Estuarine, Coastal and Shelf Science 93 (2011) 438–448

Contents lists available at ScienceDirect

Estuarine, Coastal and Shelf Science

journal homepage: www.elsevier.com/locate/ecss

A tidal creek water budget: Estimation of groundwater discharge and overland flow using hydrologic modeling in the Southern Everglades

Béatrice Michot [a,*], Ehab A. Meselhe [a], Victor H. Rivera-Monroy [b], Carlos Coronado-Molina [c], Robert R. Twilley [b]

[a] Department of Civil Engineering, University of Louisiana at Lafayette, 131 Rex Street, Lafayette, LA 70503, USA
[b] Department of Oceanography and Coastal Sciences, School of the Coast and the Environment, Louisiana State University, Baton Rouge, LA 70803, USA
[c] Wetland Watershed Sciences Division, South Florida Water Management District, West Palm Beach, FL 33406, USA

A R T I C L E I N F O

Article history:
Received 22 December 2010
Accepted 19 May 2011
Available online 27 May 2011

Keywords:
hydrology
modeling
water budget
brackish water environment
groundwater upwelling
tidal mixing zone
MIKE FLOOD

Regional index terms:
South Florida
Everglades
Taylor Slough

A B S T R A C T

Taylor Slough is one of the natural freshwater contributors to Florida Bay through a network of microtidal creeks crossing the Everglades Mangrove Ecotone Region (EMER). The EMER ecological function is critical since it mediates freshwater and nutrient inputs and controls the water quality in Eastern Florida Bay. Furthermore, this region is vulnerable to changing hydrodynamics and nutrient loadings as a result of upstream freshwater management practices proposed by the Comprehensive Everglades Restoration Program (CERP), currently the largest wetland restoration project in the USA. Despite the hydrological importance of Taylor Slough in the water budget of Florida Bay, there are no fine scale ($\sim$1 km^2) hydrodynamic models of this system that can be utilized as a tool to evaluate potential changes in water flow, salinity, and water quality. Taylor River is one of the major creeks draining Taylor Slough freshwater into Florida Bay. We performed a water budget analysis for the Taylor River area, based on long-term hydrologic data (1999–2007) and supplemented by hydrodynamic modeling using a MIKE FLOOD (DHI, http://dhigroup.com/) model to evaluate groundwater and overland water discharges. The seasonal hydrologic characteristics are very distinctive (average Taylor River wet vs. dry season outflow was 6 to 1 during 1999–2006) with a pronounced interannual variability of flow. The water budget shows a net dominance of through flow in the tidal mixing zone, while local precipitation and evapotranspiration play only a secondary role, at least in the wet season. During the dry season, the tidal flood reaches the upstream boundary of the study area during approximately 80 days per year on average. The groundwater field measurements indicate a mostly upwards-oriented leakage, which possibly equals the evapotranspiration term. The model results suggest a high importance of groundwater contribution to the water salinity in the EMER. The model performance is satisfactory during the dry season where surface flow in the area is confined to the Taylor River channel. The model also provided guidance on the importance of capturing the overland flow component, which enters the area as sheet flow during the rainy season. Overall, the modeling approach is suitable to reach better understanding of the water budget in the mangrove region. However, more detailed field data is needed to ascertain model predictions by further calibrating overland flow parameters.

1. Introduction

1.1. Background

Florida Bay is a critical region of an estuarine continuum that spans from freshwater and mangrove wetlands in the upper estuary to coral reef ecosystems along the outer edge of the Florida Keys (Fourqurean and Robblee, 1999; Rudnick et al., 1999). As a result of its position along this continuum water management practices, including changes in the timing, duration and magnitude of freshwater flow at the head of the estuary (northern Everglades) have affected salinity patterns and nutrient loading in Florida Bay. Due to the oligotrophic nature of Florida Bay, an increase in nutrient loadings could have a detrimental effect on the productivity of the region (Boyer et al., 2009; Briceno and Boyer, 2010). Thus, one of the major priorities in the Comprehensive Everglades Restoration Program (CERP), currently the largest wetland restoration project in the USA (Sklar et al., 2005), is to determine how changes in water net flux will be influenced by management decisions.

* Corresponding author.
E-mail address: bmichot@louisiana.edu (B. Michot).

0272-7714/$ – see front matter Published by Elsevier Ltd.
doi:10.1016/j.ecss.2011.05.018

Taylor Slough is one of the largest natural freshwater deliveries to Florida Bay through a network of microtidal creeks crossing the Everglades Mangrove Ecotone Region (EMER) (Rivera-Monroy et al., in press). The vegetation in this zone is dominated by scrub mangroves, which encompass more than 6000 ha between the freshwater marshes and Florida and Biscayne Bay (Simard et al., 2006). The EMER has a critical ecological role since it mediates freshwater and nutrient inputs and controls the water quality of Florida Bay (Sutula et al., 2001; Sutula et al., 2003; Childers et al., 2005). Furthermore, the EMER is not only vulnerable to changing hydrodynamics and nutrient loadings as a result of upstream freshwater management practices but also to sea level rise, as during the dry season its hydrology is dominated by tidal flow (Davis et al., 2005).

Despite the hydrological importance of Taylor Slough in the water budget of Eastern Florida Bay, there are no fine scale ($\sim 1\ km^2$) hydrodynamic models of this system that can be utilized as a tool to evaluate potential changes in water flow, salinity, and nutrients along the network of creeks. Thus hydrodynamic models are needed to help determining the potential impact of increasing freshwater discharge on the salt budget and nutrient cycling in Florida Bay, particularly in delivery points where high freshwater discharge has been identified in the last 10 years (Hittle et al., 2001; Sutula et al., 2003). There have been a number of large-scale ($>10\ km^2$) hydrological studies in Taylor Slough. For example, Swain et al. (2004) developed the Southern Inland and Coastal Systems (SICS) hydrodynamic and transport model (cell size 305 m) to evaluate impacts of anthropogenic hydrologic modifications to Taylor Slough and the EMER, especially with regard to water salinity values. Langevin et al. (2004) coupled a two-dimensional surface water flow model (SWIFT2D) with a 3-D-groundwater simulation code (SEAWAT) (cell size 305 m) to represent hydrologic processes, concluding that this approach was well suited to predict effects of changes in the hydrologic behavior of the Taylor Slough wetlands as a result of Everglades restoration efforts. This model was further developed into the FTLOADDS code (Flow and Transport in a Linked Overland/Aquifer Density Dependent System) by Wang et al. (2007) and applied to the Tides and Inflows in the Mangroves of the Everglades (TIME) domain (cell size 500 m). Similarly Sutula et al. (2001), using a box model approach, proposed a hydrological budget for the entire Taylor Slough and used it to develop nitrogen and phosphorus budgets for the period 1996–1997.

Taylor River is one of five creeks discharging from Taylor Slough into Eastern Florida Bay (Hittle et al., 2001; Sutula et al., 2003; Davis et al., 2004). These creeks cut through an approximately 30 cm high ridge following the coastline of Florida Bay, called the Buttonwood Embankment . This ridge is overtopped only by Florida Bay surges during major tropical storm events occurring with a multiannual return period. Under normal conditions it restricts overland flow of water, making the creeks point sources of freshwater input to Florida Bay. Taylor River is currently the most intensively studied creek (i.e., hydrology, biogeochemical process, primary and secondary productivity) in the region during the last 15 years (e.g., Sutula et al., 2001). As result of long-term monitoring programs (e.g., U.S. Geological Survey (USGS), Florida Coastal Everglades-Long Term Ecological Research (FCE-LTER)) there are extensive hydrological (e. g., water stage, water flow) and water quality (e.g., salinity, nitrogen, phosphorus) data bases allowing the development and calibration of small scale hydrodynamic and ecological models to be used as management decision tools within the context of CERP. The objectives of our study were:

(1) to evaluate the spatial (upstream vs. downstream) and temporal (seasonal, annual) variation in hydrology along Taylor River during the period 1999–2007;
(2) to develop a hydrodynamic model for this creek using the MIKE FLOOD platform (DHI, 2008):
(3) to identify the relative magnitude of groundwater exchange in the total water budget of Taylor River.

