Application of FTLOADDS to Simulate Flow, Salinity, and Surface-Water Stage in the Southern Everglades, Florida

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Abstract

The Comprehensive Everglades Restoration Plan requires numerical modeling to achieve a sufficient understanding of coastal freshwater flows, nutrient sources, and the evaluation of management alternatives to restore the ecosystem of southern Florida. Numerical models include a regional water-management model to represent restoration changes to the hydrology of southern Florida and a hydrodynamic model to represent the southern and western offshore waters. The coastal interface between these two systems, however, has complex surface-water/ground-water and freshwater/saltwater interactions and requires a specialized modeling effort. The Flow and Transport in a Linked Overland/Aquifer Density Dependent System (FTLOADDS) code was developed to represent connected surface- and ground-water systems with variable-density flow.

The first use of FTLOADDS is the Southern Inland and Coastal Systems (SICS) application to the southeastern part of the Everglades/Florida Bay coastal region. The need to (1) expand the domain of the numerical modeling into most of Everglades National Park and the western coastal area, and (2) better represent the effect of water-delivery control structures, led to the application of the FTLOADDS code to the Tides and Inflows in the Mangroves of the Everglades (TIME) domain. This application allows the model to address a broader range of hydrologic issues and incorporate new code modifications. The surface-water hydrology is of primary interest to water managers, and is the main focus of this study. The coupling to ground water, however, was necessary to accurately represent leakage exchange between the surface water and ground water, which transfers substantial volumes of water and salt.

Initial calibration and analysis of the TIME application produced simulated results that compare well statistically with field-measured values. A comparison of TIME simulation results to previous SICS results shows improved capabilities, particularly in the representation of coastal flows. This improvement most likely is due to a more stable numerical representation of the coastal creek outlets.

Sensitivity analyses were performed by varying frictional resistance, leakage, barriers to flow, and topography. Changing frictional resistance values in inland areas was shown to improve water-level representation locally, but to have a negligible effect on area-wide values. These changes have only local effects and are not physically based (as are the unchanged values), and thus have limited validity. Sensitivity tests indicate that the overall accuracy of the simulation is diminished if leakage between surface water and ground water is not simulated. The inclusion of a major road as a complete barrier to surface-water flow influenced the local distribution and timing of flow; however, the changes in total flow and individual creekflows were negligible. The model land-surface altitude was lowered by 0.1 meter to determine the sensitivity to topographic variation. This topographic sensitivity test produced mixed results in matching field data. Overall, the representation of stage did not improve definitively.

A final calibration utilized the results of the sensitivity analysis to refine the TIME application. To accomplish this calibration, the friction coefficient was reduced at the northern boundary inflow and increased in the southwestern corner of the model, the evapotranspiration function was varied, additional data were used for the ground-water head boundary along the southeast, and the frictional resistance of the primary coastal creek outlet was increased. The calibration improved the match between measured and simulated total flows to Florida Bay and coastal salinities. Agreement also was improved at most of the water-level sites throughout the model domain.

1 - Introduction

The Comprehensive Everglades Restoration Plan (CERP), authorized by the Water Resources Development Act of 2000, provides a framework and guide to restore, protect, and preserve the water resources of central and southern Florida, including the Everglades (U.S. Army Corps of Engineers and South Florida Water Management District, 2003). One goal of CERP is to determine the physical modifications and operational changes to the Central and Southern Florida Project necessary to restore the Everglades ecosystem of southern Florida. This requires a thorough evaluation of Florida Bay within the context of the numerous regional water-resource issues in southern Florida. To meet this need, the U.S. Army Corps of Engineers (USACE) and the South Florida Water Management District (SFWMD) initiated the Florida Bay Florida Keys Feasibility Study (FBFKFS) in 2001 (Worth and others, 2002) to (1) evaluate Florida Bay and its connections to the Everglades, Gulf of Mexico, and the Florida Keys marine ecosystems; and (2) determine the modifications that are needed to restore water-quality and ecological conditions of Florida Bay successfully, while maintaining or improving conditions in the marine ecosystem of the Florida Keys.

The need to accurately represent the Everglades flows and their respective flow alterations caused by restoration changes led the U.S. Geological Survey (USGS) to (1) develop a coupled surface-water/ground-water numerical code known as the Flow and Transport in a Linked Overland/Aquifer Density-Dependent System (FTLOADDS), and (2) apply the code to inland and coastal regions of the Everglades. The FTLOADDS code combines the two-dimensional hydrodynamic surface-water model SWIFT2D and the three-dimensional ground-water model SEAWAT, and accounts for leakage and salt flux between the surface water and ground water (Langevin and others, 2005). The code was initially applied to the Southern Inland and Coastal Systems (SICS) model domain (Swain and others, 2004; Wolfert and others, 2004). In the current effort, initiated in 2002, FTLOADDS is applied to the larger Tides and Inflows in the Mangroves of the Everglades (TIME) model domain. This ongoing effort is conducted as part of the USGS Greater Everglades Priority Ecosystem Sciences Initiative in cooperation with the SFWMD.

In order to achieve the objectives of the FBFKFS study, the TIME application is linked to a Florida Bay hydrodynamic model developed for the FBFKFS study to simulate water movement and water quality in the bay (Hamrick and Mustafa, 2003). The TIME application supplies the Florida Bay model with freshwater flow and nutrient inputs entering Florida Bay from the Everglades, and water levels and salinity on the Atlantic Ocean and Gulf of Mexico boundaries. As with the SICS application, TIME is modified to accept inland boundary conditions from the regional South Florida Water Management Model (SFWMM). This will allow the representation of proposed restoration scenarios to be input to TIME from the SFWMM, and the effects on coastal flows to be transferred from TIME to the Florida Bay model.

1.1 - Purpose and Scope

This report documents the application of the FTLOADDS code to the TIME domain to generate information for restoration objectives. Specific code enhancements to FTLOADDS and its application to the TIME domain are described in detail. The linkage of the domains to the regional southern Florida model also is described, as well as the results of scenarios using boundaries developed from the regional model. FTLOADDS is a coupled surface-water/ground-water model, but because the surface-water regime primarily controls the hydrology and is of primary interest to water managers, most of the discussion herein concerns the surface-water part of the simulation.

Parameters used as input for the TIME application are described, including topography, frictional resistance, aquifer characteristics, natural and anthropogenic barriers, rainfall and evapotranspiration, wind, water-level and salinity boundaries, and initial conditions. The application is calibrated using water levels, flows, and salinities at known stations in the model domain. Sensitivity studies of the TIME application are conducted by comparing output statistics between the calibrated application and a simulation with (1) the model-code version used for SICS, (2) local adjustment of frictional resistance, (3) no leakage, (4) a road barrier removed, and (5) lowered land surface. The sensitivity of the model to these changes is used to establish error bounds for simulation results and to identify critical factors controlling model flow and transport.

Results are presented in appendix 1 for different scenario runs conducted for the FTLOADDS application to the SICS area using boundaries generated from SFWMM runs. The TIME scenario testing is an ongoing effort, with results documented as they are produced.

1.2 - Description of Study Area

The TIME application domain consists of about 5,250 km^2 of pine uplands, cypress swamps, hardwood hammocks, wetland marsh, wet prairies, lakes, sloughs, and rivers contained within the Everglades National Park/Big Cypress National Preserve areas. The TIME domain contains the SICS domain and is bounded to the north by Tamiami Trail (U.S. Highway 41); to the west by U.S. Highway 29 and the Gulf of Mexico; to the south by Florida Bay; and to the east by Levee 31N, Levee 31W, and U.S. Highway 1 (fig. 1).

Several major drainage features, including sloughs and topographic depressions, intersect the approximately 85- × 75-km TIME domain. The largest feature is Shark River Slough, which extends southwest from the northeastern corner of the domain to the west coast shoreline. Taylor Slough is a smaller drainage feature in the southeastern corner of the domain and, together with several coastal creeks, is the main source of runoff to northeastern Florida Bay. The northwestern part of the domain has several additional sloughs

