Rehabilitation of impounded estuarine wetlands by hydrologic reconnection to the Indian River Lagoon, Florida (USA)

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Abstract

Salt marshes of the Indian River Lagoon, Florida (USA) were once prolific producers of mosquitoes. Mosquitoes lay their eggs on the infrequently-flooded high marsh surface when the soil surface is exposed. The eggs hatch when the high marsh is flooded by the infrequent high tides or summer rains. To control mosquito production, most of the salt marshes (over 16,200 ha) were impounded by the early 1970s. Flooding, usually by pumping water from the Lagoon, effectively controlled mosquitoes.

However, impounding had a profoundly negative impact on the wetland plant, fish, and invertebrate communities. Isolation from the Lagoon cut off aquatic access by transient estuarine species that used the wetlands for feeding or as nursery area. In one study, the number of fish species dropped from 16 to 5 after impounding. Wetland vegetation within some impoundments was totally eliminated; other impoundments developed into freshwater systems.

When tidal exchange is restored through hydrologic connection, usually by culverts installed through the perimeter dike, recovery to more natural conditions is often rapid. In one impoundment where wetland vegetation was totally eliminated, recovery of salt-tolerant plants began almost immediately. In another, cover of salt-tolerant plants increased 1,056% in less than 3 years. Fisheries species that benefitted the most were snook, ladyfish, and striped mullet. Over 1,500 juvenile snook were captured in a single 3-hr flood-tide culvert trap as they attempted to migrate into an impoundment. The zooplankton community rapidly returned to the more typical marsh-Lagoon community. Water quality and sediment sulfides returned to typical marsh values. Overall, reconnection enhances natural productivity and diversity, although water quality in the perimeter ditch, an artifact of dike construction, remains problematic.

Earlier experiments demonstrated that flooding only during the summer mosquito breeding season provided as effective mosquito control as year-round flooding. In standard management, the impoundment is flooded in summer, then left open to the Lagoon through culverts the rest of the year. Culverts are typically opened when the fall sea level rise first floods the high marsh.

Impoundment reconnection is being implemented by a multi-agency partnership. The total reconnected area is expected to reach 9,454 ha by the end of 1998, representing 60% of the impounded wetlands in the entire IRL system. One stumbling block is private ownership of many of the remaining isolated impoundments.

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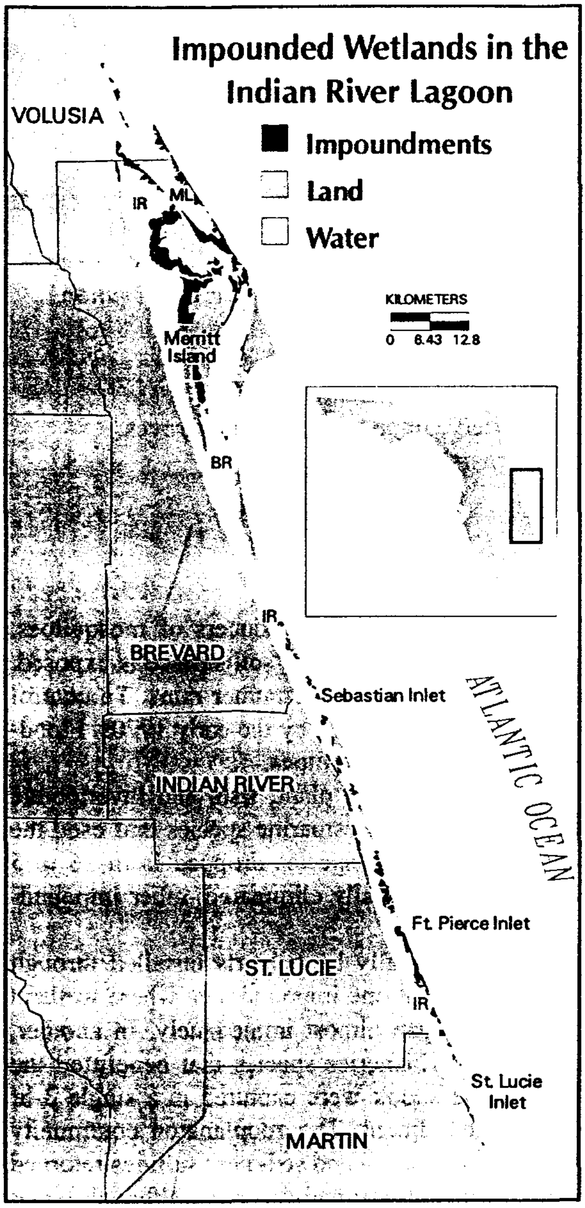

Fig. 1. Map of the Indian River Lagoon region showing distribution of impounded wetlands. These 16,200 ha represent almost all the estuarine wetlands in this five county region. Only those near inlets are tidally influenced. ML = Mosquito Lagoon; IR = Indian River; BR = Banana River.

Introduction

Impounding of the salt marshes and mangrove swamps along the Indian River Lagoon (IRL) for mosquito control during the 1950s and 1960s had a profoundly negative impact on native estuarine wetland vegetation and on fisheries dependent on these systems. Re-establishing a hydrologic connection between these wetland systems and the IRL can restore many of their lost ecological functions. This paper describes the setting, the history of impounding and its impacts, and the development of restoration techniques. A review of research conducted in isolated and reconnected impoundments demonstrates the effectiveness of restoration. Finally, the cooperative restoration program, the cost/benefits of these efforts, and a look at the future are described.

Physical and biological setting of the Indian River Lagoon

Due to their geologic history, salt marshes of the Indian River Lagoon are variable, both in space and in time. A brackish or saltwater lagoon for only 5–6,000 years (Almasi 1983), the IRL system is a series of inter-connected shallow (mean depth ~1.0 m) lagoons between the mainland of Florida's east coast and a series of barrier islands from 26°56.73' to 29°04.27'N (Fig. 1). Most of the wetlands on the barrier island developed either on washover fans or on the tidal deltas of former and present inlets. The Sebastian, Ft. Pierce, and St. Lucie Inlets in the southern half of the Lagoon (Clapp 1987) were only recently constructed or reconfigured and stabilized – in 1948, 1921, and 1898, respectively. The wetlands are quite young, having adapted to a highly variable environment, and might be expected to respond rapidly to changing conditions.

Wetlands vary with location in the IRL. They are most abundant in the north, either on or around Merritt Island or in northern Mosquito Lagoon (Fig. 1). The northern marshes are primarily temperate herbaceous marshes with only a few freeze-stunted mangroves (Schmalzer 1995). Southern marshes are more tropical, presently dominated by mangroves. A typical profile of a natural marsh consists of red mangroves (*Rhizophora mangle*) or cordgrass (*Spartina alterniflora*) at the waters edge with flat high marsh areas of herbaceous halophytes (*e.g.*, *Batis maritima*, *Salicornia virginica* and *S. bigelovii*) mixed with scattered black mangroves (*Avicennia germinans*).

