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Hydrologic Manipulations of the Channelized Kissimmee River

Implications for restoration

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Historically, much of south-central Florida was dominated by a contiguous wetland system that extended from the headwater lakes of the Kissimmee River basin to Florida Bay. During the past half century, this wetland landscape has been compartmentalized with a network of canals, levees, and water-control structures (gated spillways; Figure 1). This network is used to manage hydrologic regimes of the regional hydrosystem, primarily for flood-control purposes (Light and Dineen 1994, Toth and Aumen 1994).

Modifications of the physical configuration and hydrology of the South Florida landscape have affected the Everglades, Lake Okeechobee, and the 7800 km^2 Kissimmee River basin, where an extensive flood-control project was constructed from 1962 to 1971. Lakes in the river's headwater basin were connected by canals and partitioned into flood-storage reservoirs; a 90 km long, 9 m deep, and 100 m wide drainage canal was excavated through the river–floodplain ecosystem; and the channelized river was transformed by levees and water-control structures into five pools with stabilized water levels.

Restoration of floodplain ecosystems requires the reestablishment of a broader range of hydrologic regimes than is possible through manipulations of managed hydrosystems

The Kissimmee River flood-control project lowered both average and peak flood stages, reduced or eliminated water-level fluctuations, and drastically modified discharge regimes throughout the basin, but the hydrologic impacts were particularly severe within the channelized river–floodplain ecosystem. In contrast to the upper Mississippi River, in which maintenance of constant water levels upstream of navigation dams has increased open water and marsh habitats (Sparks 1995, Sparks et al. 1998), two-thirds (10,000 ha) of the Kissimmee's historic floodplain wetlands were drained by the lowering and stabilization of water levels (Toth et al. 1995). Even the most extreme post-channelization flood flows have been contained entirely within the banks of the constructed canal, and most of the floodplain wetlands that remain occur in the lower impounded portion of each pool and at the confluence of major tributary slough systems.

The modified hydrology and loss of wetland habitat have severely affected the structural and functional integrity of the floodplain (Toth 1993). Use of the river–floodplain system by wintering waterfowl has declined by 92% (Perrin et al. 1982). The naturalized cattle egret (*Bubulcus ibis*), a species that is primarily associated with cattle on pastures and other ruderal terrestrial habitats, has replaced the diverse complement of wading birds, including the endangered wood stork, that once used the floodplain wetlands (Toland 1990). A nationally renowned largemouth bass fishery and populations of other game fish species continue to decline, and the fish community is dominated by species tolerant of the altered habitat conditions of the channelized system (FGFWFC 1994). In addition to the loss of fish and wildlife habitat, drainage of floodplain wetlands has affected trophic resources that fueled the riverine food web (Toth 1990). Elimination of the nutrient-filtration function that was provided by the river's floodplain wetlands has exacerbated elevated nutrient loadings and transport to Lake Okeechobee, which is undergoing accelerated eutrophication due to intensive agricultural land uses (e.g., dairies) in contributing watersheds (Toth and Aumen 1994, Aumen 1995).

