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Phosphorus run-off assessment in a watershed†

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The Watershed Assessment Model was used to simulate the runoff volume, peak flows, and non-point source phosphorus loadings from the 5870 km^2 Lake Okeechobee watershed as a case study. The results were compared to on-site monitoring to verify the accuracy of the method and to estimate the observed/simulated error. In 2008, the total simulated phosphorus contribution was 9634, 6524 and 3908 kg (P) y^{-1} from sod farms, citrus farms and row crop farmlands, respectively. Although the dairies represent less than 1% of the total area of Kissimmee basin, the simulated P load from the dairies (9283 kg (P) y^{-1} in 2008) made up 5.4% of the total P load during 2008. On average, the modeled P yield rates from dairies, sod farms and row crop farmlands are 3.85, 2.01 and 0.86 kg (P) ha^{-1} y^{-1}, respectively. The maximum sediment simulated phosphorus yield rate is about 2 kg (P) ha^{-1} and the particulate simulated phosphorus contribution from urban, improved pastures and dairies to the total phosphorus load was estimated at 9%, 3.5%, and 1%, respectively. Land parcels with P oversaturated soil as well as the land parcels with high phosphorus assimilation and high total phosphorus contribution were located. The most critical sub-basin was identified for eventual targeting by enforced agricultural best management practices. Phosphorus load, including stream assimilation, incoming to Lake Okeechobee from two selected dairies was also determined.

Introduction

Water quality degradation in many watersheds caused by phosphorus and nitrogen-laden runoffs from farmed fields is known to be responsible for significant ecological changes throughout entire ecosystems. Freshwater as well as marine ecosystems are carelessly damaged by the introduction of increasing levels of nutrients leading to eutrophication. Phosphorus (P) levels in Lake Erie (Canada and USA) have been steadily increasing since the 1990s causing severe blue-green algae blooms.[1] The 730 square-mile Lake Okeechobee (LO) ecosystem (South Central Florida, USA) has become more eutrophic and less efficient at retaining nutrients due to its exposure to higher nutrient levels from agriculture and urban activities within its watershed.[2–4] The total maximum phosphorus load (TMDL) for LO has been established at 140 mtons y^{-1} (equivalent to 383.5 kg day^{-1}) by the State of Florida.[5] During 2004 and 2005, the monitored total phosphorus load brought into LO exceeded 930 and 830 mtons y^{-1}, respectively.[6] Although best management practices (BMPs) in agriculture have been implemented in LO watershed since 1970s, the phosphorus concentration in the lake increased from ~60 μg L^{-1} in 1975 to ~210 μg L^{-1} in 2008.[7] Research on agricultural management practices that aim to reduce phosphorus in runoff from agricultural land, dairy farms and residential areas has been hampered by the need to study large watersheds over relatively long time periods to account for both the temporal and spatial effects of scale. The diffuse non-point phosphorus inputs derived from many sources makes it difficult to manage its levels when compared to point source pollution.

Lake Okeechobee watersheds are characterized by surface water and groundwater flows, most of the time occurring in an integrated fashion because of the relatively low land surface elevations coupled with shallow water tables. Significant degradation of the surface water quality originates from non-point source polluting discharges, in addition to direct surface water discharges.[8] For many non-point source pollutants, measurement of these discharges is not technically or economically feasible and monitoring non-point source loadings is particularly

Environmental impact

A novel environmental modeling and analytical method was presented to assess the non-point source phosphorus loadings from a large watershed draining into a lake and the nutrient transport through the stream network. Specific locations where elevated levels of non-point source phosphorus may be expected were pointed out. This method has broad applicability for the assessment of nutrient and non-point source loadings into large shallow lakes where monitored data may be lacking. It could also be used in the control of non-point source discharges so as to facilitate the meeting of regulatory rules.

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difficult and expensive. Several spatial computer models using the geographic information system (GIS) have been developed to assess the water quality (based on point and non-point sources) and nutrient transport based on land-use conditions, soil type, topography, hydrology, and other factors.[9]

The objective of the present work is to assess the phosphorus loading from the Kissimmee basin, north of LO, using the Watershed Assessment Model (WAM), a water quality/hydrology model with a GIS interface. The predictive capabilities of the WAM model with respect to runoff volume, peak flows, non-point source phosphorus loading (soluble and particulate) to LO from the 5870 km^2 watershed was estimated from the period between 1998 and 2008. The results have been compared to those from on-site monitoring to verify the accuracy of the method. The nutrient transport over the landscape and through a stream network was simulated for the purposes of the watershed nutrient pollution investigation. Specific locations where elevated levels of phosphorus may be expected were highlighted and specific phosphorus loadings to the lake from two selected dairies were verified. Although this study was directed specifically at quantification of P loadings from agricultural fields in a specific watershed for a single lake, results have important implications for many other lakes in similar landscapes that are facing the same problems. In addition, the cost-effective method described here has broad applicability for the assessment of non-point source nutrient loadings into large shallow lakes.

Experimental section

Watershed Assessment Model (WAM) description

The WAM model,[10,11] developed and calibrated by the Soil Water Engineering Technology, Inc. (SWET: www.swet.com, Gainesville, FL), is based on a GIS continuous time model that operates on a daily time step and is schematically represented in Fig. S1.† The WAM model was used to assess the phosphorus loadings from the Kissimmee basin to LO. Details regarding the model are reported in the ESI.† Briefly, the model uses a cell grid-based system to assess the spatial impact of existing and modified land uses on water quality and quantity. The grid cell representation allows for the identification of surface and groundwater flows and phosphorus concentrations for each cell. The BUCSHELL (Basin Unique Cell) cell model integrates three well-known subroutine modules that are identified as (1) Everglades Agricultural Area Model (EAAMOD)[12] to model transport in high water table soils, (2) Groundwater Loading Effects of Agricultural Management Systems (GLEAMS) to simulate the nutrient transport in deeper water table areas,[13] and (3) Field Hydrology and Nutrient Movement (FHANTM)[14] for dairy runoffs and a category of special functions to capture the functionality of wetlands, mining, aquaculture and urban areas. These cell models are used to simulate the hydrologic contaminant transport by first modeling the grid cell combinations of land use, soil types and rain zone. The model then "routes" the surface water and groundwater flows from the cells to assess the flow and phosphorus levels throughout the watershed. This dynamic routing is performed using the BLASROUTE module for the determination of the attenuation coefficients. These attenuation factors for each water quality parameter are based on a complex combination of transport, dispersion, and assimilation factors dependent on land uses and wetland types and are based on published assimilation rates.[15,16] The boundary conditions are based on the studied area and its outlets.

