everglades system. Canals dug from 1907 to 1928 by the Everglades Drainage District were effective at Lake Okeechobee and along the coast, leading to saltwater intrusion (which was not corrected until the 1950s). However, after the canals were dug, no further drainage took place for nearly 20 years. The deeper central core of the Everglades never was properly drained, and the drainage effects there remained minimal, especially after the early canals began to fill in as maintenance was neglected. It was the limited drainage capacity of these canals that led to catastrophic floods in the 1940s, which resulted in the reformation of a flood control district, which then began the process of enclosing the virtually undrainable Everglades from reclaimable lands to the north and east. The program was not totally operational until 1967, with additions continuing thereafter. It is important to realize that, although local effects of drainage stretch back 100 years, alteration of the hydrological character of the core Everglades proper is a relatively recent phenomenon.

Kissimmee River

In the Kissimmee floodplain, the historic flow patterns have been totally modified by the installation of the water control structures and their operation. In 1882, canals were cut between Lake Kissimmee and Cypress Lake to the north, and between Lake Tohopekaliga and East Lake Tohopekaliga. Thereafter, the nearby upgradient lakes were connected to the river via Lake Kissimmee. Farther south, Lakes Arbuckle and Istokpoga were connected directly to the river. Although the canals were dug initially for transportation, by 1894 the Kissimmee River was the primary drainage conduit for Central Florida from the Kissimmee chain of lakes south to Lake Okeechobee.

From 1961 to 1971, the Kissimmee River was canalized, reducing its length 90 km, and increasing its width and depth to 60 m and 9 m, respectively. The uncanalized 70 km of river was transmuted into isolated ox-bow lakes. Five dams intercepted flows, creating reservoir pools that stabilized water depths behind them. As much as 80% of the basin's wetlands was lost, and the rest altered. Dams were also used to reduce and control water level fluctuations in the connected lakes.

Water flows in the Kissimmee Canal and its tributaries are now determined primarily by local rainfall and operation of structures at each of the constituent lakes. In the river, water is stepped down across the five pools. Water flow in the river now varies from 566 to 850 m^3s^{-1} (20,000 to 30,000 ft^3s^{-1}), seasonally. Stabilization of lake and pool water levels results in decreased outflows in the dry season and increased drainage in the wet season.

Lake Okeechobee

Lake Okeechobee was connected to the Caloosahatchee River in the 1880s, providing more efficient drainage to the Gulf of Mexico. Beginning in 1921, the lake was surrounded by an earthwork levee, the Herbert Hoover Dike, which eliminated surface water connection to the fringing marshes and swamps and offered control of all water outflow. The St. Lucie Canal was constructed in the 1920s to provide an eastern outlet. Water can now be released through gated structures in the Caloosahatchee and St. Lucie canals or southward via four other canals (Figure 8.4), to achieve regulation levels in the Lake. Thus, all flow out of Lake Okeechobee is controlled by stage management procedures. Water flows south via the canals only in the dry season, when it is potentially available for dry season recharge of the Biscayne Aquifer. For most of the year, and recently in most years, no water is discharged southward from the lake.

