# Synthesis, Guidance, and Knowledge Gaps of the Science Plan for the Everglades Stormwater Treatment Areas

SFWMD-2025-001

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South Florida Water Management District
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# EXECUTIVE SUMMARY

The *Science Plan for the Everglades Stormwater Treatment Areas* (Science Plan) was developed in 2013 and revised in 2018 as a framework to guide scientific research of key mechanisms and factors affecting phosphorus (P)[1] retention in the Everglades Stormwater Treatment Areas (STAs) (SFWMD 2013, 2018a). Studies included in the Science Plan were developed primarily to support the design, operation, and management of STAs to achieve and sustain total phosphorus (TP)[2] concentrations to meet the water quality-based effluent limit (WQBEL)[3]. The implementation of the Science Plan was mandated under Consent Orders (Office of General Counsel OGC Files No. 12-1148 and 12-1149) with the National Pollutant Discharge Elimination System (NPDES) and Everglades Forever Act (EFA) Watershed Permit (No. 0311207), issued in 2012 and amended in 2017 and 2022. The 2012 *Restoration Strategies Regional Water Quality Plan* identified a suite of projects designed to achieve the WQBEL, specifically flow equalization basins (FEBs), STA expansions and associated infrastructure, conveyance improvements, and Science Plan development and implementation (SFWMD 2012b).

The 21 Science Plan studies evaluated hydrologic, physical, chemical, and biological processes that affect TP concentrations discharged from the STAs to the Everglades Protection Area. Processes that affect STA performance and sustainability were considered. A list of key questions and sub-questions based on knowledge gaps and uncertainties from the 2013 Science Plan was reevaluated and revised to reflect updated priorities in the 2018 Science Plan. The revised questions were based on information gained during the initial 5 years of implementation. New studies were added as a result of the 2018 revised Science Plan.

An improved understanding of P cycling, P retention, and factors reducing P retention within the STAs was gained from the studies undertaken and the questions answered through the implementation of the Science Plan. Much of this knowledge verified previous understanding of constructed treatment wetlands. Collectively, the answers to these questions have led to a set of proposed options that support management to achieve the WQBEL. Several of the Science Plan questions remain unanswered and new questions arose.

## OVERALL FINDINGS OF SCIENCE PLAN

- P retention varies among the flow-ways (FWs). The variations are attributed to one or more factors: (1) land use before conversion to STAs, (2) soil types, (3) soil TP content, (4) inflow waters, (5) topography, (6) plants, (7) hydrology, and (8) type, location, and number of control structures.
- Rooted aquatic plants remove P from the soil into the aboveground shoots and leaves where it can be returned to the water column. These plants are not P limited despite P limited conditions in the water column of outflow regions.
- Emergent aquatic vegetation (EAV) reduces flow velocity and redistributes inflowing water allowing particulate P (PP) to settle out.
- Cattails, the major species of EAV in the STAs, exhibits signs of stress when water depths are at 2.8 feet (ft) or greater for more than 4 weeks.

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[1] P is often a subset of total phosphorus (TP), which is comprised of P species, dissolved P, and particulate P. P also is used when referring to an action such as load, retention, and storage.

[2] TP is used here to denote the sum of all P forms in a given matrix (water or soil).

[3] The WQBEL has two parts: (1) TP as an annual flow-weighted mean concentration (FWMC) discharged from each STA shall not exceed 13 micrograms per liter (µg/L) in more than 3 out of 5 water years on a rolling basis; and (2) the annual FWMC from each STA shall not exceed 19 µg/L in any water year (FDEP 2012b).

- Cattails respond to deep water of 2.8 ft or greater by elongating their leaves, which allows them to maintain gas exchange and photosynthesis but can weaken them structurally.
- Cattails exposed to deep water of 3.5 ft or more for over 8 weeks elongate their leaves to reach the water surface. If water depths decline rapidly after 8 weeks, these cattail will fall over (lodge), because elongated leaves are too weak to hold the plant upright without support from the buoyancy of the water column.
- Rooted submerged aquatic vegetation (SAV) can remove P from the water column and soils. Unrooted SAV, primarily *Chara*, removes P from the water column and may absorb P diffusing from underlying soils. The process of photosynthesis by SAV creates the conditions for particulate calcium carbonate ($CaCO_3$) formation, which removes P from the water column through co-precipitation.
- The live and dead shoots and leaves of EAV and SAV provide surface area for periphyton (attached algae and other microbial organisms) that directly absorb P from the water column and mineralize organic P to simpler forms through enzymes. Photosynthesis by periphyton and SAV, increases the water pH, causing a chemical reaction to create $CaCO_3$, a particulate, which co-precipitates P into the soils.
- Litter accumulating in EAV areas accretes into organic soil. Based on soil extraction chemistry, approximately 25% of this recently accreted organic P soil is non-reactive (recalcitrant and unavailable for plant uptake), 50% is reactive (available for plant uptake), and 25% is highly reactive (labile organic P, dissolved inorganic P and microbial P).
- Marl soil, an amalgam of calcium (Ca) minerals including $CaCO_3$ and calcium phosphate ($CaPO_4$), accumulates in SAV areas. While it can be resuspended, it settles out quickly because of its heavy bulk density.
- Open areas where sunlight can penetrate the water column contribute to the breakdown of organic material (and organic P forms) into simpler compounds, which can be further mineralized by periphyton enzymes and removed by SAV and periphyton.
- Fish and other fauna consume plants and floc, excreting P back into the water column. The amount of P excreted by small fish is estimated to be similar in amount to the external P loads.
- Bioturbation of P (biotic resuspension of soil) by large fish is an order of magnitude smaller than small fish excretion. However, bioturbation activities, especially nesting, may result in increased P concentrations in outflow regions. The construction of nests in these areas dislodges some plants and buries others under soil as a result of digging.
- Internal P loading (iPLR) from soil resuspension, translocation by rooted plants, and faunal bioturbation and excretion can be as substantial as external loads.
- P removal by particle settling, chemical transformation, and uptake by periphyton and non-rooted aquatic vegetation greatly exceeds the sum of iPLR and external P loading rate (PLR), effectively retaining up to 80% of the external P load and reducing TP water column concentration at the outflow region of STA FWs.
- There is a trend in the water column, soils, and plants along well performing FWs from high TP content at the inflow to low TP content at the outflow. Internal loads also decrease from inflow to outflow regions in these well performing FWs.

- Periphyton store excess P as polyphosphate chains; these chains are found in PP of the outflow water column of well performing FWs and may be retained in soils through chemical reactions with $CaCO_3$.
- Soluble reactive P and PP decline substantially along a well performing FW.
- The content of dissolved organic P (DOP) changes very little along FWs, however the chemical composition of DOP does change as plants, fauna, and microbes absorb, break down, and release a variety of DOP molecules.
- Ultrafine particulate P, between 3 kilo Daltons (kDaltons) and 0.25 microns, makes up a large percent of the discharge P from well performing FWs. Conversely, truly dissolved P (less than 3 kDaltons), which is very biologically active, is a small portion in the discharge from well performing FWs.
- When cattail density is high, water velocity is low, and water depth is shallow, the water is dispersed more evenly within a FW.

## RECOMMENDATIONS OF SCIENCE PLAN[4]

- Maintain annual PLRs below 1.3 grams P per square meter per year (g P/m$^2$/yr) for each individual FW.
- Maintain hydraulic loading rates between 5 and 15 centimeters per day (cm/d) during flow periods.
- Maintain hydraulic loading rates between 1.7 and 3.5 cm/d on an average annual basis.
- Avoid continuous water depths of 2.8 ft or more for more than 8 consecutive weeks in cattail regions.
- Avoid rapid water depth reductions after water depths have been kept above 3 ft for more than 4 to 6 weeks in cattail regions.
- In outflow cells/regions, maintain mixed EAV/SAV communities.
- Maintain EAV as windrows in outflow cells to protect SAV communities.
- Manage EAV in outflow cells to prevent overgrowth into SAV areas.
- If further P retention is needed to meet the WQBEL, a periphyton-based STA (PSTA), which is constructed by removing muck soils to caprock may be an option.
- If PSTA implementation is not feasible, in lieu of muck removal, cap soils with 0.5 to 0.7 ft of limerock at outflow regions of FWs.
- Where floating wetlands (formerly known as tussocks) formation is observed or imminent, lower water depths below 1 ft if possible.
- Plant deep rooted plants (e.g., spikerush or bulrush) to anchor cattail.
- Limit fish density and nesting in STA outlet regions through selective EAV planting.
- Manage fish populations by reducing water depths to 1.5 ft or lower, especially in the dry season.

[4] **Table 2** provides the background information that led to these recommendations.

- Avoid high P-loading to SAV communities.
- Where SAV communities have collapsed, if possible, reduce water depths as low as possible for a month and then maintain low water depths (1.64 ft or below) for at least 5 weeks before returning to normal outflow operations.
- Maintain SAV regions to enhance photolysis.
- SAV ecotopes, which are relatively homogenous communities of plants exposed to similar chemical and physical environmental conditions, of *Chara* and naiad should be encouraged at STA outflow regions.
- In outflow regions of the FWs, remove rooted floating aquatic vegetation.
- After substantial periods of no-flow (weeks to months) introduce low flows gradually to reduce effects of high TP and high flows, which influence the annual flow weighted mean concentration.

## KNOWLEDGE GAPS

- What are the best structural design features for delivering water to and from the STAs and FEBs?
- What are the effects of topography on STA performance?
- What is the effect of wading birds on fish, invertebrates, aquatic vegetation, and P cycling?
- What is the effect of ducks on SAV sustainability?
- Are there methods beyond maintenance of water depths to discourage endangered bird nesting in STA cells?
- Can prescribed fire be used to improve water flow, P retention, and SAV/cattail health?
- What is the effect of alligators on fish, aquatic vegetation, and P cycling?
- Does laminar flow result in lower TP outflow concentrations?
- Can periphyton enhance marl adhesion?
- How long and under what conditions does marl become rock?
- How deep can marl be before it cannot be colonized by rooted SAV?
- What length/area of PSTA is needed to consistently attain WQBEL with inflow P concentrations ranging from 15 to 20 micrograms per liter (µg/L)?
- What depth of limerock cap is needed to simulate PSTA?
- Can marl accumulation effectively create PSTA?
- Do fungi provide a significant role in P cycling?
- Can environmental DNA, often measured from water column samples, surveys be used to evaluate plant community diversity and can this be related to P retention?
- Does the increase in the concentration of carbon dioxide ($CO_2$) in the atmosphere affect P retention or plant growth?
- Can rafts of mussels be used to reduce PP in canals and the L-8 FEB?

# CONTRIBUTORS

The South Florida Water Management District (SFWMD) gratefully acknowledges the many professionals who have carried out studies and contributed to Science Plan studies. The professionalism and dedication of the high-caliber technical experts who contributed to understanding how STAs remove and retain P is recognized and sincerely appreciated. This document borrows heavily from previous reports: the Restoration Strategies Science Plan (SFWMD 2018a), the Data Analysis, Integration and Synthesis Plan (SFWMD et al. 2018), and the summary reports for each study posted on SFWMD's external website (https://www.sfwmd.gov/our-work/restoration-strategies/science-plan.

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# ACRONYMS, ABBREVIATIONS, AND UNITS OF MEASUREMENT[5]

| | |
|---|---|
| µg/L | microgram(s) per liter |
| µm | micron(s) |
| ac | acre(s) |
| ac-ft | acre-foot or acre-feet |
| Al | aluminum |
| BGC model | Biogeochemical model |
| C | carbon |
| Ca | calcium |
| $CaCO_3$ | calcium carbonate |
| $CaPO_4$ | calcium phosphate |
| CASM | Comprehensive Aquatic Ecosystem Model |
| CEPP | Central Everglades Planning Project |
| cfs | cubic feet per second |
| cm | centimeter(s) |
| cm/d | centimeter(s) per day |
| DIP | dissolved inorganic phosphorus |
| DOC | dissolved organic carbon |
| DOM | dissolved organic matter |
| DOP | dissolved organic phosphorus |
| EAA | Everglades Agricultural Area |
| EAV | emergent aquatic vegetation |
| EFA | Everglades Forever Act |
| EPA | Everglades Protection Area |
| EPC | equilibrium phosphorus concentration |
| FAV | floating aquatic vegetation |
| FDEP | Florida Department of Environmental Protection |
| Fe | iron |
| FEB | flow equalization basin |
| Framework Agreement | Everglades Water Quality Restoration Framework Agreement between U.S. Environmental Protection Agency, Region IV, and Florida Department of Environmental Protection |
| ft | foot or feet |
| FW | flow-way |
| FWMC | flow-weighted mean concentration |
| g $P/m^2/yr$ | gram(s) phosphorus per square meter per year |
| g/kg | gram(s) per kilogram |
| HLR | hydraulic loading rate |

[5] See **Appendix A** for short titles and full titles of the Restoration Strategies Science Plan Studies.

| | |
|---|---|
| iModel-RSOPD | iModel for Restoration Strategies Operational Protocol Development |
| iPlR | internal phosphorus loading rate |
| K | potassium |
| kDalton | kilo Dalton(s) |
| kg | kilogram |
| LPWEM | Low Phosphorus Wetland Event Model |
| $m^2$ | square meter(s) |
| Mg | magnesium |
| mg P/$m^2$/yr | milligram(s) phosphorus per square meter per year |
| mg/kg | milligram(s) per kilogram |
| Mn | manganese |
| N | nitrogen |
| NPDES | National Pollutant Discharge Elimination System |
| P | phosphorus |
| PLR | phosphorus loading rate |
| PP | particulate phosphorus |
| PSTA | periphyton-based stormwater treatment area |
| RAS | recently accreted soil |
| rFAV | rooted floating aquatic vegetation |
| RSM | Regional Simulation Model |
| RSOP | Restoration Strategies Operational Protocol |
| SAV | submerged aquatic vegetation |
| SCADA | supervisory control and data acquisition |
| Science Plan | *Science Plan for the Everglades Stormwater Treatment Areas*[6] |
| SEM | statistical structure equation model |
| SFWMD | South Florida Water Management District |
| SOP | standard operating procedure |
| SRP | soluble reactive phosphorus |
| STA | stormwater treatment area |
| t | metric ton |
| TP | total phosphorus |
| TVDLF | Total Variation Diminishing Lax-Friedricks model |
| UAS | unmanned aircraft system |
| UV | ultraviolet |
| WCA | water conservation area |
| WDAT | Water Depth Assessment Tool |
| WQBEL | water quality-based effluent limit |
| WY | water year (begins May 1 of the previous year and ends April 30 of the following [water] year) |

[6] SFWMD (2013, 2018a).

# INTRODUCTION

In accordance with the 2012 Everglades Water Quality Restoration Framework Agreement between U.S. Environmental Protection Agency, Region IV, and Florida Department of Environmental Protection (Framework Agreement) and the *Restoration Strategies Regional Water Quality Plan* (SFWMD 2012b), the *Science Plan for the Everglades Stormwater Treatment Areas* (Restoration Strategies Science Plan or Science Plan; SFWMD 2013) was developed and implemented to investigate factors influencing total phosphorus (TP) retention in the Everglades Stormwater Treatment Areas (STAs). The Science Plan was mandated under Consent Orders (Office of General Counsel OGC Files No. 12-1148 and 12-1149, dated August 15, 2012) with the National Pollutant Discharge Elimination System (NPDES) and Everglades Forever Act (EFA) watershed permits for the Everglades STAs (Florida Department of Environmental Protection [FDEP] Permit Numbers FL0778451 and 0311207-006, respectively), issued to the South Florida Water Management District (SFWMD) in 2012 (FDEP 2012a, b) and amended in 2017 (FDEP 2017) and 2022 (FDEP 2022a, b). Key topics covered in the Science Plan include vegetation sustainability, faunal effects, phosphorus (P) cycling and biogeochemistry, internal P loads, and hydrology. This synthesis, guidance, and gap analysis of studies implemented through the Science Plan support the design, operation, and management of the STAs to achieve discharge water quality requirements for TP.

