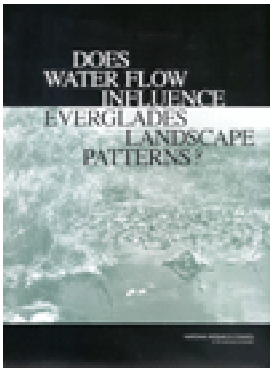

Does Water Flow Influence Everglades Landscape Patterns?

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

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DOES WATER FLOW INFLUENCE EVERGLADES LANDSCAPE PATTERNS?

Committee on Restoration of the Greater Everglades Ecosystem

Water Science and Technology Board

Board on Environmental Studies and Toxicology

Division on Earth and Life Studies

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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] A subgroup consisting of CROGEE members Ken Potter (chair), Barbara Bedford, Linda Blum, Wayne Huber, Steve Humphrey, Pete Loucks, Scott Nixon, and Jeff Walters, with support from NRC senior staff officer William Logan and staff associate Patricia Jones Kershaw, took the lead in drafting this report.

Preface

This report is a product of the 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 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 of the Water Science and Technology Board and the Board on Environmental Studies and Toxicology of the National Research Council.

The CROGEE's mandate (see Box ES-1) 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 efforts. One such topic addressed by the Committee, under the purview of its approved CROGEE task category of Ecological Indicators, is the methods by which hydrologic performance measures are identified for the Comprehensive Everglades Restoration Plan and the way that these measures will be used to assess the restoration process.

The *Workshop on Flows and Levels in the Ridge and Slough Region of the Everglades,* held by the CROGEE in Miami, Florida, on October 15, 2002, examined how flow might be incorporated into hydrologic performance measures for restoration, and what the practical implications of this might be. The workshop was open to the public and was attended by about 50 people from federal, state, and local government, universities, consulting firms, and environmental organizations. The agenda and list of attendees are shown in Appendix A.

The basis for the workshop was the Science Coordination Team's (SCT) August 2002 draft White Paper titled *The Role of Flow in the Everglades Ridge and Slough Landscape*. Reviewers' comments on this draft were also available. A panel of experts was assembled to give presentations, participate in discussions, and answer questions on the theme of the workshop. Subsequent to the workshop, the CROGEE deliberated the issues on several occasions. The conclusions and recommendations of this report take into account a subsequent revision of the White Paper by the SCT. The executive summary of the final version of the White Paper is in Appendix E, and the full report is available online at http://www.sfrestore.org/sct/docs/.

The CROGEE is grateful for the assistance of the scientists and engineers at the workshop who freely shared their insights. These included (listed alphabetically): Tom Armentano (National Park Service), Nick Aumen (National Park Service), Ronnie Best (U.S. Geological Survey), Dan Childers (Florida International University), Billy Cypress (Miccosukee Tribe of Indians), Elizabeth Crisfield (National Park Service), Steve Davis

(South Florida Water Management District), Robert Fennema (SAIC), Harry Jenter (U.S. Geological Survey), Bob Johnson (National Park Service), Bill Loftus (U.S. Geological Survey), Tom MacVicar (MacVicar, Federico & Lamb, Inc.), Christopher McVoy (South Florida Water Management District), John Ogden (South Florida Water Management District), Terry Rice (independent consultant), Fred Sklar (South Florida Water Management District), Kim Taplin (U.S. Army Corps of Engineers), Tom Van Lent (National Park Service), Randy Van Zee (South Florida Water Management District), and Dewey Worth (South Florida Water Management District). I thank the CROGEE members for their work on this report, especially a subgroup led by Ken Potter and including Barbara Bedford, Linda Blum, Wayne Huber, Steve Humphrey, Pete Loucks, Scott Nixon, and Jeff Walters. With assistance from NRC staff officer William Logan and staff associate Patricia Jones Kershaw, they took the lead in drafting this report.

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:

John W. Day, Jr., Louisiana State University
Paul H. Glaser, University of Minnesota
Denise Janet Reed, University of New Orleans
Bruce L. Rhoads, University of Illinois
Rebecca R. Sharitz, University of Georgia and Savannah River Ecology Laboratory
Raymond Torres, University of South Carolina

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 Stephen J. Burges, University of Washington, Seattle. Appointed by the National Research Council, Dr. Burges was 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

Contents

Executive Summary

The Everglades of south Florida has been altered extensively to accommodate human settlement. This has contributed to 85-95 percent declines of wading bird populations; 68 plant and animal species becoming threatened or endangered; extensive infestation with invasive, exotic plants; and widespread mercury contamination.

In response to these trends, the federal Water Resources Development Act of 1992 authorized a comprehensive review of the Central and South Florida Project to examine the potential for restoration of the Greater Everglades Ecosystem. The result of the review was the Comprehensive Everglades Restoration Plan (CERP, or "Restoration Plan")—the largest ecosystem restoration effort ever pursued. The National Research Council Committee on the Restoration of the Greater Everglades Ecosystem (CROGEE) was established in 1999 in response to a request from the U.S. Department of the Interior on behalf of the South Florida Ecosystem Restoration Task Force (SFERTF) to provide advice on scientific aspects of the design and implementation of the Restoration Plan. This report evaluates conclusions and recommendations developed by the Science Coordination Team (SCT)[1] of the SFERTF with respect to the environmental significance, creation, maintenance, degradation, research needs, and performance measures for flow in the ridge and slough landscape.

The CROGEE's mandate (see Box ES-1) 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 efforts. One such topic that the committee has addressed is the methods by which hydrologic performance measures are identified for the Restoration Plan and the way that these measures will be used to assess the restoration process.

One of the commonly stated goals of the Restoration Plan is to "get the water right." This has largely meant restoring the timing and duration of water levels and the water quality in various portions of the Everglades. Water flow has been considered mainly in the context of discharge to estuaries, but not elsewhere. There are several legitimate reasons why flow (in terms of direction, speed, and rate) has not been emphasized in the Restoration Plan. The most important of these is a relative lack of field information on both pre- and post-disturbance flow, except at flow structures and in canals. Further, modeling of surface water flow has not been very helpful for local flow estimates. This is due to both model

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[1] The SCT serves as the senior science advisory group to the SFERTF and the SFERTF Working Group. The SCT is responsible for recommending research plans and priorities; and facilitating the integration, synthesis, and application of the best scientific information (including the Social Sciences) available for the South Florida Ecosystem Restoration effort. For more information, see <http://www.sfrestore.org/sct/sctcharter.html>.

BOX ES-1

Committee on Restoration of the Greater Everglades Ecosystem Statement of Task

The CROGEE provides scientific guidance to multiple agencies charged with restoration and preservation of the Central and South Florida aquatic ecosystem, i.e., the Greater Everglades. The NRC 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.

Topics such as the following (to be determined to the mutual agreement of the restoration program management and the NRC) are expected to form the bases for the committee's investigations:

(1) Program goals, objectives, and planning approach;
(2) Data and information aspects, including needs for basic hydrologic and water quality data, environmental resources information, display and dissemination, and monitoring needs;
(3) Use of hydrological and hydroecological simulation models;
(4) Technological aspects of civil works facilities;
(5) Best agricultural and management practices of nutrients management;
(6) Wildlife management;
(7) Decision support systems; and
(8) Research requirements to support analyses for decision making and implementation.

constraints such as a coarse grid size, and natural factors such as low gradients, complex microtopography, and dense vegetation.

There are, however, compelling reasons to believe that flow affects important physical, chemical, and biological processes in the Everglades. Flow in wetlands generally enhances mixing, and it transports biologically important materials including nutrients, organic matter, gases, seeds, and spores. More important, there are major landforms in the Everglades—notably parallel ridges and sloughs, and tree islands—that are ecologically important and aligned with present and past flow directions. This alignment suggests that their genesis and maintenance have been importantly shaped by flow. For this reason, better understanding of the role of flow in shaping Everglades landscapes is critical to the restoration effort.

To focus on this issue, the SCT sponsored a flow workshop at the Greater Everglades Ecosystem Restoration conference in December 2000. It then prepared a white paper on the role of flow in the Everglades ridge and slough landscape, had it peer-reviewed, and released it in final form in January 2003. Between the peer review and the final release, the CROGEE held a Workshop on Flows and Levels in the Ridge and Slough Region of the Everglades in Miami, Florida on October 15, 2002 to gather additional background and information and to discuss the science informing the White Paper's conclusions and recommendations.

CONCLUSIONS AND RECOMMENDATIONS

The current understanding of flow effects, and the origin and maintenance of the ridge and slough landscape, is well summarized in a recently published Science Coordination Team White Paper (SCT, 2003). The ecological importance of the topographic structure in this landscape is well documented, as is the degradation of that structure in many areas, particularly in association with major linear structures (levees, canals, etc.) that inhibit flow. The development and use of performance measures that quantify changes through time in the geometry of ridges, sloughs, and tree islands, as proposed in the White Paper, are well justified. Performance measures that incorporate remote sensing are attractive because they are relatively inexpensive yet provide integrated information about the ecosystem condition. However, since considerable flattening of the landscape may occur before degradation is detectable by remote sensing, a network of transects to monitor microtopographic changes is also a high priority.

Several plausible explanations of the mechanisms for the formation and maintenance of the ridge and slough landscape have been proposed, and some involve flow, but none have been investigated in depth. Evidence of the importance of flow is circumstantial rather than based on support for a particular mechanism. Nonetheless, despite the scant quantitative data, the circumstantial evidence is strong that direction, speed, and rate of flow have important effects on the parallel ridges, sloughs, and tree islands in the central Everglades. Ignoring flow introduces an important source of uncertainty in the implementation of the Restoration Plan.

Alternative mechanisms can to some extent be evaluated from readily accomplished work such as analysis of underlying bedrock topography, detailed surface topographic mapping, and measuring accumulation of organic sediment. Nonetheless, more extensive, focused research will also be necessary. Most of the essential elements of such a research program are described in the White Paper. Immediate attention should be given to the development of alternative conceptual models of the formation and maintenance of the ridge and slough landscape, and the most compelling models should be used to develop research hypotheses and questions that can be used to guide the design of a research program. Paired comparisons between relatively intact landscapes and degraded ones may be particularly informative.

