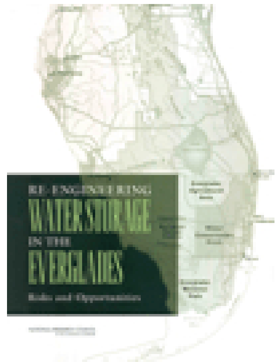

Re-Engineering Water Storage in the Everglades: Risks and Opportunities

Committee on Restoration of the Greater Everglades Ecosystem, National Research Council

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RE-ENGINEERING WATER STORAGE IN THE EVERGLADES

Risks and Opportunities

Committee on Restoration of the Greater Everglades Ecosystem

Water Science and Technology Board
Board on Environmental Studies and Toxicology
Division on Earth and Life Sciences

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COMMITTEE ON RESTORATION OF THE GREATER EVERGLADES ECOSYSTEM (CROGEE)[1,2]

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[1] The activities of the Committee on Restoration of the Greater Everglades Ecosystem (CROGEE) are overseen and supported by the NRC's Water Science and Technology Board (lead) and Board on Environmental Studies and Toxicology (see Appendix B).

[2] Biographical sketches of committee members are contained in Appendix C.

[3] Lead NRC staff supporting the drafting of this report.

Preface

The Everglades of south Florida is truly a unique ecosystem. Nowhere else on Earth is there the same combination of a warm and alternately wet-dry climate, relatively flat topography, and predominantly limestone geology that came together in south Florida to create a vast wetland unlike any other. The animals and plants that live there have evolved in a unique environment and thus the biological community is unique as well. The ecological value of this ecosystem is reflected in the approval by Congress in 2000 of nearly $8 billion for its restoration. And restoration is needed: the changes that have occurred in south Florida over the past century have been dramatic. They include the development of large cities along Florida's coasts; the development of agriculture in the region, especially to the south of Lake Okeechobee; and the construction of canals, levees, dikes, roads, and other structures in and around the Everglades designed to move water and people and to protect people and their structures from floods.

Restoring the ecosystem—or even successfully preventing further degradation—is an enormous and exciting challenge. There is no successful model to follow anywhere. Many components of the restoration plan depend on relatively new technologies, untried at the scale envisioned for the Everglades. A host of financial, political, social, environmental, ecological, administrative, and legal challenges make the effort even more complex. The stakes are high.

This is the seventh and final report[1] of the National Research Council's (NRC) Committee on Restoration of the Greater Everglades Ecosystem (CROGEE), which provides consensus advice to the South Florida Ecosystem Restoration Task Force ("Task Force"). The Task Force was established in 1993 and was codified in the 1996 Water Resources Development Act (WRDA); its responsibilities include facilitating the coordination of the development of a comprehensive plan for restoring, preserving, and protecting the south Florida ecosystem, and the coordination of related research. The CROGEE, established in 1999, works under the auspices

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[1] The six previous reports are: Aquifer Storage and Recovery in the Comprehensive Everglades Restoration Plan: A Critique of the Pilot Projects and Related Plans for ASR in the Lake Okeechobee and Western Hillsboro Areas (2001); Regional Issues in Aquifer Storage and Recovery for Everglades Restoration (2002); Florida Bay Research Programs and their Relation to the Comprehensive Everglades Restoration Plan (2002); Adaptive Monitoring and Assessment for the Comprehensive Everglades Restoration Plan (2003); Science and the Greater Everglades Ecosystem Restoration: An Assessment of the Critical Ecosystem Initiative (2003); and Does Water Flow Influence Everglades Landscape Patterns? (2003).

of the National Research Council's Water Science and Technology Board and Board on Environmental Studies and Toxicology.

The CROGEE's mandate includes providing the Task Force with scientific overview and technical assessment of the restoration activities and plans, while also providing focused advice on technical topics of importance to the restoration effort. The main topic of this report is the storage options in the restoration program. Replacing the natural storage and flow-damping functions within the Greater Everglades that have been lost through more than a century of drainage and development in south Florida is at the heart of the Restoration Plan's goal of "getting the water right." Thus, the success of this multidecadal, multibillion dollar restoration project hinges on the many project components related to storage, some conventional and some novel.

Over the past five years, the CROGEE has devoted several meetings to reviews of hydrologic and ecological analyses and other considerations with respect to water storage components proposed in the restoration effort. Those meetings included workshops, field trips, and public sessions. This final report of the CROGEE is based on information obtained during these meetings as well as additional review of literature and project documents by committee members. The Restoration Plan continues to evolve, and some recent changes that occurred after this report entered review were not evaluated by the committee. Whereas this report focuses on storage, because of the critical role played by storage components in the Restoration Plan, it also touches on and has implications for broader issues related to the scientific basis of the plan, some of which have not been fully explored in previous committee reports.

The entire committee, with valuable assistance from NRC staff David Policansky, William Logan, and Patricia Jones Kershaw, was involved in the development and writing of this report. The director of the Water Science and Technology Board, Stephen Parker, guided the overall effort and contributed substantively to the committee's deliberations. Working with them has been educational and productive, and I am grateful to them all. The CROGEE is grateful for the numerous meeting presentations, assistance in data gathering, clarification of project documents, and fact checking provided by many individuals from the Army Corps of Engineers, the South Florida Water Management District, Everglades National Park, and other partners in the Restoration Plan. The committee has been impressed with the quality of service the staff of those agencies and others are providing to the public. They are dedicated, thoughtful, and able. We suspect that they, like the committee, are motivated at least in part by the wonders of the ecosystem we all have been focusing on. It is difficult to single any of them out for the help they gave to this committee, but I would be remiss not to give special thanks to Stuart Appelbaum, Nick Aumen, Ronnie Best, Michael Chimney, Steve Davis, Bob Johnson, Jayantha Obeysekera, John Ogden, Peter Ortner, and Kenneth Tarboten for their clear briefings, willingness to provide information, and their patient answering of the committee's questions.

This report has been reviewed in draft form by individuals chosen for their diverse perspectives and technical expertise in accordance with procedures approved by the NRC's Report Review Committee. The purpose of this independent review is to provide candid and critical comments that will assist the institution in making its published report as sound as possible and to ensure that the report meets institutional standards for objectivity, evidence, and responsiveness to the study charge. The review comments and draft manuscript remain confidential to protect the integrity of the deliberative process.

We wish to thank the following individuals for their review of this report:

David L. Freyberg, Stanford University
Steven P. Gloss, U.S. Geological Survey and University of Arizona
Louis J. Gross, University of Tennessee
Frances C. James, Florida State University
Stuart L. Pimm, Duke University
Rutherford H. Platt, University of Massachusetts, Amherst
Jerald L. Schnoor, University of Iowa
Leonard Shabman, Resources for the Future
John Vecchioli, Odessa, Florida

Although the reviewers listed above have provided many constructive comments and suggestions, they were not asked to endorse the conclusions or recommendations nor did they see the final draft of the report before its release. The review of this report was overseen by George M. Hornberger, University of Virginia and Frank H. Stillinger, Princeton University. Appointed by the National Research Council, they were responsible for making certain that an independent examination of this report was carried out in accordance with institutional procedures and that all review comments were carefully considered. Responsibility for the final content of this report rests entirely with the authoring committee and the institution.

Jean M. Bahr, Chair
Committee on Restoration of the Greater Everglades Ecosystem

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APPENDIXES

Executive Summary

The Everglades of south Florida once encompassed about 4,600 mi^2 (three million acres) of slow-moving water and associated biota that stretched from the Lake Okeechobee drainage basin in the north to Florida Bay in the south (Figure ES-1).[1] Today, human settlements and associated flood-control structures have reduced the Everglades to about half its original size.

To remedy the degradation of the Everglades, the Comprehensive Everglades Restoration Plan ("Restoration Plan"), was unveiled in 1999 with the goal of restoring the original hydrologic conditions to what remains of the natural ecosystem. Also in 1999, the National Academies established the Committee on Restoration of the Greater Everglades Ecosystem in response to a request from the Department of the Interior on behalf of the South Florida Ecosystem Restoration Task Force. The committee's task (see Box ES-1) was to provide the Task Force with scientific advice in respect to the restoration activities and plans. This report evaluates the many storage options considered by Everglades restoration planners, including some options that are not in the Restoration Plan. Storage is a critical aspect of the Everglades ecosystem and of the Restoration Plan, but other critical factors, such as timing of land acquisition, intermediate states of restoration, and evaluating tradeoffs among competing goals or ecosystem components, provide the context for choosing and implementing storage options. Therefore, this report considers them as well.

WHY IS STORAGE IMPORTANT?

A basic premise of the Restoration Plan is that if the water is "right," then the ecosystem will become "right" as well. The amount of water in the Greater Everglades Ecosystem today, and its spatial and temporal distributions, are very different from conditions in the natural system, which included the Kissimmee River drainage north of Lake Okeechobee, the lake, and the Everglades system south of the lake. Before drainage and other human modifications to the landscape that began in the late 1800s, seasonal variations in the amount and distribution of water in the system were strongly damped and the system was not as prone as it is today to rapid water-level changes that cause flooding and drying. In addition, the human demand for water in south Florida is much greater than it was 100 years ago, and there often are competing goals for the use of stored water.

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[1] The Greater Everglades Ecosystem includes uplands, wetlands, and other landscape types and extends from the headwaters of the Kissimmee River near Orlando through Lake Okeechobee and Everglades National Park into Florida Bay and ultimately the Florida Keys. In this report we refer to the areas of sawgrass and marl prairie and other wetlands south of Lake Okeechobee as "The Everglades" or "the Everglades ecosystem." We always use "Greater Everglades Ecosystem" for the larger area, and only for that area.

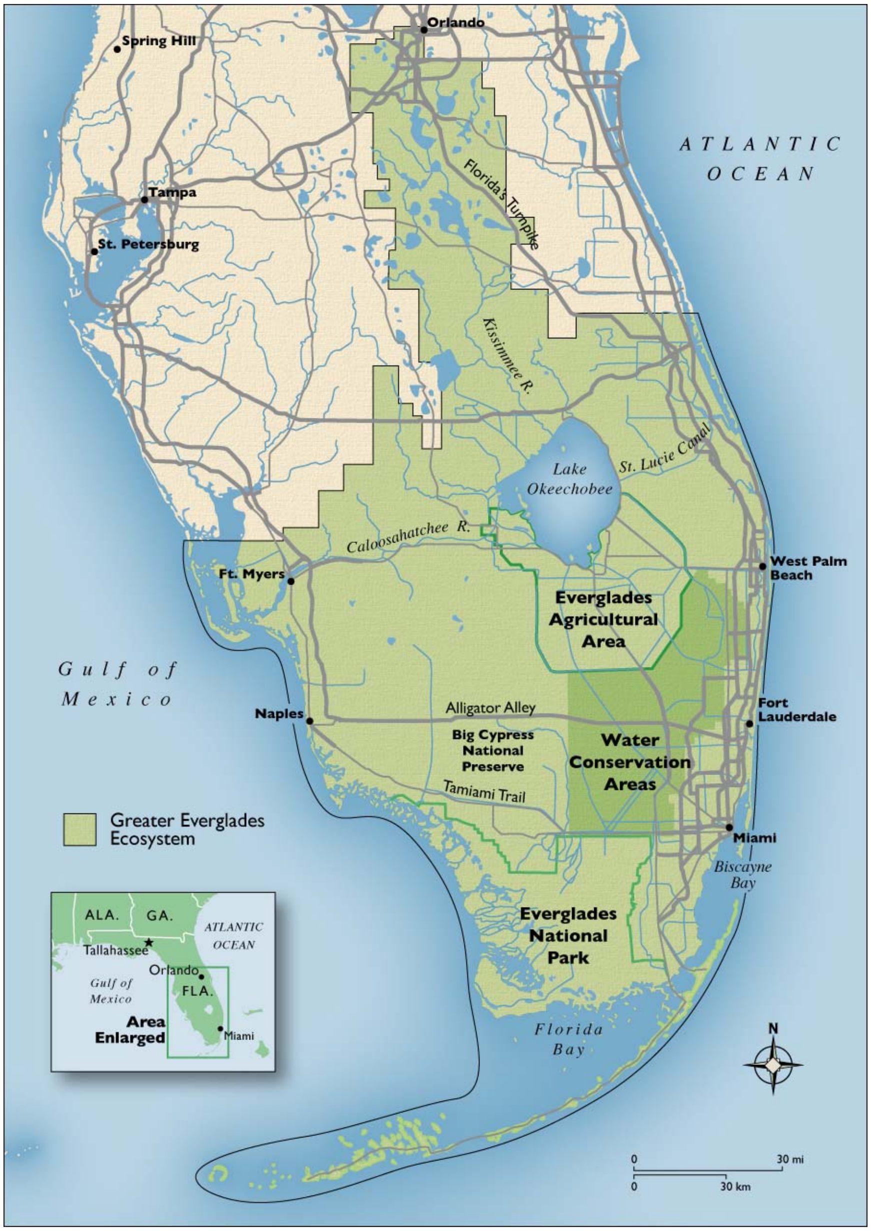

FIGURE ES-1. The Greater Everglades Ecosystem. SOURCE: Data from USACE and SFWMD.

BOX ES-1

Committee Statement of Task

This NRC activity (CROGEE) provides scientific guidance to multiple agencies (the South Florida Ecosystem Restoration Task Force, or SFERTF) charged with restoration and preservation of the Central and South Florida aquatic ecosystem, i.e., the greater Everglades. The activity provides a scientific overview and technical assessment of the many complicated, interrelated activities and plans that are occurring at the federal, state, and nongovernmental levels. In addition to strategic assessments and guidance, the NRC provides more focused advice on technical topics of importance to the restoration efforts when appropriate.

A major feature of the restoration plan is providing enough water storage capacity to meet human needs while also providing the needs of the greater Everglades ecosystem. One of the primary assumptions of the restoration effort has been that “getting the water right” is the most important single factor leading to sustainable ecologic restoration. Given the importance of storage to the restoration effort the CROGEE, with the SFERTF endorsement and cooperation, undertook a review of hydrologic and ecological analysis and other considerations with respect to analysis of size and location of water storage components proposed in the Restudy.

Early modifications to the landscape drained many areas and increased peak flows in others. Overall, they reduced the amount of water stored within the Everglades Ecosystem and thus increased the risk of desiccation of wetlands in the southern part of the system during droughts. However, at the same time, these modifications increased the risk of flooding in many areas. For all those reasons, many control structures such as levees and canals were built, and the Water Conservation Areas (WCAs) were created. The result is that parts of the Everglades are water-starved at times, other parts are submerged, and the natural timing and amplitudes of high-water and drying events have been severely disrupted. Large pulses of fresh water diverted to sea have also had detrimental effects on estuaries. As a result, the Restoration Plan includes large amounts of new, constructed storage to replace lost natural storage and supply the water that is needed for both people and the ecosystem when and where it is currently in shortest supply.

It is not clear exactly what ecological conditions will accompany hydrologic change, but there is merit in concluding that more natural hydrologic conditions will lead to improved ecosystem functioning. Thus attempting to “get the water right” (or at least better) is a reasonable approach to restoration.

MAJOR STORAGE AND WATER-CONSERVATION COMPONENTS IN THE RESTORATION PLAN

The major aspects of the Restoration Plan involve currently available and planned storage facilities. The largest existing storage components are Lake Okeechobee and the WCAs. Additional components are in place or planned for the completed Restoration Plan.

Lake Okeechobee

Lake Okeechobee historically was the key hydrologic link between the mainly upland ecosystems to the north and the wetlands ecosystems to the south. The lake receives an annual average of 1.6 million acre-feet of water through the Kissimmee River and discharges 416,000 acre-feet to the sea through the Caloosahatchee River and the St. Lucie Canal. Additional water is discharged to the WCAs and to adjacent agricultural areas.

Despite many hydrologic changes to the system, the lake still provides substantial water storage. While current operating rules are not designed primarily to maximize storage, they do permit up to 470,000 acre-feet of storage capacity for each foot of drawdown. Planned modifications to the operating rules, which are intended to reduce fluctuations in lake level to protect the littoral zone, water supply, and levee integrity, will decrease available storage capacity in the lake.

Lake Okeechobee has higher nutrient concentrations, especially phosphorus, than would be ideal as a source of water for the Everglades, despite extensive efforts to limit nutrient inputs. These concentrations are substantially above stated goals for the lake. It is a goal of the Restoration Plan to reduce nutrient concentrations in the lake, largely by reducing nutrient inflows.

Water Conservation Areas

The central Everglades was converted into surface reservoirs called WCAs when levees were completed in 1963. They are currently used to detain excess surface water. WCAs serve many competing uses, including controlling floods, storing water to augment supplies along the east coast and in Everglades National Park, recharging groundwater, reducing seepage of water to the coast, and providing habitat for wildlife. Their combined storage capacity is 1,882,000 acre-feet. The WCAs still contain substantial remnants of original Everglades landscapes and thus offer a major opportunity for restoration. Restoration Plan projects are planned to “decompartmentalize” the WCAs and enhance sheetflow.

Conventional Surface Reservoirs

The Restoration Plan includes large conventional reservoirs in the Kissimmee basin north of Lake Okeechobee, the Everglades Agricultural Area, and the Upper East Coast plus additional smaller reservoirs and stormwater treatment areas (STAs) to remove nutrients, especially phosphorus. Together these features will provide new storage capacity of about 1,120,000 acre-feet.

Land acquisition costs for new reservoirs would be significant, especially for the Upper East Coast reservoirs. The long-term effectiveness of STAs is still untested, but their lifespans are finite. Some water-quality issues remain to be resolved.

Aquifer Storage and Recovery (ASR)

ASR involves pumping water into subsurface geologic formations, then recovering it as needed. It has a planned annual average capacity of over 500,000 acre-feet of storage and a cumulative capacity of more than 4 million acre-feet. Even with 30 percent loss of water during injection (as assumed in simulations by the SFWMD), the ASR systems account for about three-quarters of the new storage capacity of the Restoration Plan. ASR would not require large amounts of land; in addition, water stored underground would not experience evaporative losses. However, ASR—especially on as large a scale as envisioned in the Restoration Plan—is an untested technology. It also will require large amounts of energy for injecting and recovering water, and the water might need treatment to meet quality standards.

In-Ground Storage

This component is planned to consist of reservoirs constructed in former quarries up to 80 feet deep with a storage capacity of about 330,000 acre-feet. Two of these west of Miami are anticipated to cover 9,700 acres; the area likely will be mined whether or not the quarries are converted to reservoirs. The conversion will require seepage barriers. As is true for ASR, the technology for creating such barriers at this scale has not been developed or tested, and so costs and feasibility of this option are uncertain. Therefore, pilot studies are planned, but these are not yet under way. Estimated construction costs are higher than for conventional surface reservoirs, and the seepage barriers will likely incur maintenance and repair costs over the long term. Water quality issues also are unresolved at present.

Seepage Management

Seepage across levees that bound the WCAs and Everglades National Park can exceed one million acre-feet per year. Seepage management reduces this loss or recovers it and returns it to the interior. It is not a storage component, but as a water-conservation component it would have the same net effect as storage.

Water Reuse and Conservation

This component envisions two wastewater-reuse facilities in Miami-Dade County, ultimately slated to produce 220 million gallons per day or about 250,000 acre-feet per year. It requires advanced waste treatment with high capital and maintenance costs. This option involves conservation rather than storage, to be implemented in the likely event that more economical sources of water are not available.

Costs and Effectiveness

The storage options can be compared in terms of their costs and effectiveness in several ways. Of the new storage components that will be created by the Restoration Plan, conventional storage reservoirs have the advantages of using proven technology and of needing less input of energy and money than water reuse or ASR. ASR systems are the most expensive to site and build when compared on the basis of average annual outflow, but they are the least expensive when compared on the basis of the maximum storage they can provide in a single year. Other factors, such as reliability, environmental consequences, and social and political acceptability also are important.

SEQUENCING

The creation of new water-storage capacity through implementation of the Restoration Plan involves large-scale re-engineering of much of the Greater Everglades Ecosystem and it consists of many individual projects. With so many components and constraints on this ambitious project, how the components are ordered in space, and especially in time, can profoundly affect the outcomes of the project.

The project's overall plan does impose some constraints on sequencing of its components, as is true for any construction project. The committee judged two criteria to be most important in deciding how to sequence components of such a project.

Protect Against Additional Habitat Loss

The first criterion is that the sequencing should protect the system against any damaging changes in external or environmental conditions—especially for habitat that is or has the potential to be ecologically valuable—that would adversely affect the project's success and that could not be reversed if such changes occurred. In the case of the Restoration Plan, the most striking such environmental change would be the loss or irreversible[2] alteration of land-surface required to implement the plan. The most urgent and overriding sequencing criterion should be to protect from irreversible development all land that is or potentially could be included in the Restoration Plan. This kind of protection can be achieved by acquisition of the land, by obtaining easements, by zoning restrictions, or other methods. The Restoration Plan specifies that the method to be used is acquisition. Despite annual expenditures for land acquisition of between $100 million and $200 million, the plan for acquisition of the needed lands that have not yet been acquired extends over more than two decades. Irreversible development of land not yet acquired and increases in the price of land are almost certain. Therefore, delays in acquiring or protecting critical lands risk compromising the outcome of the Restoration Plan.

Provide Ecological Benefits as Early as Possible

The second criterion is that the sequencing should provide ecological benefits as early as possible. As the restoration of the Everglades begins, there is continuing reduction in species' distributions and loss of habitats distinctive of the Everglades. There is high potential for these losses to be irreversible. In addition, invasive species continue to increase in number and distribution in the Everglades, despite efforts to eliminate some of them. As the ridge-and-slough and tree-island landscapes continue to erode, there is increased homogeneity of Everglades land-

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[2] The term "irreversible" here refers to changes that cannot be reversed at an acceptable cost or within the time frame of the Restoration Plan (50 years), i.e., changes that are practically irreversible; or at all, i.e., absolutely irreversible changes. Extinctions are absolutely irreversible; development of residential, commercial, or industrial infrastructure is practically irreversible.

scapes. Communities of marl prairies and periphyton mats continue to diminish in areal coverage, and nutrient loading continues to be above historic levels. These continuing losses and degradation of habitat and ecological functioning and the great uncertainty associated with implementation of the Restoration Plan and ecological restoration goals all argue for increased emphasis on achieving near-term ecological results. Those uncertainties are discussed below.

SYSTEM UNCERTAINTIES

The ability of the various storage technologies in the Restoration Plan to provide the quantity and quality of water required to achieve the Plan's goals is surrounded by a variety of uncertainties. Some uncertainties are inherent in measurement and interpretation of both hydrologic and ecological data. In addition, there are uncertainties related to natural variability and unpredictability of ecological systems (process uncertainty) and model applications. Natural system uncertainties include processes such as climate change—certain to occur, but uncertain in magnitude, rate, and direction—and ecological system responses to such changes. Model uncertainty arises from the use of simplified, abstract representations of complex systems and from model error, i.e., misunderstanding of variables and the functional form of the model. There also is uncertainty about historical information on the system, which is used for the Natural System Model to identify hydrologic goals for the Restoration Plan. Further, model projections are based on a fully implemented Restoration Plan, but there is uncertainty about what hydrologic and ecological conditions will occur during the transition from current conditions to the final restored conditions. Finally, there is uncertainty about what the restored hydrologic and especially ecological conditions will be, when they will be attained, and how variable they will be. These unavoidable uncertainties underscore the importance of procedures that can accommodate them.

Large uncertainties surround the future population size and its distribution in the region, and human activities, both in and outside the region. Population projections for south Florida have a history of being too low. At some unknown future time, however, population growth will slow and stop, and the slowing likely will not be well predicted either. Other uncertainties are associated with changes in societal values and restoration policy, including uncertainty about the location, size and timing of future stressors to the system. Funding for the Restoration Plan will be influenced by changes in values and policies. Events outside the region also are likely to affect what happens in the region.

Specific issues that introduce uncertainties include the Endangered Species Act (ESA) and its effect on implementation of water management, even though recovery of endangered species is an explicit objective of the Restoration Plan. For example, even management actions that could have beneficial effects on the Everglades in terms of Restoration Plan goals could be prevented, by Fish and Wildlife Service regulation or litigation by others if those actions adversely affected an endangered species, even temporarily. As discussed in Chapter 3, lawsuits based on the Clean Water Act also have introduced uncertainty to the implementation of the Restoration Plan.

Another issue is the effect of invasive and irruptive species. The Everglades has many nonnative invasive species, notably the Australian bottle brush tree, Brazilian pepper, and Australian pine. The native cattail seems to have dramatically increased its presence in the Everglades as a result of higher phosphorus concentrations, deeper water, and longer periods of inundation. Several tropical fish species have become established in the Everglades as well.

SUSTAINABILITY OF THE RESTORATION PLAN

The Restoration Plan relies very heavily on engineered solutions such as ASR and the Lake Belt storage system. Although there is a clear need for additional storage to implement the Restoration Plan, experience suggests that natural restoration processes usually produce more satisfactory restoration outcomes than engineered ones. However, opportunities to restore a system in which flows are controlled only by natural processes in natural areas are severely constrained in south Florida. This is the result of the restricted footprint of the remaining natural areas in the Everglades, the proximity of urban and agricultural lands that cannot be subjected to flooding without significant loss of property values, and the current and future demands for urban and agricultural water supply. Many of the natural storage features of the system, which provided essential damping of seasonal and storm-driven flows, have been lost permanently as a result of agricultural and urban development. Simply routing excess water from Lake Okeechobee to the southern Everglades through pipes or other structures that bypass the agricultural area would reduce the detrimental pulses of freshwater discharged to estuaries, but it would generate unnatural timing and magnitudes of flows and water levels, as well as high nutrient concentrations, in the terrestrial ecosystem and in Florida Bay.

Some of the natural storage and damping could be restored if agricultural land south of Lake Okeechobee were converted into a restored corridor connecting the lake to the southern Everglades. However, subsidence due to peat loss in the agricultural area south of Lake Okeechobee has caused the land surface to be lower than in areas to the south. This means that even if the Herbert Hoover Dike were breached, slow sheet flow to the south would not be restored in the area that was historically a sawgrass plain. Instead, the subsided region would become an extension of the lake itself. An expanded lake of this type would provide significant storage and damping of southward flows, but it would also inundate established communities and agricultural lands surrounding the current perimeter of the lake and increase the flooding hazard in other areas to the south and southeast. This type of restoration, therefore, would require additional engineering measures for flood control.

Clearly, some degree of engineering control will be necessary in any plan to restore more natural water levels and flows in the southern Everglades. The framework developed by an earlier NRC committee to consider options for interventions to enhance wild salmon runs in the Pacific Northwest is applicable to the Everglades restoration as well. The earlier committee recognized, as we do, that engineering techniques would be needed, at least in the short term, but recommended that they be used with the ultimate goal of rehabilitating ecosystems to the point where human inputs can be substantially reduced, if not eliminated.

There is a considerable range in the degree to which various proposed storage components involve complex design and construction measures, rely on active controls and frequent equipment maintenance, and require fossil fuels or other energy sources for operation. Storage components that have fewer of those requirements are likely to be less vulnerable to failure and hence are likely to be more sustainable in the long term.

A SECOND LOOK AT CONSTRAINTS, BOUNDARIES, AND ADAPTATION

The planning framework that led to the Restoration Plan resulted from a process of adaptation and compromise among interests and concerns of myriad stakeholders in south Florida, including governments. As new information becomes available and as the effectiveness and feasibility of various restoration components become clearer, some of the earlier adaptation and compromises probably will need to be revisited if the restoration is to meet its goals. Unanticipated changes that occur will likely require rapid responses. Therefore, it is even more important to deal with changes that can be anticipated in a timely and proactive way. The progressive loss of soil in the Everglades Agricultural Area is an example of a change that can be anticipated in advance. In addition, it is likely to become ever clearer that not all current interests and conditions can be protected while preserving restoration options. We discuss two examples here, the Everglades Agricultural Area and Lake Okeechobee.

Everglades Agricultural Area

The Everglades Agricultural Area (EAA) immediately south of Lake Okeechobee was an important conduit for sheetflow in the unaltered Everglades. Today, this area of rich peat soils is devoted mainly to sugarcane production. The total agricultural value of its produce is more than $640 million annually. However, agricultural drainage has led to oxidation of the peat soils and subsequent subsidence. It is certain that unchecked, subsidence will eliminate the topsoil, making agriculture at best extremely expensive, although it is not certain just when that will occur. The EAA has a variety of potential fates. The worst from the point of view of Everglades restoration would be commercial, residential, and industrial development of the area. It is not clear what continued agricultural production would require, but it is likely that eventually the required treatments would make the area less amenable to restoration. Another possibility would be to consider uses of the EAA more aligned with restoration needs. Those might include turning parts or all of it into a wetland with a cattail-sawgrass gradient. Perhaps it could simply be flooded and the water used for storage and to enhance sheetflow.

As discussed in Chapter 4, many factors unrelated to the Restoration Plan, such as import restrictions on sugar, the number and distribution of people living in south Florida, energy costs, and so on are likely to change, and those changes will affect calculations related to potential uses of the EAA. For these reasons, this committee recommends a re-evaluation of the EAA's future role in Everglades restoration. This is a complex analysis, requiring estimates of the costs of land acquisition, the feasibility and likely costs of various options, and other matters. Such analysis should begin as soon as possible.

Lake Okeechobee

Lake Okeechobee is a major component of the Everglades ecosystem. It was a key natural hydrologic link between upland ecosystems to its north and the marshes and prairies of the Everglades to the south, and, especially before the hydrologic modifications made in the twentieth century, it moderated the effects of variations in rainfall. It also provides drinking water to nearby communities and recreational opportunities. The lake has the capacity to provide much more storage than it does under its current operating rules. Several issues, including water quality, flood control, and the extent and functioning of the littoral zone, need careful consideration if the lake is to serve the latter purpose.

Several options available for increasing the storage capacity of the lake have been considered in the development of the Restoration Plan; they would have extreme effects on lake levels and would diminish the lake's ecological value and its value for fishing. Other more moderate options or combinations might have a better array of costs and benefits. Given the possibility that some of the components of the Restoration will be more costly or less effective than envisioned, the committee judges that the use of Lake Okeechobee for storage should be revisited. Other storage options have their own environmental and financial costs, and the analysis could lead to a beneficial change in the overall plan. For both the EAA and Lake Okeechobee, any actions taken after the re-evaluations should be done using adaptive management. An added incentive for the re-evaluation is the potential to provide ecological benefits earlier in the restoration.

ANALYZING TRADEOFFS

A Conceptual Restoration System Performance Measure

In previous reports of this committee, the importance of evaluating the restoration effort was discussed. This has been a major focus of the Restoration Plan scientists as well. Major difficulties are associated with such evaluations. One is translating the general and societal goals of the Restoration Plan into realistic targets and performance measures. Restoration of the ecosystem to its pristine state, however that might be defined, is not possible, because so much has changed in south Florida. Another difficulty is that restoration of one aspect of ecosystem functioning or of biological diversity might have to come at the expense of another. And not all aspects of ecosystem structure and functioning are equally valued by all sectors of the public or even by all agencies in the region. Thus, any overall restoration goal will require tradeoffs among subsets of ecosystem goals and among desired endpoints. For these reasons, the committee proposes a system performance measure based on multi-attribute decision making that could be used to help evaluate restoration progress and alternatives. The measure is akin to a utility function in economics, is based on hydrologic performance measures, and can be expressed mathematically as the weighted sum of individual performance measures.

The performance measure is intended to complement rather than replace other evaluation tools already in place. Its main value would be in the context of an inclusive process involving stakeholders to evaluate policy and management tradeoffs and alternatives. Its properties are described in Chapter 5, and its use as an analytic tool is recommended. In addition to the numerical performance measure, and based in part on it, there is a need to embed learning into the processes of project planning, evaluation, implementation, and operation (adaptive management).

MAJOR FINDINGS AND RECOMMENDATIONS

Finding 1. The historic resilience of the ecosystem was a direct consequence of the continuity and the diverse mosaic of natural system communities found over a wide range of spatial scales. As the spatial extent of the ecosystem is reduced, the resiliency of the system is reduced and susceptibility to unexpected and irreversible change is increased. Although a considerable amount of money ($100-200 million annually) is allocated to land acquisition, it seems certain that some land not soon acquired will be developed or become significantly more expensive before the two-decade-long acquisition program can be completed. Protecting the potential for restoration, i.e., protecting the land, is essential for successful restoration.

Recommendation 1. Preservation of the remaining areal extent of the potential natural system should be a priority. Land should be purchased or conservation easements should be obtained now to prevent additional loss of land to development and to provide a buffer between the built and natural environments. (Chapter 3.)

Finding 2. A restoration as ambitious and complex as the Everglades Restoration Plan has the potential to allow—and perhaps even cause—irreversible changes to the Everglades ecosystem as it proceeds. Some processes of deterioration might continue to an undesirable endpoint before the restoration is complete, and in some cases, it is possible that an intermediate stage between current conditions and the restoration goal could result in additional damage.

Recommendation 2. Efforts should be made to prevent irreparable damage to the ecosystem during the restoration. The focus should be on interim changes in the system as well as the end point of the restoration to avoid losses in the short-term that will prevent ecosystem restoration in the long term. (Chapter 3.)

Finding 3. Some aspects of the restoration are likely to benefit the target ecosystem components while adversely affecting others, at least until the restoration is completed. In other cases, finite resources and other factors are likely to lead to differing restoration goals for different parts of the ecosystem and among different stakeholders.

Recommendation 3. Methods should be developed to allow tradeoffs to be assessed over broad spatial and long temporal scales, especially for the entire ecosystem. Development of methods now, such as the overall performance indicator described in Chapter 5, will allow alternatives to be tested quickly and modifications to the restoration to be developed when surprises do occur. (Chapters 3, 4, and 5.)

Finding 4. It is likely that some components of the Restoration Plan will be more costly or less effective than envisioned. The high degree of uncertainty associated with all phases (economic, social, political, engineering, and ecological) of the Restoration Plan necessitates the allocation of significant effort to establish alternative approaches to restoration (contingency planning). Even if the Restoration Plan "gets the water right," there are circumstances that might prevent restoration of the Everglades to the conditions envisioned by the plan. The multi-species recovery plan, efforts to eradicate invasive species, changes in water-quality legislation, and many other factors may have major influences on the restoration effort.

Recommendation 4. In addition to the contingency planning that already is being undertaken, more intensive and extensive planning should be pursued. In particular, options such as those discussed in Chapter 4 should be considered for using the Everglades Agricultural Area and Lake Okeechobee as elements of the Restoration Plan in ways that are not now part of the plan. Any such change in the use of EAA and Lake Okeechobee should be undertaken using adaptive management, and it has the potential to bring ecological benefits earlier. (Chapter 4.)

Finding 5. A variety of economic, political, financial, engineering, and other factors and constraints have resulted in a restoration plan that provides most of its ecological benefits towards the end of the process. Some of the delay is unavoidable, because some engineering structures must be in place before other elements of the plan can be implemented. However, the longer the provision of such benefits is delayed, the more likely that continued degradation will occur, that loss of species and habitats will continue, and that at least some political support will be lost as well. These factors argue for increased emphasis on ecological results earlier in the plan.

Recommendation 5. Restoration projects should be implemented in a way that provides benefits to the natural system sooner rather than later by accelerating storage projects that are not as reliant on technology or use short-term storage solutions to achieve benefits to the natural system until more technologically advanced methods are proven. An example of such a benefit to the natural system would be providing more natural flows (in terms of seasonal timing, volume, and flow velocity) to Everglades National Park. Doing so might not require large-scale changes in sequencing; instead, incremental changes could add up to be significant. (Chapter 3.)

Finding 6. Many projects that will contribute to or otherwise affect the restoration of the Everglades are not part of the Restoration Plan. To the degree that there is coordination or at least communication among those projects, benefits of economy and of effectiveness are likely.

Recommendation 6. Coordination and communication among the various restoration efforts should continue to receive high priority. (Chapter 3.)

Finding 7. Considering the 40-year time frame of the Restoration Plan and perhaps a century of system response, a regional information synthesis center would enable the systematic provision of evolving, reliable knowledge in support of the policy process and the interested public who affect and are affected by the program. Such a center also would help implement adaptive management on a system-wide basis.

Recommendation 7. Incorporation of integrated assessment models, long-range-development scenarios, and a regional information-synthesis center into an adaptive-management and assessment program in the Restoration Plan should be considered. Monitoring is an essential part of adaptive management, and models have the potential to help design, assess, and evaluate the results of monitoring programs. (Chapter 3.)

1

Introduction

The Everglades of south Florida once encompassed about 4,600 mi^2 (three million acres) of slow-moving water and associated biota that stretched from the Lake Okeechobee drainage basin in the north to Florida Bay in the south (Figure 1-1) (Davis et al., 1994). The drainage basin for Lake Okeechobee extends north to a series of lakes near Orlando, and thus the Everglades drainage basin covers an area of approximately 10,890 mi^2 (seven million acres) (Light and Dineen, 1994; Ogden et al., 2003). Today, human settlements and associated flood-control structures have reduced the Everglades itself to about half its original size (Davis et al., 1994). Everglades National Park includes areas such as Florida Bay and coastal mangroves that are not usually considered part of the "true Everglades" (Davis et al., 1994).

To remedy the degradation of the Everglades, the Comprehensive Everglades Restoration Plan (the CERP, referred to in this report as "the Restoration Plan"; USACE and SFWMD, 1999), was unveiled in 1999 with the goal of restoring hydrologic characteristics as close as possible to their original conditions in what remains of the natural ecosystem. Also in 1999 the National Academies established the Committee on the Restoration of the Greater Everglades Ecosystem (CROGEE) in response to a request from the Department of the Interior on behalf of the South Florida Ecosystem Restoration Task Force (SFERTF[1]). The committee's task (see Box ES-1) was to provide the Task Force with scientific overview and technical assessment of the restoration activities and plans, while also providing focused advice on technical topics of importance to the restoration efforts. This report does both. It evaluates the many storage options considered by Everglades scientists, engineers, and planners, including some that are not in the Restoration Plan. Storage is a critical aspect of the functioning of the Everglades ecosystem and of the Restoration Plan, but other critical factors, such as timing of land acquisition, intermediate states of restoration, and evaluating tradeoffs among competing goals or ecosystem components, provide the context for choosing and implementing storage options. Therefore, this report considers them as well.

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[1] The SFERTF was established by the Water Resources Development Act of 1996, which also specified its composition. Its 14 members include the secretaries of Interior (chair), Commerce, Army, Agriculture, and Transportation; the Attorney General, and the Administrator of the Environmental Protection Agency, or their designees. One member each is appointed by the Secretary of the Interior from the Seminole Tribe of Florida and the Miccosukee Tribe of Indians of Florida. The Secretary of the Interior also appoints, based on recommendations of the Governor of Florida, two representatives of the State of Florida, one representative of the South Florida Water Management District, and two representatives of local Florida governments. Current membership and information about the SFERTF are available at *http://www.sfrestore.org/.*

In its several previous reports, the NRC has provided scientific and technical advice about aquifer storage and recovery (NRC, 2001a), regional issues in aquifer storage and recovery (NRC, 2002a), research programs in Florida Bay (NRC, 2002b), the planning and organization of science (NRC, 2003a), adaptive monitoring and assessment (NRC, 2003b), and the importance of water flow in shaping the Everglades landscapes (NRC, 2003c).

THE EVERGLADES ECOSYSTEM

Florida's Everglades, often referred to as the splendid River of Grass, is a rich and unique ecosystem. Shaped by the flow of slow-moving water, its flourishing landscape of sawgrass plains, ridges, sloughs and tree islands is a home to alligators, many kinds of wading birds, and other plant and animal life, some of which is found in few or no other locations. By the mid-twentieth century, a vast network of canals and levees, built to drain water for flood control, water supply, agriculture, and urban development, had profoundly altered the region's wetlands and reduced the Everglades to half its original size. Today, the wading bird population has sharply declined, and 70 plant and animal species in South Florida are threatened or endangered. Throughout the past century, the Everglades has epitomized the American conflict between economic development and environmental conservation. In recent years, the governmental agencies and the people in the region have embraced the challenge of protecting and restoring native species and ecosystems while still meeting human needs for space and natural resources.

Restoration of the Everglades is a daunting task. It is extremely complicated for several reasons. First, the Greater Everglades ecosystem is huge, stretching from the Kissimmee River drainage basin to Florida Bay and adjoining coral reefs (see Figure 1-1). Second, the Restoration Plan must attempt to balance the interests of many stakeholders. Third, restoration goals must consider and resolve the complex and often competing needs of different plant and animal species. Fourth, the plan must be robust in the face of unknown factors such as future climate change and urban population growth. Finally, and perhaps most important, there are competing visions of what will constitute successful restoration.

Since 1993, a coalition of local, state, and federal agencies, as well as non-government organizations, local tribes, and citizens, has been working to reverse the damage to the Everglades. The effort is led by two organizations that have considerable expertise regarding the water resources of south Florida—the U.S. Army Corps of Engineers (USACE), which built most of the canals and levees in the Everglades, and the South Florida Water Management District, which has primary responsibility for operating and maintaining this complicated water collection and distribution system. In 1999, the USACE issued its blueprint for the restoration effort, the Comprehensive Everglades Restoration Plan (the Restoration Plan). The plan, which was approved by Congress in the Water Resources Development Act of 2000, seeks to "get the water right" —that is, to deliver the right amount and quality of water to the right places at the right times. The plan proposes more than 50 major projects to be constructed over an estimated 36 years at a cost of approximately $7.8 billion.[2]

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[2] All costs, including construction, real-state, and operations and maintenance costs, are in 1999 dollars. See Appendix A for list and schedule of projects.