## GOALS AND OBJECTIVES

The Science Plan (SFWMD 2013, 2018a) provided the overall framework for development and coordination of science activities to identify the critical factors influencing P reduction and treatment performance to meet the water quality based effluent limit (WQBEL) for the Everglades STAs.

The Framework Agreement specifies three objectives of the Science Plan that are evaluated in this current document:

1. Identify the critical factors that collectively govern P treatment performance.
2. Maximize the understanding that can be gained from existing data, designs, and operations.
3. Identify the critical information gaps and research areas that will further treatment objectives to meet the WQBEL at each STA.

These objectives were included in the Consent Orders associated with the EFA and NPDES watershed permits. The Consent Orders identified key areas for further scientific studies, which was a starting point for the Science Plan:

1. P loading rates (PLR)
2. Inflow P concentration
3. Hydraulic loading rates (HLR)
4. Inflow water volumes, timing, pulsing, peak flows, and water depth
5. P speciation at inflows and outflows
6. Effects of microbial activity and enzymes on P uptake
7. P resuspension and flux and flux management measures
8. Stability of accreted P
9. P concentrations and forms in soil and floc
10. Influence of water quality constituents such as calcium (Ca)

11. Emergent and submerged aquatic vegetation (EAV and SAV) speciation, density, and cover
12. Weather conditions such as hurricanes and drought
13. Interrelationships among these factors

The 21 studies, including the Data Integration and Analysis Study, which is completed by this report, are summarized here based on the objectives of the Framework Agreement and the questions posed in the Science Plan (SFWMD 2018a) and *Data Analysis, Synthesis, and Integration Plan* (SFWMD et al. 2018). Specific objectives are as follows:

1. Summarize the studies and their results.
2. Answer key questions from the Science Plan (SFWMD 2018a).
3. Define knowledge gaps based on these questions.
4. Provide a list of recommendations for management of the STAs to support attaining the WQBEL.

## WATER QUALITY BASED EFFLUENT LIMIT

The WQBEL is a numeric limit applied to all permitted discharges from the Everglades STAs to ensure such discharges do not cause or contribute to exceedances of the 10 micrograms per liter (µg/L) TP criterion within the Everglades Protection Area (EPA) in accordance with Rule 62-302.540, Florida Administrative Code (SFWMD 2012d). WQBEL compliance is monitored at individual discharge points from each STA. The WQBEL includes two criteria:

1. Discharge from each STA cannot exceed 13 µg/L as an annual flow-weighted mean in more than 3 of 5 water years (WYs[7]) on a rolling basis.
2. Discharge from each STA cannot exceed 19 µg/L as an annual flow-weighted mean in any water year.

The two parts of the WQBEL were developed to allow for annual variability in the STA discharge TP concentration while attaining the long-term TP criterion in the EPA described in the Consent Orders (FDEP 2012a).

# STA AND FEB OVERVIEW

## GENERAL DESCRIPTION

The Everglades STAs, mandated by the EFA (Section 373.4592, Florida Statutes), were constructed south of Lake Okeechobee to reduce TP from runoff water prior to entering the EPA (**Figure 1**). STA-1E, STA-1W, STA-2, STA-3/4, and STA-5/6 are operated, maintained, and managed by SFWMD. The Everglades STAs currently encompass 62,000 acres (ac) with an additional 1,800 ac (STA-1W Expansion #2) that was completed in 2024. **Appendix C** contains detailed STA and flow equalization basin (FEB) schematics. In addition, two FEBs, A-1 FEB and L-8 FEB, were completed in 2015 and 2018, respectively, as part of the *Restoration Strategies Regional Water Quality Plan* and are operated to attenuate peak stormwater flows and improve inflow delivery rates to downstream STAs (**Figure 1**). The A-1 FEB is a shallow 15,000-ac impoundment with a capacity of approximately 60,000 acre-feet (ac-ft); the L-8 FEB is a deep 950-ac facility with a capacity of approximately 45,000 ac-ft. An additional FEB included in

[7] A water year begins on May 1 and ends in on April 30 of the next year (e.g., WY2024 is from May 2023 to April 2024).

Restoration Strategies is the C-139 FEB. This 2,800-ac facility, which has a capacity of approximately 11,000 ac-ft, has been constructed and should be operational in WY2025.

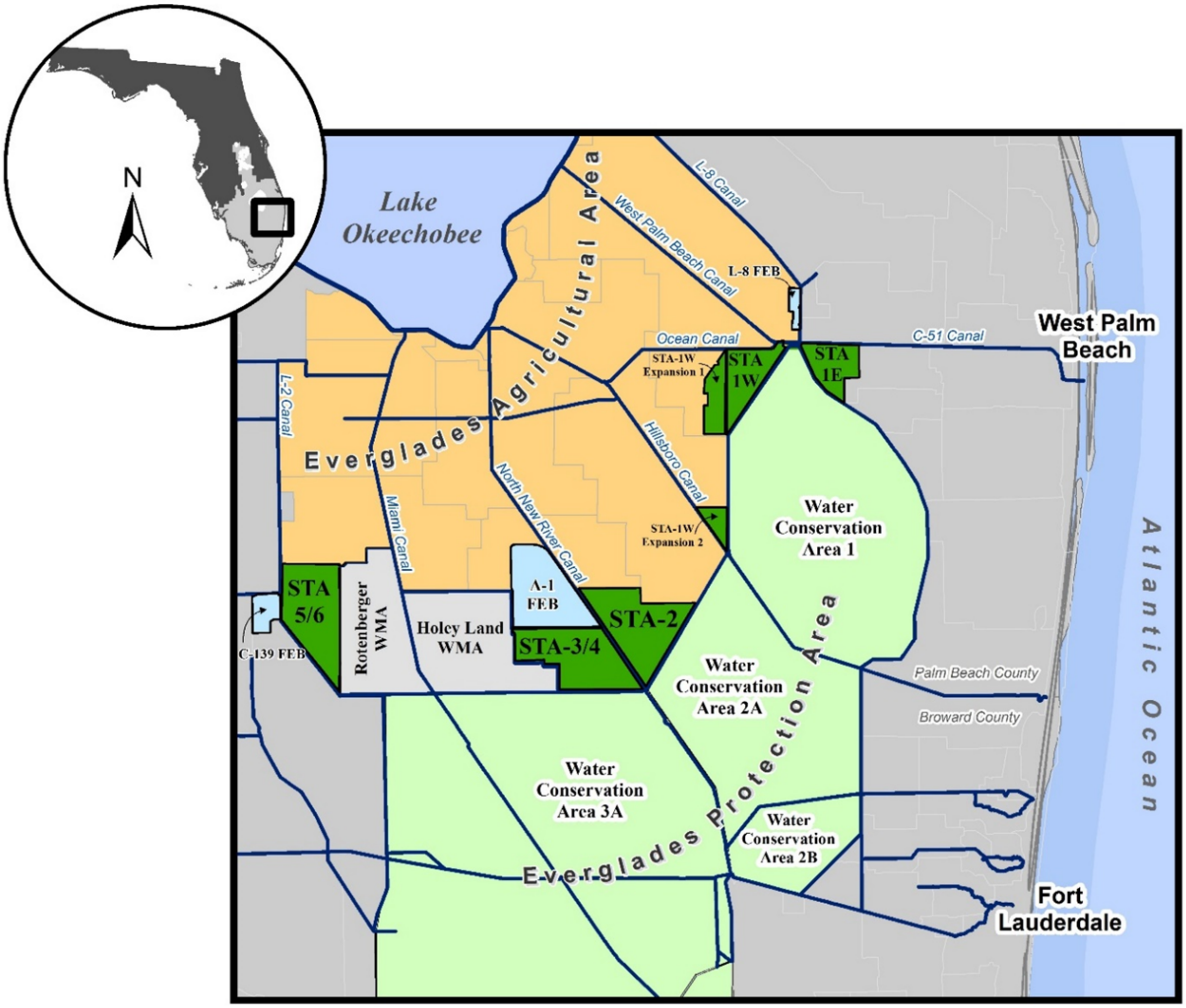



**Figure 1.** Map of the Everglades STAs and FEBs.

The STAs retain P through a number of mechanisms: plant nutrient uptake and litter accumulation, sorption, co-precipitation with minerals, particulate settling, and microbial uptake (**Figure 2**). Varying in size, configuration, and period of operation, the STAs are divided into treatment cells and flow-ways (FWs) by interior levees. Water flows through these systems via water control structures (e.g., pump stations, gates, culverts). The dominant plant communities in the treatment cells are broadly classified as EAV and SAV. In many cells, various species of floating aquatic vegetation (FAV) are present; however, there is a continuing effort to control nuisance FAV species. Cells generally have mixed vegetation types at varying proportions. Under favorable conditions, periphyton communities are interspersed among these vegetation communities.

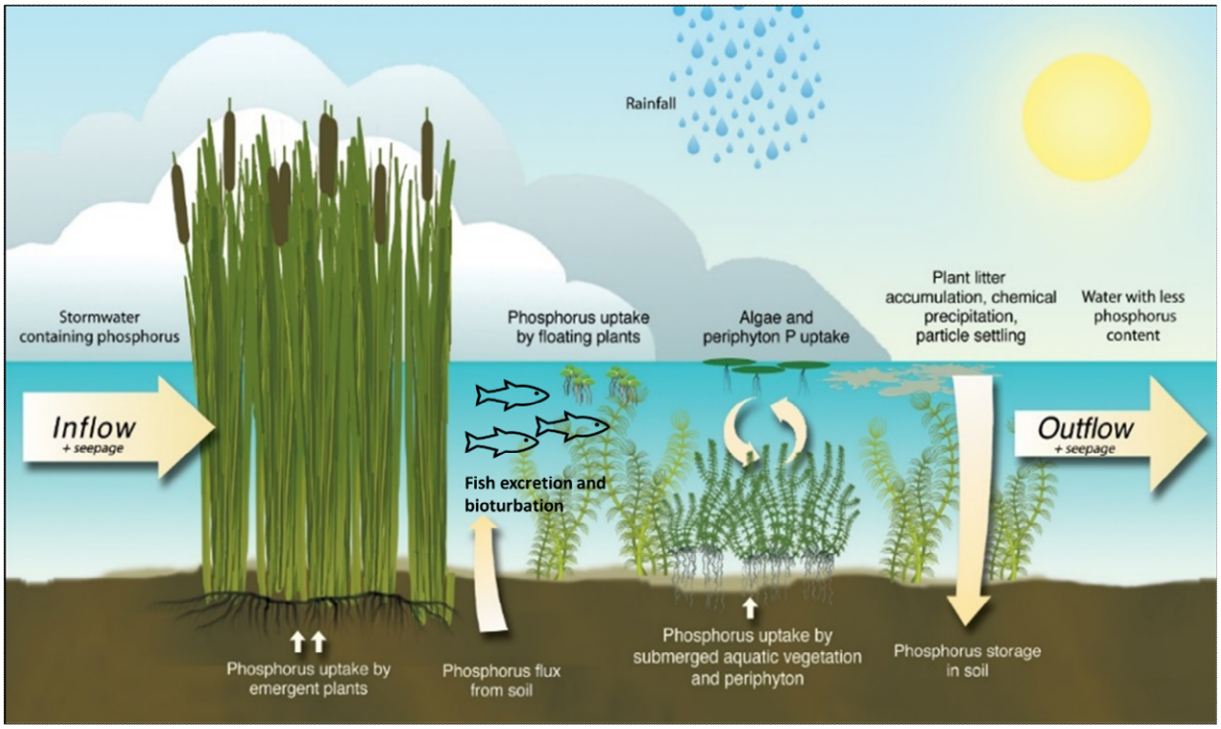



**Figure 2.** Schematic of P retention process and mechanisms in the STAs.

The SFWMD uses an adaptive approach to manage the STAs. Weekly data of inflow and outflow volumes, TP loads, TP concentrations, HLR, and PLR are compiled and reviewed for each STA FW (**Table 1**). FEB status, STA water depths, vegetation condition, vegetation management activities, construction, and any wildlife restriction issues, are also considered. This adaptive approach considers inclusion of Lake Okeechobee regulatory releases to the STAs, when capacity exists, for delivery south to the Everglades. Supplemental water from Lake Okeechobee is delivered to the STAs during dry periods, if needed. The FEBs are designed to attenuate peak stormwater flows and improve inflow delivery rates to the STAs. Improved inflow delivery provides enhanced operation and P treatment performance to achieve the WQBEL.

**Table 1.** An example of weekly STA performance summary. Summary for STA-2 showing annual (WY2024; 365 days), monthly (April 2024; 28 days), and weekly (7 days) estimates of flow, TP load and TP concentration. Sheets for each STA are generated and evaluated weekly.

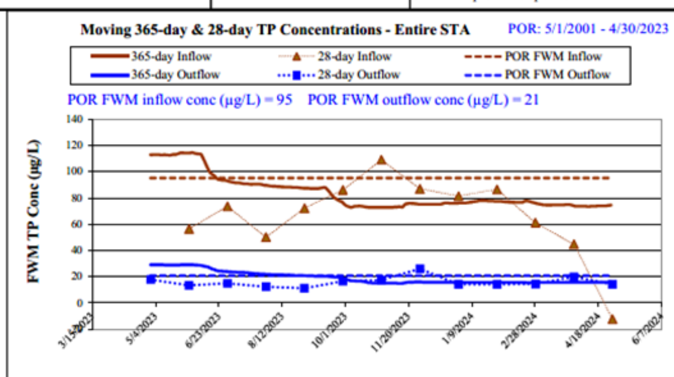
**WEEKLY STA PERFORMANCE SUMMARY**

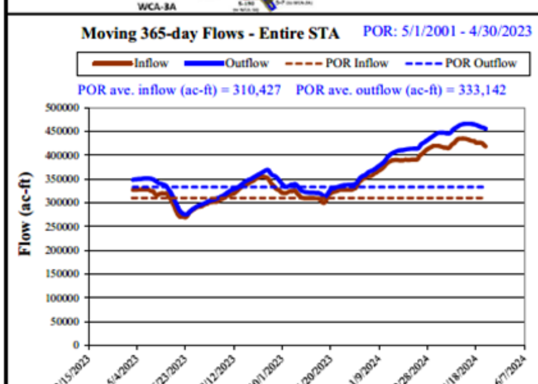
**PROJECT STA-2 DATE 4/29/2024 LATEST DATA 4/28/2024**

