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Phosphorus storage capacity of uplands, wetlands and streams of the Lake Okeechobee Watershed, Florida

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Abstract

Lake Okeechobee, a subtropical, shallow lake in south Florida, is severely affected from eutrophication resulting from non-point source agricultural phosphorus (P) loading. The Lower Kissimmee River and Taylor Creek/Nubbin Slough watersheds are major contributors of P to Lake Okeechobee with 57% of the total P load attributed to these two watersheds. Major land use in these watersheds are dairy and beef pastures. Soils are dominated by Spodosols. The P storage capacity of uplands, wetlands and streams in the Lake Okeechobee Watershed was estimated based on the analysis of soil and vegetation, and imports of P into the watershed. Results showed that about 70% of the total P imported into the watershed is stored in uplands, and an additional 18% is stored in wetlands and streams. Phosphorus retention in soils was strongly associated with Al and Fe oxides and total organic carbon. Phosphorus storage in vegetation was found to be short-term and accounted for less than 5% of the total P storage. Phosphorus retention characteristics of soils and sediments suggest that about 75% and 45% of the storage capacity is still available for additional retention in uplands, wetlands and stream sediments, respectively. Although the watershed has a large capacity to store P, continuous loading can decrease the P buffering capacity of soils and sediments and increase P levels in surface and sub-surface flow.

Keywords: Phosphorus storage; Upland soil; Wetland soil; Stream sediment

1. Introduction

Phosphorus (P) has been shown to be a major nutrient controlling eutrophication in many aquatic systems (Logan, 1982; Sonzogni et al., 1982). Non-point sources of P from agricultural runoff contribute a significant portion of P inputs to aquatic systems (Sharpley et al., 1994). Thus, in many situations, alternative land use management practices have been implemented in an effort to reduce the overall load to receiving water bodies. For example, watershed management practices in the Lake Okeechobee Watershed have been shown to have a significant impact on water quality of Lake Okeechobee (Federico et al., 1981). This shallow subtropical lake may be moving from a naturally eutrophic state to a hypereutrophic state due to P loading from the surrounding watershed (Maceina and Soballe, 1990; Janus et al., 1990).

Phosphorus imported to a watershed through fer-

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tilizers and animal feed, results in P in animal wastes and organic residues that tend to accumulate in soils and sediments, and vegetation. The amount of P leaving the watershed depends on the hydrologic characteristics (i.e. surface and sub-surface flow), vegetation type, characteristics of soils and sediments, and management strategies.

Although many point sources of P discharges have been controlled or reduced, nonpoint sources through surface and sub-surface flow pose a greater danger in increasing loads to adjacent water bodies (Sharpley et al., 1994). To abate this problem, many state and federal agencies are in the process of developing watershed management strategies to reduce P loads into the water bodies. For example, the International Joint Commission between the US and Canada made recommendations on several P management strategies to reduce loads to the Great Lakes (Rochlich and O'Connor, 1980). Similarly, the Florida Legislature passed the Surface Water Improvement and Management Act (SWIM) in 1987 and management plans have been implemented to decrease nutrient loads to lakes and estuaries and specifically to reduce P loads to Lake Okeechobee (SFWMD, 1993). Historical loads to Lake Okeechobee have been estimated to be about 600 t year^{-1} (Fluck et al., 1992). However, the Lake Okeechobee SWIM plan has set a goal to reduce the annual load to an average of 400 t year^{-1} (SFWMD, 1993). The planned load reduction is to be achieved by reducing the P concentration of the water leaving the watershed to 0.18 mg l^{-1}.

The ability of uplands and wetlands in a watershed to retain P within the system is critical for developing effective land management strategies. Phosphorus added to the watershed moves via surface and sub-surface flow within the upland and wetland components, followed by flow through tributaries and streams, which feed into major inflows and finally into the lake. Thus, to accomplish this goal of reducing P load, a thorough understanding of the P storage capacity within the watershed's major components, including uplands, wetlands and streams is needed.

The objectives of this paper were: (i) to determine the ambient P storage in soils, sediments, and vegetation in the watershed, and (ii) to estimate the additional P retention capacity of various components of the watershed including uplands, wetlands and streams.

2. Description of the watershed

The Lake Okeechobee Watershed is divided into six regions: Lower Kissimmee River (LKR), Taylor Creek/Nubbin Slough (TCNS), Fisheating Creek, Indian Prairie/Harney Pond, the lakeshore, and the Everglades Agricultural Area (Fig. 1(a)). Among these six regions, LKR and TCNS regions contribute about 57% of the total P load to the lake, compared with 11% from Fisheating Creek and 18% from the Harney Pond/Indian Prairie regions (Fluck et al., 1992). The Everglades Agricultural Area, located south of Lake Okeechobee, contributes about 10% of the total P load, while the remaining small watersheds contribute less than 4%. The LKR Watershed is divided into two sub-watersheds: LKR-North (S65A, S-65B, and S-65C) and LKR-South (S-65D, S-65E, and S-154) (Fig. 1(b)). Because of the importance of these two watersheds in overall P load, we will focus primarily on the P storage capacities of uplands, wetlands and streams in LKR and TCNS watersheds (Table 1).

The watershed is characterized by a subtropical climate with a wet summer season. Most of the watershed has little relief and the water table is near or at the soil surface during much of the wet season (Blatie, 1980). Drainage has been improved through ditching fields and dredging of canals for conveyance of storm runoff to the lake. The smaller canals are connected to a system of primary canals that convey runoff through gated control structures to Lake Okeechobee.

Land uses in the LKR and TCNS region are primarily beef cattle ranching and dairy farming (Table 1). Beef cattle ranching exists on both improved and unimproved pastures. Some beef cattle pastures have been improved with site drainage, establishment of improved forage grasses and application of inorganic fertilizers. Improved pasture accounts for 31% of the land area in LKR and 62% of the land area in TCNS. The area of improved pastures increased by 500% from 1950 to 1970, and currently has an area of approximately 87000 ha (Flaig and Havens, 1995). Fertilizer usage on improved pastures accounted for 34% of P imports to the watershed (Boggess et al., 1995). Other P imports include mineral supplements and cattle feed supplements in winter pasture. Unimproved pastures and rangelands account for 37% of the land area in LKR and 7% of the land area in TCNS. Wetlands accounted for 20% of the land in LKR and 13% of the land in TCNS.