1.2. Study area

Taylor River is an approximately 4 km long small channel (10–20 m wide; 1–2 m deep) connecting a number of small, shallow ponds, which act as storage points for both nutrients and water. The hydrology in Taylor Slough is dominated by the cyclic flooding during the neotropical wet season from June to November, during which 80% of the annual precipitation occurs (Childers et al., 2005). With the progression of the dry season, the flow concentrates in the channel system, and parts of the Slough dry out. The tidal mixing zone is at this time influenced by tidal flow from Florida Bay. During the months of March through June, the flow direction in Taylor River changes with the tide, conveying saline Bay water into the EMER. The wind also influences the flow direction in the channel. The karstic geology fosters groundwater leakage in the area, driven by the prevailing hydraulic head of the infiltrating water. According to Langevin et al. (2005), as well as documented by the groundwater observation time series in Taylor River Upstream (U.S. Geological Survey, 1996–2008b), the groundwater leakage in our study area is mostly upward (negative infiltration). The groundwater salinity is high (e.g., Fitterman and Deszcz-Pan, 1999), as confirmed by the data recorded at the abovementioned station. Surface water salinity (0–50) and groundwater salinity (12–40) along Taylor River change seasonally (U.S. Geological Survey, 1996–2008a,b). Pore water salinity ranges from 1 to 46 (Poret et al., 2007).

The study area encompasses a mangrove area of approximately $2.5\ km^2$ crossed by the Taylor River channel extent located between the upstream (3.2 km) Taylor River gage and the Taylor River at mouth gage (hence referred to as upstream and mouth stations, installed and maintained by the USGS). Unrecorded overland flow occurs during the rainy season across the northern, western and eastern boundaries when the water level rises above the banks of Taylor River (e.g., Langevin et al., 2004).

2. Methods

2.1. Water budget analysis

2.1.1. Long-term water budget

Water stage, discharge and salinity recorded at the USGS upstream and downstream Taylor River stations from August 1999 to September 2006 were used to estimate the water budget of the study area, The equation used to calculate the general water budget is:

$$Q_{in} - Q_{out} + P - ET - \Delta S + \epsilon = 0 \tag{1}$$

where Q_{in} is the net channel inflow as recorded at the Upstream Taylor River gage site (Tup), Q_{out} is the net outflow measured at Taylor River mouth (Tm), P is the precipitation, ET the actual evapotranspiration, ΔS is the increase in storage volume in the study area, and ϵ is the budget closure term. This term includes measurement and extrapolation errors as well as an estimate of the unrecorded overland sheet flow across the flooded area boundaries, and the groundwater exchange component. To facilitate comparison among water budget components (e.g., precipitation, evaporation), river discharge units (Q, $m^3\ s^{-1}$) were converted to millimeters taking into account the total surface ($2517\ km^2$) of the model area (i.e., $1\ m^3\ s^{-1}/2{,}517{,}000\ m^2 = 3.973 \times 10^{-7}\ m\ s^{-1}$ depth on the area).

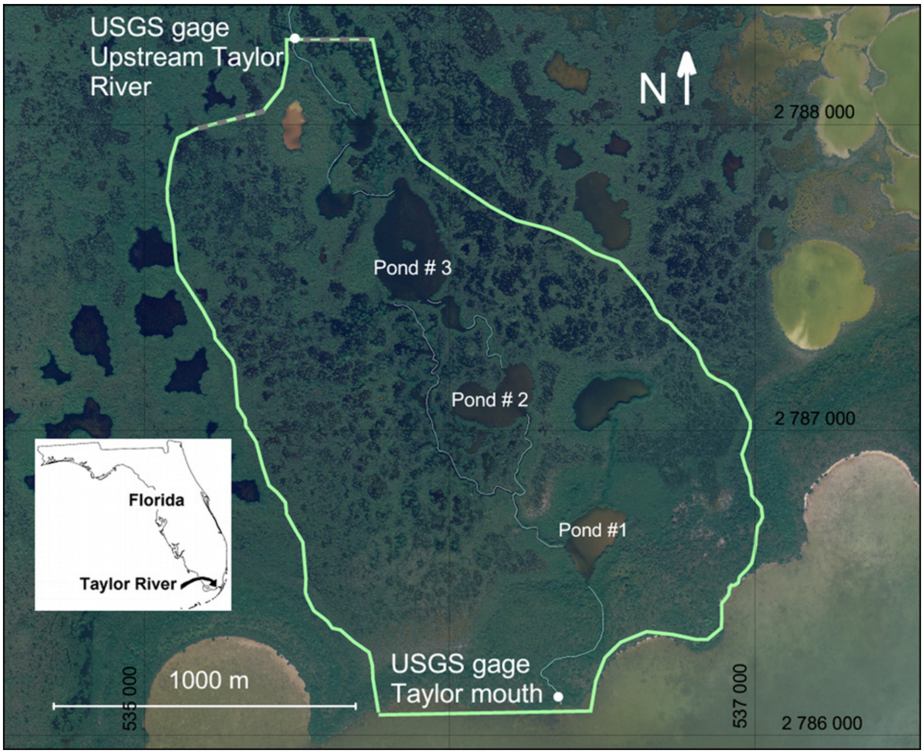


Fig. 1. Study site location and Taylor River modeling area boundaries (based on DOQQ by FDEP/BSM 2004).

Previous water budget studies in this region generally identified low and high water flows in the dry and rainy seasons, respectively (e.g., Sutula et al., 2001). Thus, to delimit the temporal extent of the seasons, we calculated a long-term average of available water level and precipitation data measured at the upstream Taylor River station (stage regime) over the period August 1999–September 2007 (Fig. 2). This stage regime shows that the long-term average water surface elevation at Taylor upstream falls below −0.10 m between December and June. This elevation also constitutes the average water level for the period during which the tidal flow from Florida Bay regularly reaches beyond the Taylor upstream station, indicating low freshwater discharge. (For the period of 1999–2007, the tidal flood reached the upstream boundary of our study area during about 80 days per year on average.) We assumed that an elevation of −0.10 m can be used as the approximate water level below which the surface water movement can be neglected. The assumption about minimum water movement is supported by the bank elevation (−0.20 m) recorded during the topographic survey conducted in November 2007. For water surface elevations between −0.10 m and −0.20 m, we recognize that vegetation cover, accumulated detritus, and other microtopographic resistance factors prevent noticeable flow. Therefore, although water levels at the beginning and end of the rainy season are subject to a large natural variability, for practical reasons we defined the wet period for this study from June 1 to November 30, and the dry season from December 1 to May 31; the latter period corresponds to the long-term average phase without significant overland flow. To confirm this seasonal partition, we evaluated the accumulated volume of outflow measured at Taylor mouth for the thus defined dry and wet seasons from December 1998 to May 2007 (Table 1). These values represent a net outflow since the inflow from Florida Bay is considered as negative outflow. Particularly during the dry season, water flow entering through Taylor River mouth could prevail as observed in 2001 (negative flow balance during the dry season). Indeed, water flow is very distinct between seasons with an average wet vs. dry season flow ratio of 6.5:1. However, it shows a significant interannual variability (wet season outflow maximum 50.8×10^6 m^3 vs. minimum 19.0×10^6 m^3, ratio 2.7).

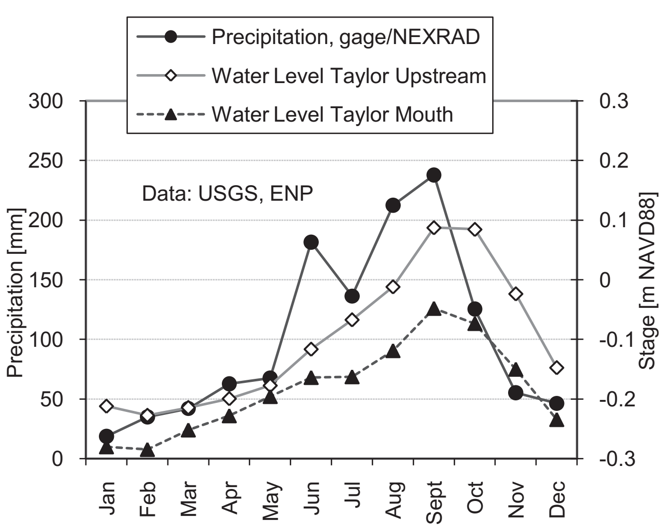


Fig. 2. Taylor River stage and precipitation regime, August 1999–September 2007 (USGS, 1996–2008a,b; U.S. Geological Survey, 2008a,b).

Precipitation (P) was estimated using gage adjusted NEXRAD radar data published by the USGS' Everglades Depth Estimation Network (EDEN) (U.S. Geological Survey, 2008b). Because no precipitation data was available for the period 1999–2001 on the USGS Eden website, we used a spatially averaged precipitation recorded in monitoring sites near Taylor River. These stations were Taylor River (TR) and Little Madeira (LM), which are part of the Everglades National Park (ENP) monitoring network (South Florida Natural Resources Center 2008). Evaporation (ET) estimates were also retrieved from the USGS EDEN databank (U.S. Geological

Table 1
Accumulated seasonal outflow at Taylor mouth ($\times 10^6$ m^3) for the period December 1998 to May 2007 (U.S. Geological Survey, 1996–2008a).

