NUTRIENT TRANSPORT IN GROUNDWATER NEAR ISOLATED WETLANDS AND DRAINAGE DITCHES: IMPLICATIONS TO BEST MANAGEMENT PRACTICES

By

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

BMP	Best management practices
BTT	Break through time
DWSM	Dynamic Watershed Simulation Model
GIS	Geographic Information System
ΔH	Head difference
HSPF	Hydrological Simulation Program-Fortran
IGW	Interactive Ground Water
K	Hydraulic conductivity
Kd	Partitioning coefficient
m/day	Meters per day
NPDS	National pollutant discharge system
PFM	Passive flux meter
PNFM	Passive nutrient flux meter
Ppb	Parts per billion
Ppm	Parts per million
SFWMD	South Florida Water Management District
SWAT	Soil and Water Assessment Tool
TMDL	Total maximum daily load
TP	Total phosphate
WAM	Watershed Assessment Model

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Using the Interactive Groundwater (IGW) program, computer modeling of phosphate transport from isolated wetlands into a drainage ditch provides insight into the trends of subsurface phosphate transport around isolated wetlands. The passive nutrient flux meter (PNFM) was utilized to measure groundwater and phosphate flux from isolated wetlands in the Lake Okeechobee basin. The groundwater and phosphate flux measurements were collected to provide baseline values for general phosphate flux estimates from the isolated wetlands. The phosphate flux was measured from isolated wetlands to the subsurface discharging into the drainage ditch. Field measurements from a transect of wells near a drainage ditch were also completed. The phosphate flux measurements and knowledge of the trends related to isolated wetlands and phosphate transport were used to scale up phosphate mass loads from single isolated wetlands and a drainage ditch to basin-wide phosphate mass loads. With an estimate of the area of the wetlands in the basin, the amount of phosphate retained by each wetland was calculated to provide the tons per year of phosphate loads that could be eliminated or delayed from entering Lake Okeechobee by increasing the effectiveness of best management practices (BMPs).

If BMPs are focused on drainage ditches the total phosphate load to Lake Okeechobee from overland and subsurface transport through the drainage ditches could be eliminated. Basin-wide estimates of phosphate loads from isolated wetlands and drainage ditches ranged from 2 to 16 metric tons per year. The basin-wide estimates confirm that there is the possibility of reducing at the very least one to two metric tons of phosphorus per year from entering Lake Okeechobee by increasing the effectiveness of BMPs in isolated wetlands and drainage ditches.

CHAPTER 1
INTRODUCTION

The Lake Okeechobee Watershed Phosphate Problem

Lake Okeechobee is located in south Florida and has an area of 730 square miles with an average depth of 8.6 feet (US EPA Region 4, 2006). The Lake Okeechobee watershed covers 3.5 million acres including north to south Orlando and the areas south, east and west surrounding the lake (Figure 1-1). The lake supplies water for the surrounding agriculture, urban areas, and environment. Lake Okeechobee provides flood protection for the surrounding community, a mult-million dollar sport fishing industry, and habitat for wading birds, migratory waterfowl, and the Everglades Snail Kite, an endangered animal (US EPA Region 4, 2006).

In 1986, one of the largest algae blooms ever documented covered 120 square miles of the western quarter of the lake. It was determined that the algae bloom could be controlled by phosphorus regulation (Rechcigl, 1997). In 2001, the Total Maximum Daily Load (TMDL) proposed an annual load of 140 metric tons of phosphorus in order to reach the in-lake goal of 40 ppb phosphorus (FDEP, 2001). Point sources to Lake Okeechobee are regulated by National Pollutant Discharge Elimination System (NPDES) permits and do not make up any portion of the TMDL to Lake Okeechobee. Nonpoint sources of phosphorus to the lake include agriculture, wildlife, septic systems, and stormwater runoff. Cattle and dairy pasture lands are the primary agricultural activities north and northwest of the lake, while cropland, sugarcane and vegetables dominate south and east of the lake. Agricultural activities produce 98% of the phosphorus that is imported into the watershed (US EPA Region 4, 2006).

Land uses for the Lake Okeechobee basin can be seen in Figure 1-1. Major land uses in the northern Lake Okeechobee watershed include improved pastures (36%), wetlands/water bodies (21%), rangeland/unimproved pastures (16%), forested uplands (10%), citrus (5%), urban

(3%), sugarcane field (2%), dairy farm (2%), sod farm (0.9%), ornamentals (0.6%), and row crops (0.6%) (Hiscock et al., 2003). Best management practices (BMPs) for phosphorus have been established for all the land uses (FDEP, 2001). This paper will focus on cattle pasture BMPs. Cattle pasture BMPs include structural improvements such as fencing and water tanks to deter cattle from waterways, berms and culverts/risers to retain surface water on pastures, herd and pasture management by rotational grazing, altered feeding and fertilizer regimes, and chemical amendments (Graham, 2006).

Hiscock, Thourot and Zhang's 2003 phosphorus budget for the northern Lake Okeechobee watershed indicated that 74% of the phosphorus inputs per year are stored on-site in upland soils and vegetation, 26% is discharged to runoff. The net phosphate imports from each land use can be seen in Table 1.1. Of the phosphorus inputs from the runoff 32% is stored in the wetlands and 68% is loaded to Lake Okeechobee (Hiscock et al., 2003). By retaining the runoff on the pastures or in the isolated wetlands located throughout the watershed phosphorus is stored in the soil instead of flowing over the pasture lands into ditches draining to Lake Okeechobee (Gathumbi et al., 2005; Dunne et al., 2006). The isolated wetlands can also provide high quality forage production, areas for the cattle to cool themselves, wildlife habitats and greater vegetation productivity (Gathumbi et al., 2005).

The objective of this study was to extend field measurements collected by Hamilton (2005) of phosphate flux from isolated wetlands in the Lake Okeechobee watershed. Additional wetland sites were assessed and a drainage ditch instrumented to quantify phosphate flux. The field measurements of phosphate flux provide a baseline for a general phosphate flux estimate from the isolated wetlands. Computer modeling of phosphate transport through groundwater provides insight into subsurface phosphate transport trends between isolated wetlands and the drainage ditch. With the estimated phosphate flux from isolated wetland and knowledge of the trends related to isolated wetlands and phosphate transport the phosphate loads were scaled up from the phosphate retention capacity of a single isolated wetland and drainage ditch to determine the Lake Okeechobee watershed's retention capacity for phosphate though water retention in isolated wetlands. With an estimate of the area of the wetlands in the basin, the amount of phosphate retained by each wetland was calculated to provide the tons per year of phosphate inflows that could be eliminated or delayed from entering Lake Okeechobee with an increase in retention time of surface water runoff. The objectives of the research were to:

- Model groundwater flow and phosphate transport between an isolated wetland and the drainage ditch discharging from the wetland under varying conditions
- Quantify and compare phosphate flux around five isolated wetlands on ranch lands (two conducted as part of this study) and a transect of a drainage ditch on ranch lands
- Scale up the findings to provide a basin-wide conclusion about the benefits of water detention in isolated wetlands for reduction of phosphate to Lake Okeechobee and phosphate loads attributed to groundwater discharge to drainage ditches.

Isolated Wetlands

The Basics of Phosphorus in Wetlands

Phosphate in soil is a key ingredient in productive agricultural lands however natural topsoil is often phosphate deficient, 0.05-1.1 g phosphate kg^{-1} soil (Reynolds and Davies, 2001). The common primary inorganic forms of phosphate in soil are apatite and phosphates of aluminum and iron. These inorganic forms become bioavailable as soil water soluble reactive phosphates after weathering and dissolution. Plants readily take up and assimilate the soil water soluble reactive phosphates. However the plants are competing with the soluble reactive phosphate's mineral binding affinity. The inorganic phosphate becomes a part of secondary minerals, not bioavailable to plants, such as hydrous sesquioxides, amorphous iron, aluminum oxides or hydroxides. Phosphorus in biomass of plants may eventually find its way back to the soil by leaf-fall, decomposition, consumption or excrement by animals.

Phosphate levels in natural soils are quite stable and low which leads to fertilization for agriculture and subsequently runoff of phosphates into nearby water bodies. Non-point inputs of bioavailable phosphate from agricultural lands have been shown in several studies to be a major contributor to phosphate loading of drainage waters (Reynolds and Davies, 2001).

Wetlands Phosphate Cycle

Naturally occurring inputs of phosphate into wetlands include surface inflows and atmospheric deposition. Outputs of phosphate include surface runoff and infiltration to groundwater. Phosphorus is found in wetlands in many different forms and interconversions of these forms occur.

Figure 1-2 depicts the phosphate cycle in a wetland including the storages and transfers of phosphate. Soluble reactive phosphate can be converted to tissue phosphate by plants or sorbed to wetland soils and sediments. Insoluble phosphate precipitates form and may re-dissolve under certain conditions (Kadlec and Knight, 1996). Wetland vegetation plays a large role in phosphate assimilation and storage. Because of rapid turnover the phosphate storage is short term and phosphate is released during plant decomposition. While some vegetation absorbs phosphate directly from the water column most uptake phosphorus from the soil porewater creating gradients between the phosphorus in soil porewater and the water column. When the concentration of phosphate in the water column is higher than in the soil or sediment porewater the phosphate diffuses into the sediment/soil (Reddy et al., 1999).

The principal phosphate compounds found in wetlands are dissolved phosphate, solid mineral phosphate, and solid organic phosphate. The principal inorganic species of phosphate are related by pH-dependent dissolution series:

$$H_3PO_4 = H_2PO_4^- + H^+$$
$$H_2PO_4^- = HPO_4^{-2} + H^+$$
$$HPO_4^{-2} = PO_4^{-3} + H^+$$

Some important phosphate precipitate cations that are found in wetlands under certain conditions include: apatite ($Ca_5(Cl,F)(PO_4)^3$), hydroxylapatite ($Ca_5(OH)(PO_4)_3$), variscite ($Al(PO_4)(2H_2O)$), strengite ($Fe(PO_4)2H_2O$), vivianite ($Fe_3(PO_4)_28H_2O$), and wavellite ($Al_3(OH)_3(PO_4)_2(5H_2O)$). Phosphate also forms co-precipitates with other minerals such as ferric oxyhyroxide and carbonate minerals. Overall phosphate mineral chemistry is very complex (Kadlec and Knight, 1996).

Wetlands can serve as sources or sinks for phosphate depending on the soils sorption capacities. Fluctuating waterlogged and drained conditions on wetlands can alter the redox potential and thus retention and release phosphate occurs. The redox potential is influenced by organic matter input and affects phosphate solubility (Reddy et al., 1998).

Phosphate Transport through Isolated Wetlands to Lake Okeechobee

Phosphate is transported first from the surrounding environment into the ditches and isolated wetlands that eventually drain to Lake Okeechobee. Isolated wetlands are depressions that have no permanent connection to the surrounding water bodies. However, intermittent overland flow, subsurface flow and drainage ditches can hydrologically connect the isolated wetlands to surrounding water bodies and other wetlands (Dunne et al., 2003). Overland and subsurface flow transports phosphate both into the isolated wetlands from the surrounding environments and out of the wetland into the surrounding environment (Reddy et al., 1999). Campbell et al. documented phosphorus transport by runoff and groundwater during large and small rainfall events on several experimental pasture sites (Campbell et al., 1995).

Phosphate inputs to the Lake Okeechobee watershed are primarily in the form of pasture fertilizer and dairy feed (Hiscock et al., 2003). Advective transport is the main transport process that moves phosphorus from the surrounding environment overland and through the drainage ditches into the isolated wetlands. Land with lower relief has a tendency to flood and discharge phosphorus by overland flow to ditches (Campbell et al., 1995).

Subsurface transport of phosphate by advective transport depends on the velocity of groundwater flow. Land with greater relief, more rapid groundwater flow and little overland flow generates subsurface discharges of phosphate to ditches and wetlands (Campbell et al., 1995). Groundwater flow is driven by the water pressure gradient or hydraulic head between the saturated soil surface and the aquifer. The velocity of groundwater flow is affected by the soils hydraulic conductivity (Reddy et al., 1999). Winter and LaBaugh illustrated how elevation and impermeable soil layers effect groundwater flows between isolated wetlands in Figures 1-3 and 1-4 (Winter and LaBaugh, 2003). The spodic layer can simulate the impermeable layers depicted in Figure 1-5. The spodic layer in the Lake Okeechobee watershed is very tight however in some locations there are holes or voids in which water can move easily. Horizontal water movement can occur entirely above or below the spodic layer as well as intersect the spodic layer and flow above and below the spodic layer (Haan, 1995). The vertical flows of groundwater are driven by gravity and plant uptake to support transpiration (Reddy et al., 1999).

Once in the isolated wetlands, horizontal flows from diffusion and dispersion processes move the phosphate through the isolated wetlands (Reddy et al., 1999). Phosphate is mobilized in the isolated wetlands between sediments and the overlying water column by advection, dispersion, diffusion, seepage, resuspension, sedimentation and bioturbation (Reddy et al., 1999).

Advective transport through either ditch flow or subsurface flow transports phosphate from the surrounding environment into ditches and isolated wetlands that drain to Lake Okeechobee.

Computer Modeling of Isolated Wetlands and Ditches

Recently the Watershed Assessment Model (WAM) was applied to evaluate the effects of water detention in depressions on a beef cattle ranch in the Lake Okeechobee watershed. WAM is a physically based model that performs watershed-related hydrological and water quality analyses. Land use, soil, weather, and land management practices were all input into WAM with the use of Geographic Information System (GIS) functions which overlay the ranch features (Zhang et al., 2006).

The WAM modeled a 3,295-ha area that included improved, unimproved, semi-improved, woodland pastures, wetlands, upland forest, and citrus land uses were included. A major drainage canal surrounds three sides of the modeled area and several rainfall stations are in the area. Water quality parameters included soluble nitrogen, particulate nitrogen, groundwater nitrogen, soluble phosphorus, particulate phosphorus, groundwater phosphorus, sediment phosphorus and biological oxygen demand (Zhang et al., 2006).

WAM used the above input and output parameters to assess the stormwater retention for three pasture land uses that were suitable to retain water for the ranch. The stormwater storage was simulated by defining a detention depth or the ratio of detention depth to land use area. The stormwater storage was assumed to be low lying areas or existing wetlands. Several scenarios using detention depths of 0.25 and 0.5 inches and the three land uses were evaluated.

Overall, it was found that a 20% reduction in phosphorus load can be accomplished with a detention range of 0.25 to 0.5 inches over all three land uses. A reduction of 16% of phosphorus load was found when 0.25 inch detention depth was used on all the land types. While use of 0.25 inch on the beef pastures, 0.5 inch on the woodland and unimproved pastures provided a 19% reduction in phosphorous levels. A 4% reduction in phosphorus load was found with a detention depth of 0.25 inch for the unimproved and woodland pastures. With an increase in detention depth to 0.5 inch over the two land uses the percent reduction in phosphorus moves to 7% (Zhang et al., 2006).

The applicability of the above study to this research is obvious and the most relevant study found pertaining to the assessment of BMP's or isolated wetlands through computer modeling. The use of computer models to simulate water quality including the phosphorus cycle was evaluated in Borah and Bera's *Water-Scale Hydrologic and Nonpoint-Source Pollution Models: Review of Applications* (Borah and Bera, 2004).

Borah and Bera selected three models from an evaluation of eleven to provide a review of each model's numerous applications. SWAT, or Soil and Water Assessment Tool, is a model for long-term continuous simulations in predominately agricultural watersheds. SWAT's applications indicated the primary use for phosphorus modeling is assessing the impacts of dairy management practices on dairy manure phosphate loading. The third model is DWSM, or Dynamic Watershed Simulation Model, is a storm event simulation model for agricultural and suburban watersheds. DWSM provided an application showing the effects to phosphorus loads during storm events (Borah and Bera, 2004).

Including phosphorus loading applications of models in the three models reviewed indicates that there is on going work towards more accurate phosphorus loading in groundwater modeling. Arnold and Fohrer's review of SWAT2000 suggested that future work should strengthen SWAT2000's phosphorus interactions with soils and different soil types (Arnold and Fohrer, 2005).

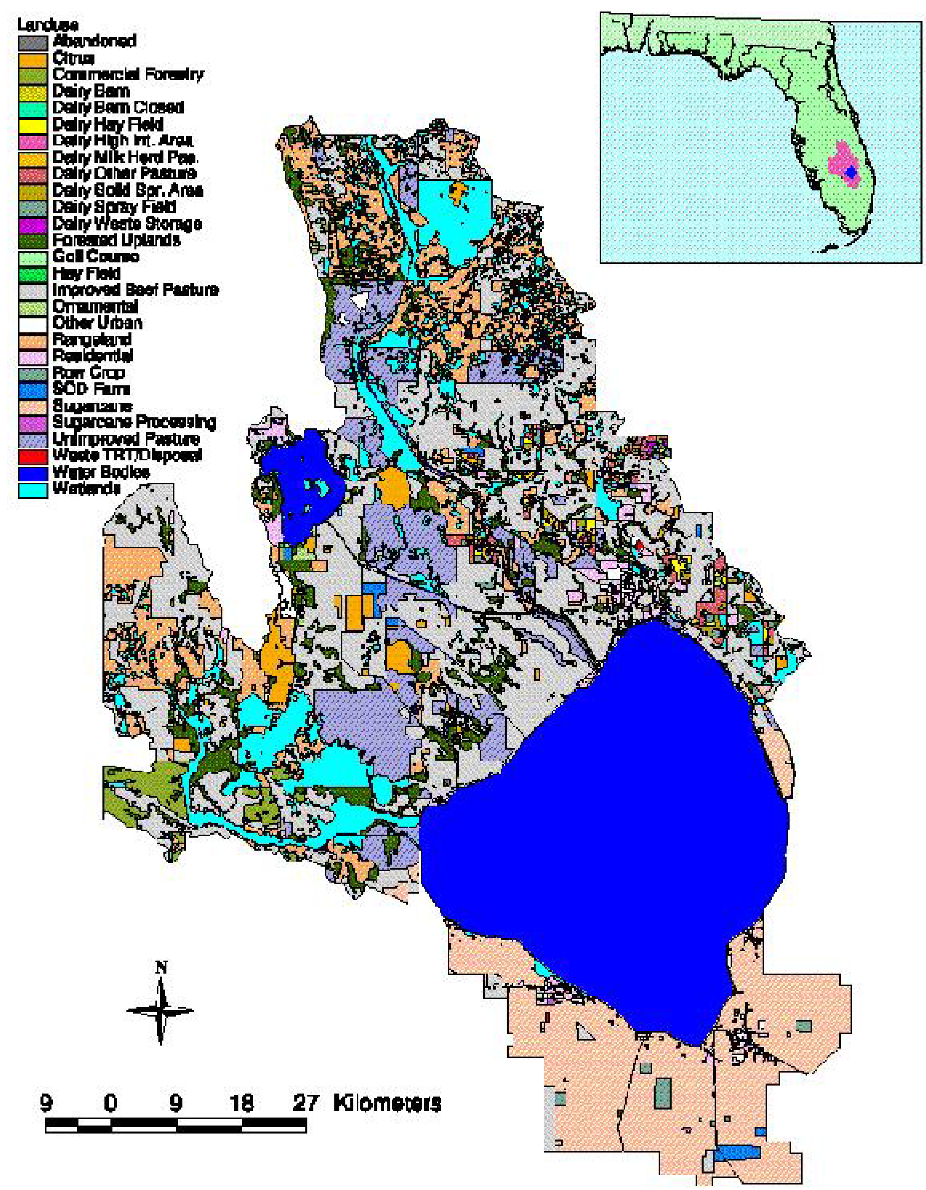

Figure 1. Land Use Types in the Lake Okeechobee Watershed

Figure 1-1. Location and land uses in the Lake Okeechobee watershed (Guan et al., 2007).

Table 1-1. Land use and net phosphorus imports in the northern Lake Okeechobee watershed.