Dairy farming is the most intensive land use in the watershed. Dairy operations began in the 1950s with many dairies starting near the lake shore and expanding throughout LKR and TCNS sub-watersheds during the next 30 years. Phosphorus imports in cattle feed by dairies increased from approximately 360 t P $year^{-1}$ in 1960 to 1200 t P $year^{-1}$ in 1990 (Flaig and Havens, 1995; Boggess et

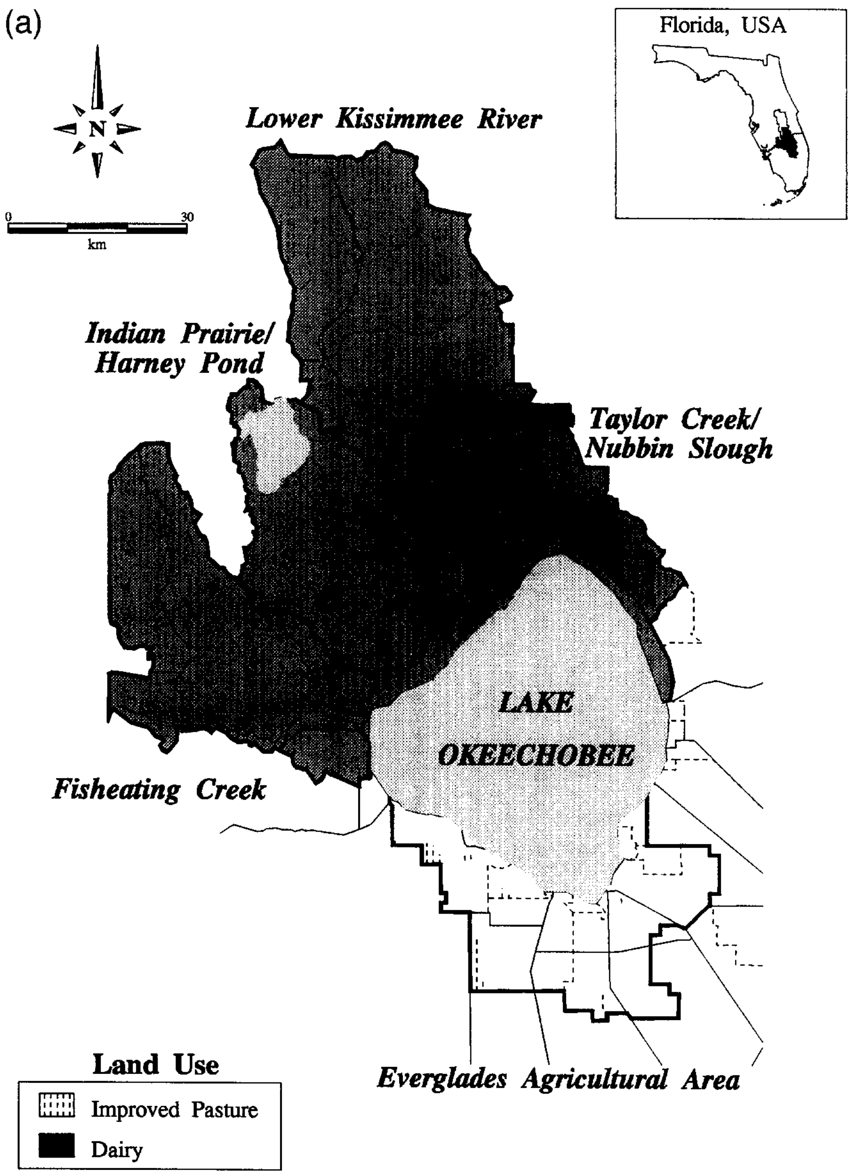

Fig. 1. (a) A map showing the major land use in the Okeechobee Watershed. (b) A map showing three sub-watersheds in the Okeechobee Watershed.

al., 1995). Dairy feed represented 35% of P imports to the watershed. However, P imports have decreased since 1990 due to closing of 19 of the 49 dairies through a dairy buyout program designed to reduce P loads to the lake.

About 65% of the upland soils in the Lake Okeechobee Watershed are Spodosols, dominated by three soil series including Myakka, Immokalee and Pomello (Burgoa, 1989). The soils consist of an acid, sandy, surface A horizon, which typically varies in depth from 10 to 50 cm. This horizon has significant accumulation of organic matter. An elluvial zone, (E horizon) exists beneath the A horizon with an average depth of 72 ± 54 cm. Both A and E horizons have high hydraulic conductivities, greater than 20 cm h^{-1}. Underlying the E horizon is the spodic (Bh) horizon, characterized by an accumulation of iron (Fe), aluminum (Al), and organic matter (Soil Survey Staff, 1975), which is often cemented and exhibits low hydraulic conductivity. The thickness and permeability of the spodic horizon is highly variable in areal and vertical extent (Burgoa, 1989).