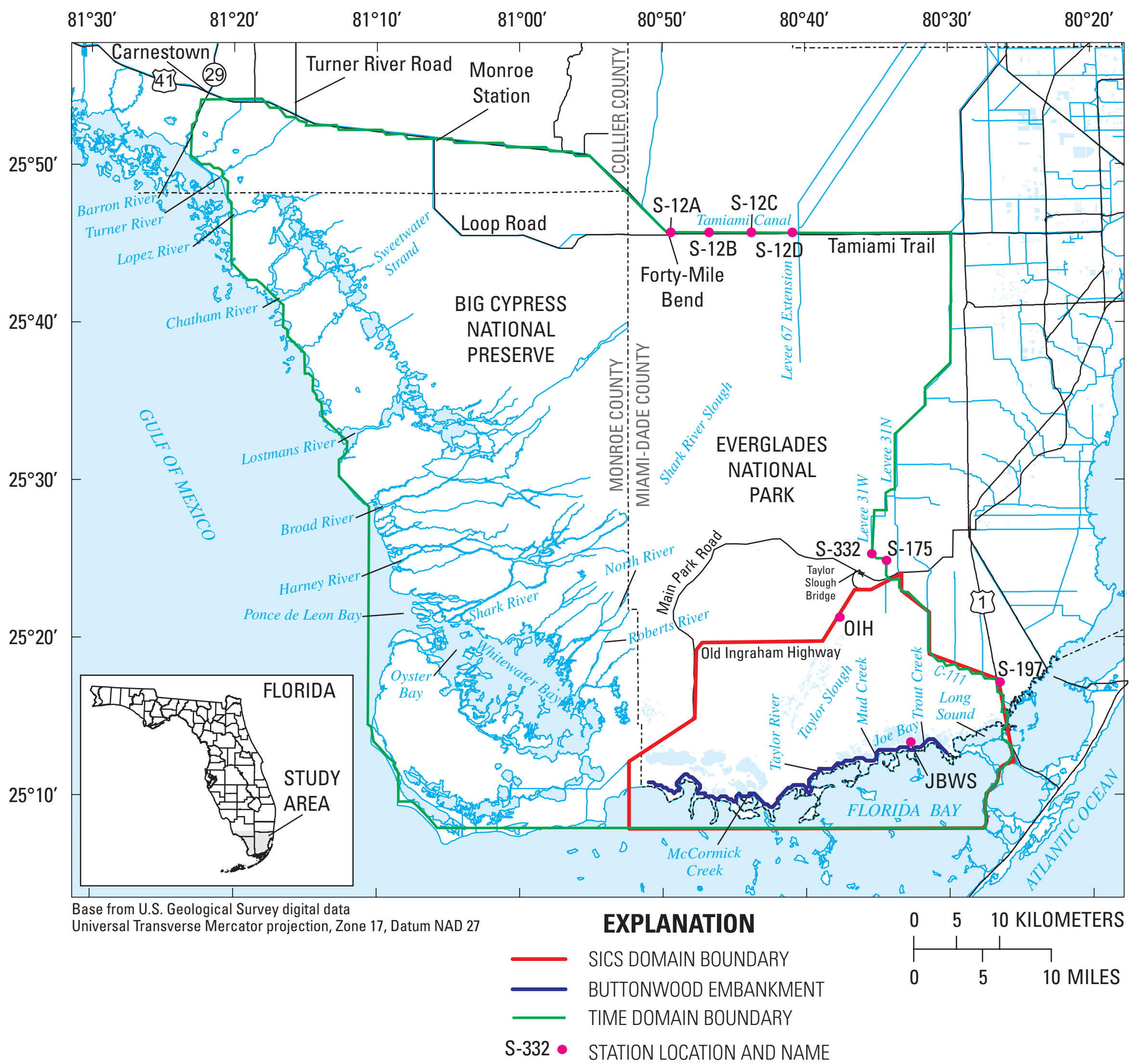

Figure 1. Location of the TIME and SICS domains, geographic features, and water-management features.

and rivers that are connected by the Wilderness Waterway and discharge to the coast. The major west coast rivers from north to the south include Barron River, Turner River, Lopez River, Chatham River, Lostmans River, Broad River, and Harney River (fig. 1). Other major west coast rivers include the Shark River, which flows into Oyster Bay, and the North and Roberts Rivers, which flow into Whitewater Bay. A higher elevation feature along the southeastern coast, the Buttonwood Embankment (fig. 1), is estimated to be about 15 cm higher than the surrounding marsh (Holmes and others, 2000).

The climate of southern Florida is characterized by a wet season from May to September and a dry season from October to April. Sixty percent of the total rainfall occurs during this wet season. Daily rainfall patterns during the wet season and dry season are characterized by local, small-scale afternoon showers and frontal patterns, respectively.

The highly permeable surficial aquifer system extends over most of the Everglades National Park/Big Cypress National Preserve area and underlies a thin peat layer in some areas. The surficial aquifer system generally thins toward the west in the study area.

1.3 - Acknowledgments

The majority of support for this model development comes from the USGS Greater Everglades Priority Ecosystem Studies Initiative. Dewey Worth of the SFWMD provided support of TIME application development with the FKFBFS. Appreciation also is extended to the Interagency Modeling Center for their consultation, advice, and reviews.

2 - Development of the FTLOADDS Model Code

The USGS developed the FTLOADDS model code by combining the SWIFT2D and SEAWAT models to provide insight into the Everglades system and supply freshwater flow information to the Florida Bay model. The FTLOADDS code integrates surface- and ground-water flow and transport (Langevin and others, 2004) and is designed to simulate two-dimensional variable-density overland flow (Schaffranek, 2004; Swain, 2005), as well as three-dimensional, fully-saturated variable-density ground-water flow (Guo and Langevin, 2002). The original FTLOADDS application (code versions 1.0 and 1.1) used only the SWIFT2D surface-water code. In subsequent applications (code versions 2.1 and 2.2), SWIFT2D was coupled to the SEAWAT ground-water model code and additional enhancements were made.

The original SICS application utilizes the SWIFT2D surface-water code only (Swain and others, 2004), and later, the coupled surface-water/ground-water FTLOADDS version 2.1 (Langevin and others, 2005). The larger TIME domain (fig. 1) utilizes the enhanced version 2.2 code.

2.1 - Version 2.1 of the FTLOADDS Code

The SWIFT2D model algorithms in version 2.1 of FTLOADDS are described by Swain and others (2004) and Swain (2005), and the SEAWAT algorithms in version 2.1 of FTLOADDS are described by Langevin and others (2004). The version of the SWIFT2D surface-water code that existed prior to the Everglades application is described by Schaffranek (2004). The primary features that distinguish the surface-water component of version 2.1 from this pre-Everglades SWIFT2D code are: (1) incorporation of rainfall and evapotranspiration effects; (2) a depth-varying Manning's friction coefficient for wetlands; (3) a wind-sheltering coefficient to represent emergent vegetation; and (4) the coupling to the ground-water model to represent leakage (transfer between surface water and ground water) with included salinity flux.

2.2 - Version 2.2

Version 2.2 of FTLOADDS has several enhancements not available in version 2.1. These enhancements can be classified as either generic code modifications or specific application modifications. The classifications do not include model input differences between applications.The generic SWIFT2D code modifications include the following:

- The wetting and drying algorithm has been modified to allow for rewetting directly from rainfall recharge.
- Frictional resistance terms are defined at cell faces in version 2.2 rather than at cell centers as in version 2.1.
- Evapotranspiration is computed using the modified Penman method (Eagleson, 1970), rather than cell-by-cell according to the best-fit equation discussed by Swain and others (2004).

Specific application modifications include the following:

- In version 2.1, rainfall is specified at 15-minute intervals and is spatially interpolated for each model cell. In version 2.2, rainfall is spatially uniform over defined zones and specified as 6-hour averages.
- In version 2.1, obstructions to surface-water flow, such as the coastal Buttonwood Embankment (fig. 1) is defined by the barriers formulation originally designed to represent weirs, and the coastal rivers are defined as low barriers with a representative flow coefficient. In version 2.2, the coastal embankment is defined by modified cell-face frictional-resistance terms, and coastal creeks are represented as gaps with specified friction terms.

A discussion of the generic code modifications follows, including those associated with drying and flooding, friction coefficients, and evapotranspiration. Specific application modifications for the study area are discussed later as part of the version 2.2 application to the TIME domain. Background information on the SWIFT2D model structure is available in Schaffranek (2004) and Swain (2005).

2.2.1 - Drying and Flooding

The SWIFT2D model requires the representation of surface-water cells in wet and dry states, as well as transitions between states. This must be represented empirically, because the hydrodynamic flow equations do not support a transition to zero flow depth. The SWIFT2D code used in version 2.1 of FTLOADDS represented drying and flooding of surface-water grid cells by a method found to be slow, prone to instabilities, and not entirely consistent between subroutines. One technique used to increase model performance in version 2.1 involved increasing the user-prescribed water depth limit at which the wet and dry transition is assumed to occur. This caused substantial water retention, however, in cells assumed to be dry. Additionally, the multiple use of the Chezy parameter, used also as a flag to denote a dry cell in the model, introduced unnecessary complexity in the code and is no longer beneficial because of the increased memory available on current computer platforms.

These issues have been resolved in version 2.2, which computes the land-surface altitude used to indicate the dry/wet state differently than version 2.1. To determine the dry/wet state for a grid cell (centered on a water-level point), version 2.2 represents the effective land-surface altitude by the maximum corner elevation of a cell plus a threshold depth where the element is considered to have no surface water. This threshold depth is typically set to 0.001 m instead of 0 m to avoid dividing by zero in the flow equations. This land-surface definition is not used in the flow calculations; the actual grid-cell corner altitudes are used to estimate flow cross sections along a cell side. Thus, for computing the dry/wet state, land surface in a cell is represented as horizontal, which eliminates the problem of partially wet cells and associated inconsistencies in mass balance. In the constituent solution, an average of the corner land altitudes is used to calculate cell volume. This introduces the concept of captured volume, defined as the volume between the average land surface (for a specified area) and the water surface at the effective land-surface altitude defined above. Captured volume is always present in the cell and affects constituent concentrations even though the volume is hydrodynamically inactive. This volume can be visualized as water confined in depressions and ponds.

To differentiate between wet and dry states, the user defines a "marginal depth" (Schaffranek, 2004, p. 79). When the water-surface elevation is greater than the effective land-surface altitude plus one-half the marginal depth for at least three time steps, the cell is wet and the full Chezy friction coefficient is used.