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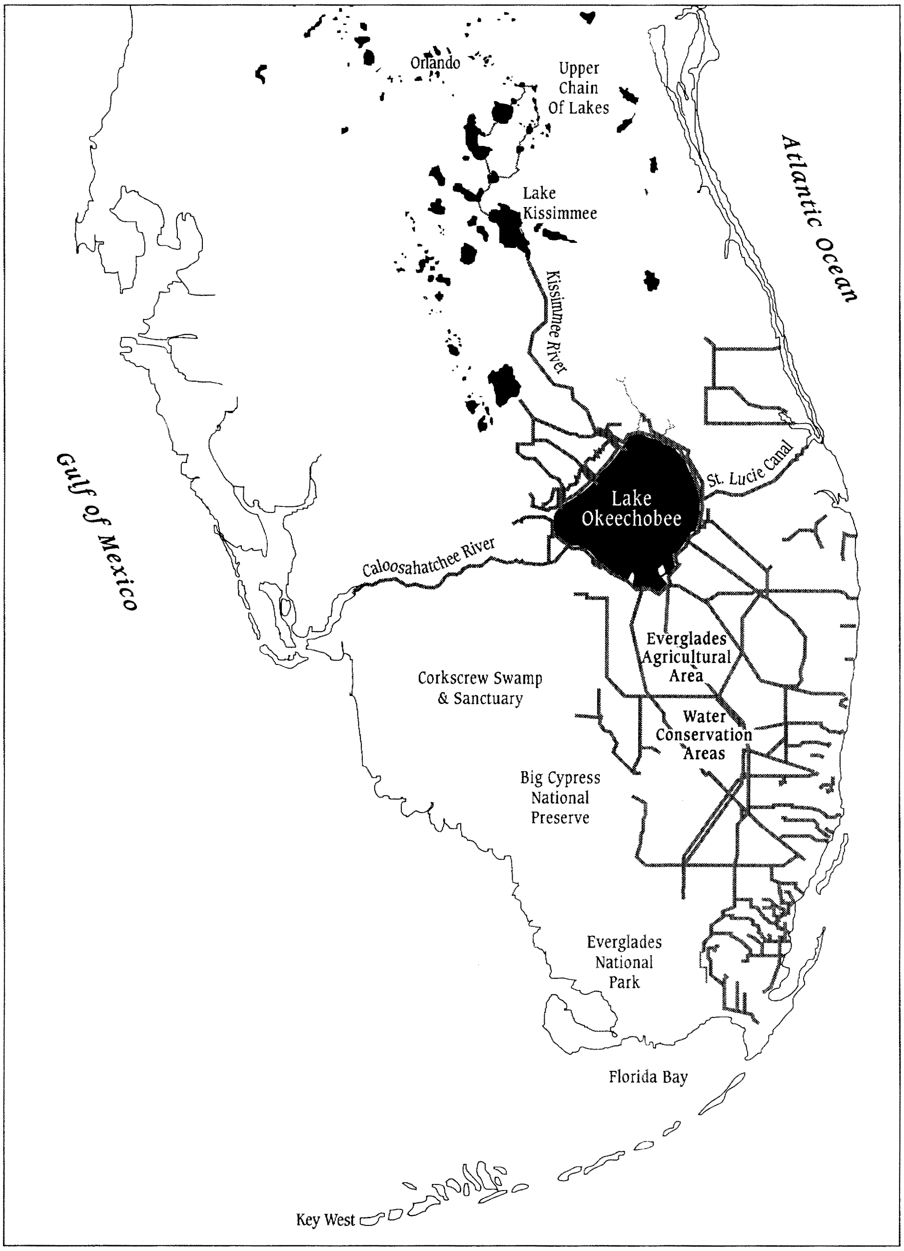


Figure 1. Map of south–central Florida showing network of flood-control canals and levees.

Shortly after the Kissimmee River was channelized, a sequence of hydrologic manipulations was initiated to reduce or alleviate some of the impacts to the system's ecology and natural resources. In this article, we discuss the successes and shortcomings of these experimental measures as potential restoration plan components for river–floodplain ecosystems.

Historic hydrology and ecology

Historical flooding regimes along the Kissimmee River were unique among North American rivers (Toth et al. 1995). Water levels on the floodplain typically varied according to subtropical, rainfall-driven seasonal cycles. Except during rare droughts, significant portions of the floodplain often remained continuously inundated. As much as 77% of the floodplain had mean annual hydroperiods (length of inundation) of at least 265 days (Figure 2), with depths commonly exceeding 1.0 m on the inner portions of the floodplain (Figure 3), which flanked the river channel. Peripheral floodplain elevations had more variable hydroperiods but were generally inundated during at least a portion of the wet season (July–November).

Prolonged floodplain inundation regimes were facilitated by protracted basin inflows and geomorphic characteristics that led to slow drainage rates and sustained extensive hydrologic connectivity between the river channel and floodplain. Although discharges exceeded the capacity of the river channel during 35–50% of the historical period for which hydrologic records are available (1934–1960), the flat topography and absence of a continuous natural levee along the river kept portions of the floodplain inundated at less than bankfull stages. The floodplain was also inundated by inflows from lateral tributary sloughs, in which water was delivered to the floodplain as overland sheet flow. Rates of drainage were moderated by the low gradient (0.07 m/km), meandering channel, dense wetland vegetation, and high water-retention capacity of the organic floodplain soils (Parker 1955). Prechannelization stages typically receded at rates of less than 0.3 m/month (Toth et al. 1993).

