Title: AN OVERVIEW OF THE SOUTHERN INLAND AND COASTAL SYSTEM PROJECT OF THE U. S. GEOLOGICAL SURVEY SOUTH FLORIDA ECOSYSTEM PROGRAM

Presenters: Raymond W. Schaffranek, Henry A. Ruhl, and Maria E. Hansler, U.S. Geological Survey, 430 National Center, 12201 Sunrise Valley Drive, Reston, VA 20192

Keywords: Flow Model, Everglades, Ecosystem, Interdisciplinary Study, Wetlands, Hydrologic Studies, and Restoration.

Abstract

The U.S. Geological Survey is conducting an interdisciplinary study of the complex ecosystem processes at the interface of the southern Everglades with Florida Bay. Scientific findings derived from hydrologic studies and extensive data collected to characterize the ecosystem properties are being synthesized and integrated into the development of a research tool and management model of the ecosystem. Simulation results produced by the model are being made available for integration with ecological analyses to evaluate the effects of variations in regulated inflows on flora and fauna. Insight that the model provides on sheet flow and tidal interaction along the wetland and Bay boundary is also being provided to the U.S. Army Corps of Engineers for development of a circulation model for Florida Bay and to agencies such the National Park Service and the South Florida Water Management District for the development and evaluation of ecosystem restoration plans.

2. Introduction

The interface of the interconnected wetlands of Taylor Slough and C-111 canal with the nearshore embayments of Florida Bay constitutes a critical component of the south Florida ecosystem. Flora and fauna in the wetlands and aquatic life in the Bay are mutually dependent on the magnitude, duration, timing, and quality of freshwater inflows. Anthropogenic influences such as the construction of hydraulic-control structures, roads, canals, and levees have shifted the seasonal distribution of flow and patterns of wetland inundation and, at the same time, contributed to the development of hypersaline conditions in nearshore embayments. Such changes are altering the ecosystem and creating stresses on living resources including federally listed, endangered, and threatened species such as the Cape Sable seaside sparrow, American crocodile, wood stork, and roseate spoonbill. Current restoration efforts are focused on sustaining hydroperiods in the wetlands and salinity levels in the embayments that are consistent with habitat requirements.

In 1995, multidisciplinary hydrologic, cartographic, and geologic studies were initiated by the U.S. Geological Survey (USGS) for the mainland of south Florida, Florida Bay, and the Florida Keys within the South Florida Ecosystem Program (McPherson and others, 1995). The USGS is now synthesizing scientific findings from these process studies, analyzing the data collected to characterize the ecosystem properties and functions, and using these findings and data to develop a research tool and management model for the Southern Inland and Coastal System (SICS) area encompassing the interface of the southern Everglades with Florida Bay. Investigations of the resistance effects of vegetation, wind-forcing dynamics, evapotranspiration mechanisms, ground-water/surface-water exchanges, canal/wetland interactions, and biogeochemical processes have been conducted to define the hydrologic and hydraulic properties needed to support development of the model. Data quantifying the land-surface elevations and vegetation characteristics of the wetlands, bathymetry and bottom composition of nearshore tidal embayments, and internal and boundary flow conditions have been collected for model implementation and calibration. Additionally, the history of the ecosystem is being reconstructed to provide a perspective on natural processes and pre-anthropogenic conditions. The results of these efforts are being synthesized to support development of the model for use in determining wetland hydroperiods, flow patterns, and the potential transport of nutrients in response to varied inflows that can affect living resources.

Scientists from all four disciplinary divisions of the USGS, i.e., Biological Resources, Geology, National Mapping, and Water Resources, are contributing basic data and process-study results for development and implementation of the model. An overview of the projects contributing to the model development and their interrelation to the description and simulation of ecosystem processes is presented herein. Preliminary and more recent findings of individual projects within the USGS South Florida Ecosystem Program are presented by Gerould and Higer (1997, 1999). Numerous fact sheets that identify scientific approaches, data-collection methods, analytical findings, and contact information for project investigators are available at the South Florida Information Exchange web site http://sofia.usgs.gov. The web site also contains a data exchange page plus additional information about the South Florida Ecosystem Program. An overview of the environmental setting in south Florida and its relationship to developing scientific programs can be found in McPherson and Halley (1997).