As noted in the White Paper, the conditions responsible for the development of the ridge and slough landscape may be different from those responsible for its maintenance. Research on maintenance of the landscape has a more direct impact on restoration, and should have higher priority than research on the original conditions governing its formation (see Box 2-1). The White Paper's recommendation to conduct a comprehensive multidisciplinary study of the paleoenvironmental history of the ridge and slough landscape is well justified in this regard.

Because it is not clear whether the ridge and slough landscape is maintained by average or extreme conditions, it is important that monitoring be designed to provide integrated measurements of flow and sediment transport for the full range of flow conditions, especially including extreme events. This will be challenging and expensive, and measurement sites should be co-located with sites where other related research on the ridge and slough landscape is occurring. In this context, the connectivity of sloughs at different water elevations might prove useful in understanding directions and magnitudes of flow under different conditions. This measure will depend heavily on detailed and highly precise topographic information across the landscape.

Given the potential role of flow in landscape maintenance, restoration efforts should attempt to incorporate flows approximating historical discharges, velocities (speed and direction), timing, and distribution in their design. However, development of numeric performance measures for speed of flow would not be appropriate until there is a better scientific understanding of the processes that underlie maintenance of ridges and sloughs, including water flows, water levels, extreme events, fire, and their interactions. At present, neither a minimum nor a maximum flow speed to preserve the landscape can be established.

1
Introduction

The Everglades' ecosystem of South Florida, aptly described as a "river of grass" (Douglas, 1947), once encompassed about three million acres of slow-moving water from Lake Okeechobee drainage basin to Florida Bay (Figure 1-1). Today, it has decreased to about half of its original size as the result of drainage and flood control projects employed to support expanding human settlements. The consequences of these projects have altered the ecosystem to its current degraded state.

As a consequence of decades of effort, in 1999 the Comprehensive Everglades Restoration Plan (CERP, referred to throughout this report as "the Restoration Plan") was unveiled with the overarching goal of restoring the historical hydrologic conditions to what remains of the natural ecosystem. The main purpose of the Restoration Plan is to achieve restoration by "getting the water right", i.e., improving the quality, quantity, timing and distribution of the water in the Everglades, while also providing for the water supply and flood control needs of the south Florida region (USACE and SFWMD, 1999). The Restoration Plan is the world's largest ecosystem restoration project; it will cost an estimated $7.8 billion (1999 price level) and take more than 20 years to complete. Appendix D provides a more detailed background and history of Everglades restoration.

"Getting the water right" has largely meant restoring the timing and duration of water levels and the water quality in various portions of the Everglades. Water flow has been considered mainly in the context of discharge to estuaries, but not elsewhere. There are a number of legitimate reasons why flow, in terms of direction, speed, and rate, has not been emphasized in the Restoration Plan. There exists very little information on pre-disturbance flow, and what is available is relatively imprecise. Post-disturbance flows are poorly quantified, except at flow structures and in canals.

Modeling of water flow is not very helpful for quantifying flows. Although the Natural System Model and the South Florida Water Management Model provide useful estimates of gross system inflows and outflows, estimates of flows within the system are much less accurate (Bales et al., 1997). Furthermore, neither model currently resolves overland flows at scales smaller than the two-mile by two-mile grid system. Low gradients, complex microtopography,

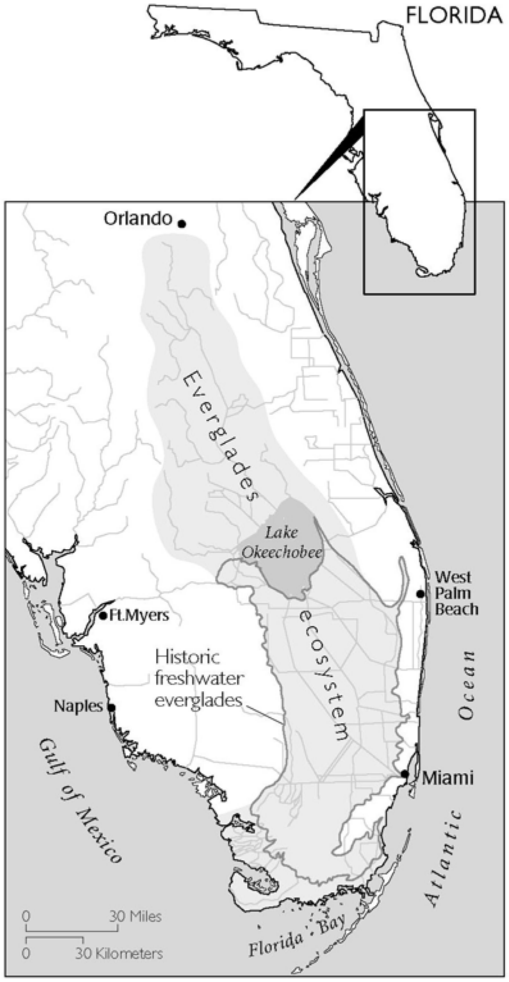


FIGURE 1-1 Greater Everglades Ecosystem. Source: Galloway et al., 1999.

and dense vegetation make it extremely challenging to model overland flows in the Everglades at a much finer scale.

There is, however, strong circumstantial evidence that flow affects important physical, chemical, and biological processes in the Everglades. Flow enhances mixing, particularly across the water-substrate interface. Flow, even at very low rates, is likely to transport biologically important materials including nutrients, organic matter, gases, and reproductive propagules such as seeds and spores (Mitsch and Gosselink, 2000). Furthermore, since flux (quantity/time) is the product of concentration (quantity/volume) x flow rate (volume/time), transport rates generally increase with flow rate (unless there are supply limitations).

More importantly, there are major landforms in the Everglades, most notably parallel sawgrass ridges, open-water sloughs, and tree islands, that are ecologically significant and aligned with present and past flow directions (see Figures 2-1, 2-2, and 2-3). This alignment suggests that their genesis and maintenance have been importantly shaped by flow.

During the last few years there has been an increasing concern about whether the ecological objectives of the Restoration Plan can be achieved to the extent desired without greater attention to the issue of flow. To focus on this issue, the Science Coordination Team sponsored a flow workshop at the Greater Everglades Ecosystem Restoration (GEER) conference, held in Naples, Florida in December 2000. They then prepared a white paper on the role of flow velocity in the Everglades ridge and slough landscape, had it peer-reviewed, and released it in final form in January 2003 (SCT, 2003). Between the peer review and the final release, the CROGEE held a *Workshop on Flows and Levels in the Ridge and Slough Region of the Everglades* in Miami, FL on October 15, 2002 to gather additional background and information and to discuss the science underpinning the White Paper's conclusions and recommendations (see Preface and Appendix A). Another flow workshop was held at the April 2003 GEER conference.

This report evaluates the SCT White Paper's conclusions and recommendations with respect to the environmental significance, creation, maintenance, degradation, research needs, and performance measures for flow in the ridge and slough landscape.

2

The Ridge and Slough Landscape: Significance, Degradation, Origin, and Maintenance

Historically the peat-based ridge and slough landscape was the predominant feature of the central Everglades, encompassing what are now Water Conservation Areas 1 (Loxahatchee National Wildlife Refuge), 2, and 3, and extending into Shark River Slough (Figure 2-1). This landscape is composed of a parallel arrangement of rather evenly spaced sawgrass ridges and open water sloughs characterized by aquatic vegetation and generally the year-round presence of water above the soil surface (Figure 2-2). In its pristine state, the soil surface of ridges is two to three feet (60 to 90 cm) higher than that of the sloughs (Wright, 1912; and Baldwin and Hawker, 1915 cited in SCT, 2003). In spite of this elevation difference, ridges are also covered with water for most or all of the year. Ridges can dry out entirely during the dry season. Tree islands (Figures 2-2 and 2-3) are a third element in this landscape. Tree islands are even higher in elevation than ridges, and tend to have exposed soil at all times except during periods of unusually high water.

OVERVIEW OF THE WHITE PAPER

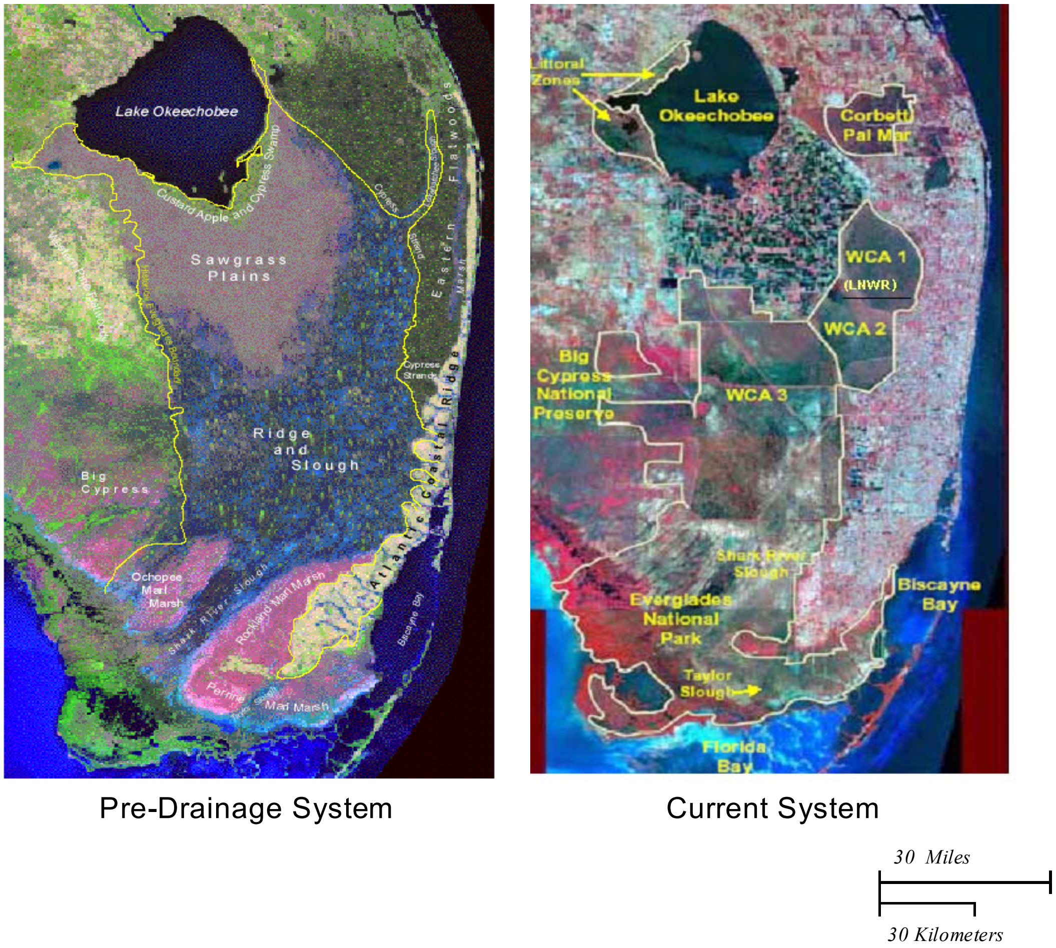
The SCT White Paper (SCT, 2003) makes, and provides support for, the following assertions:

- The ridge and slough landscape is highly significant ecologically.
- The landscape is severely degrading in a number of locations, i.e., it is being replaced with a landscape that is more uniform in terms of both topography and vegetation, and has less directionality.
- This degradation is due both to changes in water depths and hydroperiods and to changes in the spatial pattern of flow velocity (speed and direction).
- The exact mechanism for degradation is not known.
- The landscape will degrade further unless the appropriate water velocities (speed and direction), timing, and distribution are restored.

Based on these assertions, the White Paper:

- outlines priorities for research to determine the processes that maintain the ridge and slough landscape, and
- suggests new performance measures based on ridge and slough geometry.

The White Paper stops short of recommending that performance measures directly related to flow be instituted at this time. Instead it points out that there are tradeoffs involved with attempts to restore water flow, water levels, and hydroperiods, largely because there is not enough water. Until more is known about the role of flows, restoration emphasis should be placed on levels and hydroperiods.



Pre-Drainage System

Current System

FIGURE 2-1. The ridge and slough landscape in the context of the major features of the historic and current Everglades. WCA = Water Conservation Area [1, 2, and 3], LEC SVC. = Lower East Coast Service [Areas 1, 2, and 3]. LNWR = Loxahatchee National Wildlife Refuge. The pre-drainage system depicted above is a synthetic satellite image reconstructed by the SFWMD Hydrologic Systems Modeling Division using the Natural System Model (NSM) Version 4.5. The NSM simulates the hydrologic response of the pre-drainage Everglades system to historical (1965-95) meteorologic data. This is the view of the landscape that was likely to have existed circa 1850. This image can be found on http://sofia.usgs.gov/sfrsf/rooms/hydrology/water/wherebefore.html. Current system from Adaptive Assessment Team (2003).

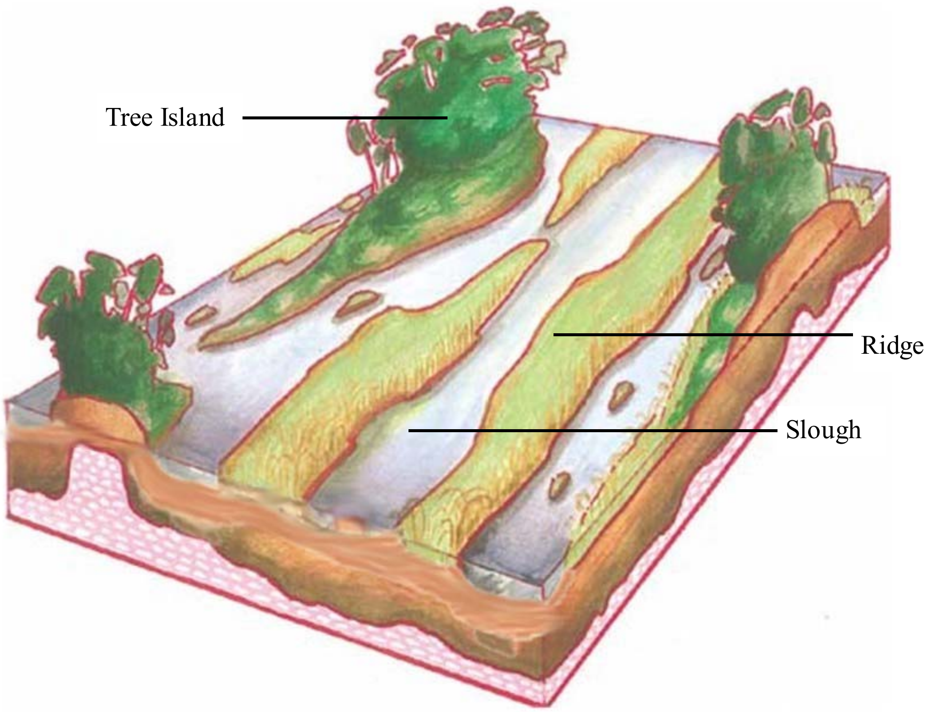


Figure 2-2. Artist's reconstruction of the pre-drainage condition of the ridge and slough landscape. The open water sloughs are characterized by submerged and floating vegetation, including periphyton mats, and may be somewhat more sinuous than shown in the figure. The generally submerged ridges that separate them are dominated by sawgrass. The figure is approximately 1.5 miles long by 1.0 mile wide, and vertical exaggeration is on the order of 10x. Source: modified from Science Coordination Team (2003).

Figure 2-3. Tree islands in background with sawgrass in foreground. For a sense of scale, refer to Figure 2-2. Source: U. S. Geological Survey, available on:
http://sofia.usgs.gov/virtual_tour/images/photos/alalley/tat_treeislands.jpg.

ECOLOGICAL SIGNIFICANCE OF THE RIDGE & SLOUGH LANDSCAPE

The White Paper asserts that the topographic and vegetation heterogeneity of ridge and slough landscape contributes directly to both the productivity and diversity of fishes and birds. During periods of high water, fishes use expansive ephemeral wetlands, including sawgrass stands, as foraging grounds and refugia from predation. This results in both increased reproduction and reduced mortality, leading to large increases in fish abundance. During the dry season, birds exploit the concentration of prey that occurs when these fish populations withdraw into sloughs and alligator holes (Kushlan, 1980). A growing body of scientific literature supports the assertion that wading bird use of Everglades habitats is highly dependent on these cycles in prey abundance and availability, and the microtopography that enables them (Lorenz, 2000; Russell et al., 2002; Gawlik, 2002). Current use of ridge and slough habitat by wading birds is related to the extent of microtopographic relief that remains (Bancroft et al., 2002). Generally sloughs are species-rich microhabitats (Loftus and Kushlan, 1987; Trexler et al. 2002), and their filling in with sawgrass reduces biodiversity. Tree islands are also important for nesting of alligators and roosting birds. Thus, the assertion that preservation of the ridge and slough landscape is important ecologically appears to be well grounded in science.

EVIDENCE OF DEGRADATION OF RIDGE AND SLOUGH LANDSCAPE

The White Paper defines degradation of the ridge and slough landscape in terms of both topographic and vegetation changes. The topographic changes entail a net decrease in the relief between ridge crests and slough bottoms. The vegetation changes include increases in the area of dense sawgrass and decreases in the area of open water, resulting in blurring of the directional ridge and slough pattern. Very little quantitative documentation of this landscape degradation exists, with the exception of data on tree-island loss (Sklar and van der Valk, 2003). Only recently has a detailed, comprehensive program of topographic and vegetation mapping been initiated in the Everglades. However, the White Paper provides visual evidence through aerial photographs and other imagery of pattern blurring.

In historic times, changes in water levels in the ridge and slough landscape appear to have led to changes in vegetation (Sklar et al., 2002). The lowering of water levels in some parts of the water conservation areas has led to replacement of the floating and submerged vegetation of sloughs (e.g., periphyton, a major food source for fish and invertebrates) by sawgrass and other emergent species. The raising of water levels in other areas has produced the opposite effect, "drowning" tree islands that have been impacted by fire (either human or lightning caused) and increasing the spatial extent of sloughs and their vegetation. Clearly, altered water levels and hydroperiods might have contributed to changes in ridge and slough vegetation patterns.

The White Paper asserts, however, that alteration of water levels and hydroperiods alone is not sufficient to cause the large-scale degradation of the landscape. Rather, alteration of the spatial pattern of flow magnitude and direction—associated with the construction of canals, roads, and levees and the institution of water management practices directed towards water supply and flood control—is also required. For example, extensive degradation in the water conservation areas is particularly notable near major linear structures such as Alligator Alley (Interstate 75), Tamiami Trail, and the L-67 levees and canals (Figure 2-4).

The visual evidence of ridge and slough degradation is compelling. Aerial photographs show clear differences between sites that are strongly patterned and others that are not. The association between pattern degradation and linear structures is also convincing. Furthermore, information from aerial photographs and anecdotal information indicate that the areas currently showing pattern degradation were not degraded earlier in the 20th century. It is clear that the ridge and slough landscape is degrading and that the most severe degradation is geographically associated with major linear structures that inhibit flow. (This argues against more generalized degradation mechanisms such as changes in precipitation or evapotranspiration rates in recent decades.) However, there are very few data that can be used to quantify this degradation.

POSSIBLE MECHANISMS FOR RIDGE AND SLOUGH FORMATION AND MAINTENANCE

The White Paper offers potential mechanisms for both the formation and maintenance of the ridge and slough landscape, and suggests that it is likely that several of these mechanisms act in concert. These mechanisms are summarized below.

- The initial ridge and slough pattern could be inherited from a pattern on the underlying bedrock surface, or could have been initiated by the erosional effect of moving water over the newly-forming peat surface.

- Differential rates of peat accumulation could be initiated by variations in microtopography that in turn lead to altered plant production or vegetation type.

- Water flow might be required to prevent the accumulation of organic sediment in the sloughs. Accumulation leads to their degradation by effectively lowering water depth and permitting growth of emergent vegetation. Transport of organic sediment by flowing water could be continuous or highly episodic.

