OVERVIEW OF THE "TIDES AND INFLOWS IN THE MANGROVES OF THE EVERGLADES" (TIME) PROJECT OF THE U. S. GEOLOGICAL SURVEY'S SOUTH FLORIDA ECOSYSTEM PROGRAM

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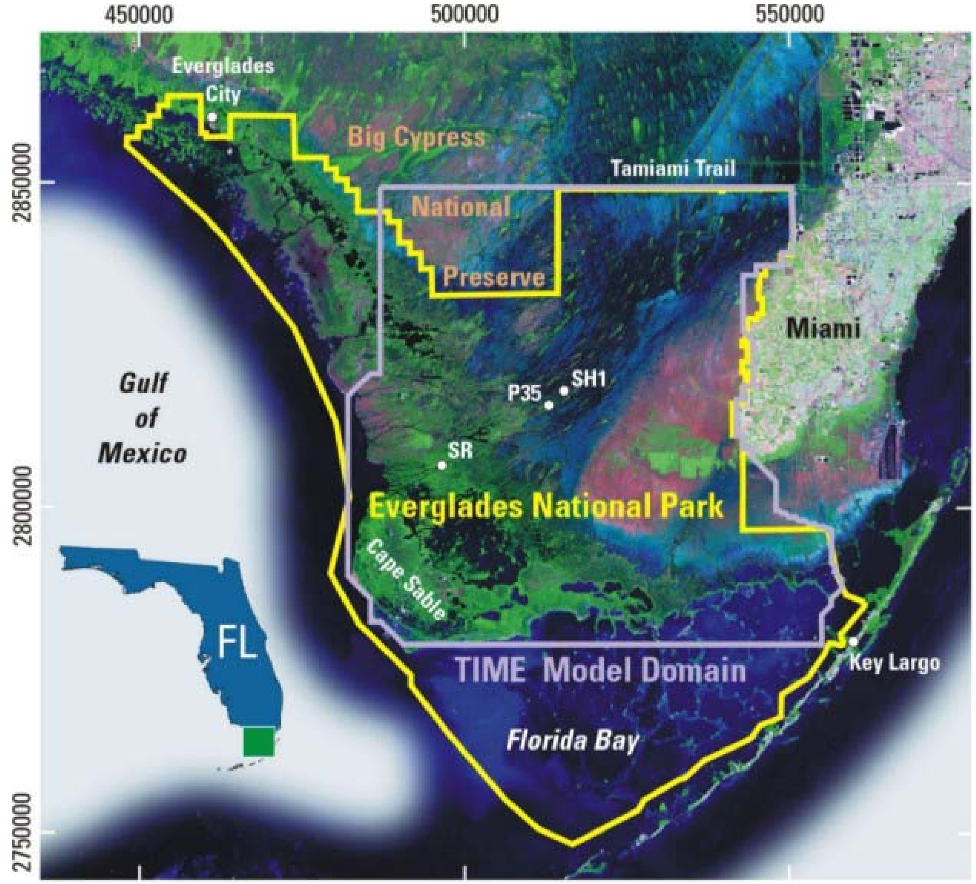
Abstract: The U.S. Geological Survey is contributing scientific findings and synthesized results from its South Florida Ecosystem Program toward development and implementation of the Comprehensive Everglades Restoration Plan. Findings derived from hydrological and ecological studies and extensive data collected to monitor and characterize the Everglades ecosystem are being integrated into the development of numerical models to guide and evaluate restoration decisions. A coupled surface-water/groundwater hydrodynamic/transport model is being developed for the coastal marine and freshwater wetland ecosystems of Everglades National Park. The multi-dimensional model is facilitating the development of estuarine ecological models by providing insight into the nature and extent of saltwater/freshwater mixing in the land-margin ecosystems that encompass the mangrove ecotone. Dynamic salinity transport simulations are being designed and generated to test the development of estuarine indicator species models for use as performance measures to evaluate the effectiveness of restoration actions. Projects contributing hydrologic process-study findings and data for development of the hydrodynamic/transport model are identified and the integration and use of the study results and data in the model are discussed in this paper.

