Evaluation of Agricultural Impoundments for Reducing Farm-scale P Discharge in South Florida

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Table of Contents

Executive Summary

This report discusses the results of a one year study to quantify the phosphorus (P) treatment efficiency and identify strategies to enhance P retention of an above ground impoundment (AGI) located at a vegetable farm within the C-139 Basin in South Florida. The study was funded by the South Florida Water Management District (SFWMD) in support of the mandatory Phosphorus Source Control Program (BMP Program) established by Part IV of 40E-63, F.A.C., for the C-139 Basin. The C-139 Basin is the second largest source of P in runoff to the Everglades.

The AGI was instrumented to collect water quantity and quality data (into and out of the AGI) for the July, 2009 - July 2010 period. The inflow to the AGI, through three pumps that drain seepage and drip irrigated fields, was estimated by using the RPM and head measurements. Outflow from the AGI was estimated using the hydraulic head at the discharge structure. Inflow and outflow water quality samples, taken through automated samplers, were analyzed for total phosphorus (TP). Flow data was combined with TP concentration, to calculate inflow and outflow TP loads. A topographic survey was conducted to characterize the bathymetry and stage-volume relationship. Soil and plant data were also collected to quantify the P stored within the AGI. Soil sampling included taking surface (0-10 cm) and subsurface (10-20 cm) samples at the beginning and at the end of the monitoring period. The samples collected at the beginning of the study were analyzed for Mehlic-1 (M1) P, M1Fe, and M1Al to calculate Soil Phosphorus Storage Capacity (SPSC) for evaluating the soil P retention potential. Both beginning and end soil samples were analyzed for TP to determine the spatial patterns and net change in TP storage. Aerial survey and field visits conducted to characterize vegetation within the AGI were combined with plant TP content to quantify biomass P storage.

Results from the study indicated that water inflow and outflow volumes from the AGI were almost equal for the dry (Nov-May) and wet (June-Oct) periods. High dry period flows were due to the higher than average rainfall during this period combined with the fact that crops are grown mostly within the dry period (Aug-May) and their water management needs are greater. Drainage to the AGI occurred from two different types of production fields (east and west), located on different sides of the AGI and irrigated through seepage (Pumps 1 and 2) and drip (Pump 3). Pumps 1 and 2 had higher flow volume than Pump 3, as a result of the higher water tables (reduced rainfall storage) maintained for the seepage irrigated fields. The average TP concentrations for Pumps 1 and 2 were 460 and 678 μg/L, respectively, while for Pump 3 it was 489 μg/L. Unusually

high TP concentrations were observed for Pumps 1 and 2 in July 2010, likely due to the effects of ditch cleaning that coincided with the timing of these concentrations. The outflow TP load from the AGI was 838 kg/year less than the inflow loads of 1043 kg, indicating that the AGI treated 20% of the inflow TP loads. High rainfall events during the dry period, especially during March and April, resulted in filling up the storage capacity of the AGI which resulted in most of the inflow TP loads being discharged out of the AGI without much retention. It should be noted that the AGI was designed as per the guidelines of the SFWMD and was approved by the SFWMD. TP outflow loads during the March12-April 3 period accounted for 38% of the annual TP outflow.

Soil analyses results indicated that there is limited capacity left in the soil to retain P and that the AGI could become a potential source of P. There exists a relationship between the inundation area and surface soil P retention capacity in the AGI. Areas that are inundated when the AGI water level reaches top of the outflow structure, had limited to no soil P retention capacity left. Among different plant species, biomass P storage was highest in mixed grass (134 kg) followed by water lettuce (105 kg).

Analyses of hydrologic, TP loads, SPSC, and biomass P showed potential modifications that can be made to enhance the P retention in the AGI. These modifications included structural and managerial strategies to achieve additional P retention through a variety of avenues which included increasing the available storage in the AGI, modulating flow volumes and rates by modifying the outflow control structure, relocating inflow structures to increase residence time, dividing the AGI into multiple cells to route the water through areas that have additional soil P retention potential and increasing the residence time, and harvesting the biomass (outside the three jurisdictional wetland) for removal of P.

1. Introduction

This report describes the activities completed during the project titled "Evaluation of Agricultural Impoundments for Reducing Farm-scale P Discharge in South Florida" in accordance with Task 4 (Deliverables 4.1 and 4.2) of the Scope of Work (Exhibit C) of Contract Number 4600001715.

The C-139 Basin is the second largest tributary of phosphorus (P) to the Everglades Protection Area (EPA). The Everglades Forever Act (EFA) mandates that landowners within the C-139 Basin shall collectively maintain historic total P loads observed during the baseline period. In 2002, the C-139 Basin Regulatory Program was initiated to ensure that historic P loads are met. The Regulatory Program is based on mandatory implementation of Best Management Practices (BMPs), as defined in Chapter 40E-63, F.A.C, as "a practice or combination of practices determined by the SFWMD, in cooperation with the Department of Environmental Protection and the Florida Department of Agriculture and Consumer Services (FDACS), based on research, field testing, and expert review, to be the most effective and practicable on-location means, including economic and technological considerations, of improving water quality in agricultural discharges to a level that balances water quality improvements, and agricultural productivity as applicable." (F.S. 373.4592) The BMP level is based on an annual assessment of compliance with historical P loads. Because the historic P loads were not achieved for WY2003 through WY2006, rule development to amend Chapter 40E-63 was initiated in January 2007. A key component of the proposed rule is the optimization of water management BMPs based on sound scientific and engineering data.

AGIs are commonly proposed as a water management BMP in the C-139 Basin. The role of AGIs in affecting nutrient loads in discharges is especially important for vegetable crops. Vegetable growers typically use higher P application rates and more intensive water table management relative to other crops in the C-139 Basin. However, limited scientific and engineering data exists on the actual effectiveness of AGIs to reduce P in discharges. Further, physical characteristics of ponds, such as length to width ratio, compartmentalizing, inlet/outlet placement are important factors that should be considered for enhancing the nutrient treatment efficiency of the impoundment. However, the optimal design criteria for impoundments are not currently available (Bottcher, 2008; Shukla and Knowles, 2008; and Shukla and Jaber, 2008). Developing design criteria requires experienced professionals in water management, agriculture, and water quality research and growers that are willing to have water quality data collected at their farms.

Due to general lack of knowledge concerning AGIs' role in water quality and the need for continued efforts in reducing the P loads from the C-139 Basin, it is important to gain and understanding of the P dynamics in typical AGIs in the basin to better comprehend and guide the activities to ensure that the basin, as a whole, is able to meet the requirements set forth by the EFA. A project was proposed by Shukla and Knowles (2008) and funded by the Everglades Regulation Division of the SFWMD to address the knowledge gaps identified above. This project was proposed to be conducted in three phases with the individual objectives described below. This report only includes Phase I. An amendment, or a separate contract, will be required to address Phases II and III. However, a complete overview of the project is provided here to illustrate final expectations and benefits to the C-139 Basin and other basins with similar land use and hydrology.

Phase I
1) Quantify the P nutrient treatment efficiency of an AGI located in a vegetable farm,

2) Identify AGI design modifications (e.g. increasing residence times by changing inflow locations, dividing the AGIs into multiple treatment cells, etc.) to increase its treatment efficiency,

Phase II
1) Conduct a basin-wide assessment on the characteristics of AGIs

2) Implement and evaluate the effectiveness of the modified AGI in enhancing the nutrient treatment efficiency,

Phase III
1) Use hydrologic/water quality models to evaluate different modifications with regards to nutrient discharges,

2) Conduct an economic analysis of the AGI modifications and combine it with the modeling results to rank different modifications based on cost and nutrient treatment efficiency, and

3) Develop design guidelines for constructing new AGIs or modifying existing AGIs to optimize the basin-wide nutrient treatment efficiency.

2. Materials & Methods

2.1 Study Area

This study was conducted at an AGI located within the C&B Farms near Clewiston, FL. The farm is situated on four adjacent parcels totaling 1677.4 acres of which approximately 1225 acres are under cultivation. The farm is located at the far southeast corner of the C-139 Basin and immediately west of the SFWMD Stormwater Treatment Area 5/6 (Figure 1). The cultivated areas of the farm are characterized primarily by Myakka and Immokalee fine sand soils (Figure 2). These two soils are characteristic of the South Florida flatwoods landscape and are described as being deep or very deep, poorly drained or very poorly drained soils that formed in sandy marine sediments. There are smaller sections of the farm that contain the following soil types: Basinger sand, Okeelanta muck, Margate sand, Delray sand and Holopaw sand. These soil types, although present in some of the cultivated areas, are principally located in isolated wetlands and in the agricultural AGIs located throughout the farm (NRCS, 2006).

The cultivated areas within the farm are irrigated with a combination of drip and seepage irrigation. For both types of irrigation, the source water comes from both groundwater and surface water. The farm drainage system takes advantage of the same conveyance canal system to route drainage water towards the AGI. The drainage water is pumped into the AGI by surface water pumps commonly called 'throw-out pumps' that are distributed around the AGI's perimeter. The farm is divided into drainage basins to more efficiently drain the farm when necessary. In other words, by adjusting the flashboards in the risers located in the canals, water is routed to the nearest pump during drainage events. The pumps and the AGIs were designed and sized according to the area of their corresponding drainage basins and the potential runoff.

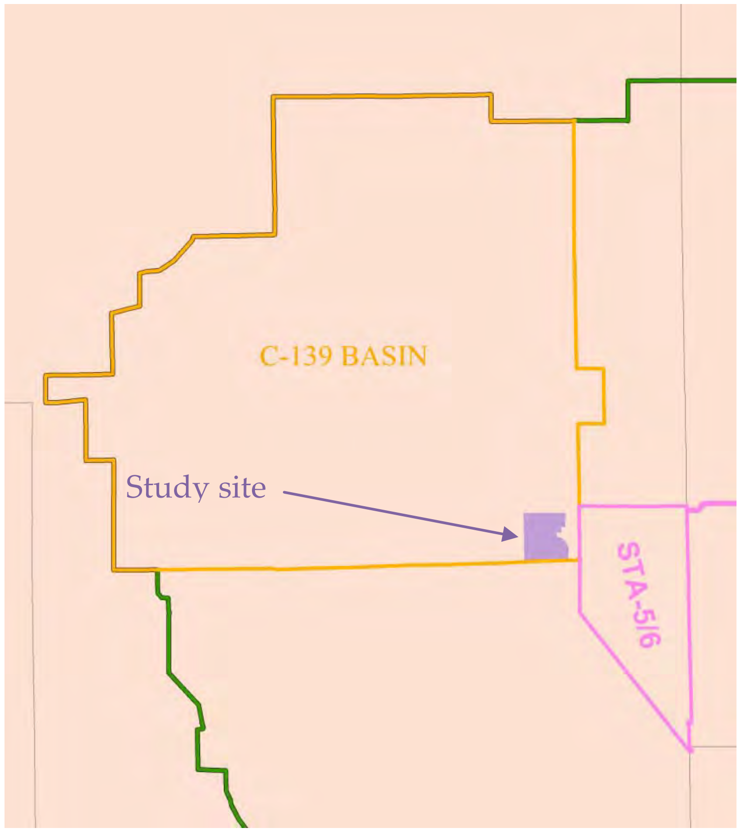

Figure 1. Location of the study site

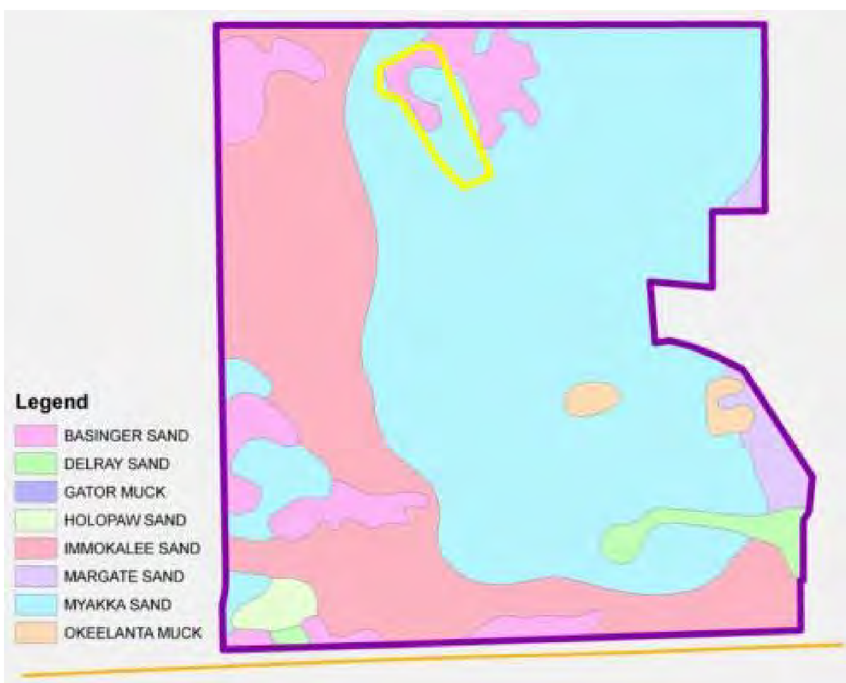

Figure 2. Soil map of C&B Farms (study site).

The AGI studied in this project will be the northernmost AGI (yellow boundary in Figure 3). This AGI has an area of approximately 36.7 acres and was designed to receive drainage from approximately 276 acres of the farm. Drainage water is pumped into the AGI via three diesel-operated surface-water axial flow pumps (Figure 4). Maximum flow rate for each pump is approximately 5,000 gallons per minute (GPM). The discharge structure of the AGI is located at the southern extreme of the AGI and consists of two sharp crested weirs set at 19.5′ NGVD29 (18.12′ NAVD88). A 'borrow ditch' is located around almost the entire interior perimeter of the AGI. This 'borrow ditch' was created during AGI construction when material inside the AGI was excavated to provide the necessary soil to construct the AGI embankment. The remaining interior of the AGI is characterized by flat, nearly level ground with the exception of four depressions, three of which are jurisdictional wetlands. The predominant soil types within the AGI are Myakka fine sand and Basinger fine sand (NRCS, 2006).

Figure 3. Aerial view of AGI and drainage basins.

Figure 4. Locations of inflow pumps and discharge structure.

The three jurisdictional wetlands (Figure 5) in the AGI, Wetlands 1 (area = 0.45 ha), 2 (area = 0.75 ha), and 3 (area = 0.64 ha), are dominated by different wetland species (Keltner, 2009; Personal Communication). The predominant species in Wetland 1 is smartweed (*Polygonum* spp.). Wetland 2 is covered mainly by smartweed and primrose willow (*Ludwigia peruviana*) with cattails (*Typha* spp.) scattered in pockets throughout the wetland footprint. The western perimeter of Wetland 2 consists of Carolina willow (*Salix caroliniana*). The vegetation of Wetland 3 is similar to that of Wetland 2 with the exception of cattails.

Figure 5. Location of jurisdictional wetlands.

2.2 Topographic Data

A topographic survey of the AGI was conducted in March of 2009 to characterize the bathymetry of the AGI (Figure 6). The elevation data was used to perform analyses related to AGI storage capacity and time to discharge. Location of the specific survey points are presented in Figure 7.

Figure 6. Collection of topographic data at one of the internal borrow ditches.

Figure 7. Location of topographic survey data points (green circles).

2.3 Hydrologic and Water Quality Monitoring

The P nutrient treatment efficiency of the AGI was quantified according to the monitoring system design described in detail below. The calculation of treatment efficiency requires the quantification of two main components: 1) the nutrient loads entering the AGI (inflow) and 2) the nutrient loads leaving the AGI (outputs).

The primary nutrient inputs to the AGI were from the pumped drainage via the three discharge pumps (1, 2 and 3) and the rainfall. Other smaller inputs (not measured) include mineralization of plant and soil organic matter, atmospheric deposition (e.g. rainfall), subsurface lateral inflows, and wildlife inputs. Surface discharge via the AGI discharge structure will be the primary nutrient output from the AGI. Other outputs might include: subsurface (lateral and vertical) outflows or retention of nutrients via chemical, physical, or biological processes. The treatment efficiency of the AGI was calculated using the following equation:

Eq. 1

where E_f = nutrient treatment efficiency,

$\sum$i = sum of nutrient inputs, and

$\sum$o = sum of nutrient outputs.

2.3.1 Inflow

2.3.1.1 Water Quantity Monitoring

Of the inputs mentioned above, the two that were measured as part of this study were pumped drainage (from the discharge pumps) and rainfall. Rainfall was measured at the weather station located at the study site (Figure 8, Table 1).

Table 1. Summary of hydrologic and weather data collected at C&B Farms.