Land use	Area Ha	Phosphate net import tons/year
Abandoned dairy	2,344	7
Citrus	25,392	184
Commercial forestry	13,299	-2
Dairy	8,525	458
Field crop	2,276	16
Forested upland	49,887	-8
Golf course	377	4
Improved pasture	183,778	558
Ornamentals	3,212	30
Rangeland	46,641	1
Residential	9,740	151
Row crops	2,868	545
Sod farm	4,816	-235
Sugarcane	8,755	9
Unimproved pasture	33,453	0
Wetland	95,423	0
Water and other land uses	25,215	0
Total	516,000	1,717

Hiscock, J. G., Thourot, C. S., Zhang, J., 2003. Phosphorus Budget-land use relationships for the northern Lake Okeechobee watershed, Florida. Eco. Eng., 21: 63-74, Table 2.

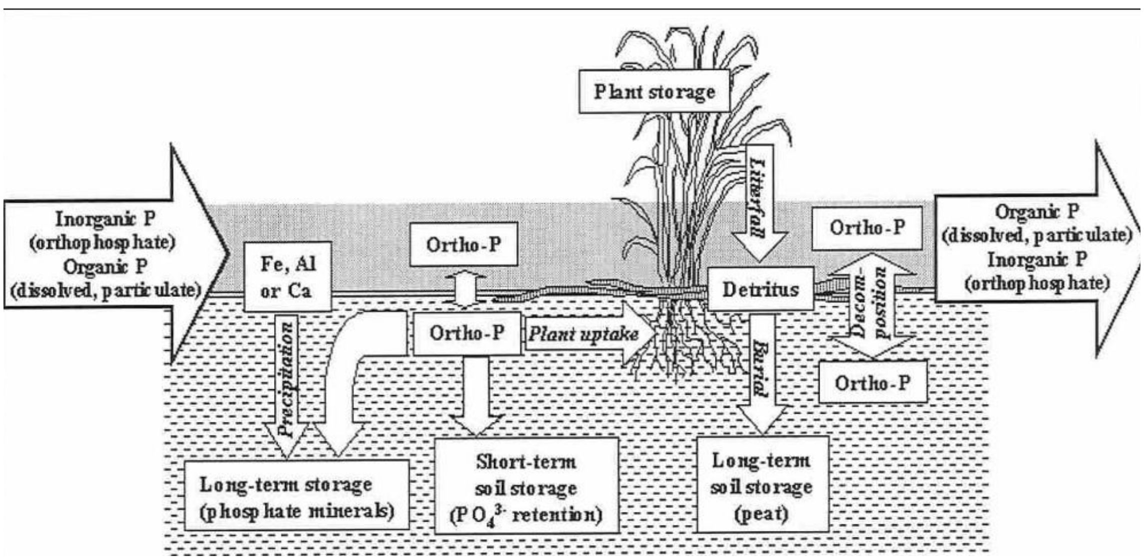

Figure 1-2. Phosphate cycle in wetlands (IFAS, 1999).

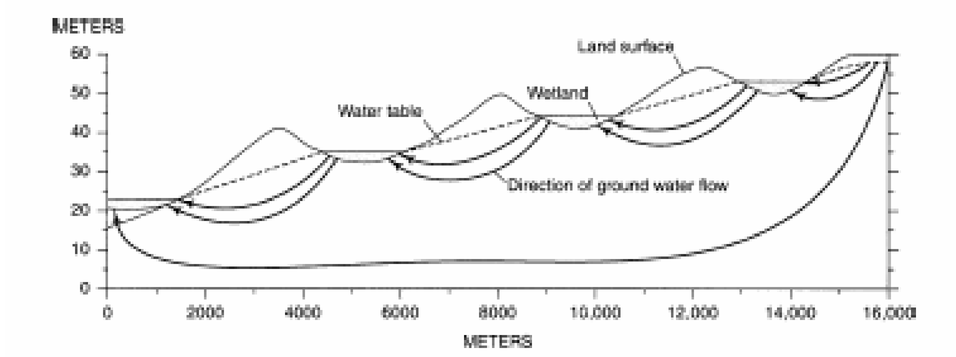

Figure 1-3. Groundwater flow system with flow through groundwater between wetlands (Winter and LaBaugh, 2003).

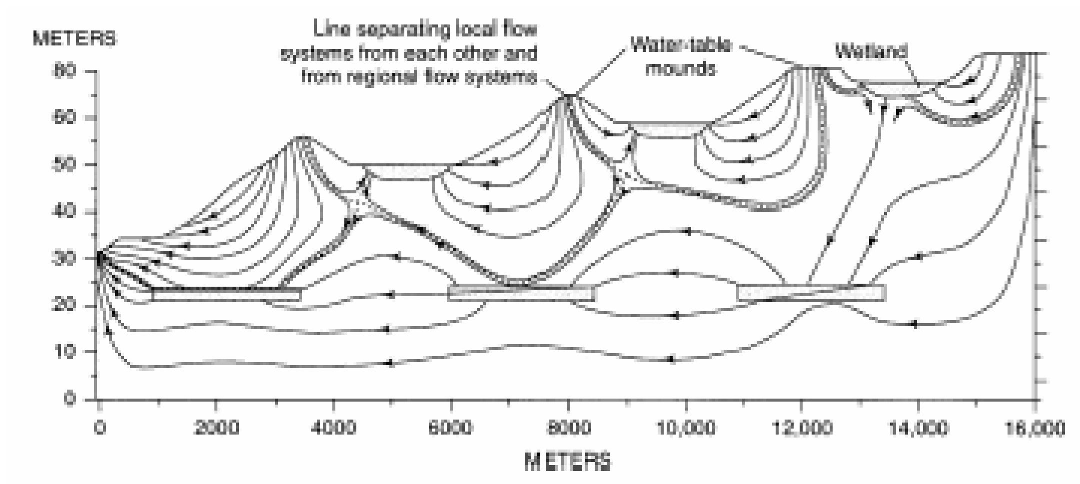

Figure 1-4. Groundwater flow system with impermeable layers present. Local flow lines as well as regional are shown (Winter and LaBaugh, 2003).

CHAPTER 2
INTERACTIVE GROUNDWATER MODEL

Interactive Groundwater Program and Capabilities

The Interactive Groundwater (IGW) Model is a software package for real time, unified deterministic and stochastic 2D and 3D groundwater modeling (Li and Liu, 2006). The IGW Model eliminates the bottlenecks in traditional modeling technologies allowing the full utilization of today's increased computing power (Li and Liu, 2003). Efficient computational algorithms allow IGW to simulate complex 2D and 3D flows and transport in saturated aquifers. These flows and transport mechanisms are subject to systemic and "random" stresses as well as geological and chemical heterogeneity (Liao et al., 2003). The IGW Model was utilized for this analysis due to its real-time modeling, visualization and analysis capabilities.

The IGW Model was utilized to model phosphate transport in groundwater from isolated wetlands towards an outflow ditch. Water budgets preformed for the wetlands indicate groundwater recharge from the isolated wetland (Perkins and Jawitz, 2007). Transport variables were identified and assessed as major factors to phosphate transport. The effect of each variable on phosphate break through time (BTT) was determined. Phosphate BTT was investigated to evaluate how long phosphate is detained by isolated wetlands due to transport through the groundwater. The management practice investigated here is the use of structures at the outlet of wetlands or filling in of ditches to retain water in the wetlands for longer time periods. The transport variables used in the IGW model include media hydraulic conductivity, phosphate partitioning coefficient, head difference between wetland and outflow ditch, wetland size and ditch distance from wetlands. By exploring the effects the variables have on the phosphate BTT the practices designed for detention of water in isolated wetlands can be evaluated.

IGW Model Design and Description

The basic design of the model was a circular wetland with a single ditch leaving the wetland. Located along the ditch, several groundwater monitoring wells provided observations of phosphate concentration over time. These observation points are used to determine BTT. For the base case the wetland was modeled as approximately 180 meters in diameter and the ditch was 375 meters in length. The basic layout of the model can be seen in Figure 2-1.

The wetland was created within IGW as one layer with two zones. A zone enables the modeler to assign physical and chemical properties, sources, sinks, and aquifer elevations. The whole grid or work space was assigned a zone and given Lake Okeechobee soil characteristics; this will be referred to as the aquifer zone. The wetland was created by defining a circular zone and assigning wetland characteristics. The wetland boundary was overlain by a polyline to enable a constant head to be assigned to the wetland perimeter. The ditch was also represented as a polyline and begins two grid cells or 24 meters below the wetland edge. The wetland and ditch are separated to enable accurate flow lines to be depicted, Figure 2-2. Monitoring wells were placed along the ditch.

The aquifer in the soil and wetland zones was assigned a surface elevation of ten meters, a top elevation of ten meters and a bottom elevation of eight meters. This represents an aquifer that is two meters saturated thickness similar to the wetlands used in this study.

The soil and wetland parameters assigned to the zones include hydraulic conductivity, partitioning coefficient, effective porosity, phosphate concentration in the wetland and phosphate concentration in the porewater. A literature search was completed on each parameter to provide the best values for the Lake Okeechobee basin isolated wetlands. The variables were selected to facilitate model runs to establish functional relationships. Once established those relationships were used to assess parameters appropriate to for the sites.

The range applied for hydraulic conductivity was based on slug tests preformed at Larson Dixie Ranch (Bhadha, 2006). The results of the slug test are shown in Table 2-1; see Figure 3-1 for well locations. The measured hydraulic conductivity from four wells surrounding the wetland ranged from 0.08 to 0.25 m/day. The average hydraulic conductivity of the wells is 0.15 m/day. The IGW model used a hydraulic conductivity of 100 m/day to facilitate model run times.

Soil tests for phosphate partitioning coefficient were not available for the Lake Okeechobee wetland sites. Thus a phosphate partitioning coefficient for a similar wetland was used 4.94e-3 m^3/kg (Reddy et al., 1995).

A study of south Florida found the porosity of the aquifers to be 0.3 (Meyer, 1989). A porosity of 0.3 was used throughout the IGW model.

The concentration of phosphate in the wetland water found on the Larson Dixie site ranged from on average 2 to 3 ppm (Bhadha, 2006). This range is based on depth profiles measured for total phosphate in the wetlands. The total phosphate value was used since the measured dissolved and soluble reactive phosphate measurements were similar values to the total phosphate.

Groundwater samples were collected from November 2004 to March 2005 from specific monitoring wells at Larson Dixie Ranch, see Figure 3-1 for well locations (Perkins, 2006). The total phosphate concentrations in the groundwater are shown in Table 2-2. Groundwater samples of total phosphate in LW2MW1, LW2MW2 and LW2MW6 provided a range of values as well as an average for these monitoring well. LW2MW3, LW2MW4 and LW2MW5 had only one or two samples providing only an average total phosphate concentration. An overall average of 0.33 ppm and overall range is 0.1 to 1 ppm is calculated. To simplify the IGW model the initial phosphate concentration in groundwater was assumed to zero. This allows for the model to determine the net effect of detaining water in the wetlands.

IGW Model Methods and Results

The IGW modeling objective was to assess the effect of system variables on the phosphate transport time through the aquifer to the drainage ditch. The modeling results provide estimates on how long holding water is the wetland will delay loads to Lake Okeechobee. The transport variables evaluated in the IGW model include aquifer hydraulic conductivity, phosphate partitioning coefficient, head difference between the wetland and ditch, wetland size and ditch distance from wetland.

The BTT is the time at which ten percent of the original concentration of phosphate in the wetland is found in the monitoring wells located along the ditch. The wetland phosphate concentration in all runs was 3 ppm thus the BTT is defined as the year that 0.3 ppm is found in the monitoring wells located along the ditch.

Each transport variable was evaluated in the model independently, that is no other parameters were changed in the model during the specific runs. Table 2-3 shows the parameters used throughout the runs unless otherwise discussed below.

Hydraulic Conductivity (K)

Hydraulic conductivity (K) is a main transport variable effecting the BTT of phosphate. Model runs were completed with K from 50 to 250 meters per day in 50 unit increments. Two monitoring wells were placed along the ditch at 100 and 250 meters from the wetlands. The results of the runs are displayed in Figure 2-3; the best fit lines characterize the inverse relationship observed.

Partitioning Coefficient (Kd)

The partitioning or distribution coefficient, relates the amount of solute, or phosphorus in the model, sorbed onto the soil to the amount that is dissolved in water (Liao et al., 2003). This measure of phosphate partitioning was evaluated to determine how much of a difference one degree of freedom has with regards to BTT. Seven partitioning coefficients were evaluated and are shown in Table 2-1. Two monitoring wells were placed along the ditch at 100 and 250 meters from the wetlands. Figure 2-4 shows the general trend of increasing partitioning coefficient increasing BTT. After regression analysis, R^2=0.997 and R^2=1, indicating a near perfect linear relationship between partitioning coefficient and BTT.

Head Difference (∆H)

A weir between the outlet of the wetland and the ditch can be manipulated to increase the amount of water held in the wetland. This forces more water to flow through the aquifer rather than directly through surface water. This variable was manipulated by changing the head difference between the wetland and ditch polylines. The wetland constant head boundary was arbitrarily assigned 100 meters while the ditch constant head boundary changes to enable the effect of head differences to be observed. The ditch constant head boundary changes from 99.0 to 99.75 meters in 0.25 meter increments.

The monitoring well that observed the BTT was located 100 meters from the wetland. Figure 2-5 depicts the observations of the phosphorus BTT with changing head difference including a best fit line depicting the power relationship. Generally as the head difference between the wetland and the ditch become smaller the longer the time required for the phosphate to reach 100 meters from the wetland in the ditch.

Wetland Size

Several different size wetlands were modeled to determine the influence of wetland size on phosphate transport time to the drainage ditch. Wetland sizes of 50, 100, 200 and 400 meters in diameter were modeled. The BTT was found at four points along the ditch from monitoring wells placed at 24, 104, 184, and 264 meters from the wetland. Figure 2-6 shows that there is little effect on BTT with an increase in wetland size until larger wetland sizes are reaches such at 400 meters in diameter.

Distance from Wetland

Four monitoring wells were placed long the ditch at 80 meters a part beginning at 20 meters from the wetland. The model was run and the BTT was found for each well. The BTT approximately doubled from well to well as it covered the same distance. This can be seen in Figure 2-7.

An instantaneous BTT for the well at 20 meters from the wetland (Figure 2-7) can be misleading. Figure 2-8 shows the actual BTT is reached around two months and not instantaneously. Figure 2-8 is created from the plume mass balance provided by the IGW model. The ditch's starting point was moved by 25 meters for each run beginning at 25 meters and ending at 100 meters from the wetland. This enabled the BTT to be found on the plume mass balance for the four different ditch starting points. The distance from the wetland relates to a BMP of filling in the drainage ditch which requires the water to flow underground to reach the drainage ditch. Figure 2-8 clarifies that the phosphate takes time to flow underground to the ditch. The lines indicate that filling the drainage ditch in by about 20 meters the BTT is near 1.5 years.

Interactive Groundwater Model Conclusions

Inverse relationships were found between the BTT and hydraulic conductivity and head difference. Linear relationships were found between the BTT and partitioning coefficient and the distance from the wetland. The wetlands size showed very little effect on BTT unless the wetland diameter became larger then 400 meters which was larger than the six isolated wetlands studied in the Lake Okeechobee basin.

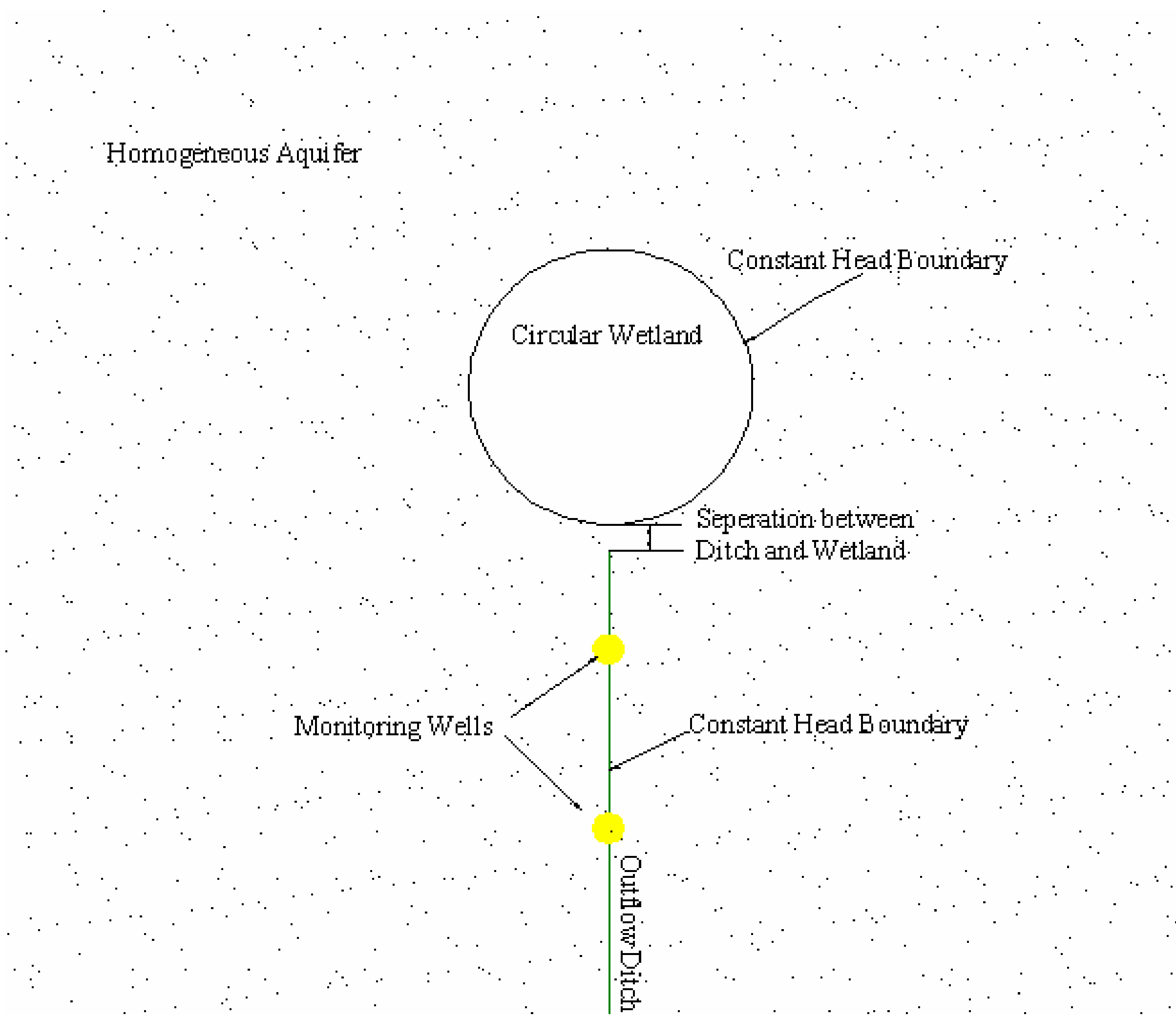

Figure 2-1. Diagram of the basic model layout it shown above with the wetland shown in black and the ditch in green leaving the wetland below. Two monitoring wells, in yellow, are shown along the ditch.

