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Phosphorus budget—land use relationships for the northern Lake Okeechobee watershed, Florida

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Abstract

Eutrophication of Lake Okeechobee, Florida, has been accelerated by excessive phosphorus (P) loading to the lake from land use practices involving phosphorus-containing materials. Average annual P budgets were estimated for each of the 25 tributary basins in the northern Lake Okeechobee watershed for current land uses and land use practices. Phosphorus import, export, and net import coefficients in terms of kg P ha^{-1} per year were determined for each land use being practiced in the watershed based on landowner surveys and literature data. The net P coefficient for each land use was applied to the appropriate land use area with a Geographic Information System (GIS) to obtain a basin-wide P budget. Phosphorus runoff load was estimated based on measured data and literature values of P concentrations and runoff estimates for each land use. The P loads to the lake were measured at discharge structures from each basin. On-site P storage and wetland assimilation values were estimated using a mass balance approach for each basin. For the northern Lake Okeechobee watershed, total net P imports from land use activities were estimated at 1717 metric tonnes (t) per year, which is about 28% lower than the previous P budget conducted in 1991. Other P import, export, and storage components were obtained, and results were compared with the previous budget data. Linear regression was performed to determine which basin/landscape characteristics influence lake loading. Runoff phosphorus, the amount of developed land, and net P imports had the strongest correlation when related to lake loading. Using multiple linear regression, the annual changes in P retention correlated well with net P import intensity and stream/canal density, and the net P import and length of streams/canals correlated well with lake loading.

Keywords: Phosphorus budget; Import and export; Nutrient management; Land use; Water quality; Landscape characteristics; GIS; Lake Okeechobee watershed

1. Introduction

Lake Okeechobee is centrally located in the southern portion of the State of Florida. It is fed by the Kissimmee River and other tributaries from the north and discharges to the south through various canals that connect to the Everglades. Over the years, impacts from farming in the watershed have increased the total P content within the lake. Recent changes in technology and agricultural practices have helped to reduce the amount of P entering the lake somewhat, but the problem still exists.

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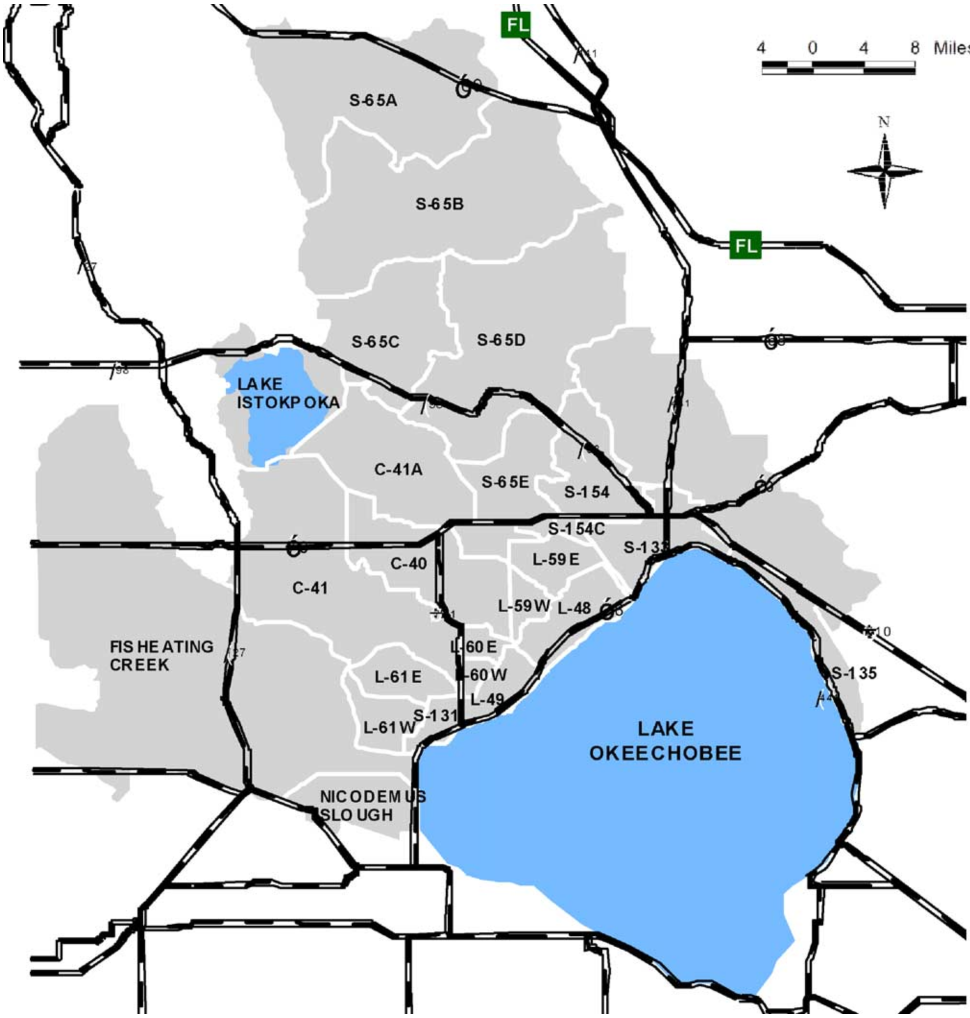

