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Application of MIKE SHE/MIKE 11 Model to Structural BMPs in S191 Basin, Florida

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ABSTRACT. The S191 basin contributes significant phosphorous (P) loads to Lake Okeechobee, Florida (the Lake). This basin is located northeast of the Lake, and extensive nonstructural and structural Best Management Practices (BMPs) have been implemented to reduce total P (TP) loads. The Davie Dairy Best Available Technologies (Davie Dairy BAT) and The Taylor Creek Stormwater Treatment Area (Taylor Creek STA) are two of the structural BMP projects. The Taylor Creek STA reduces P loads to the Lake through detention, plant growth and soil sorption. The Davie Dairy BAT project reduces the P loads to the Lake through detention and chemical treatment. The objective of this study was to develop a model tool to simulate the structural BMP projects' daily flow rate and long term treatment volume under different weather scenarios. The MIKE SHE/MIKE 11 coupled model was selected for this study because of its capability to simulate the dynamic exchanges between the overland flow plain, groundwater system, and the river system. This study developed, calibrated and validated a MIKE SHE/MIKE 11 coupled model for this basin. The simulated daily flow rates at structure S191 compared favorably with measured values for a calibration and validation time period. Simulated groundwater levels for calibration were reasonably consistent with the measured groundwater levels. The calibrated and validated model was applied for long term simulation to evaluate the two structural BMP projects' long term treatment performance, annual average TP load reduction, using the observed hydrology and the water quality data.

Keywords: MIKE SHE, MIKE 11, BMP, modeling, storm water treatment area, Dairy Best Available Technologies

1. Introduction

Lake Okeechobee is the largest lake in Florida and the southeastern United States covering a surface area of 173,000 ha (Figure 1). It is a recreational destination in south Florida and is used for water supply, flood control, and irrigation for the surrounding regions and the downstream ecosystem. The watershed of the Lake spans from the Upper Kissimmee Region to areas that border the Lake on the south east and west and covers approximately 1,396,000 ha. The Lake has experienced accelerated eutrophication due to excessive P load (Havens et al., 1996). To address the excessive loads, the Florida Department of Environmental Protection adopted a P Total Maximum Daily Load (TMDL) of 140 metric tons (Chapter 62 ~ 304.700, F.A.C.) in August 2001. The Lake Okeechobee Protection Act (LOPA, Section 373.4595, F.S.), passed by the 2000 Florida Legislature, established a restoration and protection program for the Lake. This program is a watershed-based, phased, comprehensive, and innovative protection program designed to reduce P loads and implement long term solutions based upon the Lake Okeechobee TMDL (Zhang et al., 2007). One of the priority basins, which produce large TP loads to the lake and where BMP activities have been concentrated, is the S191 basin.

The S191 basin is located northeast of Lake Okeechobee. The basin is 48,868 ha in area and is characterized by flat topography and sandy soils. The long term average annual rainfall for this study area is 1,168 mm (Abtew et al., 2006) with the majority of rainfall occurring during a wet season that extends from May through November. From 1991 to 2005, the annual average runoff is 13,400 ha-m. The annual average flow weighted TP concentration to the lake is 644 ppb and the annual average TP loads are 86.4 metric tons (Zhang et al., 2009). The largest P imports to the basin are from dairy and beef pasture operations.

Extensive nonstructural and structural Best Management Practices have been implemented in this basin to reduce TP loads. Davie Dairy Best Available Technology project and Taylor Creek Stormwater Treatment Area are two types of the structural BMP projects (Figure 2). The Davie Dairy BAT project reduces the P loads to the Lake through water detention and chemical treatment. The Taylor Creek STA is a constructed wetland. It reduces P loads to the Lake through detention, plant growth and soil sorption. However, due to the limited data collection period after project implementation, the TP loads reduction under different hydrologic conditions over a long term period is unknown. A better understanding of the project long term performance will benefit the future BMP implementation decision making and funding allocation.

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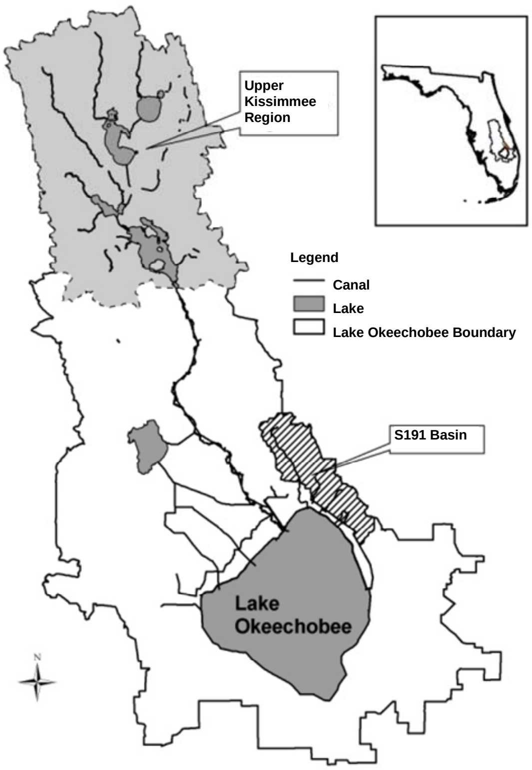

Figure 1. Lake Okeechobee and S191 drainage basin.