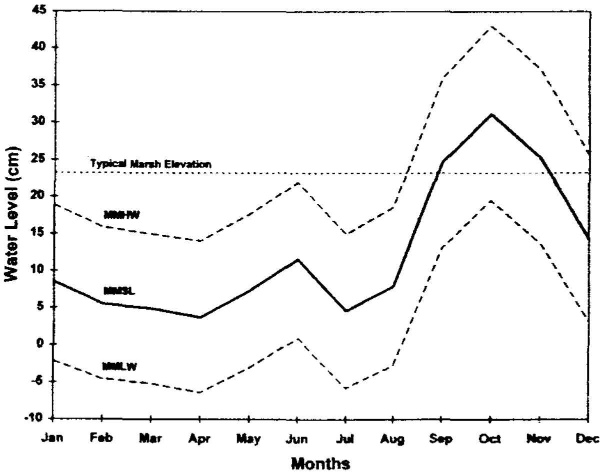

Fig. 2. Multi-year (1959–1980) monthly mean water level (MMSL) and mean high and low water lines (MMHW, MMLW) at Oslo Road near the southern end of Indian River County. Water levels referenced to mean low water datum, 1960–1978 (after Smith 1986). Due to the fall sea level rise, mean monthly low water in October is higher than mean monthly high water in July. MMSL exceeds a typical marsh elevation only during September, October, and November.

The Lagoon is microtidal with the daily tidal regime of a marsh dependent on its proximity to ocean inlets (Smith 1987). Daily water level changes in marshes near the southern three inlets are dominated by lunar tides, but the majority of the marshes, including all of Merritt Island, have lunar tides of <5 cm (Smith 1987). In these areas, short term water level changes are a function of wind direction. Dominant water level changes for the Lagoon, however, are of much longer duration than daily tides. Beginning in September, a seasonal increase in water level of about 27 cm (Fig. 2) dictates much of marsh structure, function, and management (Provost 1973, Smith 1986). Thus, many of the marshes may be inundated from September through November and only occasionally the rest of the year, due to storms, frontal weather systems, etc.

The seasonal weather pattern in the region consists of warm wet summers and mild dry winters. The rainy season starts in May or June and continues through September or October (Rao 1987).

History of impounding

The marshes and swamps along the IRL system were historically prolific breeders of salt marsh mosquitoes (*Aedes* spp.) and biting sandflies (*Culicoides*). These mosquitoes lay their eggs on the exposed moist surface of the marsh, but will not oviposit in standing water (Provost 1969). When this surface is flooded by rainfall or tides, the eggs hatch and within 7 to 15 days (depending on the ambient temperature) huge clouds of biting adults emerge (Provost 1977a). In extreme cases when the marsh has not been flooded for a prolonged period (dry weather and low tides), the density of mosquito eggs on the marsh surface can exceed 100,000/m^2 (Harrington and Harrington 1961). During the summer in the IRL, the intermittent high tides and periodic rains produce ideal conditions for breeding.

This problem continued unabated until 1926, when organized mosquito control was begun (Platts *et al.* 1943). The first effort to control these pests was ditching of the wetlands. Hundreds of miles of shallow parallel hand-dug ditches (200 linear m/ha) were designed to allow predatory mosquitofish, *Gambusia* spp., access to all parts of the wetland (Platts *et al.* 1943). These ditches were temporarily effective against the mosquitoes, but did little to affect the population of sand flies. Some mosquito breeding still took place in the areas between ditches, and many miles of ditches were constructed through areas that did not breed mosquitoes. Even where initially effective, blockage of these ditches by debris and wave action at the Lagoon edge ultimately reduced their effectiveness against salt marsh mosquitoes.

An experiment in the 1930s demonstrated that impounding wetlands and flooding them with Lagoon water eliminated nearly all sandfly and salt marsh mosquito breeding (Hull and Dove 1939). Because water loss due to evaporation and seepage made the practice cost-prohibitive, a pump was used to drain the impoundment. This technique proved to be effective at mosquito control, and a total of over 405 ha was impounded under this type of management (Hull and Dove 1939, Hull *et al.* 1943). By the early 1940s, however, the emphasis of mosquito control shifted to the application of pesticides, including DDT. After the World War II, pesticides were used almost exclusively through the early 1950s. By the mid 1950s, pesticide resistance and questions about the toxic effects on non-target organisms led to a search for an inexpensive alternative (Provost 1969, 1977a, 1977b). Brevard County placed renewed emphasis on impounding in 1954, and the other IRL counties followed suit shortly thereafter (Provost 1977b).

By 1959, over 3,240 ha of wetlands were impounded in the IRL (Provost 1959), and ultimately over 16,200 ha were impounded by the early 1970s (Fig. 1; Rey and Kain 1989). Nearly 10,950 ha of these impoundments (67.5%) are within the Merritt Island National Wildlife Refuge (MINWR; lands associated with the Kennedy Space Center). Impoundments range in size from <1 to 1,215 ha (Rey and Kain 1989) and were flooded by either artesian wells or by pumps from the Lagoon. The impoundment dike was typically built by a dragline at about the mean high water mark, just behind the red mangrove fringe (Provost 1969). The material used in the dike was most often taken from the marsh itself, leaving behind a deep-water perimeter ditch paralleling the dike.

Impacts of impounding

Impounding has had a profoundly negative impact on these wetland systems. Two of the most pronounced and obvious areas of change were in the plant and fish communities. Isolation, the amount and type of water used in flooding, evaporation, and seepage of water through the dike caused a variety of changes in dominant vegetation types and in the structure of the vegetative community. Access to these wetlands by transient estuarine species for feeding or nursery purposes was eliminated.

Vegetation

Wetland vegetation within some impoundments was totally eliminated because of the level of flooding (Fig. 3A; Harrington and Harrington 1982, Gilmore *et al.* 1982, Rey *et al.* 1990a). Impoundments were flooded to higher levels than necessary for mosquito control to assure that sufficient water still remained on the marsh surface during the summer. Because of the high water levels, herbaceous halophytes such as *Batis maritima*, *Salicornia virginica* and *S. bigelovii* disappeared from some of these marshes. Likewise, black mangroves were eliminated because their short pneumatophores cannot tolerate complete submergence for more than a week or two (Provost 1974). Even if water levels are maintained at the minimum required for mosquito control, impacts to vegetation can still occur (Rey *et al.* 1990a). Storm induced flooding can cause severe damage to vegetation in impoundments that cannot be quickly drained to the Lagoon (Rey *et al.* 1990a).