Monitoring Station	Parameter	Frequency
Pump sites	Canal stage elevation	5-minute readings averaged every 15 minutes
	Pump RPM	15 minute average
Discharge site	Discharge stage elevation	5-minute readings averaged every 15 minutes
	Discharge flowrate	Estimated for every 15 minutes using the stage data
Weather station	Rainfall	5-second readings summed every 15 minutes
	Air temperature	5-second readings averaged every 15 minutes
	Relative humidity	5-second readings averaged every 15 minutes
	Solar radiation	5-second readings averaged every 15 minutes
	Wind speed and direction	5-second readings averaged every 15 minutes

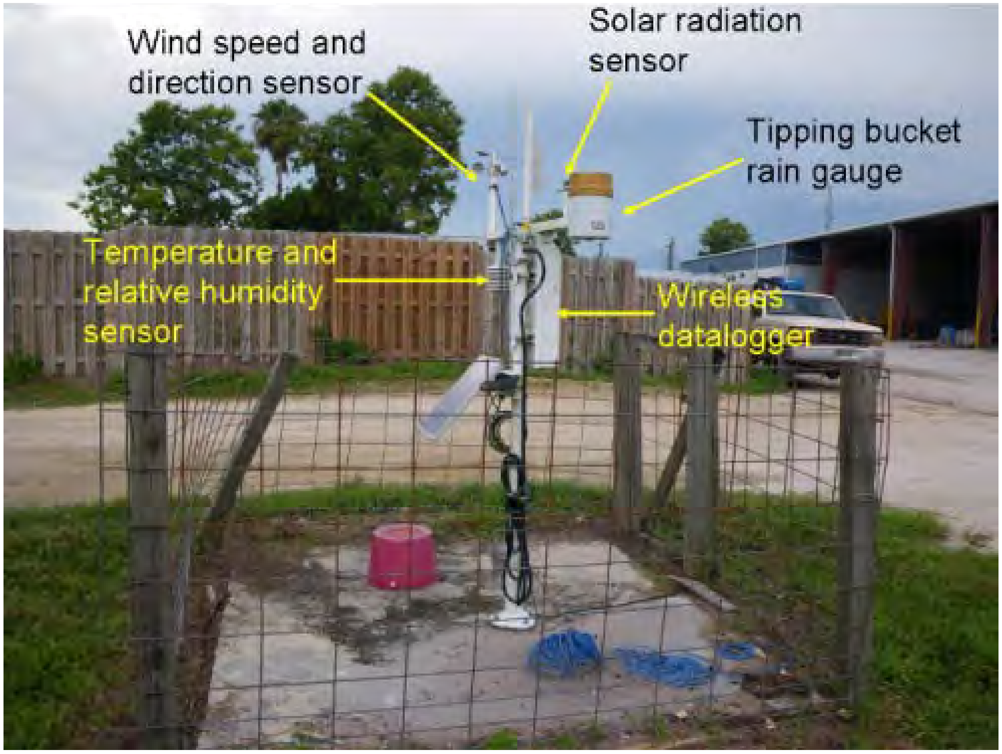

Figure 8. Weather station at C&B Farms.

Inflows into the AGI are delivered through the use of three discharge pumps (Pump 1 displayed in Figure 9; other pumps are similarly equipped). Each discharge pump was outfitted with a pump speed sensor that measured revolutions per minute (RPM). Close to the intake of each pump, the suction line of an autosampler was installed. The autosampler was connected to a datalogger. The pump RPM data were used by the datalogger in conjunction with a pump equation to calculate the rate and volume of drainage every 15 minutes.

Since all three pumps are locally manufactured, their characteristic pump curves were not available requiring that a pump calibration be performed for each pump. The pump calibration was an arduous task since it required the use of mechanical flowmeters. Calibration was performed by installing a propeller type flow meter on the discharge pipe of the pump for collecting the necessary data. To ensure that the calibration was conducted under the full pipe flow conditions, baffles were installed at the end of the pipe. For calibration (Figure 10), pumps were ran at different speeds while the elapsed time was noted for each 10,000 gallons of water pumped. The time for each run was used to compute gallons per minute (GPM) using the equation: GPM = 10,000/minutes elapsed during each run.

In addition to the GPM, the stage of water in the outside borrow ditch was also monitored during each run. A regression analysis was performed to develop pump equations to predict GPM as a function of the RPM and stage in the outside borrow ditch. Pump 1 was operated more frequently than the other two pumps; it ran longer and for a varied range of ditch stages. The flow rates for Pump 1 varied considerably for different stages and RPM combinations. Efforts were made to develop a single pump equation, however, the R^2 for the regression equation was 0.16. To improve the regression equation, four equations were developed for Pump 1 for different ranges of stage. Among the four equations for Pump 1, three of the R^2 are greater than 0.95. The R^2 for the stage range of 4.5 to 5.0 ft, although lower than the R^2s for other stage ranges, was considered satisfactory considering that this head range was observed only 13% of the time and represented only 5% of the total flow volume. The inverse relationship between GPM and RPM for this range could be due to the unstable head- RPM-flow characteristics and vibrations at higher RPMs. Since the pumps at the study site are locally built, the design/operating (RPM and head) specifications and pump characteristics are not available. Therefore, it is not possible to identify causative factors that resulted in decrease in flow with increase in RPM for the stage range of 4.5 to 5.0 ft. The equations for the three pumps are presented in Table 2.

Table 2. Pump equations for predicting discharge volume (GPM) as a function of pump revolutions per minute (RPM) and stage.

Site	Stage (ft)	Regression Equation	R^2
PUMP 1	3.0<=STAGE<=4.0	GPM = -15908.2+(6.8*RPM)+(727.7*STAGE)	0.99
	4.0<STAGE<=4.5	GPM = -13047+(4.94*RPM)	0.99
	4.5<STAGE<=5.0	GPM = 5642.8 +(-0.98*RPM)	0.77
	STAGE >5.0	GPM = -44131.1 +(-2.43*RPM) +(10382.15* STAGE)	0.95
PUMP 2	All stage values	GPM= - 18602.38 + (13.56*RPM)+ (1214.52* STAGE)	0.91
PUMP 3	All stage values	GPM = - 105 +(0.77 RPM) + (125*STAGE)	0.90

3.2.0.1 2.3.1.2 Water Quality Monitoring

Autosamplers were triggered based on elapsed time between samples during the times when the discharge pumps were operating. Samples were taken at the beginning of each pumping event and then at the following fixed intervals between consecutive samples: 15 minutes, 30 minutes, 1 hour, 4 hours and 8 hours. If the pump was operated for longer than 13:45 hours, subsequent samples were taken at 8 hour intervals. For each sample trigger, a discrete water sample was collected and analyzed for TP. In addition, grab samples were collected and analyzed for soluble reactive P (SRP) and TP for two flow events. The grab sampling was included to help evaluate the effectiveness of the

AGI to affect SRP versus TP (plus unreactive soluble P). The TP concentrations were used in conjunction with the flow volume to calculate TP loadings into the AGI.

Figure 9. Surface water quantity and quality monitoring system installed at pump 1

Figure 10. Pump calibration using propeller-type flow meter, elapsed time, pump speed and borrow ditch stage level

2.3.2 Outflow

2.3.2.1 Water Quantity and Quality Monitoring

The AGI has two side-by-side discharge structures (36″ culverts with 48″ headers/risers), each equipped with a rectangular sharp-crested weir (Figure 11). The weir flow was estimated using head values (height of water above the weir) recorded with a pressure transducer that was connected to a datalogger equipped with wireless radio. Flow volume was calculated every 15 minutes through the use of a non-linear weir discharge equation which predicted the flow as a function of the head. The standard weir equation with two end contractions was first used to estimate the flow through the weir but it was observed that there were many instances when the weir was completely submerged which resulted in no nappe formation. Under submerged flow conditions, the standard weir equation failed to estimate the actual flow. Therefore, the weir was calibrated by performing a nonlinear regression analysis on flow measurements obtained from an Acoustic Doppler Velocimeter (ADV).

Similar to pumped inflow, grab samples were collected and analyzed for SRP and TP for two flow events. To collect water quality samples, an autosampler was connected to the datalogger and triggered based on elapsed time between samples (Figure 12). Samples were taken at the beginning of each discharge event then at the following fixed intervals between consecutive samples: 15 minutes, 30 minutes, 1 hour, 4 hours and 8 hours. If the pump was operated for longer than 13:45 hours, subsequent samples were taken at 8 hour intervals. Phosphorus discharge from the AGI was calculated by multiplying the P concentration by the flow volume.

Figure 11. Water control structures and associated control elevation at the discharge site.

Figure 12. Surface water quantity and quality monitoring system installed at the discharge site.

3.2.1.1 2.3.2.2 Evapotranspiration (ET)

To account for the various components in the water balance, reference evapotranspiration (RET) estimates were computed from the meteorological parameters (wind speed, air temperature, relative humidity and solar radiation) collected at the on-site weather station using the FAO-56 Penman-Monteith grass reference evapotranspiration method (Allen et al., 1998).

2.3.3 Data Quality

All water quality samples at the inflow and outflow locations were collected and handled according to the FDEP Standard Operating Procedures (SOP). Due to the fact that samples collected by the autosampler are collected in bottles pre-preserved with sulfuric acid, it was not possible to measure the pH of these samples. Samples were retrieved from the field site at least once a weekly basis. Since grab sample bottles are not pre-preserved, the following additional parameters were measured for these samples: temperature, pH and electrical conductivity. The autosampler and grab samples were analyzed for TP while only the grab samples were analyzed for SRP. All samples were analyzed at the Analytical Research Laboratory (ARL), University of Florida, Gainesville, FL and at Florida Testing Services (dba Xenco Laboratories), Boca Raton, FL.

2.4 Soil and Plant Monitoring

Soil and plant sampling was included as a component of the project to better understand the P stored in these two components in the AGI. Different P species are present in the water flowing through the system and these forms of P can be retained by the soil and vegetation inside the AGI. To evaluate the role of these components in the system's P dynamics, it is necessary to know the relative proportion of P that they contain and how this may change over time.

2.4.1 Soil

Soil samples were taken prior to the commencement of monitoring and again at the end of the monitoring period. Twenty-six soil sample locations were selected randomly from a 100 ft x 100 ft grid overlaid on the AGI in order to have a representative sample population (Figure 13). Soil samples at each location were taken at two depths, 0-10 cm and 10-20 cm (Figure 14). The samples taken at the beginning were analyzed for TP, Mehlich-1 Al (M1), Mehlich-1 Fe (M1Fe), Mehlich-1 P(M1Al), organic matter and bulk density at the ARL. Samples taken at the end were only analyzed for TP in order to evaluate changes in P content and soil P storage during the monitoring period. The Mehlich-1 analyses (Fe, Al, and P) were used to calculate the soil P storage capacity (SPSC) for the 0-20 cm (A horizon) depth. This value provides an indication as to whether a soil will be a P source or sink taking into account the previous P loading the soil has undergone and its P sorption capacity (Nair et al., 2010). SPSC is calculated using the soil P saturation ratio (PSR, Equation 2) and a threshold PSR of 0.1 for the A horizon (Equation 3).

$$Soil \cdot PSR_{M1} = \frac{\frac{M1 \cdot P}{31}}{\frac{M1 \cdot Fe}{56} + \frac{M1 \cdot Al}{27}} \qquad \text{Eq. 2}$$

$$SPSC = \left(Threshold \cdot PSR_{M1} - Soil \cdot PSR_{M1}\right) * \left(\frac{M1 \cdot Fe}{56} + \frac{M1 \cdot Al}{27}\right) * 31 * 1.3 \qquad \text{Eq. 3}$$

Figure 13. Location of the soil sample sites.

Figure 14. Collection of an intact soil core in the water lettuce area.

2.4.2 Plant

Plant samples taken at the end of the monitoring period were analyzed to evaluate the P storage in the above-ground biomass within AGI. The AGI was divided into areas depending upon the type of predominant vegetation present. On October 22, 2010, a helicopter flight was taken with SFWMD personnel to evaluate the aerial extent of the vegetation within the AGI. Combination of aerial and on-ground assessment of vegetation in the AGI was used to create an approximate vegetation map. Two locations from each vegetation category were selected and sampled. A 1 m square quadrant was used to sample the above-ground vegetation at each sampling location (Figure 15). The samples collected were clipped, shredded and oven-dried for three days. After drying, samples were ground to 1 mm and delivered to the ARL for TP analysis. The TP content (mg/kg) was used in conjunction with the vegetation map to determine mass of P stored in the above-ground biomass.

Figure 15. One meter square quadrant used to collect representative vegetation samples.

2.5 Water and Phosphorus Dynamics and Treatment Efficiency

2.5.1 Water Dynamics

A water balance was constructed using the measured hydrologic inputs and outputs. The water balance equation is presented below.

$$P + G_{in} + Q_{in} = ET + Q_{out} + G_{out} + \Delta S \qquad \text{Eq. 4}$$

Where P = precipitation (in)

G_{in} = groundwater seepage gains into the AGI (in)

Q_{in} = pumped inflow (in)

ET = evapotranspiration (in)

G_{out} = groundwater seepage losses from the AGI into surrounding fields (in)

Q_{out} = discharge at the outflow structure (in)

ΔS = change in AGI storage (in)

The groundwater seepage losses and gains from the AGI were not monitored and not included in the above water balance equation. Change in AGI storage was assumed to be negligible.

2.5.2 Phosphorus Dynamics

The time series of inflow and outflow TP concentrations and loads were examined along with the water dynamics to characterize the temporal variability in TP and TP dynamics in the AGI. The water and TP contributions of individual pumps to the total inflow were examined for different periods (dry versus wet periods and year) along with the stage-volume relationship to quantify P treatment and identify potential modifications that can be made to improve the P treatment efficiency. The TP treatment efficiency, discussed in section 2.3 was calculated using the total inflow and outflow TP loads (Equation 1).

3. Results

3.1 Weather

The monitoring period included most of the 2009 wet period (July-October), the complete 2009 dry period (November 2009 – May 2010) but only part of the 2010 wet period (June and July). The rainfall during the 2009 wet period was lower than the long-term average (1895-2011) for the area, receiving 72% of the average rainfall from July to October (Table 4) (NCDC, 2011; average was calculated from all available stations included in the NCDC database). The dry period (November 2009-May 2010) received 198 mm more rainfall than the long-term average (414 mm) for this period. Higher than average rainfall conditions during the dry period resulted in higher than average drainage events (Figure 17, Figure 18, and Figure 19). Another reason for higher than normal drainage events, although relatively small with regards to the total drainage events, was the unusually low temperatures observed during January 2010 which required the water table to be artificially raised higher than normal (both drip and seepage irrigated fields) for freeze protection (Table 3). Raising the water table for freeze protection is carried out in both drip and seepage irrigated fields since it is one of the more economical ways to mitigate the negative effects of freezing temperatures. Water table increases related to freeze control may also result in seepage inflows to the AGI due to potentially higher water table in the outer borrow ditches compared to the water table in the AGI.

Table 3. List of freeze events during January 2010.

Date	Minimum Temperature (°C)
January 6, 2010	-0.5
January 10, 2010	-0.8
January 11, 2010	-1.8

Table 4. Summary of monthly average weather data. Long-term average rainfall for the Everglades and Southwest Florida Coast climatological division (calculated from long-term data from NCDC, 2011) is included along with the C&B Farm's deviation from this average.

