

Verification of a Payment for Water Treatment Services Program for Agricultural Lands in the Northern Everglades



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Contract No. 024017

Deliverable 1

DECEMBER 31, 2017

Florida Department of Agriculture & Consumer Services (FDACS)
Tallahassee, FL.

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Introduction

Unnatural flows and nutrient loads have impacted ecosystems, globally. These excessive flows and loads emanate from a spectrum of reasons including alteration of historic flow regimes, urbanization, and intensification of agriculture. To help restore the impacted waters, regulatory targets that are protective of the water quality and flow levels are established. Examples of target-based programs include the water framework directive in Europe (Kay et al., 2009) and the total maximum daily load (TMDL) approach in the United States. Despite the TMDL program, it has not been able to consistently achieve the water quality targets (Endres and Walker, 2014). Endres and Walker (2014) noted that one of the reasons for the failure has been the excessive degradation of watersheds and the state being assigned the primary responsibility to address the environmental concerns. With the state funds being the primary driver of programs such as TMDL, environmental governance becomes a costly affair (Roberts et al., 2012). After decades of government funded programs' implementation, there are numerous ecosystems in United States such as the Greater Everglades (GE) that remain impacted. Various programs to achieve the water quality targets and desired flows to the estuary have been designed and implemented in the GE. These programs range from the Comprehensive Everglades Restoration Plan (CERP) to agricultural best management practices (BMPs).

Historically, the GE was a mosaic of dry and wet prairies, freshwater marshes, wetland tree islands, pine flatwoods, mangrove swamps, and coastal wetlands (NRC, 2012). It stretched from Orlando to Florida keys with Lake Okeechobee in the middle receiving water from the Kissimmee river. During the wet season, excess water from the lake overflowed forming the "River of Grass" between the lake and Florida Bay via sheet flow

(Kim et al., 2014; NRC, 2012). Today, the GE can be described as a combination of two distinct hydrologic units, the northern Everglades (NE) and the southern Everglades (SE). The NE basin includes the LO, Caloosahatchee, and St. Lucie river basins and SE extends southward of these basins to the Florida Bay. Over the last century, the GE ecosystem has experienced alteration from its natural state given the significant development and change in landuse (Richardson et al., 2014). Construction of flood protection structures such as levees, canals for diverting water, and urban development has resulted in loss of 50% of the GE's spatial extent and significant changes in its hydrological and ecological functions (Aumen et al., 2015).

The compartmentalization of ecosystem which was once a "River of Grass" characterized by slow sheet flow of water via the marshes has not only led to the hydrologic alteration and degradation but also altered its oligotrophic nature with low phosphorus (P) availability to primary producers (Sullivan et al., 2014). Water quality of rivers and lakes in the GE exceed the targets concentration and loads of phosphorous (P) and nitrogen (N). Both Lake Okeechobee (LO) and the Everglades National Park are P limited ecosystems. Current P load to the LO is 609 metric tonnes/year which exceed the federally mandated Total Maximum Daily Load of 140 metric tonnes/year by 335%. A class III numerical phosphorus water quality target for the Everglades Protection Area (EPA) has been set at 10 µg/l. Given ecohydrological complexity and extent of degradation, the state and federal initiatives for restoration of the GE ecosystem have been expensive. An important state initiative has been the storage of water and P thereby, reducing the P loading. To help achieve the water quality target, 23,000 ha of wetlands known as stormwater treatment areas (STAs) have been constructed south of LO (Mitch, 2016). These STAs are used for temporary storage of water during wet season when most damaging flows occur and retain P to maintain the ecological integrity of the Everglades. Despite the existing STAs and projected construction of a 20,000 ac facility (17,500 ac reservoir and a 2,500 ac STA) in the NE basin, there are concerns stemming from the 1) failure to achieve the P targets for the Everglades in the past; and 2) unusual flooding events as a result of excessive rainfall.

It has been estimated that an additional 40,000 ha of stormwater treatment wetlands are required to temporarily store and treat water in the NE basin (Mitch, 2016). Although the construction of the proposed reservoir and treatment area will greatly assist in achieving the targeted water storage and nutrient treatment, it will be an expensive undertaking especially because more than 50% of the LO basin (3.4 million acre) is primarily used for agriculture (Graham et al., 2015). Keeping in mind the required investment and logistics of the constructing the reservoirs and STAs, alternative storage and treatment options were explored and the idea of 'dispersed water management (DWM)' was formed. Unlike STAs and reservoirs where water is conveyed and stored in a designated area primarily managed by the state (end-of-watershed storage approach), the DWM technique refers to the use of existing, available water retention opportunities on private and public lands scattered throughout the watershed. Approximately 34 million dollars were budgeted between 2012 and 2016 for dispersed water management (SFWMD, 2017). Distributed storage has been postulated to improve groundwater recharge, reduce flow velocities leading to reduced erosion, and longer residence time for nutrient treatment (Graham et al., 2015).

The impetus for the DWM initiative was partly provided by a multi-agency and multi-institution initiative, called FRESP (Florida Ranchlands Environmental Services Project) involving the South Florida Water Management District (SFWMD), Florida Department of Agriculture and Consumer Services (FDACS), Florida Department of Environmental Protection (FDEP), Florida Fish and Wildlife Fund (FFWF), University of Florida (UF), Archbold Biological Station (ABS), Florida Cattlemen's Association (FCA), and World Wildlife Fund (WWF). The FRESP was designed and implemented between 2006 and 2012 to quantify the benefits from DWM on working agricultural lands (Bohlen et al., 2009). Given that FRESP was availing private ranchlands to complement public investment, a 'payment for environmental services (PES)' component was also added to the project thus contributing towards rancher's financial sustainability. The PES program not only provided financial incentive but also encouraged ranchers to not steer towards

conversion of ranch to urban development which could have adverse impacts on the hydrology and ecology of the watershed.

The PES approach entails a contract like arrangement under which the willing beneficiaries pay the provider for offering well-defined environmental service(s) (Sattler and Matzdorf, 2013; Pattanayal et al., 2010). Although scientifically still young, the PES concept has attracted considerable attention since 1996 (Wunder, 2015; Ferraro, 2011). An approach characterized by interdisciplinary, with economics as its theoretical base, the government-financed PES concept has now mainstreamed into environmental policy making process (Wunder, 2015). However, implementation of such a program is challenging given the difficulty in quantifying the service provided, dealing with spatial and temporal variability in environmental conditions, and deciding on the financial incentive provided to the land owner in lieu of the services (Bohlen et al., 2009). To tackle these challenges, quantify the effectiveness of a PES program in storing excess water and reducing nutrient loads, evaluate a market-based system to pay for environmental services on private lands, and facilitate a basin-scale implementation of FRESP like programs, seven water storage sites and one water treatment site were authorized to be instrumented and monitored. This report describes the effectiveness of the water treatment service.

The PES-treatment site is a privately-owned, 2500-ac impoundment- marsh system where water pumped from a public canal is passed through the marsh for nutrient removal after which water is discharged back to the canal. This report analyzes long-term (2008-2017) hydrologic, water quality, and soil data to verify that the N and P treatment services are provided by the impoundment-marsh site and estimate the cost of P treatment (\$/kg of P treated). Phosphorus treatment was the basis for this PES site since P is the limiting nutrient for the Everglades. However, in this report we not only quantify treatment of P but also N along with the water storage service. Specific objectives include 1) use long-term (2008-2017) hydrologic, water quality, and soils' data to construct water, N, and P budgets at an impounded marsh to quantify the long-

term P and N removal and water storage services; and 2) evaluate the applicability and relative cost effectiveness of treating surface water with a publicly funded PES program.

Methods and Materials

Site Description and PES Management

The PES-nutrient treatment site is a 960 ha impounded marsh owned by Lykes Brothers Inc., located in a cattle ranch in the northern Glades county in the C-40 basin, Northern LO watershed (Fig. 1). The site is surrounded by an embankment and characterized by wetlands as well as upland areas. Considering the relatively flat topography of South Florida, the elevation at the site varies significantly ranging from 6.9 m to 10.7 m above mean sea level (1991 North American vertical datum established, NAVD 88). The predominant soil types in the impoundment-marsh mainly comprise of Floridana fine sand (35%), Felda fine sand (32%), and Pineda fine sand (18%). The remaining 15% soils consist of Gator muck, Malabar, Pople, and Basinger fine sand. The Floridana series are characterized by very deep, very poorly drained, slowly to very slowly permeable soils (0.15-0.5 cm/hr) found in low broad flats, flood plains, and in depressional areas (USDA-NRCS, 2017). Felda and Pineda soils possess slightly higher saturated hydraulic conductivities (1.5-15 cm/hr) compared to the Floridana soils. Natural water table lies within 25 cm of the soil surface and depressional areas are typically ponded for at least 6 months in a year.