3. The SICS Study Area

The SICS study area is located in the southeast quadrant of Everglades National Park (ENP). It encompasses the interface of the wetlands of the Taylor Slough and southern C-111 canal drainage basins with nearshore tidal embayments of Florida Bay (fig. 1). The study area and model domain (outlined in figure 1) are bounded on the east by U.S. Highway 1, and C-111 canal and levee; on the north and west by ENP Road (SR

27) and Old Ingraham Highway; and on the south by Florida Bay. The freshwater wetlands of the upland portion of the study area are characterized by a mixture of plant communities comprising tree islands, sawgrass marshes, and wet prairies. Areas with little or no emergent vegetation, such as ponds, creeks, and canals, are also prevalent. The brackish and saltwater wetlands of the southern portion of the study area are comprised mainly of expansive communities of spikerush and mangroves. Several large lakes and tidal embayments line the interface of the wetlands with Florida Bay (see figure 1). A distinct terrain feature of variably high elevation, referred to as the Buttonwood Embankment, extends along the shoreline and acts intermittently as a hydraulic barrier confining wetland and Bay flow exchanges primarily to intervening creeks (Holmes and others, *in* Gerould and Higer, 1999). Principal sources of surface-water inflows to the study area consist of hydraulic control-structure releases at the Taylor Slough headwaters, discharges from L-31W canal, overbank flows from C-111 canal, and exchanges through road culverts. The extremely low relief of the wetland terrain yields low surface-water velocities and shallow water-surface gradients typical of wetland sheet flow. Tides propagating through several shallow narrow creeks that transect the Buttonwood Embankment also affect flows in the adjoining wetlands. The area is underlain by a highly permeable surficial aquifer that is recharged by rainfall.

