AN INTEGRATED MEDIA, INTEGRATED PROCESSES WATERSHED MODEL – WASH123D: PART 5 – INTEGRATED MODELING OF SURFACE WATER AND GROUNDWATER INTERACTIONS IN A CONSTRUCTED WETLAND

GUOBIAO HUANG[1] GOUR-TSYH YEH[2]

[1]*Sutron Corporation, 6903 Vista Parkway Suite 5, West Palm Beach, FL 33411 USA*

[2]*Dept of Civil and Environmental Engineering, University of Central Florida, Orlando, FL 32816 USA*

ABSTRACT

A pilot constructed wetland in south Florida, USA, the Everglades Nutrient Removal (ENR) project was modeled with a physics-based integrated approach with WASH123D. Stormwater is routed into the treatment wetland for phosphorus removal by plant and sediment intake. It overlies a highly permeable surficial groundwater aquifer. Strong surface water and groundwater interactions are a key component of the hydrologic processes. The site has extensive field measurements and monitoring that provide point scale and distributed data on surface water levels, groundwater levels and physical range of hydraulic parameters and hydrologic fluxes. Previous hydrologic and hydrodynamic modeling studies have treated seepage losses empirically by some simple regression equations and only surface water flows are modeled in detail. Several years of operational data are available and were used in model calibration and validation. The validity of diffusion wave approximation for 2-D overland flow in the region with very flat topography was also tested. The uniqueness of this modeling study includes (1) the point scale and distributed comparison of model results with observed data; for example, the spatial distribution of measured vertical flux in the wetland is available. (2) model parameters are based on available field test data. (3) water flows in the study area consist of 2-D overland flow, hydraulic structures/levees, 3-D subsurface flow and 1-D canal flow and their interactions. This study demonstrates the need and the utility of a physics-based modeling approach for strong surface water and groundwater interactions.

1. INTRODUCTION

Man-made treatment wetlands have been extensively used for wastewater treatment or stormwater nutrient removal in USA. Typically, these surface water impoundments are built for flow-through treatment of stormwater by plant and sediment uptakes of nutrients or pollutants. In South Florida, the Everglades restoration effort has led to the design and construction of a series of constructed wetlands called Stormwater Treatment Areas (STAs) to reduce phosphorus level from stormwater runoff before they can enter the Everglades protection areas. These constructed wetlands were located on former natural wetlands or farmland. The Everglades Nutrient Removal (ENR) project is a pilot constructed wetland for STAs.

In south Florida, the regional hydrogeology was characterized by the surficial aquifer (Fish, 1988). Wetlands in the region have strong hydraulic connection with the underlying highly conductive surficial aquifer. Harvey et al. (2002) studied the surface and groundwater interactions in ENR and surrounding wetlands by field investigations. Guardo studied water budget in ENR with a simple water mass balance approach (Guardo, 1999). Simple regression models were used to estimate groundwater seepages in ENR and the whole ENR was treated as a point for water budget. Guardo and Tomasello (1995) simulated overland flow in ENR with a steady hydrodynamic model.

Some popular hydrodynamic computer codes currently used for modeling wetland hydraulics are originally developed for coastal hydrodynamic modeling. Some limitations need to be addressed before they can be applied for wetland simulation. The incorporation of hydraulic structures, explicit representation of rainfall and evaporation and treatment of wetting and drying are some examples. Swain et al. (2004) has described their experience in adapting and modifying the USGS SWIFT2D, originally developed for coastal tidal flow, to simulate the southern Everglades wetland hydrology. A watershed model code such as WASH123D (Yeh et al., 2005; 2006) does not have these limitations. This WASH123D application is an example of coupled surface/subsurface water flows in a constructed wetland for stormwater treatment in south Florida.

Wetland hydrological modeling studies have been increasingly reported in the hydrology literature. Feng and Molz (Feng and Molz, 1997) developed a surface water flow model for wetlands with the diffusion wave approximation of the 2-D shallow water equations. The model was tested with a field application. However, model calibration and history matching were not reported. Few integrated wetland hydrologic modeling studies have been reported. MIKE SHE was applied to a natural wetland in England (Thompson et al., 2004). A coastal natural wetland was modeled by coupling SWIFT2D and MODFLOW (Langevin et al., 2005).