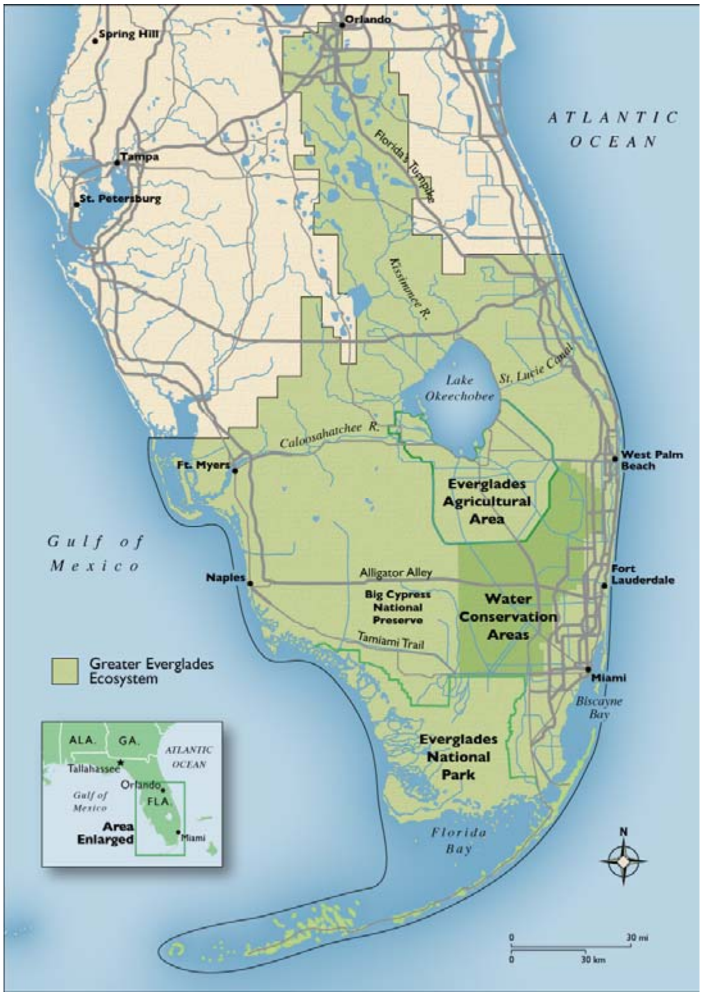

FIGURE 1-1. Much bigger than just Everglades National Park, the Greater Everglades Ecosystem (or south Florida ecosystem) extends south from the Kissimmee River watershed to Lake Okeechobee, through the remaining Everglades, and on to the waters of Florida Bay and the coral reefs. SOURCE: Information on locations of existing and proposed storage components from USACE and SFWMD.

Since the publication of the Restoration Plan in 1999, the USACE, after public comment, established programmatic regulations to set the procedural framework for implementing the plan. The key provisions include

- a process for establishing interim goals to provide hydrologic, water-quality, and ecological targets against which to measure restoration progress;
- the establishment of an interagency group called "RECOVER" (Restoration, Coordination and Verification) that assesses the individual projects to ensure that the system-wide goals and purposes of the Restoration Plan are achieved;
- the establishment of an adaptive management program to assess whether the responses of the natural system to restoration plan activities match expectations, and to recommend modifications to the plan based on new information; and

- a process for establishing an independent scientific review [committee of the National Research Council] of the National Academy of Sciences to review progress in meeting the restoration goals. (*http://www.evergladesplan.org/pm/pm_docs/prog_regulations/110403_prog_regs_faq_final.pdf*)

The Restoration Plan continues to be modified. For example, an aquifer storage and recovery (ASR) regional study has been added to address issues raised by this committee (2001a) and others, including potential effects of the ASR program on communities, industry, other groundwater users, and the environment (*http://www.evergladesplan.org/pm/projects/proj_44_asr_regional.cfm*). On a broader scale, the hydrologic models are in the process of being updated and recalibrated with 1996-2000 data, improved topography, and other information through a process known as the "Initial CERP update" (*http://www.evergladesplan.org/pm/recover/icu.cfm*). Generally speaking, however, the simulations, analysis, and budgets done for the Restoration Plan still form the most consistent and internally comparable data set available, and accordingly this report makes broad use of those data.

The Restoration Plan is divided into components—conceptual parts of the plan, like decompartmentalization—and individual projects. The proposed schedule for construction of the projects of the Restoration Plan is called the Master Implementation Sequencing Plan (MISP) and it is described at the Everglades Restoration web site at *http://www.evergladesplan.org/pm/misp.cfm*. The MISP includes the sequencing and scheduling of all of the projects of the Restoration Plan, including pilot projects and operational elements. The latest version of the MISP no longer gives specific dates for completion of the projects; instead, the sequence is divided into seven 5-year bands during each of which a number of projects are scheduled for completion. Appendix A of this report is a table that compares the initial schedule of projects with the current MISP.

MAJOR STORAGE AND WATER-CONSERVATION COMPONENTS IN THE RESTORATION PLAN

Major components of the restoration include operational modifications, modifications to existing structures and canals, decompartmentalization of the Water Conservation Areas, stormwater treatment areas, water reuse, expanded storage capacity and seepage management. Water reuse, storage and seepage management are introduced in the following section and described in detail in Chapter 3.

In the current water management system, the major storage components are Lake Okeechobee and the Water Conservation Areas. Together these provide over four million acre-feet of storage. Several additional components either are included in the Restoration Plan or could contribute to total storage.

- Kissimmee surface reservoirs include an above-ground reservoir of approximately 200,000 acre-feet of storage and a 2,500-acre stormwater treatment area (STA).
- The Everglades Agricultural Area (EAA) and vicinity. The area covered by the EAA stored considerable amounts of water in the natural Everglades system, and although its character has changed, it could provide for substantial surface storage capacity in the future. Two projects that are included in the Restoration Plan will create above-ground reservoirs within the EAA (*http://www.evergladesplan.org/pm/projects/proj_08_eaa_*

phase_1.cfm and http://www.evergladesplan.org/pm/projects/proj_09_eaa_phase_2.cfm). Together they will have a capacity of about 360,000 acre-feet.

- Aquifer Storage and Recovery (ASR). This is the largest planned storage component in the Restoration Plan, anticipated to accommodate an average of more than 500,000 ac-ft of water added to storage each year, and a capacity for accumulated recoverable storage of more than four million acre-feet (based on the cumulative volume in storage at the end of the D13R[3] 31-year simulation after the assumed 30 percent injection loss.
- Lake Belt Storage. This component is planned to consist of in-ground reservoirs developed from converted limestone quarries. Two reservoirs are planned in Miami-Dade County, both up to 80 feet deep with a combined storage capacity of nearly 280,000 acre-feet.
- Seepage Management. Although not a storage component, this water-conservation component aims to reduce water flow across levees, reservoir walls and other containment structures, and it would have the same net effect as a storage component. It is essential to the success of some storage components, particularly Lake Belt storage.
- Water Reuse and Conservation. Advanced wastewater treatment technology will be used to reclaim urban wastewater from Miami-Dade Counties to supplement water in natural areas such as the West Palm Beach's Catchment Area, Biscayne National Park, and the Bird Drive basin.
- A number of smaller, conventional reservoirs and stormwater treatment areas in the Upper East Coast. These are included in the Indian River Lagoon–South component of the Restoration Plan and will provide an addition of approximately 170,000 acre-feet of storage.

WHY IS STORAGE IMPORTANT?

A basic premise of the Restoration Plan is that if the water is "right," then the ecosystem will become "right" as well. That implies that the water is not "right" today, and indeed the amount of water in the Greater Everglades Ecosystem, and its spatial and temporal distributions, are very different from conditions in the natural system. (The history of human efforts to control water in south Florida and the resulting changes in the system are well reviewed by Light and Dineen [1994], the Science Sub-Group [1993], and on the Restoration Plan's web site.) More than half of the original Everglades wetlands have been converted to human use, thus reducing water storage and flux that buffered extremes of flood and drought. As things now stand in the Everglades and in the surrounding human settlements, there is more water at some times and places than occurred under pre-European settlement conditions, and at other times and other places water levels and/or flows are much lower than occurred naturally. In particular, drought conditions are longer, more severe, and cover wider areas in the current system than under pre-settlement conditions, and efforts to mitigate these droughts involve storage of water in "Conservation Areas" northeast of Everglades National Park that previously had (on average) lower water levels. In addition, some restoration goals compete with the ecological goals for the use of stored water. For example, the human demand for water in south Florida is much greater than it

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[3] Simulation D13R uses the same projected land use and water demands as in the 2050 Base simulation, but also assumes a completed Restoration Plan (and other) projects. It is known as alternative D13R based on its sequence in a series of simulations.

was 100 years ago, and the need for flood control in developed areas does not necessarily enhance the availability of water for ecological restoration.

As a result, the Restoration Plan includes large amounts of new storage as a mechanism for supplying the water that is needed for both people and the ecosystem and changes in the delivery system that enable water to be supplied at the times and in the places where it is currently in shortest supply. Below we describe the general changes that have occurred to the hydrologic system of the Everglades and their effects on water supply and the need for storage. The description is based on many papers in Davis and Ogden (1994) and on hydrologic principles.

The natural system included the Kissimmee River drainage north of Lake Okeechobee, the lake, and the Everglades system south of the lake. Before drainage and other human modifications to the landscape that began in the late 1800s, seasonal variations in the amount and distribution of water in the system must have been strongly damped by the combined effects of storage in wetlands and Lake Okeechobee in the northern part of the system, and by relatively slow flows through the meandering channels of the Kissimmee River. Thus, despite strong daily and seasonal variations in rainfall and potential evapotranspiration, the system would not have been as prone as it is today to rapid water-level changes that cause flooding. Lake Okeechobee would have been free to contract or expand its large surface area into surrounding areas containing extensive wetlands and pond-apple forests. This would have provided additional buffering against droughts as water eventually flowed from the sawgrass plain to the south of the lake. Topographic variations within the ridge-and-slough landscape beyond the sawgrass plain must have provided further damping. Damping in the north must have provided a buffer to the southern portion of the system against the effects of seasonal and multiyear dry spells, which readily lead to desiccation under current conditions. The natural system in the south would still have experienced seasonal and shorter-term variations in water flows and levels, which probably were important to the development and functioning of the ecosystem. Those fluctuations would have resulted mainly from local rainfall patterns and would have been smaller and more gradual than would be expected without upstream damping.

Initial modifications to the system were made between 1881 and 1894. These included Hamilton Disston's projects to make "channel improvements" (i.e., dredging and straightening) in the Kissimmee River, to construct new channels in the headwaters of the Kissimmee River basin, and to connect Lake Okeechobee to the Caloosahatchee River, providing an outlet from the lake to the Gulf of Mexico. These projects drained areas north of Lake Okeechobee and most likely increased peak flows in the Kissimmee River. These increases in peak flow caused rapid expansion of the lake area. The diversion of water from the lake to the Gulf through the Caloosahatchee River reduced the amount of water stored within the Everglades ecosystem, reducing water available to maintain flows to the south during dry periods.

A second major drainage effort, spanning the period 1905-1928, focused on the area south of Lake Okeechobee that is now the Everglades Agricultural Area. Drainage canals extending through this area to the Lower East Coast lowered water levels to allow for farming. Construction of the St. Lucie Canal, connecting Lake Okeechobee to the Atlantic, and further dredging of the Caloosahatchee River increased the efficiency of rainfall runoff diversion to further reduce the potential for flooding south of the lake. The result of these diversions was further reduction in the amount of water stored within the Everglades Ecosystem and the potential for enhanced desiccation of wetlands in the southern part of the system during droughts.

Despite the flood control provided by diversions from Lake Okeechobee to the St. Lucie Canal and the Caloosahatchee River, flooding of the Everglades Agricultural Area (EAA) was still a problem, particularly during severe hurricanes in 1926 and 1928 when winds and torrential rains caused overflow from Lake Okeechobee. Construction of the Herbert Hoover Dike between 1932 and 1938 was undertaken to provide additional flood control. On its completion, the dike dramatically altered the functioning of Lake Okeechobee. It was no longer free to expand or contract its boundaries within the historical littoral zone and water levels were now managed by a number of control structures.

While flooding potential was reduced with completion of the dike, another problem became apparent during successive dry years between 1931 and 1945. During this drought, the lowered water levels created by agricultural drains, coupled with the reduced storage resulting from diversion of runoff to the Gulf and Atlantic, led to regional lowering of the water table, resulting in desiccation of many of the remaining wetland areas and a threat of saltwater intrusion into the coastal aquifer. This highlighted the need to develop additional storage capacity to provide water to wetlands and the canals during dry seasons and extended droughts. This capacity eventually was developed in the Water Conservation Areas (WCAs), south of the EAA, in a region that was historically dominated by ridges, sloughs, and tree islands. Storage of water in the WCAs, which increased water levels in parts of them, altered the vegetation community and landscape patterns.

The drought broke in 1947, during which year 100 inches of rain fell and severe flooding covered 90 percent of southeastern Florida. At this point it was clear that a water management strategy was required to address flooding and drought hazards, as well as water supply and environmental issues. The Central and Southern Florida (C&SF) project, designed by the USACE and authorized in the federal Flood Control Act of June 30, 1948, was intended to meet these needs by providing flood control, water level control, water conservation, prevention of saltwater intrusion, and preservation of fish and wildlife. While some new storage was created in the WCAs, additional flood control measures have continued to shunt the majority of runoff water out of the terrestrial system and into the Gulf and the Atlantic via the Caloosahatchee River and St. Lucie Canal. To avoid flooding private lands that lie west of the Miami ridge in the southern Everglades, much of the water in this portion of the Everglades is diverted from east to west.

The result of the many changes in the Everglades hydrologic system made in the twentieth century is that parts of the Everglades are water-starved at times, other parts are submerged, and the natural timing and amplitudes of high-water and drying events have been severely disrupted. Large pulses of fresh water diverted to the coasts also have had detrimental effects on estuaries. This, then, describes how the water is "wrong" and why a major goal of the Restoration Plan is "to get the water right."

All the options for "getting the water right" envisioned by the Restoration Plan—indeed, any option envisioned by anyone—will require additional, and at least short-term, storage, as well as alterations in how water is directed through the system. Decompartmentalization—the dismantling of some water control structures, such as dams and levees, to convert the Everglades from the hydrologically-compartmentalized system that exists today—is critical to restoring sheet flow that characterized the natural system; other components will enable the timing and direction of sheet flow to be restored. Simply diverting the runoff pulses that currently are discharged to the Gulf and Atlantic and routing them into the southern Everglades might restore the historical volumes of flow on an annual basis. However, because the damping that once was provided by upstream features—in the Kissimmee River basin, Lake Okeechobee, the sawgrass plain, and northern ridge-and-slough landscapes—has been removed from the system, the timing and magnitudes of water level fluctuations would be very different from those in the historical system and these could have detrimental effects on the ecosystem.

Furthermore, the additional demand for water in south Florida by the growing human population almost surely will require additional and possibly longer-term storage. Water demand in south Florida is projected to grow from 3.5 billion gallons per day (BGD) in 1995 to nearly 4.5 BGD in 2020 due to an expected 43 percent increase in human population during the period (Kranzer, 2003). Because there is less water in the system and greater demand for water than before, and because of the degree to which the system has been engineered, moving any part of the water to a place where it is needed or removing any structure that impedes its flow implies the likelihood of water shortages elsewhere, increased risk of flooding, or both, unless additional storage is available. For example, if the levees and canals in the WCAs were breached to decompartmentalize that portion of the system, with no other change, the adjacent areas would once again be short of water in the dry season, as they had been before construction of the WCAs, and the lack of buffering resulting from the channelization of the system would make the same areas prone to flooding during wet periods. This is why the Restoration Plan has such a large component devoted to providing additional storage.

It is not clear exactly what ecological conditions will accompany hydrologic change, but there is merit in concluding that more natural hydrologic conditions will lead to improved ecosystem functioning. Thus attempting to "get the water right" (or at least better) is a reasonable approach to restoration.

STORAGE, FLOW, AND RESTORATION OF THE EVERGLADES ECOSYSTEM

In executing its task of providing advice about the technical and scientific aspects of restoration and planning (Box ES-1), the committee was mindful of previously published approaches for restoring aquatic ecosystems (e.g., NRC, 1992, 2001b; Science Sub-Group, 1993). The committee judges that the Restoration Plan is proceeding in accordance with many such principles, but not in all aspects. In particular, the committee has concern that too little weight has been given to the following principles of sustainable restoration.

- Prevent additional habitat loss. The first priority in a restoration project is to secure it against the risk of additional damage. For most projects this means protecting from additional damage the remaining habitat and areas that potentially could provide usable habitat. In particular, protecting against irreversible habitat loss should be the first priority of a restoration program. This principle implies that heavy emphasis should be placed on purchasing land intended to be part of the restored system or obtaining conservation easements on such lands as soon as possible.
- Provide ecological benefits as early as possible. Restoration projects often have other goals in addition to ecological restoration, and compromises often must be made with other goals (e.g., flood control) or constraints (e.g., budget or the need to compensate for previously degraded aspects of the environment). To the extent that the project can achieve ecological goals early, the outcome is likely to be improved.

These principles are discussed in detail in Chapter 3 in the context of sequencing components of the Restoration Plan.

Two other issues are important in addition to those mentioned above. The first—a difficulty acknowledged by the Restoration Plan—is that ecological outcomes are quite uncertain, and some outcomes could be seen as unacceptable. The committee has taken seriously the advice of the 1990s Science Sub-Group of the South Florida Management and Coordination Working Group (Science Sub-Group, 1993) to consider the whole system and to take a regional approach in this regard, and consequently this report examines problems of diminished areal extent of the restored ecosystem, endangered species, invasive exotic plants, and water quality to assess the likelihood that uncertainty can be reduced and its consequences managed, and that unacceptable outcomes can be avoided.

Finally, the report addresses the expectation that adaptive management will provide an early opportunity to repair possible shortfalls in the Restoration Plan. An example of such a shortfall might be the occurrence of a real estate market boom that prevents the planned footprint from being acquired. Because the restored system will be highly engineered, it also will be vulnerable to failure of the engineered systems to function as intended or to unexpected changes in conditions considered external to system design and operation. Examples of the latter are climate change, sea level rise, extraordinary population growth, large-scale land-use change, elevated energy costs, and reduction or elimination of crop subsidies. Adaptive management can lead to the improvement of design details and operating practices within the overall design concept, but it cannot easily address violations of the contextual and efficacy assumptions made in the engineering design. The possibility of unexpected shifts in external drivers should be addressed through concerted attention to contingency planning, including reconsideration of alternatives already discarded such as those related to Lake Okeechobee and the EAA. This planning should be directed at major decision points that have already been passed or that will arrive soon, rather than at fine adjustments of the extant Restoration Plan. Contingency planning should be allowed to lead to re-design of the conceptual plan if that becomes necessary, possibly more than once. The opportunity provided by adaptive management may also yield an early warning of unexpected outcomes and hence the need for implementation of contingency plans.

REPORT ORGANIZATION

Chapter 2 describes each of the major storage components of the plan, emphasizing sequencing and water-quality issues and the potential to rely on natural as opposed to engineered processes. Chapter 3 discusses cross-cutting issues that the committee considered in evaluating the science underlying the implementation of the plan, especially with respect to storage. They include the ordering of the Restoration Plan's components in space and time, including criteria and uncertainties associated with that sequencing; ecological uncertainties; contingency planning; adaptive management; and the relative merits of using natural versus highly engineered processes in the restoration. Chapter 4 discusses the potential need to reconsider the full range of available storage options as an adaptive management strategy during the course of implementation of the Restoration Plan. Chapter 5 suggests a quantitative framework that could be used to evaluate restoration progress and alternatives, including re-evaluation and refinement of restoration goals. Chapter 6 summarizes the committee's major findings and recommendations.

2

Major Storage Components

Storage is at the heart of any attempt to restore the Everglades. A brief examination of the Restoration Plan components (Figure 2-1) shows that many of them either directly or indirectly involve storage. This chapter contains a summary and comparison of the major existing storage components (Lake Okeechobee and the Water Conservation Areas), conventional above-ground surface reservoirs (Kissimmee Basin, Everglades Agricultural Area and vicinity, and the Upper East Coast region), below-ground storage using aquifer storage and recovery (ASR; multiple projects), and in-ground storage in the Lake Belt region. Water-quality considerations are also discussed for each component in this chapter.

While seepage management and water reuse and conservation, strictly speaking, are not storage projects, they also are discussed because they affect the overall water budget and ultimately the amount of storage required in the system. Water-quality considerations are also discussed for each component. Conversely, while stormwater treatment areas provide some storage, they are addressed only with respect to their primary function of improving water quality and where they are closely associated with major storage components. Other Restoration Plan features that are not discussed in detail in this chapter include features that are small or were designed primarily as "flow-through" structures in conjunction with ASR projects.

To understand the storage components and the fluxes between them, it is helpful to be familiar with how the Everglades planners have conceptualized and modeled the hydrologic system. The primary tool used to physically model the system in the past, present, and future is the South Florida Water Management Model (SFWMM). The SFWMM simulates the hydrologic regime and the management of the system from Lake Okeechobee to Florida Bay using both lumped and distributed modeling techniques. Most of the domain is covered with a finite-difference mesh of 2 mile × 2 mile cells. However, Lake Okeechobee is modeled (or "lumped") as a single point in space, and a simple flow balance procedure is used for other areas. The model simulates rainfall, evapotranspiration, infiltration, overland and groundwater flow, canal flow, canal-groundwater seepage, levee seepage and groundwater pumping. It incorporates current or proposed water management control structures and current or proposed operational rules (SFWMD, 1997a).

The model has been used to simulate numerous scenarios, of which three are applicable to this chapter. The first (Figure 2-2) is of the system infrastructure and operations as they were around 1995 (the "1995 Base," often referred to as the "current condition" or "existing condition"). The input data include a 31-year climatic record (1965-1991), recently extended in the Initial Comprehensive Everglades Restoration Plan (CERP) Update to 36 years. Both very wet and very dry years are included. The update, which is ongoing, will soon be reflected in new

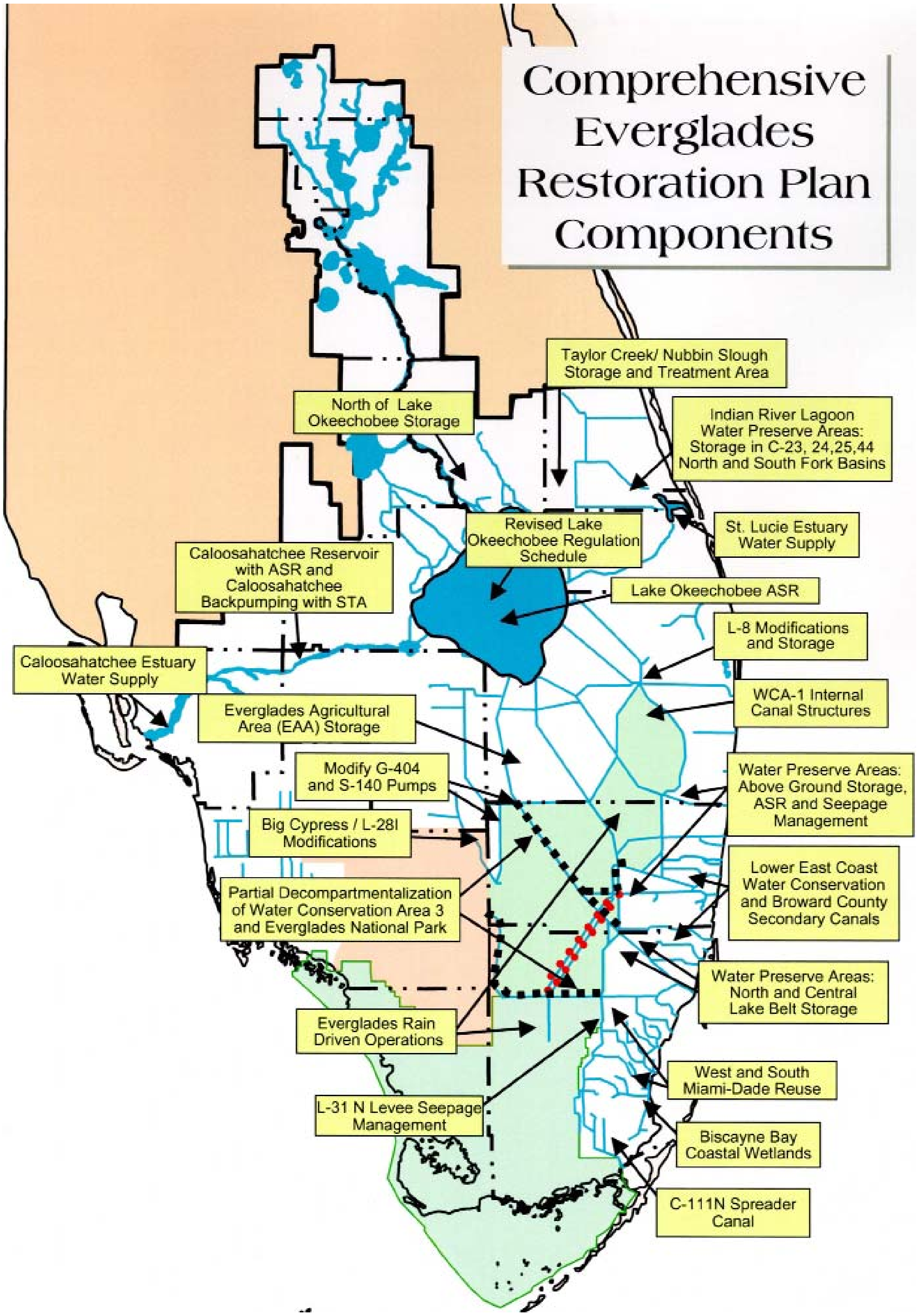


FIGURE 2-1. Restoration Plan components.
SOURCE: Available online at *http://www.evergladesplan.org/images/cerpmap_200.jpg.*

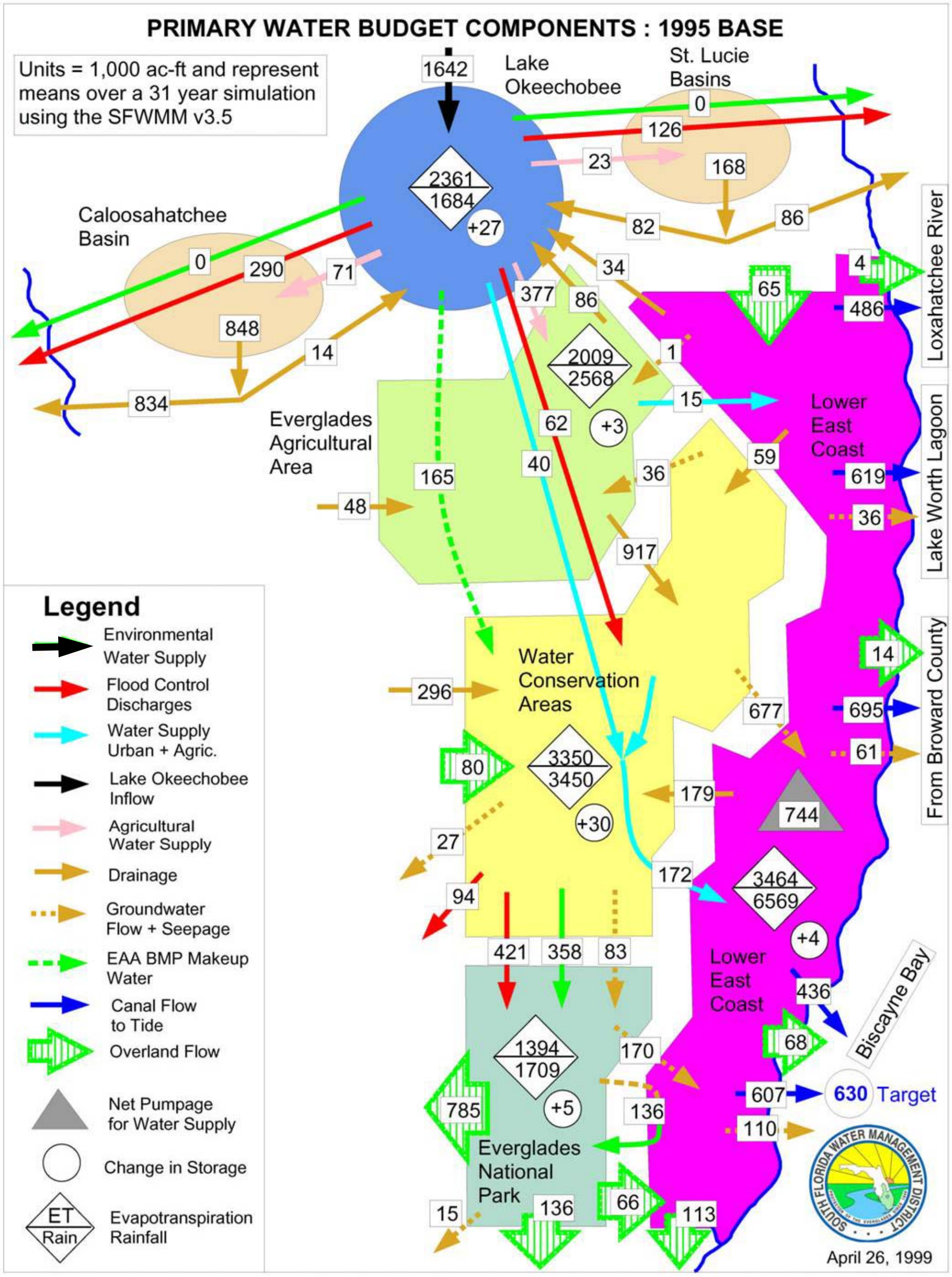


FIGURE 2-2. Primary water budget components for a 31-year simulation of the SFWMD model using the structures in place in 1995 (the “1995 Base” case of the Restoration Plan). It is considered by restoration managers to reflect the typical “current condition” of the system.
SOURCE: Available online at *http://www.sfwmd.gov/org/pld/restudy/hpm/frame1/maps/mapdir/95BSR/WBUD/95BSR.pdf.*

base scenarios and model runs, but until then, the 1999 CERP still is the reference. Information on the update is at *http://www.evergladesplan.org/pm/recover/icu.cfm*.

The second scenario uses the same climatic record as the 1995 Base, but reflects the likely system infrastructure and operations as they would be around 2050 without any of the Restoration Plan projects in place (the "2050 Base," also referred to as the "future without project" condition or the "no-action alternative"). Despite increased water-use demands and other differences, this has many similarities with the 1995 Base and is not shown here. The third (Figure 2-3) is a simulation using the same projected land use and water demands as in the 2050 Base, but also assuming completed Restoration Plan (and other) projects. It is known as alternative D13R after its SFWMM run number. Note the additional components in Figure 2-3 relative to Figure 2-2, including aquifer storage and recovery, surface storage, and wastewater reuse. Comparing the storage and flows estimated by alternative D13R and similar runs with those of the 1995 Base and 2050 Base is a major approach used to evaluate potential achievement of hydrologic goals for the restoration effort. We use the simulation results for the 1995 Base and the alternative D13R to provide estimates of storage capacity for various current and planned storage components. This committee has not conducted a critique of the SFWMM, and recognizes—as do the USACE and the SFWMD—that it probably is not a perfect representation of current or future conditions. Nonetheless, the simulation results are useful for comparing the relative magnitudes of storage capacity associated with current and planned elements of the Restoration Plan. Figure 2-4 illustrates, qualitatively, an estimate of flow patterns before any of the human modifications to the system that began in the 1880s.

CURRENT STORAGE COMPONENTS

In the current system, the major available storage components are Lake Okeechobee and the Water Conservation Areas (Table 2-1; Figures 2-1 and 2-2). When fully implemented, the Restoration Plan anticipates capturing a large amount of the water currently discharged to the sea and storing it using a variety of structures and operational strategies that are major components of the plan. The major storage components of the plan discussed in this chapter are described in subsequent sections in terms of land requirements; costs for construction, operation and maintenance; constraints on sequencing of construction or implementation; design and operational complexity and flexibility; potential environmental risks and benefits; water quality issues; and advantages and disadvantages relative to other storage options. A map of existing facilities and structures managed by the South Florida Water Management District can be found at *http://www.sfwmd.gov/images/pdfs/facility_map_overview.pdf.*

Lake Okeechobee

Historically, the lake (Figures 1-1 and 2-5) served as the key hydrologic link between the mostly upland ecosystems in its large drainage basin to the north—the Kissimmee River Basin—and the sawgrass marshes and prairies of the Everglades proper to the south. Water storage provided by the large lake moderated the effects of low rainfall periods on the Everglades. Over the past century, the lake and its drainage basin have been greatly modified for flood control and other water management purposes, and it has become a highly engineered reservoir with numerous options for managing inflows, outflows, and water levels.

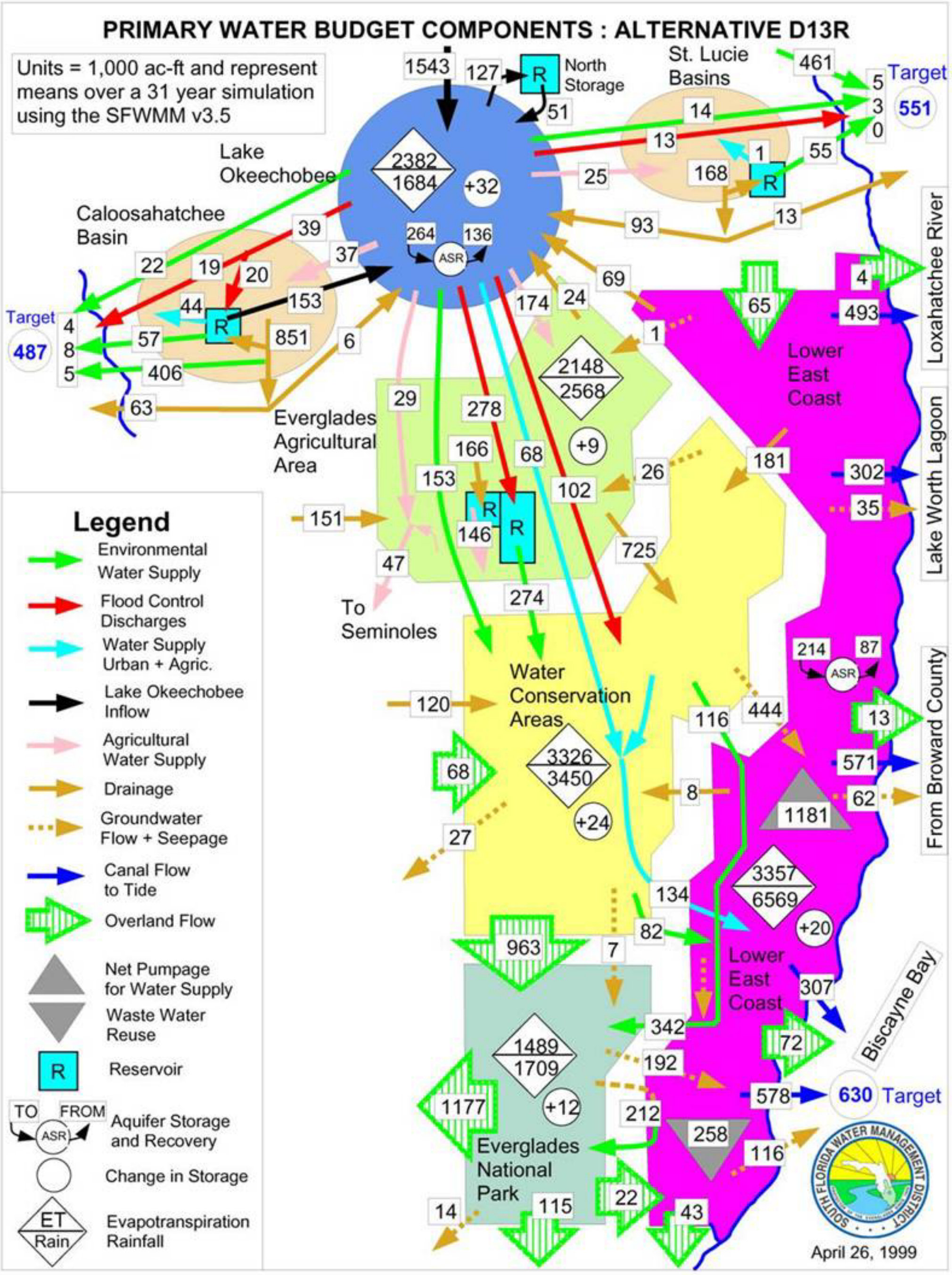


FIGURE 2-3. Primary water budget components for the June 1998 model run D13R of the Restoration Plan. This is a simulation using the same 31-year climatic record (1965–1991) as the 1995 (and 2050) Base simulations, but using projected 2050 land use and water demands and assuming the Restoration Plan and other related projects have been implemented. There are very slight differences in the flows in this figure and the flows in Table 2-1, which is based on a slightly updated (November 1998) version of D13R.
SOURCE: *http://www.sfwmd.gov/org/pld/restudy/hpm/frame1/maps/mapdir/ALTD13R/WBUD/D13R.pdf.*

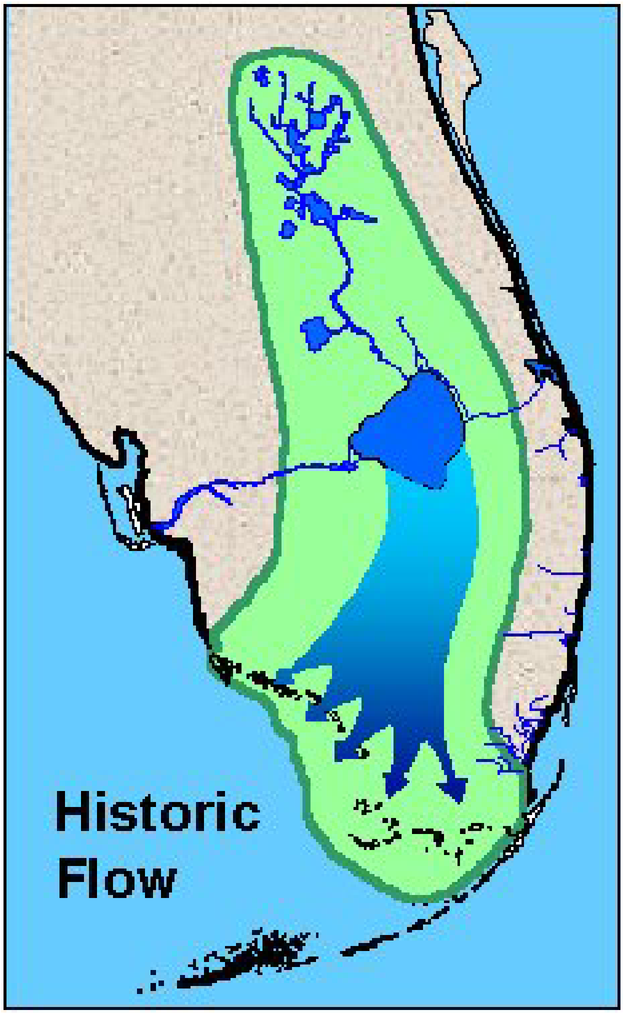


FIGURE 2-4. A qualitative depiction of the original flow patterns in the Everglades.
SOURCE: Available online at *http://www.evergladesplan.org/maps/historic_flow.jpeg.*

On an annual basis under current operating conditions, Lake Okeechobee receives approximately 1.6 million acre-feet of inflow from the Kissimmee River and discharges approximately 416,000 acre-feet of coastal waters through the Caloosahatchee River and St. Lucie Canal. An additional 227,000 acre-feet of water are discharged to the Water Conservation Areas from Lake Okeechobee in a combination of regulatory releases to control stage in Lake Okeechobee and environmental releases to replace reductions of flow due to implementation of best management practices (BMPs). A total of 471,000 acre-feet from Lake Okeechobee is sent to agricultural areas in the Caloosahatchee and St. Lucie Basins to the west and east, and to the Everglades Agricultural Area to the south. The Water Conservation Areas (WCAs) receive additional inflow from drainage canals in the Everglades Agricultural Area (EAA; 917,000 acre-feet) and other adjacent areas (Figure 2-2).