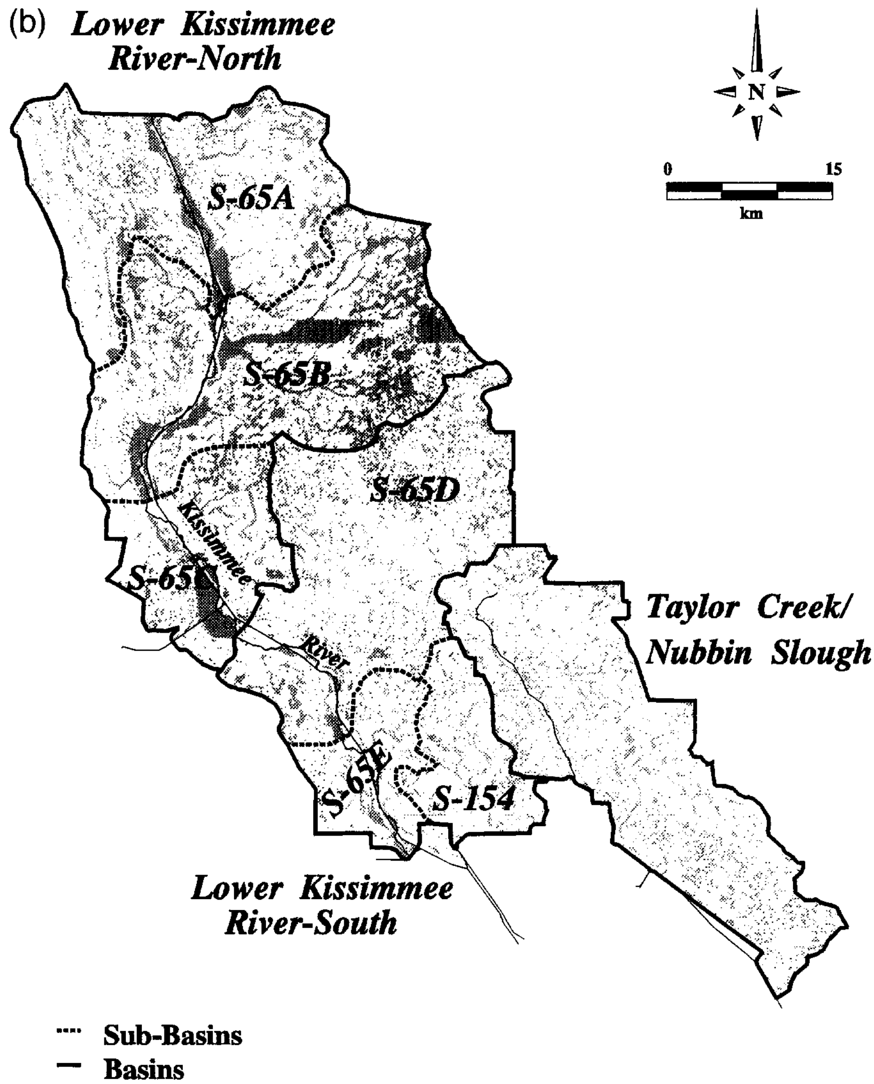

Fig. 1 (continued).

Table 1
Major land use of the Taylor Creek/Nubbin Slough and Lower Kissimmee Watersheds (University of Florida, 1992). Values are expressed in hectares

Land use	Lower Kissimmee River Drainage Watersheds						Total	Taylor Creek	Nubbin Slough	Total
	North			South						
	S-65A	S-65B	S-65C	S-65D	S-65E	S-154				
Rangeland	13600	19600	590	8900	870	750	44300	2080	0	2080
Sugarcane	0	0	0	0	0	0	–	–	190	190
Truck crops	0	0	0	0	0	0	220	120	16	140
Citrus	460	56	900	180	30	2	1630	670	510	1180
Sod	0	0	0	580	–	–	580	100	790	890
Dairy impacted areas	0	0	2	60	30	28	120	169	120	290
Improved pastures	7500	7050	7420	21900	6460	6790	57100	15700	14600	30300
Unimproved pastures	2790	8680	4900	4050	1840	1710	24000	760	490	1250
Forestland	4080	3220	320	2830	960	430	11800	1740	1700	3440
Wetland	12900	12500	6080	5520	320	130	37500	4160	2240	6400
Urban and other	490	830	220	3160	1070	2950	8700	1630	980	2610
Total	41800	51900	20400	47200	11800	12800	186000	27100	21600	48800

Phosphorus transport in Spodosols is by a combination of surface runoff and sub-surface flow (Campbell et al., 1995). Due to low permeability, movement of water through the Bh is slow. Water flow through the soil occurs predominantly as lateral sub-surface flow in the A and E horizons, providing contact along the surface of the Bh horizon. During the summer rainy periods, flat topography results in shallow water tables and intense rainstorms, common in this region, produce surface runoff. In soils where the spodic horizon is less developed, soluble P may be transported downward through the fractured zones of the spodic horizon. In areas with well-drained soil, P is transported by sub-surface flow resulting in greater interaction of P with deeper soil layers (Allen, 1987; Campbell et al., 1995). In many agricultural watersheds, sediment control measures can effectively reduce P discharge (Sharpley et al., 1994). However, in the Lake Okeechobee Watershed, sediment transport is negligible.

3. Phosphorus storage in soils and sediments

Upland and wetland soils and stream sediments are major sinks for P imported into the watershed. Many studies conducted in the Lake Okeechobee Watershed have characterized P in the upland (Allen, 1987; Nair and Graetz, 1995; Graetz et al., 1996), and wetland soils (Scinto, 1991; Reddy et al., 1995) and stream sediments (Reddy et al., 1995). Average total P content of the soils under native flora, pasture, forage and intensive areas is presented in Table 2. Detailed methods and results related to these data are presented by Graetz and Nair (1995), Nair and Graetz (1995) and Graetz et al. (1996). Phosphorus content of the upland soils was in the order of native < forage < pasture < intensive areas.

Soil P content varied both with soil depth and land use type. Total P content of unimpacted soils (native) was in the range of 15–59 mg kg^{-1} in all horizons, with low values observed in the E horizon and high values in the Bh horizon. Labile P content (defined as P in sorbed phase, which is potentially mobile and bioavailable) in the Bh horizon of native, forage and pasture areas were less than 2% of the total P, while up to 10% of the total P was found as labile P in surface horizons. In intensive areas, up to 40% of the total P was in labile pool.