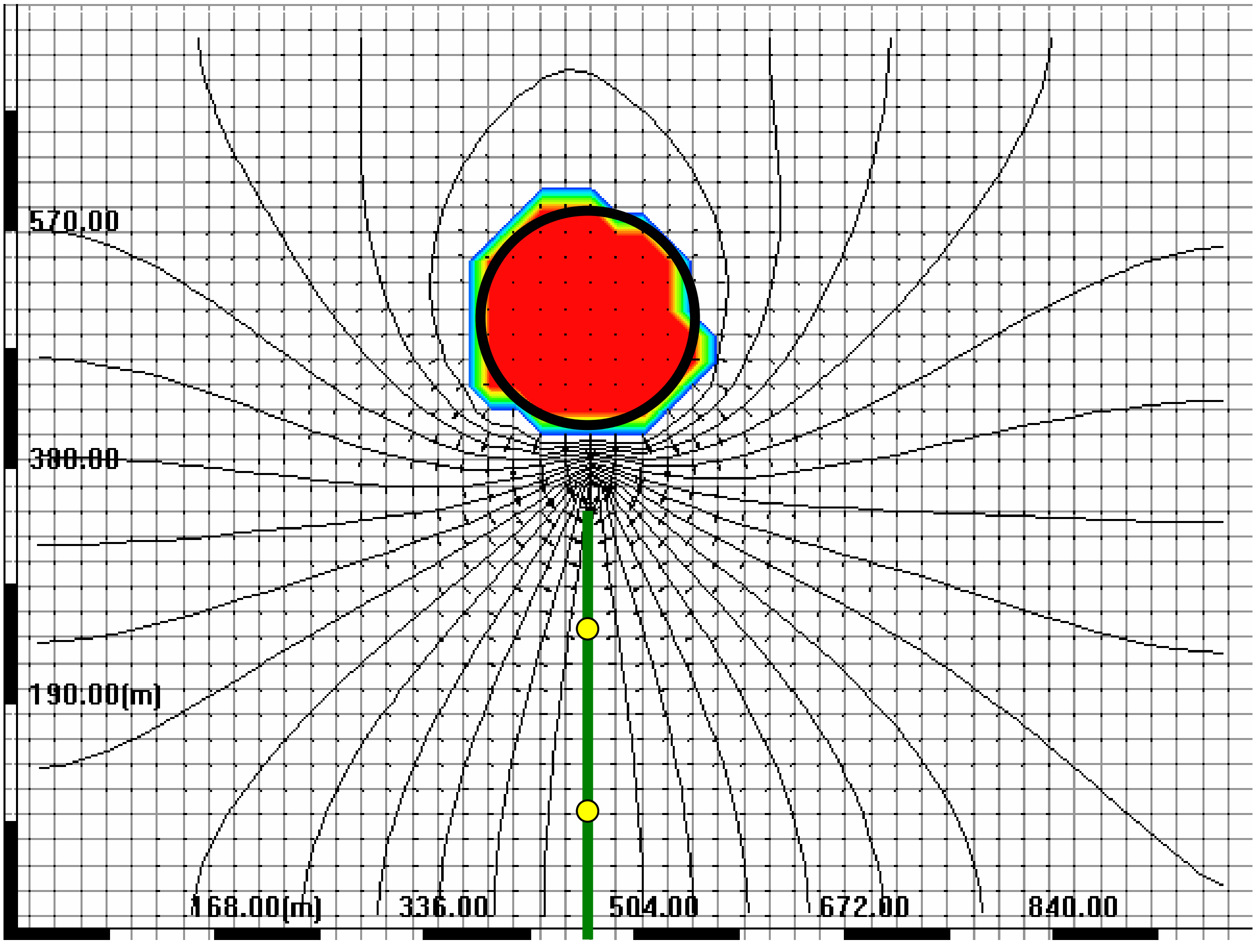

Figure 2-2. Basic model layout is shown above with the wetland shown in black and the ditch in green leaving the wetland below. The red within the wetland indicates the highest phosphate concentration. Two monitoring wells, in yellow, are shown along the ditch. Flow lines are also depicted showing phosphate transport path from the wetland into the ditch.

Table 2-1. Hydraulic conductivity of soil determined by slug test preformed at Larson Dixie Ranch

	Measured hydraulic conductivity	
Well ID	cm/hr	m/day
LWMW2	1.100	0.25
LWMW5	0.520	0.13
LWMW3	0.340	0.08
LWMW6	0.490	0.12
LWMW1	0.130	0.03
Average in soil surrounding wetland=	0.060	0.15

Bhadha, J., 2006. Dixie Larson Ranch: Wetland Measured Phosphate Concentrations and Hydraulic Conductivity. Unpublished raw data.).

Table 2-2. Measured porewater total phosphate values for Larson Dixie Ranch

Well ID	Range of total phosphate (ppm)	Average total phosphate (ppm)
LW2MW1	0.42 to 0.66	0.51
LW2MW2	0.12 to 1.02	0.36
LW2MW3	--	0.37
LW2MW4	--	0.34
LW2MW5	--	0.12
LW2MW6	0.11 to 0.42	0.25

Perkins, D.B., 2006. Dixie Larson Ranch: Porewater Phosphate Concentrations. Unpublished raw data.

Table 2-3. IGW model wetland and soil parameters

Model and soil parameters	Value used
Hydraulic conductivity (K)	100 m/day
Wetland size	180 meters
Partitioning coefficient (kd)	4.94e-3 m^3/kg
Effective porosity	0.3
Head difference (ΔH)	1 meter
Constant phosphorus concentration in the wetland	3ppm

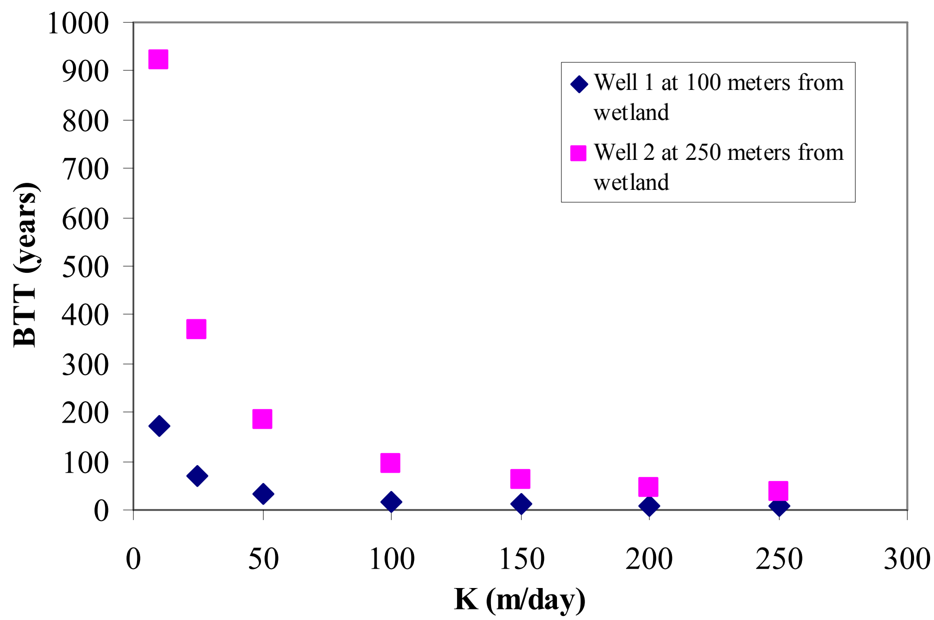

Figure 2-3. Hydraulic Conductivity versus Break Through Time

Table 2-4. Partitioning coefficient values.

Partitioning coefficient values liters per kilogram
4.94e-6
2.00e-6
3.5e-6
4.94e-7
4.94e-8
4.94e-9
0.0

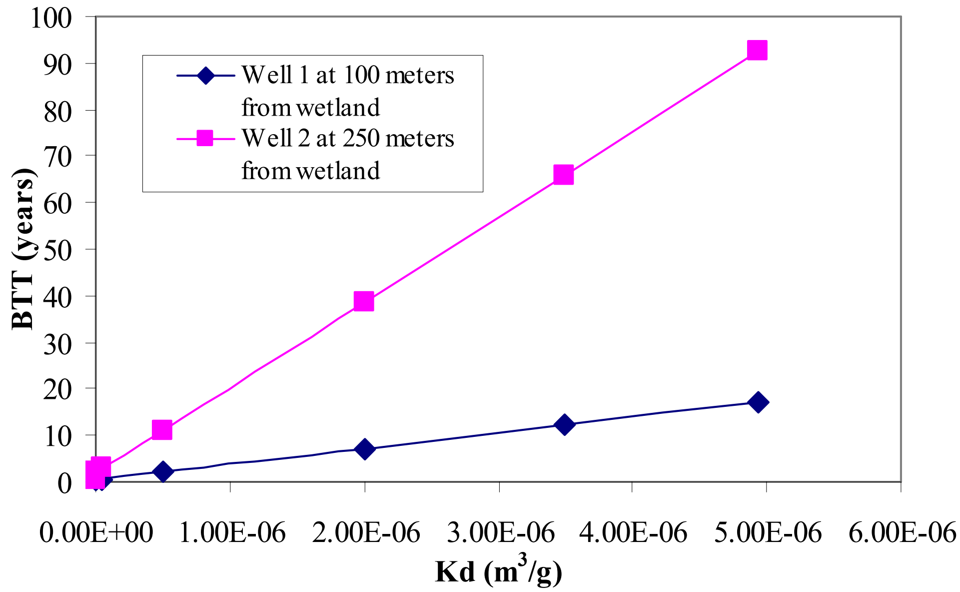

Figure 2-4. Partitioning Coefficient versus Break Through Time

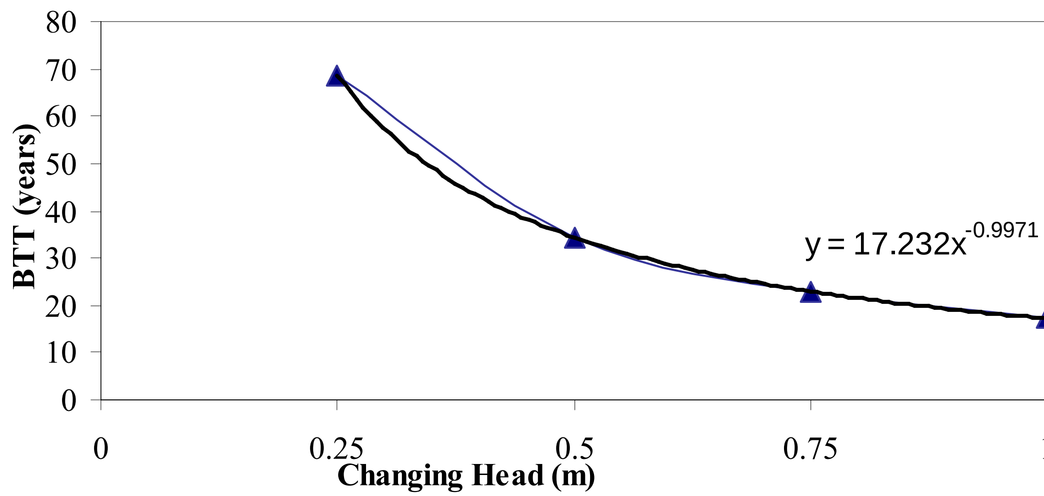

Figure 2-5. Head Difference versus Break Through Time

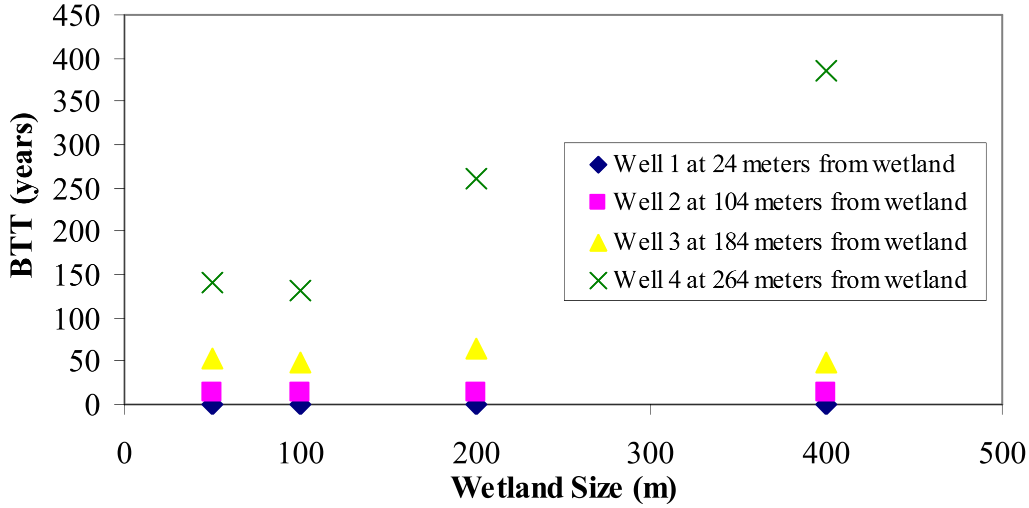

Figure 2-6. Size of Wetland versus Break Through Time

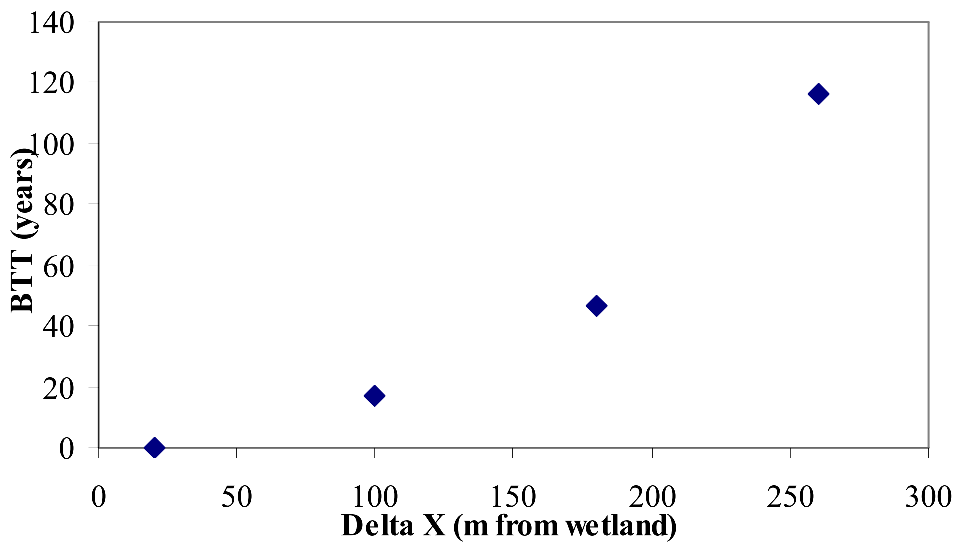

Figure 2-7. Distance from wetland versus Break Through Time

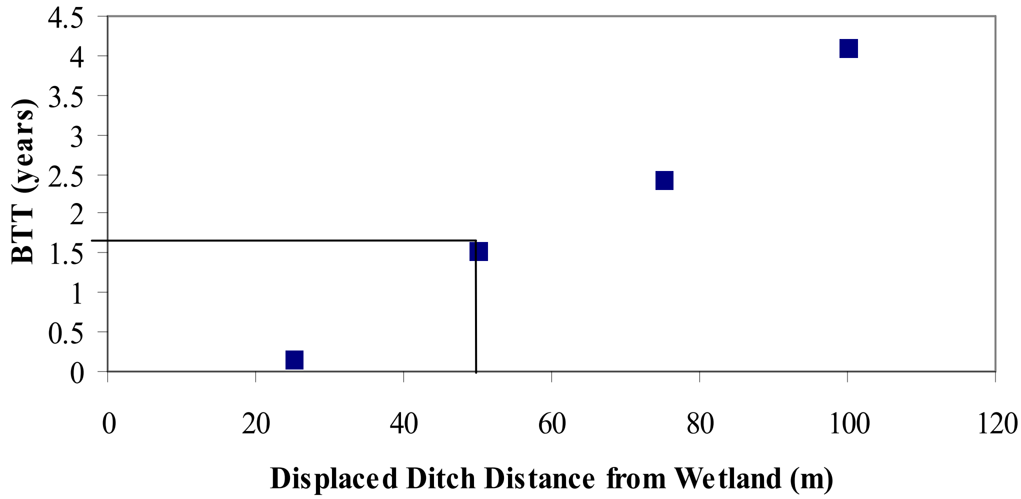

Figure 2-8. Distance of Ditch from Wetlands verse Break Through Time

CHAPTER 3
PASSIVE NUTRIENT FLUX METER FIELD DATA

Site Description

Three ranches, Larson Dixie, Beaty and Pelaez Ranch, were used to test the Passive Nutrient Flux Meter (PNFM). Field data was collect at Larson Dixie and Beaty Ranches in July 2005 by Kelly Hamilton and at Pelaez in September 2006 (Hamilton, 2005). All the ranches are located within the Lake Okeechobee watershed in Okeechobee County, Florida. The ranches all support cow-calf operations and allowed access to the sites for continuous research. The three ranches all have drained, isolated wetlands with connecting ditches that transport water off the ranch. The wetlands have fluctuating water levels depending on rainfall events. The local water table and thus the wetland water levels fluctuate from flooded to dry often within a few days to weeks. All three ranches are dominated by Myakka-Immokalee-basiner soils. These soils are poorly drained, nearly level, sandy soils that dominate most of Okeechobee County (Lewis et al., 2001). The ranches are dominated by Bahia grass (*Paspalum natatum* Fluegge`) (Dunne et al., 2006).

Larson Dixie Ranch is located at N 027° 20.966’, W 080°56.465’, Beaty Ranch is located at N 027° 24.665’, W 080° 56.940’ and Pelaez Ranch is located at N 27° 16.422’, W 080°56.453’ (Google Earth, 2007). The wetlands, well locations, flumes and general layout of each of the ranches are shown in Figures 3-1-3-3. The well identification numbers describe the location and type of well such as LW2MW5 describes a monitoring well located at Larson Dixie wetland 2 or PTFM5 describes a flux meter well at the Pelaez Ranch transect.

Methods

Passive Nutrient Flux Meter Description

The Passive Flux Meter (PFM) technology is a method of determining contaminant and groundwater fluxes in the saturated zone of an aquifer (Hatfield et al., 2004). The PFM has been laboratory and field tested at hazardous waste sites and proven to be a reliable measure of fluxes (Annable et al., 2005). The PNFM has been designed to measure nutrient fluxes including phosphorus (Cho et al., 2007). The PNFM may provide a means to decrease the cost and time necessary in measuring nutrient fluxes in groundwater.

After deployment and recovery, the PFM samples are collected and analyzed for the mass of tracer remaining and the mass of contaminant intercepted which are used to calculate the local cumulative water and contaminant fluxes (Annable et al., 2005). If reversible, linear, instantaneous resident tracer partitioning takes place between the sorbent and water, the specific discharge (q) through the PFM at a specific well depth can be found by equation 3-1:

$$q = \frac{[1.67 r \theta R_d (1 - M_R)]}{t} \tag{3-1}$$

where r is the radius of the flux meter cylinder, θ is the water content of the flux meter sorbent, R_d is the retardation of the resident tracer on the sorbent, M_R is the relative mass of the tracer remaining within the flux meter, and t is the sampling duration (Annable et al., 2005).

The contaminant mass flux (Jc) can be determined by using equation 3-2:

$$J_c = \frac{qM_c}{\alpha \pi r^2 L (1 - M_{RC}) \theta R_{dc}} \tag{3-2}$$

where q is the specific discharge, M_c is the mass of contaminant sorbed, α is the convergence or divergence of flow around the flux meter, r is the radius of the flux meter cylinder, L is the length of the sorbent matrix, M_{RC} is the relative mass of a hypothetical resident tracer retained after time period t where that tracer has the same retardation as R_{dc}. Equation 2 assumes reversible, linear and instantaneous contaminant partitioning between the sorbent and the water (Annable et al., 2005). For a more in depth discussion on the PFM technology see Annable et al., 2005, Hatfield et al., 2004, or Cho et al., 2007.

The PNFM and PFM use similar designs including a permeable, sorptive media contained in a cylindrical casing which fits snugly into wells below the water table. The sorbent in the PNFM facilitates rapid adsorption and desorption of inorganic and organic substances. The PNFM uses a strongly basic, macroporous-type, anion exchange resin known as Lewatit S 6328 A (Sybron Chemicals Inc Birmingham, NJ). Lewatit S 6328 has a matrix consisting of cross-linked polymer made of styrene and divinylbenzene with a relatively uniform charge distribution of ion-active sites throughout the structure (Cho et al., 2007).

The sorptive media was equilibrated with alcohol tracers that desorb as groundwater flows through the device. The alcohol tracers provide the groundwater flux while the resin allows for measurement of phosphorus flux. The alcohol tracers suite used at Larson Dixie and Beaty Ranch included 2,4-dimethyl-3-pentanol, 1-Hexanol, 1-Heptanol, 1-Octanol, 2-Octanol and 2-ethyl-1-hexanol (Hamilton, 2005). Pelaez Ranch used 1-Hexanol, 1-Heptanol, and 1-Octanol as the alcohol tracers.

Figure 3-4 shows a cross section of a PNFM installed in a well. The device is made with an inner PVC rod, clamps at the bottom and top holding in place a nylon mesh sock filled with the resin. The PNFM was designed to be approximately 91 cm long with a diameter of 3.18 cm. The length used was based on the well screen intervals ranging from 107 to 201 cm. The PNFM was divided into four sections to help reduce vertical flow, each about 23 cm containing an estimated 240 ml of resin.