In some areas of the southern Lagoon, the normal high marsh vegetation was replaced by almost monospecific stands of red mangroves, which tolerate flooding better because of their long arching prop roots. The developing red mangrove canopy often contributed to the elimination of the remaining herbaceous layer by shading any remaining patches (Rey *et al.* 1990a).

In isolated impoundments flooded by artesian well or by upland drainage, the plant assemblage became characteristic of freshwater systems, typically dominated by cattails (*Typha* spp.; Clements and Rogers 1964). The degree of the transformation is dependent upon the integrity and height of the dike, which determines seepage and Lagoon-marsh exchange over the dike. In some areas, invasion by exotic and/or upland species has become a serious problem.

In contrast, hypersalinity may occur in impoundments that are flooded by pumps but are then left closed without further management. In these cases, seepage and evaporation often result in extremely hypersaline conditions in both surface (>200 ppt) and pore waters, and may result in elimination of all vegetation and most aquatic life (Gilmore *et al.* 1982, Rey *et al.* 1990a).

Fisheries

The impacts of impounding were illustrated by the reduced number of fish species utilizing closed impoundments (Harrington and Harrington 1961, 1982, Gilmore *et al.* 1982, Gilmore 1987).

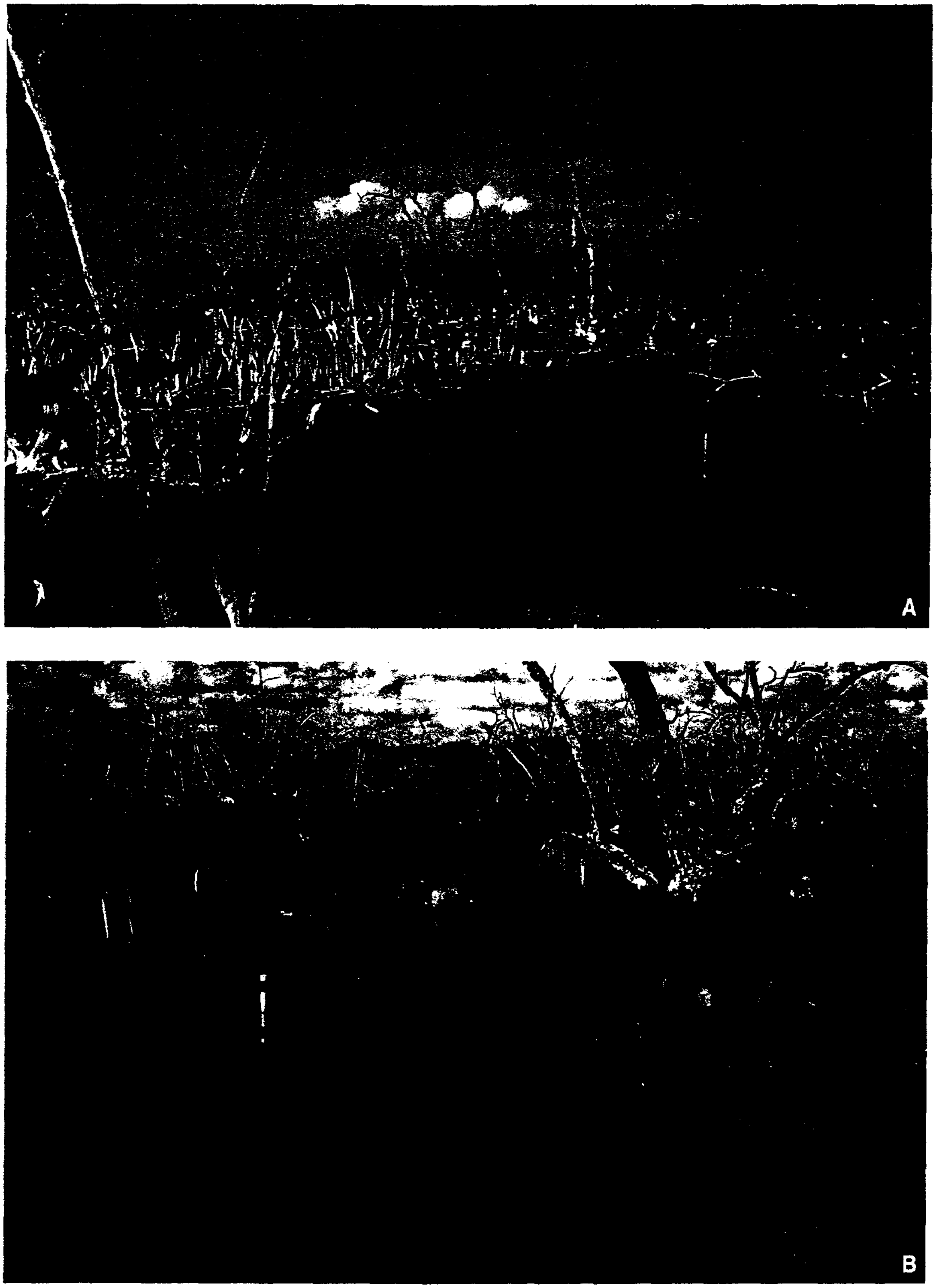

Fig. 3. Photographs of the Impoundment #12 site at the Indian River / St. Lucie County line (A) after impounding and (B) after reconnection. A. In 1980, note dead mangrove trees and lack of herbaceous vegetation; the muddy surface was littered with dead snails. B. In 1985, within a year of re-opening, note the recovery of high marsh vegetation, consisting mostly of *Batis* and *Salicornia*.

Harrington found a reduction in the number of fish species from 16 to 5 after impounding. The five remaining species were small resident fish that completed their entire life history within the wetland. Species eliminated by impounding included the larvae/juveniles of many important fisheries species, such as the tarpon, *Megalops atlanticus*, common snook, *Centropomus undecimalis*, ladyfish, *Elops saurus*, and mullets, *Mugil cephalus* and *M. curema* (Harrington and Harrington 1961, 1982, Gilmore *et al.* 1982). These species normally use the marsh during a portion of their life history after recruiting from oceanic or nearby open estuarine waters. While within the wetland they complete early development in protected waters, growing rapidly and feeding on the abundant forage found in these very productive and often eutrophic ecosystems. The value of these wetlands for the "maintenance of offshore commercial and game fish populations" was identified early by Provost (1959).