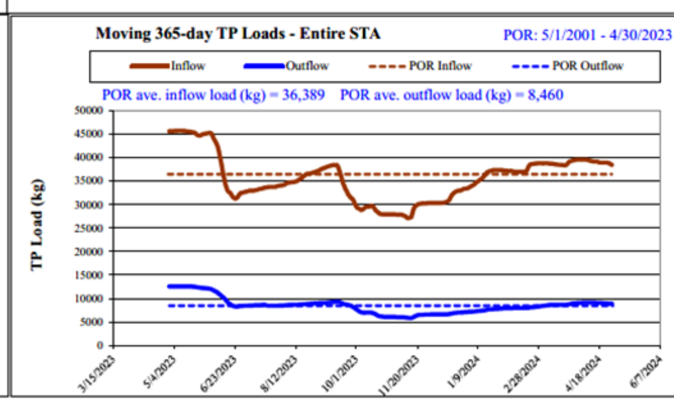
| WY2024 to Date Flow-weighted Mean Conc (μg/L) Inflow: 74 Outflow: 16 | | Entire STA | Flow-way 5 | Flow-way 4 | Flow-way 3 | Flow-way 2 | Flow-way 1 |
|---|---|---|---|---|---|---|---|
| 365-day Values | Inflow Volume (ac-ft) | 418,624 | 37,688 | 162,715 | 86,890 | 88,538 | 78,757 |
| | Inflow Load (kg) | 38,401 | 1,886 | 14,358 | 7,473 | 8,372 | 8,883 |
| | Inflow Flow-weighted Mean Conc (μg/L) | 74 | 41 | 72 | 70 | 77 | 91 |
| | Outflow Volume (ac-ft) | 456,024 | 35,131 | 145,907 | 100,563 | 100,463 | 105,290 |
| | Outflow Load (kg) | 8,867 | 427 | 1,674 | 2,732 | 2,531 | 1,355 |
| | Outflow Flow-weighted Mean Conc (μg/L) | 16 | 10 | 9 | 22 | 20 | 10 |
| 365-day load reduction (kg) | | 29,534 | 1,459 | 12,684 | 4,741 | 5,840 | 7,528 |
| 28-day Values | Inflow Volume (ac-ft) | 568 | 73 | 409 | 880 | no flow | 294 |
| | Inflow Load (kg) | -9 | 2 | 12 | 27 | no flow | 12 |
| | Inflow Flow-weighted Mean Conc (μg/L) | -12 | 27 | 24 | 24 | no flow | 32 |
| | Outflow Volume (ac-ft) | 7,761 | 913 | 3,376 | 2,058 | 244 | 1,003 |
| | Outflow Load (kg) | 137 | 13 | 53 | 48 | 9 | 13 |
| | Outflow Flow-weighted Mean Conc (μg/L) | 14 | 11 | 13 | 19 | 29 | 11 |
| 7-day Values | Inflow Volume (ac-ft) | no flow | no flow | no flow | no flow | no flow | no flow |
| | Inflow Flow-weighted Mean Conc (μg/L) | no flow | no flow | no flow | no flow | no flow | no flow |
| | Outflow Volume (ac-ft) | 307 | no flow | 165 | no flow | no flow | 9 |
| | Outflow Flow-weighted Mean Conc (μg/L) | 15 | no flow | 19 | no flow | no flow | 13 |
| 365-day phosphorus loading rate ($g/m^2/yr$) | | 0.6 | 0.2 | 0.6 | 0.8 | 1.2 | 1.2 |
| 6-month trend in outflow TP concentration (- means decrease; μg/L) | | -1 | 0 | 0 | 0 | -6 | -1 |

**Flow-Way Information (Research projects, stage-duration, vegetation, etc.)**

| Flow-way 5 | Flow-way 4 | Flow-way 3 | Flow-way 2 | Flow-way 1 |
|---|---|---|---|---|
| On-line | On-line | On-line | On-line | On-line |
| | On-line with restrictions for vegetation managements activities starting on 10/28/2019. | | On-line with restrictions for vegetation management activities starting on 08/14/2023. | On-line with restrictions for a topographic survey starting on 4/21/2024. Contains nest(s) of MBTA-protected species. |


The data provided in this summary report were developed using a combination of provisional and quality-assured flow and water quality data. In some cases, best professional judgment was used to estimate missing data or revise questionable data. Values provided are not considered final, but are appropriate for use in STA operational decision-making. The PLRs being reported on the weekly sheets are adjusted to account for length of time and/or treatment area offline.

## KEY FACTORS AND CHALLENGES TO STA PERFORMANCE

P retention in STAs is variable and affected by internal and external factors. Internal factors include antecedent land use, health of SAV and EAV communities, periphyton activities, soil P dynamics, and STA cell topography, size, and shape. External factors include weather patterns, inflow P concentrations, PLRs, variable water delivery rates that result in changing HLRs, water depths, hydropatterns (continuously flooded versus periodic dry out), maintenance and enhancement activities, regional operations, and wildlife use. The STAs are not operated in isolation as they are integral components of a complex water management system with multiple objectives, including flood control, water supply, and ecosystem restoration.

The primary source of water to the STAs is stormwater runoff, which must be treated before it is discharged to the EPA. Flow volume, P loads, and TP concentrations associated with stormwater runoff vary seasonally and annually. High loadings and extended periods of deepwater conditions can occur, which can adversely affect STA performance. During the dry season, particularly during droughts when sufficient water is not always available, some cells may partially or entirely dry out. Prolonged dry out conditions result in high water column TP concentrations upon rehydration. FEBs are designed to attenuate peak stormwater flows, temporarily store stormwater runoff, and improve delivery rates to the STAs. The FEBs may also be used to assist in maintaining minimum water depths and reducing the frequency of dry out conditions in the STAs. SFWMD implements a drought contingency strategy to minimize drought effects on STA performance. STA operations also are affected by wildlife use; in particular, species protected under the Migratory Bird Treaty Act and Endangered Species Act. STA water depths and flow conditions may be modified based on the *Avian Protection Plan for Black-necked Stilts and Burrowing Owls Nesting in the Everglades Agricultural Area Stormwater Treatment Areas* (Pandion Systems 2008).[8]

Effective management of desirable and undesirable vegetation in the STAs is critical to achieve and sustain required treatment performance. Herbicides are routinely used in the STAs for exotic/nuisance species control. This is particularly critical for FAV, which can shade out and adversely affect SAV community health. To accelerate SAV recruitment in areas converting from EAV to SAV, and in SAV areas undergoing rehabilitation, these cells are inoculated with SAV spores, seeds, and plant parts using equipment on land, in water, and in air via helicopter (Chimney 2024). EAV are planted in SAV areas to protect SAV from strong winds and flows. SFWMD has been planting alternative EAV, such as bulrush (*Schoenoplectus californicus*) and fire flag (*Thalia geniculata*) in areas of the EAV treatment cells that have experienced chronic cattail decline and loss.

The STAs are highly managed systems involving various personnel for routine operation and maintenance of pumps, gates, structures, planting of desired vegetation, and removal of unwanted vegetation. Scientists and engineers provide technical information and evaluation to ensure proper operation and optimal management, including collection and analysis of water quality, soil, vegetation, flow, and performance data. Cross disciplinary teams participate in weekly, biweekly, and monthly communication and coordination meetings. Water depths in each cell are monitored, and target stages are set from average ground elevations, depending on the dominant vegetation community and condition of the treatment cell. Site managers and scientists frequently visit the STAs. Following extreme weather conditions (e.g., droughts, tropical cyclones, significant rain events), plant communities and infrastructure components of the STAs are assessed. When desired performance is not being achieved, the technical team examines potential causes and implements corrective actions when feasible. Corrective actions can be operational such as reducing inflow loading to one flow way by redirecting flows to another flow way or reducing

[8] The Avian Protection Plan for Black-necked Stilts and Burrowing Owls Nesting in the Everglades Agricultural Area Stormwater Treatment Areas provides a framework to modify Everglades STA operations to minimize potential impacts to active nests of either species. This is accomplished by diverting water around cells or regulating inflow to these cells to avoid raising water levels and flooding nests.

target stages to allow vegetation to rejuvenate. Corrective actions also can include major rehabilitation activities or drawdowns for vegetation reestablishment.

# SCIENCE PLAN QUESTIONS

## BACKGROUND

The 2013 Science Plan was structured around 6 key questions and 39 sub-questions formulated through a series of workshops and meetings and based on a review of existing knowledge and information gaps regarding P reduction mechanisms and regulating factors, including physical, chemical, and biological processes (SFWMD 2013). Each STA was evaluated qualitatively to isolate issues affecting P reduction performance, identify areas for further investigation, and consider possible remedies.

This 2018 Science Plan (SFWMD 2018a) built on the original key questions and sub-questions. The key questions were used to guide and prioritize studies, which supported the goals and objectives of this plan and the Restoration Strategies Program. The sub-questions were reviewed, and several sub-questions were revised in the 2018 update for clarity and generalized to encompass multiple variables. Some of the original sub-questions were archived (Appendix D in SFWMD 2018). In addition, new sub-questions were formulated, based on remaining knowledge gaps and uncertainties (**Table 2**). The 2018 update added some new studies, and some studies were added after the 2018 update. Answers to the sub-questions from the 21 studies carried out under this Science Plan, as well as supporting information, are added to this table and further discussed in the text below.

**Table 2.** Science Plan for the Everglades STAs key questions and associated sub-questions.[1]

| Key Question | Sub-questions | Comments | References |
|---|---|---|---|
| 1. How can the FEBs/reservoirs be designed and operated to moderate inflow P concentrations and optimize PLR and HLR in the STAs, possibly in combination with water treatment technologies or inflow canal management? | How should storage in the FEBs/reservoirs be managed throughout the year so water can be delivered to the STAs in a manner that allows them to achieve the lowest outflow P concentrations? | The WaveBot application was originally designed to adjust gates to deliver water pulses to an STA cell to evaluate resistance based on wave period and frequency. A supervisory control and data acquisition (SCADA) system was developed using information from operational experience and the flow control program is consistent with tools such as WaveBot (Lal 2017). The SCADA system can automatically adjust gate operations to maintain near constant flow as headwater and tailwater change throughout the day. | Lal (2017) |
| | | The iModel was used to demonstrate that the flexibility of FEB deliveries to the STAs can result in improved (lower) outflow TP concentration. | Ali (2018) |
| 2. What operational or design refinements could be implemented at existing STAs and future features, including the STA expansions and FEBs/reservoirs, to improve and sustain STA treatment performance? | Are there operational refinements or improvements to the regional water management system that can be implemented to enhance FEB and STA performance while maintaining existing levels of flood protection? | A real-time version of the iModel is available to support flow distribution. | Ali (2015) |

**Table 2.** Continued.

| Key Question | Sub-questions | Comments | References |
|---|---|---|---|
| | | The power loss equation method replaced "Manning's n" in the Regional Simulation Model (RSM) leading to improved flow estimates within the STAs.<br>The power loss equations have been used by contractors in STA design.<br>The use of the power loss equation to estimate water depths along STA FWs increases the accuracy of Water Depth Assessment Tool (WDAT) results over the flat pool assumption; this has not been applied but could be useful to define areas of deep water, which can negatively affect the plant communities (e.g., cattail) if prolonged. | Lal (2017) |
| | Will reduced advective loading from the soil to the water column reduce P concentrations out of the STAs? | Indirect estimates of advective loading were evaluated using water and P budgets of selected STA cells. The uncertainty of these budgets was greater than any method to determine an advective load. | WSP Inc. (2022) |
| | | Using a simple model of an STA FW, the Low-P Wetland Event Model (LPWEM), and adding advective water and P load did not result in significant changes to outflow TP concentrations.<br>Management of advective loading will not reduce water column P. | WSP Inc. and Dynamic Solutions (2022) |
| | What are the best structural design features for delivering water to and from the STAs and FEBs? | Operation guidance for STAs and FEBs model efforts partially answered this question.<br>Field trials of various structures are not cost effective. Some modeling could be used to evaluate this question. This question remains a knowledge gap. | |
| | What are the effects of topography on STA performance? | In the past five years, there has been major construction in the STAs to improve the topography of given FWs.<br>Results of these improvements will be evaluated in post-Science Plan research. | Chimney (2024) |
| 3. What measures can be taken to enhance vegetation-based treatment in the STAs? | What key factors affect and what management strategies could improve system resilience of SAV communities? | Marl, muck, or aged muck soils do not affect non-rooting SAV growth.<br>High P loads can lead to dense SAV, which may then decline due to anaerobic conditions, low light levels and increased sulfite production.<br>SAV can germinate in bare areas rather quickly after a drawdown. | DB Environmental (2023b) |
| | | Herbivory can significantly impair SAV reestablishment especially of young growth plants, Herbivory is less of a factor in plants encrusted with Ca.<br>Bioturbation by fish can pull up rooted SAV plants and/or bury plants under soil moved by excavation for nests. | Goeke and Dorn (2024a) |
| | What key factors affect and what management strategies could improve system resilience of EAV communities? | Avoid continuous water depths of 2.8 feet (ft) or more for more than 8 consecutive weeks: cattail experience signs of stress and leaf elongation.<br>Avoid rapid water level declines after water depths have been kept above 2.8 ft for more than 4 to 6 weeks. Cattails' long leaves cannot support the weight when water declines and fall over (lodge) potentially dying and creating floating wetlands (formerly known as tussocks) when water depths increase in cattail regions. | Diaz et al. 2023 |

**Table 2.** Continued.

| Key Question | Sub-questions | Comments | References |
|---|---|---|---|
| | What are the differences in long-term P reduction between pure SAV communities and mixed SAV/EAV communities? | TP concentrations in SAV communities (ecotopes) in outflow cells were lower than cattail communities, especially in the wet season. | Powers (2024) |
| | Can various vegetation types (subtypes) enhance P uptake and reduction in SAV cells? | *Chara*, a non-rooting SAV, provides the best P retention of all SAV for waters at low P concentrations. | DB Environmental (2020)<br>Powers (2024) |
| | What are the short-term and long-term P reduction capacities of the dominant and other vegetation species in the STAs? | *Chara* is best for both short-and long-term P reduction for areas with low P concentrations (≤ 19 µg/L). | Powers (2024) |
| | | P reduction by *Chara* is affected by numerous conditions: flow, load, soil P content, and water depths. The percent removal can vary from over 80 to 20%. | DB Environmental (2023b) |
| 4. How can internal loading of P to the water column be reduced or controlled, especially in the lower reaches of the STAs? | What are the key physicochemical factors influencing P cycling in very low P environments? | During no flow conditions in outflow regions (SAV), particulate P (PP) and TP concentrations increase.<br>As flow returns, PP and TP concentrations decline. | Villapando et al. (2024) |
| | | Removal of high P soils reduces internal P loads and results in ultra-low P in outflow. | Zamorano et al. (2023) |
| | | In SAV regions, photosynthesis by SAV and periphyton results in chemical reactions that produce particulate calcium carbonate ($CaCO_3$) that precipitates out various P forms to create marl soils. | Reddy et al. (2021) |
| | | Photolysis can mineralize organic P forms to simpler molecules that can be taken up by periphyton or further reduced enzymatically. | Schafer et al. (2023) |
| | Are there design or operational changes that can be implemented in the STAs to reduce PP and dissolved organic P (DOP) in the water column? | Reduction of turbulent flow increased porous-media flow, reduced short circuiting.<br>Porous flow should increase P retention. | Lal (2017) |
| | | PP in SAV outflow regions increase during no-flow periods. After no-flow periods, when possible, slowly increase outflow. | Villapando et al. (2024) |
| 5. How can the biogeochemical or physical mechanisms, including internal flux of P, be managed to further reduce soluble reactive P (SRP), PP, and DOP concentrations at the outflow of the STAs? | What is the treatment efficacy, long-term stability, and potential impact of soil amendment or soil management? | Organic soil amendments to dried consolidated marl does not improve P retention. | DB Environmental (2023a) |
| | | Mesocosms that included SAV and 0.5 ft of limerock over muck soils reduced inflow concentration of 18 to 12 µg/l. | Grace et al. (2023) |
| | | Flipping of soils reduced the P flux from soil cores. | Josan et al. (2018) |
| | | Field studies could not demonstrate improved P conditions with flipped soils due to different hydrologic and vegetative conditions between the cell with flipped soils and the cell with non-flipped soils. | DB Environmental (2022b) |
| | What are the sources, forms, and transformation mechanisms controlling residual P pools within the STAs, and how do they compare to the natural system? | Accrued soils in EAV regions are primarily organic.<br>Internal loadings are affected by nutrient uptake by roots and translocation to vegetation, sloughing, death and mineralization and deposition into litter. | UF-WBL. (2019)<br>Bhomia (2013)<br>James et al. (2024) |
| | | Accrued soils in SAV are primarily inorganic.<br>Marl ($CaCO_3$) containing P amalgams are the primary inorganic form of accrued soils are relatively recalcitrant. | Reddy et al. (2021) |