When the water-surface elevation is between the effective land-surface altitude and one-half the marginal depth above this, the cell is considered semidry. Volume and mass exchange still occur in the semidry condition, with wet cells using simplified transfer rules instead of the full equations of motion. This allows cells to either continue draining until completely dry or to fill up and become wet again, depending on the water elevation of the neighboring wet cell. No transfer occurs between cells that are both semidry. Leakage and rainfall accumulation occur regardless of cell status, whereas evaporation/evapotranspiration is removed only when adequate surface water is available. Totally dry cells (when the water-surface elevation drops to the effective land-surface altitude) have the same flux calculations as semidry cells.

The wet to semidry transition is checked in subroutines SEPU, SEPV, and CVAL (Schaffranek, 2004). The semidry to wet transition is checked in subroutine FLO and occurs (once per time step) after the first sweep of the Alternating Direction Implicit (ADI) solution. The marginal depth is set to 0.01 m for applications described herein.

2.2.2 - Friction Coefficient

A change was made in the SWIFT2D simulation grid location where the frictional resistance term, Manning's *n*, is defined. In the FTLOADDS version 2.1 code, friction coefficients are assigned to cell centers, but flows are calculated at the sides of each grid cell. The friction coefficient used in the flow calculation is the mean of the friction coefficients for the two cells adjacent to the side. The version 2.1 formulation does not lend itself to anisotropic situations, such as a flow barrier along a cell side. To make the friction at the side sufficiently large to simulate a barrier, the cell friction must be set to a large value, which affects flow calculations across all sides of that cell. To alleviate this problem, version 2.2 uses an alternate formulation in which each cell face has an independently prescribed friction coefficient. For cases with a barrier such as an elevated road or other flow control, the cell-face friction coefficients in version 2.2 can be prescribed directly at the appropriate cell side to block flow until the barrier or road crown is inundated.

For backward compatibility, a frictional scheme in version 2.1 can be duplicated in version 2.2 by setting the cell-face friction coefficients to the mean of the adjacent cell friction coefficients. Other possible uses for side friction coefficients exist; for example, to represent subgrid-scale flow features such as poorly resolved channels.

2.2.3 - Evapotranspiration

Evaporation and transpiration, collectively referred to as evapotranspiration (ET) herein, are major components of the water budget in southern Florida. In FTLOADDS version 2.1, ET rates are calculated in the SWIFT2D code by a best-fit equation based on solar radiation and water depth (Swain and others, 2004). The empirical nature of this formulation is of concern, and the importance of ET must be considered in developing the FTLOADDS version 2.2 formulation. The total water budget for the domain is derived largely from the difference between ET and precipitation. ET can represent a large part of the overall water budget, so caution is necessary when estimating ET; relatively small errors in ET estimates can cause substantial water-budget changes. Because this study primarily concerns a water-budget temporal scale on the order of days or weeks, ET estimates must be as accurate as possible at those time scales. Furthermore, the ET formulation must be sufficiently robust to be used both under historically measured conditions and also under possible climatic and hydrologic scenarios proposed by CERP. These scenarios are expected to involve substantial changes to flows, stages, and hydroperiods. Therefore, the ET formulation in the FTLOADDS version 2.2 code needs to be more physically based than the formulation in version 2.1.

The regression technique in FTLOADDS version 2.1 (Swain and others, 2004) uses the Priestly-Taylor (PT) equation (Linsley and others, 1982, p. 162-163) as a "guide" for the relation between parameters. A coefficient was regressed against solar radiation and water depth to develop a best-fit equation. This coefficient then was considered regionally valid and used as an independent variable, along with solar radiation, in another least-squares best fit to measured ET values. This best-fit equation matched measured values with a multiple correlation coefficient of 0.8. The inherent assumptions were that: (1) the regressed coefficient is a representative variable that roughly corresponds to a coefficient in the PT equation, (2) solar radiation is an acceptable surrogate for net radiation, and (3) the variability of other terms in the PT equation has negligible effects. Because the PT equation is not implicitly used, this can be considered as more of an empirical equation than a physically based equation.

Although reasonable results were obtained for the range of field conditions represented in the application of FTLOADDS version 2.1 to the SICS domain, concerns about applying the formulation outside the range of field conditions in the calibration period (as well as concerns stated earlier) led to the approach presented here.

Several investigators (Abtew, 1996; German, 2000; Abtew and others, 2003) have found that measured ET rates can be reproduced with models that vary in complexity. The simpler models require adjustment coefficients but, when properly calibrated, they can provide ET hindcasts with accuracy comparable to hindcasts from models that incorporate more complete model physics. For prediction of ET, which includes the calculation of ET when conditions are different from those of the calibration period, the simplified methods may become less accurate and their use more difficult to defend. Therefore, using the empirical ET formulation in FTLOADDS version 2.1 could be problematic at other locations with different water depths and under restoration scenarios in which water depths are expected to vary substantially from historical records.

A more generally valid ET formulation was developed for the FTLOADDS version 2.2. The approach uses the Penman-Monteith (PM) formulation for vegetated sites to calculate potential evapotranspiration (PET) and to derive actual ET by modifying PET according to a measure of available water (Eagleson, 1970). The following analysis describes the calibration of the PM formula and the derivation of an available water function using available data.

The basis of the analysis presented here is provided by the data collected and reported by German (2000) and more recent data also collected by E.R. German (U.S. Geological Survey, written commun., 2005). In these studies, two open-water and seven vegetated sites were instrumented to determine ET rates (table 1) using the Bowen ratio and energy-balance method (Oke, 1978). Data collection at the stations began in January 1996 and ended between 1997 and 2002. This report discusses analyses of ET only at the vegetated sites. The collected data represent the best available information for determining actual ET at sites in the Everglades; however, additional wind-velocity profile data, such as aerodynamic roughness and boundary layer displacement, were not collected. These data would be required to apply a theoretical formulation such as the PM equation.

All observations with negative net radiation (resulting in a computed latent heat gain to the system) were assumed to be associated with zero PET. Negative net radiation was relatively small and may have resulted from soil and water heat storage rather than condensation. It was difficult to ascertain whether condensation events actually occurred because humidity sensors typically do not function well at 100 percent relative humidity—the assumed indicator for condensation. Condensation amounts probably were small; therefore, this process was ignored in version 2.2 of the FTLOADDS model.

The modified Penman formulation (alternatively, the combined or combination method) is a widely used energy balance method to estimate evaporation over open water and originally was proposed by Eagleson (1970). The basic equation of the formulation is:

$$\frac{Q_e}{A_s} = \rho_e L_e E = \frac{\Delta(Q_a / A_s) + (\rho C_p / r_a)(e_{s2} - e_2)}{\Delta + \gamma} \quad , \qquad (1)$$

where:

Q_e/A_s is evaporative heat flux per unit horizontal area;
ρ_e is density of evaporated liquid water;
L_e is latent heat of evaporation;
E is evaporation;
Δ is slope of the saturation vapor-pressure curve;
Q_a/A_s is available energy per unit horizontal area;
ρ is air density;
C_p is specific heat of air;
r_a is the aerodynamic resistance term;
e_{s2} is saturation vapor pressure at level 2;
e_2 is vapor pressure at level 2, located slightly above boundary layer displacement; and
γ is the psychometric constant.

The aerodynamic resistance term, r_a, is given by the following:

$$r_a = \frac{K_m}{K_h} \frac{1}{\kappa^2 u_z} \frac{z_e - D}{z_u - D} \ln^2 \frac{(z_u - D)}{z_o} \quad , \qquad (2)$$

where:

K_m is moisture eddy diffusivity;
K_h is heat eddy diffusivity;
κ is von Karman constant;
u_z is wind speed;
z_e is height of vapor pressure sensor;
D is boundary layer displacement height;
z_u is height of wind sensor; and
z_o is aerodynamic roughness.

For vegetated sites, this formulation was modified to estimate PET by including a resistance term that represents the resistance to flow through plant stomata. This PM formula is (Eagleson, 1970; Jacobs and Sudheer, 2001):

$$\frac{Q_e}{A_s} = \rho_e L_e PET = \frac{\Delta(Q_n / A_s) + (\rho C_p / r_a)(e_{s2} - e_2)}{\Delta + \gamma(1 + r_s / r_a)} \quad , \qquad (3)$$

where PET is potential evapotranspiration, and r_s is the average resistance of evaporative surfaces.

More sophisticated formulations exist that explicitly account for the multiple sources of evaporation in cases involving ET at vegetated sites with standing water or sites

Table 1. Evapotranspiration monitoring site characteristics.

[Site locations are shown in German (2000, fig. 1). THP, air temperature and humidity sensor]

Site number	Latitude/ longitude	Plant community	Vegetation	Lower THP	Wind sensor	Comments
			Height above land surface (meters)			
1	263910/0802432	Cattails	3.0	4.3	0.3	Considerab1e flow regulation, nutrient-rich water, abundant duckweed
2	263740/0802612	Open water	.0	1.5	None	
3	263120/0801011	Open water	.0	1.4	2.4	Some lily pads at times
4	261855/0801257	Dense sawgrass	19.8	3.0	5.8	
5	261530/0804417	Medium sawgrass	1.8	2.5	5.5	Dry part of some years
6	254443/0803011	Medium sawgrass	1.8	2.7	4.0	
7	253659/0804208	Sparse sawgrass	1.5	22.3	4.3	
8	252111/0803802	Sparse rushes	.9	1.2	3.7	Dry part of each year
9	252135/0803146	Sparse sawgrass	10.7	1.6	3.7	Dry part of each year

with humid soil. The simpler PM formula was tested for the current study, however, using a resistance value that represents an average of all evaporative surfaces; this is occasionally referred to as the "big-leaf" approximation. This simpler approach was used primarily because more advanced methodologies require additional data that were not available.