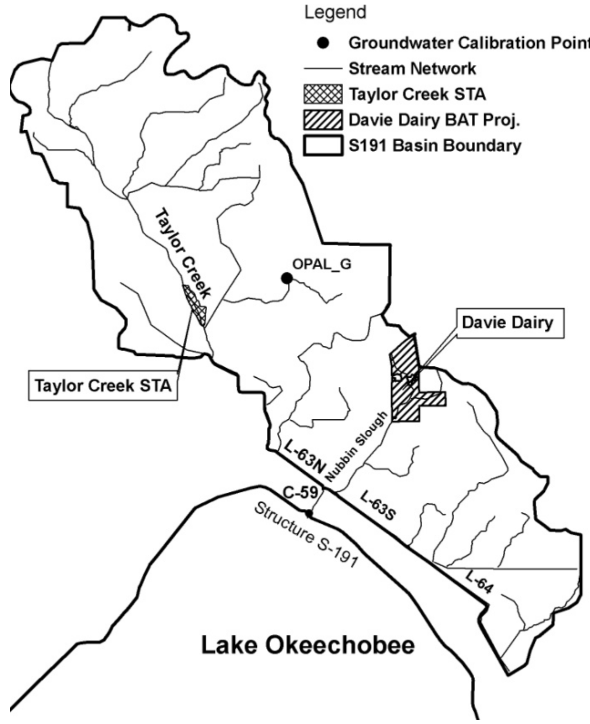

Figure 2. Two structural BMP projects and calibration points in S191 basin.

The objectives of this study were to: 1) develop a MIKE SHE/MIKE 11 coupled model to simulate the structural BMP projects' daily flow rate and long term treatment volume under different hydrological and meteorological conditions for the S191 Basin; 2) calibrate and validate the model with measured data; 3) perform long term simulation using the hydrology and meteorology data from 1994 to 2009; 4) estimate the annual average TP loads reductions that can be achieved by the two BMP projects using simulated daily flow time series and the available water quality data.

2. Model and Data

2.1. Model Description

The MIKE SHE/MIKE 11 coupled model has been selected for this study. MIKE SHE is a grid-based dynamic modeling system that can simulate integrated surface water and groundwater systems. It can simulate all the major land phase hydrological processes and is comprised of several independent modules that represent each hydrological process. A number of numerical approaches and/or conceptualizations are available within each module and allow users to tailor the model to meet the objectives and data constraints of a given project. The basic hydrologic flow processes incorporated into MIKE SHE include rainfall, evapotranspiration, runoff, seepage, surface flow and groundwater flow. MIKE 11 is a fully dynamic, one dimensional modeling tool for the detailed analysis, design, management and operation of both simple and complex river and channel systems. When MIKE 11 is coupled with MIKE SHE, dynamic exchanges between the overland flow plain, groundwater system and the river system are simulated. In this study, the selected hydrologic/hydraulic processes and numerical approaches are summarized below:

- Overland flow (OL): Finite difference method
- Evapotranspiration (ET) process: Simplified ET for the two-layer water balance method (Yan and Smith, 1994)
- Unsaturated flow process (UZ): Two-layer water balance method
- Saturated flow process: 3D finite difference method
- Open channel flow (OC): MIKE 11 model with hydrodynamic method

2.2. Overland Flow

The overland flow module incorporated a grid-based finite difference method that was driven by the discretized model topography. This method used a two-dimensional finite difference diffusive wave approximation of the Saint Venant equations (Saint-Venant, 1871). This approximation ignored momentum losses due to convective acceleration and lateral inflows perpendicular to the flow direction (DHI, 2006). The approximation was further simplified by substituting Manning's equation into the diffusive wave approximation momenmentum equations. An explicit or iterative linear matrix modified Gauss Seidel method was then used to solve the numerical solution for the entire grid simultaneously (DHI, 2006).

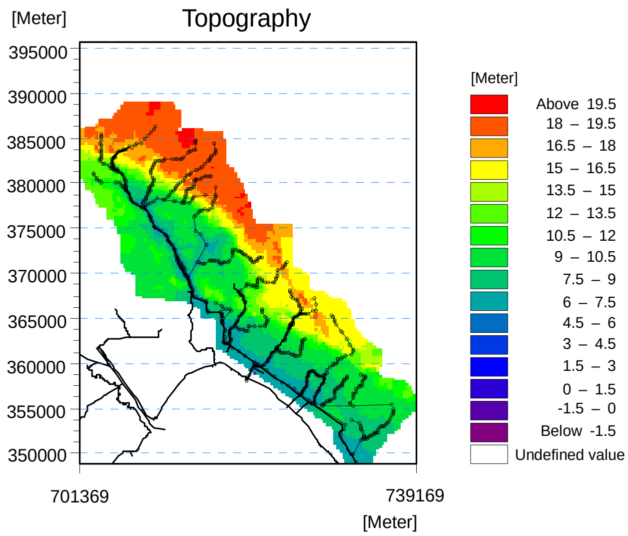

Figure 3. Basin topography.

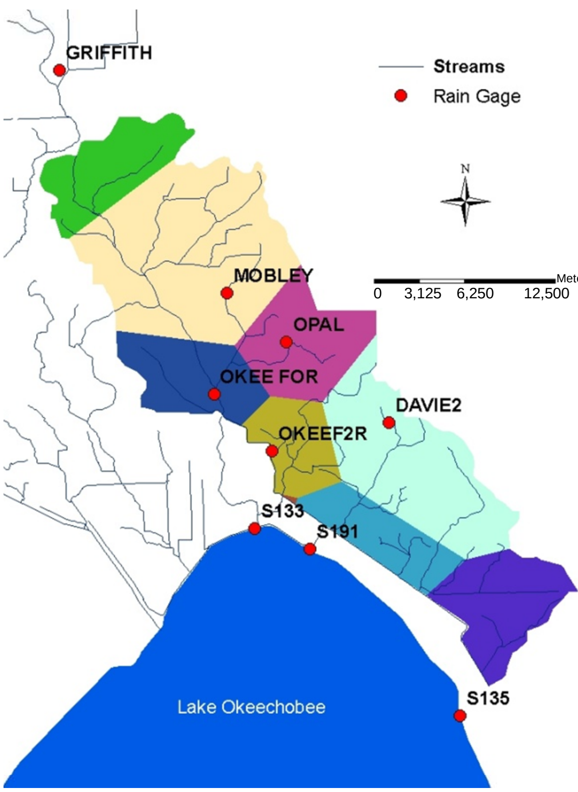

Figure 4. S-191 basin rainfall distribution by station.

