Modeling Hydrologic Flow across a Marsh-Mangrove Ecotone in Ten Thousand Islands National Wildlife Refuge

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Introduction

Ten Thousand Islands National Wildlife Refuge (TTINWR) is part of a project to restore freshwater flow across the Tamiami Trail (U.S. Hwy. 41) into the Northern Everglades. As sea level rises and saltwater intrudes inland, TTINWR's mangrove vegetation has been migrating north, thus gradually taking over the marsh estuary and potentially disrupting foraging patterns of resident and migrant water birds. Hydrologic analysis is essential for understanding how the proposed freshwater flow can be used by refuge managers at TTINWR to aid refuge-specific restoration objectives and to predict attributes of future change in the balance of marsh and mangrove.

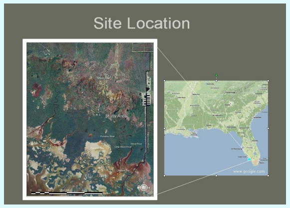

Figure 1: General map showing the boundaries of the Ten Thousand Islands National Wildlife Refuge

Numerical models are useful tools in better understanding the hydrologic and ecologic conditions, as well as assisting with planning, decision analysis, and assessment of coastal protection and restoration measures.

A compartment model based on the platform Berkeley Madonna is developed to simulate hydrodynamics and salinity for the TTINWR. Berkeley Madonna is a proprietary software that solves ordinary differential equations (www.berkeleymadonna.com). This study will develop a model to gain better understanding of hydrology, salinity distribution, and ecology of the TTINWR. In addition, the model will be utilized to evaluate protection and restoration measures.

Research Objectives

- Develop a model for predicting stage and salinity in the domain
- Utilize the model (s) to assess and evaluate a variety of restoration and protection measures

Compartment Setup

The model domain of the refuge is partitioned into ten hydrologically and geographically designed cells. Their arrangement results from comparing the stage data, digital elevation model (DEM), and the vegetation map.

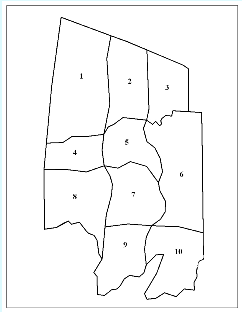

Figure 2: Division of compartments

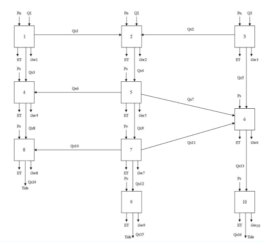

Figure 3: Link node diagram showing exchange between different cells

Data Collection

Monitoring stations were placed across TTINWR in a quasi-grid formation that extends from Pumpkin Bay and Santina Bay northward to just south of the Tamiami Trial and from the Faka Union River westward. Stage was measured at all stations hourly. Precipitation and salinity well data were collected in the northwest, south central, and center portions of the refuge, while meteorological data were collected from a station in the northwestern portion of TTINWR. Stream flow data were collected under two Tamiami Trial bridges by the USGS Florida Water Science Center in Ft. Myers, and flow through the Faka Union Canal was also included.

Additionally, salinity measurements are recorded at stations with longitudinal and latitudinal gradients in the refuge. Water depth data at Pumpkin Bay and Faka Union Bay were also acquired from Rookery Bay NERR water level recorders.

Data Collection

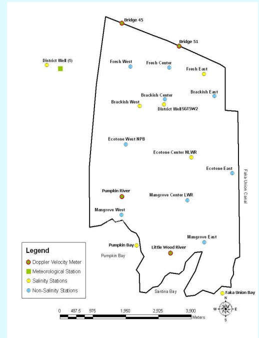

Figure 4: Stations Layout for Ten Thousand Islands National Wildlife Refuge

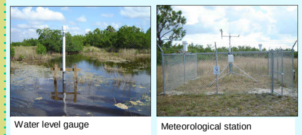

Figure 5: Equipments deployed to collect data in Ten Thousand Islands National Wildlife Refuge