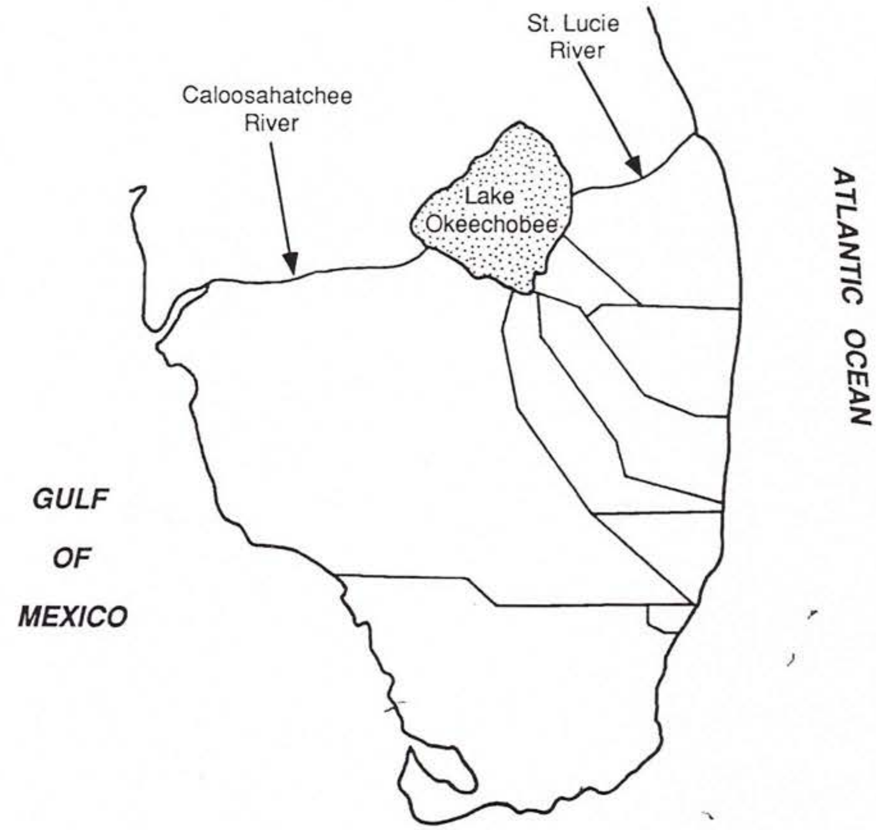

Figure 8.4. Location of early canals draining the Everglades and Lake Okeechobee (redrawn from Fernald and Patton, 1984).

The Everglades

Immediately south of Lake Okeechobee, the former wetland has been drained and farmed since the 1920s. Water levels in the Everglades Agricultural Area (EAA) (Figure 8.1) are controlled by pumping and gravity flow. For many years, water was backpumped from the farmlands into Lake Okeechobee, but since 1983, excess water has drained southward. The eastern portion of the Everglades has also been drained for farming and subsequently for suburban and even urban development. The edge of the Everglades, which in some places almost reached the East Coast, has been pushed back as many as 32 km. Currently, 65% of the original Everglades marsh proper has been drained. In the EAA, dried peat has subsided at a rate of 3 cm/yr, resulting in changes in land slope (Stephens, 1984). There is no evidence of similar subsidence of organic soil in still-watered portions of the Everglades.

Except for a single gap on the west, the entire northern Everglades is enclosed by levees, and the southern Everglades is bounded by an eastern levee system (Figure 8.1). These structures effectively hold back Everglades waters from the developed East Coast and retain them in the remaining core of the Everglades basin. The levees around the northern Everglades, from the EAA to Tamiami Trail (U.S. 41), form three shallow reservoirs called Water Conservation Areas. The southern Everglades, south of Tamiami Trail, includes Everglades National Park and the remaining adjacent marshlands to the east. These eastern Everglades wetlands are on higher ground and have shorter hydroperiods than does Shark River Slough.

Water movement through the Everglades is now controlled by the levees and gated structures and moves predominantly through canals (see Leach et al., 1972 and Klein et al., 1975 for details). Surface water continues to enter the Everglades from the Big Cypress Swamp. From the north, water from the Everglades Agricultural Area is transferred into the Water Conservation Areas, through which it moves primarily via perimeter canals into Area 3. Much of the movement of water within Area 3 also is by canals, and this flow discharges south at Tamiami Trail into Everglades National Park and via a canal directly into Taylor Slough, or bypassing the slough into the eastern "panhandle" of the Park (Figure 8.2). Water from the latter canal also can be discharged directly into Biscayne Bay.

Water enters the main Shark Slough channel through four gated structures along Tamiami Trail. In recent years, flow into the eastern portion of Shark Slough has been restored via the Tamiami Canal, passing through the old culverts under the roadbed. Most of the volume enters the park through a canal at its northeastern corner. Water flowing down Shark River Slough moves via marsh flow downgradient, finally through the mangrove swamps to the Gulf of Mexico.

From the previous account, it should be clear that, today, prior to entering the main Shark River Slough drainage, the bulk of water movement in the Everglades is by canals, bypassing the marsh. Overland marsh flow is of much more limited importance in the movement of water through the northern Everglades than it was historically.