Fig. 1. Phosphorus budget study basins in the northern Lake Okeechobee watershed.

The northern Lake Okeechobee watershed comprises roughly 5160 km^2 and contains 25 drainage basins that contribute nutrient-enriched runoff to Lake Okeechobee (Fig. 1). Phosphorus (P) is of particular concern in this system because it has been identified as the key element that contributes to the eutrophication of the lake (Davis and Marshall, 1975; Federico et al., 1981). Early research indicated that P loads originated from agricultural non-point sources, mainly beef cattle ranches and dairy farms (MicGill et al., 1976). A previous study, based on data from 1985 to 1989 (Fonyo et al., 1991; Boggess et al., 1995), estimated that the total net P import into the northern Lake Okeechobee watershed was about 2380 metric tonnes (t) per year. The net import of P is the sum of the P imports minus P exported in agricultural products. The P import was primarily in the form of pasture fertilizer and dairy feed. The total P export was primarily in the form of milk, cows, and crops. This imbalance between import versus export contributes to the net build-up of P in the northern Lake Okeechobee watershed. This has resulted in the concern that unless P imports are controlled, attempts to restore Lake Okeechobee will be delayed or fail altogether.

The previous study by Fonyo et al. (1991) was based on P and materials budget information collected from 1985 to 1989, which is prior to the implementation of many Best Management Practice (BMP) programs. Since then, land uses and associated management practices have changed dramatically. The overall objective of this study was to update the P budget information using data collected from the recent 5-year period of 1997–2001 to account for many land management changes that have occurred in recent years. This new P budget also examined P sources that were not explored in the previous P budget analysis, such as sludge application, poultry manure, and on-site septic systems. This study is important to understand how recent BMPs and strategies implemented have affected lake loading. Also, determining how land use practices and basin characteristics have recently affected lake P loading will help assess ways of achieving goals and refining related strategies of the Surface Water Improvement and Management (SWIM) Plan and Lake Okeechobee Protection Program water quality objectives (SFWMD, 1997, 2002).

To accomplish the overall objective, four specific tasks were conducted. First, the average annual P import, P export, and net P export (also called P import, P export, and net P export coefficients) for each land use were developed in terms of $\mathrm{kg\,ha^{-1}}$ per year. Second, these P coefficients for each land use was applied to the corresponding land use area with a Geographic Information System (GIS) to obtain a basin-wide P budget. Third, the basin scale results were contrasted with the previous ones to determine the change of net P imports to the watershed over the past decade. Finally, the strength of relationships between lake loading data and landscape characteristics (land use type, soil type, stream length and density, etc.) for each basin were analyzed using linear and multi-linear regression analyses, and landscape characteristics that affected lake P loading were identified.

2. Materials and methods

2.1. Basin characteristics

The spatial extent of this study and the previous study (Fonyo et al., 1991) is the same (Fig. 1). However, the previous study merged several smaller drainage basins into large ones whereas the current study used the 25 existing drainage basins. In the previous study, basins L-59W and L-60E were previously part of C-40, basins L-60W and L-61E were previously part of C-41, basin L-61W was previously part of Nicodemus Slough, and S-154C was previously part of S-154.

Basin and landscape characteristics were determined from the previous study as presented in a subsequent article (Boggess et al., 1995) and other sources including updated survey information, and coordination with landowners. Satellite imagery was also utilized along with limited ground verification.

The 100,000:1 scale GIS coverage for the 1995 land use was obtained from South Florida Water Management District (SFWMD). Land use changes from 1996 to 2001 were determined based on satellite imagery and ground verification, and the 1995 land use coverage was updated. Comparing with the previous study, there has been an increase in the areal extent of improved pasture, row crop, and sugarcane and a decrease in dairy farms. While the areal extent of some land uses truly did change, some changes may be the result of previous mapping errors or changes in assigned land use categories. Major land uses in terms of area included improved pasture (36%), wetlands/water bodies (21%), rangeland/unimproved pasture (16%), forested uplands (10%), citrus (5%), urban (3%), sugarcane field (2%), dairy farm (2%), sod farm (0.9%), ornamentals (0.6%), and row crops (0.6%).