Total P content of wetland soils and stream sediments was determined for the top 30 cm depth with an assumption that P stored below depth did not exchange with overlying floodwater. There was no distinct horizon differentiation in these soils, except accumulation of organic matter in the surface soil. The total P content of stream sediments was higher than wetland soils. Total P content of the wetland soils and stream sediments was higher than upland

Table 2
Total phosphorus storage of upland and wetland soils and stream sediments. Values in parentheses are standard deviations (Graetz and Nair, 1995; Reddy et al., 1996)

Land use	Horizon thickness (cm)	Total P ($mg kg^{-1}$)	Labile P ($mg kg^{-1}$)	Total P storage ($g m^{-2}$)
Upland soils				
A-horizon				
Native	18 (3)	30 (17)	5.3 (8.5)	7 (3)
Forage	16 (5)	46 (20)	3.0 (3.2)	11 (8)
Pasture	20 (11)	84 (129)	7.6 (20.6)	36 (103)
Intensive	24 (8)	1792 (1567)	154 (134)	585 (494)
E-horizon				
Native	53 (22)	15 (4)	0.3 (0.3)	13 (7)
Forage	51 (31)	21 (10)	1.7 (1.5)	16 (13)
Pasture	72 (54)	33 (37)	2.0 (2.6)	38 (41)
Intensive	89 (57)	133 (127)	49 (68)	123 (113)
Bh-horizon				
Native	28 (16)	59 (32)	0.9 (0.8)	24 (18)
Forage	27 (17)	50 (19)	0.8 (0.8)	19 (12)
Pasture	27 (17)	88 (60)	0.6 (0.3)	28 (17)
Intensive	23 (9)	197 (124)	30 (45)	58 (34)
Streams and wetlands				
Streams	30	436 (480)	6.1 (5.3)	116 (116)
Wetlands	30	232 (156)	2.1 (2.4)	75 (52)

soils. The labile P pool in both wetland soils and stream sediments accounted for less than 2% of the total P (Table 2).

Total P stored in the soil profile increased with intensity of land use, with native unimpacted areas containing 44 g P m^{-2} (average profile depth 99 cm), followed by forage (46 g P m^{-2}; soil depth 94 cm), pasture (102 g P m^{-2}; soil depth 119 cm) and intensive areas (766 g P m^{-2}; soil depth 136 cm). In contrast, stream sediments and wetlands soils contained 116 g P m^{-2} and 75 g P m^{-2} in 30 cm sediment and soil depths, respectively.

4. Phosphorus retention characteristics of soils and sediments

Phosphorus retention/release characteristics are dependent on P loading and physico-chemical properties of soils and sediments, such as mineralogy, clay content, pH and organic matter content. Research conducted for the past several decades has concluded that: (i) in acid soils, P is retained as Fe and Al-phosphates, if activities of these cations are high; (ii) in alkaline soils, P retention is governed by the activities of Ca and Mg; (iii) P availability is high in soils with slightly acidic to neutral pH.

The P retention characteristics of upland, and wetland soils and stream sediments in the Lake Okeechobee Watershed have been presented by Graetz and Nair (1995) and Reddy et al. (1992). Data obtained from laboratory P sorption studies includes maximum P retention capacity (S_{max}) and equilibrium P concentration (EPC) (Table 3). The S_{max} represents the maximum amount of P that can be retained by soils and sediments (Berkheiser et al., 1980). The S_{max} of Bh horizons was about three to four times higher than the surface A and E horizons

Table 3
Phosphorus retention capacity of upland and wetland soils, and stream sediments. Values in parentheses are standard deviations (Graetz and Nair, 1995; Reddy et al., 1995). EPC, equilibrium phosphorus concentration

Land use	EPC	Additional phosphorus retention capacity	
		Soil weight basis	Area basis
	($mg l^{-1}$)	($mg kg^{-1}$)	($g m^{-2}$)
Upland soils [a]			
A-horizon			
Forage	10.6 (8.9)	30 (6)	6 (4)
Pasture	5.3 (3.6)	138 (165)	27 (32)
Intensive	7.5	N/A	N/A
E-horizon			
Forage	2.2 (2.2)	55	27
Pasture	1.6 (1.7)	82 (61)	100 (94)
Intensive	1.6 (0.2)	209 (268)	64 (42)
Bh-horizon			
Forage	0.26 (0.38)	372 (219)	139 (92)
Pasture	0.21 (0.25)	427 (183)	193 (124)
Intensive	1.7 (2.6)	392 (224)	137 (74)
Streams and wetlands			
Streams		188 (114)	49 (26)
Wetlands	0.79 (0.62)	233 (160)	70 (41)

[a] Soils of the Okeechobee Watershed in general have S_{max} values for Bh horizons, three to four times higher than the surface A and E horizons.

(Table 3). High EPC (equilibrium P concentration when net adsorption equals zero) values for soils in the A and E horizons suggest poor retention capacity, while low EPC values of Bh horizon indicate strong affinity for P. The high EPC values of soils in the intensive areas reflect high P loading.

The S_{max} was found to be highly correlated with oxalate-extractable Fe and Al, and total carbon contents of the soil. Oxalate-extractable Fe and Al represent amorphous and poorly crystalline forms. The following regression equations shows the relationship between P retention capacity and selected soil properties.

Upland soils

$$S_{max} = 84.2 + 0.14[\mathrm{Ox-Al}] + 8.02[\mathrm{TOC}]$$

$$R^2 = 0.687 \quad N = 77$$

Stream sediments and wetland soils:

$$S_{max} = 2.17[\mathrm{TOC}] + 0.095[\mathrm{Ox-Fe}] + 0.238[\mathrm{Ox-Al}] - 1.2$$

$$R^2 = 0.925 \quad N = 55$$

In both equations, S_{max} represents the phosphorus retention maximum (mg kg^{-1}); [Ox-Al] is oxalate-extractable Al (mg kg^{-1}); TOC is total organic carbon (g kg^{-1}); and [Ox-Fe] is oxalate-extractable Fe (mg kg^{-1}).

