Supplementary Material (ESI) for Journal of Environmental Monitoring

Supporting Information Section

Phosphorus run-off assessment in a watershed

Yirgalem Chebud, Ghinwa Naja* and Rosanna Rivero

Everglades Foundation, Science Department, Miami, Florida 33157

** Corresponding author. Tel.: +1-305-251-0001 (ext.229); Fax: +1-305-251-0039*

Everglades Foundation, 18001 Old Cutler Road, Miami, FL 33157

E-mail: mnaja@evergladesfoundation.org

Evaluation of the models

Erosion Productivity Impact Calculator (EPIC) is a comprehensive model designed to simulate crop yields at field level and to determine the relationship between soil erosion and soil productivity for various agricultural management practices. The model integrates the major processes that occur in the soil–crop–atmosphere management system, including: hydrology, weather, erosion, nutrients, plant growth, soil temperature, tillage, plant environmental control, and economics [1]. EPIC is well suited for relative comparisons of soils, crops, and management scenarios and has a good accuracy to estimate field yields [2].

Chemicals, Runoff, Erosion from Agricultural Management Systems (CREAMS) is a model developed to evaluate the impacts of agricultural management systems on the movement of agricultural chemicals within and through the root zone [3]. It contains a sophisticated erosion component based, in part, on the USLE (Universal Soil Loss Equation) and also on flow hydraulics and the processes of sediment detachment, transport and deposition. The CREAMS erosion component also calculates erosion by concentrated flow, the contributions of ephemeral gullies, and deposition in backwater and impoundments.

Water Erosion Prediction Project (WEPP) model was developed to predict water erosion [4]. It is intended for use on small agricultural watersheds (less than 260 ha) to identify zones of sediment deposition and detachment within permanent channels or ephemeral gullies, to account for the effects of backwater on sediment detachment, transport and deposition within channels, and to represent spatial and temporal variability in erosion and deposition processes as a result of agricultural management practices. This model has been widely applied to predict runoff and sediment yield at field and watershed scales.

ANSWERS [5] (*Areal Nonpoint Source Watershed Environmental Response Simulation*) or AGNPS [6] (*Agricultural Non-Point Source*) models were developed to estimate the runoff water quality from agricultural watersheds ranging in size from a few hectares to 20,200 ha. These models are limited in the size of watershed they can deal with. The major limitations of these models are due to the high requirements for handling large amount of input data and analyzing model results.

SWAT (*Soil and Water Assessment Tool*) model was developed [7] to predict the effect of alternative management practices on water, sediment, and chemical yields for applications to large, heterogeneous rural basins. SWAT model is a powerful tool for non-point as well as point source nutrient transport simulation and it has also proven effective both for field scale as well as watershed level studies. It allows simultaneous computations on several hundred sub-watersheds (up to 2,500 sub-basins). The major components of the model include surface hydrology, weather, sedimentation, soil temperature, crop growth, nutrients, pesticides, ground water and lateral flow, and agricultural management.

WASP (*Water Quality Analysis Simulation Program*) was developed by U.S. EPA to simulate surface water quality and 3-dimensional fate and transport of solutes in either a steady-state or a dynamic mode [8]. Transport processes simulated in WASP include loadings of point and non-point source water and constituents, including those from tributaries, groundwater, and runoff; advection, dispersion and diffusion in stream segments; adsorption/desorption associated with sediment; precipitation/dissolution; and sediment transport and settling/scour of particulates.

Model selection

Various models have been developed to predict the non-point and point source nutrient loadings to water bodies and their impact on the quality of surface water, including EPIC (Erosion Productivity Impact Calculator), CREAMS (Chemicals, Runoff, Erosion from Agricultural Management Systems), WEPP (Water Erosion Prediction Project), ANSWERS (Aerial Nonpoint Source Watershed Environment Response Simulation), SWAT (Soil and Water Assessment Tool) and AGNPS (AGricultural NonPoint Source). For our purposes, the selected model needs to simulate the natural hydrological process and to be adaptable during the calibration processes. Accordingly, several process based models (listed in Table S1) that satisfy these requirements were identified and assessed.

Each one of these models addresses specific issues in water quality areas along with a set of assumptions, and input requirements that vary significantly (Table S1). The evaluation criteria at preliminary screening level were based on discrete vs. continuous time, spatial scales, computation time steps, and user friendliness. For example, models are either non-spatially distributed (EPIC, CREAMS), or spatially distributed (ANSWERS, AGNPS, SWRRB); single-event (AGNPS, ANSWERS) or continuous-time scale (EPIC, CREAMS, SWRRB, ROTO); field-scale (WEPP, EPIC, CREAMS), or watershed/basin-wide (ANSWERS, AGNPS, SWRRB).

The amount of time, expertise, and costs required for acquiring input data, running the models, and analyzing the results are growing, and the complexity level varies across the models. For example, as the models begin to address several water quality and quantity concerns, the information needed to execute the models has increased significantly (a simple model like USLE requires only six inputs, while a spatially-distributed, single-event model like AGNPS requires 22 inputs for each cell or grid within a studied area), thereby tremendously increasing the costs, time, and complexity of analyzing results.