TABLE 2-1 Storage Components of the Restoration Plan

STORAGE COMPONENT	Avg Annual Acre-feet in	Avg Annual Acre-feet out	MaxAnnual Acre-feet In	MaxAnnual Acre-feet out	Max annual inflow-outflow	Total Capacity Acre-feet	ASR capacity for 30% inj loss	Construction Costs	O&M Costs (per yr)	Land Acres	Land Costs
Lake Okeechobee	2,537,300	1,803,400	4,263,200	4,022,700	2,231,900	2,250,000					
Water Conservation Areas	1,633,200	316,100	3,138,600	567,200	2,879,200	1,882,000					
Conventional Surface Reservoirs											
North Storage Reservoir (Kissimmee)	127,000	51,700	450,200	311,700	267,000	200,000		95,134,000	1,515,245	20,000	189,720,000
EAA Reservoirs	440,900	418,100	1,036,900	959,400	260,700	360,000		350,112,000	14,458,409	17,500	86,536,000
C-44 Reservoir	19,530	9,550	57,960	58,870	43,820	33,150		118,859,000	?	3,315	125,879,375
Other Upper East Coast Reservoirs						97,000		174,199,000	?	9,458	130,055,433
Taylor Creek/Nubbin Slough		93,700		168,800		50,000		79,326,000	2,164,114	10,000	189,720
Caloosahatchee (C-43) Basin	395,140	337,650	725,570	661,810	167,590	160,000		inc. in C-43 ASR	inc. in C-43 ASR	20,000	132,621,000
Central Palm Beach Reservoir	77,200	73,200	106,400	96,100	20,000	19,920		inc in CPB ASR	Inc. in CPB ASR	1,660	57,657,000
Site 1 Reservoir	81,200	82,200	116,000	116,500	5,700	14,760		inc in Site 1 ASR	inc in Site 1 ASR	2,458	23,587,000
Bird Drive Reservoir	138,300	18,800	150,900	38,000	147,800	11,600		52,459,000	1,470,869	2,877	71,625,000
Acme Basin						4,950					
Seminole Tribe Big Cypress						7,440					
Total conventional reservoirs	**1,279,270**	**1,084,900**	**2,643,930**	**2,411,180**	**912,610**	**958,820**		**870,089,000**	**19,608,637**	**87,268**	**817,870,528**
ASRs											
Lake Okeechobee ASR	259,100	134,600	1,120,100	521,700	1,120,100	3,859,500	1,449,870	1,108,797,000	25,000,000	300	7,515,000
Caloosahatchee (C-43) Basin ASR	97,910	47,630	170,500	139,200	170,500	1,558,680	648,117	313,574,000	6,707,889	inc. in C43 res	
C-51 (North Palm Beach II) ASR	80,500	24,200	135,700	73,000	132,000	1,745,300	996,650	122,391,000	1,496,000	34	9,945,000
West Palm Beach ASR (L-8 ASR)	37,800	11,700	54,600	32,800	54,600	809,100	457,560	53,428,000	?	?	?
Central Palm Beach Reservoir ASR	42,300	28,500	74,700	48,700	59,500	427,800	34,410	66,442,000	1,019,500	inc in CPB res	
Site 1 Impoundment (Hillsboro) ASR	55,700	23,000	106,800	56,200	100,300	1,013,700	495,690	116,792,000	2,052,608	inc in site 1 res	
Total ASRs	**573,310**	**269,630**	**1,662,400**	**871,600**	**1,637,000**	**9,414,080**	**4,082,297**	**1,781,424,000**	**36,275,997**	**334**	**17,460,000**
In Ground Reservoirs											
North Lake Belt	146,600	142,600	180,400	189,600	34,300	90,000		381,193,000	1,241,234	5,861	154,868,000
Central Lake Belt	100,500	95,000	237,100	238,700	196,000	190,000		402,502,000	1,964,519	5,770	100,359,000
L-8 Basin	76,000	76,700	101,900	118,600	55,300	48,000		?	?	1,200	?
Total in-ground reservoirs	**323,100**	**314,300**	**519,400**	**546,900**	**285,600**	**328,000**	**0**	**783,695,000**	**3,205,753**	**12,831**	**255,227,000**
Seepage Management											
WCA3A/3B Levee Seepage Mgmt		128,600						57,526,000	783,432	5,887	167,646,000
C-11 Reservoir (part of 3A/3B seepage)	68,300	80,700	121,300	144,000	0 (gw inflow makes up deficit)						
L-31N Seepage Mgmt		161,900						89,514,000	4,647,234	3,947	94,704,000
Total seepage management		**371,200**						***147,040,000***	***5,430,666***		***262,350,000***
Water Reuse											
West Miami-Dade Water Reuse		111,000	to Bird Dr. Rech	112400(to Bird Dr. Rech)				435,998,000	36,500,000	100	3,540,000
South Miami-Dade Water Reuse		73,730	(south to C-102)					359,700,000	47,815,000	200	3,324,000
		73,000	(north to C-100)								
Total water reuse		**257,730**						***795,698,000***	***84,315,000***		***6,864,000***

Notes follow on next page

Data sources and other notes for Table 2-1

Many values in the table are based on simulation output, which are reported to more significant figures than can be verified. These values provide only general comparisons of the magnitudes of flows and storage capacity, as no quantitative estimates of uncertainty are available. While every attempt has been made to verify the information in this table, the Restoration Plan is continually being modified, so storage, flux, acreage, and cost information are evolving with it. Likewise, quantitative information for closely related projects, such as reservoirs and stormwater treatment facilities, is sometimes lumped. Up-to-date information on these projects can be obtained at any time from the USACE and SFWMD. There are very slight differences in the flows given in this table and those shown in Figure 2-3. Both are based primarily on output from alternative D13R of the South Florida Water Management Model; however, this table is based on a slightly updated (November 1998) version of D13R relative to Figure 2-3, which is based on a June 1998 version of D13R.

Fluxes

Most fluxes are from water budget for D13R (11/98 version)
(*http://www.sfwmd.gov/org/pld/restudy/hpm/frame1/maps/mapdir/D13R1198/WBUD/annbud*).
South and West Miami-Dade water reuse fluxes from Appendix B, section B.3.5.8.1, p. B-192 of USACE and SFWMD (1999), except for Average Annual West Miami-Dade Reuse, which is from M. Irizarry, SFWMD, personal communication, November 2004.
See Fig. B.3-88 for bar graph of volumetric savings from water use reductions.
Inputs to reservoirs do not include local precipitation or seepage.
Outputs from reservoirs do not include evapotranspiration or ASR injection losses.
Water fluxes to and from Water Conservation Areas (WCAs) include overland flow and groundwater seepage.
Seepage management "annual acre-ft out" for WCA3A/3B and L31-N from J. Obeysekera, SFWMD, written commun., May 2004, and computed as "seepage prevented" between D13R and 2050base.

Capacities

Most capacities are from individual project descriptions at *http://www.evergladesplan.org/pm/projects/project_list.cfm.*
Reservoir capacities for C-44 and Upper East Coast Reservoirs taken from the Indian River Lagoon Project Implementation Report
Lake Okeechobee capacity approximated from data summarized in table 3-2 of this report, and is the volume at max allowable stage (18.5 NGVD) minus the volume at min allowable stage (13.5 NGVD).

WCA capacity from Light and Dineen (1994); also based on current regulation schedule.

ASR "capacities" refer to injected water remaining in the aquifer after the 31 year simulation and are calculated as (avg. annual acre-feet in - avg. annual acre-feet out) x 31 years

ASR "capacities" for 30% injection loss refer to usable (non-saline) water remaining in the aquifer after the 31 year simulation and are calculated as (0.7 x avg. annual acre-feet in - 1 x avg. annual acre-feet out) x 31 years.

Construction, O&M, and Land Costs; Acreage

Acreages from Table 9-1 of USACE and SFWMD (1999).
Construction and Real Estate Costs in 1999 dollars from Table 9-2 of USACE and SFWMD (1999).
O&M Costs in 1999 dollars from Table 9-3 of USACE and SFWMD (1999). Construction and land costs for C-44 and Upper East Coast Reservoirs taken from the Indian River Lagoon Project Implementation Report. These costs are in 2003 dollars.

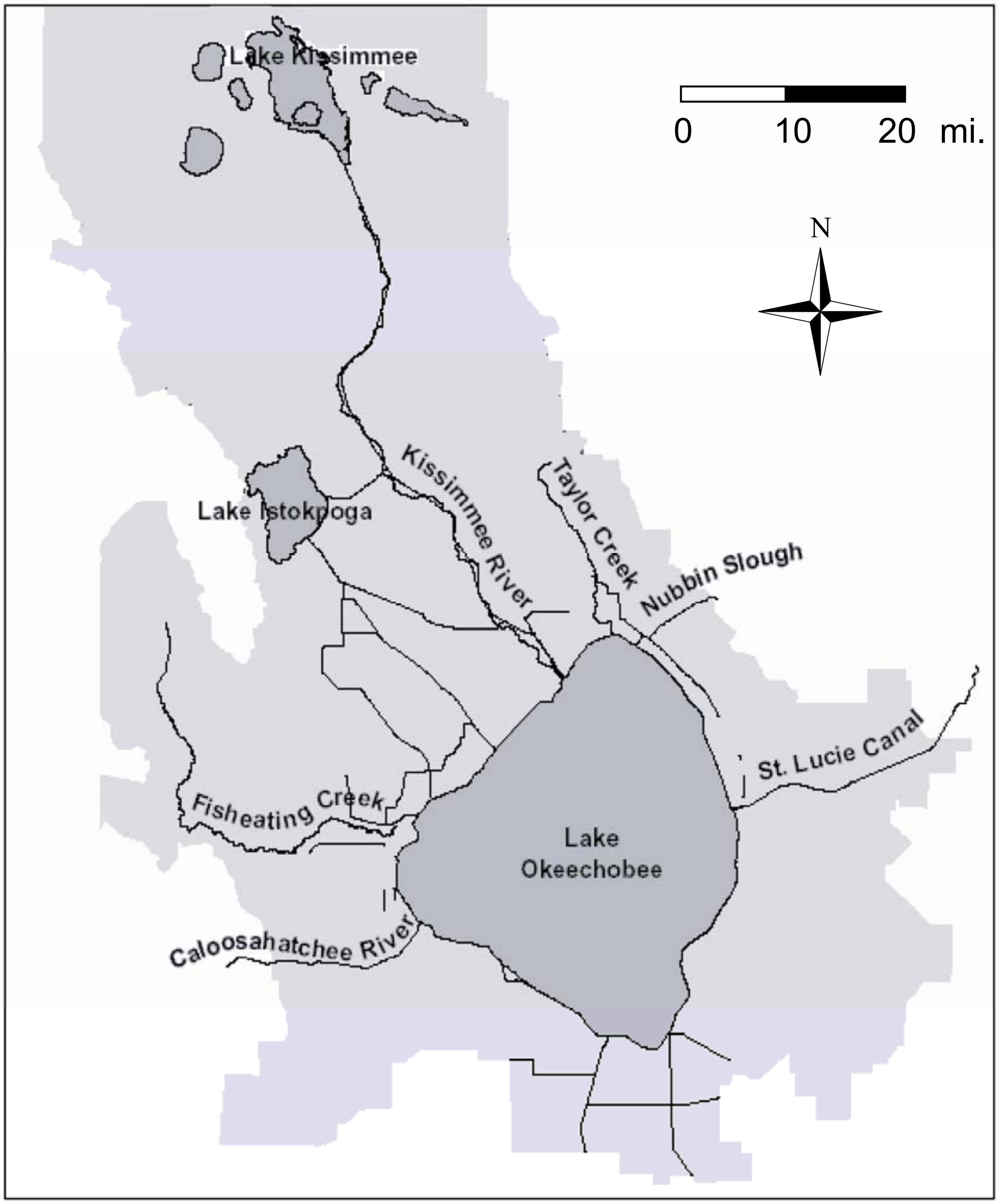


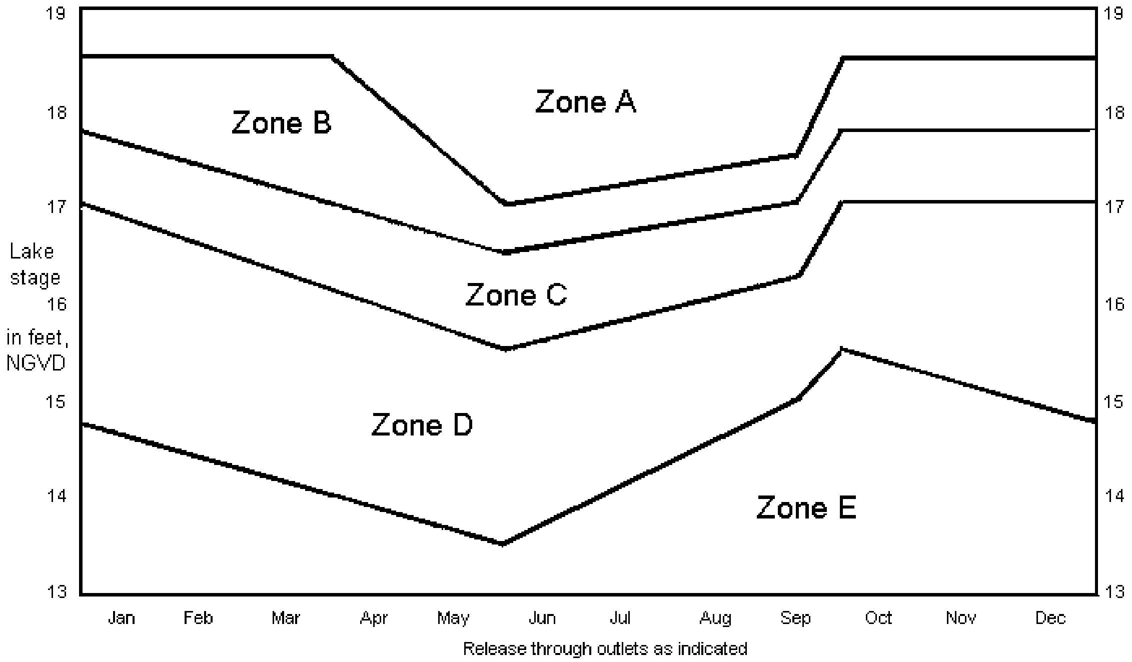
FIGURE 2-5. Drainage basin of Lake Okeechobee.
SOURCE: SFWMD et al. (2004).

Although Lake Okeechobee no longer provides the hydrologic services to the Everglades that it provided in its natural state, it still provides substantial water storage under current operating conditions. The lake's surface elevation and associated area and volume vary considerably both intra-annually and inter-annually in response to wet and dry climatic conditions, but at a normal high-water stage of 15 feet (4.6 m) above mean sea level, the lake has a surface area of 700 mi^2 (1814 km^2), an average depth of 9 ft (~2.7 m), a maximum depth of 15.5 ft (4.6 m), and a volume of 4.0×10^6 ac-ft (4.9×10^9 m^3). The lake has a maximum north-south (open-water) length of 35 miles (56.5 km) and maximum east-west length of 29.6 miles (48 km).

The natural drainage basin for Lake Okeechobee is primarily north of the lake (Figure 2-5), and the Kissimmee River is by far the largest tributary. The Kissimmee River Basin extends north almost 100 miles to near Orlando, Florida and accounts for about 60 percent of the lake's 5,022 mi^2 (13,000 km^2) drainage basin (including the area of the lake itself) (*http://www.esg.montana.edu/gl/huc/03090101.html*). As noted above, annual water inputs to the lake vary substantially, but typical values are in the range 1,500,000 to 3,300,000 ac-ft ($2.0\text{-}4.7 \times 10^9$ m^3), resulting in a range of water residence times in the lake of about 1-3 years.

A lake-stage regulation schedule has been used to manage lake levels for several decades. The schedule is modified periodically to reflect changes in management goals. The most recent of these is the "Water Supply/Environmental" (WSE) regulation schedule that was approved in July 2000 (*http://www.sfwmd.gov/org/pld/hsm/reg_app/lok_reg/*). In general, the schedule provides for maximum lake stage in winter and spring and lower stage during summer and fall to provide storage capacity for inflows associated with the summer rainy period and hurricane season. The storage volume available in Lake Okeechobee is a function of the regulation schedule (Figure 2-6). The maximum available storage under current operating conditions may be considered simply as the difference between the maximum allowed stage, 18.5 ft NVGD (National Vertical Geodetic Datum, essentially equivalent to mean sea level) and the minimum stage under which regulatory discharge is allowed (13.5 ft NVGD), if we assume that over a wet-dry climatic cycle there is no net loss of this storage to the sea. This volume (interpolated from Table 2-2) is 2,250,000 acre-feet (3.2×10^9 m^3). This maximum storage volume is insufficient to accommodate the average annual inflows of approximately 2.5 million acre-feet from sources excluding local precipitation during the 31-year record used to evaluate the Restoration Plan and is much smaller than the maximum annual inflow of over 4 million acre-feet in that record. The Restoration Plan will modify the current operating rules, but the objective of these modifications is not to provide additional water storage. Based on the maximum change in lake storage simulated in the D13R run, 2,231,800 acre-feet (Table 3-1), the potential storage capacity of the lake will be virtually unchanged by implementation of the Restoration Plan.

Use of Lake Okeechobee as a storage option was explored in a screening phase of the Restudy (i.e., the formal evaluation process that culminated in the Restoration Plan) but was not included in any of the project alternatives. The goals used in the screening evaluation of Lake Okeechobee were to prevent discharge to the Caloosahatchee and St. Lucie estuaries, provide water supply, and maintain water levels in the lake that were consistent with levee stability and healthy lake conditions. In the initial modeling runs the latter objectives were ignored, in that no restrictions were placed on water levels. These runs demonstrated that maximal use of storage in Lake Okeechobee would be "cost effective and hydrologically efficient" (USACE and SFWMD, 1999). They also demonstrated that such use would cause extreme fluctuations in lake levels, fluctuations that would be expected to adversely affect the littoral zone of the lake. The planned



Zone	Agricultural canals to WCAs (1,2)	Caloosahatchee River at S-77 (1,2,4)	St. Lucie Canal at S-80 (1,2,4)
A	Pump maximum practicable	Up to maximum capacity	Up to maximum capacity
B (3)	Maximum practicable releases	Releases per decision tree (these can range from maximum pulse release up to maximum capacity)	Releases per decision tree (these can range from maximum pulse release up to maximum capacity)
C (3)	Maximum practicable releases	Releases per decision tree (these can range from no discharge up to 6500 cfs)	Releases per decision tree (these can range from no discharge up to 3500 cfs)
D (3,5)	As needed to minimize adverse impacts to the littoral zone while not adversely impacting the Everglades (see note 5).	Releases per decision tree (these can range from no discharge up to 4500 cfs)	Releases per decision tree (these can range from no discharge up to 2500 cfs)
E	No regulatory discharge	No regulatory discharge	No regulatory discharge

(1) Subject to first removal of runoff from downstream basins
(2) Guidelines for wet, dry and normal conditions are based on 1) selected climatic indices and tropical forecasts and 2) projected inflow conditions. Releases are subject to the guidelines in the WSE operational decision tree, parts 1 and 2.
(3) Releases through various outlets may be modified to minimize damages or obtain additional benefits. Consultation with Everglades and estuarine biologists is encouraged to minimize adverse effect to downstream ecosystems.
(4) Pulse releases are made to minimize adverse impacts to the estuaries
(5) Only when the WCAs are below their respective schedules

Central and Southern Florida Interim Regulation Schedule - Lake Okeechobee, Dept. of the Army, Jacksonville District, 5 November 1999

WSE (with climate outlook)

FIGURE 2-6. "Water Supply/Environmental" (WSE) regulation schedule for Lake Okeechobee. SOURCE: Redrafted from *http://sfwmd.gov/org/pld/hsm/reg_app/lok_reg/wse_support/ wse_sched.pdf*.

TABLE 2-2 Stage-Volume and Stage-Area Relations for Lake Okeechobee

Stage (ft.)	Volume (acre-feet)	Surface area (acres)
0	0	
8	1,442,000	284,000
9	1,729,000	299,000
10	2,039,000	316,000
11	2,366,000	339,000
12	2,722,000	371,000
13	3,108,000	395,000
14	3,527,000	436,000
15	3,980,000	448,200
16	4,425,000	452,200
17	4,875,000	466,000
18	5,335,000	459,000
19	5,790,000	462,400
20	6,260,000	466,000
21	6,730,000	470,200
22	7,195,000	475,000

SOURCE: Available online at *http://www.sfwmd.gov/org/pld/hsm/reg_app/opln/orm/input_new.orm.*

modifications that were ultimately incorporated in the Restoration Plan are intended to further reduce stage fluctuations that may have detrimental effects on the littoral zone habitat, water supply for surrounding communities and agriculture, and levee integrity. Thus, these modified rules will likely reduce the available storage in the lake in any year compared to the current operating rules.

Water-Quality Considerations

Much of the water that eventually makes its way to the southern Everglades, both under current conditions and those anticipated in the plan, passes through Lake Okeechobee. Thus, water quality in the lake can affect water quality elsewhere in the system, with effects greater in the northern parts of the system (Weaver and Payne, 2004). It also can affect the lake's ecological status.

In terms of basic water chemistry and limnology, Lake Okeechobee is a hard-water, alkaline lake with moderately high dissolved solids, high pH, elevated concentrations of nutrients and dissolved organic matter, and (usually) low water clarity (Table 2-3). The lake is considered eutrophic; it has high nutrient and chlorophyll concentrations. Water quality conditions are not constant across the lake but vary in response to local inputs and conditions. For example, humic color tends to be highest in western and northwestern areas of the lake because of high loadings from tributaries (e.g., Fisheating Creek) draining extensive wetland areas. Water clarity varies considerably over time as well as in a spatial context. Low water clarity conditions generally reflect high concentrations of suspended solids from resuspension of fine-grained, organic-rich bottom sediments and/or from algal blooms, but low clarity (in terms of light penetration) also occurs in areas with high levels of humic color.

The main issues of concern regarding water quality in the lake and its effects on use of the lake as a water source for the Everglades all are related to nutrient overenrichment, which has been the primary concern of lake managers and limnologists throughout the period of modern studies on the lake. These studies began around 1970 and are described in more detail and in a historical context in chapter 4. Phosphorus is the primary nutrient of concern, although high external loadings of nitrogen contribute to the problem, and very high concentrations of nitrogen in surface runoff from the EAA led to the limitations on backpumping EAA water into the lake in the 1980s.

The effects of high nutrient loadings on the lake are essentially the standard ones leading to lake eutrophication: high concentrations of algae and increased frequency of algal "blooms" (visible growths of algae); increased dominance of blue green algae (cyanobacteria), which are a nuisance form of algae; and increased suspended solids concentration in the water column, with attendant loss of water clarity. Eutrophication typically results in changes in the higher trophic levels of a lake's food web, and these likely have occurred in Lake Okeechobee in the form of changes in the zooplankton and fish communities. Despite those changes (e.g., an increased population of planktivorous threadfin shad, *Dorosoma petenense*), it remains a prized resource for largemouth bass (*Micropterus salmoides*). Changes in the littoral-zone macrophyte community also have occurred over the past 30-40 years, including increased occurrence of nonnative invasive species, but other factors (including changes in lake levels) also affect the distribution and abundance of macrophyte species, and it is difficult to attribute these directly to the lake's high nutrient loadings.

TABLE 2-3 Summary of Lake Okeechobee Water Quality Characteristics, 1994-2003[*]

Characteristic	Units[†]	n[‡]	Mean	Median	Range	Std. Deviation
Specific conductivity	µS cm^{-1} 1305	469	460	132-863	89	
Color	PCU	1309	42	33	2-600	35
Dissolved oxygen	mg L^{-1}	1287	8.2	8.1	4.4-13.5	1.1
pH		1297	8.2	8.2	4.5-9.2	0.4
Total alkalinity	meq L^{-1}	1250	2.04	2.04	0.52-4.02	0.36
Chloride	mg L^{-1}	1232	59	57	0.5-95	15
Total suspended solids	mg L^{-1}	3610	19	13	1-234	19
Turbidity	NTU	1335	28	20	2-173	23
Secchi depth	cm	3349	50	49	5-220	27
Soluble reactive phosphorus	mg m^{-3}	3516	25	16	4-1123	29
Total phosphorus	mg m^{-3}	3572	94	83	4-1060	53
Ammonium-N	mg m^{-3}	3533	13	10	9-445	13
Nitrate-N + Nitrite-N	mg m^{-3}	3468	118	25	4-1022	155
Total organic N[¶]	mg m^{-3}	3521	1370	1320	440-4080	330
Total chlorophyll *a*	mg m^{-3}	3429	27	23	1-146	17
Corrected chlorophyll *a*[±]	mg m^{-3}	3420	23	18	0-122	15

Notes:
[*] Values for South Florida Water Management District sampling stations L001-L008; From T. James, SFWMD, written communication, July 2004. Some units were changed and the numbers converted from the SFWMD data.
[†] Explanation of units: µS cm^{-1} = microSiemens per centimeter; PCU = platinum-cobalt units; mg L^{-1} = milligrams per liter; meq L^{-1} = milliequivalents per liter; NTU = nephelometric turbidity units; cm = centimeters; mg m^{-3} = milligrams per cubic meter.
[‡] n = number of measurements over all stations and years.
[¶] Calculated from measured total Kjeldahl N minus ammonium-N.
[±] Total chlorophyll *a* minus phaeophytin *a*; an estimate of chlorophyll *a* in living cells.

The high levels of suspended solids and algae in the lake water also lead to secondary impacts on treatability of the water for drinking purposes (e.g., taste and odor problems, increased chlorine demand, difficulties in clarifying the water, and increased formation of toxic disinfection by-products such as trihalomethanes).

Efforts to manage nutrient loadings (especially phosphorus) to the lake have been underway since the mid-1970s (see Chapter 4 for details), but these have been only partially successful and have not resulted in reducing phosphorus concentrations in the lake itself. In fact, phosphorus concentrations are substantially higher in the lake today than they were when these efforts began. These trends may be explained at least in part by an increasing role of internal phosphorus loading (from the bottom sediments) in maintaining high phosphorus concentrations in the water. Over a period of decades, excessive external loadings of phosphorus to the lake resulted in a build-up of phosphorus concentrations in the near-surface sediments and also probably led to the build-up of more flocculent and less cohesive organic sediments at the sediment surface. Such flocculent sediments are more easily resuspended by wind-induced turbulence than more cohesive mineral sediments would be. The net effect is that Lake Okeechobee may have been transformed effectively into a self-sustaining eutrophic system by the decades of high external nutrient loading such that it no longer relies primarily on external nutrient sources to support its high algal productivity. If this is the case, further management of external phosphorus loads to the level in a proposed TMDL (Havens and Walker, 2002) will not quickly produce predicted benefits in water quality. However, on a longer time-scale (probably measured in decades), the lake should become a net exporter of phosphorus as it readjusts to the new (smaller) external loads—that is, some of the phosphorus recycled from the sediments will be lost from the lake in surface outflows each year, and over time the sediments will become a less important contributor to maintenance of high algal abundance in the lake.

Implications of the above discussion on use of Lake Okeechobee for additional water storage are fairly clear, at least in the short term. Nutrient concentrations in the lake are high relative to the very low concentrations in the Everglades, and some treatment of the water by passage through wetland marshes in the northern part of the Everglades (EAA, northern Water Conservation Areas) should be done (Odum and Odum, 2003) before the lake water reaches those oligotrophic areas. However, phosphorus concentrations in the lake still are low compared with those currently in EAA water and other contaminated stormwater in the system. Over time (decades), as management of external loads to the lake is achieved and the lake is allowed to purge itself of its contaminated sediments, phosphorus concentrations will decline in the lake. It is unlikely that they ever will be as low as those in the southern Everglades, but this also was probably true even in the pristine system. Current water discharges from the lake to the Everglades already receive treatment by STAs, although STAs might not remove enough phosphorus to help achieve the phosphorus criterion for the Everglades Protection Area, discussed in more detail in the Kissimmee Basin Section.

Water Conservation Areas

The central Everglades were converted into surface-water reservoirs called the Water Conservation Areas (WCAs) (Figure 2-7) when levees were completed in 1961-63. This state-owned region contains the southern portion of the sawgrass plain and the northern portion of the ridge-and-slough landscape. Currently the WCAs are managed to detain excess surface water from the EAA and parts of the east coast region. Water in the WCAs serves many competing uses: providing flood control, augmenting water supply along the east coast and in Everglades National Park, recharging groundwater in the Biscayne Aquifer, reducing seepage, and providing habitat for Everglades wildlife (USACE and SFWMD, 1999).

The WCAs have a combined storage capacity of 1,882,000 acre-ft (Light and Dineen, 1994). Under the current water-regulation schedule, the WCAs receive average inflows of almost 1,800,000 acre-ft per year through a combination of flood control and environmental discharges from Lake Okeechobee and the EAA, plus drainage from surrounding areas. The WCAs discharge 862,000 acre-ft per year to Everglades National Park through a combination of groundwater seepage and releases for flood control and environmental water supply. Water supply deliveries plus groundwater flow and seepage discharge an additional 849,000 acre-ft per year to the Lower East Coast (Figure 2-2). The WCA water regulation schedules are driven by two objectives inconsistent with natural system requirements: minimizing flood risk during hurricane season and maximizing storage during the dry season. The ecological values of the WCAs thus are compromised by pulsed rather than attenuated water flow, altered hydroperiods, localized pooling and over-drainage associated with canals and levees, and reduced flow of water southward (Light and Dineen, 1994).

FIGURE 2-7. Location of water conservation areas. SOURCE: Information on locations of existing and proposed storage components from USACE and SFWMD.

Because the WCAs still contain significant remnants of the original sawgrass plain, ridge-and-slough wet prairies, and tree islands, they offer a major opportunity for Everglades restoration. Current additions and removals of water from the WCAs reflect their use as reservoirs of the water variously desired or unneeded by surrounding managed areas. The levees that form the WCA impoundments also create pooled waters that are too shallow at the upstream end and too deep downstream. Ecologically appropriate water depths occur only in some portions of the WCAs. If a more natural sheetflow and hydroperiod can be established, a single, physically free-flowing freshwater landscape will exist in the combined state and federal properties, improving prospects for recovery of the ecological systems and dynamics in about half of the original Everglades. The central location and function of the WCAs causes them to affect or be affected by other restoration projects.

To restore more natural water levels and flows within the WCAs, a set of Restoration Plan projects is planned to decompartmentalize the WCAs by removing a number of barriers to sheetflow such as portions of the Miami Canal, which would be backfilled for several miles, and the Tamiami Trail, which will be elevated by installing a set of bridges; and removal of the levee L-29. These activities are described in the Project Management Plan for the WCA-3 Decompartmentalization and Sheetflow Enhancement Project Part 1 (*http://www.evergladesplan.org/pm/program/program_docs/pmp_12_wca/decomp_main_apr_2002.pdf*).

Currently, paths of uninterrupted water flow through the ridge-and-slough landscape are only 30 miles long, less than one-third of their original length. If decompartmentalization is completely successful, 70 miles of continuous flow paths will be restored, from the terminus of the Everglades Agricultural Area to Whitewater Bay. Water depths in the restored area are projected to slope continuously, without discontinuities, from the southern border of the Everglades Agricultural Area to Whitewater Bay. Water levels will rise and fall seasonally under the combined influence of rainfall and rainfall-driven additions of water along the upstream boundary of the restored area. Flows will approximate pre-drainage flows through the landscape, and they will protect tree islands from excessive water depths at the end of the wet season and damaging soil oxidation during the dry season. Water will not flow exactly as it did before drainage, however, because of the canals and levees to the east and north of the present-day Everglades.

These "decompartmentalization" components will alter the water sources to the WCAs, with a larger portion of the annual inflow coming in the form of overland flow. However, the total average inflow will increase only slightly, from approximately 1,800,000 to nearly 1,900,000 ac-ft/yr. Outflows to Everglades National Park will increase. (A careful examination of the simulation results summarized in Table 2-1 shows that the maximum difference between inflows and outflows over a year of the D13R simulation, 2,879,000 ac-ft, significantly exceeds the storage capacity for current operations. That might suggest that the Restoration Plan will lead to large increases in water storage in the WCAs. But the large volume of water lost to evapotranspiration from the WCAs will result in an average annual change in WCA storage of only 19,900 ac-ft as simulated by D13R. The maximum change in storage in any year is 1,523,100 ac-ft, somewhat lower than the storage capacity for current conditions.)

However, as impressive as the engineering will be, this is not the end in itself: the end is maintenance and restoration of the original landscape pattern. Simultaneous restoration of unimpeded flows and correct water depth variations is, along with restoration of water quality, the critical driving force that will maintain and restore the pattern of peat landscape originally present in this portion of the Everglades. The patterning of ridges, sloughs, and tree islands, each originally of different elevation, is a key to supporting the wildlife of the pre-drainage Everglades. The multitudes of otters and alligators once present and the populations of multi-year, larger fish all depended on persistence of the ridge and slough pattern to provide year-round aquatic habitat. Persistence of peat-based tree islands themselves may have been closely tied to the pattern of flows and water depths (NRC, 2003c).

Water-Quality Considerations

Given the physical location of the WCAs between the EAA and Lake Okeechobee to the north and west and Everglades National Park to the south, it is no surprise that water quality issues related to restoration of the WCAs are closely related to those in these adjoining areas. The primary concern is the potential for detrimental effects of excessive inputs of nutrients, especially phosphorus, from the EAA (and to a smaller extent from eutrophic Lake Okeechobee), on plant communities (both emergent macrophytes and periphyton) in the WCAs. As mentioned in the EAA discussion, phosphorus concentrations are highest in the north and lowest in the south (Payne and Weaver, 2004). Insofar as decompartmentalization of the WCAs should allow water to move more rapidly through the Everglades area now occupied by the WCAs, this restoration component might enhance the movement of relatively high nutrient water from the northern portions of the WCAs to more southerly areas. Stormwater Treatment Areas (STAs), which are engineered wetlands designed to remove nutrients from water by growing plants such as cattail, are supposed to mitigate the detrimental effects of excessive nutrients on plant communities in the Everglades, and are indeed reducing phosphorus concentrations. However, as noted elsewhere in this report, no STA yet constructed has produced effluent water with a phosphorus concentration as low as 10 micrograms per liter ($\mu g\ L^{-1}$). (See "Water Quality Considerations" sub-section of "Kissimmee Basin" section later in this chapter for additional discussion of issues associated with STAs and phosphorus concentrations.)

High sulfate loadings from the EAA (see discussion below) also are a concern as a possible cause for sawgrass replacement by cattails. High sulfate levels in water lead to high sulfide levels in anoxic, organic-rich sediments, and sulfide toxicity may contribute to the loss of native plant communities in parts of the WCAs that receive high-sulfate and nutrient-rich water from the EAA. In addition, high sulfate levels may exacerbate the mercury pollution problem by stimulating the growth of sulfate-reducing bacteria (SRBs) in sediments and periphyton; SRBs are thought to be the principal agents of mercury methylation in the environment. Mercury issues are described further in the section "Mercury Deposition, Mobilization, and Bioaccumulation" (Chapter 3) and in the section "EAA and Vicinity," subsection "Water Quality Considerations" later in this chapter. Of particular relevance for restoration of the WCAs is the likelihood that decompartmentalization will lead to more frequent and larger changes in water levels and more wet-dry cycles in the sediments, which are thought to stimulate pulses of mercury methylation (Krabbenhoft et al., 2000).

Conventional Surface Reservoirs

Surface-water reservoirs are a well established technology for water management. The Restoration Plan includes construction of a number of large conventional reservoirs in three main regions: the Kissimmee Basin (north of Lake Okeechobee), the Everglades Agricultural Area, and the Upper East Coast (Figure 2-8). Together, these reservoirs will provide new storage capacity of about 690,000 acre-feet. The following discussion focuses on these major reservoirs. The Restoration Plan also calls for construction of a number of other reservoirs for use in conjunction with planned ASR systems and for more local management of stormwater. Storage capacities and flux estimates (if available from the D13R water budget output) for these reservoirs are also listed in Table 2-1. These other reservoirs will provide an additional storage capacity of about 270,000 acre-feet. Additional new storage of approximately 160,000 acre-feet will be provided by numerous stormwater treatment areas (not listed in Table 2-1), designed primarily for water-quality improvement rather than storage per se.

Advantages of conventional reservoirs are the solid base of engineering design and operational principles for these structures. Disadvantages include the need for relatively large amounts of land and losses of water to evaporation during long periods of storage. Construction schedules for these features are constrained by land-acquisition schedules as well as by the availability

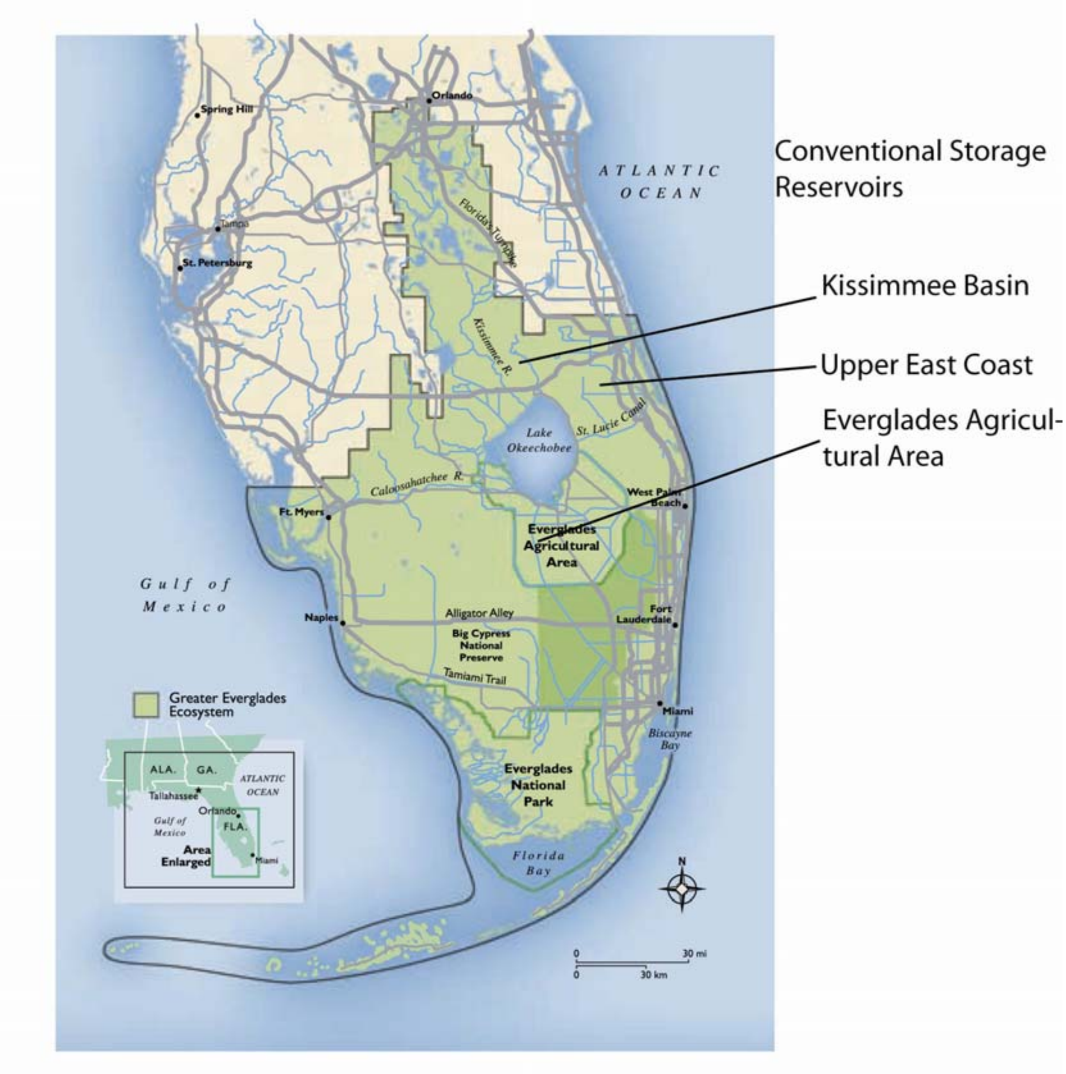


FIGURE 2-8. Location of conventional storage reservoirs. SOURCE: Information on locations of existing and proposed storage components from USACE and SFWMD.

of funds. Overall, however, these storage features are among the earliest for which construction will be completed, with planned completion dates according to the original implementation schedule ranging from 2010 for the Upper East Coast Reservoirs to 2014 for the second phase of the Everglades Agricultural Area reservoirs. The following sections provide additional information on each of the major conventional reservoir components.

Kissimmee Basin

The Restoration Plan includes a construction feature called the North of Lake Okeechobee Storage Reservoir, to be located in the Kissimmee River Region. This component includes an above-ground reservoir and a 2,500-acre stormwater treatment area (STA) for a total storage capacity of approximately 200,000 acre-feet. The specific location of this facility has not been identified; however, it is anticipated that the facility will be located in Glades, Highlands, or Okeechobee Counties. The initial design of this component assumed a 20,000-acre facility (17,500-acre reservoir and 2,500-acre treatment area) with water levels in the reservoir fluctuating up to 11.5 feet above grade. The final size, depth, and configuration of this facility will be determined through more detailed planning, land suitability analyses, and design. Future detailed planning and design activities also will include an evaluation of degraded water bodies within the watersheds of the storage/treatment facility to determine appropriate pollution load reduction targets, and other water quality restoration targets for the watershed.

The Restoration Plan estimated real estate costs of almost $190 million. Construction is planned to be completed by 2013 according to the most recent version (December 2003) of the project management plan for the Lake Okeechobee Watershed component. This deadline could be optimistic if difficulties are encountered during land acquisition, which cannot begin until a final site for the reservoir is selected.