These unique hydrologic characteristics were the principal determinants of the ecological structure and function of the Kissimmee River floodplain. The historic floodplain supported a mosaic of habitats (Pierce et al. 1982), including backwater lakes and ponds and three dominant wetland plant communities, which were distributed according to lengths and depths of inundation (Toth et al. 1995). Floodplain elevations exposed to prolonged, deep hydroperiods were covered by coastal-plain willow (*Salix caroliniana*) and buttonbush (*Cephalanthus occidentalis*) shrub communities and by a predominantly herbaceous, broadleaf marsh composed of pickerelweed (*Pontederia cordata*), arrowhead (*Sagittaria lancifolia*), cutgrass (*Leersia hexandra*), and maidencane (*Panicum hemitomon*). Plant species diversity was greatest along peripheral floodplain elevations, where shorter and shallower hydroperiods selected for wet prairie communities composed of a mixture of forbs, grasses, and sedges. Other wetland habitats included cypress (*Taxodium distichum*) swamps, red maple (*Acer rubrum*) and popash (*Fraxinus caroliniana*) forests, and a sand cordgrass (*Spartina bakeri*) ecotone along the upland boundary of the floodplain. Although the distributions of these habitats were determined by prevailing hydroperiods, the persistence of this mosaic of floodplain habitats depended on the stochastic and widely varying inundation regimes. These regimes included extreme flood flows and, especially, rare but periodic droughts, which were the principal sources of disturbance (Pickett and White 1985) that regulated habitat dynamics of the historic floodplain landscape.

Hydrologic characteristics also affected use of the historic floodplain by fishes. By providing productive feeding areas, spawning sites, and refugia for young fishes, the availability of floodplain habitats can be a key factor influencing recruitment and population dynamics of many riverine fish species (Junk et al. 1989, Schlosser 1991, Gehrke 1992). In the prechannelized Kissimmee River, protracted floodplain inundation provided vast habitat for small-bodied fishes, including live bearers (e.g., Eastern mosquitofish, *Gambusia holbrooki*; least killifish, *Heterandria formosa*; and sailfin molly, *Poecilia latipinna*) and species that depend on vegetation for spawning (e.g., Florida flagfish, *Jordanella floridae*; Everglades pygmy sunfish, *Elassoma evergladei*; and swamp darter, *Etheostoma fusiforme*).

The densely vegetated floodplain habitats also provided refugia for larvae and juveniles of larger riverine species. In a 1957 survey, 90% of the fish found in a floodplain marsh were less than 100 mm long, and young game fish species comprised 41% of the sample (FGFWFC 1957). Use of the floodplain, particularly the broadleaf marshes, by large-bodied fish species was probably limited by vegetation density to the deeper marsh habitats that flanked the river channel. However, as in larger river–floodplain systems (Junk et al. 1989), accessibility increased during rising hydrographs, when large portions of the floodplain provided spawning habitat for pikes (*Esox americanus* and *Esox niger*) and gar (*Lepisosteus occeus* and *Lepisosteus platyrhincus*) and productive foraging areas for game-fish species such as bluegill (*Lepomis macrochirus*), largemouth bass (*Micropterus salmoides*), and black crappie (*Pomoxis nigromaculatus*; Trexler 1995).