At the Pelaez Ranch, monitoring wells were constructed with an inside joint protruding into the well requiring modification of the PNFM deployment method. A nine foot long expandable protective netting (Cole-Parmer Poly-Net U-09405-30) was used with a second three foot section of netting located around the bottom end of the nine foot length to assist in inserting the PNFM through the well joint. The nine foot and three foot sleeves were inserted into the well so that the three foot section was below the well joint. Then a PNFM with a third layer of protective netting was inserted into the well through the nine foot section to seat adjacent to the three foot section at the bottom of the well. This technique allowed the PNFM to slide easily past the well joint yet still fit snuggly to the well walls due to the three layers of expandable mesh. See Figure 3-5 for a cross section of the installed PNFM. The diameter of the Pelaez Ranch PNFM's was 5.08 cm and all other specifications of the PNFM were the same as PNFM used at Larson Dixie Ranch and Beaty Ranch.

Well Design

At the Larson Dixie and Beaty Ranches the flux wells were installed using a hand auger, most were located an estimated one meter from a monitoring well. The monitoring wells were used to obtain water samples for phosphorus measurements and to deploy transducers to monitor water levels. PVC pipe (3.175 cm diameter) and sections of well screen ranging from 122 to 152 cm long were used to construct the wells. See Figures 3-1 and 3-2 for well locations. The well casing was terminated at ground level to protect from animal disturbances. The wells were covered with a 20 cm PVC cap even with the ground surface (Hamilton, 2005).

The Pelaez Ranch wells were installed using a hollow stem auger drill rig with radius of 5.08 cm and depths similar to Larson Dixie and Beaty Ranch. Most of the flux wells were paired with shallow monitoring wells screened to a depth of one to two feet and were above the spodic horizon. All of these wells were dry during the PNFM deployments. Pelaez Ranch well locations are shown in Figure 3-3.

PNFM Deployment

Deployment of the PNFM took place at all sites during wet periods. At the Larson Dixie Ranch several wells (LW1MW8, LW2MW2, LW2MW4, LW2MW5) were submerged at the time of deployment. In this case, a PVC coupler with a casing extension was used to insert the PNFM (Hamilton, 2005). In total, seven PNFM were deployed at Larson Dixie Ranch, five around one wetland and two around the second wetland. Four PNFMs were deployed at the Beaty Ranch, two at each wetland. See Figure 3-1 and 3-2 for well locations. Water table values were recorded throughout the deployment period at Larson Dixie Ranch and Beaty Ranch. The PNFM's at Larson Dixie and Beaty Ranch were deployed for a period of 34 days.

Eighteen PNFMs were deployed at the Pelaez Ranch, four around each wetland and ten at the transect crossing the ditch location. See Figure 3-3 for well locations. Water table levels were recorded for five of the wells. The Pelaez Ranch PNFM's were deployed for a period of 33 days.

PNFM Removal

All the ranches used the same removal technique. The PNFMs were extracted from the wells fully intact. Then the resin was carefully removed in sections from the sock. In a clean bowl, each 20 cm section of the PNFM was mixed to homogenize the sample. Two samples of the resin were taken from the homogenized mixture and added to vials with extraction solution. The first vial contained 60 ml of 2M KCl in a 125 ml sample bottle with approximately 25 g of resin added. The second sample was approximately 10 g placed into 30 ml isopropyl alcohol in a 40 ml sample vial. Each of the 4 sections per PNFM were sampled in this manner. All vials were pre-weighed then weighed after the samples were collected to determine the mass of sample added. All the samples were rotated and equilibrated for 24 hours.

Analysis

The amount of residual alcohol tracer was determined by subsampling the isopropyl alcohol vial after it had settled for 24 hours. This sample was analyzed using a gas chromatograph to obtain the concentration of each tracer.

A 5 ml sample was obtained from the top of the 2M KCl vial after settling for 24 hours and used for the Total Phosphorus (TP) (Hach Method 8190, 2003). The TP method was used since many of the samples had an organic color that would interfere with the Orthophosphate Method 8178 (Hach Method 8178, 2003). The TP method, while still using colorimetric comparison, was based on the change in color intensity once the reagents were added as opposed to the Orthophosphate Method that compared the color change intensity in the vial to a single calibration measurement at the beginning of sampling.

Sources of error within the PNFM application can be significant. Error can be potentially generated at any step in the process. Water table fluctuations can interfere with the sorption and cause volatilization of the resident tracers. Not obtaining a homogenous mixture of resin during the retrieval process can introduce error. The analysis stage may introduce error when fine particles stay suspended within the solution after extraction. Care must be taken to ensure settling of the particulates.

Results

The water table elevations during the deployment periods for each of the wetlands are shown in Figures 3-6 to 3-10. Water table elevation data was not obtained for Pelaez wetland 1. The water table observations were used to obtain gradient calculations and exposure/submergence durations for the PNFMs in each well, see Figure 3-11. From these observations it is clear that some of the PNFMs had a greater volume of resin within the saturated zone then others. The desaturated zones of the PNFMs may result in volatilization of the alcohol tracers and inaccurate flux estimates.

Washers were installed in the PNFMs to prevent vertical flow however several storm events at each of the sites may have created periods of desaturation and saturation. Figure 3-11 shows that the Beaty and Pelaez sites remained saturated throughout the deployment. Pelaez water table elevations were based on wetland water levels as opposed to well water levels thus the saturation times have been interpolated for all of Pelaez wetland 4 wells. Wells LW2MW6 and LW2MW5 were not paired with transducers and the water table elevations were interpolated for these locations. At the Larson Dixie sites, the rapid water table fluctuations interfered with phosphorus and water flux measurements to a depth of 90 cm. The locations of the PNFM in the Larson wells dictated whether the water table fluctuations interfered with the flux measurements.

Water Flux Measurements

Since the groundwater flux was unknown at each of the wetlands a suite of several resident tracers were applied to the resin in the PNFMs. The average mass remaining and the coefficients of variation for each tracer used at Larson Dixie and Beaty Ranches are shown in Table 3-1. For the Larson Dixie and Beaty Ranch deployment it was determined that 1-Heptanol would provide the most reliable water flux data. The coefficients of variation are compared among the mass remaining in each PNFM. For Larson Dixie and Beaty sites 1-Heptonal and 2-Octanol had the smallest variations. However, 2-Octanol had more mass remaining than the initial concentration thus the data is considered unreliable. The 1-Octanol had similar results to 1-Heptanol with more variation between fluxes and provided a similar flux pattern but within a larger range (0.01 to 0.06 m/day) (Hamilton, 2005).

The average mass remaining and the coefficients of variation for each tracer used at Pelaez Ranch are shown in Table 3-2. The largest quantity of mass remaining for the alcohol tracers at the Pelaez site was 1-Octanol. However for the PNFMs used in wells PW1FM21, PW1FM25 and PW4FM11 1-heptanol had the most mass remaining thus 1-heptanol was used to determine the water flux at those locations. The water flux was determined to be higher at the Pelaez site thus in the future a shorter deployment time should be used in order to ensure that more tracer mass remains to improve accuracy of the water flux measurements.

The water flux profile with depth based on the PNFM deployment for each of the wetlands is relatively constant around 3 cm/day at the Larson Dixie and Beaty wetlands as shown in Figures 3-12, and 3-13. More variation in water flux is seen at the Pelaez Ranch with a range from 0 to 7.5 cm/day, Figure 3-14. While a constant water flux with depth is expected the Larson Dixie sites were unexpectedly similar. Either the water flux was as constant as reported or all the wells were exposed to similar biological activity that reduced all the 1-Heptanol to the same level of remaining mass within the PNFMs. Additional deployments would be helpful to validate the results.

Pelaez wells PTFM1-10 provide phosphate flux along a transect of the ditch which drains the wetland and surrounding areas, see Figure 3-3 for well locations. The water flux along the transect is shown in Figure 3-15 and has a similar range to Pelaez Ranch wetlands.

Phosphate Flux Measurements

Phosphate mass flux found for each well, grouped by wetland, can be seen in Figure 3-16 through 3-20. Larson Dixie and Beaty Ranch's phosphate flux shows a very distinguished trend where the phosphate flux increases closer to the ground surface and the remains at a constant low value at deeper depths. No trend can be seen from Pelaez wetland 1 phosphate flux which may be due to the distance between wells and the wetland. The Pelaez wetland 4 indicates a trend of increasing phosphate flux as depth increases. The difference in trends between Pelaez wetland 4, Larson Dixie and Beaty wetlands maybe due to land practices or differing water flux between sites.

The phosphate flux along the Pelaez ditch site transect is shown in Figure 3-21. Figure 3-21 indicates there that there are higher phosphate fluxes on the east side of the ditch then the west side and on average the phosphate flux is higher along the ditch then in the flux observed at the wetlands. The east side also shows a similar trend to Larson Dixie and Beaty wetlands in that the phosphate flux is higher at the surface and remains a constant low value at deeper depths. The west side of the transect shows a trend of similar to Pelaez wetland 4 where the phosphate flux increased with depth. This variation in phosphate flux maybe due to land use practices or different water flux on each side of the ditch, shown in Figure 3-15. In future deployments along the transect transducers should be used to observe the surrounding water table to determine the direction of groundwater flow into or out of the drainage ditch.

Measured and Calculated Data Comparisons

The Darcy Flux was measured directly from the PNFM were compared to values calculated using Darcy's Law (equation 3-3), Table 3-3.

$$q = -K \frac{dh}{dl} \tag{3-3}$$

Where q is Darcy flux (cm/day), K is the hydraulic conductivity (cm/day) and dh represents the change in head over a distance dl (cm). The gradients, or dh/dl, were determined using the average change in head difference during the time of deployment from the water table data (Figures 3-6 to 3-10) and dividing by average radius of the wetland. The radius of each wetland was estimated using aerial imagery from Google Earth. While slug tests preformed at

Larson Dixie Ranch provided an average hydraulic conductivity of 0.15 m/day, 3 m/day was used to calculate Darcy flux. The larger hydraulic conductivity of 3 m/day provided comparable estimates to the measured Darcy flux values (Bhadha, 2006).

The Darcy flux averages presented in Table 3-3 indicate that the calculated Darcy fluxes are less than those measured using the PNFM. The measured Darcy flux is very consistent at all the sites with the Pelaez sites having a slightly higher Darcy flux. The calculated Darcy flux has a wider range of values possibly due to the difference in size of the wetlands or the variability in the quality and quantity of water table data. Recall that Pelaez wetland 4 does not have any water table observations thus the gradient could not be calculated for the wetland.

Mass load (mg/day) was calculated from the local contaminant mass flux (J_c) values presented in Tables 3-1 and 3-2. J_c was calculated using equation 3-2. The mass load, M_0, was calculated by multiplying J_c by the vertical cross sectional area of flow from the wetland, equations 3-4.

$$M_0 = J_c \times 2\pi r \times depth \tag{3-4}$$

Where r is the radius from the center of the wetland to the PFM wells and depth is the length of the PFM, 3 feet or 0.91 meters for all the PNFMs. The J_c and M_0 for each section of NPFM for each well, average mass load per well and average mass load for each wetland is provided in Table 3-4. Table 3-5 provides a summary of the average mass load from the wetland to the aquifer for each wetland in g/day.

The range of mass loads per wetland is from 0.82 to 3.23 g/day. Pelaez wetland 1 is by far the largest wetland thus has the largest mass load. Beaty wetland 2 has the lowest mass load which maybe due to the well placement being north of the wetland and the wetland draining south.

The water table plots were used to determine the flow into and out of the wetlands, Figures 3-6 to 3-10. When the water table is above the ground surface the water is flowing into the wetland. When the water table is below ground level, which is the majority of the time, the flow is out of the wetland, Table 3-7. The grams of phosphate transported into and out of the wetland are calculated from the average wetland mass loads determined in Table 3-5 and can be found in Table 3-6. The cumulative mass phosphate leaving the wetlands range from 25 to 95 grams during the deployments, 33 to 34 days ,and it is assumed that the majority of phosphate is leaving the wetlands through groundwater flow. During future deployments surface water phosphate samples taken during the deployment period would enable verification of phosphate transport mechanisms.

Table 3-8 shows the mass flux measured by the PNFM and the mass flux found from calculated Darcy velocity using total phosphate measurements at each well. The mass of phosphorus that left the wetland through groundwater was estimated through an initial total phosphate sample at the surface of the wetland during the deployment of the PNFMs. The concentration was then multiplied by the volume of water in the wetland resulting in a mass. The calculated mass flux on average is higher than the measured mass flux. The calculated mass flux could be better estimated with more samples of total phosphate since this is based on only one measurement. The Larson Dixie wetland 1 and Beaty wetland 1 both had total phosphate levels greater than one milligram per liter which explains their larger values. The mass flux estimated at Pelaez transect is on average much larger than the mass flux the wetlands, Table 3-9. Wells PTFM3, PTFM4, PTFM5, PTFM6, PTFM7 and PTFM8 are within a meter of the drainage ditch with PTFM7 and PTFM8 having larger mass flux than any of the average wetland values.

Conclusions

The data provided above allow a range of estimated phosphate parameters, including Darcy flux, mass loads and mass flux per wetland and mass flux per ditch, to be established for wetlands and ditches, Table 3-10. Water flux for Larson Dixie and Beaty Ranches were consistently around 3 cm/day while Pelaez Ranch had a larger range of water flux, from 0 to 7.5 cm/day. The Pelaez Ranch transect shows a similar range in water flux to the Pelaez wetlands. Phosphate flux was found to increase closer to the ground surface at Larson Dixie and Beaty Ranches while Pelaez Ranch showed the inverse trend at one wetland and not distinct trend at the other wetland. The Pelaez Ranch transect had higher phosphate flux then the wetlands and higher phosphate flux on the east side of the drainage ditch.

The measured Darcy flux is very consistent at all the sites with the Pelaez sites having a slightly higher Darcy flux. The calculated Darcy flux had a wider range of values then the measured Darcy flux. The mass loads per wetland range from 0.82 to 3.23 g/day. Pelaez wetland 1 has the largest mass load. The cumulative mass phosphate leaving the wetlands during the deployment ranges from 25 to 95 grams. The calculated mass flux on average is higher than the measured mass flux. The mass flux estimated at the Pelaez transect is on average much higher than the mass flux in the wetlands.

Additional deployments are needed to validate the results presented here. Further deployments should include a more comprehensive set of surface water samples and water table measurement.

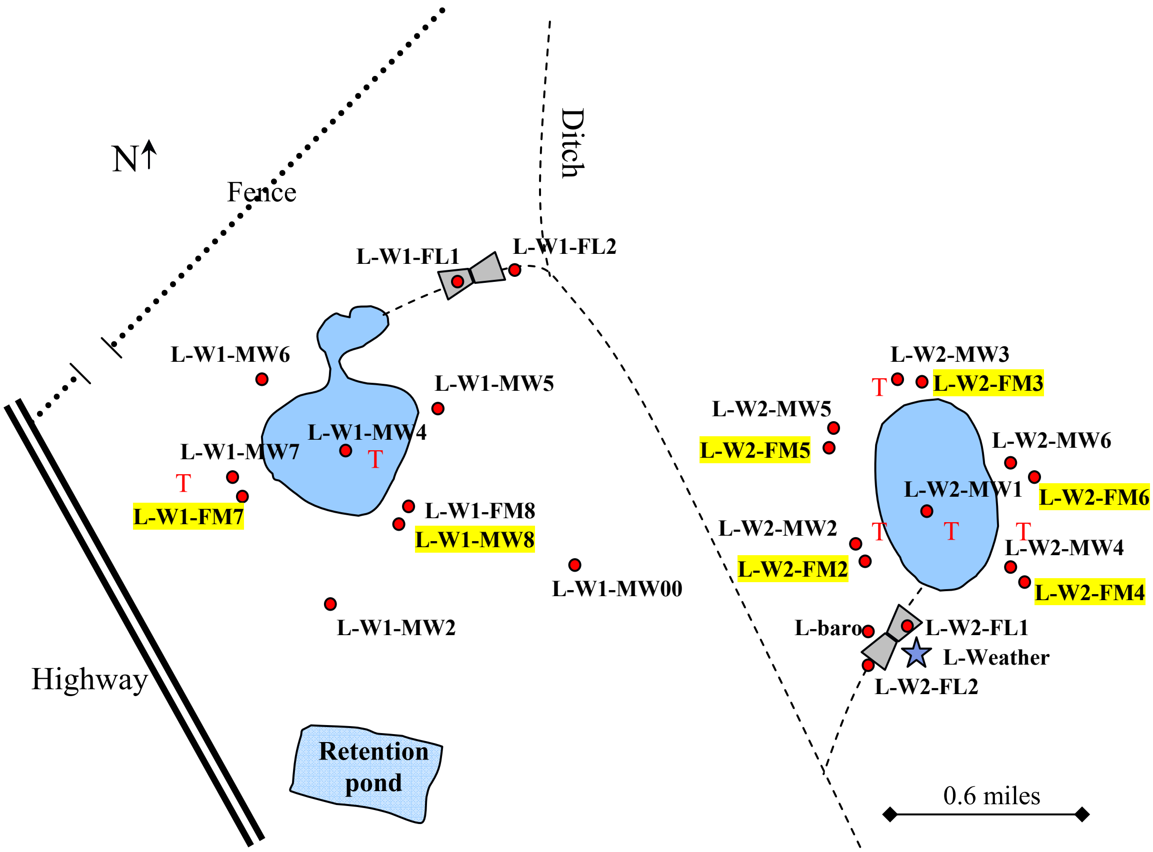

Figure 3-1. Larson Dixie Ranch - The highlighted wells contained PNFM and the red T indicates a transducer in the monitoring well.

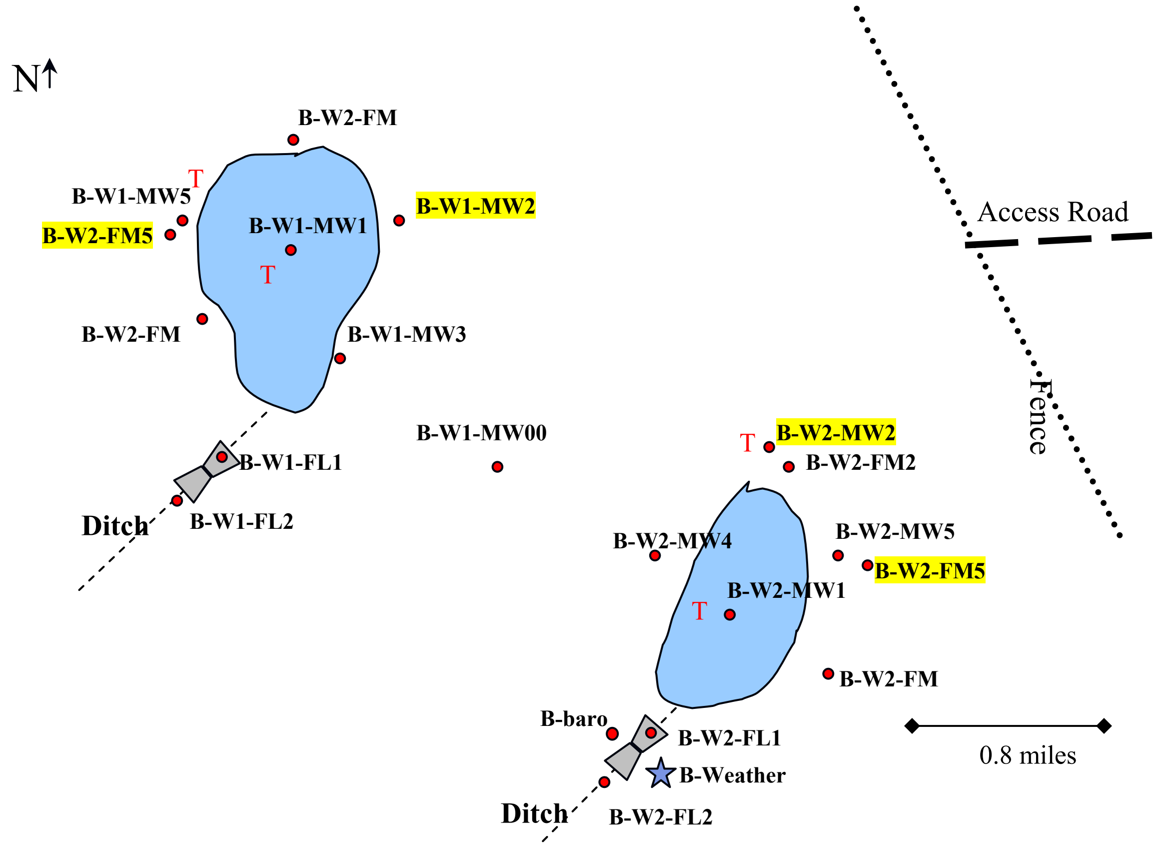

Figure 3-2. Beaty Ranch - The highlighted wells contained PNFM and the red T indicates a transducer in the monitoring well.