The geographic information system (GIS) interface is an effective tool to generate, manipulate, and organize the spatially disparate data for modeling. This interface can eliminate many of the limitations associated with the use of these models. There have been a number of successful applications of models linked to GIS for management of non-point source nutrient transport and loading. Indeed, many authors attempted to integrate the GIS component into distributed parameter, single-event, water quality models such as AGNPS and ANSWERS [9, 10] as well as continuous-time, basin large-scale water quality models such as SWAT model [11]. These linkages proved to be an effective way to collect, manipulate, visualize, and analyze the input and output data of water quality models.

The Watershed Assessment Model (WAM), developed by Soil Water Engineering Technology (SWET) [12, 13] and used in the present study, is a comprehensive GIS-based program that has been used extensively for large and small scale hydrologic and water quality evaluations. The model simulates the primary physical processes for hydrologic and pollutant transport and it can be used in the simulation of a variety of physical and chemical processes to evaluate current conditions or alternatives. The advantage of this model over others is its ability to assess the spatial impact of existing and modified land uses on water quality and quantity for tributaries within the Lake Okeechobee watershed. Furthermore, this model was developed, adapted and calibrated for the South Floridian context to simulate the flat topography, the dominance of several depression sites attributable to the flat topography and Karstic geology, sandy soil and high water-table (continuity of the flow both at surface and subsurface level) of South Florida and to the local land uses (agricultural, wetlands, urban areas and water treatment sites) as well as to the best management practices in the region. This model was used in the present case to assess the impact of land use on the water quality and quantity in the studied basin. The different modules of WAM (Fig. S1) are developed to model the water runoff at a field, watershed and basin scales with a daily time step. The model also simulates the hydrological processes of surface water and subsurface flows as well as nutrient attenuation. The model interface is also user friendly and was upgraded to run with Arc GIS 9.x.

Flow and phosphorus loading parameterization and budgeting (synthesized from WAM documentation)

EAAMOD in within the WAM model assumes a stack of parallel columns of soil as a cell with a definite water balance budget. The horizontal layer of the soil is simulated by three layers of soils with a low conductivity layer embedded in the middle representing a consolidated organic layer. The water balance at each time step, considering inflow, outflow and sources or sinks, is formulated using Equation (S-1):

$$\Delta S = Q_{i+1} - Q_i + R_i - ET_i - P_i + Ir_i / Dr_i \quad \text{(S-1)}$$

where ΔS is the storage change in a soil column i, Q_{i+1} is the saturated inflow from the neighbor soil column, Q_i is the flux, R_t is the rainfall, ET_i is the evapotranspiration, P_i is the percolation, Ir_i is the irrigation and Dr the drainage.

The percolation term P is estimated based on the mass balance as well as the hydraulic head difference of the water table in the top layer versus the pressured head below the middle layer. The change in storage is used to account for the void space or porosity to determine the level of saturation and simulate the aerobic and anaerobic conditions. The porosity is estimated for the wetting and drying processes related to the groundwater levels.

GLEAMS in within the WAM model uses a simplistic water budget estimating the outflow following Equation (S-2):

$$Q = A^* (I + V_{stor}) \quad \text{(S-2)}$$

where A is the storage coefficient, I is the infiltration and V_{stor} is the storage volume. The storage coefficient A is determined by the travel time in each soil layer which is a function of the difference in soil moisture storage and the field capacity, divisible by the saturated hydraulic conductivity.

In both EAAMOD and GLEAMS models, runoff and evapotranspiration are estimated using the SCS curve number and Penman Monteith methods respectively.

Similarly, in phosphorus transport considerations a mass balance approach is assumed with inflows of phosphorus from rainfall, fertilizer application, irrigation water and mineralization by aerobic and anaerobic microbial activity. Outflow includes transport of soluble and sediment enriched phosphorus by runoff to the field ditches. The removal by crop uptake, leaching to the water table, transport by drainage water as soluble and suspended particulate phosphorus outflows are also accounted for. The source and sink terms in the phosphorus transport include the P vertical transport between the saturated and marl layer followed by its partition into soluble and adsorbed phases.

The estimation of the P mass balance is closely related to the water inflows and outflows and to the hydraulic properties and variables. However, critical parameterizations influencing the phosphorus availability for transport is determined by the aerobic/anaerobic mineralization and the P sorption processes. The mineralization process was captured by the Arrhenius equation as defined by Equation (S-3).

$$P_{min} = A*B^{(T-20)} \qquad \text{(S-3)}$$

A is the mineralization rate at 20^{o}C (representing the mean values for aerobic (A_1) and anaerobic (A_2) conditions) moderated for the mean daily temperature by B (reflecting B_1 or B_2 for the aerobic or anaerobic cases, respectively).