2.2.1. Topography

The model domain was set to the entire S-191 basin and further divided into grids with a size of 30 m X 30 m. A basin wide digital elevation model (DEM) available from the United States Geological Survey's (USGS) National Elevation Dataset was used to define the basin topography. For the S-191 basin, the topography in the model domain area ranges from approximately 20 to 4.5 meters NGVD 29 (Figure 3). In general, the topography slopes from northeast toward the Lake (southwest). The highest elevation is found on the northeast corner.

2.2.2. Precipitation Data

Data from nine rainfall stations were inputs into the model to distribute precipitation spatially (Figure 4). Thiesson polygon method was used to define the area for each rainfall station. These data are available from the South Florida Water Management District's (SFWMD) DBHYDRO database (SFWMD, 2009).

2.2.3. Landuse Data

The landuse data (SFWMD, 2006a) were grouped into 11 categories based on the Florida Landuse Classification Code (FLUCC) categories (FDOT, 1999) and the hydrology similarity. The landuse categories and the corresponding areas were summarized in Table 1. The dominant landuse types are pasture, urban low density, forest, wetland and dairy. Four landuse parameters affecting hydrologic process are leaf area index (LAI), root depths (Root), and crop coefficients (Kc), and Manning's M values. These parameters were defined as follows:

- LAI: the area of leaves above a unit area of the ground surface. The LAI varies between 0 and 7. The LAI relates the ratio of total leaf area to total area for a particular vegetation category during the growing cycle. It is one of the primary variables used by MIKE SHE to calculate evapotranspiration (ET) fluxes.
- Root: the root depth is defined as the maximum depth of active roots in the root zone.
- Kc: the crop coefficient is used to adjust the reference evapotranspiration relative to the actual ET. A Kc value of 1 means that the maximum evapotranspiration rate equals the reference evapotranspiration rate.
- Manning's M value: This value, which is equal to the reciprocal of Manning's n value, lumps the friction effects due to different landuse/land cover and the natural morphology. It directly affected the velocity of overland flow. The Manning's M values were constant over the entire simulation period and spatially distributed based on the specified landuse types.

Values of LAI, Root, Kc, and Manning's M (Tables 1, 2 and 3) were obtained from the Kissimmee Basin Modeling and Operations Study (KBMOS) (Earth Tech and DHI, 2007).

2.3. Evapotranspiration

The reference evapotranspiration (RET) is the rate of ET from a reference surface with an unlimited amount of water. The RET is the basis from which the simulated ET values are calculated on a cell-by-cell basis. The two-layer water balance evapotranspiration and the actual soil moisture status in the root zone are calculated from the reference evaporation rate,

Table 1. Landuse Types and Related Parameters

Landuse Type	Total Area (ha)	Percentage	MIKE SHE Code	Detention Storage (mm)	Manning's M
Pasture	23,507	48.1%	1	25.4	7.14
Urban Low Density	6,354	13.0%	2	63.5	7.14
Dairies	4,356	8.9%	3	38.1	7.14
Wetland	4,426	9.1%	4	31.8	3.33
Forest	5,098	10.4%	5	31.8	5.00
Nurseries	254	0.5%	6	63.5	7.14
Urban Medium Density	2,201	4.5%	7	63.5	8.33
Water	520	1.1%	8	0.0	0.00
Crop	353	0.7%	9	1.5	5.88
Citrus	1,356	2.8%	10	29.2	5.88
Natural Areas	441	0.9%	11	31.8	2.50
Total	48,868	100%	/	/	/

Table 2. Monthly Leaf Area Index

Land Use Type	MIKE SHE Code	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Pasture	1	3.00	3.50	4.00	4.00	4.00	4.00	4.00	4.00	4.00	4.00	3.50	3.00
Urban Low Density	2	0.90	1.25	1.60	1.60	1.60	1.60	1.60	1.60	1.60	1.60	1.25	0.90
Dairy	3	3.00	3.50	4.00	4.00	4.00	4.00	4.00	4.00	4.00	4.00	3.50	3.00
Wetland	4	2.00	3.00	4.00	4.00	4.00	4.00	4.00	4.00	4.00	4.00	3.00	2.00
Forest	5	2.50	3.25	4.00	4.00	4.00	4.00	4.00	4.00	4.00	4.00	3.25	2.5
Nurseries	6	2.00	2.50	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	2.50	2.00
Urban Medium Density	7	0.80	1.13	1.45	1.45	1.45	1.45	1.45	1.45	1.45	1.45	1.13	0.80
Water	8	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Crops	9	3.75	4.50	3.00	3.75	4.5	3.00	3.00	3.00	3.00	3.00	3.75	4.50
Citrus	10	3.38	3.38	3.75	4.12	4.50	4.50	4.50	4.50	4.50	3.38	3.38	3.38
Natural Area	11	3.00	3.50	4.00	4.00	4.00	4.00	4.00	4.00	4.00	4.00	3.50	3.00

Table 3. Crop Coefficients and Root Depth

Land Use Type	MIKE SHE Code	Kc	Root (mm)
Pasture	1	0.69	749
Urban Low Density	2	0.62	201
Dairy	3	0.69	749
Wetland	4	0.64	152
Forest	5	0.64	1,524
Nurseries	6	0.62	749
Urban Medium Density	7	0.62	201
Water	8	1.00	0
Crops	9	0.80	450
Citrus	10	0.52	1,250
Natural Area	11	0.69	749

along with maximum root depth, leaf area index, and the moisture content in the root zone.

2.4. Unsaturated Flow

This model used a two-layer water balance method to represent unsaturated zone flow. It assumes a uniform soil profile for the entire depth and an evapotranspiration surface depth. The four principle parameters related to each soil type were saturated water content, field capacity, wilting point and infiltration rate. The soil distribution was developed using the available soil GIS coverage developed by the National Resource Conservation Service (NRCS, 2006). The individual soil series were grouped into 23 unique classes. The physical hydrologic soil parameters (Table 4) were calculated based on the Florida Soils Characterization Database developed by the University of Florida (UF, 2007).