INTRODUCTION

The coastal interface of the freshwater Everglades with Florida Bay and the Gulf of Mexico is primarily within Everglades National Park (ENP) (fig. 1). This region provides nesting habitat and is a primary productivity area for the food web of several endangered species. Land-margin ecosystems, composed mainly of mangrove thickets, brackish marshes, tidal creeks, and coastal embayments, constitute roughly 40 percent of ENP. Endangered species that depend on these ecosystems necessitate the preservation and restoration of hydrological and ecological conditions that are consistent with their habitat requirements. This need is particularly problematic for water-management agencies responsible for implementing the Comprehensive Everglades Restoration Plan (CERP), http://www.evergladesplan.org/the_plan/2lev_restoration_plan.shtml,



Base from U.S. Geological Survey South Florida satellite image map, 1993
Geographic Coordinates, NAD 83, Zone 17 Meters

Figure 1. Satellite image of Everglades National Park (yellow outline) showing the TIME model domain (purple outline), delineated April 2002.

due to the delicate balance that exists among freshwater inflows, tidal fluxes, meteorological forces, and resultant salt concentrations. The development of a numerical model to facilitate ecological analyses and investigation of the potential intrusion of saline water into the freshwater wetlands and surficial aquifer of ENP is a principal focus of the Tides and Inflows in the Mangroves of the Everglades (TIME) Project (Schaffranek, 2001), http://time.er.usgs.gov/.

The primary objective of the TIME project is to develop an integrated surface-water/groundwater hydrodynamic/transport model capable of investigating saltwater/freshwater mixing in the land-margin ecosystems of ENP, which is not considered in existing management models of the south Florida ecosystem. A preliminary and partial model grid of 500-meter-square cells covering the Dade and eastern Monroe County portions of ENP wetlands has been generated from 400-meter-spaced land-surface elevation data collected in an ongoing mapping effort. A companion multi-layered model grid of the groundwater system also is under development (Langevin et al., 2002). Once fully developed and applied to the entire computational domain, the TIME model will provide a mechanism to address questions critical to preserving these coastal marine ecosystems within the context of upland freshwater management. Upon its completion, the coupled model will be able to simulate flow exchanges and salt fluxes between the surface-water and groundwater systems constituting the interface of the Everglades with Florida Bay and the southwest Gulf coast of Florida. In this paper, findings from hydrologic process studies and data obtained from monitoring projects in support of the surface-water model development are identified and their use in developing the TIME model is discussed.

TIME PROJECT

Objectives: The overall objectives of the TIME project are to develop, implement, and provide a mathematical model to study the interaction of overland flow and tidal forces, including flow exchanges and salt fluxes between the surface-water and groundwater systems, in the mangrove-dominated transition zone between the freshwater wetlands and coastal-marine ecosystems of the Everglades. The TIME project and model development are focused on providing the means to address the following key questions pertaining to restoration actions and management decisions:

- How do the Everglades freshwater-wetland and coastal-marine ecosystems respond concurrently, both hydrologically and ecologically, to regulation of inflow?
- Will upland restoration actions affect the transformation of freshwater wetlands to brackish and marine marshes and subsequently to mangrove marsh ecotones?
- How will changes in freshwater inflows act in concert with predicted increases in sea level to affect migration of the saltwater/freshwater interface within the surface and subsurface flow systems?
- What hydrologic and hydraulic factors influence salt concentrations in the coastal mixing zone and how do these affect wildlife habitat areas?
- How will external dynamic forcing factors, such as sea-level rise or meteorological effects, adversely affect upland regulatory plans?
- What concurrent changes in wetland hydroperiods and coastal salinities are likely to occur in response to various proposed restoration and management plans?

Collaborating Projects: The TIME project, which began in October 1999, is utilizing scientific findings and monitoring results from projects conducted by multidisciplinary scientists within the USGS South Florida Ecosystem Program (McPherson et al., 1999). Hydrologists are evaluating hydrologic processes and hydraulic forces, including the resistance effects of vegetation on flow, evapotranspiration mechanisms, wind-stress effects on flow through vegetated water columns, surface-water/groundwater exchanges, and canal/wetland interactions, to provide critically needed empirical coefficients, process descriptions, and equation formulations for model development (Schaffranek, 1999). Geologists are investigating anthropogenic influences on hydrologic changes in the freshwater wetlands and the historical impacts of sea-level rise on coastal marine ecosystems. Geographers are providing detailed measurements of the land-surface elevation that define topographic gradients in the wetlands and that quantify the relief of unique terrain features such as the mangrove fringe along the southwest Gulf coast and Florida Bay. A major collaborative effort by hydrologists and remote-sensing specialists is underway to sample, classify, and map the wetland vegetation to provide detailed information on species composition, plant characteristics, vegetative structure, and biomass for quantification of hydrologic processes. A joint effort between hydrologists and biologists is aimed at integrating hydrological and ecological findings at scales of resolution required for the development of new species models (Cline and Swain, 2002). The primary focus of these collaborations is extension of the present suite of ecological indicator models within the Across Trophic Level Simulation System (ATLSS) (http://www.atlss.org/), used extensively in development of CERP (Comiskey and Gross, 2000), to include estuarine species (DeAngelis, 2000). TIME model results that define, for example, salinity changes in marine habitat areas will enable development of estuarine fish (Cline et al., 2000; McIvor and Whaley, 2000), crocodile (Mazzotti et al., 2000), and wading bird models. Projects supporting the TIME model development effort within the USGS South Florida Ecosystem Program and others of related scientific interest are described in abstracts published in Eggleston et al. (2000) and in Fact Sheets available at the USGS South Florida Information Access (SOFIA) (http://sofia.usgs.gov/) website. Projects directly contributing or collaborating in the TIME model development include:

Across Trophic Level System Simulation (D. L. DeAngelis, Project Chief)
High Accuracy Elevation Data Collection (G. B. Desmond, Project Chief)
Geophysical Studies of the Southwest Florida Coast (D. V. Fitterman, Project Chief)
Regional Evaluation of Evapotranspiration in the Everglades (E. R. German, Project Chief)
Groundwater/Surface-Water Exchange Fluxes in the Everglades (J. W. Harvey, Project Chief)
Groundwater Flow and Transport for SICS and TIME Models (C. D. Langevin, Project Chief)
Freshwater Flows into Northeastern Florida Bay (C. D. Hittle, Project Chief)
Vegetative Resistance to Flow (H. L. Jenter, Project Chief)
Land Characteristics from Remote Sensing (J. W. Jones, Project Chief)
Water Flows and Nutrient Fluxes to Southwest Coast (E. Patino, Project Chief)
Southwest Coastal and Wetland Systems Monitoring (E. Patino, Project Chief)
Land Margin Ecosystem Program (T. J. Smith III, Project Chief)
Coupling Surface-Water/Groundwater Flow and Transport Models (E. D. Swain, Project Chief)

Study Area: The study area of the TIME project is the southern region of the Everglades within ENP (fig. 1). It includes the flow area of the principal sloughs and marshes of the wetlands and the tidal creeks and sub-tidal embayments within the mangrove ecotone along the northernmost coastline of Florida Bay and the southwest Gulf coast of Florida. Tides propagating through creeks in the mangrove ecotone that connect the freshwater wetlands with Florida Bay and the Gulf of Mexico affect flow exchanges between these ecosystems and produce a mixing zone for saline and fresh water. The water-level data shown in figure 2, collected at three monitoring stations (sites SR, P35, and SH1 in fig. 1), illustrate the effects of tides on flows that originate in the wetlands and propagate through the mangrove ecotone of the southwest Gulf coast. The semi-diurnal tide range (approximately 50 to 80 cm) in the mangrove creeks is on the order of the maximum water depth in the freshwater wetlands. The extensive wetlands, numerous sub-tidal embayments, dendritic systems of tidal creeks, and underlying shallow aquifer of this ecosystem represent a geometrically complex, physically diverse, and dynamic environment that governs the flow of water and transport of constituents. The extremely shallow relief of the wetland terrain with its inherent low flow velocities and small water-surface gradients necessitates the collection of accurate and extensive data to characterize and represent the geometric properties, hydrologic processes, and hydraulic factors that govern flow and transport.

Model Formulation: The surface-water/groundwater hydrodynamic/transport model being developed to simulate flow and transport through the coastal land-margin ecosystems of the southern Everglades represents a coupling and extension of existing models. The two-dimensional, depth-averaged, Surface Water Integrated Flow and Transport (SWIFT2D) model (Leendertse, 1987) has been coupled to the three-dimensional, variable-density, groundwater model SEAWAT. SEAWAT is a coupled version of the Modular Groundwater Flow (MODFLOW) model (McDonald and Harbaugh, 1988) and the solute-transport model MT3D (Zheng, 1990). A numerical algorithm has been developed to synchronize SWIFT2D tidal-compatible time steps with SEAWAT stress periods. Revised numerical expressions and algorithms derived from ongoing hydrologic process studies have been formulated for incorporation into SWIFT2D to better simulate hydrologic conditions affecting the wetland flow regime. These expressions and algorithms link evapotranspiration, flow-resistance, and wind-stress effects to vegetative properties and to the extremely slow flows and shallow depths typical of the low-gradient Everglades wetlands.