The sorption process was modeled by the Langmuir adsorption isotherm as determined by Equation (S-4).

$$P_{sol} = \frac{TP_{soil}}{\left[A \times R_z \times \left(\varepsilon + K \times DEN\right)\right]} \tag{S-4}$$

Where P_{sol} is the soluble phosphorus concentration in soil water (gL^{-1}), TP_{soil} is the total phosphorus amount in soil zone (kg), *A* is the surface area of the cell (m^2), R_Z is the root zone thickness (m), *ε* is the porosity of the soil, *K* is the partitioning coefficient (Lg^{-1}) i.e. the amount of phosphorus in water divided by the amount of phosphorus in the adsorbed phase and DEN is the bulk density of soil (gL^{-1}).

Lastly the sediment enriched phosphorus transport from overland (ditch eroded sediment P) and waterways (surface eroded sediment P) was estimated using exponential relationships following Equations (S-5) and (S-6), respectively.

$$D_P(mgL^{-1}) = C_1 \times V^{C2} \tag{S-5}$$

$$S_P(mgL^{-1}) = S_1 \times R^{S2} \tag{S-6}$$

Where C_1 and C_2 are coefficients representing the unit coefficient for ditch sediment P equation (mgL^{-1} per mhr^{-1}) (typically in range of 0.005 to 0.05) and the exponent for ditch erosion coefficient (typically 1.0). V is the flow velocity (mhr^{-1}) and R is the discharge rate for surface runoff (cmhr^{-1}). S_1 and S_2 are constants representing the unit coefficient for surface sediment P (mgL^{-1} per

$cmhr^{-1}$ (runoff rate)) (typically in range of 0.005 to 0.05) and the exponent for the surface sediment P equation (typically 2.0), respectively.

Sensitivity analysis of the model

The sensitivity analysis of the model was originally conducted by Izuno and Bottcher [14] using the following parameters: initial phosphorus content in the aerobic and anaerobic zones, in the marl zone and in the irrigation water, coefficients of aerobic and anaerobic mineralization, porosity of soil/marl, bulk density, partition coefficient for aerobic and anerobic marl, phosphorus concentration in rainfall, thickness of the surface zone, exponent for the ditch erosion equation, coefficient for the ditch sediment equation, exponent for the surface sediment – P equation, hydraulic conductivity of the top soil / middle / bottom (marl), depth of the impending soil, drained porosity wetting / drying curve, both drained porosity (wetting and drying), phosphorus fertilization rate, evapotranspiration and number of cells. Using a sensitivity ratio test with ± 50% output changes against ± 50% changes of the input, only eight of the parameters were found sensitive and affecting flow [14]. The process is most sensitive to the depth of the impending layer, actual evapotranapiration, drained porosity wetting/drying, both wetting and drying, hydraulic conductivities of the top/bottom and impermeable layers. In the case of phosphorus loading, it was established to be sensitive to 21 of the parameters, amongst which 8 hydraulic parameters were important for their high influence on the flow. Two from the remaining 13 parameters used in the ditch erosion equation were found important for sediment phosphorus enrichment.

In the case of soluble phosphorus loading, four influential parameters were highlighted including the amount of phosphorus applied to the field, the exponent in the anaerobic mineralization equation, the partition coefficient for the aerobic soil and the thickness of the surface zone. The directional sensitivity showed that the flow had positive correlations with the depth of the impermeable layer and the lower limit of drained porosity for drying, while the outflow was negatively correlated with the evapotranspiration with non-linear responses for the former two.

The routine for phosphorus estimation was originally brought from the EPIC model [15]. A similar response was observed for the soluble phosphorus and sediment enriched loadings. For soluble phosphorus a negative correlation was observed with the hydraulic conductivity of the impermeable and bottom layers, drained porosity for drying and drained porosity for wetting. Sediment enriched phosphorus loading showed changes in the direction of the outflow. The drained porosity of wetting, drying and drying-wetting had a greater effect.

References

1. J. R. Williams, P. T. Dyke, W. W. Fuchs, V. W. Benson, O. W. Rice and E. D. Taylor, *EPIC-Erosion/Productivity Impact Calculator*, Technical Bulletin Number 1768, United State Department of Agriculture, Agricultural Research Service, Springfield, VA, USA, 1990.

2. A. Bouzaher, J. F. Shogren, D. Holtkamp, P. Gassman, D. Archer, P. Lakshminarayuan, A. Carriquiry, R. Reese, W. H. Furtan, R. C. Izaurralde and J. R. Kiniry, *Agricultural policies and soil degradation in western Canada: An agro-ecological economic assessment*, *Technical Report 5/93*, Agriculture Canada, Policy Branch, Ottawa, ON, 1993, p. 110.

3. W. G. Knisel, *CREAMS: A field-scale model for chemicals, runoff and erosion from agricultural management systems*, US Department of Agricuture - Agricultural Research Service, Washington, DC, 1980.

