Final Report

Task 2
EVALUATION OF EXISTING INFORMATION

For Project Entitled

Technical Assistance in Review and Analysis of Existing Data for Evaluation of Legacy Phosphorus in the Lake Okeechobee Watershed

Prepared for

South Florida Water Management District

by

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In association with

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List of Abbreviations

AgNMPs	Agricultural Nutrient Management Plan
Al	Aluminum
BAT	Best Available Technologies
BMP	Best Management Practice
Ca	Calcium
CERP	Comprehensive Everglades Restoration Plan
cm	Centimeters
DAP	Double Acid Phosphorus
DPS	Degree of Phosphorus Saturation
EMC	Event Mean Concentration
EPA	Environmental Protection Agency
FDACS	Florida Department of Agriculture and Consumer Services
FDEP	Florida Department of Environmental Protection
Fe	Ferric
FWS	Fish and Wildlife Service
GIS	Geographic Information System
GUI	Graphical User Interface

ha	Hectares
HWTT	Hybrid Wetland Treatment Technology
IFAS	Institute of Food and Agricultural Sciences
kg	Kilograms
LOER	Lake Okeechobee & Estuary Recovery
LOFT	Lake Okeechobee Fast Track projects.
MAX	Maximum
mg	Milligrams
Mg	Magnesium
MIN	Minimum
mt	Metric Tons
NPDES	National Pollutant Discharge Elimination System
NRCS	Natural Resources Conservation Service
P	Phosphorus
ppm	Parts per million
PQT	Phosphorus Quick Test
RASTA	Reservoir Assisted Stormwater Treatment Area
SAV	Submerged Aquatic Vegetation
SFER	South Florida Environmental Report
SFWMD	South Florida Water Management District
STA	Stormwater Treatment Area
STD	Standard Deviation
TP	Total Phosphorus
UF	University of Florida
USACE	United States Army Corps of Engineers
WSP	Water Soluble Phosphorus
WTR	Water Treatment Residual
yr	Year

1.0 INTRODUCTION

Legacy phosphorus (P) is defined as phosphorus within the watershed that is present as the result of anthropogenic activities and has transport potential to Lake Okeechobee. Antecedent P is defined as the P that occurs naturally in soils based on the properties of the soils and atmospheric deposition and rainfall. Anthropogenic activities in the Lake Okeechobee watershed have resulted in more imported P into the watershed, as fertilizer, animal feed, and domestic goods, than has been exported resulting in the accumulation of P in soils, waste storage facilities, and landfills. Though the process of P accumulation has been occurring since the late eighteen hundreds, the majority of the accumulation has occurred over the past fifty years. The first major import of P was as fertilizer used for a developing vegetable crop industry around 1915 to 1920, but the vegetable farms disappeared after a brief time due to hard freezes and therefore little P accumulation occurred (VanLandingham and Hetherington, 1978). From 1930 to 1940, a significant increase in the cattle business occurred with beef cattle going from 17,000 head in Okeechobee County in 1930 to 45,000 in 1940. Phosphorus fertilizer was used on beef pasture at this time, but was fairly limited due to costs and low animal densities. Beef cattle pastures were fertilized more aggressively starting in the 1940s and up through the 1980s, which is the period of the greater legacy P build up. Phosphorus fertilization on beef pastures was essentially stopped during the 1990s.

The period starting in the late 1940s through the early 1960s saw dairy farms from the southeast coast of Florida move into the area. At their peak during the 1970s there were more than 45 dairies in the northern Okeechobee basins. More than half of these dairies have since closed as part of the Dairy Buyout Program in the mid to late 1980s and economic pressures. Most of these dairies operated without waste management systems until the 1960s when the US Soil Conservation Service constructed lagoons and seepage fields on most of the dairies. Other best management practices, such as stream fencing, were started on the dairies in 1979. By 1988, all of the dairies were operating under FDEP Dairy Rule permits that required BMPs on all dairies. As these permits were transferred to NPDES (EPA) permits, starting about the year 2000, each dairy was required to show nutrient balancing across the dairy, which in some cases required additional BMPs.

Residential and urban development also increased in the basin with its most rapid growth occurring during the last 20 years. The legacy P associated with residential and urban development is from landscape fertilization, the accumulation of P in drain fields and septic tanks, municipal sludge from wastewater treatment plants, and landfills.

The legacy P literature and data reserves that were identified during the first task were reviewed and evaluated for their ability to quantify legacy P and address the associated legacy P questions of mobility and abatement within the Okeechobee basins. The evaluation first reviewed available studies and data to determine if the amount of legacy P present in the basin could be estimated to a reasonable degree of accuracy. Next, these and other studies were reviewed to estimate the mobility of the existing legacy P for transport to Lake Okeechobee, which relates directly to determining the longevity of this legacy P influence and what potential practices or treatment technologies are available to reduce P loads to the lake.

2.0 QUANTIFICATION OF LEGACY P

It will be necessary to quantify the spatial distribution of legacy P within the watershed to understand the current and future impact of legacy P on Lake Okeechobee. The two primary pools of legacy P are those that can become mobile and move to Lake Okeechobee and those that are contained or become irreversibly sorbed on soil particles and thereby have little or no chance of moving to the lake. Most of the mobile forms are located within the soils across the watershed and therefore soil test data will be the most useful tool for quantifying this pool of legacy P whereas the non-mobile pools, such as waste ponds and landfills, can only be estimated based on net P balances. The P that becomes strongly sorbed to soil particles that may eventually become irreversibly sorbed is not well known, but is expected to be a relatively small fraction so for this assessment irreversibly sorbed P was assumed negligible.

Reddy et al. (1996) completed the first comprehensive study to quantify legacy P or as they called it "storage" P in the Northern Lake Okeechobee basin, i.e. they did include the Upper Chain of Lakes or Lake Istokpoga basins (see Figure 10 in later section for basins layout). They used available soils data from their own work as well as others to estimate the native and net accumulated TP or legacy P for animal operations. They estimated the net accumulative TP for uplands and wetlands in the Northern Lake Okeechobee basin to be about 150,000 and 22,400 metric tons (mt), respectively. Our current study follows an approach similar to Reddy et al. (1996) for estimating legacy P, but covers mobility and abatement strategies in greater detail.

2.1 Legacy P Estimates Based on Field Research and Soil Testing

This section summarizes the results of various studies that were conducted in and around the Lake Okeechobee watershed to evaluate the soil P levels as influenced by various land use activities. The objective for reviewing these data was to establish legacy P values by comparing soil P levels between impacted and non-impacted (native) areas. The estimated legacy P results from the evaluated studies are summarized in Table 1 and are discussed below. The types of P analyses done in these studies included total P (TP), water soluble P (WSP), Mehlich-1 or double acid P (DAP), Mehlich-3 P, a sequential extraction procedure to determine labile P, Al/Fe-P, and Ca/Mg-P, and a Kjeldahl digestion procedure to fractionate organic versus inorganic P. Only TP, WSP, and Mehlich-1 P are presented in Table 1 because they were the most common and relevant to legacy P determination. Legacy P in Table 1 was determined based on the difference between concentrations of TP for the impacted soil and TP for most comparable non-impacted soil. Where studies did not measure TP directly, TP was estimated based on correlations to other P analyses as determined from other studies on similar soils that did both analyses. Legacy P, in terms of kg/ha, was calculated based on the Legacy P concentration, specific weight of the soils, and the assumed soil depths per soil horizon (typically, A = 15cm, E = 45cm, Bh = 30cm and Bw = 32cm). The resulting formula is:

$$\text{Legacy P (kg/ha)} = \text{TP (mg/l)}/[10000(\text{mg/l/\%})] \times \text{Layer Thickness (cm)} \times [\text{Soil (Sand) Specific Weight} = 14570\ (\text{kg/ha/cm}_{depth})]$$

Table 1. Soil P and Associated Legacy P Data from Various Research and Technical Sources.

Land Use	Horizon Class/cm	TP (mg/kg)	Mehlich-1 (mg/kg)	DPS-1[1] (%)	WSP (mg/kg)	Legacy P[2] (mg/kg)	Legacy P[2] (kg/ha)	Relative Mobility[4]	Source
Intensive -Dairy	A	1885	400		69	1855	4860	High	Graetz and Nair (1995)
	E	152	42		15	136	821	High/Medium/Low[3]	
	Bh	183	79		17	116	515	Very Low	
	Bw	155	61		18	95	456	Very Low	
Holding –Dairy	A	685	453		53	655	1716	High	Graetz and Nair (1995)
	E	70	20		10	54	326	High/Medium/Low[3]	
	Bh	148	48		8	81	360	Very Low	
	Bw	104	20		4	44	211	Very Low	
Dairy Low Impact Areas	A	146	20		11	116	304	High	Graetz and Nair (1995)
& Beef Pasture	E	29	6		2	13	79	High/Medium/Low[3]	
	Bh	10	39		2	0	0		
	Bw	15	6		1	0	0		
Dairy Forage Crop	A	45	10		2	15	39	High	Graetz and Nair (1995)
	E	21	3		1	5	30	High/Medium/Low[3]	
	Bh	52	13		1	0	0		
	Bw	50	7		0	0	0		
Native Soils	A	30	3		1	0	0		Graetz and Nair (1995)
	E	16	5		1	0	0		
	Bh	67	6		0	0	0		
	Bw	60	8		0	0	0		
Wetlands Improved	Ap	550	-		-	100	44	High	Gathumbi et al. (2005)
Beef Pastures	Eg	210	-		-	20	44	High/Medium/Low[3]	
	Bt	60	-		-	10	22	Very Low	
	Cg	40	-		-	0	0		
Wetlands Semi-native	Ap	450	-		-	0	0		Gathumbi et al. (2005)
Beef Pastures	Eg	190	-		-	0	0		
	Bt	50	-		-	0	0		
	Cg	50	-		-	0	0		
Improved Beef Pasture	A	367	-		-	258	564	High	Zielinski et al. (2006)
	E	44	-		-	0	0		
Semi-Native	A	263	-		-	154	337	High	Zielinski et al. (2006)
	E	16	-		-	0	0		

Land Use	**Horizon** Class/cm	**TP** (mg/kg)	**Mehlich-1** (mg/kg)	**DPS-1**[1] (%)	**WSP** (mg/kg)	**Legacy P** (mg/kg)	(kg/ha)	**Relative Mobility**	**Source**
Iso. Wetland - Dairy	0-10	1080	-	-	-	577	841	Low	Reddy et al. (2004)
Iso. Wetl. - Imp Past.	0-10	576	-	-	-	73	106	Low	Reddy et al. (2004)
Iso. Wetl. - Unimp Past.	0-10	503	-	-	-	0	0		Reddy et al. (2004)
Native	A	109	-		-	0	0		Zielinski et al. (2006)
	E	47	-		-	0	0		
Summer Beef Pasture	0-5	80	* 40	-	35	51	37	High	Capece et al. (2007)
Improved	5-10	27	14	-	6	13	10	High/Medium/Low[3]	
	10-20	17	9	-	2	12	17	High/Medium/Low[3]	
	20-30	14	7	-	1	12	17	Low	
Winter Beef Pasture	0-5	29	15	-	10	0	0	High	Capece et al. (2007)
Semi-Native	5-10	14	7	-	3	0	0	High/Medium/Low[3]	
	10-20	5	3	-	1	0	0	High/Medium/Low[3]	
	20-30	2	1	-	0	0	0	Low	
Abandoned - Intensive	A	2530	1360	480	33	2496	5458	High	Nair and Graetz (2002)
	E	147	124	381	13	133	874	High/Medium/Low[3]	
	Bh	572	362	227	22	496	2171	Very Low	
	Bw	246	118	83	12	179	834	Very Low	
Abandoned - Holding	A	574	419	193	16	540	1181	High	Nair and Graetz (2002)
	E	111	78	595	14	97	638	High/Medium/Low[3]	
	Bh	609	435	42	17	533	2332	Very Low	
	Bw	270	90	11	4	203	946	Very Low	
Active - Intensive	A	1900	309	113	72	1866	4080	High	Nair and Graetz (2002)
	E	251	66	82	23	237	1556	High/Medium/Low[3]	
	Bh	183	79	10	17	107	470	Very Low	
	Bw	151	66	13	19	84	391	Very Low	
Active - Holding	A	514	268	107	31	480	1050	High	Nair and Graetz (2002)
	E	82.6	16	28	8	69	452	High/Medium/Low[3]	
	Bh	156	47	2	6	80	352	Very Low	
	Bw	132	18	2	1	65	303	Very Low	
Pasture	A	46	7	6	2	13	28	High	Nair and Graetz (2002)
	E	23	4	11	1	9	60	High/Medium/Low[3]	
	Bh	82	43	4	2	6	28	Very Low	
	Bw	44	5	1	0	0	0		

Land Use	Horizon	TP	Mehlich-1	DPS-1[1]	WSP	Legacy P		Relative	Source
	Class/cm	(mg/kg)	(mg/kg)	(%)	(mg/kg)	(mg/kg)	(kg/ha)	**Mobility**	
Beef Pasture	A	44	15	20	2	10	22	High	Nair and Graetz (2002)
	E	24	2	4	1	10	64	High/Medium/Low[3]	
	Bh	32	5	1	1	0	0		
	Bw	65	8	1	1	0	0		
Forage	A	38	6	5	1	4	9	High	Nair and Graetz (2002)
	E	21	3	4	0	7	46	High/Medium/Low[3]	
	Bh	57	14	1	0	0	0		
	Bw	67	8	1	0	0	0		
Native	A	34	3	1	1	0	0		Nair and Graetz (2002)
	E	14	1	4	0	0	0		
	Bh	76	6	0	0	0	0		
	Bw	67	8	3	0	0	0		
Abandoned - Intensive	A	477	116	0	13	355	776	High	Pant et al. (2002)
	E	55	34	0	11	21	138	High/Medium/Low[3]	
	Bh	365	218	0	9	300	1312	Very Low	
Active - Intensive	A	324	125	0	7	202	442	High	Pant et al. (2002)
	E	54	28	0	5	20	131	High/Medium/Low[3]	
	Bh	98	40	0	4	33	144	Very Low	
Pasture/Forage	A	103	10	0	3	0	0		Pant et al. (2002)
	E	26	6	0	1	0	0		
	Bh	63	21	0	1	0	0		
Sprayfield	A	73	4	0	2	0	0		Pant et al. (2002)
	E	4	1	0	0	0	0		
	Bh	67	22	0	1	2	9	Very Low	
Grazing Pasture	A	132	11	0	4	10	22	High	Pant et al. (2002)
	E	13	1	0	0	0	0		
	Bh	65	30	0	2	0	0		
Native	A	122	4	0	4	0	0		Pant et al. (2002)
	E	34	4	0	1	0	0		
	Bh	65	4	0	0	0	0		
Abandoned - Impacted	A	2091	-	-	-	1987	8688	High	Josan et al. (2005)
Active Dairy - Impacted	A	2334	-	-	-	2230	9751	High	Josan et al. (2005)
Minimally - Impacted	A	104	-	-	-	0	0	Low	Josan et al. (2005)

Land Use	**Horizon**	**TP**	**Mehlich-1**	**DPS-1**[1]	**WSP**	**Legacy P**		**Relative**	**Source**
	Class/cm	(mg/kg)	(mg/kg)	(%)	(mg/kg)	(mg/kg)	(kg/ha)	**Mobility**	
Citrus	A	284	-	-	23	180	394	Low	Yu et al. (2006)
	A	115	-	-	16	11	24	Low	
	A	196	-	-	22	92	201	Low	
	A	205	-	-	25	101	221	Low	
	A	262	-	-	10	158	345	Low	
	A	96	48	-	-	46	173	Low	Mylavarapu (2007)
Improved Pasture –Bahia	A	82	41	-	-	32	143	High	Mylavarapu (2007)
Improved Pasture-Other	A	74	37	-	-	24	125	High	Mylavarapu (2007)
Lawns	A	90	45	-	-	40	160	High	Mylavarapu (2007)
Hay - Forage	A	78	39	-	-	28	134	High	Mylavarapu (2007)

* Orange indicated that the values were calculated based on Mehlich-1 P

[1] DSP-1 is the Degree of P Saturation (%) as calculated using an oxalate extractant = DAP/ [α (OxFe +OxAl)] x 100

[2] The legacy P is calculated as the soil's TP minus

[3] Medium/High for well drained soils and Low if poorly drained

[4] The relative mobility is based on the relative hydraulic transport and extractability of P from the P.