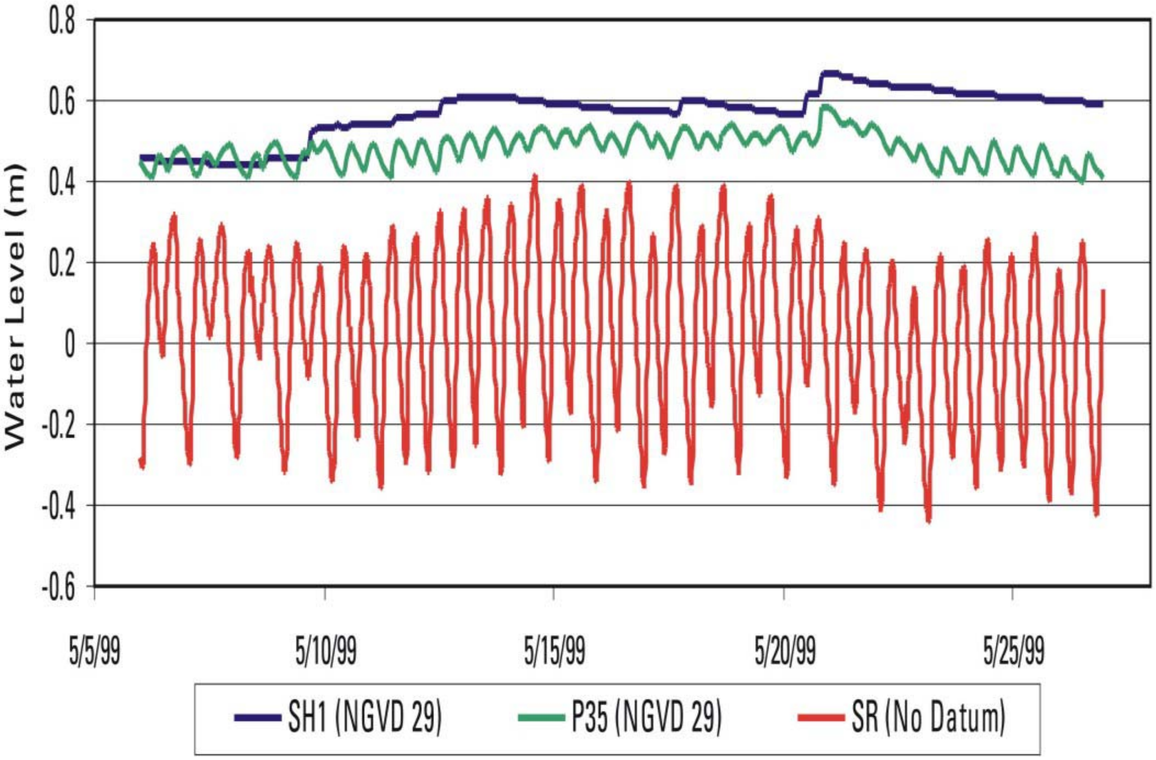


Figure 2. Water levels recorded in Shark River (SR) and Shark River Slough (P35 and SH1). (P35 data from NPS/ENP, SH1 data from USGS Land Margin Ecosystem Program, and SR data from USGS Water Flows and Nutrient Fluxes to Southwest Coast Project.)

HYDROLOGIC PROCESSES

Evapotranspiration: One of the most important components of the Everglades water budget is evapotranspiration (ET). 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 in the Everglades has provided the micro-meteorological and basic hydrologic data needed for ET evaluation (German, 2000). Data for 1996 and 1997 have been analyzed and used to determine the annual amount and seasonal distribution of ET losses and to identify the most important factors that contribute to ET. Spatial variability in ET mostly reflects local availability of water and density of vegetative cover. Continuous evaluation of ET at selected sites has enabled the development of regional ET models based on the Bowen-ratio energy-budget method (Bowen, 1926) that can be used to estimate ET at other times and locations throughout the Everglades. Solar radiation and energy flux measured at the ET sites, three of which are within the TIME model domain, are provided as input to the TIME model. These inputs enable continuous regional evaluation of ET as a function of changing water depth, which is simulated by the TIME model, through application of the site-specific ET model appropriate to the local vegetation.

