Water Budget and Hydrodynamic Modeling of the A.R.M. Loxahatchee Refuge

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Abstract

The Arthur R. Marshall Loxahatchee National Wildlife Refuge is the only remnant of the northern Everglades in Palm Beach County, Florida (USFWS, 2000). It includes 143,238 acres (58,000 ha) and is located seven miles west of the city of Boynton Beach. The U.S. Fish and Wildlife Service (USFWS) has indicated that changes in water quantity, timing and quality are introducing negative impacts to the Loxahatchee Refuge's ecosystem. According to the USFWS (2000) changes in hydroperiod and water depths' pattern affect wading birds feeding pattern, apple snail reproductive output, and alligator nesting, and also alter the distribution of aquatic vegetation and tree islands. In addition, high nutrient runoff causes proliferation of cattails, and other undesirable species that negatively affect the ecosystem's balance. It is a priority for the Loxahatchee Refuge to ensure an appropriate water regulation schedule that will produce maximum benefits for flood control, water supply, fish and wildlife; and also to better understand and minimize the impacts of the excessive nutrients' loading.

This study presents the development of water budget and hydrodynamic models that are being used to provide a quantitative framework for management decisions related to inflow and outflow quantities, timing, and quality. The water budget model was developed as a double-box model that predicts canal and marsh stages. This model was calibrated for the 5-year period of record between January 1995 and December 1999, and validated with data for the 5-year period of record between January 2000 and December 2004. Statistical analyses demonstrate the applicability of this model to predict temporal variation of water levels in both the marsh and the Refuge rim canal. A two-dimensional hydrodynamic model was set up for the Refuge using the unstructured finite volume model FVCOM (Chen et al., 2004). This model is being used to predict spatial and temporal distribution of water inside the Refuge, and the results show very good agreement between observed and predicted stages at specific locations. Efforts are underway to model the transport of conservative tracer and the dynamics of total phosphorus in the Refuge.

INTRODUCTION AND BACKGROUND

It is well known that changes in water quantity, timing and quality are introducing negative impacts to the Everglades ecosystem. Historically, the Kissimmee River discharges into Lake Okeechobee, and during wet cycles the lake would overflow its south bank, providing additional flow to the Everglades. This water would sheet flow across the Everglades, but now, water flows through canals and structures, and through a series of water storage areas (Water Conservation Areas, WCA) and finally on to the Everglades National Park. The Arthur R. Marshall Loxahatchee National Wildlife Refuge, also known as WCA-1, includes an area of 143,238 acres and is the only remnant of the northern Everglades in Palm Beach County, Florida. As shown in Figure 1, the Loxahatchee Refuge is bordered on the northwest by drained agricultural land, the Everglades Agricultural Area (EAA), and by mainly an urban development at the east. WCA-2A is located at the southwest of the Refuge.

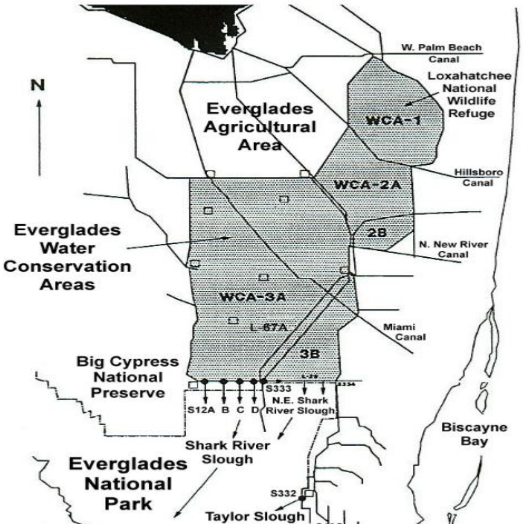

Figure 1. Map of Water Conservation Areas (WCAs).
[Adapted from the Reef Relief Website, http://www.reefrelief.org/Floridabay/report_page4.html]

The U.S. Fish and Wildlife Service (USFWS, 2000) indicated that changes in natural timing of water levels in the Loxahatchee Refuge affect wading birds feeding patterns, apple snail reproductive output, and alligator nesting. Similarly, changes in water depths' patterns alter the distribution of aquatic vegetation and tree islands. In addition, and particularly during the dry season, lower water levels increase the potential for fire and damage to vegetation, soils and wildlife. Along with the changes in water quantity and timing, the changes in water quality are an important threat to the Everglades ecosystem. High nutrients runoff (specifically phosphorus) from agricultural areas causes proliferation of cattails, and other undesirable species that negatively affect the ecosystem's balance. The USFWS (2000) indicated that different areas in the Loxahatchee Refuge continue to be eutrophied by the influx of high nutrients runoff.