Season	Year										
	1999	2000	2001	2002	2003	2004	2005	2006	2007	Mean	SD
Dry*	3.3	7.7	−1.3	7.3	10.9	8.6	0	5.5	3.6	5.1	5.5
Wet	34.4	22.9	34.6	36	36.7	19	50.8	32.8	N/A	33.4	9.1

SD = standard deviation.
* dry season values for each year include flow from the previous month of December in this study.

Survey, 2008a). Those estimates are produced using solar radiation obtained from Geostationary Operational Environmental Satellites (GOES). The measurements have a spatial resolution of 2 km (Jacobs et al., 2008); the datasets from Taylor River and Taylor upstream cover our modeling area. Given the uncertainties in the overall extrapolations, we did not assess the relatively small discharge and stage measurement errors. The increase in storage volume, ΔS, was estimated by the difference between monthly stage readings at upstream Taylor River. Small data gaps were filled by interpolation or comparison with the nearest ENP gages.

Due to the region's karstic geomorphology, a groundwater exchange term was considered using information collected since 2002 by the USGS in two wells located near the upstream Taylor River station. The gages record the groundwater head and the salinity at −4.3 m (G-3763) and −1.5 m (G-3764) (U.S. Geological Survey, 1996–2008b). The difference between the groundwater head in the shallower well and the ambient water level was multiplied by a factor reflecting the hydraulic conductivity in order to estimate groundwater leakage in the area. However, as no direct measurement of the groundwater discharge is available, this factor could only be calibrated via hydrologic and salinity transport modeling and therefore was not integrated in the long-term seasonal water budget analysis.

2.2. Hydrodynamic model

A hydrologic model simulating the hydrodynamics and salinity transport in the Taylor River area was set up using the MIKE FLOOD software platform (DHI, 2008) (Fig. 3). This model integrates a MIKE 21 two-dimensional grid and a MIKE 11 channel flow simulation tool, with explicit links at the channel/pond interfaces, and implicit simulation of lateral exchange when the water level rises above the channel banks. Both modules solve the non-linear St. Venant equations of continuity and momentum conservation. While MIKE 11 integrates the flow over the channel cross section and implements fully dynamic wave routing, the MIKE 21 module solves the vertically integrated flow equations in two dimensions and routes the flow from cell to cell. Hydraulic resistance is computed based on Manning's coefficients for channel reaches and for every MIKE 21 grid cell. MIKE FLOOD is capable of simulating cell dry-out and re-flooding either by rising water levels in adjacent cells or by precipitation input. An advection-dispersion (AD) module allows for computation of the salt load conveyed by the flow.

2.2.1. Model setup

The model is based on bathymetry data from two different sources: a comprehensive survey of elevation points throughout Taylor Slough with a resolution of 400 × 400 m collected by USGS in 2002 (U.S. Geological Survey, 2007), and detailed channel cross section elevations surveyed in 15 transects extending from the mouth of Taylor River to 4 km upstream. The cross section data was used to define the channel and pond profiles, interpolating linearly between the measured elevations. For purposes of the model, the horizontal data were converted to UTM coordinates, and elevations to meters (datum NAVD 88). A denser network of elevations was interpolated to create a 50 × 50 m model grid taking into account the natural features (channels, ponds, ridges) as well as vegetation patterns appearing on aerial orthophotos (FDEP/BSM 2004). Given the low resolution of the Slough survey data, the bathymetry bears a certain degree of uncertainty, especially regarding the elevations of channel banks with dense vegetation.

At the open boundaries, the MIKE 11 component is driven by observed water level and discharge data (U.S. Geological Survey, 1996–2008a). The upstream Taylor River discharge time series is applied at the northern MIKE 11 boundary, while the water level recorded at Taylor River mouth represents the southern channel boundary. For wet season simulations, the overland flow component in MIKE 21 is driven either by the water level measured at upstream Taylor River, or by information from the TIME application of the FTLOADDS model code (Wang et al., 2007, simulation provided by Dr. E. Swain) at the open part of the northern and northwestern model boundary. The remaining model boundaries are considered closed: to the south, the elevated Buttonwood Ridge prohibits the boundary exchange; to the west the aerial image shows densely vegetated rims along a series of ponds. In Section 4.2, we discuss the errors related to the assumption of closed boundaries to the east.

Precipitation and evapotranspiration are applied to every cell at an hourly time step. The daily cumulated precipitation from EDEN NEXRAD (U.S. Geological Survey, 2008b) was prorated to hourly values based on the temporal pattern of the rainfall time series measured by the ENP ground gage at the monitoring station TR. The daily potential evapotranspiration (PET) data retrieved from USGS EDEN (U.S. Geological Survey, 2008a) was refined into an hourly dataset using a bell-shaped curve weighting daily values. Following recommendations by Shoemaker and Sumner (2006) for wetland evapotranspiration estimates, a factor of 0.8 was applied to the PET data to obtain actual evapotranspiration. Further calibration of this factor was not pursued.

Three modeling periods were defined in this study:

(1) a dry period with minimum water budget closure term, i.e. minimum overland flow, to calibrate the hydrodynamics (January to June 2001);
(2) a dry season period with available groundwater data from December 2003 to June 2004 to determine the groundwater leakage factor, extended until May 2005 for salinity transport calibration;
(3) a period including overland flow simulation (March–October 2002), allowing to verify the hypothesis that the remaining budget closure term consists in overland flow. During the hydrodynamic model calibration process, several parameters were adjusted, such as channel and slough roughness coefficients, i.e. hydraulic resistance (Manning's n, Chow et al., 1988), groundwater leakage factor, and drying/flooding depths. The "best fit" was chosen by comparing the resulting simulated discharge time series with the observed values at Taylor River mouth (U.S. Geological Survey, 1996–2008a), both graphically and by calculating statistical indices including the root mean square deviation (RMSD), the NSE Index (Nash-Sutcliffe Efficiency, Nash and Sutcliffe, 1970), and the "index of agreement" (d) developed by Willmott (1981).

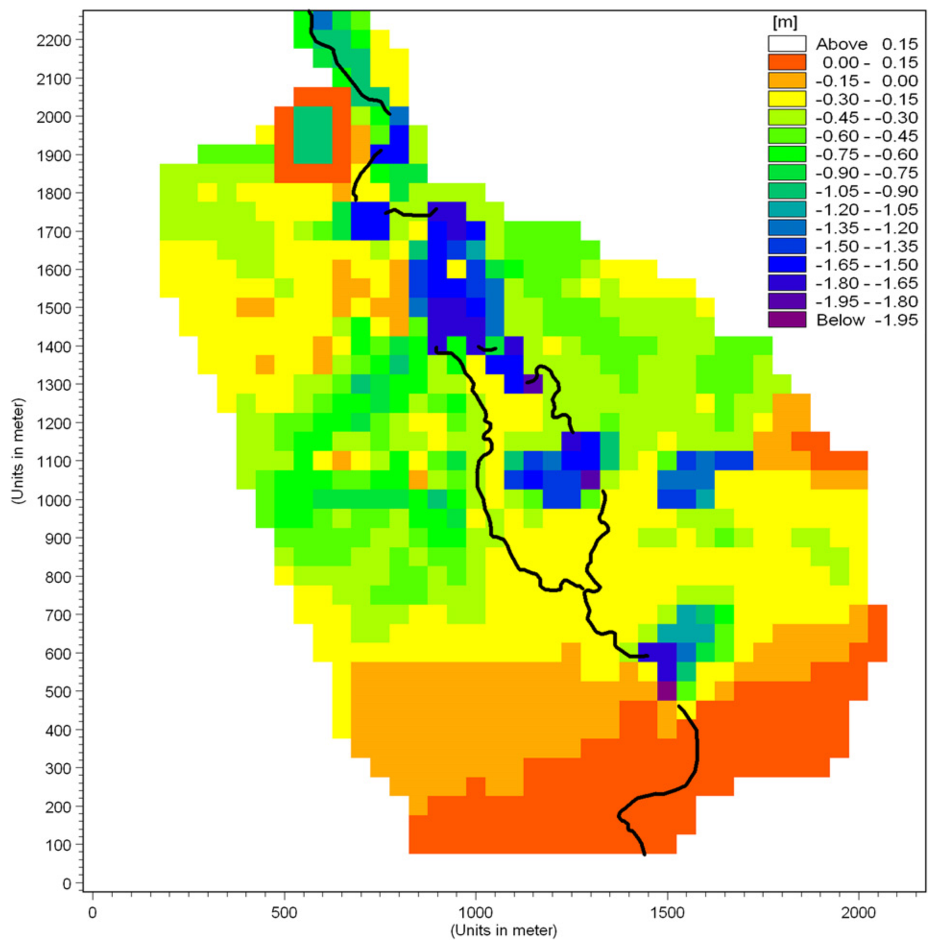


Fig. 3. MIKE FLOOD model setup: MIKE 21 two-dimensional grid and MIKE 11 channels (black lines). Elevation grid is relative to NAVD 88.