2.5. Saturated Zone

This model represented the saturated zone with the three-dimensional finite difference option. This option required specification of data for geological layers and computational layers. This model simulated three aquifer layers: the surficial aquifer system (SAS), the intermediate aquifer system and intermediate confining unit (ICU), and the upper Floridan aquifer (UFA). Each geologic layer contained a lower level, horizontal hydraulic conductivity, vertical hydraulic conductivity, specific yield and specific storage coefficient. The lower level represented a surface dividing one geologic layer from another. The horizontal (K_h) and vertical hydraulic conductivities (K_v) represented the hydraulic properties of the geologic layer. The specific yield (S_y) was the unit volume fraction of water that drains from the geologic layer under the influence of gravity alone. The specific storage coefficient (S_s) was a parameter used to calculate the unit volume fraction of water released from storage in a confined aquifer per unit change in hydraulic head and was related to aquifer and water compressibility. These values (Table 5) were obtained from Lower

Figure 5. S-191 structure.

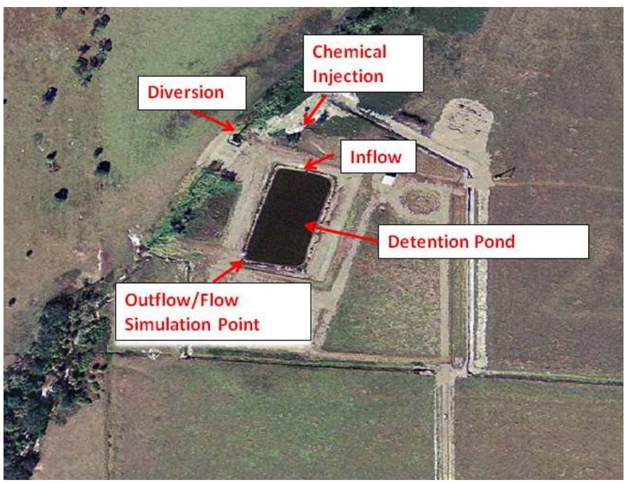

Figure 6. Davie Dairy BAT project site plan.

Kissimmee Basin Groundwater Model Study (LKBGMS) (SFWMD, 2006b) and the USGS Mega Model (Sepulveda, 2003).

2.6. Open Channel Flow

The major drainage in the S-191 basin is through large interceptor canals, Taylor Creek, L-63S, L-63N, L-64, and C-59, built to transport storm water from the secondary system and field ditches (not shown) in the basin. The excavated field ditches feed the mostly natural secondary drainage systems. Some sloughs and creeks have been dredged to improve drainage conditions for agricultural and rural development. In this study, the secondary and major streams were simulated (Figure 2). Totally, the MIKE 11 module included 29 streams and 96 cross sections. The distance between cross sections varies. The resistance number is specified as Manning's n. The Manning's n value for the main channel and banks were adju- sted during the calibration process.

The discharge point from this basin is S-191 structure, a fixed crest, reinforced concrete spillway with three gates (Figure 5). The structure parameters are as follows:

- Weir net length: 24.69 m
- Weir crest elevation: 2.25 m
- Water level which will by-pass structure: 7.47 m
- Gate size: 5.36 m high × 8.47 m wide

This control structure was modeled using the newly added feature of MIKE 11 (2007 version), which has the SFWMD structure flow equations built into the model.

2.7. Coupling MIKE 11 to MIKE SHE

All streams included in MIKE 11 were coupled to the MIKE SHE model. The MIKE SHE river links function defined the locations where the overland, drainage and baseflow components interacted with MIKE 11. The full contact river-aquifer option was specified for all MIKE 11 streams.

2.8. Two Structural BMP Projects

2.8.1. Davie Dairy Best Available Technologies Project

Davie Dairy is a 1,380 ha dairy located in Okeechobee County, Florida (Figure 2). Approximately 607 ha of the property drain to Nubbin Slough. TP concentration of the water discharged from the farm to Nubbin Slough ranges from 200 to 600 ppb. The BAT project is a chemical treatment system (Figure 6). It was designed to reduce the TP concentrations in discharges to below 40 ppb (ERD, 2003). An earthen dam with three corrugated metal pipe culverts with gate structures was constructed across the slough to create a small detention area behind the dam. The steep gradients along the lower section of the property border and the wetlands within the slough reduce detention. The primary purpose of the earth dam was to divert water to a chemical treatment system, not to detain water. Therefore, this system was considered a flow-through instead of detention based system. A four-foot diameter pipe extended from the slough upstream of the culvert structure to deliver water via gravity to the chemical treatment system. The system was designed to handle 100 percent of the runoff from storms up to 88.9 mm per day (SWET, 2008). A flow meter was installed in the inlet pipe to the treatment pond to regulate the chemical feed/injector pumps and maintain a constant chemical dosing concentration. The chemical dosed water flows into a large flocculation/settling pond before discharging back into Nubbin Slough downstream of the diversion structure. Sludge in the flocculation/settling pond can be hydraulically pumped into above ground drying beds for sludge dewatering prior to land application. The storage volume behind the dam holds back about 7.6 mm of runoff from the drainage area. The BAT project began operating in September 2005.

2.8.2. Taylor Creek Stormwater Treatment Area

The Taylor Creek Stormwater Treatment Area is constructed wetland system. It is a critical restoration project, authorized by Congress under Section 528 of the Water Resources Development Act of 1996 and designed and built by the U. S. Army Corps of Engineers. This pilot-scale STA project captures and reduces the mass of total phosphorus from the Taylor Creek Basin before it reaches Lake Okeechobee. The long term