The relative mobility of P, if discussed in these soils studies will also be presented, but mobility will be further discussed in the following section.

Chen and Ma (2001) did a statewide study to evaluate the TP levels in impacted and non-impacted soils across Florida by soil order. They evaluated 448 soil samples from a pool of over 8,000 samples to evaluate the TP in the surface horizon for the seven major soil orders in Florida including (listed by dominance in basin) spodosols, entisols, histosols, and alfisols, which are the dominant soil orders in the Lake Okeechobee watershed. Though this study did not focus on the Lake Okeechobee watershed, their results for the non-impacted areas provide a good estimate of the mean and range of TP values for the various soil orders across the watershed as provided in Table 2. Their paper also provides a map of TP levels across Florida which clearly shows that the watershed has some of the lowest native TP levels in Florida because of the dominance of the spodosols. The entisols (well drained sands) have slightly higher TP levels than the spodosols, while the histosols (organic soils in pocketed and isolated wetlands) have relatively high native TP levels.

Table 2. TP Levels in Non-Impacted Soils across Florida (Chen and Ma, 2001).

Soil Order	Range of TP (mg/kg)	Mean of TP (mg/kg)
Spodosols	5-320	24
Entisols	5-1360	53
Histosols	50-1360	350
Alfisols	10-490	54

Reddy et al. (2004) conducted a comprehensive study to evaluate P retention and storage by isolated and constructed wetlands in the four Okeechobee priority drainage basins. They did extensive work identifying and categorizing wetlands using GIS and aerial imagery. They categorized isolated wetlands as either being associated with dairies, improved pastures, or unimproved pastures. They collected and evaluated data for over 110 wetlands for P content, distribution, and speciation (Figure 1). They noted that the land use variability for dairies confounded the statistical assessment, but the results still showed higher P levels for dairies as compared to improved and unimproved pastures with unimproved pastures having the least P (Table 1). The legacy P within isolated wetlands was estimated based on the assumption that unimproved pastures would be relatively un-impacted. Using their estimate of over 12,000 ha of isolated wetlands in the four priority basins of which about 8% were associated with dairies, 56% with improved pastures, and 17 % with unimproved pastures, it can be calculated that approximately 800 and 700 mt of legacy P exists in dairy and improved pasture isolated wetlands, respectively. The study also evaluated the dynamics and related modeling approaches for P transport in isolated and constructed wetlands, which will be discussed further in the later section on mobility.

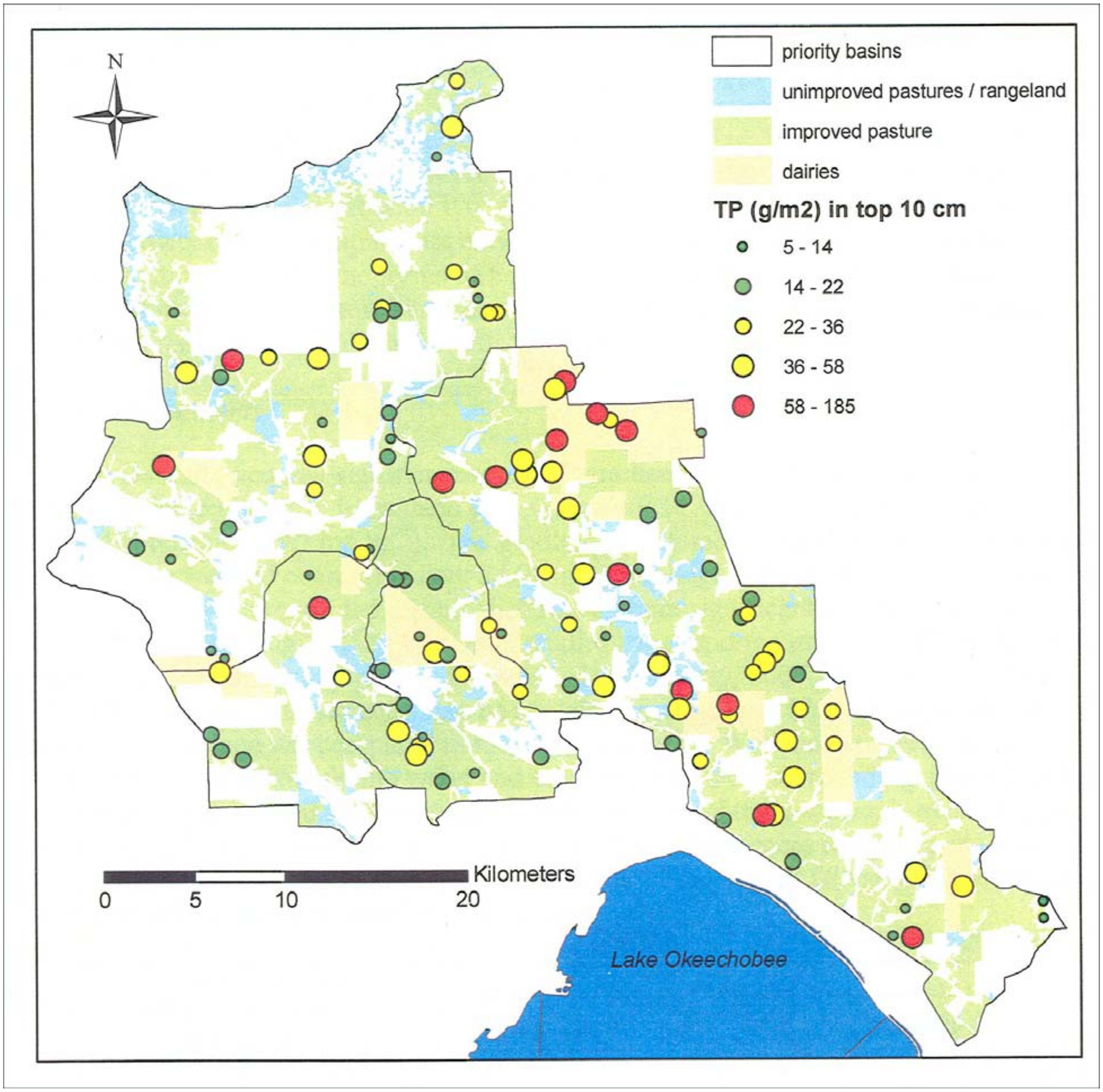

Figure 1. Land Uses (2003) and TP (g/m^2) Stored in Surface Soils (0-10cm) [Reddy et al].

Another study of nutrient enrichment in wetland vegetation and sediments in subtropical pastures was conducted by Gathumbi et al. (2005). They found that wetland areas within improved pastures had higher TP in the organic detritus materials and the top 15 cm of sediment than for similar wetlands within semi-native pasture that did not have historic fertilization (Table 1). Sediment below 15 cm did not show a difference. They found about 15 - 25% higher TP levels in the shallow sediments for wetland soils in the improved over semi-native pastures. Another study by Zielinski et al. (2006) tried to assess the amount of fertilizer sourced P in non-wetland improved pastures by comparing TP and isotopes of uranium and sulfur to low impact native and semi-native soils (Table 1). The sulfur analyses proved to be inconclusive because of high native sulfur levels, but the TP levels were found to be sufficiently elevated in the improved pastures and appeared to be sourced from fertilizer based on the uranium data. The improved pasture TP concentrations were about three times higher than the native soils for the upper 15 cm of soil, but were not significantly different from the semi-native pastures. Below 15 cm the TP levels were similar indicating limited downward movement of P. The uranium data also verified limited downward movement of P below 15 cm. Zielinski et al. also assessed uranium and TP in runoff and found that P and uranium were getting into the runoff that was mainly coming from mineralization of organic matter and sediment erosion, and therefore suggested that practices should focus on these sources.

Capece et al. (2007) evaluated the effect of grazing and fertilization practices for two pasture types at the Buck Island Ranch. This study was part of a larger integrated ecological and economic research program for the ranch (Swain et al., 2007). For Capece et al.'s study, the pasture types were referred to as summer and winter grazing, which appeared to follow the general definition of improved versus semi-native pastures. The winter pastures were generally wetter areas with greater non-grass vegetation. Capece et al. found that P concentrations in runoff from the summer pastures was about 4.2 times greater than the winter pastures and that P loads in runoff were about 7-fold greater. Mehlich-1 and water-soluble P (WSP) by soil depth also showed a similar P concentration difference down to 30 cm where P levels were between 2 to 3 times greater in the summer pastures as compared to the winter pastures (Table 1). This study did indicate that P was migrating deeper into the soil than some of the other studies. The primary conclusion for the P differences was associated with historic fertilization practices and not grazing densities.

Dunne et al. (2007) studied P levels in field ditches and its implications for water quality. They postulated that field ditches would likely accumulate P from upland areas, but they found that the soil P levels were more similar to the uplands than the downstream wetlands. Considering the relatively small area of fields in the basin, it was assumed for our legacy P assessment that field ditch P could be assumed to be part of the upland soil legacy P assessment.

Graetz and Nair at the University of Florida conducted several studies to evaluate the status and fate of P in dairy and beef manure impacted soils (Graetz and Nair, 1995; Graetz et al. 1999; Nair et al.,1995; Nair et al.,1998; Nair et al.,1999; Nair et al.,2003). These comprehensive studies measured the TP and several fractionations of P, such as WSP, DAP (Mehlich-1), labile P, Al/Fe-P and Ca/Mg-P concentrations for the A, E, and Bh horizons for high (dairy only), low (dairy and beef), and non-impacted (forested) areas. They found that the A horizon had the highest TP levels for each land use as compared to the non-impacted area, but the lower E, Bh, and Bw horizons were only higher for the high manure laden areas, such as the holding areas and intensive pastures (Table 1). The fractionation and additional adsorption isotherm analyses for the P make this study extremely valuable for both quantifying the amounts of P and ranking its potential mobility. The P in the high manure laden fields was found to be associated/bonded with calcium and magnesium complexes as compared to the P in the lower layers being more associated with aluminum and iron, particularly in the Bh horizon (spodic). The Ca/Mg-P bonds tend to be weaker and more dependent on pH levels than the Al/Fe bonds, which increases the mobility of the Ca/Mg-P. This does indicate that the lowering of pH in the high manure impacted fields could result in increased releases of P to runoff. Nair and Graetz (2002) used the field data from their earlier studies to develop a degree of P saturation (DPS) parameter that can be used to determine the soil's ability to retain or adsorb additional applied P. Chrysostome, et al (2007) extended the DPS concept into the Soil P Storage Capacity (SPSC). These parameters are based on P sorption isotherms that were done in the laboratory for each of the soil horizons. When they compared DPS to WSP they found that WSP did not increase significantly until the DPS values were above about 25%, which could be considered a saturation point. This means that the soils below this DPS level could potentially hold additional P without increasing P concentrations in discharge water. They found that the A, E, and Bh horizons for high manure impacted soils were saturated by as much as five-fold (A horizon) and that only the Bw horizon below the spodic horizon had not exceeded the saturation point. The soils in the forage and pasture areas were only between 4 to 80% of this saturation point, which meant that they could retain additional applied P without increasing P concentration significantly.

Villapando and Graetz (2001a;2001b) further investigated the importance of the Bh or spodic horizon for P adsorption and desorption processes. They found that Bh horizon had a significant but limited adsorptive capacity and that Al played the dominant role in this process. They evaluated the influence of water table movement through the horizon and found that adsorption rates were only mildly influenced by the anaerobic incubation and that nearly 70% of the adsorbed P was irreversibly bonded. Their results appear to indicate that the spodic horizon can retain a significant amount of P, which would limit P movement through the Bh horizon until P saturation is reached. P saturation was only found in high in manure laden soil on dairies (Nair and Graetz, 2002). However, much of the accumulated P would be available to plants, but a very limited amount would likely be available for lateral groundwater flow above the Bh horizon.

Pant et al. (2002) completed a study on the Newcomer and New Palm abandoned dairy sites, which was similar to the Graetz and Nair series of studies. This study was completed to evaluate the potential impacts on a future stormwater treatment area (STA) being proposed at these sites. The results were very similar to the Graetz and Nair studies and were added to the legacy P data source spreadsheet that was developed for this study (Table 1). They assessed the potential P release rate of the DAP into the STA once flooded and found it could take up to three years before the DAP would stop fluxing into the water column. Josan et al. (2005) studied the P content and mobility of P from active and abandoned dairy soils and minimally impacted soils. They found that the A horizon P levels in abandoned (2,100 mg/kg) were only slightly less than those (2,300 mg/kg) found on active dairies, which means that after ten years of abandonment these previous dairies still have nearly the same potential for P losses as active dairies.

Wang et al. (1995) also investigated the leaching potential of dairy manure impacted soils, but they additionally looked at an associated stream sediment samples. They found that the stability of P bonding is in the following order: Ca and Mg > Al and Fe for alkaline conditions, but is reversed for acidity conditions, which is more common condition in Okeechobee soils. They also found that there are poisoning ions that limit the preferred Ca bonding, which results in high P losses. They suggested that pH control and soil amendments could encourage the more favorable binding, but did not test these during their study.

To further evaluate the potential legacy P of abandoned and active dairies, a series of animal nutrient management assessments (EWR, 2003; SWET, 1999) that were completed for the Florida Department of Agriculture and Consumer Services (FDACS) were reviewed. These studies included all of the active dairies and most of the abandoned dairies in the basin. As part of the assessments, the dairy soils were intensively sampled and analyzed by the UF Soil Testing Laboratory for Mehlich-1 P. These soils data were reviewed to determine a mean Mehlich-1 P by land use across all of the dairies as provided in Table 3. Because only Mehlich-1 P was analyzed, a correlation between Mehlich-1 P and TP, which was determined from Graetz and Nair's work, had to be used where TP was found to be approximately 5 times Mehlich-1 P. Therefore, the legacy P values in Table 3 should be considered as very rough estimates with uncertainties in the order of ±30%.

Table 3. Mean Mehlich-1 P Concentrations across 19 Active and 5 Abandoned Dairies for Surface A Horizon.

Land Use	**Mean Mehlich-1 P (ppm)**	**TP (mg/kg)**	**Legacy P (kg/ha)**
High Intensive Areas	587	2935	6387
Lactating/Holding Pastures	351	1755	3807
Dry Cow Pastures	167	835	1795
Sprayfields	23	115	221
Hayfields	22	110	210
Minimum Impact Areas	3	14	0

Yu et al. (2006) studied P fractions in the top soils for five citrus groves in South Florida. The TP levels and other P fractions of soils under citrus were higher (Table 1) than were observed for native soils from other studies. They correlated phosphatase activities as fractionated by the Hedley fractionation procedure to P concentrations in runoff that ranged from 0.51 to 2.64 mg/l. Runoff P was found to be correlated with most of the extractable fractions of P.

Studies in other areas, such as Allen et al. (2005) and Allen and Mallarino (2006) in Iowa and Haggard and Soerens (2006) in the Illinois River basin showed similar responses for TP and extractable forms of P to fertilizer and manure applications. Allen and Mallarino (2006) evaluated the relationships between extractable soil P and P saturation for long-term organic and inorganic fertilizer applications. Their findings verify that the accumulation of P from both fertilizer sources is substantial and that P buildup was faster for organic fertilizers due to the higher application rate needed to compensate for the slower release of the P. This phenomenon was also found by Edmeades (2003) in his research review of fertilizer studies from around the world including the United States. Hooda et al. (2000) tried to develop a relationship between TP and adsorption properties for soils and found that TP and adsorption properties were poorly correlated with P runoff or leaching, but they did find that the degree of P adsorptive saturation was correlated, but its actual relationship for individual soils would have to be determined. Unfortunately none of the above studies were conducted in Florida, so their results have limited use for Okeechobee conditions.