Water-Quality Considerations

The primary water-quality issue related to this storage element is likely to be elevated nutrient concentrations, particularly phosphorus, in runoff water that will feed the reservoir. The inclusion of an STA in the plan recognizes this fact. Results from existing STAs indicate that these engineered wetlands can provide substantial removal of nutrients (especially phosphorus). However, thus far no STA has produced effluent water with as little as 10 $\mu g\ L^{-1}$. That concentration of total phosphorus was established as an overall criterion for the Everglades Protection Area (the Water Conservation Areas and Everglades National Park) by the Environmental Regulation Commission (ERC) in 2003 (Piccone et al., 2004). Details of the rule and methods for achieving it are contained in Florida Administrative Code 62-302.540. However, from an *ecological* perspective, it may not be critical that outflows from a reservoir this far north in the system precisely meet the criterion. The Everglades plant communities that require such low phosphorus levels occur further south. If the outflow from the Kissimmee reservoir were to be used, for example, to recharge Lake Okeechobee, outflow phosphorus concentrations somewhat higher than 10 $\mu g\ L^{-1}$ might be reasonable.

The long-term effectiveness of STAs (over many decades) in providing a high degree of phosphorus removal remains to be tested. Clearly, the longevity of a treatment facility depends on its size relative to the loadings it must assimilate. In theory, STAs can be constructed to provide adequate capacity for many decades of inputs if sufficient acreage is provided. At some point, however, water quality and the composition of the plant communities (which is related to chemical water quality) within STAs themselves will become issues of concern. If STAs are relatively small in size, the public likely will view them as a "necessary evil," but as they grow in number and size and occupy a larger fraction of the landscape in south Florida, the public might begin to view them as semi-natural systems that also should provide ecological amenities (beyond serving as nutrient removal basins). This is more likely to become an issue in the Conservation Areas south and east of Lake Okeechobee than in upland areas north of the lake because the former in fact represent lands that were part of the original Everglades.

EAA and Vicinity

An above-ground reservoir system is planned for construction in the Talisman Land acquisition of the Everglades Agricultural Area (EAA), on land that is currently under sugar cane cultivation. The total storage capacity of the system will be approximately 360,000 acre-feet, divided into three equal-sized compartments that each can accommodate water-level fluctuations of up to 6 feet above grade. Compartment 1 will store excess runoff from the EAA to meet future irrigation demands. The other two compartments will be operated as dry storage reservoirs with discharges down to 18 inches below ground level to accommodate Lake Okeechobee regulatory releases and overflow from Compartment 1. Discharges from these compartments will be managed to improve timing of environmental releases to the Water Conservation Areas.

Land acquisition costs for these reservoirs are expected to be relatively low compared to those for the other two major reservoir systems because of the leverage provided by the Farm Bill. The total real estate costs estimated in the Restoration Plan are approximately $87 million. The first phase of the reservoir construction is scheduled to be completed in 2009, and the final phase in 2014.

Water-Quality Considerations

Use of land within the EAA and vicinity for surface water storage would entail at least two potentially important water-quality issues: (a) high nutrient levels in the soils, a legacy of many decades of intensive agriculture, and (b) exacerbation of the mercury pollution problem in the Everglades. EAA nutrient issues may involve both nitrogen and phosphorus. Within the Everglades Protection Area, both total phosphorus and total nitrogen concentrations are highest in the north; this primarily reflects agricultural runoff from the EAA (Payne and Weaver, 2004). Because the Everglades ecosystem is strongly limited by phosphorus and because plant communities in the Everglades are adapted to these low levels, phosphorus is the primary nutrient of concern in the Everglades itself. Nonetheless, elevated nitrogen concentrations would be a concern if water from EAA storage facilities reached nitrogen-limited parts of Florida Bay (NRC, 2002b). The Restoration Plan assumes that STAs would be required to treat water from EAA storage reservoirs before it was released to the Everglades, and the considerations discussed previously with regard to the effectiveness and sustainability of STAs apply here. STAs rely primarily on plant assimilation for nutrient removal. Thus, they should be reasonably effective for nitrogen as well as phosphorus—provided that the incoming waters have reasonably well-balanced ratios of nitrogen to phosphorus relative to plant growth requirements. Because of the proximity of EAA lands to Everglades lands that are adapted to low levels of phosphorus, attainment of the 10 $\mu g\ L^{-1}$ effluent criterion is likely to be critical to avoid alteration of the oligotrophic plant and periphyton communities associated with the Everglades.

EAA storage reservoirs pose a risk of mercury pollution to the Everglades by at least two mechanisms. First, recent work (Krabbenhoft et al., 2000) has demonstrated that conversion of mercury to the toxic methylmercury form, which bioaccumulates in food webs, is enhanced under conditions where soils and sediments undergo cycles of wetting and drying. Exposure of wet soils to air under drying conditions promotes oxidation of reduced sulfur species in soil to form sulfate, the electron acceptor required by sulfate-reducing bacteria to grow when the soils again are inundated and anoxic conditions develop. Sulfate-reducing bacteria are thought to be the primary agents of mercury methylation in soil and sediment environments. Krabbenhoft et al.

(2000) showed that enhanced mercury methylation occurs in mesocosms containing Everglades soils subjected to repeated wet-dry cycles. EAA surface reservoirs for Everglades restoration will involve cycles of storage and draw-down that will expose the soils to repeated wet-dry cycles, and thus they may promote the formation of methylmercury that can be transported into the Everglades when water is released from the storage reservoirs.

Second, EAA soils have elevated levels of sulfur from past agricultural management practices; elemental sulfur is added to sugarcane grown on organic soils (300-500 lb S/acre) as an acidifying agent to mobilize micronutrients. (Oxidation of elemental sulfur to sulfate produces hydrogen ions and lowers the soil pH, thus enhancing trace metal availability for plant growth.) This practice explains the relatively high sulfate levels of EAA runoff that flows into WCA-1 and WCA-2 (59 ± 19 mg L^{-1} and 52 ± 19 mg L^{-1}, respectively in 2003; Weaver and Payne, 2004). In contrast, sulfate levels in surface waters of the southern parts of the Everglades tend to be very low (~1-3 mg L^{-1} for waters within Everglades National Park; Table 2A-7, SFWMD and Florida DEP, 2004), reflecting atmospheric deposition as the primary source, and possibly representing sub-optimal conditions for mercury methylation by sulfate-reducing bacteria.

Upper East Coast

Four reservoirs are to be constructed in the Upper East Coast as part of the Indian River Lagoon–South component of the Restoration Plan. Together, the new C-44 Reservoir (replacing an older reservoir in the basin), the C-23/24 North and South Reservoirs, and the C-25 Reservoir and associated stormwater treatment areas will provide a total of 135,000 acre-feet of storage capacity. Additional storage of approximately 30,000 acre-feet will be provided by restoration of approximately 90,000 acres of uplands and wetlands in Martin, St. Lucie, and Okeechobee Counties.

Real-estate costs for these reservoirs are anticipated to be the highest among the three reservoir systems, at over $500 million, presumably because these reservoirs will displace or preclude commercial and residential uses in an urbanized area. Construction of these reservoirs is scheduled for completion by 2010.

The Indian River Lagoon–South projects are fairly independent from most of the other Restoration Plan projects. Indeed, it is estimated that 100 percent of the watershed benefits and 88 percent of the total estuary benefits of the project will be achieved even if other Restoration Plan projects are never constructed (USACE and SFWMD, 2004).

Water-Quality Considerations

According to the Final Project Implementation Report, or PIR (USACE and SFWMD, 2004), the combination of reservoirs, constructed stormwater treatment areas, and restored wetlands are expected to reduce nutrient and sediment loading to the estuary. The report also notes that surface water stored in reservoirs will be lower in alkalinity and chloride than water pumped from the Floridan Aquifer, which will make it a preferred source of irrigation water in this region.

An independent scientific review panel (Bartell et al., 2004) was generally supportive of the project, saying that the plans as presented in the report "have a high likelihood of meeting the restoration objectives." The panel did express concerns that the PIR did not present evidence as to what "thresholds of restoration measures" will support a more natural regime of algal blooms. That is, what specific changes in freshwater residence time, and what levels of reduction of nutrient loading, will significantly influence patterns of phytoplankton production in the estuary? While adaptive management can resolve this issue to some extent, given the importance of these factors to the estuary, a better understanding is needed of the relationships of the freshwater timing and quality to improvements in the algal bloom regime. That panel was also concerned that the PIR does not include as a performance measure dissolved oxygen, and does not discuss how system responses may change dissolved oxygen concentrations in time and space.

OTHER TECHNOLOGIES AND STRATEGIES

In addition to existing storage areas (such as Lake Okeechobee and the Water Conservation Areas), and conventional surface reservoirs, the Restoration Plan envisions the use of other technologies. These include storing water underground, known as "aquifer storage and recovery," use of completed quarries for storage (such as the so-called "Lake Belt reservoirs"), seepage management, and water reuse. While worth exploring as alternative methods of storing and conserving water, each of these technologies brings concomitant risks and uncertainties with them.

Aquifer Storage and Recovery

Aquifer Storage and Recovery (ASR) (Figure 2-9a) involves pumping water into the subsurface through deep wells for storage and then recovering the water when it is needed by extracting water from the same wells. Plans include a large-scale ASR system in the Lake Okeechobee region (Figure 2-10) and smaller systems in several other locations in south Florida that will involve over 330 wells, assuming a capacity of 5 million gallons per day (MGD) per well, corresponding to a maximum annual capacity of 1.85 million acre-feet for all wells pumping simultaneously and continuously. On an annual basis, these wells are anticipated to accommodate an average of over 500,000 acre-feet of injected water, well below the maximum annual capacity. However, the maximum estimated annual injection rates (totaling 1.66 million acre-feet according to the SFWMD model simulation results; see Table 2-1) indicate that during very wet years the ASR systems will operate near 90 percent of the total annual capacity.

Determining a total storage capacity of an ASR system for comparison with capacities of other storage components is complicated because, at least in theory, the total capacity is limited only by the available pore volume of the aquifer. However, estimates of potential capacity can be obtained by examining the water budget outputs of the 31 year simulations used to evaluate the Restoration Plan. Based on these model simulations, almost 4,000,000 acre-feet of injected water would remain in storage within the Lake Okeechobee ASR system at the end of 31 years. Of this injected water, approximately 1,500,000 acre-feet would be recoverable assuming the 30 percent injection losses that were used for the water management model computations. The simulations include a three-year period during which 1,233,600 acre-feet are recovered from the Lake Okeechobee ASR system while no water is added to ASR storage. Even assuming 30 percent injection losses, the ASR systems together make up about three-quarters of the new stor-

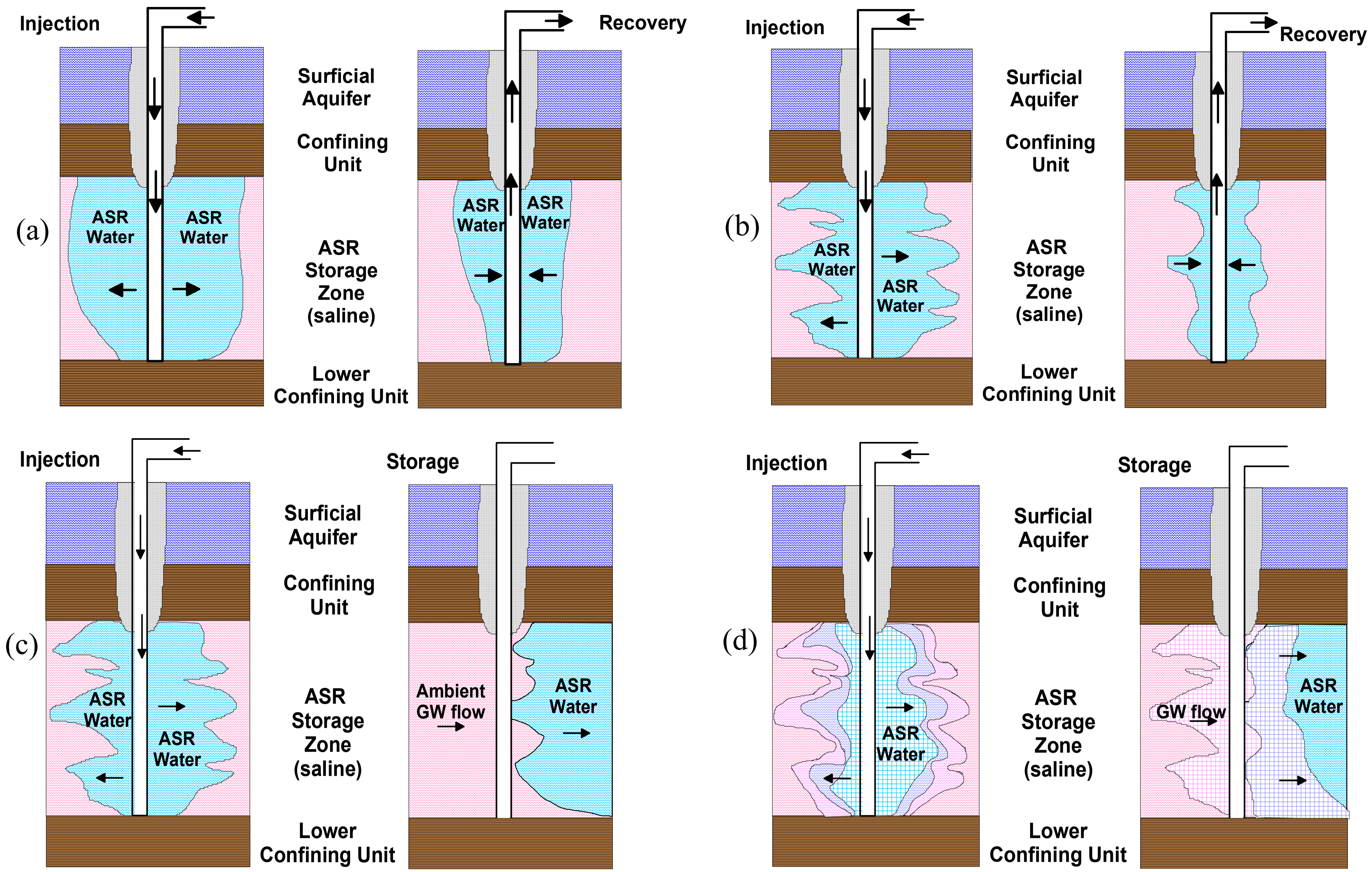


FIGURE 2-9. (a) Idealized aquifer storage and recovery system, and potential effects of (b) aquifer heterogeneity, (c) ambient flow and transport, and (d) mixing and water rock interactions. The first two panels (a and b) illustrate effects on recovery; the second two (c and d) illustrate effects during storage.

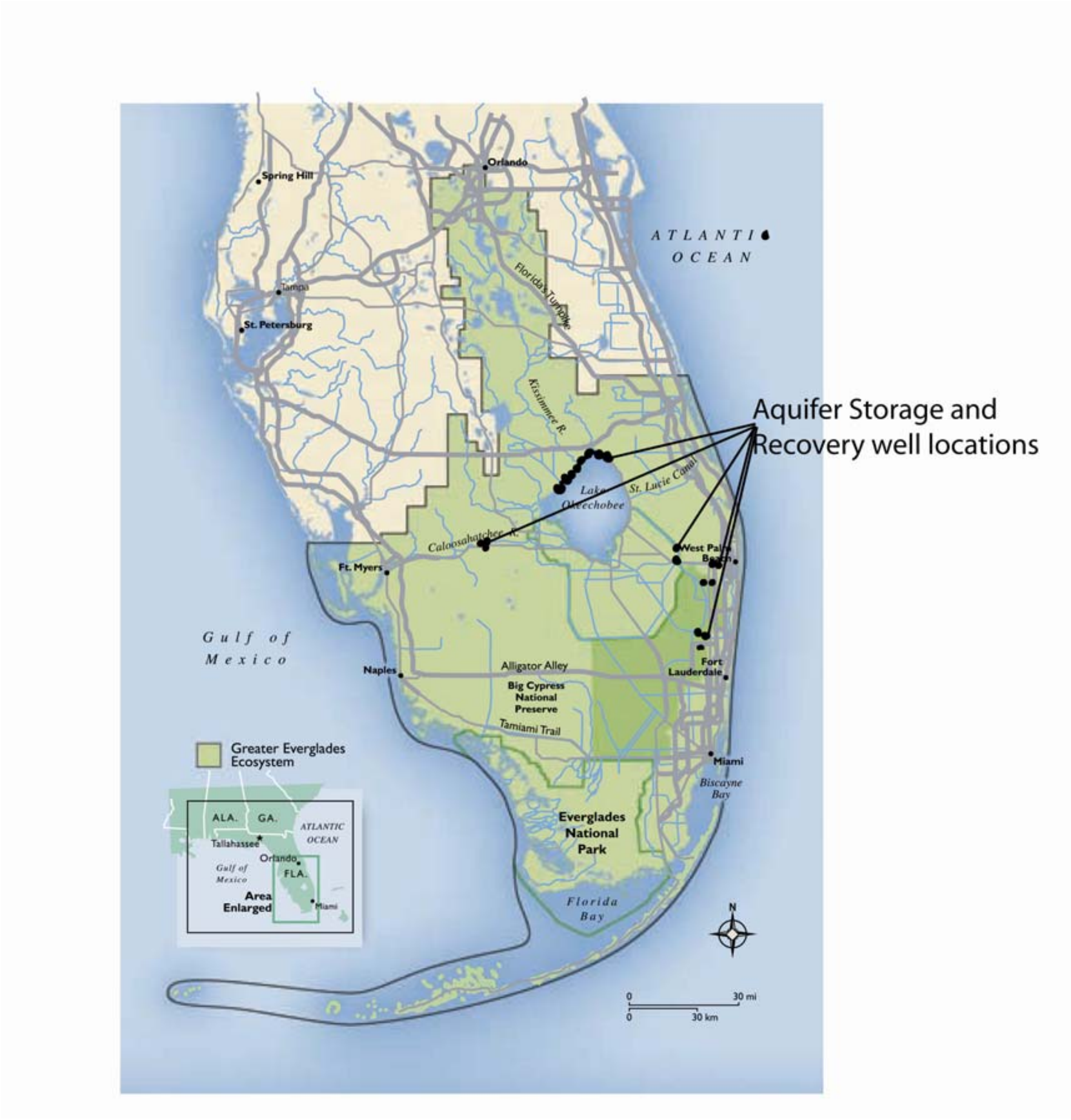


FIGURE 2-10. Approximate location of ASR wells. SOURCE: Information on locations of existing and proposed storage components from USACE and SFWMD.

age capacity of the Restoration Plan. A more extensive discussion of this technology is included in previous committee reports (NRC 2001a, 2002a).

ASR was initially explored as a storage option because it appeared to offer several advantages relative to surface storage and because initial cost estimates indicated that it would be less expensive than constructing additional surface reservoirs (Appendix A of USACE and SFWMD, 1999). Because ASR does not require large amounts of land, it would not displace other activities, such as agriculture, nor would it occupy large areas of land that could become part of the restored footprint. Because the water is stored underground, losses to evaporation will not decrease the volume of stored water, as would be the case for surface reservoirs. In principle, because of the lack of evaporation and because the available subsurface storage zone is effectively unlimited in size, ASR can allow for continuous storage with opportunities to add more water over a number of years.

A disadvantage of ASR, relative to surface storage, is that it is a highly engineered storage technology, with significant long-term energy requirements for injecting and recovering water from the subsurface. In addition, well and pump maintenance for a distributed system of hundreds of wells is necessary. The water may require pre-injection or post-recovery treatment to meet regulatory standards or environmental requirements. Perhaps the greatest potential disadvantage stems from uncertainties associated with feasibility of the technology. In the current plan, the regional ASR systems have been planned using an anticipated injection rate of 5 MGD per well; whether this injection rate can be achieved consistently remains to be tested during pilot studies. During the initial phases of the Restudy, when cost comparisons to surface storage were used to select ASR, the wells were assumed to have a 10 MGD injection capacity. If, in the end, the average capacity of ASR wells is 5 MGD (or less), cost comparisons to surface storage would likely be less favorable.

Although ASR will not be subject to evaporative losses, it probably will not be possible to recover a volume equal to that injected. Mixing of injected water with more saline ambient aquifer water during storage (Figure 2-9b, d) or replacement of injected water by advective transport of aquifer water (Figure 2-9c) could render some of the injected water inaccessible to recovery. Even in the absence of significant aquifer flow, water-quality changes, induced by mixing with ambient brackish water or as a result of subsurface geochemical and biogeochemical reactions (Figure 2-9d), could limit the amount of stored water that is suitable for recovery and release to the ecosystem. The Restoration Plan design assumes a recovery efficiency of 70 percent (30 percent loss during injection), which may be an overestimate or underestimate.

Land-acquisition costs for the ASR systems, estimated in the Restoration Plan at approximately $231 million, are considerably lower than the $800 million estimated for the surface reservoirs described previously. In contrast, estimated annual operation and maintenance costs for the ASR systems exceed $36 million, while those for surface reservoirs total approximately $25 million. Furthermore, ASR operation and maintenance costs are highly uncertain due to uncertainties in future energy prices.

Several pilot studies are under way (ASR Regional Study, Hillsboro and Lake Okeechobee ASR Pilot projects) to address the uncertainties associated with ASR feasibility, recovery efficiency, and water quality changes. The time required to conduct these pilot studies (5-10 years) is a major constraint on sequencing of ASR within the Restoration Plan construction schedule. In the original implementation schedule, completion of the Lake Okeechobee Regional ASR system is not expected before 2026. The other, smaller ASR systems have scheduled completion dates ranging from 2017 to 2020.

The pilot studies might confirm that ASR has the potential to provide (or exceed) the storage capacity assumed for this technology in the design of the Restoration Plan. However, if the pilot studies indicate that ASR cannot provide the anticipated storage capacity, other sources of storage will likely need to be identified. Given the uncertainties associated with this technology, contingency planning prior to completion of the pilot studies is essential to limit further delays should the pilot studies yield unfavorable results. Recognizing this need, the USACE and SFWMD are working on an ASR contingency study.

Water-Quality Considerations

As is the case for all storage components, capture of water that currently flows to the sea and storing it in an ASR system would reduce damaging pulses of freshwater entering estuaries.

If the water can be recovered efficiently and if it is of suitable quality, the release of the stored water to the ecosystem during dry years would help to maintain critical water levels and flows in the southern Everglades. Use of ASR as an alternative to storage in Lake Okeechobee or the Water Conservation Areas would reduce environmental damages associated with extreme water level fluctuations in the existing storage features.

As for negative effects of ASR, a primary concern is potential damage to the ecosystem associated with the quality of the water recovered from ASR wells. As noted above, the injected water may experience changes in chemical composition as a result of mixing or subsurface geochemical and biogeochemical reactions. Although moderate changes in such characteristics as pH, hardness, or salinity might have no consequence for the suitability of the recovered water for human water supply, ecosystems might be quite sensitive to these changes. For example, an expanding coverage of calcareous periphyton in the Everglades has been attributed to introduction of $CaCO_3$-rich water via canals that are in contact with mineralized groundwater (Browder et al., 1994). In addition, changes in concentrations of dissolved constituents such as sulfate may influence the speciation and bioavailability of contaminants such as mercury.

Another water-quality concern is the chemical and microbial contamination of the aquifer by low-quality surface water. This issue could be resolved by requiring pre-treatment of surface water, including disinfection, before it is pumped into the aquifer, and legal requirements regarding the microbiological quality of water recharged to ground-water aquifers may necessitate this strategy. However, pre-treatment likely would increase the costs of ASR dramatically, and it also could cause other problems, including the formation of potentially toxic disinfection by-products from reaction of chlorine (a likely disinfectant) with natural organic matter occurring in the recharge water (Krasner et al., 1989). Surface waters in the areas where ASR is proposed tend to be high in natural organic matter, promoting the formation of disinfection by-products and also tending to make pre-treatment a more costly and difficult proposition.

Degradation of water quality during storage in the aquifer as a result of reactions between the water and mineral solid-phases could lead to elevated concentrations of radionuclides, which are naturally abundant in the aquifer minerals, and possible increases in certain trace heavy metals. Other water-quality issues associated with ASR were discussed in greater detail in a previous report by this committee (NRC, 2001a).

An additional concern is the potential that the increased pressure in the storage zone of the Floridan Aquifer resulting from injection could induce fracturing of the overlying Hawthorn confining unit, providing a pathway for brackish ambient water or the stored water to migrate upwards into the overlying freshwater aquifer. Finally, the cumulative effect of a large-scale injection and recovery operations could alter ambient flow in the Floridan Aquifer over a larger region than that covered by the ASR wells. Changes to regional flow patterns could have consequences in locations where the Floridan Aquifer contains fresh water and is used for water supply.

The ASR Regional Study is intended to address questions related to each of these potential impacts of ASR implementation. Depending on the outcomes of this pilot study, as well as on issues related to regulatory compliance, pre-injection or post-injection treatment of the water may be required.

In-Ground Reservoirs

Two in-ground reservoirs constructed in former quarries are planned for the Lake Belt area of Miami-Dade County. A third smaller, shallower in-ground reservoir also is planned for western Palm Beach County near the L-8 canal. The following discussion focuses on the proposed reservoirs in the Lake Belt, but similar construction concerns may apply to the L-8 reservoir as well.

After mining companies have quarried 1.7 billion tons of limerock over a 30+ year period, surface reservoirs extending to depths of approximately 80 feet are planned in the Lake Belt rock mining area of Miami-Dade County, west of the City of Miami (Figures 2-1, 2-11, 2-12). Two quarries with a total surface area of 9,700 acres and a total storage capacity of 280,000 acre-feet are anticipated to accommodate inflows averaging approximately 250,000 acre-feet annually.

The reservoirs will occupy 9,700 acres of land in a region that is currently undeveloped and could, in theory, be part of the land acquired for restoration. However, these areas are within a footprint for which mining companies already have requested permits to excavate, and they are likely to be mined whether or not the quarries are eventually converted into storage reservoirs. To convert the quarries at the end of active mining into reservoirs that can store water for use as a supply to the Everglades during dry weather periods, seepage barriers must be created to limit the infiltration of groundwater from the surrounding aquifer and to hold the stored water within the reservoirs. (Indeed, the quarries are currently filled with water from groundwater infiltration during the mining period.) The technology required to create these seepage barriers at the required scale in permeable limestone has not yet been developed or tested, and hence both costs and feasibility associated with this storage component are uncertain. As in the case of any surface reservoir, water will be lost to evaporation from the free surface. However, the net evaporative losses will not exceed evaporative losses that would occur from standing water in a quarry lake of equivalent size that was filled with water that had infiltrated from the surrounding aquifer. In other words, replacing a quarry lake with a quarry reservoir will have no net effect on evaporative losses from the system as a whole.

Timing of construction of the Lake Belt reservoirs is constrained by a number of factors. First, the pilot studies to assess costs and feasibility of technologies for creating seepage barriers must be completed, and in turn, these require completion of excavation at the quarries to be used in the pilot studies. The pilot-project management plan indicates that the pilot project will not be completed until after 2010 (USACE and SFWMD, 2002b). Following selection of final sites and sizes of the reservoirs, mining activities may take a decade or more before the quarries will be available for water storage, resulting in an estimated date of 2036 for completion of the final phases of construction. There also are questions about whether the selected seepage technology will be able to withstand blasting occurring in nearby, active quarries (USACE and SFWMD, 2002b). If the technology is sensitive to blasting effects, construction could be further delayed until mining is completed at other quarries in the vicinity.

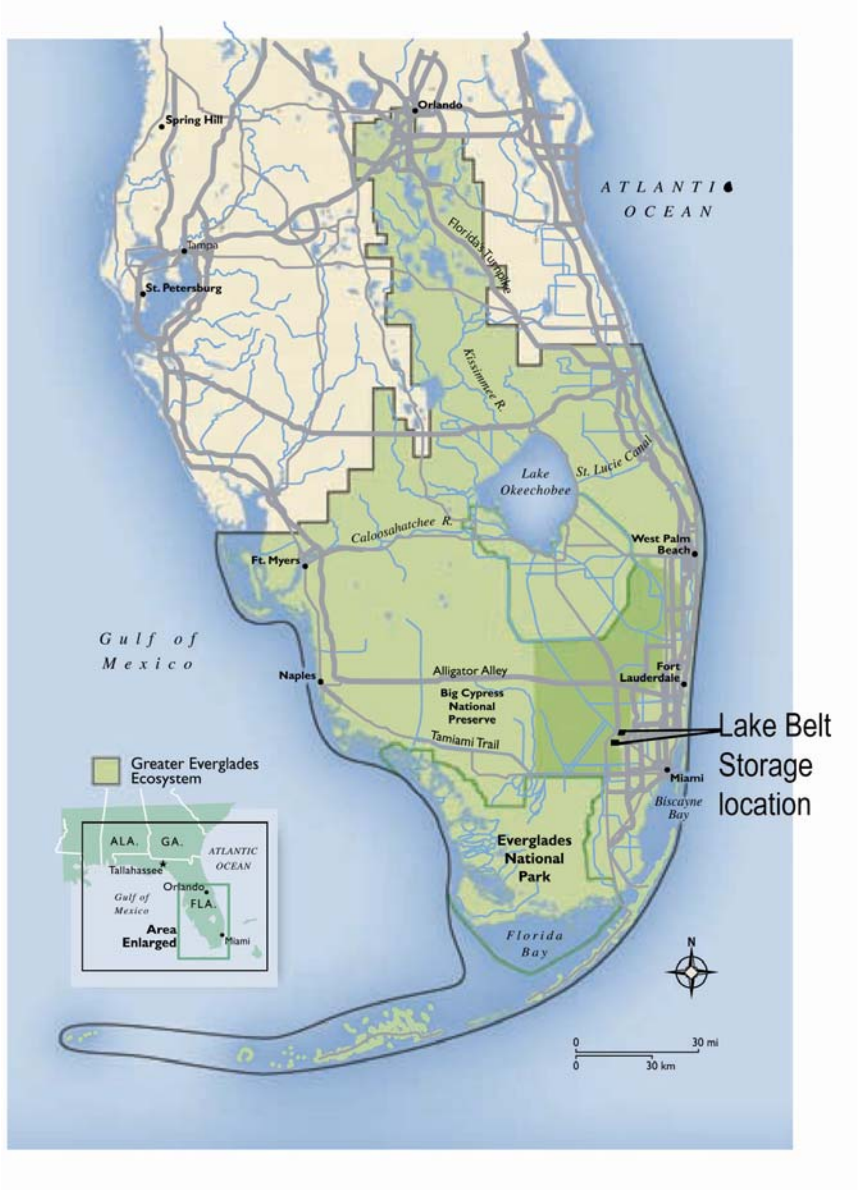


FIGURE 2-11. Approximate location of Lake Belt storage. SOURCE: Information on locations of existing and proposed storage components from USACE and SFWMD.

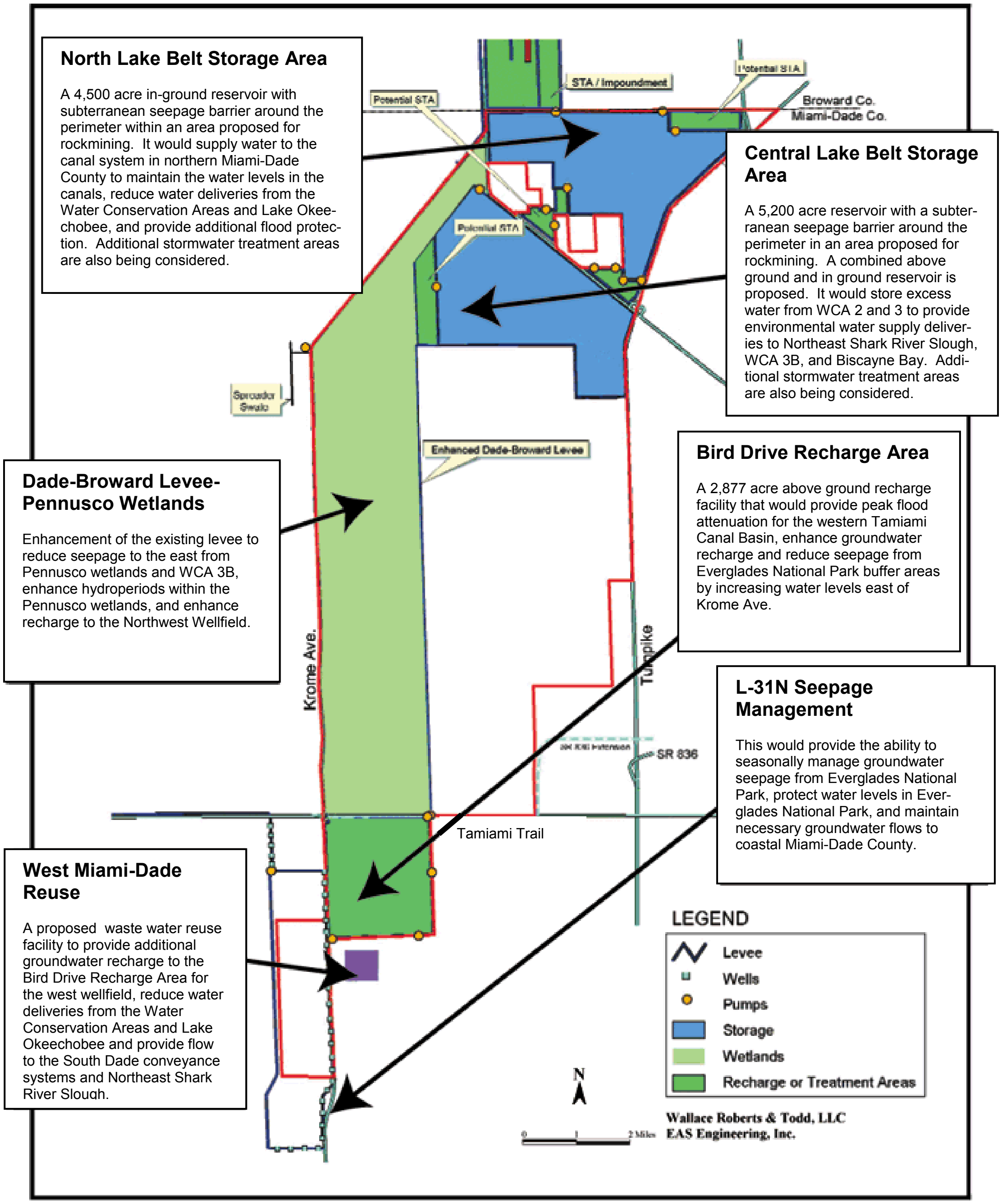
Although development of the Lake Belt reservoirs involves loss of wetland or other habitat in an area adjacent to the restoration footprint, this land likely would be lost to the restoration in any case (based on current land-use plans for the Lake Belt region). While the reservoirs will not displace agricultural activities or urban development, the estimated land costs totaling over $255 million provided in the plan suggest that land costs per acre for these reservoirs will exceed those for the conventional reservoirs in the Kissimmee Basin and the EAA. In addition, construction costs associated with creating the seepage barriers will be high. The estimated construction costs of $783 million far exceed the total construction costs for the conventional surface-water reservoirs. Depending on the long-term integrity of the seepage barriers, there may be additional maintenance and repair costs to consider as well. Operational costs in terms of pumping and distribution should be similar to those of other surface reservoirs.

Water-Quality Considerations

Water quality of the stormwater runoff used to supply Lake Belt reservoirs will depend on land uses in the drainage areas from which the runoff is derived. The Northern Lake Belt reservoir will receive local basin runoff and, ultimately, some water recovered from WCA 3A/3B seepage-management efforts. The Central Lake Belt reservoirs are intended to store excess water from WCAs 2 and 3, routed to the reservoirs via improved L-37 and L-33 borrow canals. Most local basins likely will be in urban/suburban land use, but some lands used for intensive agriculture also may contribute runoff. Consequently, some water supplying these reservoirs is likely to be contaminated with constituents usually associated with these land uses: elevated nutrients (nitrogen and phosphorus) and oxygen-demanding biodegradable natural organic matter; suspended solids; potentially pathogenic microorganisms of animal and possibly human origin; a variety of heavy metals, including zinc, cadmium, and lead; and low levels of a wide variety of synthetic organic contaminants (e.g., herbicides, pesticides, and polycyclic aromatic hydrocarbons) used on urban landscapes or formed in urban environments.

Certain characteristics of the reservoirs may lead to improvements in the quality of the water stored there for extended periods. The morphometry of the reservoirs—steeply sloping sides, small littoral zones, and large mean and maximum depths—should promote settling of suspended material and minimize resuspension of bottom sediments by wind-induced mixing. If annual nutrient loading rates are not too high and water residence times are fairly long, nutrients will be assimilated by algae and conveyed to the bottom by natural settling processes, such that the reservoirs may have moderately high water clarity and relatively low chlorophyll levels, making them suitable for certain kinds of aquatic-based recreational activities.

On the other hand, reservoir morphometry also is likely to promote strong thermal stratification in the water column that may persist for long periods (possibly several years). This will lead to highly anoxic conditions in the stagnant hypolimnion (cooler bottom layer of water), which is likely to comprise a large fraction of the total volume of Lake Belt reservoirs, and to the build-up of undesirable constituents, including sulfide, ammonia, methane, dissolved iron, and manganese. This will cause a large fraction of the stored water to be unsuitable for municipal water supply—or at least render it much more difficult and expensive to treat. In addition, such water would violate state water-quality standards for direct release into surface drainage canals in the Everglades drainage network, although it could be made to meet state standards by treatment involving aeration before release. Alternatively, it may be desirable to maintain oxygenated conditions throughout the water column of Lake Belt reservoirs by installing aeration devices in the reservoirs. Although such devices are technically feasible, they would be costly to operate and maintain, given the size and depths of the reservoirs (and the volumes of water that would need to be aerated).



North Lake Belt Storage Area

A 4,500 acre in-ground reservoir with subterranean seepage barrier around the perimeter within an area proposed for rockmining. It would supply water to the canal system in northern Miami-Dade County to maintain the water levels in the canals, reduce water deliveries from the Water Conservation Areas and Lake Okeechobee, and provide additional flood protection. Additional stormwater treatment areas are also being considered.

Central Lake Belt Storage Area

A 5,200 acre reservoir with a subterranean seepage barrier around the perimeter in an area proposed for rockmining. A combined above ground and in ground reservoir is proposed. It would store excess water from WCA 2 and 3 to provide environmental water supply deliveries to Northeast Shark River Slough, WCA 3B, and Biscayne Bay. Additional stormwater treatment areas are also being considered.

Bird Drive Recharge Area

A 2,877 acre above ground recharge facility that would provide peak flood attenuation for the western Tamiami Canal Basin, enhance groundwater recharge and reduce seepage from Everglades National Park buffer areas by increasing water levels east of Krome Ave.

Dade-Broward Levee-Pennusco Wetlands

Enhancement of the existing levee to reduce seepage to the east from Pennusco wetlands and WCA 3B, enhance hydroperiods within the Pennusco wetlands, and enhance recharge to the Northwest Wellfield.

L-31N Seepage Management

This would provide the ability to seasonally manage groundwater seepage from Everglades National Park, protect water levels in Everglades National Park, and maintain necessary groundwater flows to coastal Miami-Dade County.

West Miami-Dade Reuse

A proposed waste water reuse facility to provide additional groundwater recharge to the Bird Drive Recharge Area for the west wellfield, reduce water deliveries from the Water Conservation Areas and Lake Okeechobee and provide flow to the South Dade conveyance systems and Northeast Shark River Slough.

FIGURE 2-12. Map showing the location of the proposed Central and North Lake Belt Storage Areas, L-31N Seepage Management, and the West Miami-Dade Wastewater Reuse Facility. Water Conservation Areas 3A and 3B Levee Seepage Management would be located just north of this map and the proposed reuse facility associated with the Miami-Dade South Wastewater Treatment Plant about 15 miles to the south.
SOURCE: Available online at *http://sflwww.er.usgs.gov/publications/ofr/02-325/introduction.html.*

The major ion composition of the lakes also could be an issue. Constructed in a limestone stratum, the lakes will have hard water (high in calcium, magnesium and bicarbonate alkalinity). Although these constituents are desirable from many perspectives, they have the potential to substantially increase the hardness and ionic strength of water flowing through the southern Everglades, a system driven primarily by rainfall chemistry and thus historically a soft-water environment. The flora and possibly associated fauna of this part of the Everglades are adapted to soft water, and major shifts in plant community composition could result from use of the Lake Belt to supplement water flows to the Everglades during periods of low rainfall.

Finally, water-quality concerns regarding the Lake Belt reservoirs include the potential for contamination of the shallow Biscayne Aquifer, which is used for drinking-water supply. This potential depends on the source and level of pre-storage treatment applied to water that will be added to the reservoirs, as well as on the hydraulic connection that remains between the reservoirs and the aquifer once seepage barriers have been constructed. The Lake Belt Pilot Project includes a water-quality evaluation to address these concerns.

Changes in the groundwater flow field associated with reservoir construction and operation could also affect operations at municipal well-fields near the Lake Belt. The pilot project includes a regional hydrologic evaluation to evaluate these potential impacts.