For upland soils, P sorption data includes A, E, and Bh horizons of the soil profile from forage, pasture, and intensive areas (Graetz and Nair, 1995). About 69% of the variability in P retention maximum was accounted for by oxalate-extractable Al and total organic carbon in upland soils. About 93% of the variability in P retention maximum in stream sediments was accounted for by oxalate-extractable Fe and Al, and total organic carbon.

Maximum P retention capacity (on an areal basis of soils) also increased with depth. The E horizon, with poor retention characteristics, exhibited large storage for P (113 g P m^{-2}) as compared to other land use sites (Table 3). However, soils in this horizon have high EPC values, suggesting poor buffering capacity. For upland soils, the ratio between S_{max} and ambient P storage increased with depth (Table 3), indicating the role of sub-surface horizons in P storage. However, for stream sediments and wetland soils the EPC values were lower, suggesting strong binding capacity.

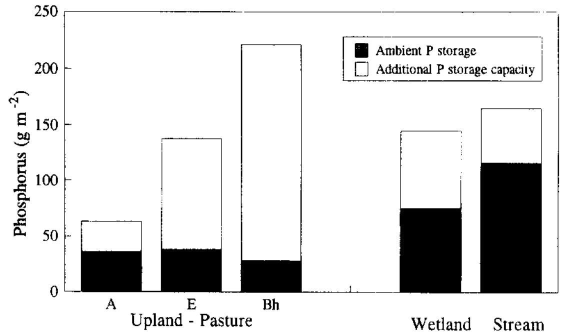

Fig. 2. Phosphorus storage in upland and wetland soils, and stream sediments. Upland soils (A, 20 cm; E, 72 cm; Bh, 27 cm soil depth); wetland soils and stream sediments (30 cm depth).

Additional P storage capacity of uplands, wetlands and streams was estimated using S_{max} (Table 3). These estimates suggest that additional storage is available for upland soils in the A, E and Bh horizons (Fig. 2). For streams and wetlands, 42 and 48% of the additional storage is available, respectively. However, the time required to saturate the soils for use of this additional storage depends on the rate and amount of P loading to the system.

5. Phosphorus storage in vegetation

5.1. Upland vegetation

Pastures and rangeland comprise about 70% of the upland area in LKR and TCNS watersheds. Bahiagrass grown on unfertilized Spodosols removed 2 g P m^{-2} year^{-1} during a 2 year period (Rechcigl and Bottcher, 1995). Under fertilized conditions, P uptake by bahiagrass was found to be in the range 2–4 g m^{-2} year^{-1}. Phosphorus uptake by this grass is approximately equal to fertilizer application, thus the net effect of vegetation on P storage is negligible (Rechcigl and Bottcher, 1995). Due to limited acreage under crops other than bahiagrass, P removal/release by crops, other than pastures, grown in uplands was assumed to be minimal.

5.2. Aquatic vegetation

The P storage capacity of aquatic plants depends upon their growth rate, supportive tissue (biomass), available P in the soil/sediment and water column, and physico-chemical characteristics of soils and sediments. The net storage mediated by aquatic vegetation is determined by the balance between total P uptake in the biomass and P release during decomposition. Data on P uptake and release by emergent macrophytes is available for three sites in the watershed: (i) two wetlands impacted by runoff from adjacent dairies (Reddy et al., 1995) and (ii) Otter Creek, a tributary in the Taylor Creek/Nubbin Slough Watershed (Reddy et al., 1996).

In wetlands, annual net P storage in the aboveground biomass of emergent macrophytes was in the range 0.3–4.3 g m^{-2}. For example, *Hydrocotyle* sp. showed maximum storage of 4.3 g m^{-2} while lower storages were exhibited by *Polygonum* sp. (0.8–2.3 g m^{-2}) and *Panicum* sp. (0.9–2.9 g m^{-2}) in a wetland receiving high P loading (Reddy et al., 1992). For Otter Creek, P storage by a variety of aquatic vegetation during their active growth phase accounted for 2.5 g m^{-2} (Reddy et al., 1996). However, the P storage in vegetation is not permanent, because the die-back of the above ground biomass results in the release of up to 80% of the stored P in the water column (Reddy et al., 1992). Phosphorus release by plant species was in the order of *Pisitia* > *Hydrocotyle* > *Polygonum* > *Pontedaria* > *Panicum* > *Juncus* (Reddy et al., 1992). Thus, it can be concluded that during a growing season, less than 20% of the P stored in the aboveground biomass is retained in the wetland and eventually becomes an integral part of the soil. Long-term storage P in the below-ground biomass was included in the total P storage estimates of the soil.

6. Phosphorus storage in the watershed

To estimate the P storage capacity in LKR and TCNS sub-watersheds of uplands and wetlands in the Lake Okeechobee Watershed, we have determined two parameters: (i) ambient P storage estimated using current total P content of the soil in the soil profile and (ii) maximum P retention capacity as estimated from batch isotherms and Langmuir equation parameters. Storage in aboveground biomass of vegetation was not included in watershed storage estimates because there is little long-term P storage in vegetation. Calculated P storage in uplands and wetlands is given in Tables 4 and 5, respectively. Average soil profile depth of upland soils was 119 cm (A, 20 cm; E, 72 cm; Bh, 27 cm). Soil depth used for calculating P storage in wetlands and stream sediments was 30 cm.