4. G. R. Foster, *User Requirements: USDA-Water Erosion Prediction Project (WEPP).* National Soil Erosion Research Laboratory Report No. 1. National Soil Erosion Research Laboratory - US Department of Agricuture-Agricultural Research Service, W. Lafayette, IN., 1987.

5. D. B. Beasley, L. F. Huggins and E. J. Monke, *Trans. ASAE*, 1980, **23**, 938-944.

6. R. A. Young, C. A. Onstad, D. D. Bosch and W. P. Anderson, *J. Soil Water Conserv.*, 1989, **44**, 168-173.

7. J. G. Arnold, *Spatial scale variability in model development and parameterization*. Purdue University, W. Lafayette, IN., 1992. p. 183.

8. R. B. Ambrose, T. A. Wool and J. L. Martin, *WASP 5, the water quality analysis simulation program version 5.00*. AscI Corporation, AscI Corporation, Athens, GA., 1993.

9. B. A. Engel, R. Srinivasan, J. Arnold, C. Rewerts and S. J. Brown, *Water Sci. Technol.*, 1993, **28**, 685-690.

10. J. K. Mitchell, B. A. Engel, R. Srinivasan and S. S. Y. Wang, *Water Resour. Bull.*, 1993, **29**, 833-842.

11. R. Srinivasan and J. G. Arnold, *Water Resour. Bull.*, 1994, **30**, 453-462.

12. B. M. Jacobson, A. B. Bottcher, N. B. Pickering and J. G. Hiscock, *ASAE Paper, Am. Soc. of Agr. Eng.*, 1998, No. **98-2237**, St. Joseph, MI.

13. A. B. Bottcher, J. G. Hiscock and B. M. Jacobson, Proceedings of the Watershed 2002, Pre-Conference Modeling Workshop., Fort Lauderdale, FL., 2002.

14. F. T. Izuno and A. B. Bottcher, *The effects of on-farm agricultural practices in the organic soils of the EAA on phosphorus and nitrogen transport*, South Florida Water Management District (SFWMD), West Palm Beach, FL, 1987, p. 596.

15. D. R. Lewis and M. B. McGechan, *Biosystems Eng.*, 2002, **82**, 359-380.

TABLE S1. Nutrient transport main models and their characteristics

Model	Time scale		Spatial Scale					Computational time step			
	event	contin.	point	field	watershed	basin	regional	sec	hr	day	year
ADAPT (GIS interface)		X		X	X					X	
AGNPS (GIS interface)	X				X						
ANSWERS 2000 (GIS interface)	X	X		X	X			X			
CREAMS		X		X					X	X	
DRAINMOD		X		X					X	X	X
GLEAMS		X		x					X	X	
SWAT (GIS interface)		X			X					X	
WEPP (GIS interface)	X	X		X					X	X	X
WAM (GIS interface)		X			X					X	

where ADAPT is the Agricultural Drainage and Pesticide transport, AGNPS is the Agricultural Nonpoint Source, ANSWERS is the Aerial Nonpoint Source Watershed Environmental Response Simulation, CREAMS is the Chemicals, Runoff and Erosion from Agricultural Management System, DRAIN MOD is the Drainage and Water Management Systems Model, GLEAMS is the Groundwater Loading Effects of Agricultural Management Systems, SWAT is the Soil and Water Assessment Tool, WEPP is the Water Erosion Prediction Project and WAM is the Watershed Assessment Model.

Table S2.

Attenuation coefficient values “a” and “b” obtained from the WAM database.

Land use	Attenuation coefficients	
	a	b
Freshwater Marshes	0.00001	0.65
Hardwoods	0.000009	0.65
Transportation Corridors	0	0.6
Open Water	0.00002	0.8
Undeveloped Urban Land	0	0.6
Scrub and Brushland	0.0000095	0.65
Cypress	0.000009	0.65
Hardwood Conifer Mixed	0.000004	0.65
Barren Land	0	0.6
Low Density Residential	0	0.6
Commercial and Services	0	0.6
Wetland Forested Mixed	0.000009	0.65
Industrial	0	0.6
Citrus Groves	0	0.6
Open Water	0.0005	0.7
Freshwater Marshes	0.00001	0.65
Woodland Pastures	0.000004	0.65

Figure captions:

Fig. S1. Watershed Assessment Model schematic diagram.

Fig. S2. A regional map of the selected studied area in Florida (USA).

Fig. S3. Total measured and simulated flow (m^3 s^{-1}) to Lake Okeechobee from Kissimmee basin (S65 E, S71 and S72 outlets).

Fig. S4. Total measured and simulated daily load (Kg day^{-1}) to Lake Okeechobee from Kissimmee basin (S65 E, S71 and S72 outlets).

Fig. S5. Location of the two selected dairies – upper dairy 1 and lower dairy 2 and their stream connection to Lake Okeechobee.