Water is diverted from the C-40 canal (Fig. 1), also known as the Indian Prairie canal into the treatment site, to treat N and P and attenuate peak flows in the LO located at the downstream end of the canal. To accurately measure the flows and nutrient loads, a small detention pond was constructed and a circular weir was installed. The pond receives the treated water from the impounded marsh through three culverts fitted with movable boards. The treated water is routed back to the public canal. To better distribute the pumpage from the canal to the marsh, a diversion berm was built which compartmentalized the treatment site into two cells (Fig. 1).

Monitoring and Data Acquisition

Meteorological Data

A Weather station, managed by the SFWMD, located near the site was used to acquire meteorological data (Fig.1). The meteorological parameters included rainfall, daily temperature (min and max), daily relative humidity (min and max), solar radiation (w/m^2) and wind speed. The aforementioned parameters were used to calculate ASCE standardized FAO-56 Penman-Monteith reference-ET (ET_{ref}) utilizing the RefET software (Allen, 2013). Monthly crop coefficients developed by Wu et al. (2016) for wetlands located in the LO basin were used to calculate actual ET.

Nitrogen contributions from atmospheric deposition were estimated by using rainfall N data collected at a nearby site managed by the National Atmospheric Deposition Program (NADP). Phosphorous deposition was estimated by using an average rainfall-P concentration of 9.38 ppb reported by Ahn (1998) and Ahn and James (2001).

Hydrologic Data

The treatment site receives inflow from two pumps (Fig 1). The first pump (C-40 pump, capacity= $189 \text{ m}^3/\text{min}$) located on the north-eastern side pumps water from the C-40 canal. In Jan 2010, the pump was relocated (Fig. 1) and the diversion berm culverts were fitted with boards to increase the hydraulic residence time and improve the water distribution through the marsh. The second pump (grove pump), on the southern end of the treatment site, pumps water from a ditch collecting drainage from a citrus grove (Fig. 1). The grove pump consists of two individual pumps with a combined capacity of $286 \text{ m}^3/\text{min}$. The C-40 pump operation schedule was determined by SFWMD based on availability of excess flows in the C-40 canal. Both the C-40 and grove pump sites (Fig. 1) are instrumented with a KPSI 500 pressure transducer (Measurement Specialties Inc, VA, USA) to measure height of water above the pump impeller (pump lift head). A magnetic sensor (Ai-Tek Instruments LLC, Connecticut, USA) installed at both sites measured the rotations per minute (RPM) of the pump impeller. The lift head was measured every 5 seconds and the values were averaged over a span of 15 minutes.

The RPM values were also averaged for a 15-minute timespan. The 15-minute lift head and RPM values were used to quantify the pumped volume using the pump characteristic curves provided by the manufacturer.

A pressure transducer (Measurement Specialties Inc, VA, USA) was used to measure stage at the outflow weir (Fig. 1). The outflow was quantified utilizing the stage data via the standard Francis weir equation (Eq. 1).

$$q = 3.33 \times b \times h^{3/2} \quad (1)$$

where q is the flow rate (ft^3/s), b is the circumference (ft) of the circular weir, and h is the hydraulic head at the weir (ft) obtained from subtracting the weir elevation from measured surface water stage.

The surface water storage in the impoundment-marsh was estimated using the water level data measured with a pressure transducer (Measurement Specialties Inc, VA, USA) installed inside the impoundment-marsh (Fig 1). LiDar data was used to develop a high resolution (1 m) digitized elevation model (DEM) of the site using the ArcGIS software (Version 10.3, ESRI, Redlands, CA, USA). The DEM, along with the stage data, was used to develop a stage-volume relationship. The stage-volume relation was utilized to quantify the surface storage in the impoundment-marsh on a daily basis.

Water Quality Data

All inflow (C-40 and grove pumps) and outflow (weir) locations were instrumented with automatic samplers (Teledyne ISCO, Nebraska, USA) to collect flow-weighted water quality samples. The samples were analyzed for nitrite-N ($\text{NO}_2\text{-N}$), nitrate-N ($\text{NO}_3\text{-N}$), ammonium-N ($\text{NH}_4\text{-N}$), total Kjeldahl N (TKN), and total phosphorus (TP) at a laboratory certified by the National Environmental Laboratory Accreditation Conference (NELAC).

Soils Data

Soil samples were collected twice in the impoundment-marsh to analyze any changes in soil P status. Initial soil samples were collected on March 8-9, 2008 and the second soil sampling was carried out on 28th September, 2012 (Shukla, 2012). Soil sampling

locations for 2012 were same as 2008. Soil samples were collected using a 7-cm clear polycarbonate coring tube with stainless steel cutting head. Soils were extruded from the core tube and sectioned at 10 cm length. After sectioning, samples were placed in re-sealable plastic bags and immediately preserved in a cooler on wet ice for transport to the laboratory for analyses. The samples were analyzed for TP, soluble reactive phosphorus (SRP), and equilibrium phosphorus concentration (EPC).

Hydrologic and Water Quality Data Analyses

Hydrologic and water quality data collected during July 8, 2008 to July 7, 2014 and July 8, 2016 to July 7, 2017 (seven years), were used to evaluate the effectiveness of the PES treatment site in removing N and P from public water diverted from the C-40 canal. Hydrologic and water quality monitoring began on July 8, 2008. For this project, a year such as 2008-2009 is defined as a period between 8th July 2008 to 7th July 2009. July 8, 2014 - July 7, 2016 data were not included in the analyses because of combination of missing data and pump maintenance during this period. A water balance (Eq. 2) for the impoundment-marsh was constructed using measured/estimated surface inflows, outflows and storage changes.

$$\Delta S = (SW_{in} + R + S_i) - (O + ET + S_f) \quad (2)$$

where SW_{in} is the pumped inflow from the C-40 and grove pump, R is rainfall, S_i and S_f are the initial and final surface water storage calculated using the stage-volume relationship developed for the site, O is the surface water outflow from the site, ET is the actual evapotranspiration, and ΔS is the change in storage. The above equation was solved for ΔS on a daily-basis. The ΔS includes lateral as well as vertical groundwater losses and gains for the site as well as error in estimating other mass balance components on the right-hand side of Equation 2. Assuming the errors to be zero, ΔS can be assumed to be subsurface losses/gains. Water retention (WR) efficiency for the impoundment-marsh was calculated as:

$$WR\ Efficiency = \begin{cases} 100 * \frac{(SW_{in}+R+S_i)-(O+S_f)}{(R+S_i+SW_{in})} & \text{if } S_i - S_f > 0 \\ 100 * \frac{(SW_{in}+R)-(O)}{(SW_{in}+R)} & \text{if } S_i - S_f < 0 \end{cases} \quad (3)$$

Similar to the water budget, N and P budgets were also developed for the site. The nutrient loads (TN and TP) were quantified by multiplying the flow data with corresponding nutrient concentration. Nutrient load retention and treatment efficiency for the site was calculated as follows:

$$Nutrient\ Retained = \begin{cases} SW_{N-in} + A_N + S_{N-i} - (O_{N-out} + S_{N-f}) & \text{if } S_{N-i} - S_{N-f} > 0 \\ SW_{N-in} + A_N - O_{N-out} & \text{if } S_{N-i} - S_{N-f} < 0 \end{cases} \quad (4)$$

$$Treatment\ efficiency = \begin{cases} 100 * \frac{Nutrient\ retained}{SW_{N-in}+A_N+S_{N-i}}, & \text{if } S_{N-i} - S_{N-t} > 0 \\ 100 * \frac{Nutrient\ retained}{SW_{N-in}+A_N}, & \text{if } S_{N-i} - S_{N-t} < 0 \end{cases} \quad (5)$$

Where SW_{N-in} is the pumped nutrient load (C-40 and grove pump), A_N is atmospheric nutrient deposition (wet and dry), S_{N-i} and S_{N-f} are the initial and final nutrient mass in the water stored inside the impoundment-marsh and O_{N-out} is load discharged through the outflow weir. What did not leave the system through the weir was assumed to be retained inside the impoundment-marsh.

Economic Analyses

Unit cost of P treatment (\$/kg of P treated) was chosen as the cost-effectiveness index for the study. Unit cost of treatment for state-managed STAs are available (Sano et al., 2011). A lower unit cost of treatment compared to the STAs was considered to be the measure of cost-effectiveness of the PES project. Costs involved in conversion of the existing impoundment-marsh to a nutrient treatment PES site for the FRESP were provided by the Lykes Bros Inc. Initial investment for the project included the cost of planning, acquiring permits, and construction of the diversion berm. The recurring expenses mainly included the cost of maintaining the berm, pump maintenance and repair, fuel, personnel cost for managing the pump operation, vegetation management inside the impoundment-marsh, and data collection. The cost involved in the hydrologic

monitoring and data analyses was not considered. The economic feasibility of the project was evaluated using the 'net present worth (NPW)' method. The NPW method is used to estimate the present value of a project by summing both positive and negative, discounted cash flows during useful life of the project. In this case, the NPW method was used to calculate the 20-year, discounted value of the investment made by the landowner and the state, utilizing equation 6 below.

$$\text{present worth of the investment} = -C_0 - \sum_{i=1}^t \frac{C_i}{(1 + D)^i} \quad (6)$$

In the equation above, C_0 is the initial investment, C_i represents the investment during year i , D is the discount rate (3.325%), and t is useful life of the project assumed to be 20 years in this case. The negative sign represents the negative cash flow i.e. investment.