Table 4. Soil Parameters

Soil Class	Area (ha)	Percentage (%)	Water Content			Infiltration rate (m/s)
			Saturated Condition (1/10 bar)	Field Capacity (1/3 bar)	Wilting Point (15 bar)	
Basinger	19,943	40.94	0.206	0.046	0.028	5.0×10^{-6}
Candler	185	0.38	0.043	0.030	0.011	4.7×10^{-5}
Chobee	167	0.34	0.377	0.329	0.115	1.4×10^{-7}
Floridana	5,914	12.14	0.258	0.251	0.156	9.4×10^{-7}
Holopaw	5,187	10.65	0.264	0.184	0.048	6.4×10^{-7}
Immokalee	3,326	6.83	0.130	0.095	0.018	1.4×10^{-6}
Malabar	530	1.00	0.210	0.159	0.048	9.2×10^{-7}
Manatee	707	1.45	0.247	0.167	0.046	4.4×10^{-7}
Myakka	1,568	3.22	0.212	0.025	0.023	3.3×10^{-6}
Oldsmar	154	0.32	0.171	0.148	0.056	1.2×10^{-6}
Parkwood	431	0.89	0.317	0.242	0.083	4.8×10^{-7}
Pinellas	992	2.04	0.242	0.167	0.047	3.4×10^{-7}
Placid	2,522	5.18	0.205	0.085	0.027	3.3×10^{-6}
Pomello	443	0.91	0.061	0.048	0.009	7.8×10^{-6}
Pompano	11	0.02	0.234	0.191	0.113	2.8×10^{-6}
Riviera	1,192	2.45	0.183	0.125	0.048	1.7×10^{-7}
Samsula	1,341	2.75	0.537	0.448	0.030	6.7×10^{-6}
St. Johns	553	1.14	0.271	0.190	0.048	3.0×10^{-7}
Gator	2,391	4.91	0.276	0.241	0.142	1.7×10^{-7}
Valkaria	149	0.31	0.121	0.053	0.010	5.3×10^{-6}
Wabasso	390	0.80	0.150	0.111	0.062	6.4×10^{-7}
Water	72	0.15	0.628	0.500	0.055	1.1×10^{-5}
Waveland	543	1.11	0.154	0.126	0.042	6.2×10^{-7}
Total (ha)	48,711	100	/	/	/	/

Table 5. Aquifer Parameters

Aquifer	Thickness	K_h	K_v	S_y	S_s
SAS	0 – 90 m	1.4×10^{-5} to 1.8×10^{-4} m/s	initial value: $1/10 \times K_h$	0.1	1×10^{-5} 1/m
ICU	5-175 m	3×10^{-5} to 3×10^{-4} m/s	1×10^{-8} to 7×10^{-8} m/s	0.1	1×10^{-5} 1/m
UFA	20-136 m	1.8×10^{-4} to 7.1×10^{-4} m/s	1.8×10^{-5} to 7.1×10^{-5} m/s	0.1	1×10^{-5} 1/m

phosphorus storage mechanism within this STA, is through accretion of new organic sediment. The site is approximately 81 ha with a treatment area of 58 ha (Figure 7) (Goforth, 2005). An inflow pump station removes water from Taylor Creek at the north end of the STA. Treatment occurs through natural biogeochemical processes as the water slowly flows by gravity southeasterly through the 20-ha Cell 1 and subsequently through the 38-ha Cell 2 before being discharged back into Taylor Creek. Water levels and flow rates through the treatment cells are controlled by individual structures located at the south end of each cell. Normal operation of this STA began in August 2008.

3. Model Calibration and Validation

Standard calibration statistics defined in the MIKE SHE reference manual were used to measure calibration efficiency (DHI, 2006). These four statistics, mean error (ME), root mean square error (RMSE), coefficient of correlation (R), and percentage of Volume Error were calculated based on the differ-rences between the measured and the calculated values at the calibration point. Nash Sutcliffe Correlation Coefficient (NSCC) proposed by Nash and Sutcliffee (1970) is also a common efficiency criteria used to measure model performance (Krausel et al., 2005). The NSCC was also calculated in this study:

$$ME_i = \frac{\sum_t (Obs_{i,t} - Calc_{i,t})}{n} \tag{1}$$

$$RMSE = \frac{\sqrt{\sum_t (Obs_{i,t} - Calc_{i,t})^2}}{n} \tag{2}$$

$$NSCC_i = 1 - \frac{\sum_t (Obs_{i,t} - Calc_{i,t})^2}{\sum_t (Obs_{i,t} - \overline{Obs_i})^2} \tag{3}$$

$$R = \sqrt{\frac{\sum_t (Calc_{i,t} - \overline{Obs_i})^2}{\sum_t (Obs_{i,t} - \overline{Obs_i})^2}} \tag{4}$$

$$Volume\ Error\% = \frac{\sum_t (Obs_{i,t} - Calc_{i,t})}{\sum_t (Obs_{i,t})}\% \tag{5}$$

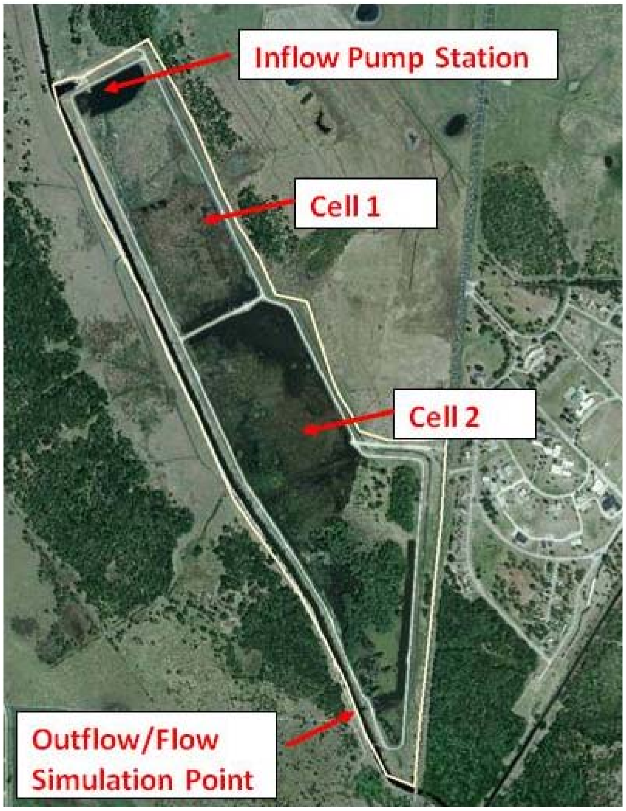

Figure 7. Taylor creek STA site plan.