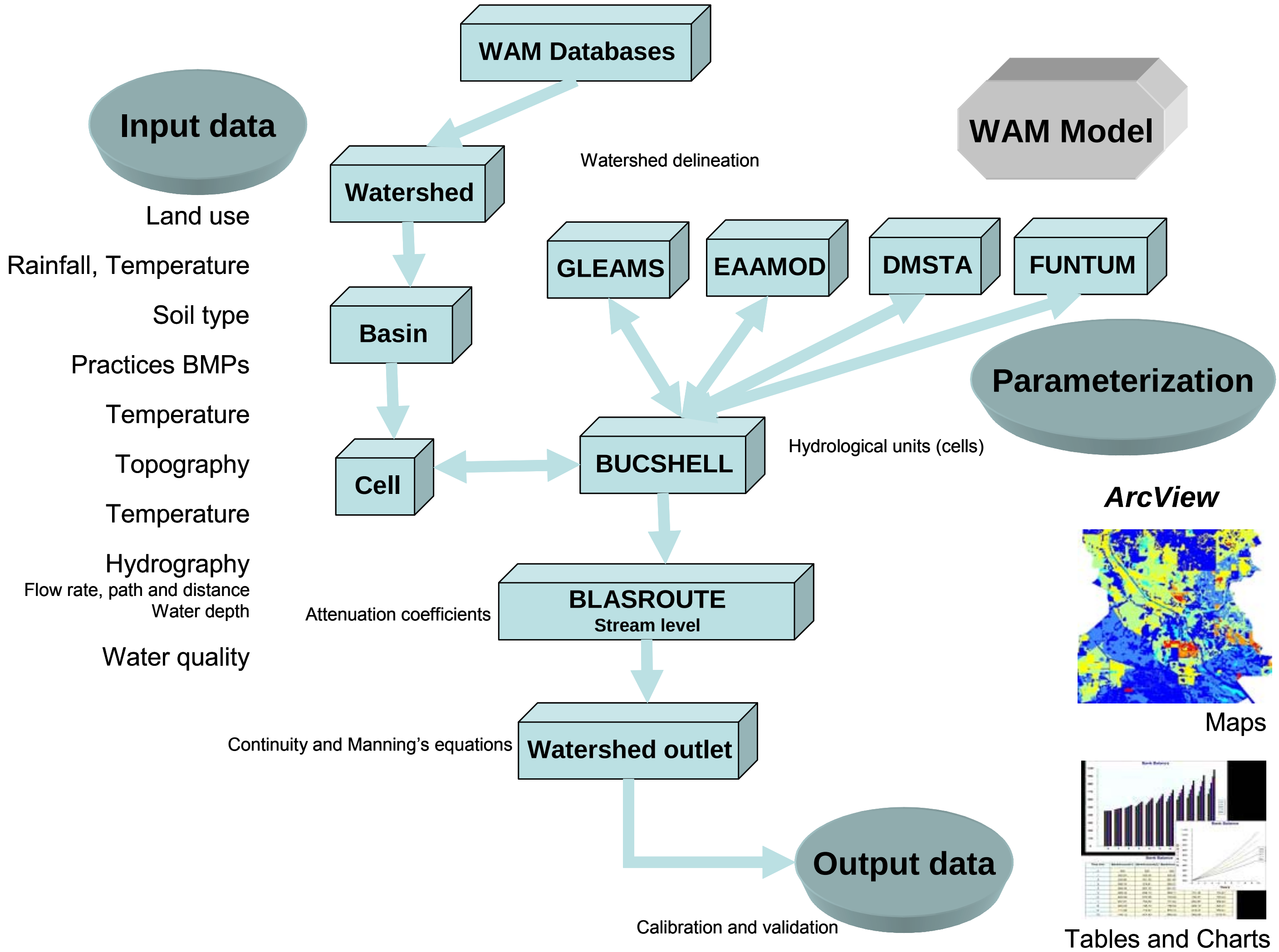

WAM Databases
Input data
WAM Model
Land use
Rainfall, Temperature
Soil type
Practices BMPs
Temperature
Topography
Temperature
Hydrography
Flow rate, path and distance
Water depth
Water quality
Watershed
Watershed delineation
Basin
GLEAMS
EAAMOD
DMSTA
FUNTUM
Parameterization
Cell
BUCSHELL
Hydrological units (cells)
ArcView
Attenuation coefficients
BLASROUTE
Stream level
Maps
Continuity and Manning's equations
Watershed outlet
Output data
Calibration and validation
Tables and Charts