**Table 2.** Continued.

| Key Question | Sub-questions | Comments | References |
|---|---|---|---|
| | | Organic P and poly P forms are found in PP, the latter related to periphyton, which are reasonably recalcitrant and can be transformed into calcium phosphate ($CaPO_4$). | Fisher et al. (2024) |
| | What is the role of vegetation in modifying P availability in low P environments, including the transformation of refractory forms of P? | EAV removes P from soil, deposits some of it as organic litter.<br>SAV litter returns more P as orthophosphate to the water column.<br>Polyphosphates are prevalent in waters near outflows of well performing FWs. | Morrison et al. (2024)<br>Fisher et al. (2024) |
| | Do water level drawdowns improve soil consolidation and compaction? | Yes, for a short period after rehydration.<br>Within a week or so, P flux from rehydrated soils exceeds P flux from non-dried soils.<br>After a few weeks, the P flux declines to pre-dried conditions. | DB Environmental (2023a) |
| 6. What is the influence of wildlife and fisheries on the reduction of P in the STAs? | What are the direct and indirect effects of wildlife communities at temporal and spatial scales on P cycling (i.e., are they net sinks or sources)? | STA fauna (fish) biomass is much larger than in the Everglades. Large fish accumulate in canals at low water depths, and small fish densities varied based on SAV vegetation type and density. | Goeke and Dorn (2022) |
| | | Small fish excretion is higher than large fish due to higher individual excretion and higher abundance.<br>Invertebrates excrete a fair amount of P. | Goeke et al. (2024)<br>Goeke and Dorn (2023b) |
| | | Excretion varies depending on season.<br>Per area excretion rate is larger than external loads.<br>Bioturbation is much smaller than excretion in P flux to water column, however it can have localized effects including disturbance of SAV. | Barton et al. (2023) |
| | What options are there for mitigating or reducing the impacts of fish and wildlife on STA performance through wildlife management or changes in operations? | Reduce water depths to less than 1.5 ft to allow bird predation on fish and macroinvertebrates during bird breeding season.<br>Breeding season is simultaneous with the dry season (late winter to early spring).<br>Slowly raise waters in outflow regions after a drawdown to allow SAV to germinate and grow to reduce the effect of large fish herbivory. | Goeke and Dorn (2024a) |

## Key Question 1

*How can the FEBs/reservoirs be designed and operated to moderate inflow P concentrations and optimize PLR and HLR in the STAs, possibly in combination with water treatment technologies or inflow canal management?*

FEBs are impoundments constructed to attenuate peak stormwater flows, temporarily store stormwater runoff, and improve inflow delivery rates to downstream STAs, thereby enhancing operation and P treatment performance (Shuford et al. 2024). FEBs provide some flexibility of timing and amount of discharge to the STAs. This supports STA performance through reducing high flows and extreme high and low water depths. The value of FEBs was recognized through a modeling exercise using the iModel that demonstrated the WQBEL could be reached by appropriate distribution of FEB waters to the individual FWs (Ali 2018).

Reducing peak stormwater flows is a key objective to maintain STA performance; therefore, FEBs are included for all three project flow paths (**Table 3**). Two FEBs (A-1, L-8) are operational and one (C-139) has been constructed and will be operational soon (Shuford et al. 2024). The A-1 FEB primarily supports STA-3/4 but can also support STA-2. The L-8 FEB supports STA-1E and STA-1W; and the C-139 FEB will support STA-5/6 (**Figure 1**). In the last five years, the A-1 FEB has captured an average of 252,000 ac-ft of water per year while releasing 169,000 ac-ft to the STAs (**Table 4**). This shallow FEB provided an additional benefit, reducing TP concentrations from an inflow flow-weighted mean concentration (FWMC) of 91 µg/L to an outflow FWMC of 16 µg/L (Hutchins et al. 2024). This 83% reduction in concentration equated to an 89% reduction in load due to the lower discharge compared to inflow. The L-8 FEB operation has varied, primarily due to outflow pump repairs and replacement of valves during WY2023, which stopped discharge for much of the year. As this is a deep reservoir with little aquatic vegetation, the resulting substantial decrease of TP concentration from inflow to outflow was unexpected (**Table 5**), as zero removal was assumed during the design of this project. Overall, in the last five years, the L-8 FEB TP concentration reduction was 57% and TP load reduction was 53%.

**Table 3.** Operational and planned FEBs for the Everglades STAs.

| Flow Path | FEB | Storage Volume (ac-ft) | Area (acres) | Storage Depth (ft) | Vegetated | Operational Start Date | Supplies Water To |
|---|---|---|---|---|---|---|---|
| Eastern | L-8 FEB | 45,000 | 950 | 47.4 | No | 2017 | STA-1E<br>STA-1W |
| Central | A-1 FEB | 60,000 | 15,000 | 4.0 | Yes | 2015 | STA-2<br>STA-3/4 |
| Western | C-139 FEB | 11,000 | 2,800 | 4.0 | Yes | 2024 | STA-5/6 |

The A-2 Reservoir (with a volume of 240,000 ac-ft, area of 10,500 ac, and storage depth of 22.9 feet or ft) is being constructed as part of the Central Everglades Planning Project (CEPP) with a planned completion date of 2029, to increase storage, treatment and conveyance of Lake Okeechobee water south to the Everglades. A-2 Reservoir discharges will be delivered to the A-2 STA, A-1 FEB, STA-2, and STA-3/4.

**Table 4.** A-1 FEB performance matrix (Hutchins et al. 2024).

| Performance Metric | Unit | WY2019 | WY2020 | WY2021 | WY2022 | WY2023 | Average |
|---|---|---|---|---|---|---|---|
| Inflow Volume | ac-ft | 380,918 | 299,313 | 273,628 | 119,688 | 184,610 | 251,631 |
| Outflow Volume | ac-ft | 282,908 | 209,767 | 207,599 | 56,653 | 90,540 | 169,493 |
| Flow Reduction | ac-ft | 98,010 | 89,546 | 66,029 | 63,035 | 94,070 | 82,138 |
| % Flow Reduction | % | 26% | 30% | 24% | 53% | 51% | 33% |
| Inflow TP FWMC | µg/L | 106 | 82 | 78 | 87 | 96 | 91 |
| Outflow TP FWMC | µg/L | 14 | 15 | 17 | 16 | 19 | 16 |
| TP Concentration Reduction | % | 87% | 82% | 78% | 82% | 80% | 83% |
| Inflow TP Load | metric tons (t) | 50 | 30.3 | 26.5 | 12.9 | 21.8 | 28.3 |
| Outflow TP Load | t | 4.8 | 4 | 4.3 | 1 | 2.1 | 3.2 |
| TP Load Reduction | t | 45.2 | 26.3 | 22.2 | 11.9 | 19.7 | 25.1 |
| Percent TP Load Reduction | % | 90% | 87% | 84% | 92% | 90% | 89% |

**Table 5.** L-8 FEB performance measures (from Xue 2024).

| Performance Metric | Units | WY2019 | WY2020 | WY2021 | WY2022 | WY2023 | Average |
|---|---|---|---|---|---|---|---|
| Inflow Volume | ac-ft | 49,897 | 53,356 | 42,264 | 42,076 | 35,821 | 44,683 |
| Outflow Volume | ac-ft | 57,487 | 59,766 | 56,620 | 44,565 | 26,135 | 48,915 |
| Flow Reduction | ac-ft | -7,590 | -6,410 | -14,356 | -2,489 | 9,686 | -4,232 |
| Percent Flow Reduction | % | -15% | -12% | -34% | -6% | 27% | -9% |
| Inflow TP FWMC | µg/L | 246 | 140 | 60 | 180 | 73 | 145 |
| Outflow TP FWMC | µg/L | 95 | 50 | 47 | 68 | 41 | 62 |
| Percent Concentration Reduction | % | 61% | 64% | 22% | 62% | 44% | 57% |
| Inflow TP Load | metric tons (t) | 15.1 | 9.2 | 3.1 | 9.4 | 3.2 | 8 |
| Outflow TP Load | t | 6.7 | 3.7 | 3.3 | 3.7 | 1.3 | 3.7 |
| TP Load Reduction | t | 8.4 | 5.5 | -0.2 | 5.7 | 1.9 | 4.3 |
| Percent TP Load Reduction | % | 56% | 60% | -6% | 61% | 59% | 53% |

### *Sub-question: Storage in FEB/Reservoirs*

*How should storage in the FEBs/reservoirs be managed throughout the year so water can be delivered to the STAs in a manner that allows them to achieve the lowest outflow TP concentrations?*

The operation of the Central Flow Path FEB (A-1) initially was evaluated using the iModel for Restoration Strategies Operational Protocol Development (iModel-RSOPD; Ali 2018). Specifically, the iModel-RSOPD was used to optimize water flow through the FWs of STA-3/4 and STA-2 such that discharge TP concentrations met the WQBEL. Results showed the increased flexibility to reduce peak flows to the STAs using the A-1 FEB improved overall performance of these STAs.

Reports of flow, loads, and FWMCs of P into and out of each FEB and STA FW, and for each entire STA on a 7-day (weekly), 28-day (monthly) and 365-day (annual) period are developed each week (**Table 1**). Managers, scientists, and engineers meet weekly to evaluate these data and make recommendations for flow to the STAs based on numerous factors: current water depths, FW conditions, water quality, vegetation management activities, bird nesting, and meteorology (Hutchins et al. 2024). Guidelines for management, presented later in this document, support the decision managers make to optimize flow and TP retention. When decisions for flow are set, operators can use a system developed in the supervisory control and data acquisition (SCADA) system to set target flows to the various FWs. This SCADA system was developed using information from operational experience and the flow control program is consistent with tools such as the WaveBot application (Lal 2017). The SCADA system can automatically adjust gate operations to maintain near constant flow as headwater and tailwater change throughout the day.

**Knowledge Gap.** As the L-8 FEB has been fully operational in the past year (WY2024) and the C-139 FEB will begin operational testing soon, actual observed data of the influence of these storage facilities on the STAs that they support, (L-8: STA-1E and STA-1W; C-139: STA 5/6) has not been obtained. Continued monitoring of TP and flow from these FEBs and the STAs will continue into the future and will improve understanding of how FEB management influences STA performance. Performance and operational data and the use of analytical tools such as the iModel-RSOPD will be reevaluated. The effects of reduced loading (PLR) and HLR are evaluated in the STA Water and P Budget Improvements (Water and P Budget) Study (Zhao and Piccone 2020).

## Key Question 2

*What operational or design refinements could be implemented at existing STAs and future features, including the STA expansions and FEBs/reservoirs, to improve and sustain STA treatment performance?*

Over the past 11 years numerous Science Plan studies have considered various aspects related to this question. Given ideal conditions where no disturbance has occurred over a three-year period, data mining demonstrated that an annual FWMC of 19 µg/L was attainable when PLR was less than or equal to 1.3 grams P per square meter per year g $P/m^2/yr$ (DB Environmental 2024). Additionally, while periods with low or no flow do occur, it is recommended that the transition from no flow-to-flow discharge be carried out slowly, as TP concentrations are higher at the outflow regions of FWs when there is low or no flow conditions. The TP concentrations tend to decline as water flows increase (Villapando et al. 2024). As the WQBEL is based on annual TP FWMCs, if the amount of flow with high TP concentrations is minimized, these high TP concentrations have less effect on the annual FWMC. Vegetation conditions are also important. Outflow concentrations typically were at or below 19 µg/L in cells where *Chara* was abundant (Figure 30 in DB Environmental 2020). Weekly operations meetings include discussions about many of these items in relation to weekly STA performance summaries (**Table 5**). These discussions include operational strategies to balance the PLRs among the STA FWs while considering various other factors that may affect outflow P concentrations.

The timing of STA discharges may affect outflow TP concentrations through factors such as diurnal changes in photosynthesis and diel movements of phytoplankton and microfauna (Powers et al. 2023). Diurnal factors result in small but significant differences over a day; however, these differences are smaller than the influence of other parameters (water depth, season).

Occasionally, water depths in individual cells are drawn down (or dried out) to allow for construction activities, planting, or vegetation rejuvenation. SAV areas are kept hydrated, even during dry periods, through supplemental water deliveries from Lake Okeechobee or from FEB releases if available. Maintaining this hydration avoids a flush of TP to the water column that occurs upon rewetting of dried out STA soils (DB Environmental 2023a). Consolidation of the dried marl soils temporarily increases the stability of the soil (up to 12 weeks) but the drying results in increased flux of dissolved P into the water column. More importantly, drying of marl soils can enhance germination of SAV after rewetting (DB Environmental 2022a). An additional benefit of drawdowns is the relocation of large herbivorous fish into surrounding canals, which may increase predation and thereby reduce the effects of fish herbivory on SAV growth (Goeke and Dorn 2023a). SAV allowed to germinate in the absence of these herbivorous fish leads to improved growth. In addition, if floating wetlands (formerly called tussocks) are observed, lower water depths can promote deeper root growth in those cattails that are still rooted, providing an anchor to reduce and or prevent further floating mat formation (Clark 2022).

**Knowledge Gap.** The potential of STA soil dry-out to enhance SAV growth in bare regions of a cell or improve rooting of cattail in areas prone to floating mat formation has not been completely evaluated in the field. An effort is underway for the upcoming dry season 2025 to improve SAV coverage in STA-2 Cell 3. This project will draw down STA-2 Cell 3 in efforts to get SAV to germinate and to reduce fish populations through predation. These types of projects will continue, if successful, to enhance overall vegetation conditions in the STAs.

### *Sub-question: Operational Refinements*

*Are there operational refinements or improvements to the regional water management system that can be implemented to enhance FEB and STA performance while maintaining existing levels of flood protection?*

Under ideal conditions, water flows uniformly through an STA as sheet flow for optimal interaction with EAV, SAV, and periphyton. Improved hydraulic conditions can increase hydraulic residence time and reduce localized advective velocities and turbulence. However, short-circuits do occur, affecting the flow patterns in part or all of a FW. Short-circuits in STAs can result from non-uniform flow distribution across inflow/outflow levees (i.e., structures behaving as point sources), spatial variation in topography across treatment cells, and changes in vegetation condition/density and resulting differences in flow resistance. Energy dissipaters have been installed downstream of the inflow structures to disperse the flow more evenly across the inflow region and thereby reduce erosion and short-circuiting at the front end of the cell.

To address short-circuiting, one successful method used by the SFWMD's Vegetation Management Section is to plant bulrush in deeper areas. Bulrush produce deep roots that can anchor other plants, preventing floating mat formation. They grow quickly and can be used to reduce open water in EAV and SAV areas, which reduces flow velocities through short-circuits.

A 100-ft straight flume was used to evaluate the combined effects of flow rate, water depths, and cattail densities on mixing (dispersion). In this flume, cattails grown in for 3 months had a density of approximately 19 to 24 plants per square meter ($m^2$), after 6 months the densities were greater than 31 plants/$m^2$. Higher dispersion of inflow water (based on conductivity measurements of added salt) was found with the higher density of cattail (South Florida Engineering and Consulting LLC 2024).

Restoration Strategies projects that are nearly complete as of 2024 include selected treatment cell topographic leveling (STA-1E Cells 5 and 7, STA-5/6 Cells 2A and 3A). In addition to the Restoration Strategies projects, a suite of STA refurbishment projects has been implemented in various treatment cells that include plugging preferential flow paths of hydraulic short circuits to improve hydraulics and thereby maximize nutrient removal, and additional topographic leveling to remove remnant farm roads and raise low-lying areas to reduce hydraulic short circuits and to achieve water depths needed for EAV sustainability. Vegetation management is continually used to address storm damage, the effects of high flow events, floating wetlands, and encroachment from floating or invasive plant species. The effects of these activities have not been directly measured, but the suite of projects to improve flow patterns and vegetation conditions likely have contributed to the trend of reduced TP concentrations in STA discharges.