Seepage Management

Differences in hydraulic head across levees that bound the Water Conservation Areas and Everglades National Park result in significant seepage losses to the east, toward the coast through adjacent canals. For the overall Everglades system, the Governor's Commission for a Sustainable South Florida (1997) estimated seepage losses at over one million acre-feet per year, a significant amount in relation to other components of the Restoration Plan. Seepage management reduces the losses or recovers this water and returns it to the Everglades as a water conservation measure. Two locations are planned for this Restoration Plan component:

- *Everglades National Park Seepage Management*. The purpose of this project (Figure 2-12) is to improve water deliveries to Northeast Shark River Slough and restore wetland hydropatterns in Everglades National Park by reducing levee and groundwater seepage and increasing sheet flow. This will be accomplished by a levee cutoff wall along levee L-31N, south of the Tamiami Trail, which reduces groundwater flows during the wet season and by capturing the groundwater with a series of wells adjacent to L-31N, then back-pumping those flows to Everglades National Park. This project is expected to conserve about 162,000 acre feet annually (J. Obeysekera, SFWMD, written communication, May 2004). This conserved volume, and the value for WCA 3A/3B below, is estimated from modeling the difference between seepage at these sites without the Restoration Plan (2050 Base) and with it (D13R).
- *Water Conservation Areas 3A and 3B Levee Seepage Management*. The goal of this project is to reduce seepage loss from these WCAs in order to improve hydroperiods within the Conservation Areas by allowing higher water levels in the borrow canals and longer inundation within the marsh areas that are located east of the WCAs and west of US Highway 27. New levees will be constructed west of US Highway 27 from the North New River Canal to the Miami (C-6) Canal to separate seepage water from the urban

runoff in the C-11 diversion canal. Higher-quality seepage from the WCAs and marshes will be collected and returned to the Water Conservation Areas via features associated with the C-11 Impoundment project or stored in either the C-9 or C-11 Impoundment. Collected seepage water will further be transported by canal to the Central Lake Belt, for distribution to Everglades National Park (S. Applebaum, personal communication, January 2005). The Western C-11 Diversion Impoundment and Canal will capture lower-quality water from urban runoff and agricultural areas that is presently back-pumped into WCA 3A through the S-9 pump station and discharge it either into the North Lake Belt Storage Area (once it is on line), C-9 Impoundment, or WCA 3A after treatment (USACE and SFWMD, 1999, p. 9-19). This project is expected to conserve about 129,000 ac-ft annually (J. Obeysekera, SFWMD, written communication, May 2004). The S-9 pump station will also be used to divert excess water above WCA 3A/3B target depths to the Central Lake Belt Storage Area or Shark River Slough via the improved L-37 or L-33 borrow canals, respectively.

At the L-31N site, a pilot project will evaluate technologies to reduce levee seepage flow across L-31N adjacent to ENP via a levee cutoff wall (vertical subsurface barrier with a confining layer at its base) and to reduce groundwater flows during the wet season by capturing the groundwater with a series of wells adjacent to L-31N, then back-pumping those flows to ENP through the S-356 pump station (to be replaced by two new stations: S-356A and S-356B). Other technologies may also be explored, such as those reviewed and described in the Technical Advisory Report on Seepage Management (Governor's Commission for a Sustainable South Florida, 1997).

Uncertainties about these techniques are similar to those for creation of barriers to flow for the Lake Belt quarries. The L-31N pilot project is expected to contribute to a refined design and better understanding of construction technologies upon its completion. This activity is especially important given the 100 percent effectiveness (recovery of seepage) assumed for this Restoration Plan component (USACE and SFWMD, 1999). The final seepage-management strategies developed must not only reduce the loss of water from the Everglades but also prevent significant downstream impacts to water supplies, flood control, and wetland and estuarine systems.

There is some urgency to initiate these projects because both are on the boundaries of the natural system, and adjacent land is threatened by urbanization. Using the November 2004 Draft Master Implementation Sequencing Plan (MISP, *http://www.evergladesplan.org/pm/misp.cfm#docs*) for estimates of "streamlined" completion dates and Figure M-1 from SFWMD and USACE (1999) for estimates of construction duration, the WCA 3A/3B project is scheduled to be completed in 2008 after about four years of construction, the Everglades National Park seepage-management project is scheduled to be completed in 2009 after about four years of construction, and the L-31N pilot project is scheduled to be completed in 2008 after about one year of construction (to which will be added an additional year of monitoring). Setbacks could occur if the cutoff wall technologies are unable to stem the loss of water through the levees.

The anticipated cost for the L-31N pilot project is about $10 million (USACE and SFWMD, 2002a). The overall Everglades National Park seepage-management project will be constructed in conjunction with modifications to structure S-356, for an overall construction cost of about $90 million. Similarly, the WCA 3A/3B seepage-management project will be constructed in conjunction with the canal C-11 diversion impoundment, for an overall projected construction cost of about $58 million. Even though the SFWMD owns the levees themselves, total land requirements for the Everglades National Park and WCA 3A/3B projects are 3,900 acres and 5,887 acres, respectively, corresponding to estimated real-estate costs of $95 million and $168 million (Tables 9-1 and 9-2, USACE and SFWMD, 1999). (The current web site, 8/27/04, for the WCA 3A/3B project lowers the land requirement to 4,323 acres, with 2,970 acres currently acquired.) The L-31N Pilot Project will be constructed entirely on public land and not require any land acquisition.

The Everglades National Park seepage-management project involves back-pumping of recovered water into the park itself. Hence, there will be continuing operation and maintenance costs associated with this option compared to installation of the seepage barrier itself, which will be a one-time capital cost. The selection of seepage-management technology will include an evaluation of the trade-offs between higher capital costs (e.g., slurry walls, grout curtains) and higher operation and maintenance costs (e.g., back-pumping). Annual operation and maintenance costs estimated in the plan for this component approach $5 million.

Environmental Considerations

The proposed technologies to control seepage may have unintended consequences that must be investigated before full-scale implementation of the proposed project features; hence, the Everglades National Park project includes the L-31N pilot project intended to investigate seepage-management technologies. Possible unintended consequences to be investigated as part of this pilot project include negative impacts on the Miami-Dade West Well Field located just east of the project site; reduction of freshwater flows toward Biscayne Bay; and the potential to attract contaminated agricultural runoff due to the pumping component.

Furthermore, this project includes relocation of the Modified Water Deliveries structure S-357 to provide more effective water deliveries to Everglades National Park. New discharges to Everglades National Park must be designed to meet applicable water-quality criteria. The Everglades National Park project is also dependent upon modification to S-356 structures to provide more effective water deliveries to the Park.

Water Reuse and Conservation

Treated wastewater from the Miami-Dade South Wastewater Treatment Plant currently is pumped over 2,000 ft deep into the "boulder zone" of the Floridan Aquifer. The Wastewater Reuse Technology Pilot Project for West and South Miami-Dade envisions two wastewater reuse facilities to increase the quantity of water available for ecological restoration. One facility would be associated with the existing Miami-Dade South treatment facility at the southern end of Biscayne Bay, and the other would be associated with a proposed wastewater treatment plant in the west Miami-Dade area near Bird Drive (Figure 2-12). Ultimately, reclaimed wastewater from the two plants is anticipated to provide an average of 230 MGD (258,000 ac-ft/yr) and maximum of 231 MGD (259,000 ac-ft/yr) (USACE and SFWMD, 1999, pp. 9-23 and 9-24; M. Irizarry, SFWMD, personal communication, November 2004) for restoration. The 131 MGD (147,000 ac-ft/yr) South Miami-Dade reclaimed wastewaters will be used primarily to augment freshwater flows to south Biscayne Bay that might otherwise be lost through restoration efforts closer to and within the Everglades. South Miami-Dade reclaimed flows are estimated to be 74,000 ac-ft/yr directed south toward C-102 and 73,000 ac-ft/yr directed north to C-100 (USACE and SFWMD, 1999, p. A4-43). The 100 MGD (112,000 ac-ft/yr) West Miami-Dade reclaimed wastewaters will be used to elevate water levels in the Bird Drive Basin and thus reduce seepage losses from Everglades National Park buffer areas and enhance water supply for groundwater recharge, South Dade conveyance system demands, and northeast Shark River Slough demands.

Other conservation efforts applied to water use (e.g., reduction of per capita potable water requirements) have not been factored into the plan explicitly. Rather, different future potable water-use requirements in 2050 range from 1,200 to 1,450 MGD (1.344 million to 1.769 million ac-ft/yr) reflecting greater or lesser conservation practices. These estimates are reflected in the background planning for the Restoration Plan (USACE and SFWMD, 1999). Overall, water conservation is expected to yield about 63 MGD or about 71,000 ac-ft/yr (J. Obeysekera, SFWMD, personal communication, May 2004).

Although the Restoration Plan anticipated that the reused water would be treated to a level needed to sustain estuarine and wetland biological communities in the Bay area, the technology that will be required to effect this treatment and the associated costs are not well established. The Technology Pilot Project at the existing South Miami-Dade treatment plant is designed to address these issues. The plan anticipates adding a pretreatment and membrane treatment system to the existing secondary treatment facility (CDM, 2004). The plant will have a capacity of 131 MGD. It is anticipated that phosphorus will be the primary constituent of concern in the reclaimed water. Therefore, the treatment will be designed to remove total phosphorus to acceptable levels. Evaluating whether this system will perform as anticipated is another reason for the Pilot Project. The dual-membrane technology to be used is relatively new (NRC, 1998), and although it has been applied at several locations (del Pino and Durham, 1999), performance and costs are uncertain.

The West Miami-Dade Wastewater Treatment Plant has not yet been constructed. Discharge of reclaimed water from this plant is planned for the Bird Drive Basin in western Miami-Dade County, east of Krome Avenue. In addition to the Miami-Dade facilities, the City of West Palm Beach is constructing a pilot facility to treat wastewater from the East Central Regional Wastewater Treatment Facility using advanced wastewater-treatment processes to remove nitrogen and phosphorus. After treatment, the wastewater will be used to restore 1500 acres of wetlands and to recharge wetlands surrounding West Palm Beach's well field, as well as to recharge a nearby residential lake system. Results of this study will be used to evaluate the similar plan for distribution of reclaimed waters from the planned West Miami-Dade Plant. The assumption is that conditions will be similar at the two locations.

Advanced waste treatment is expensive both in capital costs and in operation and maintenance costs. Depending on the treatment technology used, anticipated capital and annual operation and maintenance costs are about $800 million and $84 million/year, respectively (Table 2-1; USACE and SFWMD [1999] Tables 9-2 and 9-3), making this one of the costlier components of the Restoration Plan. Indeed, costs for the 1 MGD South Miami-Dade pilot plant are estimated at about $8.9 million capital costs and $645,000/year O&M costs for the membrane technology that meets the low required effluent levels (described below) (CDM, 2004). Costs could increase or decrease by the 2013 target for completion of the pilot project, including four years of assessment (USACE and SFWMD, 2003). Decreasing costs are possible as a result of improvements in membrane and related technologies that may occur in the intervening decades before implementation of this Restoration Plan component (NRC, 2004c). However, large cost reductions (i.e., >50 percent by 2020) will not likely be achieved through incremental improvements in existing technologies, but will require novel technologies.

The South Miami-Dade reclamation plan must wait on the outcome of its pilot project in 2013, and the West Miami-Dade plan must wait on the outcome of the West Palm Beach Pilot Project. In essence, the wastewater reclamation scheme already is a contingency plan, inasmuch as it will be implemented only in the likely event that more economical sources of water are not discovered during the courses of the pilot projects.

Water-Quality Considerations

Biscayne Bay was designated a priority water body by the Florida Legislature pursuant to the Surface Water Management and Improvement Act of 1987. The area south of Biscayne National Park is included in the Florida Keys National Marine Sanctuary. Waters of Biscayne Bay Aquatic Preserve and Biscayne National Park are classified as Outstanding Florida Waters (OFWs), and as such are subject to the most stringent regulations, including Florida anti-degradation standards, which prohibit permitted discharges that will degrade ambient water quality. Because reclaimed water from the South Miami-Dade Waste Water Treatment Plant is considered “new” water (as opposed to surface runoff that might be diverted toward the bay), the plant discharge must meet the most stringent OFW criteria for the bay, even though plant discharge will reach the bay via discharge to the adjacent brackish wetlands, which are classified as State of Florida Class III waters. Because of these stringent regulations, the quality of reclaimed wastewater from the South Miami-Dade Plant is likely to substantially exceed the quality of ambient waters in the coastal marshes. The standards are compared in Table 2-4 (CDM, 2004) from which it is clear that the total nitrogen and total phosphorus standards for the Biscayne Bay OFW necessitate a very high level of treatment for the South Miami-Dade Waste Water Treatment Plant.

This highly conservative approach regarding effluent quality will result in correspondingly high treatment costs. In the recent study by Camp Dresser & McKee (2004), reverse-osmosis membrane technology was the only one sufficient to meet the rigorous total nitrogen and total phosphorus OFW criteria. Capital costs for this scheme—for the 1 MGD pilot plant project —are estimated by CDM at $8.9/gallon; in contrast, 1993 capital costs for most wastewater reclamation were much less, in the range of $200-1,500 per acre-foot or about $0.00061-0.0046/gal (NRC, 1993), because of the much-less stringent water-quality requirements. High costs are recognized in the Restoration Plan, with the caveat that costly reclamation will be used only if “…other, more appropriate sources are not available…” (USACE and SFWMD, 1999). “Other sources” might consist of surface drainage that could be diverted toward Biscayne Bay that would not have to meet the OFW criteria, only the Class III criteria for the coastal wetlands. But if the reclaimed wastewater from the South Miami-Dade Waste Water Treatment Plant is not used to supply fresh water to Biscayne Bay, the (lower) cost of reclamation will not be funded by the Restoration Plan, creating other financial issues.

It is difficult to foresee a south Florida future in which the non-saline wastewater from a population of millions will not be required for at least a part of the water-supply needs of the region. Consideration should be given to revisiting or possibly appealing the decision to require the stringent total nitrogen and total phosphorus effluent standards for reclaimed wastewater that will first pass through brackish coastal wetlands before entering Biscayne Bay, in order to ensure the most responsible expenditure of Restoration Plan funds for wastewater reuse.

TABLE 2-4 Comparison of Water Quality Criteria for South Miami-Dade WWTP

Variable	Raw Wastewater	1999-2004 SMDWWTP[a] Effluent	Reuse[b]	Class III[c]	Biscayne Bay OFW
Total Suspended Solids, mg/L	110	9.06		5	3.5
Biological Oxygen Demand 5, mg/L	110		5	5	12
Total Nitrogen, mg/L	40	18.4		3	0.27
Total Phosphorus, mg/L		1.09		1	0.005
Fecal Coliform, no./100 mL		55,385	2.2	2.2	2.2

[a] South Miami-Dade Waste Water Treatment Plant
[b] State of Florida standards for reuse of reclaimed water and land application (Chapter 62-610, FAC): meet at a minimum secondary treatment and the requirements for public access irrigation with a TSS concentration of 5.0 mg/L or less, and high level of disinfection.
[c] Chapter 62-611 FAC.
All values taken from CDM (2004).

SUMMARY AND COMPARISON

The conventional reservoirs, ASR systems, in-ground reservoirs, and stormwater treatment areas included in the Restoration Plan will provide a total of approximately 5.5 billion acre-feet of new storage, of which approximately 4 billion acre-feet can be attributed to ASR systems (assuming 30% injection loss). Values listed in Table 2-1 can be used to compare major storage features in terms of storage capacity, costs, and land requirements. The main storage components can also be compared on the basis of sequencing, potential water quality impacts, and the degree to which the technology is proven and requires active operation (Table 2-5). Of the new storage that will be created by the Restoration Plan, conventional storage reservoirs have clear advantages of using proven technology and of requiring less active operation than water reuse or ASR.

Overall, the sequencing of storage components makes sense considering questions related to engineering feasibility. The storage components that rely on proven technology, namely the surface reservoirs, are slated to be completed considerably earlier than those that require pilot projects, i.e., the ASR systems, the in-ground reservoirs, and seepage management using subsurface permeability barriers. In addition, most of the novel technologies are associated with potential water-quality impacts, which must be carefully evaluated prior to construction. However, because these latter components make up approximately 80 percent of the new storage provided by the Restoration Plan, the long lead time required for their evaluation and construction is a major constraint on the availability of water that could provide earlier environmental benefits.

Although Table 2-1 provides information on costs for each component, more informative cost comparisons might be those that include consideration of the water-storage benefits provided by the components. Several such comparisons are shown in Figure 2-13, 2-14, and 2-15. These figures are only illustrative of the kinds of comparisons that can be made; not all projects in each storage category were used due to incomplete information on costs, and results would vary somewhat with a more complete data set. In Figure 2-13, construction and land acquisition costs are normalized by average annual outflows during the 31-year simulation period for each type of component. This comparison indicates that ASR systems are the most costly to site and

TABLE 2-5 Comparison of Selected Storage Components in Terms of Sequencing, Water Quality and Technology Characteristics

STORAGE COMPONENT	Construction Complete	Water Quality Impacts	Proven Technology?	Passive/Active Operation
Lake Okeechobee			YES	Intermediate
Water Conservation Areas			YES	Relatively passive
Conventional Surface Reservoirs			YES	Intermediate
North Storage Reservoir (Kissimmee)	2013	+		
EAA Reservoirs	2014	-		
Upper East Coast Reservoirs+STAs+natural storage	2010	+		
ASRs		-	NO	Very Active
Lake Okeechobee ASR	2026			
C43 Basin	2018			
C51 ASR (North Palm Beach II)	2020			
West Palm Beach ASR (N Palm Beach II, L-8 ASR)	2020			
Central Palm Beach Reservoir ASR	2019			
Site 1 Impoundment ASR (Hillsboro)	2017			
Lake Belt Reservoirs		0	NO	Intermediate
North Lake Belt	2036			
Central Lake Belt	2036			
Seepage Management			NO	
WCA3A/3B Levee Seepage Mgmt	2008	+		Intermediate (some back-pumping)
C11 Reservoir (part of 3A/3B seepage)				
L31-N Seepage Mgmt	2013	0		Passive
Water Reuse		+	YES	Very Active
West Miami-Dade Water Reuse				
South Miami-Dade Water Reuse				

Note: Water quality impact key: + likely no negative impact, 0 unknown, - unresolved concern.

construct. A similar normalization of operation and maintenance costs, illustrated in Figure 2-14, indicates that waste-water reuse incurs the highest annual costs, followed by ASRs.

While ASR systems are the most expensive to site and build when compared on the basis of average annual outflow, they are probably the least expensive when compared on the basis of the maximum storage they can provide in a year, based on dividing the land and construction costs by the maximum difference between inflows and outflows in any year of the D13R simulations. This comparison is illustrated in Figure 2-15.

The issue of providing ecological benefits as soon as possible has not been considered in the committee's analyses in this chapter. Some approaches to considering that important matter are discussed in the following chapters.

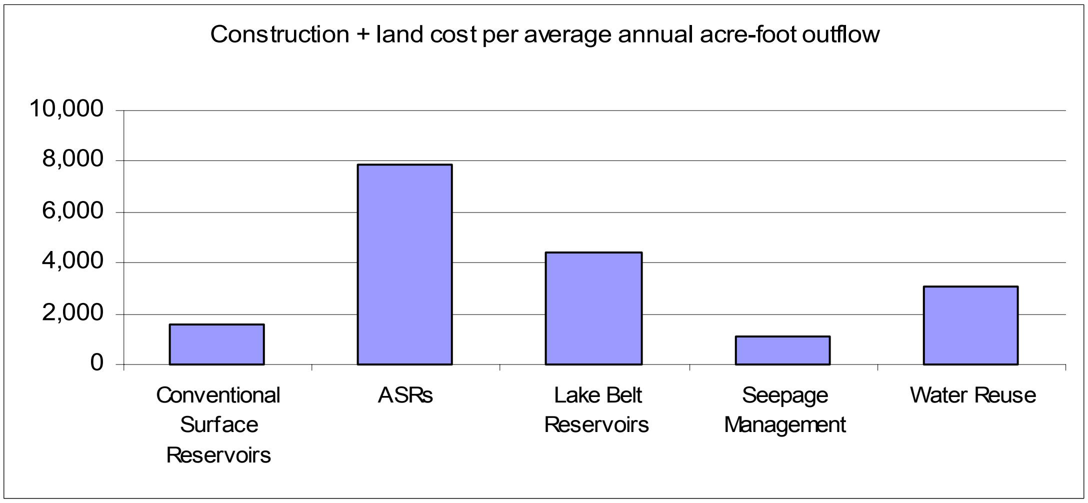


FIGURE 2-13. Construction plus land costs in 1999 dollars normalized by average annual acre-foot of outflow. Data taken from Table 2-1. The analyses represented in Figures 2-13, 2-14, and 2-15 are illustrative only. A fuller economic analysis might discount expenditures based on timing of costs and benefits, convert all costs (i.e., capital and O&M) to present value, and account for uncertainty. Conventional surface reservoirs are North Storage (Kissimmee) and EAA reservoirs only. ASRs represent C-51 (North Palm Beach II) and Lake Okeechobee ASR only. The graphs shown in Figures 2-13, 2-14, and 2-15 would change somewhat with more complete cost information.

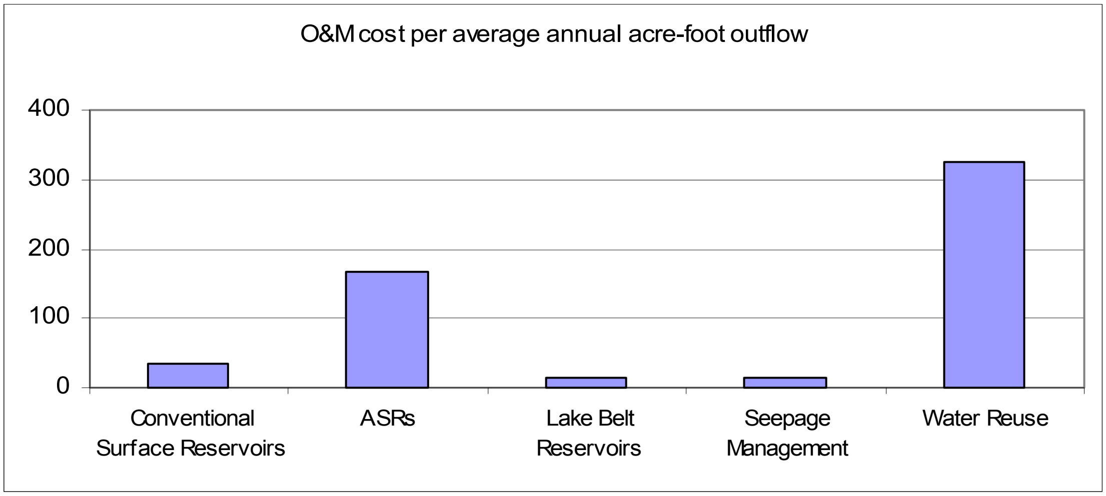


FIGURE 2-14. Operation and maintenance costs in 1999 dollars normalized by average annual acre-foot of outflow. Data taken from Table 2-1.

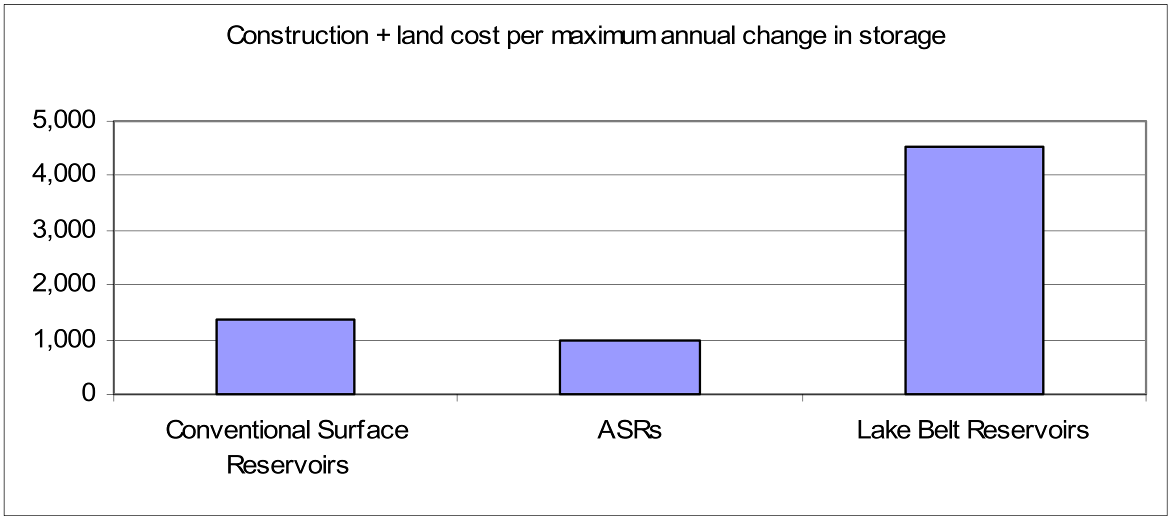


FIGURE 2-15. Construction plus land costs in 1999 dollars normalized by maximum annual change in storage. Data taken from Table 2-1.

3

Cross-Cutting Issues

The previous chapter described the major storage components individually and offered some general comparisons among them. This chapter discusses cross-cutting issues related to implementation of storage components, considering lessons of other large restoration projects and principles of restoration ecology (e.g., NRC, 1992, 2001b; Science Sub-Group, 1993). The general considerations used in the following evaluations included sequencing of projects and the factors that should influence sequencing, ecological uncertainties associated with the interventions and with natural ecological processes, contingency planning, adaptive management, and the effectiveness of natural versus engineered processes. These considerations, and their application to the Restoration Plan, are discussed below.

SEQUENCING

As described in Chapter 1, the Restoration Plan involves large-scale hydrologic re-engineering for much of the Greater Everglades Ecosystem, and it consists of many individual projects, which are described in Chapter 2. In addition, other crucial projects are related to the Restoration Plan, such as Modified Water Deliveries to Everglades National Park. With so many components and so many constraints on this ambitious project, the way that the components are ordered in space, and especially in time, can profoundly affect the outcomes of the project.

The project's overall plan imposes some constraints on sequencing of its components, as is true, of course, for any construction project. The committee judged two criteria to be most important in deciding how to sequence components of a major construction or engineering project (the Restoration Plan): 1) protect against habitat loss and 2) provide ecological benefits as early as possible.

Protect Against Additional Habitat Loss

The first criterion is that the sequencing should protect the project against any damaging changes in external or environmental conditions, especially of ecologically valuable habitat and habitat that is potentially of ecological value, which would adversely affect the project's completion and that could not be reversed if they occurred. In the case of the Everglades Restoration Plan, the most striking such environmental change would be the loss or irreversible alteration of land-surface required to implement the plan. The population of south Florida's lower East Coast is projected to swell from 4.8 million in 1998 to 6.6 million in 2020 (Kranzer, 2003). If present patterns of development continue, development will consume 311,000 acres in the five southeastern counties between 1995 and 2020 (Burchell et al., 1999). The most urgent and overriding sequencing criterion should be to protect from irreversible development all land that is or potentially could be included in the Restoration Plan. This kind of protection can be achieved by acquisition of the land, by obtaining easements, by zoning restrictions, or other methods. In the Restoration Plan, the primary method to be used is acquisition. A large amount has been spent on acquisition (Table 3-1), which reflects a recognition of the importance of protecting land for use in the restoration.

The acquisitions listed in Table 3-1 began in 1991. Before then, Florida had various land-acquisition programs that operated in the region, including the Central and South Florida Project, Environmentally Endangered Lands, Save Our Rivers, and Save Our Everglades. Pre-1991-acquisitions date as far back as 1948 (Water Conservation Areas 1, 2, and 3). The 1991 and subsequent acquisitions reflect the startup of the 10-year Preservation 2000 program ($300 million per year statewide) and its successor Florida Forever program (another 10 years). In addition to those projects, since 1996, Florida agencies have acquired lands using grants from $200 million provided by the Federal Agriculture Improvement Act of 1996 (the Farm Bill) and $151 million from the Land and Water Conservation Fund (GAO, 2000). For the past several years, the governor and the legislature have pledged to budget $100 million per year for Everglades restoration land purchases. The additional funds for land acquisition (in excess of $100 million) are significant; the average spent yearly from 1999 to 2004 is $128.9 million.

As of June 30, 2004, the estimated amount of land needed for the proposed projects in the Everglades restoration is 405,322 acres, with 206,109 acres (51%) already in SFWMD, state, or local-government ownership (LATT 2004). The figures in Table 3-1 reflect the slightly lower estimates of land needed in the 1999 Yellow Book, with land acquired as of March 2004.

Despite the large amount of money devoted to land acquisition each year, and the large amount of land already acquired, the land remaining to be acquired is so extensive that the plan for land acquisition extends over more than two decades, during which time irreversible development of some land not yet protected is likely and an increase in the price of land is almost certain. To the degree that the land-acquisition part of the Restoration Plan departs from immediate acquisition or protection of all the land in the plan, the outcome of the Restoration Plan risks being compromised. Indeed some land within the footprint of the Restoration Plan already has been lost to uses incompatible with the plan, and further losses are occurring. Land adjacent to or in the CERP footprint and that has a pending application for an environmental resource permit currently is high on the acquisition priority list. Environmental resource permits are required by the SFWMD for activities that could affect wetlands, alter surface flows, or contribute to water pollution. The owners of that land include religious institutions; small businesses; large corporations, including real-estate development; federal and state agencies, and individuals. Land use and application information for those permits is available at *http://www.sfwmd.gov/org/reg/rim/cerp/sheet1_1.html.*

Provide Ecological Benefits as Early as Possible

As the restoration of the Everglades begins, reductions in distributions of some native species and loss of habitats distinctive of the Everglades continue. There is high potential for these losses to be irreversible. In addition, invasive species continue to increase in number and distribution in the Everglades, despite efforts to eliminate some of them. As the ridge-and-slough and tree-island landscapes continue to deteriorate, Everglades landscapes become increasingly homogeneous. Communities of marl prairies and periphyton mats continue to diminish in areal coverage, and nutrient loading continues to be above historic levels. These factors and the great uncertainty associated with implementation of the Restoration Plan and ecological restoration goals all argue for increased emphasis on achieving near-term ecological results in the process. One example of this would be providing more natural flows (in terms of seasonal timing, volume, and flow velocity) to Everglades National Park. Doing so might not require large-scale

TABLE 3-1 South Florida Water Management District Land Acquisition[*] for CERP

SFWMD Fiscal Year	Acres Purchased for CERP Lands	Dollars Spent for CERP Lands	Average Price Per Acre for CERP Lands
SFWMD FY04[†] - Projected	12,411	$123,280,005	$9,933
SFWMD FY03	11,116	$215,090,573	$19,350
SFWMD FY02	15,851	$147,303,278	$9,293
SFWMD FY01	13,922	$82,992,095	$5,961
SFWMD FY00	4,475	$48,379,665	$10,811
SFWMD FY99	57,145	$156,262,777	$2,734
SFWMD FY98	2,627	$5,762,600	$2,194
SFWMD FY97	5,086	$31,201,884	$6,135
SFWMD FY96	2,154	$19,766,055	$9,176
SFWMD FY95	29	$318,650	$10,988
SFWMD FY94	3,686	$5,740,026	$1,557
SFWMD FY93	1,429	$20,111,079	$14,074
SFWMD FY92	73	$1,315,800	$18,025
SFWMD FY91	1,420	$19,571,730	$13,783
SFWMD before 10/01/1991[§]	23,639	$9,803,764	$415
Miami-Dade Biscayne Bay Coastal Wetlands	2,397	$2,253,265	$940
DEP - Southern Golden Gates Estates	50,807	$89,584,311	$1,763
TOTALS	208,267	$978,737,557	$4,699
Total CERP Project Boundary Acres	402,479		Source CERPMaster 31-Mar-04
Total Estimated Cost		$2,304,097,501	Source CERPMaster 31-Mar-04

[*] Except for FY04, estimates as of 24-Feb-02, will change as individual project boundaries are modified during planning and implementation.

[†] SFWMD fiscal year is 1-Oct to 31-Sep.

[§] Includes lands acquired by or deeded to SFWMD starting in 1948, e.g. from the Central and South Florida Project.

SOURCE: Data provided by South Florida Water Management District. These totals do not include other land-acquisition programs described in the text.

changes in sequencing; instead, incremental changes could add up to be significant. As noted in Chapter 2, novel storage techniques requiring long-term pilot studies make up approximately 80 percent of the new storage provided by the Restoration Plan. That degree of reliance on novel techniques places major constraints on the ability of the Restoration Plan to provide early ecological benefits. Interim measures, such as modified operating rules for flows into and out of Lake Okeechobee and the WCAs, or construction of additional conventional surface reservoirs, might be necessary in the near term to reduce or mitigate the loss of animal and plant populations and habitat. The recent plan to accelerate the pace for completing some of the Restoration Plan's scheduled projects (called "Acceler8") was made public too late for this committee's evaluation, but it is intended to "provide immediate environmental, social, and economic benefits" (Florida DEP, 2004).

SYSTEM UNCERTAINTIES

All restoration efforts involving complex systems confront a diversity of ecological uncertainties, and the Everglades restoration is no exception. As a result of the quantity and quality of available science, and the extensive, thorough planning effort in support of the Restoration Plan, uncertainty from some sources is less than in most restoration efforts. These sources include observation uncertainty (i.e., inaccurate measurement of the state of the ecological system) and subjective uncertainty (i.e., uncertainty arising from the interpretation of incomplete data) (Regan et al., 2002; SEI, 2003). Process uncertainty (i.e., natural variation and inherent stochasticity of ecological systems) assuredly is a major concern in the Everglades. Indeed, it is the variability and unpredictability of magnitudes and patterns of rainfall that have caused water management to be such a critical issue in south Florida, ultimately resulting in the creation of the Restoration Plan. The process uncertainty within the Restoration Plan has been explored somewhat for the hydrologic processes that drive ecosystem change through use of simulation modeling based on a multi-decadal rainfall record that incorporates unusually wet and dry years. The Restoration Plan is designed to provide a consistent source of water to the natural and human systems despite process uncertainty. However, little has been published concerning process uncertainty for the ecological models.

A fundamental reason for uncertain restoration outcomes is that the Restoration Plan does not intend to restore the full natural range of physical processes that created and maintained the Greater Everglades Ecosystem. In particular, extremes of naturally occurring wet and dry periods harmful to the coastal metropolis or adjacent agriculture will not be allowed in the engineered, restored system. It is an open question whether the lesser variation of physical processes will restore or maintain a reasonable facsimile of the original Everglades. Indeed, it is not even certain as to what the final restored hydrologic and ecological conditions will be, when they will be attained, or how variable they will be. For example, Trexler and his colleagues have shown that hydrologic variations alone are not sufficient to explain variations in fish populations in south Florida, at least in part because nonnative fishes now present in the ecosystem make fish communities respond differently than the original native communities did to changes in water levels and duration of high and low water (Trexler et al., 2002; Kobza et al., 2004; Gaff et al., 2004).

More problematic where the ecological response to the Restoration Plan is concerned are model uncertainties (i.e., use of oversimplified or over-parameterized models to predict the response of managed systems to management actions) and model errors (i.e., fundamental misunderstanding of variables and the functional form of the model) (Regan et al., 2002; SEI, 2003). Ecological models exist, including system-wide models such as the Across Trophic Level System Simulation (ATLSS), and the Everglades Landscape Model (ELM), conceptual models of ecological communities, and detailed models of the biology of individual species of interest (e.g., DeAngelis et al., 1998; Sklar et al., 2001). However, because the appropriate spatial scale for the ecological models generally is not the 2 x 2 mile scale used in the major hydrologic models (i.e., Natural System Model and South Florida Water Management Model), simulating anticipated ecological conditions is problematic. This is a source of considerable model uncertainty in projections of the ecological response to the Restoration Plan, beyond the usual uncertainty that comes with attempting to capture the dynamics of a complex system in a model. Also, despite the availability of several good ecological models, some important conceptual linkages between hydrologic and ecological variables have not been fully explored. The linkages include those between planned alterations in hydroperiod and spread of invasive species, patterns of mercury accumulation in biota, and expansion of the current area of eutrophication. The lack of linkage results in additional uncertainty about some ecological responses of the system.

Model error will certainly exist in conceptualizations of the relationship between hydrologic variables and plant community composition and structure, and of the relationships of animals to plant communities. In some cases, relationships between the plant community and hydrologic variables are well understood and provide solid evidence that restoration can be accomplished. For example, evidence exists that areas of marl prairie that have been converted from muhly grass to sawgrass can be restored by altering hydroperiod (Nott et al., 1998). In contrast, it is not entirely clear that tree islands and ridge-and-slough landscapes can be restored by restoring historic water levels and altering flow patterns (NRC, 2003c). Habitat degradation is not always reversible, because the path from degraded condition to restored condition is not identical to the path that produced the original condition. Even if hydrologic conditions identical to historic ones can be recreated, whether the same ecological communities will be recreated is uncertain.

Two other sources of uncertainty are related to conceptual and mathematical models specific to the structure of the Restoration Plan. First, there is uncertainty with respect to the model used to identify hydrologic goals for the Restoration Plan, the Natural System Model. A review of the NSM version 4.3 by Bales et al. (1997) estimated total uncertainty (i.e., uncertainty related to parameters, algorithms, and data) in water levels of about plus or minus one foot. This estimate is consistent with the more exhaustive uncertainty analysis done for the modern equivalent of the NSM, the South Florida Water Management Model (Trimble, 1995). Trimble's estimates for the half-width of the 95 percent confidence interval for total uncertainty ranged from about 0.6 to 0.9 ft, depending on the region. Relatively scant data on evapotranspiration, and to a lesser extent, on roughness coefficients and precipitation, are large contributors to the uncertainty (Trimble, 1995; Jayantha Obeysekera, SFWMD, personal communication February 28, 2000). Given that mean water depths in much of the system are of similar magnitude to the total uncertainty of the model estimates, use of the model may result in inappropriate hydrologic targets for particular locations (Bales et al., 1997; Ingebritsen et al., 1999).

Second, model simulations have focused on a fully implemented Restoration Plan. Hence, regardless of the accuracy of these projections, there is uncertainty about what the hydrologic conditions and resulting ecological response will be during the transition from current conditions to a fully implemented Restoration Plan. It is possible that irreversible changes could occur during the transition that would preclude successful restoration when the Restoration Plan is fully implemented.

Thus, the potential is high for several unanticipated outcomes to occur as a function of various types of ecological uncertainties. Because these outcomes include changes in the state of the Everglades system that could be irreversible in the time scale of the Restoration Plan, contingency plans must be developed in the near term to avert them insofar as possible. To that end, the following sections discuss specific uncertainties that, if not resolved and addressed, could undermine the fundamental goals of the restoration.

Endangered Species

The Endangered Species Act (ESA) has the potential to profoundly affect the implementation of the Restoration Plan by preventing or modifying implementation of water-management plans that are required for system restoration but that might have unanticipated detrimental effects on endangered species. The threat or actuality of litigation or enforcement related to the ESA influence all large-scale environmental management activities in the United States (e.g., NRC, 1995, 2004a, b), and the Everglades restoration is no exception. ESA decisions in general are characterized by law suits filed by diverse interest groups against each other and the agencies, sometimes even when other more cooperative avenues seem to be available (Ruhl, 2004).

Recovery of endangered species is an explicit objective of the Restoration Plan (USACE and SFWMD, 1999), and much attention has been paid to the needs of endangered species in the Everglades. If the restoration is successful, the ecosystem will ultimately provide habitat for all the endangered species in it (e.g., SEI, 2003), and the U.S. Fish and Wildlife Service has legally supported this conclusion through the consultation process and development of recovery plans (USFWS, 1999).

Yet despite the best planning, it is impossible to accurately predict how the ecosystem will move from the current state to a restored state, and in the transition endangered species may be adversely affected. An occurrence like this could mean that restoration of water to historic levels, timing, and distribution could fall victim to legal challenges.

In recent years, management of the Everglades has been accompanied by constant litigation, much of it involving endangered species (see e.g., Rizzardi, 2001a). This pattern of litigation likely will continue, and attempts at restoration will not be immune from it: even temporary impacts on endangered species could provide fodder for those who wish to pose legal challenges to the restoration.

In the Everglades, attention has focused mostly on endangered birds, and especially on one subspecies, the Cape Sable seaside sparrow (*Ammodramus maritimus mirabilis*). The desirability of a multi-species approach to endangered species management is recognized in the South Florida Multi-Species Recovery Plan for developed by the U.S. Fish and Wildlife Service (USFWS, 1999). While the Restoration Plan can be viewed as a revision of that multi-species plan, protection of single species under the ESA still can determine management. Indeed, after the numbers of Cape Sable seaside sparrows declined sharply in the mid-1990s, water deliveries to the southern Everglades have been designed to protect the sparrow, first in the form of modifications to the existing water-management plan, and later as a new interim management plan.

Other endangered bird species in the Everglades are the wood stork (*Mycteria americana*), roseate spoonbill (*Ajaia ajaja*), and snail kite (*Rostrhamus sociabilis*). Because of their mobility and life histories, those species may be sufficiently resilient to persist through the changes, anticipated and unanticipated, in the ecosystem caused by the Restoration Plan (SEI, 2003). But no clear evidence of similar resiliency exists for the Cape Sable seaside sparrow, which instead appears to be a highly sedentary bird with a short lifespan and limited capacity to colonize new habitat (Walters et al., 2000; Lockwood et al., 2001; SEI, 2003). Recent history indicates that increasing periods of high water in areas where sparrow populations currently reside can alter habitat and reduce nesting success and thereby significantly reduce or even eliminate those populations in only a few years (Curnutt et al., 1998; Nott et al., 1998; Jenkins et al., 2003). However, because of the sparrows' limited capacity for dispersal, areas that currently are too wet for sparrows may not be readily occupied by the birds when the high-water period is shortened and habitat thereby improved (Walters et al., 2000; Lockwood et al., 2001). For this reason, a significant decline of Cape Sable seaside sparrows could occur at some point during the implementation of the Restoration Plan, and such declines could occur for other endangered birds. In addition, other endangered species than birds could similarly affect the Restoration Plan.