Fig. S1

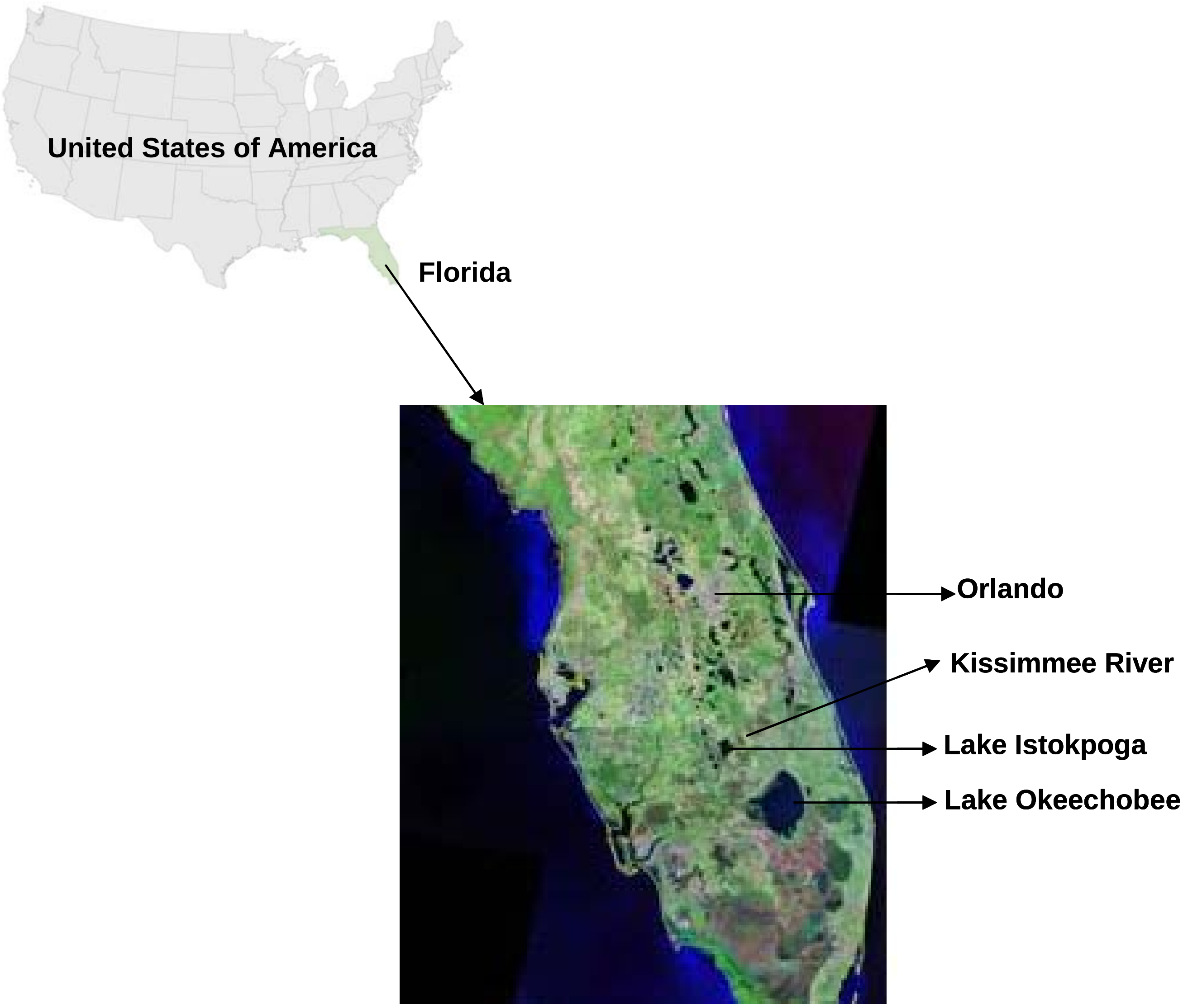

United States of America
Florida
Orlando
Kissimmee River
Lake Istokpoga
Lake Okeechobee