A somewhat different expression for the aerodynamic resistance term than that given in equation 2 has been proposed by others (for example, Abtew and Obeysekera, 1995). In evaluating r_a, equation 3 assumes the eddy diffusivity ratio (K_m/K_h) is 1. Equation 3 further assumes that wind frictional effects are spatially homogeneous and that heat storage in soil, water, and plants is minimal.

To prescribe the heat-flux and net-radiation variables in these formulas, it is usually also necessary to know air temperature and water-surface temperature. These data were collected by German (2000) and, therefore, are not only readily available but can be assumed to be reasonably constant in space.

A conceptual difficulty arises when selecting the temperature to use for the saturated vapor pressure/temperature slope Δ in equations 1 and 3. The slope should be estimated at the location where vapor pressure is saturated. For open water, it is appropriate to use the temperature at the water surface. For vegetated sites, however, it may be more appropriate to use the air temperature at the surface where evaporation takes place. Such a location is not uniquely determined, because evaporation can occur from both water and vegetation surfaces. Some combination of water-surface temperature and leaf-surface temperature, may therefore, be appropriate. In the PM formulation used in version 2.2 of the model, this location is assumed to be the same level where the log velocity profile indicates zero velocity, for example, at the top of the aerodynamic roughness height z_o.

A few of the input variables for equations 1, 2, and 3 (D, r_s, and z_o) are not measured and must be estimated from the measured ET data set. As guidance for determining these parameters, D is about equal to an average canopy height; r_s is on the order of 100 s/m, and z_o ranges from one to tens of centimeters over vegetation (Oke, 1978; Perrier and Tuzet, 1991; and Stannard, 1993). Actual ET can be derived from PM/PET estimates based on available water, which is formulated herein as a function of water level. The second term in the numerator on the right-hand side of equation 1, $(\rho C_p / r_a)(e_{s2} - e_2)$, is referred to as the aerodynamic term. This term is zero when the air is assumed to be saturated.

Version 2.2 of the FTLOADDS code uses the formulation in equation 3 with the assumptions described in this section to compute ET rates. Section 3.3.7 contains further discussion of the development of parameters for the TIME application.

3 - Application of FTLOADDS to Tides and Inflows in the Mangroves of the Everglades (TIME)

The application of the FTLOADDS version 2.2 code to the TIME domain is the first successful representation of this area's hydrology by such a complex model. Primary among the purposes of TIME is to represent the coastal area of Everglades National Park and link the inland regional management model to the offshore hydrodynamic model. Figure 2 shows the linkage between the models used to simulate various restoration scenarios and their effects on Florida Bay. The SFWMM, which is the primary regional tool used to assess CERP scenarios and also known as the "2 × 2 model" because of its 2- × 2-mi grid cells, provides stage and flow inputs to the SICS and TIME applications for restoration model scenarios (Wolfert and others, 2004). Additionally, the TIME domain extends south of the Florida Bay coastline (fig. 2), and provides flow and salinity inputs to the Florida Bay hydrodynamic model along its northern boundary and receives stages and salinities from the Florida Bay model in subsequent model simulations.

After the FTLOADDS code was implemented successfully for the SICS application (Swain and others, 2004; Langevin and others, 2005), and applied to restoration scenarios as shown in appendix 1, the model area was expanded to encompass the TIME domain (fig. 1). This expanded application utilizes 500-m grid spacing, and allows FTLOADDS to represent the complete coastline as well as the coastal flows used in the Florida Bay hydrodynamic model. Additionally, the water-management controls along Tamiami Canal and Levee 31N Canal (fig. 1) can be represented directly as boundary conditions in the TIME domain. The objective of the TIME application, given the limited time and effort that can be put into the calibration in order to be responsive to the restoration effort, is not to obtain the best possible fit, but rather to make timely and necessary adjustments to bring model physics in accordance with the physics illustrated in the data.

The TIME input is derived from multiple sources and makes use of the large amount of field information that has been collected in the area. A total of 157 simulations were made for model calibration and sensitivity analysis. Simulation number 142 was used as a base to compare with subsequent sensitivity simulations, and the information derived from these comparisons was used to develop simulation 157.

The calibration of the TIME application described is appropriate for use as a tool to represent system changes caused by restoration scenarios. Further refinements beyond this level of calibration were not necessary because they are not needed to make decisions on restoration management. Because the emphasis of the restoration effort is the relation of coastal flows and water deliveries, the salinity transport representation is not as refined as the flow representation.

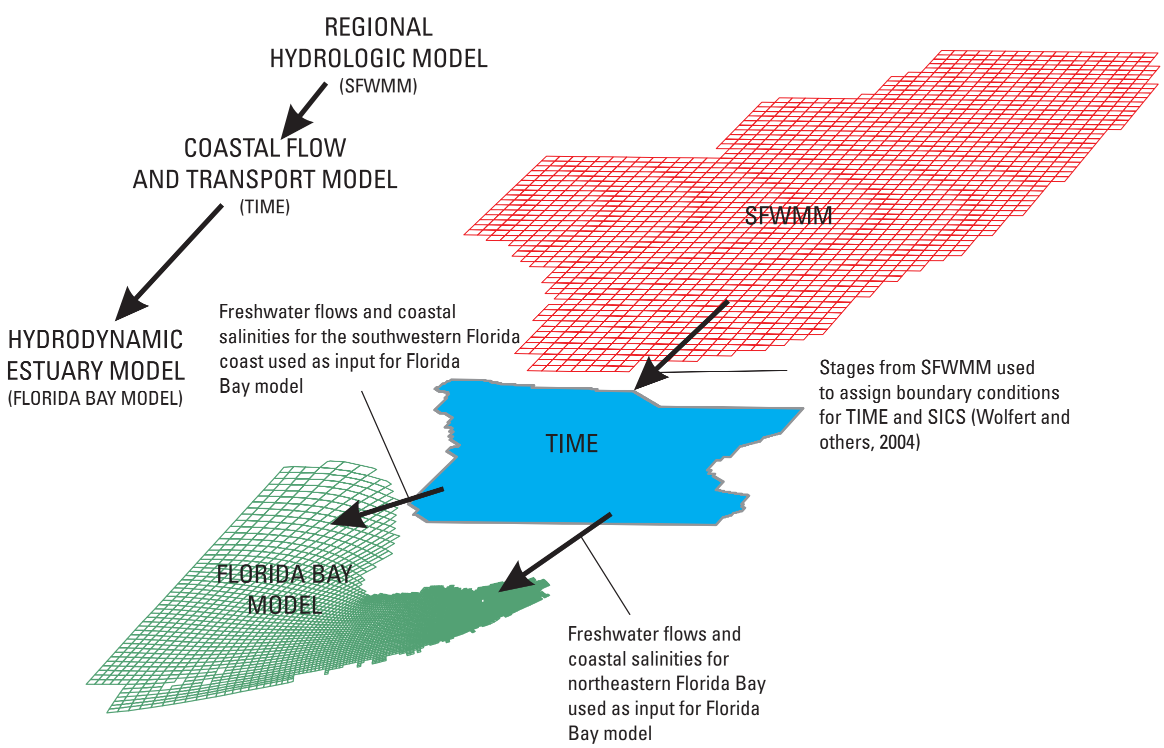

Figure 2. Linkage between models used to simulate various restoration scenarios. SFWMM is South Florida Water Management Model.

3.1 - Simulation Period

Field-measured stage, flow, and salinity data from January 1, 1996, to December 31, 2002, were used to calibrate and verify the TIME application. This 7-year Standard Data Period (SDP) was selected because it provides a more comprehensive and more complete field data set than had existed previously.

When used for CERP scenario simulations, the TIME application is driven by boundary inputs from the numerical regional water-management model (SFWMM). The CERP scenarios are designed to use the measured hydrologic conditions for the period ending in 2000. The SFWMD presently has no plans to extend SFWMM runs beyond the year 2000. Originally, the plan was to run TIME scenario simulations for the same 7-year SDP used for model calibration. In discussions between the USGS and FBFKFS Modeling Subteam, however, the following points were noted about different simulation periods:

- The 1996-2002 period may be too short to adequately assess biological performance measures under different hydrologic conditions. This period would be reduced to 5 years if the simulation is required to end at 2000.

- The 1996-2000 period may not contain representative years of dry or wet conditions.

- Given a time period of at least 10 years to encompass a variety of conditions using data from the SFWMM ending in the year 2000, choosing the 1990-2000 period represents a general compromise, considering the extra effort required to assemble input data and the need for higher model run times to represent the desired longer duration of simulation runs.

The flows and stages in the TIME domain respond to direct input such as rainfall and evapotranspiration, but also to lateral boundary input through culverts, bridge openings, structures, and ground-water flows. These model lateral-boundary input variables are available for the SDP as continuously monitored data or are modeled using rating curves and appropriate stages. Ground-water flows are determined through leakage interactions with the ground-water model. Stage data, creek/river flow data, and salinity data are used for calibration.

3.2 - Model Grid

Square grid cells centered on the water-level points are used in the FTLOADDS model for computational efficiency because the solution method for the surface-water equations assumes equal cell dimensions in both directions. Flow is defined at the center of each vertical cell face. This configuration facilitates easy formulation of mass conservation and head-gradient driven flows.