It is a priority for the Loxahatchee Refuge to ensure an appropriate water regulation schedule that will produce maximum benefits for flood control, water supply, fish and wildlife, and also to better understand and minimize the impacts of the excessive nutrients' loading. The objective of this study is to develop a water budget model and a two dimensional hydrodynamic and water quality model for the Refuge that will provide a quantitative framework for management decisions related to inflow and outflow quantity, timing, and quality. This modeling effort will provide projections of water movement and water quality resulting under alternative scenarios of structure operation, stormwater treatment areas performance, and structural changes within the Refuge.

Bathymetry, Inflows, Outflows, Precipitation and Evapotranspiration

The Refuge bathymetry is characterized by a fairly flat interior marsh elevation and a varying-section rim canal. The latest marsh elevation data for the Refuge are available from the United State Geological Survey (USGS) on a 400 by 400 meter grid (Desmond, 2003). The bathymetry contours (excluding the rim channel) range from 18.50 to 10.61 ft-NGVD29, with a mean elevation of about 15.00 ft-NGVD29 (4.57 m). The Refuge is bordered by the L-7 and L-39 Canals to the west and the L-40 Canal to the east. For the western canals, the sediment surface elevations range between 7.0 and -1.5 ft-NGVD29, and between 6.7 and -5.7 ft-NGVD29 for the L-40 Canal. The top width ranges between 120 and 205 ft for the western canals, and between 88 and 173 ft for the L-40 Canal (Daroub et al, 2002).

The water entering the Loxahatchee Refuge comes from agricultural and urban runoff, and rainfall, with rainfall constituting approximately 56 to 60 percent of the total input as reported by USFWS (2000) and Richardson et al. (1990). The annual average rainfall for the Refuge is 50.3 inches for the period of record between 1995 and 2004. This period was selected as period of record (POR) for this study. For the mentioned POR, the average annual ET estimated for the Refuge is 52 inches (Meselhe et al., 2005).

There are nineteen hydraulic structures associated with the water management of the Refuge. These structures are shown in Figure 2. For details on structures operation and water management of the Refuge, the reader is referred to Meselhe et al. (2005) and USFWS (2000). For the POR, the yearly average inflow to the Refuge was 579,038 acre-ft.

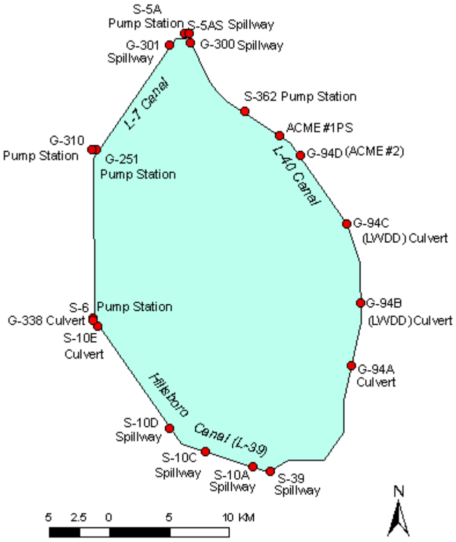

Figure 2. Location of hydraulic structures in the Loxahatchee Refuge.

MODELING EFFORT

Mass Balance Model

A double box water budget – mass balance model was developed for the Loxahatchee Refuge (a schematic representation of this model is presented in Figure 3). This model predicts canal and marsh stages from observed inflow, outflow, precipitation, and evapotranspiration.