Vegetative Resistance: Vegetation plays a pivotal role in controlling the speed and direction of flows in the highly frictional Everglades environment. Numerous laboratory and field experiments have been conducted in order to quantify the resistance effect of vegetation on flow conditions (Lee et al., 2002). Analysis of co-located velocity and vegetation-characteristic profiles has shown that the drag force on flow is a function of both a Reynolds number based on average spacing between plant stems and the ratio of this stem spacing to water depth. This relationship has been verified using laboratory and field measurements. Current research is being conducted to correlate the difficult-to-measure average stem spacing to other vegetative characteristics that are more readily determined using remote sensing techniques. Numerical algorithms are being developed to apply these findings on the resistance effects of vegetation at the spatial resolution scale of the TIME model.

Wind Effects: The ability of wind to affect flow conditions in the Everglades has been a topic of debate. Laboratory experiments by Jenter and Duff (1999) have shown that winds of 32 kilometers per hour (20 miles per hour) can accelerate or decelerate the top 20 or so centimeters of the water column in moderately dense sawgrass. In addition, observations of temperature profiles in the Everglades by Schaffranek and Jenter (2001) indicate that high winds can cause mixing in the upper part of the water column, e.g., top few tens of centimeters. Both studies show that the effects of the wind on flow in the vegetated wetlands are significantly damped relative to their effects in open water. Defining the wind's diminished ability to affect flow in vegetated wetlands is the focus of current research. This vegetation effect is incorporated into the quadratic wind-stress term of the TIME model through use of a sheltering coefficient multiplied by the open-water drag coefficient (Large and Pond, 1981). Due to the lack of quantitative measurements of these sheltering coefficients, a value 0.1 (Reid and Whitaker, 1976) presently has been applied to all vegetated grid cells within the model domain. Ongoing field measurements are focused on defining the effects of wind in different types and densities of vegetation to assign more definitive coefficients to evaluate varied sheltering effects.

TIME MODEL DESCRIPTION

Computational Domain: The TIME project study area encompasses the full model domain that extends from an eastern boundary at canal levees west of Miami to a western boundary along the Gulf coast from Cape Sable to Everglades City and from a northern boundary along Tamiami Trail to a southern boundary in Florida Bay from Key Largo to Cape Sable (fig. 1). The extensive model domain enables direct and concurrent simulation of coastal driving forces and freshwater flows into ENP. At present, the western boundary of the TIME model domain ends approximately 25 km east of Everglades City (fig. 1), which is the extent of available topographic data. Water-level, rainfall, flow-velocity, and discharge data collected in the wetlands, canals, culverts, and tidal creeks throughout the study area are being used to evaluate empirical coefficients, to account for internal flow sources, to quantify external open-boundary flows, and to calibrate the model.

Internal Sources and Sinks: Precipitation is the largest internal flow source within the model domain and groundwater flow exchanges are a secondary internal surface-water source or sink. Measured rainfall is interpolated spatially and temporally using Geographic Information System techniques to generate time-series maps for model input. Surface-water/groundwater exchanges are explicitly treated by coupling the SWIFT2D surface-water and SEAWAT groundwater models through Darcy's Law (Langevin et al., 2002).

Topography: Extensive elevation data are required to define the topography of the wetlands and the bathymetry of tidal creeks and coastal embayments in the mangrove ecotone. A preliminary partial grid of land-surface elevation data (500-meter-square cells), referenced to North American Vertical Datum 1988 (NAVD88), has been generated from data points surveyed using geodetic-quality differential global positioning system technology to represent the topography (Desmond et al., 2000) and bathymetry (Hansen, 1997) (fig. 3). The land-surface elevation grid