Categorized financial investments were available for the nine (July, 2008 – July, 2017) out of 20 years. Given the 20-year analyses, the average annual investment estimated from the available data were used for the remaining years. All costs were converted to 2017-dollar value before being utilized for the present worth analysis, using the gross domestic product implicit deflator (Eq. 7).

$$\text{Deflated Dollar Value} = C \times A/B \quad (7)$$

In equation 7, C is the original dollar value, A is the index value of the year (2017) to which the original dollar value needs to be converted, and B is the index value of the original year. The index values were obtained from the United States bureau of economic analysis (<https://fred.stlouisfed.org/data/GDPDEF.txt>).

A conservative approach was taken to estimate the amount of P retained during the project life of 20 years. Phosphorus retention estimated using the observed hydrologic and water quality data was used for seven years (2008-2014 and 2016-2017). For the remaining 13 years, P retained was assumed to be 3,110 kg, lowest annual retention

(2009-2010) during the seven years of monitoring. The unit cost of treatment was quantified using equation 8.

$$\text{Unit cost of treatment} = \frac{\text{20-year worth of investment}}{P \text{ retained in 20 years}} \quad (8)$$

Results and Discussion

Water Balance and Dynamics

Rainfall during the study period varied from a maximum of 162.4 cm in 2012-2013 to a minimum of 82.1 cm in 2010-2011 with an average of 120.7 cm (Table 1). Two years of the study period recorded above-average rainfall and two years below-average rainfall. Rainfall during 2008-2009 (147.8 cm) and 2012-2013 (162.4 cm) was above the long-term average of 132 cm (NCDC, 2011), while 2010-2011 (82.1 cm) and 2016-2017 (95.6 cm) received 25% less rainfall than the average and could be considered dry/drought years. The monitoring period therefore, is representative of the long-term variation in rainfall for the region.

Pumped inflow varied from 72.8 cm in 2009-2010 to 328.5 cm in 2012-2013, depending mainly on the rainfall (Table 1) and the availability of “excess” water, as determined by the SFWMD, to be routed through the impoundment-marsh. Pumping from canal was initiated by the landowner whenever the state agency deemed that the canal had “excess” flows. Most of the pumping occurred during periods of high rainfall and surface flows in the canal (Fig. 2). On average, 23.4% of the canal flow was pumped into the impoundment-marsh during the study period. Slightly over half (51.7%) of the average total inflow (pumping + rain) passed through the impoundment-marsh and returned back to the C-40 canal. ET accounted for 38.9% of the total inflows. Subsurface losses, calculated as the residual term in the water balance neglecting component errors (Eq. 2), accounted for 9.1% of the total inflows. Subsurface loss is a net term and thus includes vertical and lateral seepage losses from the impoundment-marsh and errors in

quantifying the terms in Eq. 2. For example, if ET was overestimated, the subsurface or seepage losses would be underestimated.

Wet season (June-Oct) pumping accounted for 65% of the total pumping except for 2009-2010 (Fig 3). In 2009-2010, three-quarter of the total pumping occurred during the dry season (Nov-May), which received almost double (59.7 cm) the average dry season rainfall (34.7 cm). The dry season of 2009-2010 could be considered as one of the wettest dry seasons recorded in the region while the wet season received less than average rainfall. The lack of “excess” water in the canal, mainly due to low wet season rainfall (62.1 cm), was the main reason for limited pumping during the 2009-2010 wet season. Significant pumping during dry seasons of 2012-2013 and 2013-2014 occurred mainly due to high flow conditions in the canal (Fig. 2), canal flows during these two periods were about double the observed average dry season flow. Higher canal pumping during wetter seasons/years indicates that implementation of the PES on similar agricultural impoundments can potentially provide water retention services during the periods when it is needed most.

Tropical storm Fay resulted in the direct input of 18 cm (1.7 million m³) of rainfall into the impoundment-marsh on 19th August, 2008. Despite this inflow from Fay and subsequent pumping from the C-40 canal, the peak daily water storage occurred 42 days after this storm (1st October 2008, Fig.3). Additional pumped inflows from C-40 canal after October 2008 did not increase the storage in the impoundment-marsh as outflow almost balanced inflow during this time. Continuous pumping for 53 days from 9/19/2008 to 11/9/2008 in combination with Fay rainfall kept the impoundment-marsh almost full during Oct-Dec 2008. On the other hand, lowest average daily wet season storage (29.4 cm) occurred during 2009-2010, which received only 62.1 cm of rainfall with relatively low (18.4 cm) pumping during this period. Average daily dry season storage was highest in 2012-2013 (68.9 cm) and 2008-2009 (68.4 cm) due to high wet season rainfall and pumping which increased the antecedent storage in the impoundment-marsh.

Water retention efficiency (Eq 3) of the impoundment-marsh varied from 24.9% in 2012-2013 to 82.7% in 2011-2012 with an average of 51.9% (Fig 4). Lowest observed outflow (39.7 cm) and high subsurface (67.1 cm) losses resulted in highest water retention efficiency during 2011-2012 (Table 1). Lowest water retention efficiency during 2012-2013 was due to high inflows (pumping and rainfall) combined with high outflows resulting partially from lack of available storage in the impoundment-marsh (Fig 3 and 4). High wet season rainfall (116.3 cm) during 2012-2013 resulted in high storage in the impoundment-marsh resulting in outflow being higher than pumped inflow (Table 1). Highest daily average dry season storage (68.9 cm) in the impoundment-marsh during 2012-2013, resulted in the outflow (125.3 cm) being close to the dry season pumping (130.2 cm). Overall, although the site was primarily designed for nutrient retention services, results show the PES can also provide water storage service and help reduce surface flows to LO which can help reduce releases to estuaries. Although part of the water retained at the impoundment-marsh may flow back to LO through subsurface pathways, it will be of different volume and phase which is an environmental service.

Nutrient Treatment

Phosphorus and Nitrogen Loads

Over the seven-year study period, the impoundment-marsh received a total of 61,407 kg of P through pumping and atmospheric deposition while it discharged 7,407 kg through surface flows. Annually retained P varied from 3,111 kg in 2009-2010 to 20,620 kg in 2016-2017 and P treatment efficiency varied from 56.5% in 2008-2009 to 96.6% in 2016-2017 with an average of 85.1% (Fig 5). Except the first year (2008-2009), P treatment efficiency was higher than 80% for all the years. Increased residence time and reduced short circuiting of pumped inflow due to enhanced distribution of pumped water within the marsh achieved from the diversion berm and pump relocation in Jan 2010 helped increase the P retention efficiency after 2008-2009. Phosphorus treatment efficiency varied mainly as a factor of TP concentration in the inflow and outflow (Fig. 6). For 2008-2009, average P concentration in the outflow samples (0.17 mg/l) was about half of the pumped samples (0.34 mg/l). However, for the remaining six years, the

average TP concentration in outflow (0.06 mg/l) was about 8 times lower than the inflows (0.46 mg/l). Despite low water retention efficiency (<50%), phosphorus treatment efficiency was greater than 80% during the last three years (2012-2013, 2013-2014, 2016-2017) of monitoring (Table 1, Fig 5), mainly due to higher reductions in outflow P concentrations relative to the inflow concentration (Fig 6). This difference in P concentration is due to a combination of settling of sediment bound P, soil sorption, biological uptake, and dilution. High nutrient concentration in the inflow samples during June-August 2016 period were mainly due to the canal cleaning upstream of the pumping site, although outflow concentration didn't show similar changes (Fig 6).

The impoundment-marsh received total of 494,603 kg nitrogen through pumping and atmospheric deposition and discharged 181,278 kg through surface flows. The nitrogen treatment efficiency varied from 41.2% in 2012-2013 to 87.5% in 2011-2012 with an average of 63.4% (Fig 5). Nitrogen treatment efficiency closely followed the water retention efficiency for first three years (2008-2011) mainly because the N concentrations in the inflows were only slightly higher than the outflow, as compared to the remaining years (Fig 6). For 2011-2012, although the average N concentration in inflow (3.67 mg/l) was more than twice the outflow (1.67 mg/l), N-treatment efficiency (87.5%) didn't increase proportionally due to already high water retention efficiency (82.7%). For last three years (2012-2013, 2013-2014 and 2016-2017), N-treatment efficiency was mainly governed by N-concentration in inflow and outflows (Fig 5 and 6). Despite low water retention efficiencies during these years (Fig 4), N-treatment efficiencies were comparatively higher due to high N concentration in inflows and low N concentration in the outflow (Fig 5 and 6).