Designing the Restoration Plan to totally avoid the possibility of conflict with the ESA is unrealistic. But it is possible to develop contingency plans for addressing such conflicts, and more could be done to anticipate them. Endangered species should figure prominently in contingency plans for addressing uncertainties in the relationship between ecology and hydrology. In addition, more analysis of the range of conditions anticipated during the transition from current conditions to a fully implemented Restoration Plan would be useful. Insufficiency of habitat for Cape Sable seaside sparrows and other endangered species is a much greater concern during the transition than when the Restoration Plan is fully implemented (SEI, 2003). Simulation modeling in support of the Restoration Plan has focused almost exclusively on the fully implemented system, and the transition period has received virtually no attention. Thus it is not clear whether, even without considering uncertainties, conflicts between the Restoration Plan and endangered species management are anticipated during the transition. We endorse recent efforts to conduct simulations of transitional scenarios, and to more closely examine potential conflicts between the Restoration Plan and ESA requirements (e.g., SEI, 2003), as a means to reduce the potential for endangered species to derail ecosystem restoration.

Invasive and Irruptive Species

The Restoration Plan could get the water right, but an irreversible change could occur as a result of invasive species dominating the system. Currently, a number of invasive species are problematic. The Everglades is a center of human activity that facilitates invasion of exotic species by creating disturbances in a region where the climatic conditions are favorable to a wide diversity of organisms from both the tropics and the sub-tropics. Construction and removal of earthworks during the restoration projects may create many new disturbance sites and remove barriers to establishment and dispersal of invasive species.

An invasive species is defined as "a species that is 1) non-native (or alien) to the ecosystem under consideration and 2) whose introduction causes or is likely to cause economic or environmental harm or harm to human health (Executive Order 13112 of the National Invasive Species Council, 1999). Of the approximately 950 plant species (Avery and Loope 1983) in Everglades National Park, 221 are nonnative (Whiteaker and Doren, 1989). Of these species, three have been particularly troublesome: Australian bottle brush tree (*Melaleuca quinquenervia*), Brazilian pepper (*Schinus terebinthifolius*), and Australian pine (*Casuarina equisetifolia*). In each case, the plant was introduced with a desirable goal in mind, but the outcome on the Everglades ecosystem has been severe and unanticipated. Another nonnative species, the Old World climbing fern (*Lygodium microphyllum*), has emerged more recently as an especially aggressive species in the Everglades system (Brandt et al., 2002; Langeland and Burks, 1998).

Many wildlife species also have been introduced in the Everglades; often they were pets that the owner discarded. In particular, invasive species of fish from home aquaria, aquacultural activities, and other sources have been found in the Everglades. Examples include blue tilapia (*Oreochromis aureus*), spotted tilapia (*Tilapia mariae*), walking catfish (*Clarias batrachus*), and Asian swamp eel (*Monopterus albus*) (see examples of wildlife species introduced in the Everglades at *http://www.flmnh.ufl.edu/fish/southflorida/everglades/Marshes/Exotic.html*).

Invasive species are not restricted to species from outside North America but can include North American species that are not native to the ecosystem of concern. In addition, species that are native to the ecosystem can irrupt, i.e., they can experience sudden increases in their numbers when ecological conditions change to favor them. In the Everglades ecosystem, the cattail (*Typha domingensis*) seems to be such an irruptive species that has been stimulated in the Everglades as a result of higher phosphorus concentrations, deeper water, and longer periods of high water in areas such as the WCAs and STAs that are created for storage (Davis, 1994). Under such conditions, cattail has replaced both sawgrass (*Cladium jamaicense*) and the diverse communities of green and blue-green algae, desmids, and diatoms that comprise periphyton mats, signature species of the Everglades (McCormick and Scinto, 1999).

Indeed, the expansion of cattail has been so extensive in WCA 2A and along canals throughout the Everglades system that it has been a focus of law suits concerning water quality (John, 1994; Rizzardi, 2001a,b; Fumero and Rizzardi, 2001) and is one of the primary trends the Restoration Plan intends to reverse. Extensive research on cattail's interactions with sawgrass, however, gives reason for concern that cattail will replace sawgrass over even greater areas before the Restoration is complete. While well adapted to periodic drought, fire, and the extremely low phosphorus levels of the native Everglades system, sawgrass performs less well than cattail under even mildly elevated phosphorus concentrations and longer periods of high water (Urban et al., 1993; Davis et al., 1994; Newman et al., 1996). Furthermore, cattail's opportunistic pattern of phosphorus uptake, allocation, and growth allows it to take advantage of temporal variations in phosphorus inputs (Davis, 1994). Sawgrass is the superior competitor only under highly infertile conditions (Newman et al., 1996; Noe et al., 2001). Thus, cattail is likely to expand its distribution in the northern Everglades until phosphorus inputs and periods of high water are reduced.

The number of invasive species already in the Everglades demonstrates the difficulty of controlling human activities that may intentionally or inadvertently lead to their introduction. The extent to which some of them have replaced native species and now dominate large areas of the system underscores the difficulty of predicting ecological outcomes. Research associated with invasive species in the Everglades should focus on the pathways of introduction for nonnative species and the prospect for an introduced species to become invasive in the Everglades. Limiting the spread of invasive species already established in the Everglades will reduce other costs and increase the probability of success of the restoration program.

Disappearance of Unique Everglades Communities

Whether one considers the Everglades landscape from the level of the microscopic communities of periphyton mats or the entire assemblage of different plant and animal communities that constitute it, the term "unique" can be applied correctly. The Everglades is the only subtropical wetland within the United States. In fact, the particular combination of a warm and alternately wet-dry climate, relatively flat topography, and predominantly limestone geology that come together in south Florida has created a wetland that is unlike any other in the world – a subtropical, oligotrophic, calcareous, peat-based wetland. The organisms that inhabit this environment have evolved specific adaptations that allow them to survive frequent shallow inundation, low nutrient availability, periodic but extended drought, and episodic severe fire. Temporal and spatial variability in these factors over south Florida, as well as feedbacks between the biota and environment, produced a temporally dynamic landscape consisting of several distinctive vegetation types (Gunderson, 1994; Davis et al., 1994). Davis (1943) identified and mapped thirteen different vegetation types in the Everglades.

At present, half of Everglades wetlands have been lost to agriculture and urban development, and diversity at both the community and landscape scales has been reduced in the remaining Everglades (Davis et al., 1994). Of the vegetation types mapped by Davis (1943), custard apple forest, peripheral wet prairie, and cypress forest have disappeared completely under human disturbance (Davis et al., 1994). Other types have been reduced substantially in area, notably the sawgrass plains and, to a lesser extent, southern marl-forming marshes. These two categories encompass five of Davis's (1943) vegetation types, which Davis and others (1994) group into two pre-drainage landscapes—the sawgrass-dominated mosaic and the wet prairie-slough-sawgrass-tree island mosaic. In some of these latter areas, the former mosaic is losing its heterogeneity and becoming more uniform. Of particular concern is the loss of marl prairies (home to the endangered Cape Sable seaside sparrow, see above), tree islands, and open sloughs of submerged vegetation and periphyton mats.

Many studies have attributed changes outside the areas where cattail now dominates to the past several decades of water and fire management in the water conservation areas, as well as to loss of flows throughout the system (Davis et al., 1994; SCT, 2003; NRC, 2003c). Numerous studies now are under way to reduce uncertainties in these attributions (Sklar et al., 2004). Insofar as the attributions have any validity, those involved in the restoration must recognize that the longer it takes to implement new water and fire management strategies, the more likely are further losses in the unique communities that are the Everglades.

Loss of Tree Islands and Ridge-and-Slough Topography

Tree islands, ridges, and sloughs hold a central place in people's images of the Everglades system. "Ridge and slough" is one of nine major physiographic regions recognized within the Greater Everglades Ecosystem for modeling the restoration (USACE and SFWMD, 1999). "Landscape pattern" is one of only five functional groups into which all ecological performance measures have been aggregated for monitoring the restoration (AAT, 2001). Recovery of the acreage and number of tree islands is one of the specific restoration targets identified by the Task Force and RECOVER (Ogden and McLean, 1999). Tree islands have been the focus of an entire book (Sklar and van der Valk, 2003), and the role of water flow in maintaining tree islands and ridge-and-slough topography has been the focus of reports by both the Science Coordination Team (SCT, 2003) and the National Research Council (2003c).

Degradation of the landscape pattern of teardrop-shaped tree islands and sawgrass ridges (typically covered by shallow water) alternating with those of open-water sloughs seems apparent in aerial photographs and other imagery of the central Everglades (SCT, 2003). In a number of areas in the central Everglades, a strongly patterned landscape is being replaced by one in which topography and vegetation are more uniform. In the western part of Water Conservation Area 3, Sklar et al. (2003) found that differences in elevation between ridges and sloughs had decreased from between 30 and 90 cm to about 20 cm. The mechanisms by which the degradation is occurring, however, remain uncertain, as do the mechanisms by which the patterns initially formed. Several plausible mechanisms—e.g., underlying bedrock topography, differential rates of peat accumulation, transport of organic matter by flowing water, extreme hydrologic events, fire—have been proposed, but none has been examined in detail nor tested through process-based research (SCT, 2003; NRC, 2003c). A notable exception is the study by Conner et al. (2003) on the differential tolerance of tree species to changes in water depth. Furthermore, as noted by the SCT (2003), mechanisms that generated these features may differ from mechanisms that maintain them.

Strong circumstantial evidence suggests that the direction and rate of water flow through the system play critical roles in maintaining the ridge and slough landscape (SCT, 2003). Of particular relevance is that the orientation of tree islands and the parallel ridges and sloughs align with inferred pre-disturbance patterns of water flow (Ingebritsen et al., 1999). Neither direction nor rate of water flow, however, enter explicitly into the Restoration Plan, which focuses instead on the timing and duration of water levels and water quality (NRC, 2003c). Water levels undoubtedly have effects on landscape patterns but they are not sufficient to explain how they are maintained (SCT, 2003; NRC, 2003c).

Thus, the uncertainty surrounding the effects of the Restoration Plan on tree islands and ridge-and-slough topography is high. However, several specific approaches to reducing that uncertainty are available and have been identified by the Science Coordination Team (2003) and the National Research Council (2003c). Given that degradation already has occurred and is likely to continue under present conditions, placing a high priority on pursuing these approaches seems warranted.

Expansion of Eutrophic Conditions

One of the primary factors motivating restoration is the dramatic change in system state that has occurred in northern portions of the Everglades, where an oligotrophic ecosystem has been replaced by a eutrophic one (Davis, 1994). The most obvious manifestation of this state change is the advancing front of cattail that now dominates large areas once characterized by sawgrass, spike rushes (*Eleocharis* spp.), submerged and floating aquatic plants, and the species-rich assemblages of bacteria and algae associated with periphyton mats (Davis, 1994; Childers et al., 2003). At a more fundamental level, however, eutrophication means that the functioning, as well as the structure, of the entire system has changed as the result of nutrient inputs higher than those under which the Everglades system developed over the past 5,000 years (Gleason and Stone, 1994; Davis, 1994; Daoust and Childers, 1999; Miao and Debusk, 1999). Rates of nutrient uptake, biomass production, and decomposition have increased, as have many microbially mediated processes that circulate nutrients within the systems (Reddy et al., 1999). These changes in system metabolism are reflected in higher concentrations of total and biologically available phosphorus in the detrital layer and shallow soils of phosphorus-enriched than of unenriched areas of the Everglades (Reddy et al., 1999; Childers et al., 2003).

While the mechanisms by which cattail has replaced sawgrass and periphyton mats are well studied (Craft and Richardson, 1993; Newman et al., 1996; Newman et al., 1998; Miao and Debusk, 1999; McCormick and Scinto, 1999), and effects on overall system metabolism also have been much studied (Reddy et al., 1999), substantial uncertainty surrounds the question of whether or not the eutrophication process is reversible for the Everglades. In phosphorus-enriched areas of the Everglades, excess phosphorus has set up a positive feedback cycle in which increased microbial biomass results in higher rates of organic matter breakdown, greater release of inorganic forms of phosphorus and nitrogen from soils and litter layers, and consequently increased nutrient availability to plants (Reddy et al., 1999). With higher nutrient availability, the slow-growing, nutrient-conserving species of algae and vascular plants characteristic of the oligotrophic Everglades do less well than cattail, a fast-growing, nutrient-demanding species of eutrophic conditions (Newman et al., 1996). In turn, cattail produces more biomass, and its nutrient-rich litter supports higher microbial biomass, and decomposes more rapidly. This fuels an internal cycle of uptake and release of the inorganic forms of phosphorus that favors cattail growth. Shading by cattail then decreases the abundance of periphyton mats, which further drives eutrophication by reducing oxygen production and the removal and storage of phosphorus by periphyton (McCormick and Scinto, 1999). The development of oxygen limitation changes the composition of the microbial community and greatly increases the activity of anaerobes (Drake et al., 1996). Limiting periphyton growth also affects formation of calcareous soils, the basis of the marl prairies.

The process of eutrophication is exacerbated by interactions with sulfate, which enters the Everglades from anthropogenic atmospheric sources and especially from agriculture (elemental sulfur is added to muck soils in the EAA as an acidifying agent to promote trace metal availability to crops, and the elemental sulfur is readily oxidized in the soil to sulfate). As limnologists have known for over fifty years, the release of phosphorus (as phosphate ion) from lake sediments can increase significantly when sulfate concentrations are increased (Hasler and Einsele, 1948). High sulfate concentrations in organic-rich, anoxic water and sediments promote the formation of sulfide. The anoxic conditions and high sulfide levels also promote the reduction of iron oxyhydroxides in sediments leading to the formation of ferrous sulfides. The net effect is to decrease the abundance of iron forms that can bind with phosphate in sediment (e.g., Wetzel, 1999). High sulfide concentrations also can be toxic to animals and plants and might explain changes in species composition associated with eutrophic regions in the Everglades. Consideration of the supply and spatial distribution of sulfate within the Everglades must therefore be part of any effort to understand and limit expansion of areas already converted to eutrophic states.

Given that eutrophication effects a fundamental change in the system, and that once started it may become internally maintained, one must ask how long it might take to reverse the process after external phosphorus inputs are reduced. High phosphorus concentrations in sediments, plants, litter, and microbial biomass will continue to result in release of inorganic phosphorus to overlying waters—possibly for many decades—until fresh inputs of sediments with lower nutrient concentrations cover the nutrient-rich deposits or until the slow export of phosphorus in flowing water gradually depletes the system's phosphorus stores. Given the number of processes involved and the complexity of their interactions, it is not clear when that might be.

Hence, preventing expansion of the areas where the system already has become eutrophic should be a high priority for the restoration.

Mercury Deposition, Mobilization, and Bioaccumulation

Processes occurring outside the system can change the Greater Everglades Ecosystem. One such process is atmospheric deposition of mercury (Hg). The factors controlling Hg deposition, transformation from unavailable to biologically available states, accumulation up the food chain (magnification), and implications to individual species are quite complicated. Impacts on higher trophic-level organisms could alter the way in which the Greater Everglades Ecosystem functions.

The identification of high mercury concentrations in sediments (Drexel et al., 2000); water (Mauro et al., 2002); fish (Burger et al., 2004); birds (Frederick et al., 2002); alligators (Heaton Jones et al., 1997); and mammals (Facemire et al., 1995), including humans (Fleming et al., 1995) of the Everglades, is a reflection of the power of external forces to insert themselves unplanned into the restoration. While processes occurring within Everglades wetlands determine the rates at which mercury is converted from the unavailable to bioavailable form, and bioaccumulated within food webs, the sources of mercury lie largely outside these wetlands. Sulfate, which facilitates mercury methylation at low and moderate concentrations (Gilmour et al., 1998), also arrives from elsewhere. Insofar as the Greater Everglades Ecosystem is a precipitation-driven system, and methylation rates in part are a function of alternating wet and dry cycles, climate is a major external force that will affect achievement of restoration goals. Similarly, transport of mercury to and within the Everglades system is affected by climatic effects on wet and dry deposition. Restoration goals pertaining to animals, especially fish, higher trophic levels, and human health, and to providing recreational opportunities for human populations could be thwarted if insufficient attention is given to mitigating the mercury problem.

As in most wetlands, the organic sediments in the Everglades accumulate inorganic mercury forms from a variety of atmospheric sources (Dvonch et al., 1998, 1999; Atkeson et al., 2003). However, under appropriate conditions, which occur in coastal and freshwater wetlands like the Everglades, these forms (primarily mercuric ion, Hg^{2+}, in various complexes) are transformed to methylmercury. Methylmercury is a highly toxic form of mercury that is bioaccumulated within food webs. Effects on human health can be severe and include numerous forms of neurological damage to adults and neurodevelopmental deficits in children whose mothers are exposed to chronic low doses (NRC, 2000). Similar detrimental effects are observed in other higher trophic-level organisms–e.g., alligators, birds, and panthers.

Cleckner et al. (1999) found that methylation of mercury occurs within the periphyton communities that occur throughout the Everglades. As defined by Cleckner et al., these communities consist of algae and bacteria growing in filamentous mats on top of the peat substrate, attached to macrophytes, or as free-floating mats. Rapid rates of methylation were found in periphyton communities where sulfur oxidation by photosynthetic bacteria was coupled with bacterial sulfate-reduction—specifically, a cycle in which bacterial sulfate-reduction is coupled to sulfide oxidation by photosynthetic sulfur bacteria. This finding is significant because periphytic communities serve as a direct food source to higher trophic levels (zooplankton and fish) and thus provide a tighter link between methylation and bioaccumulation of mercury by fish than is the case for the usually cited location of methylation—the bottom sediments.

Several kinds of bacteria can methylate mercury. In wetland sediments, sulfate-reducing bacteria such as *Desulfovibrio* spp. and *Desulfobulbus proprionicus* are responsible for the transformation (Choi et al., 1994; Benoit et al., 1999, 2001). The relationships among sulfate concentrations, activity of sulfate-reducing bacteria, geographic location within the Everglades, and other factors that affect the rate of methylation of mercury, including the concentration of methylmercury itself, are complex and are not fully understood (Benoit et al., 1999; Krabbenhoft et al., 2000). Whatever the precise relationships are, the concerns about mercury pollution in the Everglades make it critical to understand how sulfate affects the concentrations and species of mercury present in the Everglades.

The State of Florida has taken some steps to control the Everglades mercury problem. Local atmospheric emissions of mercury in south Florida are estimated to have declined by over 90 percent from their peak levels in the late 1980s to early 1990s (Atkeson et al., 2003). Mercury concentrations in wet deposition in south Florida have declined by only about 25 percent since late 1993 (Atkeson et al., 2003), and the difference in the two numbers was attributed by Atkeson et al. at least in part to the fact that much of the decline in local emissions in south Florida occurred before wet deposition monitoring for mercury began in late 1993. The decline was found to be statistically significant and not related to changes in the amount of precipitation. Nonetheless, considerable uncertainty remains about the importance of long-range (continental and hemispheric) scales of transport as a contributor to mercury deposition in south Florida. According to Atkeson et al., various studies estimate that long-range sources contribute from 25 to more than 60 percent of the mercury to south Florida. Estimates for other parts of the country tend to be at the high end of this range (Engstrom and Swain, 1997; Fitzgerald et al., 1998).

It is encouraging that declines in concentrations of mercury in largemouth bass and great egret chicks of about 80 percent have been observed at several locations in the Everglades over the past decade (Atkeson et al., 2003). These trends suggest that local emission controls have been successful in decreasing the magnitude of the mercury problem in south Florida. The trends might be explained by the nature of the mercury emission sources in south Florida, which were dominated by municipal and medical waste incineration (~86 percent of total emissions for Dade and Broward Counties in 1995-96). The mercury in these emission sources had a high fraction (~75 percent) of reactive gaseous mercury (thought to be mercuric ion, Hg^{2+}), which is scavenged rapidly from the atmosphere by rainfall and settling particles and thus tends to be deposited locally. In contrast, most of the mercury in emissions from coal-fired power plants is thought to be elemental mercury, Hg^0, which reacts very slowly in the atmosphere and has an atmospheric residence time of about one year, allowing it to be transported across the hemisphere many times before being deposited.

Nonetheless, the above positive trends do not guarantee that the mercury problem in the Everglades is solved or will be solved simply by controlling local emission sources. Insufficient data are available to reliably define temporal trends in mercury levels in fish communities and other animals in the Everglades. Moreover, changes in the wet-dry cycle of the system, which are likely to result from the restoration process, might exacerbate the problem by stimulating more active methylation of mercury than under current conditions (see Chapter 2, section on EAA Reservoirs). Finally, methylmercury in water and its biota in the Everglades will be affected by seawater intrusion and other factors that alter water chemistry, including perhaps aquifer storage and recovery (ASR).

Regional Climate Change and Sea-Level Rise

Climate change always has occurred and always will. The most important regional climatic factors subject to change are precipitation patterns (quantity, timing) and temperature. How those factors might change over the next several decades cannot be predicted with any accuracy, and thus there is an important source of uncertainty in modeling of the system. Though future climate is uncertain, the temperature is more likely to go up than down, and the variability in precipitation, including the frequency of extreme events, is more likely to increase than to decrease (IPCC, 2001). The frequency and severity of fires also could be affected by climate change (Davis and Ogden, 1994).

For the Everglades, the most important global factor related to climate and subject to change is sea level. If significant global warming occurs, then for several reasons sea level is likely to rise. Current predictions are for a rise of approximately 0.6 to 1.5 m over the next century, but much uncertainty accompanies the predictions (IPCC, 1995). Because much of the Everglades, and much of south Florida, is so low-lying, a one-meter rise in sea level would have profound consequences for both natural and built environments there. According to Titus and Richman (2001), for example, 12,251 km^2 of Florida's 139,853 km^2 of land (7.6 percent) is within 1.5 m of sea level. Much of that low land is in the south.

CONTINGENCY PLANNING

Because significant hydrologic and ecological uncertainties are to be expected as the Restoration Plan is implemented, we have recommended that a method of evaluating tradeoffs be developed (Chapter 5) so that options are not excluded. Consistent with this recommendation is the need for contingency planning, which is necessary to identify other options that should be available for consideration. Finally, as an assessment and management framework within which the need for implementation of contingency plans can be determined rapidly, active adaptive management should be considered.

The need for both flexibility and adaptive management arises because initial actions will not always result in desired outcomes; surprises will occur and modifications to management actions will be necessary. In addition, as described in Chapter 2, approximately 80 percent of the new storage to be provided by the Restoration Plan involves novel technologies. Therefore, for an adaptive management strategy to be effective and flexible, contingency plans should be developed so that revised management actions can be efficiently implemented.

For example, the Restoration Plan may not get the water right to achieve the desired ecological response. Active adaptive management is important to provide an early indicator of problems. Beyond that, flexibility in design and operations so that reasonable alternatives can be implemented is crucial. For contingency planning, assessment and modeling of perhaps less likely, but still possible, scenarios would be prudent. The scenarios for which contingency planning is needed should include both external forcing functions, such as climate change, increased water demand due to population growth, or greatly increased energy costs, as well as previously eliminated options, such as the EAA and Lake Okeechobee.

Even if the water is made "right", habitat modification that has already occurred is not always reversible. As noted above, populations of endangered species such as the Cape Sable seaside sparrow may not respond as predicted. What scenarios other than the predicted outcome might arise? What might happen during the transition period? Given the resources invested in the

Restoration Plan, and the consequences of unanticipated outcomes, it is important to think through questions of this nature and develop appropriate contingency plans.

Clearly not all possible outcomes can be anticipated, which is underscored by using the word "surprise" to characterize some unanticipated outcomes. A strategy that includes contingency planning for alternative scenarios, flexibility to implement the contingency plans if needed, and active adaptive management to rapidly ascertain if the contingency plans are needed is strongly recommended.

As a framework for contingency planning, long-range scenarios for development in the urban and agricultural parts of the Greater Everglades Ecosystem, making explicit the external forcing functions of the restored Everglades, will be essential. Such scenarios are essential tools to embed learning in the quest for sustainability (NRC, 1999). Long-range development scenarios sketch alternative long-range visions of how the system could change given what is known about trends, human desires, uncertainties and possible surprises, and pathways by which conditions might change. They make explicit the assumptions about values, lifestyles, and institutions, and they reveal the range of possible futures that should be contemplated.

ADAPTIVE MANAGEMENT

Adaptive management—implementing management policies as experiments (Holling, 1978; Walters, 1986)—has a large and rich scientific literature. Although it is not universally adopted as management practice—it can be difficult, time-consuming, and perhaps risky—there is much experience with its use and especially guidance on how to apply it (e.g., Carpenter, 1990; Walters and Holling, 1990; Gibbs et al., 1999; Gunderson and Holling, 2002; Meffe et al., 2002; Oglethorpe, 2002; Anderson et al., 2003). The Restoration Plan is committed to adaptive management, but it relies on passive, rather than active, adaptive management. The relative merits of the two approaches, and the consequences for the Restoration Plan of adopting a passive approach, were discussed in detail in an earlier NRC report (NRC, 2003b). We briefly summarize the critical points of that assessment here.

Ideally, adaptive management allows resource managers to act despite acknowledged uncertainty, designing management actions to reduce uncertainty over time while permitting changes in response to surprising outcomes. Effective active adaptive management involves integration of model forecasts with post-implementation monitoring and large-scale management experiments; the combination of model forecasts and the new information (from monitoring and experimentation) should help to refine management actions and improve models over time. In contrast, passive adaptive management as proposed in the Restoration Plan does not include large-scale management experiments, but instead relies on an approach in which learning is based on each incremental step in the implementation plan. Adopting a passive-management approach represents a decision to limit power to obtain additional knowledge in order to avoid costs to the ecosystem (e.g., harm to endangered species) of obtaining knowledge. We recommend augmenting the passive approach with active adaptive management wherever possible to enhance conclusions about cause and effect and improve forecasting models. This is particularly important for assessing ecological responses to restoration actions.

Examples of Restoration Plan components suited to active adaptive management include the pilot projects on ASR and other technologies, which should be tested in an experimental framework. Other possibilities might include experimental management to see whether (or to what degree and at what ecological cost) eutrophication is reversible; options for controlling invasive species; the nutrient concentrations required to promote the growth of sawgrass instead of cattails; and so on.

We are concerned that the Restoration Plan may not be sufficiently flexible, because anticipated outcomes are based on the fully implemented system, and the extent to which outcomes of individual projects can lead to changes in the design of later projects is unclear. It would be useful to assess the design and operational flexibility of the 68 proposed major projects that comprise the Restoration Plan in order to prioritize monitoring, experimental, and modeling activities, and to examine the relative ease with which projects could be modified in an adaptive-management process. To be effective, the process requires an explicit feedback mechanism for learning from management actions. This mechanism should begin with systematic, iterative monitoring followed by comparison of results with model predictions and project goals. Establishing formal linkages between scientists and decision-makers would ensure that scientific information is available and accessible to the decision-making process. Taken together, the monitoring by scientists and provision of conclusions to decision-makers would make possible the well-known engineering practice of feedback and control. Considering the 40-year time frame of the Restoration Plan and perhaps a century of system response, a regional information synthesis center (NRC, 1999) would enable the systematic provision of evolving, reliable knowledge in support of the policy process and the interested public who affect and are affected by the program. The center's activities should include restoration activities that are not officially part of the Restoration Plan.

A similar recommendation was made by a recent NRC committee reviewing the Critical Ecosystems Studies Initiative (NRC, 2003a). That committee recommended that south Florida restoration managers "should consider the benefits of a central and independent restoration science entity that strives to inform the greater restoration effort (including the [Restoration Plan], current non-[Restoration Plan] initiatives, and future restoration projects) with the best science available. Such a central science body could serve as a resource for scientific information, provide a mechanism for science coordination, and create a forum for visionary science synthesis." We agree with the earlier committee that the entity should not influence or be responsible for restoration *policy* and decision making.

Finally, while management objectives are an essential foundation for adaptive management, they themselves should be subject to change through the adaptive-management process. Much effort has been expended on defining restoration goals, objectives, and targets, and many general and specific ones have been identified. Yet it is still not clear exactly what a successful restoration will look like, and not all specific goals and targets are internally consistent. Adaptive management can be helpful here, since it need not be restricted to improving scientific knowledge and assessment. In fact, adaptive management is compatible with a dynamic decision process in which the knowledge gained through large-scale experiments may suggest that management objectives need to be re-examined and possibly reformulated.

SUSTAINABILITY OF THE RESTORATION PLAN

Large environmental restorations of ecosystems—especially aquatic ecosystems—usually face a tension between the need for human subsidies in the form of energy, time, and money, typically for the construction and maintenance of control structures, and the desirability of relying on natural processes to achieve the restoration program's goals. Designing engineered systems and specifying their parameters often is easier than relying on natural systems. Engineered systems allow for the provision of services unrelated to ecosystem functioning, such as drinking water, flood control, and recreation, and ecosystems can respond more quickly to changes in engineered systems than to many natural processes. In addition, many aquatic ecosystems to be restored already have many control structures in place, such as dams, levees, and pumps. However, experience with ecological restoration shows that goals are realized more often when natural processes are encouraged than when engineering solutions are substituted for natural processes (e.g., NRC, 1992; NRC, 1996a; NRC, 2001b).

It is obvious even on superficial inspection that the Restoration Plan for the Everglades relies very heavily on engineered solutions. Aquifer storage and recovery (ASR) and the Lake Belt reservoirs are two components of the plan that will require large initial investments in engineered structures; ASR will require large continuing investments in its operation and maintenance as well. The Everglades shares with many other large aquatic ecosystems the presence of many control structures and many competing demands on its water supply. Therefore, opportunities to restore the system to one in which flows are controlled only by natural processes of rainfall, runoff, and storage in natural areas are severely constrained. This is the result of the restricted footprint (area) of the remaining natural areas in the Everglades, the proximity of urban and agricultural lands that cannot be subjected to flooding without significant loss of property values, and the current and future demands for urban and agricultural water supply. Many of the natural storage features of the system, which provided essential damping of seasonal and storm-driven flows, have been lost permanently as a result of agricultural and urban development. As described previously, simply routing excess water from Lake Okeechobee to the southern Everglades through pipes or other structures that bypass the agricultural area is also not an acceptable option. Although this would reduce the detrimental pulses of freshwater discharged to estuaries, it would generate unnaturally high flows and water levels in the terrestrial ecosystem.

Although some of the natural storage and damping could be restored if agricultural land south of Lake Okeechobee were converted into a restored corridor connecting the lake to the southern Everglades, subsidence due to peat loss in the agricultural area south of Lake Okeechobee has altered the topography to the extent that the land surface is now lower than in areas to the south. Therefore, even if intensive agriculture were ended in the EAA (or large parts of it) and the area converted to wetlands, slow sheet flow to the south would not be restored in the area that was historically a sawgrass plain. Instead, water would need to be pumped out of the subsided region into areas of the Everglades to the south. A large wetland of this type would, of course, provide significant storage and damping of southward flows, and it would remove a substantial amount of nutrients from the water. However, depending on the water levels maintained in the former agricultural lands, this land conversion also could result in the inundation of established urban and industrial areas and agricultural lands surrounding the current perimeter of the lake, and it would increase the flooding hazard of other developed areas to the south and southeast. This potential restoration component, therefore, would require additional engineering measures for flood control.

The inevitable conclusion is that some degree of engineering control will be necessary in any attempt to restore more natural water levels and flows in the southern Everglades. However, as is evident from the descriptions of storage components in Chapter 2, there is a considerable range in the degrees to which various proposed storage components involve complex design and construction measures, rely on active controls and frequent equipment maintenance, and require fossil fuels or other energy sources for operation. We therefore discuss the approaches for dealing with this issue in some detail, and suggest considerations that enter into evaluating options on that basis.

In discussing options for interventions to enhance the wild salmon runs of the Pacific Northwest, an earlier NRC committee (NRC, 1996) provided a framework that is largely applicable to the Everglades restoration as well. That committee considered four general approaches for dealing with the problem of declining salmon runs: allowing continued degradation, restoration, substitution, and rehabilitation. Other than the first, the approaches are not mutually exclusive. As was true for that committee, allowing continued degradation is outside this committee's charge and is not considered further. We discuss the remaining three approaches below, based on the 1996 NRC report.

- **Restoration.** *Restoration* implies a return of the system to some former, specified condition (NRC, 1992). Restoration of the Everglades is no longer possible in many parts of the former ecosystem. Parts of the ecosystem have been so altered that it is impossible to know what the pristine condition was, and even intermediate historical conditions cannot be accurately defined. Other parts of the system have been irreversibly altered by human development. In addition, as the NRC's 1996 report pointed out with respect to the Pacific Northwest, "the process by which the environment reached its current condition is not totally reversible. Genetic variability has been lost; evolution has occurred; exotic species have been introduced; human populations in the region have increased, and people have developed dependencies on a variety of modern technologies, cultures, and economic systems; and other natural and anthropogenic environmental changes have changed the range of biophysical and socioeconomic possibilities for future states of the system. In brief, the past provides opportunities for the future, but also constrains it."

- **Substitution.** By *substitution*, the 1996 NRC committee meant "investing substantial energy, time, and money on a continuing basis to replace natural ecosystem processes that have been destroyed or degraded." Examples of proposed Restoration Plan components that constitute substitution in the Everglades are obvious: they include ASR; Lake Belt Storage; the system of canals, levees, and pumps used to transport water; and treatment plants for reuse of wastewater for Miami. As in the case of salmon in the Pacific Northwest, substitution for natural processes to maintain hydrologic regimes in the Everglades is possible, at least in some respects. However, it is expensive—the current, probably low estimate for restoring the Everglades is $7.8 billion for construction and land-acquisition alone, with annual operating and maintenance costs of at least $150 million. The cost in human and financial resources is likely to increase rather than decrease or stabilize in the future. And as the earlier committee warned, "…as the ability of human actions to make up for natural processes lags behind expectations, the danger is that either more and more drastic interventions will be undertaken or the whole effort will be abandoned and the salmon will be lost" (NRC, 1996a). That danger seems to apply to the Everglades restoration as well.

- **Rehabilitation.** By *rehabilitation*, the earlier NRC committee meant "a process of human intervention to modify degraded ecosystems and habitats to make it possible for natural processes of reproduction and production to take place. Rehabilitation would protect what remains in an ecosystem context and regenerate natural processes where cost-

> effective opportunities exist. It might be necessary to use the technologies and techniques suggested in the preceding paragraph to maintain the essential ecosystem components in the short term, but the ultimate goal is to modify (i.e., rehabilitate) the systems to the point where human input is substantially reduced or even stopped altogether. Substantial local opportunities for local ecosystem rehabilitation exist throughout the region and they should be taken advantage of. Although this framework implies reduced management costs over the long term, it requires a long-term commitment to achieve positive results."

Restoring the Everglades is not a perfect analogy with reversing the declines of Pacific salmon in the northwestern United States, but there are many parallels that are useful in this case. Before discussing those specifics, we briefly describe some examples of the use of a rehabilitation approach to environmental restoration elsewhere. In longleaf pine savannas, the historical habitat structure was characterized by open pine stands with little hardwood midstory and a rich groundcover. Managers can return this structure to degraded habitats by using the natural disturbance that maintained it formerly—growing-season fire—or through less-natural techniques such as removal of hardwood midstory vegetation mechanically or use of herbicides. All these techniques restore the desired open habitat structure, but use of fire resulted in higher diversity of virtually all kinds of organisms in the community (Litt et al., 2001; Provencher et al., 2001, 2002, 2003).

More relevant to the Everglades are examples of restoration of rivers and riparian habitats. The Greater Everglades Ecosystem is like a river in many ways, albeit a very wide and shallow one, whose flow is dominated by the effects of a water-control infrastructure. The dams of this infrastructure are lower than similar structures on other systems, but they nonetheless control the timing, magnitude, duration, and rates of change of flow through the system just as dams on other rivers do. The restoration of aquatic and riparian habitats for the benefit of species and general ecosystem functioning is a process that begins with the physical components of the system. The flows of water, in turn, control the movement of sediment, nutrients, and contaminants through the river system, often with temporary internal storage. The inorganic parts of the ecosystem form the foundation step toward a restored ecosystem. Reconstruction of this foundation by controlling flows of water to mimic the natural hydrologic regime has proven much more effective than physical reconstruction of the inorganic parts of the ecosystem in the absence of restored flows. Thus the general objective in physical restoration is to combine artificially designed features with a modified set of natural processes to effect a naturalization of the existing engineered system (Rhoads and Herricks, 1996). The result is a set of forms and processes that are as close to natural as possible, but that also accommodate some human-derived components. The restored river system is often a scaled-down version of the pre-human one, because water diversions for purposes other than in-stream flows make it impossible to sustain an active channel and riparian system of the original size (Graf, 2001). The issue in the case of the Everglades is whether the Restoration Plan represents a system that is as close to natural as is achievable given existing constraints, especially with respect to storage.

The effectiveness of natural process in restoration does not preclude an important role for management and engineering. Indeed, restoration of riparian habitat illustrates that considerable progress toward more natural ecosystem conditions is possible through the use of existing water-control infrastructures. Dams are sometimes thought of as major impediments to restoration, but because they represent control valves on flows in the watershed and its river, they also provide an opportunity for modifications that could restore more natural flows and water levels in parts of the system. Glen Canyon Dam on the Colorado River, for example, caused substantial changes in water flows and sediment transport downstream of the dam in Grand Canyon (Carothers and Brown, 1991). Continuing adjustments and fine-tuning of the releases is a part of an adaptive-management effort to improve the hydrologic regime for ecological purposes (Collier et al., 1997). Controlled releases on other rivers have had similar restoration objectives, including on the Trinity River of California below Trinity and Lewiston dams (Pitlick, 1992), the Gunnison River in Colorado below Crystal Dam (Chase, 1992), and several rivers in the eastern United States, including small streams in New England and larger ones such as the Ocoee River of Tennessee. The many water-control structures in the Everglades could be operated to support similar restoration objectives.

The ultimate technique for using natural process in restoration of riparian ecosystems is dam removal, and this is more and more frequently the option of choice when other human demands on the system do not preclude it (Heinz Center, 2002). More than 400 documented cases of dam removal throughout the United States in recent decades provide ample experience in considering this option (American Rivers et al., 1999; Heinz Center, 2002; Pohl, 2003). In most cases, the structures that have been removed have been obsolete, low-head dams similar to many of those in central and south Florida. Most of the structures stored small quantities of water and sediment, and their influence on the hydrologic regime was limited. Their presence in the channel system inhibited movement of organisms up- and down-stream, however, and the dams therefore affected an important component of the ecosystem. Removal of the structures resulted in an increase in populations for a variety of species ranging from micro-organisms to endangered fish species (Hart et al., 2002). A cautionary note based on experiences elsewhere is that decision-makers must take account of the fate of sediments stored upstream from structures to be removed, because such materials are likely to be re-mobilized along with any contaminants that might be attached to them. The movement of invasive species into habitats formerly free of them also is likely to be one result of removing dams or other water-control structures, such as those in the Everglades, or other impediments to water flow, such as roads.

Application of Rehabilitation Approach to Evaluation of Everglades Restoration Options

In considering options for restoring the Everglades hydrologic regime to a more natural condition, many factors need to be considered. As discussed elsewhere in this report, they include human demands for clean and stable water supplies, flood control, agriculture, and recreation, in addition to the ecological needs of the Everglades. Those demands must be balanced against considerations of construction costs, operation and maintenance costs over decades if not centuries, water quality, the susceptibility of the components to mechanical or power failure, and the changing human and natural environments that will characterize south Florida for the foreseeable future.

Some components of the Restoration Plan or associated activities already appear to have been motivated by an approach similar to what we call the rehabilitation approach. For example, the Kissimmee River restoration project is of special interest to the Restoration Plan because it represents one of the relatively uncommon instances in which hydraulic structures and channels have been decommissioned in an effort to restore natural hydrologic and ecological functioning.

This is in contrast to the planned construction of wells, pumping stations, seepage barriers, and advanced wastewater treatment characteristic of many other aspects of the greater Everglades restoration effort. That effort is described in some detail at *http://www.saj.usace.army.mil/dp/Kissimmee/Kissimmee2.html.*

The Kissimmee River restoration is only partial and represents a reversion of a "highly engineered" flood channel (C-38) to portions of its hydrologically simpler, historical, meandering self. Whether or not these efforts will provide the hoped-for hydrologic, ecological, and water-quality benefits remains to be determined; an extensive Kissimmee River Restoration Evaluation Program is designed to track initial and long-term responses to the reconstruction efforts.

Similarly, efforts to "decompartmentalize" the Everglades ecosystem by removing various canals and flood-control structures and by altering parts of the Tamiami Trail (U.S. Route 41) where it crosses the Everglades so as to increase sheetflow also reflect a rehabilitation approach. Finally, the use of stormwater treatment areas (STAs), which are engineered wetlands but which rely to some degree on natural processes, represents some degree of the rehabilitation approach, especially as compared with the water-treatment facilities planned for the Miami wastewater reuse. On the other hand, ASR and Lake Belt Storage are firmly in the substitution category.

The committee describes elsewhere in this report how pre-existing constraints; new demands on the system; the possibility that one or more of the proposed components of the Restoration Plan will be unable to function as proposed; the accumulating costs of building, operating, and maintaining the Restoration Plan; ecological uncertainties; and the specifications of the Restoration Plan far into the future make it virtually certain that the plan will have to be re-evaluated periodically. Options that had been previously ruled out or not considered at all might become the only options available to achieve even some of the Restoration Plan's goals.