Optimal operation of the FEB-STA system includes evaluation of volume and inflows to determine how such operations affect the water storage capacity of the FEBs and TP loading into the STAs. For example, near-real-time forecasting of Everglades Agricultural Area (EAA) canal levels and flows can benefit near-real-time water control operations to balance flood control in the EAA and treatment efficiencies of the STAs. Forecasting EAA canal levels and conveyance may enhance the flexibility of FEB and STA operations to achieve optimal water quality improvements. Planning level forecasting of EAA canals and conveyance has been done using EAA Regional Simulation Model (RSM) – Basin (SFWMD 2005a, b). Such planning level forecast studies would be valuable to estimate the range of flow options available for STA operations.

**Knowledge Gap.** Construction projects on FEBs, STAs, and the inflow canals increase the flexibility of timing and deliveries to the STAs, which should enhance performance of the system. Continued monitoring of the system will document the improvements in performance of these various construction projects.

### *Sub-question: Vertical Advective Loading*

*Will reduced advective loading from the soil to the water column reduce P concentrations in STA outflow?*

Vertical advective loading is one mechanism of P translocation from the soil to the water column in an STA. Other exchanges involve physical, chemical, and biological processes such as turbulent resuspension and deposition, macrophyte mining, plant transpiration induced flux, bioturbation, and chemical diffusion. Combined, these processes in the lower end of the STAs reach an equilibrium, resulting in a minimum TP concentration in the water column. A proof-of-concept study was carried out to determine if vertical advection (e.g., inflow to the STAs from groundwater) affected water volume or P concentration in selected STA outflow cells (WSP Inc. 2022). The study could not find any evidence that vertical advection added to the water volume or P concentrations in these regions. Further, a simple computer model was developed, based on the Low Phosphorus Wetland Model (LPWEM; Juston and Kadlec 2019). Neither increased estimated inflow from advective loading nor increased TP concentration in the advective loading changed the TP concentration predicted by the model to a substantial degree (WSP Inc. and Dynamic Solutions 2022). Therefore, reduced vertical advective loading from the soil to the water column will not reduce P concentrations in the STA outflow.

### *Sub-question: Design Features*

*What are the best structural design features for delivering water to and from the STAs and FEBs?*

Flows to and from STAs and FEBs are managed through different configurations of canals, pumps, gated culverts, gated spillways, and weirs. Gated structures are needed to control flows into individual FWs, and these structures are point sources of flow. FEBs do not require even flow distribution to achieve their operational purpose, which is to capture peak flows associated with stormwater runoff and release it to the STAs at a lower flow rate. Therefore, they have fewer control structures and less compartmentalization than an equivalent-sized STA. For STAs, the goal is to enhance STA performance through even distribution of flow, which is accomplished using spreader canals downstream of inflow structures. To mitigate the effect of point source flow associated with inflow structures, energy dissipaters (e.g., rock piles) and EAV-bulrush plantings have been used to reduce velocity and deflect flow from continuing straight down the FW. At the outflow region of FWs, water is discharged via gated culverts, spillways, weirs, or pumps. Like the inflow region, outflow spreader/distribution canals have been constructed in STA cells to evenly move water from the marsh to the outflow structures. Ideally, outflow structures from the STAs should minimize soil buildup and transport to downstream receiving areas.

**Knowledge Gap.** This question was difficult to pursue as it is very difficult to evaluate different types of structures (V weirs, flat weirs, gates that open from the top, bottom or middle, and pumps) under similar hydraulic conditions to compare effects on outflow TP concentrations. As each FW is different based on history, topography, source water, etc., comparing different structures on different FWs would not provide meaningful results. The time and costs that would be associated with the construction of an experimental facility to provide reliable results also supported the decision to not pursue this question. As particulate P (PP) is a major component of outflow TP concentrations from the STAs, flow and turbidity monitoring (a surrogate for PP), continuously and periodically at a synoptic spatial scale, should determine the effectiveness of the structures and barriers given the specific FW and hydrologic conditions.

### *Sub-question: Topography*

*What are the effects of topography on STA performance?*

Ideally, STA topography should be relatively level to provide even sheet flow across the marsh and to minimize short-circuiting. Furthermore, even topography will result in relatively consistent water depths throughout a treatment cell to promote favorable conditions for target vegetation throughout the cell. To achieve this in STA cells, farm ditches and borrow canals parallel to flow typically are filled (or plugged) as part of construction. However, some cells still have variations in topography that affect hydraulics and the ability to maintain water depths to sustain the desired wetland vegetation. Topographic variability occurs in several existing STA cells and may contribute to their poor performance (Pietro et al. 2010, Ivanoff et al. 2013).

The two-dimensional RSM (Total Variation Diminishing Lax-Friedrichs model or TVDLF; Lal 2017) has successfully simulated the hydraulics of two treatment cells within STA-3/4. The model demonstrated the complex internal flow patterns that exist even in a well performing treatment cell due to vegetation, short-circuiting flows, and variable topographic features. This model has been used to support designs of STA FWs constructed after the TVDLF model was developed.

**Knowledge Gap.** Surveys of topography of STA FWs can provide more accurate measurements of depth throughout the FWs using the Water Depth Assessment Tool (WDAT) software to promote optimal hydrologic conditions. Both continued inflow and outflow monitoring and periodic synoptic spatial analyses of water quality can evaluate the effects of topography, vegetation, and short-circuits. Updating topographic surveys of all the STAs can support optimization of these systems.

## Key Question 3

*What measures can be taken to enhance vegetation-based treatment in the STAs?*

In wetlands designed to treat surface water for nutrient reduction, macrophytes reduce water column nutrients through physical, biological, and biochemical processes. Macrophytes provide resistance to flows that result in particulate settling; decrease soil and floc resuspension and transport; and provide a large surface area for particle impaction, interception, and settling (Kadlec and Wallace 2009). Reduced water velocity allows for increased settling of PP, while reduced turbulent mixing, particularly at the soil/water interface; stabilizes the soil surface; and minimizes movement of superficial soil and floc. Periphyton can attach to the leaves of these plants, mineralizing DOP through enzyme activity (Pietro et al. 2023) and removing soluble reactive P (SRP). The root systems of EAV plants store P, increase soil stability, and reduce soil resuspension and P flux into the water column. Improved sediment stability is beneficial for growth and maintenance of EAV and SAV. EAV is used as a management tool in areas where short circuits have occurred, allowing more even flow throughout each cell, thereby optimizing treatment performance. However, these plants move P from the soils through the roots and into the leaf tissue. When these leaves senesce and die, they can be considered an internal source of P as much of the dead plant tissue decomposes adding dissolved P to the water column (DB Environmental 2017).

Photosynthesis within dense beds of SAV elevates the water column pH, which facilitates co-precipitation of P with cationic minerals such as Ca (Reddy and DeLaune 2008, Kadlec and Wallace 2009, Brix et al. 2010). Macrophytes also provide contact surface for microbes and periphyton, which can reduce SRP from the water column by storing it as cellular organic P or inorganic biologically generated poly-P (Fisher et al. 2024) and/or through extracellular processes of metal-phosphate deposition, co-precipitation with Ca and magnesium (Mg), and adsorption to inorganic compounds like calcium carbonate ($CaCO_3$) (Hagerthey et al. 2011).

Certain factors related to plant structure and density can alter P reduction by macrophytes or result in net P addition to the water column. Dense emergent vegetation cover can inhibit periphyton establishment, which also could negatively affect P reduction in the water column. P can be released from periphyton and macrophytes following death, desiccation, and subsequent rehydration. Macrophytes primarily take up nutrients from the soil root zone. P is translocated from macrophyte roots to the leaves, where it may reside or be solubilized directly to the water column or indirectly through periphyton uptake, mineralization of organic P, and release. This translocation can be an important internal source of P, particularly in P enriched soil areas (Noe and Childers 2007, DB Environmental 2017).

Alternatively, macrophytes move P down into the roots, and storage belowground in roots and tubers can exceed the amount of P stored aboveground (Reddy and DeLaune 2008). Eventually, dead and detrital plant biomass decomposes, with some nutrients released back into the water column. Mineralization of macrophyte detritus can create residuals and accrete P through burial in soils. The importance of this mechanism is evident from the rapid turnover of macrophyte biomass, which can be up to five times per year in subtropical settings (Davis 1994).

These vegetation-based processes of P reduction demonstrate the value of sustaining a healthy plant community throughout treatment cells. Understanding the conditions for optimal vegetation growth and P uptake mechanisms is important and will serve as a basis in formulating recommendations for STA performance improvements.

### *Sub-question: SAV Resilience*

*What key factors affect and what management strategies could improve system resilience of SAV communities?*

Numerous factors have been investigated that could affect SAV communities:

- Soil characteristics
- Water quality and nutrient loadings
- Water depths (dry to flood); rate of change and duration of extreme values
- Light penetration
- Community composition, cover, and density
- *Chara* subtypes and distribution

Mesocosm studies evaluated the effects of soils, nutrient loads, and water depths on *Chara* growth (DB Environmental 2023b). Marl, muck, or aged muck soils did not have an appreciable effect on *Chara*. Further while high P loads resulted in dense SAV in these mesocosms, declines due to anaerobic conditions, low light levels and increased sulfite production that can occur at these high densities did not result in a crash of SAV. This study did find that SAV can germinate in bare areas rather quickly after a drawdown (DB Environmental 2023b), however herbivory can be significant impediment especially in young growth plants, but less of a factor in plants encrusted with Ca (Goeke and Dorn 2024a). In addition, fish bioturbation also can affect SAV growth. The condition where SAV growth was least robust was under low P loads and soils with low P content (DB Environmental 2023b).

An SAV resilience study was used to investigate operational (e.g., water depth, flow velocity, nutrient concentration, mineral concentration) and environmental (e.g., seasonality, light penetration, water clarity) conditions that support healthy and diverse SAV communities in the STAs. Overall, these factors did affect the SAV but did not result in substantial declines. Under low P loading and soil with low P content, the *Chara* abundance was lower (DB Environmental 2023b).

Bi-annual monitoring of SAV community composition in the STA cells has been carried out over the past decade. Temporal changes in community composition may indicate declining sustainability and P retention performance. Loss of SAV generally results in reduced P retention. A sudden loss of SAV (particularly *Chara* and *Hydrilla*) typically causes an immediate increase in water column turbidity and nutrient concentration, which often results in temporarily increased phytoplankton productivity. If water column turbidity persists, it inhibits reestablishment of SAV. Such a situation was observed in STA-1W from 2004 to 2006 when entire cells lost their SAV communities and required major rehabilitation to regrow the vegetation. In some cases, SFWMD vegetation management teams inoculate STA cells with desired SAV species such as spiny naiad (*Najas marina*), southern naiad (*Najas guadalupensis*), *Vallisneria* spp., *Potamogeton* spp., and subtypes of *Chara* to expedite their establishment and improve STA cell functionality.

Event-related stressors can affect SAV communities. Increasing water depths and flow are related to increased nutrient load and turbidity, which can affect SAV through light limitation, scouring, poor water quality, and potential die-off. Dry outs, although rare due to drought management operations, can result in desiccation and death of SAV. Wind events, including hurricanes and thunderstorms, can increase turbulence and scouring of SAV as well. EAV is currently planted as a barrier that reduces the effects of wind/wave disturbance on SAV communities. In some cases, the EAV has encroached into and replaced the SAV communities, which may affect the FW abilities to retain P. Herbicides have been used in a limited amount to manage the encroachment.

**Knowledge Gaps.** Additional factors could affect SAV communities:

- EAV planting, rotation, distribution, and abundance
- Photolytic degradation (e.g., hydrogen peroxide [$H_2O_2$], dissolved organic matter degradation products)
- Flow velocity
- Use of herbicides to manage the EAV encroachment into the SAV areas

Flow velocity has been studied in flumes, specifically to evaluate the effects on resuspension of attached particles (Fugate and Thomas 2024). A similar study could evaluate higher flows on SAV. The other factors not yet studied that may reduce SAV resilience include herbicides and photolytic degradation. Herbicides from vegetation management activities or agricultural runoff may hinder SAV growth. Ultraviolet light can degrade dissolved organics in the water column and produce toxins, including hydrogen peroxide, which may affect SAV growth.

### *Sub-question: EAV Resilience*

*What key factors affect and what management strategies could improve system resilience of EAV communities?* A few of these factors have been investigated under the Science Plan:

- Soil characteristics
- Rate of change and duration of water depths
- Dry out
- Floating wetland (tussock) formation

The inflow regions of STA cells are dominated by dense stands of cattail, which typically are very hardy plants with rapid and sustained growth in enriched environments. However, die-backs occur in the STAs, reducing the ability of the emergent wetland to reduce P from the water column. Continuous periods of deepwater conditions sometimes are associated with cattail stress and mortality (Chen et al. 2010, Diaz and Vaughan 2019).

Target depths for STA cells range from 1.25 to 1.50 ft during no flow events, based on prior experience in wetlands and observations in the STAs. However, during peak flow events, water depths can increase well above target and remain high for extended periods of time. These factors have been observed to coincide with cattail community decline. Results from earlier studies indicated that 6 weeks of continuous inundation at water depths between 3.0 and 4.5 ft produced multiple signs of stress in cattail communities (Chen et al. 2010, 2013).

From 2014 to 2017, SFWMD conducted a cattail sustainability investigation that included in situ monitoring of cattail growth and productivity in STA-1W Cell 2A and STA-3/4 Cell 2A (Diaz and Vaughan

2019). Results suggested water depth likely was a factor in cattail community decline in one of the study cells, but it is uncertain if other factors (e.g., soil characteristics, presence of floating wetlands, and competitive interactions with FAV) contributed to the decline.

A controlled experiment at 15 STA-1W north test cells (0.5-ac cells) found constant water depths above 2.8 ft resulted in declines of juvenile (suggesting reduced clonal reproduction) and adult cattail, increased leaf elongation, increased ramet weight, and increased tussock formation (floating cattail) (Diaz et al. 2023). Measurements of photosynthesis, and gas and water exchange through the leaves, all signs of stress, did not change significantly. This was attributed to the increased leaf elongation that allowed the plants to continue to survive. Chlorosis, a sign of stress, was observed from 4 to 8 weeks in deeper water. At the end of this study, water depths were reduced quickly, resulting in lodging (falling over) of the elongated plants in the deeper waters (above 0.85 m). Results from this study suggest that water depths should be maintained below 3 ft in cattail regions. If water depths do increase above 3 ft, it is recommended that they be reduced within 4 to 8 weeks to allow the cattail to recover.

A study also was conducted to determine factors that affect floating wetland (tussock) formation (Clark et al. 2024). This study found three major factors that increased the potential for floating wetland formation in an STA cell were past agriculture use, low P soil content, and high water depths. The first two factors cannot be controlled but indicate areas that are more susceptible to floating wetland formation. The latter is consistent with the recommended water depth where cattails are not stressed.

Prescribed burns have not been studied in STAs, but a previous study did evaluate the effects in areas of Water Conservation Area (WCA) 2A (Miao and Thomas 2011). This WCA received high TP loads and concentrations at inflows from the canals, and as this water dispersed along the flow path, TP declined in the water column as it was retained in the soils. Due to the high TP concentrations accumulating in the soils of this WCA, this oligotrophic sawgrass marsh transformed to a cattail marsh. The data collected from this WCA was used to develop the STA-design model.

A study was carried out to determine if controlled burns could change these cattail areas back to sawgrass. These burns were completed in cattail areas of different TP concentrations in the soil and water column. Results from this study were evaluated to determine if prescribed burns can enhance overall STA performance by (1) improving hydraulic conditions through reduction of excessive biomass obstructing desired flow distribution within a cell; (2) translocating or reducing P by burning excessive biomass in strategic locations within a cell; (3) improving cattail community sustainability; and (4) reducing the depth of accrued soil through drawdown following a prescribed burn.

**Knowledge Gaps.** If burning is considered for management of STA cells, pre- and post-monitoring of burned areas and a set of unburned controls will be needed to determine the proximate and long-term effects of burning on P concentrations. Hydraulic efficiency, sheet flow, nutrient sequestration, and plant community health should be evaluated.