Water flows in the Everglades canals vary substantially from near zero in the dry season to a few m^3s^{-1} (several hundred ft^3s^{-1}) in the wet season. Water flow out of the Conservation Area into Everglades National Park has averaged about 11.2 m^3s^{-1} (400 ft^3s^{-1}) but has often been zero when gates are closed; it exceeds 134.4 m^3s^{-1} (4,800 ft^3s^1) during extremely high water periods when the gates are wide open. As was the case historically, water depths in much of the Everglades, including Everglades National Park, vary from zero to about 1.0 m. However, they now may exceed 1.6 m where water accumulates at the southern, downstream end of the water conservation areas.

The most critical concept to grasp regarding the effects of hydrological alteration of water flow in the Everglades is that these changes have substantially increased water levels and hydroperiods over most of the remnant marshland, while simultaneously reducing or eliminating standing water on high marshlands, most of which are now developed. Water flows into Everglades National Park at the southern end of the drainage have increased markedly, both seasonally and overall. Comparing the amount of water flowing into Everglades National Park during the historic period of record (1941-1962) to the period of water management (1963-1970), Klein et al. (1975) demonstrate that flows into the park increased 25% above those that occurred naturally. Furthermore, the seasonal distribution of these flows has been altered substantially in most years. As Klein et al. (1975) point out, "Large variation with or between annual cycles can be as destructive [to the ecosystem within the park] as insufficient flow." In recent years, the increased and badly timed flow has accounted for much of the adverse ecological impact evident in the Everglades of Everglades National Park.

Increased water flows into the southern Everglades are the result of several changes: the reduction in total wetland in the northern and eastern reaches of the Everglades, the stoppage of eastward flows under and through the coastal ridge, the storage of additional water on remnant wetland, and the rapid movement of water downgradient via canal flow. The latter change bypasses the baffling effect of the marsh vegetation, which would otherwise increase residence time and therefore evaporative losses.

Thus, in the Everglades proper, two interrelated anthropogenous changes are the fundamental causes of the environmental disruption. The first, and clearly the most drastic, is the drainage and reclamation of the larger percentage of the naturally occurring wetland. By the 1980s, nearly 65% of the primitive Everglades had been drained. Lands not completely drained have also been affected by lowered water tables. These especially include higher wetlands peripheral to the core Everglades, the intermittently flooded lands around Lake Okeechobee, and wetland portions of the Kissimmee Prairie.

The second, and less obvious cause of disruption, is the manipulation of water flow and, therefore, water levels on the remaining wetland. Because the Everglades is now managed for the multiple uses of flood control, water supplies, recreation, and nature conservation, its hydrology is heavily manipulated. The Conservation Areas are designed to increase storage for water supplies going into the dry season and reduce the flood threat during the rainy (and hurricane) season. Currently, the northern Everglades reservoirs encompass 3500 km^2, holding a regulation storage of 1,600,000 acre-feet. Within the Conservation Areas, the impoundment tends to create deep flooding in the southern portions, and reduced hydroperiods in the upstream northern portions.

For most of the past 30 years, the downstream 6% of the Everglades marsh in Everglades National Park has been delivered water at the behest of water management needs upstream. In 1970, a national law guaranteed certain amounts of water flow in certain seasonality to the park. However, no provision was made in designing the Conservation Areas to vent excess water other than southward into the park. Since there is more water in these areas than under natural conditions, the amounts of water flowing into the park are higher than those that would have been expected naturally, as was well demonstrated by Klein et al. (1975). The control of downgradient water movement by cross-drainage levees, which block flow, and canals, which can rapidly inject water flows into the marsh, can cause discharges that are frequently out of synchrony with the seasonal rainfall pattern.

Water Quality

As discussed previously, nutrient levels throughout the system were naturally low. Currently, nutrient levels in the Kissimmee chain of lakes, which are downstream of the Orlando metropolitan area, are rather high (phosphorus and nitrogen, 0.3-0.4 mgl^{-1} on average). As water flows down the Kissimmee River, some decrease in concentrations occurs along its upper reaches. Drainage from improved pasturelands and dairy farms, however, again elevates nutrient levels in the lower reaches of the river.

In his study of Lake Okeechobee, Joyner (1975) found that nutrient concentrations entering from Taylor Creek were particularly high. During periods of high run-off, nutrient levels can reach concentrations sufficient to cause localized phytoplankton blooms. The lake is currently a sink for nutrients, which are retained in the organic sediment, a role it did not play historically when it had a clear sandy bottom. The total dissolved solids in the lake have increased from 190 mgl^{-1} in 1940 to 1941 to 288 mgl^{-1} 20 years later. In the mid 1970s, Joyner concluded that the lake was in an early eutrophic stage, with periodically severe episodes of nutrient enrichment.