To evaluate the legacy P in the soils/sediments in flow conveyance systems, the Sediment Removal Feasibility Study conducted by Mock, Roos & Associates (MRA, 1997, Deliverable 7) was used. In this study representative sediment samples were collected across the entire basin for four stream classes, which were field ditches, tertiary (small streams and sloughs), secondary(large stream and major sloughs), and primary canals. The study collected cores from 85 sites for calculating TP for A, B, and C layers, which were defined by points of obvious layer characteristic change and averaged 11, 20, and 16 cm thickness, respectively (see Figure 2 for P results for the A layer). Surface sediment samples were collected from an additional 48 sites and would provide estimates for the "A" layer only. The TP settling/resuspension and P adsorption properties were evaluated for all samples. A comparison of the TP in low impacted areas to impacted areas provides an estimate of the legacy P that would be associated with these systems, but is subject to significant error because of the natural variations in organic contents between the different areas. The study results were presented in terms of TP per unit length and area of the flow system where TP levels varied from <.01 to 3.0 kg/m^2 or <.005 to 0.4 kg/m^2, with average TP values for the "A" layer being about 514 mt across the lower Okeechobee basins (up to the 65D basin) with the "B" and "C" layers adding another 1,000 mt of TP. The amount of TP that could be associated with legacy P is assumed to be the difference between 25th (0.15 kg-P/m) and 75th (0.35 kg-P/m) percentiles of the values for the various tributary types for both the A and B layers. Considering the 4,300 kilometers of tributaries in the lower basins, the estimated legacy P in the tributary sediments would be roughly 860 mt and would be expected to be distributed in a similar fashion as shown in Figure 2. A secondary assessment flow network legacy P is presented in a later section which uses the upstream land use sourced legacy P.

The above assessment did not include accumulations in lakes such as Lake Istokpoga or any of the Upper Chain of Lakes. The amount of legacy P in these lakes is best estimated based on net P balance, i.e. inputs minus outputs. This was not done for each lake for this study because it was beyond the scope and resources of this project. However, the net accumulation of P in these lakes can be roughly estimated based on average concentration reductions through these lakes and net P loads leaving the lakes adjusted for rainfall inputs of P using the following formula:

Accum. P = (Output P load / (100- % P reduction through lake) – Output P – Rain P

For Lake Istokpoga based on 1991- 2005 annual estimates SFWMD (2007 –draft) and DBHydro data, the annual P accumulation would be about 20 mt/year and the Upper Chain of Lakes including Lake Kissimmee would be about 80 mt/year assuming about a 50% P concentration reduction on average. This would mean that assuming about 50 year period of accumulation would yield about 5000 mt of legacy P in these lakes. A more definitive study for each lake is suggested to refine these estimates.

Dr. Rao Mylavarapu, who is the director of the Soil Testing Laboratory at the University of Florida provided Mehlich-1 P soil test results for all soil samples collected within Okeechobee, Highlands, and Osceola counties since 2001. These data were grouped by crop type and analyzed for mean, standard deviation (STD), and median values (Table 4). The advantage of these data is that a number of crop types that were not part of other research projects had data, particularly for urban landscapes. It also provided comparative data for the research results.

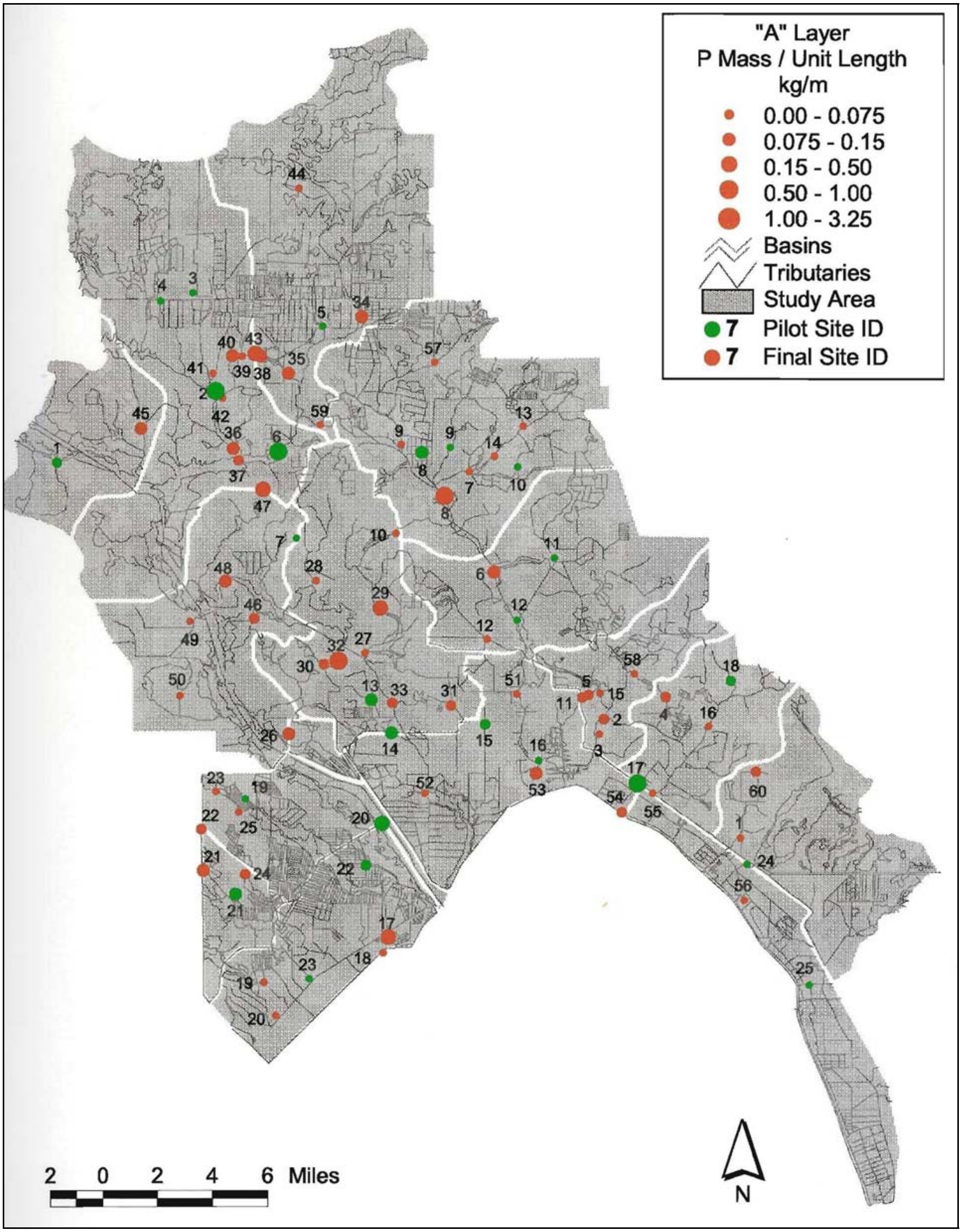

Figure 2. Tributary TP Levels for Lower Okeechobee Basins

Table 4. Legacy P Estimates Based on UF Soil Test Data for Okeechobee, Highlands, and Osceola Counties.

Land Use Description	No. Samples	Mehlich 1 P (mg/kg)					Estimated P (mg/kg)*	
		Mean	STD	MAX	MIN	Median	TP	Legacy P
No Crop Code Specified	1579	169	309	2572	0	31	337	317
Corn, nonirrigated	3	9	3	12	5	9	18	0
Corn, irrigated	13	34	29	104	7	31	68	48
Grain sorghum	1	128	n/a	128	128	128	257	237
Peanuts	1	16	n/a	16	16	16	32	12
Soybeans	5	127	256	584	9	14	254	234
Summer forages	5	127	256	584	9	14	254	234
Warm season Legumes or legume-grass mixtures	43	128	319	1650	0	13	256	236
Cool season Legumes or legume-grass mixtures(clovers,lupines,vetches)	13	11	24	88	0	4	21	1
Alfalfa	5	20	38	88	0	4	40	20
Improved perennial grasses other than bahiagrass(bermuda,digit,limpo,star)	223	37	112	1299	1	8	74	54
Cool season annual grass (small grains and rye grass)	18	31	36	152	3	15	62	42
Wheat for grain	7	9	10	30	2	5	17	0
Perennial peanuts	4	44	11	53	31	46	88	68
Bahiagrass, central and south Florida	1428	41	104	1182	0	6	81	61
Bahiagrass, north Florida	6	16	18	47	2	10	33	13
Hay or Silage (perennial grass)	108	39	157	1154	1	3	78	58
Limpograss	8	4	3	9	0	3	7	0
Citrus (establishment)	26	56	73	305	4	33	113	93
Citrus (bearing trees)	265	40	49	382	6	26	80	60
Dooryard citrus	14	111	124	450	3	78	223	203
Blueberries	21	40	47	186	3	31	79	59
Athletic field, Golf green, Tee or Fairway	34	43	34	137	2	40	87	67
Bahiagrass Lawn	97	42	75	553	0	16	83	63
Bermudagrass Lawn	38	45	25	105	3	46	91	71
Centipedegrass Lawn	3	10	8	19	2	10	21	1
Ryegrass Lawn	6	11	2	12	7	11	21	1
St. Augustinegrass Lawn	84	47	38	197	2	43	95	75

Zoysiagrass Lawn	1	119	n/a	119	119	119	238	218
Vegetable Garden	63	119	189	1103	1	42	238	218
Tomato - Cherry or Slicing	1	5	n/a	5	5	5	9	0
Eggplant	3	36	51	95	3	51	72	52
Cabbage,Collard,Chinese	1	77	n/a	77	77	77	153	133
Broccoli,Brussel Sprouts,Cauliflower	1	78	n/a	78	78	78	155	135
Bean - Lima, Pole, Snap	6	45	39	110	2	39	91	71
Watermelon	4	36	53	115	3	14	73	53
Eggplant	3	46	65	121	2	15	92	72
Com. woody ornamental Nursery-other than azaleas,camelias,gardenias,hibiscus,ix	9	21	14	44	0	19	41	21
Com. Nursery-azaleas,camellias,gardenias,hibiscus or ixora growing in ground	3	10	14	44	0	19	20	0
Woody orn/trees in the landscape	38	72	132	818	1	35	143	123
Landscape Azaleas, Camellias, Gardenias, Hibiscus or Ixora	21	85	132	818	1	35	169	149

*TP = Mean x 5 and *Legacy P = [Mean - background (assumed 10)] x 5

These Mehlich-1 P concentrations were adjusted in Table 1 by the adjustment factor of 5:1 discussed earlier to obtain estimates of legacy P.

Dr. Rao Mylavarapu also provided preliminary unpublished results for his FDACS improved bahiagrass pasture study where Mehlich-1 P levels for four depths in the soil were compared to P levels in plant tissue. He found that the average Mehlich-1 P concentrations for the 0-15 cm, 15-45 cm, 45-75 cm, and 75-105 cm depths were 5.17, 1.92, 14.03, and 23.68 mg/kg, respectively, and plant tissue P was about 0.15%. The data show a positive correlation between subsoil Mehlich-1 P and tissue P, which supports that spodosols can provide P to the plants. His results were for a limited number of soils and were similar to previously presented data and therefore are not included in Table 1. However, when his study is completed it should be further reviewed to see if legacy P values for improved bahiagrass pastures can be improved.

2.2 Legacy P for Urban Land Uses

The legacy P associated with urban areas is mostly associated with the historic fertilization practices and sewage treatment systems, particular septic tanks. It was assumed for this assessment that the areas on centralized treatment systems do not have sewage sourced legacy P and that the treatment plants would either fully contain accumulated P or the effluent is spread at agronomic rates as is the case with the City of Okeechobee treatment plant, where it is spread on a citrus grove. Table 5 shows the assumptions and resulting legacy P for the different urban land uses.

Table 5. Estimated Urban Legacy P Levels.

Urban Sewage and Fertilization Assumptions for Legacy P

Waste Load	265kg/person/day (75 gal/person/day)
P in Waste Load	0.0025%
P Load	0.006625kg/person/day (0.0146 lbs/person/day)

Landuse Category	**People Density**	**Time of Accumulation**	**P Fertilizer**	**Septic**	**Runoff P Load**	**Legacy P A horizon**	**Legacy P Lower Horizon***
	(# / ha)	(yrs)	(kg/ha/yr)	(kg/ha/yr)	(kg/ha/yr)	(kg/ha)	(kg/ha)
Low Density	4.1	20	5	10	1.00	80	198
Medium Density	14.4	20	10	35	1.00	180	696
High Density	49	20	7	118	0.85	123	2370
Industrial	10	20	3	24	0.55	49	484
Commercial	10	20	3	24	0.50	50	484
Recreational	2	20	5	5	1.00	80	97

* If on central sewage treatment, then there would be no lower horizon legacy P

2.3 Evaluation of Phosphorus Budget Studies

Previous P budget studies have used a materials balance approach to phosphorus management to estimate the total amount of phosphorus that enters and exits the watershed on an annual basis. Though the P budgeting approach does not provide direct measurements of legacy P, it does provide an excellent backup of potential soil based legacy P. Phosphorus cycling in the environment is a function of both natural processes (e.g. plant uptake, senescence, and mineralization of organic matter) and anthropogenic factors (e.g. agriculture, fertilization, mining, and human consumption). The effects of these processes on the accumulation of legacy P and its associated impact on water quality are determined by land use patterns and management and phosphorus discharge associated with each land use.

There have been several studies within different regions that contribute runoff to Lake Okeechobee. These regions are shown in Figure 3. The first P budget study within the Lake Okeechobee watershed was conducted in 1991 and published later (Boggess et al., 1995). This study utilized information from 1985 to 1989 and focused solely on the northern Lake Okeechobee region. The study estimated that the total net P import into the region was about 2,380 mt per year.

In 2002, an update of the P budget analysis was conducted for the northern Lake Okeechobee region (Hiscock et al., 2003) using data collected from 1997 to 2001. This analysis included the development of a graphical user interface (GUI), known as P-Budget, written in ArcView^{TM} (Version 3.2a) Avenue^{TM}. This interface allows a user to select one or more (or all) basins of the watershed within a GIS environment and apply phosphorus controls to the specified land uses to assess the effects on phosphorus import, export and net import. This study found that in the 11 years since the previous study, total net P import into northern Lake Okeechobee region had fallen annually 16% to 2,001 mt per year. The reductions were attributed to BMPs and the governmental buyout of some local dairies.

The findings were influenced by truck crops, historically associated with high phosphorus import, that were expanding in the basin. Figure 4 shows the breakdown of net P import contributions from the primary land use sources. Improved pasture is the largest land use in the region, representing approximately 50% of all anthropogenic land uses in the region, but it contributes less than a quarter of the net P import. This is due in large part to efforts of the SFWMD and FDACS to convince cattle ranches to use less or no P in their fertilizer. In contrast, truck crops represent less than 2 percent of the anthropogenic land uses in the region, but contribute 42.5% of the net P import. Dairies, though improved, still contribute over 22.4% of the net P import while representing less than 4% of the anthropogenic land uses. It should be noted that BMPs applied to dairies between the original and updated studies were focused more on controlling P discharges than on P imports. Since the updated study was performed, FDACS has developed Agricultural Nutrient Management Plans (AgNMPs) for each of the dairies that are designed to bring the dairies into a closer balance in terms of P import and export. The plans prescribe reduced P content of imported materials, recycling of P through spray fields, stormwater retention and, in some cases, edge-of-farm treatment including chemical coagulants. Retained or chemically treated P will be periodically removed from settling basins and will either taken offsite or stored where it cannot be released into surface or groundwater.