A few factors have not been studied directly to determine EAV resilience:

- Community composition, cover, and density
- Nutrient loadings
- EAV planting, rotation, distribution, and abundance

Strips of EAV (e.g., bulrush) have been planted in large areas within STA cells that were initially managed to be primarily SAV but were decimated due to large storm events (see the Sub-question: Mixed Vegetation section). Also, in the originally designated "SAV cells", cattail was routinely treated with herbicides to maintain open areas for SAV establishment. In the STA-3/4 downstream cells, and STA-2 Cells 2 and 3, these open areas were well defined squares surrounded by cattail, which was described as a checkerboard pattern. In recent years, these SAV areas have not been maintained and in many cases the EAV expanded into the SAV areas. A plan of herbicide and or burning of the expanded EAV in the SAV areas is currently being implemented. This will provide an opportunity to evaluate the effects of herbicides and burning on both communities and the effect on P retention.

### *Sub-question: Mixed Vegetation*

*What are the differences in long-term P reduction between pure SAV communities and mixed SAV/EAV communities?*

The difference between SAV dominated and EAV dominated cells has been thoroughly evaluated in the Evaluation of P Sources, Forms, Flux, and Transformation Processes in the STAs (P Flux) Study (Villapando et al. 2024). In this study, the major difference is the mechanism for P retention is primarily organic in EAV areas and inorganic in SAV areas. These differences are observed at most scales, with recently accreted sediments (RAS) in EAV regions primarily originated from organic plant litter and the SAV region RAS being primarily marl ($CaCO_3$ with additional metals and P).

Vast expanses of SAV beds are highly susceptible to uprooting by wind and high flows. Strips of EAV to compartmentalize SAV cells can buffer the effects of wind and flow events. For instance, STA-3/4 Cell 3B has a high proportion (40%) of EAV cover and retained a substantial amount of SAV after Hurricane Irma (SFWMD 2018b).

Understanding the relative effectiveness of SAV versus SAV mixed with EAV in reducing water column P has been addressed in the P Removal Performance of Ecotopes in the STAs (Ecotope) Study (see the Sub-question: Other vegetation section).

**Knowledge Gaps.** EAV communities have been introduced in the SAV areas as buffers and to stabilize soils but the effects on community resilience and P retention have not been studied specifically. The relative value of placing EAV strips in various arrays have not been evaluated in the field to determine the optimal size and distribution of EAV strips to sustain SAV cover. Also, the utility of rotating SAV and EAV to enhance SAV sustainability, stabilize accrued material, and increase microbial activity has not been considered.

### *Sub-question: Other Vegetation*

*Can various vegetation types (subtypes) enhance P uptake and removal in SAV cells?*

The following species were evaluated for their ability to remove P:

- Cattail (*Typha* spp.)
- Musk grass (*Chara* spp.)
- Naiad (*Najas guadalupensis*)
- American lotus (*Nelumbo lutea*)
- White water lily (*Nymphaea odorata*)
- Yellowpond lily (*Nuphar lutea*)
- Spatterdock (*Nuphar advena* spp. *advena*)

A study investigating P removal by rooted floating aquatic vegetation (rFAV) in SAV cells determined that SAV was better or as good as rFAV (DB Environmental 2018b). Areas of lily and lotus that were studied shaded out SAV and died in the dry season, resulting in higher P concentrations in the water column compared to a nearby SAV area used as a control. P concentration in a third area of rFAV (spatterdock) was not substantially different from the control patch of SAV. Active planting of rFAV in the outflow regions of STAs has been discontinued but active removal has not yet been pursued.

A few SAV and one EAV ecotope (plant communities and their environment) were compared to determine the best ecotopes for P removal in the outflow regions of selected FWs (Powers 2023, 2024). This included ecotopes of *Chara*, *Najas*, and *Chara* mixed, cattail, and bare soil. While *Chara* ecotope TP concentrations were lowest overall, they were not significantly different from the others. Seasonal differences were greater than the differences among the various ecotopes. A review of outflow region nutrient, vegetation, and soil data collected over the past 20 years demonstrated that the lowest TP concentrations are consistently found in outflow cells with dense *Chara* beds (DB Environmental 2020).

**Knowledge Gaps.** While other ecotopes of SAV exist in the STAs, they are not as prevalent nor widespread. However, a number are planted to support other aquatic vegetation communities. Mesocosm experiments could be used to evaluate differences among a number of species:

- Fire flag (*Thalia geniculata*)
- Denseflower knotweed (*Persicaria glabra*)
- Bulrush (*Schoenoplectus californicus*)
- Illinois pondweed (*Potamogeton illinoensis*)
- American eelgrass (*Vallisneria americana*)
- Sawgrass (*Cladium jamaicense*)

Less dominant vegetation, such as sawgrass, can be studied at a larger scale to determine optimum hydraulic regimes (water depth and flow rate) for nutrient reduction efficacy. Sawgrass communities established near the STA outflows should achieve lower outflow TP concentrations. Other promising macrophyte species could be tested specifically on how they translocate and store P in the rhizosphere. The species-specific ecologies of native vegetation types are expected to improve P reduction and enhance STA performance, especially near the outflows.

There are other species-specific studies besides those involving Everglades oligotrophic species. Fire flag and denseflower knotweed may be used to increase plant diversity and provide vegetation-based treatment in areas where other dominant plant species do not occur or persist, and to complement P uptake and reduction in emergent cells.

### *Sub-question: Vegetation P Reduction Capabilities*

*What are the relative short-term and long-term P reduction capacities of the dominant and other vegetation species in the STAs?*

The most common vegetation species in the STAs have been investigated under the Science Plan:

- Cattail – EAV
- Southern naiad – SAV
- Muskgrass (*Chara*) – SAV
- American lotus – FAV
- Spatterdock – FAV
- White water lily – FAV

Aquatic plant species vary in their nutrient uptake mechanisms (e.g., from water column, soils, or both) and nutrient storage capacities. Understanding these differences could help inform decisions on optimal species assemblages. For example, in nutrient poor regions of wetlands (e.g., the Everglades), plants remove and sequester P, resulting in a tight P cycle and reduced internal loads (Miao and Zou 2012). As described above, one study has investigated plant ecotope areas over two years and has gathered information on TP and other water quality measurements to compare their ability to remove and retain P (Powers 2023, 2024).

**Knowledge Gaps.** The following have not been studied directly in the STAs although they have been observed primarily in bi-annual surveys:

- Fire flag – EAV
- Bulrush – EAV
- Sawgrass – EAV

## Key Question 4

*How can internal loading of P to the water column be reduced or controlled, especially in the lower reaches of the STAs?*

Most water column P near the outflow of well performing STAs is in the form of dissolved organic P (DOP) and/or PP; therefore, processes of mineralization (biological or photolytic), particulate settling microbial activity, and resuspension/diffusion affect these concentrations (**Figure 3**). Initial findings indicate that some PP is associated with phytoplankton. Any dissolved inorganic phosphorus (DIP) that is released is removed rapidly by periphyton and SAV. Other processes that affect DIP concentrations are adsorption and desorption with mineral surfaces. In general, reduction of DIP and DOP through adsorption onto particulates and the settling and consolidation of particulates into the soil helps reduce water column P concentrations.

In properly functioning STAs, TP concentrations decline along the inflow-to-outflow gradient, with the most rapid change in the first third of the FW (Villapando et al. 2024). At some point along the FW, typically in the lower reaches of the downstream cells, the values reach a minimum. Where P values no longer change (i.e., no further decline), the processes that remove and release P from/to the water column are assumed to be in dynamic equilibrium.

The effects of internal loading also have been studied in the STAs (Juston and Kadlec 2019, Jerauld et al. 2020). Internal loads can be controlled through capping of soils (Grace et al. 2023) or the removal of high P content soils (Zamorano et al. 2023). Soil management (inversion and amendments) was also explored and had some potential (Josan et al. 2018, Chimney 2015), however the amendments were very expensive and the effects on the downstream Everglades were unknown. Additionally, a field test to bury high TP content soils by inverting deep soils to the surface of a STA cell was inconclusive because the control (not flipped) cell had different hydrology and aquatic vegetation composition.

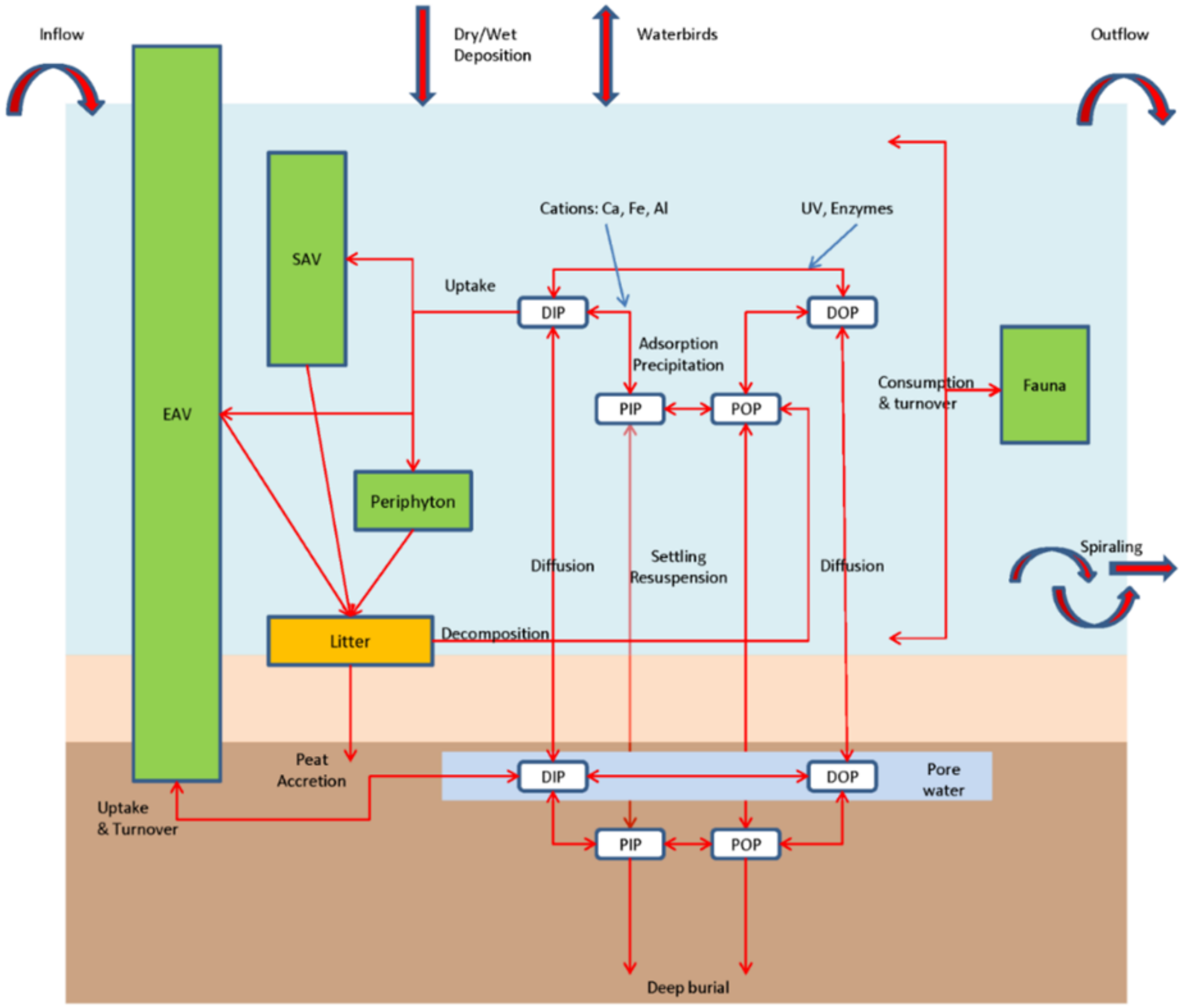



**Figure 3.** Schematic of chemical, physical, and biological processes that can influence changes in P concentrations between the soil and water column.

### ***Sub-question: Physicochemical Factors***

*What are the key physicochemical factors influencing P cycling in very low-P environments?*

Key factors influencing P reduction in surface water of wetland systems include the size of the treatment area; vegetation type, coverage, and condition; HLR; PLR; hydraulic retention time; hydraulic efficiency; and soil biogeochemical properties, including redox potential, pH, mineral content (e.g., iron [Fe], Ca, aluminum [Al]), and the soil P concentration (Richardson 1985, Nungesser and Chimney 2001, Reddy and DeLaune 2008). Manipulating some of these factors is key to effective management of the STAs.

STA FW sizes vary from a few hundred acres (FW 6, 7, 8 of STA-5/6) to over 6,000 ac (Eastern FW of STA-3/4) (**Table 6**). Over the past 10 years, the operational FWs have reduced the P loads by 40 to 87%. Comparing TP outflow concentrations to area and length of all of the FWs combined, there is a point of diminishing return that appears around 2,000 to 3,000 ac (**Figure 4**).

**Table 6.** STA FW areas, lengths [a], annual loads in and out [b], and percent load reduction over the past decade.

| STA | FW [c] | Area (acres) | Length (ft) | Annual TP Load In (metric tons) | Annual TP Load Out (metric tons) | % TP Reduction |
|---|---|---|---|---|---|---|
| STA-1E | EFW | 1,082 | 2,898 | 6.0 | 1.0 | 83% |
| | CFW | 1,939 | 5,050 | 11.4 | 3.3 | 71% |
| | WFW | 1,973 | 3,638 | 5.0 | 2.3 | 54% |
| | Total | 4,994 | 3,862 | 22.3 | 6.6 | 71% |
| STA-1W | EFW | 2,171 | 4,224 | 9.4 | 2.5 | 74% |
| | NFW | 2,654 | 5,265 | 16.8 | 2.6 | 84% |
| | WFW | 1,719 | 3,737 | 7.3 | 1.5 | 80% |
| | Total | 6,544 | 4,409 | 33.5 | 6.6 | 80% |
| STA-2 | FW1 | 1,840 | 5,319 | 8.0 | 1.1 | 86% |
| | FW2 | 2,373 | 4,635 | 9.9 | 4.4 | 56% |
| | FW3 | 2,296 | 4,618 | 11.2 | 3.6 | 68% |
| | FW4 | 5,990 | 5,949 | 12.2 | 2.0 | 84% |
| | FW5 | 2,995 | 7,305 | 1.5 | 0.4 | 75% |
| | Total | 15,494 | 5,565 | 42.8 | 11.5 | 73% |
| STA-3/4 | CFW | 5,349 | 6,754 | 11.8 | 2.1 | 82% |
| | EFW | 6,476 | 7,059 | 10.0 | 1.6 | 84% |
| | WFW | 4,502 | 3,578 | 13.4 | 2.5 | 82% |
| | Total | 16,327 | 5,797 | 35.2 | 6.2 | 82% |
| STA-5/6 | FW1 | 2,418 | 6,283 | 4.7 | 0.6 | 87% |
| | FW2 | 2,433 | 6,318 | 3.2 | 0.8 | 75% |
| | FW3 | 2,211 | 6,301 | 5.4 | 1.0 | 81% |
| | FW4 | 1,871 | 6,266 | 0.01 | 1.2 | N/A |
| | FW5 | 2,642 | 5,089 | 6.4 | 1.4 | 78% |
| | FW6 | 1,900 | 3,540 | 5.7 | 2.6 | 54% |
| | FW7 | 621 | 1,922 | 2.8 | 1.4 | 49% |
| | FW8 | 242 | 772 | 0.7 | 0.4 | 40% |
| | Total | 14,338 | 4,561 | 28.8 | 9.4 | 67% |
| All STAs [d] | Total | 52,703 | 20,332 | 140.3 | 33.7 | 76% |

a. Length estimated from Geospatial Open Data Site (https://geo-sfwmd.hub.arcgis.com/).

b. Flows from weekly STA performance data sheets.

c. FW acronyms are CFW – Central FW, EFW – Eastern FW, NFW – Northern FW, and WFW – Western FW.

d. Total load reductions for entire STAs during WY2014 to WY2023 (Chimney 2024).