- Extreme hydrologic events—hurricanes and tropical storms—would have affected the Everglades south of Lake Okeechobee to a far greater extent during pre-development conditions than now. Presently, the Caloosahatchee, St. Lucie, and other canals partially discharge these extreme flows to the sea. Although the ability of extreme flows to transport large amounts of particulates and the potential for erosion in a fragile landscape are hard to quantify, they are possible mechanisms for maintenance of the historical ridge and slough landscape.

- Fires, which frequently occurred before alteration of the system by humans, but which are now suppressed, may have affected the evolution of the ridge and slough terrain. Fires are known to have burned selectively along the drier ridges, potentially converting them to sloughs. This reversal implies that even if the ridge and slough pattern was initiated by an underlying bedrock pattern, the two patterns may no longer be coherent. This lack of correlation is confirmed by six recent transects through areas of ridge and slough landscape (Sklar et al., 2003). In this study, in which relative elevations of the peat and underlying bedrock relative to the water surface were measured in triplicate with one-meter spacing every 50 m along the 2 km-long transects, no correlation between peat surface and bedrock elevations was apparent.

Although some of these mechanisms have intuitive appeal, virtually none has been investigated seriously. (A notable exception involves tree islands, in which tree species tolerances have been examined in the context of changes in water depth, e.g., Conner et al., 2003). Hence the White Paper makes no attempt to argue for or against any of the mechanisms. Also, mechanisms of origin and mechanisms of maintenance may differ (Box 2-1).

In the absence of a compelling mechanism, the White Paper relies on circumstantial evidence for supporting its assertion that maintenance of the ridge and slough landscape requires flow. For example, the White Paper offers ridge and slough degradation in Shark River Slough (Figure 2-4, lower left part) and Water Conservation Area 1 (Figure 2-1) as cases where degradation is not due to changes in water levels. Aerial photographs of the areas show degradation over the period between 1968 and 1984. Water-level data for the same period do not show any changes in stage. Hence the White Paper concludes that the degradation must be due to changes in flow.

It is probable, however, that water levels did change as a result of the creation of the water conservation areas in the early 1960s, although there are no data to document this change. Since noticeable ridge and slough degradation presumably requires years to decades to occur after changes in water levels, these pre-1968 water level changes also may have played a role – even if not the primary one – in the degradation.

The White Paper makes a more general argument for the importance of flow based on the alignment of flow and the landscape pattern. All available evidence indicates that the ridge and slough landscape is generally aligned with the pre-disturbance pattern of flow. For example, hydrologic simulations using the Natural System Model (NSM) and based on inferred topography make a strong case for this alignment. (Since ridge and slough features are not resolved by the NSM, the simulations are not artifacts of the features.) Based on the NSM simulations, under equilibrium pre-disturbance conditions, large quantities of water moved over the landscape each year. In many years this water was the result of local rainfall. In wet years, however, additional water would have spilled from the southern edge of Lake Okeechobee, spread uniformly over the relatively featureless sawgrass plains, and then flowed through the ridge and slough landscape (with some escaping to the east through coastal channels). Given the relative flatness of the peat in the east-west direction perpendicular to flow, the flow through both the sawgrass plains and the ridge and slough landscape must have been uniformly distributed across the full width of the flow path (except, of course, for the local concentration of flow in the sloughs). This pattern of flow would have persisted over the several thousand-year history of the Everglades (Gleason and Stone, 1994) as the ecosystem developed.

Hence the White Paper argues that, as with many wetlands, flow probably plays a "vital role" in the ridge and slough ecosystem, and that maintenance of this ecosystem requires some degree of maintenance of the associated flow regime, even if the details are not understood. This report concurs with the White Paper's conclusion, even though this is largely based on experience and judgment rather than on the results of process-based research.

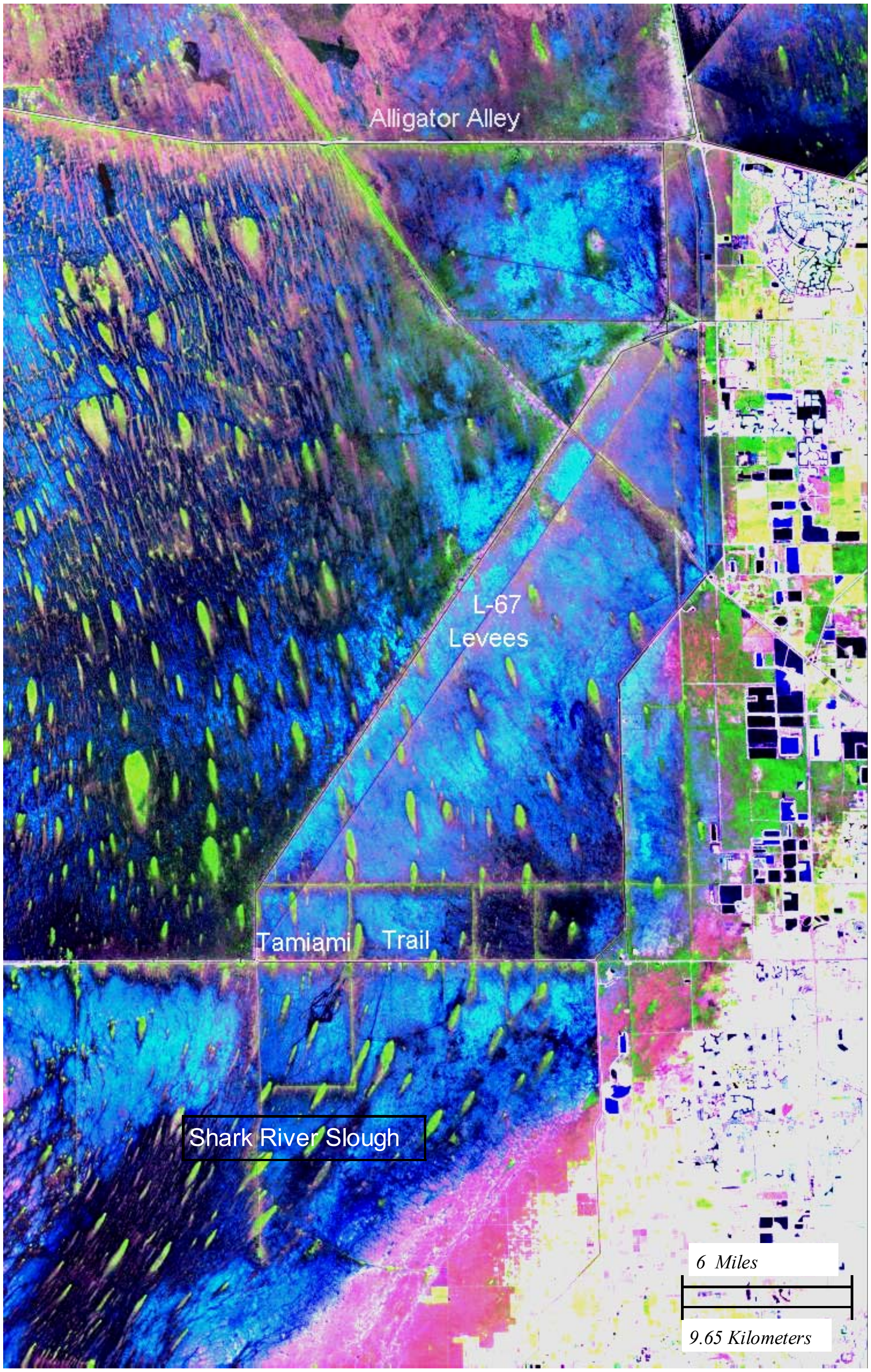


Figure 2-4. Detailed image of the ridge and slough landscape. The light teardrop-shaped areas are tree islands. Note the shift in alignment of the tree islands south of the Tamiami Trail where the direction of flow also changes. SOURCE: Florida Satellite Image, section 22, of South Florida Water Management District, accessed online at http://www.evergladesvillage.net/sat/everglades/.

BOX 2-1

ORIGIN OF THE RIDGE AND SLOUGH LANDSCAPE

The White Paper recognizes that the conditions responsible for the development of the ridge and slough landscape may be different from those responsible for its maintenance. This committee concurs. For example, ridge and slough landforms may have been initiated by preferential formation of peat in bedrock depressions as peat deposits were first forming in the Everglades 5000 years ago. As these deposits mounded above the surrounding bedrock, they would have diverted flow. Peat may have preferentially accreted downstream of the mounds, thereby causing the mounds to elongate. Over time the system of elongated mounds and intervening depressions then may have evolved into the present system. Under this model, once the ridge and slough pattern became established, the bedrock would not be a factor in maintaining the pattern. (This does not appear to be the case with tree islands that have bedrock at the head.)

The absence of ridge and slough landforms in the sawgrass prairie south of Lake Okeechobee is consistent with this hypothesis. When wetlands first formed in this area about 5000 years ago, overflow from the lake was likely diverted around them by the bedrock Loxahatchee Channel (a broad topographic low area in the bedrock draining to the east and southeast). As a result, the initial deposits consisted of calcitic mud, which blanketed the bedrock surface south of the lake and which undoubtedly reduced surface heterogeneity. (Modern calcitic muds are associated with periphyton, and form in place of peat if the period of inundation is relatively short. Without Lake Okeechobee as a source of water, the hydroperiod in the region would have been relatively short compared to the hydroperiod in the Loxahatchee region.) After the Loxahatchee Channel filled with peat and Lake Okeechobee began flooding the sawgrass prairie region, there may have been no irregularities to trigger the formation of peat mounds and initiate the formation of ridges and sloughs.

3

Research Needs and Performance Measures

RESEARCH NEEDS

The White Paper offers numerous prioritized recommendations for research on the influence of flow in the Everglades, with particular focus on the ridge and slough landscape. The "higher" and "medium" priority recommendations are summarized below.

The White Paper makes the following high-priority recommendations.

1. Conduct a comprehensive multidisciplinary study of the paleoenvironmental history of the Everglades to determine the historical extent and the pre-and post-disturbance dynamics of the ridge and slough landscape and other landscape types.