The GIS coverage for soils was obtained from the SFWMD. The primary soil associations in the northern Lake Okeechobee watershed are Myakka–Basinger–Immokalee–Smyrna (48%), Placid–Pamico–Felda–Hicoria (12%), Pompono–Basinger–Charlotte–Placid (12%), and Manatee–Delray–Kaliga–Tequesta (7%). Most of these soils have a poor P retention capacity (Graetz and Nair, 1995).

For the purpose of this update, canal and stream lengths were assumed not to have changed since the previous study. The canal and stream lengths were taken from the previous study. Basins C-40, C-41, S-154, and Nicodemus Slough were included as parts of larger basins in the previous study. The lengths of streams and canals for each of these basins, therefore, were estimated according to the area-prorated amount of the larger, previous basin. Although the previous study indicated that physical basin characteristics had no significant influences on P lake loading, various tributary basin characteristics were reviewed. Area, perimeter, shape, distance to Lake Okeechobee, and other characteristics were reviewed for possible correlation to P loading to the lake.

2.2. Phosphorus loads to Lake Okeechobee

Updated P loads to the lake and flow-weighted P concentrations by basin for a 5-year period of 1997–2001 were obtained from SFWMD. The previous study (Fonyo et al., 1991) utilized average annual P load, areal P load, and flow-weighted P concentrations from a 5-year period of 1985–1989. However, based on data availability, loading averages from 1995 to 2000 were used for basins C-40, C-41, L-48, L-49, S-154C, and S-65A–E.

The loads reported from Lake Istokpoga were adjusted to account for the fact that there are additional areas draining through the Lake that are not in the study area. Based on United State Geological Survey (USGS) basin information, only 12.4% of the actual watershed is included in the study area.

2.3. Phosphorus in rainfall and runoff

Phosphorus concentration in rainfall was obtained from the 1999 Lake Okeechobee Action Plan (USEPA and SFWMD, 1999). The average rainfall amount for the northern Lake Okeechobee watershed was obtained from Zhang et al. (2002). The SCS curve number method was utilized to estimate the runoff volumes based on the updated rainfall and estimated impervious percentages. A long-term average annual runoff volume of 34.2 cm was used for pervious areas including agriculture and forests, and 63.9 cm was used for areas estimated at approximately 30% impervious including residential. Wetlands and water bodies themselves were considered to have a runoff volume of zero as per the assumptions previously used in Lake Okeechobee Agricultural Decision Support System (LOADSS) (Negahban et al., 1995). LOADSS is a GIS-based modeling tool used for assessing water quality within the Lake Okeechobee watershed.

The average annual total P concentration ($\mathrm{mg\,l^{-1}}$) of runoff for a specific land use was obtained where measured data were available, otherwise data were taken from the previous study (Fonyo et al., 1991). For example, the average annual total P concentration for dairy runoff was obtained from Ray and Zhang (2001) and the concentration for improved pasture was obtained from Gornak and Zhang (1999). Other measured concentrations were obtained from SFWMD's Works of the District 2002 Permit Database, which includes monitoring data as required by permit for various land uses within the watershed. The updated phosphorus concentrations and runoff estimates were used to calculate the average annual amount of P in runoff for each land use.

2.4. Basin P budgets characteristics

Phosphorus budgets were developed through integration of GIS data sets, satellite imagery, landowner surveys/research, and field reconnaissance. Both tabular and graphical landowner and basin level P budgets and data structures were used in the analysis. A graphical user interface (GUI) was created to view and modify input data (farms, drainage basins, hydrographic features, land uses, and soil types) and P budget results (import and export) using Environmental Research System Institute (ESRI™) GIS software ArcView™, version 3.2.

The onsite P storage was calculated as the sum of net P imports (I_{imports}) and rainfall P loading (I_{precip}) minus P runoff (R_{L}). This value relates to the P accumulated in the tributary basin and stored in the soils and vegetation. Wetland P storage was estimated as the difference in runoff P and lake loading. This amount represents the P that is filtered out and removed from flows before lake loading occurs. The total basin P storage was the sum of on-site and wetland P storage. These P storage values were used for the purpose of completing the P mass balance and for comparing the current values to the previous study (Fonyo et al., 1991).