The grid for the TIME application consists of 174 rows and 194 columns of cells (fig. 3). The 500-m resolution noted earlier was chosen as a compromise between accurately representing available topographic data and obtaining reasonable run times. Of particular concern was the need to make hundreds of multiyear runs. The east-west and north-south alignment of rows and columns was not a requirement, but was chosen in this case because of the road and levee features. Grid rows are numbered from 1 to 174 (south-north) in the SWIFT2D surface-water module and from 1 to 174 (north-south) in the SEAWAT ground-water module. The reversed numbering schemes were necessary to preserve the numbering conventions used by SWIFT2D and SEAWAT in their original forms. Columns in both modules are numbered from west to east. The surface-water cell indexing used in this report is consistent with a normal right-handed Cartesian coordinate system.

The TIME model grid was referenced to Universal Transverse Mercator (UTM) coordinates for input and post processing, with the center of cell (1,1) located at the NAD 83 and UTM zone 17 coordinates listed below:

Longitude (degrees, minutes, seconds west)	Latitude (degrees, minutes seconds north)	Longitude (decimal degree west)	Latitude (decimal degree north)	UTM easting (meters)	UTM northing (meters)
81:23:12.76427	25:07:35.04428	81.38687896	25.12640119	461000	2779000

The surface-water model represents two-dimensional horizontal flow and consists of a single layer of variable water depth consistent with the vertically averaged equations of motion, whereas the ground-water model represents three-dimensional flow using 10 vertically stacked layers. Although the layers in the ground-water model can be varied in height, all layers except the surface layer (layer 1) are 7 m thick. Layer 1 is variable in thickness because the bottom of the layer is at a constant altitude of 7 m below NAVD 88, and the top represents model land surface. The numbers of layers and thickness of each were dictated by the need to accurately represent local stratigraphy and minimize model run times.

Each module requires input that specifies whether a cell is active or inactive. The governing equations are solved only for active cells to minimize computational effort. Active SWIFT2D cells correspond to those within the TIME domain boundary shown in figure 3. The active layer 1 cells in SEAWAT have the same areal extent as corresponding cells in SWIFT2D. The extent of active SEAWAT cells in lower layers is reduced as dictated by stratigraphy.

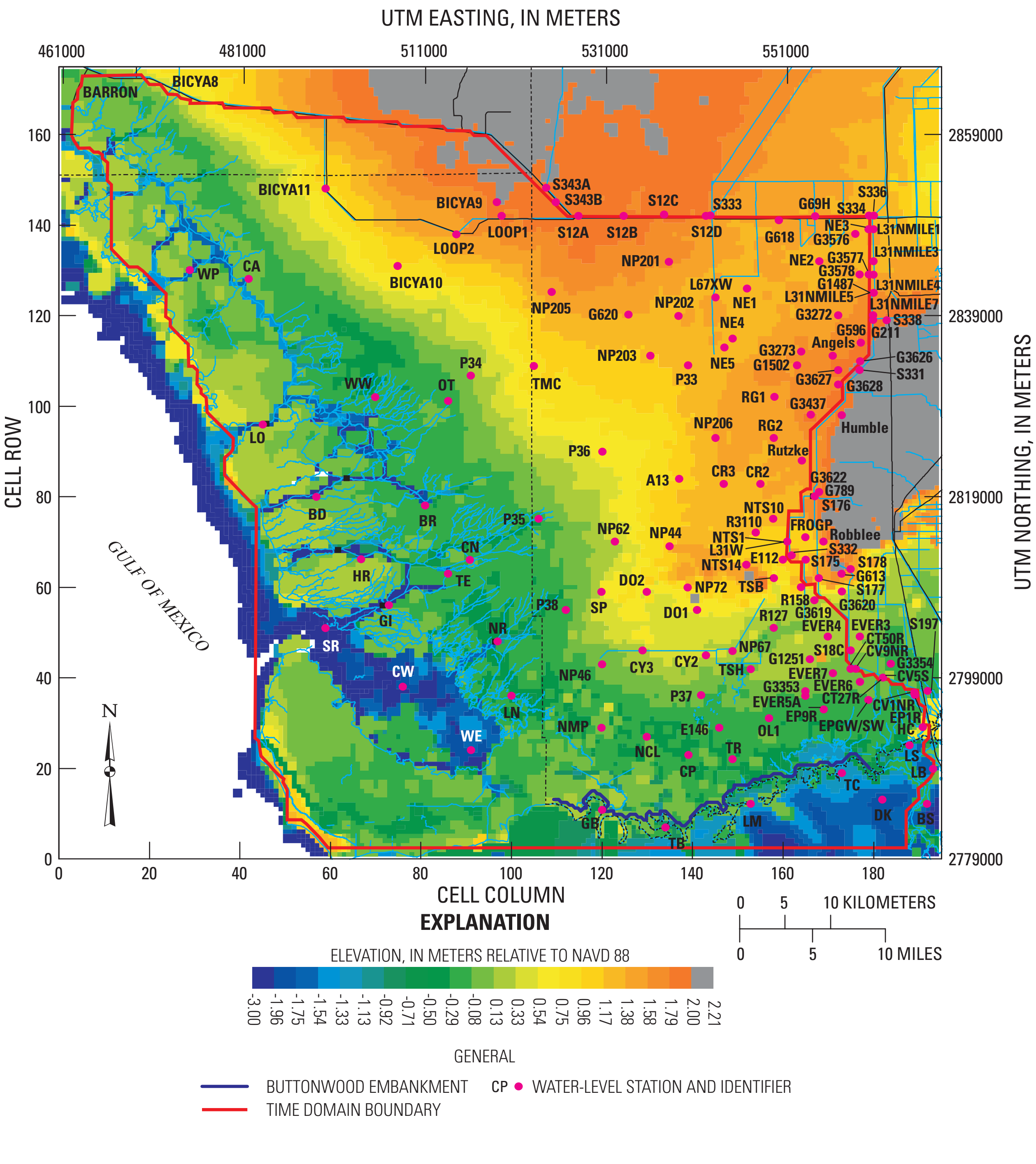

Figure 3. Extent of active cells and land-surface altitudes in the TIME area.

3.3 - Model Input

The subsequent sections describe the parameters used as input for the TIME application. These parameters include topography; Manning's *n*; soil stratigraphy; hydraulic conductivities; thin layer characteristics; roads, bridges, culverts, and structure flows; stage; rainfall; potential evapotranspiration (PET); wind; coastal water levels and salinities; and ground-water boundary conditions.

3.3.1 - Topography and Bathymetry

Topography for the TIME application, including submerged and unsubmerged inland areas plus offshore bathymetry, is derived from data collected by Desmond (2003), National Oceanographic and Atmospheric Administration (NOAA) topographic data (Hansen and Dewitt, 1999), and the National Hydrographic Database Regional Drainage coverage. The model topography is shown in figure 3, with all altitudes referenced to NAVD 88. Although the original topography for this model was obtained from the modeling effort of R.W. Schaffranek and others (U.S. Geological Survey, written commun., 2003), substantial changes have been made to the model topography to better reflect altitude data in the TIME domain. The present model topography can be reconstructed most nearly by using all altitude data points in a kriging scheme to obtain model land-surface altitudes and then modifying this topography to account for major lakes and rivers. These data also define the top of layer 1 in the ground-water input data. The files containing the topography for the surface-water model and the ground-water model are listed in appendix 2.

3.3.2 - Defining Manning's *n* at Cell Faces

A description of the frictional resistance to flow for surface water must be provided as input to SWIFT2D in the form of Manning's *n*. The Manning formulation was derived for fully developed turbulent rough flow. The TIME application uses Manning's *n* in a conventional manner; however, the meaning of *n* as a measure of roughness is compromised. In this case, *n* represents an equivalent roughness that describes the skin friction and form drag against the land surface and any vegetation within the water column. Additionally, the value of *n* is modified by subgrid-scale topography. Thus, Manning's *n* values for cells in the TIME application can differ substantially from the 0.03 *n* value typical for natural channels.

The SICS application used remotely sensed vegetation type and density to estimate Manning's *n*. For the TIME application, remote-sensed maps were obtained from John Jones (U.S. Geological Survey, written commun., 2003) at 500-m grid resolution and *n* values were derived based on previously established relations (Lee and Carter, 1999). Cells that are completely under water and have little vegetation were assigned Manning's *n* values closer to the 0.03 value as part of the calibration procedure. The calibration indicated that flow conveyance was globally too high; consequently, all *n* values were increased by 20 percent. The distribution of Manning's *n* values used in the TIME application is shown in figure 4.

The Buttonwood Embankment (fig. 1) is implemented as an obstruction to flow by setting the cell-side Chezy coefficient to 0.0001 to yield negligible flow. This coefficient cannot be set to zero because it appears in an equation denominator.

Where the Florida Bay creeks cut through the Buttonwood Embankment, the cell-side Chezy coefficient is adjusted to match calculated flows with measured flows. Using the equation Chezy coefficient = Depth$^{1/6}$/Manning's *n*, the equivalent Manning's *n* values for the individual creeks are 0.4 for Alligator Creek, 0.7 for McCormick Creek, 1.0 for Taylor River, 0.7 for Mud Creek, 0.08 for Trout Creek. The files that define the Manning's *n* for the wetland, Buttonwood Embankment, and coastal rivers are listed in appendix 2.