2. By means of a broad and thorough geomorphic review, develop alternative conceptual models of the formation and maintenance of the ridge and slough landscape; develop lists of specific questions and hypotheses that could be used to evaluate each model; and select the most likely conceptual models and use them to inform the design of further research.

3. Quantify the spatial and temporal distribution of sediment transport in the ridge and slough landscape to assess its role in landscape formation and maintenance.

4. Conduct synoptic measurements of flow over short temporal scales and large spatial scales to quantify current flow patterns.

The White Paper makes the following medium-priority recommendations.

1. Develop a simple carbon balance model for the ridge and slough landscape that can provide a basis for understanding peat accumulation and decomposition in ridges and sloughs; and collect the necessary data to quantify a carbon budget for the landscape.

2. Continue to collect and analyze remotely sensed images of the ridge and slough landscape in order to track changes due both to degradation and restoration; and develop systems models and estimate their parameters, collecting new field data (such as surface geophysics) where necessary.

3. Develop a seasonal water balance for the entire Everglades; and use the water balance to estimate pre- and post-disturbance flows into the ridge and slough landscape.

In general, these research recommendations will address many of the important gaps in our understanding of the role of flow, as identified in the White Paper and elsewhere in the scientific literature. It is important that a flow research program be carefully designed and focused to provide useful information in a timeframe relevant to the restoration. Immediate attention should be given to the development of alternative conceptual models of the formation and maintenance of the ridge and slough landscape (White Paper higher priority recommendation 2). This could be achieved at least partially by convening a workshop on peat accumulation and decomposition. As recommended in the White Paper, the most compelling models should be used to develop research hypotheses and questions that can be used to guide the design of a research program. Careful attention should be paid to research on well-studied peat landscapes with similar features, such as the wetlands of the Okavango Delta in Africa (McCarthy et al, 1986, for related research see <http://www.wits.ac.za/science/geology/vango_research.htm>) and the patterned peatlands of the boreal zone (Glaser et al., 1981; Glaser, 1983; Glaser and Janssens, 1986), though these are not entirely analogous.

As is stated in the White Paper, a research program on flow in the Everglades should include a study of the paleoenvironmental history of the Everglades. It should also include the following: measurements of flow and sediment transport and accumulation, development of carbon budgets, monitoring and analysis of remotely sensed data on landscape geometry, and development of seasonal water balances for Everglades landscapes. All studies should be designed to address questions and hypotheses associated with the leading conceptual models of landscape formation and maintenance, primarily focusing on ridges, sloughs, and tree islands. Whenever possible, studies should be paired between relatively intact landscapes and degraded ones.

Regarding flow and sediment, the committee agrees with the White Paper that research should be conducted to better understand processes. It is particularly important to measure flow and sediment flux during extreme events. This will be challenging and expensive, and should be co-located with sites where other related research on the ridge and slough landscape is occurring. The White Paper's recommendation of "synoptic measurements of flow...conducted over short time scales and large spatial scales in order to quantify ranges of flow velocity and direction and to delineate major flow pathways" may provide useful information. However, barring technological advances, such measurements will be very expensive to make and may have limited value in view of the likely importance of large events in the system.

Simple measurements of organic sediment accumulation can also provide useful information on sediment transport. For example, the hypothesis that maintenance of the ridge and slough pattern requires transport of organic sediment can be tested readily by measuring accumulations of this sediment at major barriers to flow, such as in the canals flanking Alligator Alley and the Tamiami Trail.

In addition to collecting remotely-sensed images of the ridge and slough landscape, water and soil surface elevations should be monitored on selected portions of the landscape. Topographic mapping at a spatial resolution of 1-3 m and vertical accuracy of 0.1-0.25 m would allow analysis of scale-dependent landscape pattern, microtopography and geomorphic processes. Airborne LIDAR (Light Detection and Ranging) offers a good option for such monitoring, although there are technical challenges to operational monitoring using this technology (Ritchie, 1996; Marks and Bates, 2000; Mertes, 2002; Schmugge et al., 2002). Such data could be tied to the sparser grid of high-precision elevation control points being collected by the U.S. Geological Survey (for more information on the measuring and mapping the topography of the Florida Everglades for ecosystem restoration, see <http://erg.usgs.gov/isb/pubs/factsheets/fs02103.html>). LIDAR output could be applied to characterizing ridge and slough topography and flowpaths, and used to drive more detailed hydrological models of selected areas to explore the relationship between water levels and flow regime. Multi-temporal imaging could be used to evaluate impacts of large storms and changes in water management over the ridge and slough landscape, as demonstrated in the Dade County East-West Transect study (<http://www.ihc.fiu.edu/ihc/lcrweb/e-w_fiu.htm>).

Topographic data also would provide information on whether all sloughs in relatively intact areas are unrestricted flow paths. Aerial photographs of such areas show sloughs that appear to dead end. Under a natural flow regime, the flow rate required to create flow connectivity of the sloughs might be a critical threshold.

Finally, if major linear structures are blocking the transport of organic sediment, it should be possible to document its resulting accumulation at or near these structures.

PERFORMANCE MEASURES

One major purpose of performance measures is to show how well restoration efforts are working. They form the basis of the Restoration Plan's monitoring program, recently evaluated in NRC (2003). The Restoration Plan's Monitoring and Assessment Plan (MAP) describes performance measures as quantitative measures of conditions in the natural and human systems that have been selected as targets for restoration. They are environmental response variables or system attributes that are expected to change as a consequence of alterations in water depth, hydroperiod, and/or water quality and are ecosystem characteristics that could be monitored to determine progress towards restoration goals and objectives (e.g., number of nesting wading birds). Some of the performance measures (e.g., extent of plant cover) have characteristics of broad ecological indicators such as measures of ecological condition, ecosystem functioning, or ecological capital, as described by the NRC (2000). Others are more site-specific (e.g., phosphorus concentration).

For monitoring and assessment of the Everglades restoration, the White Paper recommends consideration of new performance measures that quantify temporal variations in the geometry of ridges, sloughs, and tree islands. The recommended measures, all of which can be obtained from remotely sensed data, are areal extent and spatial orientation of the three landform types and average length-to-width ratios of ridges and sloughs. These are potentially good measures that fit the definition of ecological indicators as described by the NRC (2000). They are particularly attractive because they are low cost in comparison to many of the performance measures, yet they provide integrated information about the condition of the ecosystem.

Work is currently under way to define the spatial characteristics of the ridge and slough, and tree island patterns thought to represent well-preserved to highly degraded patterns with respect to historical landscape patterns (Nungesser et al., 2003; Wu et al., 2003). Such characteristics include number of ridges and tree islands, area of ridge/tree islands in the landscape, length-to-width ratio of ridges/tree islands, perimeter-to-area ratios of these features, orientation of ridges and tree islands in the landscape, and average length and width of uninterrupted slough along north-to-south and west-to-east transects, respectively.

These indicators, while useful, are insufficient for determining how the landscape is responding to water level, hydroperiod, and flow, because major changes in elevation may occur before degradation is reflected in such indicators. For example, a region in western Water Conservation Area 3 (Figure 2-1)– previously classified as “pristine” based on length-to-width ratio and perimeter-area relationships–has now been recognized as being “degraded” because the elevation difference between the ridges and sloughs is now about 20 cm, whereas historically the difference was between 30 and 90 cm (Sklar et al., 2003). To monitor the response of the ridge and slough system, it will be necessary to consider the topographic relationship between ridges and sloughs, as well as area, directionality, and connectivity of the landscape patterns.

Regardless of the mechanism(s) responsible for creation and maintenance of the ridge and slough and tree island patterns, performance measures must be developed so that these patterns can be monitored. Once there is sufficient scientific evidence to establish the role of flow and the flow rates required to maintain these landscape patterns, flow-related performance measures should be developed and added to the MAP. How these new performance measures are incorporated into the Restoration Plan will be a test of the plan’s ability to incorporate new information in a framework of adaptive management.

4

Conclusions and Recommendations

The current understanding of the effects of flow on wetland ecosystems and the origin and maintenance of the ridge and slough landscape is well summarized in the recently published Science Coordination Team White Paper (SCT, 2003). The ecological importance of the topographic structure in this landscape is well documented, as is the degradation of that structure in many areas, particularly in association with major linear structures that inhibit flow. The development and use of performance measures that quantify changes through time in the geometry of ridges, sloughs, and tree islands, as proposed in the White Paper, are well justified. Performance measures that incorporate remote sensing are attractive because they are relatively inexpensive yet provide integrated information about the ecosystem condition. However, since considerable flattening of the landscape may occur before degradation is detectable by remote sensing, a network of transects to monitor microtopographic changes is also a high priority.

Several plausible mechanisms for the formation and maintenance of the ridge and slough landscape have been proposed, and some involve flow, but none have been investigated in detail. Evidence of the importance of flow is circumstantial rather than based on support for a particular mechanism. Nonetheless, despite the scant quantitative data, the circumstantial evidence is strong that direction, velocity, and rate of flow (i.e., discharge) have important effects on the parallel ridges, sloughs, and tree islands in the central Everglades. Ignoring flow introduces an important source of uncertainty in the implementation of the Restoration Plan.

Alternative mechanisms can be evaluated to some extent from readily accomplished work such as analysis of underlying bedrock topography, detailed surface topographic mapping and measuring accumulation of organic sediment. Nonetheless, more extensive, focused research will also be necessary. Most of the essential elements of such a research program are described in the White Paper. Immediate attention should be given to the development of alternative conceptual models of the formation and maintenance of the ridge and slough landscape, and the most compelling models should be used to develop research hypotheses and questions that can be used to guide the design of a research program. Paired comparisons between relatively intact landscapes and degraded ones may be particularly informative.

As noted in the White Paper, the conditions responsible for the development of the ridge and slough landscape may be different from those responsible for its maintenance. Research on maintenance of the landscape has a more direct impact on restoration, and should have higher priority than research on the original conditions governing its formation (see Box 2-1). The White Paper's recommendation to conduct a comprehensive multidisciplinary study of the paleoenvironmental history of the ridge and slough landscape is justified in this regard.