The basin P budgets may be expressed by a series of simple mass balance equations as defined in the previous study:

$$\Delta S_{\mathrm{b}} = \sum_{i=1}^{a} I_i - \sum_{i=1}^{a} O_{\mathrm{L}i} \qquad (1)$$

where

$$I_i = I_{\mathrm{imports}} + I_{\mathrm{precip}} \qquad (2)$$

and

$$\Delta S_b = \Delta S_o + \Delta S_a \quad (3)$$

$$\Delta S_o = \sum_{i=1}^{a} I_i - \sum_{i=1}^{a} R_{Li} \quad (4)$$

$$\Delta S_a = \sum_{i=1}^{a} R_{Li} - \sum_{i=1}^{a} O_{Li} \quad (5)$$

where ΔS_b is basin P retention, ΔS_o is on-site P retention, ΔS_a is wetland P assimilation, I_i is total P inputs, $I_{imports}$ is net P imports by land use activities, I_{precip} is rainfall P load, O_{Li} is basin P load to Lake Okeechobee, R_{Li} is average annual off-site runoff P load, and the superscript "*a*" is the number of tributary basins within the northern Lake Okeechobee watershed. All P terms are in units of metric tonnes per year (t P per year).

Table 1
Basin and landscape characteristics used in regression analysis

P budget indices	
AF	Assimilation factor ($\Delta S_a/R_L$); fraction of off-site P load assimilated in wetlands
BPLI	Basin P load index (O_L/I); fraction of total P inputs exported to the lake
OPLI	Off-site P load index (R/I); fraction of total P inputs in off-site runoff
Basin P budget characteristics	
DS	Total annual change in P retention (kg per year)
ΔS_a	Wetland P assimilation in the basin along the flow path to the lake (t per year)
ΔS_o	Upland P retention (t per year)
ΔS_b	Total basin P retention (upland retention plus wetland assimilation) (t per year)
$I_{imports}$	Net P imports by land use activities (t per year)
I_{precip}	Rainfall P load (t per year)
I	Total net P import (t per year)
R_L	Off-site P load in runoff (t per year)
O_L	Basin P load to lake (t per year)
PLAC	Areal lake P load (kg ha^{-1})
PLFW	Flow-weighted P loading rate (mg l^{-1})
NPAC	Areal net P imports (kg ha^{-1})
DS/AC	Areal total annual change in P retention (kg ha^{-1})
Landscape characteristics	
AREA	Basin area (ha)
PERIM	Basin perimeter (km)
SHAPE	Basin shape, perimeter area (m ha^{-1})
LDIST	Distance from basin centroid to Lake Okeechobee (km)
DEVAC	Area of land uses in the basin with associated flows of P-containing materials (ha)
INTS	DEVAC divided by basin area, measure of the extensiveness of P use in the basin
STREAM1	Total length of naturally flowing water (except braided streams) in the basin (km)
STREAM2	Basin stream density, STREAM1/basin area (m ha^{-1})
WATER1	Total length of streams and canals in the basin (km)
WATER2	Basin drainage density (streams and canals) (m ha^{-1})
WETLANDS	Total area of wetlands of all types within the basin (ha)
WETPER	Basin area in wetlands (%)
WETEMP	Basin area in wetlands with emergent vegetation (%)
APP	Basin area in Placid–Pamlico soil association (ha)
ABM	Basin area in Myakka–Basinger soil association (ha)
AMD	Basin area in Manatee–Delray soil association (ha)
APB	Basin area in Pompano–Basinger soil association (ha)
PPSL	Percent basin area in Placid–Pamlico soil association (%)
BMSL	Percent basin area in Myakka–Basinger soil association (%)
MDSL	Percent basin area in Manatee–Delray soil association (%)
PBSL	Percent basin area in Pompano–Basinger soil association (%)

2.5. Regression analysis

A matrix of variables and basin characteristics were used for regression analysis to determine the correlation between these variables and P loading to Lake Okeechobee. The best-fit line for each relationship was calculated with Microsoft™ Excel™ 2000 using the least squares method of regression. The variables considered in this study were the same as those used in the previous study (Fonyo et al., 1991). Table 1 lists these variables, along with their description and units of measurement.

2.6. Phosphorus budget indices

Phosphorus budget indices were developed for each basin in the northern Lake Okeechobee watershed. Off-site P load index, OPLI, is the fraction of basin net P imports in runoff. Basin P load index, BPLI, is the fraction of basin net P imports that reach Lake Okeechobee. Assimilation factor, AF, is the fraction of off-site P loads assimilated in wetlands. OPLI and BPLI normalize P runoff and loading, respectively, by the net P imports for each basin. AF is used to determine how wetland P retention efficiency is related to P loading and other basin characteristics.