The low-gradient hydrologic system in the TIME domain does not respond markedly to subtle changes in Manning's *n*. When implementing sensitivity analyses and to quantify the effect of large-scale frictional changes, Manning's *n* was adjusted in the three rectangular areas shown in figure 5. The effects of this empirical test are discussed subsequently in section 3.7.2.

3.3.3 - Soil Stratigraphy, Hydraulic Conductivities, and Thin Layer Characteristics

The aquifer properties used in the ground-water module of the TIME application are based on those presented by Reese and Cunningham (2000) and Fish and Stewart (1991). Underlying the Biscayne aquifer is a semiconfining unit that becomes less confining near the east coast. Below this semiconfining layer lies the gray limestone aquifer, which becomes the surficial aquifer toward the west. As described earlier, the TIME application discretizes this stratigraphy using 10 horizontal layers, each of which (except for the top layer) is 7 m thick. Horizontal hydraulic conductivities are estimated to range between 50 and 5,000 m/d, and vertical conductivities are about 10 m/d. As examples, the hydraulic conductivity in layer 1 and the transmissivity in layer 5 are shown in figures 6 and 7, respectively. The input file for aquifer conductivities is named in appendix 2.

A thin-layer conceptual model was designed to account for a layer of peat at the soil surface. Although some observations of peat thickness exist (Cohen and Spackman, 1984; Scheidt and others, 2000), the areal coverage is sparse and maps were not available. Thus, an idealized thin layer (0.5 m thick) was implemented throughout the domain with an initially assumed vertical conductivity of 0.004 m/d. Tests indicated that decreasing the vertical conductivity of the topmost aquifer layer: (1) substantially reduced leakage and generally increased surface flows to Florida Bay, (2) substantially increased flows in Shark River and North River (fig. 1), and (3) changed flow slightly at other west coast rivers. Modeled flows with and without ground-water/surface-water leakage are presented in table 2.

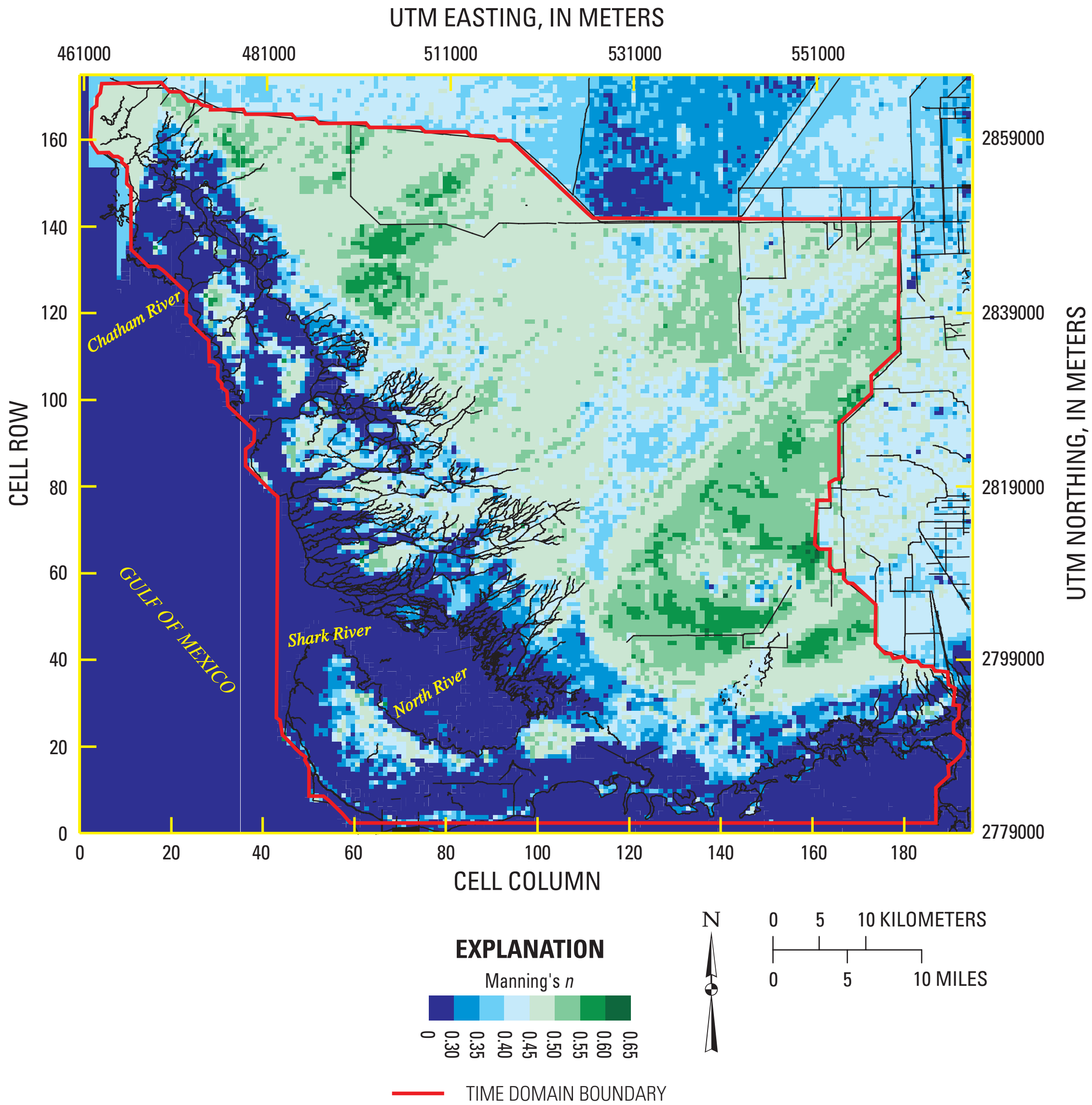

Figure 4. Distribution of Manning's *n* values in the TIME area.

Increasing vertical conductivity causes ground-water head to rise more quickly, but has little effect on total leakage unless the soil is unsaturated. An investigation was not conducted to determine the possible effects of increased vertical conductivity in areas where the soil is unsaturated.

3.3.4 - Incorporation of Roads, Bridges, Culverts, and Structure Flows

Main Park Road and Old Ingraham Highway have the potential to impede flow within Everglades National Park, even though both have numerous culverts (fig. 1). Main Park Road is an elevated paved road, whereas Old Ingraham Highway is unpaved, slightly elevated, and has been removed in some areas. A study of flows through the culverts along Main Park Road indicated that, on an event-based temporal scale of 1 day to a few days, water is impounded on the upstream side of the road, causing substantial flow through the culverts in many places (Stewart and others, 2002). Flow through the culverts seems sufficient to minimize substantial backwater effects on long time scales, allowing surface-water flow to continue coastward. The main influence of the road is hypothesized, therefore, to affect mainly the local flow pattern, and possibly a small delayed reaction in coastal flows. This study also found that flow through culverts along the southern part of Main Park Road is almost exclusively to the west.

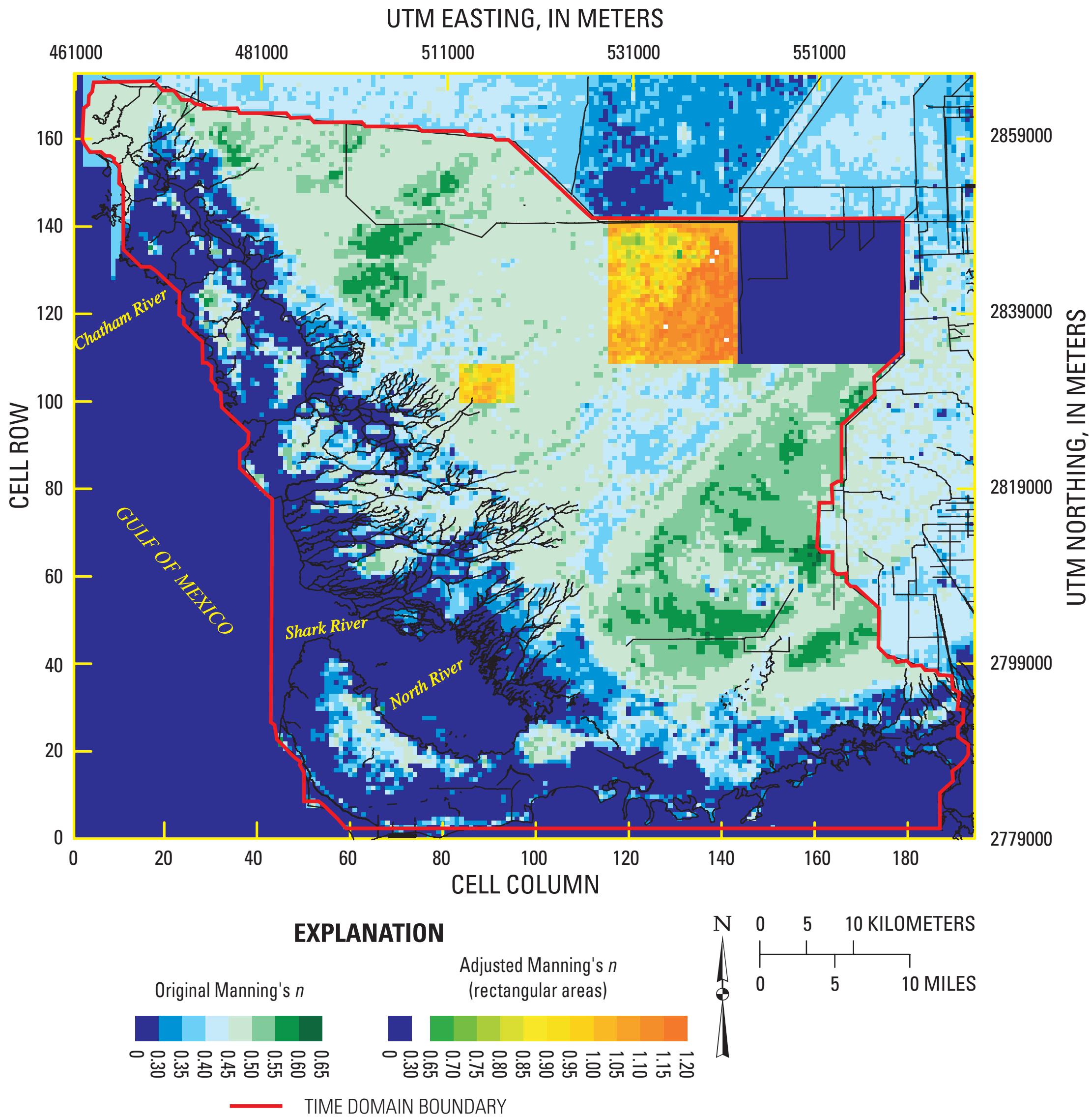

Figure 5. Adjustments to Manning's *n* values in the TIME area.