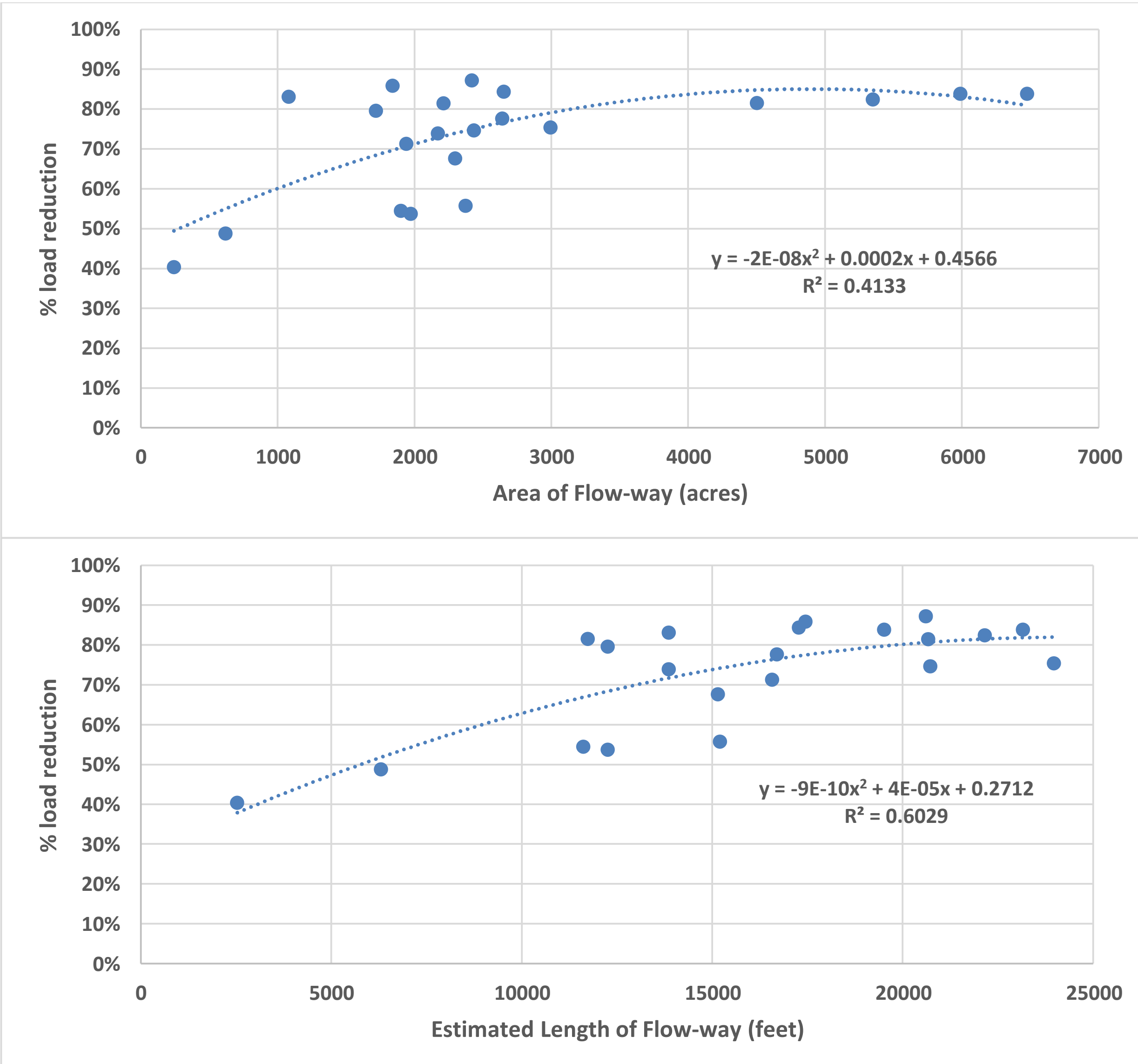



**Figure 4.** Percent load reduction in the past 10 years for each FW plotted against area (top panel) and length (bottom panel).

To compare FWs directly, flow and load are divided by the treatment area to determine HLR and PLR. For well performing STA FWs that consistently discharge annual TP FWMC of 19 or less, the PLR is less than or equal to 1.3 g P/$m^2$/yr (DB Environmental 2024, Zhao and Piccone 2020). HLR of 1.1 cm/d or less is also related to lower outflow TP FWMC (Zhao and Piccone 2020). Outflow regions with healthy populations of *Chara* typically meet low TP FWMC (DB Environmental 2020).

Because most P in the water column near the outflows of well performing STAs is in the form of DOP and/or PP, analyses of the molecular forms, as well as the effects of photo degradation and mineralization are important to understand P retention. Evaluation of the dissolved organic carbon (DOC) found a 20% decrease from inflow to outflow in STA-2 FW3 (SAV/EAV mixed) and a 4% increase in STA-2 FW1 (primarily EAV) (Schafer et al. 2023). This is likely the combination of lower photolysis in the STA-2 FW1 due to shading by *Typha*. Fresh SAV litter leaches more DOC than fresh *Typha* litter normalized for weight (15.8 ± 0.7 and 6.1 ± 0.5, respectively; Morrison et al. 2024). Because *Typha* biomass in outflow region of

STA-2 FW1 was 3.04 ± 0.24 compared to SAV biomass per area in STA-2 FW3 of 0.20 ± 0.04 (Dombrowski et al. 2023), it is likely that more DOC is produced in STA-2 FW1. The studies by Schafer et al. (2023) demonstrated that photolysis of DOC and DOP occurs in the STAs particularly in SAV regions with less shading. The mineralization of DOP to SRP could lead to greater uptake of the resultant SRP, reducing P concentrations in the outflow. In these regions, there is also higher enzyme activity to degrade organic P (Pietro et al. 2023). The role of microorganisms in the transformation of organic P to inorganic P in the water column and soils is well recognized. Enzyme activity occurs in the regions with low P concentrations (Pietro et al. 2023).

P metabolism enzymes have been measured in an outflow cell with low P concentrations and in experimental microcosms where DOP was added (Feeney et al. 2024). While the life cycle of microbes is short, with a quick turnover of nutrients, storage molecules of pyrophosphate and polyphosphate (chains of inorganic phosphates) are a major component of PP in water of outflow regions of STA FWs (Fisher et al. 2024). These polyphosphate compounds likely accumulate in floc and RAS where they can be transformed to $CaPO_4$ (Morrison et al. 2024). Schafer et al. (2023) also demonstrated that both dissolved organic matter (DOM) from both *Typha* and *Chara* leachates are degraded by photolysis, and increased DOP mineralization occurs after photolysis. Because there are differences in enzyme activity among EAV and SAV regions of outflow cells in the STA where P is limiting, it is likely that nutrient cycling would be enhanced in areas where EAV and SAV are mixed.

The role of metallic cations (e.g., Ca, Mg, Fe, Al) in the STAs, particularly at the very low P regions, have been evaluated. Ca-related P reduction in an alkaline wetland environment occurs via two pathways: (1) sorption of P onto calcareous soil particles, limestone surfaces, and marl-based detrital material; and (2) co-precipitation with Ca in the water column or porewater (Reddy et al. 2021). Under the right conditions, P will co-precipitate with Ca and Mg in more alkaline systems and with Fe in more acidic systems (Reddy and DeLaune 2008). Various mesocosm studies have demonstrated that P co-precipitation with Ca occurs most significantly when both Ca and TP concentrations are high—77 milligrams Ca per Liter (mg Ca/L) and 160 µg TP/L (Jerauld et al. 2024). While soil cations are important to plant health, soil composition does not appear to affect composition in plants, in only potassium (K) and manganese (Mn) were less in soils than in SAV (DB Environmental 2023b). The influence of other factors such as redox potential, pH, alkalinity, and sulfate on P cycling under very low P environments have been measured in mesocosms (DB Environmental 2023b) but have not been explored extensively.

Shallow water, reduced water turbidity, and open areas may induce increased photolytic degradation. Understanding the role of photolytic degradation in the STAs may help determine ways to further decrease outflow P concentrations.

### *Sub-question: Operational Changes to Reduce PP and DOP*

*Are there design or operational changes that can be implemented in the STAs to reduce PP and DOP in the water column?*

To identify methods to reduce P in the water column, the forms, storages, and biogeochemical transformations of P in the STAs have been evaluated (**Figure 3**). P forms include DIP, PP (inorganic P attached to metallic cations [e.g., Ca, Mg, Fe], pyro and polyphosphates), DOP and particle-bound organic P. Storages of P in the STAs include the water column (Villapando et al. 2024); vegetation biomass (aboveground and belowground, Dombrowski et al. 2023); periphyton and phytoplankton (Feeney et al. 2024); litter (primarily dead SAV and EAV), floc (a mixture of litter and microbial communities), soil (Bhomia et al. 2011, Reddy et al. 2021), and aquatic fauna (Goeke and Dorn 2023a). Many biogeochemical and physical mechanisms can reduce PP and DOP concentrations in the water column. PP can be reduced through incorporation into biological assemblages (periphyton mats; Pietro 1998), filtering by EAV and SAV (Lal 2017), decomposition, and settling. DOP can be taken up by periphyton or microbial organisms, and microbial transformation may make this form more readily available for uptake by EAV and SAV, phytoplankton, and bacteria. DOP also can be reduced through photolytic degradation (Amaral et al. 2023, Schafer et al. 2023), co-precipitation with minerals (Bhomia et al. 2015, Reddy et al. 2021), and sorption (e.g., on Fe or Al). Overall, maintaining both EAV and SAV communities in the outflow regions of STA FWs provide complementary mechanisms of DOP transformation and removal (Feeney et al. 2024). Reducing fish abundance through inclusion of EAV areas in outflow regions could also reduce recycling of P through fish excretion and reduce bioturbation by fish nesting.

Transfer of PP from or to the soil primarily occurs through deposition or resuspension of particulate matter (Reddy et al. 1999). During resuspension of particulates, P can return to the water column and reduce wetland treatment efficiency (Chimney and Pietro 2006). High flow velocity, storm events, and mechanical disturbance (e.g., structure operation, bioturbation) can increase resuspension of particulate matter to the water column. Also, recent findings suggest PP could increase as a result of phytoplankton growth or epiphyton detachment (Fugate et al. 2021, Fugate and Thomas 2024 ). Identifying the internal sources of PP, quantifying their relative contributions to the TP concentration observed at the outflow does indicate the importance of periphyton/phytoplankton in PP production (Fisher et al. 2024).

Organic P in aquatic systems can occur as dissolved (DOP) or particulate form and can originate from external or internal sources (e.g., from external loadings, decomposition of organic matter, or flux from floc or soil layers). The DOP fraction is poorly characterized and considered diverse in terms of complexity and lability, ranging from simple organic phosphates such as sugar phosphates to more complex molecules such as phospholipids (Reddy and DeLaune 2008, Morrison 2023, Fisher et al. 2024). DOP usually is measured in water samples that have been passed through a 0.45-micron filter; however smaller ultrafine particles have been measured in outflow waters (Buchanan et al. 2023). Particulate-bound organic P typically is associated with detrital matter (e.g., dead and decomposing microbial cells, decomposing biomass from plants and animals, organic material attached to particulates). Transformation of organic P depends on biological activity and is influenced by environmental conditions. Microorganisms play an important role in the mineralization of organic matter and eventual release of P, which can be readily assimilated into microbial biomass (Inglett et al. 2022, Pietro et al. 2023). Organic P degradation also can result from abiotic processes, including leaching of DOP from necromass, abiotic hydrolysis of P esters, and photolysis.

P mineralization is slower under continuous inundation (i.e., flooding) than under oxidized conditions (i.e., dryout). In areas where the soil and accrued material are highly organic, P spikes commonly are observed following dryout periods. This is particularly problematic as the newly accreted P in floc and the surface soil layer in the STAs generally is highly labile, and a large fraction of stored P can be quickly released back into the water column upon rehydration.

The resulting P spike depends on several factors, including the amount of labile organic P in the oxidized soil layer and the microbial and SAV uptake of P. Microbial communities associated with senescing material rapidly assimilate the released P, while excess P can remain in the water column and eventually reach the outflow structures. Due to the higher organic content in accreted material within EAV cells, the effects of dryout/oxidation on P flux generally are greater in these cells (Ivanoff et al. 2013). However, loss of vegetation when an SAV cell dries out can result in increased P flux and generally high turbidity after rehydration. Once rehydrated the internally generated P can be reabsorbed by the system through sorption, plant and microbial uptake, Ca and Fe binding, and settling. However, when water is discharged shortly after initial rehydration, high P concentrations occur in the FW or STA outflow structures. Soil P flux can be accelerated through repeated cycles of dryout and flooding.

Since the completion of a marsh dryout study (Moustafa et al. 2011, 2012), considerable experience has been gained about the effects of soil P flux on STA performance during start-up and reflooding after droughts. Findings from this study, along with operational experience in the STAs, have led to the establishment of minimum water depth targets for the STAs. When there is not sufficient water to maintain hydration, if possible, maintaining moist soil can minimize P release (Aldous et al. 2005).

Dryout or brief drawdown periods can benefit SAV by consolidating soils followed by increased germination (DB Environmental 2023b). Such new plant growth occurs more rapidly in the absence of large herbivorous fish (Goeke and Dorn 2024a). As the large herbivorous fish are absent at low water depths (Goeke and Dorn 2023a), maintaining lower water depths for as little as five weeks after rehydration of STA cells that experienced dry out can lead to healthy SAV communities that remove P from the water column and result in ultra-low P concentrations that can be discharged.

A number of studies have observed increased PP and TP in the water column of outflow SAV regions that occur during no flow periods (Powers 2024, Villapando et al. 2024, Herteux et al. 2025). These studies indicate that after no flow periods, allow outflow to ramp up slowly to prevent high outflow of high TP concentration. Alternatively, maintaining a low outflow during dry periods may prevent higher TP concentrations. An additional study looking at diurnal factors did find a small but significant difference in TP concentrations over the course of a day (Powers et al. 2023) with TP concentrations between midnight and 4 am being 6% lower than midafternoon concentrations. In addition, flow discharge and water depth are important factors that may be considered as well.

**Knowledge Gap.** Dryouts followed by rehydration can result in higher TP concentrations in the water column and to enhanced germination of SAV. SAV grows faster in the absence of herbivorous fish, which tend to avoid shallow (1.25 ft) waters. Opportunistic (droughts conditions or FW offline) field investigations can determine if dryout followed by rehydration for at least 5 weeks at 1.25 ft of water or less results in the reestablishment of an SAV community. If the community is reestablished, then the effect on TP concentrations can be evaluated.

## Key Question 5

*How can the biogeochemical or physical mechanisms, including internal flux of P, be managed to further reduce SRP, PP, and DOP concentrations at the outflow of the STAs?*

As a result of the gradient between the water column and P-enriched floc and surface soil layers, P can flux from the soil to the water column, elevating water column P concentrations. This process is influenced by various chemical, physical, and biological processes, including diffusion and advection via wind or flow, bioturbation, vegetation-mediated flux, redox conditions, diagenetic processes at surface of sediments, and abiotic and biotic processes in the water column (Reddy and DeLaune 2008). The simplest and least important internal load is diffusion of dissolved P from the soil to water column (DB Environmental 2017). Loading is more substantial through resuspension of PP by waves and water flow (Fugate et al. 2021) or through bioturbation and excretion by fish and invertebrates (Barton et al. 2023, Goeke et al. 2024). The largest internal load is translocation of P from the soil through plant root uptake and vegetation growth, death, and sloughing of plant tissue, followed by plant tissue mineralization returning P back to the water column (UF-WBL 2019, Grace et al. 2023).