3. Results and discussion

3.1. Net P imports

3.1.1. By land use

The net phosphorus import coefficients represent the average annual amount of net phosphorus imported per hectare of a specific land use. The summary of current and previous net P coefficients and the primary contributor of the change in coefficients are listed in Table 2. Most land uses have shown a decrease from the previous study (Fonyo et al., 1991) in net phosphorus import coefficient due to less fertilizer usage. The notable changes in land use and land use practices during the past 10 years have been rapid urbanization and row crop increase. The land uses with the most influence within the northern Lake Okeechobee watershed in terms of net P import were improved pasture with 558 t per year, row crop with 545 t per year, and dairy with 458 t per year (Table 3). Other noteworthy land uses in terms of percent of net watershed P import (positive or negative) were sod farm with −235 t per year and citrus with 183 t per year. The overall net import to the watershed based on land use activities was 1717 t P per year.

Table 2
Summary and comparison of net P import coefficients for land uses in the northern Lake Okeechobee watershed

Land use	1995 article[a] (kg ha^{-1} per year)	Current study (kg ha^{-1} per year)	Primary contributor
Abandoned dairy	N/A	3.04	Fertilizer
Citrus	10.00	7.22	Fertilizer
Commercial forestry	−0.16	−0.14	N/A
Dairy	65.00	53.68	Stocking rate
Field crop	N/A	6.90	N/A
Forested upland	−0.16	−0.14	N/A
Golf course	27.00	10.27	Fertilizer
Improved pasture	5.60	3.04	Fertilizer
Ornamentals	24.00	9.48	Fertilizer
Rangeland	0	0.01	Supplement
Residential—low density	1.70	6.93	Feed import computation
Residential—medium density	15.00	26.81	Feed import computation
Residential—high density	N/A	57.44	Feed import computation
Residential—mobile home unit	N/A	41.33	Feed import computation
Row crops	160.00	189.95	Farming intensity
Sod farm	−11.00	−48.83	Fertilizer
Sugarcane	8.20	0.99	Cane production
Unimproved pasture	0.06	0.01	Supplement

[a] Boggess et al. (1995).

Table 3
Changes of land use area and net phosphorus import in the northern Lake Okeechobee watershed

Land use	Area (ha)		Net import (t P per year)		
	1995 article[a]	This study	1995 article[a]	This study	Change (%)
Abandoned dairy	N/A	2344	N/A	7	N/A
Citrus	13000	25392	130	184	41
Commercial forestry	N/A	13299	N/A	−2	N/A
Dairy	18000	8525	1170	458	−61
Field crop	N/A	2276	N/A	16	N/A
Forested upland	49700	49887	−8	−8	0
Golf course	90	377	3	4	29
Improved pasture	181000	183778	1010	558	−45
Ornamentals	730	3212	18	30	69
Rangeland	74000	46641	0	1	N/A
Residential	7800	9740	48	151	215
Row crops	450	2868	72	545	657
Sod farm	6400	4816	−70	−235	236
Sugarcane	370	8755	3	9	188
Unimproved pasture	62000	33453	4	0.3	−93
Wetland	78000	95423	0	0	0
Water and other land uses	N/A	25215	N/A	0	N/A
Total		516000	2380	1717	

[a] Boggess et al. (1995).

3.1.2. *By basin*

The C-40 basin was a net P exporter of 24 t P per year because of the amount of sod grown and harvested in that basin (Table 4). Basin S-65D contributed the highest net P import of any tributary basin with 418 t P per year. A dominant land use was assigned to each tributary basin based on the land use that contributed the largest value of net P imports to that basin. For example, row crop was the dominant land use in terms of net P import to basin S-65D. Not including basin S-65D, the highest P importing tributary basins in order of decreasing magnitude were S-191 (dairy dominant), S-65E (truck crop dominant), Fisheating Creek (improved pasture dominant), and S-154 (dairy dominant). These five basins accounted for 75% of the total net P imports to the northern Lake Okeechobee watershed.

3.2. *Phosphorus loads in rainfall and runoff*

Phosphorus load and concentration in rainfall were obtained from the 1999 Lake Okeechobee Action Plan (USEPA and SFWMD, 1999). According to the Action Plan, the average annual rainfall P loading to the lake was 58 t and concentration was 0.028 mg l^{-1}. The average annual rainfall for the Lake Okeechobee watershed was 127 cm (Zhang et al., 2002). Based on these data, the average P import from rainfall was 0.356 kg P ha per year. The total drainage area for the northern Lake Okeechobee watershed is 5160 km^2. Therefore, the total rainfall P load to the lake was 184 t.

The previous study (Fonyo et al., 1991) utilized an average P concentration value of 6.8 mg l^{-1} for dairy land use. This value represented the intensive dairy land use. In this study, dairy land use included both intensive and outer pastures. Review of the existing dairy coverage indicated that 50% of dairy area was outer pasture, and 50% was dairy intensive land use. The average concentration value for dairy runoff used in this study was calculated to be 1.32 mg l^{-1}. This value was calculated based on the assumption that 50% of dairy intensive area having an average P concentration of 2.19 mg l^{-1} (Ray and Zhang, 2001) and 50% of the outer pasture having an average P concentration value of 0.45 mg l^{-1}. The value of 0.45 mg l^{-1} was obtained from Gornak and Zhang (1999) for improved pasture.