Average total P storage in upland pastures and rangeland was estimated to be about 1.02 t ha^{-1}. The total P storage in the watershed was 150000 t and 43000 t in LKR and TCNS watersheds, respectively (Table 4). However, the dairies in the LKR watershed are present in 65D, 65E and S-154 sub-

Table 4
Estimates of phosphorus retention capacity of upland soils in Lower Kissimmee River and Taylor Creek/Nubbin Slough watersheds

	Soil horizons		
	A	A+E	A+E+Bh
Soil depth (cm)	20	92	119
Lower Kissimmee River (North)			
Ambient P storage (t)	29800	61200	84400
Native P (t)	5800	16500	36400
Net accumulation (t)	24000	44700	48000
P import (t $year^{-1}$) [a]	253	253	253
P discharge (t $year^{-1}$) [a]	68	68	68
Net P retention (t $year^{-1}$)	185	185	185
P accumulation period (years)	130	240	260
Maximum P retention capacity (t)	22300	105000	264700
P saturation period (years)	120	570	1430
Lower Kissimmee River (South)			
Ambient P storage (t)	23100	47400	65400
Native P (t)	4500	12800	28200
Net accumulation (t)	18600	34600	37200
P import (t $year^{-1}$) [a]	545	545	545
P discharge (t $year^{-1}$) [a]	164	164	164
Net P retention (t $year^{-1}$)	381	381	381
P accumulation period (years)	49	90	98
Maximum P retention capacity (t)	17300	81400	205100
P saturation period (years)	45	210	540
Taylor Creek/Nubbin Slough			
Ambient P storage (t)	15200	31350	43200
Native P (t)	3000	8500	18600
Net accumulation (t)	12200	22850	24600
P import (t $year^{-1}$) [a]	811	811	811
P discharge (t $year^{-1}$) [a]	253	253	253
Net P retention (t $year^{-1}$)	558	558	558
P accumulation period (years)	22	41	44
Maximum P retention capacity (t)	11400	53800	135600
P saturation period (years)	20	96	240

[a] Values reported by Boggess et al. (1995).

Table 5
Estimates of phosphorus retention capacity of wetland soils in Lower Kissimmee River and Taylor Creek/Nubbin Slough Watersheds. Soil depth 30 cm

	Lower Kissimmee River		Taylor Creek/ Nubbin Slough
	North	South	
Ambient P storage (t)	23600	4500	4800
Native P (t) [a]	7600	1400	1500
Net accumulation (t)	16000	3100	3300
P import (t $year^{-1}$) [b]	68	164	253
P discharge (t $year^{-1}$) [b]	19	97	80
Net P retention (t $year^{-1}$)	49	67	173
P accumulation period (years)	327	46	19
Maximum P retention capacity (t)	22000	4100	4500
P saturation period (years)	449	61	26

[a] Phosphorus storage in native unimpacted wetlands was estimated to be 0.24 t P ha^{-1}.
[b] Values reported by Boggess et al. (1995).

watersheds. These sub-watersheds accounted for 43% of the total P stored in the whole watershed, which is approximately equivalent to 65 000 t. About 43% of the total P in the soil profile was accounted for by background levels, based on P storage in unimpacted native sites. Thus, in both watersheds, about 103 000 t were derived from inputs such as fertilizers, rainfall and wastes. This estimate assumes that P added was in contact with all three horizons of the soil profile. However, shallow water tables promote lateral flow and there may be limited contact with the Bh horizon. Thus, estimated P storages for A and A + E horizons were compared with the storages in all three horizons (Table 4). Estimated P imported into these two watersheds was 1600 t $year^{-1}$, and discharge from uplands was estimated to be 480 t $year^{-1}$, suggesting 70% retention in soils and vegetation (Boggess et al., 1995). The estimate for P accumulation in LKR may be high due to overestimation of the acreage of improved pasture relative to unimproved pasture. These estimates seem to be reasonable because the dairies and beef pasture were active in these watersheds only for the past 40 years.

Phosphorus storage in A, A + E and A + E + Bh horizons was estimated to be 0.36 t P ha^{-1}, 0.74 t P ha^{-1} and 1.02 t P ha^{-1}, respectively (Table 4). Results of these estimates suggest that at the current loading rate, P accumulation in A and E horizons had occurred during the past 90 and 40 years in the LKR-South and TCNS watersheds, respectively. Based on current P loads, there remains an additional 210 and 96 years to saturate all P sorption sites in the A and E horizons in the LKR-South and TCNS watersheds (Table 4).

Phosphorus discharged from uplands passes through wetlands and associated streams before it reaches the lake. Phosphorus stored in the surface 30 cm of wetland soils or stream sediments was estimated for both watersheds (Table 5). Ambient P storage was greater in LKR-North, as compared to storage in LKR-South and TCNS watersheds. Estimated P loads to wetlands are 0.3 g P m^{-2} $year^{-1}$, 2.8 g P m^{-2} $year^{-1}$, and 4 g P m^{-2} $year^{-1}$, in LKR-North, LKR-South and TCNS watersheds, respectively (Boggess et al., 1995). At these loadings, the P accumulation in wetlands represents 40 years and 24 years in LKR-South and TCNS watersheds, respectively, which approximately agrees with the P accumulation period in uplands.

7. Discussion

7.1. Phosphorus retention in uplands

Phosphorus imports to uplands occur primarily through animal feed and fertilizers, while the manure generated in the watershed is applied on the land as nutrient source. Fertilizer P is primarily in inorganic form, while manure P is in both inorganic and organic forms. The proportion of these forms are important to P availability for plant uptake and for transport in leaching and surface runoff. In a wide range of manure samples, (Paperzak et al., 1959) reported about 27% of the total P was in organic forms, and the remaining in inorganic forms. Data obtained for different types of manures indicate that the ratio of soluble P to total P is in the range 0.24–0.70, suggesting that a significant portion of P is associated with manure particles (Reddy et al., 1978). During heavy rainfall events, some manure particles can be transported in the surface runoff, resulting in transport of organic P. Most of the inorganic P added to surface soils is retained in the A horizon, thus increasing total P content (Graetz et al., 1996). For example, the amount of P accumulated in these soils was related to cattle density and dairy age (Graetz and Nair, 1995). The total P content of the soils increased 50–60 fold in intensive areas as a result of P loading from manure, while the P content of soils in the pasture areas increased three to four fold. Increases in P concentration were observed in all three horizons of the upland soil profile.