Stewart and others (2002) suggested that actual flow near Main Park Road with its culverts is expected to resemble the base case in which the road is neglected; that is, its effect is considered to be minimal. An upper bound on the possible effect of the barrier was established by simulating the case in which the road is treated as a complete flow obstruction.

Another potential barrier is Loop Road in the northwestern part of the TIME domain (fig. 1). The road is paralleled by a borrow canal that is connected directly to Tamiami Canal beneath the bridge at U.S. Highway 41. Robert Sobczak (Big Cypress National Preserve, oral commun., 2004) indicated that:

- The borrow canal (fig. 1) supplies water to Sweetwater Strand, which drains into Chatham River; this flow is large enough to drain the prairies near Monroe Station (fig. 1).
- The culverts under Loop Road are numerous, and some are in questionable condition.
- Most of the surface-water flow from Monroe Station to Forty-Mile Bend probably moves toward Sweetwater Strand and Chatham River.
- Numerous box culverts and regular culverts along the southern part of Loop Road probably drain through Dayhoff Slough into Lostmans River.

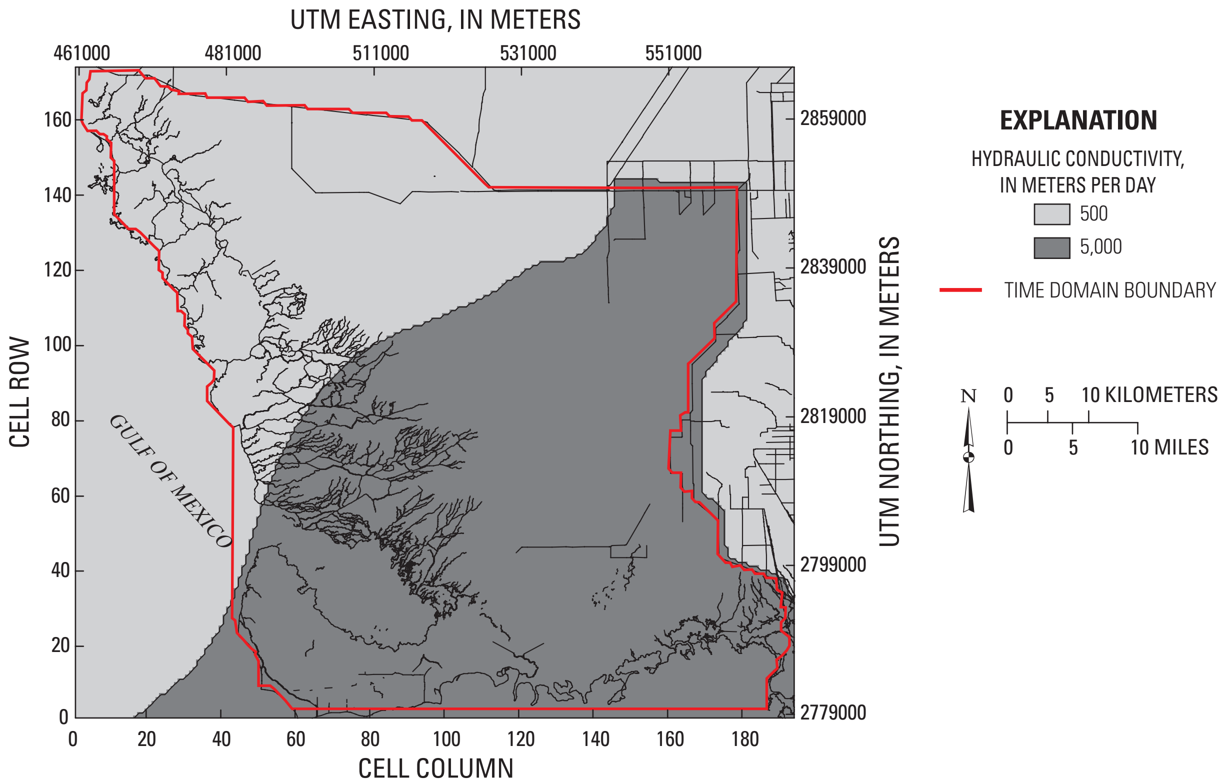

Figure 6. Hydraulic conductivities in layer 1 in the TIME area.

Based on this information, it seems justified to consider Loop Road's obstruction to be negligible.

Flows under Tamiami Trail into Everglades National Park are monitored and recorded by the USGS. The SFWMD data from the DBHYDRO database and the USGS data from the SOFIA database were used to force the model. Because stage was a primary calibration variable, it was not specified along the model boundaries except at the coastal interface. Culvert flows were grouped into three segments along the Tamiami Trail: Carnestown to Monroe Station, Monroe Station to Forty-Mile Bend, and Levee 67 extension to Levee 31N (fig. 1). Recorded inflows then were applied along each of these segments in a nearly uniform manner. Between Forty-Mile Bend and the Levee 67 extension, four major structures (S-12A to S-12D) release water into the Everglades through bridged openings (fig. 1). In this case, flows were applied across the entire side of the cell nearest to each structure.

Inflows were prescribed along the Levee 31W Canal at the S-332 pump structures and S-175 structure, and along the C-111 Canal (fig. 1). Flow from the C-111 Canal was assumed to equal the difference in flows through structures S-18C and S-197. The S-175 discharge was distributed as source flow along the length of the canal. The S-332 pump flows were treated in the same manner as flows through the S-12 structures. The input files for surface-water inflows are listed in appendix 2.

The flow quantities and relative magnitude of cumulative flows from the different structures are depicted in figure 8; structures S-12A to S-12D contribute the most flow. Collective flow beneath the Tamiami Trail west of Forty-Mile Bend nearly equals the S-12 flows, and collective flow east of S-12D equals about half of the S-12 flows.

3.3.5 - Stage Data for Boundaries

Numerous (105) water-level monitoring stations were identified, with more than 2 years of data recorded within the Everglades National Park/Big Cypress National Preserve area. These stations are distributed throughout the TIME domain, but most are located in the eastern part of the domain (fig. 9). These stations include ground-water sites (noted by the G prefix), surface-water sites, and a combination of both.

Because some areas periodically flood and dry, it was often difficult to differentiate between surface-water and ground-water measurement sites. Precise descriptions were not found regarding the type of water-level data collected at each site, which depends on exactly how each well was installed. For example, well casings are cemented in the ground at some sites and not at others—this determines whether the surface water or underlying ground water is being measured.