Since MIKE 21 does not include a groundwater interface to account for groundwater exchange, the model was configured to simulate this term by adding upwelling groundwater to the precipitation term, and a downward oriented leakage to the ET term. The prevailing hydraulic head drives the groundwater leakage, thus a time series was constructed based on the difference between the water level of the upper groundwater compartment (i.e., USGS groundwater observation site ID# G-3764) and the ambient water level at the upstream Taylor River station. This water level difference was multiplied by a factor which was calibrated using the hydrologic model (0.002). Because of the low sensitivity of the hydrodynamic model to groundwater discharge, simulation of salinity dynamics was necessary to calibrate the groundwater leakage factor. Given the high salinity of the upwelling groundwater, the salinity modeling results were more explicit. The salinity dynamics throughout the model area were simulated using the MIKE FLOOD advection-dispersion (AD) module. Boundary conditions were provided by salinity time series measured at USGS Taylor upstream and Taylor mouth gages as well as groundwater salinity data from the USGS well at Taylor upstream. The simulated salinity values were compared to a set of discrete observation data (Rivera-Monroy, unpublished data). Finally, the salt load transported by the leaking groundwater was estimated by multiplying the salinity measured in the groundwater well by the calibrated unit groundwater discharge, and entered into the model as deposition on each cell.

We applied modeled flow data at the northern grid boundary to evaluate the effect of an overland flow component on the wet season simulation results. This dataset was provided by the TIME (http://time.er.usgs.gov/) application of the FTLOADDS model code (Wang et al., 2007). The TIME model boundary encompasses a large region of the Everglades National Park but the resolution is coarser (500 × 500 m cell size), and the model does not consider channel flow separately. In order to get only the overland component of the modeled flow, we subtracted the channel flow component recorded at the Taylor River upstream station from the TIME modeled inflow at the northern boundary. Also, we set the overland discharge to 0 for a recorded Taylor upstream stage lower than −0.15 m, assuming that at a water depth <10 cm, Slough surface flow is virtually halted. The coarser resolution of the TIME model also required bathymetric adjustments at the interface locations to suite the resolution of the model applied herein. The adjusted model boundary flows had to be proportionally reduced to half of their values at the western boundary in order to model the period from March to October 2002. Unfortunately, the flows simulated by the TIME model at the eastern boundary (mostly outflow) could not be implemented because of scale-induced bathymetry discrepancies.

2.2.2. *Model application–seasonal water budgets for the year 2002*

The application of the calibrated numerical model for the year 2002 including groundwater flow enabled us to estimate a detailed water budget. Results of the model were used to estimate parameters for which field observations were lacking (e.g. boundary overland flow and groundwater leakage). Data gaps were filled using regression functions based on neighboring stage

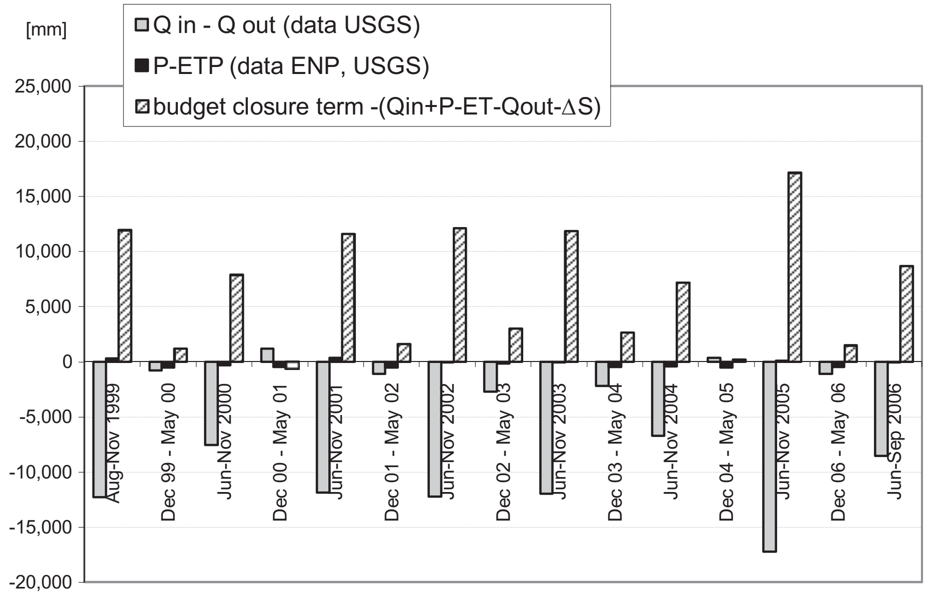


Fig. 4. Taylor River seasonal water budget; dry season is from December to May and wet season from June–November (USGS, 1996–2008a,b; U.S. Geological Survey, 2008a,b).

datasets. For comparison purposes, the flow terms were converted to areal depths (mm, see Section 2.1.1). We subdivided the annual data into two periods: January through mid-June 2002, and mid-June to the end of December 2002 to properly render dry and wet conditions.

3. Results

3.1. Long-term water budget

The comparison of precipitation and stage regimes (Fig. 2) reveals a shift between rainfall and runoff characteristics. Although the rainy season ends in October–November, the EMER in the Taylor Slough region does not dry out significantly until January. In contrast, at the beginning of the rainy season, the peat layer in the Slough first absorbs the rainwater, before excess water accumulates to flow down to Florida Bay.

The water budget estimated for the period 1999–2006 indicates a strong seasonality of the budget closure term ϵ, as well as for the net difference between inflow and outflow (Fig. 4). This pattern is most evident when aggregating results for low and high water flow (i.e., June to November and December to May). Given the magnitude of long-term flow accumulations, the change in storage can be neglected.

The temporal variation of the budget closure term can be explained to a large extent by the flow balance $Q_{in} - Q_{out}$ (the coefficient of determination R^2 for the monthly averages was 96.9%). As described above, two options have to be considered in the study area for unrecorded flow across the model boundaries, i.e., either overland flow if the water level exceeds the Taylor River bank elevation (about −0.2 m NAVD 88), or groundwater leakage. Previous studies have shown that these processes occur in the study area and need to be considered in the estimation of water budgets and net outflow, particularly in this karstic region (Sutula et al., 2001; Langevin et al. 2004; Langevin et al. 2005; Harvey and McCormick, 2009). The next section presents the results of the hydrologic modeling performed to partition the importance of groundwater leakage and boundary overland flow.

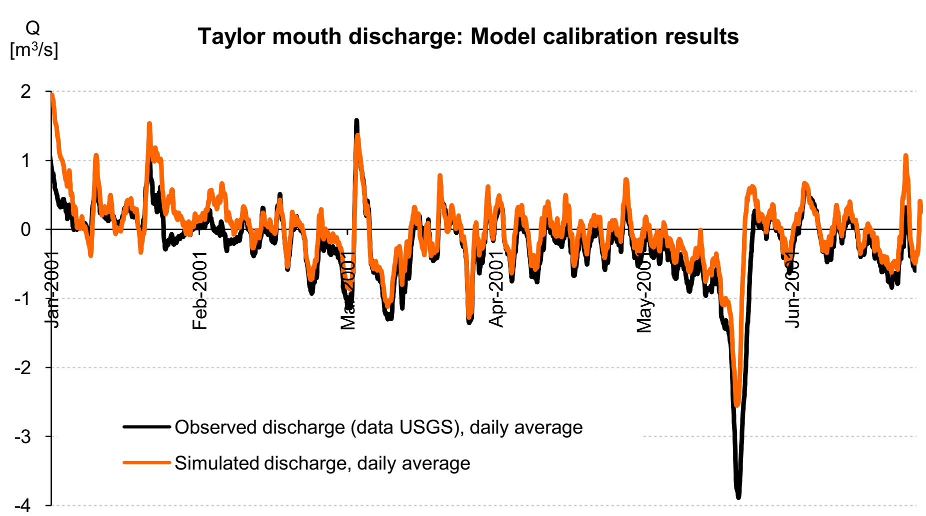


Fig. 5. Hydrodynamic calibration results at Taylor mouth using data from January to June 2001.