Because it is not clear whether the ridge and slough landscape is maintained by average or extreme conditions, it is important that monitoring be designed to provide integrated measurements of flow and sediment transport for the full range of flow conditions, especially including extreme events. This will be challenging and expensive, and measurement sites should be co-located with sites where other related research on the ridge and slough landscape is occurring. In this context, the connectivity of sloughs at different water elevations might prove useful in understanding directions and magnitudes of flow under different conditions. This measure will depend heavily on detailed and highly precise topographic information in the landscape.

Given the potential role of flow in landscape maintenance, restoration efforts should attempt to incorporate flows approximating historical discharges, velocities (speed and direction), timing, and distribution in their design. However, development of numeric performance measures for speed of flow would not be appropriate until there is a better scientific understanding of the processes that underlie maintenance of ridges and sloughs, including flows, levels, extreme events, and fire, and their interactions. At present neither a minimum nor a maximum flow to preserve the landscape can be established.

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Appendix A
AGENDA

Committee on Restoration of the Greater Everglades Ecosystem
Meeting #10
and
Workshop on Flows and Levels in the Ridge and Slough Region of the Everglades
October 14-16, 2002
Miccosukee Resort and Convention Center
Ballroom B
Miami, Florida

Agenda

8:30 – 8:45 a.m. Welcoming Remarks — Chairman Billy Cypress, Miccosukee Tribe

8:45 – 9:00 Introductions and review of motivation and objectives of workshop — Jean Bahr, CROGEE Chair

9:00 – 10:15 Science supporting estimates of historical water levels (distribution, timing, etc.) in the Ridge and Slough — Robert Fennema (Dhasaan, Inc.)

A major goal of the CERP has been matching historical water levels. But how well do we know these? We will review how the SFWMM (and thence the NSM) was and is calibrated for the CERP; what have we learned in the ~3 years since then? We will also examine other kinds of evidence.

Questions and discussion

Discussants: Chris McVoy (SFWMD), Tom MacVicar (MacVicar, Federico, and Lamb), Bill Loftus (USGS), Fred Sklar (SFWMD)

10:00 – 10:15 Discussion of monitoring and research needs to reduce uncertainty and test hypotheses.

10:15 – 10:30	Break
10:30 – 12:00	Science supporting estimates of historical flows in the Ridge and Slough, and the state of knowledge of the relationship between levels and flows in the Ridge and Slough.

Flow may be important to the ecology and geomorphology of the Ridge and Slough landscape. What are the best estimates of flow in the Ridge and Slough and adjoining areas, and how well do we know these? What have we learned in the last ~3 years since the CERP was created?

10:30 – 10:45	Chris McVoy (SFWMD)—Historical Spatial Distribution and Orientation of Flow
10:45 – 10:55	Harry Jenter (USGS)—USGS flow measurements in the Everglades wetlands
10:55 – 11:45	Questions and discussion

Discussants: Randy van Zee (SFWMD), Robert Fennema (Dhasaan, Inc.), Elizabeth Crisfield (NPS)

11:45 – 12:00	Discussion of monitoring and research needs to reduce uncertainty and test hypotheses.
12:00 – 1:00 p.m.	Lunch
1:00 – 2:45	Science supporting hypotheses related to the roles of levels and flows in creating and maintaining the Ridge and Slough ecosystem

What are the alternative hypotheses that would support a link between flow and the creation and maintenance of the Ridge and Slough landscape in general and tree islands in particular? What might be the relative roles of (a) flow velocity and distribution, (b) sediment transport, (c) nutrient transport, and (d) aquatic species transport?

1:00 – 1:25	Nick Aumen (NPS) Dan Childers (FIU)
1:25 – 2:30	Questions and discussion

Discussants: Ronnie Best (USGS), Tom Van Lent (NPS), Tom Armentano (NPS), Steve Davis (SFWMD)

2:30 – 2:45	Discussion of monitoring and research needs to reduce uncertainty and test hypotheses.
2:45 – 3:00	Break

3:00 – 4:30 Discussion of implications for CERP performance measures and project design in light of current scientific understanding

There are various CERP and non-CERP projects that impact, and may be impacted by, the processes discussed at the workshop. How should what we know, and what we still do not know, about flows and levels in the Ridge and Slough feed into our choice of performance measures in the area? What are the implications for CERP and related projects?

Panel discussion
Moderator: Jean Bahr, CROGEE Chair

Fred Sklar (SFWMD)
John Ogden (SFWMD)
Stu Appelbaum (USACE)
Bob Johnson (NPS)
Kim Taplin (USACE)
Dewey Worth (SFWMD)
Terry Rice (Miccosukee Tribe)
Ronnie Best (USGS)

4:30 – 5:00 Other discussion, wrap-up

Attendees:

Stu Appelbaum, USACE
Tom Armentano, National Park Service
Nick Aumen, National Park Service
Jim Baker, USACE
Ronnie Best, USGS
Kevin Burger, SFERTF
Dan Childers, FIU
Elizabeth Crisfield, National Park Service
Janet Cushing, U.S. Army Corps of Engineers
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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 a Senior Research Associate at Cornell University. She joined the Department of Natural Resources 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. Current projects include: (a) relationship of groundwater hydrology and chemistry to nutrient availability, plant productivity, and plant species diversity; (b) inter-relationships among nutrient availability, plant tissue chemistry, and plant species diversity; (c) landscape control of wetland biogeochemistry and hydrology; (d) effects of removing cattails on fen species composition and diversity; and plant species diversity in phosphorus-poor wetlands. She teaches courses in Wetland Ecology and Management and Landscape Analysis. 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. from Marquette University in 1968, and her M.S. and Ph.D. from the University of Wisconsin at Madison in 1977 and 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.

WILLIAM L. GRAF is Education Foundation University Professor and Professor of Geography at the University of South Carolina. His specialties include fluvial geomorphology and hydrology, as well as policy for public land and water. His research and teaching have focused on river-channel change, human impacts on river processes, morphology, and ecology, along with contaminant transport and storage in river systems. In the arena of public policy, he has emphasized the interaction of science and decision making, and the resolution of conflicts among economic development, historical preservation, and environmental restoration for rivers. He has authored or edited 7 books, written more than 120 scientific papers, book chapters, and reports, and given more than 90 public presentations. He is past President of the Association of American Geographers and has been an officer in the Geological Society of America. President Clinton appointed him to the Presidential Commission on American Heritage Rivers. His NRC service includes past membership on the Water Science and Technology Board and present membership on the Board on Earth Sciences and Resources. He chaired the NRC Committee on Research Priorities in Geography at the U.S. Geological Survey and the Committee on Watershed Management, and was a member of several other NRC committees. He is a National Associate of the National Academies. His Ph.D. is from the University of Wisconsin, Madison.

WAYNE C. HUBER is professor in the Department of Civil, Construction, and Environmental Engineering at Oregon State University. Prior to moving to Oregon State in 1991, he served 23 years on the faculty of the Department of Environmental Engineering Sciences at the University of Florida where he engaged in several studies involving the hydrology and water quality of south Florida regions. His technical interests are principally in the areas of surface hydrology, stormwater management, nonpoint source pollution, and transport processes related to water quality. He is one of the original authors of the Environmental Protection Agency's Storm Water Management Model (SWMM) and continues to maintain the model for the EPA. Dr. Huber holds a B.S. in engineering from the California Institute of Technology and an M.S. and Ph.D. in civil engineering from the Massachusetts Institute of Technology.

STEPHEN R. HUMPHREY is dean of the College of Natural Resources and Environment at the University of Florida where he also serves as affiliate professor of Latin American studies, wildlife ecology, and zoology. He also has been the curator in ecology for the Florida Museum of Natural History since 1980. Dr. Humphrey has authored and co-authored numerous articles and books on the effects of urbanization on wildlife. He holds B.A. in biology from Earlham College in Richmond, Indiana and a Ph.D. in zoology from Oklahoma State University. He is former chair of the Environmental Regulatory Commission of the Florida Department of Environmental Regulation and a member of the Florida Panther Technical Advisory Council of the Florida Game Commission.

DANIEL P. LOUCKS is professor of civil and environmental engineering at Cornell University. His research, teaching, and consulting interests are in the application of economics, engineering, and systems theory to problems involving environmental and water resources development and management. Dr. Loucks has taught at a number of universities in the United States and abroad and has worked for the World Bank, and the International Institute for Applied Systems Analysis. He also served as a consultant to a variety of government and international organizations concerned with resource development and management. He is a member of the National Academy of Engineering and has served on several National Research Council committees.

KENNETH W. POTTER is professor of civil and environmental engineering at the University of Wisconsin-Madison. His expertise is in hydrology and water resources, including hydrologic modeling, estimation of hydrologic risk, estimation of hydrologic budgets, watershed monitoring and assessment, and aquatic ecosystem restoration. He received his B.S. in geology from Louisiana State University and his Ph.D. in geography and environmental engineering from The Johns Hopkins University. He has served as a member of the NRC's Water Science and Technology Board and several of its committees.

KENNETH H. RECKHOW is a professor of water resources at Duke University and is the director of the Water Resources Research Institute at North Carolina State University. Dr. Reckhow's research interests focus on the development, evaluation, and application of models for the management of water quality. In particular, he is interested in the effect of uncertainty on model specification, parameter estimation, and model applications. Recent work has expanded this theme to consider the effect of scientific uncertainties on water quality decision making. He recently chaired the NRC Committee to Assess the Scientific Basis of the Total Maximum Daily Load Approach to Water Pollution Reduction. He was also a member of the NRC Committee to Improve the U.S. Geological Survey National Water Quality Assessment Program. Dr. Reckhow received a B.S. in engineering physics from Cornell University and an M.S. and Ph.D. in environmental science and engineering from Harvard University.

LARRY ROBINSON is director of the Environmental Sciences Institute at Florida A&M University where he is also a professor. At Florida A&M University he has led efforts to establish B.S. and Ph.D. programs in environmental science in 1998 and 1999, respectively. His research interests include environmental chemistry and the application of nuclear methods to detect trace elements in environmental matrices and environmental policy and management. Previously he was group leader of a neutron activation analysis laboratory at Oak Ridge National Laboratory (ORNL). At ORNL he served on the National Laboratory Diversity Council and was President of the Oak Ridge Branch of the NAACP. Dr. Robinson earned a B.S. in chemistry, summa cum laude, from Memphis State University and a Ph.D. in nuclear chemistry from Washington University in St. Louis, Missouri.