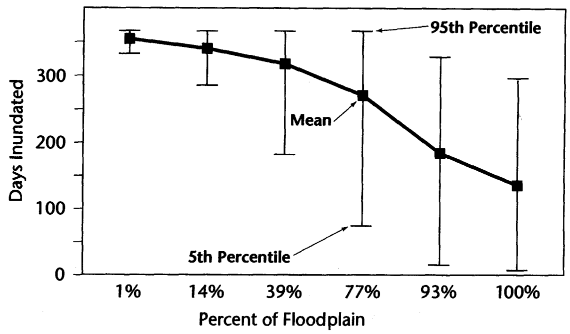
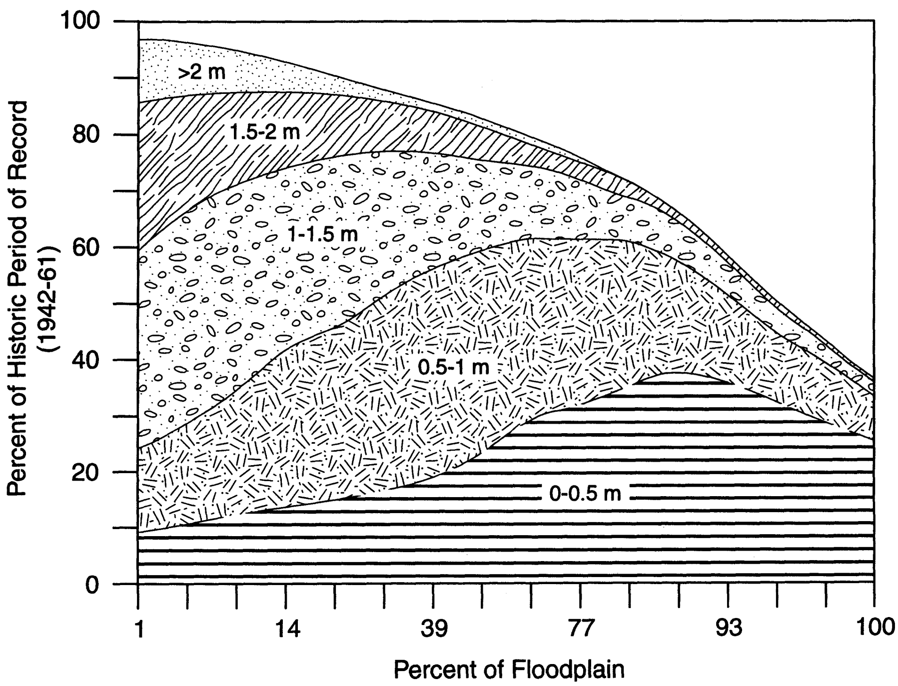


Figure 2. Historic (1942–1961) mean annual hydroperiods for the floodplain area (1.7 km^2) adjacent to the Fort Kissimmee gauging station (river km 51). Means represent the average annual number of days that given proportions of the floodplain were inundated during this historic period. The 5th and 95th percentile show 90% of the range of variability of annual hydroperiods for these portions of the floodplain.

The variety of floodplain habitats and range of water depths supported a diverse complement of avian species, including three endangered species: snail kite (*Rostrhamus sociabilis*), wood stork (*Mycteria americana*), and bald eagle (*Haliaeetus leucocephalus*; FGFWFC 1957, USFWS 1959, Howell and Heinzman 1967, Perrin et al. 1982). Deep, open-water habitats provided overwintering foraging areas for coots (*Fulica americana*) and migratory diving ducks (Chamberlain 1960, Bellrose 1968). Deep water may also have been a critical requirement for the reproductive ecology of several other bird groups. Many wading birds that lived on the historic floodplain form breeding colonies in low shrubs and trees surrounded by deep water, which protects nests from mammalian predation (Frederick and Collopy 1989). The snail kite also prefers to nest over deep-water wetlands with long hydroperiods (Sykes et al. 1995), which provide a stable habitat for production of their principal food source, the apple snail (*Pomacea paludosa*).

In addition to providing nesting sites for wading birds, willow and buttonbush swamps provided habitat for neotropical passerines, in-

Figure 3. Historic (1942–1961) frequencies of water depths for the floodplain area (1.7 km^2) adjacent to the Fort Kissimmee gauging station (river km 51). Graph shows the percentage of this period in which depths on given percentages of the floodplain ranged from 0.1 m to more than 2.5 m.



cluding migratory warblers and flycatchers. The densely vegetated broadleaf marshes probably supported resident populations of limpkins, rails, and bitterns, although historic data on these cryptic species are limited. However, much of the avian utilization of the historic floodplain was concentrated in the shallower, outer elevations (particularly wet prairie habitats), where the dynamics of the advancing and retreating water's edge played a prominent role in the reproductive and foraging ecology of dabbling ducks and of a variety of short- and long-legged wading birds (Weller 1995). The formation of isolated floodplain pools during receding hydrographs provided concentrated fish and invertebrate prey for nesting wading birds and overwintering waterfowl. The temporal availability of these concentrated energy resources is critical to spring waterfowl migrations (Fredrickson 1991) and to wading bird nesting success and recruitment (Powell 1987, Frederick and Collopy 1989, Bancroft et al. 1990). Drying pools also provided prey for bald eagles.