Table 2
Simulation result statistics for the calibration and validation procedures during selected periods.

Criteria	Modeling period	Taylor Mouth mean observed Q*/Std. dev.($m^3\ s^{-1}$)	Model Bias ($m^3\ s^{-1}$)	RMSD		NSE†	d‡
				$m^3\ s^{-1}$	% of Range		
Low flow calibration	January–June 2001	−0.21/0.799	+0.19	0.4	5.5	0.73	N/A
Validation	December 2003–May 2004	0.326/1.233	−0.16	0.6	7.9	0.72	0.9
Leakage calibration	December 2003–May 2005	0.651/1.737	+0.27	0.8	6.1	0.74	0.9
Validation overland flow	March–October 2002	1.629/2.224	+0.24	0.9	9.0	0.83	0.95

* Q = flow.
† Nash-Sutcliffe Efficiency index (Nash and Sutcliffe, 1970).
‡ Index of agreement (Willmott, 1981).

3.2. Simulation

3.2.1. Hydrodynamic calibration

To minimize the effect of the unrecorded flow component in the water budget, the hydrologic model was calibrated during a period showing a small budget closure term. The period of January–June 2001 was selected for this calibration, as this period provided adequate flow data for statistical evaluation. The model run was performed using hourly values, although a daily moving average was used to visually compare the two time series (observed vs. simulated) (Fig. 5). The model slightly overestimates the discharge at Taylor mouth as reflected also by the model bias of +0.19 m^3/s (Table 2). Since the selected modeling period encompasses the dry season with reduced overland flow, the northern overland boundary was considered closed (i.e., zero flow), and thus the most important calibration parameter is the channel roughness. The best calibration results were obtained with an overall channel Manning's n of 0.10 s $m^{-1/3}$. The model results could not be improved by spatially varying channel roughness. The MIKE 21 overland flow resistance for open water (ponds) was set to 0.02 s $m^{-1/3}$, while an average Manning's n of 0.4 s $m^{-1/3}$ for the vegetated area of the Slough provided the best calibration results. The Nash-Sutcliffe efficiency (NSE) index (Nash and Sutcliffe, 1970), for the final calibration run was 0.73 with a root mean square error of 0.418 $m^3\ s^{-1}$ (i.e., 5.5% of the range of observed values, Table 2).

3.2.2. Validation of the hydrodynamic model and groundwater leakage calibration

We validated the model parameter set calibrated for the period January–June 2001 by applying the model to a second low flow period (December 2003–July 2004) (see Fig. 6, showing monthly moving averages to help interpretation). The NSE index for this validation was 0.72 with a model bias of −0.16 $m^3\ s^{-1}$ (Table 2). Fig. 6 also includes a scenario with an open overland boundary (light green line) where the water level recorded at Upstream Taylor River was imposed at the MIKE 21 northern limit, allowing overland flow to enter the area. The simulated outflow resulting from this scenario is closer to the observed discharge during the months of January to March 2004, whereas the closed boundary run has better agreement with the measurements at the end of the dry season (April–July). This difference is probably due to the higher proportion of actual overland flow at the beginning of the dry season in 2004 compared to the dryer calibration period of 2001. Indeed, the average water level recorded at upstream Taylor River gage was −0.16 m during the first three months of the validation, while during the calibration period the water level was −0.19 m (i.e., 3 cm lower). Yet, toward the end of the validation period, the average upstream water level was similar to the value observed during the calibration period (i.e., no overland flow). The simulation applying an open northern boundary then overestimates the overland flow (April to July 2004, Fig. 6). This overestimation might be due to the fact that the modeled overland boundary, driven by the Taylor upstream water level, allows too much water to enter the model area as a result of overestimated flow cross sections: given the bathymetry uncertainties between the overland survey points, it is possible that we assumed a greater than actual depth. This error will have a relatively higher impact on the conveyed discharge at low stages than when the water level is high.

We were able to include a groundwater term for the validation period (December 2003–July 2004) using the USGS Taylor upstream well data to simulate groundwater heads and salinities.

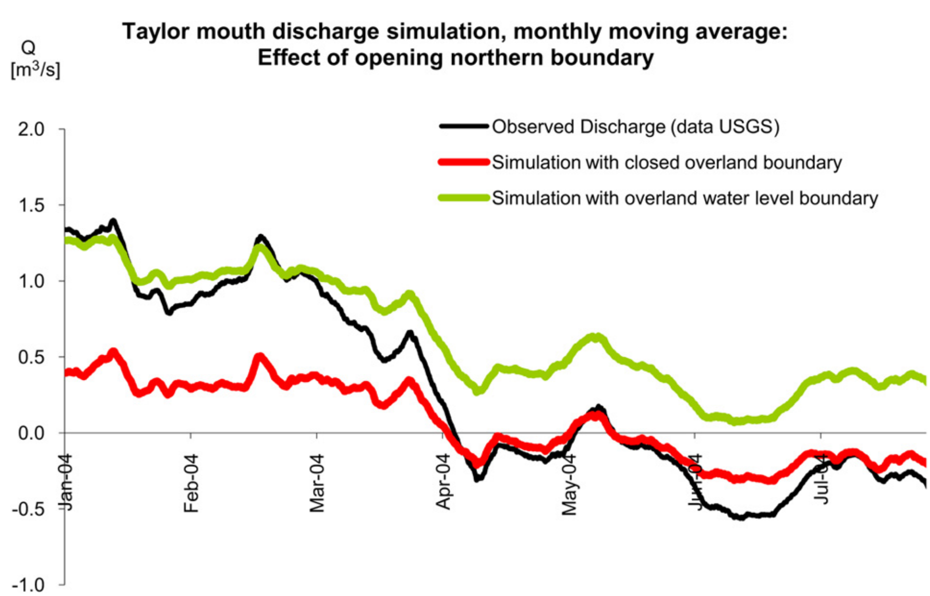


Fig. 6. Hydrodynamic model validation at Taylor mouth from December 2003 to July 2004 (monthly moving averages).

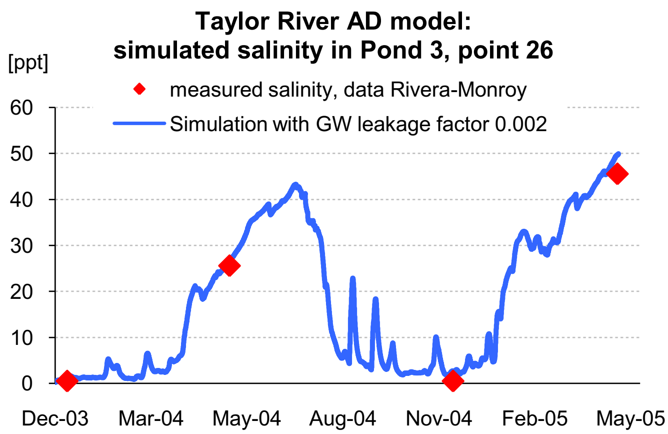


Fig. 7. Salinity simulation in Pond #3 located along Taylor River. Model simulation encompasses the period from December 2003 to May 2005.

The best fit for the leakage factor could not be achieved based on hydrodynamic considerations only. Thus, we used the AD salinity simulations to guide the calibration of this parameter. In order to increase reliability of the simulation results, the modeling period was extended until May 2005 to include all the available salinity observation data (Rivera-Monroy, unpublished data). Dispersion was assumed to be 5 m^2 s^{-1} as recommended in the MIKE 21 manual (DHI 2008). This value could not be calibrated due to the scarcity of salinity field measurements in the overland mangrove area. Thus, calibration was performed graphically, as the small number of observed data did not allow for statistical interpretation. The best calibration result for the period from December 2003 to May 2005 was achieved by applying the Taylor mouth discharge at the southern boundary of the MIKE 11 model channel, and a groundwater leakage factor of 0.002.

We assessed the salinity differences between observed and simulation data at the locations where discrete seasonal measurements were available for the years 2003–2005 (Rivera-Monroy, unpublished data). Fig. 7 shows the discrete observation data and the simulated salinity at Pond #3 located in the center of the modeling area (see Fig. 1). The overall pattern of salinity dynamics is well captured by the model. Additional salinity measurements, especially during the peak period in July, would have strengthened the reliability of the model simulation. The slight overestimation of the salinities in December 2004 and May 2005 might be due to the underestimated overland freshwater flow at the northern model boundary. This flow underestimation when applying the water level at the northern boundary shows also during the wet season in the period June–July 2002 (Fig. 8). This figure also presents the daily precipitation.