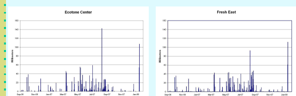

Figure 6: Rainfall measured in two different stations in Ten Thousand Island National Wildlife Refuge

Model Setup

The stage will be predicted in Cells 1-10 based on the volume at a given time:

$$\frac{d(vol)}{dt} = (P - ET - G_w)\cdot Area \pm Q_{exchange} \pm Q_{boundary}$$

Where:

- $\frac{d(vol)}{dt}$ = the change in volume, m^3/day
- P= precipitation, m/day
- ET = evapotranspiration, m/day, calculated
- Gw =ground water loss, m/day, observed
- $Area$ = cell area, m^2, calculated via ArcGIS
- $Q_{exchange}$= exchange flow, m3/day, between cells, (+) flow in, (-) flow out
- $Q_{boundary}$ = flow, m3/day, into or out of a boundary cell, (+) flow in, (-) flow out.

Model Setup

Evapotranspiration is calculated with the Penman-Monteith ET Equation (Allen et al, 1996);

$$ET = \frac{\Delta(R_n - G) + \rho_a \cdot c_p \cdot \frac{\delta}{r_a}}{\Delta + \gamma\cdot\left(1+\frac{r_s}{r_a}\right)\cdot\lambda}$$

Where

- ET = evapotranspiration, m/day
- Δ= slope of vapor pressure curve, kPa/ ºC
- R_n = net radiation, MJ/m^2/day
- G = soil heat flux, MJ/m^2/day
- ρ_a =mean air density at constant pressure, kg/m^3
- c_p = specific heat of air, MJ/kg/ºC
- δ = vapor pressure deficit, kPa
- r_a = aerodynamic resistance, s/m
- γ = psychrometric constant, kPa/ ºC
- r_s = bulk surface resistance to water vapor, s/m
- λ = latent heat of vaporization, MJ/kg.

The Power Law Equation (Kadlec and Knight, 1996) is used to calculate the exchange flow between cells:

$$Q_{x\#} = \frac{10^7\left(B\cdot w\cdot \min(H_{up}, H_{down})^3\right)}{R}\left(E_{up} - E_{down}\right)$$

Where

- $Q_{x\#}$ = the exchange flow number
- B = the transport coefficient, 1/m/day, calibrated
- w = the cell exchange width, m, measured in ArcGIS
- H_{up} = the depth of cell up of the flow direction
- H_{down} = the depth of cell down of the flow direction, m, measured in ArcGIS
- E = the water stage = elevation + H, m, observed
- E_{up} = the stage of cell up of flow direction
- E_{down} = the stage of cell down of flow direction.

Figure 3 shows how the model uses these equations as well as other parameters to simulate the interaction between cells.

Result and Calibration

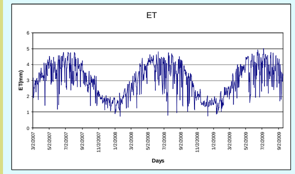

Figure 7: ET Calculated using Penman-Monteith method

Model Parameters		
k_{sat}	7.93	m/day
$B(1)^2$	225	(1/m/day)
B(2)	45	(1/m/day)
B(3)	37.5	(1/m/day)
B(4)	9.25	(1/m/day)
B(5)	675	(1/m/day)
B(6)	0.13	(1/m/day)
B(7)	70	(1/m/day)
B(8)	11.75	(1/m/day)
B(9)	14	(1/m/day)
B(10)	1.25	(1/m/day)
B(11)	17.25	(1/m/day)
B(12)	37.5	(1/m/day)
B(13)	20.75	(1/m/day)
B(14)	18	(1/m/day)
B(15)	22	(1/m/day)
B(16)	11.5	(1/m/day)