Study area and model input/output parameters

A phosphorus runoff simulation was performed to predict the soluble phosphorus and sediment phosphorus-enriched loads to the adjacent streams at a grid size of 0.01 km^2. The selected area for the present study was the Kissimmee basin within the LO watershed (Fig. S2†) that encompasses the lower Kissimmee (S65A-E basins, 1737 km^2) and the upper Kissimmee (4130 km^2) basins, including different types of land uses (Fig. 1a) as well as 16 water quality, 21 flow and 30 rainfall monitoring stations (Fig. 1b). The study period covered 11 years (from January 1, 1998 to December 31, 2008). Three monitoring stations are located at the area of discharge into LO (Stations S72, S71 and S65E).

The data input into the model included the land use, soil and BMP types, topography, hydrography and rainfall zones, basin boundaries, climate data, point sources and service area coverage (as detailed in Fig. S1†). The inputs for monitored parameters such as the rainfall (from 30 stations), land use practices, phosphorus and flow monitoring data were downloaded for each of the stations from the South Florida Water Management District database that is available from the web site (http://www.sfwmd.gov/dbhydroplsql/show_dbkey_info.main_menu).

The monitoring station data were fed into the model—the flow was measured on a daily basis and the nutrient concentration bi-weekly. The observed mean annual rainfall in the Kissimmee basin averaged around 1255 mm and the temperature ranged between min −1 °C and max 30.5 °C, with an average around 22.3 °C. It is worth noting that the P loading to Lake Okeechobee mainly occurs during the wet season (June–October, characterized by heavy rainfall), thus making the non-point runoff a challenging problem from a P management perspective.

The simulated variables were a daily time series of the surface and groundwater flow, and the water quality at source cells, sub-basins and individual stream reaches. The model-simulated water quality parameters derived from the model run were the suspended solids, sediment nitrogen, sediment phosphorus, soluble nitrogen, soluble phosphorus and the biochemical oxygen demand. The model also provided several other output data such as the ranking of land uses by load source and the comparative displays of different BMP scenarios.

The simulated P loadings were derived from daily simulated flows and concentrations. The estimation of P loads at the basin outlet is determined using a routing process combining transport, dispersion, and assimilation that, in most cases, will result in an attenuation, or decrease, in P concentration. Most of this attenuation will occur in the surface water. Once the runoff has left the source cell, it is attenuated to the streams based on flow rate, characteristics of flowpath, flow distance and land use. Separate coefficients for different land uses and wetland types and background concentrations are stored within the WAM model.[10]

Model testing and accuracy

The WAM model accuracy was tested taking into account the changes in land uses throughout the years and their effect on

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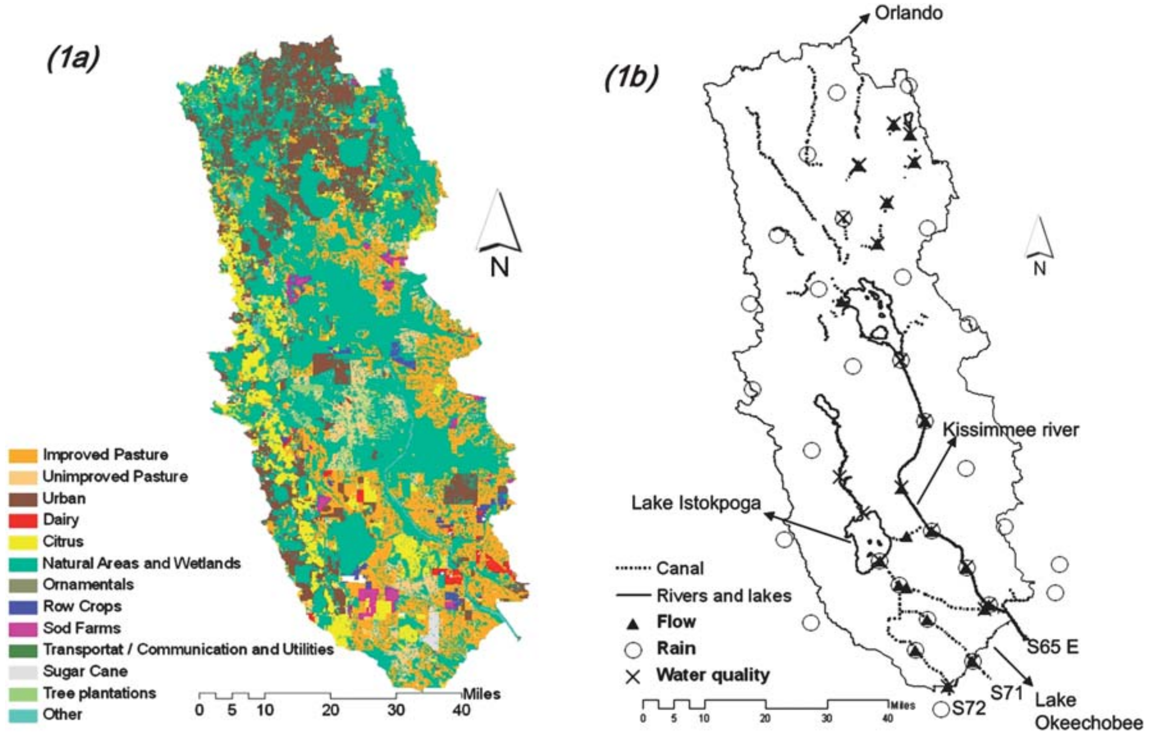