The boundary discharge generated by the TIME application was used to evaluate if simulating the missing overland flow term would improve model performance. A MIKE FLOOD model run was set up for the year 2002 using TIME output overland flow at the northern boundary. The modeling period was limited by groundwater data availability to the period March–September 2002. This approach produced better results than applying a water level at the upper boundary (Fig. 8), showing the importance of taking overland discharge into account for wet season simulations. The model bias (i.e. the deviation of the mean of simulated discharges from the observed mean) was +0.24 m^3 s^{-1} (Table 2). The absolute root mean square deviation (RMSD) was 0.9 m^3 s^{-1}, corresponding to 9.0% of the range of observed values. The NSE Index and "index of agreement" (d) were 0.83 and 0.95, respectively.

3.3. Seasonal water budgets

We estimated seasonal water budgets for the year 2002 using available field and model output datasets for the Taylor River area (Fig. 9). On an annual basis, the major budget term of this estuarine area is the outflow at Taylor mouth (Tmouth Q_{out}, 17,265 mm y^{-1}), while the surface water flow (SW, outside of the Taylor River channel) is negligible during the dry season (71 mm y^{-1}), but it represents almost 80% of the outflow during the rainy season (12,638 mm y^{-1}) (Fig. 9). Year-round, local precipitation has only a small influence on the water budget. The effect of evapotranspiration, as well as groundwater leakage, is proportionally more important during the dry season when surface flow is small, but non-significant in the wet season compared to surface flow. Groundwater (GW) in this low part of the Slough is mostly upwelling (dry season: 665; wet season: 737 mm $season^{-1}$).

Hydrology in the Taylor River area is dominated by the accumulation of water retained by the Buttonwood embankment.

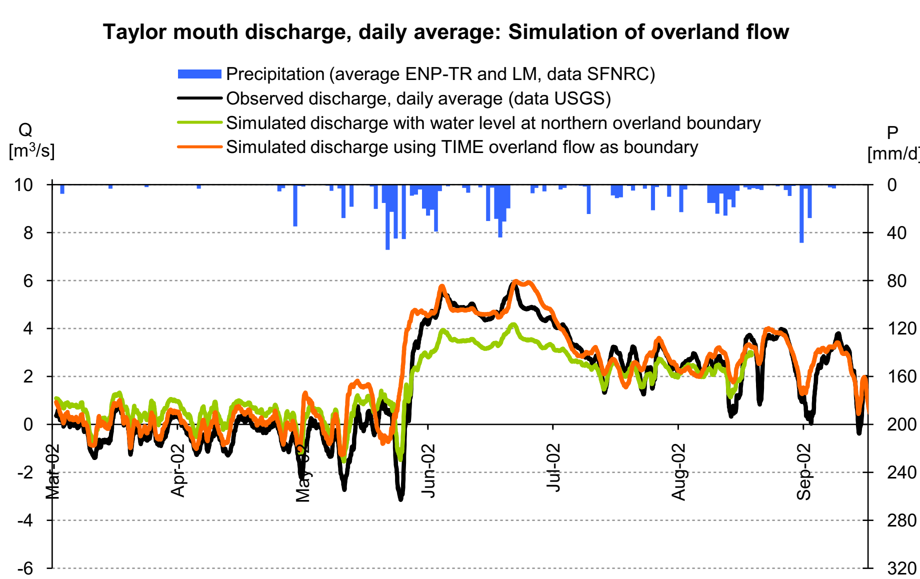
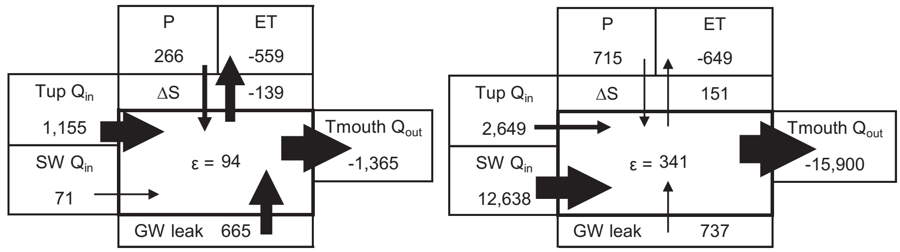


Fig. 8. Overland flow simulations in the Taylor River modeling area (March–September 2002).



a dry season: January – mid-June 2002 **b** wet season: mid-June - December 2002

P = Precipitation from EDEN NEXRAD, average of Upstream Taylor River and Taylor Mouth data

ET = 80% of the Potential Evapotranspiration as given on the USGS Eden website for Taylor Upstream

SW = Surface water overland flow as simulated by Eric Swain's model, calibrated with MF model

Tup Q_{in} = Cumulated measured discharge at USGS Upstream Taylor River gage, in mm/season

Tmouth Q_{out} = Cumulated measured discharge at USGS Taylor River at Mouth gage, in mm/season

GW leak = Groundwater leakage estimate based on difference between GW head and stage at Tupstream, calibrated with Mike Flood (DHI 2008) AD model

ΔS = Change in storage in the area, estimated by the stage difference at the beginning/end of the period

ε = P+ET+Tup+SW+GW+Tmouth+ΔS = Budget closure term

Fig. 9. Taylor River cumulated water flow (mm/season). Direction of arrows indicates flow direction; positive and negative values indicate input and output, respectively. Arrow size is proportional to flow and weighted separately for each season.

Water from a large part of the Slough converges at Taylor River mouth where it flows into Eastern Florida Bay. Thus, the water input through surface water in our modeling area is large relative to precipitation. In this budget scheme, the budget closure term, ϵ, includes a seasonal balance of all error terms. This term represents -6.9% and -2.1% of the observed outflow at Taylor mouth during the dry and wet seasons, respectively.

4. Discussion

4.1. Sensitivity analysis

Given the assumptions included in the model setup (e.g., interpolated bathymetry data, gaps in the boundary conditions) as well as the scarcity of field data to adequately calibrate the model, it was not possible to quantify the error affecting the water budgets. In order to estimate the variability of the different terms, and the overall uncertainty of the modeling results, we performed a sensitivity analysis on the simulated discharge at Taylor mouth. Below we discuss each model component uncertainty in the context of the hydrodynamic model performance.

Bathymetry. We investigated the uncertainty in the elevation data interpolated for the slough area between the surveyed 400×400 m elevation points. To evaluate the impact of bathymetry errors, the elevation of the entire model domain was raised by 0.1 m, and then lowered by 0.2 m. The NSE model efficiency index lost 6% for the first scenario and 11% for the second (from 0.79 it went down to 0.74, then to 0.70). The impact of bathymetry errors is especially important during the low flow season, the influence being relatively smaller as the water level rises. No sensitivity analysis has been performed for the channel profile, as the cross sections in the outflow branch were well surveyed in their deepest regions. One model run was performed with a reduced channel width in the lowermost creek branch, the results were almost identical.

Evapotranspiration (*ET*). Reducing the potential evapotranspiration (PET) rate by 25% (from 80% of the PET to 60%) showed that the sensitivity of the hydrodynamic model results to this term (expressed as Taylor mouth discharge) is small. The NSE index changed only by 0.002 points (i.e., from 0.812 to 0.814). A fine-tuning of the correction factor to be applied for calculating actual ET from PET was not feasible under those conditions. However, especially for long-term simulations, the rate of evapotranspiration seems to have a more noticeable impact on salinity of water overlying wetlands. As no salinity measurements in the vegetated area outside of channels or ponds are available, no statistics could be calculated to evaluate the model performance in those areas.

Precipitation. Another error source is the uncertainty of the precipitation input, as there was no rain gage located inside the modeling area. However, changing the precipitation input from gage data to the NEXRAD radar data (the two datasets showing a correlation coefficient of 85%) did not have a measurable effect on the simulation results, showing the low model sensitivity to precipitation. This result was expected given the small contribution of direct rainfall to the water budget (Fig. 9).

Roughness. The sensitivity of the modeled discharge at Taylor mouth to the value of the channel roughness coefficient is highly significant since changing the channel Manning's n from 0.15 s $m^{-1/3}$ to 0.10 s $m^{-1/3}$ improved the NSE Index by more than 10%. Swain et al. (2004) measured flow velocity and estimated a value of $n = 0.121$ s $m^{-1/3}$ (SD $\pm$ 0.078 s $m^{-1/3}$) using Manning's formula. The SICS model calibration resulted in a value of 0.152 s $m^{-1/3}$, but this model does not consider channel flow separately. Thus, SICS' Manning's n reflects an average between channel and overland flow roughness.