These changes in the water quality in Lake Okeechobee can be traced to a combination of increased nutrient loads from the Kissimmee River, nutrient enrichment from cattle operations elsewhere in the basin and elimination of southward discharge. Back-pumping from the EAA accounted for nutrient inputs in the past.

In the Everglades, water quality changes can be directly related to the movement of water by canals through the conservation areas, including the L 67 canal that delivers water to Everglades National Park. Concentrations of sodium, chloride, magnesium, as well as color and conductivity, have increased in recent years (Waller and Earle, 1975, Flora and Rosendahl, 1982). Part of this increase is caused by mineralization from contact with the limestone in the canals, and part is from runoff. The quality of water coming off the EAA is high in nitrogen, at times exceeding 5 mgl^{-1}. At present, the potential for the rapid movement of water through the canal system means that nutrient-rich water from whatever source can be moved rapidly down the Everglades. Development of holding wetlands for the refurbishment of this water and elimination of movement of water via canals could decrease nutrient-loading as water moved southward.

Plants and Animals

Both plant and animal communities have been much altered throughout the system (Haeney and Huber, 1975; Perrin et al., 1982; Kushlan, 1989a). Most fundamentally, plant and animal populations have been affected by the loss of large portions of the natural wetlands of southern Florida, including the Kissimmee Valley, along the margins of Lake Okeechobee, and on the higher fringes of the Everglades.

Water level stabilization has increased deep water plant communities in the downstream portions of impoundments. In the southern end of the Kissimmee pools, deep, stable water has led to the invasion of deeper-water aquatic vegetation as well as floating mats of swamp vegetation. This general pattern is repeated in the reservoir pools of the Conservation Areas, where impoundment has led to near lake-like conditions in the southern ends. The coverage of tree islands has decreased, being replaced by sawgrass and willows, whereas in the deeper areas, flag marshes, submersed marsh, and water lily marsh have increased.

Drainage and the natural downgradient runoff of water from the higher northern portions of impoundments have increased the abundance plants species that can withstand shorter hydroperiods. Most of the fringes of Lake Okeechobee, now outside the levee, are either farmland or improved pasturage. In the Everglades, willows (*Salix*), malaleuca (*Malaleuca*) and other swamp trees have invaded into the now drier northern portions of the Conservation Areas. The challenge to native plant communities by the invasion of the Australian malaleuca can scarcely be overstated, as it threatens to turn most of the shorter hydroperiod marshes of the Everglades into swamp forests. Sawgrass has also increased in Everglades areas where hydroperiod has decreased, and species such as muhly grass (*Muhlenbergia*) now dominate large areas of higher marsh where they were once scarce. Conversely, water lily marshes have decreased in these areas.

The plant communities of the southern Everglades are probably the most like their pristine counterparts. Minor shifts have occurred among willow heads, sawgrass, and flag marsh. Recently, cattails appear to have expanded. The lack of fire in some parts of the southern Everglades has also led to changes, particularly the periodic dying off of sawgrass strands.

Effects on animal populations have also been drastic, particularly affecting their numbers and distribution. Populations of herons, ibises, and storks have decreased in the past several decades coincident with the imposition of water management practices (Kushlan and Frohring, 1986; Frohring et al., 1988). These have been the most adversely affected of any species, undoubtedly because of their dependence on very specific water conditions for successful reproduction. The best known, the wood stork, has essentially abandoned nesting in the Everglades. By 1982, the Everglades population had dropped by 75% of its 1967 numbers because of repeated nesting failures, which can be attributed to retardation of the rate of dry season water recession.

Some species have benefitted from anthropogenous changes. The Cape Sable sparrow (*Ammodramus maritimus*) has increased from its near extinction, occupying higher land on the edge of the Everglades, which probably now has a shorter hydroperiod (Werner and Woolfenden, 1983; Kushlan and Bass, 1983). The snail kite has increased over the period of water management owing to the creation of deep-water pools in the southern end of Conservation Area 3, where the species now nests (Sykes, 1983). They also continue to nest along the margins of Lake Okeechobee.