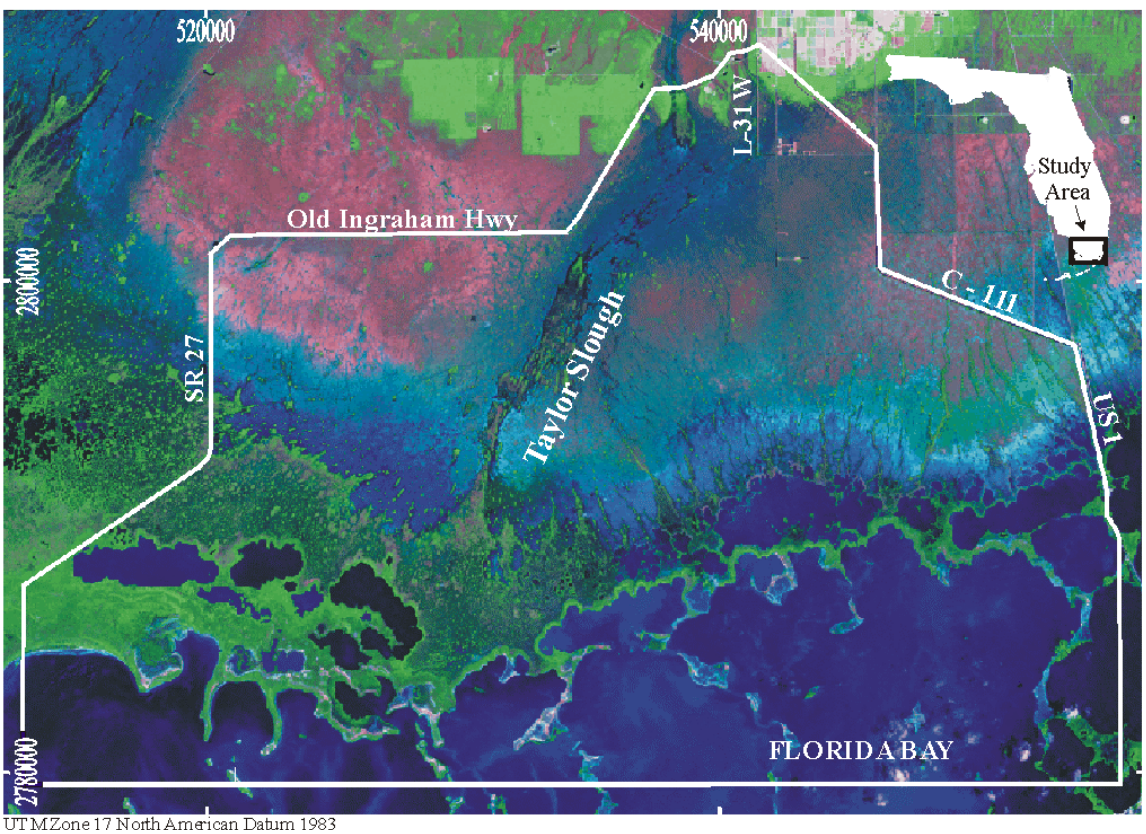

Figure 1. Satellite image showing SICS study area

4. Ecosystem Processes

The complex interaction of hydraulic, hydrologic, and ecological processes in the SICS study area determines and influences surface-water flows through the ecosystem as illustrated in figure 2. Inflows from structures, canals, and culverts are augmented by rainfall, altered by evaporation and plant-transpiration mechanisms, affected by ground-water exchanges, and impeded by the resistance effects of vegetation, all the while being subject to the dynamic external forces of winds and tides. Data describing the land-surface gradient of the wetlands, bathymetry of the tidal embayments, characteristics of the vegetation, and underlying aquifer conditions are fundamental pieces of information needed to study and evaluate flows through the ecosystem. Moreover, empirical coefficients and process rates are needed to quantify the local and external effects of vegetative resistance, evapotranspiration mechanisms, ground-water exchanges, winds, salinity variations, and tidal influences.