Month	Min Temp (C)	Max Temp (C)	Min Relative Humidity	Max Relative Humidity	Wind Speed (m/s)	Solar Radiation (W/m2)	Total Reference ET (mm)	Total Rainfall (mm)	Long-term Average Rainfall (mm)	Difference in C&B Rainfall and Long-term Rainfall Average (mm)
Jun-09	22.9	32.0	56.7%	94.2%	1.9	188.7	40.0	122.9	219.1	-96.2
Jul-09	23.0	33.6	48.5%	94.7%	1.3	217.2	201.6	161.3	194.8	-33.5
Aug-09	23.3	34.1	48.0%	94.5%	1.4	223.6	208.6	172.2	195.5	-23.3
Sep-09	22.7	32.8	52.0%	96.1%	1.2	193.3	170.8	144.0	194.9	-50.9
Oct-09	20.3	32.2	44.8%	94.0%	1.3	180.1	169.9	23.1	102.4	-79.3
Nov-09	15.8	27.8	46.7%	94.2%	1.7	135.4	126.3	25.9	43.2	-17.3
Dec-09	14.3	25.3	55.8%	94.9%	2.0	114.5	106.0	61.5	40.9	+20.6
Jan-10	8.4	21.3	44.2%	94.1%	2.3	129.1	111.6	58.7	46.2	+12.5
Feb-10	9.3	21.2	44.4%	92.9%	2.6	155.8	115.6	104.9	49.6	+55.3
Mar-10	10.9	23.4	42.6%	94.0%	2.8	194.1	161.5	154.4	62.6	+91.8
Apr-10	16.6	27.7	47.1%	95.3%	2.7	226.0	192.8	130.6	59.5	+71.1
May-10	20.8	32.1	45.3%	95.5%	2.1	258.9	236.1	76.2	111.7	-35.5
Jun-10	23.1	34.2	47.6%	95.0%	1.7	244.7	222.0	225.6	219.1	+6.5
Jul-10	23.4	33.4	49.7%	94.2%	1.8	228.4	138.3	151.1	194.8	-43.7

3.2 Water Dynamics

Daily time series of drainage inflows and rainfall for pumps 1, 2, and 3 are presented in Figures 17, 18, and 19, respectively, showing that the number of drainage events during the dry period, which also covers most of the crop growing season (August-May), were higher than the number of drainage events during the wet period. The irrigation and drainage basin on the west side, drained through pumps 1 and 2, uses seepage irrigation which involves artificially raising the water table within the 46-62 cm of the soil surface to provide water to plant roots through upflux. The basin to the east of the AGI, drained through pump 3, is mainly irrigated with drip irrigation which does not require maintaining high water table. Lower water table for the drip irrigation resulted in lower volumes of drainage from the east basin (pump 3) compared to the west basin (pumps 1 and 2). Pump 1 had the highest frequency and volume of drainage compared to pumps 2 and 3 (Table 5). Pumps 1 and 2 are located in the same feeder canal and therefore drain the same cultivated areas. Pump 2 was operated less than pump 1 due to it being out of service for an extended period of time. Even when pump 2 was operational, it was use less frequently than pump 1 due to one or more of the of following reasons: 1) pump 1 involves belt transmission and is similar to other pumps at the farm which makes it easy to repair since spare parts are readily available; 2) pump 2 involves gear transmission and is difficult to repair; and 3) pump 1 is closer to the farm office than pump2. Unusually high rainfall events during the dry period resulted in frequent use of pump 1 to drain seepage irrigated fields. The highest daily rainfall occurred during the dry period when 7.1 cm of rain fell on 3/12/2010. In preparation for and as a result, all three pumps were operated more than usual resulting in a total input of 55 cm which accounts for over 5% of the total inflow into the AGI. Other high rainfall events occurred during this period as well contributing 4.2 cm on 3/29/2010, 3.9 cm on 4/18/2010, and 4.1 cm on 4/26/2010. During the months of March and April when these high rainfall events occurred, a total of almost 300 cm of drainage was pumped into the AGI accounting for almost 30% of the monitoring period's total. Drainage during the dry period was mainly due to the combination of two factors, the vegetable crops being grown and unusual high rainfall. Although higher than normal drainage during the dry period is likely to occur for other crops such as citrus within the C-139 Basin, the relative drainage volume for vegetable crops is likely to be higher.

Table 5. Flow volumes in depth (cm) for all inputs and losses and the percentage of total for the water balance.

		FLOW (cm)	% OF ALL INPUTS
INPUTS	PUMP 1	742	63
	PUMP 2	141	12
	PUMP 3	168	14
	RAINFALL	135	11
	TOTAL	**1186**	**100**
LOSSES		**FLOW (cm)**	**% OF ALL LOSSES**
	DISCHARGE	1155	91
	ET	116	9
	TOTAL	**1271**	**100**

Following the same pattern observed for the inflow pumps, most of the discharges from the AGI occurred during the dry period. The highest period of discharge occurred between 3/12/2010 and 4/3/2010 accounting for 277 cm of discharge and 24% of the total discharge observed during the monitoring period. The discharge period began as a result of the March 12th rainfall mentioned above and continued until April 3rd due to continued rainfall and drainage. The high discharge volumes produced during this period were partly due to the fact that the AGI's storage capacity was mostly utilized prior to the pumping and rainfall associated with the March 12th event. On March 11th, prior to pumping and rainfall, almost 50% of the interior surface area of the AGI was inundated and 75% of the available storage volume was already occupied (Figure 16). The total rainfall during this period was 13.6 cm or 10% of the total rainfall received during the entire monitoring period. High rainfall and drainage during this period resulted in filling the AGI storage capacity and therefore inflow being almost equal to the outflow (Table 5, Figure 16).

Rainfall during March and April combined with pumping resulted in outflow exceeding the pumped inflow on April 21, 2010 (Figure 21). However, when rainfall inputs were added to get the total inflow (drainage + rainfall), the outflow did not exceed the total inflow for the March-April period. There were only five days (July 10 to July 14) when the outflow exceeded the total inflow by 0.8 to 3.4 cm; these relatively small exceedances may be due to uncertainties associated with flow measurements. Comparison of the drainage from the three pumps and discharges at the outflow structures shows that not all drainage events resulted in outflow. The rainfall continued to occur regularly (35 out of 81 days) throughout the rest of the monitoring period which resulted in outflow being close to the inflow (rainfall + drainage) after April 21, 2010.

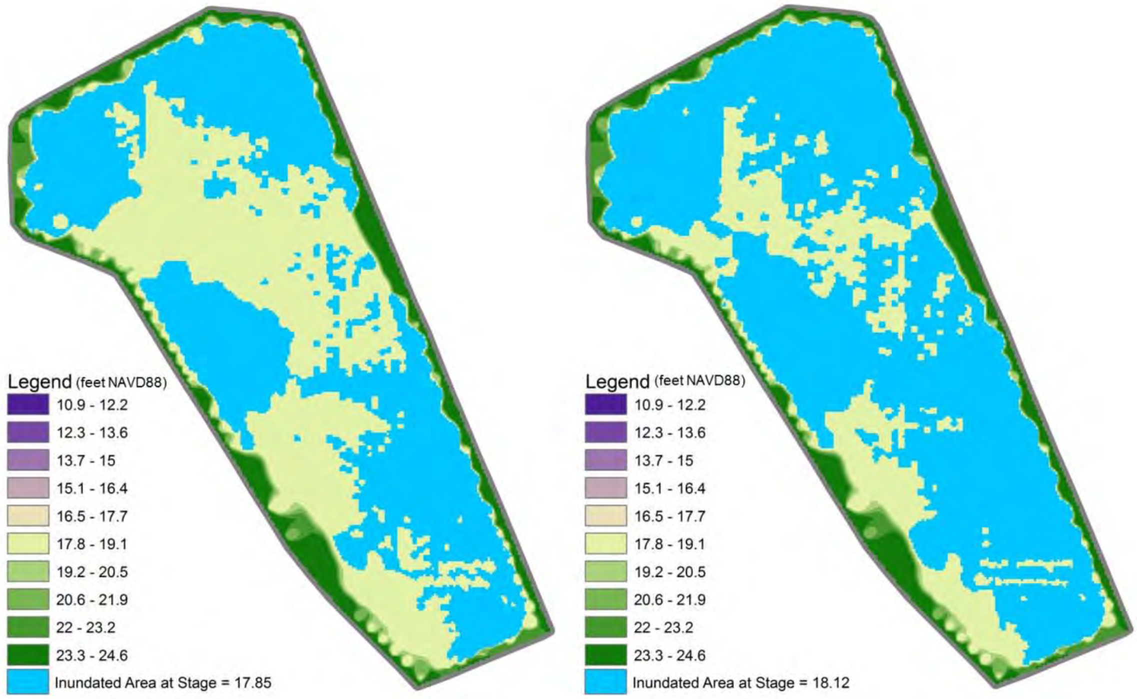

Figure 16. Inundated area before (left) and after (right) the storm event on March 12th, 2010

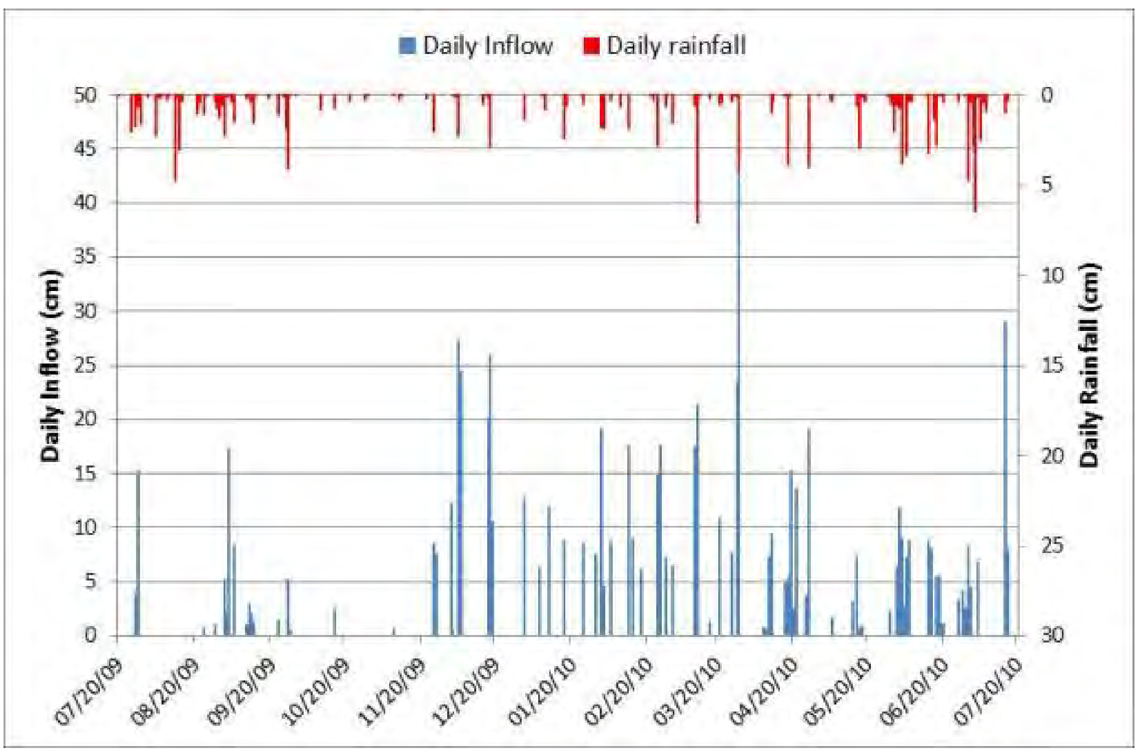

Figure 17. Daily rainfall and flow at Pump 1.

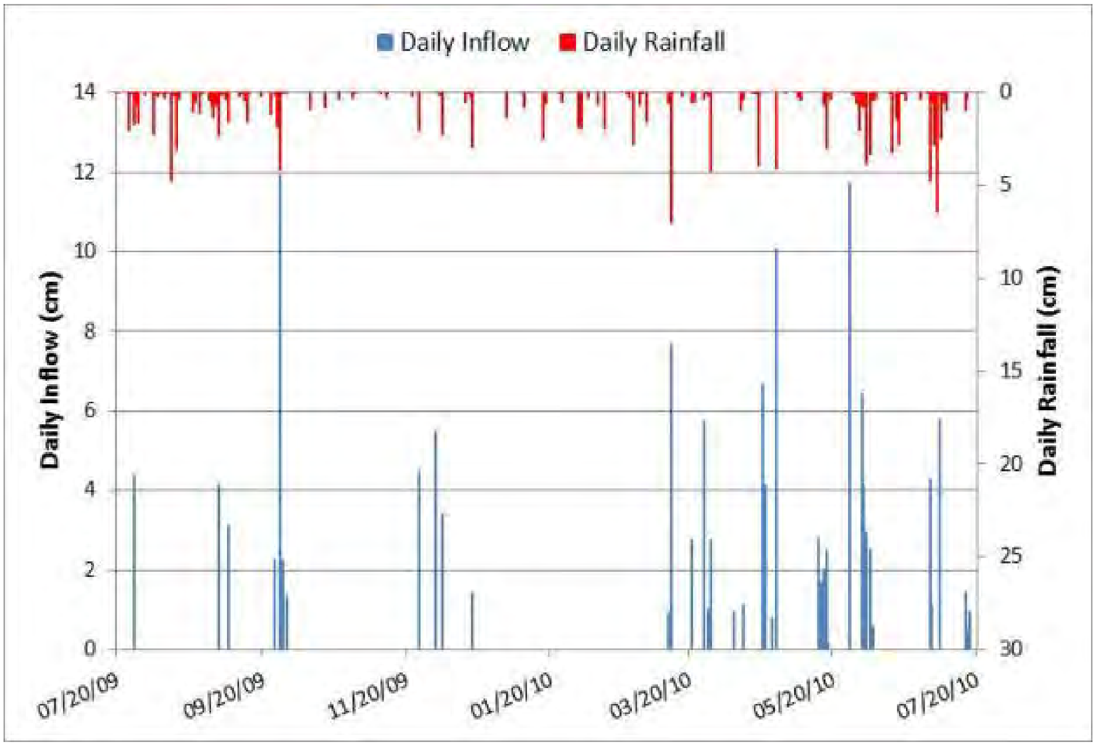

Figure 18. Daily rainfall and flow at Pump 2.

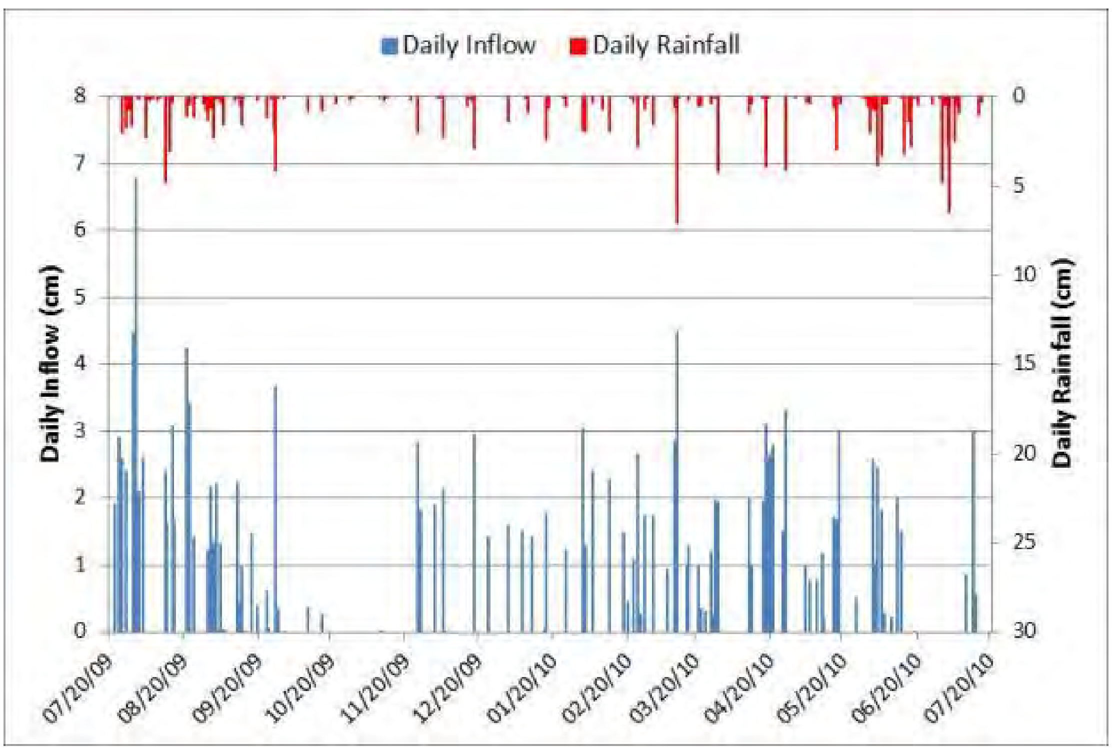

Figure 19. Daily rainfall and flow at Pump 3.