The average P runoff concentration value for truck crops decreased substantially from the previous study, from 6 to 0.55 mg l^{-1}. The decrease reflects the

Table 4
Summary of P budget annual results for basins in the northern Lake Okeechobee watershed with the highest net P import (metric tons used)

Basin[a] and dominant land use in terms of net P import	Net P imports ($I_{imports}$)	Rain P load (I_{precip})	Runoff P load (R_L)	Onsite P storage (ΔS_o)	P load to lake (O_L)	Wetland retention (ΔS_a)	Total P in basin (ΔS_b)
S-65D (truck crops)	418.1	16.9	53.5	381.5	37.7	15.8	397.3
S-191 (dairy)	379.4	17.4	78.9	317.9	73.8	5.1	323.0
S-65E (truck crops)	231.0	4.2	18.1	217.1	24.1	6.0	211.1
Fisheating Creek (improved pasture)	150.3	40.8	80.4	110.7	64.1	16.3	127.0

[a] The final project report (Mock Roos Team, 2002) includes a full list of the basins within the Lake Okeechobee watershed.

incorporation of BMPs between 1991 and the current study. The 1991 value also represents an estimation versus actual measured data available in SFWMD's Works of the District 2002 Permit Database. Improved pasture showed a small reduction in the average concentration from 0.5 to 0.45 mg l^{-1} (Gornak and Zhang, 1999) while the P concentration value for citrus land use increased from 0.2 to 0.52 mg l^{-1} (SFWMD Works of the District Database, 2002).

The total amount of P runoff was 488 t P per year (Table 4). The most noteworthy tributary basins with regard to P runoff loading and percent of total P runoff were Fisheating Creek with 80 t P per year or 16%, S-191 with 79 t P per year or 16%, S-65D with 54 t P per year or 11%, and C-41 with 43 t P per year or 9%. The three primary land uses contributing to P runoff or percent of total P runoff were improved pasture with 283 t P per year or 58%, citrus with 45 t P per year or 9%, and dairy with 38 t P per year or 8% (data not shown).

3.3. Phosphorus loads to Lake Okeechobee

The total P loading to the lake from the 25 drainage basins studied was 332 t P per year (Table 4). Three basins accounted for over 50% of lake loading. These basins included basin S-191 with 74 t P per year, Fisheating Creek with 64 t P per year, and S-65D with 38 t P per year. The S-154, C-41, and S-65E basins accounted for a combined 24% of total lake loading.

3.4. Phosphorus budget for the northern Lake Okeechobee watershed

Phosphorus input from rainfall is 184 t per year. Therefore, the total net phosphorus imports including rainfall to the northern Lake Okeechobee watershed is 1901 t P per year. Approximately 1413 t P per year (74%) of the total net P import was stored on-site in upland soils and vegetation while 488 t P per year (26%) was discharged in runoff. Approximately 156 t P per year (32%) of the runoff P was stored in wetlands, while approximately 332 t P per year (68%) was loaded to the lake. Overall, 8% of the total phosphorus imports to the northern Lake Okeechobee watershed end up being stored in wetlands and 17% is loaded to the lake.

3.5. Phosphorus budget indices

Following the protocol by Boggess et al. (1995), P budget indices were computed to determine which landscape characteristics influenced lake P loading. Table 5 shows values for P budget indices that were computed from the landscape characteristics shown in Table 1. Each basin in the study was considered as a data point for landscape characteristics and annual P lake loading. Regression analysis utilized all basin data points to determine correlation relation. Linear, logarithmic, and multi-linear regression analyses were performed to find strong-correlated relationships that may influence P retention and transport within the watershed.

3.6. Phosphorus loading relationships

3.6.1. Linear/logarithmic regression analyses

One of the highest correlations determined as related to P lake loading was basin P runoff, R_L. Based on linear regression, basin runoff (R_L) accounts for 88% of the variation in the lake loading (O_L) data (Fig. 2).

$$O_L = -2.94 + 0.83 \times R_L, \quad r^2 = 0.88 \tag{6}$$

Table 5
Basin areal loading rate, flow-weighted concentration, and P budget indices for basin within the northern Lake Okeechobee watershed with the highest net P import

