HYDROLOGIC STUDIES IN SUPPORT OF SOUTH FLORIDA ECOSYSTEM RESTORATION[1]

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Abstract

The U. S. Geological Survey (USGS), which is the principal science agency of the Department of the Interior, has a prominent role in the Federal Government's initiative aimed at restoration of the south Florida ecosystem. USGS scientists, in cooperation with researchers from other Federal and State agencies, as well as academia, are undertaking a comprehensive program to document the ecosystem's physical characteristics and properties in order to provide the basic data and scientific information needed to ensure its survivability. The objective is to invoke the latest scientific findings in the decision-making process of land and resource managers for planning, evaluating, and executing restoration actions. One major component of the program is focused on investigating the hydrologic and hydraulic factors that affect the flow of water through the ecosystem. Hydrologic studies are yielding scientific findings that are helping to quantify hydroperiods and flow patterns that define wet-season durations critical to sustaining habitat for flora and fauna. In addition, the results of these discrete process studies are serving to improve numerical models that are being used to investigate cause-and-effect relations among hydrologic processes. In this paper, several hydrologic studies that are being conducted in support of the development of a numerical model of the interface of the Everglades ecosystem with Florida Bay are described, some preliminary findings of these process studies are presented, and the role of these scientific findings in the development of models for the south Florida ecosystem is discussed.

Introduction

The south Florida ecosystem extends from Lake Okeechobee in the south central part of Florida to Florida Bay and encompasses the Everglades—the largest remaining subtropical wilderness in the continental United States. A vast network of interlaced canals, rimmed with levees and fitted with hydraulic control structures, and highways, built on elevated embankments that are lined by drainage ditches and underlain by culverts, act in concert with the extensive Everglades wetland to confine, control, and direct the flow of water. As water flows south from Lake Okeechobee in the canals and wetland past the city of Miami, it is augmented by seasonably variable precipitation, is diminished by eastward diversions to the Atlantic Ocean, sustains losses through evapotranspiration, and interacts with groundwater. Along its path, the flow of water is subject to the resistance effects of variably dense vegetation and the shear-stress effects of winds, all the while serving as a conduit for the potential transport of nutrients and(or) contaminants.

About 40 percent of the water that originally flowed from Lake Okeechobee into the Everglades is now diverted directly to the Gulf of Mexico and the Atlantic Ocean. For more than a decade, various State and Federal agencies have been working jointly on design modifications to hydraulic control structures and improved operational strategies to

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reestablish more natural surface flows through the Everglades and into Florida Bay. Hydroperiods, which relate to the duration, timing, and extent of wetland inundation, in the southern part of the Everglades have been greatly distorted to the detriment of plant and animal life as indicated by shifts in biologic and vegetative species. Freshwater flows through the Everglades that reach the southern coastline of Florida principally discharge to the southwest into the Gulf of Mexico through Shark River Slough and to the south into Florida Bay through Taylor Slough. The quantity, timing, and distribution of freshwater flows to sub-tidal embayments along the coastline of Florida Bay, namely, from east-to-west, Long Sound, Joe Bay, Little Madeira Bay, Madeira Bay, and Terrapin Bay, have been affected by modification of inflows from the headwaters of Taylor Slough and canal C-111 drainage from the east. Changes in these inflows are thought to be a contributor to the development of hyper-salinity conditions, i.e., salt content in excess of the 35 ppt, in the sub-tidal embayments of Florida Bay.

One component of the South Florida Ecosystem Program of the USGS, referred to as the Southern Inland and Coastal Systems (SICS) Project, is focused on synthesizing and integrating findings from hydrologic process studies into a comprehensive research tool and management model for the Everglades wetland interface with Florida Bay. The objectives of the SICS project are to develop, implement, calibrate, and verify, with field-collected data, a mathematical/numerical hydrodynamic/transport model to compute overland flow through the Taylor Slough drainage basin of Everglades National Park (ENP). Taylor Slough extends about 30 km north of the coastal mangrove fringe of Florida Bay and gradually narrows along its course to a hydraulic control structure near its headwaters about 3 km north of ENP road. Sensitivity experiments are presently being conducted with the model to study the significance of terrain features, such as the elevated ridge along the north shore boundaries of the sub-tidal embayments referred to as the Buttonwood Embankment, and to evaluate the importance of dynamic effects, such as those produced by winds and the passage of weather fronts, on flow patterns and salinity conditions. Once the model is fully developed and calibrated, it will be useful for determining, by numerical simulations, the effects of freshwater inflows on hydroperiods and flow patterns in Taylor Slough in conjunction with forcing mechanisms that affect flow and salinity conditions in the sub-tidal embayments of Florida Bay. An additional objective of the model development is to determine flows and salinity exchanges at the coastline for use as boundary conditions by other simulation models being separately and independently developed solely for the Everglades wetland and solely for Florida Bay.