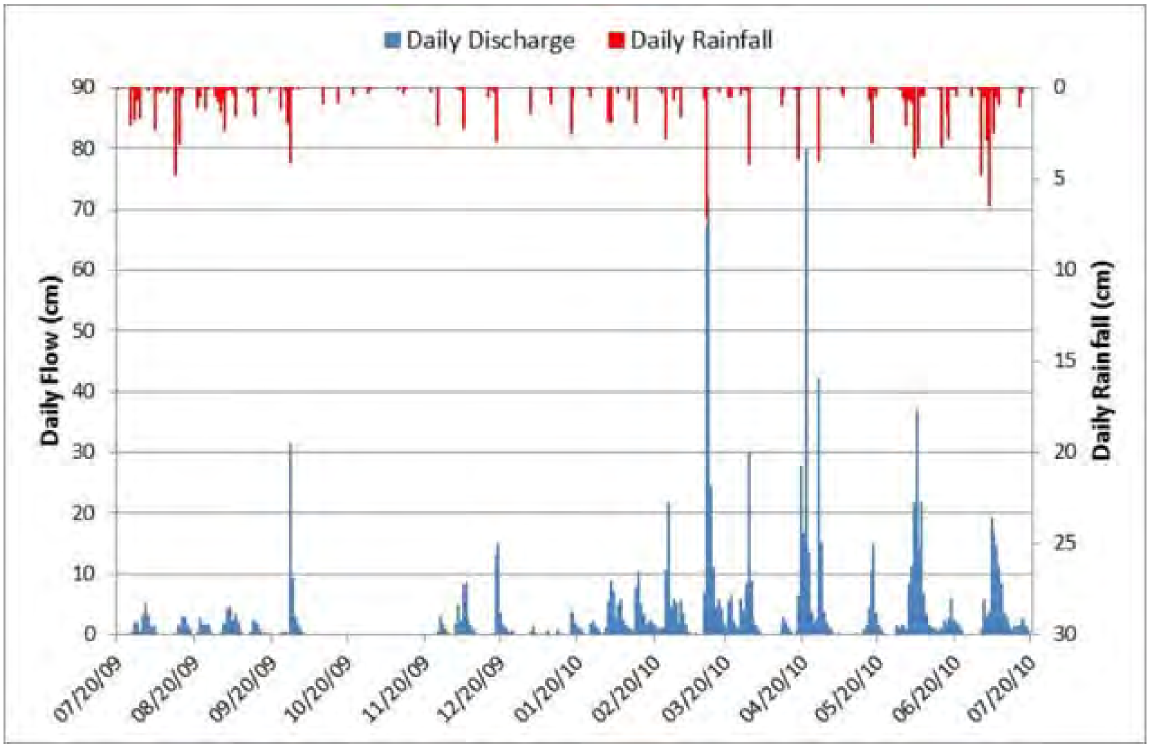

Figure 20. Daily rainfall and flow at the discharge site.

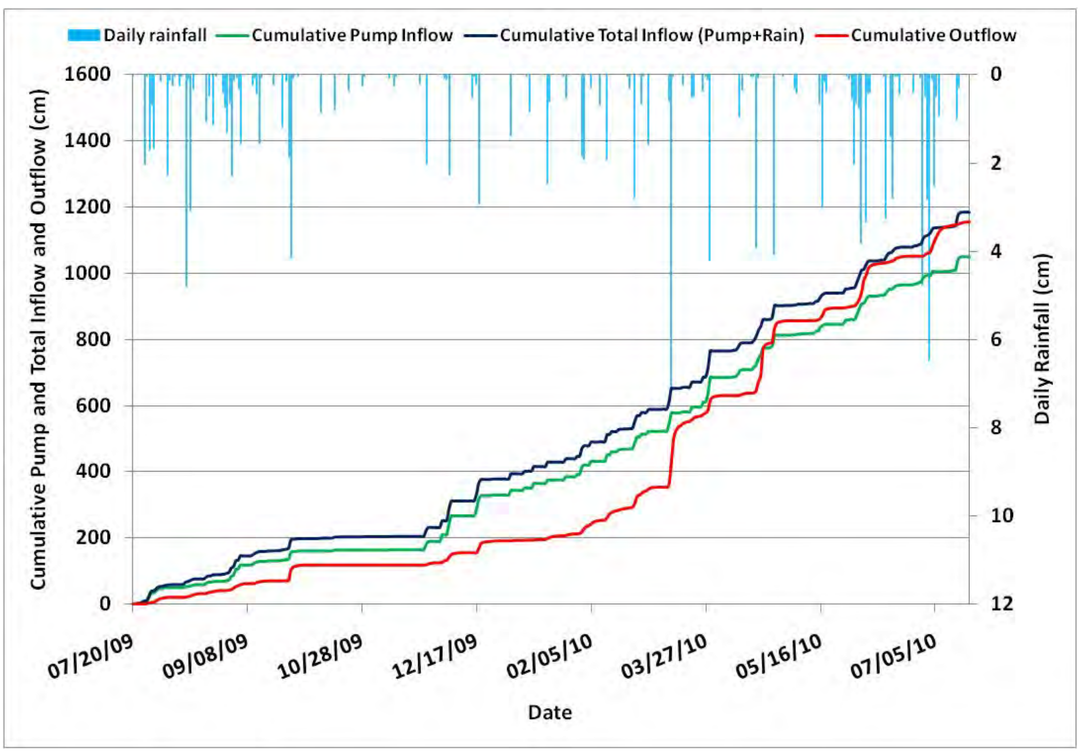

Figure 21. Daily rainfall and cumulative pumped inflow, total inflow (pumped inflow + rainfall), and outflow.

The annual water balance for the AGI presented in Table 5 shows that of the total inflow (three pumps + rainfall), pump 1 contributed approximately 65% of the total input while pumps 2 and 3 contributed 25%. Rainfall accounted for 10% of the total inflow. Discharge was responsible for 91% of the measured total outputs while ET (RET) accounted for the rest. Change in storage within the AGI was calculated to be 0.06% so was deemed to be negligible. The water balance indicated that losses were 7% higher than inputs; these higher losses could be due to uncertainties in estimating the ET, inflows, and discharge as well as unaccounted groundwater fluxes. It should be noted that the ET losses presented in Table 5 are reference ET values which are likely to be different from actual ET. Accurate estimation of ET will require vegetation specific coefficients which are not currently available for all the vegetation types in the AGI.

3.3 Phosphorus Dynamics

3.3.1 Total Phosphorus Concentration

The inflow TP concentrations presented in Figure 22 and Figure 23 show a large variability in concentrations for pumps 1 and 2. The highest concentrations for pumps 1 (11,484.4 μg/L; July 15, 2010) and 2 (9536.0 μg/L; July 16, 2010) were observed towards the end of the monitoring period. Potential causes of such high concentrations could be the pumping for the ditch cleaning (observed by staff on July 14, 2010, but likely performed over various days) and drainage (due to 1.3 cm rainfall during July 15-16, 2010). Ditch cleaning is an agricultural BMP needed to maintain the conveyance capacity of the drainage ditches (Shukla et al., 2010). Ditch cleaning was conducted in July due to the nature of the vegetable operation and length of the growing season (Sep-June). Availability of personnel and the presence of crops during the September-June period made it difficult for the grower to conduct ditch cleaning during the recommended period. Given the observed P loading into the AGI because of the scheduling of this operation, the BMP would be to conduct ditch cleaning during quiescent conditions or in conjunction with irrigation (Diaz, O. A. et al., 2005).

High concentrations were not observed on the east side of the AGI which could be due to the use of drip irrigation resulting in less nutrient runoff volume as well as P leaching (Figure 24).

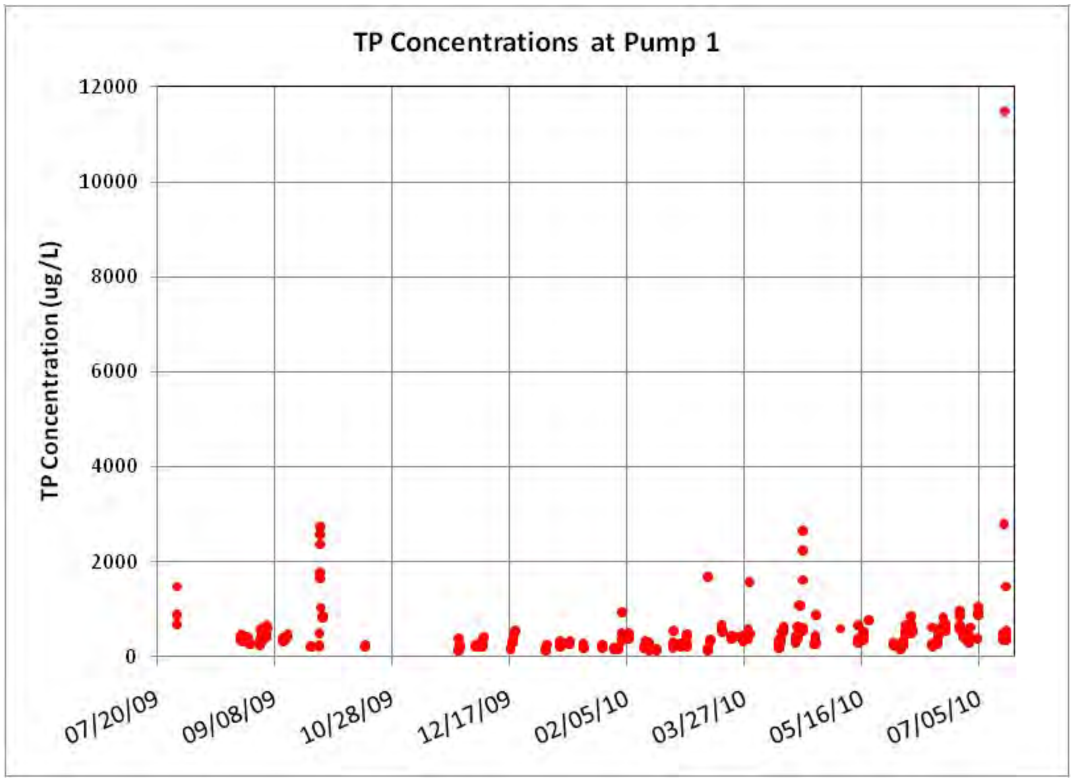

Figure 22. Total phosphorus (TP) concentrations at Pump 1.

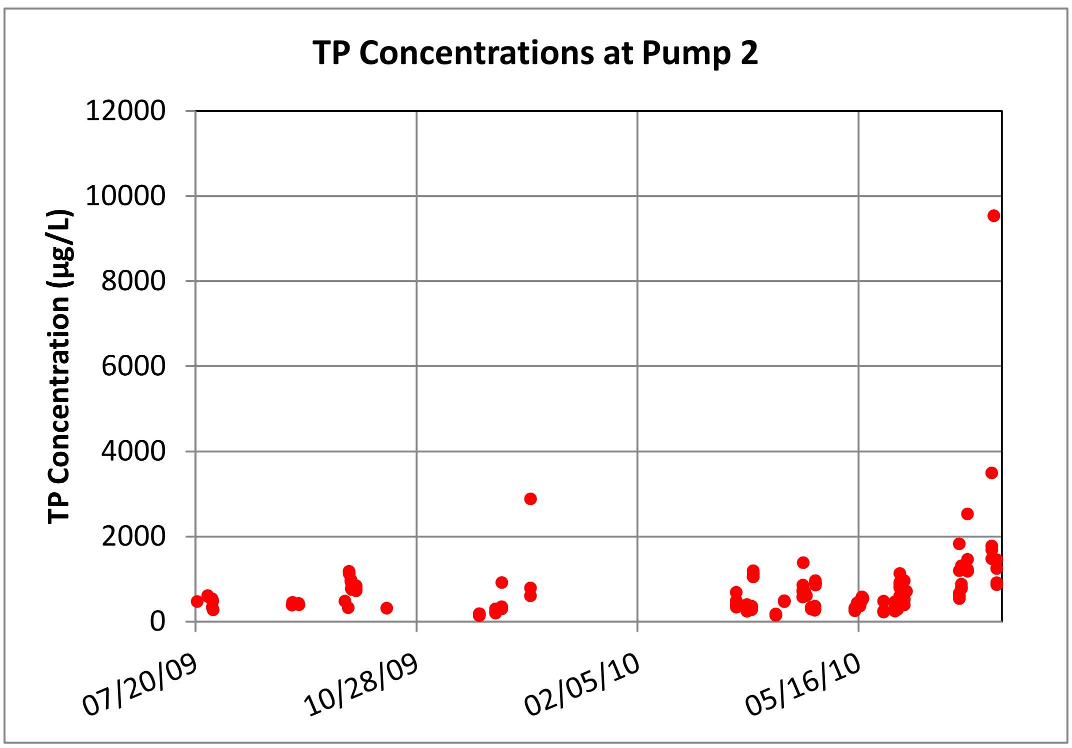

Figure 23. Total phosphorus (TP) concentrations at Pump 2.

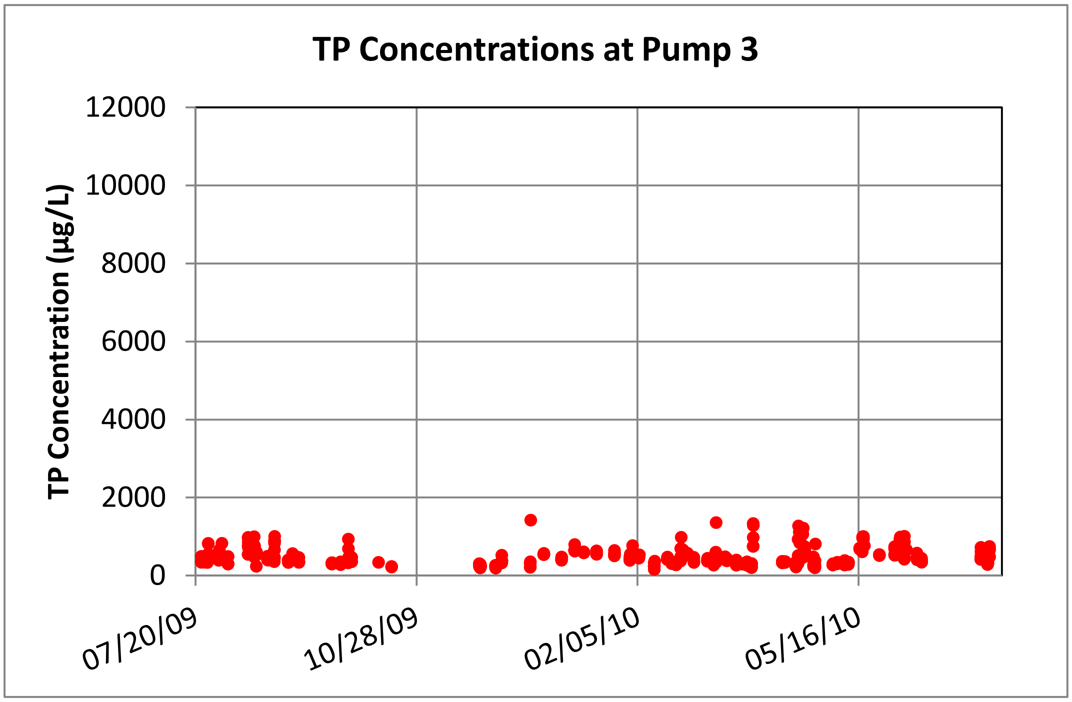

Figure 24. Total phosphorus (TP) concentrations at Pump 3.

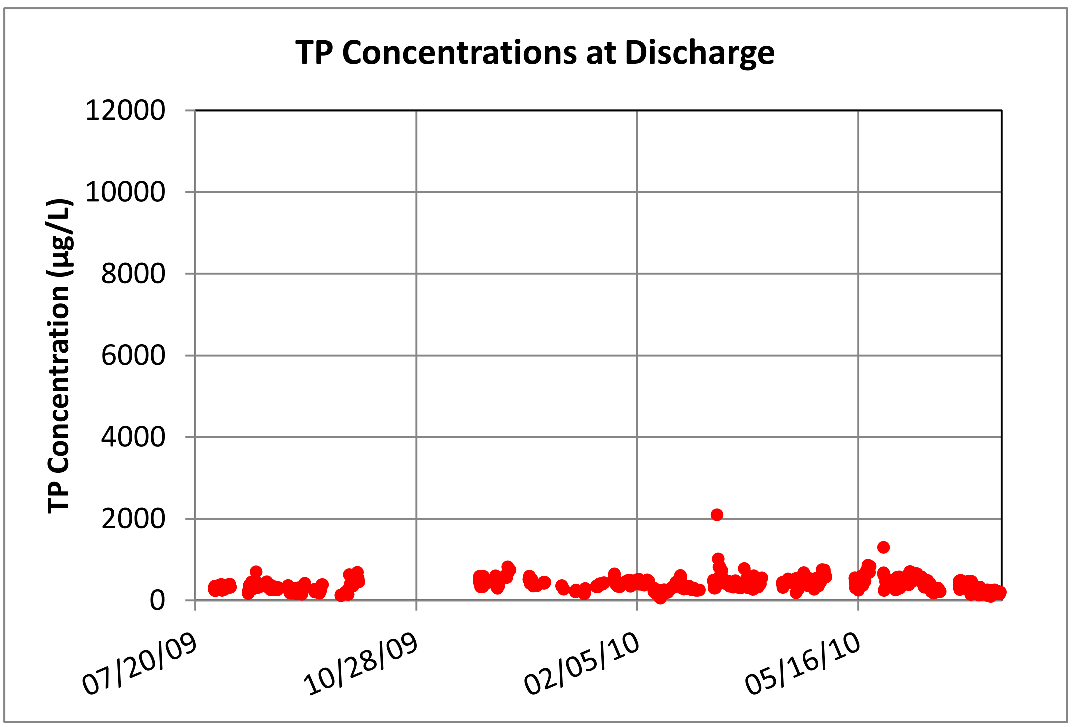

Figure 25. Total phosphorus (TP) concentrations at the discharge site.