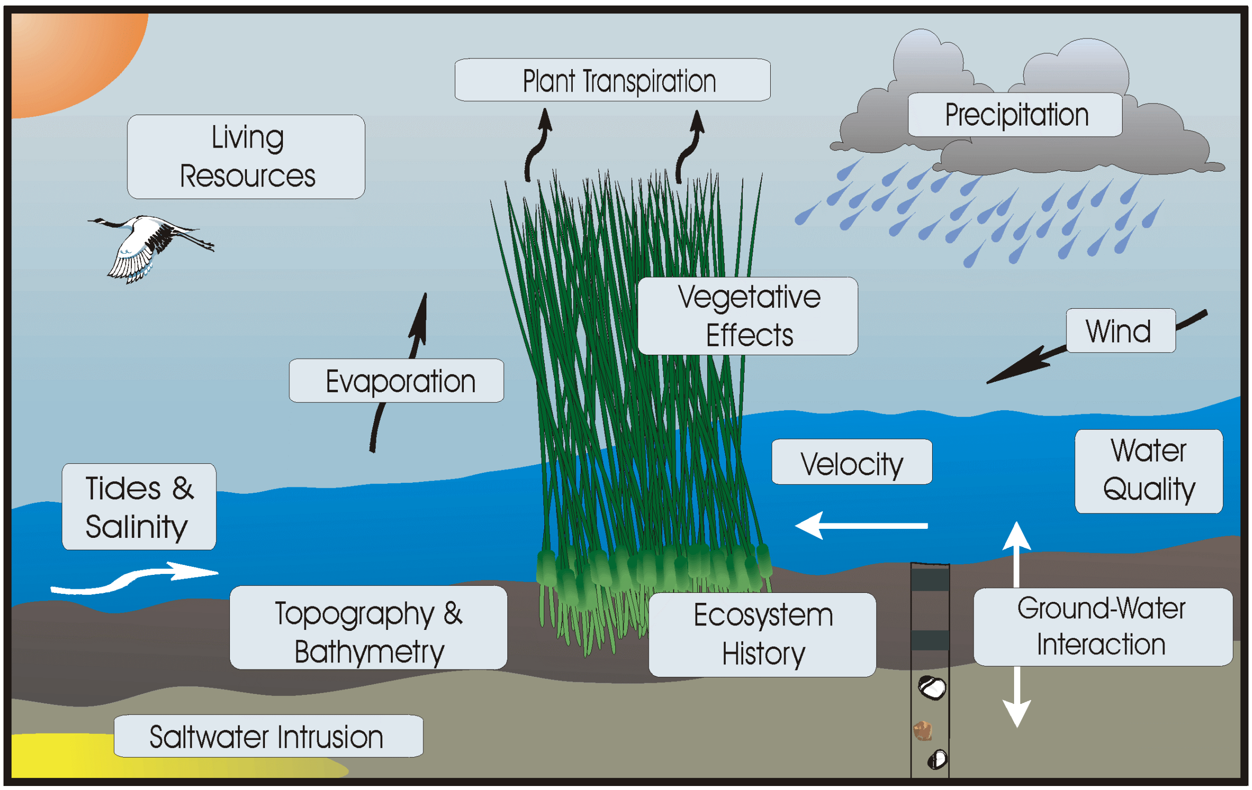

Figure 2. Interrelation of processes in the SICS ecosystem.

In order to formulate appropriate restoration plans for this ecosystem, information is needed to quantify and describe antecedent, i.e. pre-drainage, conditions. USGS scientists are using remote sensing imagery coupled with isotope and pollen analyses of sediment cores to reconstruct the time frame of past changes in vegetation (Brewster-Wingard and others, *in* Gerould and Higer, 1999; Holmes and Marot, *in* Gerould and Higer, 1999; Willard and others, *in* Gerould and Higer, 1999). Ecologists and geologists are also studying vegetation dynamics across sharp ecotones, such as the shoreline of Florida Bay, and the phenomenon of "mangrove die-off" (Smith and others, *in* Gerould and Higer, 1999; Smith and Whelan, *in* Gerould and Higer, 1999). Historical information obtained from these investigations is providing a baseline with which to compare the future impacts of hydrologic alterations.

5. Model Requirements

The SICS model simulates sheet flow through the wetlands of the Taylor Slough and C-111 canal drainage basins concurrent with tidal flows in the nearshore embayments of Florida Bay. Thus, the model enables the effects of freshwater inflows on hydroperiods and flow patterns in the wetlands to be evaluated simultaneously with dynamic forces that affect flow and salinity conditions in the tidal embayments. A sound mathematical model of this complex interconnected canal, wetland, and tidal ecosystem must, therefore, include terms in its governing equations that properly represent all relevant hydrologic processes in the wetlands and hydraulic forces in the Bay. Moreover, high-quality data that define these processes and forces, depict the geometric properties of the ecosystem, and describe typical flow conditions are required to develop, implement, and calibrate the model, as well as to evaluate and establish the accuracy of simulation results. A brief description of hydrologic studies and hydraulic measurements conducted in support of the SICS model development follows.

5.1 Boundary and Internal Flows

Water-level, velocity, discharge, and rainfall data are collected in canals, culverts, wetlands, and tidal creeks throughout the SICS study area (Patino, *in* Gerould and Higer, 1999; Schaffranek, *in* Gerould and Higer, 1999). These data are used to define external inflows, evaluate empirical coefficients, account for internal flow sources, and calibrate the model. Mean flow velocities in the wetlands are derived from point values measured using portable acoustic Doppler current meters that have a resolution of 0.1 mm/s. Measured wetland flow velocities are typically less than 1 cm/s. Satellite imagery and digital orthophoto quadrangle maps, produced from recent color infrared photographs, are used to aid in interpretation of measured boundary and internal flows, as well as for visualization of numerical simulation results. In figure 3, velocity vectors, depth-averaged from point values, are overlaid on a satellite image to illustrate flow patterns in the wetlands.