In uplands, the two major P storage components that store P are vegetation and soils (Fig. 3). The most common pasture is bahiagrass and P uptake capacity of this grass is limited. This uptake accounts for about 3000–7000 t of P in the whole LKR and TCNS watersheds, representing about 2–4% of total P storage. Since P bound in the grass is grazed by cattle, much of it is returned to the soil as manure. Thus, P cycling associated with application of fertilizers maintains annual net P storage in the vegetation in the range of 2–4 g P m^{-2}. During senescence, a significant portion of the grass can be accumulated as detrital material, thus increasing the organic P pool in the A horizon. No information is available on the contribution of detrital P to overall soil P storage, although estimates presented in Table 4 include this pool of P. The P bound in the residual organic pool (i.e. the detrital tissue resistant to decomposition) represents long-term storage while P in the live vegetation represents short-term storage.

Phosphorus stored in soils can be grouped into the following major pools: (i) labile inorganic P; (ii) P bound to Fe and Al minerals; (iii) P bound to Ca and Mg minerals; (iv) P bound in labile organic forms; (v) residual organic P. Phosphorus present in the labile pool is of major concern, because this pool potentially can be removed from the soil during rainfall events. The P stored in this pool increased with P loading (Table 2). In the A, E and Bh horizons of the soils in the pasture areas (Table 2), up to 9, 6, and 0.7% of the total P was in labile pool, respectively. Repeated water extractions of soils from several dairy sites resulted in removal of 2–18% of total P (Graetz and Nair, 1995). Under field conditions P would probably be released at slower rates than those observed under laboratory conditions. During most runoff events, P is leached into the soil from decomposing manure and increases the porewater concentration that temporarily increases the labile fraction. A significant proportion of labile P is removed from the soil during the first event, followed by a steady decrease with time.

Phosphorus leached from the surface A horizon accumulates in sub-surface E and Bh horizons. The

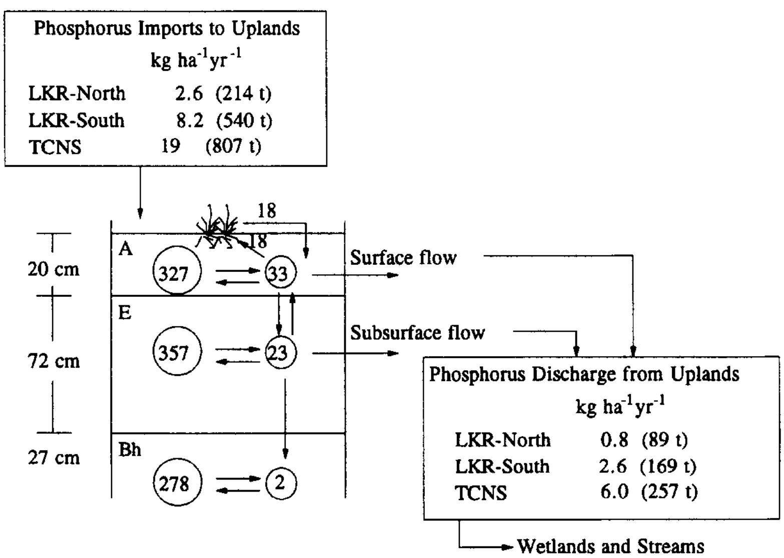

Fig. 3. Phosphorus budget for uplands (pasture areas) of Lower Kissimmee River and Taylor Creek/Nubbin Slough Watersheds. All storages are expressed as kg P ha^{-1}.

E horizon is sandy, low in Al and Fe oxides, and has poor P retention capacity (Yuan and Lucas, 1982; Graetz and Nair, 1995). These conditions result in rapid movement of P through this horizon into the underlying Bh horizon, which has a high retention capacity. High P sorption capacity of the spodic horizon represents long-term P storage. However, water flow through spodic horizon is limited, and much of the flow is through sub-surface. Thus, the contact of P containing water with spodic horizon is limited to surface layers of Bh horizon. Phosphorus bound to Al and Fe oxides in the spodic horizon is stable. Highly significant correlation between P retention capacity and oxalate-extractable Al and Fe indicates the dominant role of Al and Fe in retaining P (McKeague and Day, 1966). In addition to retention of inorganic P, Graetz and Nair (1995) also observed 14–20% of P in the A horizon to be alkali-extractable organic P, compared with 30–59% in the E horizon and 25–50% of that in the Bh horizon. The large pool of organic P in E and Bh horizons supports the hypothesis that organic P is mobile in the soil profile. However, P in surface and sub-surface flow leaving the watershed is predominantly in inorganic form, suggesting most of the soluble organic P is retained within the profile or mineralized into inorganic forms. Results of soil P fractionation reported by (Graetz and Nair, 1995) show that up to 90% of the total P is in stable form, and only 10% is labile and potentially available for transport. However, the labile pool is continuously regenerated either through application of fertilizers and organic residues or through new equilibrium conditions between stable and labile pools.

Upland soils play a major role in P retention in the Lake Okeechobee Watershed. Of the total P retained in the watershed, up to 85% is in the uplands, while the remaining 15% is in wetlands and streams. Although upland soils have a large capacity to retain P, continuous P loading will decrease retention capacity of soils and increase EPC, resulting in elevated levels of P in surface and sub-surface flows (Reddy et al., 1978).