Fig. 1 Kissimmee basin map. (1a) Land use distribution and location. (1b) Monitoring stations (flow, rain and water quality) and outlets (S65 E, S-71 and S-72).

water quality, nutrient runoff and soil properties. The simulated time series and cumulative flow (total and deviation points) based on water flow (peaks, base and transitions) and stage (minimum and maximum time series) were compared to the data points from monitoring stations that were analyzed for spatial and temporal patterns. A ground-truth visit was also conducted to the land parcels showing the highest total phosphorus load for a land-use adjustment. The ground-truthing was done on crop lands, dairies, citrus farms, tree nurseries, sod farms and improved pastures.

Results and discussion

Basin land use

As phosphorus surface runoffs are directly linked to land uses in the region, it is important to accurately determine the land use distribution. The land use distribution considered in this work corresponded to the most recent one acquired by the South Florida Water Management District in 2006. Fig. 2 shows the land use distribution in the Kissimmee basin watershed (Fig. 2a) compared to the land use of the entire LO watershed (Fig. 2b). Similar land use categories are found in the Kissimmee basin and in the entire LO watershed. The dominant land use is clearly the “natural areas” that respectively represent 46% and 36% of the total area in the Kissimmee basin and the LO watershed. Improved (18%) and unimproved pastures (4%), woodland and rangeland (7%), urban (16%) and citrus (5%) represent 50% of the total land use in the Kissimmee basin (Fig. 2a). Improved (20%) and unimproved pastures (4%), woodland and rangeland (5%), urban (11%) and citrus (7%) represent 47% of the total land use in the entire LO watershed (Fig. 2b). Some land uses are worth noting such as dairies, sod farms or row crops because of their high phosphorus load to LO despite their relatively small surface.[17]

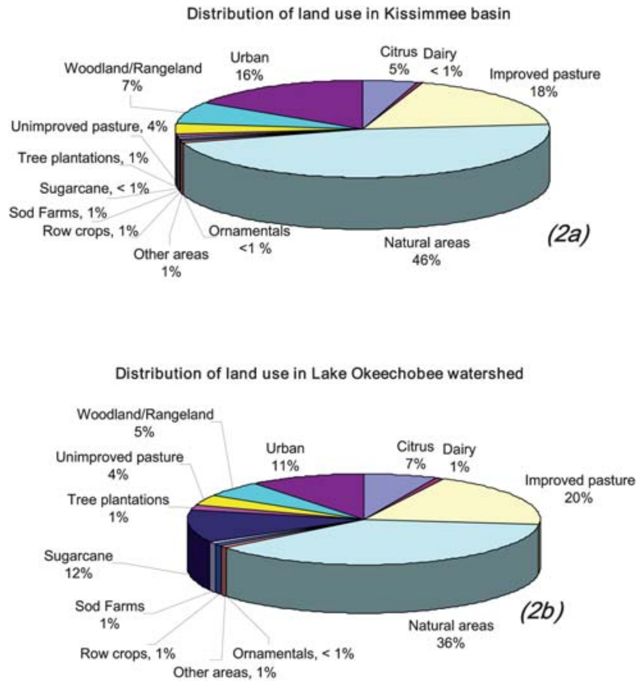

Fig. 2 Land use surface area distribution (%) in the Kissimmee basin (2a) compared to the entire Lake Okeechobee watershed (2b).

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Table 1 The total simulated phosphorus (P) load from land use classes in the Kissimmee basin during 2008. The average simulated P yield rate kg ha^{-1} y^{-1} values by the land use and by the region (upper Kissimmee and S65) are compared to other studies.

			Average P yield rate/kg ha^{-1} y^{-1}			
Land uses	Area/ha	Total P load/kg y^{-1}	Overall	Upper Kissimmee	S65	ref. 17[c]
Improved pasture	108, 589	46 118 (27%)	0.42			0.43
Unimproved pasture	20 759	5556 (3.3%)	0.27			0.29
Urban	87 883	42 468 (25%)	0.48	0.46	0.43	0.39
Dairies	2408	9283 (5.4%)	3.85	2.43	3.89	2.03
Citrus	27 982	6524 (3.8%)	0.23	0.26	0.09	0.97
Natural areas[a]	273 376	40 455(23.7%)	0.14			0.12
Ornamentals	80	365 (0.2%)	4.56			2.46
Row crops	4535	3908 (2.3%)	0.86	1.78	0.45	3.79
Sod farms	4791	9634 (5.6%)	2.01	1.90	2.44	1.51
Woodland/Rangeland	47 730	1101 (0.65%)	0.02			0.16
Transportation[b]	4694	1311 (0.77%)	0.28			—
Other areas	4352	3680 (2.2%)	0.84			0.42
Total	587 179	170 405 (100%)				

[a] Natural areas include the wetlands. [b] Transportation areas include the communication and utilities. [c] P load per 2006 land use for Lake Okeechobee watershed area excluding upper Kissimmee basin—2006 values transformed to fit the last five year average load to Lake Okeechobee.