Fig. S2

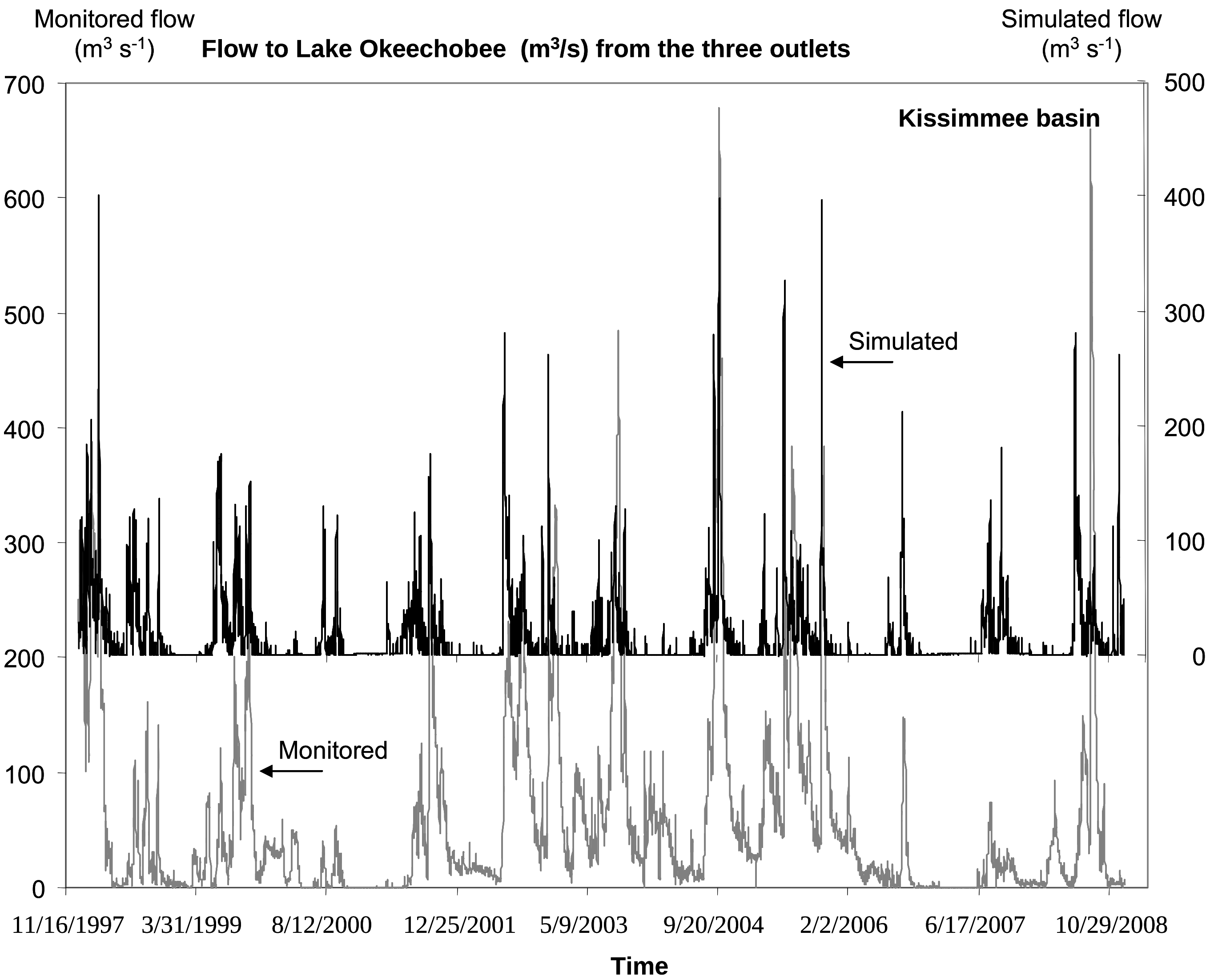
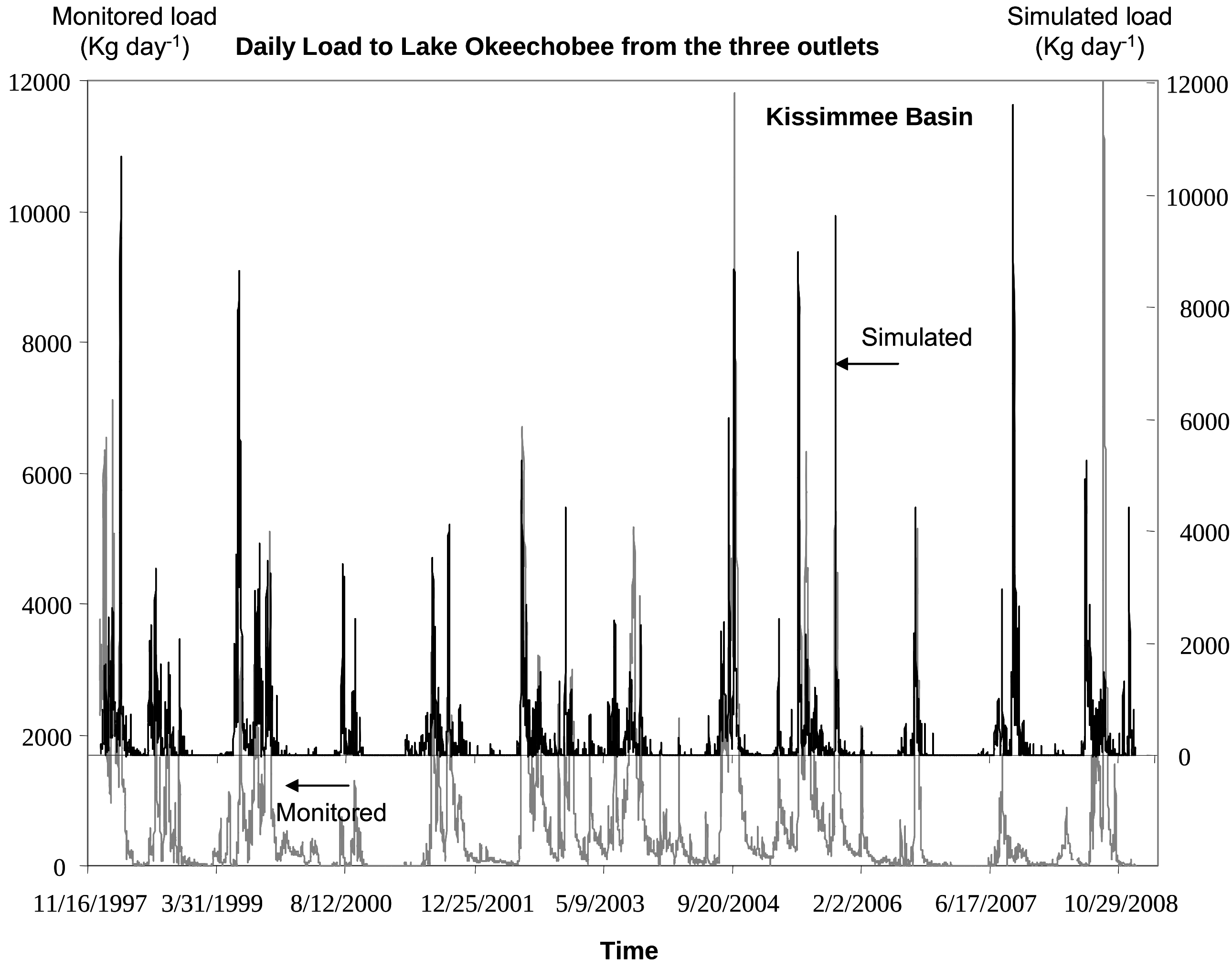