Experimental hydrologic manipulations

Although the historically dominant broadleaf marsh and willow communities were well adapted to persist in the stabilized–water level regimes of the channelized system, the more diverse wet-prairie communities that depended on seasonal wet-dry cycles along the periphery of the floodplain were largely eliminated. The first post-channelization hydrologic manipulations began in 1971, the year the flood-control project was completed; they were intended to explore the potential for mitigating this loss of wet prairie by attempting to encourage germination and reestablishment of annual plant species through seasonal (60–90 day) drawdowns of water levels in several of the channelized pools. Although a diverse assemblage of both annuals, particularly wild millet (*Echinochloa walteri*), and perennials colonized exposed river banks, shoals, and areas in which vegetation was burned, mechanically removed, or chemically treated, these drawdowns failed to change plant community composition in otherwise undisturbed wetlands, in which dense stands of established dominant plants, such as pickerelweed, Cuban bulrush (*Scirpus cubensis*), and water hyacinth (*Eichornia crassipes*), prevented reestablishment of other plant species (Goodrick and Milleson 1974). However, the rapid recovery potential of other floodplain resources was documented during the reflooding period as densities of small fish, crayfish, and grass shrimp (*Palaemonetes paludosus*) showed linear increases with water levels (Milleson 1976).

The ability to raise pool stages and thereby reinundate drained floodplain was limited by infrastructure constraints (e.g., the stability of the water-control structures), but water-management options were increased through the construction of diked floodplain impoundments. In one 672 ha impoundment, in which water levels were manipulated over a 1.5 m range (0.9 m higher than the stabilized pool stage), the reestablishment of seasonal inundation regimes led to ecologically significant changes in plant community structure on much of the previously drained floodplain. The portion of the community represented by annuals and other wetland plants, including important waterfowl food sources, increased, while coverage of the dominant pasture grasses that had become established on this section of floodplain decreased (Perrin et al. 1982). In another experimental impoundment (49 ha), which was created to evaluate the nutrient removal and retention capability of reflooded floodplain, pumped overland flow and an annual 0.9 m water level–fluctuation schedule led to reestablishment of a marsh that consistently retained 71% of the phosphorus inputs (Moustafa et al. 1996).

Experimental water-level manipulations (seasonal, pool-stage fluctuations) continued throughout the 1970s, but by the early 1980s more extensive restoration plans were being developed and evaluated (USACE 1985). Between 1984 and 1989, a demonstration project was constructed to evaluate more thoroughly the feasibility of restoring key biological resources and the relative utility of several recommended restoration approaches (Toth 1993). As in previous manipulations, a primary objective of the demonstration project was to reestablish floodplain inundation regimes. A 120 ha impoundment was created on a floodplain pasture, and pool stage fluctuations were used to seasonally inundate another 525 ha of drained floodplain. Three weirs were constructed across the flood-control canal to divert flow through adjacent remnant river channels. During high-discharge periods, water-surface profiles were elevated upstream of each weir, resulting in "backwater effects" that provided additional floodplain inundation.

The demonstration project's effects on vegetation communities were most evident on those portions of the floodplain that were subjected to prolonged inundation. The most striking change occurred in the impoundment, in which reestablishment of a 7–9-month annual hydroperiod led to rapid colonization by the broadleaf marsh species that had existed on this portion of the floodplain prior to channelization. The distribution of wetland plant species, particularly dotted smartweed (*Polygonum punctatum*), maidencane, and coastal-plain willow, also expanded in response to the increased floodplain inundation that resulted from pool stage fluctuation and the backwater effects of weirs (Toth 1993). As in the impoundment, a coastal-plain willow community reestablished on the same portion of floodplain where it had occurred historically, and coastal-plain willow replaced wax myrtle (*Myrica cerifera*) as the dominant riparian species along the banks of river channels adjacent to the weirs. These results demonstrated the viability and recolonization potential of both the vestigial seed bank and remnant propagules of hygrophytic species (Wienhold and van der Valk 1989) and verified the feasibility of restoring historic wetland plant communities on the floodplain.