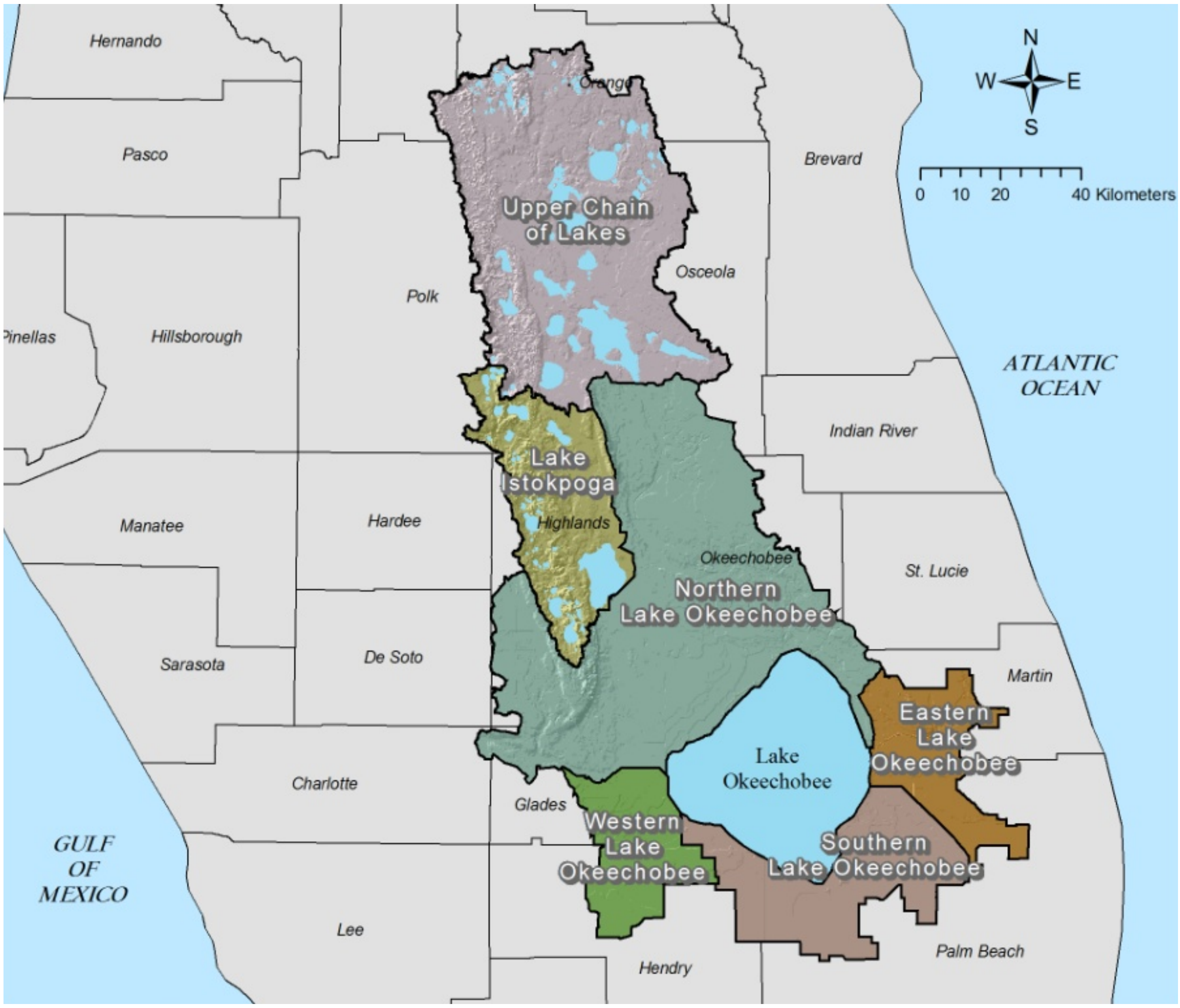

Figure 3. Basins Studied During the P Budget Projects.

In 2003, a similar phosphorus budget analysis was conducted for the basins located within the Lake Istokpoga and Upper Chain of Lakes regions (Mock-Roos, 2003). These regions were added to the P-Budget interface. The interface was updated at this time to include the phosphorus runoff results from the public domain Watershed Assessment Model (WAM) to replace the Event Mean Concentration (EMC) approach used in the northern Lake Okeechobee watershed. WAM is a physical-based model that uses site-specific information such as soils, rainfall, fertilization practices, and location within the watershed to estimate phosphorus concentrations of both direct runoff and attenuated discharge to the lake. The total net import for the Lake Istokpoga and Upper Chain of Lakes regions in 2003 were 665 and 2,927 mt per year, respectively. The dominant land use in terms of net P import in both of these regions was urban (Figures 5 and 6). Of particular concern is the amount of P potentially accumulating in the Upper Chain of Lakes region. Most of the urban development there has occurred in the past 25 years and has been required to obtain surface water permits with criteria for retention. Phosphorus discharges from this region have been relatively low suggesting that P is being retained onsite and also within the lakes in the region. Some of this P, however, could be

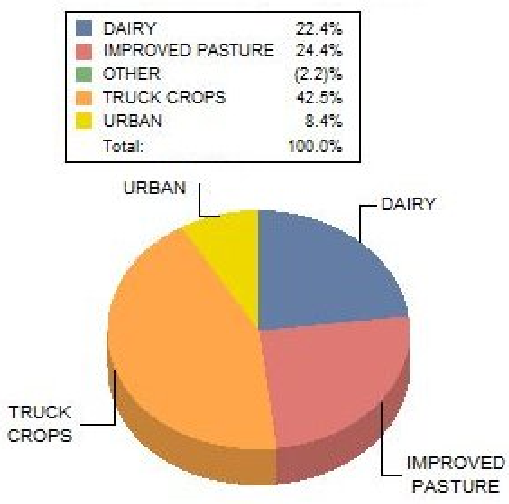

Figure 5. Net P Import Sources in the Northern Lake Okeechobee Region.

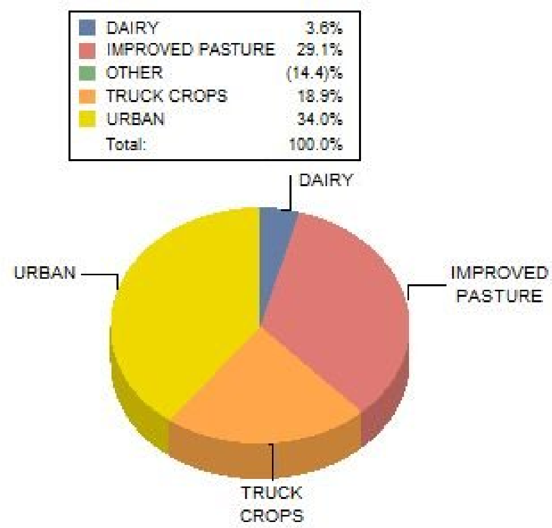

Figure 4. Net P Import Sources in the Lake Istokpoga Region.

released in the future through leaching or mixing caused by heavy storms. The SFWMD also completed phosphorus budget analyses for the southern and eastern Lake Okeechobee drainage basins (Zhang et al., 2003a; 2003b). The western Lake Okeechobee drainage basin is the only remaining region that has not been analyzed. However, this basin contributes a relatively small amount of discharge and associated phosphorus load to the lake. These areas, however, are not relevant to the current legacy P study.

In 2005, all of the previous P budget analyses were compiled together into an updated GIS interface. The updates included moving to the ArcGIS™ platform, adding tools for site-specific assessments and integrating the WAM model. By integrating the WAM model, P-Budget could properly reflect the changes to P in the runoff based on imposed P control methods. The interface was further updated in 2007 to conform to newer versions of ArcGIS™ and Crystal Reports™. Spatial output from P-Budget is presented in Figures 7 through 9 for the three regions associated with this study.

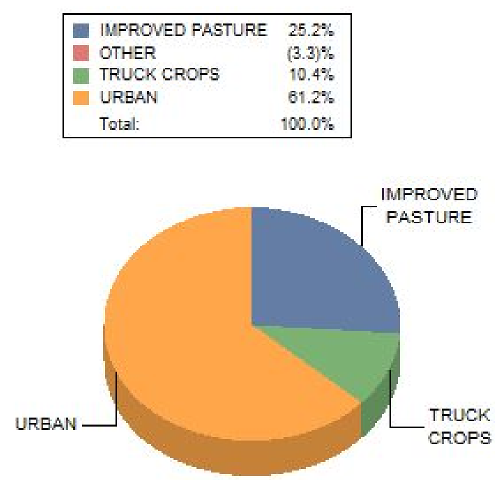

Figure 6. Net P Import Sources in the Upper Chain of Lakes Region.

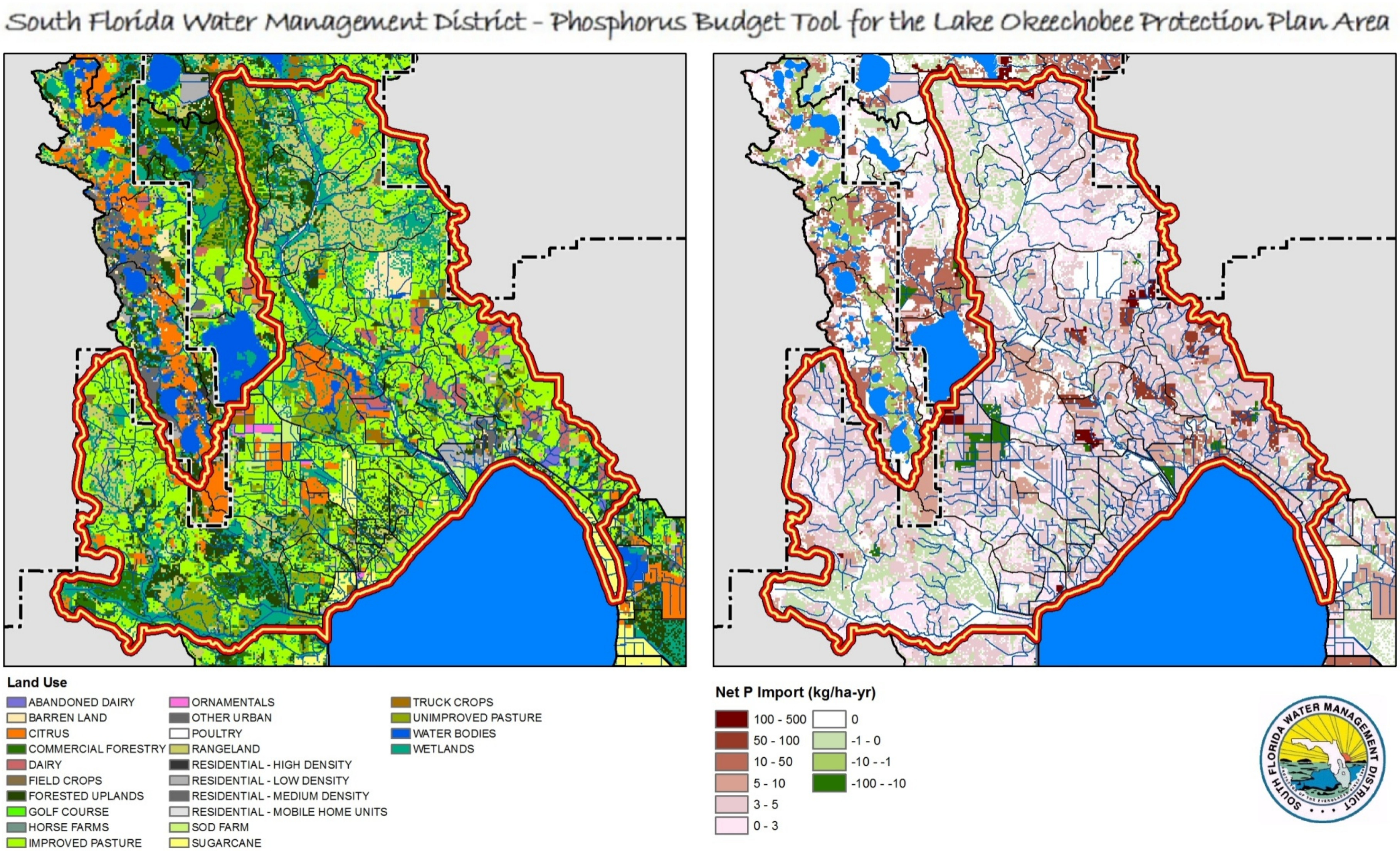

Figure 7. Land Use vs. Annual Net P Import for the Northern Lake Okeechobee Region.

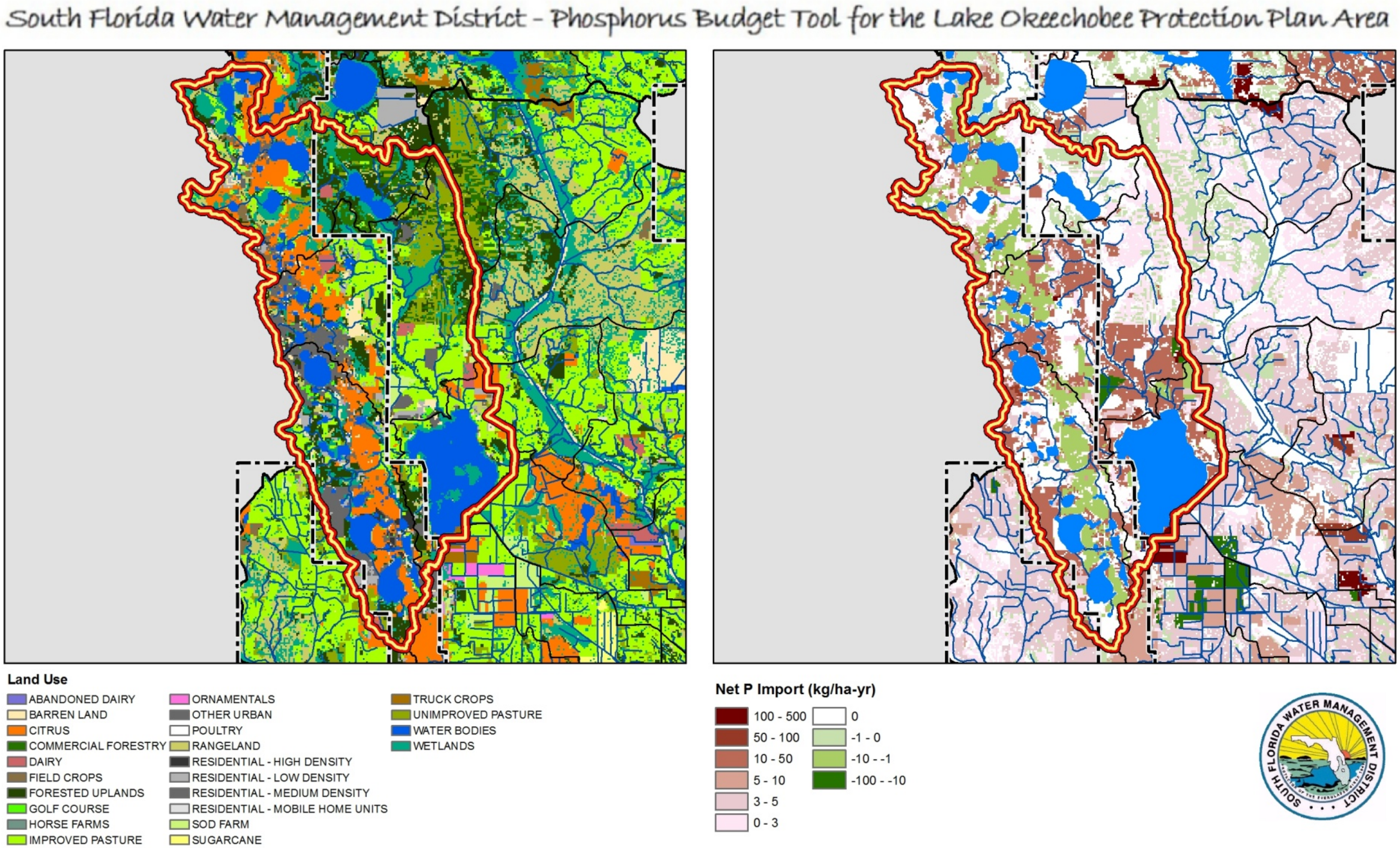

Figure 8. Land Use vs. Annual Net P Import for the Lake Istokpoga Region.