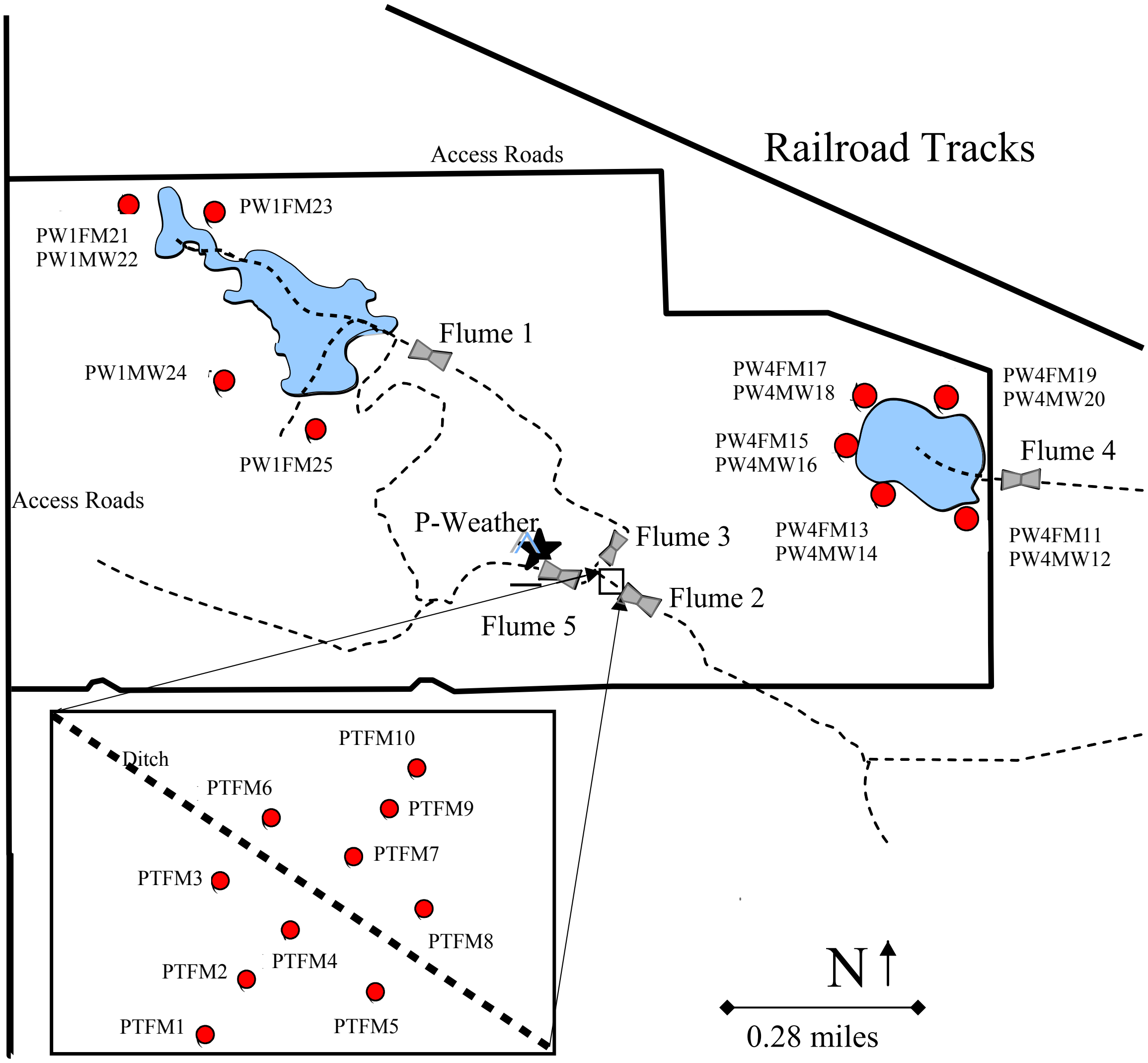

Figure 3-3. Pelaez Ranch - All the flux meter (FM) wells contained PNFM and only wetland 4 contained a transducer in the wetland.

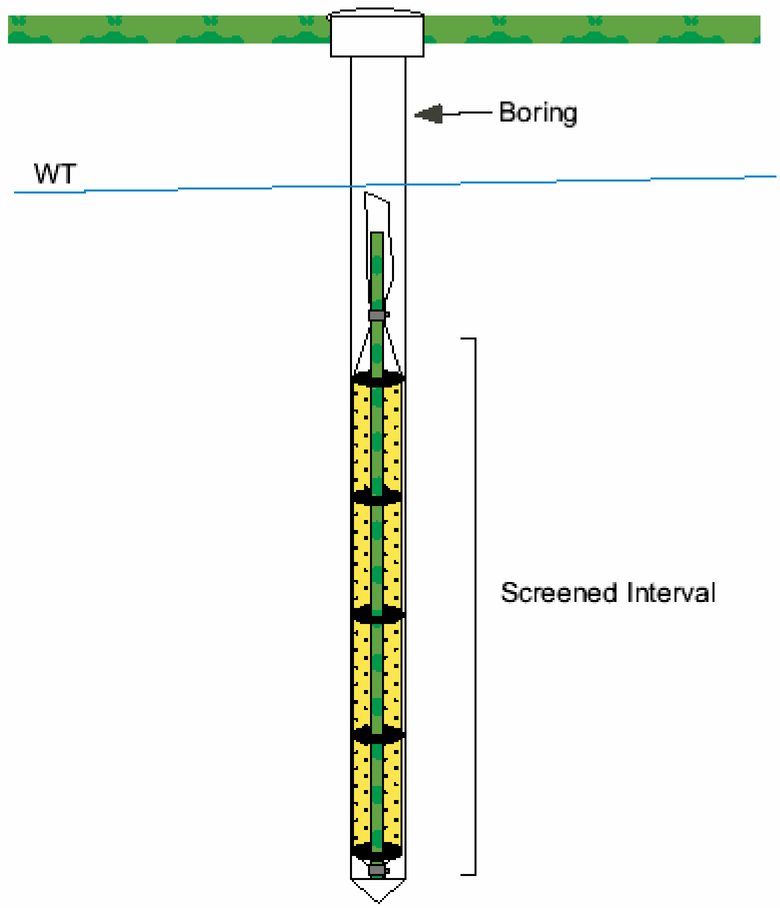

Figure 3-4. Cross section of PNFM installed in well (Hamilton, 2005).

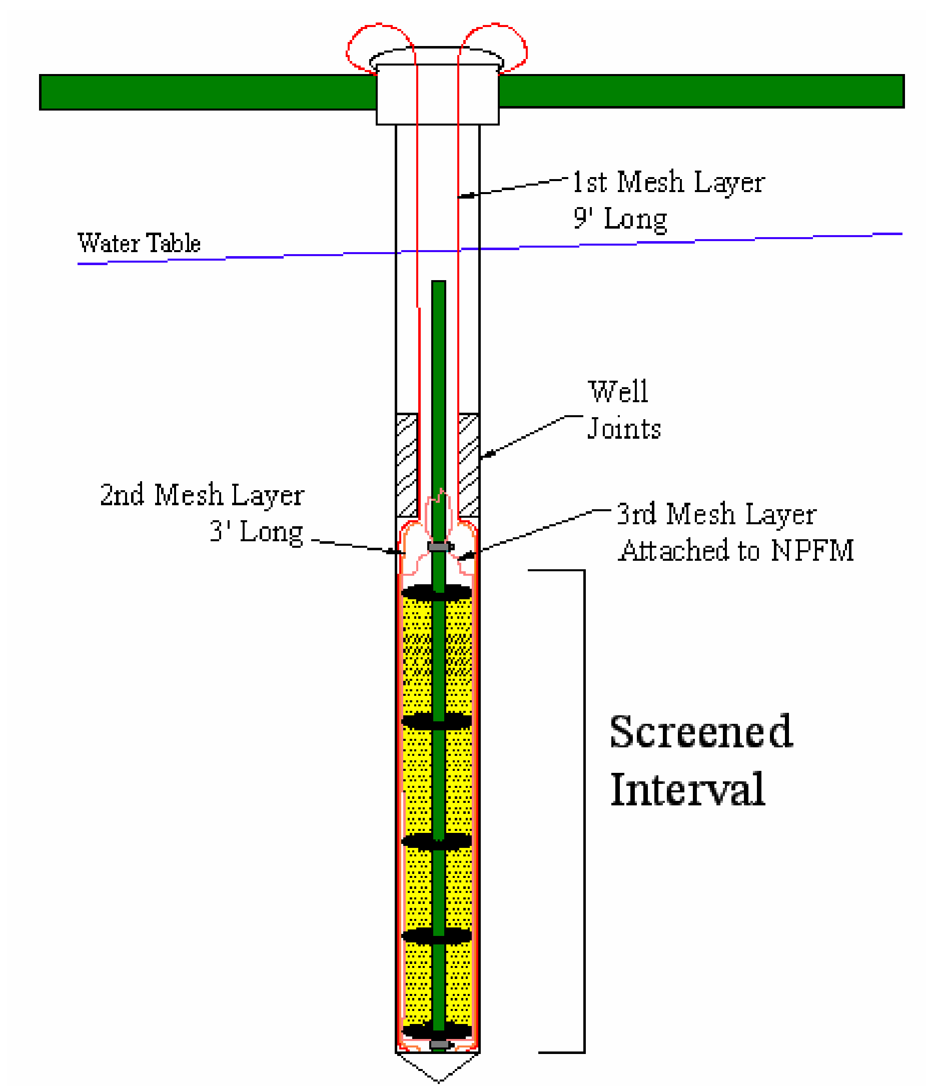

Figure 3-5. Cross section of PNFM installation at Pelaez Ranch.

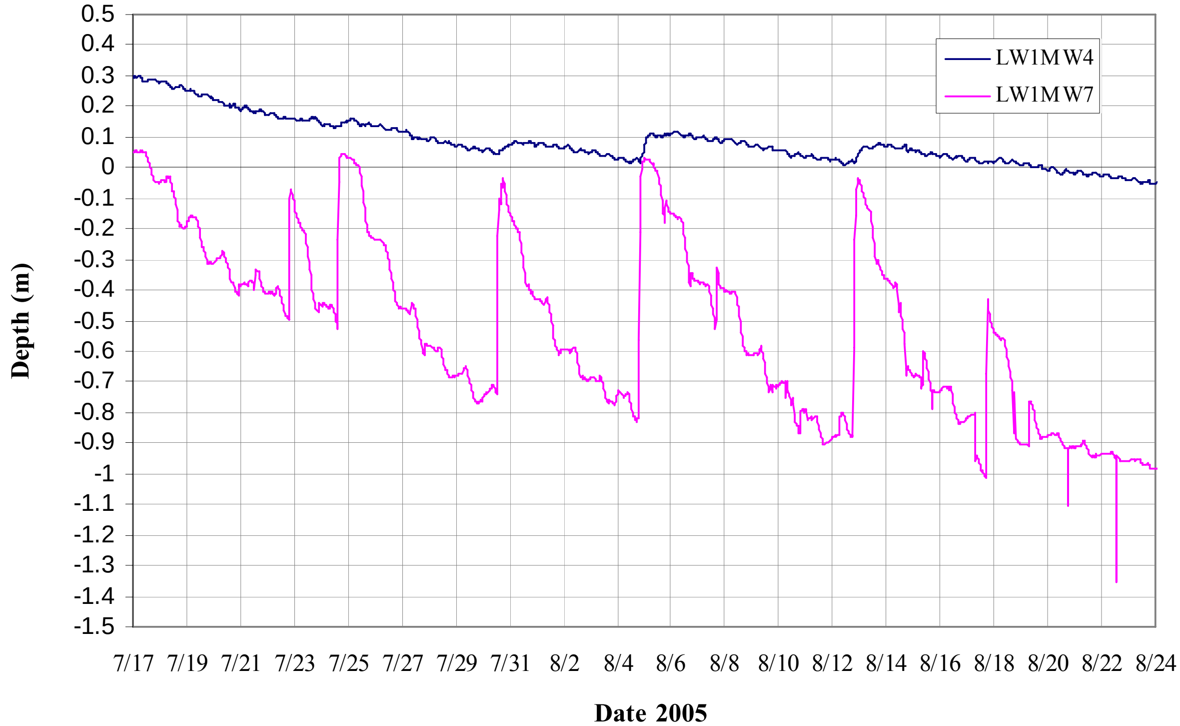

Figure 3-6. Water table elevation observations for Larson Dixie Wetland 1.

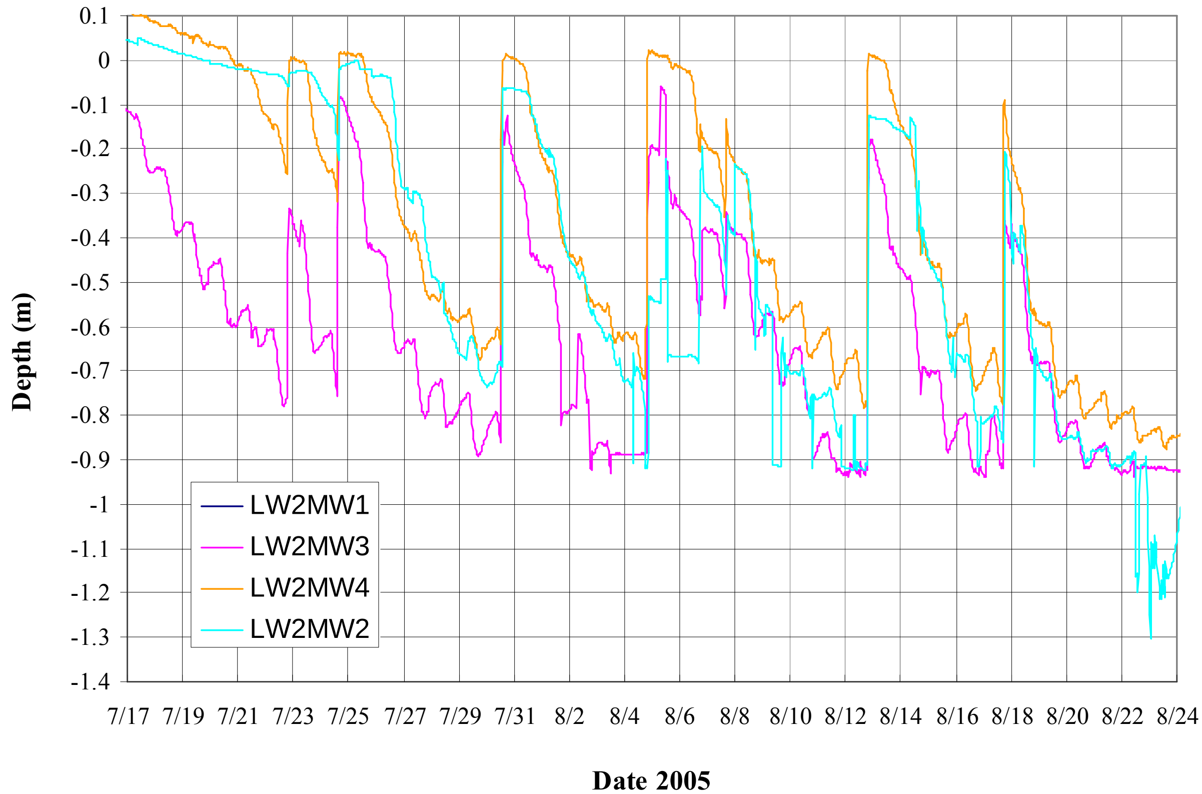

Figure 3-7. Water table elevation observations for Larson Dixie Wetland 2.

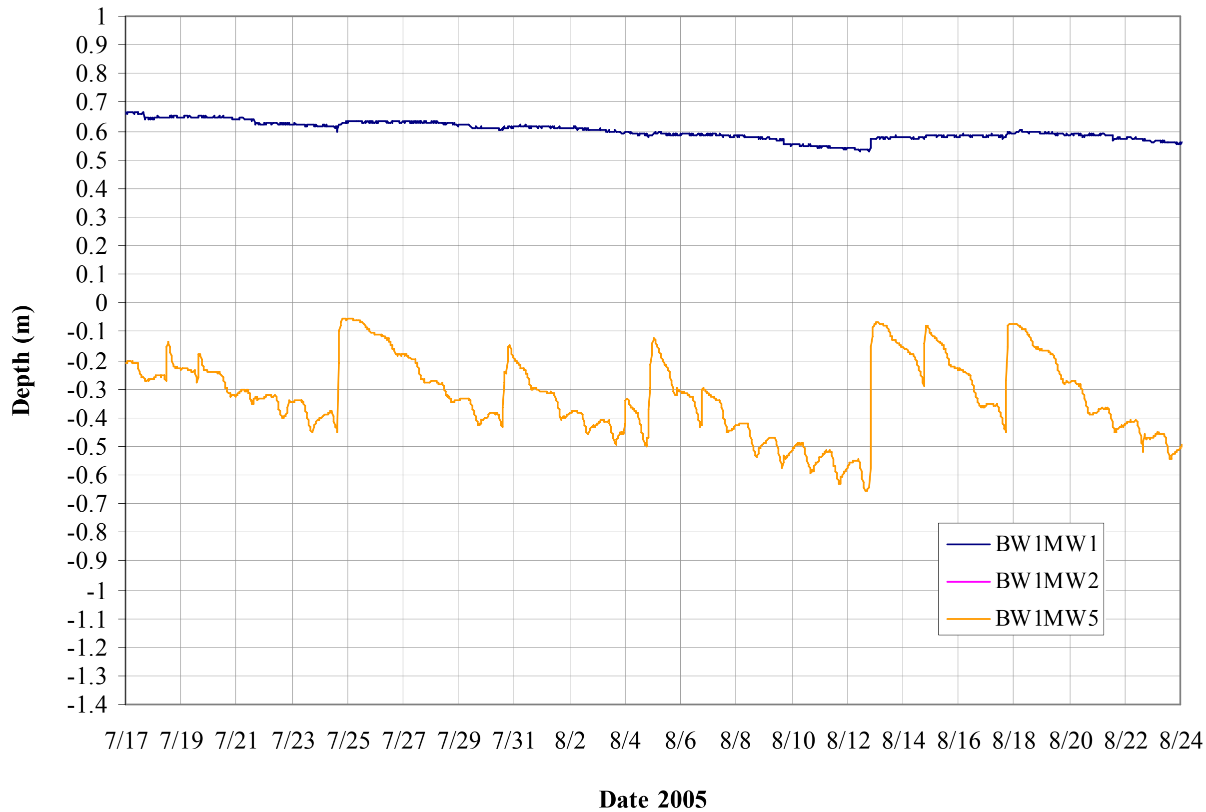

Figure 3-8. Water table elevation observations for Beaty Wetland 1.