Resource Management

The fundamental reason for the changes in the Everglades system has been its competition with humans for space and water. Annually, there is a tremendous amount of water passing through the south Florida peninsula, owing to an average rainfall of 1.6 m (5 ft). However, with increasing human population the need for water supplies can only increase, and shortages may become severe more frequently in dry years. It is likely that additional water conservation, in both storage and use, will be essential in the future.

The competition for land seems nearly over. Given laws inhibiting development in wetlands, it is likely that the reclamation of the Everglades has been completed and very little additional land will be dewatered. However, management of the remaining wetlands looms as an increasingly large issue. The appropriate approaches to managing and conserving the Everglades system have been debated for decades, and this debate will continue. It is of importance to realize, however, how far the Everglades has changed from its pristine conditions. Although some restoration, such as around the Kissimmee River is possible, over most of the former Everglades landscape, it is unlikely than any close semblance to the pristine system could be recreated. Most of the wetlands have already been lost to the system, and the economic costs of total restoration to agriculture and the millions of residents dependent on the Everglades for water supplies and flood control are incalculable.

However, it remains possible to create a unified management scheme for the Everglades to accommodate most of its users. It is becoming increasingly recognized worldwide that the way to conserve and manage wetlands is through their sustainable management for multiple use. Wetlands can provide important economic benefits to human populations, and these can be maximized while maintaining natural functions. Planners could do worse than by imitating approaches being developed elsewhere in the world. In south Florida, the Everglades is essential for water supplies, flood control, and water quality enhancement. If a regional planner had been able to map out the most appropriate zoning for southern Florida, a master plan would look very much as south Florida has indeed developed: urban populations on the coast, agriculture in higher seasonal wetlands, an interconnected series of reservoirs, and a national park at the southern end of the flow-way. It should be kept in mind that, from an economic perspective, the present water management system has been quite a success.

For all these reasons, many if not most of the changes that have taken place in the greater Everglades ecosystem will not be reversed. Nonetheless, by appropriate management, aspects of wetland function may be maintained. And, by maintaining a functioning system, many economic services (flood control, water supply, waste water renovation) can continue to be supplied by the Everglades, relatively inexpensively.

The few detailed studies of Florida wetlands have iterated on common solutions for management [see Kushlan (1990) for a review]. If the goals are to reinstate a more natural fluctuation of water levels in remaining wetland patches, this can be achieved through active management of semi-natural controls on water flow. By restoration of more natural water fluctuation-affecting depth, recession rates, and hydroperiod-the basic functioning of the system can be re-established to the benefit of the plants and animals and their communities that are finely tuned to these fluctuations. Kushlan (1987, 1989a) demonstrated how an understanding of the cause-and-effect relationships between hydrological variables and animal population responses can be used to guide management in re-establishing a predictable pattern of within-year water level change. Real-time management decisions involving current hydrological conditions remain necessary to provide appropriate timing of discharge events. Water quality must also be managed. This might be accomplished best by the reestablishment of flow retention features.

Settling and filtration basins, elimination of canal flows, and diversions of water that recreate marsh flow are keys to accomplishing this. In these ways the remaining wetlands can function as filters and sinks.

With respect to dollars spent, the Everglades system is probably the most examined wetland system in the world. However, definitive studies of cause-and-effect relationships are few and, except for hydrological data, the volume of consistently gathered, technically sound long-term information is slim. Nonetheless, a basic understanding of various components of the system is available. It is important to establish studies at several scales, including the exploration of cause-and-effect relationships, a watershed-
technically sound long-term information is slim. Nonetheless, a basic understanding of various components of the system is available. It is important to establish studies at several scales, including the exploration of cause-and-effect relationships, a watershed-
level approach (which has proven appropriate in river systems), and adoption of international approaches to wetland management.

Based on these considerations, four specific research approaches are called for: the study of additional relationships between hydrological fluctuation and system responses; the establishment of long-term data gathering networks that are technically and statistically sound and not subject to idiosyncratic interventions; the amalgamation and synthesis of available information on a practical, rather than theoretical, level; and the meshing of practices in the Everglades with multiple use wetland conservation measures worldwide. The Everglades is not basically different from other flowing wetland systems in the state or elsewhere, and fundamental understandings of the ecology of both wetlands and riverine systems should be transferable to establishing appropriate management options for maintaining the sustained use of the River of Grass.

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