Basin[a] and dominant land use in terms of net P import	Basin area, AREA (ha)	Areal P loading rate, PLAC ($kg\,ha^{-1}$ per year)	Flow-weighted P concentration, PLFW ($mg\,l^{-1}$)	Basin P load index, BPLI (O_L/I)	Runoff P load index, OPLI (R_L/I)	Assimilation factor, AF ($\Delta S_a/R_L$)
S-65D (truck crops)	41187	0.92	0.231	0.09	0.12	0.30
S-191 (dairy)	48668	1.52	0.651	0.19	0.20	0.06
S-65E (truck crops)	11799	2.04	0.231	0.10	0.08	−0.33
Fisheating Creek (improved pasture)	114229	0.56	0.178	0.34	0.42	0.20

[a] The final project report (Mock Roos Team, 2002) includes a full list of the basins within the Lake Okeechobee watershed.

Excluding P runoff, the variables highly correlated with lake loading in order of rank included developed land ($r^2 = 0.82$) and net P input to the basin ($r^2 = 0.80$). Other variables with fair correlation with lake P loading were on-site P storage ($r^2 = 0.75$), tributary basin perimeter ($r^2 = 0.72$), and total basin P storage ($r^2 = 0.72$). Fair correlation with lake loading was found for rainfall P import ($r^2 = 0.68$), tributary basin area ($r^2 = 0.68$), area of Myakka soil type ($r^2 = 0.67$), and length of streams ($r^2 = 0.66$). A fair correlation was also determined between areal lake loading and areal net imports ($r^2 = 0.60$). This relationship was previously poor ($r^2 = 0.36$).

3.6.2. Multi-linear regression analysis

Multiple linear regression analysis was performed to update the models previously examined in the previous study (Fonyo et al., 1991) and as presented in a subsequent article (Boggess et al., 1995). Model 1 from the previous study was used to examine effects of net P import intensity, NPAC, stream and canal density, WATER2, and percent of wetlands, WETPER, on

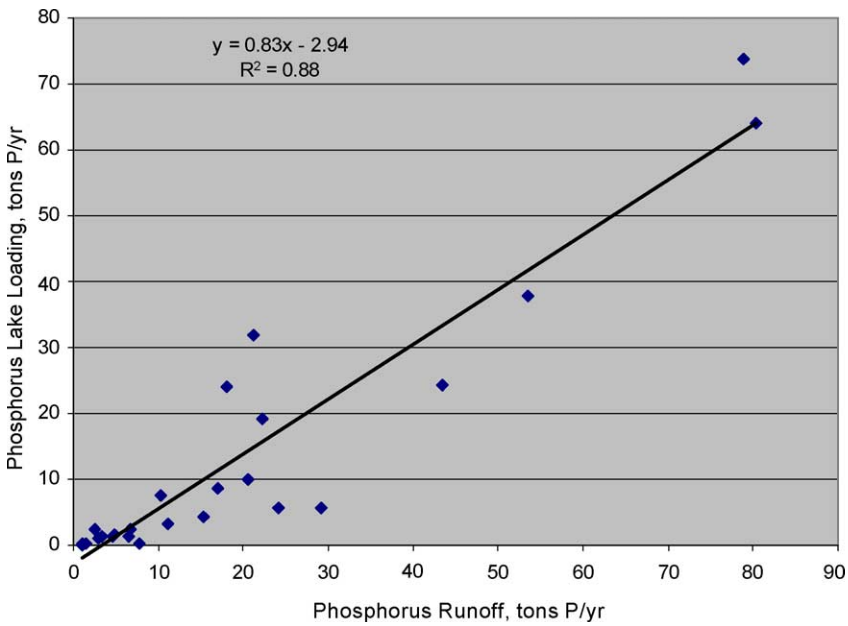

Fig. 2. Phosphorus lake loading vs. runoff phosphorus (metric tonnes used).

the total annual change in P retention per unit area, DS/AC.

Model 1:

$$\frac{DS}{AC} = 0.20 + 0.97 \times \mathrm{NPAC} - 4.19 \times \mathrm{WATER2} + 0.20 \times \mathrm{WETPER}, \quad r^2 = 0.98 \tag{7}$$

As the previous Model 1 indicated and as expected, the intercept was not considerably different from zero. The positive coefficient of NPAC was expected and was the same order of magnitude, 0.97, as the 1.022 value previously determined. The positive NPAC coefficient inferred that increased net P intensity leads to increased basin P storage intensity. The negative sign of the revised stream and canal density coefficient was consistent with the previous model, but much larger in magnitude. This coefficient suggested that an increase in drainage density would reduce the amount of P retention in a basin. The coefficient for wetland percent suggested that an increase in wetlands in a basin would increase the P storage intensity in that basin.