In contrast, the sensitivity of our hydrodynamic model to overland flow resistance was low, as changing the overland Manning's n from 0.4 s $m^{-1/3}$ to 0.45 s $m^{-1/3}$ had almost no effect on the model efficiency even when the water level was high. Thus, no distinction was made between different vegetation covers. Swain et al. (2004) used a value of 0.43 s $m^{-1/3}$ for sawgrass and 0.38 s $m^{-1/3}$ for rush/sawgrass. We did not find published Manning's n estimates for mangrove wetlands, which is the dominant vegetation in our model area.

Groundwater Leakage. Since no groundwater level time series were available for the model calibration period (January–June 2001), the first model validation (December 2003–July 2004) was performed without groundwater component, yielding a RMSE of 8.1%. After calibration of the groundwater leakage factor using the AD simulation, the RMSE was reduced to 7.9%, while the NSE index improved from 0.71 to 0.72. The AD model is more sensitive to the leakage factor as groundwater contributes a significant amount to the salt budget within the model domain. However, no statistics could be calculated for the AD simulations, given the scarcity of the field observations available for calibration. Therefore, the evaluation relied on graphical inspection. The MIKE 21 AD module does not account for salt deposition on dry cells. This feature introduced an error since groundwater upwelling adds salt to cells that may be initially dry. However, our analysis indicates that this error is not significant.

Boundary Overland flow. The largest modeling error is certainly induced by the unknown boundary overland flow term. For the December 2003–May 2005 simulation, the model results were significantly impacted when an estimated boundary overland flow was introduced. The RMSE improved from 8.3% to 6.1% while the NSE index improved from 0.52 to 0.74. We strongly recommend gathering field measurements of boundary overland flow considering that it is the largest term in the water budget during the wet season.

4.2. Relative importance of the overland flow component

Due to the spatial resolution of the elevation survey used to build our model grid at the landscape level, local topographic features are missing and are not captured by the numerical model. In addition, since field measurements of overland flow velocities are not available, an overland upstream stage was imposed. Thus, errors in the marsh elevation would translate into an error in the volume of overland flow entering the model domain. During six months per year the water level is above −0.15 m (Fig. 2). This water level exceeds the channel banks and inundates the wetland areas. To correctly reproduce the regional flow dynamics, a more detailed bathymetry survey is needed, especially at the model domain boundary locations. Water flow or at least stage recordings at crucial boundary limits would enhance our understanding of hydroperiod and hydrodynamics in the region.

The model only considers through-flow at the northern and northwestern boundary, while the results of the flow model developed by Langevin et al. (2004) show also lateral flow in the eastern part of our modeling area. An attempt to apply a flow time series simulated by the TIME model (Wang et al., 2007) at the eastern boundary was not successful due to the bathymetric discrepancies between the two models. However, observation of natural features in the area, as well as modeling results with observed discharges applied at both Taylor upstream and mouth (causing the water level in the modeling area to rise above the measured values) suggest that water might indeed leave the area in some part of the overland boundary.

4.3. Magnitude of the groundwater component

We used the USGS Upstream Taylor River groundwater level time series to estimate the groundwater contribution. It is overreaching to consider one single observation point as representative for the whole area, particularly in a karstic environment as in the case of Taylor River. However, in absence of groundwater discharge data (e.g. Price et al., 2006), this method is the only available alternative. The best simulation result – with a leakage factor of 0.002 – yielded an average daily groundwater upwelling of 3.6 mm d^{-1} during the record period of December 2003–September 2007, with a maximum value of 7.9 mm d^{-1} on January 18, 2005, and a minimum value of −0.3 mm d^{-1} (downward leakage) on June 1, 2004. Langevin et al. (2004) performed a regional hydrologic numerical simulation including surface water/groundwater exchange and determined an average upwelling leakage of 0.9 mm d^{-1} in the vicinity of the Florida Bay for the period 1996–2002.

4.4. Reverse flow component at the mouth of Taylor River

The hydrodynamic model often underestimates the reverse (i.e., negative = flow in the upstream direction) discharge peaks at Taylor mouth (e.g. Fig. 6, in May 2001). It appears that during flood tide, when the Bay water enters Taylor River and flows north, the model underestimates the absolute flow value. This underestimation is the result of the water level applied at this boundary, which does not reflect the convective acceleration term pushing the flow upstream (as current or wind friction). This causes the model to underestimate the volume of water pushed inland through the river mouth. Sutula et al. (2003) analyzed the influence of wind-driven forcing on flow direction in tidal creeks cutting through the coastal ridge into Florida Bay and showed the influence of wind on creek discharges. Langevin et al. (2004) also pointed out the importance of wind friction, especially for salinity modeling. A graphical comparison of our simulation results with wind direction data measured at Joe Bay, about 10 km to the east (South Florida Natural Resources Center (SFNRC), 2008), showed the influence of wind direction on channel discharge. Since the Taylor River estuary is roughly oriented in a N–S direction, southern winds from about 180° ± 45° would induce upstream flow. All the upstream flow peaks corresponded to southern wind events.

An attempt was made to include the wind effect into the model simulation, but the effect within the modeling area is not sufficient. Two approaches can be evaluated in the future to overcome this problem; one is to expand the model domain to include a portion of Florida Bay. However, this approach would require a bathymetric survey of the bay. Another approach is to impose the observed Taylor mouth discharge time series as a boundary condition, and use interior monitoring stations for calibration. This option will require installing additional continuous monitoring stations for stage, salinity, and nutrient concentrations.

5. Conclusion

We analyzed hydrologic data available in the Taylor River area from 1999 to 2007 to estimate a water budget for the model domain and develop a hydrodynamic model. A water budget analysis for this system showed that although the rainy season ends in October–November, the mangrove ecotone zone does not dry out significantly until January. This seasonal pattern is primarily because the predominant groundwater head, the debris layer impeding drainage, and the water retention by the Buttonwood Ridge prevent a faster dry-out. In contrast, at the beginning of the rainy season, the peat layer in the Slough first absorbs the rainwater, before excess water accumulates to flow down to Florida Bay. The seasonal hydrologic characteristics are very distinctive (average Taylor River wet vs. dry season outflow was 6 to 1 during 1999–2006) with a pronounced interannual variability of flow.

The water budget analysis of channel discharge data collected between 1999 and 2006 by the USGS in the Taylor River was supplemented by a hydrologic modeling effort to determine groundwater and overland flow contributions. The water budget shows a net dominance of through flow in the tidal mixing zone, while local precipitation and evapotranspiration play only a secondary role, at least in the wet season. The groundwater well data indicates a mostly upwards-oriented leakage, which possibly equals the evapotranspiration term. This finding resulted from the hydrologic simulation of water and salt dynamics in the area. While the groundwater term is negligible for the hydrodynamics on an annual basis, its contribution to the salinity of the area is significant given the high salt concentrations of the upwelling groundwater.

The model performance is satisfactory during the dry season where surface flow in the area is confined to the Taylor River channel. The model also provided guidance on the importance of capturing the overland flow component, which enters the area as sheet flow during the rainy season. Nesting the local model presented herein with regional hydrologic models improved the model results during the wet season, showing the ability of this model to correctly capture the hydrodynamic processes in the area provided that accurate boundary data is available. In order to model constituent dynamics in this tidal mixing zone with greater degree of certainty, we recommend gathering detailed field information on overland flow discharges, as well as on salinity and nutrient concentrations in the mangrove wetland region. This sampling approach will allow for a thorough calibration of numerical models that can be used to assess various hydrological restoration scenarios and water management strategies.

Role of the funding source

The South Florida Water Management District (PO No. 450001265) supported this study.

Partial funding was also provided by the Florida Coastal Everglades-Long Term Ecological Research (FCE-LTER) program funded by the National Science Foundation (Grants #DBI-0620409 and #DEB-9910514).

Acknowledgments

We would like to thank Richard J. Ewing from Coastal Engineering Consultants for their technical and field support during elevation surveys. Special thanks to Eric Swain (U.S Geological Survey) for kindly providing data and modeling output used during model calibration. We also appreciate the help of Dr. Mark Zucker, USGS Florida, in obtaining gage data for USGS Taylor Upstream gages, and Dr. Erik Stabenau's assistance with data downloads from Everglades National Park stations. We want also to thank David Rudnick, Fred Sklar, and Christopher Madden (SFWMD) for advice during project planning and implementation. Thanks to the Florida Bay Interagency Science Center-Everglades National Park for its logistic support during the study.

References

Boyer, J.N., Kelble, C.R., Ortner, P.B., Rudnick, D.T., 2009. Phytoplankton bloom status: chlorophyll a biomass as an indicator of water quality condition in the southern estuaries of Florida, USA. Ecological Indicators 9, S56–S67.