SICS Support Projects

The interdisciplinary SICS project is supported by a number of individual research project efforts that are being conducted by scientists from all disciplinary divisions (Water Resources, Geologic, National Mapping and Biological Resources) of the USGS. Investigations by scientists in the Water Resources Division are aimed at evaluating and representing hydrologic processes and hydraulic conditions, such as vegetative resistance, evapotranspiration (ET), wind forcing mechanisms, ground-water/surface-water exchanges, and canal/wetland interactions, to provide critically needed empirical coefficients, process descriptions, and(or) equation formulations. In concert with these investigations, a major effort is being undertaken to sample, classify, and map the varied wetland vegetation to provide detailed information on species composition, plant characteristics, vegetative structure, and biomass, and to extrapolate this information to regional scales for correlation of vegetation with hydrologic processes. Projects by Geologic Division scientists are focused on investigating bay-bottom materials and sea-level rise effects to characterize mechanisms controlling local driving forces within the sub-tidal embayments. An important by-product of these efforts is an improved representation of the bathymetry of the sub-tidal embayments, which has not been systematically mapped in more than 30 years. In addition, specific projects within the National Mapping Division are providing measurements of land-surface elevations that define landscape gradients in the wetland of Taylor Slough and identify the relief of unique terrain features, such as the Buttonwood Embankment along the mangrove fringe of Florida Bay. A new project effort is focused on integrating hydrologic findings and model results into the Across-Trophic-Level Simulation System project of the Biological Resources Division to investigate, for example, the ecological effects of hydroperiod changes on flora and fauna. These projects, as well as other related scientific efforts within the South Florida Ecosystem Program, are described in greater detail in Gerould and Higer (1997) and in a series of USGS Fact Sheets that can be accessed at the following website: http://sflwww.er.usgs.gov.

Study Area

The study area of the SICS project is the southern region of the Everglades that is bounded by the ENP road to the north and west and US Highway 1 to the east. It encompasses the principal flow area of the Taylor Slough and C-111 drainage basins, as well as the sub-tidal embayments between the mangrove fringe and Buttonwood Embankment in the northernmost part of Florida Bay. The canals, drainage culverts, extensive wetland, sub-tidal embayments, and underlying shallow aquifer of this interconnected southern inland and coastal ecosystem represent a geometrically complex, physically diverse, and dynamically changing environment that governs both the flow of water and transport of waterborne constituents. The study area is complicated by the extremely low relief of the wetland terrain and the resultant low velocities and shallow water-surface gradients that necessitate highly precise field measurements of geometric properties and hydraulic conditions.

Model Requirements

A sound mathematical model of this complex interconnected canal, wetland, and tidal ecosystem must include terms in its governing equations that properly represent all relevant hydrologic processes and hydraulic forces. Moreover, high-quality data that accurately depict the geometric properties and fully define these flow-controlling processes and forces are required for detailed development and implementation of the model, as well as for precise evaluation and correct interpretation of simulation results. For purposes of model calibration and verification, concurrent sets of hydraulic data are being collected and used to evaluate and confirm empirical coefficient values to accurately simulate flow and transport conditions. A brief description of the hydraulic measurements and hydrologic studies being conducted in support of the SICS model development follows.