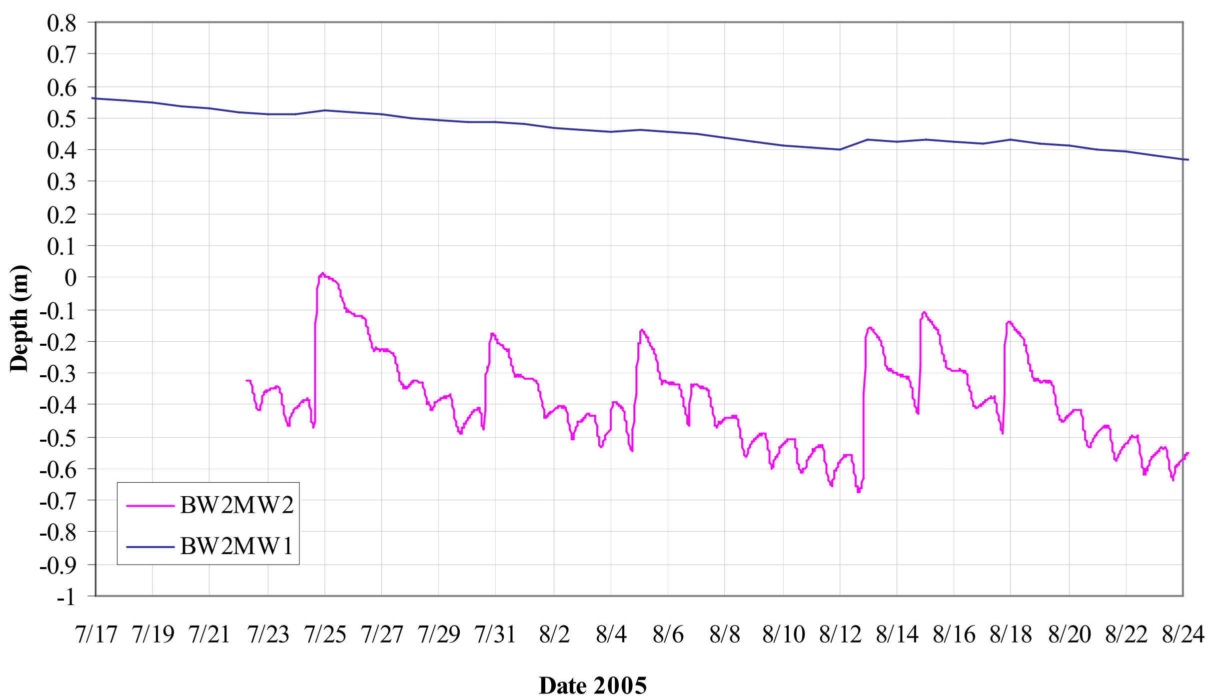

Figure 3-9. Water table elevation observations for Beaty Wetland 2.

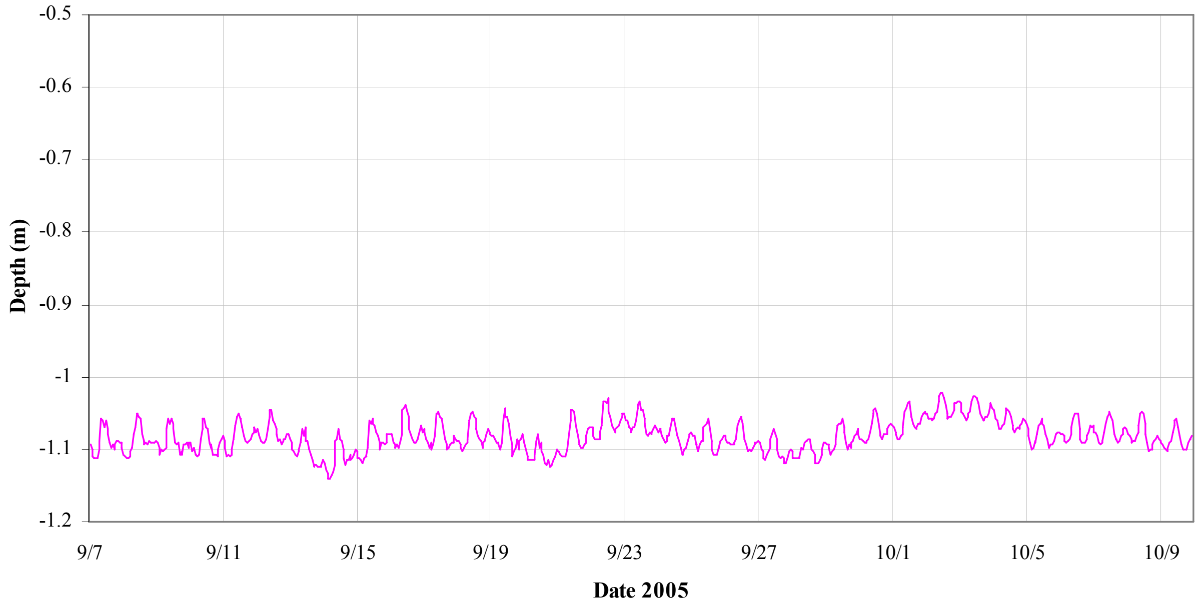

Figure 3-10. Water table elevation observations for Pelaez Wetland 4.

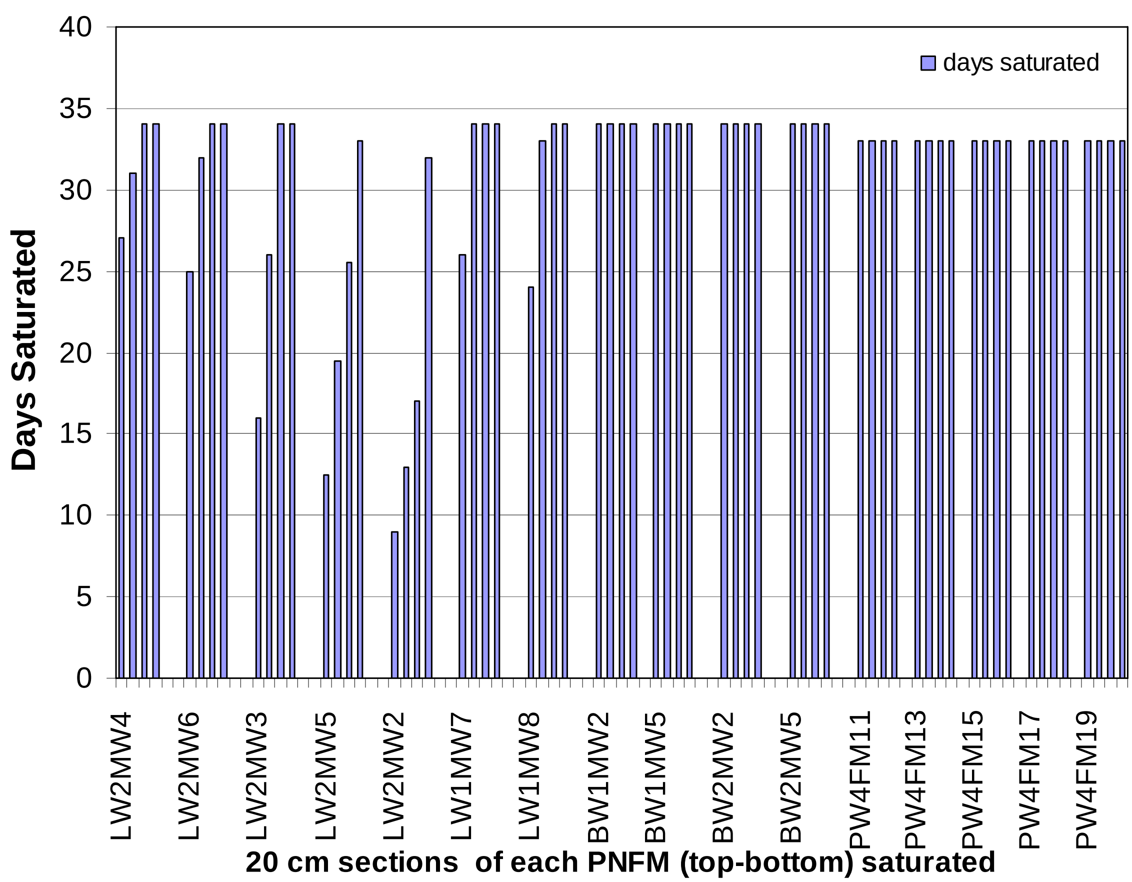

Figure 3-11. Days and sections of PNFM's saturated throughout deployment.

Table 3-1. Comparison of averages and coefficients of variation between resident tracer mass remaining on resin for Larson Dixie and Beaty wetlands.

Well ID		Mass remaining 2,4 DMP	Mass remaining 1-heptanol	Mass remaining 2-octanol	Mass remaining 2E1H	Mass remaining 1-Octanol
LW2MW4	avg	0.334	0.179	1.099	0.979	0.571
	std	0.142	0.007	0.048	0.034	0.159
	cv	0.424	0.038	0.044	0.035	0.278
LW2MW6	avg	0.065	0.163	0.892	0.940	0.462
	std	0.014	0.027	0.074	0.175	0.047
	cv	0.222	0.167	0.083	0.186	0.102
LW2MW3	avg	0.371	0.160	1.131	0.837	0.318
	std	0.168	0.019	0.080	0.355	0.060
	cv	0.453	0.116	0.070	0.424	0.188
LW2MW5	avg	0.400	0.151	1.181	1.131	0.273
	std	0.142	0.017	0.136	0.356	0.093
	cv	0.354	0.113	0.115	0.315	0.340
LW2MW2	avg	0.243	0.166	0.990	0.556	0.326
	std	0.213	0.016	0.201	0.417	0.076
	cv	0.876	0.097	0.203	0.749	0.234
LW1MW8	avg	0.105	0.149	0.936	0.826	0.338
	std	0.065	0.016	0.131	0.297	0.031
	cv	0.616	0.111	0.139	0.360	0.090
LW1MW7	avg	0.276	0.159	0.915	0.396	0.365
	std	0.054	0.019	0.157	0.078	0.036
	cv	0.198	0.117	0.171	0.196	0.099
BW1MW5	avg	0.003	0.128	0.663	0.122	0.403
	std	0.001	0.014	0.073	0.121	0.093
	cv	0.194	0.107	0.110	0.993	0.232
BW1MW2	avg	0.077	0.153	0.889	0.592	0.328
	std	0.016	0.006	0.023	0.200	0.015
	cv	0.210	0.038	0.026	0.338	0.045
BW2MW2	avg	0.073	0.180	0.651	0.941	0.345
	std	0.016	0.041	0.088	0.120	0.080
	cv	0.213	0.229	0.136	0.127	0.232
BW2MW5	avg	0.020	0.123	0.750	0.313	0.182
	std	0.003	0.020	0.127	0.067	0.031
	cv	0.164	0.166	0.169	0.215	0.168

Table 3-1. (continued)

Well ID		Mass remaining 2,4 DMP	Mass remaining 1-heptanol	Mass remaining 2-octanol	Mass remaining 2E1H	Mass remaining 1-Octanol
All Wells	avg	0.179	0.155	0.918	0.694	0.356
	std	0.148	0.018	0.178	0.320	0.100
	cv	0.829	0.116	0.194	0.461	0.282

Table 3-2. Comparison of averages and coefficients of variation between resident tracer mass remaining on resin for Pelaez wetlands.

Well ID		Mass remaining 1-hexanol	Mass remaining 1-heptanol	Mass remaining 1-Octanol
PTFM1	avg	0.013	0.189	0.525
	std	0.008	0.034	0.041
	cv	0.585	0.181	0.077
PTFM2	avg	0.024	0.220	0.566
	std	0.004	0.020	0.049
	cv	0.151	0.089	0.086
PTFM3	avg	0.004	0.174	0.559
	std	0.005	0.096	0.120
	cv	1.236	0.550	0.215
PTFM4	avg	0.006	0.074	0.222
	std	0.008	0.072	0.149
	cv	1.325	0.975	0.674
PTFM5	avg	0.010	0.175	0.445
	std	0.010	0.042	0.050
	cv	0.986	0.242	0.111
PTFM10	avg	0.000	0.118	0.452
	std	0.000	0.019	0.020
	cv	NA	0.162	0.044
PTFM9	avg	0.000	0.023	0.269
	std	0.000	0.028	0.137
	cv	NA	1.197	0.509
PTFM8	avg	0.000	0.039	0.189
	std	0.000	0.024	0.023
	cv	NA	0.609	0.121
PTFM7	avg	0.002	0.066	0.231
	std	0.003	0.032	0.039
	cv	1.732	0.490	0.169
PTFM6	avg	0.003	0.106	0.493
	std	0.005	0.063	0.065
	cv	2.000	0.593	0.133
PW4FM19	avg	0.011	0.116	0.340
	std	0.019	0.109	0.126
	cv	1.732	0.938	0.369
PW4FM17	avg	0.075	0.278	0.485
	std	0.102	0.174	0.218
	cv	1.352	0.626	0.450
PW4FM15	avg	0.060	0.302	0.636

Table 3-3. (continued)

Well ID		Mass remaining 1-hexanol	Mass remaining 1-heptanol	Mass remaining 1-Octanol
	std	0.066	0.119	0.162
	cv	1.103	0.395	0.255
PW4FM13	avg	0.042	0.325	0.674
	std	0.013	0.035	0.029
	cv	0.305	0.108	0.043
PW4FM11	avg	0.454	0.714	0.807
	std	0.212	0.245	0.155
	cv	0.467	0.343	0.193
PW1FM25	avg	0.111	0.379	0.667
	std	0.101	0.216	0.242
	cv	0.908	0.570	0.362
PW1FM23	avg	0.018	0.152	0.348
	std	0.007	0.031	0.060
	cv	0.411	0.204	0.173
PW1FM21	avg	0.253	0.440	0.528
	std	0.018	0.062	0.087
	cv	0.070	0.141	0.164
All Wells	avg	0.062	0.221	0.474
	std	0.121	0.186	0.198
	cv	1.958	0.843	0.418

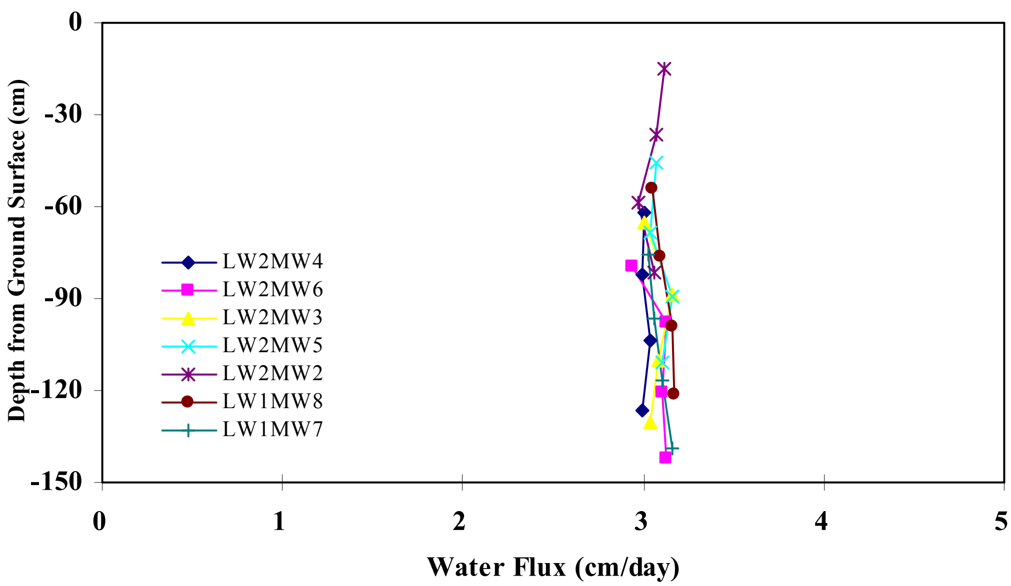

Figure 3-12. Water flux verse depth at Larson Dixie Wetland for each well location.

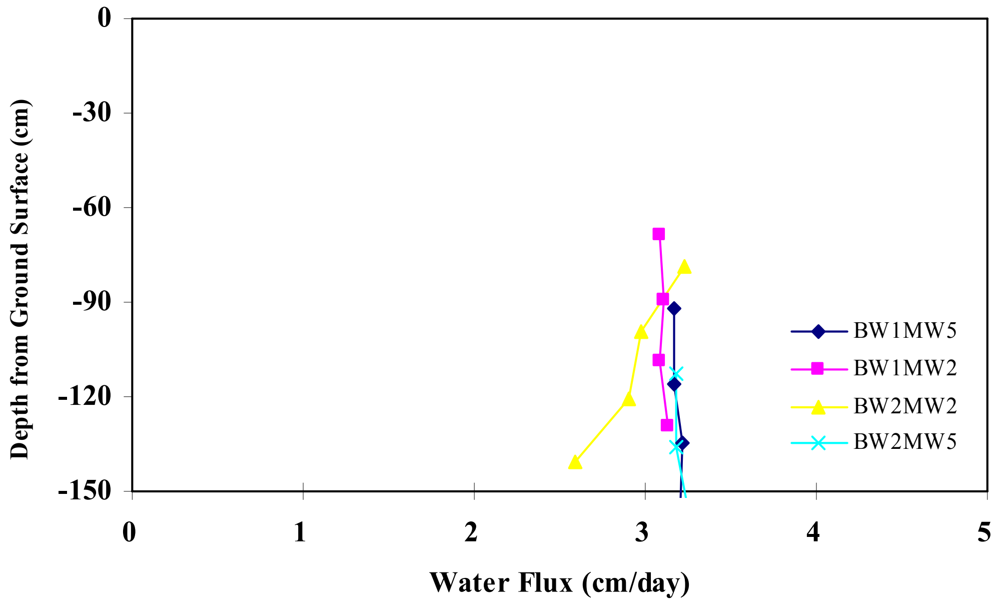

Figure 3-13. Water flux verse depth at Beaty wetland for each well location.

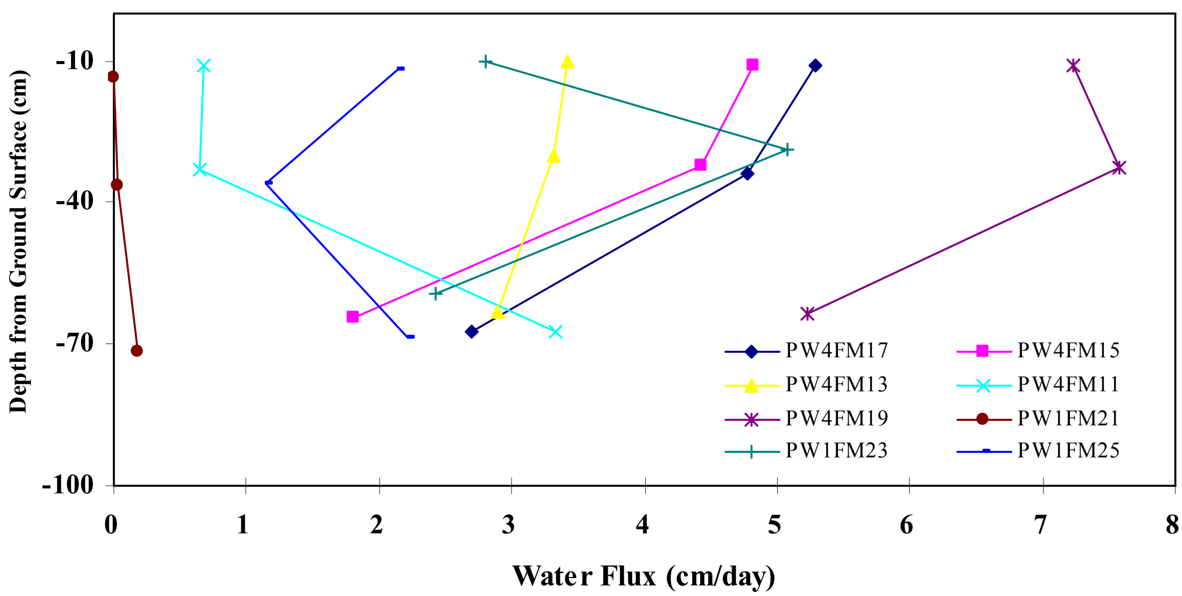

Figure 3-14. Water flux verse depth at Pelaez wetland for each well location.