Development of the current reconnection technique

In the late 1950s and early 1960s, experiments with seasonal flooding during the summer months were found to be as effective at controlling mosquitoes as year-round flooding (Clements and Rogers 1964). In some of the test cells in this experiment, the water levels were allowed to fluctuate with the tides during the late fall, winter, and early spring via a single culvert through the dike. Flapgates placed on these culverts assisted in capturing water to flood the impoundments, though they were not sufficient to sustain water levels throughout the summer. A portion of the native salt marsh vegetation survived in these cells. In other cells held flooded with fresh artesian well water throughout the year, *Typha* spp. soon dominated (Clements and Rogers 1964). This work led to the inclusion of single culverts in the construction of some subsequent impoundments to protect native vegetation from damage (J. David, St. Lucie Mosquito Control District, pers. comm.).

Provost (1968) was one of the earliest advocates of restoring or maintaining estuarine connection for purposes other than the protection of vegetation. He cited work by Harrington and others that document the utilization of these habitats by aquatic fauna with commercial and recreational fisheries value and noted that this use diminished after impounding. By the early 1970s, after the impounding of nearly 16,200 ha of wetlands, environmental regulators began to restrict the construction of new impoundments.

To secure approval for one of the last impoundments constructed, a plan was developed by Provost and the Brevard Mosquito Control District (Provost 1974). The plan required a water management scheme that, in addition to providing adequate mosquito control, "would (1) retain as much as possible of the existing woody vegetation, chiefly black mangroves, (2) permit ingress and egress of fish and other forms of life inhabiting Banana River, and (3) allow adequate flushing of the impoundment to permit the movement of its nutrient detritus into Banana River" (Provost 1974). These goals were accomplished by the inclusion of four culverts, a spillway, and a pump in the design of the impoundment. During the mosquito non-breeding season, the culverts were completely open to the estuary. Two of the culverts had flapgates to trap tidal water during the breeding season and allow exchange of organisms and water when Lagoon levels exceeded the water levels inside the impoundment. The other culverts had flashboard risers set at a level that would provide adequate flooding for mosquito control while releasing excess water that could damage vegetation. The pump was used to initially flood the impoundment and to supplement levels to maintain mosquito control. The spillway was constructed to protect vegetation from prolonged flooding resulting from tropical storm events which may exceed the release capacity of the culverts. This project was the first successful implementation of what has subsequently become known as Rotational Impoundment Management (RIM; Provost 1977a, Carlson and Carroll 1985).

The protocol for retrofitting existing impoundments to implement RIM was developed through the actions of an inter-agency group currently known as the Subcommittee on Managed Marshes (SOMM; Carlson and Carroll 1985, Carlson *et al.* 1991). This group was instrumental in:

(1) guiding policy and prioritizing research needs in an effort to remediate the impacts of impounding while maintaining adequate mosquito control
(2) providing a forum for the exchange of information between various participating governmental entities and the wetlands research community
(3) producing guidelines for management plans used to implement RIM in isolated impoundments (Carlson and Carroll 1985).

These guidelines have been used by regulators to help insure successful mitigation for other wetland impacts. SOMM also encouraged research to document the benefits of impoundment reconnection and to refine and improve the basic RIM plan.

Research examining the effects of reconnection

This section describes the results of some of that research and others conducted to examine the effects of restoration through hydrologic reconnection of impoundments to the estuary. Reported here are the research results regarding impoundment vegetation, fisheries, zooplankton, sediments, and water quality, as well as seagrass adjacent to reconnected impoundments. Information on the response of other ecosystem components is not available.

Vegetation

If tidal exchange is restored to impacted marshes, vegetation recovery is often rapid. For example, at Impoundment #12 between Sebastian and Ft. Pierce Inlets in Indian River County the vegetation was totally eliminated by overflooding and by hypersalinity that developed after the culverts connecting the marsh with the Lagoon were "permanently" closed in 1980 at the request of the property owner (Fig. 3A). After culverts were reopened 3 years later, recovery of herbaceous halophytes began almost immediately (Fig. 3B). However, after 7 years, total cover by *Batis maritima* and *Salicornia* spp. remained well below the original 75%, and black mangroves were still not evident in the marsh (Rey *et al.* 1990a).

MINWR staff and others have had success in controlling exotics and nuisance species (freshwater species like cattail, *Typha domingensis,* and willow, *Salix caroliniana*) by reconnecting isolated marshes with the Lagoon via culverts (Schmalzer 1995). As an example, in a 1,215-ha impoundment at MINWR, 13 91-cm diameter culverts were installed in 1993 to re-establish hydrologic connection to the Lagoon. Two months prior to reconnection, 15 permanent 15-m transects were established to monitor vegetation changes over several years. A Global Positioning System (GPS) was used to locate each transect. Live vegetation was sampled using a line intercept transect method (Mueller-Dombois and Ellenberg, 1974) in October, 1993. During the next year, there was a marked die-off of cattails. A successful attempt was made to burn this area in February 1995 to remove seed material and dead vegetation from the marsh surface. In March 1996, the transects were resampled using the same methods. The total cover of each species was divided by the length of the transect, giving a percent cover per species. Species were grouped into vegetation classes: freshwater species (including *Typha domingensis*), salt-tolerant species, and a special class to analyze *Typha* alone.

All classes were tested using Kolmogorov-Smirnov (Norusis 1993) and found to be normally distributed ($P>0.200$). The salt-tolerant class showed an increase in coverage of 1,056% while the freshwater class decreased by 74%. A comparison between classes using a paired *t*-test indicated significant differences between years for both of these classes ($P<0.05$). While the *t*-test did not indicate a significant difference between years for the special *Typha* class, the coverage declined 56% from 1993 to 1996. In addition to coverage, the number of salt tolerant species rose from 7 to 8, while the freshwater species declined from 13 to 1 (*Typha*).

Another area of concern with wetland impoundments is their effects on primary production. Very little data are available on the effects of impounding upon mangrove production. Growth rates of red, black, and white (*Laguncularia racemosa*) mangroves in a closed impoundment were generally higher than growth rates reported from other unimpounded areas (Rey 1994). However, the stands measured were young and growing in low salinity areas, both conditions known to promote high growth rates in mangroves (Soto and Jiménez 1983, Ellison and Farnsworth 1993).

Red mangrove litter production in impounded wetlands may be higher than that reported from other places in Florida (Rey *et al.* 1986). Lahmann (1988) reported that biomass accumulation and litter production by red mangroves was higher in impounded than in unimpounded marshes during the open period, but the situation was reversed during the period when the culverts were closed for mosquito control.