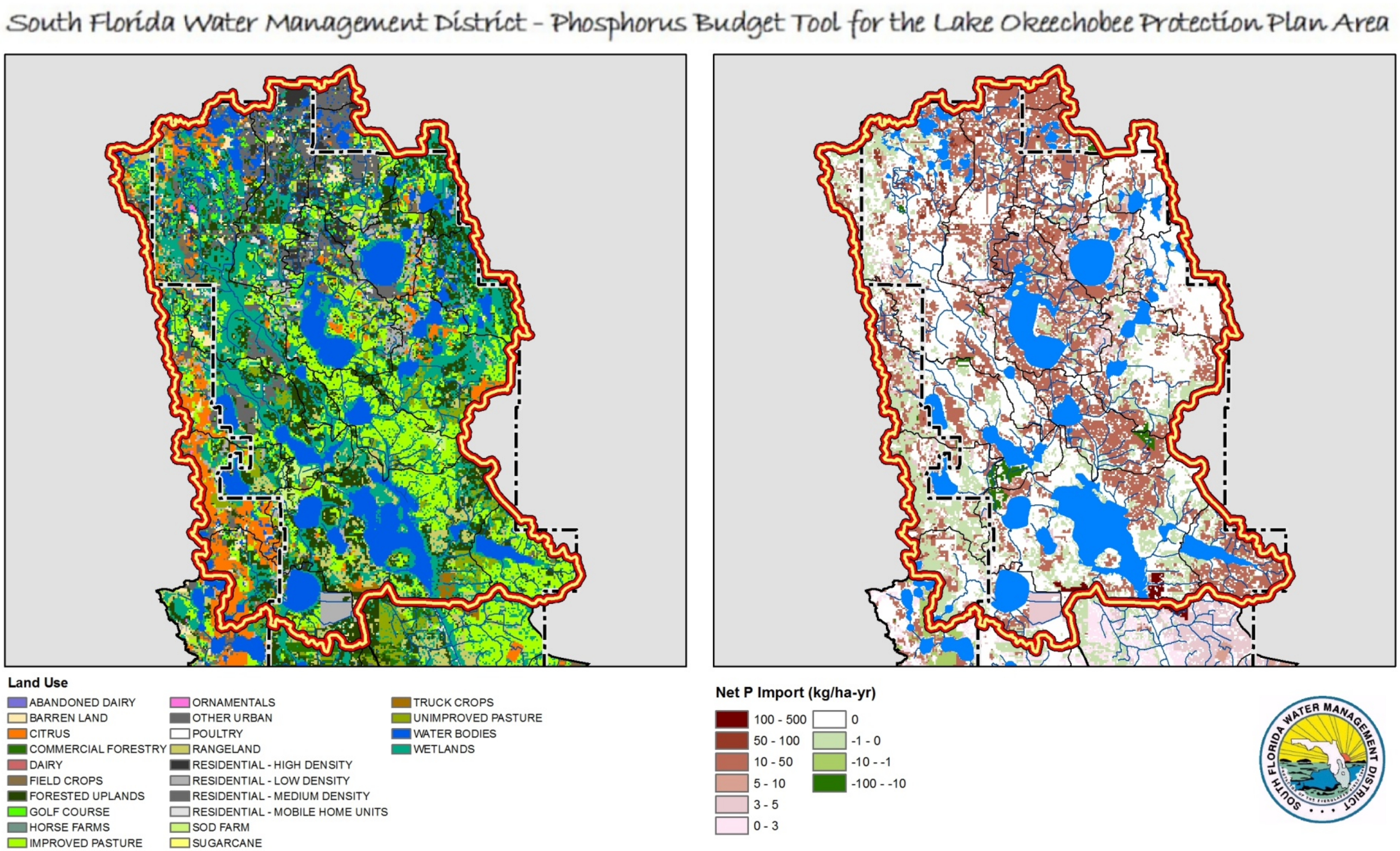

Figure 9. Land Use vs. Annual Net P Import for the Upper Chain of Lakes Region.

Table 6 shows the P amounts for the various budget components for each of the three regions. Onsite P represents the estimated amount of P stored in the soils each year, ultimately becoming legacy P. The total Onsite P for the study area is 4,872.5 mt annually, which should correspond to annual accumulation of legacy P. If it is assumed that this accumulation has been occurring over the past 25 years on average, then the amount of legacy P in the basin would be about 120,000 mt. The magnitude of this P component suggests that controls of P import should be considered as an integral part of any future abatement program.

Table 6. Estimated Annual Phosphorus Budget by Region (in mt).

Regions	Area (ha)	Imports	Exports	Net Import	Rainfall P	Runoff P	Onsite P
Lake Istokpoga	157,837	987	320	665	31	163	534
Northern Lake Okeechobee	484,276	3,308	1,307	2,001	90	407	1,683
Upper Chain of Lakes	416,561	3,536	607	2,927	82	353	2,656
Total	**1,058,674**	**7,831**	**2,234**	**5,593**	**202**	**923**	**4,873**

2.4 Calculation of Legacy P Distribution

The quantification of soils and flow conveyance system legacy P (Table 7) were determined based on land use and stream reach characteristics data (Tables 1 – 6) discussed in the previous sections. The mean of available legacy P estimates for each land use was calculated. The statistical variance and associated error for these estimates were not calculated due to variable and limited data sources, but would be estimated to be in order of ± 30% based on observation. Though absolute magnitudes of legacy P by land use are subject to significant error, their relative presence in the basin can be estimated and mapped with reasonable accuracy because of the quality of the available land use spatial data.

The land use legacy P data were applied spatially based on available land use and stream reach GIS coverages. The land use raster used in the P-Budget interface (JGH et al., 2005) was utilized as a base coverage because it included SFWMD's most recent land use information (2006) along with abandoned dairies that were specifically incorporated for the P-Budget model.

Even with the inclusion of abandoned dairies, more detail was needed to further break down land uses within the dairies such as sprayfields, lactating pastures, etc. This information was available from a SFWMD coverage known as Dairy2k. The coverage was further refined in 2002 by NRCS. The NRCS version was used primarily and Dairy2K was used for dairies not found in the NRCS version. An additional attribute was

Table 7. Code System and Legacy P Estimates for Land Uses.

Landuse	LEGPCODE	Legacy P (kg/ha)	
		A Horizon	Below A Horizon
Other, Non-relevant	0	0	0
Low Density Residential	1	80	198
Medium Density Residential, septic	2	180	696
Medium Density Residential, central	3	180	0
High Density Residential, septic	4	123	2,370
High Density Residential, central	5	123	0
Industrial, septic	6	49	484
Industrial, central	7	49	0
Commerical, septic	8	50	484
Commerical, central	9	50	0
Recreational	10	200	97
Native Areas	11	0	0
Isolated Wetlands in Imp. Pastures	12	44	66
Impacted Sloughs	13	30	40
Semi-Improved Beef Pasture	14	110	5
Improved Beef Pasture	15	314	62
Hayland	16	150	38
Dairy Dry Cow Pastures	17	314	62
Dairy Sprayfields	18	189	28
Dairy Intensive Lactating Pastures	19	1069	760
Dairy High Intensive Holding Pastures	20	6,230	2,105
Abandoned Dairy Intensive	21	4,974	2,664
Vegetables	22	650	50
Citrus	23	250	50
Overall Dairy - Active	24	500	200
Overall Dairy - Abandoned	25	450	180
Sod	26	0	20
Ornamentals	27	300	50
Sugarcane	28	0	0
Poultry	29	200	20
Isolated Wetlands in Dairy Pastures	30	841	100

applied to identify which dairies were no longer active based on the P-Budget base coverage.

Isolated wetlands in pastures were determined by selecting all wetlands within close vicinity of pastures. Any wetlands that were within close vicinity of other land uses (non-pasture or wetland) were then removed from the selection. The results were further revised to eliminate any wetlands adjacent to other wetlands that had been previously removed from the selection. This effectively removed any slough systems that may have contained multiple wetland types and polygons.

An overall coverage of wastewater treatment plant service areas is not available. Therefore, it was necessary to assume service based on the urban land use type. For the purposes of this assessment, all urban land uses with the exception of low density residential were assumed to be served by central wastewater collection systems.

The additional layers of information as described above were converted to rasters and merged on top of the base land use raster to create a new raster of legacy P codes shown in Table 6. The legacy P estimates for the A and E (and deeper) soil horizons for each of the legacy P codes were then joined to the new raster's attribute table. The raster was then reclassified twice to create raster coverages for the surface and subsurface horizons, which arepresented in Figures 10 and 11. Tables 8, 9 and 10 provide the A and E (and lower) horizons accumulative legacy P across regions, basins and land use, respectively. As can be seen, the majority of the legacy P is in the northern Okeechobee basins, particularly on a per unit area basis. Table 11 shows how the legacy P by the region compares with estimates of accumulative stored P in the P-Budget studies (Hiscock et al., 2003). The comparison says that it would take between 20 and 64 years at the P-Budget P storage annual accumulation rate to produce the legacy P estimated from the soil data. These times seem reasonable considering the locations where growth that has occurred and the fact that the P storage rate was based on 2002 conditions.

A separate algorithm was needed to create the stream coverage of relative legacy P impacts. In order to create this coverage, the percentiles of upstream land uses were needed for each reach stream segment within the study area. The P-Budget interface includes a detailed stream network and a tool that calculates the upstream contributing drainage area of any selected reach segment. The Visual Basic™ code for this tool was used and modified to automate the process for each of the 1,782 reaches within the study area. The algorithm also performed a statistical analysis of each contributing area over the legacy P code raster to determine the land use areas. Each set of areas were then inserted into a master table of all of the reaches.

The master table was imported as a single spreadsheet and converted to percentiles. The upstream land use percentiles for each reach were multiplied by the associated land use legacy P in Table 6 and then summed for all land use categories. This intermediate reach legacy P factor was further adjusted by an arbitrary conveyance reach type factor of stream = 1, slough = 2, and lake = 3, which were the only conveyance type distinctions available in the reach GIS coverage. This adjustment is roughly based on the estimates of legacy P by stream type obtained from the Sediment Removal Feasibility Study (1997, Deliverable 7) and that lakes have very high P assimilation capacities compared to streams while sloughs would have an intermediate P assimilation capacities between streams and lakes. The resulting legacy P factors provide a reasonable relative view of the likely streambeds legacy P for each reach. The results were assigned a relative impact from low to very high and then joined to the stream reach attribute table and used for the mapping display provided in Figure 12.

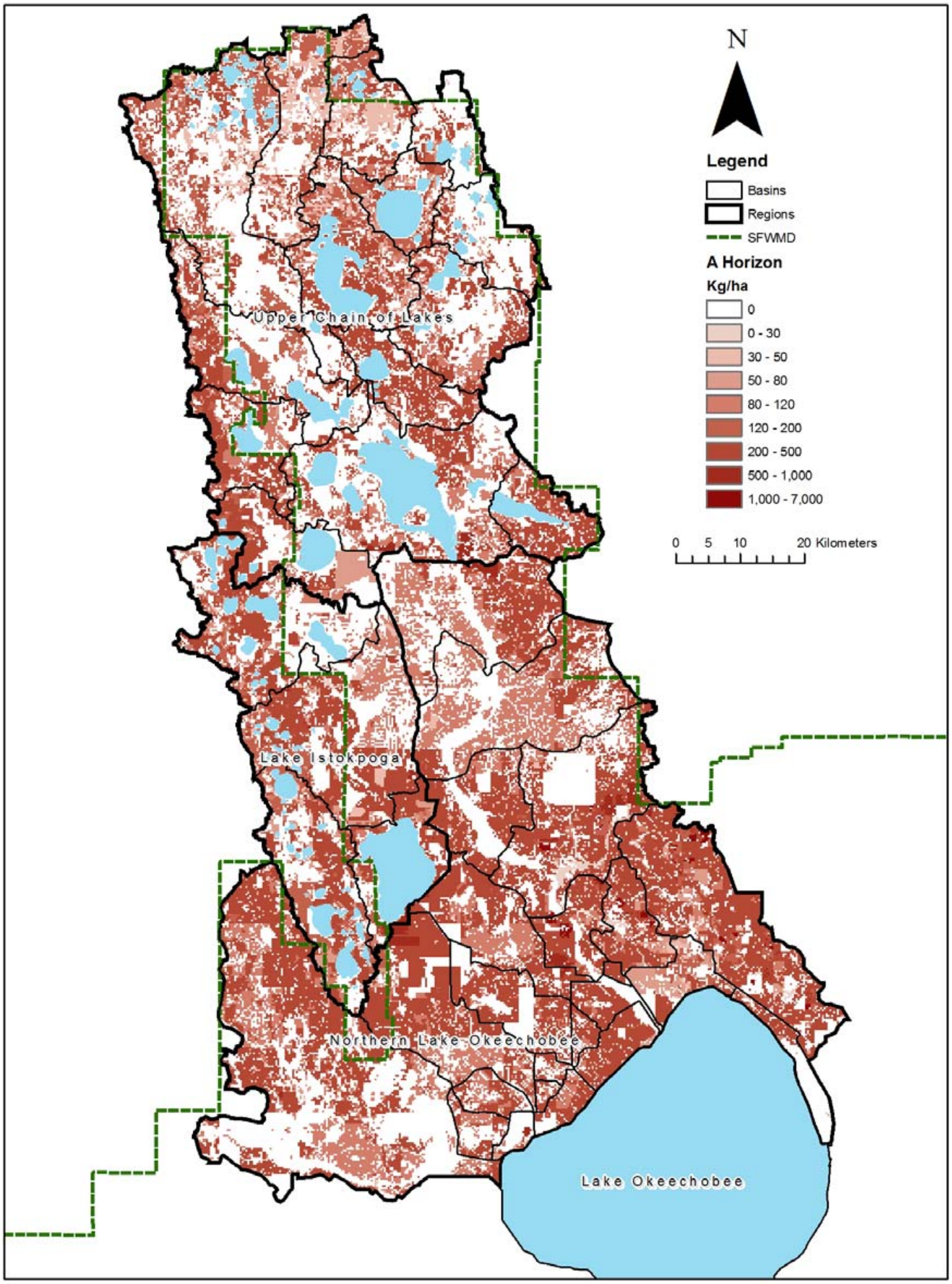

Figure 10. Legacy P Distribution for the "A" Horizon.

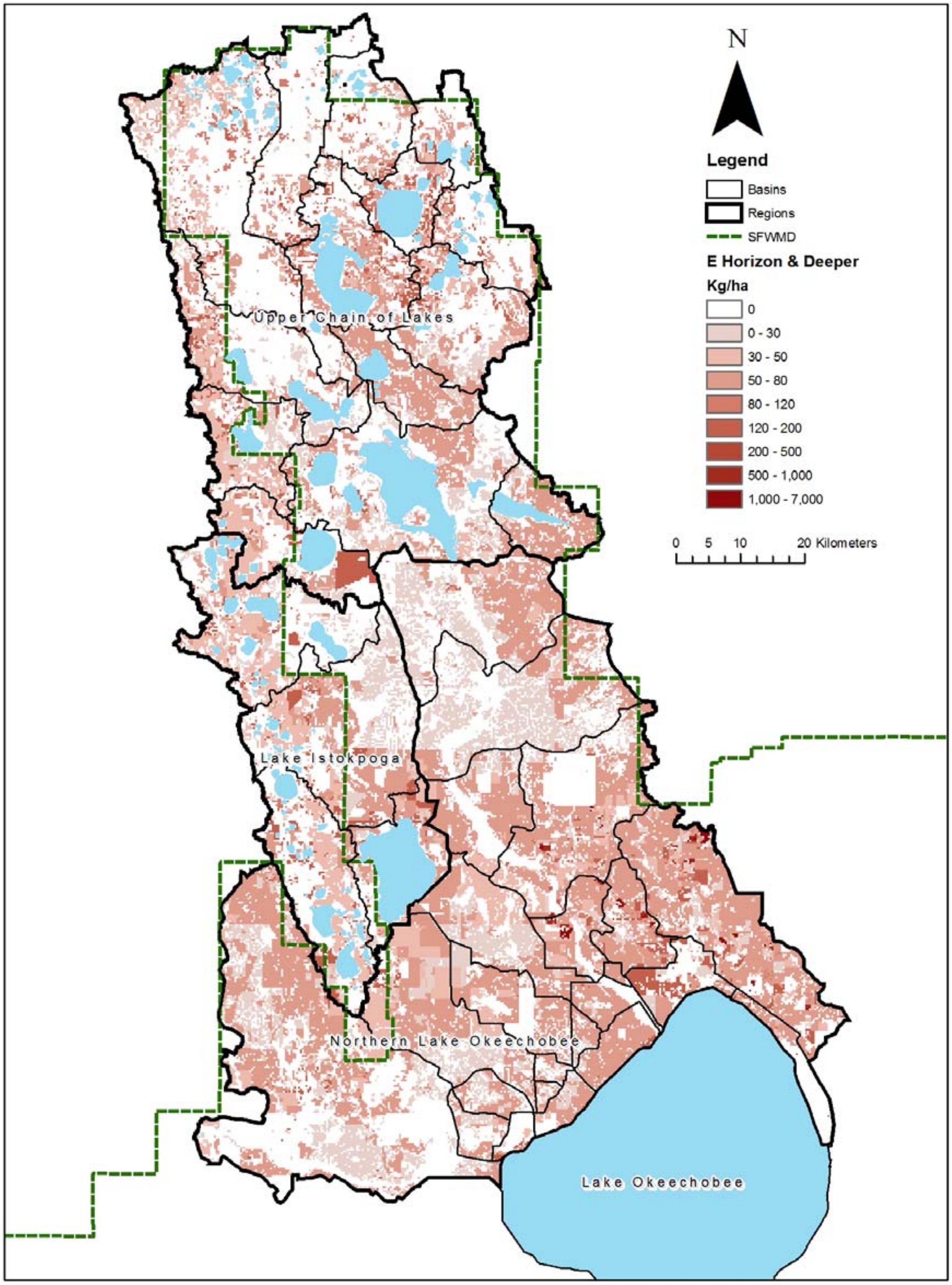

Figure 11. Legacy P Distribution Below the "A" Horizon (E, Bh, and Bw Horizons).