The objective of this modeling study is to demonstrate and validate the applicability of a physics-based, integrated modeling approach for surface water and groundwater interactions in wetlands and how field data from previous field studies can be used in building the integrated model with minimum model calibration. Historical time series data and field test results were applied in evaluating the model performance.

2. SITE DESCRIPTION

The Everglades Nutrient Removal (ENR) project was built as a prototype treatment wetland in south Florida, USA for the Everglades restoration (SFWMD, 2000). It was operated for five years (1994 to 1999) and is now incorporated into the Stormwater Treatment Area 1 west (STA-1W).

The total surface area of ENR is about 16 square kilometers. The land surface elevations were based on previous field survey data. Marsh area elevations range from 2.0 m NGVD29 (National Geodetic Vertical Datum of 1929) to 4.0 m NGVD29. The average land surface gradient is 0.001. The ENR basin topography is very flat that is typical in South Florida.

The vegetations in ENR were spatially varied and changed over time. The main treatment plants were emergent cattail and submerged aquatic vegetation (SAV). There were also some local distribution canals and remnant farm ditches in the marsh areas.

The ENR basin has been extensively monitored and studied by the South Florida Water Management District (SFWMD) and USGS (SFWMD, 2000; Harvey et al., 2002). The measured time series data were recorded in the SFWMD corporate database DBHYDRO (SFWMD, 2005).

Subsurface Flow: As can be seen in Figure 1, the ENR basin is separated from surrounding areas by a perimeter levee. The eastern boundary of subsurface flow is controlled by water levels in the Water Conservation Area 1 (WCA-1). The Seepage Canal running along the western and northern boundary controls the remaining boundaries. The bottom boundary can be considered impermeable, since the field studies have found that groundwater flow in the surficial aquifer is predominantly horizontal. Generally, groundwater got recharge from WCA-1 where the water levels were normally regulated between 4.88 m NGVD to 5.18 m NGVD (16 –17 ft NGVD) and discharge was mainly through the seepage canal. Subsurface flow also obtained recharge through infiltration from overland flow.