Phosphorus treatment efficiency of the impoundment-marsh was higher than N treatment efficiency especially during last three years of monitoring. Nitrogen is more soluble and less reactive than P resulting in less retention of N while passing through the impoundment-marsh, however a larger fraction of sediment and dissolved P was retained (settling and adsorbed) by soil within the impoundment-marsh. The pattern of increasing P treatment efficiency until 2011 and a stabilization thereafter (Fig 5) could

partly be due to changes in vegetation including the expansion of cattails within the impoundment-marsh. The expansion of cattails was observed by the FRESP team including the scientist from the Archbold Biological Station (Dr Elizabeth Boughton, personal communication) and the principal author. As the area of cattails increased throughout the impoundment-marsh, resistance to surface flows, and travel time for surface flows may have increased. With increased travel times for flows through the impoundment-marsh, sedimentation of suspended particles (inorganic with P and organic with N and P) carried by surface flows also increased. Overall, increased hydraulic residence time due to board installation in diversion berm culverts, pump relocation and changes in vegetation enhanced the treatment efficiency after the first year of monitoring.

For nutrient treatment calculation, subsurface losses were not considered. If 10% of the average inflow is lost through the subsurface according to our estimates, an equivalent portion of the N and P retained can move out of the impoundment-marsh through subsurface pathways. However, a significant part of this subsurface loss can be retained in the subsurface soil before it is returned to the C-40 canal or other downstream locations.

Subsurface losses can be estimated if hydraulic heads of surficial and confined aquifers outside and inside the impoundment-marsh and hydraulic conductivity of various layers are known. Considering that hydraulic conductivity of the soil and aquifer material can vary considerably and were not measured as part of this study, the quantification of subsurface losses through Darcy's approach was not attempted. A part of the total inflow to the impoundment-marsh could have been lost through subsurface losses. Although a part of the subsurface P losses can move back to the canal and other areas outside, the amount of P is likely to be much reduced due to adsorption and biological uptake as it travels subsurface before emerging in the C-40 canal or other downstream locations.

Overall, the impoundment-marsh, over a period of seven years, removed 54,765 kg of phosphorus (85.1% treatment efficiency) and 321,239 kg of nitrogen (63.4% treatment efficiency). Average unit area treatment was 48 and 8 kg/ha/yr of N and P, respectively, for the seven years of monitoring. These results show that the impoundment-marsh was successful in providing a high level of environmental services of both N and P retention. The impoundment-marsh can be classified as a net assimilator of P and N. In the long-term, there is a limit to how much P can be retained in the impoundment-marsh, even though N can continue to be removed for longer periods of time, if suitable conditions (saturation) are present to promote denitrification. Several biophysicochemical processes account for nutrient retention in the impoundment-marsh. These include sedimentation, nutrient uptake by plants and microorganisms, adsorption onto organic and inorganic components of the soils, and water retention. The significance of each of these processes mainly depends on the fractions of the N and P in dissolved and particulate forms in inflow, hydraulic residence time, and soil and vegetation characteristics. Increased P treatment efficiency after pump relocation and installation and management of culvert boards in the intermediate berm indicate that enhanced distribution of inflow through the marsh may increase the nutrient treatment efficiency of similar PES sites. Utilization of storage capacity of the impoundment-marsh especially during high nutrient concentration periods in the canal may further increase N and P retention and treatment efficiency.

Soil P Changes

Location and results of soil samples for SRP, TP and EPC (Shukla et al., 2012) are presented in Fig. 7. EPC data show that the low lying areas closer to the outflow location have higher potential to adsorb P than upland areas (Fig 7). Total P concentrations in the surface (10 cm) soil generally decreased from 2008 to 2012 in the impoundment-marsh (Fig. 8) (Shukla, 2012). In 2008 soil TP concentrations ranged from 8.70 to 783.4 mg/kg and in 2012, it ranged from 30.86 to 474.0 mg/kg. The change in soil TP concentration between 2008 and 2012 ranged from -752.5 to 425.2 mg/kg.

Large spatial variability in soil TP for both 2008 and 2012 (Fig 8) may partly be responsible for not observing increased soil TP as a result of pumped inflow of P.

An average of TP measured for individual soil samples taken throughout the impoundment-marsh for 2008 and 2012, showed that P was generally removed (-376 kg TP/ha) from the soil over the period. Removal of P from the soil may partially be explained by changes in vegetation. Davis (1991) found that $0.64 - 4.16 \text{ g m}^{-2} \text{ yr}^{-1}$ ($6.4 - 41.6 \text{ kg ha}^{-1} \text{ yr}^{-1}$) of P were stored in the growing leaves of cattail plants found in a Water Conservation Area located in south Florida; i.e., $25.6 - 166.4 \text{ kg ha}^{-1}$ over a four year period (2008 – 2012). This does not include the P stored in 40 % of the plant's biomass located below ground. The growth of cattails in the impoundment-marsh in certain area can partially be due to the uptake of P from the soil between 2008 and 2012.

Economic Analyses

The process of converting the existing impounded marsh into a water quality treatment study site for the FRESP started in 2006. Between January, 2006 and July, 2008 when the monitoring began, approximately \$250,000 were invested mainly in planning, obtaining the permits, constructing the diversion berm, and purchase of the C-40 pump. Among all categories, the average annual investment was maximum for fuel for the C-40 pump (\$55,000) followed by vegetation maintenance in the impoundment-marsh (\$8,000), personnel to manage the pump operation (\$6,000), pump maintenance and repair (\$5,000), berm maintenance (\$3,000), and structure/culvert maintenance (\$500). The 20-year present value of the investment was estimated to be approximately \$1,483,000. Based on the amount invested in a particular year and P retained during that year, 2016-2017 proved to be the most effective year with a cost of treatment of \$3.60/kg of P treated followed by 2010-2011 (\$10.85), 2011-2012 (\$13.22), 2012-2013 (\$14.11), 2009-2010 (\$18.71), 2013-2014 (\$19.22), and 2008-2009 (\$22.82) (Fig. 9).

Sano et al. (2005) conducted a cost analyses of several state-managed STAs. Each STA received water from the Everglades Agricultural Area and was assumed to have a

life span of 50 year. Data reported by Sano et al. (2005) showed that the cost of treatment ranged from \$32 to \$1775 per kg of P treated. The average cost of treatment was reported to be \$720 per kg of P treated. The estimated cost of P treatment for the treatment PES site was \$15.51 per kg of P treated. The unit cost of treatment was calculated from the 20-year worth of investment and conservative P retention estimates (using minimum of the seven years, 95,559 kg). With a treatment cost less than half of the minimum amount (\$32/kg P) the state invests in treating P through STAs, the PES approach proved to be highly cost-efficient. Sano et al. (2011) also considered water storage benefits while conducting the cost-effectiveness analysis. Although, primarily a PES, nutrient treatment site, the impounded marsh reduces nutrient loads by targeting both nutrient concentrations and volume.

The water retention function of the site which led to reduction in peak flow rate was an additional service provided by the landowner. The financial incentive provided by the state to the landowner in lieu of additional water storage service on private lands, is about \$100 per acre-foot of additional storage (SFWMD, 2014). A conservative estimate of 20-year present worth of the water storage services provided by the PES site was approximately \$13,000,000. Assuming that the state at least pays \$32 for every kg of P removed by the STAs which is the minimum unit cost of removal among all STAs estimated by Sano et al. (2005), the 20-year worth of P removal services provided by the PES site was conservatively estimated to be \$2,322,000. In essence, an investment of \$1,483,000 would yield services worth at least \$15,322,000 amounting to a benefit of \$13,839,000 to the state. If the state decided to pay just 50% of this benefit to the landowner distributed over a span of 20 years, it would amount to an additional income of \$346,000 per year to the landowner.

Summary and Conclusion

The key for successful implementation of a payment for ecosystem services (PES) program is the accurate quantification of the services being provided. The focus of the PES program at the nutrient treatment site was the removal of P from public waters

diverted from the C-40 canal, using a privately owned impoundment-marsh system. Seven years of observed hydrologic and water quality data were utilized to quantify the nutrient removal services yielded by the site. Although, primarily a nutrient removal site, additional service of water retention provided by the PES site was also quantified. The overall water retention efficiency of the impoundment-marsh was 51.9% with the annual efficiency varying from 24.9% to 82.7%. The site removed 54,765 kg (8 kg/ha/yr) of P and 321,239 kg (48 kg/ha/yr) of N during the monitoring period which might have otherwise be discharged to the Lake Okeechobee. The overall average annual TP treatment efficiency was 85.1% while the TN treatment efficiency was 63.4%. The P treatment efficiency for the site is already high. Further increases in P treatment and reductions in loads could be achieved by utilizing the storage capacity of the impounded-marsh especially during periods with high nutrient concentrations.

During the nine-year study, the PES site served as a net sink of not only P but also N. A long-term study on changes in soils P and vegetation patterns would be needed to determine how long and under what circumstances the impoundment-marsh will continue to serve as a sink. The impoundment-marsh experienced some changes in vegetation. A stand of cattail developed in several portions of the impoundment-marsh after the implementation of PES represents a potential shift in vegetation. In planning for wetland management at the regional scale, the trade-off between nutrient retention/water storage and biodiversity could be considered to maintain a wide array of wetland ecosystem services. The goal of the PES project was to reduce the P loads to the Lake Okeechobee. Therefore, the change in vegetation in the impounded-marsh can be considered as an acceptable trade-off given the spatiotemporal changes in inundation and nutrient inputs.