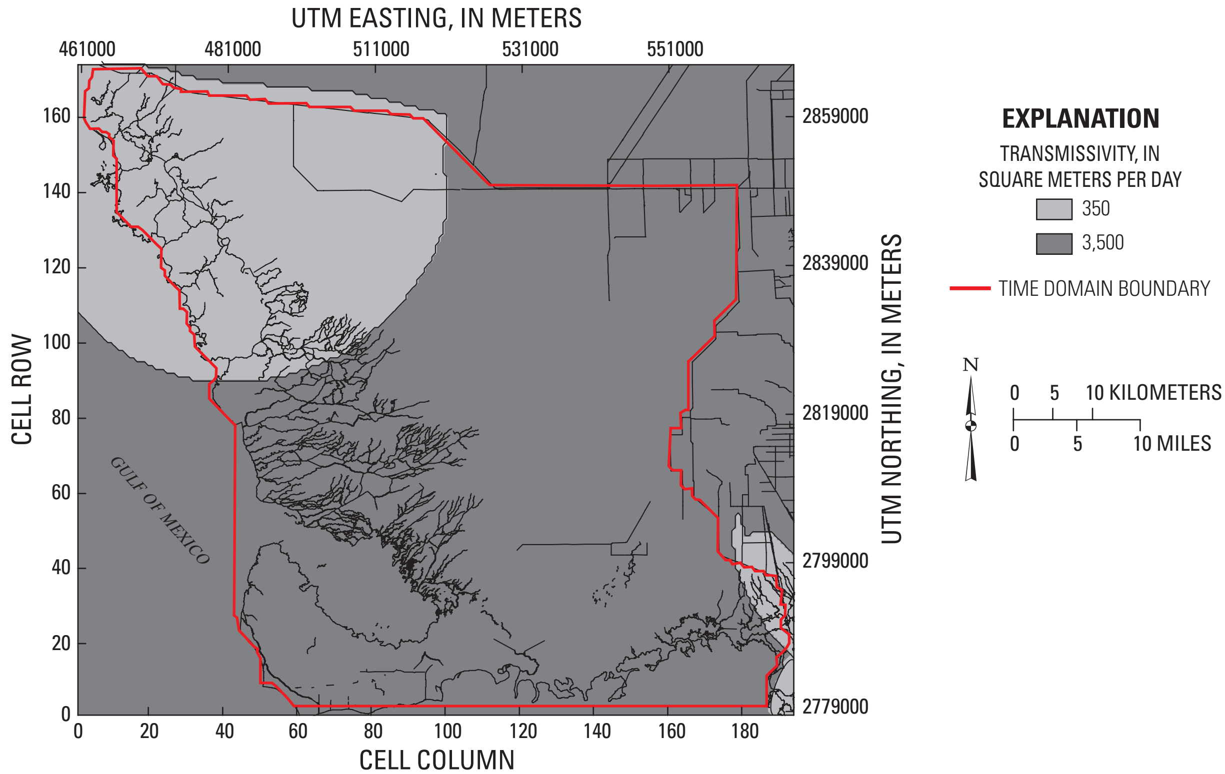

Figure 7. Transmissivity in layer 5 in the TIME area.

Table 2. Net average total flow (Q) and freshwater flow (Q_f) toward the coast for the standard data period.

[Site locations are shown in figure 1, ALAYC, vertical hydraulic conductivity; m/d, meter per day; m³/s, cubic meter per second; Q, runoff volume; Q_f, net freshwater runoff with salt diffusion accounted for]

Location	Flow with leakage ALAYC = 0.004 m/d		Flow without leakage ALAYC = 0 m/d	
	Q (m³/s)	Q_f (m³/s)	Q (m³/s)	Q_f (m³/s)
Taylor Slough Bridge	4.57	4.57	5.97	5.96
Trout Creek	11.16	9.67	13.06	10.95
Mud Creek	1.08	.75	1.27	.87
Taylor River	1.16	.77	1.39	.91
McCormick Creek	1.15	.87	1.34	.98
Long Sound	1.39	.82	1.38	.80
Chatham River	18.29	5.26	18.46	5.16
Lostmans River	38.31	30.40	39.29	30.44
Broad River	10.65	6.24	10.97	6.29
Shark River	18.06	11.99	19.06	12.64
North River	7.11	6.12	7.56	6.80

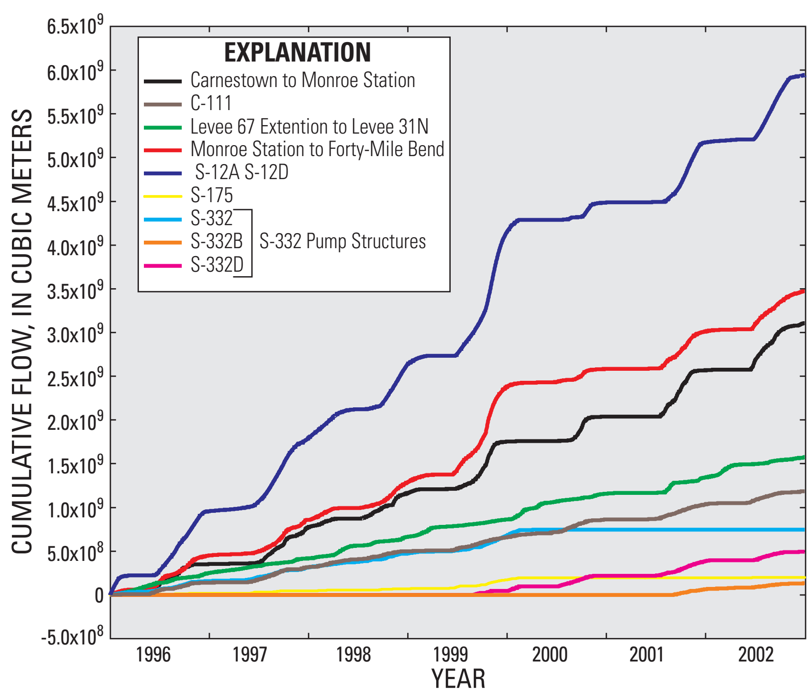

Figure 8. Cumulative flows at selected control structures in the TIME area.

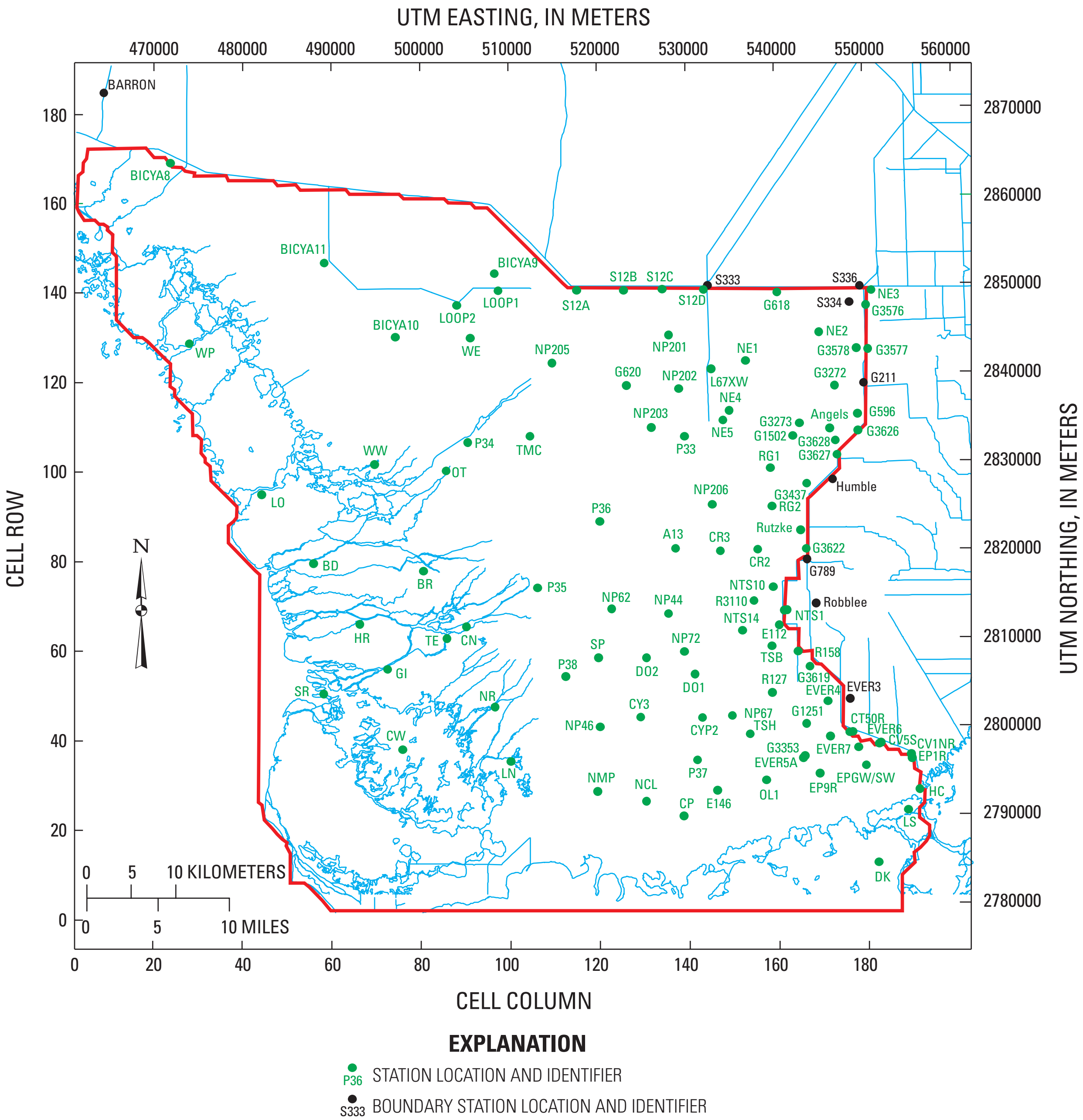

Figure 9. Location of stage recording stations in the TIME area.

For comparison with the model, gage measurements were assumed to represent surface-water stage or, when surface water was absent, ground-water head.

Most elevation records were referenced to NGVD 29, and therefore, were converted to NAVD 88 using the CorpsCon geodetic program (U.S. Army Corps of Engineers, 1999). Comparison with model results was difficult when the land-surface altitude adjacent to the gage and the corresponding model cell differed substantially. In such instances, the wetting, drying, and general water-level behavior were not directly comparable when surface-water depths were small.

Because the stage recordings are well distributed throughout the domain and records are available at most locations for a substantial portion of the SDP, stage is the primary variable used for model calibration. For this reason, stage values were not specified as boundary conditions in the model, except at the marine interface where tidal- and wind-induced water-level fluctuations must be prescribed. Several factors are responsible for the incomplete record at some of the sites. For example, Hurricane Irene damaged water-level gages as it moved up the Shark River Slough (fig. 1) in October 1999, resulting in the loss of several months of data.