Briceno, H.O., Boyer, J.N., 2010. Climatic controls on phytoplankton biomass in a sub-tropical estuary, Florida Bay, USA. Estuaries and Coasts 33, 541–553.

Childers, D.L., Boyer, J.N., Davis, S., Madden, C.J., Rudnick, D., Sklar, F., 2005. Relating precipitation and water management to nutrient concentrations in the oligotrophic "upside down" estuaries of the Florida Everglades. Limnology and Oceanography 50.

Chow, V.T., Maidment, D., Mays, L., 1988. Applied Hydrology. McGraw-Hill, New York.

Davis, S., Cabl, e J., Childers, D.L., Coronado-Molina, C., Day, J.W.J., Hittle, C., Madden, C.J., Reyes, E., Rudnick, D., Sklar, F., 2004. Importance of storm events in controlling ecosystem structure and function in a Florida Gulf Coast estuary. Journal of Coastal Research 20, 1198–1208.

Davis, S.M., Childers, D.L., Lorenz, J.J., Wanless, H.R., Hopkins, T.E., 2005. A conceptual model of ecological interactions in the mangrove estuaries of the Florida Everglades. Wetlands 25, 832–884.

DHI, 2008. Integrated Flood Modeling Software. MIKE FLOOD. Denmark.

FDEP/BSM, 2004. Florida Department of Environmental Protection, Bureau of Survey and Mapping: Land Boundary Information System. Q1006NE. Digital Orthographic Quarter Quad (DOQQ). http://data.labins.org/2003.

Fitterman, D.V., Deszcz-Pan, M., 1999. Geophysical mapping of saltwater intrusion in Everglades National Park (on CD-ROM). In 3rd International Symposium on Ecohydraulics, Salt Lake City, Utah, 12–16 July 1999, p. 18 (on CD-ROM).

Fourqurean, J.W., Robblee, M.B., 1999. Florida Bay: a history of recent ecological changes. Estuaries 22, 345–357.

Harvey, J.W., McCormick, P.V., 2009. Groundwater's significance to changing hydrology, water chemistry, and biological communities of a floodplain eco system, Everglades, South Florida. Hydrogeology Journal 17 (1), 185–201.

Hittle, C., Patino, E., Zucker, M., 2001. Freshwater Flow from Estuarine Creeks into Northeastern Florida Bay U.S. Geological Survey Water-Resources Investigations Report 01–4164.

Jacobs, J., Mecikalski, J., Paech, S., 2008. Satellite-based Solar Radiation, Net Radiation, and Potential and Reference Evapotranspiration. Technical Report. http://hdwp.er.usgs.gov/ET/GOES_FinalReport.pdf (accessed 4.8.11.).

Langevin, C.D., Swain, E.D., Wolfert, M.A., 2004. Simulation of Integrated Surface-water/Ground-water Flow and Salinity for a Coastal Wetland and Adjacent Estuary US Geological Survey Open-File Report 2004–1097.

Langevin, C.D., Swain, E.D., Wolfert, M.A., 2005. Simulation of integrated surface-water/ground-water flow and salinity for a coastal wetland and adjacent estuary. Journal of Hydrology 314, 212–234.

Nash, J.E., Sutcliffe, J.V., 1970. River flow forecasting through conceptual models part I — a discussion of principles. Journal of Hydrology 10 (3), 282–290.

Poret, N., Twilley, R.R., Rivera-Monroy, V.H., Coronado-Molina, C., 2007. Below-ground decomposition of mangrove roots in Florida Coastal Everglades. Estuaries and Coasts 30 (3), 491–496.

Price, R.M., Swart, P.K., Fourqurean, J.W., 2006. Terrestrial brackish groundwater discharge — a significant source of phosphorus for the oligotrophic wetlands of the Everglades. Hydrobiologia 569.

Rivera-Monroy, V.H., Twlley, R.R., Davis, S.E., Childers, D., Simard, M., Chambers, D.P., Jaffe, R., Boyer, J.N., Rudnick, D.T., Zhang, K., Castaneda-Moya, E., Ewe, S.L.M., Price, R.M., Coronado-Molina, C., Ross, M., Smith, T.J., Michot, B., Meselhe, E., Nuttle, W., Troxler, T., Noe, G.B. The Role of the Everglades Mangrove Ecotone Region (EMER) in regulating nutrient cycling and wetland productivity in South Florida. Reviews in Environmental Science and Technology, in press.

Rudnick, D.T., Chen, Z., Childers, D.L., Fontaine, T.D., 1999. Phosphorous and nitrogen inputs to Florida Bay: the importance of the Everglades watershed. Estuaries 22, 398–416.

Shoemaker, W.B., Sumner, D.M., 2006. Alternate corrections for estimating actual wetland evapotranspiration from potential evapotranspiration. Wetlands 26 (2), 528–543.

Simard, M., Zhang, K.Q., Rivera-Monroy, V.H., Ross, M.S., Ruiz, P.L., Castaneda-Moya, E., Twilley, R.R., Rodriguez, E., 2006. Mapping height and biomass of mangrove forests in Everglades National Park with SRTM elevation data. Photogrammetric Engineering and Remote Sensing 72, 299–311.

Sklar, F.H., Chimney, M.J., Newman, S., McCormick, P., Gawlik, D., Miao, S.L., McVoy, C., Said, W., Newman, J., Coronado, C., Crozier, G., Korvela, M., Rutchey, K., 2005. The ecological-societal underpinnings of Everglades restoration. Frontiers in Ecology and the Environment 3, 161–169.

South Florida Natural Resources Center (SFNRC), 2008. DataForEVER Dataset, Everglades National Park, Homestead, FL. generated by Erik Stabenau using Appa server software. http://www.appaserver.com Sacramento, CA, Public URL not currently available, please send data requests to EVER_data_request@nps.gov, retrieved 28.8.08.

Sutula, M., Day, J., Cable, J., Rudnick, D.T., 2001. Hydrological and nutrient budgets of freshwater and estuarine wetlands of Taylor Slough in Southern Everglades, Florida (U.S.A.). Biogeochemistry 56, 287–310.

Sutula, M.A., Perez, B.C., Reyes, E., Childers, D.L., Davis, S., Day, J.W., Rudnick, D., Sklar, F., 2003. Factors affecting spatial and temporal variability in material exchange between the Southern Everglades wetlands and Floriday Bay (USA). Estuarine, Coastal and Shelf Science 57, 757–781.

Swain, E.D., Wolfert, M.A., Bales, J.D., Goodwin, C.R., 2004. Two-dimensional Hydrodynamic Simulation of Surface-water Flow and Transport to Florida Bay Through the Southern Inland and Coastal Systems (SICS). USGS Water-Resources Investigations Report 03-4287, 56 pp.

U.S. Geological Survey, 1996–2008a. South Florida Information Access Data Exchange–Hydrology Data: Upstream Taylor River and Taylor River at mouth. http://sofia.usgs.gov/exchange/zucker_woods_patino/index.html (accessed 14.02.08.).

U.S. Geological Survey, 1996–2008b. South Florida Information Access Data Exchange–Hydrology Data: Groundwater Wells at Upstream Taylor River. http://sofia.usgs.gov/exchange/zucker_woods_patino/index.html (accessed 18.08.08.).

U.S. Geological Survey, 2007. South Florida Information Access. High Accuracy Elevation Data: Water Conservation Areas and Greater Everglades Region. Online dataset, http://sofia.usgs.gov/exchange/desmond/desmondelev.html (accessed 09.08.08.).

U.S. Geological Survey, 2008a. South Florida Information Access. Everglades Depth Estimation Network (EDEN): Evapotranspiration Data, Florida Bay. Online dataset, 208 KB, http://sofia.usgs.gov/eden/data/evapotrans/FLBAY_1995-2004_ET.zip (accessed 12.11.08.).

U.S. Geological Survey, 2008b. South Florida Information Access. Everglades Depth Estimation Network (EDEN): Rainfall Data, Florida Bay. Online dataset, 36 KB, http://sofia.usgs.gov/eden/data/nexrad/FLBAY_2002-2007_rainfall.zip (accessed 06.19.09.).

Wang, J.D., Swain, E.D., Wolfert, M.A., Langevin, C.D., James, D.E., Telis, P.A., 2007. Applications of Flow and Transport in a Linked Overland/Aquifer Density Dependent System (FTLOADDS) to Simulate Flow, Salinity, and Surface-water Stage in the Southern Everglades, Florida U.S. Geological Survey Scientific Investigations Report 2007–5010.

Willmott, C.J., 1981. On the validation of models. Physical Geography 2, 184–194.