A conservative economic feasibility analyses showed the cost of treatment using PES site to be \$15.15/kg of P treated. If the average P treatment observed during the monitoring period was to continue, the treatment cost will be \$9.41/kg of P. This study verifies that agricultural lands can cost efficiently provide the environmental service of treating N and P. Additional analyses showed that if the water retention services are

also considered payable by the state, it would lead to an additional income of \$346,000/yr to the landowner. Similar agricultural sites in Florida could be used to provide water storage and treatment services at a fraction of state-funded projects on public lands (e.g. STAs, reservoirs). Future efforts could be directed at quantifying the subsurface flows and exploring the avenues to maintain the N and P removal. Recent studies (Shukla et al., 2017a, b, and c) have shown that aged agricultural impoundments can become saturated with P due to decades of continued input of P and could become a potential source of P. To circumvent such conditions at the PES sites, alternative management approaches such as biomass harvesting (Shukla et al., 2017c) which can mine accrued P from the system to partially restore the P adsorption capacity should be explored. The biomass removed can be used for beneficial purposes on the farm. Overall, history of low P inputs and presence of deeper, permanently inundated sections at the impoundment-marsh is likely to maintain this site a net P sink. Given the high level of water/nutrient retention at the impoundment-marsh site, agricultural lands with similar conditions and in close proximity of waterways should be explored to find a win-win solution for the agencies and agriculture.

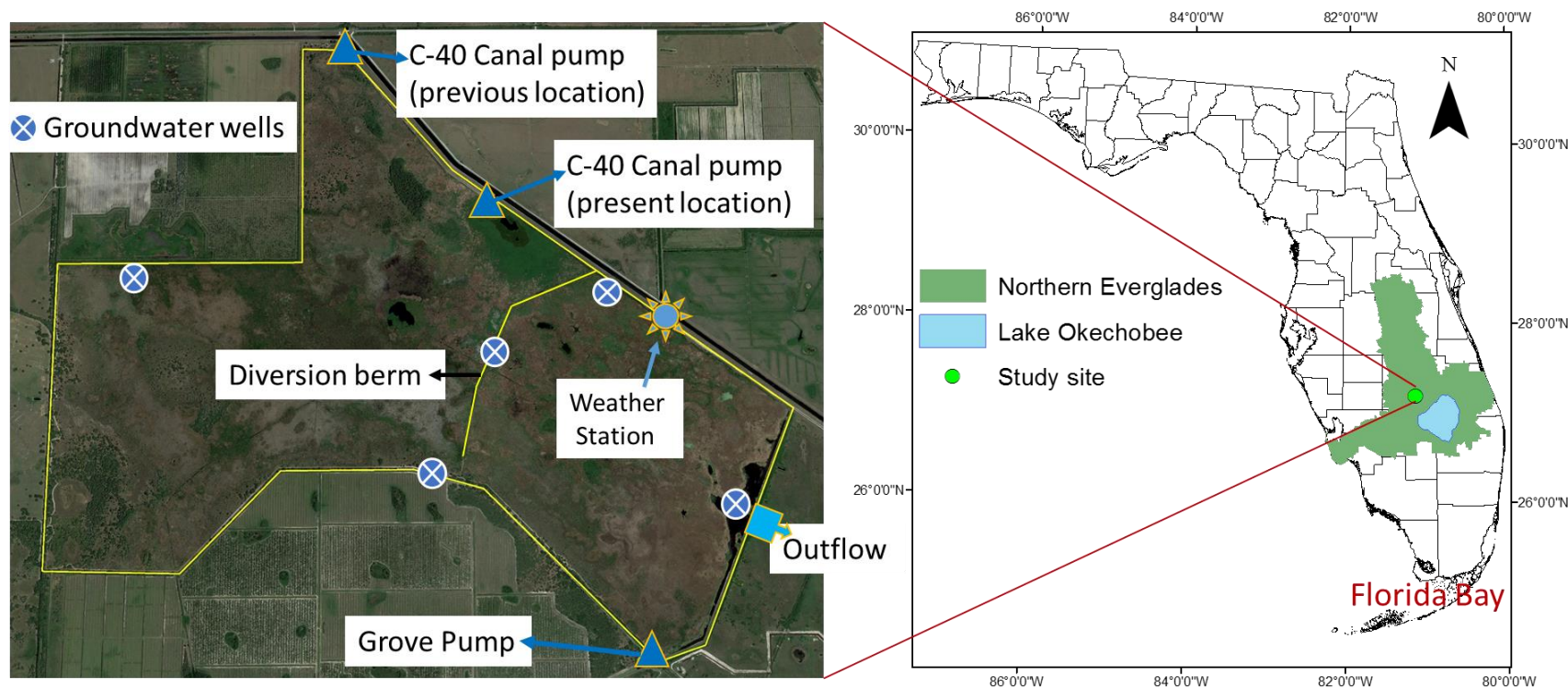


Fig. 1. Study site in the Northern Everglades basin, Florida. The C-40 Canal pump diverts the Canal water through the impoundment-marsh and the grove pump drains a citrus grove located north of the impoundment (960 ha). The diversion berm in the middle of the impoundment helps spreading the pumped water and reduces short circuiting of water to the outlet. The C-40 pump was moved to a new location in January 2010.

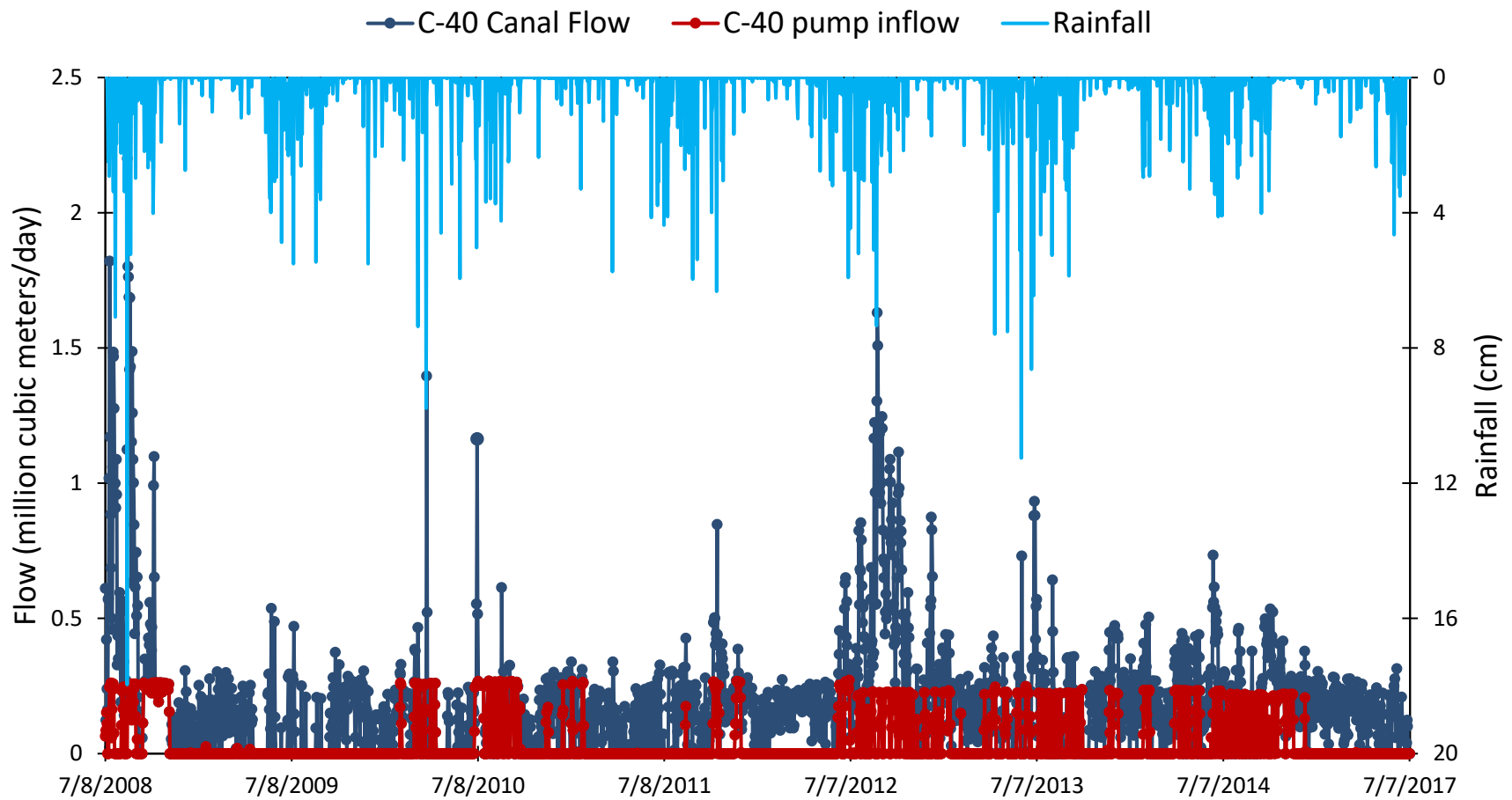


Fig. 2. Daily pumped inflow from C-40 canal into the impoundment-marsh (960 ha), C-40 canal flow, and rainfall for the 2008-2017 period. The missing data period was between 7/8/2014-7/7/2016.