Phosphorus load and yield rate

All the land uses described above are generating phosphorus and contributing to the total phosphorus load to LO.[18] Table 1 summarizes the average simulated P load from land-use classes in 2008, calculated from the daily simulated flows and concentrations. The total simulated P load (170 mtons y^{-1}) from the Kissimmee basin exceeded the TMDL (total maximum daily load) for LO by 22%. In 2008, the highest simulated contribution was 46 118 kg (P) y^{-1} and 42 468 kg (P) y^{-1} from improved pastures and urban areas, respectively. Jointly, they accounted for 52% of the total P load coming from the studied basin. In 2008, the total simulated incoming P load was 9634 kg (P) y^{-1} from sod farms and 3908 kg (P) y^{-1} from row crops. Although some BMPs target agricultural areas, applications of high-phosphorus chemical and organic fertilizers to agricultural soils most often exceed the crop requirements and they are responsible for heavily phosphorus-loaded runoff.[19] Dairies also generate significant phosphorus quantities through cow manure production which is rich in P. Although dairies represent less than 1% of the total surface of the Kissimmee basin, the simulated P load from the dairies (9283 kg (P) y^{-1} in 2008) represented 5.4% of the total LO phosphorus load during 2008.

Simulated phosphorus load contributions to the adjacent streams are presented in Fig. 3a. Phosphorus loads to adjacent streams, driven by flows and concentrations, was not homogeneous in the basin. Natural areas were among the lowest P contributors to the streams with only <0.5 kg (P) ha^{-1} y^{-1} yield rate and <0.05 mg L^{-1} concentrations. Some lakes (Fig. 3a) actually represented a negative load because of their assimilation

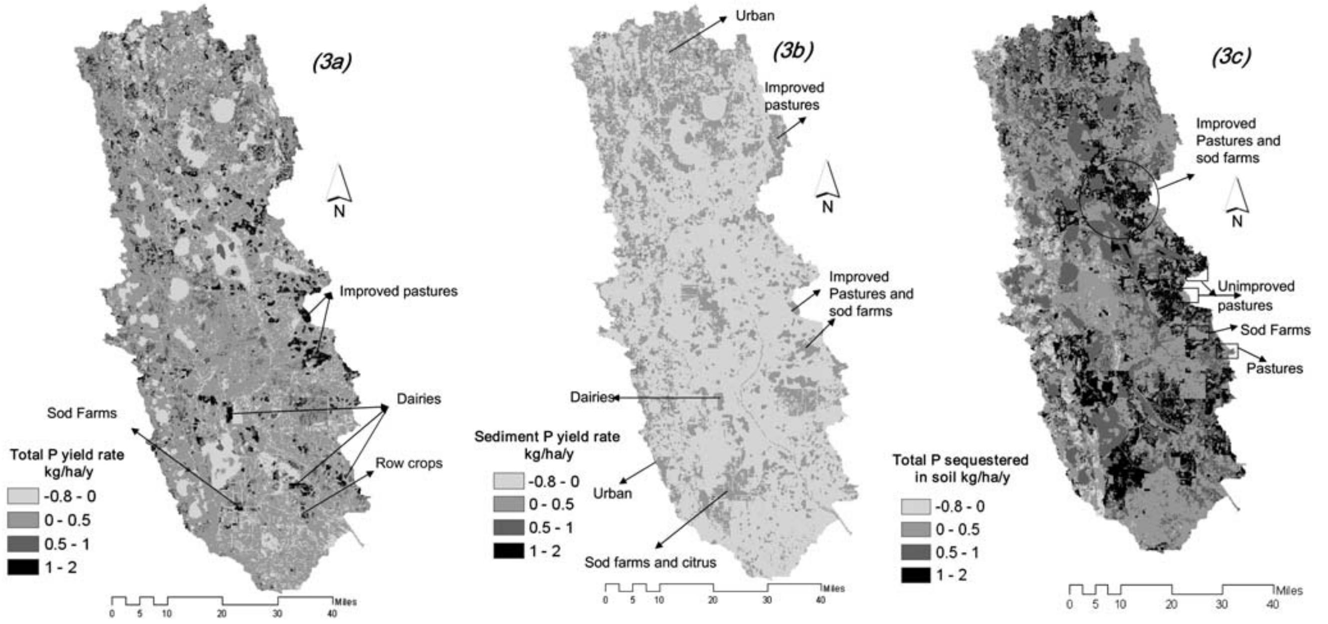

Fig. 3 Maps of the total simulated phosphorus yield rate (3a); simulated sediment phosphorus yield rate (3b); and total simulated phosphorus amount sequestered in soil (3c) from the different lands to the nearby streams.

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of phosphorus (biota) and retention in sediments. The land uses contributing the highest total P load to the nearby streams were the dairies, row crops, sod farms and improved pastures.

Table 1 lists the average simulated total phosphorus yield rates by region and by land use as an output of the WAM model for the Kissimmee basin in 2008. These averages were calculated from the total simulated P load by land use and by property. Generally, the simulated P load is proportional to the individual farm area (having the same stocking density). The larger the farmed or urban area, the higher the P loads originating from it as run-off. The highest phosphorus load per hectare originated from the dairies, sod farms and row crops. This confirms the values represented in Fig. 3a. As an average, the simulated P yield rates of dairies, sod farms and row crop farmlands were 3.85 kg (P) ha^{-1} y^{-1}, 2.01 kg (P) ha^{-1} y^{-1} and 0.86 kg (P) ha^{-1} y^{-1}, respectively. The urban areas in the basin include high, medium and low densities and their respective contribution of P to the streams depended on the area density (Table 1).

The values for the entire LO watershed (except upper Kissimmee) published by Bottcher[17] (Table 1) and those in the present paper fall in the same range for many land uses. It should not be forgotten that when studying P load from farms and dairies, the loads differ depending on the basin and the region. Indeed, the surface runoff and sediment P load (or export) coefficients are highly dependent on many variables such as rain, topography, basin, tributary location, groundwater elevation and on whether a high percentage of the basin farmers are applying some BMPs to control the runoff. These quantities could be averaged on a basin or on a sub-basin level but averaging them at a watershed level would lead to a higher uncertainty because of the spatial and temporal variability leading to larger uncertainties in the load estimation. Published data[20,21] demonstrated the spatial variability of P in soil across agricultural landscapes and within agricultural fields, leading to a spatial heterogeneity affecting the phosphorus loss to runoff. These heterogeneities are highlighted in Table 1 which also presents the simulated phosphorus load determined for S65 and for the upper Kissimmee basins. These values could be compared to the overall one for the entire Kissimmee basin. Dairies and sod farms are perfect examples. Dairies, more concentrated in the S65 basin, showed a higher modeled P yield rate (3.89 kg (P) ha^{-1} y^{-1}) when compared to the dairies in the upper Kissimmee basin (2.43 kg (P) ha^{-1} y^{-1}). The same observation applies to the sod farms that had an average modeled yield rate of 2.44 kg (P) ha^{-1} y^{-1} in S65 and only 1.90 kg (P) ha^{-1} y^{-1} in the upper Kissimmee basin. This spatial heterogeneity generally tends to increase the P loading estimation uncertainty when averaging the values on a watershed level.