Model 2 examined the relation of the same independent variables assessed in Model 1 with lake P load intensity, PLAC. As with Model 1, wetland percent was found to have a very poor correlation with lake loading intensity ($r^2 = 0.02$). Wetland percent was removed from Model 2 with no resulting change in the Model 2 correlation coefficient. The multiple regression analysis yielded the following results for the revised Model 2:

Model 2:

$$\mathrm{PLAC} = 0.15 + 0.11 \times \mathrm{NPAC} + 3.51 \times \mathrm{WATER2}, \quad r^2 = 0.60 \tag{8}$$

The previous Model 2 correlation was higher ($r^2 = 0.91$) than the updated Model 2. The positive signs of the revised NPAC and WATER2 coefficients are consistent with those previously determined. The order of magnitude of these two coefficients is much larger than previously determined (previously 0.028 and 0.011 for NPAC and WATER2, respectively).

Model 3 examined the relation of net P imports I_{imports}, total length of steams and canals, WATER1, and wetland factor, WETPER, with lake P load, O_{L}. As with Model 2, the wetlands factor was found to be individually correlated very poorly ($r^2 = 0.23$). When the wetland factor was removed from the multiple linear regression equation, the correlation coefficient and the independent variable coefficients did not change in the decimal places reported:

Model 3:

$$O_{\mathrm{L}} = -3.46 + 0.08 \times I_{\mathrm{imports}} + 0.05 \times \mathrm{WATER1}, \quad r^2 = 0.80 \tag{9}$$

The previous Model 3 correlation was higher ($r^2 = 0.91$) than the updated Model 3. The positive signs of the revised P import and WATER1 coefficients are consistent with those previously determined. The order of magnitude for the updated net P import is larger (0.0176 previously) and the revised WATER1 coefficient is similar (0.046 previously) to the previous corresponding Model 3 values.

4. Summary and conclusions

The P budget analysis for the northern Lake Okeechobee watershed conducted in 1991 was updated using current land use data, current land use net P import coefficients, and more recent rainfall, runoff, and lake P values. Based on data collected from 1997 to 2001, approximately 1717 t of P was imported into the northern Lake Okeechobee watershed annually for anthropogenic land use activities. Five basins account for 75% of the total net P imports to the northern Lake Okeechobee watershed. Approximately 74% of the total net P import was stored on-site in upland soils and vegetation, while 26% was lost in runoff. Approximately 32% of that runoff P was stored in wetlands, while approximately 68% was loaded to Lake Okeechobee. Overall, 8% of the total P imports to the northern Lake Okeechobee watershed end up being stored in wetlands and 17% is loaded to the lake.

The current P budget data was compared to the previous P budget (Boggess et al., 1995). Net P imports decreased by 28% from the previous budget, from 2380 to 1717 t P, primarily due to changes in four land uses. Land uses with the largest change in net P import included dairy from 1170 to 458 t P, improved pasture from 1010 to 559 t P, row crops from 72 to 545 t P, and sod farms from −70 to −239 t P. Dairy net P imports changed primarily due to fewer dairies and also changes in management practices. Improved pasture net P imports decreased due to a lower net P import coefficient, which resulted from lower fertilizer application and higher live weight export. Truck crop net P imports changed due to a five-fold increase in truck crop area, and an increase in the P import coefficient, which reflects an increased farming intensity. Sod farm net P import decreased due to lower fertilizer application on this land use.

The overall P budget indicated that annual amount of onsite storage of P had decreased by 26% from the previous study (Fonyo et al., 1991). Based on the current information, the overall wetland assimilation factor, which is the percent of wetlands loading that is retained in the wetland, had changed from 61 to 32%. The reduction was not a result of a wetland area, but a result of reduced P assimilation potential. Overall, 83% of net imported P was stored in the watershed, which was previously determined to be 90%.

Lake loading could be reduced more effectively by decreasing P runoff and net P imports in each tributary basin. The correlation between net P imports and lake loading was higher than previously determined. The net P import regression equation accounted for 80% of the variability in lake loading data whereas the best regressed equation only accounted for 70% of variability in lake loading previously. The relationship between net P imports and lake loading was the highest correlation to lake loading in the previous study.

The improved pasture land use remained a considerable contributor of net P imports (33% currently, 49% previously); truck crops have become a more influential land use (32% currently, 3% previously); and dairy has decreased in contribution significance (27% currently, 42% previously). With regard to P management, improved pasture and dairy land uses should continue to be land uses of focus, but truck crops should receive increased attention. To further reduce P loads to the lake, additional strategies/programs need to be evaluated (Steinman et al., 1999). These strategies include restoring isolated and riverine wetlands in the watershed, developing Best Management Practices for beef cattle operations and row crops, detaining water in storm water treatment areas, and improving dairy management.

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