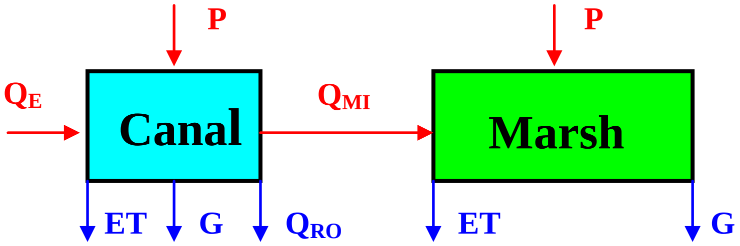

Figure 3. Sketch of the Water Budget Double Box Model.

The model was based on the water and constituent mass model developed by Dr. Bill Walker (Walker, 2000). Significant modifications were introduced in order to fit the needs of using the model as a management and analysis tool. Between the major modifications to the original Walker's model are: (1) the new model predicts canal and marsh stages instead of outflows, (2) seepage was included in the balance, (3) additional stations were used in the precipitation analysis, and (4) reduction factors were introduced in the evapotranspiration calculations based on the marsh conditions.

The following equations where used to determine the canal (E_T) and the marsh stage (E_M):

Canal Stage: $$\frac{dE_T}{dt} = P - ET - G + (Q_E - Q_{MI} - Q_{RO}) / A_C \qquad (1)$$

Marsh Stage: $$\frac{dE_M}{dt} = P - ET - G + Q_{MI} / A_M \qquad (2)$$

where E_T is the average stage in the rim canal, E_M is the average stage in the marsh; A_C and A_M are the rim canal and marsh areas, respectively; P is the precipitation; ET is the evapotranspiration; G is the seepage; Q_E is the external inflow to the rim canal, Q_{RO} if the outflow from the rim canal; and Q_{MI} is the flow from the rim canal to the marsh.

The evapotranspiration data was obtained as observed ET from DBHYDRO website for a station located inside the Refuge. This data was used to obtain actual ET using the following equation:

$$ET = f_{ET} \, ET_{obs} \qquad (3)$$

where $f_{ET} = Maximum(f_{ET\min}, Minimum(1, \frac{H}{H_{ET}}))$; f_{ETmin} is the minimum reduction of ET because of shallow depth = 20%; H is the marsh water depth in meters so that $H = Maximum(0, E_M - E_0)$; E_0 is the marsh ground elevation = 4.57 m; and H_{ET} is the depth above which ET is reduced = 0.25 m.

The rate of loss of groundwater recharge in the canal or marsh is calculated using the following equation:

$$G_i = r_{seep}(E_i - E_B) \tag{4}$$

where $i = t \text{ or } m$ for canal or marsh, respectively; r_{seep} is the seepage rate constant = 0.0004 d^{-1} (Lin and Gregg, 1988); and E_B is the boundary water surface elevation = 3.5 m. The flow from the canal to the marsh was calculated based on the “power law model” (Kadlec and Knight, 1996):

$$Q_{MI} = CH^3(E_T - E_M) \tag{5}$$

where $C = 10^7 BW/R = 2\pi 10^7 B$ = 1.88x10^9 $m^{-1}d^{-1}$; $H = Maximum(0, E_M - E_0)$; W is the average marsh perimeter =8.15x10^4 m; R is the average radius of the marsh = 1.30x10^4 m (this value was obtained assuming an approximated circular geometry; and B is a calibrated transport coefficient = 30 $m^{-1}d^{-1}$.

The differential equations for canal and marsh stage are calculated using the Euler numerical integration method with a one-day time step. This provides a fast solution and is easily implemented using the available daily average time-series data. However, one problem with this technique is that when net canal flow is large, stage change over one day is so large that the assumption of “small” change in the integration algorithm is not satisfied. This can result in failure of convergence and instability. Here, a heuristic approach is used to stabilize the solution that is otherwise unstable at times. This heuristic approach limits the magnitude of the canal stage, and maintains conservation of water volume by shifting flow directly to the marsh. Such an approach is reasonable because under these conditions flow between the marsh and canal is likely being underestimated by the Eulerian method with a daily time-step. Denoting the revised stage derivative with an asterisk, this heuristic scheme is