Hydraulic Measurements and Hydrologic Studies

Flows and Nutrient Loads into Northeastern Florida Bay: This project provides flow and salinity data along the mangrove fringe of Florida Bay for SICS model development (Patino, 1996). The majority of overland runoff from the Taylor Slough and C-111 basins flows through the sub-tidal embayments and is channeled through several tidal creeks along the Buttonwood Embankment before reaching Florida Bay, except during extreme high-water conditions when sheet flow can occur through intervening low-lying mangrove areas. The project effort consists of the establishment of continuous monitoring stations at five of these key tidal creeks. From east to west, the station locations are West Highway Creek in Long Sound, Trout Creek in east Joe Bay, Mud Creek in west Joe Bay, Taylor River in Little Madeira Bay, and McCormick Creek in Terrapin Bay. These hydrologic stations, which have been in operation for more than three years, are equipped with acoustic velocity meters, water-level recorders, specific-conductance and temperature sensors, and telemetry instrumentation to monitor and record parameters continuously for determination of flow discharges and salt concentrations. Real-time and historical data from these stations can be accessed at http://www.sflorida.er.usgs.gov. Periodic measurements of flow discharges are also made at these five sites and at several other creeks to calibrate and verify stage/discharge ratings developed to compute discharges from continuously recorded stage data. Water samples for nutrient analysis (nitrogen and phosphorus) are collected on a monthly basis at the five continuous monitoring stations for "total" nutrient evaluation to complement work by other agencies and to determine trends in nutrient fluxes. Analysis of flow data collected to date indicates that Trout Creek in east Joe Bay conveys a volume of water about equal to the sum of the other tidal creeks; however, the source of this water is presently unknown and is being investigated by using the SICS model and supplemental field data.

Flow Velocity and Mass Flux Measurements Along Transects: Concurrent measurements of flow discharges and water-surface slopes are made at strategic transect locations within the Taylor Slough wetland to supplement those data being collected for model calibration at outflow points along the mangrove fringe of Florida Bay. Intensive flow measurements were made in July, September, and November of 1997 and in July of 1998. Flow velocities were measured along three transect lines that bisect the Taylor Slough basin from east to west roughly perpendicular to the principal flow direction. These flow velocities are used to compute mass transport through the cross-sectional transects and to evaluate frictional resistance coefficients using concurrently determined water-surface slopes. Measured flow velocities are found to be typically less than 1 cm/s and water-surface slopes on the order of 0.00001, i.e., about 1 cm/km. Principal water-quality parameters, e.g., temperature, specific conductance, dissolved oxygen, and pH, were also measured concurrently with the flow data to provide additional information for related process-study efforts. Long-term synoptic measurements are being made at the transect locations during varied freshwater inflow conditions to provide a representative set of data for hydroperiod evaluation and model calibration.

Vegetation Effects on Water Movement: The resistance exerted on flow by submersed vegetation is one of the dominant but least understood forces that affects Everglades surface-water flows. In the project effort to study these affects, experiments were initially conducted in a hydraulic flume to investigate the correlation of flow resistance with vegetation characteristics under controlled hydraulic conditions (Lee and Carter, 1996). Field hydraulic measurements of flow depths, flow velocities, and water-surface slopes are also being made throughout the Everglades wetland. These data are being analyzed to define flow resistance both in areas of homogeneous vegetation of approximately uniform density and areas of mixed vegetation of variable density, as typically found in the Everglades. Vegetation is sampled at all hydraulic measurement sites to investigate the dependence of flow resistance on vegetation characteristics. Biomass per unit area, number of stems and leaves per unit area, and leaf and stem width as a function of distance from the bed are determined to characterize the vegetation. Various expressions for flow resistance are derived from these field-measured parameters. Preliminary analysis of data from 15 locations in Shark River Slough yielded an average value of the frictional-resistance Manning's n coefficient between 0.42 and 0.44 for sawgrass of sparse to medium density, sparse rushes, mixed rushes and sawgrass, and cattails, whereas an average value of 0.48 was determined for very dense sawgrass. Developed expressions and empirical coefficient values are considered appropriate for quantifying flow resistance of typical Everglades plant communities in large-scale hydrodynamic models or regional hydrologic models.

Evaluation of Evapotranspiration: One of most important components of the Everglades water budget is evapotranspiration. Recent advances in instrumentation and measurement techniques have made it possible to monitor and record the parameters needed to evaluate ET continuously. A network of nine monitoring stations at sites that represent the various types of hydrologic and vegetative environments found in the Everglades is providing the micro-meteorological and basic hydrologic data needed for ET evaluation (German, 1996). Data for 1996 and 1997 have been analyzed and used to determine the annual amount and seasonal distribution of ET losses, as well as to identify the most important factors that contribute to ET. A preliminary evaluation based on data from these nine sites indicates a spatially variable annual ET that ranges from 107 to 139 cm. Spatial variability mostly reflects local availability of water and density of vegetative cover. Continuous measurement of parameters to evaluate ET at these sites is enabling the development of regional models that can be used to estimate ET at other times and locations throughout the Everglades.