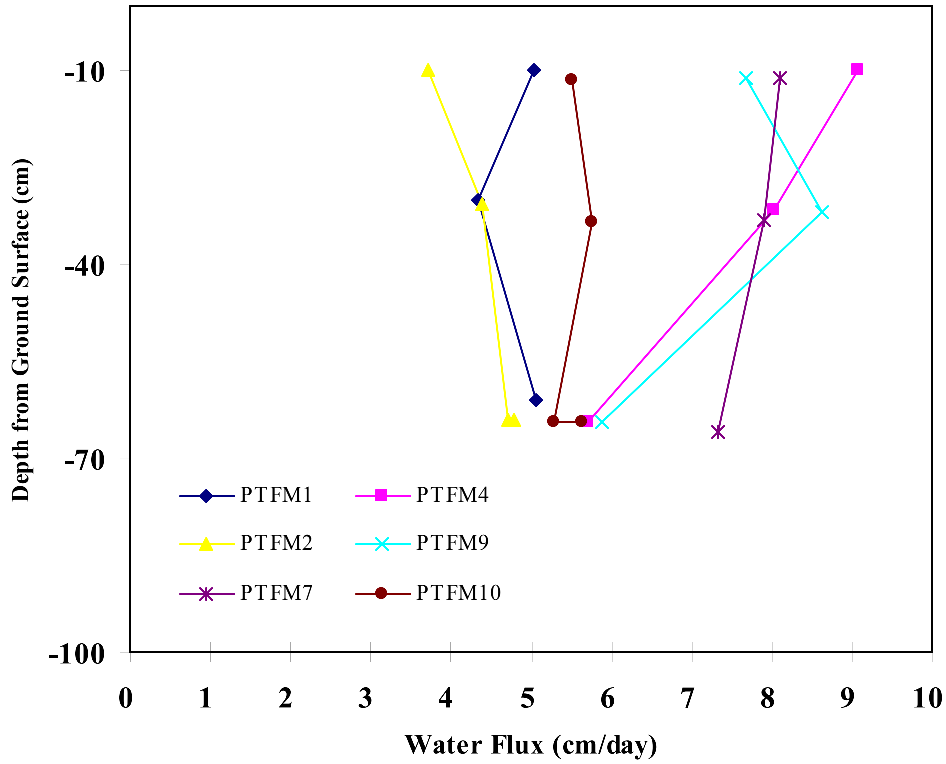

Figure 3-15. Water flux verse depth at Pelaez transect for each well location.

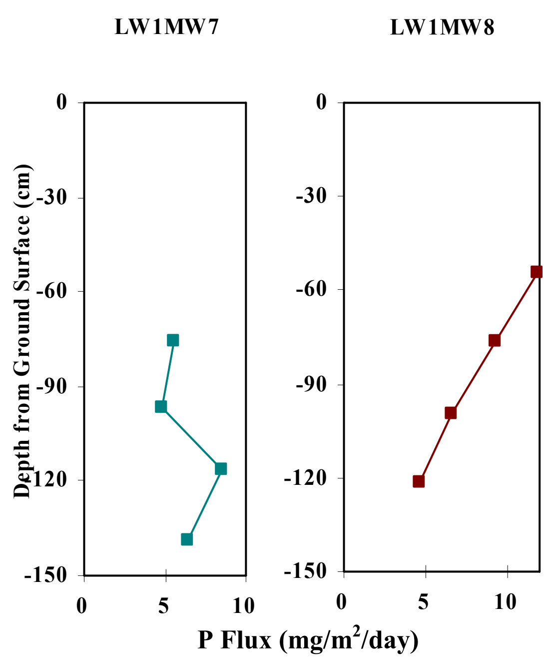

Figure 3-16. Larson Dixie wetland 1 phosphate flux verse depth at each well location.

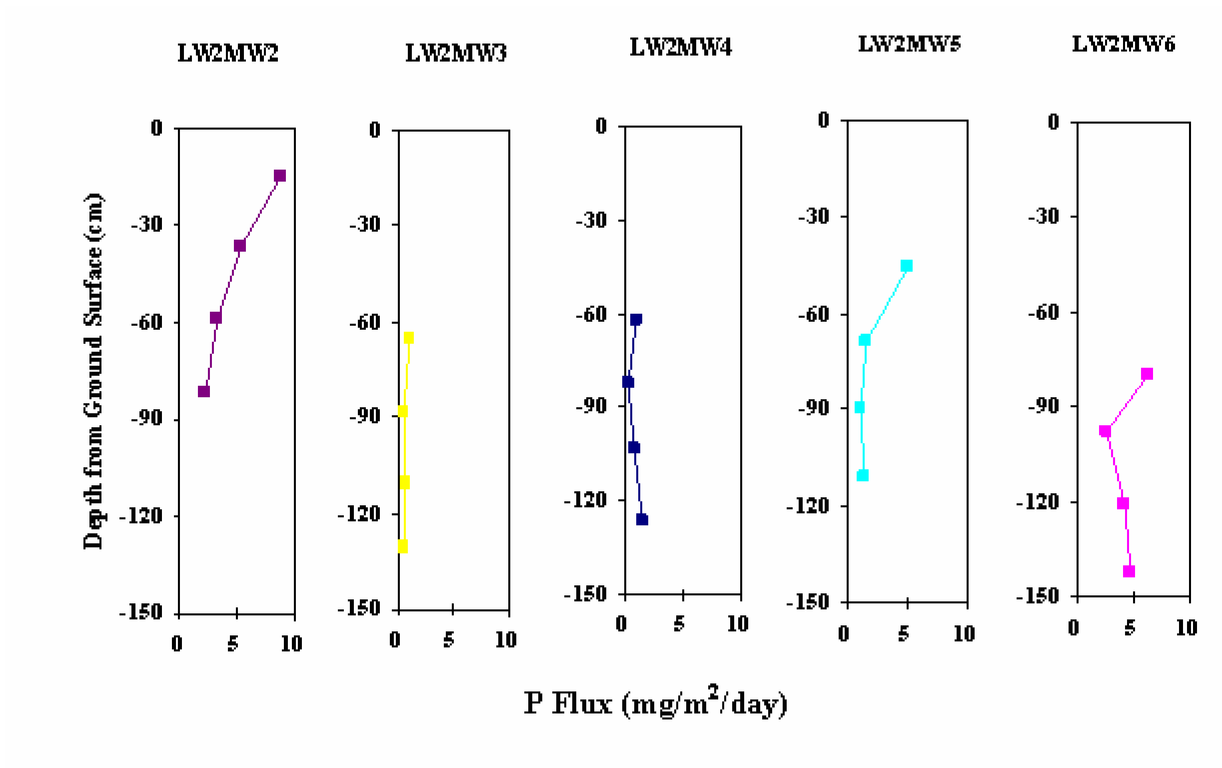

Figure 3-17. Larson Dixie wetland 2 phosphate flux verse depth at each well location.

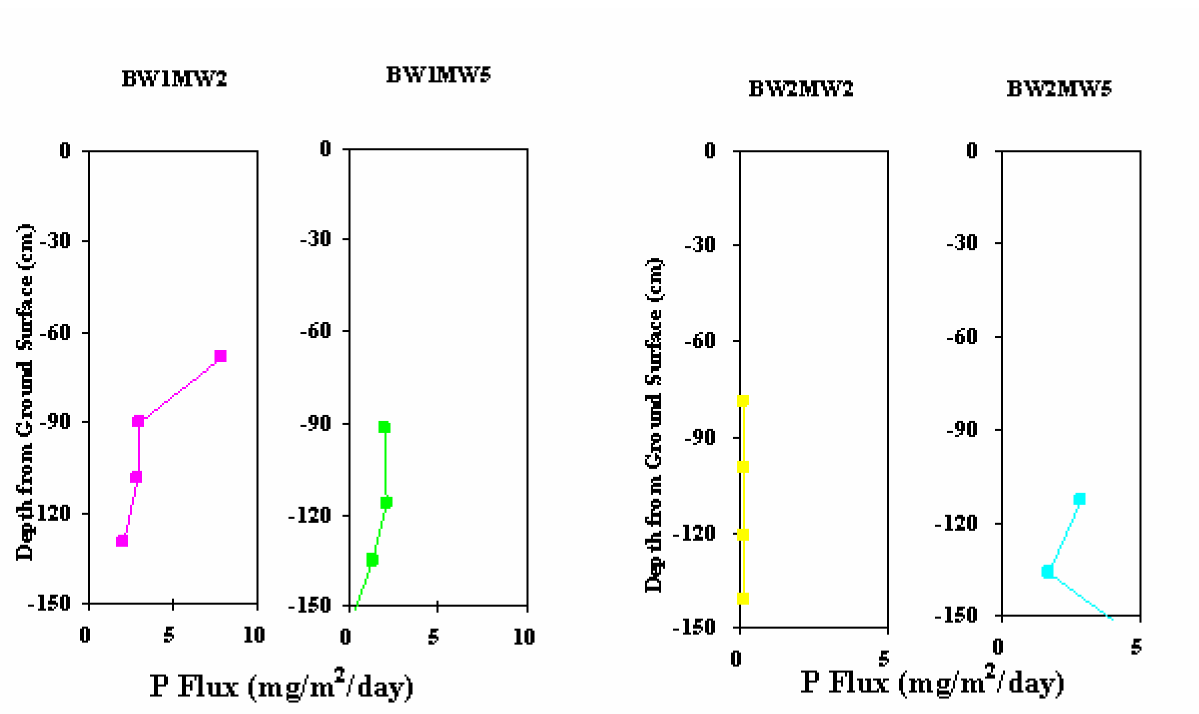

Figure 3-18. Beaty wetland phosphate flux verse depth at each well location.

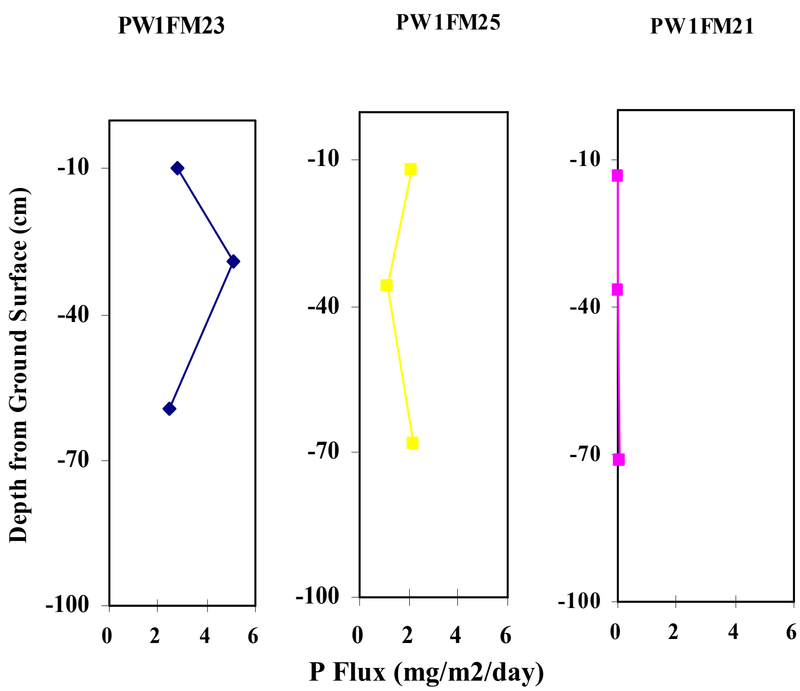

Figure 3-19. Pelaez wetland 1 phosphate flux verse depth at each well location

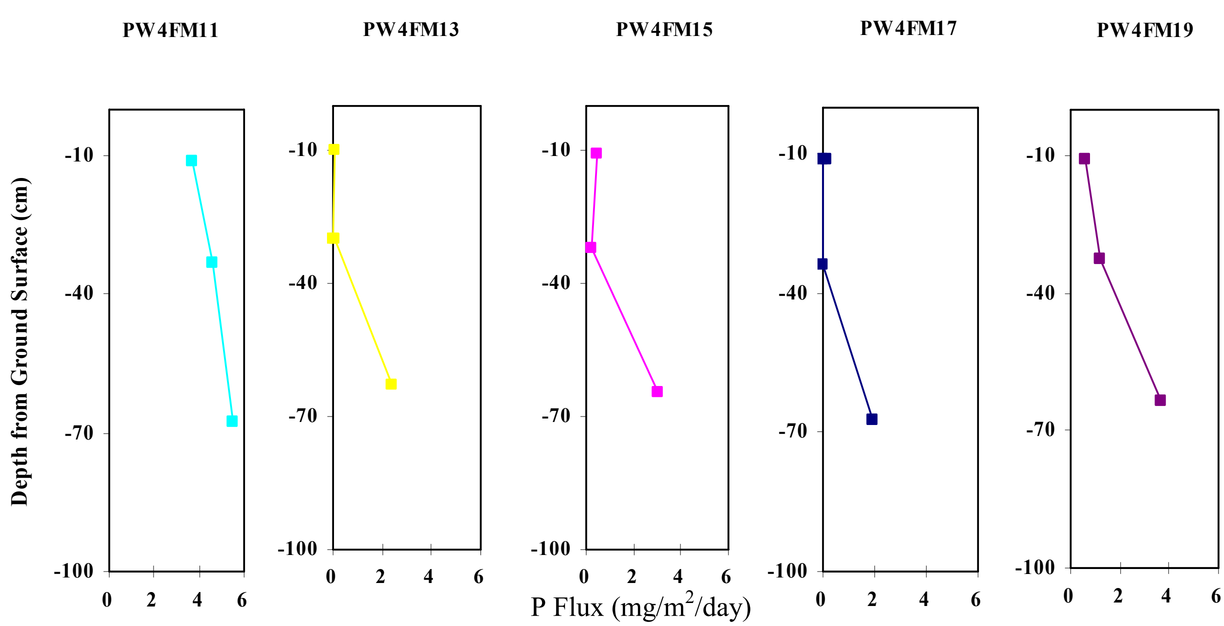

Figure 3-20. Pelaez wetland 4 phosphate flux verse depth at each well location.

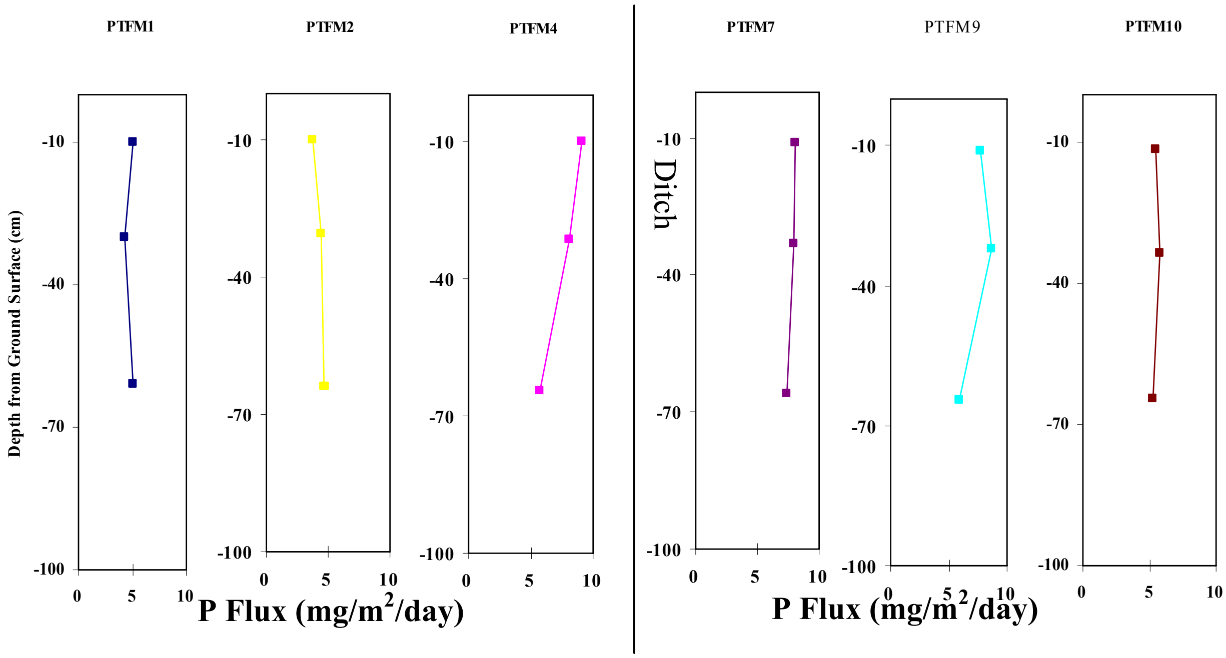

Figure 3.21. Pelaez transect phosphate flux verse depth at each well location. Note: The axis for phosphate flux on well PTFM9.

Table 3-4. PNFM Darcy flux estimates compared to the Darcy flux estimated by the calculated gradient (K=3 m/day).

Wetland	Darcy flux estimated by the PNFM cm/day	Darcy flux estimated by calculated gradients cm/day
LW1	3.10	3.98
LW2	3.06	3.29
BW1	3.14	1.36
BW2	3.06	2.19
PW1	4.60	--
PW4	4.08	1.70
Average	3.51	2.50

Table 3-5. Mass flux for each section in each PNFM and mass load estimates using the areas of the wetland.

Wetland ID	J_{c*} mg/m^2/day	Mass load mg/day
LW1MW7	6.4	2425.0
LW1MW7	8.5	3213.2
LW1MW7	4.8	1816.9
LW1MW7	5.5	2089.7
LW1MW8	4.7	1781.5
LW1MW8	6.6	2516.5
LW1MW8	9.3	3543.6
LW1MW8	11.9	4521.5
LW2MW2	2.2	1009.5
LW2MW2	3.3	1537.6
LW2MW2	5.3	2422.0
LW2MW2	8.7	4010.1
LW2MW3	0.6	260.1
LW2MW3	0.8	360.0
LW2MW3	0.5	250.7
LW2MW3	1.0	452.3
LW2MW4	1.5	700.0
LW2MW4	0.9	426.3
LW2MW4	0.4	193.6
LW2MW4	1.1	486.0
LW2MW5	1.6	714.9
LW2MW5	1.2	553.0
LW2MW5	1.6	746.6

Table 3-5. (continued)

Wetland ID	Jc* mg/m2/day	Mass load mg/day
LW2MW5	5.1	2368.2
LW2MW6	4.7	2175.2
LW2MW6	4.3	1969.3
LW2MW6	2.6	1212.0
LW2MW6	6.3	2905.2
BW1MW2	2.1	995.3
BW1MW2	2.9	1359.8
BW1MW2	3.0	1438.2
BW1MW2	7.8	3699.4
BW1MW5	0.2	72.5
BW1MW5	1.4	639.1
BW1MW5	2.1	973.7
BW1MW5	2.0	931.7
BW2MW2	0.1	55.5
BW2MW2	0.1	45.8
BW2MW2	0.1	52.3
BW2MW2	0.2	71.6
BW2MW5	5.1	2246.0
BW2MW5	4.8	2096.1
BW2MW5	1.7	735.6
BW2MW5	2.8	1243.8
PW1FM25	2.1	3921.9
PW1FM25	1.1	2100.3
PW1FM25	2.2	4041.6
PW1FM25	1.8	3247.3
PW1FM25	1.7	3129.7
PW1FM23	2.8	5112.5
PW1FM23	5.1	9296.0
PW1FM23	2.4	4439.8
PW1FM23	3.4	6282.8
PW1FM21	0.0	0.0
PW1FM21	0.0	0.0
PW1FM21	0.0	66.6
PW1FM21	0.2	323.6
PW1FM21	0.1	130.1
PW4FM19	0.6	593.3

Table 3-5. (continued)

Wetland ID	Jc* mg/m2/day	Mass load mg/day
PW4FM19	1.2	1148.7
PW4FM19	3.7	3565.6
PW4FM19	1.8	1769.2
PW4FM17	0.2	172.2
PW4FM17	0.0	0.0
PW4FM17	0.0	0.0
PW4FM17	1.9	1897.0
PW4FM17	0.6	632.3
PW4FM15	0.5	466.3
PW4FM15	0.2	193.7
PW4FM15	3.1	2976.2
PW4FM15	1.2	1212.0
PW4FM13	0.0	38.1
PW4FM13	0.0	35.1
PW4FM13	0.1	73.4
PW4FM13	2.4	2319.3
PW4FM13	0.8	809.3
PW4FM11	3.7	3644.9
PW4FM11	4.6	4472.2
PW4FM11	5.5	5410.2
PW4FM11	4.6	4509.1

Table 3-6. Summary table of the average phosphate mass load per wetland.

Wetland	Average phosphate mass load g/day
LW1	2.74
LW2	1.24
BW1	1.26
BW2	0.82
PW1	3.23
PW4	1.45

Table 3-7. Number of days water gradient was into and out of the wetlands and grams of phosphate measured throughout deployment period.