The maximum TP concentration observed at pump 3 (1423 µg/L, December 18, 2009) was much lower than those in pumps 1 and 2. The time series of TP concentrations show that all but one sample for pumps 1 and 2 had concentrations below 4000 µg/L.

All the samples taken from Pump 3 had TP concentrations below 2000 µg/L. The variability in TP concentrations for pumps 1 and 2 that drained the seepage irrigated fields was higher than in pump 3. This may be due to the relatively higher rate of P leaching from the seepage irrigated fields compared to the drip irrigated fields (pump 3) and the relatively longer run time and volume (compared to pump 3). The high TP concentrations observed towards the end of the wet period in 2009, could potentially be due to higher water table maintained for crop establishment purposes. Despite several instances of high concentrations observed for pumps 1 and 2, the descending order for the average TP concentrations for the three pumps was pump2 > pump 3 > pump1 (Table 6). The maximum TP concentration (2102 µg/L) at the discharge site occurred a day after the highest rainfall (7.1 cm, March 12, 2010). The second highest discharge concentration of 1022 µg/L (multiple samples taken on the same day due to discrete sampling) also occurred on the same day. The likely cause of these high discharge concentrations was that the AGI was at its maximum storage point and passed most of the incoming TP without much treatment. The daily average water level of 19.4 ft observed on March 13 was the maximum during the study period. Another cause of such high TP concentration could be the transport of P deposited from earlier drainage events and/or mineralized soil and plant P. Such high levels of TP at the maximum storage seem to suggest that particulate P from the pumped drainage may not have had enough residence time to facilitate settling. The analyses from grab samples collected for two events at the inflow and outflow locations indicated that the average particulate P concentration at the discharge site was 17% of the TP while it was 33% for the pumped inflow. Part of the particulate P from the pumped inflow may have passed without settling on March 13 due to short circuiting and high turbulence in the AGI due to longer than normal pump run time to accommodate large drainage required for such a high rainfall event. Note that during this period, pumps were operated at lower RPMs (2400-2700) rather than at the maximum RPM (3500) observed during the study period.

Table 6. Maximum, minimum and average total phosphorus (TP) concentrations for pumps 1, 2, and 3, and discharge. Standard deviation and number of samples for each monitoring site are also included.

SITE	TOTAL PHOSPHORUS (µg/L)				NUMBER OF SAMPLES
	MAXIMUM	MINIMUM	AVERAGE	STANDARD DEVIATION	
PUMP 1	11,484	121	460	640	429
PUMP 2	9,536	140	678	817	176
PUMP 3	1,423	160	489	205	448*
DISCHARGE	2,102	60	368	148	857

* The number of samples for pump 3 are higher than other pumps because this pump was operated more frequently during earlier part of the study when the frequency of sampling was higher than the later part of the study. Due to

the implemented sampling strategy more samples are taken when the pump is initially turned on. Pump 3 was turned on often, but operated for shorter duration resulting in a quantity of samples comparable to Pump 1.

3.3.2 Total Phosphorus Loads

In contrast to the cumulative water fluxes (the inflow being almost the same as the outflow), the cumulative outflow TP flux was less than the inflow TP flux indicating that the AGI was effective in treating the P. The time series for the inflow TP loads for the three pumps show that pump 1 contributed almost two-thirds of the total inflow TP loads (Figure 26 and Table 7). Percent contributions of TP loads from pumps 1, 2, and 3 were 73%, 14%, and 13 %, respectively. The rainfall input of TP, calculated using a TP concentration of 10 ppb was relatively small and can be ignored (Table 7). The 10 ppb value was selected based on the mean rainfall TP concentration of 9.5 and 9.4 ppb reported by Ahn (1998) and Ahn and James (2001) for South Florida. Of the total inflow TP loads (1040 kg), wet (7/20/2009 – 10/31/2009 and 6/1/2010 – 7/19/2010; 529 kg) and dry season (11/1/2009-5/31/2010; 511 kg) contributions were similar (the terms "wet season" and "dry season" used here refer to the typical wet and dry periods normally experienced in South Florida). However, for the outflow TP loads, the dry season loads accounted for 76% (637 kg) of the total annual load (838 kg). Higher percent TP outflow loads during the dry season were mainly due to the fact that dry season water outflows were 66% of the annual outflow.

Table 7. Total phosphorus (TP) loads for pumps 1, 2 and 3 and the discharge structure.

		TOTAL TP LOAD (kg)	% TOTAL INPUT
INPUTS	PUMP 1	757	73
	PUMP 2	151	14
	PUMP 3	133	13
	RAINFALL	2	0.2
	TOTAL	**1043**	**100**
LOSSES	DISCHARGE	838	80

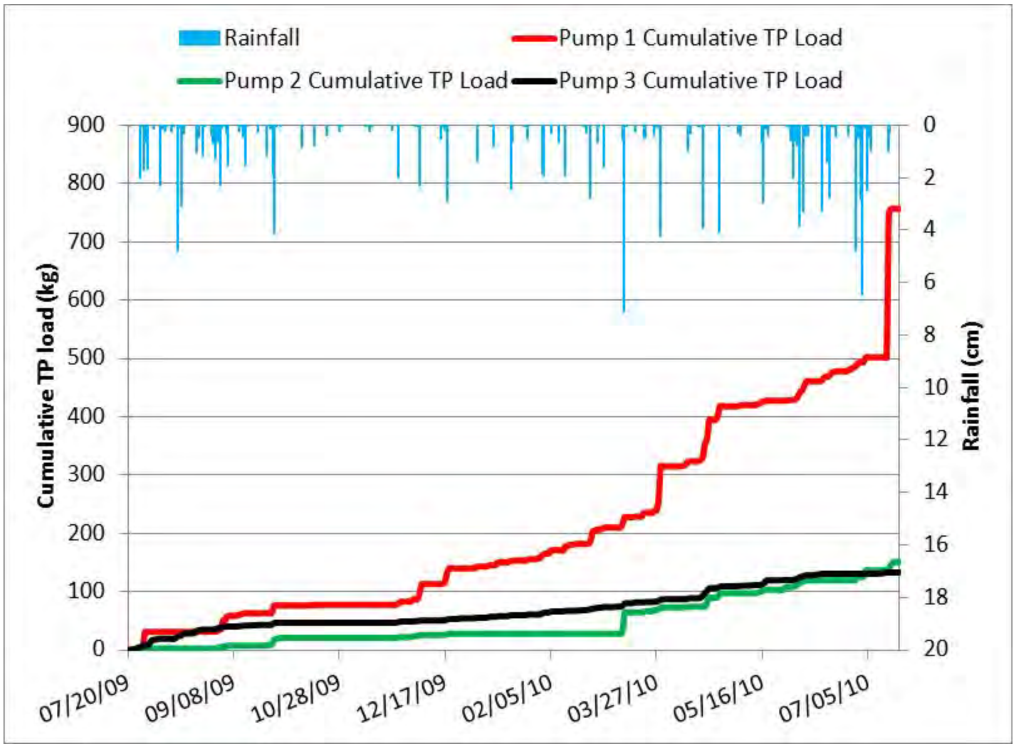

Figure 26. Daily rainfall and cumulative total phosphorus (TP) inflow load at pumps 1, 2 and 3.

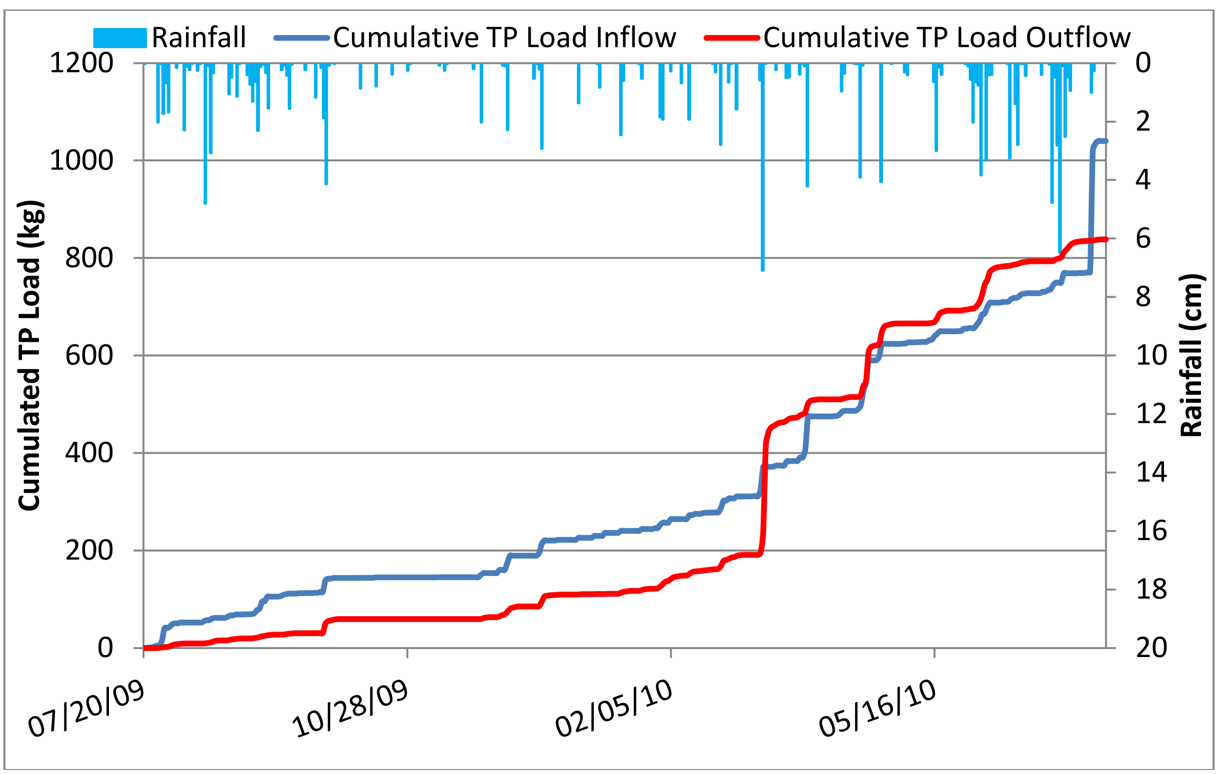

Figure 27. Daily rainfall and cumulative total phosphorus (TP) inflow load and cumulative TP outflow load.

The maximum one day inflow load of 249 kg (24% of annual inflow load) occurred on July 15, 2010, the day the ditch cleaning was observed. Almost all of this maximum TP load was contributed by pump 1 (245 kg). For pump 3, the maximum TP inflow load occurred on July 31, 2009, which was mainly in response to the 6.2 cm rainfall which occurred between July 25-30, 2009. The maximum TP inflow load for pump 2 (32.7 kg) on March 12, 2010, coincided with the day of the maximum daily rainfall (7.1 cm). The maximum one day outflow TP load of 178.4 kg occurred on March 13, 2010, a day after the maximum daily rainfall. This was due to the earlier stated reasons of the highest outflow TP concentrations combined with the second highest daily outflow (71.5 cm) and inflow volumes (40.5 cm) and the highest water levels inside the AGI. The highest outflow TP load on the day after the maximum rainfall and the high TP inflow loads indicate that most of the TP inflow loads passed through the AGI without much retention. A close examination of the March 12-13, 2010, event indicates that the flow at the discharge structure started on March 12, 2010, and continued until April 3, 2010 (Figure 20). During this period, a total of 163.5 kg of the TP (16% of annual inflow load) was pumped into the AGI while the TP discharge was 319 kg (38% of the total annual outflow load) indicating that the AGI was not effective in retaining the TP. These high outflow TP loads were mainly due to: (a) the AGI had almost no available storage; (b) the drainage P accumulated inside the AGI prior to March 12; and (c) the transport of soil and plant derived P. High outflow TP loads discharging from an AGI with very little available water storage capacity could partly be due to short-circuiting of the flow pathways from inflow to outflow which reduced the retention of P, especially particulate P. Note that pump 2, located closest to the discharge structure, was operated during the March 12-13 period. Similar trends were also observed during other periods of high rainfall (e.g. 4/11/2010 – 5/02/2010). Examination of inflow and outflow loads indicated that the AGI was less effective in retaining TP after large rainfall events. Increasing the residence time of the pumped inflow in the AGI may reduce the TP outflow and increase its treatment efficiency.

Overall, the annual outflow TP load (838 kg) was less than the inflow TP load (1042 kg) indicating that on an annual basis, the AGI was effective in treating the TP. The treatment efficiency (Equation 1) for the AGI was 20% and the unit area TP treatment in the AGI was 14 kg/ha (Figure 28). The observed treatment efficiency of the AGI appears to be less than the efficiency reported for the urban detention area and constructed wetlands (USEPA, 1999; Middleton and Barrett, 2008). Predominance of subsurface flows (drainage) in the cropped areas of South Florida compared to predominantly overland flow in the urban areas could be one of the possible reasons for relatively lower particulate P and treatment efficiency for the agricultural AGI compared to urban detention areas.

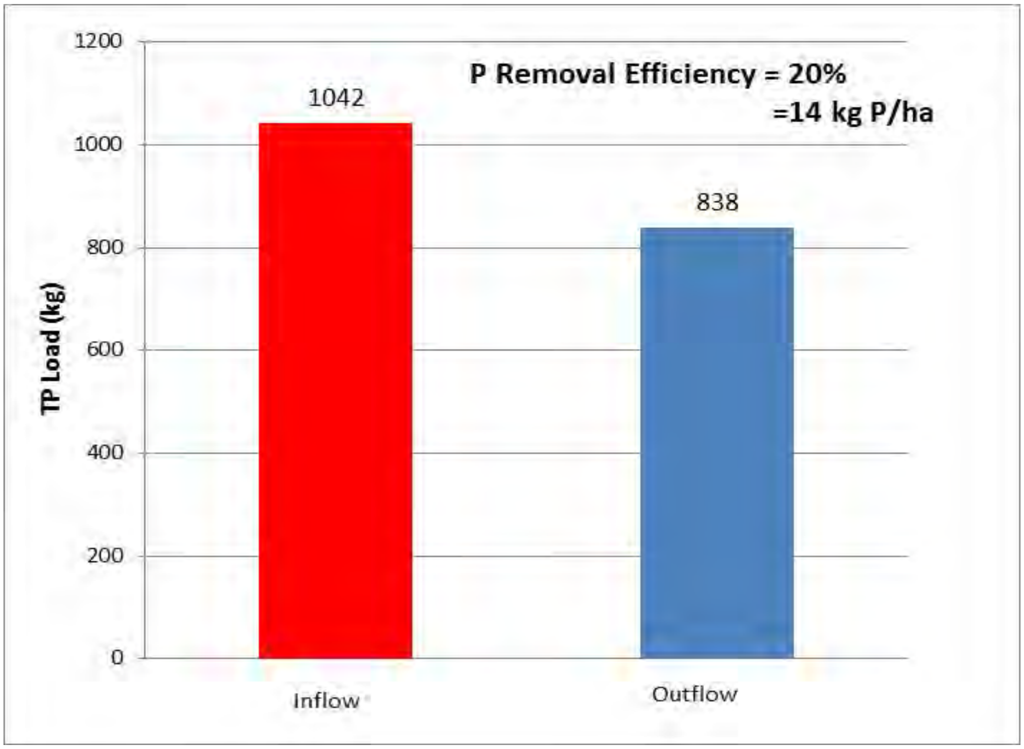

Figure 28. TP load inflow and outflow with estimated P removal efficiency.

3.4 Soil and Plant Phosphorus

3.4.1 Soil Phosphorus

Results from soil sample analyses show that the AGI currently contains considerable TP stored in the soil and limited capacity to store additional P contributed from the drainage inflows. The soil samples collected before the hydrologic and water quality monitoring period for the surface (0-10 cm) and subsurface (10-20 cm) depths were analyzed for M1P, M1Al, M1Fe and soil TP to calculate the total soil P storage as well as the P storage capacity (SPSC) of the AGI (Table 8). Additional analyses included percent organic matter (OM) and bulk density (BD). Soil samples taken at the end were only analyzed for TP in order to evaluate changes in P content and soil P storage during the monitoring period. The sample numbers (SN) in Table 8 correspond to the sample IDs shown in Figure 13. The M1P, M1Fe, and M1Al represent the analyses results obtained from the Mehlich-1 soil extraction procedure to determine the amounts of P, Al, and Fe for the mineral soil. Analyses of M1Fe and M1Al facilitate the calculation of SPSC since Fe plus Al is used as a surrogate for the amount of P a soil can retain. The SPSC accounts for P loss risks arising from previous loading as well as inherently low P sorption capacity and provides a direct estimate of the amount of P that a soil can store before exceeding a threshold soil equilibrium concentration (Nair et al., 2010).