Rey *et al.* (1990b) studied the above-ground primary production by *Batis* and *Salicornia* in two unimpounded marshes (one ditched and one unditched) and in an impounded marsh connected to the Lagoon by culverts. During the first year, culverts at the impounded marsh were closed and the marsh flooded for mosquito control from late May to early October. During the second year, the culverts were left open the entire year. Results of the study indicate that yearly production at all three marshes compared favorably with those reported from *Batis–Salicornia* marshes in California (Onuf *et al.* 1978, Zedler 1982), Georgia (Antlfinger and Dunn 1979), and Massachusetts (Ruber and Murray 1978).

Yearly production at the unditched marsh averaged 2,150 g/m^2 and was significantly higher than at the other marshes, but there were no consistent differences between the unimpounded, ditched marsh and the impounded marsh. Comparison of summer production at the impounded site between the first and second year of the study indicated that summer flooding does inhibit primary production, but the effects upon total yearly production are minor because in this area, production is normally at a minimum during summer because of high temperatures and high interstitial salinities (Rey *et al.* 1990b).

This study also indicates that litter residence time is longer in impounded than in unimpounded marshes. Consequently, the organic content of litter is higher in impounded marshes. This phenomenon, in conjunction with the often higher rates of litter production caused by vegetation damage during the summer flooding, results in accumulations of litter that may often function as nutrient reservoirs in impounded marshes. A similar phenomenon was reported by Lahmann (1988) for red mangrove litter.

Fisheries

From 1968 to 1980, fish and crustacean collections in reconnected and isolated wetlands of the IRL not only demonstrated the deleterious effect of impounding (Harrington and Harrington, 1982), but also the potential remediation of these impacts with the installation of a single culvert in a 16-ha impoundment (Gilmore *et al.* 1982, Gilmore 1987). The latter workers made biweekly 24-hr quantitative collections in and around three separate impounded sites under managed and unmanaged hydrologic conditions. The several hundred thousand specimens collected allowed the classification of wetland fish populations into two basic categories based on life history parameters (Table 1). Thirteen nekton species were designated as *residents* based on the capability to complete their entire life cycle within an impounded wetland (Gilmore 1987). A far richer nekton group including 94 species was designated as *transient* as they must complete necessary life history activities such as reproduction in adjacent open estuarine or neritic/oceanic waters. Any aquatic access point that will allow their migration in and out of the wetland is used as a migratory pathway, including manmade devices such as culverts. Resident species made up 94% of individuals collected and 46% of the biomass, while individual resident species occurred in 0.55 to 43.27% of the collections (Gilmore 1987; Table 2). Residents were least impacted by wetland impoundment and in some cases even enhanced by impoundment construction. Although transients contributed only 6% of the total number of individuals, they contributed the majority of the wetland biomass (54%) and were very seasonal in their occurrence (0.40–23.53% occurrence by species; Gilmore 1987; Table 2). Transient species were most impacted by wetland isolation from the adjacent estuary. Over 80% of the transient species are sport and commercial fishery species. Thus, wetland impoundment not only impacted aquatic nektonic communities, but also has a significant economic impact on Florida east coast fisheries.

Table 1. The top 20 Indian River Lagoon wetland resident and transient nekton species collected at three RIM-managed impoundments, 1982–1986, Gilmore (1987). * Species most impacted by impoundment construction and subsequently enhanced by hydrologic restoration. † The only 5 species found by Harrington and Harrington (1982) in an isolated impoundment. **Bold** species are fishery species.

No. Individuals[1]		Weight[2] (g)		% Occurrence[3]	
C. variegatus†	188,480	*C. variegatus*†	129,579	*G. holbrooki*†	43
G. holbrooki†	141,237	***M. cephalus****	**120,930**	*Palaemonetes*	40
P. latipinna†	63,642	*P. latipinna*†	41,760	*P. latipinna*†	36
Palaemonetes	38,566	***M. curema****	**36,428**	*C. variegatus*†	33
M. cephalus*	**5,451**	***C. sapidus****	**25,669**	***M. cephalus****	**24**
E. saurus*	**5,238**	*G. holbrooki*†	24,540	***C. undecimalis****	**16**
C. undecimalis*	**4,752**	***C. undecimalis****	**13,919**	***E. saurus****	**16**
M. curema*	**2,665**	***E. saurus****	**9,418**	***Penaeus* spp.***	**14**
*F. confluentus**†	2,499	***M. atlanticus****	**6,283**	***C. sapidus****	13
C. sapidus*	**1,364**	*Palaemonetes*	4,818	***M. curema****	**13**
M. beryllina	1,253	***L. rhomboides****	**4,457**	*F. confluentus**†	11
Penaeus* spp.	**1,247**	***L. griseus****	**4,229**	***D. auratus****	**9**
D. auratus*	**1,054**	*F. confluentus**†	2,796	***G. cinereus****	**7**
*L. parva**†	951	***A. probatocephalus****	**2,746**	*D. maculatus**	7
G. cinereus*	**740**	***Penaeus* spp.***	**2,440**	*E. harengulus**	4
*E. harengulus**	721	*D. maculatus**	2,204	*Menidia* spp.	4
*A. mitchilli**	707	*A. mitchilli**	1,712	*F. grandis**	4
Menidia spp.	393	***D. auratus****	**1,684**	*L. parva**†	3
L. xanthurus*	**383**	*E. gula**	1,345	*A. lineatus**	3
*E. gula**	350	*M. beryllina*	891	***M. atlanticus****	**3**

[1] Taken from a total of 465,310 individuals.
[2] Taken from a total of 449,525 g.
[3] Taken from 2,006 collections.

Table 2. Percentage of nekton faunal contribution by residential category out of 2,006 samples at three RIM-managed impoundments, 1982–1986, Gilmore (1987). The Occurrence Range represents the range of % occurrences for individual species in each category.

	Number Individuals	Wet Weight (g)	Occurrence Range
Residents	437,573 (94%)	207,193 (46%)	0.55–43.27%
Transients	27,737 (6%)	242,332 (54%)	0.40–23.53%

Resident wetland species were numerically dominated by atherinomorph fishes which are typically physiologically adapted to the rigorous hydrological conditions associated with wetland ecosystems. IRL impoundments had water salinity ranges of 0–166 ppt, temperatures of 0–43°C, and oxygen levels of 0–10 ppm. Nearly all of these ranges are within the physiological tolerance limits for at least one or two local resident species. This high tolerance demonstrates their co-evolution with these hydrologically harsh ecosystems. These physiological abilities and high reproductive rates have allowed them to produce a high biomass, whether the wetland is impounded or not. The most numerous regional resident species are the sheepshead minnow, *Cyprinodon variegatus*, eastern mosquitofish, *Gambusia holbrooki*, sailfin molly, *Poecilia latipinna,* and the marsh killifish, *Fundulus confluentus*. These species form the trophic base and primary prey for many of the secondary and tertiary consumers, which are typically transient fishery species (Harrington and Harrington 1961).