HENRY J. VAUX, JR. is professor of resource economics at the University of California, Riverside. He currently serves as Associate Vice President - Agricultural and Natural Resource Programs for the University of California system. He previously served as Director of the University of California Water Resource Center. His principal research interests are the economics of water use and water quality. Prior to joining the University of California he worked at the Office of Management and Budget and served on the staff of the National Water Commission. He received a Ph.D. in economics from the University of Michigan in 1973. He recently served as chair of the Water Science and Technology Board, has served on many NRC committees, and is a National Associate of the National Academies.

JOHN VECCHIOLI retired as a hydrologist with the U.S. Geological Survey's Water Resources Division in Tallahassee, Florida and as chief of the Florida District Program. Previously, he was responsible for quality assurance of all technical aspects of ground water programs in Florida. His research interests have included study of hydraulic and geochemical aspects of waste injection in Florida and of artificial recharge in Long Island, N.Y. He has also done research on ground water-surface water interactions in New Jersey and Florida. Mr. Vecchioli received his B.S. and M.S. in geology from Rutgers University. Mr. Vecchioli previously served on the NRC's Committee on Ground Water Recharge.

JEFFREY R. WALTERS is Bailey Professor of Biology at Virginia Polytechnic Institute and State University, a position he has held since 1994. His professional experience includes assistant, associate, and full professorships at North Carolina State University from 1980 until 1994. Dr. Walters has done extensive research and published many articles on the red-cockaded woodpeckers in North Carolina and Florida and he chaired an American Ornithologists Union Conservation Committee Review that looked at the biology, status, and management of the Cape Sable Seaside Sparrow, a bird native to the Everglades. He is a fellow of the American Ornithologist Union, a member of Sigma Xi, American Society of Naturalists, Animal Behavior Society, Audubon Society, Cooper Ornithological Society, Ecological Society of America, Phi Beta Kappa, and many other scientific organizations. His research interests are in cooperative breeding in birds; reproductive biology of precocial birds; primate intragroup social behavior; evolution of cooperative breeding in birds; ecological basis of sensitivity to habitat fragmentation; kinship effects on behavior; and parental behavior on precocial birds. He holds a B.A. from West Virginia University and a Ph.D. from the University of Chicago.

Appendix D

A BRIEF HISTORY OF THE EVERGLADES

(Adapted from: National Research Council. 2003. Adaptive Monitoring and Assessment for the Comprehensive Everglades Restoration Plan. Washington, D.C.: National Academies Press.)

The South Florida ecosystem (Figure D-1 and 2-1) stretches from north of Lake Okeechobee to the Florida Reef Tract, and includes parts of 16 counties (USACE and SFWMD, 1999). While part of the system lies on ancient limestones, the Everglades peatland formed only during the past 5,000 years as sea level rose from its Ice Age low to its present level (Gleason and Stone, 1994). Alteration of the natural system began on a small scale in the mid-1800s, as over 50,000 acres north and west of Lake Okeechobee were ditched, drained, cleared, and planted for agriculture (Trustees, 1881). In 1907 Governor Napoleon Bonaparte Broward created the Everglades Drainage District (Blake, 1980), and by the early 1930s, 440 miles of canals dissecting the Everglades had been constructed (Lewis, 1948).

At least as early as the 1920s, private citizens had been calling attention to the degradation of the Florida Everglades (Blake, 1980). However, by the time Marjorie Stoneman Douglas' classic book *The Everglades: River of Grass* was published in 1947 (the same year that Everglades National Park was dedicated), the Greater Everglades Ecosystem had already been altered extensively to accommodate human habitation of the region, industry, and agriculture.

This trend only accelerated when disastrous floods of 1947-1948 led to the Central and Southern Florida Project for Flood Control and Other Purposes. This initiative employed levees, water storage, channel improvements, and large-scale pumping to supplement gravity drainage of the Everglades. It also created a 100-mile perimeter levee to separate the Everglades from urban development, effectively eliminating 160 square miles of Everglades that had historically extended east of the levee to the coastal ridge (Light and Dineen, 1994; Lord, 1993). The project then partitioned the remaining northern sawgrass and wet prairie (Figure D-1) into conservation areas (Figure 2-1), separated by levees, designed primarily for water supply and flood control, with some provision for wildlife habitat and recreation. The Everglades Agricultural Area (EAA) was created just south of Lake Okeechobee (Figure 2-1), facilitated by the construction of a dike spanning the entire circumference of the lake.

These and other projects were undertaken primarily for flood control, to support agriculture, and to provide dry land for development, and they have led to severe ecological consequences. Currently, by comparison with the earliest available estimates of the ecosystem and its components, populations of wading birds have declined by 85-95 percent; 68 plant and animal species are threatened or endangered; over 1.5 million acres are infested with invasive, exotic plants; and 1 million acres are contaminated with mercury (McPherson and Halley, 1996).

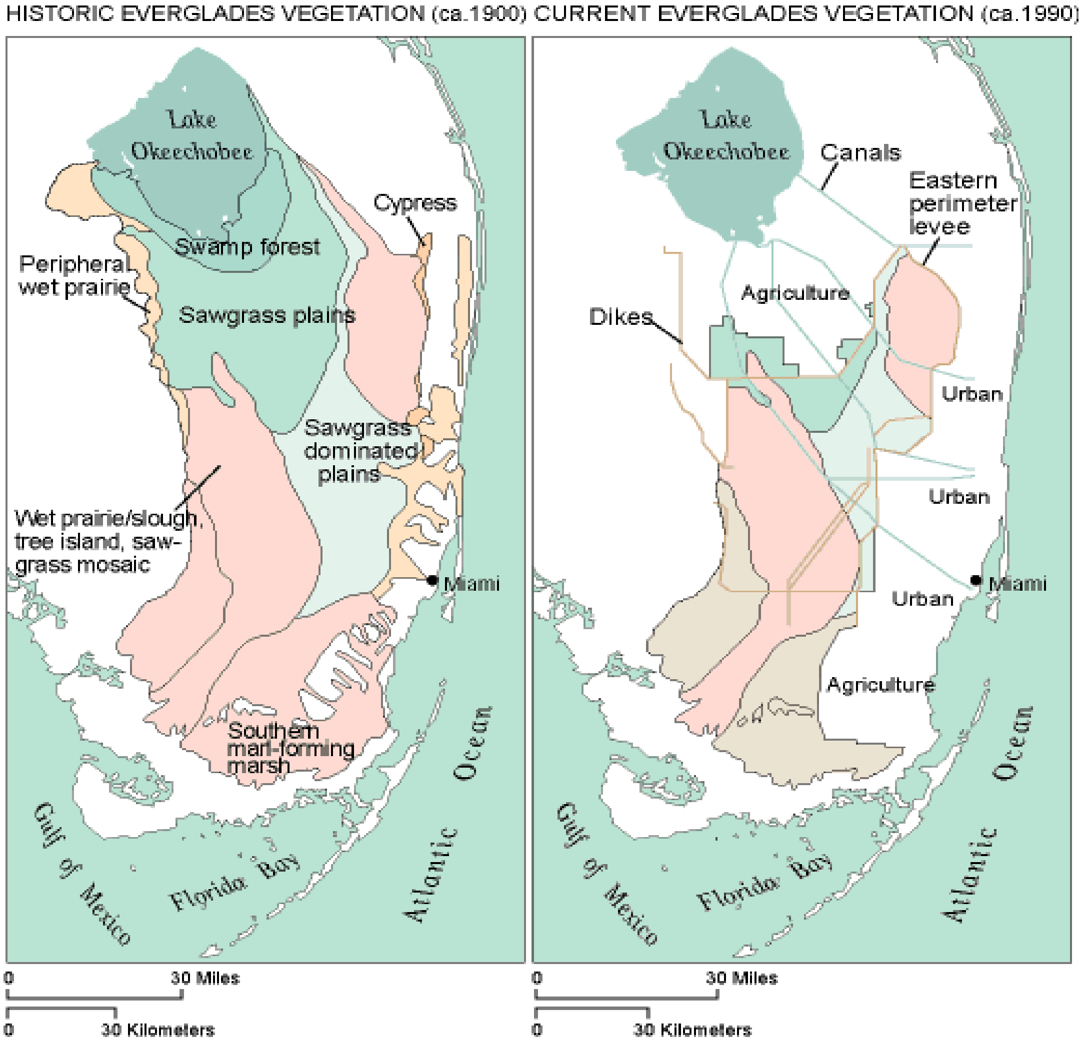

FIGURE D-1. Historic and current Everglades vegetation. Source: Galloway et al., 1999.

In response to these alarming ecological trends, the federal Water Resources Development Act of 1992 (WRDA) authorized a massive and comprehensive review of the Central and Southern Florida Project to examine the potential for restoration of the Greater Everglades Ecosystem. The result of the review, known as the Restudy, was the Comprehensive Everglades Restoration Plan (CERP). The National Research Council's (NRC's) Committee on the Restoration of the Greater Everglades Ecosystem (CROGEE) was established in response to requests from the U.S. Department of the Interior and the U.S. Congress to provide advice on scientific aspects of the design and implementation of the restoration plan. The charge to the CROGEE that resulted in this effort is described in the executive summary. The WRDA of 2000 required an "assessment of ecological indicators and other measures of progress in restoring the natural system," and this report also provides some basis for such an assessment.

THE RESTORATION PLAN

The Comprehensive Everglades Restoration Plan (hereafter referred to as "the Restoration Plan") is the largest restoration effort ever pursued from the standpoint of the size of the ecosystem (28,000 square kilometers) and the number of individual construction/destruction projects (nearly 200). The current Restoration Plan and its individual projects are designed to achieve more natural controls of the half of the Everglades ecosystem that remains after more than a century of extensive human alterations to the ecosystem (Figure D-1). The broad goals of the Restoration Plan are "to restore the natural hydrology of south Florida, to enhance and recover native habitats and species, and revitalize urban core areas to reduce the outward migration of suburbs and improve the quality of life in core areas" (SFERTF, 1998) (Box D-1). The plan is led by a federal agency, the U.S. Army Corps of Engineers, and a state agency, the South Florida Water Management District.