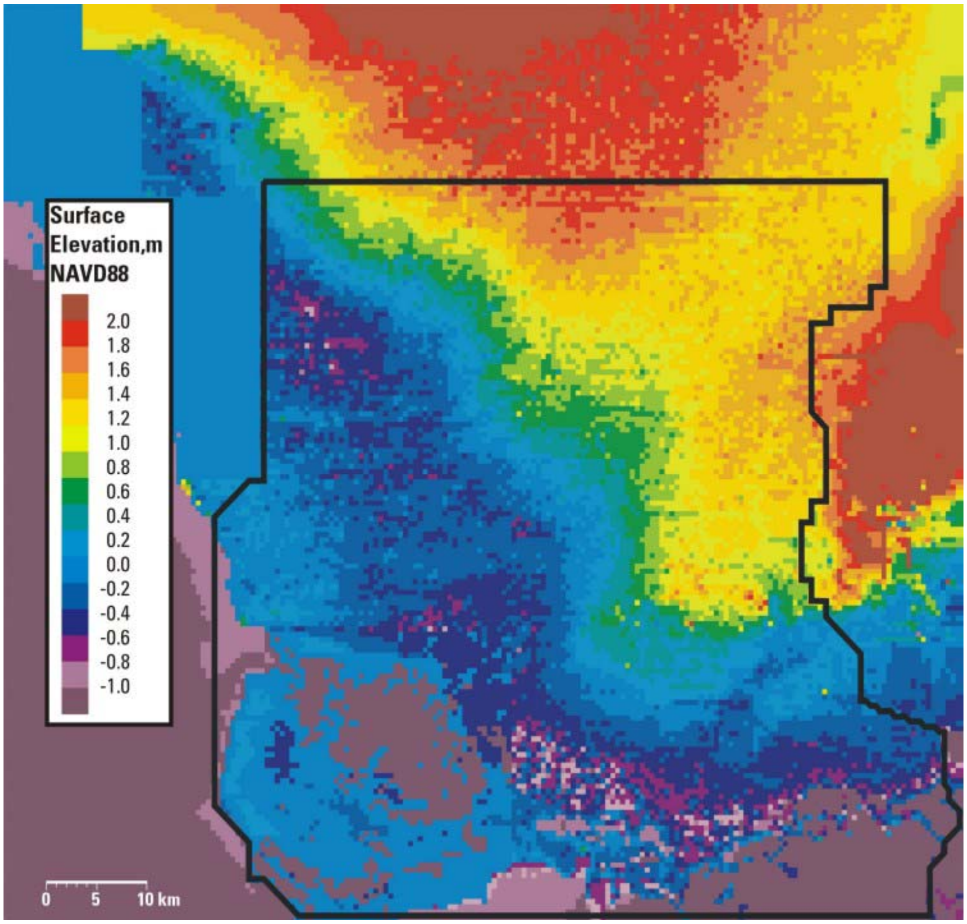


Figure 3. Surface elevation grid (500-m cells) for the TIME model (black outline).

is being updated and expanded continually as new survey data become available from the ongoing mapping effort. No topographic data are available for the western mangrove ecotone along the interface of the Everglades wetlands with the Gulf of Mexico. In the model grid shown in figure 3, topography in the vicinity of Cape Sable and along the Gulf coast, as well as the bathymetry of Whitewater Bay and tidal creeks in the mangrove ecotone, have been estimated.

Vegetation: A vegetation-classification scheme has been developed specifically to serve as the basis for quantifying hydrologic processes in the TIME model. Vegetation classes are defined to evaluate evapotranspiration, frictional-resistance effects, and wind-stress conditions. Twenty land-cover classes, derived from 1997 Landsat Thematic Mapper imagery (Jones, 2000), were subsequently combined into seven vegetation classes and one open-water class using field information on vegetative composition and structure as well as extensive ground-truth observations. The vegetation-classification grid for the TIME model in figure 4 shows the open water and seven vegetation classes, i.e., sawgrass, sawgrass/bunchgrass, mixed sawgrass/rush, rush/other grasses, evergreen, mangrove, and sparse sawgrass/rush/water. These vegetation classes presently are serving as the basis for quantifying hydrologic processes within the model; however, they are being further analyzed and refined as more recent Landsat images and ground-truth data become available. Other remote sensing data and image analysis techniques are under study to further define vegetation characteristics for improved hydrologic process representation.