$$\begin{aligned} \frac{dE_T^*}{dt} &= \frac{dE_T}{dt} \qquad when \left|\frac{dE_T}{dt}\right| \le E'_{T\max} \\ \frac{dE_T^*}{dt} &= \frac{\left(\frac{dE_T}{dt}\right)}{\left|\frac{dE_T}{dt}\right|} E'_{T\max} \qquad when \left|\frac{dE_T}{dt}\right| > E'_{T\max} \end{aligned} \tag{3}$$

where E'_{Tmax} is equal to 0.10 m.

The additional flow into the marsh, Q_{MI}^*, is

$$Q_{MI}^* = \left(\frac{dE_T}{dt} - \frac{dE_T^*}{dt} \right) A_C \tag{4}$$

and,

$$\frac{dE_M^*}{dt} = \frac{dE_M}{dt} + \frac{Q_{MI}^*}{A_M} \tag{5}$$

Results Water Budget Model

The water budget model was calibrated using the period from 1995 to 1999, and validated with the data from 2000 to 2004. The major calibration parameter is the transport coefficient (B) in Eq. 5, and it was found that a value equal to 30 $m^{-1}d^{-1}$ produced the best agreement between observed and predicted values. Figure 4 shows the comparison between the calculated and the observed canal stages for the calibration and validation periods, and Figure 5 shows the same information for the marsh stages. As can been seen in these Figures observed and predicted values are in good agreement.

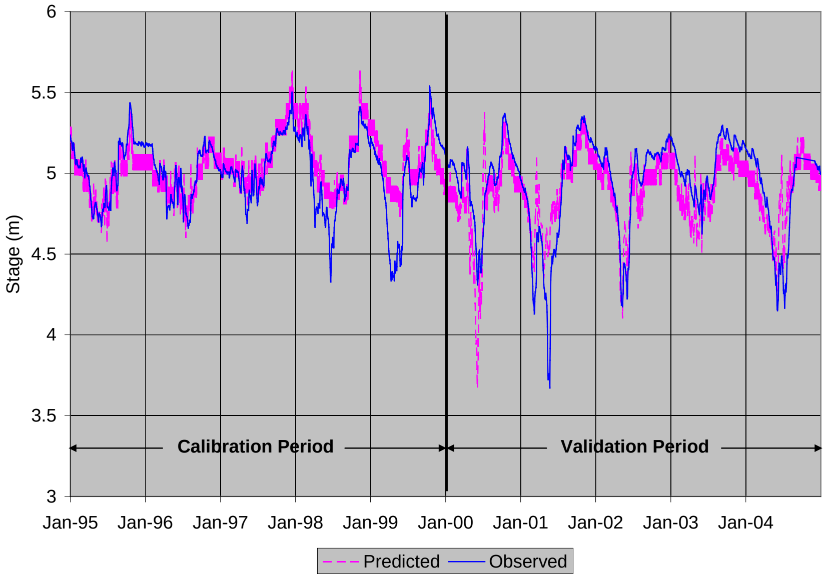

Figure 4. Observed vs. Predicted Canal Stages for the Calibration and Validation Periods.