Table 6. Calibrated Parameters

Parameter	Values
Overland-ground Water Leakance (1/s)	5×10^{-7}
River Aquifer Leakage Coefficient (1/s)	1×10^{-6}
Manning's n for Streams ($s/m^{1/3}$)	0.03 for the main stream and 0.15 for the left and right side banks
SAS Vertical Hydraulic Conductivity (m/s)	8.8×10^{-5} for grids adjacent to rivers and lakes 2.5×10^{-5} for other grids

where t is the simulation time in day, n is the total simulation days, i is the calibration point i, $Obs_{i,t}$ is the observed daily flow rate at location i at day t, $\overline{Obs_i}$ is the mean of the observed flow rate at location i for the simulation period, and $Calc_{i,t}$ is the simulated flow rate at location i at day t.

Hydrographs measured at the watershed outlet are the synergistic outcomes of rainfall, infiltration, overland flow and flow routing. For surface flow, the model was calibrated to fit the measured daily flow rate at the basin outlet, structure S191. The traditional split sample approach (Gunasekara and Cunnane, 1992) was used for model calibration and validation. The calibration period was from January 1, 2005 to June 30, 2008. The validation period is from July 1, 2008 to December 31, 2009. The last time step of the calibration phase was used as the starting point for the validation phase. The groundwater level was calibrated at well OPAL_G. For a distributed hydrological model such as MIKE SHE, the number of parameters subjected to adjustment during calibration should be as small as possible (Refsgarrd and Storm, 1995). For surface water, the adjusted parameters included overland-groundwater leakance, river-aquifer leakage coefficient, and Manning's n. To calibrate groundwater, the Surficial Aquifer System (SAS) vertical hydraulic conductivity was adjusted (Table 6). The calibration was performed by perturbing one parameter while maintaining all other parameters at their initial values. Values of a selected model parameter were varied iteratively within a reasonable range for a series of calibration runs until a satisfactory agreement between measured and simulated daily flow rate was obtained.

A favorable agreement (Figure 8) was attained between measured and simulated daily flow rates at structure S191 with correlation coefficients of 0.87 and 0.82 for calibration and validation periods, respectively. MEs for both periods were less than 0.1 m^3/s (Table 7). Very limited flow measurements for Davie Dairy BAT project are available based on the landowner's flow log. These data were plotted against the simulated flow at the same discharge points. The simulated values match the flow log well (Figure 9). For Taylor Creek STA, flow data is available for part of year 2008. The measured flow data from September to November 2008 are lower than the simulated data (Figure 10). It may be explained by the temporary shutdown of two pumps during this period (USACE, 2009).

Simulated groundwater levels for calibration were reasonably consistent with the measured groundwater levels at OPAL_G (Figure 11). Increasing of horizontal hydraulic conductivities could further improve the groundwater simulation performance; however the surface water calibration was compromised with an increase percentage on volume error. In this study, the calibration of surface water is more critical, so the horizontal hydraulic conductivities were not adjusted.

4. Structural BMP Projects Long Term Evaluation

The calibrated and validated S191 model was applied for long term simulation to estimate the structural BMP projects' daily flow rates and long term annual treatment volume for the period of January 1, 1994 to December 31, 2009. This period was chosen because it represents a combination of dry, average, and wet years. The average annual rainfall for this study area is 1,168 mm (Abtew et al., 2006). During this period, seven years of annual rainfall data (1996, 2000, 2001, 2002, 2003, 2006, and 2007) were below average annual rainfall data. The data for the other years were above average annual rainfall.

The simulated time series at structure S191 was in agreement with the observation values (Figure 12). The simulated annual runoff at S191 was 3,977 ha-m/year and the measured annual runoff was 3,770 ha-m/year, a difference of 5.1% (Table 7). Because of the small detention volumes of the two BMP projects, they had no observable affect on S191 flow pattern or flow rates. Both projects treat the runoff and discharge the water back to their original downstream canals.

Table 7. Statistical Measures of Simulation Performance

	ME (m^3/s)	RMSE (m^3/s)	R	NSCC	Volume Error (%)
Calibration (at structure S191)	-0.089	1.47	0.87	0.77	0.27%
Validation (at structure S191)	0.098	1.59	0.82	0.60	5.2%
Long Term Simulation (at structure S191)	-0.130	2.62	0.78	0.56	5.1%
Groundwater Calibration (OPAL_G)	0.03	0.307	0.62	0.51	N/A

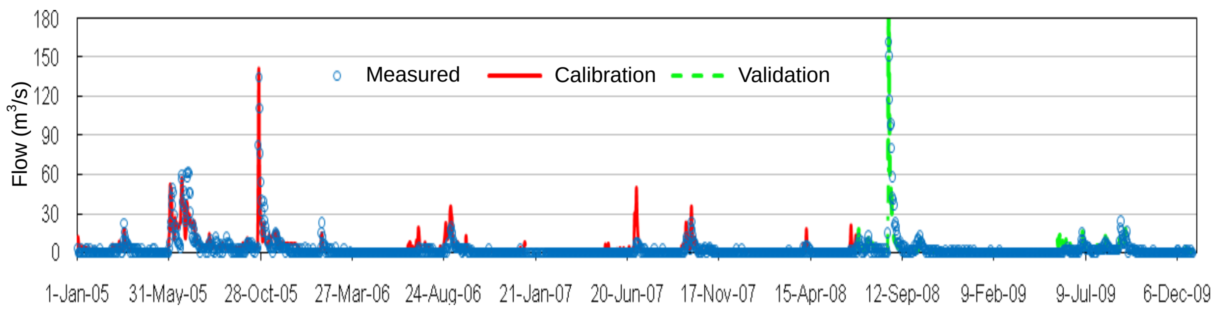

Figure 8. Calibrated, validated and measured daily flow rates at structure S191.