Table 8. Total of Legacy P by Region

Region	Area (ha)	A-Horizon (kg)	E-Horizon & Deeper (kg)
Northern Lake Okeechobee	483,796	83,596,949	18,452,770
Lake Istokpoga	157,724	16,969,143	3,903,803
Upper Chain of Lakes	415,970	37,583,523	9,324,861

Table 9. Total of Legacy P by Land Use

Legacy P Land Use	Area (ha)	A-Horizon (kg)	E-Horizon & Deeper (kg)
Other, Non-relevant	124,741	-	-
Low Density Residential	30,197	2,415,760	5,979,010
Medium Density Residential, central	30,566	5,501,880	-
High Density Residential, central	10,307	1,267,760	-
Industrial, central	3,430	168,070	-
Commercial, central	20,879	1,043,950	-
Recreational	4,446	889,200	426,816
Native Areas	320,661	-	-
Isolated Wetlands in Pastures	14,799	636,357	961,935
Impacted Sloughs	2,837	85,110	113,480
Semi-Improved Beef Pasture	124,617	13,707,900	623,085
Improved Beef Pasture	252,832	79,352,348	15,456,147
Hayland	11,196	1,679,400	425,448
Dairy Dry Cow Pastures	1,627	510,640	99,462
Dairy Sprayfields	1,064	201,096	29,792
Dairy Intensive Lactating Pastures	881	941,789	668,679
Dairy High Intensive Holding Pastures	561	3,495,030	1,180,910
Abandoned Dairy Intensive	362	1,800,590	964,368
Vegetables	6,790	4,413,500	339,500
Citrus	70,989	17,747,300	3,549,450
Overall Dairy - Active	2,043	1,021,500	408,600
Overall Dairy - Abandoned	742	333,900	133,560
Sod	9,515	-	190,300
Ornamentals	2,336	700,800	116,800
Sugarcane	9,727	-	-
Poultry	55	11,000	1,100
Isolated Wetlands in Dairy Pastures	474	398,634	47,400

Table 10. Total of Legacy P by Basin

Basin	Area (ha)	A-Horizon (kg)	E-Horizon & Deeper (kg)
S-65A	41,826	6,131,060	1,026,090
S-65B	51,863	5,683,410	828,512
S-65C	20,404	4,120,330	790,581
Arbuckle Creek	54,967	8,026,540	1,635,310
Lake Arbuckle	42,960	4,109,330	878,813
Josephine Creek	36,893	4,268,980	1,123,640
Lake Istokpoga	22,904	2,391,550	526,695
Boggy Creek	20,733	2,011,990	349,584
East Lake Tohopekali	15,029	1,192,970	515,187
Lake Cypress	18,018	3,606,340	708,368
Lake Hart	12,898	712,517	226,968
Lake Hatchineha	37,328	3,651,330	764,808
Lake Kissimmee	65,590	5,868,750	1,043,750
Lake Marian	16,140	3,117,800	614,645
Lake Myrtle	18,443	1,265,550	368,048
Lake Pierce	21,275	2,817,210	659,397
Lake Tohopekaliga	32,763	4,032,910	1,119,320
Lake Weohyakapka	25,189	2,641,860	1,057,110
Reedy Creek	70,728	5,492,030	1,239,570
S-63A	30,541	3,555,800	921,513
Shingle Creek	31,295	2,435,530	424,010
S-65D	45,670	9,040,890	2,000,870
C-41A	23,743	4,425,060	793,992
S-154	12,810	3,955,670	1,246,390
Fisheating Creek	114,906	16,362,700	2,999,130
S-65E	11,793	4,265,730	1,287,720
C-41	36,645	7,755,080	1,455,200
S-133	10,383	1,190,790	717,778
C-40	17,770	3,032,190	613,041
S-154C	884	258,113	49,453
L-59E	5,844	1,228,050	240,858
S-135	7,297	617,564	168,139
L-48	8,395	2,217,540	469,417
L-59W	2,609	549,651	97,762
L-60E	2,047	262,984	50,493
L-61E	5,783	977,202	169,162
L-49	4,887	943,525	168,152
L-60W	1,329	242,227	42,309
L-61W	5,496	694,898	110,495
S-131	2,878	193,453	68,894
S-191	48,534	15,053,600	3,857,890

Table 11. Comparison of Legacy P Estimates Based on Soils Data to P-Budget Accumulation Rates.

Region	Area	Legacy P Based on Soil Data			Legacy P Accumulation	Years to Accumulate
	(ha)	A-Horizon (mt)	E-Horizon & Deeper (mt)	Total (mt)	Rate Based P-Budget (mt/year)	Soil Legacy P
Northern Lake Okeechobee	483,796	83,597	18,453	102,050	1,683	60
Lake Istokpoga	157,724	16,969	3,904	20,873	534	39
Upper Chain of Lakes	415,970	37,584	9,325	46,908	2,656	18
Total	**1,057,490**	138,150	31,681	169,831	**4,873**	39(average)

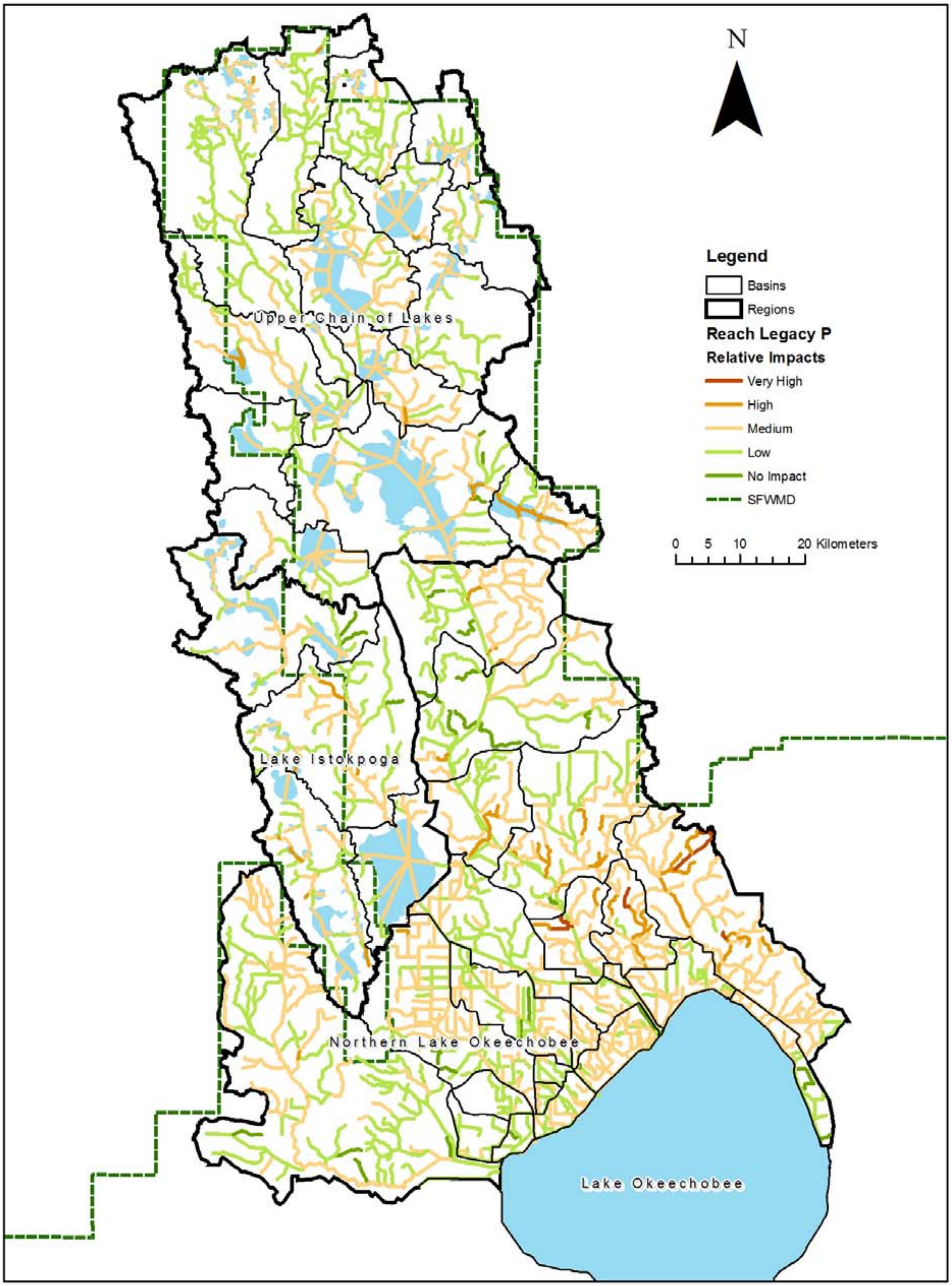

Figure 12. Estimated Relative Legacy P for Hydrologic Reaches.

3.0 MOBILITY OF LEGACY P

The mobility of legacy P is the other half of the story as far as determining the ultimate impact of the accumulated legacy P in the watershed on the lake. Understanding the processes controlling mobility is critically important for determining the present and future movement of legacy P to the lake as influenced by land management and abatement practices. Figure 13 shows a general transport model for legacy P for the Okeechobee watershed that will be further detailed in this section. As shown in Figure 13, runoff is the most dominant flow path for washing legacy P from the upland soils and delivering water to down gradient wetlands and streams and ultimately Lake Okeechobee. Under native conditions very little interflow or deep seepage occurs due to the very low groundwater gradient, however drainage improvements can significantly increase relative groundwater contributions thus exposing subsoil legacy P to transport. Wetlands can act as either a sink or source for P depending P levels in the wetland relative to inflow P concentrations. The primary process for P removal or export in wetlands is detritus buildup or decomposition, respectively, resulting from macrophyte and algal growth and dieback. The same P transformation processes occur in streams and canals as in wetlands, but the sediment interactions and erosion processes are more important.

Figure 14 provides a general flow diagram of the P transformation processes within a soil/plant environment, where inputs include fertilizers, biosolids, and animal wastes and outputs include plant uptake and harvest and losses in surface runoff and groundwater flows. This section will review and discuss studies that address these legacy P mobility processes as related to land use and treatment technologies.

3.1 Mobility of Legacy P Based on Observed P Concentration Data

The mobility of legacy P that has built up in the Okeechobee soils is best estimated by evaluating the resulting P concentrations found in runoff and shallow groundwater leaving the soils. One of the first and benchmark P runoff studies was done in the early 1970s by Allen et al. (1975), which measured the water quality impacts associated with intensive agricultural land use and specifically dairies in the Taylor Creek watershed. Subsequent monitoring programs have verified these findings and have shown that P continued to increase until the early 1980s when dairy BMPs, fencing cows from streams in particular, started reducing P losses (see Figure 15). This response was most apparent for the S-191 and S-154 subbasins because of their higher density of dairies. For S-191 (Taylor Creek/Nubbin Slough) P concentration continued to decrease up through the mid 1990s until P levels from dairies and other land uses such as urban, beef, and vegetables seem to have stabilized and remained fairly constant until about 2004 when the P control projects started to provide additional reductions. However, P loading to the lake is a combination of P concentration and runoff volume and therefore the dominant factor affecting P loads to the lake remains rainfall because of its direct correlation to runoff. Though these large scale monitoring programs are useful, they do not provide the land

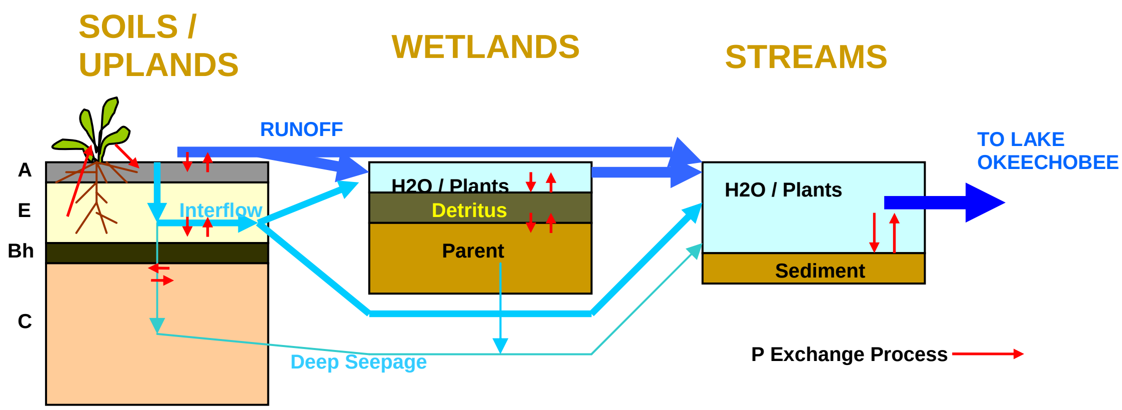

Figure 13. General Flow anad P Transport Model for Okeechobee Watershed Conditions.