However, reestablished seasonal hydroperiods did not eliminate many of the upland plant species that had colonized the drained floodplain since channelization (Figure 4), including ragweed (*Ambrosia artemisiifolia*), dog fennel (*Eupatorium capillifolium*), wax myrtle, purple rattle-bush

(*Sesbania punicea*), and caesar weed (*Urena lobata*). These invasive weed species are capable of persisting in a wide range of edaphic (e.g., soil moisture) conditions (Clewell et al. 1982, Marshall et al. 1985, Lowe 1986, Patton and Judd 1988), and they can provide formidable competition for reestablishment of wetland vegetation (Baird 1989), particularly in reflooded habitats with short, intermittent hydroperiods.

Fish and avian communities also showed mixed responses to the demonstration project. Higher pool stages led to increased densities of resident livebearing fish (e.g., mosquitofish) and some utilization of the floodplain by larger species, such as largemouth bass (FGFWFC 1994). However, fish species richness in all floodplain habitats affected by the demonstration project remained less than one-third of that in the historic floodplain (Figure 5). Fish colonization of the impoundment was impeded by the levee, which blocked hydrologic connectivity with canal and remnant river habitats. In other enhanced habitats, water levels did not get deep enough or did not remain sufficiently deep for long enough (Kushlan 1976) to accommodate extensive use of the floodplain, particularly the remaining densely vegetated broadleaf marshes, by the larger fish species that are found in the canal and remnant river channels.

Fish use of the floodplain may also have been limited by the chronically low dissolved oxygen levels that persisted within the demonstration project area. Before channelization, fish immigration onto the floodplain was probably tied to, and perhaps stimulated by, annual wet-season flooding, which flushed deoxygenated water from the floodplain, much as wet-season pulses of water rejuvenate the Sudd swamps of the Nile River (Howell et al. 1988). Thus, the demonstration project showed that a simple manipulation (rise) of water levels in the channelized pools does not reproduce the functionality of flood pulses over the floodplain landscape.

Within two years after reflooding, the demonstration project impoundment had the highest wading bird and waterfowl density in the channelized pools (Toland 1990). Although increased floodplain inundation caused by the weirs and by pool stage fluctuation also led to higher densities of wading birds, recent surveys indicate that the number of wading birds using the demonstration project area is not significantly different from numbers using other pools within the channelized system. However, the enhanced wetland habitat has led to a shift in avian community structure as the proportion of the community represented by cattle egrets has continued to decline, from 65% in 1978–1980 (Toland 1990) to 28% in 1996 (Stefani L. Melvin, unpublished data).

Most of the shortcomings of plant, fish, and avian responses to the demonstration project were due to the limited degree to which the project reproduced key hydrologic characteristics that determined the structure and function of the historic ecosystem. For example, pool stage fluctuations influenced hydroperiods on approximately 50% of the floodplain within the demonstration project area, but they did not reestablish historical depth regimes or, perhaps more important, the wide range of stage variability that maintained the mosaic of wetland habitats on the prechannelized floodplain. Backwater effects of the weirs increased the range of stage variability but only slightly increased the amount and duration of floodplain inundation. The influence of weirs on these inundation characteristics was limited by the flood-control canal, which rapidly drained the floodplain after peak discharges (i.e., during declining legs of discharge hydrographs). The resulting spiked hydrographs reduced the functionality of reflooded habitats by limiting the time available for development and production of integral components of the floodplain food web, such as invertebrate shredders (Toth 1993). Rapid stage recession rates also precluded the formation of drying pools with concentrated densities of fish and invertebrate prey, which are critical to the foraging ecology of wading birds and waterfowl. In addition, two major fish kills, in 1985 and 1988, resulted from anoxic conditions caused by rapid drainage of water off the floodplain (Toth et al. 1990).