Effect of Wind on Surface-Water Flows: Surface-water flows through the Everglades wetland are characterized by shallow (<1 m) depths and very low (<2 cm/s) velocities. These flows are driven or controlled at various scales by gravity, pressure, resistance, and wind forcing. Little is known about the effects of wind forcing on flow through emergent or submerged vegetation, such as variously found in the Everglades. The research approach being used in this project to study these effects consists of three principal components: (1) conducting a series of controlled flow and wind experiments using an enclosed cowling constructed on top of an indoor flume that contains live vegetation, (2) collection of a number of contemporaneous time-series measurements of wind speed and direction from instruments deployed at various field locations, and (3) synthesis of results from these two efforts into the development of an improved formulation of the wind-forcing term (Jenter, in press). The response of water velocity to wind is being studied as a function of wind speed, water depth, concurrent slope of the water surface, and vegetation characteristics. Insight into these functional relationships that is gained from the controlled flume experiments, and insight into the scales at which wind forcing data must be collected for model input that is gained from the field efforts, is serving to improve treatment of wind forcing in the SICS model.

Vertical Exchange of Ground Water and Surface Water: Knowledge about hydrologic exchange between surface water and ground water is critical to understanding the movement of water and dissolved chemical constituents (solutes) in the south Florida ecosystem. At present, estimates of vertical exchange are subject to considerable uncertainty in the Everglades. The objectives of this project are to (1) quantify vertical exchange of water between ground water and surface water (also referred to as seepage), (2) use seepage estimates to assist in the development of chemical mass balances for mercury and nutrients, and (3) relate seepage fluxes to subsurface hydrogeologic properties, to management of surface-water levels in canals and water conservation areas, and to regional water balance in eastern ENP (Harvey, 1996). Areally averaged seepage fluxes are being calculated from the system water balance by using measurements of surface-water and water-table elevation, surface-water flows, and estimates of precipitation and evapotranspiration. Environmental tracers in natural waters of the Everglades are being used to further constrain estimates of seepage, as well as source areas of water and travel times of water and solutes. By delineating seepage fluxes, this project is contributing key information to assess the effectiveness of restoration in this area of the Everglades, including possible effects on water quality.

Canal/Wetland Interactions: Within this research project, field measurement techniques, analytical and numerical approaches, and simulation methods are being developed and tested to evaluate flow exchanges between canals and wetlands (Schaffranek, 1996). The canal and wetland interaction of particular significance in terms of flow-distribution analyses in the SICS study area is the drainage basin of the canal identified as C-111 that lies to the east of Taylor Slough. Two hydraulic structures control flow into and out of C-111 within the SICS study area. Operation of these structures principally determines the amount of flow that can over-top the southwest bank of the canal and contribute to sheet flow through the wetland and into nearshore sub-tidal embayments of Florida Bay. Recent construction modifications, as part of the new restoration effort, included complete removal of residual spoil mounds that existed along the southwest bank of the canal with the intention being to enhance sheet flows. New measurement techniques and approaches that employ portable acoustic Doppler velocity meters are being used to collect data to quantify these canal and wetland flow exchanges. These data are needed to evaluate the effectiveness of spoil removal efforts and to test numerical methods to simulate canal to sheet flow transitions. These project efforts contribute information on boundary condition effects and inflow distribution patterns from the C-111 canal to the SICS study area for model development and flow simulation.

Model Development and Implementation

The SICS modeling project is focused on further development of a generic two-dimensional model and implementation of the model to the study area. Findings derived from hydrologic studies and hydraulic-measurement projects are being used to particularize the USGS two-dimensional Surface-Water Integrated Flow and Transport model (SWIFT2D) to this mixed wetland, canal, and tidal flow regime. SWIFT2D numerically solves finite-difference forms of the depth-integrated equations of mass and momentum conservation in conjunction with transport equations for heat, salt, and constituent fluxes. The computational algorithm is designed to account for the effects of hydraulic barriers such as a partially or fully submerged weir, a gate structure, or an impervious topographic boundary. The time-variable flooding and drying of tidal flats and wetlands are simulated by the model. The variations of frictional resistance due to changes in the flow depth and the shear-stress effects of winds are treated. The model is being enhanced to account for the regional effects of precipitation, ET, and groundwater exchanges. Findings derived from the wind forcing and vegetative resistance projects are providing critically needed empirical coefficient values and functional relationships for improved representation of these effects within the model and simulation scenarios.