Phosphorus sequestration in soil and sediment transport

The phosphorus load into LO is composed of soluble phosphorus and phosphorus in particulate forms transported with the runoff that ends up in the receiving lake[22] as demonstrated in Fig. 3b. Haygarth and Jarvis[23] elaborated on the three processes for P transfer from agricultural fields namely dissolution, incidental and physical transfers. The physical transfer is the opposite of dissolution, based on the mechanisms of detachment and soil erosion involving the physical displacement and entrainment of colloids and submicron-sized material. These particles contain phosphorus molecules, bound with soil minerals and other organic compounds, which could be remobilized when biological and/or physico-chemical conditions change. The proportion of particulate P in the total phosphorus in surface runoff varies with soil types and hydrological conditions.[24] Fig. 3b shows the modeling results concerning phosphorus yield rate to the streams originating from sediment transport. The highest modeled sediment phosphorus yield rate is about 1 kg (P) ha^{-1} y^{-1} transported *via* rivers, streams and water bodies as seen from Fig. 3b.

The model estimated the particulate phosphorus contribution to the total phosphorus load from urban, improved pasture areas and dairies, respectively at 9%, 3.5%, and 1%. The urban areas (South of Orlando) in the north LO watershed showed the highest phosphorus contribution through particulate transport (Fig. 3b). Some dairies, sod farms and improved pastures that generate a high phosphorus load in a dissolved form also contribute phosphorus through particulate transport (Fig. 3b), indicating that the soil within these land uses is phosphorus saturated (heavy leaching) with some erosion occurring. He *et al.*[25] studied the transport of phosphorus through surface runoff from agriculture lands in South Florida. Sandy soils, the dominant soil types north of LO, usually contain low levels of clay and organic matter for binding to phosphorus. There is, therefore, a good reason for concern about P losses from sandy soils in field-drains as the potential of P leaching from them is usually high.[26] The total particulate phosphorus in the runoff water reported by He *et al.*[25] varied widely, ranging from 0.01 to 19.94 mg L^{-1}, with a median of 0.23 mg L^{-1}. These numbers agree with the modeled particulate phosphorus contribution observed in the present work (Fig. 3b), whereby the highest concentration of phosphorus in the sediment was around 0.5 mg L^{-1}.

Based on Graetz and Nair,[27] the maximum P storage in surface soil of the LO watershed was 2 and 0.42 kg (P) ha^{-1} y^{-1} for the areas with pastures and non-impacted areas, respectively. The present investigation determined (by modeling) the maximum of P sequestered in soil around 2 kg ha^{-1} y^{-1} (Fig. 3c) agreeing well with the values stated above. Comparison of Fig. 3a and 3c indicates land parcels where the soil was oversaturated and leaching phosphorus (dark in Fig. 3a) with low P assimilation (light in Fig. 3c). Some of these land parcels are identified by a square in Fig. 3c. Only a few locations (improved pastures and sod farms) contributed high phosphorus to the water bodies (dark in Fig. 3a) and featured high phosphorus soil assimilation (dark in Fig. 3c). Some of these land parcels are circled in Fig. 3c.

Water balance and the annual phosphorus load to Lake Okeechobee—modeling *vs.* monitoring

To verify the accuracy of the WAM model,[28] the predicted P concentration levels from the three outlets were compared to the annual measured values (Fig. 4). Moreover, the total daily simulated flow and P load were compared to the daily monitored values as shown in Fig. S3 and S4, respectively.† Visual comparisons of measured and simulated values showed very good matches, especially during rainfall events (Fig. S3 and S4†). The yearly monitored and simulated phosphorus concentration