BOX D-1

Goals for the South Florida Restoration Effort

Greater South Florida Restoration Goals. The broad goals are "to restore the natural hydrology of south Florida, to enhance and recover native habitats and species, and revitalize urban core areas to reduce the outward migration of suburbs and improve the quality of life in core areas." (SFERTF, 1998).

Central and South Florida Restudy Goals. The overarching goal of The Restudy was to determine how best to:

- Enhance Ecological Values
  - Increase the total spatial extent of natural areas
  - Improve habitat and functional quality
  - Improve native plant and animal species abundance and diversity
- Enhance Economic Values and Social Well Being
  - Increase availability of fresh water (agricultural/municipal and industrial)
  - Reduce flood damages (agricultural/urban)
  - Provide recreational and navigational opportunities
  - Protect cultural and archeological resources and values (USACE and SFWMD, 2002b).

As broad an effort as the Restoration Plan is, it is only part of a larger restoration effort involving research by a myriad of federal, state, and local agencies, universities, and native American tribes. The South Florida Ecosystem Restoration Task Force (http://www.sfrestore.org/tf/index.html) is charged with developing the strategic plan that will integrate the projects into a single framework to restore the south Florida ecosystem.

A fundamental premise of the Restoration Plan is that restoring the historical hydrologic regime to the remaining Everglades system will reverse well-documented declines in many native species and biological communities. The cornerstone of the overall effort to restore the ecosystem is to restore the natural hydrology of the ecosystem. The basic strategy of the Restoration Plan is to capture and store freshwater currently discharged to the ocean for use during the dry season; 80 percent of the captured water is to be used for the natural system while 20 percent is for agricultural and urban uses (USACE and SFWMD, 1999). The plan calls for removal of 240 miles of levees and canals and building a network of reservoirs, underground storage wells, and pumping stations that would capture water and redistribute it to replicate natural hydroperiods. To "get the water right"—the approach of the Restoration Plan—the plan proposes construction of 68 major projects over an estimated 36 years at a cost of $7.8 billion (1999 estimate). These projects are expected to recreate historical quantities, quality, timing, and distribution of water in the natural system while meeting the needs of the built environment (and its people) for freshwater and flood protection. Clearly, getting the water right by this strategy and with these constraints will require that the Everglades continue to be an intensively managed ecosystem even after the projects outlined in the Restoration Plan are complete.

The Restoration Plan was conceived and designed based on extensive monitoring, experimental research, and modeling. However, scientists and managers involved in the restoration recognize that there are very large scientific, engineering and political uncertainties associated with a restoration project of this scope and complexity. In particular, the relationship between the historical hydrologic regime and modern ecosystem composition, structure, and functioning remains somewhat hypothetical given the greatly reduced size and altered proportions and flow ways of the modern system and the degradation of water quality. Exogenous factors such as sea-level rise, continuing human development of southern Florida, the spread of invasive exotic species, and atmospheric mercury deposition may confound the best restoration designs. There is the added uncertainty associated with some of the proposed engineering solutions such as large-scale aquifer storage and recovery, not to mention the uncertainty of project funding over its 30-year plus duration. Some uncertainties can only be resolved by taking action; even without full knowledge of how the ecosystem will respond. Interventions themselves will create change, which can only be understood in retrospect. Comprehension will always lag behind observation.

In the face of these uncertainties and surprises, the ability of the Restoration Plan to achieve its stated restoration goals depends on fully incorporating and maintaining scientific research throughout the restoration program (Box D-1). In the last decade, science's role in Everglades restoration has been formalized in two main ways. The first of these is the Science Coordination Team or SCT (http://www.sfrestore.org/sct/index.html), which has evolved from the Science Subgroup established in 1993 by the South Florida Ecosystem Restoration Task Force as an interagency science advisory team. The second is called Restoration, Coordination, and Verification, or RECOVER (http://www.evergladesplan.org/pm/recover/recover.cfm), an entity created by the agencies leading the Restoration Plan. RECOVER's goals are to evaluate and assess plan performance, recommend improvements in the plan's design and operational criteria, review the effects of other restoration projects on the plan's performance, and ensure a system-wide perspective. This focus on the Restoration Plan rather than on the broader multi-agency restoration effort makes RECOVER's mandate somewhat narrower than that of the Science Coordination Team.

COMPREHENSIVE EVERGLADES RESTORATION PLAN GOALS

The overarching goal of the CERP is to "get the water right" by restoring historic hydrologic conditions in the natural ecosystem. The objectives of the CERP are to create historic quantities, quality, timing, and distribution of water in the natural system while at the same time providing fresh water to the built environment and protecting the built environment from flooding.

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Appendix E

Executive Summary – The Role of Flow in the Everglades Ridge and Slough Landscape

The Role of Flow in the Everglades Ridge and Slough Landscape

Science Coordination Team
South Florida Ecosystem Restoration Working Group
(Approved by the SCT: January 14, 2003)

Executive Summary

The Everglades has at the core of its identity the slow movement of water across the vast, low gradient, wetland landscape. Marjory Stoneman Douglas eloquently immortalized this identity in her descriptions of the "River of Grass" (Douglas 1947). Drainage and compartmentalization efforts during the 20th century for flood control and water supply purposes interrupted this flow, as well as altering water levels, distribution, and seasonal timing. Water flows are closely linked to water levels, and their alterations have caused environmental damage. Efforts to restore the Everglades have focused on re-establishing more natural hydropatterns – the appropriate water levels, and the location, timing, and duration of these water levels. While these natural hydropatterns are widely recognized as being extremely important, much less attention has been paid to the importance of the actual movement of water, the physical and ecological roles that movement of this water plays, and how management activities have altered that flow. Thus, the Science Coordination Team has chosen understanding the science of the role of flow in the Everglades as one of its priorities. The purpose of this paper is to provide a stimulus for increasing the level of understanding and awareness of the role of flow in restoration activities, and to highlight the urgent need for research in this area.

Pre-drainage Everglades hydrology was dominated by a remarkable flow regime – a 30-milewide expanse of water moving down the low-gradient wetland landscape from north to south. Surprisingly, although Everglades hydrology has flow as one of its defining characteristics, most discussions of hydrology in the Everglades exclude mention of the role of water movement. The movement of water in aquatic ecosystems such as wetlands is a fundamental construct of ecosystem structure and function, and its ecosystem role is well-established. It is likely that water movement plays a similar vital role in the Everglades.

The ridge and slough landscape, one of several major habitat types in the Everglades, originally consisted of a peat-based system of dense sawgrass ridges interspersed with adjacent and relatively open sloughs. These parallel ridges and sloughs existed in an organized pattern, oriented parallel to the flow direction, on a slightly sloping peatland. Unfortunately, compartmentalization and related water management activities are resulting in the loss of this ridge and slough landscape. This loss is evidenced by replacement of the characteristic ridge and slough landscape with a landscape that is more topographically and vegetationally uniform. It is clear that 1) the Everglades ridge and slough landscape has changed, and is continuing to change significantly; and 2) the landscape changes are having detrimental ecological effects on Everglades plants and animals. It is likely that these changes are the result of altered water flow and hydropattern caused by human-made barriers

and shunts, interacting with corresponding changes in water depth and water level fluctuations.

The mechanisms causing the loss of ridge and slough landscape likely are complex, are occurring over a time scale of decades or more, and restoration decisions will have to be made on a time frame shorter than decades. A number of mechanisms for the formation and maintenance of the ridge and slough landscape are proposed, including: sediment transport; changes in water depth under managed conditions; differential rates of peat accumulation and decomposition; erosional formation; extreme hydrological events; fire; underlying bedrock patterns; and microhabitat differences in water chemistry. The presence of flow is necessary for almost all of these mechanisms to operate, and it is likely that a combination of several of these mechanisms operating together is responsible for formation and maintenance of the ridge and slough landscape.

The mechanisms of ridge and slough landscape degradation are not fully understood. However, it is likely that barriers to flow, including levees and canals, contribute significantly to the conversion of the ridge and slough wetland mosaic to more uniform stands of sawgrass. Conversion of the ridge and slough landscape pattern to uniform sawgrass stands has had, and will continue to have, deleterious impacts on Everglades plants and animals. An Everglades landscape increasingly dominated by dense sawgrass stands supports fewer numbers of animals and a lower diversity of animals. The control of vegetation over wading bird ecology is strong enough that Kushlan (1989) states, “Whatever determines vegetation patterns will also, to a large degree, determine bird use of wetlands.” Wading birds are an important component of the Everglades ecosystem. Their foraging and nesting success often are used as indicators of the overall health of the system, and they are one of the most visible and highly regarded fauna of the Everglades. The conversion of ridge and slough landscape to dense sawgrass stands has had a negative impact on wading birds and other important birds of the Everglades. Negative impacts of these landscape changes extend throughout the Everglades food web, including fish, which are important food for wading birds. In addition to altering flow patterns and wetland landscape patterns, barriers to flow serve as barriers to movement of aquatic animals.

Very few research studies have been conducted specifically to determine the role of flow in the Everglades ecosystem. Most of the research projects from which data are presented in this paper, while relevant to the role of flow, were not designed to determine the role of flow. It is precisely for this reason that the Science Coordination Team chose the topic of flow as one of its priorities. Recommendations for future research are prioritized, and include: a multidisciplinary paleoenvironmental study; a thorough geomorphic review; sediment transport studies; synoptic and time series measurements of flow; development of a carbon balance model; remote sensing; and others.

Finally, additional performance measures are recommended for the ridge and slough landscape for the monitoring and assessment of the Comprehensive Everglades Restoration Plan (CERP) progress. These measures, largely based on expanded collection and analysis of remotely sensed images, include: aerial extent and temporal trends of sawgrass ridge, slough, and tree island polygons; edge-to-area ratios for landscape types; average length-to-width ratio and temporal trends of sawgrass ridges or sloughs for a defined area; and spatial orientation of the three landscape types as compared to their historic orientations.