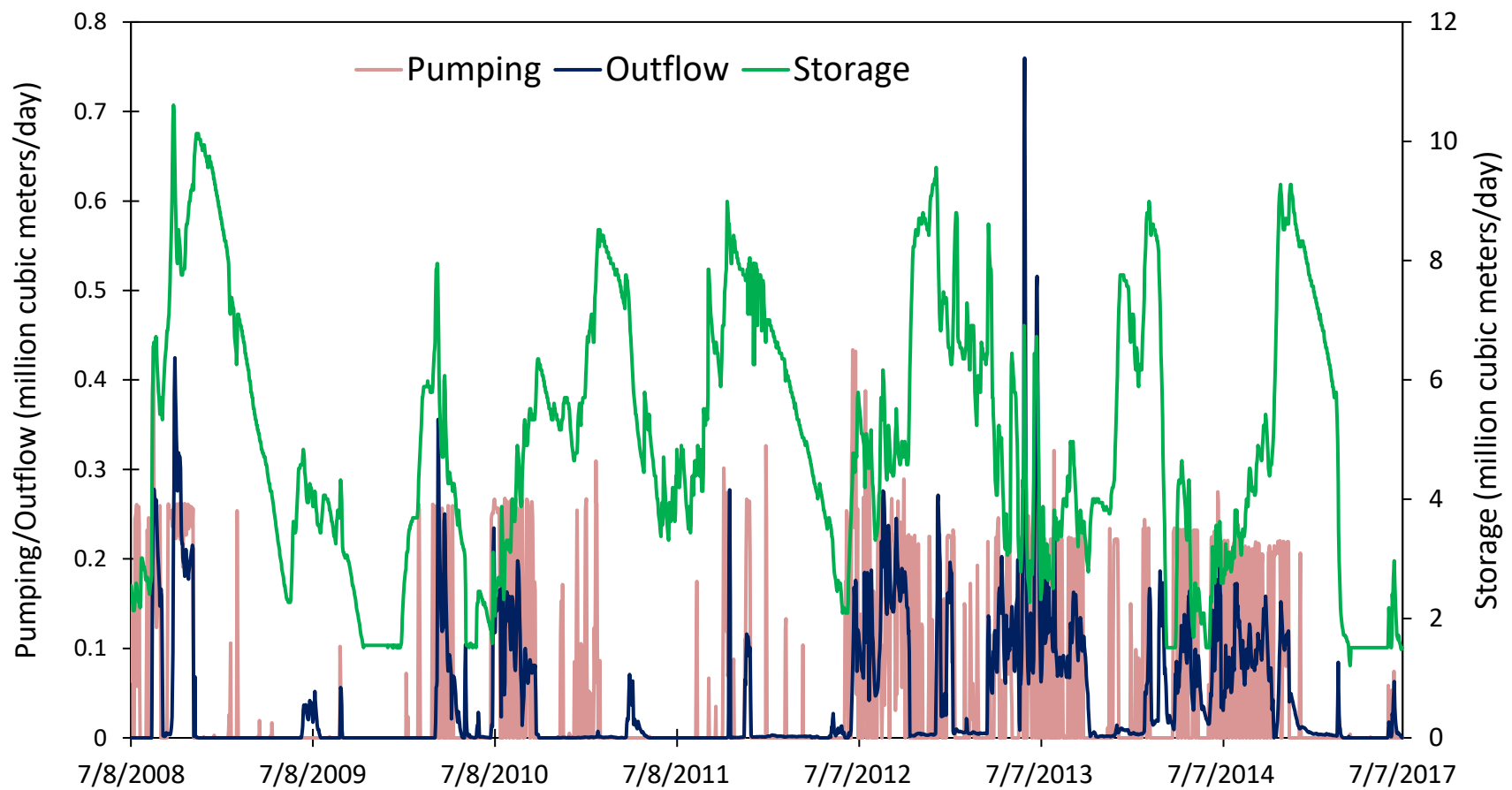


Fig. 3. Surface storage in the impoundment-marsh (960 ha), pumped volume (C-40 and grove pump) and outflow during the 2008-2017 period. The missing data period was between 7/8/2014-7/7/2016.

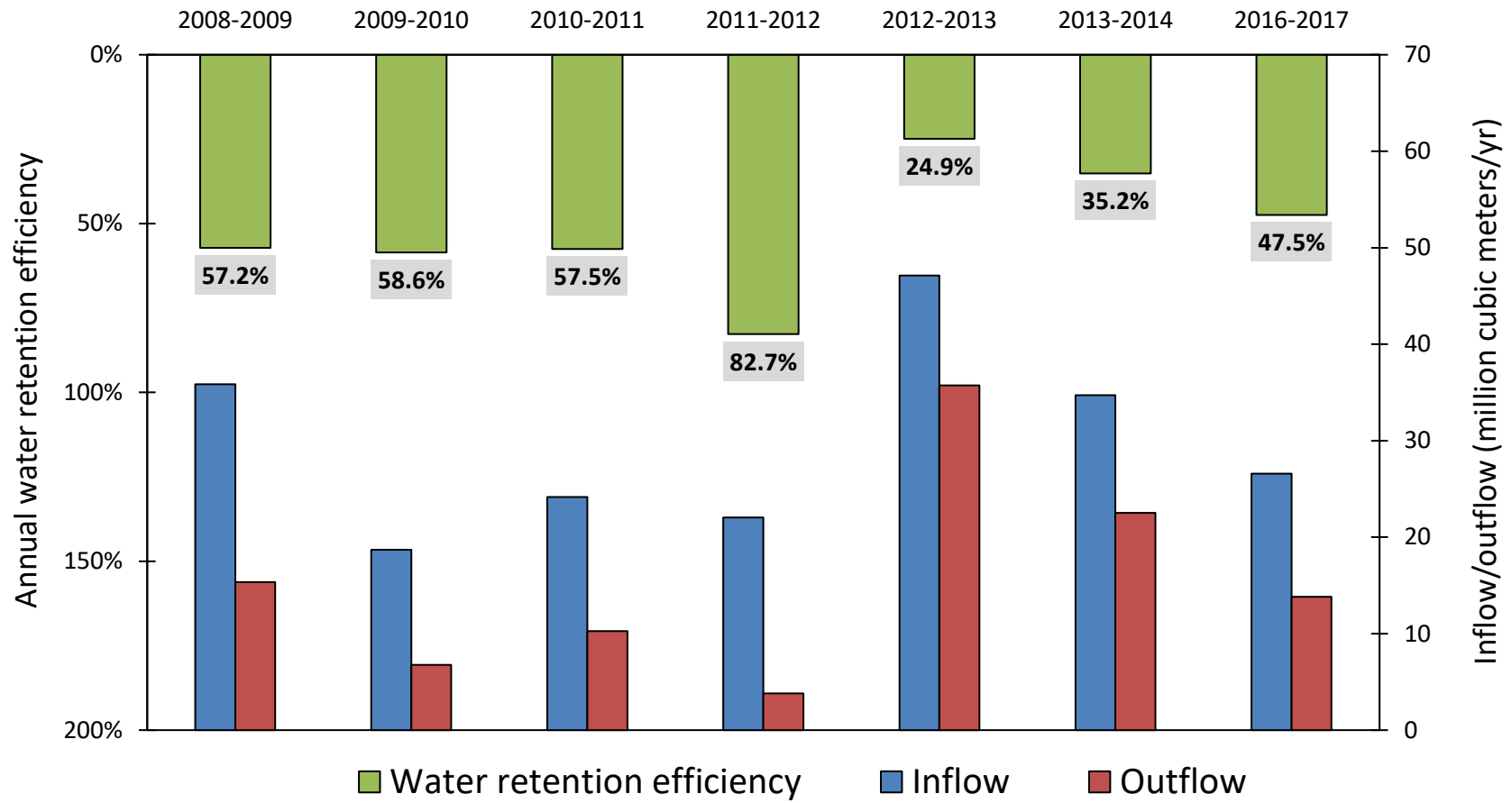


Fig. 4. Annual inflow, outflow and water retention efficiencies of the impoundment-marsh (960 ha) during 2008-2017.