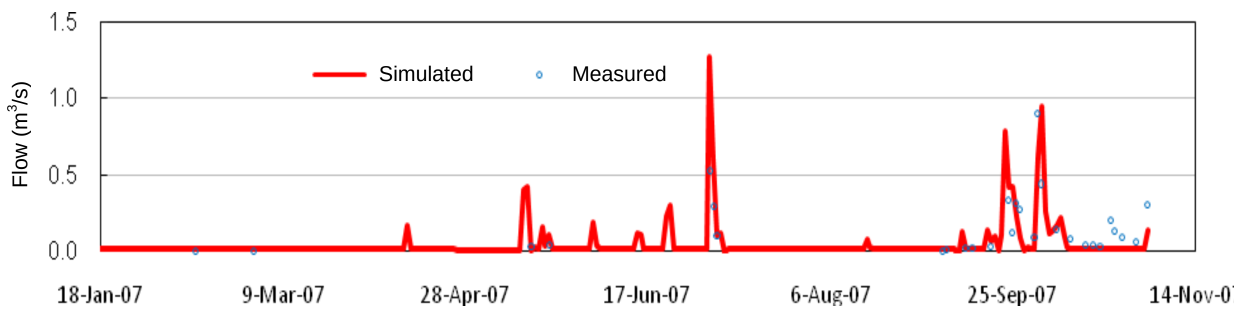

Figure 9. Simulated vs. measured daily flow rates at Davie Dairy project outflow point.

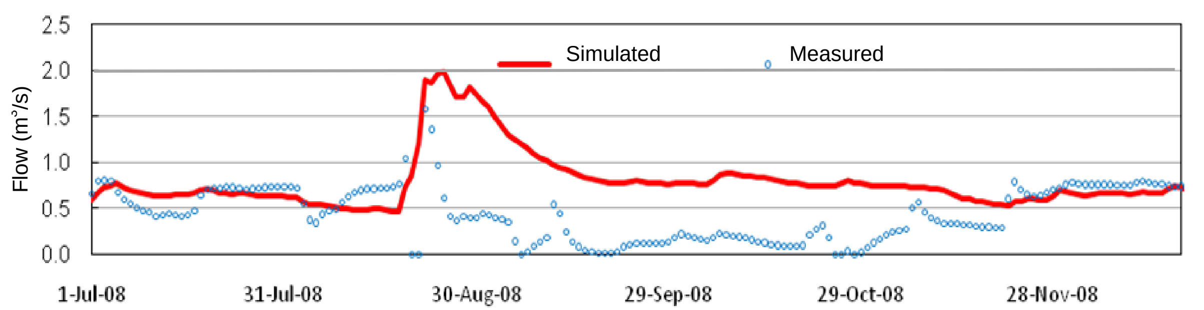

Figure 10. Simulated vs. measured daily flow rates at Taylor Creek STA outflow point.

For the Davie Dairy BATs Project, inflow and outflow plots showed insignificant flow attenuation due to the flow-thru system with a small storage (Figure 13). The simulated annual inflow to the system was 173 ha-m and the outflow from the system was 157 ha-m. The flow reduction due to other processes (ET, seepage, etc.) was 16 ha-m, or approximately 3 mm/day. The simulated annual flow through the diversion structure was 33.8 ha-m, which is about 17% of the annual runoff from the drainage area. The measured average inflow TP concentration is 836 ppb and the design treatment efficiency is 78% reduction of TP concentration (ERD, 2003). Based on this treatment efficiency, the calculated TP loads in the inflow are 1.4 metric tons and the TP load in the outflow are 0.3 metric tons, a reduction of 1.1 metric ton can be achieved. However, due to equipment malfunctions, delays in correcting problems and other issues related to the operations, it is hard to reach this high level of treatment efficiency (Soil and Water Engineering Technology, 2008).

For the Taylor Creek STA project, the simulated annual inflow to the system was 1,381 ha-m and the outflow from the system is 1,289 ha-m (Figure 14). The flow reduction due to other processes (ET, seepage, etc.) was 91 ha-m, or approximately 4.3 mm/day. The inflow TP flow weighted mean concentration, as measured from July to December 2008, was 494 ppb, and the outflow TP FWMC was 335 ppb (USACE, 2009).

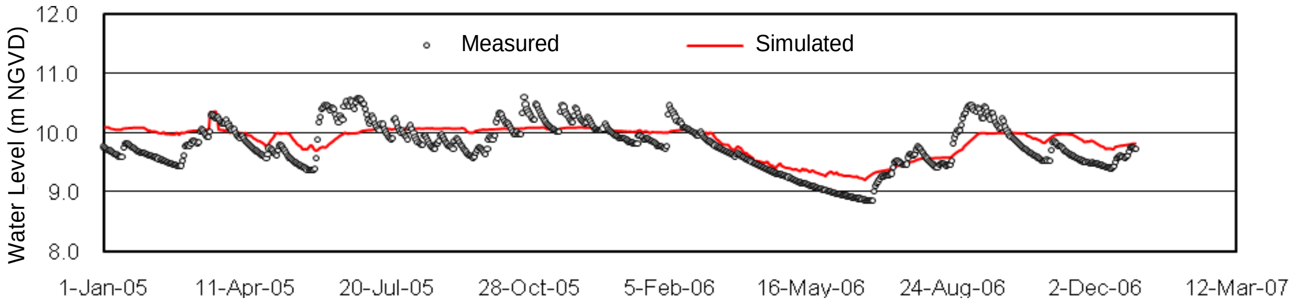

Figure 11. Simulated and measured groundwater level at Well OPAL_G.