4

Reconsidering Available Storage Options

The planning framework, boundary conditions, and planning constraints that are found in the Restoration Plan are themselves the result of a process of adaptation to the interests and concerns of the myriad stakeholders in south Florida. The constraints and conditions that emerged during the initial stages of planning were necessary to allow the project to move forward. The committee is concerned, nevertheless, that at some future time circumstances may evolve in ways that will require reconsideration of these initial boundaries and constraints if the project is ultimately to be effective and successful.

A project the size of the Florida Everglades Restoration Project will be subjected to many surprises, some caused by exogenous forces and some the consequence of the project itself. As noted earlier, project planners will need to create adaptive plans that will allow considerable flexibility in responding to unanticipated change. There are two important lessons that should guide the efforts at adaptive planning. First, it seems obvious that there will be many changes that cannot be anticipated and that will have to be accommodated through adaptations with relatively short lead times. This means that it will be vitally important to deal with changes that can be anticipated in a timely and proactive way so as to minimize surprises and retain maximum flexibility to respond to change that cannot be anticipated. The progressive loss of soil in the Everglades Agricultural Area is an example of a change that can be anticipated and should be planned for promptly as the project develops. Second, in responding to change, it may be necessary to rethink and reconsider some of the boundaries and constraints that were part of the early planning and now characterize the planning framework.

Mayer (2001) provided a useful discussion of interactions among policies unrelated to the Everglades restoration, economics, and the choice of storage options in south Florida. It simply may not be possible to protect all of the existing interests and conditions or to proceed with the project while preserving certain hydrologic and social features of the landscape in south Florida that were initially thought to be worth preserving. One example is Lake Okeechobee. The intent of existing plans is to continue to manage Lake Okeechobee in accordance with the prevailing hydrologic performance indices that govern the lake level and thereby tend to protect the existing littoral zone. This will severely constrain the extent to which Lake Okeechobee might be used for storage. With time and change, it could turn out that the only way to complete the project as envisioned would be to use Lake Okeechobee for additional storage and possibly sacrifice, to some extent, the continued preservation of the current littoral zone.

This chapter focuses on these two lessons, illustrating the importance of anticipating change and reacting to it by using the full range of available options.

EVERGLADES AGRICULTURAL AREA

The Everglades Agricultural Area (EAA) immediately south of Lake Okeechobee is characterized by rich peat soils (histosols). The area is devoted primarily to the production of sugarcane with small acreages devoted to vegetables, rice, beef cattle, and sodgrass. The annual value of production in this area in the early 1990s totaled $640 million (Alvarez et al., 1994). It is known that the peat soils oxidize on contact with the atmosphere, and this oxidation has caused the land surface to subside as progressive increments of the peat itself were lost though the twentieth century. The ultimate demise of Everglades agriculture was first predicted over 50 years ago, but there has been a long controversy over the rates of oxidation and the exact time when there would be insufficient soil over the bedrock to permit agriculture to be practiced (Douglas, 1947; Stephens and Johnson, 1951). Moreover, some have argued that agriculture could be practiced on the remaining mineral soils on a long-term sustainable basis. Indeed, economic rather than strictly agronomic factors may affect the near-term fate (next 5-20 years) of agriculture production in the EAA. Much of the EAA is devoted to sugarcane production, which effectively is subsidized by import duties on foreign-grown sugar and shielded from Cuban sugar production by import restrictions that have been in place since the 1960s (e.g., Mayer, 2001). Those restrictions may well change if there are changes in the government of Cuba, its policies, or those of the U.S. government.

Another economic stimulus for removing EAA land from agricultural production is the continuing strong migration of people to south Florida, which shows no sign of abating. At some point in the perhaps not too distant future, agricultural interests may decide that some of their land is more valuable for development into retirement communities, golf courses, and related land uses than for agricultural production. If this were to happen, it would create additional problems for the Everglades restoration because it would impose continued demands for reliable water supplies and at the same time decrease the amount of land that could be used for water storage and also possibly make it more difficult to use adjoining lands for storage.

Aside from its potential use for construction of surface reservoirs, an EAA that no longer was used (in whole or part) for agricultural production also could be flooded and allowed to revert to its natural wetland condition. It would take many centuries for the wetland to accrete the amount of peat soil present before drainage and agriculture production began, but a semblance of a natural marsh system probably could be established rather quickly. This system would tend to act as a giant stormwater treatment area, removing nutrients as the water slowly moved south. As Odum and Odum (2003) pointed out, such an approach could reestablish the original pattern of "longitudinal succession" within the Lake Okeechobee-Everglades system─that is, nutrient-rich water from the lake would pass through a eutrophic slough south of the lake and lose nutrients by plant growth and peat accretion before entering the oligotrophic Everglades to the south.

CAN LAKE OKEECHOBEE PROVIDE MORE WATER STORAGE?

Often called the liquid heart of the Everglades, Lake Okeechobee is near the geographic center of the series of ecosystems constituting the Greater Everglades. Given the attention it has received and its actual and potential importance in the Everglades restoration, it is treated in some detail here.

In terms of surface area, Lake Okeechobee is the second largest freshwater body located wholly within the United States (Lake Michigan is the largest), but its volume is very small compared with any of the Great Lakes. It also has been the center of many controversies in recent decades concerning its function in the larger system and the most appropriate strategies for its management (e.g., Steinman et al., 2001; Havens, 2002; Bachmann et al., 2003). Historically, the lake served as the key hydrologic link between the mostly upland ecosystems in its large drainage basin mostly to the north and the sawgrass marshes and prairies of the Everglades proper to the south. Water storage provided by the large lake moderated the effects of variations in rainfall (wet-dry climatic cycles) on water levels in the Everglades. The lake also serves as a drinking water supply for several communities along the southern shore, and it is renowned as a sport fishery, especially for largemouth bass. The economic importance of the sport fishery is considerable.

This section describes the physical setting of Lake Okeechobee, its historical development, current uses, and limnology. We focus on the recent history of water-quality studies and management efforts to control the large lake's nutrient problems. Preliminary analyses conducted in the Restudy regarding the lake's potential to provide water storage are summarized, and issues are identified that should be considered in detail in a contingency-planning exercise to evaluate the advantages and disadvantages of relying more on Lake Okeechobee for water storage in the overall Everglades restoration program.

Brief History and Site Description

According to Brooks (1974), the earliest recorded name for the lake (by Solis de Mera in 1567) was "Mayaimi," a Caloosa Indian word meaning "big water." The present name, Okeechobee, is derived from a Seminole Indian composite of "oki" (water) and "chubi" (big) (Bloodworth, 1959 cited in Brooks, 1974).

Although Lake Okeechobee occupies a marine depression formed in the Pliocene by oceanic currents (Hutchinson, 1957), the modern lake itself is much younger, owing its existence to the accumulation of peat deposits along the southern rim of the depression. The peat deposits also underlie what is now the 310 mi^2 (~800 km^2) Everglades Agricultural Area south of Lake Okeechobee. The process of peat accumulation began about 6,300 years ago, probably as a response to climatic changes (increased rainfall) in south Florida (Gleason et al., 1974). The early lake encompassed a larger area than the present lake and included parts of the current Water Conservation Areas. According to Brooks (1974), the modern lake, with "an ever increasing elevation as the result of organic deposition along its southern rim began to develop just over 4,000 years ago," and the historic maximum level was reached only in the third century A.D.

Under pre-drainage conditions, the lake's boundaries were diffuse and spatially variable (depending on rainfall conditions). According to Parker (1974), at lake stages exceeding about 14.6 ft NVGD (National Vertical Geodetic Datum, essentially equivalent to mean sea level) outflow from the lake occurred as diffuse overflow across the peat sill into the Everglades along two large segments of the southern shore, but Leach et al. (1971) described outflow as occurring along "a narrow reach." Some diffuse outflow also occurred to the southwest to Lake Hicpochee, the headwaters of the Caloosahatchee River (Brooks, 1974). Overflow along the south shore became more general at a stage of about 18 ft NVGD, and "sizeable volumes of water moved slowly in flat, broad sloughs toward tidewater" (Parker et al., 1955, as quoted in Leach et al., 1971). However, except during "extremely wet" years, there was no direct surficial hydrologic connection of the lake to the Everglades (Leach et al., 1971).

The hydrology and morphometry of Lake Okeechobee and its drainage basin have been modified greatly over the past 125 years, and the current system bears little resemblance to conditions that existed when early explorers visited the region in the early and mid-nineteenth century (Tebeau, 1971, 1974). Modifications began in 1881 when Hamilton Disston dredged canals connecting a series of large lakes in the upper part of the Kissimmee River basin and enlarged a shallow outlet to Lake Hicpochee and the Caloosahatchee River on the southwest side of the lake (Brooks, 1974). Disston actually was not the first to construct drainage canals around the lake. Apparently, even the Caloosa Indians and their predecessors did so (Will, 1964).

A much more drastic modification of the Kissimmee drainage basin occurred in the 1960s, when the Kissimmee River was channelized by the U.S. Army Corps of Engineers, converting a 100-mile long, slow-moving, and highly meandering river with extensive riparian wetlands into a 50-mile long, nearly straight channel. Incorporation of five locks and dams in the waterway provided a constant depth for navigation. Channelization had dramatic effects on the drainage basin, river, and Lake Okeechobee. By accelerating the movement of runoff downstream, the new channel opened large areas of the watershed that previously were inaccessible to use for cattle grazing and other agricultural pursuits. The faster travel time of runoff through the system decreased its ability to retain nutrients, and the nearly straight, steep-sided channel provided much less habitat for wetland plants and animals than the original meandering river had.

Concern about negative environmental impacts of the channelization began even before the project was completed in 1973, and efforts began to restore the river by removing the new channel. The State of Florida initiated an Everglades restoration project in the mid-1980s that included a demonstration project to restore the Kissimmee. In 1990, Congress appropriated funds to the Corps of Engineers to pursue Kissimmee River restoration, and it authorized the dechannelization of the Kissimmee River in 1992. The restoration program is still under way. The original channelization project cost an estimated $30 million, and although the dechannelization project thus far has cost an estimated $300 million, it will not restore the entire river length. Because of encroachment of human settlements on the floodplain of the lower river (near its entrance into Lake Okeechobee), it was not considered feasible to restore the original channel below approximately 12 km upstream from the river mouth.

Because the landscape of southern Florida, including the area surrounding Lake Okeechobee, is very flat, the shoreline of the lake expanded and contracted considerably, depending on rainfall conditions. Consequently, construction of levees to constrain expansion of the lake began fairly early in the history of European settlement, which began on the southern end of the lake in the late nineteenth century. By the early 1920s, a series of low, muck levees that were constructed around the southern and southwestern shore of the lake eliminated sheet flow from the lake to the Everglades and facilitated farming operations in the rich muck soils just south of the lake. The levees were not sufficient to hold back the lake waters during large flooding events, however. Major hurricanes that moved through south Florida in 1926 and 1928 breached the levees, resulting in disastrous flooding and the loss of more than 2,000 lives (Will, 1964). The 1928 disaster was caused by a giant wind-induced, resonant tide, or seiche, that formed when the eye of a hurricane passed across the north end of Lake Okeechobee on September 16. The loss of life and extensive property damage prompted federal action that resulted in the construction of a large earthen dike around the southern side of the lake by the Corps of Engineers from 1930 to 1937. In 1960-64, the levee (called the Hoover dike) was extended around the entire lake and raised to a height of 25 feet above normal lake stage, which is 15 ft above mean sea level.

By early 1883, the natural flood channel toward the Caloosahatchee River had been widened to a shallow canal (Leach et al., 1971). Construction of major drainage canals began early in the twentieth century to allow more rapid release of water from the lake, and the period 1905-1921 saw the connections of the lake to the coast via the Hillsborough Canal, the North New River Canal, the West Palm Beach Canal, and the Miami Canal (Leach et al., 1971; Light and Dineen, 1994). The St. Lucie Canal was completed in 1924 and was the main controlled outlet for regulation of the lake until about 1946 (Leach et al., 1971). Most of these historical drainage features remain a part of the south Florida landscape. Following major flooding in south Florida in 1947, a series of drainage canals was constructed (1948-63) around the southeastern side of the lake. The Everglades Agricultural Area (EAA) was formed in 1948, and although it was not a part of Lake Okeechobee's natural watershed, it became so as pumps were installed to "back-pump" water draining from the EAA into the lake for storage purposes. A large low-head pumping station (designated S-2 by the SFWMD) was constructed in 1957 to connect the lake to the Hillsboro and North New River canals near Belle Glade. Because of concerns about detrimental effects of the nutrient-rich and generally low-quality agricultural drainage water on Lake Okeechobee, the South Florida Water Management District agreed in 1979 to cease the back-pumping practice except under extreme circumstances.

Completion of the levee, drainage canals, and water-control structures (including various pumping stations) changed Lake Okeechobee from a natural lake characterized by wide fluctuations in water levels and areal extent between wet and dry periods to a highly regulated reservoir with only minor changes in area except during major droughts. A lake-stage regulation schedule (see Figure 3-4) has been used to manage lake levels for decades. In general, the schedule provides for maximum lake stage in winter and lower stage during summer and fall to provide storage capacity for inflows associated with the summer rainy period and hurricane season.

The modern lake still has extensive areas with sandy bottom sediments, but a "mud zone" with organic-rich fine sediments covers most of the northeastern portion of the open lake. These sediments have elevated levels of phosphorus, and wind-induced resuspension of these sediments is a major factor in the internal loading (recycling) of phosphorus to the water column, which maintains the lake's eutrophic and somewhat degraded water quality. The mud-zone sediments generally are underlain by marl deposits (unconsolidated calcium carbonate formed within the lake). Localized areas of peat deposits are found on the southern edge of the lake, but they constitute only a small fraction of the lake area. A ridge of exposed limestone limits water exchange between the main body of the lake and the southern bays and littoral areas, especially when water levels are low. Extensive areas of emergent aquatic vegetation occur in a large littoral zone on the western side of the lake, and a large freshwater marsh occupies the southwest section. Littoral areas on the southern end of the lake have mixed areas of submergent and emergent vegetation, but the eastern and northeastern sides of the lake have very limited areas with littoral vegetation.

Water Quality of Lake Okeechobee

The first significant investigation on the chemical and biological characteristics of Lake Okeechobee was conducted by the U.S. Geological Survey in 1969 and 1970 (Joyner 1971, 1974), and an extensive and nearly continuous monitoring and research program has been conducted by the South Florida Water Management District on the lake and its tributaries since the early 1970s. The primary focus of this work has been on nutrient-related water-quality issues. Sufficient tributary monitoring data are available for more than twenty years of annual nutrient (phosphorus and nitrogen) budgets (e.g., Janus et al., 1990; James et al., 1995), and extensive lake monitoring data are available to characterize both temporal trends and spatial variability in nutrient concentrations and related water-quality conditions such as chlorophyll levels and water clarity (Secchi disk transparency) (Aumen, 1995). Other studies have focused on the important role of the lake's sediments as an internal source of phosphorus and suspended sediment to the water column (e.g., Maceina and Soballe, 1990; Reddy et al., 1993; Sheng, 1993; James et al., 1997; Brezonik and Pollman, 1999).

Nutrient-budget studies in the 1970s focused on contributions of specific source waters to the lake and showed that Taylor Creek and Nubbin Slough (Figure 2-5), which provide minor amounts of water to the lake, were substantial contributors of phosphorus. This was attributed to extensive dairy and cattle operations in these watersheds. Four sub-basins north of Lake Okeechobee, including the Taylor Creek-Nubbin Slough basin and three sub-basins in the lower Kissimmee River, still contribute about 35 percent of the current phosphorus loading to the lake although they comprise only about 450 square miles (~12 percent of the total contributing land area in the lake's watershed). The SFWMD recognizes them as priority basins for phosphorus management and has ongoing projects to develop and implement best management practices in the basins.

Back-pumping of water from the EAA also was found in early studies to be a major nutrient source, especially for nitrogen, and EAA discharge water also was found to be generally poor in quality—high in dissolved solids and colored natural organic matter from the peat soils (e.g., Brezonik and Federico, 1975). These studies led to a decision by the SFWMD in 1979 to stop the practice of pumping EAA discharges into the lake, and except during periods of extreme drought, such as occurred in 2001 (SFWMD, 2001), back-pumping of drainage water from areas south of the lake has not been practiced.

In spite of extensive efforts to limit or manage nutrient inputs to the lake from watershed sources over the past ~30 years, phosphorus concentrations in the lake actually appear to have increased since the early 1970s (Figure 5A in Havens and Walker, 2002). For example, annual average total phosphorus concentrations in the lake's pelagic (open-water) zone were in the range 50-60 mg m^{-2} yr^{-1} in the period 1973-1977, increased to approximately 80-90 mg m^{-2} yr^{-1} in the period 1979-1983, and varied between ~90 and 120 mg m^{-2} yr^{-1} over the period 1987 to 1999. Water clarity (as measured by Secchi disk transparency) similarly declined over this period—from an average of about 60 cm in the mid-1970s to about 40 cm in the late 1990s (Havens et al., 2003).

Nutrient loadings, especially phosphorus loadings, remain substantially higher than stated SFWMD goals. Annual phosphorus inputs have increased from about 230 mg m^{-2} yr^{-1} to 850 mg m^{-2} yr^{-1} from 1910 to the 1990s (Brezonik and Engstrom, 1998). The total phosphorus input into the lake is about 498 t per year (Walker, 2000). In contrast the proposed target loading is 140 t per year. The target load is based on a model prediction of the phosphorus loading needed to attain an average total phosphorus concentration in the lake's pelagic (open-water) zone of 40 mg m^{-2} yr^{-1} (Havens and Walker, 2002). The latter value is the proposed in-lake goal for phosphorus that was used in the total maximum daily load (TMDL) process for Lake Okeechobee (Havens and Walker, 2002).

Factors controlling primary production by algae and the composition of the phytoplankton community in Lake Okeechobee have received considerable attention over the past 30 years.

The former issue is complicated by the spatial and temporal variability of nutrient levels in this large lake; at different times and locations, either phosphorus or nitrogen may be the potentially limiting nutrient for planktonic primary production (e.g., Brezonik et al., 1979), but light conditions usually are the actual limiting factor (Phlips et al., 1997; Bachmann et al., 2003), especially in the open-water area, where wind-induced sediment resuspension is responsible for low water clarity (Maceina and Soballe, 1990). Secchi disk transparency in the open lake typically is in the range of 30 to 60 cm; as a rough approximation, the euphotic zone, which is defined as the depth at which light penetration is sufficient for primary production to just exceed respiration, is about twice the Secchi depth; this is thought to occur at ~1-2 percent of incident light. Low light availability also has been suggested as a regulator of cyanobacteria (blue-green algae) species in the lake (Havens et al., 1998) and low nitrogen:phosphorus ratios in the lake water also have been used to predict the recent dominance of cyanobacteria (Havens et al., 2003).

The complexity of factors influencing phytoplankton concentrations in the lake has led to substantial disputes about the merits of developing a TMDL for phosphorus to control algal blooms in the lake. Havens and Walker (2002) concluded that the TMDL goal of 40 micrograms per liter for long-term average total phosphorus concentration in the pelagic zone of the lake would reduce the frequency of near-shore algal blooms to 2-9 percent compared with 5-33 percent under present conditions. In contrast, Bachman et al. (2003) contended that a stringent TMDL for phosphorus would not result in improved water quality; they argued that the lake has been eutrophic for over a century and had a high phosphorus loading rate (~377 metric tons per year) even in presettlement times. Such a high rate seems unlikely, however, given pre-settlement hydrology and the major agricultural and other anthropogenic phosphorus sources known to be important in the drainage basin at present. The contention that the lake was eutrophic in pre-settlement times does not agree with the descriptions of some early explorers. For example, in 1887 Heilprin, as quoted by Brooks (1974), described the lake in the following way:

> It is frequently conceived, and often reported, that Lake Okeechobee is a vast swampy lagoon, or inundated mud-flat, the miasmatic emanations arising from which render access to it a matter of considerable risk or caution. This is very far from being its true character. The Lake [sic] proper is a clear expanse of water, apparently entirely free of mud shallows, and resting … on a firm bed of sand. All our soundings and drags indicate that this sand is almost wholly destitute of aluminous matter, and nowhere, except on the immediate borders, where there is a considerable outwash of decomposed and decomposing vegetable substances, is there a semblance to a muddy bottom. The water itself, when not disturbed, is fairly clear, and practically agreeable…More generally, however, it is tossed into majestic bellows, which rake up the bottom, and bring to the surface a considerable infusion of sand, rendering the surface murky.

In addition, paleolimnological evidence based on lead-210 (^{210}Pb) dated sediment cores from eleven sites in the mud zone of the lake indicates that annual phosphorus accumulation rates in the lake's sediments have increased about fourfold since pre-settlement times, with most of the increase occurring in the past 50 years (Brezonik and Engstrom, 1998). Although difficulties were encountered in interpreting ^{210}Pb dating of cores from some locations (probably because of sediment resuspension problems), reliable dates were obtained from most sites. These studies also suggested that the lake had very low rates of accumulation of organic-rich muck sediments in pre-drainage, pre-settlement times.

Bachmann et al. (2003) proposed that water-level controls would be more effective in managing phosphorus levels (and associated algal blooms) in the lake. This is roughly in agreement with the Restoration Plan's proposed management plan for the lake (USACE and SFWMD, 2001; Havens, 2002) and is based on the findings of several earlier studies (Maceina, 1993; Havens 1997) of an association between higher water levels and higher total phosphorus concentrations in the lake. High water levels also facilitate the movement of suspended particles (and associated particle-bound phosphorus) from the mud zone in the central part of the lake to nearshore areas, especially in the south end of the lake, where a submerged limestone ridge at ~8 ft (NVDG) inhibits movement of water from the center of the lake to the southern bays at low lake stage but is ineffective at blocking large-scale circulation patterns at higher stages.

Restoration Alternatives for Lake Okeechobee

As the above description indicates, Lake Okeechobee is not just a potential water storage site for the Everglades; it is a key, albeit degraded, component of the Greater Everglades system, and it serves as an important drinking-water supply and recreational resource. It was identified as a system component to be restored by the Restoration Plan. Several parts of the comprehensive plan are focused on improving water quality in the lake. For example, the Kissimmee basin storage reservoir described in Chapter 2 is intended both to store water and to reduce nutrient loads to the lower Kissimmee River and Lake Okeechobee. This component will consist of a 17,500-acre above-ground storage reservoir and associated 2,500-acre stormwater treatment area (STA) in one of three counties north of Lake Okeechobee. A 5,000-acre reservoir and associated 5,000-acre STA in the Taylor Creek-Nubbin Slough area northeast of Lake Okeechobee is intended to serve the same purposes. The storage capacity of these two reservoirs (in sum about 250,000 acre-feet) essentially substitutes for storage that could be obtained by allowing a higher stage in Lake Okeechobee during wet periods. An increase in the maximum allowable lake stage of 0.5 feet would provide 227,500 acre-feet of additional storage (Table 4-1), over 90 percent of the storage of the two proposed reservoirs.

An increase in the maximum stage of Lake Okeechobee of 0.5 feet also would provide additional storage equivalent to about 82 percent of the total storage provided by the proposed Lake Belt. The actual stage of Lake Okeechobee reached the maximum allowable stage only a few times over the period 1931-2003.

Several additional Restoration Plan components to improve water quality in Lake Okeechobee are described in the Lake Okeechobee Surface Water Improvement Management Plan (SFWMD, 1997b). They include: (i) additional STAs on the north side of the lake; (ii) a plan to plug selected local drainage ditches, the net effect of which will be to restore about 3,000 acres of wetlands in the Okeechobee watershed; (iii) diversion of some drainage canals into wetlands; and (iv) dredging of phosphorus-rich sediment from 10 miles of primary canals in the watershed of the lake. However, despite concerns expressed by limnologists about the increasing importance of internal phosphorus loading by wind-induced resuspension of flocculent, phosphorus-rich, bottom sediments in maintaining high nutrient and algal conditions in the lake, no Restoration Plan components are designed to address this problem directly, and the plan does not include any in-lake restoration activities.

Table 4-1 Relationship of Storage in Lake Okeechobee to Maximum Stage*

Increase in Maximum Allowable Stage (ft.)	New Maximum State (ft) [NVGD]	Additional Storage (acre feet)	Additional Storage 10^8 m^3
0.5	19.0	227,500	3.23
1.0	19.5	462,500	6.57
1.5	20.0	697,500	9.90

* A description of the regulation of Lake Okeechobee, including the provision of a maximum allowable, are provided in Chapter 2. A more detailed description can be found at *http://www.sfwmd.gov/org/pld/hsm/reg_app/lok_reg/*.

The Lake Okeechobee Surface Water Improvement Management Plan eschews a more prominent role for the lake in storing water for export to the Everglades during droughts because SFWMD limnologists believe that maintaining high water levels in the lake for extended periods would be detrimental to littoral plant communities primarily on the lake's west side and also would cause poorer water quality (higher levels of turbidity and algae concentrations) in the open waters of the lake. Field data on the lake for periods of widely varying water levels during the 1990s (e.g., Maceina, 1993; Havens, 1997, 2002) support these conclusions. Nonetheless, the general argument and cited field observations that lower water levels are better for Lake Okeechobee appear at first to be contrary to a long-held limnological belief that deeper lakes tend to have better water quality because wind-induced sediment resuspension becomes less important as the depth of the water column increases. Also, a lake with a deeper mixed layer may have the same biomass of algae as a shallower lake, but in the deeper lake, the algae are suspended in a larger volume of water such that the *concentration* of algae is lower. However, when water levels in Lake Okeechobee are low, a submerged ridge along the southern edge of its central basin tends to interrupt circulation from the center of the lake, where fine sediments can be resuspended in windy conditions. It is possible that if the lake were regulated at levels several feet higher than it is at present, and if effective nutrient controls to the lake could be implemented, then poor water quality associated with higher lake levels would not be problematic.

Although higher water levels may diminish the width of the littoral zone of emergent vegetation in the northwestern area of the lake, higher water levels actually may enhance the littoral zone in the southwest part of the lake. Under current operating conditions, the large expanse of marsh south of the mouth of Fisheating Creek and northwest of the city of Moore Haven on the lake's southwest shore is very shallow and much of it cannot be traversed by boats because of insufficient water depths and dense vegetation. If maximum water levels in the lake were allowed to increase modestly (e.g., by 1-3 feet), it is likely that this large area would become more lake-like, but still littoral rather than pelagic, and less like a separate, nearly impenetrable marsh.

A recent study (Smith et al., 2004) found that low water levels (< 13-14 ft, NGVD) promote the spread of a nonnative invasive terrestrial species of grass, torpedograss (*Panicum repens*), in marshy areas of the lake where depths are less than 50 cm (1.6 ft). This exotic species has displaced more than 6,000 ha (15,000 acres) of native plants, including spikerush, and open-water habitat since it was introduced to the lake in the 1970s. (Although the plant is considered a terrestrial species, once established, it can grow in water depths of 75 cm or less, and it can survive extended periods at water depths up to 1 m.)

Given the above comments and the possibility that other storage options (e.g., ASR) may not provide the amounts of water needed to fulfill the restoration plan, the committee judges that it would be prudent to revisit the question of whether Lake Okeechobee can provide some of the sought-for water storage. A wide range of options exist. Some of them, including options explored early in the Restudy, would have extreme effects on lake levels and would diminish the value of the lake as an ecological resource and probably as a sport fishery. These options likely would be opposed by a wide range of stakeholder groups, including the sport-fishing community and environmentalists. The lake is widely considered to be a valuable aquatic resource, even in its somewhat degraded condition, and proposals that would relegate the lake primarily to use as a water-storage device are likely to be controversial. For this reason especially, any reconsideration of Lake Okeechobee's role in storage would need to include careful consideration of socioeconomic and ecological factors, including short- and long-term financial costs.

One of the more extreme options involved splitting the lake into two sections with a large dike. One section would include the littoral zones on the west side of the lake, in which water levels would be maintained within a range that would promote a healthy littoral plant community. The other section would include most of the open water portions of the lake on the east side, and water levels would be allowed to fluctuate to rather extreme highs and lows. A second option considered in early Restudy modeling runs allowed the entire lake to be used for water storage, and although the runs demonstrated that maximal use of storage in Lake Okeechobee would be "cost effective and hydrologically efficient" (USACE and SFWMD, 1999), they produced extreme fluctuations in lake levels, which likely would adversely affect the lake ecosystem. More modest fluctuations in water levels, including relatively small increases in maximum lake stage, apparently were not explored in these runs.

Smaller fluctuations and smaller increases in maximum stage of Lake Okeechobee obviously would not provide the total amount of storage that the unaltered system of the nineteenth century had and that may be required to offset the loss of another major storage component, such as ASR, should it prove infeasible. Nonetheless, moderate changes in lake stage could contribute substantially to system storage. As noted previously, an increase in maximum lake stage of only 0.5 ft would provide a water storage volume nearly equal to that of the two reservoirs (total of 22,500 acres plus an additional 7,500 acres devoted to STAs) proposed to be constructed north of Lake Okeechobee (see Chapter 2). Such changes may have only small negative effects on lake quality in the long term, especially once the problem of excessive nutrient loading to the lake is finally solved, and it may even lead to positive changes, such as a larger open-water habitat and a more accessible littoral zone on the southwest side of the lake. Thus, there is the potential to provide ecological benefits earlier in the process. Other storage options, including the proposed storage reservoirs north of Lake Okeechobee, have their own environmental costs. Any such changes should be undertaken using adaptive management to maximize learning opportunities.

5

Evaluating Ecological Tradeoffs

INTRODUCTION

The primary strategy for restoring the Everglades ecosystem is the restoration, to the extent possible, of the hydrologic regime. However, the ultimate goal is restoration of the Greater Everglades Ecosystem while meeting society's needs for flood control and water supply. Earlier in this report and in previous reports of this committee (e.g., NRC, 2003b), we have discussed the importance of evaluating the restoration effort; the NRC (2003b) also recommended that conflicts among ecological restoration targets should be identified and that system-wide indicators be developed. These issues have been a major focus of the Restoration Plan scientists as well. Major difficulties are associated with such evaluations. One is translating the general ecological and societal goals espoused in the Central and South Florida Restudy into realistic targets and practical performance measures (NRC, 2003b). Another difficulty is that restoration of one aspect of ecosystem functioning or of biological diversity might have to come at the expense of another. Furthermore, not all aspects of ecosystem structure and functioning are equally valued by all sectors of the public or even by all agencies in the region.

In addition, three major components of the Restoration Plan—aquifer storage and recovery (ASR), Lake Belt storage, and water reuse—have major uncertainties that still need to be resolved through pilot studies. For example, their efficiencies might be lower than assumed, their costs might be higher, or water-quality issues might be problematic.

All the above factors make it imperative that there be a quantitative framework for evaluating possible modifications to the plan as needed. Even if the general goals remain unchanged (and they might not), the restoration strategies and targets will need to be revisited and alternative management scenarios judged in the light of new information. Decision-makers and interest groups will probably prefer different alternatives based on how they view the tradeoffs among goals for subsets of the ecosystem and among desired endpoints. Experience suggests that a structured decision process that synthesizes information, reflects these tradeoffs, and accounts for different stakeholder preferences can promote constructive analysis and negotiation (e.g., Clemen, 1991; Ridgely and Rijsberman, 1992; NRC, 1996b; Prato, 2003; Brown et al., 2001) and thus help to operationalize adaptive management. To this end, the committee has considered multiattribute (or multicriterion) approaches to decision making. It proposes the use of a system performance measure that could be used together with specific indicators and performance measures already in place to help to evaluate restoration progress and alternatives, including re-evaluation and refinement of restoration goals.

The proposed system performance indicator does not in itself lead to decisions; instead, it allows alternative scenarios or outcomes to be evaluated. To make decisions, it will be necessary to weight various outcomes and aspects of ecosystem structure and functioning. A recent NRC committee described these considerations in identifying options for protecting Atlantic salmon in Maine (NRC, 2004a). It described the need for "differences in perspectives [to be] taken into account so that the decision is informed by the views of all parties having legitimate interests in the outcome." Like that earlier NRC committee, this committee cannot perform such weighting, because value judgments are involved, as well as scientific estimates. The best that can be attained is a clear description of a weighting algorithm so that policy makers and stakeholders in the Everglades restoration can do the hard work of agreeing on the weights to be assigned.

Characteristics of a System Performance Measure

In an ideal world, a system performance measure for evaluating alternative Everglades restoration plans would be a single measure of the degree to which a given plan meets the Restoration Plan objectives—water supply and flood control for the built environment, and ecosystem restoration. Such a system measure would need to quantify performance in a way that is consistent with societal preferences. This would mean specifying relative societal preferences both within and across the main categories of water supply, flood control, and ecosystem restoration. How does society value water supply for agriculture versus water supply for municipalities? Restoration of the ridge and slough landscape versus restoration of the marl prairie? Water supply versus flood control? Flood control versus ecosystem restoration?

Obviously, there are many conceptual and practical difficulties in developing an "ideal" system performance measure for Everglades restoration. Some of these difficulties can be avoided by excluding consideration of the built environment and measuring only the degree to which a given restoration plan meets the Restoration Plan ecosystem restoration objectives. To a large extent, Restoration Plan objectives pertaining to the built environment are legally mandated and cannot be compromised without changing the law. (Of course, laws can be changed; an overall ecological performance measure for the Restoration Plan could be used in an analysis to evaluate the degree to which current built environment mandates limit restoration success.)

The Everglades ecosystem consists of several identified, distinct components, such as marl prairie and ridge and slough terrain. Estimation of a system measure of the degree to which a particular restoration plan meets Restoration Plan objectives requires the ability to estimate how the value of a particular ecosystem component is affected by the restoration plan, as well as assignment of relative value to all identified ecosystem components. This clearly means that a system restoration performance measure must be based on restoration outcomes that can be both modeled and valued. Modeling of the Everglades is highly advanced, with respect to both hydrologic and ecosystem processes, although the latter are much more difficult to quantify. In the next section we develop a conceptual system performance measure that focuses on restoration of individual components of the Everglades ecosystem.

A Conceptual System Performance Measure

To help in its goal of restoring the hydrologic regime of the Everglades, the South Florida Water Management Model provides a quantitative tool for predicting how various restoration strategies would modify the hydrologic regime. For these reasons we base our conceptual system performance measure on hydrologic performance measures. The current set of hydrologic performance measures could be used for this purpose, although it might be desirable to modify this set. The restoration of each particular ecosystem component will depend on one or more hydrologic performance measures (i.e., system attributes). This dependence can be expressed mathematically as (in the lexicon of economics) a *utility function* that relates the numerical value of a performance measure to society's degree of satisfaction with the restoration. A separate utility function is developed for each performance measure and an overall degree of utility is then calculated by weighting and then combining utility scores.

A review of the extensive literature on methods for deriving weights and combining utility scores is beyond our scope here. Multiattribute decision-making frameworks, however, are increasingly used in ecosystem management and are appealing for their simplicity, abiltity to engage stakeholders, and their flexibility in handling nonmarket values that have challenged more traditional cost-benefit approaches (e.g., Prato, 1999). One measure of overall restoration utility is the weighted sum of such individual utility functions, a widely used formulation (Keeney, 1982; Poyhonen and Hamalainen, 2001). The functions account for the degree to which each ecosystem component is restored as a result of a hydrologic regime corresponding to the hydrologic performance measures. The weights account for the value given to each restoration component relative to other components. Hence the overall restoration hydrologic performance measure estimates the relative value of the restoration associated with alternative restoration plans. This concept is presented more formally below.

Measuring System Restoration Performance

Assume there are "n" ecosystem components and a set of hydrologic performance measures. Let $\underline{X}_0$ be the vector of all the hydrologic performance measures under pre-restoration conditions. Let $\underline{X}_T$ be the vector of the values of all the target hydrologic performance measures. For the restoration alternative j, let $\underline{X}_j$ be the corresponding vector of values of all the hydrologic performance measures. The vectors X_0, X_T, and X_j, can be obtained from simulations of the South Florida Water Management Model. Let $f_i(\underline{X}_j)$ be a multivariate function representing the expected fractional restoration of the ecosystem i under restoration alternative j. (Note that f_i will be insensitive to hydrologic performance measures that do not relate to ecosystem i.) Also, for all i, $f_i(\underline{X}_0) = 0$ and $f_i(\underline{X}_T) = 1$. In general, $f_i(\underline{X}_j)$ would be expected to vary between zero and one, although it would be possible to evaluate restoration plans that would degrade one or more ecosystem components relative to pre-restoration conditions (in which case $f_i(\underline{X}_j)$ would be less than one), or that would restore one or more components to conditions that exceed the target conditions ($f_i(\underline{X}_j) > 1$). Also, the value represented by 1 might change with the advent of new knowledge.

Let w_i be a number between zero and one representing the imputed value of ecosystem i relative to the imputed value of the most-highly valued ecosystem, where the sum of all w_i equals one. Then the system performance measure (SPM) associated with a particular restoration configuration on a set of independent hydrologic performance measures is given by

$$SPM_j = \sum_{i=1}^{n} w_i f_i(\underline{x}_j)$$

We recommend that in the initial uses of the proposed indicator, all of the weights be equal, in which case $w_i = 1/n$ for all i. If all weights are chosen equal,

$$SPM_j = 1/n \sum_{i=1}^{n} f_i(\underline{x}_j)$$

Clearly, specification of the f_i's would present the greatest challenge to the implementation of this measure. The existing ecological models would provide a scientific basis defining these functions, but some degree of subjective judgment also would be required. The Habitat Suitability Indices recently developed by the South Florida Water Management District would provide an excellent starting point. Another concern is whether the different performance measures are fully substitutable for each other, as is implied by additive weighting.

Application of Proposed System Performance Measure

A system restoration performance measure like the one described above is intended to complement rather than substitute for other evaluation tools already in place (e.g., ecological assessment models like ATLSS). Its main value would be in the context of an inclusive and explicit group-process for evaluating policy and management tradeoffs and alternatives (e.g., Ridgley and Rijsberman, 1992; Prato, 2003). As such the system performance measure could be used as a tool for re-examining restoration targets, for comparing the relative contributions of different components of the Restoration Plan to overall restoration progress, and for examining the sensitivity of measured restoration progress to differences in weights assigned by different stakeholders.

For example, during the screening studies preceding the Restoration Plan it was demonstrated that manipulations of water level in a partitioned or whole Lake Okeechobee would provide a cost-effective alternative to ASR. However, this strategy was not considered because it prevented restoration of the Lake Okeechobee littoral zone. An overall restoration performance measure would allow for a more formal examination of the balance between restoration benefits in the Lake Okeechobee ecosystem against other restoration benefits.

Simple Hypothetical Example of the Use of a System Performance Indicator

Consider two ecosystems that must share water provided by a restoration project. Assume that there is only one hydrologic performance measure for each ecosystem, the average annual flow to that ecosystem. Let x_1 and x_2 be the respective flows and let x_{1T} and x_{2T} be the respective target flows required for full restoration. Assume that $x_{1T} = x_{2T} = Q^*/2$, where Q^* is the total flow required for full restoration. Assume that the two ecosystems are equally valued, and hence $w_1 = w_2 = 0.5$.

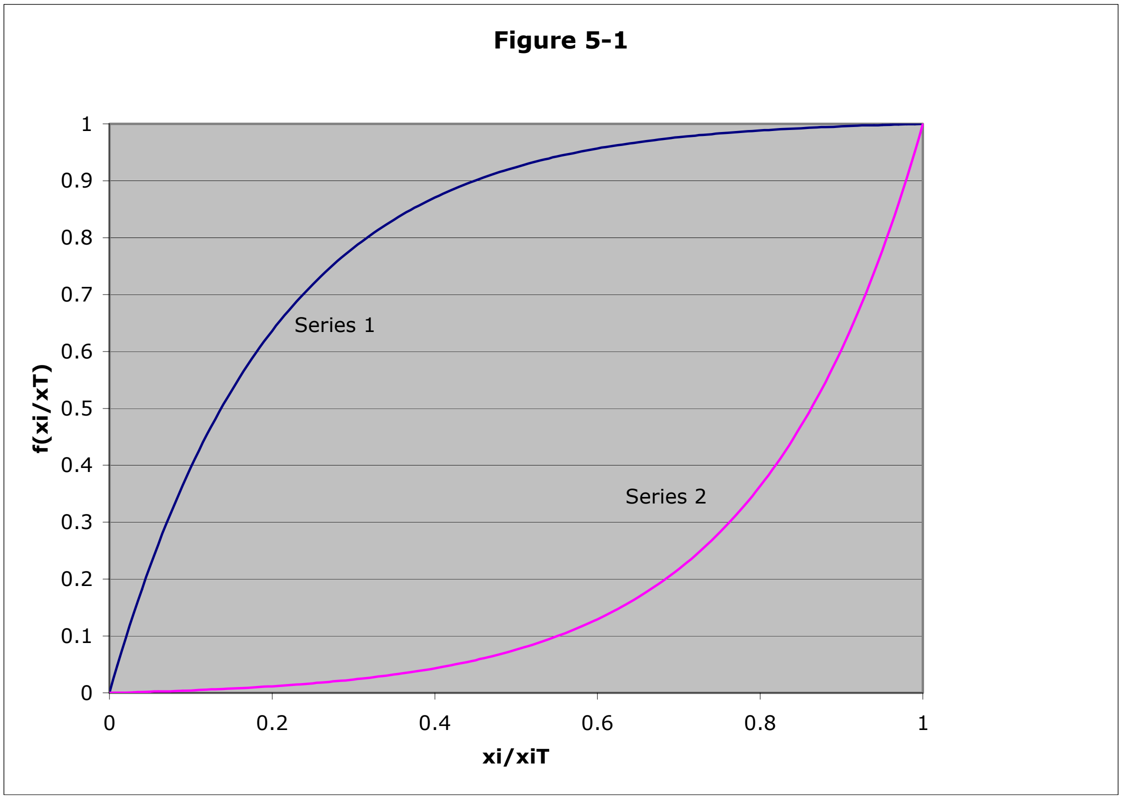


FIGURE 5-1.