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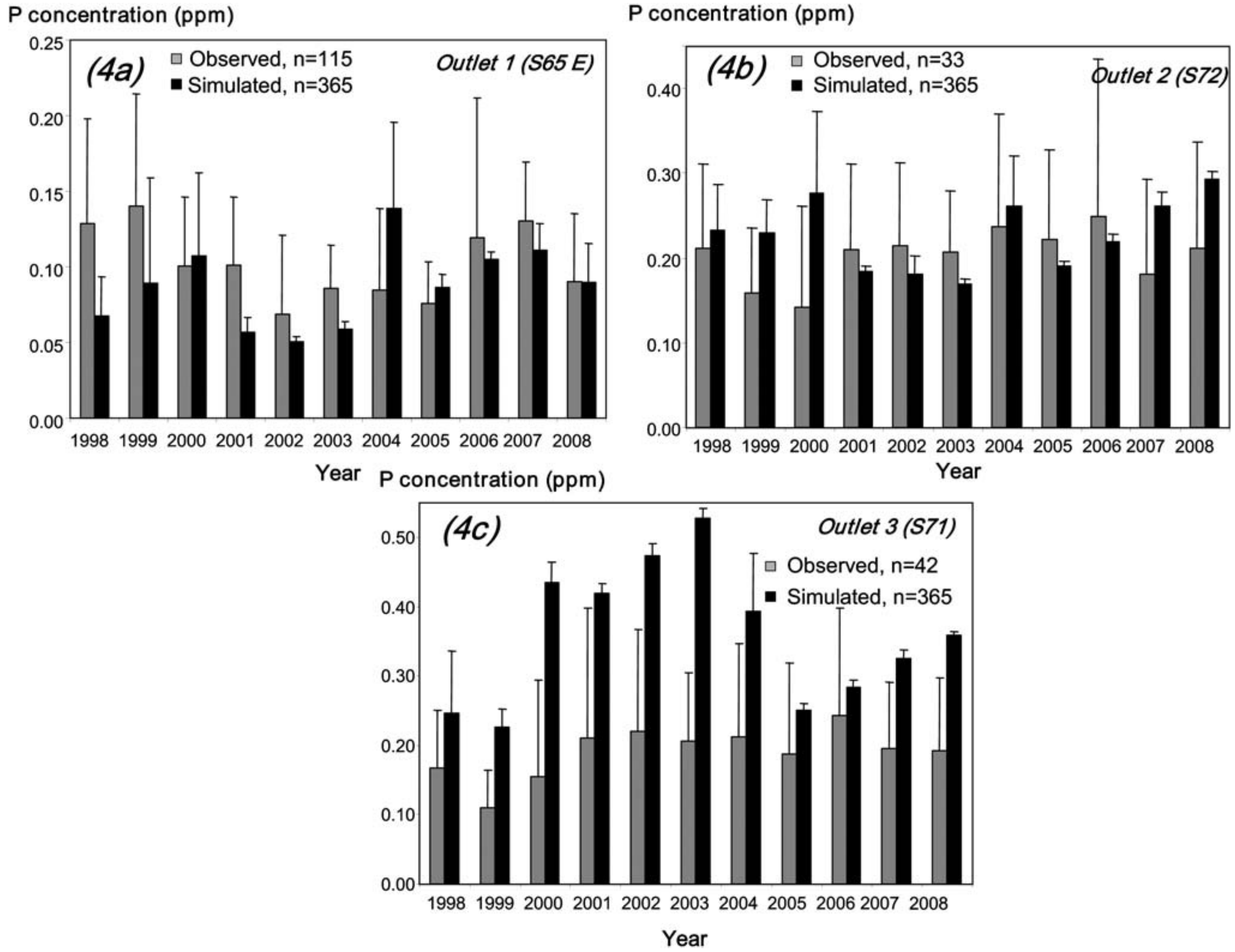

Fig. 4 Yearly simulated/observed averaged phosphorus concentration at the three outlets S65 E (4a), S-72 (4b) and S-71 (4c). The number (n) of the observed or simulated sampling points is indicated on each figure.

standard deviations differed depending on the outlet. The estimated observed/simulated error was around 13.7% for S65E, 10% for S72 and increased to 31% for S71 for the 1998–2008 period. It is worth noticing that while the simulation gives the phosphorus concentration daily, the actual measured values were based on bi-weekly sampling by monitoring stations. As an average, there were only 115, 33 and 42 phosphorus monitoring points per year for S65E, S72 and S71 outlets, respectively (Fig. 1b). The values for monitored daily concentrations were calculated by interpolating between the grab samples and the loads were then calculated from daily measured flows and so calculated interpolated concentrations. This technique would give reasonable estimates of phosphorus loads but with errors ranging between 25 and 50% of the actual loads.[29] The average measured (monitored) load to LO from S72 was 13.8 mtons (P) y^{-1} compared to 11.5 mtons (P) y^{-1} (simulated) for the 11-year period. While S65 outlet was loading 139.5 mtons (P) y^{-1} (monitored) to the lake compared to the simulated 92 mtons (P) y^{-1}, S71 outlet was loading 47.75 mtons (P) y^{-1} (monitored) to the lake compared to the simulated 30.5 mtons (P) y^{-1}.

Fig. 4 indicates that P concentration in the runoff from S65 slightly decreased during the last two years, from S71 it remained constant, and from S72 it slightly increased. These trends are to be followed during the next few years to assess the BMP application effectiveness in decreasing the P load to LO.

Identification and prioritization of critical sub-basins

Based on the P-loading and soil P-sequestration maps, the most critical sub-basin identified is presented in Fig. 5 and it encompasses a variety of land uses near Kissimmee River and Lake Istokpoga. This sub-basin was visited for ground-truthing and indeed some sod farms, row crops and dairies were identified that should be prioritized for future BMP applications. The model indicated that some of the lands in this basin, mainly dairy and row crop farms (Fig. 5b), contributed as much as 2 kg (P) ha^{-1} day^{-1} to the nearby streams. Due to their locations near the Kissimmee River, the run-off P from them will not be assimilated and will reach directly the stream and the lake. The ground-truth visit corroborated the results of the modeling whereby the non-commitment to the regulations was visually noticed. These properties should be targeted with enforced BMPs to decrease their P contribution to the streams and the lake.