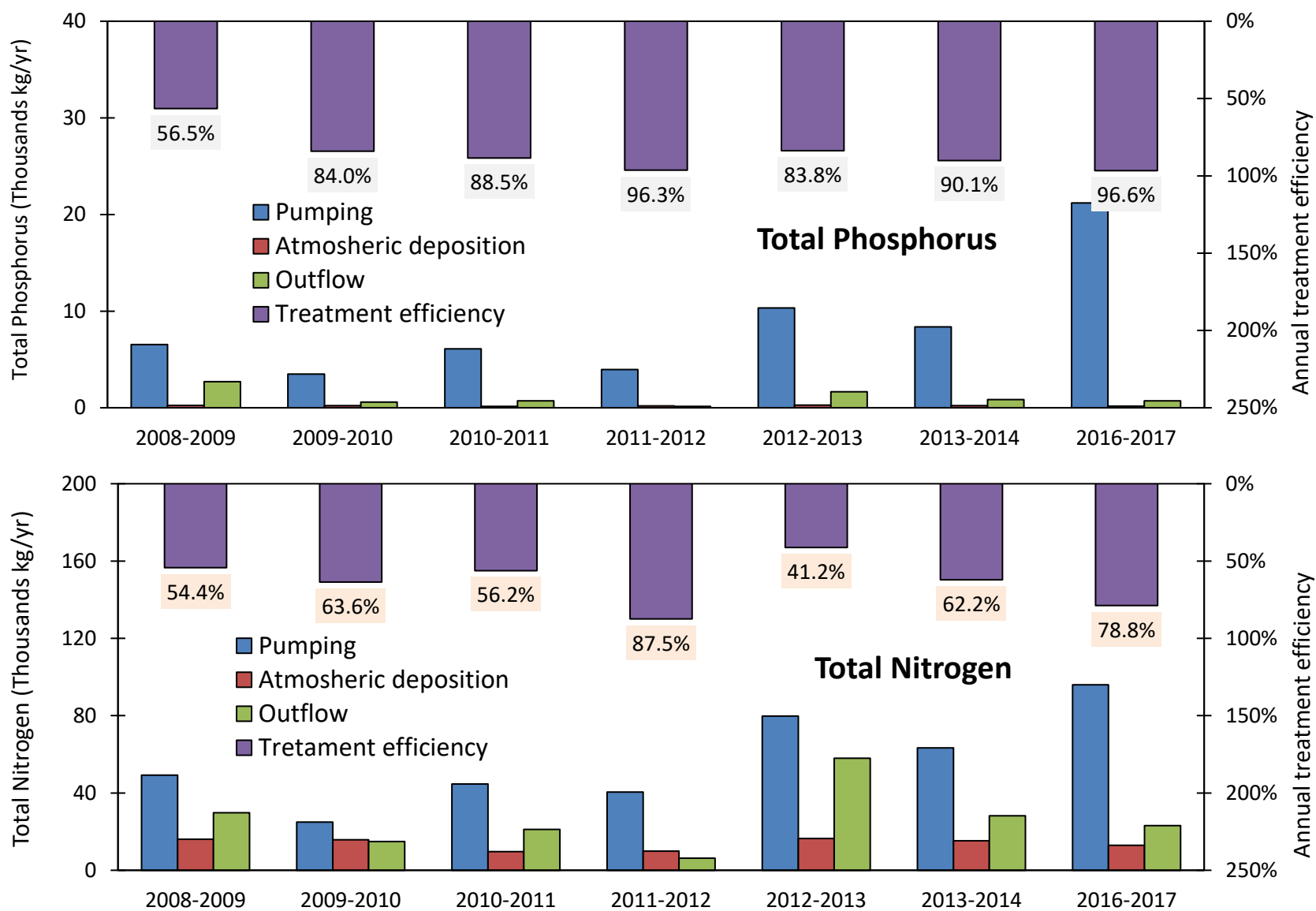


Fig. 5. Annual phosphorus and nitrogen inflow, outflow and treatment efficiencies for the impoundment-marsh (960 ha) during 2008-2017.

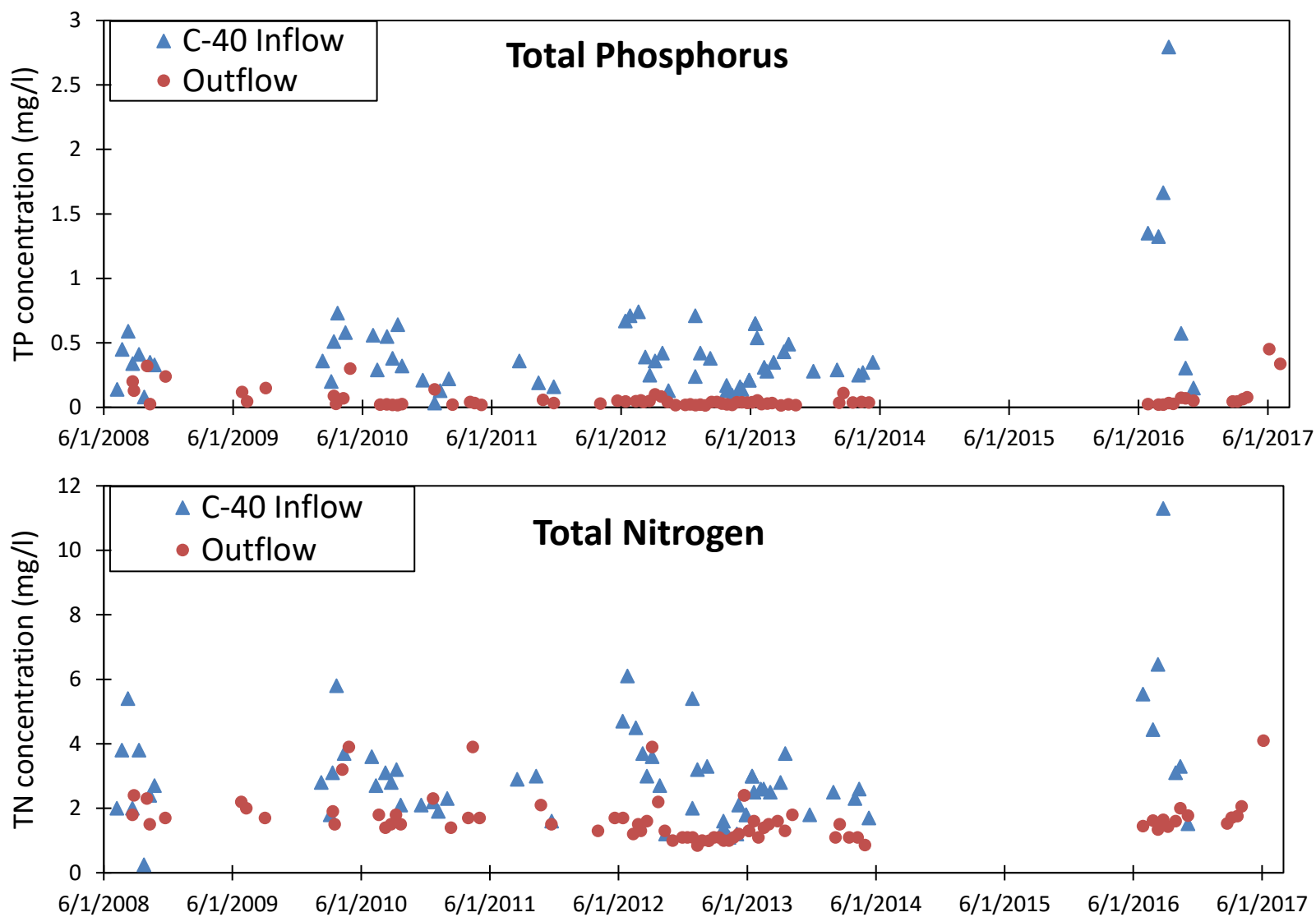


Fig. 6. Total phosphorus (TP) and total nitrogen (TN) concentrations in the inflow (C-40 pump) and outflow samples during 2008-2017 at the impoundment-marsh. The missing/incomplete data period was between 7/8/2014-7/7/2016.