7.2. Phosphorus retention in wetlands and streams

Phosphorus is discharged from uplands, usually through wetlands and streams, before being discharged into the lake, providing additional storage for P (Fig. 4). The ability of wetlands and streams to

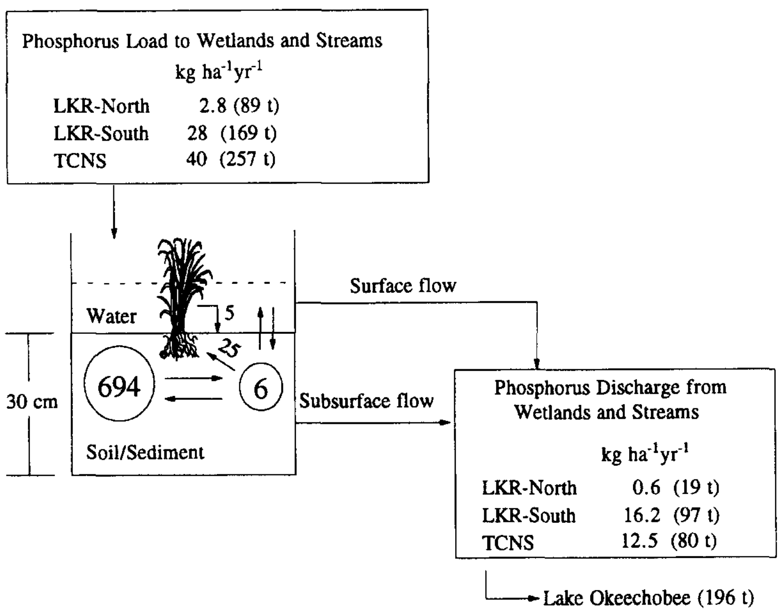

Fig. 4. Phosphorus budget for wetlands and streams located in Lower Kissimmee River and Taylor Creek/Nubbin Slough Watersheds. All storages are expressed as kg P ha^{-1}.

assimilate P depends on physical, chemical, and biological characteristics of each system. Many case studies have shown wetlands as net assimilators of P. Long-term studies at Houghton Lake (Michigan) wetland have shown consistent P removal of 97% for the past 15 years (Kadlec, 1993). After a decade of P loading at 34 g P m^{-2} $year^{-1}$ to a wetland in New Zealand, Cooke (1992) reported about 28–70% removal of P. Based on laboratory experiments (Reddy et al., 1995) and field studies (Goldstein, 1986), we estimated P removal of 45 ± 3% ($R^2 = 0.854$; $n = 21$) by various wetlands and streams in the LKR-South and TCNS watersheds.

Several biogeochemical processes account for P assimilation in wetlands and streams. These include uptake by plants (Reddy and DeBusk, 1987) and microbes (Wetzel, 1990), and adsorption onto organic and inorganic components in wetland soils and stream beds (Froelich, 1988). The significance of each of these processes depends on the physical characteristics of a wetland, flow path, hydraulic retention, type of vegetation, and characteristics of soils and sediments (Kadlec 1993).

Phosphorus storage in vegetation is usually small compared to the overall storage in soils and sediments. Plants play an important role in depleting soluble P and converting it into more stable forms. However, phosphorus storage in emergent vegetation is usually short-term, because a large portion of tissue P is released back into the water column during decomposition of detrital tissue. During dormancy phases and senescence of aboveground biomass of emergent macrophytes, a significant amount of P is translocated to below ground biomass (Wetzel, 1990). Phosphorus released from detrital tissue can be readily used by periphytic communities (Wetzel, 1990). These interactions, associated with undecomposed organic matter (derived from detrital plant and periphyton tissue) accumulate on the soil surface. The accreted organic matter, finally, becomes part of the soil. The litter from woody plants provides long-term storage, because their decomposition rates are usually slow (Reddy et al., 1992). The detrital material that is incorporated into the soil has high P content, resulting from microbial immobilization (Howarth and Fisher, 1976; Howard-Williams, 1985).

Wetland soils and stream beds are dominated by mineral matter, although the surface horizons of wetland soils in the Lake Okeechobee Watershed are highly organic (Scinto, 1991). For wetlands and stream sediments, a significant relationship was observed between oxalate-extractable P and Fe and Al ($r = 0.89$; $P = 0.001$). Association of P with these forms strongly suggests that P is either adsorbed or complexed with Al and Fe. Phosphorus fractionation of wetland soils and stream sediments revealed that most of the P is associated with amorphous and poorly crystalline forms of Al and Fe, and organic P (Reddy et al., 1995). Labile P accounted for less than 1% of the total P suggesting strong buffering capacity. For wetland soils and stream sediments high in Fe oxides, oxidation–reduction influenced by hydroperiod can potentially enhance P retention (Sah and Mikkelsen, 1986). However, in the Lake Okeechobee Watershed, P retention by Al oxides is much greater than Fe oxides, suggesting that oxidation–reduction reactions have minimal effect on P solubility.

In wetlands and streams, P retention is regulated by diffusion of P from the water column to the underlying soil or sediment or vice versa. Retention occurs primarily at the oxidized soil–floodwater interface. This associated with the accumulation of particulate matter (including detrital plant tissue), readsorption by Fe and Al oxides provides long-term P storage.

8. Conclusions

An analysis of the P storage of capacity of uplands, wetlands and streams indicated that about 80% of the total P imported into the LKR and TCNS watersheds was retained in uplands. An additional 10–15% of the total P was retained in wetlands and streams of the watershed. Upland soils, dominated by Spodosols, were found to be major sinks for P loaded to the system. Most of the P retained was in the non-labile pool, with about 10%, 6%, and 1% of the total P in labile pools in A, E and Bh horizons, respectively. Similarly, most of the P loaded to wetlands and streams were retained in soils and sediments. About 1% of the total P was stored a labile P.

Vegetation in uplands played a minor role in P storage, with much of the P removed in pasture grass cycled through dairies and returned to the soil as manure. In wetlands, over 80% of the P stored during active growth phase of vegetation was released into the water column during senescence and decomposition of the detrital tissue.

At current P loading rates, uplands have about 75% of their storage capacity remaining, compared with 45% in wetlands and streams. Accumulation of P in upland soils suggests that P retained is in relatively stable forms. However, increased P accumulation can reduce the soil buffer capacity to retain P and increase soil porewater P concentrations, which can potentially increase P concentration in surface waters.

Management strategies in uplands should include techniques to contain P on site, and improve the capacity of soils to retain P. Wetlands and streams can function as effective sinks, because they offer long flow paths between upland sites and the receiving water body. The overall P retention capacity of wetlands can be improved by altering flow paths to increase the hydraulic retention time.

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