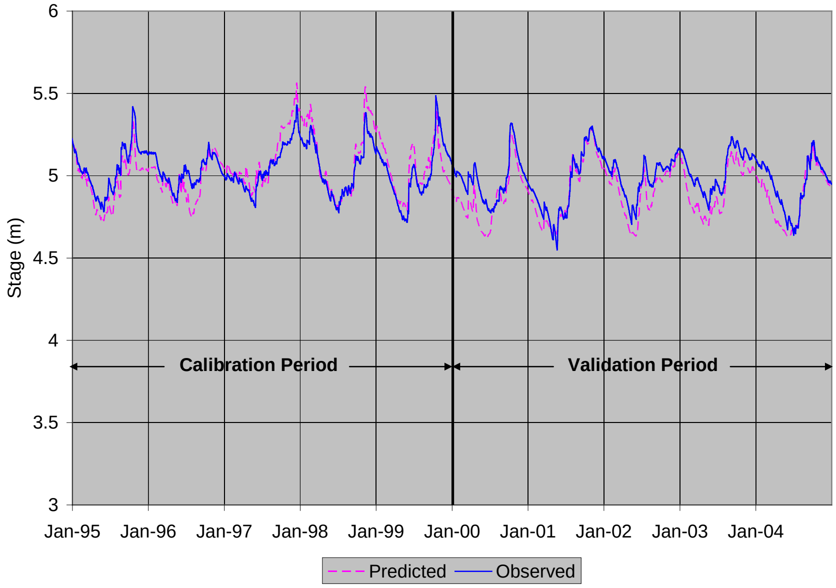

Figure 5. Observed vs. Predicted Marsh Stages for the Calibration and Validation Periods.

Statistical analyses were performed for the calibration and validation periods. The statistics included bias, root mean square error (RMSE), correlation coefficient (R), the variance reduction and the Nash Sutcliffe efficiency (Nash and Sutcliffe, 1970). These statistical parameters are shown in Table 1. As can be seen in this Table, the observed and predicted stages for the marsh are in better agreement than the observed and predicted values for the canal. There are probably three reasons for that: (1) the area for the rim canal was assumed constant, (2) the variability of the water level is stronger in the canal than in the marsh, and (3) the emphasis during the calibration was to match the observed marsh stages with the model prediction.

Table 1. Statistical Parameters for Double Box Water Budget Model.

	Marsh Model Statistics		**Canal Model Statistics**	
Statistical Parameter	**Calibration**	**Validation**	**Calibration**	**Validation**
Bias (m)	-0.001	-0.083	0.073	-0.024
RMSE (m)	0.089	0.105	0.167	0.181
Variance reduction	0.606	0.820	0.568	0.643
R (Correl Coef)	0.857	0.921	0.754	0.802
Nash-Sutcliffe Eff	0.734	0.672	0.407	0.418

Hydrodynamic Modeling

For this modeling application, the research team evaluated 20 potential candidate models based on a pool of essential and desirable features. After careful consideration the fully dynamic model FVCOM was selected to continue with the hydrodynamic-water quality simulations. FVCOM is an unstructured, finite-volume, three-dimensional model consisting of momentum, continuity, temperature, salinity and density equations closed physically and mathematically using the Mellor and Yamada level 2.5 turbulent closure submodel. The finite-volume method used in this model combines the advantages of a finite element method for geometric flexibility and a finite-difference method for simple discrete computation (Chen et al., 2004).

An unstructured triangular mesh was generated for the Loxahatchee Refuge using the MATISSE software. This grid consisted of 12,190 nodes and 22,848 elements. The smaller element sizes are about 25 meters (within and adjacent to the rim canal), and the larger element edges are about 650 meters (on the central portion of the Refuge). This grid was refined at different locations, allowing for a good representation of the rim canal, and to capture the tree islands. Figure 6 shows a sketch of the unstructured-triangular mesh for the Loxahatchee Refuge.

Results Hydrodynamic Model

Two-dimensional hydrodynamic simulations were performed forcing the model with the inflows and outflows from the hydraulic structures, and precipitation and evaporation as meteorological forcing. The seepage loss was estimated using a similar approach to the one presented by Eq. 4. Figure 7 shows the comparison between observed and predicted stages at USGS station “South” for the complete year of 2002 (see Figure 6). Table 2 shows the statistical parameters for the same period. These comparisons are part of the ongoing calibration efforts, but as can be seen in Table 2, in its current form the model predicted water levels are in very good agreement with the observed values. The calibration of the transport subroutine using chloride as conservative tracer, and the water quality simulations using total phosphorus (TP) as constituents are currently underway. These results will be presented at the conference.