Let $f_1(x_1/x_{1T})$ and $f_2(x_1/x_{1T})$ be functions quantifying fractional restoration as a function of the ratio of average annual flow to the target flow. Assume that these functions are given in Figure 5-1 above.

If the targets are met for each ecosystem, the value of the system performance measure is given by

$$
\begin{aligned}
\text{SPM} &= w_1\, f_1(x_1/x_{1T}) + w_2\, f_2(x_1/x_{1T}) \\
&= (0.5)(1) + (0.5)(1) \\
&= 1
\end{aligned}
$$

Consider the case for which the available water supply, Q, is less than Q*. If water is allocated to optimize the SPM, the values of $f_1(x_1/x_{1T})$ and $f_2(x_1/x_{1T})$ must be equal, given that the ecosystems are assumed to have equal value ($w_1 = w_2$). From Figure 5-1 it is clear that this will require that ecosystem 1 be allocated much less water, as it is much less sensitive to the supply of water. Figure 5-2 illustrates the amount of water that must be allocated to each ecosystem to maximize the SPM, for various values of Q/Q*.

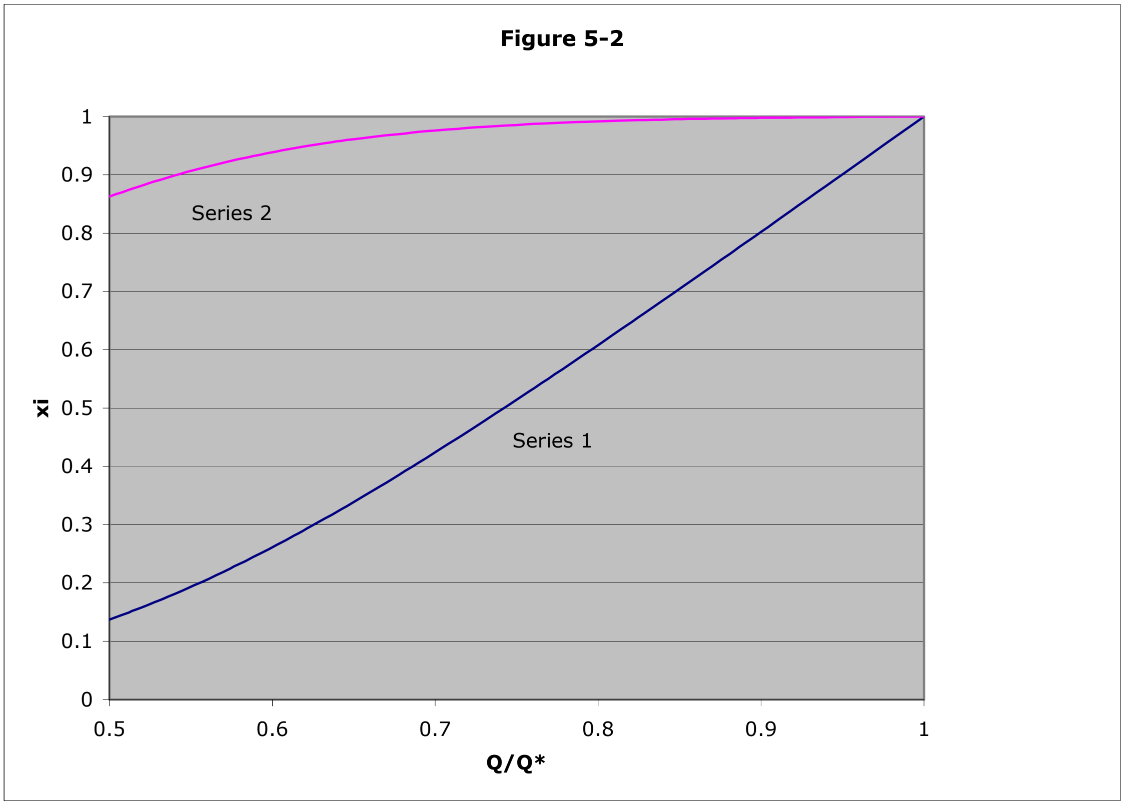


Figure 5-2. Illustration of the amount of water that must be allocated to each ecosystem to maximize the SPM, for various values of Q/Q*.

As an example, consider Q/Q* = 0.8.

Based on Figure 5-2, the optimal SPM is attained for $x_1/x_{1T} = 0.61$ and $x_2/x_{2T} = 0.99$. From Figure 5-1 it can be seen that the fractional restorations at these ratios are each 0.96. Hence the optimal SPM is 0.96.

Assume that for the case of Q/Q* = 0.8, water is instead allocated equally to ecosystems 1 and 2, that is, $x_1/x_{1T} = x_2/x_{2T} = 0.8$. From Figure 5-1 we see that

$$f_1(x_1/x_{1T}) = 0.988$$

$$f_2(x_1/x_{1T}) = 0.364$$

The resulting SPM is

$$\begin{aligned} \text{SPM} &= w_1\, f_1(x_1/x_{1T}) + w_2\, f_2(x_1/x_{1T}) \\ &= (0.5)(.988) + (0.5)(.364) \\ &= 0.64 \end{aligned}$$

This SPM is much lower than the optimal value of 0.96, indicating a very inefficient allocation of water. However, this allocation is optimal if $w_1 = 0.955$ and $w_1 = 0.45$, since for this set of weights

$$\begin{aligned} \text{SPM} &= (0.955)(.988) + (0.045)(.364) \\ &= .96 \end{aligned}$$

For every allocation of water there is a set of weights that makes that allocation optimal, and the weights are equal for only one of these allocations. In general, a restoration involving more than one ecosystem will likely involve unequal preferences unless an attempt is made to equalize preferences.

6

Findings and Recommendations

The restoration effort is associated with ecological and engineering uncertainties of several kinds that make unanticipated outcomes highly likely. Especially problematic is the potential for irreversible changes to the ecosystem to occur long before all phases of the Restoration Plan are implemented. Such changes include further expansion of invasive and irruptive plant and animal species, further erosion of the distinctive ridge and slough topography that once characterized large portions of the Everglades, continued loss of tree islands, disappearance of the communities of marl prairies and periphyton mats unique to the Everglades, loss of endangered species, expansion of areas with nutrient loading rates above historic levels, and expansion of areas with high mercury methylation rates. The overall effect of these changes will be homogenization of the landscape in which the mosaic of different community types that constitute the Everglades will be compromised. It is this mosaic that allowed the system to adjust to both short- and long-term changes in hydrology and periodic fires.

While it is clear that such irreversible changes could occur through processes already set in motion by previous alterations to the system, considerable uncertainty surrounds the relationship between implementation of the Restoration Plan and the rates at which specific changes to the ecosystem will occur. Of central concern are uncertainties in the relationships between hydrologic targets and ecological targets. In addition, regional changes in temperature and in the amount and variability of precipitation—factors that drive hydrology and fire regimes in the Everglades—will occur within the time-frame of the restoration and introduce greater uncertainty into the models under which the Restoration Plan will be implemented. The rise in mean sea level predicted to occur with climate change will have profound effects on the Everglades and much of south Florida. There also are uncertainties associated with the efficacy and costs of the various storage options, especially ASR, lake-belt storage, and wastewater reuse.

All these uncertainties emphasize the need for contingency planning, analysis of trade-offs, carefully designed pilot studies, and flexibility in implementing the program (adaptive management). More specific major findings and recommendations follow. Additional suggestions are in the individual chapters.

- **Finding 1.** The historic resilience of the ecosystem was a direct consequence of the continuity and the diverse mosaic of natural system communities found over a wide range of spatial scales. As the spatial extent of the ecosystem is reduced, the resiliency of the system is reduced and susceptibility to unexpected and irreversible change is increased. Although a considerable amount of money ($100-200 million annually) is allocated to land acquisition, it seems certain that some land not soon acquired will be developed or become significantly more expensive before the two-decade acquisition program can be completed. Protecting the potential for restoration, i.e., protecting the land, is essential for successful restoration.

- **Recommendation 1.** Preservation of the remaining areal extent of the potential natural system should be a priority. Land should be purchased or conservation easements should be obtained now to prevent additional loss of land to development and to provide a buffer between the built and natural environments. (Chapter 3.)

- **Finding 2.** A restoration as ambitious and complex as the Everglades Restoration Plan has the potential to allow—and perhaps even cause—irreversible changes to the Everglades ecosystem as it proceeds. Some processes of deterioration might continue to an undesirable endpoint before the restoration is complete, and in some cases, it is possible that an intermediate stage between current conditions and the restoration goal could result in additional damage.

- **Recommendation 2.** Efforts should be made to prevent irreparable damage to the ecosystem during the restoration. The focus should be on interim changes in the system as well as the end point of the restoration to avoid losses in the short-term that will prevent ecosystem restoration in the long term. (Chapter 3.)

- **Finding 3.** Some aspects of the restoration are likely to benefit the target ecosystem components while adversely affecting others, at least until the restoration is completed. In other cases, finite resources and other factors are likely to lead to differing restoration goals for different parts of the ecosystem and among different stakeholders.

- **Recommendation 3.** Methods should be developed to allow tradeoffs to be assessed over broad spatial and long temporal scales, especially for the entire ecosystem. Development of methods now, such as the system performance indicator described in Chapter 5, will allow alternatives to be tested quickly and modifications to the restoration to be developed when surprises do occur. (Chapters 3, 4, and 5.)

- **Finding 4.** It is likely that some components of the Restoration Plan will be more costly or less effective than envisioned. The high degree of uncertainty associated with all phases (economic, social, political, engineering, and ecological) of the Restoration Plan necessitates the allocation of significant effort to establishment of alternative approaches to restoration (contingency planning). Even if the Restoration Plan "gets the water right," there are circumstances that might prevent restoration of the Everglades to the conditions envisioned by the plan. The multi-species recovery plan, efforts to eradicate invasive species, changes in water-quality legislation, and many other factors may have major influences on the restoration effort.

- **Recommendation 4**. In addition to the contingency planning that already is being undertaken, more intensive and extensive planning should be pursued. In particular, options such as those discussed in Chapter 4 should be considered for using the Everglades Agricultural Area and Lake Okeechobee as elements of the Restoration Plan in ways that are not now part of the plan. Any such change in the use of EAA and Lake Okeechobee should be undertaken using adaptive management, and it has the potential to bring ecological benefits earlier. (Chapter 4.)

- **Finding 5.** A variety of economic, political, financial, engineering, and other factors and constraints have resulted in a restoration plan that provides most of its ecological benefits towards the end of the process. Some of that delay is unavoidable, because some engineering structures must be in place before other elements of the plan can be implemented. However, the longer the provision of such benefits is delayed, the more likely that continued degradation will occur, that loss of species and habitats will continue, and that at least some political support will be lost as well. These factors argue for increased emphasis on ecological results earlier in the plan.

- **Recommendation 5.** Restoration projects should be implemented in a way that provides benefits to the natural system sooner rather than later by accelerating storage projects that are not as reliant on technology or use short-term storage solutions to achieve benefits to the natural system until more technologically advanced methods are proven. An example of such a benefit to the natural system would be providing more natural flows (in terms of seasonal timing, volume, and flow velocity) to Everglades National Park. Doing so might not require large-scale changes in sequencing; instead, incremental changes could add up to be significant. Immediate action should be taken to identify interim ecological goals for the restoration that can be achieved in the near-term. Interim ecological goals should include preventing changes to the system that may be irreversible in a 50-100 year time frame. Of particular concern are losses of endangered species, expansion of the zones of increased nutrient loading that have shifted parts of the Everglades from oligotrophic to eutrophic systems with associated reductions in species distributions and losses of habitats, and degradation of the underlying topography that has supported the development of the rich mosaic of communities and habitats that is the essence of the Everglades system and maintains its overall resilience in the face of its natural hydrologic variability. (Chapter 3.)

- **Finding 6.** Many projects that will contribute to or otherwise affect the restoration of the Everglades are not part of the Restoration Plan. To the degree that there is coordination or at least communication among those projects, benefits of economy and of effectiveness are likely.

- **Recommendation 6.** Coordination and communication among the various restoration efforts should continue to receive high priority. (Chapter 3.)

- **Finding 7.** Considering the 40-year time frame of the Restoration Plan and perhaps a century of system response, a regional information synthesis center would enable the systematic provision of evolving, reliable knowledge in support of the policy process and the interested public who affect and are affected by the program. Such a center also would help implement adaptive management on a system wide basis.

- **Recommendation 7.** Incorporate integrated assessment models, long-range-development scenarios, and a regional information-synthesis center into an adaptive-management and assessment program in the Restoration Plan. Monitoring is an essential part of adaptive management, and models have the potential to help design, assess, and evaluate the results of monitoring programs. (Chapter 3.)

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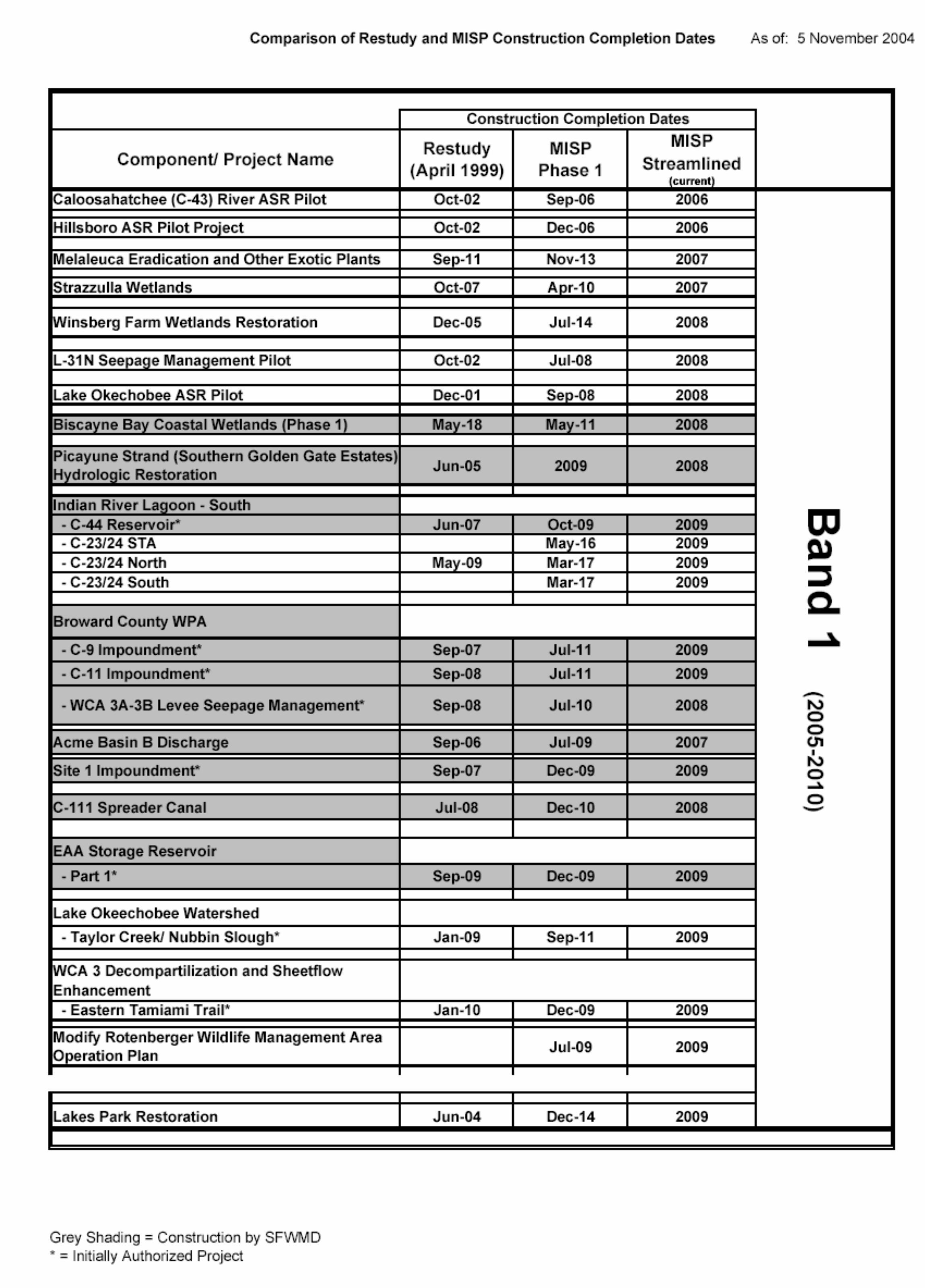
Appendix A

Master Implementation Sequencing Plan Compared to Initial Restudy Schedule

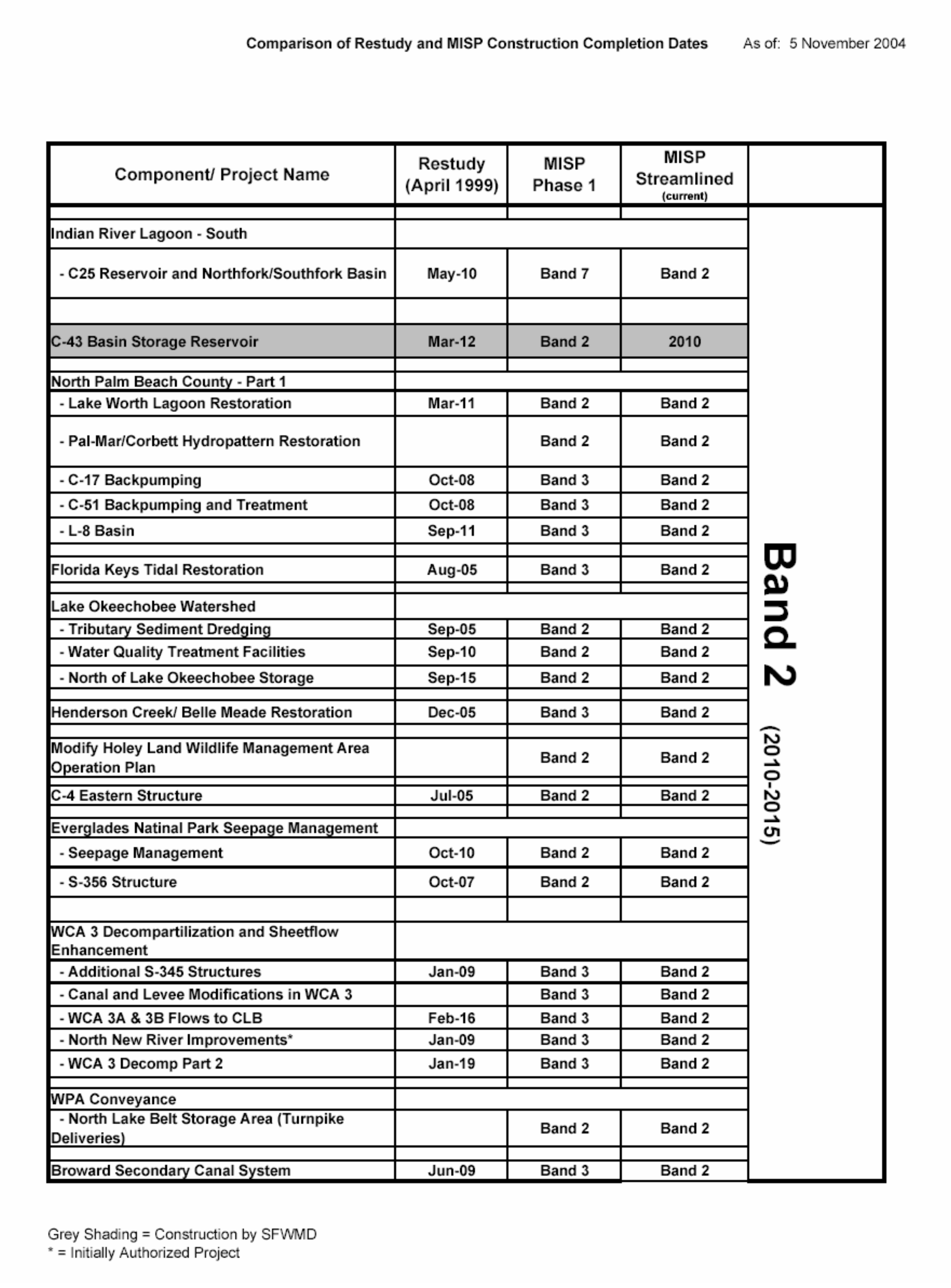
Source: Everglades Restoration web site. Available online at *http://www.evergladesplan.org/pm/misp.cfm*



Comparison of Restudy and MISP Construction Completion Dates As of: 5 November 2004

	Construction Completion Dates			
Component/ Project Name	**Restudy (April 1999)**	**MISP Phase 1**	**MISP Streamlined (current)**	
Caloosahatchee (C-43) River ASR Pilot	Oct-02	Sep-06	2006	**Band 1** (2005-2010)
Hillsboro ASR Pilot Project	Oct-02	Dec-06	2006	
Melaleuca Eradication and Other Exotic Plants	Sep-11	Nov-13	2007	
Strazzulla Wetlands	Oct-07	Apr-10	2007	
Winsberg Farm Wetlands Restoration	Dec-05	Jul-14	2008	
L-31N Seepage Management Pilot	Oct-02	Jul-08	2008	
Lake Okechobee ASR Pilot	Dec-01	Sep-08	2008	
Biscayne Bay Coastal Wetlands (Phase 1)	May-18	May-11	2008	
Picayune Strand (Southern Golden Gate Estates) Hydrologic Restoration	Jun-05	2009	2008	
Indian River Lagoon - South				
- C-44 Reservoir*	Jun-07	Oct-09	2009	
- C-23/24 STA		May-16	2009	
- C-23/24 North	May-09	Mar-17	2009	
- C-23/24 South		Mar-17	2009	
Broward County WPA				
- C-9 Impoundment*	Sep-07	Jul-11	2009	
- C-11 Impoundment*	Sep-08	Jul-11	2009	
- WCA 3A-3B Levee Seepage Management*	Sep-08	Jul-10	2008	
Acme Basin B Discharge	Sep-06	Jul-09	2007	
Site 1 Impoundment*	Sep-07	Dec-09	2009	
C-111 Spreader Canal	Jul-08	Dec-10	2008	
EAA Storage Reservoir				
- Part 1*	Sep-09	Dec-09	2009	
Lake Okeechobee Watershed				
- Taylor Creek/ Nubbin Slough*	Jan-09	Sep-11	2009	
WCA 3 Decompartilization and Sheetflow Enhancement				
- Eastern Tamiami Trail*	Jan-10	Dec-09	2009	
Modify Rotenberger Wildlife Management Area Operation Plan		Jul-09	2009	
Lakes Park Restoration	Jun-04	Dec-14	2009	

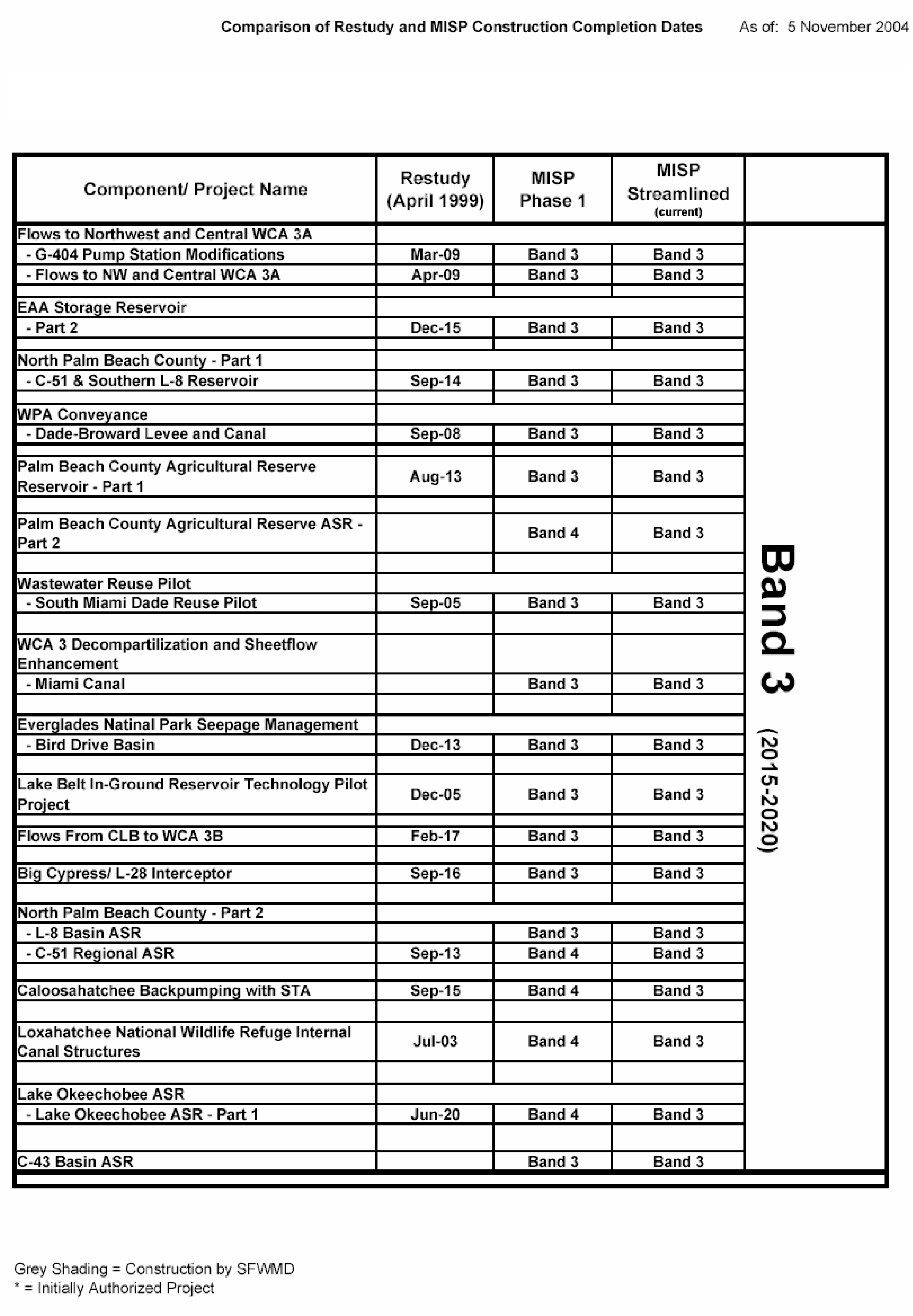
Grey Shading = Construction by SFWMD
* = Initially Authorized Project



Comparison of Restudy and MISP Construction Completion Dates As of: 5 November 2004

Component/ Project Name	Restudy (April 1999)	MISP Phase 1	MISP Streamlined (current)	
Indian River Lagoon - South				**Band 2** (2010-2015)
- C25 Reservoir and Northfork/Southfork Basin	May-10	Band 7	Band 2	
C-43 Basin Storage Reservoir	Mar-12	Band 2	2010	
North Palm Beach County - Part 1				
- Lake Worth Lagoon Restoration	Mar-11	Band 2	Band 2	
- Pal-Mar/Corbett Hydropattern Restoration		Band 2	Band 2	
- C-17 Backpumping	Oct-08	Band 3	Band 2	
- C-51 Backpumping and Treatment	Oct-08	Band 3	Band 2	
- L-8 Basin	Sep-11	Band 3	Band 2	
Florida Keys Tidal Restoration	Aug-05	Band 3	Band 2	
Lake Okeechobee Watershed				
- Tributary Sediment Dredging	Sep-05	Band 2	Band 2	
- Water Quality Treatment Facilities	Sep-10	Band 2	Band 2	
- North of Lake Okeechobee Storage	Sep-15	Band 2	Band 2	
Henderson Creek/ Belle Meade Restoration	Dec-05	Band 3	Band 2	
Modify Holey Land Wildlife Management Area Operation Plan		Band 2	Band 2	
C-4 Eastern Structure	Jul-05	Band 2	Band 2	
Everglades Natinal Park Seepage Management				
- Seepage Management	Oct-10	Band 2	Band 2	
- S-356 Structure	Oct-07	Band 2	Band 2	
WCA 3 Decompartilization and Sheetflow Enhancement				
- Additional S-345 Structures	Jan-09	Band 3	Band 2	
- Canal and Levee Modifications in WCA 3		Band 3	Band 2	
- WCA 3A & 3B Flows to CLB	Feb-16	Band 3	Band 2	
- North New River Improvements*	Jan-09	Band 3	Band 2	
- WCA 3 Decomp Part 2	Jan-19	Band 3	Band 2	
WPA Conveyance				
- North Lake Belt Storage Area (Turnpike Deliveries)		Band 2	Band 2	
Broward Secondary Canal System	Jun-09	Band 3	Band 2	

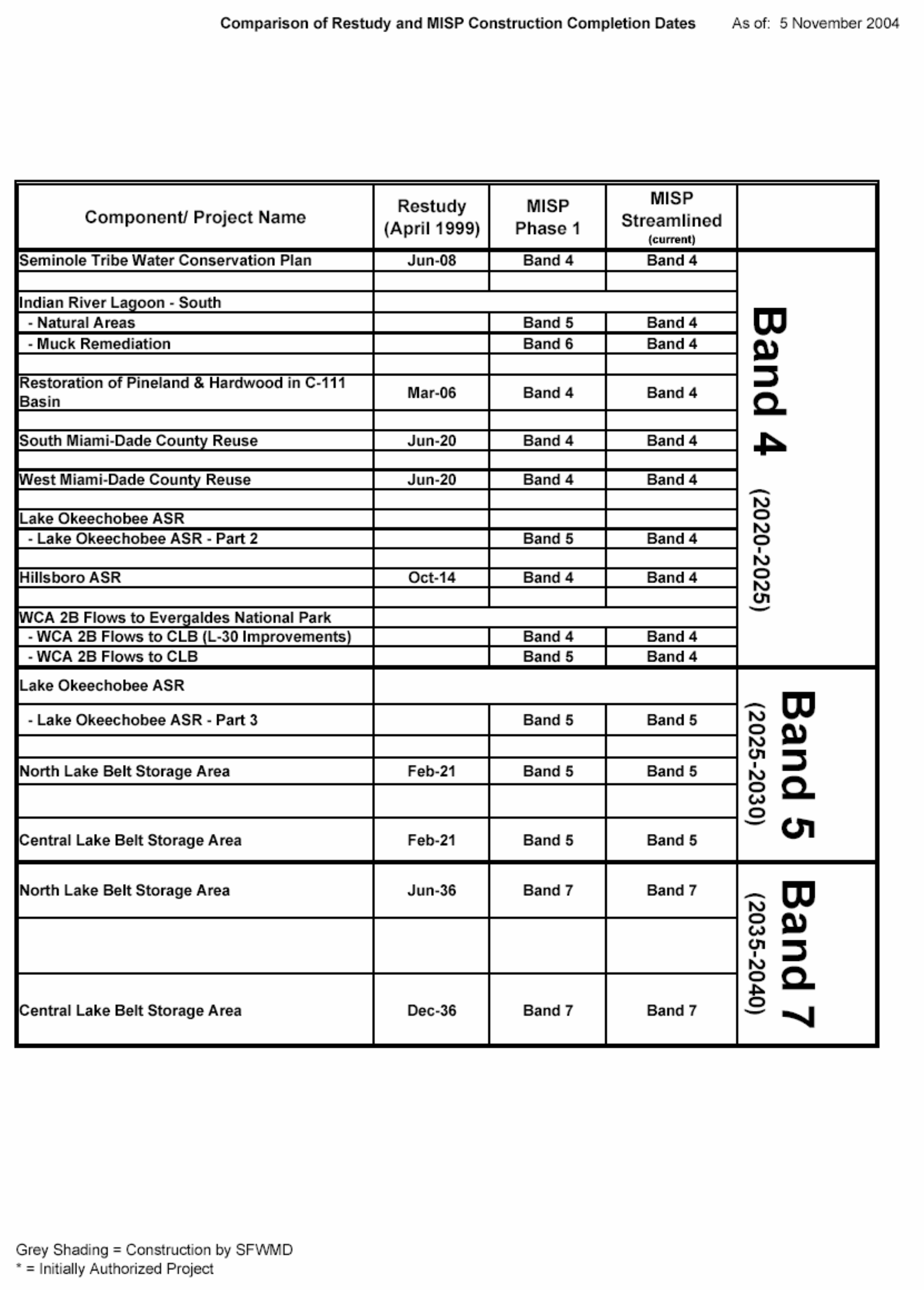
Grey Shading = Construction by SFWMD
* = Initially Authorized Project



Comparison of Restudy and MISP Construction Completion Dates As of: 5 November 2004

Component/ Project Name	Restudy (April 1999)	MISP Phase 1	MISP Streamlined (current)	
Flows to Northwest and Central WCA 3A				**Band 3** (2015-2020)
- G-404 Pump Station Modifications	Mar-09	Band 3	Band 3	
- Flows to NW and Central WCA 3A	Apr-09	Band 3	Band 3	
EAA Storage Reservoir				
- Part 2	Dec-15	Band 3	Band 3	
North Palm Beach County - Part 1				
- C-51 & Southern L-8 Reservoir	Sep-14	Band 3	Band 3	
WPA Conveyance				
- Dade-Broward Levee and Canal	Sep-08	Band 3	Band 3	
Palm Beach County Agricultural Reserve Reservoir - Part 1	Aug-13	Band 3	Band 3	
Palm Beach County Agricultural Reserve ASR - Part 2		Band 4	Band 3	
Wastewater Reuse Pilot				
- South Miami Dade Reuse Pilot	Sep-05	Band 3	Band 3	
WCA 3 Decompartilization and Sheetflow Enhancement				
- Miami Canal		Band 3	Band 3	
Everglades Natinal Park Seepage Management				
- Bird Drive Basin	Dec-13	Band 3	Band 3	
Lake Belt In-Ground Reservoir Technology Pilot Project	Dec-05	Band 3	Band 3	
Flows From CLB to WCA 3B	Feb-17	Band 3	Band 3	
Big Cypress/ L-28 Interceptor	Sep-16	Band 3	Band 3	
North Palm Beach County - Part 2				
- L-8 Basin ASR		Band 3	Band 3	
- C-51 Regional ASR	Sep-13	Band 4	Band 3	
Caloosahatchee Backpumping with STA	Sep-15	Band 4	Band 3	
Loxahatchee National Wildlife Refuge Internal Canal Structures	Jul-03	Band 4	Band 3	
Lake Okeechobee ASR				
- Lake Okeechobee ASR - Part 1	Jun-20	Band 4	Band 3	
C-43 Basin ASR		Band 3	Band 3	

Grey Shading = Construction by SFWMD
* = Initially Authorized Project



Comparison of Restudy and MISP Construction Completion Dates As of: 5 November 2004

Component/ Project Name	Restudy (April 1999)	MISP Phase 1	MISP Streamlined (current)	
Seminole Tribe Water Conservation Plan	Jun-08	Band 4	Band 4	Band 4 (2020-2025)
Indian River Lagoon - South				
- Natural Areas		Band 5	Band 4	
- Muck Remediation		Band 6	Band 4	
Restoration of Pineland & Hardwood in C-111 Basin	Mar-06	Band 4	Band 4	
South Miami-Dade County Reuse	Jun-20	Band 4	Band 4	
West Miami-Dade County Reuse	Jun-20	Band 4	Band 4	
Lake Okeechobee ASR				
- Lake Okeechobee ASR - Part 2		Band 5	Band 4	
Hillsboro ASR	Oct-14	Band 4	Band 4	
WCA 2B Flows to Evergaldes National Park				
- WCA 2B Flows to CLB (L-30 Improvements)		Band 4	Band 4	
- WCA 2B Flows to CLB		Band 5	Band 4	
Lake Okeechobee ASR				Band 5 (2025-2030)
- Lake Okeechobee ASR - Part 3		Band 5	Band 5	
North Lake Belt Storage Area	Feb-21	Band 5	Band 5	
Central Lake Belt Storage Area	Feb-21	Band 5	Band 5	
North Lake Belt Storage Area	Jun-36	Band 7	Band 7	Band 7 (2035-2040)
Central Lake Belt Storage Area	Dec-36	Band 7	Band 7	

Grey Shading = Construction by SFWMD
* = Initially Authorized Project

Appendix B

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Appendix C

Biographical Sketches of Members of the Committee on Restoration of the Greater Everglades Ecosystem

JEAN M. BAHR, CHAIR, is professor in the Department of Geology and Geophysics at the University of Wisconsin-Madison where she has been a faculty member since 1987. She served as chair of the Water Resources Management Program, UW Institute for Environmental Studies, from 1995-99 and she is also a member of the Geological Engineering Program faculty. Her current research focuses on the interactions between physical and chemical processes that control mass transport in ground water. She earned a B.A in geology from Yale University and M.S. and Ph.D. degrees in applied earth sciences (hydrogeology) from Stanford University. She has served as a member of the National Research Council's Board on Radioactive Waste Management and several of its committees. She is a National Associate of the National Academies.

SCOTT W. NIXON, VICE-CHAIR, is professor of oceanography at the University of Rhode Island. He currently teaches both graduate and undergraduate classes in oceanography and ecology. His current research interests include coastal ecology, with emphasis on estuaries, lagoons, and wetlands. He is a member of the NRC's Ocean Studies Board and has severed on several of its committees. Dr. Nixon received a B.A. in biology from the University of Delaware and a Ph.D. in botany/ecology from the University of North Carolina-Chapel Hill.

BARBARA L. BEDFORD is Senior Research Associate at Cornell University. She joined the Department of Natural Resources there in 1989, having served as the Associate Director of Cornell University's Ecosystems Research Center since 1980. Her research focuses on wetland plant diversity, what controls it, how human actions affect it, and how to manage it. She and her students work primarily in fens, bogs, riparian wetlands, and Great Lakes wetlands. She has been recognized twice by Cornell University for outstanding accomplishments in teaching, and serves on the University's selection committees for Rhodes, Marshall, and Udall Scholars. She has served on the Management Advisory Group to the Assistant Administrator for Water at the U.S. Environmental Protection Agency, the Wetland Experts Team for The Nature Conservancy's Wetland Management Network, and chaired the Scientific Oversight Committee for restoration of the Hole-in-the-Donut in Everglades National Park. She currently serves on the national advisory boards for the National Science Foundation's Long-Term Ecological Research Program and the Smithsonian Institution's Smithsonian Environmental Research Center. The Association of State Wetland Managers awarded her their first National Award for Excellence in wetland science applications and policy in 1996. In 2001 she received the National Merit Award from the Society of Wetland Scientists (SWS) for outstanding achievements in wetland science. She recently was elected vice-president of the SWS and will become president in 2006. She served on the NRC Committee on Review of Scientific Research Programs at the Smithsonian Institution, and the Committee on Wetlands Characterization. She received a B.A. in theology and philosophy from Marquette University's Honors Program in 1968, and an M.S. and Ph.D from the Institute for Environmental Studies at the University of Wisconsin, Madison in 1977and 1980, respectively.

LINDA K. BLUM is research associate professor in the Department of Environmental Sciences at the University of Virginia. Her current research projects include study of mechanisms controlling bacterial community abundance, productivity, and structure in tidal marsh creeks; impacts of microbial processes on water quality; organic matter accretion in salt marsh sediments; and rhizosphere effects on organic matter decay in anaerobic sediments. Dr. Blum earned a B.S. and M.S. in forestry from Michigan Technological University and a Ph.D. in soil science from Cornell University. She chaired the NRC committee that recently completed a study of the Critical Ecosystem Studies Initiative.

PATRICK L. BREZONIK is professor of environmental engineering and director of the Water Resources Research Center at the University of Minnesota. Prior to his appointment at the University of Minnesota in the mid-1980s, Dr. Brezonik was professor of water chemistry and environmental science at the University of Florida. His research interests focus on biogeochemical processes in aquatic systems, with special emphasis on the impacts of human activity on water quality and element cycles in lakes. He has served as a member of the National Research Council's Water Science and Technology Board and as a member of several of its committees. He earned a B.S. in chemistry from Marquette University and a M.S. and Ph.D. in water chemistry from the University of Wisconsin-Madison.

FRANK W. DAVIS is a Professor in the Donald Bren School of Environmental Science and Management at the University of California Santa Barbara (USCB). He received his B.A. in Biology from Williams College and Ph.D. from the Department of Geography and Environmental Engineering at The Johns Hopkins University. He joined UCSB in 1983, and established the UCSB Biogeography Lab in 1991. His research interests are in landscape ecology, regional conservation planning, and spatial decision support systems. He was Deputy Director of the National Center for Ecological Analysis and Synthesis between 1995 and 1998. Dr. Davis has been a member of three prior NRC committees.

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