Transient wetland species are very seasonal in occurrence and generally utilize the fringing wetland as a juvenile nursery ground. For example, tarpon, snook, and ladyfish typically enter the wetland as larvae or post-larval early juveniles, or to forage as older 1–4 year juveniles and young adults. They forage on residents most often when water levels concentrate the diminutive species in tidal creeks and ditches (Gilmore 1987). Almost all transient fish are predators except for the detritivorous striped and silver mullets. Approximately 99.5% of the transient species biomass (54% of the total wetland standing stock biomass) is contributed by valuable sport or commercial fishery species. The most numerous species dependent on wetlands to complete their life history are the mullets, tarpon, snook, ladyfish, blue crab (*Callinectes sapidus*), penaeid shrimp, gray snapper (*Lutjanus griseus*), sheepshead (*Archosargus probatocephalus*), and mojarras – yellowfin (*Gerres cinereus*) and silver (*Diapterus auratus*). These species seasonally recruit to impounded wetlands in early developmental stages at different periods of the year. Totally closed impoundments block transient fish migration into these systems (Gilmore *et al.* 1982, Harrington and Harrington 1982), while those impoundments with even a single culvert will allow transient utilization of the wetland if they are open at the appropriate period of the year (Gilmore *et al.* 1982). Unfortunately, current seasonal impoundment water management strategies do not benefit all fishery species because summer impoundment closure for mosquito control may interfere with recruitment from the more tropical species, *i.e.*, tarpon and silver mullet (Gilmore *et al.* 1982, Harrington and Harrington 1982).

The importance of wetland access has been demonstrated by the capture of large numbers of transient individuals as they passed through culverts into the wetland during major recruitment events. Common snook typically recruit to fringing estuarine and oligohaline wetlands of the IRL system from summer to fall and early winter and may pass through open culverts that do not contain flapgates during this period (Gilmore *et al.* 1982, 1983). Tarpon recruitment appears to occur principally during the summer and early fall. Wetland access to tarpon is typically limited during the summer months, June through September, as most impoundments are managed for mosquito control during this period. Therefore, the culverts are closed with flapgates during a period when tarpon recruit as larvae and transitional post-larvae. As a result, it is expected that tarpon are most greatly affected by impoundment closure and management during the summer months.

The fisheries benefits associated with impoundment reconnection, at least through culvert installation and seasonal opening (September through April), are undoubtedly large because transient species, which represent all fishery species that use the impoundments, are totally precluded from closed wetland impoundments (Gilmore *et al.* 1982, Gilmore 1987). The species that benefited most greatly were the snook, ladyfish, and striped mullet.

It is now well-documented that wetland impoundment construction and water management has had far-reaching deleterious effects on regional sport and commercial fisheries. In Florida, total fisheries are valued in the billions of dollars to the state economy (Fernald and Purdum 1992). The extent of impounded wetlands in the IRL means that their construction has had a major deleterious regional impact on fisheries and fishery related economies. It is imperative that managers take into account species survival needs during peak recruitment periods at locations that have revealed maximum fishery species use. Wetland use by fishery species must be a primary objective.

Zooplankton

Zooplankton communities represent important links in marine and estuarine food webs and are often important indicators of the overall health of their habitats (Day *et al.* 1989, Odum *et al.* 1963). Zooplankton communities of impounded marshes connected to the Lagoon through culverts are quite similar in abundance and composition to those of near-shore areas of the Lagoon, with a slight over-representation of primarily benthic organisms in the impoundments. These communities are dominated by the copepods *Acartia tonsa* and *Oithona nana*, with other copepods and meroplanktonic organisms becoming abundant at times (Rey *et al.* 1987, 1991a). Isolated pockets in the impoundments have higher abundances and lower diversities than less isolated areas. Short-term isolation of the marsh from the Lagoon by closing the

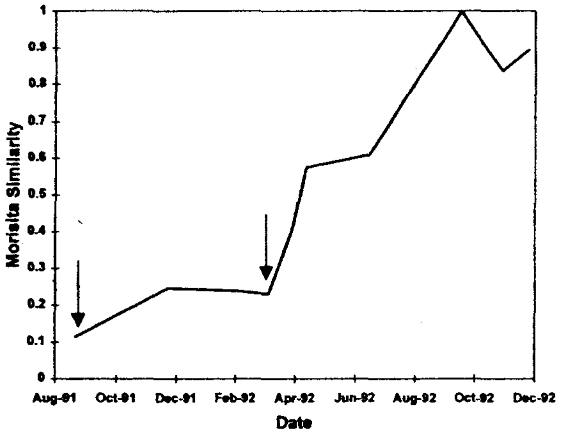

Fig. 4. Morisita Similarity Index between zooplankton collections in an impounded marsh and the adjacent open Indian River Lagoon. Culverts were installed in October 1991, but the culverts remained closed and the impoundment isolated until April 1992 (arrows). Change in community composition was rapid, becoming virtually identical within 6 months after opening.

culverts (*e.g.*, during the summer mosquito producing season) has little impact upon the marsh plankton populations, but maintaining the marsh closed during the entire year results in reduced zooplankton density and diversity (Rey *et al.* 1991a).

In impoundments that had been continuously isolated from the Lagoon for over 10 years, the normal suite of marsh zooplankters was replaced by a community more typical of freshwater areas dominated by rotifers and with very low copepod densities (Rey, unpublished data). However, reconnection of the marsh via four 76.2-cm diameter culverts resulted in a rapid return to the more typical marsh-Lagoon community as indicated by a sharp increase in similarity between impoundment and Lagoon near-shore communities within 6 months (Fig. 4).

Another area of concern relating to planktonic organisms is the fate of individuals that pass through the impoundment pumps. Preliminary data indicate little gross anatomical damage in zooplankters after passage through the pumps (Rey, unpublished data). Actual survivorship tests, however, have not been conducted.

Sediments

Comparison of sediments of several areas within impounded, breached, and natural marshes demonstrated consistent between- and within-site differences that corresponded to the degree of tidal influence in the different areas (Rey *et al.* 1989, Rey and Kain 1993). With increasing hydroperiod, patterns of increasing phosphorous and iron, and decreasing pH, organic matter, potassium, sodium, and electrical conductivity were evident. Past management and vegetation dynamics at the different stations also influenced the sediment chemistry (Rey and Kain 1993). Cluster analysis indicated that sediments near the perimeter ditch of impounded marshes were similar to high marsh stations in the natural and breached marsh. High marsh stations in the impounded marsh, however, differed significantly from those at the natural and breached marsh (Rey and Kain 1993). Current efforts to approximate natural hydroperiods inside impoundments by adjusting the number, size, and placement of culverts (J. David, St. Lucie Mosquito Control District, pers. comm.), and the avoidance of large scale vegetation damage by careful control and monitoring of water levels in impoundments should eventually reduce differences in soil chemistry between impounded and natural marshes.