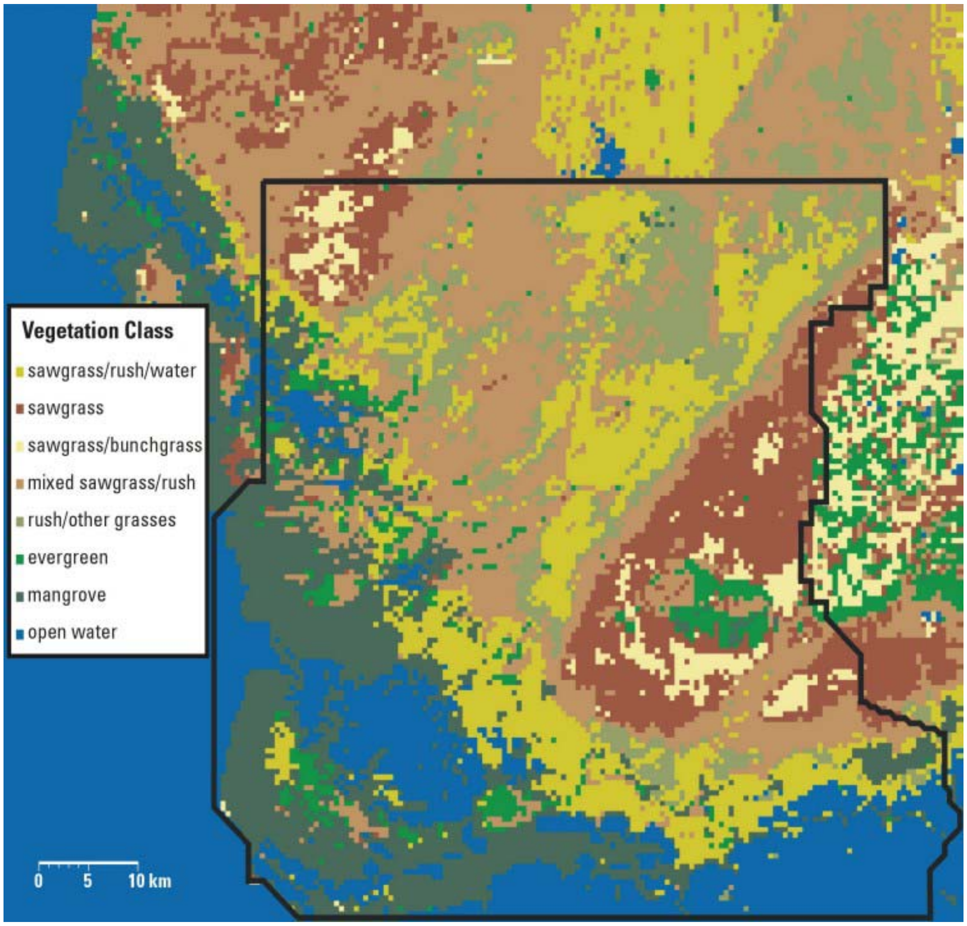


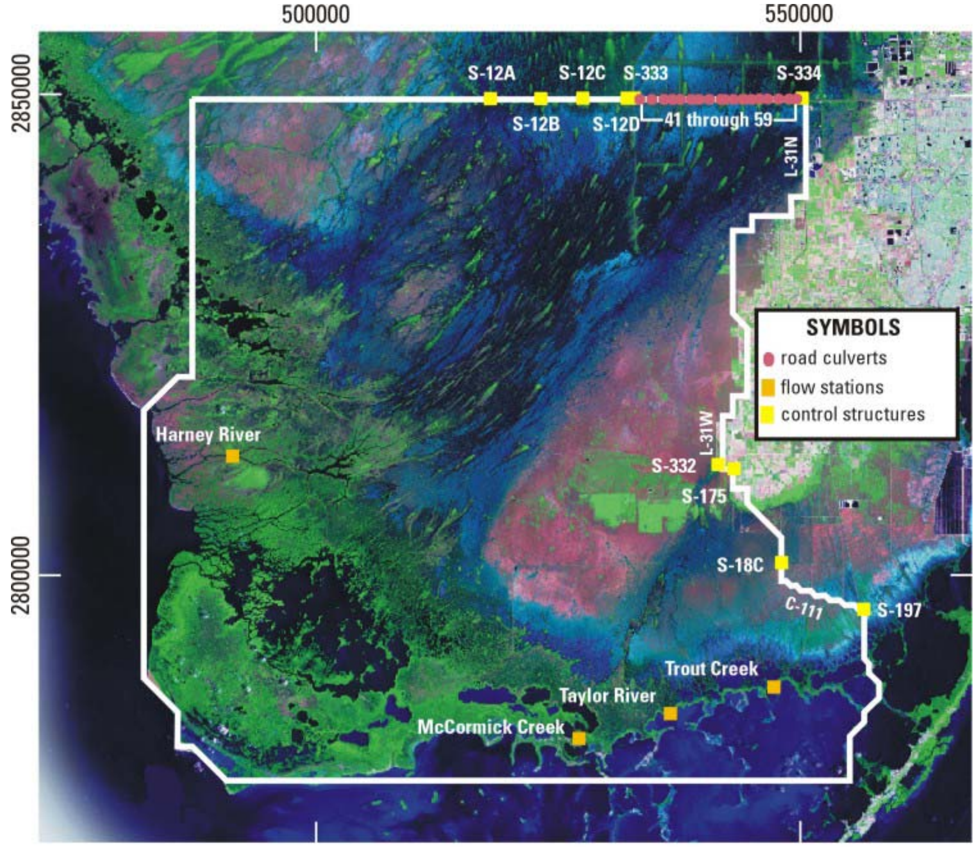
Figure 4. Vegetation-classification grid (500-m cells) for the TIME model (black outline).