Monitored flow
(m^3 s^{-1})
Flow to Lake Okeechobee (m^3/s) from the three outlets
Simulated flow
(m^3 s^{-1})
Kissimmee basin
Simulated
Monitored
700
600
500
400
300
200
100
0
500
400
300
200
100
0
11/16/1997
3/31/1999
8/12/2000
12/25/2001
5/9/2003
9/20/2004
2/2/2006
6/17/2007
10/29/2008
Time

Fig. S3



Monitored load (Kg day^{-1})
Daily Load to Lake Okeechobee from the three outlets
Simulated load (Kg day^{-1})
Kissimmee Basin
Simulated
Monitored
12000
10000
8000
6000
4000
2000
0
11/16/1997
3/31/1999
8/12/2000
12/25/2001
5/9/2003
9/20/2004
2/2/2006
6/17/2007
10/29/2008
Time

Fig. S4

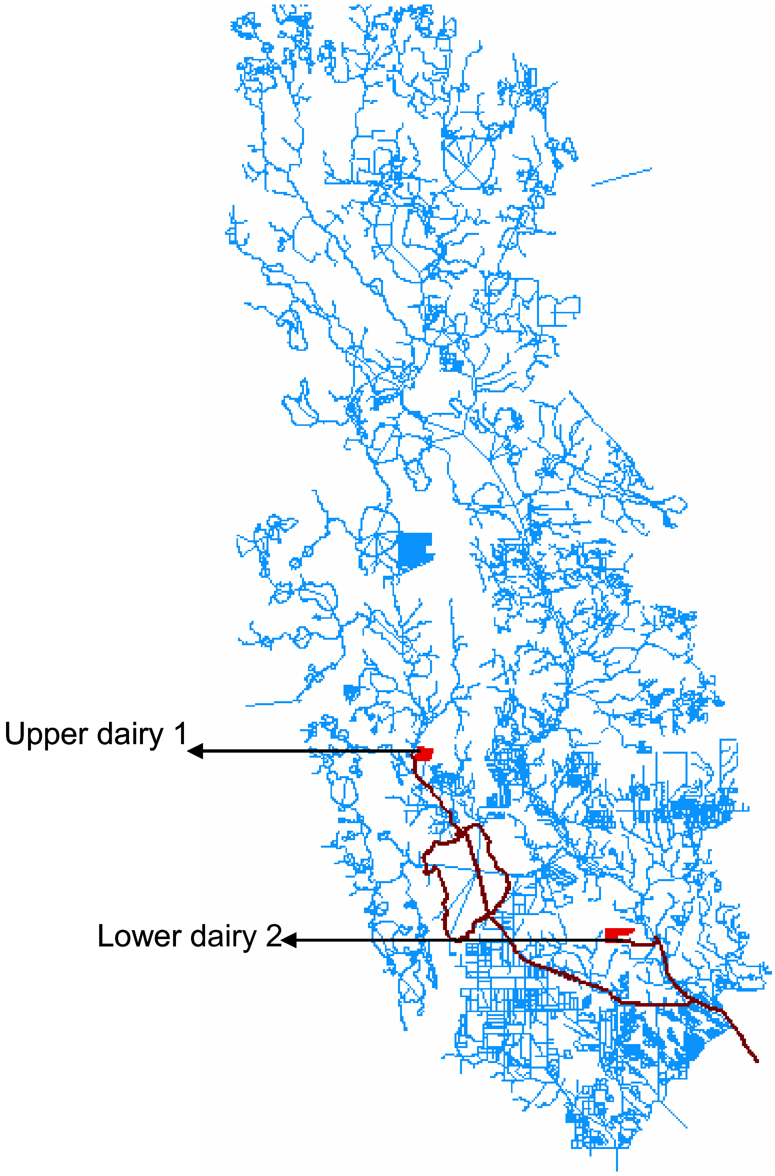


Fig. S5