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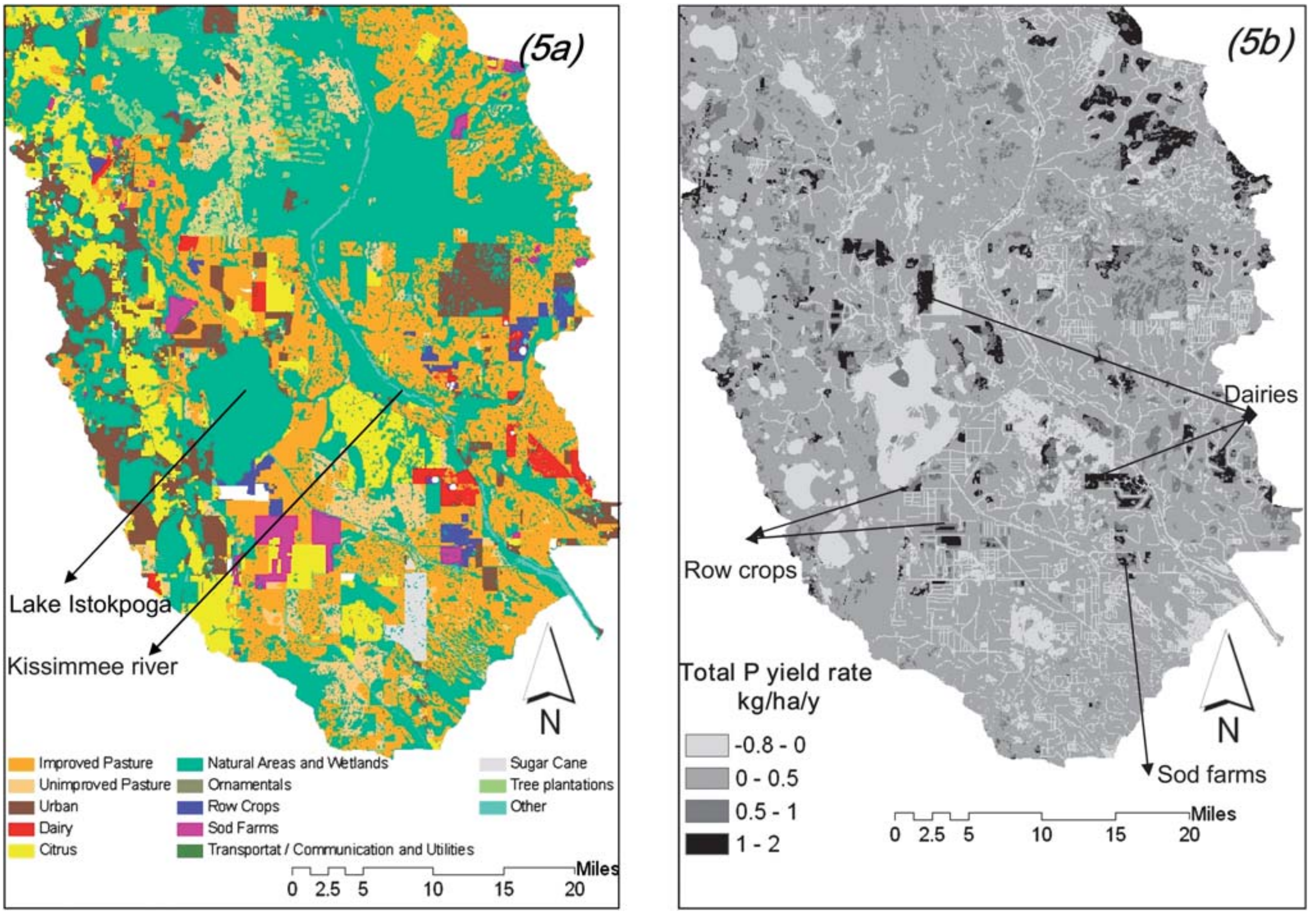

Fig. 5 Maps of the priority sub-basin. Land use (5a) and simulated phosphorus yield rate (5b) from the different lands to the nearby streams.

Phosphorus assimilation and load to lake okeechobee from two selected dairies

The phosphorus assimilation capacity of a specific land use depends on complex physical, chemical and biological parameters. The modeled loads to LO from two selected properties (Fig. S5† dairy 1, upper watershed, latitude: 27°33.09′ N; longitude: 81°21.01′ W and dairy 2, lower watershed, latitude: 27°18.8′ N; longitude: 81°4.09′ W) were determined knowing the routing process and estimating the attenuation of phosphorus concentration. This method was already used by Zhang *et al.*[30] to calculate the assimilation capacity of several sites using a simple function relating the phosphorus concentration at the outlet to the total length of transport and one single assimilation factor. A first-order decay formula (eqn (1)) was used in the present study to estimate the attenuation whereby once the runoff had left the source cell, it was attenuated to the streams based on flow rate, characteristics of flowpath, and flow distance:

$$\mathrm{d}C = (C - C_\mathrm{b}) \times e^{(-a \times q - b \times d)} \tag{1}$$

where dC is the change in concentration (mg L^{-1}), C and C_b are the current and background concentrations, respectively (mg L^{-1}), a is the attenuation multiplier, b is the attenuation exponent, q is the flow rate (m^3 s^{-1}) and $_\mathrm{d}$ is the flow distance (m).

The attenuation coefficients a and b as well as C_b were used as determined in the WAM model. Values of a and b (Table S2†), depend on the stream conveyance feature such as wetlands, lakes, or others. The dairies 1 and 2 have a surface area of 3–3.5 km^2 each and contributed 487 kg (P) y^{-1} (0.33 mg L^{-1} as soluble P) and 1612 kg (P) y^{-1} (1.4 mg L^{-1} as soluble P), respectively, to the nearby stream-modeling values. The phosphorus in the runoffs from dairy 1 and dairy 2 reaches LO after getting assimilated along 61 km and 16.3 km of different types of streams (freshwater marshes, shrub and brush land,…), respectively. Based on the present calculation, the modeled soluble P concentration originating from dairy 1 and reaching LO was 0.06 mg L^{-1}. The modeled soluble P concentration originating from dairy 2 and reaching LO was 0.21 mg L^{-1}. The modeling results indicated that dairy 1, discharging 487 kg (P) y^{-1} (1.6 kg (P) ha^{-1} y^{-1}) into the nearby stream, contributed 91 kg (P) y^{-1} (0.3 kg ha^{-1} y^{-1}) into LO whereby dairy 2, discharging 1612 kg (P) y^{-1} (4.5 kg (P) ha^{-1} y^{-1}) into the nearby stream, contributed 250 kg (P) y^{-1} (0.7 kg (P) ha^{-1} y^{-1}) into LO. The remaining phosphorus was assimilated in the farmland system and the farther away the dairy was, the more phosphorus was assimilated.