Wetland	Gradient in days	Gradient out days	Phosphate in grams	Phosphate out grams	Cumulative phosphate grams
LW1	4.0	30.0	11.0	82.2	93.1
LW2	1.5	32.5	1.9	40.2	42.1
BW1	4.0	30.0	5.1	37.9	43.0
BW2	1.0	33.0	0.8	27.0	27.8
PW4	0.0	33.0	0.0	47.8	47.8

Table 3-8. Mass flux measurements estimated from the PNFM and gradient calculations.

Wetlands	PNFM measurement mass flux mg/m2/day	Mass flux found from Darcy velocity and TP concentration mg/m2/day
LW1	7.46	64.060
LW2	2.09	8.020
BW1	2.83	14.820
BW2	1.83	7.220
PW1	1.75	--
PW4	1.74	0.120
Average	2.71	5.898

Table 3-9. Mass fluxes estimated from the PNFM for the Pelaez transect.

Pelaez transect wells	PNFM measurement mass flux mg/m2/day
PTFM1	0.67
PTFM2	5.33
PTFM3	7.23
PTFM4	1.36
PTFM5	4.00
PTFM6	5.48
PTFM7	10.93
PTFM8	8.93
PTFM9	20.62
PTFM10	10.11
Average	7.47

Table 3-10. Summary table of average and estimated range for phosphate parameters.

	Average	Estimated Range	
Darcy Flux (cm/day)	3.51	2.00	4.75
Mass Load per wetland (g/day)	1.79	1.00	3.50
Mass Flux per wetland (mg/m2/day)	2.71	1.50	8.00
Mass Flux per ditch (mg/m2/day)	7.47	0.75	14.00

CHAPTER 4
BASIN WIDE LOADS BASED ON LOCAL FLUX MEASUREMENTS

The field data collected from the six wetlands were used to create a basin-wide estimate of the total amount of phosphorus exchange between groundwater and isolated wetlands in the basin. The amount of phosphorus that could be reduced to Lake Okeechobee by detaining more water in the wetlands for a longer period of time was estimated to be similar to the measured fluxes. To estimate the amount of phosphate that could be stopped from reaching Lake Okeechobee the phosphate parameter numbers from Table 3-10 were applied to the priority basins of the Lake Okeechobee watershed.

The priority basins, S-65E, S-65D, S-154 and S-191 have consistently produced the highest levels of phosphorus concentrations of all the tributary basins to Lake Okeechobee (SFWMD and USEPA, 1999). The priority basins have abundant cow calf operations. The priority basins account for 12% of the land area in the Lake Okeechobee watershed, see Figure 4-1, and 35% of the phosphorus entering the lake (Dunne et al., 2006). The Lake Okeechobee Action Plan of 1999 states that if the priority basins met their target loads the phosphorus loading into Lake Okeechobee could be reduced by over 100 tons per year (SFWMD and USEPA, 1999).

Basin Wide Phosphorus Calculations for Isolated Wetlands

By using the characteristics of the six wetlands studied, an estimate of the amount of phosphorus produced by the all the wetlands located within the priority basins was calculated. Seven percent of the land surface in the priority basins is reported as isolated wetlands (Dunne et al., 2006). The priority basin’s total area is 974 square miles (SFWMD and USEPA, 1999). Thus there are an estimated 68 square miles of isolated wetlands within the priority basins. The average area of the Larson Dixie and Beaty ranch’s four wetlands was determined by area measurements taken over a month’s time at the wetlands on Larson Dixie and Beaty Ranches

(Perkins, 2005). The average area of the four wetlands was 7,900 square meters. Thus there is an approximate 22,400 individual isolated wetlands in the priority basins.

By taking the average and range of phosphate mass flux shown in Table 3-9 and multiplying them by the number of individual isolated wetlands estimated for the basin, the estimated mass load average and range is calculated, Table 4-1. The phosphate mass load estimated represents the priority basin's total phosphate mass load between isolated wetlands and groundwater. This calculation produces phosphorus mass load range for the priority basins of 2.6 to 14 metric tons per year with an average of 4.69 metric tons per year, Table 4-1.

Comparison of Calculated Mass Load to Literature Estimates for Isolated Wetlands

Based on other studies, if the detention of water in the isolated wetlands is capable of decreasing the mass load approximately 4 to 20 percent then between 0.10 to 2.77 metric tons per year will not reach Lake Okeechobee, see Table 4-1 (Zhang et al., 2006). South Florida Water Management District studies indicate that small on-site wetlands can potentially remove between 25 to 80% of the phosphorus they receive which would increase the anticipated phosphorus removal seen in Table 4-1 (SFWMD and USEPA, 1999). The Lake Okeechobee Annual Report for 2005 indicated that retaining water on a 410 acre wetland reduces phosphorus by 1.2 metric tons per year, a 71% reduction (Grey et al., 2005).

Literature estimates for phosphate reduction from water detention in isolated wetlands range from 4 to 80% of the wetlands phosphorus stored in the wetland. With such a broad range it is obvious that more studies are needed to confirm the effectiveness of water detention in isolated wetlands to reduce phosphate loads. However, the reduction of 100 metric tons per year of phosphate that the Lake Okeechobee Action Plan of 1999 discusses is out of the range of the above estimates (SFWMD and USEPA, 1999). SFWMD and USEPA may also have taken into consideration other phosphate BMPs.

Phosphate Retention by Drainage Ditches

Similar to isolated wetlands, drainage ditches can serve as a source or sink for phosphorus. As a temporary phosphorus sink, erosion and overland flow can transport inorganic, organic and dissolved phosphorus into drainage ditches. The reducing conditions that occur with the accumulation of standing water in the ditches may enhance solubilization of sediment bound phosphate into drainage ditches (Sallade and Sims, 1997). Phosphorus rich sediments, newly soluble phosphorus and organic matter can accumulate in drainage ditches until storm events transport the materials out of the ditch system.

The phosphate flux measurements obtained from the ditch transect at Pelaez Ranch were used as a representative measurement of phosphate flux along drainage ditches in the Lake Okeechobee priority basins. By using an estimate of the length of ditches in the priority basins and multiplying by the phosphate discharge flux the mass load of phosphate from drainage ditches in the priority basins was estimated. The mass load of phosphate from the drainage ditch was compared with the mass load of phosphate from the wetlands to determine if best management practices should be applied to the ditches or if focus should remain on the isolated wetlands.

Basin Wide Phosphorus Calculations for Drainage Ditches

Table 4-2 depicts the average and the range of phosphate mass flux from wells PTFM3 to PTFM8, which run parallel to the drainage ditch. To determine the phosphate mass load in the priority basin the total length of drainage ditches was required. Estimates of the total length of drainage ditches were sparse. The greatest ditching density found for unimproved pastures, improve pasture, intensively managed pastures and citrus and row crops was 18 km/km^2 (Haan, 1995). To determine the maximum amount of phosphorus from the drainage ditches it was assumed that all of the area in the priority basins has the greatest ditching density for land uses.

By multiplying the ditching density by the area of the priority basins a drainage ditch length of 45,000 km was determined. Steinman and Rosen describe the total linear meters of canals in the watershed north of Lake Okeechobee to be 4,000 km (Steinman and Rosen, 2000). Calculating the mass loads with each estimate of ditch length results in very different numbers. Both estimates of drainage ditch length were used in order to create a range of possible phosphate mass loads from drainage ditches into Lake Okeechobee.

To obtain a mass load, the discharge area the drainage ditches was required. The discharge area was found by using the one meter depth that the PNFM measured and multiplying it twice to represent each side of the drainage ditch. This provides a phosphate mass load of 4 and 31 metric tons per year with an average of 18 metric tons per year, Table 4-2.

Using the larger drainage ditch length of 45,000 km, the phosphate mass load range increased to 22 to 362 metric tons per year, see Table 4-3. From the estimates of phosphate loads from drainage ditches in Lake Okeechobee is shown that there was a greater opportunity in reducing the phosphate from drainage ditches than from isolated wetlands.

Conclusions

Using the phosphate flux from the six isolated wetlands studied basin wide estimates for phosphate mass loads from wetlands and drainage ditches were calculated. Using literature as a guide the reduction of phosphate mass loads to Lake Okeechobee from isolated wetlands was calculated. From these calculations it was shown that the drainage ditches and isolated wetlands may contribute the same range of phosphate mass loads to Lake Okeechobee. However depending on the drainage ditch length used the drainage ditches may play a substantially larger part in phosphate mass loads than previously thought. The phosphate mass load from isolated wetlands was calculated to range from 2.6 to 14 metric tons per year while the drainage ditches contributed 2 to 360 metric tons per year. To help reduce the range of phosphate mass load for drainage ditch and provide a more accurate estimate an up to date drainage ditch total length in the priority basins should be established. Also the isolated wetlands and ditches are inundated about 3 months out of the year (SFWMD, 2007). These seasonal variations may decrease the phosphate mass load from both the isolated wetlands and drainage ditch.

By reducing the tributaries with the highest phosphorus loads the most progress will be seen in restoring Lake Okeechobee's water quality. Hiscock reported a change in phosphorus retention in wetlands from 61% in 1991 to 31% in 2003 and blamed decreased phosphate assimilation potential for the reduction (Hiscock et al., 2003). Thus the wetland soils phosphate assimilation capacity may need to be taken into consideration during further studies. Rapid, inexpensive soil tests, such as tests for phosphate and organic matter testing for bioavailable phosphate in top sediments, could be used on drainage ditch sediments to identify the areas with greater potential to release or retain phosphate (Sallade and Sims, 1997). Further field studies involving the PNFM can help to narrow the range of phosphate mass loading and reduction. The use of PNFM before and after a detention structure is erected at an isolated wetland can provide a more accurate picture of the effects an isolated wetland has on phosphorus loading.

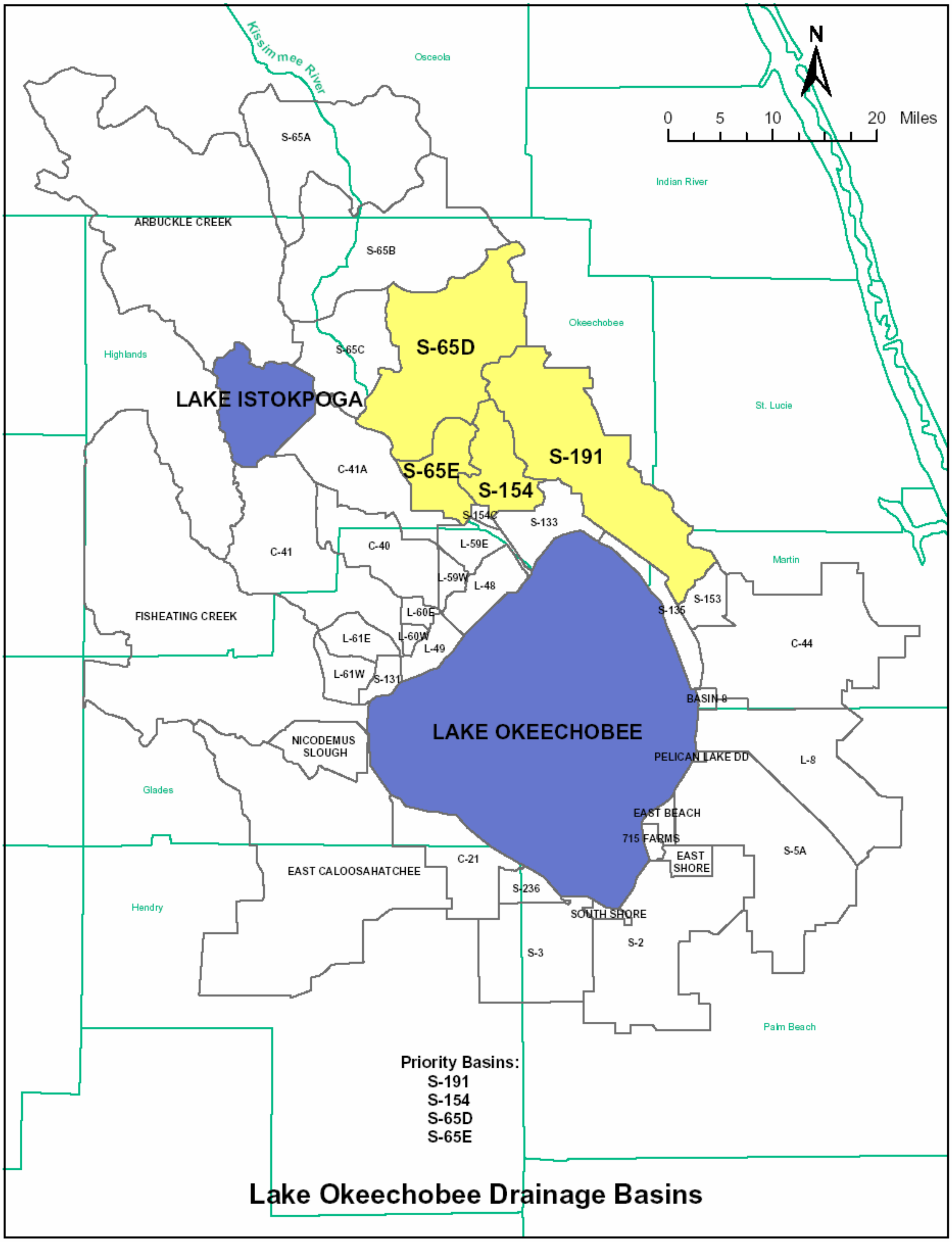

Figure 4-1. Lake Okeechobee drainage basins. The yellow basins are priority basins (SFWMD, 2007).

Table 4-1. Basin wide estimates of phosphate mass loading and reduction from isolated wetlands.

Phosphate mass flux range mg/m^2/day	Phosphate mass load range (metric tons/year)	Phosphate mass load reduction by 4% (metric tons/year)	Phosphate mass load reduction by 20% (metric tons/year)
1.50	2.59	0.10	0.52
2.71	4.69	0.19	0.94
8.00	13.84	0.55	2.77

Table 4-2. Basin wide estimates of phosphate mass loading from drainage ditches using a conservative drainage ditch length.

Phosphate mass flux range mg/m^2/day	Phosphate mass load range (metric tons/year)
1.36	3.97
6.32	18.46
10.93	31.91

Table 4-3. Basin wide estimates of phosphate mass loading from drainage ditches using a liberal drainage ditch length.

Mass flux range mg/m^2/day	Mass load range (metric tons/year)	Mass load range (metric tons/year)
1.36	22.55	45.10
6.32	104.77	209.54
10.93	181.11	362.22

CHAPTER 5
CONCLUSION

Several aspects of Lake Okeechobee's phosphate problem were explored through this research. The IGW model was used to model groundwater and phosphate flow between an isolated wetland and the drainage ditch discharging water from the wetland. Field measurements of phosphate flux were conducted using the PNFM. The field data collected from the six isolated wetlands, four under a previous study (Hamilton, 2005), and drainage ditch transect were analyzed to create general parameters for phosphate levels in the Lake Okeechobee watershed. These general phosphate parameters were used to create a basin wide estimate of the total phosphate mass load in isolated wetlands and drainage ditches. Estimates of how much phosphate could be retained in the wetlands and drainage ditches provide guidelines on which BMPs will be the most effective in reducing the phosphate load to Lake Okeechobee.

The IGW model was chosen to analyze phosphate flow and transport mechanisms throughout the isolated wetlands and drainage ditch system. The IGW was utilized for its real-time modeling, visualization and analysis capabilities. The effects of hydraulic conductivity, partitioning coefficient, head difference between the wetland and outflow ditch, wetland size and distance from wetlands on BTT, the time it takes for phosphate to reach a specific point down stream, were analyzed. The BTT given realistic conditions ranged from 15 years to 300 years. Hydraulic conductivity and head difference both showed inverse relationships to BTT. Linear relationships were seen with BTT verse partitioning coefficient and BTT verse distance from the wetland. Little effect was seen on the BTT with varying the size of the wetland. The above variables effect on BTT provides insight into which BMP will be most effective for phosphate reduction.

Three ranches used for cow calf operations in the Lake Okeechobee watershed provided an opportunity to identify general trends of phosphate in isolated wetlands and drainage ditches. The PNFM provide an accurate and inexpensive means of measuring phosphate flux in at each of the six isolated wetlands. The field data obtained from the PNFMs included water flux, phosphate flux, and provided values for comparison with calculated Darcy flux, phosphate mass loads and fluxes.

Larson Dixie and Beaty ranches exhibited similar trends in water and phosphate flux. Water flux for both ranches were consistently around 3 cm/day and phosphate flux trends increased from deepest depth to the ground surface. Pelaez ranch had a larger range of water fluxes from 0 to 7.5 cm/day and the phosphate flux increased as the depth increased. Water flux at the Pelaez transect resembles the Pelaez wetland trend in water flux. The Pelaez ranch transect indicated higher phosphate flux then the wetland and higher phosphate flux on the eastern side of the drainage ditch than the western side.

Darcy flux for each of the wetland sites was measured and also calculated using estimated wetland gradients. Darcy flux ranged from 2.0 to 4.8 cm/day. The measured Darcy flux was consistent at all the sites with the Pelaez sites having a slightly higher Darcy flux. The calculated Darcy flux had a slightly larger range of values than the measured flux. Phosphate mass loads were calculated for each of the wetlands and ranged from 0.82 to 3.2 g/day. Pelaez wetland 1 had the largest mass load. The calculated phosphate mass flux on average is higher than the measured mass flux. The mass flux estimated at the Pelaez transect is on average much higher than the mass flux in the wetlands.

Basin wide estimates of phosphate mass load for the priority basins in the Lake Okeechobee watershed were created from the field data collected. The average area of the isolated wetlands were calculated and scaled up to estimate the number and area of the isolated wetlands in the priority basins. The range and average of the phosphate mass flux from the isolated wetlands was used to estimate the total mass load from isolated wetland in the priority basins. The same types of calculations were applied to drainage ditches of the priority basin.

Basin wide isolated wetland and drainage ditch phosphate mass loads were similar in range, starting at 2.6 and 2.0 metric tons per year, respectively. The upper range from 32 to 362 metric tons per year for the drainage ditches depending on the estimate for total length of drainage ditches in the priority basins of the Lake Okeechobee watershed. With a more accurate and descriptive estimate of drainage ditches in the Lake Okeechobee priority basins a smaller range of phosphate mass load may be possible. Other studies indicate that detaining water in isolated wetlands for a longer time period, between 4 to 80% of the phosphorus stored in wetlands can be retained in the wetland (Zhang et al., 2006; SFWMD and USEPA, 1999; Grey et al., 2005).

The basin wide estimates confirm that there is potential to reduce one to two metric tons of phosphorus per year from entering Lake Okeechobee by increasing the effectiveness of BMPs in isolated wetlands and drainage ditches.

Future deployments of the PNFM at the isolated wetlands and drainage ditch transect should be completed to provide a comprehensive data set for analysis. A more comprehensive set of surface water samples should be taken during future deployments to compare with the concentration of phosphate in the groundwater. More data should be collected at the drainage ditch including water table elevations during the deployment.

To create a more accurate total basin mass load a survey of size and number of isolated wetland in the Lake Okeechobee basin could be completed. A more accurate total length of drainage ditches in the Lake Okeechobee priority basins is also needed.

The reduction of phosphorus mass load can be determined by deploying PNFMs before a weir is placed in an isolated wetland to obtain baseline measurement of groundwater and phosphate flux. PNFMs can be used after the weir is built and a comparison of phosphate changes due to the retention of water in the isolated wetland can be completed. The phosphate assimilation capacity of the soil can be observed over time to see if the reduction in phosphate decreases the longer water is retained in the wetland.

BMPs have been applied throughout the Lake Okeechobee watershed reducing the phosphate loads to the lake by tons per year (SWFMD and USEPA, 1999). With continued research on the most effective BMPs, cooperation from the land owners and efforts from the SFWMD, FDEP, and USEPA the TMDL of 140 metric tons per year of phosphorus to Lake Okeechobee can potentially be met.

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BIOGRAPHICAL SKETCH

Elizabeth Bevc studied at the University of Florida receiving both her Bachelor of Science and Master of Engineering degrees in environmental engineering sciences. Her master's class work focused on groundwater hydrology including contaminate transport. Elizabeth hopes to apply the knowledge gained at the University of Florida to remediate contaminated sites.