Table 8. Mehlich-1 P (M-1P), Mehlich-1 Al (M1-Al), Mehlich-1 Fe (M1-Fe), total phosphorus (TP), soil P storage capacity (SPSC) concentrations, organic matter, and bulk density for the soil (0-10 and 10-20 cm) samples ("Beg" = samples taken at beginning of monitoring, "End" = samples taken at end of monitoring).

*S N**	*M-1 Fe (0-10)* mg/kg	*M-1 Al (0-10)* mg/kg	*M-1 P ((0-10)* mg/kg	*M-1 Fe (10-20)* mg/kg	*M-1 Al (10-20)* mg/kg	*M1-P (10-20)* mg/kg	*TP (0-10)* mg/kg	*TP (0-10)* mg/kg	*TP (10-20)* mg/kg	*TP (10-20)* mg/kg	*OM (0-10)* %	*BD* g/cc	*SPSC (0-10) mg/kg*	*SPSC (10-20) mg/kg*
	Beg	**Beg**	**Beg**	**Beg**	**Beg**	**Beg**	**Beg**	**End**	**Beg**	**End**	**Beg**	**Beg**	**Beg**	**Beg**
1	3.11	286.80	56.04	2.60	336.00	63.68	145.60	237.03	162.60	164.49	1.75	1.61	-6.39	-5.60
2	5.79	183.60	59.84	10.06	265.20	36.72	181.90	275.02	154.10	86.36	4.83	1.61	-27.74	9.79
3	5.27	408.40	70.00	4.22	380.00	59.08	248.00	301.54	185.80	25.52	3.04	1.60	0.77	6.71
4	4.75	149.20	40.56	4.63	88.28	14.17	177.00	127.03	69.37	1291.66	4.68	1.60	-14.47	1.42
5	6.66	184.50	104.50	6.95	52.08	12.00	234.00	240.73	52.49	43.34	5.71	0.91	-72.17	-2.45
6	5.46	148.00	51.84	5.34	105.60	21.12	156.50	138.25	125.50	74.43	4.18	1.61	-25.90	-2.49
7	4.41	149.40	119.90	13.09	108.20	42.76	126.60	223.14	130.00	119.83	3.65	1.61	-93.80	-23.04
8	4.64	121.10	50.08	11.21	113.50	39.20	375.60	379.27	156.10	120.62	3.58	1.61	-28.84	-18.72
9	4.44	82.12	7.79	3.38	31.72	1.51	94.00	147.63	102.90	14.88	2.79	1.61	6.72	4.23
10	2.25	66.12	17.54	6.40	35.84	2.77	125.70	55.20	37.96	15.10	2.80	1.61	-5.97	3.93
11	4.24	48.48	5.44	7.91	41.44	10.20	231.90	58.80	22.32	15.70	3.75	1.60	3.26	-2.41
12	3.99	91.80	60.08	11.64	150.60	32.16	423.80	55.71	104.80	53.20	4.57	1.60	-43.94	-5.26
13	3.18	49.68	10.50	13.65	69.24	3.33	47.08	84.85	0.00	14.90	3.01	1.18	-1.68	9.73
14	7.31	184.90	131.80	7.11	62.12	6.30	245.20	391.23	41.96	19.58	8.40	0.91	-99.35	4.99
15	1.54	285.20	31.16	1.80	653.60	4.66	610.20	1274.73	359.80	751.54	53.25	0.60	18.09	108.05
16	2.13	38.12	50.44	4.96	29.72	2.74	122.30	61.85	18.80	6.96	3.69	1.60	-43.70	2.79
17	24.16	63.40	7.18	66.44	63.40	1.70	72.82	89.53	42.74	43.93	3.48	1.60	5.75	14.74
18	23.88	64.56	10.91	9.94	204.40	12.05	55.46	287.12	68.55	104.97	1.07	1.61	2.19	23.98
19	23.36	72.68	15.40	18.99	67.84	2.41	52.69	251.76	16.61	19.05	2.83	1.61	-0.94	10.85
20	7.29	388.80	35.68	11.96	673.20	12.52	163.60	206.15	63.68	123.07	5.89	0.90	31.89	104.41
21	4.66	208.40	12.07	9.84	352.40	23.44	100.60	107.28	16.44	69.39	2.91	1.61	24.21	38.07
22	0.00	2.78	3.83	0.00	11.19	0.26	3518.00	NS	2072.00	NS	61.82	0.60	-3.35	1.67
23	3.08	120.90	16.85	9.41	166.00	5.94	45.65	133.11	44.19	41.67	1.21	1.61	4.23	23.43
24	7.09	361.20	33.28	8.51	144.80	12.92	139.80	234.01	54.83	93.98	4.90	0.90	29.52	12.72
25	1.05	223.60	30.80	12.27	290.80	12.51	390.00	344.69	167.90	170.10	10.49	1.18	7.80	38.59
26	0.47	417.60	108.80	0.45	670.80	117.90	398.70	376.72	355.20	153.59	4.90	0.90	-36.84	-2.34
Average	**6.32**	**169.28**	**43.94**	**10.11**	**198.77**	**21.31**	**326.26**	**243.30**	**177.95**	**145.51**	**8.20**	**1.36**	**-14.26**	**13.76**

* The sample numbers (SN) correspond to the soil sampling location IDs shown in Figure 13. NS – no sample taken because the area was inaccessible due to dense vegetation, depth of water and safety concerns for sampling personnel.

The soil BD and OM were somewhat uniform with the exception of few locations where the surface layer mostly contained organic matter. The average OM and BD for the AGI were 8.20 % and 1.36 g/cc, respectively. The OM varied from 1.07 (mineral soil) to 61.82 (organic layer, muck) % while the BD varied from 1.61 to 0.60 g/cc. At the beginning of the monitoring period, TP concentrations for the surface soil showed high variability (45.65 to 3518.00 mg/kg) with an average of 326.26 mg/kg indicating that the AGI contained considerable P. At the end of the monitoring period, the average TP concentrations were 243.30 mg/kg indicating a reduction in average TP levels in the AGI. To include the BD effect on soil TP storage, the amount of TP contained in the AGI was calculated. The soil TP concentrations and BD at 26 locations were spatially extrapolated using the inverse distance weighting (IDW) technique for estimating the mass of TP contained within the AGI. The amount of pre and post monitoring TP in the surface layer of the AGI was 5955 kg and 4519 kg, respectively, indicating that there may be a net decrease in the TP levels in the AGI. The change in soil TP may be a result of the spatial variability (before and after sampling points not at the same location) in the soil TP concentrations and unavoidable errors involved in extrapolating the TP and BD values for the entire AGI. Overall, the average mass of the TP in the soil was 351 kg/ha indicating that the soil contained considerable P. Although the TP values may seem high, it does not necessarily indicate the potential transport of all of the P through discharge since part of P in the soil will be immobile. Given the 20% treatment efficiency of the AGI, it is likely that part of the P retention may have been provided by the surface and subsurface soils. To evaluate the potential of the AGI soil to retain P, the M1P, M1Fe, M1Al, and SPSC were used.

The M1P concentrations in the surface soils varied from 3.83 to 131.80 mg/kg with an average of 43.94 mg/kg. The observed average M1P concentration in the surface soil would be termed as “high” according to the UF/IFAS P fertilizer recommendation for vegetable production (Simonne and Hochmuth, 2010) meaning that if such high M1P levels existed in the production areas, it would not require additional P fertilizer application. The mention of “high” category here is only for the purposes of comparison with production soils. Although the AGI does not include cropped areas, the M1P concentrations may be high enough for optimum growth for some or all of the plant species that grow inside the AGI. Average concentrations of M1Fe and M1Al in the surface soil, surrogates of soil P retention, were 6.32 and 169.28 mg/kg, respectively, indicating soil’s ability to retain P. However, the SPSC values indicated that most of the surface soils (0-10 cm) had a negative SPSC (average = -14.26 mg/kg) indicating that the P retention capacity of these soils may have already been utilized by long-term loading of P since the AGI has been in use for more than 20 years.

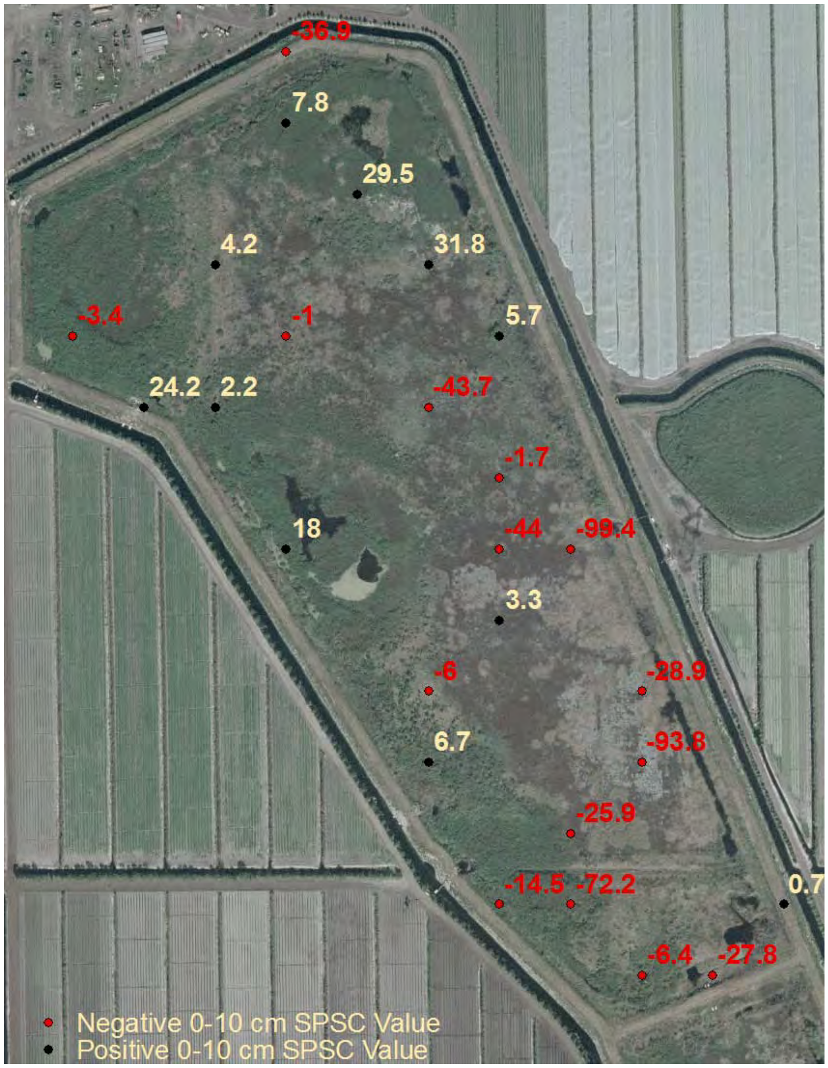

Figure 29. Soil sampling locations and corresponding 0-10 cm soil phosphorus storage capacity (SPSC) values.

Almost 60% (15 out of 26 samples) of the SPSC values associated with top 10 cm of soil were negative indicating that there is limited to almost no P adsorption capacity left in the soil at that depth (Table 8, Figure 29). The soil near these sampling locations may behave as a P source rather than sink which may partly explain the low P removal efficiency of 20%. The average phosphorus saturation ratio (PSR) was 0.45 at these locations compared to a value of 0.10 at the locations with positive SPSC values. Average value of M1P at the locations with negative SPSC values was 59 mg/kg which is higher compared to a mean value of 23 mg/kg at the locations with positive SPSC values. Comparison of inundation areas at the onset of discharge (water level in the AGI = top of the weir) with the surface soil SPSC values (Figure 30) shows that the majority of the sites with negative SPSC values for the surface soils occur in the areas that are inundated. Seven of the nine samples closest to the discharge structure have negative SPSC values. This is likely due to the fact that: a) flows from the three pumps are mixed towards the end of the AGI before being discharged; and/or b) drainage with higher dissolved and particulate P that reaches the discharge site through short circuiting of the flow pathways passes through the end section of the AGI which results in settling of P before the discharge structure. It should be noted that lower SPSC values near discharge location may be due to long-term operation of this AGI and not necessarily the effect of the pump operation during the study period. Four out of 11 positive SPSC values occur near or within the areas that are not inundated at the discharge stage (Figure 30). Overall, SPSC values indicate that most of the AGI in the top layer (0-10 cm) has limited capacity to retain additional dissolved P from the drainage and there appears to be a relationship between the inundation characteristics (areas, frequency of inundation, and hydroperiod) and the P retention in the surface soils.

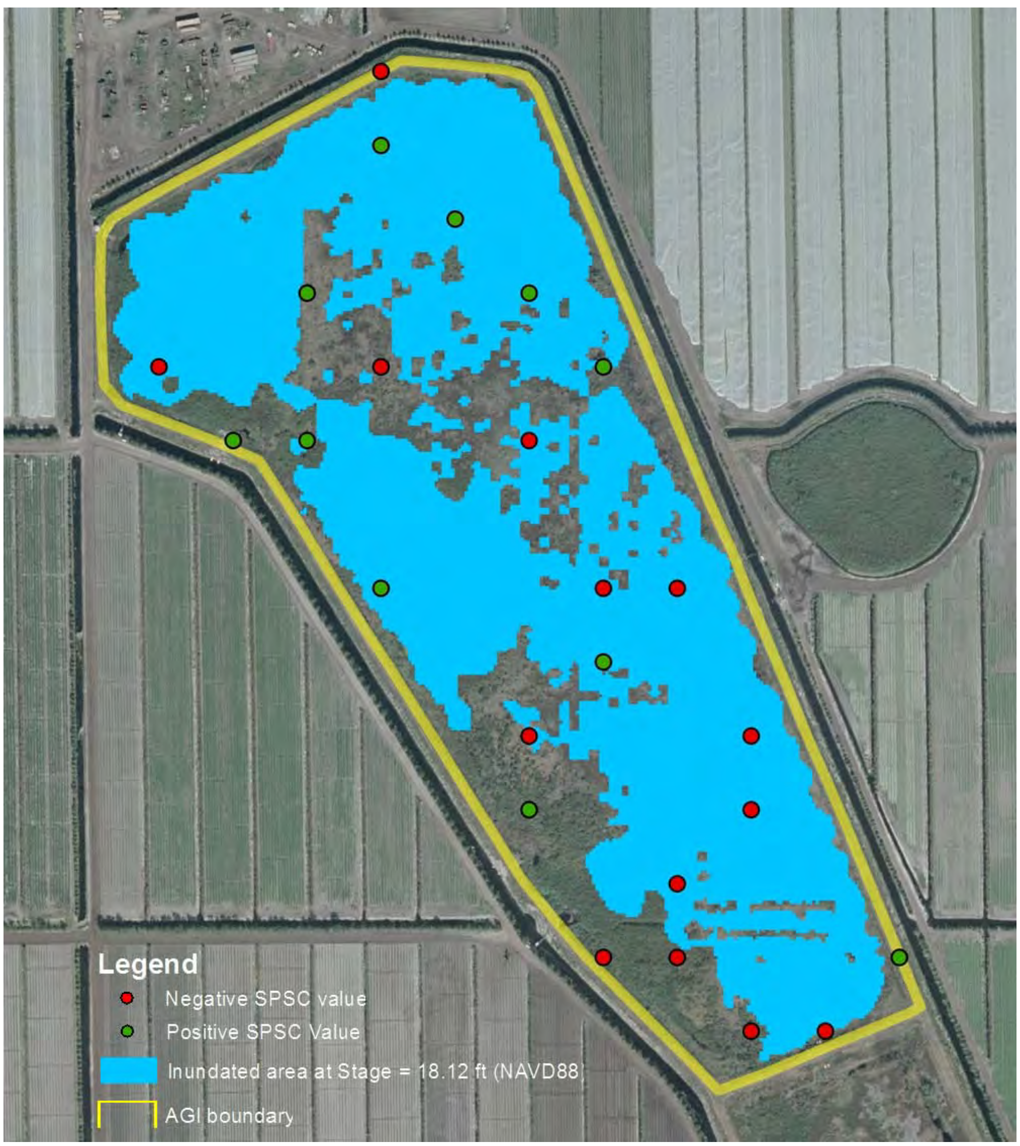

Figure 30. Soil phosphorus storage capacity (SPSC) values at the discharge stage.