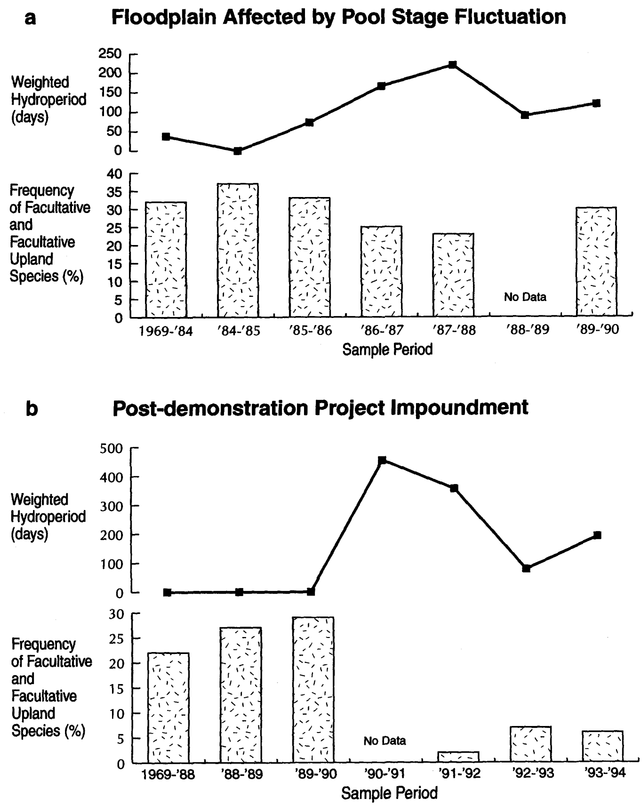


Figure 4. Hydroperiods (line graphs) and frequency of facultative and facultative upland plant species (bar graphs) along sampled transects on floodplain affected by pool stage fluctuation (**a**) and in the post–demonstration project impoundment (**b**). Hydroperiods were weighted by the frequency of sampled elevations along each transect and their associated length of inundation between each sampling period. (Sampling was generally done at intervals of 1 year, although the interval between the 1990 and 1991 sampling periods in the post–demonstration project impoundment was 450 days.) Facultative and facultative upland species are southeastern regional indicators with an estimated frequency of occurrence in nonwetland habitats of 34–99% (Reed 1988).

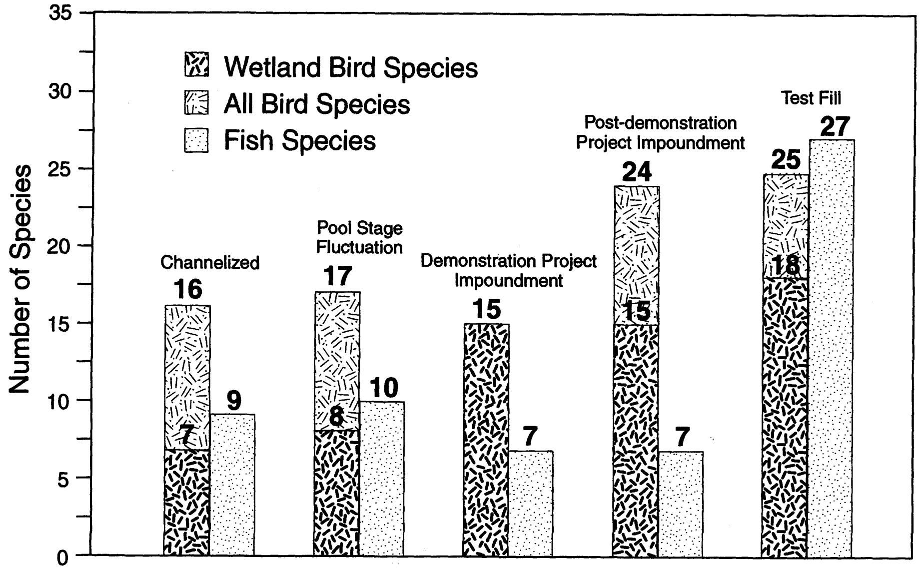


Figure 5. Fish and avian species richness on the channelized floodplain, on the floodplain affected by pool stage fluctuation (1985), within the demonstration project impoundment (1985), within the post–demonstration project impoundment (1990), and within the pilot dechannelization project area (1994). Years refer to dates when hydrologic changes occurred on affected floodplain.

Based on the results of the demonstration project, a new strategy for restoration of wetland communities was tested in another impoundment (228 ha), which was created on the channelized floodplain in 1990. This impoundment included an outlet water-control structure for managing water levels according to an operation plan that would reestablish historical inundation characteristics based on a model of pre-channelization relationships between antecedent rainfall and river stages. Before the model-based water-level manipulations were initiated, the impounded floodplain was subjected to 17 months of continuous inundation, which effectively eliminated the upland plant species that had become established on this portion of drained floodplain (Figure 4). Within two years after the manipulations, a broadleaf marsh developed over most of the impounded floodplain, and a diverse wet-prairie community composed of predominantly hygrophytic species became established on seasonally inundated peripheral elevations. As in the demonstration project, the impounded floodplain provides enhanced habitat for avian species; however, due to the lack of connectivity with the river, it continues to have a depauperate fish community (Figure 5).