Open-Boundary Flows: Water-level, velocity, and discharge data collected in the wetlands, canals, culverts, and tidal creeks are being used to evaluate empirical coefficients, to define external inflows and water-level conditions at open boundaries, and to calibrate the model. At the eastern extent of the model domain, freshwater inflows from the L-31W canal and overbank flows from canal C-111 are specified as open-boundary conditions by hourly discharges derived from ratings for the S-332, S-175, S-18C, and S-197 hydraulic control structures (fig. 5). At the northern model boundary along Tamiami Trail (fig. 1), mean daily water levels at the S-12A-D, S-333, and S-334 control structures (fig. 5) and mean daily discharges at the S-12A-D control structures are used as open-boundary conditions. Mean hourly discharges for 19 culverts, identified as numbers 41–59 in figure 5, also are specified as open-boundary inflows along Tamiami Trail. At the southern extent of the model domain in Florida Bay and at the western extent northwest of Cape Sable (fig. 1), tidal water levels are specified as open-boundary conditions. Although there are a number of water-level stations along the western Gulf coast boundary of the mangrove ecotone, the lack of vertical datum control in this remote area is problematic for their use as boundary conditions. Water levels measured at a USGS flow-monitoring station in Harney River (fig. 5), with an estimated reference adjustment applied to reflect NAVD88, are being used for the western open-boundary condition along the Gulf coast northwest of Cape Sable. Field efforts are underway to reference existing water-level stations along the Gulf coast to NAVD88 and the western boundary condition of the model will be modified at the completion of the surveys. The open-boundary condition for Florida Bay, between Key Largo and Cape Sable, has been interpolated from water-level data measured at three USGS coastal flow-monitoring stations, McCormick Creek, Trout Creek and Taylor River (fig. 5).

Wetland Flows: Flow-velocity, water-level, and salinity data collected in the wetlands and tidal creeks are being used to implement, calibrate, and verify the TIME model. The low relief of the wetland terrain yields small water-surface gradients (approximately 10^{-6}) and extremely slow flow velocities, typically on the order of 0-4 cm/s (Riscassi and Schaffranek, 2002; Schaffranek and Ball, 2000). Water levels, flow velocities, and salinities are being collected and compiled for comparison to simulation results for model adjustment and verification in the calibration process.

TIME PROJECT STATUS

Process studies and monitoring efforts within the ongoing USGS South Florida Ecosystem Program continue to produce results and data for synthesis and integration into development of the TIME model. New and refined numerical algorithms are being developed and coded into the surface-water model to reflect recent hydrologic process-study findings. Mapping efforts to quantify the physical characteristics of the wetlands and mangrove ecotone are in progress and the computational domain of the surface-water model continues to be enhanced and expanded as new data become available. Development of the groundwater model is progressing concurrently, but additional geophysical data also are needed to better characterize the aquifer system (Langevin et al., 2002). Field data-collection efforts are underway to provide the missing data needed to further develop both models for integration into the TIME model.



Base from U.S. Geological Survey South Florida satellite image map, 1993
Geographic Coordinates, NAD 83, Zone 17 Meters

Figure 5. Satellite image of south Florida showing locations of culverts, flow stations, and hydraulic control structures in the TIME model domain (white outline).

SUMMARY

The Tides and Inflows in the Mangroves of the Everglades (TIME) Project of the U. S. Geological Survey's South Florida Ecosystem Program is integrating the latest scientific findings of hydrologic process studies into development of a research and analysis tool for evaluation and restoration of the Everglades. Process-study findings are being used to extend and improve the mathematical representation of critical forcing mechanisms and to define empirical coefficients and functional relations for the development and implementation of a coupled surface-water/groundwater hydrodynamic/transport model of the southern Everglades. The model is being applied to the interface of the Everglades freshwater wetlands with Florida Bay and the Gulf of Mexico within Everglades National Park using data depicting land-surface elevations, topographic features, vegetation characteristics, and coastal bathymetry that are being collected in ongoing mapping efforts. After being fully developed, implemented, and calibrated, the model will provide the capability to investigate wetting and drying patterns and flow conditions in the freshwater wetlands concurrent with flow and salinity conditions in connected marine ecosystems in response to changing inflows and tidal effects. Salinity simulation results are being factored into the development of new estuarine ecological indicator species models for evaluation and restoration of the south Florida ecosystem.

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