Water quality

As expected, water quality within impoundments is extremely variable and depends heavily upon impoundment structure, management history, and weather. Some general patterns are discussed below.

In summer, unimpounded high marshes along the Lagoon exhibit high surface water salinities, low dissolved oxygen (DO), and high interstitial sulfide levels (Rey, unpublished data, Carlson *et al.* 1983). Summer flooding tends to lower salinities by dilution and increase DO through increased water movement (Rey *et al.* 1991b).

Nutrient concentrations of marsh surface waters in impounded marshes, particularly the high marsh areas, are higher than in natural marshes, creeks, and ditches, and the Lagoon (Rey *et al.* 1991b).

This pattern is consistent with the nutrient reservoir hypothesis mentioned above, but may be influenced by changes in the denitrification rates (Valiela and Teal 1979) and phosphorus losses (Kennish 1986, Craft *et al.* 1989, Pomeroy *et al.* 1965).

The typical hydroperiod of marshes along the IRL plays an important role in the water quality dynamics of the area. As mentioned above, high marshes along the Lagoon are almost continuously flooded for approximately 3 months of the year, starting with the seasonal rise in sea level in September. During the rest of the year, they remain essentially dry, except for interior ponds and water-holding depressions, or when flooded by storm or other unusually high tides (Provost 1973, Rey *et al.* 1990b, 1991b). Most major exchanges between marshes and the Lagoon occur when the marshes are first flooded in the fall, and when they start to drain in the winter/spring, in agreement with Wiegert's (1977) model (see also Childers and Day 1990).

Impounding modifies this exchange pattern by introducing an "exchange event" when the culverts are open after artificial flooding (if so managed), and by preventing marsh-Lagoon exchange during heavy summer rains and/or storms. The capture of summer storm water within the impoundment reduces the impacts of nutrients and other material on the Lagoon by two processes: (1) Longer residence in the marsh promotes removal of excess nutrients and other substances from the water column before export to the estuary (Rey *et al.* 1991b). (2) Retention in the marsh may mitigate impacts to the Lagoon by separating in time the flows passing through the marshes from those being discharged overland and through relief canals directly into the Lagoon. These processes, which need further investigation, may benefit the IRL by lowering the overall load being discharged into the Lagoon at any particular time and may prevent events such as temporary eutrophication and/or algal blooms associated with high nutrient inputs (Rey *et al.* 1991b).

Water quality in the impoundment perimeter ditches has received considerable attention. At the end of the summer closed period, the water column in the perimeter ditches is often sharply stratified, with an anoxic lower layer with high sulfide content, and an oxygenated upper layer with no sulfide (Carlson *et al.* 1983, Rey *et al.* 1992). Because the Lagoon water levels were usually still low when the culverts were opened, two processes combined to cause a problem: (1) the upper layer of the perimeter ditch flowed into the Lagoon as the culverts were opened, and (2) aquatic organisms which had been distributed throughout the marsh retreated to the perimeter ditch as the impoundment water levels dropped. As a consequence, transient species were stranded in the remaining anoxic layer where they could not survive, and massive fish kills were often observed in the impoundments during this late summer opening.

Several management techniques have since been developed to remedy this situation. The simplest is to delay opening until the Lagoon water levels rise in the early fall, and then open the culverts at high tide so that oxygenated water from the Lagoon (now at a higher level than the impoundment's) flows into the impoundment and mixes with the perimeter ditch water, thus breaking up the stratification. Delaying opening of culverts until Lagoon levels rise in the fall was effective in preventing entrapment of organisms in the lower anoxic, high sulfide layer. A second technique involves the use of "bottom water release" culverts. These are configured so that water from the bottom layer of the ditch is released first, thus allowing organisms to survive in the remaining water as the impoundment drains. During the summer, these "bottom water release" culverts can be combined with continuous pumping to maintain higher DO. In addition, electric aerators can be used when pumping alone is insufficient to maintain DO levels (Heck and Belanger 1989). These latter two methods have been used mainly in St. Lucie County. In the event of a pump failure, an electric aerator can also be used to temporarily protect fish which tend to congregate in the area around pumps (J. David, St. Lucie Mosquito Control District, pers. comm.). Such techniques are energy- and personnel-intensive and are used only in particularly problematic areas, or in special circumstance such as impoundments that are part of state or local parks.

Sulfide dynamics in impoundment waters have received attention because of the importance of hydrogen sulfide as an efficient scavenger of oxygen and its potential toxicity to some aquatic organisms and marsh plants (Nickerson and Thibodeau 1985). Pore and surface water sulfide concentrations were examined near the perimeter ditches of two impounded marshes (one open all year through culverts and a breach in the dike, the other managed under RIM) and a natural tidal creek (Rey *et al.* 1992). Sulfide concentrations in the impoundments were lower than reported from temperate marshes (Carlson and Forest 1982, Howarth *et al.* 1983), but similar to those reported from creekside stations in Georgia (King *et al.* 1982) and South Carolina (Gardner *et al.* 1988). Concentrations in impoundments were generally higher than those recorded by Carlson *et al.* (1983) in black mangrove zones in overwash islands nearby, but lower than concentrations found in the pore waters of red mangrove zones. Both pore and surface water sulfide concentrations were higher in the RIM-managed marsh than in the breached marsh or in the natural creek. This difference was attributed to higher organic matter content and lower water flow in the managed marsh (Rey *et al.* 1992).

Season and management affected sulfide concentration. At all stations, sulfide increased during the summer, reaching peaks during late fall, which is the time of peak litter input into the sediments (Lahmann 1988, Rey *et al.* 1992). When the culverts were opened in the fall, (at high tide after Lagoon water levels were up) pore water sulfide levels rose and peaked near the end of the receding tide; levels then dropped steadily thereafter. This pattern, and the corresponding salinity data, indicate that high sulfide water from the upper marsh was laterally transported towards the perimeter ditches as the marsh drained.

Seagrass

There is concern that seagrass beds adjacent to the impoundments might be affected by the fall opening of culverts and the release of poor quality water into the Lagoon. Preliminary observations in a recently re-connected impoundment in Martin County did not detect any differences in seagrass cover between areas under the influence of culverts and a nearby area where no culverts were present (Rey, unpublished data). No seagrass impacts are obvious based on preliminary examination of large-scale aerial photographs (unpublished). However, larger scale, long term studies are needed before we can reach conclusions about relationships between water clarity, seagrass health, and impoundments.