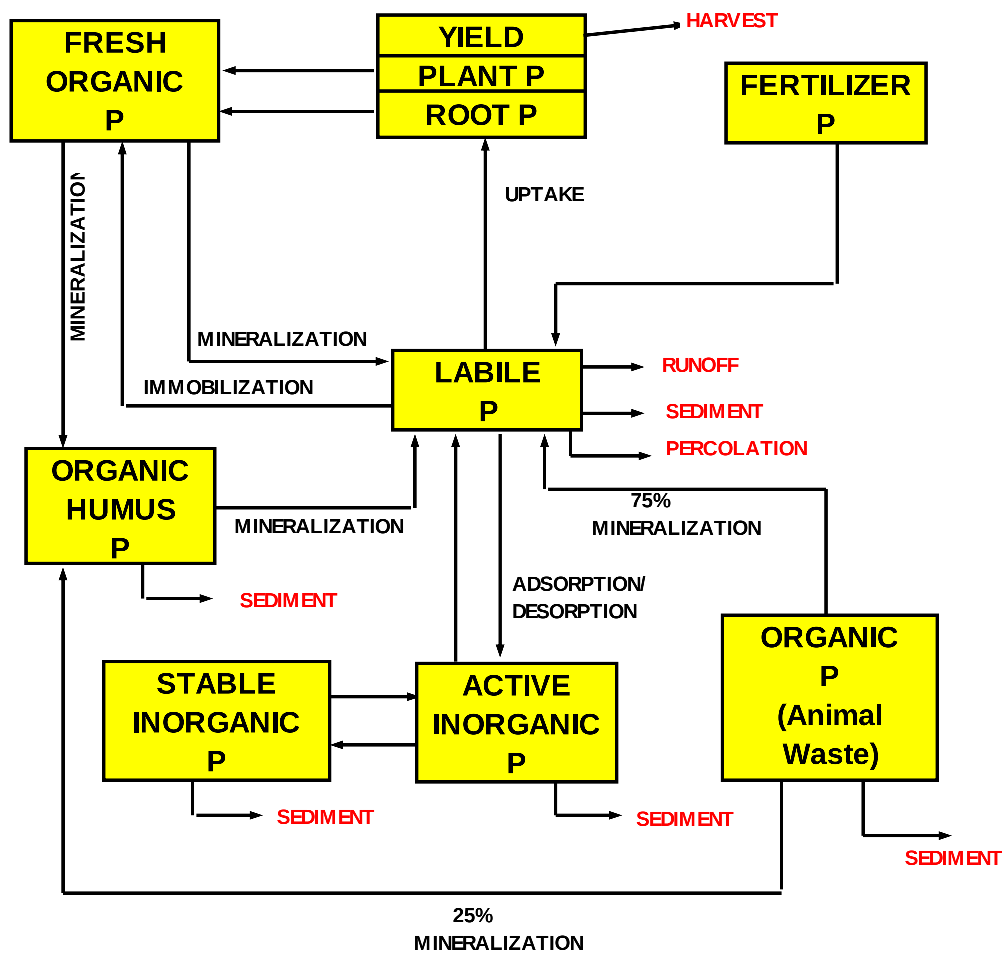

Figure 14. Phosphorus Transport Processes in the Soil/Plant Environment (Knisel, 1980)

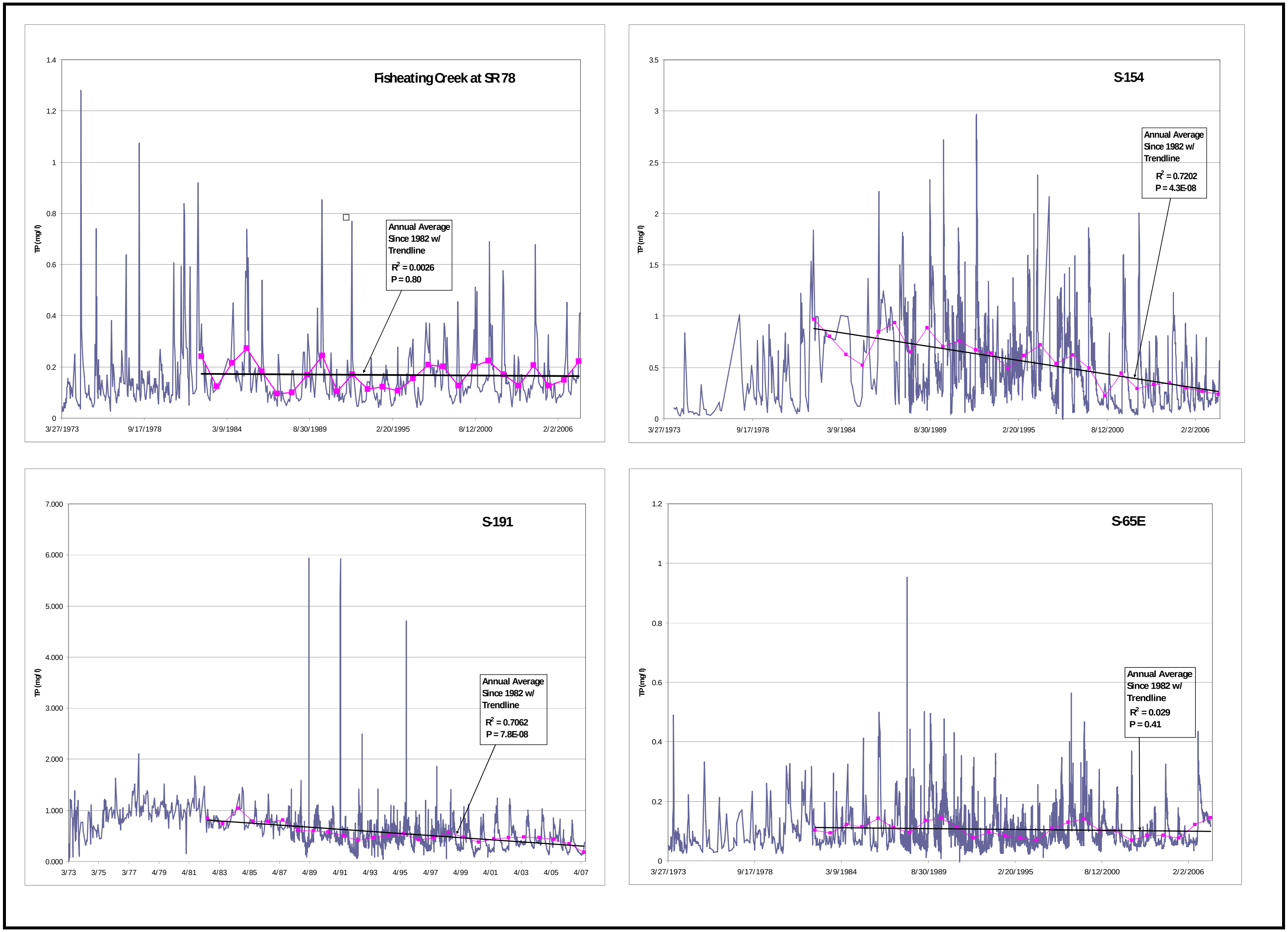

Figure 15. TP Concentration with Trend Line at Four Major Outflows to Lake Okeechobee for Past 23 Years (SFWMD DBHYDRO).

use specific information needed to correlate P reductions to individual P control practices or BMPs. Hunt et al. (2006) provides a summary of all of the SFWMD's surface water monitoring programs. They used this information to develop optimization strategies for future monitoring based on SFWMD objectives and monitoring techniques. The most comprehensive set of site specific data was collected in association with the Works of the District (WOD) compliance program where 154 sites across the Okeechobee basins were monitored between 1991 and 1999 (Zhang et al., 2002; Gornak and Zhang, 1999) for TP concentrations. These data provided a good picture of the variability of TP concentrations across various land uses, but were limited by the lack of associated flow and therefore TP loads could not be determined from measured data. Gornak and Zhang (1999) reviewed the TP data from beef pastures and also obtained landowner survey information. To estimate TP loads Zhang et al. (2002) used the CREAMS-WT model to produce flow estimates to combine with the P concentration data to produce P loads. They also used the CREAMS-WT to estimate potential TP load reductions for two in-compliance land use scenarios for the 77 out-of-compliance sites and estimated about 21 mt of P load reduction would be expected.

The soil P levels presented in Table 1 correlate well with the TP concentrations in runoff for the major agricultural land uses in the watershed that were presented by Bottcher et al. (1995),in Table 5 of their article. These were based on a number of studies done prior to 1995, and not surprisingly, the data from subsequent studies at Buck Island (Capece et al.,2007) and Williamson Ranch (Rechcigl and Bottcher, 1995; SWET, 2002) verified these assumptions. Several other studies have measured P concentrations in runoff and shallow groundwater in an attempt to evaluate the P mobility from individual land use practices including Graetz and Nair studies described earlier and the group of field studies reported by IFAS as part of their comprehensive project entitled "Biogeochemical Behavior and Transport of Phosphorus in the Lake Okeechobee Basin." These studies focused on beef and dairy pastures and measured P losses associated with abatement practices, including best management practices (BMPs), such as grazing density, and influences of soil characteristics (Campbell et al., 1995). There have been several monitoring programs by various agencies that measured the TP throughout the watershed (SWET, 2006). Over the years, a number of the monitoring programs were implemented. The usefulness of these earlier basin-wide and other short term monitoring efforts were limited by their low frequency of the collection, limited P fractionation data, and especially their lack of associated flow data. To correct these deficiencies, the USGS LOWP monitoring program was set up in 2003 and is still collecting excellent nutrient and flow data for seventeen stations across the basin. The 2008 South Florida Environmental Report (SFER) draft report (SFWMD, 2007) provides an excellent summary of the flow and nutrient data for the Lake Okeechobee basins from 1991 to present.

To evaluate the water conveyance systems' influence on P mobility to the lake SWET (2006a) conducted a study of the P assimilation properties of the major streams within the Okeechobee basins. SWET developed an updated P assimilation algorithm that reflected the P assimilation responses based on stream type, flow rate, and distance traveled within a reach. They found that low impacted (low historic P loads) sloughs had the highest potential for P assimilation and high impacted (high historic P loads) sloughs had little P assimilation capacity and could actually release P if inflow concentrations of P were reduced from past levels. Field ditches also had P assimilation capacity and responded similarly to historic P loading conditions as sloughs. Streams and canals had very little if any P assimilative capacity except for large canals that could settle particulate P, but this was limited to only about 6% of the TP. In summary, this study provides good estimates of the P assimilative capacities within the flow conveyance system and does reflect the influence of legacy P within the ditches, streams, sloughs, and canals. The usefulness of the updated P assimilation algorithm will be in watershed models as described later.

Rhue et al. (2005) developed a phosphorus quick test (PQT) for determining the relative amount of P in the soil that would be mobile or leachable. Nair et al. (2007) studied various water soluble extraction techniques to develop better correlations to the P leachability in the soil. They found that a quick WSP test using a 1:5 soil–solution ratio provided a reasonable prediction for P mobility/leachability as compared to the time consuming column studies. Therefore the PQT should be a handy tool for quickly assessing problem areas. The current drawback is that there is very little data that has been collected using this technique.

As indicated in the previous soil test results section, Graetz and Nair and their graduate students at the University of Florida conducted several studies to evaluate the status and fate of P in dairy and beef manure impacted soils (Graetz and Nair,1995; Graetz et al., 1999, Nair et al., 1995; Nair et al., 1998; Nair et al., 1999; Nair et al., 2003). These comprehensive studies measured the TP and several fractionations of P, such as WSP, DAP (Mehlich-1), labile P, Al/Fe-P, and Ca/Mg-P concentrations for the A, E, and Bh horizons for high (dairy only), low (dairy and beef), and non-impacted (forestry) areas. In general, these studies found that P mobility in the lower horizons was primarily associated with Al and Fe, while the surface or A horizon was dominated by Ca and Mg complexes. For the A horizon, Nair et al. (2003) and Josan et al. (2005) studied the mobility of P for soils on active and abandoned dairies, beef pastures, and minimally impacted soils. They found that the P being washed out of the soils was predominately associated with Mg bonded P for both the active and abandoned dairy soils, which means that continued P mobility is expected for a long time because Mg-P compounds do not tend to crystallize into stable non-mobile P forms as would Ca-P compounds. They suggest that low Mg-P based feed stuff for dairies and soil amendments to increase Ca forms of P be considered to reduce P mobility from these land uses. They found that increasing the pH of the soil would increase the Ca bonded P and reduce P mobility, but would only last if the soil is maintained at the higher pH.

As previously described, Nair and Graetz (2002) and Chrysostome, et al (2007) developed soil test procedures to describe the degree of P saturation (DPS) and associated soil P storage capacity (SPSC) of a soil. These parameters allow the relative amount of P that can be stored in a soil before raising WSP concentrations to be estimated. Since WSP directly relates to P washout potential or mobility, DPS and SPSC hold great promise for providing better estimates for the relative legacy P mobility in Okeechobee soils. Use of these parameters is limited at this time because they have only been developed for a limited number of land use and soil conditions in the Okeechobee basin.

The use of forested and other vegetated riparian buffers has been studied for the reduction of nutrients entering streams (Anbumozhi et al., 2005; Nair and Graetz, 2004), but these studies were not within the Lake Okeechobee watershed. These studies and others found that riparian buffers will reduce nutrient loadings with N reductions almost always being greater than P reductions, but the relationship between buffer characteristics and reduction efficiencies are poor. The primary processes that reduce nutrient flows going through buffers are a physical filtration of particles, plant uptake of nutrients from runoff passing through the surface vegetation and direct root uptake from the shallow groundwater flow, and perhaps the most important benefit is that the buffer zones reduce or eliminate nutrient loadings in the high P mobility zone near the streams. Nair and Graetz (2004) found similar reductions from riparian buffers as they found for in-field BMPs, but their results were for northern Florida well drained soils.

Several studies have looked at soil amendments for reducing the mobility of P from impacted soils including wetland soils (SWET, 2001b). Ann et al. (2000) looked at five soil amendments to reduce P mobility from agriculture impacted organic soils that were converted to constructed wetlands. It took 7-15 g/kg for calcite ($CaCO_3$) and $Ca(OH)_2$, 12 g/kg for alum, and 1-2 g/kg for $FeCl_3$ to effectively reduce overlying P concentrations. Dolomite [$CaMg(CO_3)_2$] was found not to be very effective. The amendments were ranked in the following order of effectiveness: FeCl3 > alum > Ca(OH)2 > calcite > dolomite. The high application rates for the amendments were caused by the "complexation of P binding cations (Ca, Fe and Al) with organic matter", and therefore would be quite expensive.

3.2 Mobility of Legacy P Based on Modeling Studies

Computer models have been used to simulate the P mobility processes within the entire Lake Okeechobee watershed. These models range from one-dimension soil P models (Mansell, 1995) to a comprehensive watershed model like WAM (Bottcher and Hiscock, 2002). The soil P model developed by Mansell et al. (1995) provides a mathematical depiction of the P adsorption / desorption processes in a Spodosol impacted by dairy waste in Okeechobee. The resulting P transport relationships were used or are similar to those used in larger scale models, such as CREAMS-WT, EAAMOD, FHANTM, and WAM.

The first field scale model used in the Okeechobee was the CREAMS-WT model developed by IFAS (Heatwole et al., 1988) and was an adapted high water table version of the USDA CREAMS model (Knisel, 1980). CREAMS-WT provided reasonable N and P responses from crop management for Okeechobee soils. The primary limitation of CREAMS-WT was its inability to handle the shallow lateral flows typical of the lower basins. To address this constraint two difference field scale models were developed. Campbell and Tremwel (1992) developed FHANTM, which added P mobility processes to the DRAINMOD high water table soil subsurface drainage model. FHANTM's strength is its ability to evaluate water management practices influence on P transport. Gornak and Zhang (1997) used FHANTM to calibrate and evaluate management alternatives for P reductions and found that it would take many years for the P levels to come down to acceptable levels due to accumulated or legacy P. A similar model, but more specific to flatwood and organic soils in south Florida is EAAMOD. SWET (2001a) upgraded EAAMOD for the Northern Lake Okeechobee region to assess BMP practices on various land uses. EAAMOD simulates the surface and shallow interflow and nutrient transport within high water table soils based on cropping, fertility, and water management. The EAAMOD results compared well with observed data and therefore verified its use as a valuable tool for BMP assessments.

The first watershed scale model for the Okeechobee basin was the BASIN model developed for the US Army Corps of Engineers (Bottcher and Baldwin, 1984). This was the first model to use GIS data for land use across the Kissimmee River Basin south of Lake Kissimmee, but was limited by being an event mean concentration (EMC) type model in that no processes were simulated and P loads were simply a summation of constant P load factors by land use only, but did demonstrate the power of GIS databases.

The LOADSS model (Negahban et al., 1995; SWET, 1999) was the next watershed scale model to take advantage of GIS information. LOADSS was developed by IFAS as a decision support tool for the implementation of BMPs and other P control programs in the Northern Lake Okeechobee region. The model is initially setup by running a comprehensive set of land use / BMP combinations using the CREAMS-WT and FHANTM models to develop a set of known P BMP responses for these combinations. The original BMPs' response coefficients were recalibrated and updated by SWET (1999) using additional field and subbasin water quality data. The power of LOADSS when there are reasonable BMP response coefficients is its complex optimization routine that can evaluate the most cost effective P control program across the watershed based on decision constraints provided by the user. The model is limited by the accuracy of the one-time calculated constant BMP effectiveness and cost input values and the unknown landowner acceptance of the selected practices.

The most comprehensive process-based watershed scale model used in the basin is the Watershed Assessment Model (WAM) (Bottcher and Hiscock, 2002; HDR, 2002;2004). The advantage of WAM is that it uses the verified EAAMOD and GLEAMS field-scale submodels and that using a robust stream routing and nutrient assimilation procedure for transporting water and nutrients through the stream network. WAM was selected and used to assess current conditions and various BMP implementation scenarios across all of the basins in the Northern Lake Okeechobee region (HDR, 2002; 2004). WAM was calibrated and verified using monitoring data and was found to be highly suitable in estimating the water and nutrient flows. The CERP recommended BMPs and P control programs were simulated and WAM showed that a moderately aggressive BMP program would result in about a 25% reduction in P to Lake Okeechobee and the other control practices could potentially add another 15 – 25 % reduction. The individual BMP reductions were similar to those reported in field studies. Zhang et al. (2006) used the WAM model to evaluate the benefit of water management practices on a beef cattle ranch for reducing P discharges. They evaluated various retention levels from 0.25 to 0.50

inches of runoff and found that these levels could produce about a 20% reduction in TP discharges.