The SICS model is being calibrated and verified by using concurrent sets of measured hydraulic data that define flow velocities and mass fluxes at strategic transect locations within the Taylor Slough wetland. Flow discharges and specific-conductance values for determination of salt concentrations that are measured at tidal creek outflow points along the mangrove fringe of Florida Bay are also being used for model calibration and verification. The present level of calibration shows strong agreement between simulated and measured flow magnitudes and distributions along the mangrove fringe in which Trout Creek is the dominant outflow point. Simulated flow velocities in the Taylor Slough wetland are in close agreement with flow patterns discerned from measured data, but additional calibration efforts await final verification of point velocities and the computation of mass fluxes through the measurement transects. Sensitivity experiments are being conducted with critical model parameters to establish error bounds for simulation results and to identify forcing mechanisms that control the flow dynamics and transport properties within the SICS study area. Boundary-condition influences are also being evaluated, demonstrated, and documented by numerical experiments.

Preliminary numerical simulations are demonstrating the ability of the model to identify the significance of hydrologic processes and the importance of treatment of external forcing mechanisms. Flow results are showing strong sensitivity to land-surface slopes, which are typically on the order of 0.00001, necessitating their precise representation. Unique terrain features are also found to have a pronounced effect on flow patterns and local hydroperiods. In one case, in particular, the ability of the Buttonwood Embankment to impound water along the mangrove fringe of Florida Bay is clearly demonstrated. Groundwater exchanges coupled with gains and losses due to precipitation and ET, which are major components of the hydrologic cycle, are also proving critical to balancing internal and external mass fluxes within the numerical simulations. Flow patterns and hydroperiods are showing their sensitivity to empirically derived frictional-resistance coefficients that have been correlated to dominant plant communities, e.g., bunchgrass, rush, sawgrass, and mangrove. In numerical simulations, water levels and flow volumes at the coastline are shown to be dominated by winds during the passage of weather fronts demonstrating the need for proper treatment of wind effects within the model domain and as an external forcing mechanism. Upon completion of these implementation and calibration efforts, the model will be useful for simulating a variety of naturally occurring and hypothetical conditions. Numerical simulations that represent past and present inflow and boundary conditions, which are designed and developed from available data or historical records, can be made to evaluate the effects of these changes on the ecosystem hydroperiod.

Summary

The Southern Inland and Coastal Systems Project of the South Florida Ecosystem Program of the U. S. Geological Survey is integrating the latest scientific findings of hydrologic process studies into a research and management tool for south Florida ecosystem evaluation and restoration. Process-study findings are being used to improve the mathematical representation of critical forcing mechanisms and(or) to define empirical coefficients and functional relations to implement a two-dimensional integrated surface-water flow and transport model to the southern Everglades ecosystem. The model is being applied to the Everglades wetland interface with Florida Bay by using the latest data depicting land-surface elevations, topographic features, vegetation characteristics, soil conditions, bottom-material classifications, and embayment bathymetry collected within ongoing process studies and mapping efforts. Thus, the findings of all hydrologic process studies and independent data-collection efforts are synthesized into a single tool for more thorough evaluation of restoration actions and plans. All relevant forcing functions that have a potential effect on restoration decisions are, thereby, concurrently and conjunctively treated in a consistent and rigorous mathematical model framework. Once fully developed, implemented, and calibrated, the model can be used to investigate hydroperiods and flow patterns that represent current conditions and to test and evaluate hypothetical restoration scenarios. Regional and local water-management officials who are charged with water-allocation and sewage-disposal responsibilities will benefit from the improved information that the model can provide for reconciling flow effects on inland areas, wetlands, well fields, and the sub-tidal embayments of Florida Bay. The principal benefactors of this project effort will be the general public, environmentalists, scientists, tourists, farmers, and commercial businesses who are directly concerned with and affected by preservation of the Everglades.

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The USGS South Florida Ecosystem Program is further described on the World Wide Web at http://sflwww.er.usgs.gov. For additional information contact Raymond W. Schaffranek, M. ASCE, Research Hydrologist, U. S. Geological Survey, National Center MS 430, 12201 Sunrise Valley Drive, Reston, VA 20192. Phone: (703) 648-5891, FAX: (703) 648-5484, E-mail: rws@usgs.gov