IRL Surface Water Improvement and Management (SWIM) Wetlands Habitat Program

In 1987, the Florida legislature passed the SWIM Act. This act identified the IRL as a state-wide priority for ecological restoration. The value of wetland function to the ecosystem and the positive benefits identified above were the justification for the inclusion of impoundment reconnection as a high priority in the state-approved IRL SWIM Plan (Steward *et al.* 1994). The St. Johns River and South Florida Water Management Districts (SJRWMD, SFWMD) jointly developed and administer this protection and restoration plan. The IRL SWIM Plan has lead to an extensive multiagency program of impounded marsh rehabilitation. Goals have been established, and implementation is well underway. Costs and benefits are briefly examined and some future activities are outlined.

Goal

The primary objectives of the IRL SWIM program for impounded wetlands are natural productivity and biodiversity – by restoration of wetland habitat and nursery areas for native estuarine animals. A secondary objective is improved water quality. These objectives will be met by restoring the estuarine wetland structure and function to the most natural state practical, by the following strategies:

(1) providing tidal access as in natural systems
(2) maintaining natural hydroperiod (if possible)
(3) managing initially to reestablish natural estuarine wetland vegetation
(4) promoting natural estuarine wetland food webs.

Not all agencies share identical priorities. Most of the impounded wetland acreage in the IRL is within MINWR, which is managed by the U.S. Fish and Wildlife Service (USFWS). The Service's management objectives include mandates to manage for listed species, water fowl, and wading birds. Despite these additional objectives, all parties recognized the potential benefits of reconnecting this vast area of wetlands. Joint management goals agreed to by the SJRWMD, USFWS, and Brevard Mosquito Control District (BMCD) are to increase exchange of water, nutrients, and animals between the Lagoon and the impoundments by maximizing periods of open tidal connection, thus enhancing wildlife and fisheries. In some impoundments, early management efforts are directed toward reducing and controlling nuisance vegetation (*e.g.*, cattails). Mosquito control still needs to be maintained.

Implementation

Implementation is through a multi-agency partnership. Since 1991, SJRWMD's IRL SWIM program has participated in the reconnection of 4,477 ha of impounded wetlands. Most of this area (4,200 ha) was reconnected under contracts with BMCD and 3,927 ha with assistance from USFWS in MINWR. Some of this area was reconnected with the assistance of Florida Department of Environmental Protection's Marine Resources Grants Program which is funded by proceeds of the State's saltwater fishing license.

The majority of isolated wetlands is still within the MINWR, and thus remains SJRWMD's highest priority for impoundment reconnection. As a result, SJRWMD has negotiated contracts with Brevard and East Volusia Mosquito Control Districts and USFWS to reconnect an additional 4,977 ha of impoundments by the end of 1998. The area reconnected through SJRWMD or under contract for reconnection totals approximately 60% of the impounded wetlands in the entire IRL system. Standard contracts provide funding for the purchase of corrugated aluminum culverts (typically 91-cm diameter) and pumps used for seasonal flooding of the impoundments. In exchange, partner agencies agree to install these items in the impoundments and to implement a SOMM-reviewed management plan for the wetland.

In the region of the Lagoon within South Florida Water Management District (SFWMD), nearly all of the impoundments have been reconnected to some degree. The St. Lucie Mosquito Control District, utilizing local resources, began reconnecting county impoundments in the 1980s. SFWMD has provided funds to reconnect the remaining impoundments, to increase the number of culverts in some marginally connected impoundments, and to purchase additional pumps and aerators to enhance water quality in managed impoundments during the summer closure period. These funds have assisted St. Lucie County in pursuing such management enhancements as bottom water releases and summer draw downs discussed earlier.

One stumbling block in the reconnection effort is the private ownership of many of the remaining isolated impoundments (Provost 1959, Carlson and Carroll 1985). In some areas, land owners have not been cooperative in the reconnection effort for fear of losing the mitigation potential of a closed impoundment. In addition, mosquito control officials may be hesitant to actively pursue a reconnection agenda because agreements which allow mosquito management of these isolated impoundments are verbal and non-binding on the owners. Both of these problems could be overcome by the public acquisition of these impoundments. This solution is being pursued by a multi-agency group that includes SJRWMD, SFWMD, the five counties, and The Nature Conservancy.

Cost/benefits of implementation

As mentioned above, the cost of implementation is shared by a multi-agency partnership. As an example, the work done in Brevard County which includes most of MINWR has had several funding sources. From 1993 through the end of the existing contracts with BMCD and USFWS (1998), an estimated $1.8 million will have been dedicated to wetland restoration by the agencies involved. This total includes (1) over $87,000 from the State's saltwater fishing license funds, (2) $31,000 from the sale of the State-sponsored Indian River

Lagoon license plates, (3) over $575,000 in IRL SWIM funds from State and SJRWMD funding sources, and (4) matching contribution of cash and in-kind services from BMCD and USFWS totaling approximately $1.1 million. By 1998, well over 8,000 ha will have been reconnected by this partnership at an average rehabilitation cost of about $225/ha ($90/acre).

Of the wide variety of benefits provided by wetlands, one of the few that has been converted to economic value in Florida is fisheries. Asset value for fully functional saltwater wetlands on the east coast of Florida, based solely on contributions to commercial and recreational fisheries, has been estimated to be $24,000/ha (Bell 1989). If only 50% of that value is restored by reconnection with culverts, the benefit-to-cost ratio is still greater than 50 to 1 for fisheries alone.

Future

Combining efforts by all agencies, public and private, over 75% of the impounded wetlands in the IRL will be reconnected by 1998. Providing this hydrologic connection will not only restore much of the wetland flora and fauna in these impoundments, but also provide substantial ecological benefit to the IRL system as a whole.

Several efforts are underway to evaluate the numerous management alternatives available after impoundment reconnection. These efforts will address issues including resource benefits, cost of implementation, specific management strategies for endangered species, and regional needs for specific management strategies. Some of these evaluations are funded through the IRL National Estuary Program. This Environmental Protection Agency program will soon adopt a Comprehensive Conservation and Management Plan (CCMP) for the IRL which includes nearly all of the IRL SWIM plan priorities for wetlands.

Although simple hydrologic reconnection restores much of the ecological function of impounded marshes, it is not the final solution. The IRL SWIM program and its partners are also pursuing alternative mosquito control techniques such as rotary ditching to institute a version of Open Marsh Water Management (Carlson *et al.* 1991). In some areas, this technique may allow the removal of impoundment dikes, restoring a more natural wetland shoreline and eliminating the summer closure period.

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