Figure 8: Values of model parameters based on calibration

	Cell 1	Cell 2	Cell 3	Cell 4	Cell 5	Cell 6	Cell 7	Cell 8	Cell 9	Cell 10
Bias (m)	0.01	0.04	-0.06	0.03	0.02	0.02	0.04	0.01	0.00	0.00
Average Simulated (m)	1.48	1.48	1.41	1.37	1.37	1.36	1.32	1.33	1.30	1.30
Average Observed (m)	1.47	1.44	1.47	1.33	1.35	1.34	1.28	1.32	1.29	1.29
RMSE (m)	0.08	0.06	0.11	0.09	0.06	0.03	0.05	0.02	0.02	0.01
SD Observed (m)	0.19	0.15	0.19	0.15	0.12	0.13	0.12	0.13	0.12	0.12
SD Model (m)	0.11	0.11	0.11	0.11	0.09	0.10	0.10	0.12	0.10	0.10
SD Error (m)	0.09	0.05	0.09	0.09	0.05	0.05	0.04	0.01	0.02	0.01
n, sample #	306	246	336	336	336	175	205	336	112	112
Variance reduction	**0.80**	**0.90**	**0.80**	**0.65**	**0.82**	**0.85**	**0.89**	**0.99**	**0.96**	**0.99**
R (Correlation Coefficient)	**0.97**	**0.97**	**0.97**	**0.81**	**0.92**	**0.91**	**0.95**	**1.00**	**0.98**	**0.99**
R^2 (Coefficient of Determination)	**0.95**	**0.94**	**0.94**	**0.66**	**0.85**	**0.83**	**0.90**	**0.99**	**0.96**	**0.98**
Nash-Sutcliffe Eff.	**0.78**	**0.78**	**0.69**	**0.60**	**0.78**	**0.82**	**0.74**	**0.98**	**0.94**	**0.97**

Figure 9: Statistics of stage simulation in each compartment of TTINWR

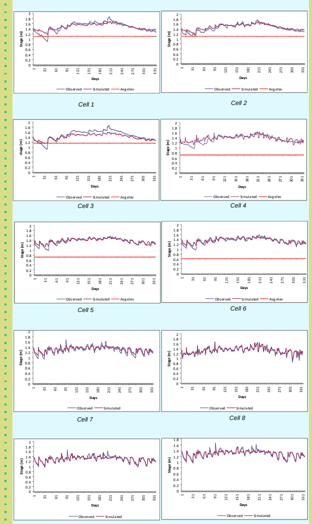

Figure 10: Spatial and temporal variation in stage

Result and Calibration

	Cell 1	Cell 5	Cell 9	Cell 10
Bias (ppt)	-3.250	-3.705	1.635	-2.531
Average Simulated (ppt)	14.298	32.933	33.940	29.774
Average Observed (ppt)	17.549	36.638	32.306	32.306
RMSE (ppt)	8.103	15.276	5.620	5.598
SD Observed (ppt)	2.501	3.168	5.811	5.811
SD Model (ppt)	3.214	8.792	3.317	9.268
SD Error (ppt)	7.770	12.779	5.385	5.000
n, sample #	229	224	336	336
R (Correlation Coefficient)	0.326	0.585	0.608	0.879
R^2 (Coefficient of Determination)	0.107	0.342	0.370	0.772
Nash-Sutcliffe Eff.	0.358	0.482	0.062	0.069

Figure 11: Statistics of salinity simulation in selected compartment of TTINWR

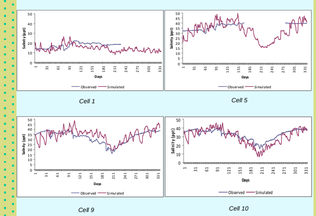

Figure 12: Spatial and temporal variation in salinity

Summary and Future Work

- Simulated stage shows good agreement with observed stage.
- Salinity couldn't be modeled in all the cells due to lack of data. Simulated salinity seems to be satisfactory.
- This model can be used to screen management, protection, and restoration strategies
- With the stations available, the number of cells is adequate for a simple model. A higher resolution complex model will better simulate the hydrology of the area.
- Our modeling work indicated that more or improved data on monitoring the boundary conditions (i.e. stream flow under Tamiami Bridges, stream flow near the marina to the east, and southern tidal flow) of the TTINWR are needed for improve the model.
- More salinity monitoring station is expected to better calibrate salinity.

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