Several wetland models have also been developed that handle the transport and internal dynamics at varying degree of complexity (Kadlec and Knight, 1996; Guardo, 1999; Raghunathan et al., 2001; Knight et al., 2003; Reddy et al., 2004). The two most focused wetland modeling efforts for the Lake Okeechobee watershed have been the development of the DMSTA model (Walker, 2003; Knight et al., 2004) and the process based model by Reddy et al. (2004). The DMSTA model simulates the nutrient transport processes with the large stormwater treatment areas being proposed in the northern Lake Okeechobee region. It uses 1st order P uptake and sediment interaction dynamics for individual cells of a wetland and then hydraulically links the cells for a cell to cell routing technique. Knight et al. (2004) successfully calibrated DMSTA for a number of sites around Florida. Reddy et al. (2004) refined a two-dimensional treatment model for spatially distributed isolated and smaller constructed wetland, which would be more appropriate for the smaller wetland systems than DMSTA. These models are the best available tools for evaluating the long term benefits of wetland restoration programs and constructed treatment wetland projects for the Okeechobee basin. The performance of the wetlands simulated by these models is discussed in the next two sections.

The above wetland models are stand alone models, i.e. they have not been integrated into watershed scale models mainly because of the lack of spatial and site specific data to properly characterize the wetlands and runtimes necessary to handle these more complex models. However, a simplified wetland submodel has been integrated into WAM (Bottcher, 2003) and work has been completed that has used WAM to provide dynamic flow and nutrient input for STA design projects. A fully linked watershed scale model is needed and should be considered a high priority for future model development work.

3.3 Retention and Mobility of Legacy P in Wetlands and other Flow Conveyances

Wetlands play a major role in the retention and transport of legacy P within the Okeechobee basins. The Wetland Biogeochemistry Laboratory at the University of Florida headed by Dr. K. Ramesh Reddy has been the lead group for most of wetland related research in the watershed. The center's publications are easily accessed through their website: http://wetlands.ifas.ufl.edu/. Reddy et al. (2005) is probably the best updated reference for the physical and biogeochemical processes associated with P retention and mobility in wetlands since Kadlec and Knight published their Treatment Wetlands book back in 1996. These are state-of-the-art references for wetland processes for P retention and mobility. Reddy et al. (2004) provides more specific information for P transport and transformation processes within the Okeechobee basin. This field study verified that large amounts of legacy P have accumulated in wetlands as the result of P migration from upland sources, as quantified in a previous section of this report. The P has primarily accumulated in the organic sediments of the wetlands, which can release this P for downstream transport if they are over drained. They indicated that more than

50% of isolated wetlands are currently drained, which means they have a high downstream P transport potential. They suggest that restoration of these drained wetlands would reduce future releases of the accumulated P.

The potential of riparian wetlands associated with sloughs and other streams and canals for assimilating P was studied by Mock Roos (1997) and SWET (2001c and 2006a). They identified primary processes for P assimilation in flow conveyance systems as settling of solids, plant uptake and related detritus deposition, and sorption/desorption interactions with bottom sediments or parent materials. Detritus accumulation of plant material was ranked as the most important process for long term assimilation of P. They ranked the relative P assimilation capacity of conveyance systems from high to low as shallow herbaceous sloughs, forested riparian sloughs, large canals, open streams, and ephemeral streams and ditches. Only the sloughs were found to have significant legacy P accumulations because of their ability to trap and hold organic sediments. However, these sloughs would become significant sources of P if the inflow P concentrations were reduced or after dry periods due to mineralization of the organic sediments.

4.0 PHOSPHORUS ABATEMENT PRACTICES AND BMPs

Several studies in the Lake Okeechobee watershed have focused on evaluating practices to reduce P movement to Lake Okeechobee. These practices have included land source control or best management practices (BMPs), edge-of-field/farm treatment systems, and regional tributary treatment systems. A few good overviews on the P fate and abatement control strategies for Okeechobee and elsewhere were provided by Flaig and Reddy (1995), Haan (1995), and Gilliam (1995), but these papers were limited on specific details of individual control practices. Bottcher et al. (1995) provided more specific detail on potential BMPs and their relative effectiveness for reducing P loads leaving various agricultural land uses. Bottcher (2003) updated the BMP effectiveness data based on additional studies and added a relative cost analysis for the BMPs. This report was expanded to include urban BMPs that were provided by Dr. Harvey Harper with Environmental Research and Design, Inc. A 2006 update of the Bottcher (2003) report was provided to the SFWMD that adjusted the net watershed P reduction values based on updated 2006 land use data. These reports provide the best available technology and in some cases best professional judgment for expected BMP P reduction efficiencies.

SWET (2001b) completed a comprehensive literature review to evaluate the best available technologies (BAT) for edge-of-field/farm treatment systems for reducing P loads leaving Okeechobee dairies, which is known as the Dairy BAT project. The study reviewed and ranked wetland, combined wetland/chemical, closed and open biological reactor, chemical, retention/detention, algal turf, and various proprietary treatment technologies for removing P from dairy runoff. This review found that a combined stormwater retention/detention system with water reuse and chemical treatment was the most cost effective edge of farm P treatment technology. Once the appropriate technology was selected, the four design/built contractors were selected to design and construct systems on four dairies (SWET, 2003). The results of these systems provided in their last quarterly report (SWET, 2006) showed that if properly operated these systems can provide consistent P reductions of 75 to 95%. Annual costs based on these reductions were calculated to be between $15 to $40 per pound of P removed for the four systems.

The SFWMD and other agencies have two major programs for the implementation of phosphorus control practices and regional projects within the northern Okeechobee basins (SFWMD, 2007). The larger regional projects are referred to as the LOFT projects while the land source area phosphorus control practices are part of the *Lake Okeechobee Watershed Phosphorus Control Program* with both of these programs being a cooperative effort among SFWMD, FDACS, USACE, FWS, and FDEP. The current status of the LOFT projects is summarized by the following excerpt from Chapter 10 of the 2008 SFER Draft Report (SFWMD, 2007):

> "Initial funding has been provided for five LOER construction projects north of Lake Okeechobee identified as LOFT projects. These LOFT projects are specifically designed to provide water quality improvements and include: (1) a 500-ac [202-hectare (ha)] expansion

of the Nubbin Slough Stormwater Treatment Area (STA), (2) a 30,000 acre-feet (ac-ft) [3,701 hectare meter (ha-m)] reservoir in association with the Taylor Creek STA, (3) a 2,700-ac (1,093 ha) STA at Lakeside Ranch, (4) the re-routing of flows from the S-133 and S-154 basins to the Lakeside Ranch STA in the S-135 basin, (5) a 150-ac (61 ha) STA on Lemkin Creek, and (6) a 1800-ac (728 ha) STA on Brady Ranch in the S-191 basin immediately east of the Lakeside Ranch site. The Nubbin Slough STA expansion and the flow re-routing projects were eliminated due to their very low cost-effectiveness in terms of TP load reductions. The remaining three projects (Taylor Creek Reservoir, Brady Ranch STA, and Lakeside Ranch STA) are in the planning/designing phase."

The *Lake Okeechobee Watershed Phosphorus Control Program* has two major subprograms headed by FDACS and SFWMD. Tables 10-5 and 10-6 in the 2008 SFER Draft Report (SFWMD, 2007) summarize these projects and the estimated overall P reduction, for these projects. Unfortunately, very little monitoring data were collected as part of these projects so P removal efficiencies were primarily estimated based on BMPs effectiveness data provided by Bottcher (2003; 2006) or nutrient balancing for the individual projects.

Rechcigl and Bottcher (2000; 2005) evaluated the effects of P application rates and soil amendments of lime and gypsum on the crop yields and soil and runoff P concentrations. They found that P losses in runoff were directly correlated with P fertilizer applications, but crop yield was not and therefore P fertility on bermuda-stargrass was set to zero. They also found that liming reduced P losses, but gypsum did not. O'Conner and Brinton (2004) evaluated ten soil amendments under laboratory conditions using Okeechobee soils. They used soil columns for evaluating leaching potential and small beds and a rainfall simulator for evaluating runoff potential using the National P Project protocol. They deselected the following amendment either because of poor P sorption capacity or because of troublesome trace elements: DuPont Fe-"humate", coal slag, Pro-sil, gypsum, Vigiron (Fe-Wastewater Treatment Residue(WTR), lime, and Ca-WTR. DinoSoil was considered effective, but considered impractical because of cost. The two amendments they recommended for further field studies were the Manatee and Okeechobee Al-WTRs. However, they pointed out that they would be ineffectual for P leaching unless they were fully incorporated in the soil.

Oladeji , et al (2007) evaluated the pros and cons of using aluminum based water treatment residues (WTR) for reducing the potential of P loses from impacted soils. They found that WTR did increase the SPSC (Chysostome et al, 2007) without negatively affecting plant growth and therefore should be considered for future P abatement strategies. They did not, however, provide an economic analysis for addressing the cost effectiveness of such an alternative.

Driscoll et al. (2007) have just completed a study looking at the effects of aluminum water treatment residual (WTR) on soil P retention and forage quality. They evaluated both surface applied and incorporated WTR at two rates (35 and 70 Mg/ha) plus a control. They found that WTR did not adversely impact yields and neutral detergent fiber. WTR did, however reduce tissue P levels, but not below acceptable limits. WTR did significantly increase the soil P sorption capacity in the A horizon with the surface applied having a larger effect than incorporated WTR. Though not quantified, it was anticipated that the increased P sorption would translate into lower soil-water P and related P transport.

Nair et al. (2007) investigated the benefit of trees within bahiagrass pastures for reducing nutrient losses. They found that the pastures with trees had lower P losses, but it was uncertain how historic pasture management and P fertility practices influenced their results.

The benefits of stormwater retention/detention on nineteen dairies in the Lake Okeechobee watershed were investigated by SWET (2003) using WAM. SWET found that retention/detention can provide between 40 to 60% TP reduction in runoff leaving the farm. Approximately half of the reduction was due to runoff volume reductions and the remainder being from TP concentration reductions in the ponds. Note that they assumed that the retention/detention ponds would be built on low impacted areas on the dairies.

Wetland treatment technologies have been a primary focus for treating P runoff in the watershed including small-scale farm level systems to large regional scale STAs. Several models and field research have been completed that assessed the P assimilative capacity of various wetland systems including those developed in the Everglades, regional treatment systems, and constructed wetlands (Moustafa et al., 1996; Kadlec and Knight, 1996; Guardo, 1999; Raghunathan et al., 2001; Knight et al., 2003). These references verify that wetlands, either constructed or natural, have long-term P removal in the form of detritus and organic sediment buildup similar to the historic processes that formed the organic soils in the area. Knight et al.(year?) found that systems dominated by submerged aquatic vegetation (SAV) could remove about 1.2 g P/m^2 per year. They cautioned that extrapolating results from short-term and small-scale mesocosm studies to full-scale, long-term operating SAV-dominated wetlands, such as the proposed reservoir assisted stormwater treatment areas (RASTAs), should be done with caution. However, their removal efficiencies are very similar to the measured performances of the stormwater treatment areas (STAs) south of Lake Okeechobee as reported in the 2008 SFER Draft Report (SFWMD, 2007), so 1.2 g P/m^2 per year should be a good estimate of the potential performances of the Okeechobee STAs or RASTAs. However, as discussed in the next paragraph, the conditions of the soils on which these wetland systems are built will have a significant impact on their performance.

Pant et al. (2002) studied the internal P loading within constructed wetlands on manure impacted dairy soils. They found that very high P up-flux from the soils to the overlying water for the first 28 days, after which the overlying P concentration dropped and stabilized at about 1.3 mg/l. This P concentration, however, is still very high and they concluded that wetlands constructed on dairy manure impacted soils would never be able to reduce P concentrations to targeted levels unless the soils are pretreated with amendments, such as alum. Unfortunately, the study did not evaluate soil amendments for this purpose.

Harvested and chemically augmented wetland systems have also been studied that use hyacinths, algae, and other floating and bottom rooted vegetation and chemical flocculents (DeBusk et al., 2001). Most of the hybrid wetland systems are being promoted by private companies, such as HydroMentia and Watershed Technologies, LLC. A pilot Algal Turf system by HydroMentia is currently being evaluated by the SFWMD with inconclusive results to date. The Hybrid Wetland Treatment Technology (HWTT) being promoted by DB Environmental Laboratories, Inc. has shown promise in small-scale systems. This system uses hyacinths as a primary P removal mechanism, but adds a chemical flocculent to achieve higher TP removal rates. The HWTT system has yet to have a full scale evaluation completed.

5.0 SUMMARY AND CONCLUSIONS

This study reviewed available relevant data and literature related to the quantification and mobility of legacy P and its associated P abatement technologies within the Lake Okeechobee watershed. Soils test data from various studies and routine sampling programs were used to quantify legacy P for upland land uses, which were then spatially distributed and summed across the entire watershed using the 2006 GIS land use coverage. Results of this analysis estimated about 170,000 mt of legacy P currently exists in the uplands (91%) and isolated wetlands (9%). Based on stream sediment studies the estimated legacy P in the sloughs, streams, and canals represent about another 860 mt while the larger lakes would have possibly another 5000 mt of legacy P. This means there would be about 176,000 mt of legacy P within the studied basin that is potentially available for transport to Lake Okeechobee. To put this into prospective, at the current TP loading rate to the lake (500 mt/y) from the basin, it would take about 350 years to wash the existing legacy P from the watershed assuming P imports and exports were immediately balanced. There is also enough legacy P in just the flow conveyance network, which does not include isolated wetlands, to sustain the current P loads for over ten years. However, it is likely that as much as 50% of the legacy P will not be very mobile due to the soil P storage capacity (SPSC) described by Chrysostome, et al (2007) and the low mobility of legacy P that has moved to lower soil layers. Even with a significant portion of the legacy P being relatively immobile it is clear that there is an abundance of mobile legacy P in the watershed to maintained elevated P levels going to Lake Okeechobee for many years. Therefore, the reduction new sources of legacy P and its mobility to the lake through abatement practices will be the only effective means of addressing P loads to the lake and that these practices must address both upland, wetlands, and streams legacy P sources.

The mobility processes and associated abatement strategies were also reviewed and evaluated for their potential for reducing P loads to the lake. Abatement strategies fall into either upland source control or downstream treatment systems. Upland strategies focus on increasing net P export through cropping practices and reducing the mobility of P by optimizing the soil P sorption by manipulation of the Al, Fe, Ca, and Mg interactions. The use of amendments was shown to have high potential for optimizing P sorption in the soils, but the long term costs and sustainability of such practices were not as well described.

Edge-of-farm or regional treatment systems show great promise for reducing P loads to the lake. Both chemical and wetland treatment technologies have been studied and demonstrated within the Okeechobee basin. Restoration of drained isolated wetlands was one recommendation because of its potential immediate benefits of reducing upland sourced P. Though not well quantified as to rates of reduction and its costs, wetland restoration was suggested as potentially one of the most cost effective practices, but will be limited as to its spatial impact. Downstream constructed wetland treatment systems, such as the proposed STAs, have the potential of about 1.2 $g/m^2/y$ of P retention, which means large areas will need to be dedicated to them, which increases their costs.

Warnings were provided that site selection for these constructed wetlands is critical because historic land use practices where they are built can significantly impact the future functionality of these systems. Water retention and reuse associated with chemical treatment was found to be a cost efficient technology for removing P at the edge-of-farm scale. Extension of this technology to regional systems has not been adequately studied.

Based on this review and evaluation of our current state-of-knowledge for legacy P in the Lake Okeechobee watershed, it believed that adequate information is currently available to formulate effective legacy P abatement strategies. The next task associated with this study will be to articulate such strategies, while identifying informational shortcoming associated with individual components of these strategies.

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