Implications of managed hydrologic manipulations

More than 20 years of experimental studies have demonstrated the restoration potential and limitations of hydrologic manipulations in the channelized Kissimmee River. Managed flooding regimes have been successful at reestablishing wetland vegetation communities and enhancing some associated functional values, including secondary production and fish and avian utilization. However, restoration of the complex structure and dynamics of natural floodplain ecosystems requires the reestablishment of a broader range of spatial and temporal hydrologic regimes than is possible through manipulations of highly managed hydrosystems such as the Kissimmee River.

As in most altered systems, societal and infrastructure constraints have limited the scope of imposed flooding regimes to prescribed water level–fluctuation schedules based on average historic conditions. These manipulation schedules have not replicated the range of predisturbance hydrologic variability, particularly the frequency and duration of high stages and associated depths. Maintenance or restoration of the full range of hydrologic variability components, including the magnitude, frequency, duration, timing, predictability, and rate of change of flood regimes, are needed to sustain the mosaic of habitats and associated biodiversity and ecological functionality of riverine floodplain ecosystems (Poff et al. 1997). The construction of floodplain impoundments allowed more innovative manipulations but compromised geomorphic features (e.g., connectivity to the river channel) that are also critical to river ecosystem structure and function (Sparks 1995, Toth 1995).

The Kissimmee River restoration plan

Hydrologic manipulations within the channelized Kissimmee River were supported, if not driven, by a politically active restoration initiative that began during the latter stages of channelization and was influential in securing both state and federal legislation in support of these and other restoration-related studies (Woody 1993, Toth and Aumen 1994). Although initially somewhat narrowly focused (e.g., on loss of floodplain wetlands and associated nutrient-filtration functions), the restoration vision expanded as evidence of the range of ecological impacts increased (Toth et al. 1997).

Results of the experimental hydrologic manipulations of the channelized system provided the scientific basis for the sociopolitical decisions that led to the development of a comprehensive restoration plan. These manipulations demonstrated the feasibility of restoring lost biological resources and led to the adoption of an ecosystem restoration goal of reestablishing the ecological integrity of the river–floodplain landscape (Toth 1995). The implicit scope of this goal, and the documented importance of reestablishing the physical form of the riverine system and the full complement of historic hydrologic characteristics, eliminated piecemeal measures such as weirs, impoundments, and pool stage fluctuation as potential restoration components. In 1990, the state of Florida endorsed a dechannelization plan for reconstructing over 100 km^2 of river–floodplain ecosystem by eliminating (backfilling) 35 continuous kilometers of the flood-control canal, removing two water-control structures, and reestablishing historical inflow regimes from the headwater lakes (Koebel 1995). The plan includes an extensive land acquisition program, which will reduce the need for flood protection in the basin (Toth and Aumen 1994). Authorization for a federal–state partnership for the implementation of this plan was provided by the 1992 Water Resources Development Act (PL 102-580).

The reconstruction of the Kissimmee River began in 1994, with a pilot dechannelization project that backfilled a 300 m long section of the flood-control canal and removed spoil (dredged sand and shell deposits from the canal excavation) from approximately 5 ha of adjacent floodplain (Toth 1996). Although the scale of this initial dechannelization was too small to restore a significant portion of the surrounding ecosystem, use of the reestablished floodplain habitat by both birds and fish has provided supporting evidence for the prospects of recovery of important riverine resources. Fish (primarily Centrarchidae) spawned on the newly created floodplain immediately after the spoil was removed, and the project area supports considerably higher avian and fish species richness than other existing floodplain wetland habitats (Figure 5).

Successful environmental restoration and management programs require adaptive, scientifically based planning (Walters 1986, Toth and Aumen 1994). The iterative planning, implementation, and monitoring of experimental hydrologic manipulations within the Kissimmee River system provided the necessary information for developing a technically and scientifically sound restoration plan. This adaptive research and evaluation paradigm will continue to be applied during the implementation of the Kissimmee River restoration project and will provide the scientific foundation for fine-tuning sequential phases of the reconstruction and for adaptively managing the recovering and restored ecosystem.

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