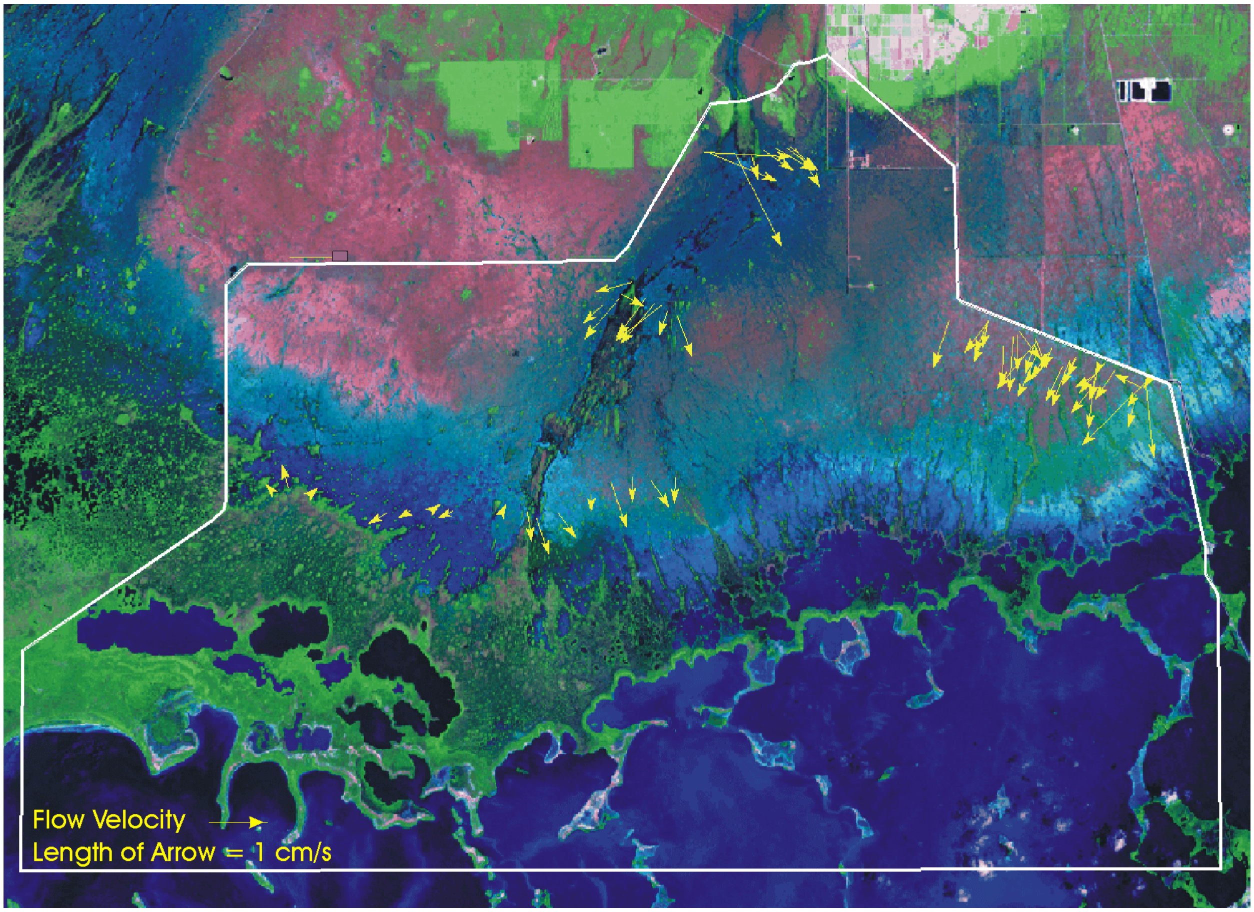

Figure 3. Vectors representing depth-averaged flow velocities overlaid on satellite image.

5.2 Topography and Bathymetry

The extremely low land-surface gradient (< 0.00001) within the SICS study area requires very accurate elevation data to define the topography of the wetlands and the bathymetry of Florida Bay and its coastal embayments within the model domain. A 148 by 98 grid of elevation data (305-m square cells), defining the topography and bathymetry of the ecosystem, was generated from point values collected using geodetic-quality differential global positioning system (DGPS) technology. DGPS-derived topographic data representing the wetlands have a stated vertical accuracy of 15 cm or better (Desmond, *in* Gerould and Higer, 1999). Bathymetric data used to depict the coastal embayments have a vertical accuracy on the order of 10 cm (Hansen, *in* Gerould and Higer, 1997). Both sets of data are referenced to North American Vertical Datum of 1988 for correlation with water-surface elevation data. Repeatability tests indicate that the collected elevation data are achieving minimum accuracy levels needed to define the shallow land-surface gradient for modeling purposes.