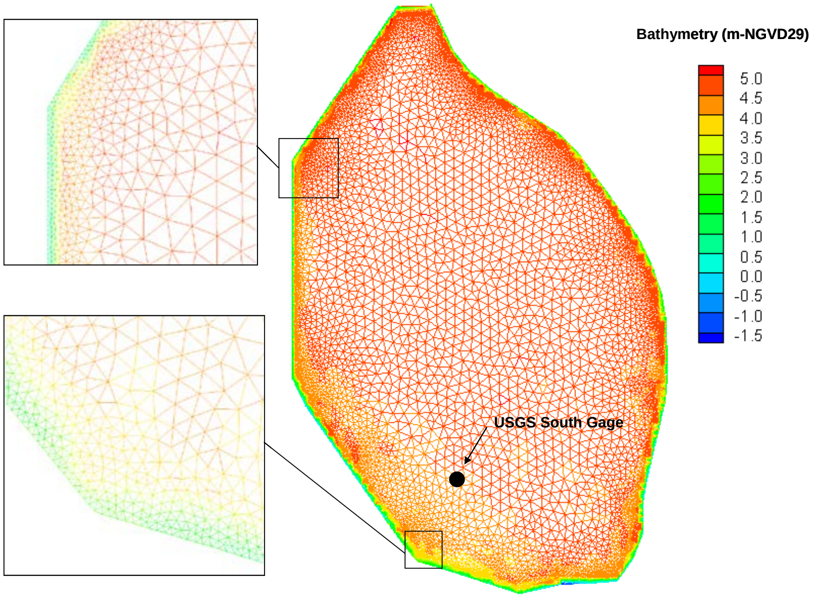

Figure 6. Unstructured grid for the A.R.M. Loxahatchee National Wildlife Refuge.

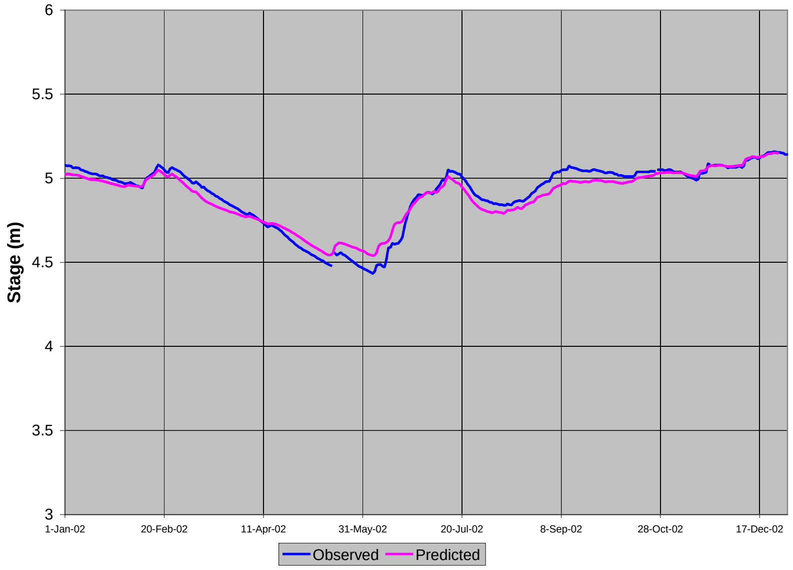

Figure 7. Observed vs. Predicted Marsh Stage for the Hydrodynamic Model.

Table 2. Statistical Parameters for Marsh Stages – Hydrodynamic Model.

	Marsh Model Statistics
Statistical Parameter	**Hydrodynami Model Calibration**
Bias (m)	-0.010
RMSE (m)	0.051
Variance reduction	0.934
R (Correl Coef)	0.978
Nash-Sutcliffe Eff	0.901

CONCLUSIONS AND CLOSING REMARKS

A double-box water budget was developed for the Loxahatchee Refuge. Statistical analyses demonstrate the applicability of this simple model to predict canal and marsh stages from observed inflow, outflow, precipitation, evapotranspiration and seepage. Additional efforts are being devoted to model the mass balance of water quality constituents as chloride and TP.

A two-dimensional hydrodynamic model is also being set up and calibrated using the FVCOM model. This model will be use to predict the spatial and temporal distribution of water and constituents inside the Refuge. Initial results show a very good agreement between observed and predicted water level at specific locations. Efforts are underway to model the transport of conservative tracer and the dynamics of TP in the Refuge.

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