In contrast to the surface soils, subsurface (10-20 cm) soils have relatively higher SPSC values. Approximately 70% of the sampled sites (18 out of 26) have positive SPSC values (Figure 31, Table 8) which shows that there is a P adsorption potential in this layer. However, locations near the discharge structure have negative SPSC values, similar to that observed for the surface soils. Saturation of P adsorption sites toward the end of the AGI may likely be due to the subsurface movement of dissolved P and higher inundation frequency for this area. Overall, there is considerable soil P retention left in the subsurface soil within the AGI.

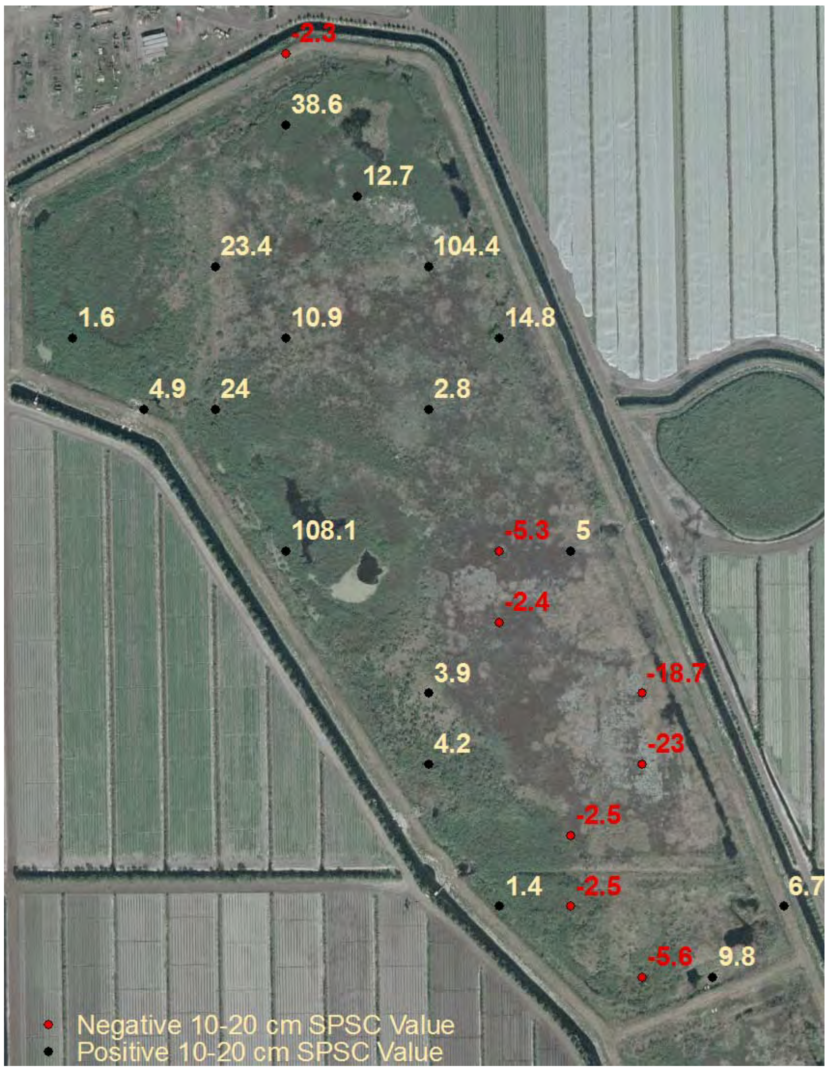

Figure 31. Soil sampling locations and the corresponding 10-20 cm soil phosphorus storage capacity (SPSC) values.

In summary, there exists a relationship between spatial variation of SPSC values in the surface and subsurface soils and the inundation characteristics. This relationship can be used to enhance the P treatment efficiency by routing the water through the areas with positive SPSC values, i.e. changing the present route of the water and forcing it to flow through the areas where there is a potential to adsorb P.

3.4.2 Plant Phosphorus

The P content of the above-ground biomass within the AGI varied according to the vegetation type. The AGI contained five dominant categories of vegetation located in different soil-hydrologic regions: mixed grass (torpedo grass - *Panicum repens* and smartweed - *Polygonum hydropiperoides*); primrose willow (*Ludwigia peruviana, Ludwigia* spp.); water lettuce (*Pistia stratiotes*); Carolina willow (*Salix caroliniana*); and cattails (*Typha* spp.). Part of the AGI contained low to sparse vegetation (mostly mixed grass). The mixed grass vegetation covered the highest fraction of the AGI area (approximately 50%) followed by water lettuce (approximately 17%). Among the five types of vegetation, the P concentration of water lettuce was highest (4531 mg/kg) while for cattails (1563 mg/kg) it was lowest (Table 9). Almost all of the water lettuce and majority of cattails were located outside the jurisdictional wetlands. Mixed grass vegetation accounted for the highest estimated biomass P storage (111 kg) in the AGI, mostly due to the highest area under this vegetation. Highest P concentration combined with second highest area resulted in 60 kg of estimated P storage for the water lettuce. Carolina willow accounted for 45 kg of P followed by primrose willow (15 kg) and cattails (9kg). The total estimated above-ground biomass P storage in the AGI was 240 kg. This estimate is likely to be conservative since the below-ground biomass (plant roots) was not considered.

Aquatic macrophytes such as water lettuce and cattails grow naturally in the nutrient rich water and have the ability to create a thin aerobic layer around the root zone by the translocation of oxygen from the leaves to the roots (Vyazamal, 2007). This property makes them effective in removing P agricultural and urban areas. Studies have shown that aquatic macrophytes can remove 40 to 55% of the total N load and 40 to 60% of the total P load depending on the type of system and inflow loads (Vymazal, 2007). Emergent macrophytes (e.g. torpedo grass, smartweed, primrose willow, Carolina willow and cattails) have been shown to be an effective avenue for removing P. Brix (1997) reported that harvesting of emergent macrophytes can remove approximately 30 to 150 kg P/ha/year. The floating macrophytes (e.g. water lettuce), have a higher uptake capacity of about 350 kg P/ha/year and 2000 kg N/ha/year (Brix, 1997). The biomass P storage in the AGI indicates that harvesting of the biomass from non-jurisdictional wetland areas has the potential to remove significant P from the AGI.

Table 9. Vegetation type, location, TP concentration, and above-ground biomass P storage.

Vegetation Category and Location	Plant Species	TP Concentration (mg/kg)	Above-ground Biomass TP* (kg)
Mixed Grass (Jurisdictional and non-jurisdictional wetland and other areas)	Torpedo grass (-*Panicum repens*) and Smartweed (*Polygonum hydropiperoides*)	1,896	111
Primrose Willow (Woody vegetation, Jurisdictional and non-jurisdictional wetland and other areas)	Primrose Willow (*Ludwigia peruviana, Ludwigia* spp.)	1,888	15
Water Lettuce (non-jurisdictional wetland)	Water Lettuce (*Pistia stratiotes*)	4,531	60
Carolina Willow (wetland and non-jurisdictional wetland)	Carolina Willow (*Salix caroliniana*)	2,655	45
Cattails (wetland and non-jurisdictional wetland)	Cattail (*Typha* spp.)	1,563	9
Total	-	-	240

* Estimated from the P concentration of different plant species and the area under different vegetation type determined from aerial and field survey

4. Enhancements for P Retention

The AGIs were originally designed and constructed primarily with flood control in mind. One of the goals of this project was to suggest design modifications and enhancements to the AGI taking into account the analysis of data collected and relevant available literature. A discussion of these enhancements and modifications is presented below.

The most straightforward modifications that can be made to the AGI are those that involve increasing the travel time and available storage. Since significant fraction of the P retention is related to the settling out of particulate P, travel or residence time will directly affect the amount of P retained by the AGI. For instance, highest TP concentrations observed for pumps 1 and 2 around the time of the ditch cleaning did not have corresponding high concentrations at the discharge during the same period. Furthermore, highest TP concentrations at the discharge site were observed after the occurrence of the highest rainfall event (rainfall = 7.1 cm) which resulted in almost filling up the AGI water storage capacity and in turn reduced the residence time. To increase the travel time, short circuiting within the AGI should be minimized. An example of this, related to the AGI involved in this study, would involve moving pumps 2 and 3 further away from the discharge structure (Figure 32). Similar suggestions have been presented by Shukla et al. (2010) and Shukla and Jaber (unpublished data) who suggested several hydraulic design modifications to enhance hydraulic and nutrient treatment efficiency of AGIs. They suggested that in some AGIs, such as the one studied here, inflow and outflow locations are close to each other, which reduces the residence time in the AGI. Increased residence time has been shown to result in P retention in a cattle ranch drainage ditch in southern Florida (Shukla and Collins, 2005). Similar results were also reported by Edwards et al. (1999), who reported on a simulated agricultural runoff event where water amended with sediment, N, and P, was passed through an experimental sedimentation basin. An average of 52% of the P that was added to the inflow was retained by a basin in Pennsylvania (Edwards et al., 1999; Shukla et al., 2010). The 3-day retention time treatment resulted in significantly more sediment retention than the 1-day treatment. The majority of the sediments and P were released within the first 12 hours during the 3-day treatment and the first 4 hours during the 1-day treatment.

In addition, the 'borrow' ditch that was created during construction provides a relatively direct pathway for water to reach the discharge structure. Inputs that take advantage of this flow path experience a reduced residence time which is further exacerbated by the proximity of the pump to the discharge structure. So, by moving the pump further away from the discharge structure and by preventing water from following this flow path, the residence time would be increased resulting in an increased level of P retention. Another associated modification for increasing the residence time could be plugging the borrow ditch at several locations to force the water to follow a longer flow pathway.

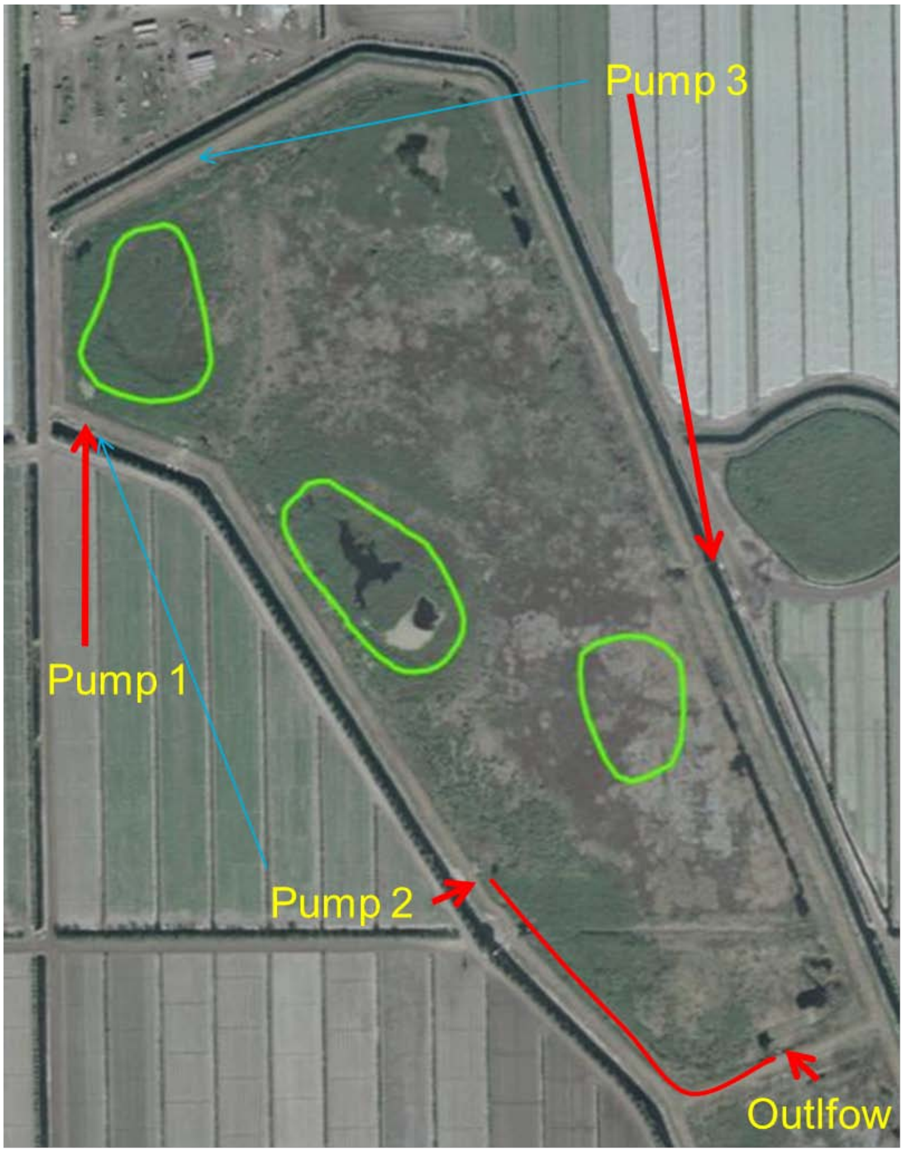

Figure 32. Example of modification to increase phosphorus removal efficiency in the AGI by moving the inflow sources (discharge pumps) further from the discharge structure (outflow) (red arrows denote current location, blue arrows denote proposed location, green denotes jurisdictional wetland). The red line from pump2 to outflow shows potential short circuiting due to presence of the inner borrow ditch.

Another method to increase residence time is to force water to circulate through cells or around berms within the AGI before reaching the discharge structure (Figure 33). This is a retrofit that has been suggested for urban stormwater treatment structures (Ellis, 1992; Nascimento et al., 1999; NCDENR, 2007), but has not been widely used yet in agricultural settings. Preliminary results from a demonstration project using multiple treatment cells within another AGI at C&B Farms suggests that this technique merits further investigation.

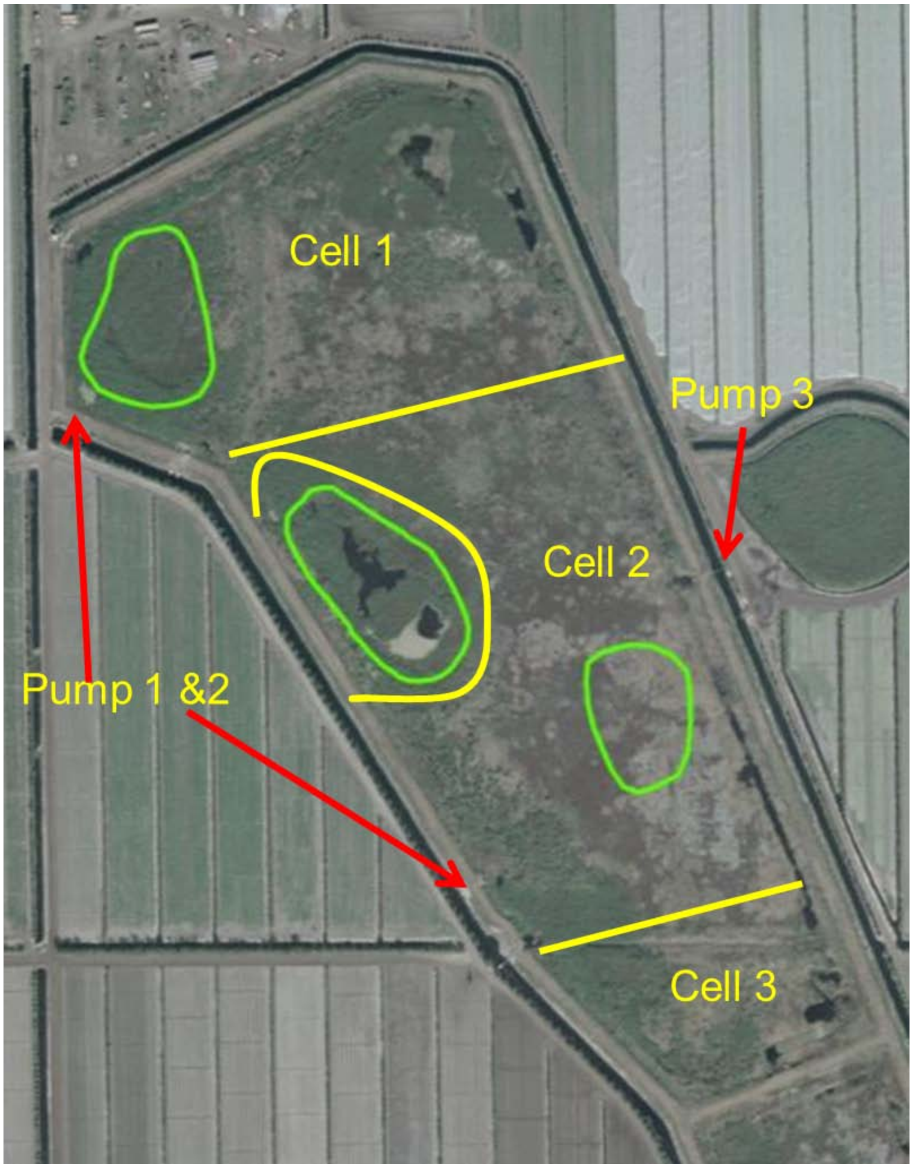

Figure 33. Example of modification to increase phosphorus removal efficiency in the AGI by constructing interior cells and berms to increase travel path and residence time.