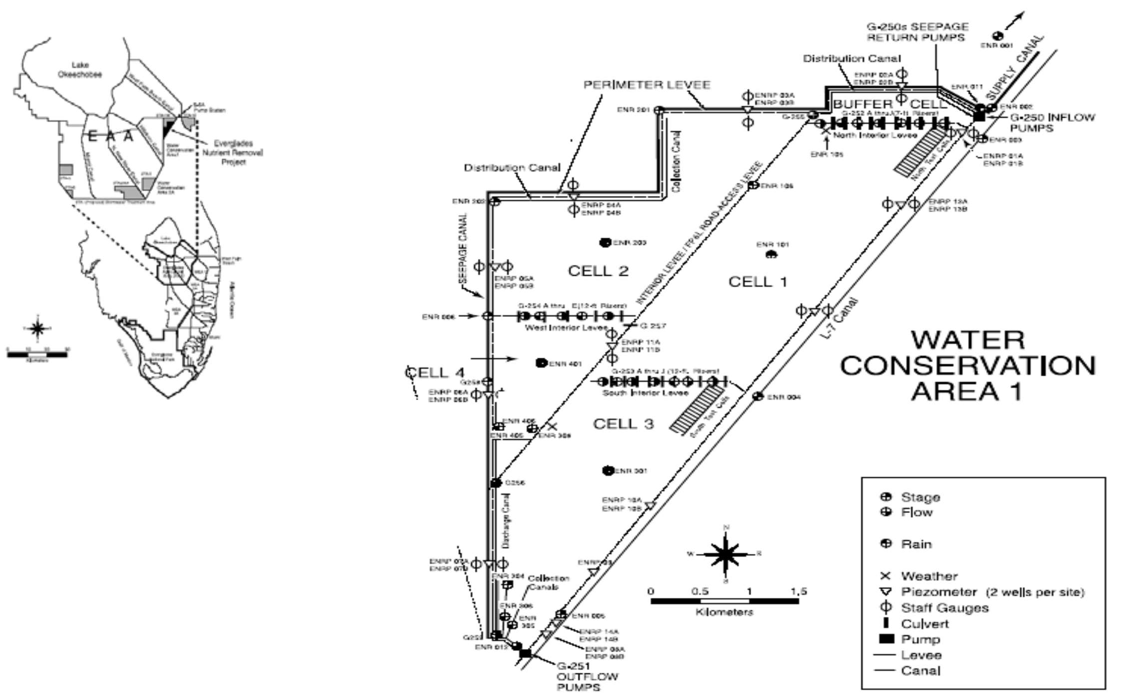


FIGURE 1. Location and Schematic Map of ENR (Modified after SFWMD, 2000)

Surface water flow in the ENR basin is controlled by a series of pump stations and gated culverts. ENR consisted of a buffer cell and four treatment cells 1-4 (Figure 1). Stormwater runoff was pumped into the buffer cell and distributed to the eastern flow way (Cell 1 and Cell 3) and the western flow way (Cell 2 and Cell 4). Interior levees separated each treatment cell from one another and a series of culverts with risers were built in the interior levees to control flows among cells. Treated water from the western flow way was directed to Cell 3 by the gated culverts G-256 and eventually, was discharged from ENR into WCA-1 through the outflow pump station G-251.

The major surface water inflow and outflow are through pumping stations G-250 and G-251. Structure inflows consisted of inflow pump station G-250 and seepage return pump G-250S. Structure outflow was through outflow pump station G-251. Discharge into the seepage canal could be made through gated structures G-258 and G-259. Current modeling study simulated the whole calendar year of 1998. During this time period, outflow from G-258 and G-259 was zero.

3. MODEL TOOL: WASH123D

This is a generic integrated surface water/groundwater interaction model code (Yeh et al., 2005; 2004). It can simulate one-dimensional channel network and two-dimensional overland flows and three-dimensional variably saturated subsurface flow separately. When needed, it can also simulate different combinations of coupled surface water and subsurface water flows.

Some adaptations and modifications were easily implemented into the source code for this modeling effort. The original WASH123D code apply constant friction coefficient (Manning' n value) for bottom shear stresses. But the dense vegetation in the marsh area requires a water depth dependent Manning's n relationship. Different depth dependent relationships can be easily applied by a tabular (depth-n) profile input in WASH123D. The calibrated flow rating equations for various hydraulic structures can also be coded in WASH123D that control the water transfer between different canal locations or from/to canal to overland (marsh area).

4. MODEL SETUP

The conceptualisation of the study area leads to a relatively closed flow system. Stormwater runoff was pumped into the buffer cell and flow into the treatment cells through control structures. The treated water is discharged at the downstream by the outflow pump station G251 and eventually entered the Water Conservation Area 1.

The surface water flows were simulated as two-dimensional overland flow. Current model simulations applied the diffusion wave approximation of the full shallow water equations for overland flow. The whole overland flow domain was discretized into 1,345 linear triangular elements and 746 nodes. The average length of a triangular side was about 160 m. The interior levee was represented by inactive elements and water could go only through it by structure flows. Known Inflow pumping rate was applied as human induced water source term for a group of elements. A specified stage boundary condition was applied at the downstream outflow location (G-251 headwater).

Time series data of rainfall, evapotranspiration, and structure flow, surface and ground water levels were retrieved from the public accessible DBHYDRO database (SFWMD, 2005).

For subsurface flow, the surficial aquifer system was simulated with the three-dimensional Richards equation for variably saturated subsurface flow. The underlying surficial aquifer was vertically divided into several layers, the top layers, extending from land surface to a few feet in thickness, is the poor permeable peat and the next layers are composed of sand or sandy lime rock. Figure 2 shows the three-dimensional finite element mesh for subsurface flow. For this preliminary simulation, the model domain was selected up to the location of the

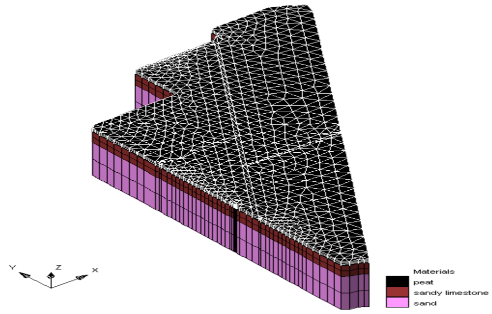


FIGURE 2. Finite Element Meshes for ENR Basin with Soil Types

seepage canal to the west and the L-7 canal to the east. These canals are hydraulic divides for subsurface flow.