5.3 Vegetation Classification

A vegetation-classification scheme has been developed specifically to serve as the basis for quantifying hydrologic processes in the SICS model (Carter and others, *in* Gerould and Higer, 1999). Vegetation classes are defined to evaluate frictional-resistance, wind-stress, and evapotranspiration effects. Twenty land-cover classes, derived from 1997 Landsat Thematic Mapper imagery (Desmond and others, *in* Gerould and Higer, 1999), were subsequently combined into seven vegetation classes and one water class using field information on vegetative composition and structure as well as extensive ground-truth observations. The seven vegetation classes are: sawgrass, sawgrass/bunchgrass, sawgrass/rush, rush/other, evergreen, mangrove/-Buttonwood, and mangrove/water. These vegetation classes are currently serving as the basis for quantifying hydrologic processes within the SICS model; however, they are being further analyzed and refined, as needed, using more recent Landsat imagery and ground-truth data. Other remote sensing data and image analysis techniques are also under investigation to further delineate vegetation characteristics for improving hydrologic process correlation.

5.4 Vegetative Resistance

Surface-water flows in the SICS study area are affected by submersed vegetation and mats of periphyton, microalgae that live on shallow submerged substrates. Resistance to flow caused by vegetation and periphyton is expressed in the model by a mathematical expression involving the Manning's n coefficient. Numerous hydraulic and vegetation measurements have been conducted to quantify Manning's n for the types of vegetation and flow conditions found in the SICS area (Lee and Carter, *in* Gerould and Higer, 1999). Hydraulic measurements of flow depths, velocities, and water-surface slopes have been made to evaluate the coefficient. Vegetation, including periphyton, was sampled in horizontal layers through the water column at all these sites to determine species composition, density, size, dry biomass, and leaf area index for correlation with the hydraulic measurements. Preliminary Manning's n coefficient values ranging between 0.42 and 0.48 have been determined for the vegetation classes and aggregated for input to the model at the grid cell level. Resistance coefficient values are adjusted dynamically during numerical simulations to account for their dependence on flow depth.

5.5 Evaporation and Transpiration

A network of nine measurement sites, representing a cross section of vegetation characteristics and inundation conditions, was established to quantify evaporation and plant-transpiration rates throughout the Everglades (German, *in* Gerould and Higer, 1999). The network consisted of two open-water sites and seven vegetated sites representing sawgrass marshes, wet prairies, and cattail environments. Vegetation characteristics were quantified and average annual evapotranspiration (ET) rates were calculated for each site from meteorological and flow data collected in 1996 and 1997. Measured average annual ET ranged from 107 cm at a vegetated site to 142 cm at an open-water site. Regional models of ET rates were then developed as a function of available energy, solar intensity, and water level. From these models, estimates of surface water loss due to evapotranspiration as a function of vegetation class and hydroperiod were determined for use in the SICS model. The use of satellite remote sensing technology to extrapolate point measurements of hydrologic processes such as ET over regional scales are also being investigated (Jones, *in* Gerould and Higer, 1997).

5.6 Wind Effects

Wind effects in Florida Bay can produce elevated water levels along the coast that impede or even reverse flows in the tidal creeks discharging from the Taylor Slough and C-111 wetlands through the Buttonwood Embankment. Wind data collected at ET stations within the wetlands and at marine monitoring sites in Florida Bay are used to generate wind fields for input to the model to account for internal effects on water movement. Wind speed and direction data are filtered, interpolated onto the model grid, and input to the model as a forcing function. Analysis of comparable simulations conducted with and without treatment of wind effects indicates that its dynamic forcing must be considered for winds of sustained magnitude and consistent direction. Winds can also produce local effects on sheet flows in the wetlands. The effect of wind on flow through the vegetated wetlands is currently under investigation using laboratory and field data on wind speed and direction, water depth, water-surface slope, and vegetation characteristics.