Conclusion

For many non-point source pollutants, measurements of nutrient discharges are not technically or economically feasible and monitoring non-point source loadings is particularly difficult and expensive. The method described in this paper was successful in

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quantifying the phosphorus loads from agricultural run-off. Specific locations where elevated levels of non-point-source phosphorus may be expected were highlighted and the phosphorus loadings from two selected dairies to the lake were estimated. This estimation of how much each land type contributes to the total phosphorus load received by LO could be used as a basis for regulating the non-point source discharges in such a way as to ensure that the total maximum daily load (TMDL) of the lake would be met. Although this study was directed specifically toward quantifying P loadings from agricultural fields in a specific watershed for a single lake, it obviously has a broad applicability for the assessment of nutrient and non-point source loadings into large shallow lakes where monitored data may be lacking.

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References

1 D. J. Schwab, D. Beletsky, J. DePinto and D. M. Dolan, *J. Great Lakes Res.*, 2009, **35**, 50–60.
2 P. L. Brezonik and D. R. Engstrom, *J. Paleolimnol.*, 1998, **20**, 31–46.
3 G. W. Redfield, *Ecol. Appl.*, 2000, **10**, 990–1005.
4 C. J. Richardson, R. S. King, S. S. Qian, P. Vaithiyanathan, R. G. Qualls and C. A. Stow, *Environ. Sci. Technol.*, 2007, **41**, 8084–8091.
5 FEDP – Florida Department of Environmental Protection, *Total Maximum Daily Load for Total Phosphorus Lake Okeechobee*, Florida Department of Environmental Protection, Tallahassee, FL., 2001.
6 SFWMD – South Florida Water Management District, *Lake Okeechobee Watershed Construction Project – Phase II Technical Plan*, South Florida Water Management District, Florida Department of Environmental Protection and Florida Department of Agriculture and Consumer Services, West Palm Beach, FL., 2008.
7 J. Zhang, R. T. James and P. McCormick, in *Volume I: The South Florida Environment*, South Florida Water Management District, West Palm Beach, FL., 2009, p. 48/84.
8 A. S. J. Donigian, B. R. Bicknell and L. C. Linker, *Proceedings of the International Symposium on Water Quality Modeling*, American Society of Agricultural Engineers, Orlando, FL., 1995.
9 G. Morse, A. Eatherall and A. Jenkins, *Water Environ. J.*, 1994, **8**, 277–286.
10 A. B. Bottcher, J. G. Hiscock and B. M. Jacobson, *Proceedings of the Watershed 2002*, Pre-Conference Modeling Workshop, Fort Lauderdale, FL., 2002.
11 B. M. Jacobson, A. B. Bottcher, N. B. Pickering and J. G. Hiscock, *ASAE Paper, Am. Soc. of Agr. Eng*, 1998, 98–2237.
12 A. B. Bottcher, N. B. Pickering and A. B. Cooper, *Drainage in the 21st Century: Food Production and the Environment*, 1998, 599–606.
13 R. A. Leonard, W. G. Knisel and D. A. Still, *Trans. ASAE*, 1987, **30**, 1403–1418.
14 K. L. Campbell, J. C. Capece and T. K. Tremwel, *Ecol. Eng.*, 1995, **5**, 301–330.
15 M. T. Brown, *Water quality and wildlife values for wetlands*, Soil and Water Engineering Technology, Inc., Gainesville, FL, 1995.
16 A. B. Cooper and A. B. Bottcher, *J. Water Resour. Plann. Manage.*, 1993, **119**, 306–323.
17 D. Bottcher, *Task 3 Report: Legacy P Abatement Plan, Technical Assistance in Review and Analysis of Existing Data for Evaluation of Legacy Phosphorus in the Lake Okeechobee Watershed*, Soil and Water Engineering Technology, Inc., South Florida Water Management District and JGH Engineering, West Palm Beach, FL., 2008.
18 J. L. Cisar, G. H. Snyder and G. S. Swanson, *Agron. J.*, 1992, **84**, 475–479.
19 A. Sharpley, T. Daniel, T. Sims, J. Lemunyon, R. Stevens and R. Parry, *Agricultural phosphorus and eutrophication*, US Department of Agriculture, Agricultural Research Service-149, USA, 1999.
20 S. Shrestha, F. Kazama and L. T. H. Newham, *Environ. Modell. Software*, 2008, **23**, 182–194.
21 C. J. Penn, R. B. Bryant, B. Needelman and P. Kleinman, *Soil Sci.*, 2007, **172**, 797–810.
22 A. J. Mehta and K. Hwang, *Fine sediment erodibility in Lake Okeechobee, Florida*, University of Florida Coastal and Oceanographic Engineering Department, Gainesville, FL, 1989, p. 161.
23 P. M. Haygarth and S. C. Jarvis, *Adv. Agron.*, 1999, **66**, 195–249.
24 R. Uusitalo, E. Turtola, T. Kauppila and T. Lilja, *J. Environ. Qual.*, 2001, **30**, 589–595.
25 Z. L. He, M. K. Zhang, P. J. Stoffella, X. E. Yang and D. J. Banks, *Soil Sci. Soc. Am. J.*, 2006, **70**, 1807–1816.
26 M. K. Zhang, Z. L. He, D. V. Calvert, P. J. Stoffella, Y. C. Li and E. M. Lamb, *J. Environ. Sci. Health, Part A: Toxic/Hazard. Subst. Environ. Eng.*, 2002, **37**, 793–809.
27 D. A. Graetz and V. D. Nair, *Ecol. Eng.*, 1995, **5**, 163–181.
28 T. M. Sohrabi, A. Shirmohammadi, T. W. Chu, H. Montas and A. P. Nejadhashemi, *Environ. Forensics*, 2003, **4**, 229–238.
29 B. M. Jacobson, *Hydrologic/water quality characterization of the watershed*, Soil and Water Engineering Technology, Inc., Gainseville, FL., 2002, p. 41.
30 J. Zhang, S. A. F. Ray and A. Steinman, *J. Am. Water Resour. Assoc.*, 2002, **38**, 1613–1624.

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