The hydrogeology was obtained from some relevant reference sources (Fish, 1988; Harvey et al, 2002). Harvey et al. (2002) described detailed local hydro-geological data for the ENR area. The value of saturated hydraulic conductivity and effective porosity used in the model runs are listed in Table 1.

Table 1. Hydraulic properties for Subsurface Flow

Soil type	Porosity	Hydraulic Conductivity	
		Horizontal	Vertical
	(-)	(cm/day)	(cm/day)
Peat	0.21	9.14	0.09
Sandy limestone	0.31	271.39	2.72
Sand	0.41	2070.20	20.7

The subsurface flow domain consisted of 9415 elements and 5968 nodes. The peat soil made up the top three layers; the next two layers were for sandy limestone and the bottom two coarser layers with the maximum depth of 36.5 m (120 ft) from land surface. This subsurface element resolution was designed to maintain a balance between run time requirements for long-term model runs and model accuracy.

Specified head boundary conditions were applied for the WCA-1 and the seepage canal for current model simulations. The seepage canal could be simulated by the one-dimensional channel flow and coupled with subsurface flow. However, the water levels in the canal were kept below 2.4 m NGVD (8 ft NGVD) to protect farmlands adjacent to ENR and canal flow was quite static. Therefore it was considered as a specified head boundary for subsurface flow and it had no hydraulic connection with the overland flow during model simulations. No interface sediment layers were assumed to exist between subsurface and overland or canal. So both continuity of pressure head and exchange flux were imposed for surface water and groundwater interactions.

5. MODEL SIMULATION RESULTS

The preliminary model simulation results (from 3/1/1998 to 12/31/1998) are presented discussed as follows. The average hydraulic conductivity values from field studies (Table 1) were used for subsurface flow and no adjustment has been made. The adjusted Manning's roughness coefficients ranged 0.038 to 0.25 for different vegetations and canals. No attempt has made to optimise the history match between observed and computed values. The model run started at 1/1/1998 and the time period between 1/1/1998 and 3/1/1998 was warm-up for initial condition effect.

6.1 Surface water flow

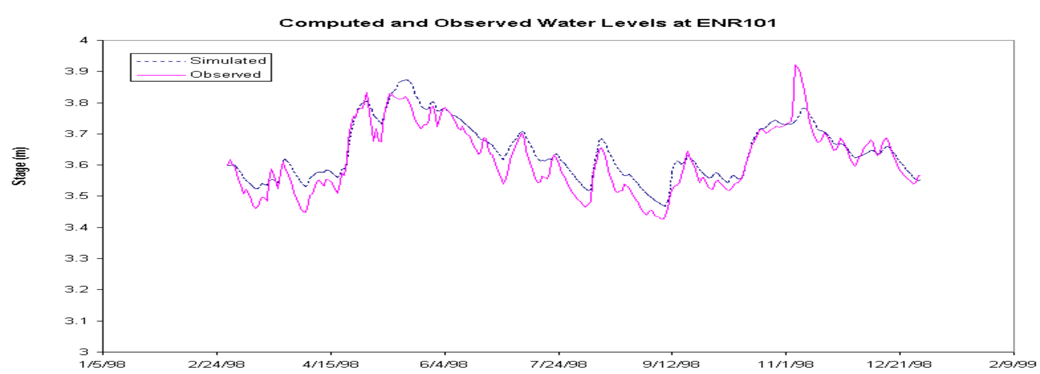
G250 inflow pumping mainly controlled two-dimensional overland flow conditions. Rainfall and evapotranspiration were a small part of the water budget. The spatial distribution of vegetation and the flow distribution among treatment cells are important factors.

The comparison of computed and observed surface water levels at the center of each treatment cell was shown in Figures 3. The variation in water levels in both the eastern and western flow ways was captured quite well. The R2 values for these four locations were 0.57 and 0.87, respectively.