5.7 Ground-water/Surface-water Exchanges

Hydrologic fluxes between surface and ground water must be evaluated and integrated with results from flow and water quality studies to accurately quantify a hydrologic budget and mass balance for the Everglades, both of which are required to simulate surface water flows. A variety of methods are used to identify ground-water/surface-water flow exchanges, one of which involves sampling and mapping environmental chemical tracers. Chemical sampling and analyses of chloride concentrations indicate that surface-water flow in Taylor Slough is augmented by water flowing beneath Old Ingraham Highway (Harvey and others, *in* Gerould and Higer, 1999). This project effort is helping quantify the volumetric rate of ground-water inflow to Taylor Slough for modeling purposes.

5.8 Subsurface Freshwater/Saltwater Interface

Airborne electromagnetic geophysical techniques are being used to locate the subsurface freshwater/saltwater interface within the SICS study area. Surveys providing samples at 10-m intervals along flight lines spaced 400 m apart have been used to define the formation resistivity at selected depths. These data show a clear transition from freshwater to saltwater occurring 8 to 20 km inland from the coast (Fitterman, *in* Gerould and Higer, 1999). Detected changes in location of the interface with depth reveal the effects of anthropogenic influences as well as areas of ground-water recharge that have implications on surface-water flow simulation.

5.9 Water Quality

Water-quality studies in the Everglades wetlands and Florida Bay are also contributing information about the current state and the history of the ecosystem that is useful for both model development and simulation purposes. Two such projects are focused on studying the nutrient geochemistry of the wetlands and salinity dynamics of Florida Bay. The identification of background levels and sources of nutrients (Orem and others, *in* Gerould and Higer, 1999) can be used to evaluate their transport in response to varied inflow conditions thereby enabling assessments of their potential effects on plant communities to be conducted. Knowledge of salinity dynamics in Florida Bay (Robblee and Smith, *in* Gerould and Higer, 1999) is needed to account for the effects of increased water density on wetland/Bay flow exchanges. Salinity and sediment surveys (Halley and others, *in* Gerould and Higer, 1997) are providing information needed to treat density variations and to characterize frictional resistance properties of nearshore embayments of Florida Bay in the model.

5.10 Simulated Surface-Water Flows

The SICS model simulates water levels, flow velocities, and mass fluxes throughout the Taylor Slough and C-111 wetland interface with Florida Bay in response to variably-regulated inflows and dynamic tidal conditions. Process-study findings have been used to formulate mathematical expressions representing critical forcing mechanisms, to define empirical coefficients and functional relations for quantifying hydrologic processes, and(or) to implement and calibrate the model. Measured flow and transport conditions are supplied to the model at its open boundaries. A sample of model output results, representing a snapshot in time, produced in response to a particular set of inflow and tidal boundary conditions is illustrated in figure 4. Water-surface elevations are shown as color-coded contours and the magnitude and direction of unit discharges are shown by scaled vectors. From these model results, wetland hydroperiods and embayment salinities can be examined and contrasted in response to varied inflows and forcing mechanisms. Analysis of model results from short- and long-term simulations are revealing flow patterns and anomalies that otherwise would be difficult to detect. Information such as this is invaluable to the evaluation and assessment of alternative ecosystem restoration scenarios.