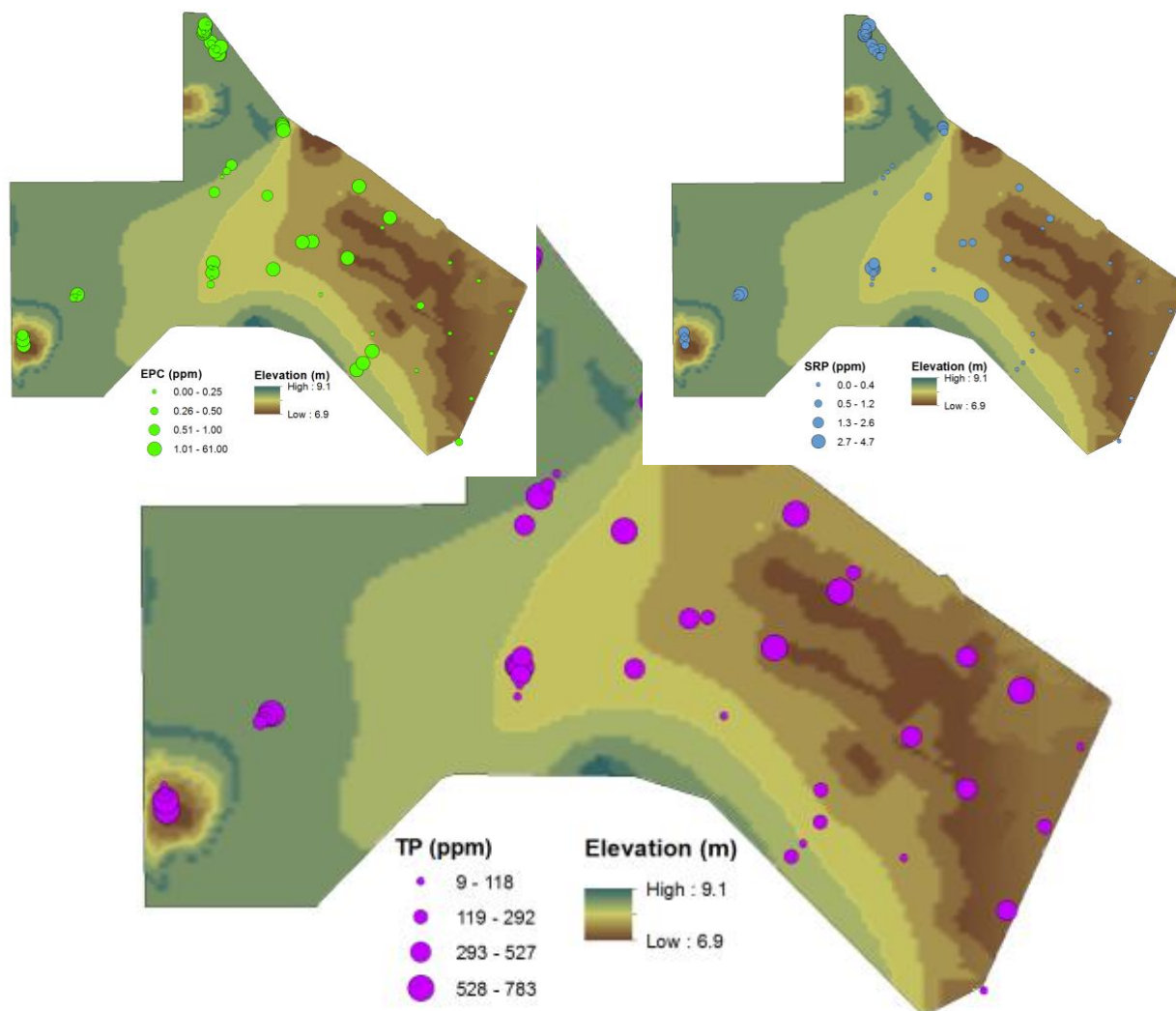


Fig. 7. Soluble reactive phosphorus (SRP), Total phosphorus (TP), and Equilibrium phosphorus concentrations (EPS) for soil sampling locations at the impoundment-marsh.

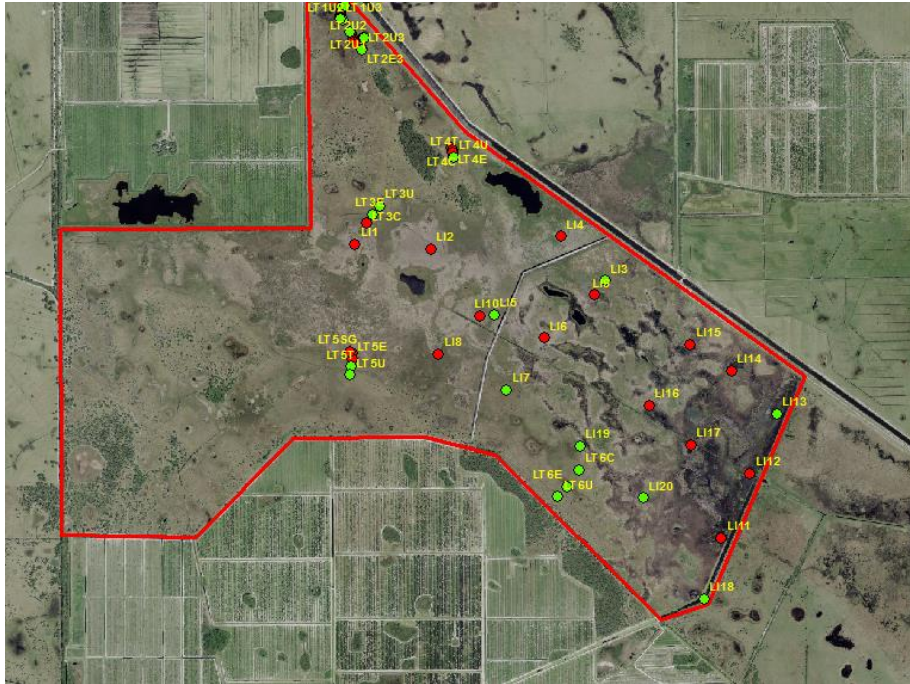


Fig.8. Locations where soil was sampled during 2008 and 2012. Green dots indicated phosphorus (P) retention and red dots indicate P removal from soil.

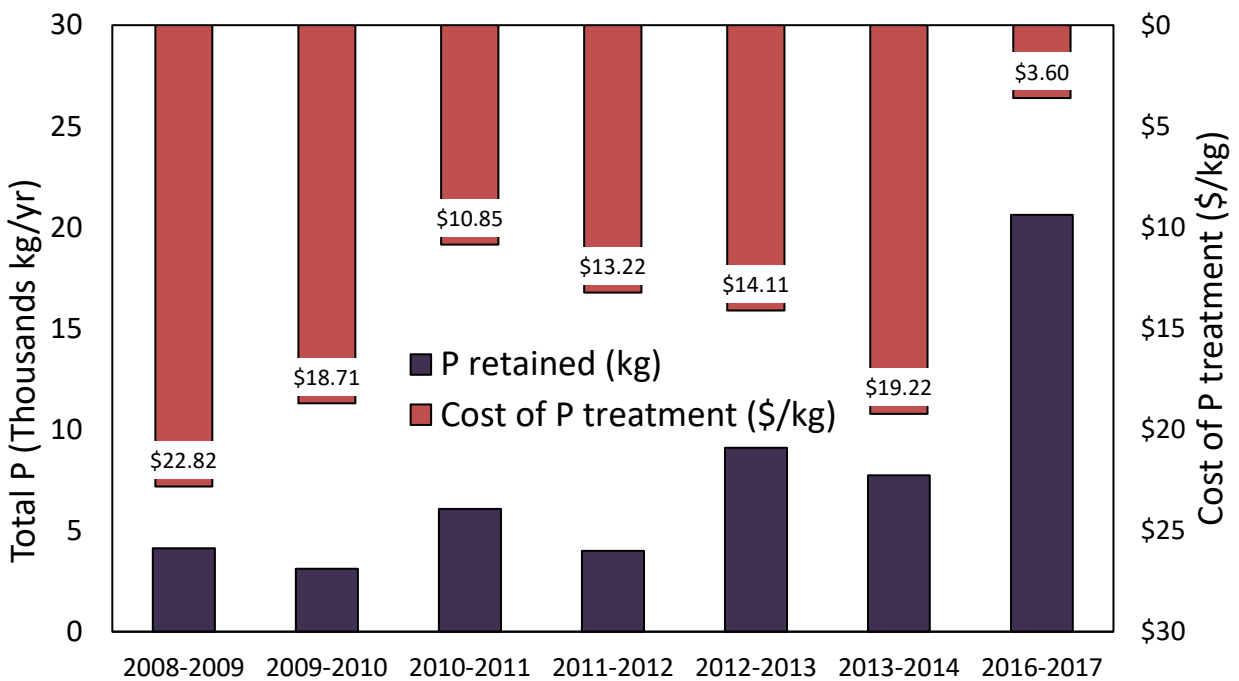


Fig. 9. Annual phosphorus (P) mass retained and the cost of P treatment for the impoundment-marsh (960 ha) during 2008-2017.

Table 1. Annual water balance components (cm) for impoundment-marsh (960 ha; 2008-2014, 2016-2017).

Year	Inflow		Losses		Change in surface storage ¹	Subsurface losses+error ²
	Pumping	Rain	Outflow	ET		
2008-2009	225.8	147.8	151.6	131.6	-15.2	66.9
2009-2010	72.8	121.8	70.3	126.1	13.4	11.6
2010-2011	169.5	82.1	106.9	126.7	-16.8	1.2
2011-2012	120.3	109.4	39.7	116.9	-13.7	59.3
2012-2013	328.5	162.4	372.3	107.5	18.6	29.7
2013-2014	235.6	126.1	234.4	113.6	-2.6	11.0
2016-2017	181.4	95.6	144.0	125.7	11.3	18.5
Average	190.6	120.7	161.1	121.2	-0.7	28.3

¹ Net change in surface storage of impoundment-marsh (initial minus final storage).

² Subsurface losses+error is a net term and indicates subsurface gains or losses plus any error in the estimation of remaining water balance components in equation 2.

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