6.2 Subsurface water flow

The observed and computed groundwater levels at ENR102GW, ENR204GW, ENR104GW and ENR303GW are compared in Figure 4. The simulation results are similar to those of surface water levels. These results show that overland flow dominates the groundwater level trends. The unsaturated zone was thin and local during the simulation period. During dry season, a large portion of the surface area could dry up and soil moisture could less than saturated and the Richards equation for variably saturated subsurface flow is justified. As a matter of fact, previous SFWMD STAs water budget studies (Huebner, 2001) applied a regression equation to account for soil water storage during dry seasons.

The total head distribution and the exchange fluxes were also obtained from the simulation and compared with field observations. They are not shown here because of page limit. The computed vertical flux values ranged from –0.75 cm/day to 2.0 cm day. These values are within the range of seepage-meter measurements during 1997-1998 at ENR site that is documented by Harvey et al. (2002).



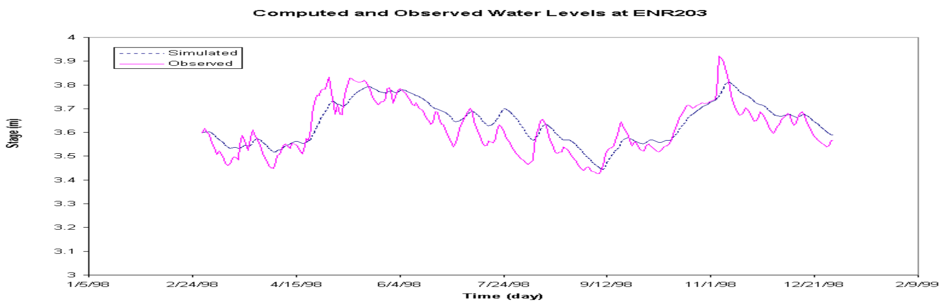


FIGURE 3. Simulated and Observed Surface Water Levels at ENR101 and ENR203

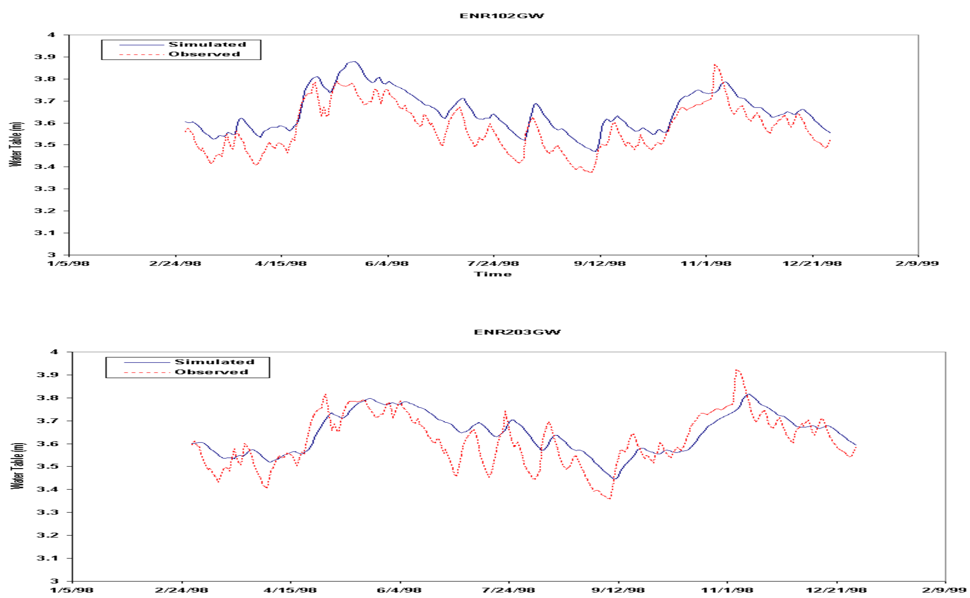


FIGURE 4. Simulated and Observed Groundwater Levels at ENR102GW and ENR203GW

6. DISCUSSIONS

Unlike some other similar integrated models, the coupling and exchange fluxes were not based on the assumption of interface discontinuity and leakage term. Both continuity of pressure head and exchange flux were imposed, this avoid the calibration of the empirical leakage coefficients for overland/subsurface, canal/subsurface interfaces. The weak permeable peat that restricts vertical subsurface flow was part of the subsurface domain. The model simulation results demonstrate that this coupling approach is aligned to the physical processes of ENR hydrology.