Another method which has become popular in the urban stormwater treatment realm is the modification of the outlet control structure which could be applicable to agricultural AGIs depending upon the presence or absence of wetlands within the AGI. Since AGIs were historically designed primarily for flood control, the degree of water quality treatment varies with different types of storm events since antecedent moisture and stage conditions are not taken into account. In the case of agricultural AGIs, design requirements specify that they be able to store the first inch of runoff which is an event that can be exceeded several times in a season. Once the AGI reaches its full storage capacity (the first inch of runoff or greater) additional runoff may pass through without significant treatment. The AGI from this study provides increased water quality treatment for small events and little treatment for larger events followed by successive small events. Note that since this AGI is the first of three AGIs at C & B Farms, additional P treatment is likely to be provided. However, not all the AGIs throughout the C139 Basin discharge into another AGI, so additional P treatment may not occur for these AGIs. It is possible that the 25-year 3-day design storm might be adequate for maintaining historic flows, but this study suggests that this design storm may be inadequate in providing the optimum water quality treatment. The results of this study showed that when the available storage in the AGI was mostly utilized and runoff continued to occur, very little P treatment was observed. An outlet control modification to increase the elevation of the discharge weir with the goal of providing additional storage for flood events that generate larger runoff volumes could be made; however, due to the presence of jurisdictional wetlands within the AGI, consultation with the regulatory agency is advised. (Figure 34).

Figure 34. Discharge control structure modification (increase elevation of weir) to increase available storage capacity in an effort to increase P removal efficiency.

A more sophisticated outlet control modification would attempt to improve P removal efficiency by retaining almost all runoff for small events, reducing peak flow rate for more severe flood events (e.g. 10-year event), but allowing release for severe events (100-year event) (Guo, 2009). This could be achieved by modifying the existing discharge weir to include small circular orifices placed near the current control elevation, a rectangular orifice slightly above the current control elevation and raising the final control elevation of the sharp-crested rectangular weir (Figure 35). An additional alternative is also presented in (Figure 35) which would be a V-notch weir instead of the rectangular orifice. The small circular orifices would allow the AGI to increase settling time for low runoff volume events while simultaneously draining the AGI creating the necessary storage for successive events which is often the case in Florida. The rectangular orifice or v-notch weir would allow for drainage of larger events and the increase of the overall control elevation could provide treatment and flood control for severe events. While these design considerations may be included in the construction of new AGIs, a large portion of existing AGIs contain simple weirs that do not provide the added benefits of this type of outlet control.

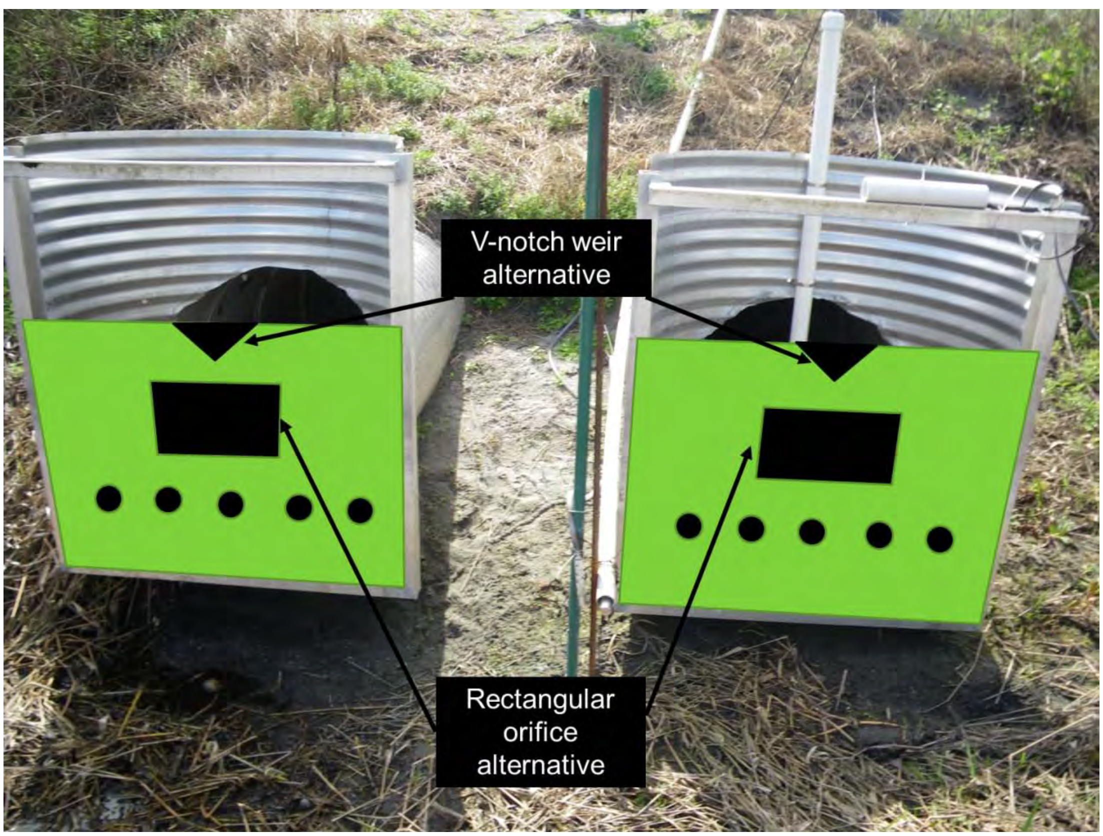

Figure 35. Additional discharge control structure modifications to increase available storage capacity in an effort to increase P removal efficiency.

Another option for AGI enhancement is active control elevation management which would involve changing the control structure elevation depending upon the rainfall outlook and the drainage needs of the agricultural system. The AGI would always be equipped with the minimum control structure elevation as required by the Environmental Resource Permit (ERP), but the land manager would increase the control structure elevation during certain times of the year to retain more water, increase settling time and, in turn, increase P removal rates. Consultation regarding the feasibility of this option with the regulatory agency is advised. An example of this would be the typical spring dry period when a land manager could increase the control structure elevation to its maximum (while maintaining the freeboard requirements) to retain the maximum amount of water and P possible. Since the spring provides for a more predictable rainfall pattern, the land manager would be able to safely manage the elevation of the control structure without the normal risks of flooding associated with the summer rainfalls which occur more frequently.

All of the enhancements mentioned above involve structural modifications either to the control structure or to the interior topography of the AGI and may require modifications to the ERP. Consultation with the corresponding regulatory agency is advised. These enhancements only target the P retention in the AGI and do not address the P removal from the AGI. An additional set of enhancements, managerial in nature, can be used to achieve the P removal from the AGI. They will allow the AGI to continue retaining some level of P due to reducing the volume of outflow and retention of particulate P. Based on the results, it is possible that the AGI at C&B Farms is close to its P storage capacity, especially the dissolved P, and will not be able to retain any additional dissolved P in the near future. Once the soils within an AGI reach their P storage capacity, new methods must be implemented to either store additional P in the system or permanently remove it from the system. One method to remove the P from the system is through biomass harvesting (Shukla et al., 2010). Even though this practice has not been implemented in agricultural AGIs, it has been proposed, studied and practiced in urban stormwater structures, wastewater treatment ponds and natural systems. Aquatic plant harvesting is included in the Urban Storm Water Drainage Criteria Manual (UDFCD, 2001) as a management recommendation for retention ponds and constructed wetland ponds as a way to permanently remove nutrients from the system. Biomass harvesting has also been proposed in a couple of scenarios as a potential feedstock for biofuels. Shukla et al. (2010) identified the harvesting of the biomass and its use as a biofuel feedstock or as an organic amendment as one of the avenues for improving the N and P retention from the AGIs in Florida. Ciria et al. (2005) evaluated the potential of *Typha latifolia* as a biomass fuel in constructed wetlands for wastewater treatment in Spain. Cicek et al. (2006) evaluated different emergent vegetation types present in a marsh system in Manitoba, Canada, for their potential as a biofuel feedstock and concluded that it could provide nutrient removal benefits and provide adequate raw material for biofuel production. Cicek et al. (2006) also considered the economic feasibility of using the aquatic plants as biofuel feedstock and determined that there is promise for it to be an economically feasible system.

Of the 240 kg biomass P in the AGI, 13% (31 kg) is in the jurisdictional wetlands, which leaves 209 kg that can be harvested. Considering that part of this remaining biomass may not be easily accessible and there are uncertainties associated with the biomass P estimates, we assume a scenario of 75% harvestability which results in 157 kg of P that can be harvested from the AGI. This harvestable P accounts for 76% of the annual retention and 19% of the annual outflow from the AGI. Therefore, removal of biomass on an annual basis is likely to result in reducing the P stored in the AGI. A significant part of the biomass in the AGI dies and decomposes every year which results in P release (Reddy et al., 1995; Chimney and Pietro, 2006; Shukla et al. 2011). This mineralized P from macrophyte decomposition can then move out of the AGI during successive storms. By harvesting the macrophytes in the AGI on an annual basis, the potential for discharge of macrophyte-derived P can be reduced. The long-term effect of biomass harvesting can eventually result in increasing the treatment efficiency of the AGI. Removal of biomass P can be considered an environmental service of P treatment. If the harvested biomass can be used as biofuel feedstock, it can provide additional revenue which can make it an economically feasible alternative that provides both nutrient removal and energy production environmental service. Another revenue source, though not considered here and would require a comprehensive study, is the value of carbon sequestration. Overall, the enhancement of biomass harvesting seems to be an attractive alternative and can provide the growers an additional source of income while providing the water quality, alternative energy, and perhaps the carbon sequestration benefits.

An additional alternative to using harvested biomass as a biofuel feedstock would be to use it as a component in a compost production system. The effects of applying compost or organic amendments to agricultural fields have previously been studied in south Florida soils and its application has been determined to provide both water quality and quantity benefits. Pandey and Shukla (2006) showed that the addition of compost allowed a lower water table while achieving similar moisture levels when compared to a field where no compost was applied. Shukla et al. (2004) also found evidence that applying compost to production fields reduced P leaching through an increase of organic matter that retained water and P in the soil instead of allowing it to move through the soil. The benefits of this nutrient recycling are several: little to no additional P would need to be applied to production fields in the form of inorganic P fertilizer, P would be removed from the reservoir through biomass harvesting reducing the available pool of mobile P that can be transported downstream and the overall mass of P stored at the farm scale would be reduced leading to lower P discharges in the future.

While organic amendments can reduce P leaching from the production fields, some studies have evaluated the possibility of applying chemical amendments to the soils inside the AGI and the inflow water entering the AGI to enhance the AGI's P retaining abilities. The goal behind chemical amendments is to convert the mobile P into a more immobile form. Lu and O'Connor (2001) showed the P retention capacity of an Immokalee sand increased after application of a biosolid with high Al and Fe concentrations. They noticed that the increases in P retention only lasted 1 to 3 years and was correlated with the persistence of the Al and Fe in the soil. A subsequent study showed that water treatment residual (a byproduct of drinking water treatment plants) could increase P-retention and immobilize P for up to 7.5 years (Agyin-Birikorang et al., 2007). They showed that an alum-based water treatment residual applied to P-impacted soils could immobilize P for up to 7.5 years after application. They also noted that even if the immobilized P eroded into surface waters that it would not be bioavailable and therefore would pose little threat to water quality. Although the chemical amendments hold promise, a systems approach that considers the ecological effects needs to be taken before implementing this strategy.

Another method of keeping the P within the farm system is by recycling the water between the AGI and the production fields to augment other irrigation water sources (Shukla et al., 2010). Shukla and Jaber (2006) explored different scenarios for using stormwater as an alternative water supply source in south Florida and showed that stormwater stored within an AGI could be used for irrigating a citrus grove for up to 13 weeks (depending on the scenario) after the summer/fall rainfall concluded. The reuse of this water would serve two purposes: 1) reduce reliance on groundwater for irrigation and 2) keep more P in the farm system. Implementing this system would involve installing pumps that can pump from the AGI to the production fields and some modifications to the AGI to reduce subsurface losses, so the cost of modifications and the environmental impacts would need to be evaluated before considering this option. Shukla et al. (2010) noted that water from an AGI, if used for irrigation, can reduce the amount of water pumped by agriculture from traditional surface and ground water sources, increasing the amount of water available to other water consumers in some southern Florida watersheds (Shukla et al., 2008).

4.1 Role of AGI in Treating P in the C-139 Basin

Use of AGIs is one of the BMPs to provide water quality and quantity treatment for vegetable, citrus and sugarcane operations in the C-139 Basin. Their current and future role in reducing P discharges from the basin is not well quantified. However, as a result of this study, the factors influencing the performance of an agricultural AGI within the C-139 Basin are now better identified and understood. While it is possible that the AGIs located in the C-139 Basin in their current state are providing a substantial level of P treatment, the results of this study discuss opportunities to improve their performance. Considering that there are over 10,000 acres of land in 60 AGIs within the C-139 Basin, the impact of AGI modifications for water quality treatment might facilitate the C-139 Basin in meeting its P discharge levels consistently and for the long-term.

These modifications need to be demonstrated and field-tested for their P treatment enhancement potential and cost effectiveness to facilitate its acceptability and basin-wide applicability. This was proposed as Phase II of this project. To better evaluate the level of improvement achievable by implementing the enhancements, more information is needed both about the current state of the AGIs in the basin and the kind of improvements that can be made through the aforementioned AGI enhancements. A first step would be to perform a survey of the AGIs in the basin (Phase II) to determine the following:

1) The similarity of the AGI in this study with other AGIs in the basin to relate the results from this study to other AGIs in the basin,
2) The level of short-circuiting that occurs (inflow and discharge locations and presence of the continuous "borrow" ditch),
3) Soil P retention characterization to determine whether AGI is potential sink or source,
4) Freeboard available in AGIs to determine if more storage is currently available,
5) Regulatory constraints to determine what modifications would be feasible,
6) Willingness of landowners to modify their AGIs to improve water quality, and
7) Willingness of landowners to harvest biomass from their AGIs and their preference for its use given different levels of economic incentives.

Once results from Phase II are available, they could be combined with the results from the survey to determine the overall impact that AGI modifications would have on reducing the P discharges from the C-139 Basin.

Conclusions

The following conclusions can be drawn from the study:

1. The treatment efficiency for the AGI in this study was 20% and the P treatment per unit area was 14 kg/ha. The AGI seems to be effective in reducing the particulate P since the peak TP concentrations observed at the discharge site were lower than the inflow.
2. Lower than expected treatment efficiency of the AGI was likely due to the non-inundation of the entire AGI before discharge occurs, long-term P loading which has used most of the soil P retention capacity, lower residence time for several events during the dry period, and one of the P sources being close to the discharge.
3. There exists potential for enhancing the P retention of the AGI by implementing structural and managerial strategies in the AGI. The proposed structural modifications aim to increase the storage capacity and modify flow pathways to increase the residence time.
4. The proposed managerial enhancements include harvesting the biomass for P removal and its use as a biofuel feedstock or as an organic amendment (compost) on the farm.
5. Some structural modifications such as increasing the weir height and moving the P sources away from the discharge location have the potential to increase the P retention. Before implementation of any of these modifications, consultation with the regulatory agency is advised due to possible modifications to the ERP. Evaluation of the effects on the crop productivity is also recommended.
6. Although there exists the potential for enhancing the P retention, these enhancements have to be tested at the same site for demonstrating that they actually work along with feasibility and associated costs followed by a basin wide survey before recommending basin-wide implementation.
7. Results from this study have demonstrated that the AGI reduced the TP discharge from a vegetable farm. Depending on the historical P loads, inflow TP loads, hydraulic characteristics, and operation, similar results can be expected for other AGIs located at citrus, sugarcane, and vegetable farms. Most of the AGIs in the basin were built to store first inch of runoff from the farms and not for optimized P treatment. Given that these AGIs already exist and are outside of the production areas, the AGIs can be modified to further decrease the P loads. Since the total AGI area in the basin is 10,000 acres and that they are

located within the farms, these structures can play an important role in achieving the P load reductions.

8. It is recognized that as with any physical sciences study, measurement errors are always present. Extended data collection would be needed to evaluate the magnitude of any measurement errors and enhance the reliability of the results.

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