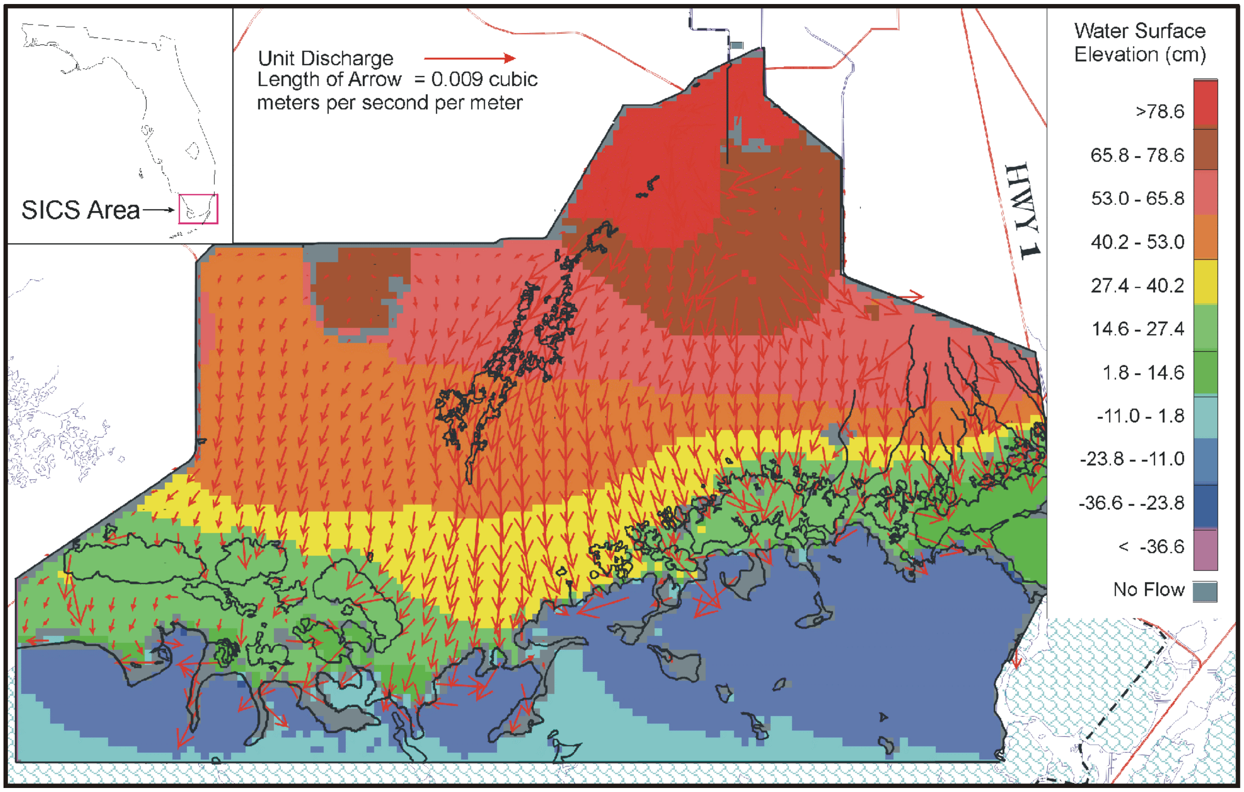

Figure 4. Numerical simulation results produced by the SICS model.

6. Summary

Surface-water flows in the Southern Inland and Coastal System (SICS) interface of the Everglades with Florida Bay are complex. The extremely low relief of the wetland terrain yields low flow velocities and shallow water-surface gradients. Tides propagating through creeks connecting nearshore embayments with Florida Bay affect flow exchanges with the adjacent wetlands and produce a mixing zone for salt and fresh water. The formulation and evaluation of restoration plans and actions for this interconnected canal, wetland, and tidal ecosystem are difficult and necessitate the use of a sophisticated analytical tool such as a mathematical model. The model developed and implemented for the ecosystem by the USGS utilizes scientific findings from hydrologic process studies and data collected recently within the South Florida Ecosystem Program to define the ecosystem properties. All forcing functions that have a potential effect on flow conditions relevant to formulation and evaluation of restoration plans and actions for this ecosystem are concurrently and collectively treated by the SICS model.

The SICS model is being used to investigate hydroperiods and flow patterns in the wetlands concurrent with flows and salinity conditions in the nearshore embayments of Florida Bay in response to inflows and tidal effects. It can also be used to test and evaluate hypothetical restoration scenarios. Hydrologic results produced by the model will, for example, be integrated with ecological analyses to evaluate the effects of variations in regulated inflows on vegetative communities, such as the Muhlenbergia prairies needed by the Cape Sable Seaside Sparrow. Hydrological/ecological causeand-effect relations will then be available for development of endangered species assessments. Insight that the model provides on sheet flow and tidal interaction along the mangrove fringe is aiding the U.S. Army Corps of Engineers in the development of a circulation model for Florida Bay and will benefit agencies such the Everglades National Park and the South Florida Water Management District in planning and evaluating restoration alternatives.

Partial funding provided by the U.S. Department of the Interior "Critical Ecosystems Studies Initiative" (administered through the National Park Service).

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