Details in area extent of vegetation types, local remnant ditches in the marsh, culvert flow computation, etc., could improve the accurate representation of two-dimensional overland flow. A dynamic wave model of overland flow to replace the diffusion wave approximation and the use of high-resolution time series data (e.g. 15 minute observed data instead of daily average data used in current model simulations) may better simulate the dynamic variations.

7. CONCLUSION

A physics-based, integrated model was developed to simulate complex hydrologic processes in a constructed wetland. The surface water and groundwater interactions were simulated by coupled two-dimensional overland flow and three-dimensional subsurface flow. Minimum model calibrations combined with model parameters estimated from field studies were able to reproduce major trends in historic surface and groundwater levels.

ACKNOWLEDGEMENTS

The background information of STA-1W was provided by SFWMD through the contract with Sutron Corporation (C-15988-WO04-05). The second author is supported by U.S. EPA-Science To Achieve Results (STAR) Program under Grant # R-82795602 with University of Central Florida.

REFERENCES

Feng K. and Molz F.J. (1997). A 2-D, diffusion-based, wetland flow model. Journal of Hydrology. 196 (1997) 230–250.

Fish, J.E., (1988), Hydrogeology, aquifer characteristics, and ground-water flow of the Surficial Aquifer system, Broward County, Florida: U.S. Geological Survey Water Resources Investigations Report 87-4034, 92 p.

Guardo, M., (1999). Hydrologic balance for a subtropical treatment wetland constructed for nutrient removal: Ecological Engineering, V. 12, P. 315-337.

Guardo M. and Tomasello, R.S., (1995). Hydrodynamic simulations of a constructed wetland in south Florida: Water Resources Bullrtin, v. 81, no.4, p. 687-701.

Harvey, J.W., et. Al, (2002), Interactions between Surface Water and Ground Water and Effects on Mercury Transport in the North-central Everglades: U.S. Geological Survey Water Resources Investigations Report 02-4050, 91 pages.

Langevin C., Swain E., Wolfert M., (2005). Simulation of integrated surface-water/ground-water flow and salinity for a coastal wetland and adjacent estuary. Journal of Hydrology. In press, 2005.

South Florida Water Management District (SFWMD), 2000. 2000 Everglades Consolidated Report, Chapter 6: Stormwater Treatment Areas. West Palm Beach, FL

SFWMD. (2005). DBHYDRO: http://www.sfwmd.gov/org/ema/dbhydro/index.html

Thompson J.R., H. Refstrup Sørenson, H. Gavin, A. Refsgaard. (2004). Application of the coupled MIKE SHE/MIKE 11 modelling system to a lowland wet grassland in southeast England. Journal of Hydrology. 293 (2004) 151–179

Swain E.D., Melinda A. Wolfert, Jerad D. Bales, and Carl R. Goodwin, (2004). Two-Dimensional Hydrodynamic Simulation of Surface-Water Flow and Transport to Florida Bay through the Southern Inland and Coastal Systems (SICS). U.S.Geological SurveyWater-Resources Investigations Report 03-4287, 2004.

Yeh, G.T., G. B. Huang, H. P. Cheng, F. Zhang, H. C. Lin, E. Edris, and D. Richards. (2005). A first principle, physics-based watershed model: WASH123D, in Watershed Models. Eds. By Singh VP and Frevert D.K., CRC Press, Boca Raton, FL, September 2005.

Yeh, G.T., G.B. Huang, H. P. Cheng, F. Zhang, H. C. Lin, E. Edris, and D. Richards. (2006). A Numerical Model of Flow, Heat Transfer, and Salinity, Sediment, and Water Quality Transport in WAterSHed Systems of 1-D Stream-River Network, 2-D Overland Regime, and 3-D Subsurface Media (WASH123D: Version 2.0). Technical Report CHL-**-**. Waterways Experiment Station, U. S. Army Corps of Engineers, Vicksburg, MS 39180-6199.