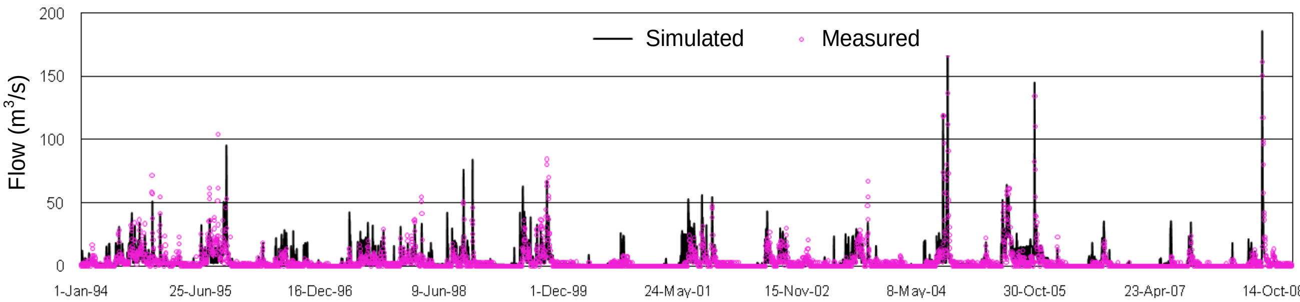

Figure 12. S191 simulated vs. measured daily flow rates (1994-2009).

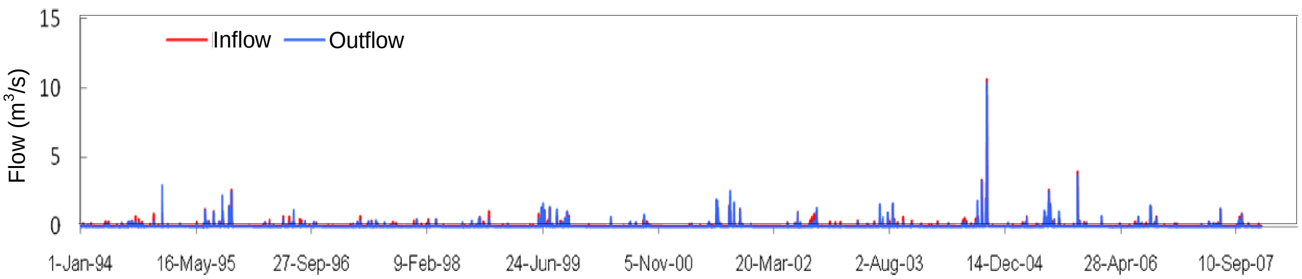

Figure 13. Davie Dairy BAT project simulated inflow vs. outflow.

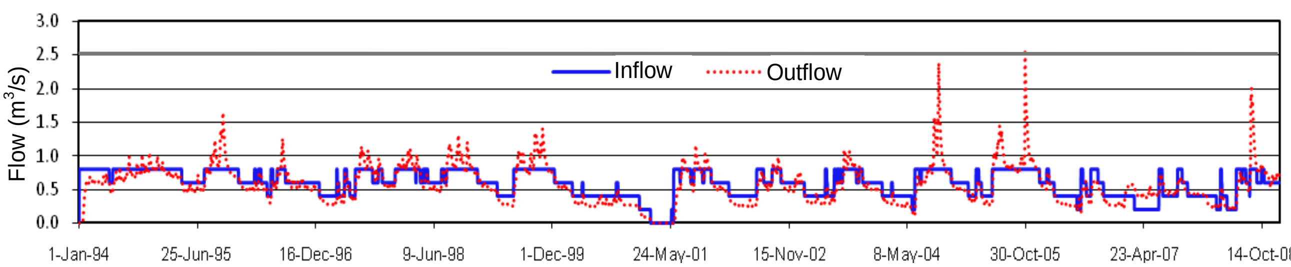

Figure 14. Taylor creek STA simulated daily flow rates, inflow vs. outflow.

Based on this STA performance, the long term annual average inflow TP load into the STA was 6.8 metric tons and the outflow TP load was 4.3 metric tons. The annual load reduction was 2.5 metric tons, or 37% of the load to the STA.

5. Summary and Discussion

The S191 MIKE SHE/MIKE 11 was calibrated and validated with measured flow data on a continuous daily scale. Both calibration and validation results were satisfactory. The calibrated and validated flow time series at basin outlet S191 compared favorably with the measured values. The calibrated and validated model was used for a 16-year long term simulation. The simulated annual runoffs at both projects' outflow points match the available monitoring data well. The simulated daily flow rates at the project outlets were used to evaluate TP load reduction. The estimated long term annual load reduction by Davie Dairy BAT project was 1.1 metric tons and the TP load reduction by Taylor Creek STA was 2.5 metric tons. For both projects, achieving this level of TP load reductions depends on the successful operation of the systems.

Extensive nonstructural and structural Best Management Practices (BMPs) have been implemented in Lake Okeechobee Watershed to reduce TP loads. SFWMD has established an extensive water quality monitoring network throughout the Lake Okeechobee Watershed. However, flow monitoring is not implemented in most of the structural BMP sites due to the technical difficulty and high cost. A good estimate of flow is crucial for load calculation. A tool is needed to quantify the flow rate at the BMP implementation sites so BMP effectiveness can be estimated by calculating load reduction. This model can be used as a design and management tool to estimate daily surface flow rate and long term annual surface runoff at different structural BMP projects inflow and outflow points. Further, the simulated long term daily flow data can be used to estimate the TP load reduction combined with the available water quality monitoring data or linked to other water quality modeling tools. The projects that can be simulated by this model tool include detention/retention ponds, STA, and Dairy BAT projects. In addition to estimates of structural BMP project flow, this model also can estimate the daily surface flow at tributaries and farm levels through minor modification to internal model setup and combination with surveyed stream and structure dimensions data. The application of the coupled MIKE SHE/MIKE 11 modeling system to the S191 basin demonstrated its potential to represent complex hydrological systems and other structural BMP projects found within Lake Okeechobee Watershed.

The large data requirements of the coupled MIKE SHE/MIKE 11 model system are a potential problem for the development and application of models to other basins. In this study, relevant literature and earlier research from adjacent basins provided much of the data for the coupled model. Further field surveys encompassing the channel cross sections and control structure dimensions would improve model flow predictions. The land use parameters that affect hydrology process, such as leaf area index, root depth, and crop coefficient should be fine tuned to improve the model performance.

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