Internal loads were measured using in situ mesocosms with windows to allow for water flow between the inside and outside waters. When these windows were closed, the change in internal P reached an asymptote in the water column, which was the result of an equilibration between internal loads and settling (Jerauld et al. 2020). Measurements in STA-2 FW 3 found that the internal load was highest at the inflow region of the FW and declined to the outflow. Diffusion of dissolved forms of P from the soils to the water column were not a major part of this internal load. Overall, the internal load was substantial, equaling the external loadings. Based on transect measurements of TP in the water column along a FW, TP concentrations decline over the first two-thirds of the FW and remain relatively constant during no flow conditions (Juston and Kadlec 2019, Villapando et al. 2024). This constant TP concentration is attributed to an equilibrium between internal loading to the water column and removal from the water column. Thus, an optimal size and length of STA FWs in terms of P retention should be observed (**Figure 4**).

If the source of internal loading is removed, further reductions of P can be achieved. The STA-3/4 Periphyton-based STA (PSTA) Cell is the best example of this (Zamorano et al. 2023). This cell was constructed by removing muck soils to bedrock (internal vegetation strips were created using a portion of the scraped material) thereby substantially reducing internal loads. Since operations began for this cell, annual outflow TP FWMCs have been at 13 µg/L or less (Zamorano et al. 2018). Mesocosm experiments of limerock on top of a layer of muck also reduced the internal load to the water column as long as there were no rooted plants (DB Environmental 2018a). Soil inversion, which could result in a limerock layer at the soil surface, was investigated at the field scale, while cores of inverted soils showed lower P loading compared to the control cores (Josan et al. 2018). Field scale measurements were equivocal; the area with the inverted soils could not be compared to the control area (where soils were not inverted) because the vegetation and hydrology were not comparable (Chimney 2023).

### ***Sub-question: Soil Amendment or Soil Management***

*What is the treatment efficacy, long-term stability, and potential impact of soil amendments or management?*

The numerous mechanisms and pathways for internal P flux pose a potential challenge to ensuring maximum and sustainable performance of the STAs. Soil management—typically characterized as physical manipulation (soil removal to limestone cap rock, disking, inversion, or capping) or addition of soil amendments—has been used in other areas to reduce P flux. In the Everglades STAs, the benefits of soil removal within a 100-acre PSTA Cell in STA-3/4 were evaluated (Zamorano et al. 2018). The annual average discharge concentrations resulting from the study successfully met the WQBEL for 16 years (Water Years 2008 to 2023; Dombrowski and Piccone 2024). Constructing PSTA areas in the discharge regions of other cells was evaluated based on location, soil type, soil depth, and elevation (Piccone and Zamorano 2020).

Chimney (2015) researched more than 100 soil amendments to control P flux in the STAs. Concerns regarding these amendments include the amount of treatment material necessary to adequately control P flux, length of time the materials will remain effective, and potential toxicity associated with various soil amendments. Therefore, follow-up studies on the role and applicability of soil management were limited to soil manipulation. A soil inversion study conducted in STA-1W Expansion #1 was inconclusive as the control and experiment were different in vegetation and hydrology (Chimney 2023).

### ***Sub-question: Sources, Forms, and Transformation of P***

*What are the sources, forms, and transformation mechanisms controlling residual P pools within the STAs, and how do they compare to the natural system?*

Three overall processes affect P retention in the STAs: (1) removal from the water column, (2) soil accretion, and (3) internal loading (Figure 3 in James et al. 2024). P removal occurs through particulate settling, chemical reactions that develop precipitates followed by settling, and biological uptake. Soil accretion occurs as organic and inorganic materials settle out of the water column and are retained as new soil. P retained in the soil is the long-term storage mechanism, often bound to recalcitrant organic compounds or as various inorganic forms of P to metals including Al, Fe, CA, and Mg. Some of this soil P can be returned to water column in dissolved and particulate forms via several pathways of internal loading. The simplest and least important internal load is diffusion of dissolved P from the soil to water column (DB Environmental 2017). Loading is more substantial through resuspension of PP by waves and water flow (Fugate et al. 2021) or through bioturbation and excretion by fish and invertebrates (Barton et al. 2023, Goeke et al. 2023). The largest internal load is translocation of P from the soil through plant root uptake and vegetation growth, death, and sloughing of plant tissue, followed by plant tissue mineralization returning P back to the water column (UF-WBL 2019, Grace et al. 2023).

EAV acting as a semipermeable barrier not only reduces water velocity (increasing the water depth as well during flow), but also filters out particles through impaction on plant surfaces. As particles settle and accumulate in the floc and soil, some of the buried organic material is mineralized to DIP or DOP, which is returned directly to the water column through diffusion and bioturbation, or translocation into plants by root uptake. As plants are consumed by fauna or age and die, the P in various dissolved and particulate forms may be added back to the water column or to the litter layer. The decay continuum of plant litter and detrital matter along the FWs, coupled with biotic and abiotic processes, regulates P release or retention in the water column (Reddy et al. 2022) on a diminishing scale along the FW, as proportionately less P is retained in the soil and less returns to the water column along the flow path. Internal loading works to counteract the amount of P retention but overall, as the water moves downstream from the inlet to the outlet, P content declines in water, plant, soil, and internal loads (DB Environmental 2017, UF-WBL 2019).

The types of organic and inorganic forms of P produced and returned are dependent on the major vegetation communities. DIP is removed directly from the water column through uptake by periphyton, SAV and, to some extent, FAV. DIP also is removed from the water column indirectly through a biological process in regions where SAV—specifically *Chara* spp. (muskgrass)—is dense. Photosynthetic processes increase the pH of the water column, promoting $CaCO_3$ formation and precipitation, often incorporating inorganic and organic dissolved and particulate forms of P (see Reddy et al. 2021). The accumulated $CaCO_3$ amalgams have a high bulk density, which reduces resuspension and enhances retention of P within the floc and soil.

The oligotrophic Everglades ecosystem is dominated by sawgrass ridges and water lily sloughs. Species that thrive in this very low nutrient environment have efficient P uptake and accumulation mechanisms and much higher tissue P concentrations relative to the external habitat. These plants retain P for long periods due to slow turnover and decomposition rates (Davis 1991, Lorenzen et al. 2001, Brix et al. 2010, Miao and Zou 2012, Miao 2014).

As the STA wetlands have long hydroperiods, they can only be compared to Everglades sloughs and *Typha* communities found in the WCAs, the latter have resulted from eutrophic conditions associated with higher P loadings that have accumulated in the soils. Unaffected sloughs in the Everglades have soil P content less than 500 milligrams per kilogram (mg/kg) while *Typha* communities have soil P content greater than 1,000 mg/kg (Noe et al. 2001). STAs are similar as the *Typha* (EAV) soil P content is approximately 1,000 mg/kg while that of SAV regions have P content of approximately 600 mg/kg (Reddy et al. 2020). Plant content of *Typha* in the WCAs ranged from 1,400 to 1,800 grams per kilogram (g/kg) and SAV in the sloughs between 300 and 850 mg/kg (Noe et al. 2001). This compares with the lower P content of *Typha* in the STAs of between 400 to 800 mg/kg and similar P content of *Chara* between 500 and 1,700 mg/kg (Dombrowski et al. 2023). Dombrowski et al. (2023) determined that rooted *Typha* were not P limited in the STA FWs. Flux of P from the soils to the water column via translocation ranged from 0.03 and 0.2 g P $m^2$/yr in oligotrophic slough and *Cladium* marsh, respectively, to 1.1 g P $m^2$/yr in partially enriched *Cladium*/*Typha*, and 1.6 g P $m^2$/yr in enriched areas (Noe and Childers 2007). The latter is similar to estimates from mesocosm studies in the STA FWs that estimated fluxes of 2.4 to 0.7 g P $m^2$/yr from the inflow to the outflow (Grace et al. 2024). An additional comparison is the biomass of fish, which has been estimated in the STAs at an order of magnitude greater than in the Everglades (Goeke and Dorn 2023a). Based solely on the biomass, the contribution of STA fish to the P cycle is likely 10 or more times greater than the contribution of Everglades fish. The biomass, the fluxes, and the soil content all indicate that while the P cycle of the eutrophic STAs and the enriched areas of the Everglades is similar, evidence from the oligotrophic Everglades is that the P is extremely limiting in the plants based on nitrogen (N):P ratios (Noe et al. 2001).

### *Sub-question: Role of Vegetation in Low-P Environments*

*What is the role of vegetation in modifying P availability in low P environments, including the transformation of refractory forms of P?*

The effects could be direct (P uptake) or indirect (e.g., increased pH due to photosynthetic activity, which facilitates co-precipitation of P with Ca). In situ chamber results suggested P flux is reduced when

EAV or SAV is present (Villapando and King 2018). Previous mesocosm studies showed the presence of SAV in limerock cap experiments resulted in higher P concentrations in the water column compared to mesocosms without SAV, suggesting SAV's role in mining P from the soil layer (DB Environmental 2018a). Comparison of areas in the STAs dominated by rFAV or SAV showed higher TP concentrations in the rFAV regions, suggesting translocation from the plant roots to the water column or shading resulting in less biomass of SAV and periphyton uptake, which allows for increased P flux from the soil into the water column (DB Environmental 2018c).

Reddy et al. (1999) indicated that aboveground plant biomass returns P to the water after dieback via leaching and decomposition, and deposits refractory residuals on the soil surface as well as redistributing nutrients to belowground portions, as necessary for storage. However, dead roots and rhizomes decompose belowground, thereby adding refractory compounds to the soil and leachates to the porewater. As such, the aboveground portion of the macrophyte cycle returns P to the water, while the belowground biomass returns P to the soil. Decay and translocation processes release most P to the water column, with the residual accreting as new soil.

DeBusk et al. (2004) indicated that low water velocities and dense stands of SAV and EAV facilitate settling of PP. Macrophyte uptake and translocation can be an important mechanism linking soil and water column TP concentrations in marsh ecosystems—this process is known as P mining (Noe and Childers 2007). However, this upward transfer is countered by two opposing processes: (1) the transpiration flux, or downward movement of water and associated P, resulting from plant transpiration; and (2) translocation of P from senescing leaves to the rhizomes (Kadlec and Wallace 2009). Because of the competing processes among plant uptake, detrital decomposition, and transpiration flux in the root zone, a vertically decreasing concentration of soil TP and porewater P in the soil profile may exist (Kadlec and Wallace 2009). SAV decomposition, particularly during low water conditions, may be responsible for the high flux of PP and SRP.

A benthic periphyton community can obtain nutrients directly from the water column or via diffusion from the soil. Therefore, benthic periphyton communities can affect net exchange of nutrients across the soil-water interface (Newman et al. 2004). Periphyton reduces P concentrations in the water column through several mechanisms, including direct uptake and storage as cellular organic P, metal phosphate deposition, co-precipitation with Ca and Mg, and adsorption to inorganic compounds such as $CaCO_3$ (Hagerthey et al. 2011). Periphyton is closely involved in wetland biogeochemical cycling, which allows for long-term storage of nutrients in soils. Periphyton assemblages can play several roles that increase retention of nutrients, including (1) removing nutrients from the water column; (2) slowing water exchange across the soil-water interface, thereby decreasing advective transport of P away from soils; (3) intercepting P diffusing from soils or senescent macrophytes that cause biochemical conditions that favor P deposition; and (4) trapping particulate material from the water column (Dodds 2003).

### *Sub-question: Water Level Drawdown*

*Do water level drawdowns improve soil consolidation and compaction?*

Within the STAs, accreted soils in EAV-dominated cells are highly organic, while accreted soils in SAV- dominated cells are primarily amorphous marl. During drought conditions, STA cells may experience dryout. As a vegetation management strategy, SAV areas are prioritized for supplemental water when available. Drawdowns have been conducted in selected cells for vegetation rehabilitation purposes. A study that evaluated methods to consolidate marl soils found that drying did enhance soil stability and reduced soil volume, but the effect on stability was negated after 12 weeks of rehydration (DB Environmental 2023a). Over an extended hydration period, as would be typical in an STA FW after a dryout event, consolidation alone is not an effective long-term STA soil management practice but may provide a temporary window of opportunity for SAV germination and regrowth.

## Key Question 6

*What is the influence of wildlife and fisheries on the reduction of P in the STAs?*

The role of wildlife and fisheries in P cycling and reduction in the STAs had not been investigated prior to implementation of the 2013 Science Plan (SFWMD 2013). P interactions between fauna and the water column in STAs are relatively complex (**Figure 5**). For treatment wetlands, Kadlec and Wallace (2009) emphasized that birds and other grazing animals are important components of the P cycle through feeding and excretion and through transporting P during daily and seasonal movements. Kadlec and Wallace (2009) indicated fecal production rates by bird flocks in treatment wetlands "may influence the ability of treatment wetlands to achieve ultra-low P concentrations".

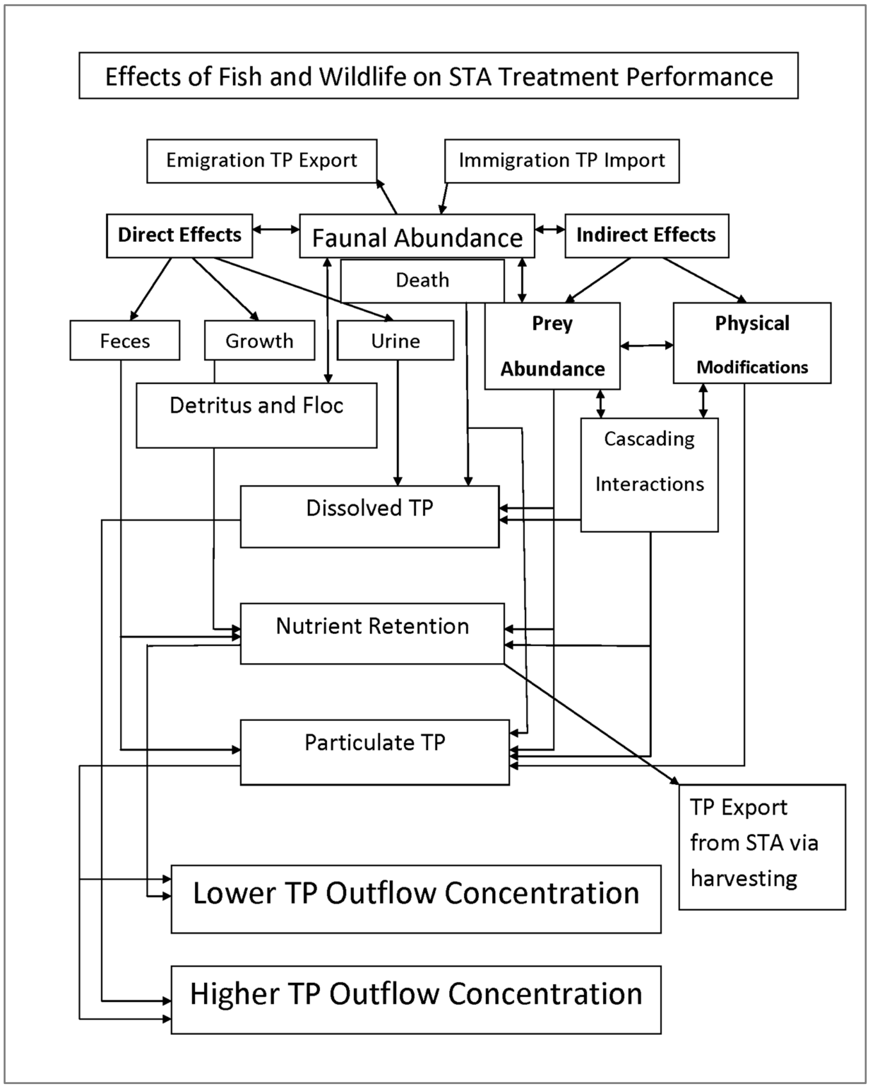



**Figure 5.** Conceptual diagram of interactions between fauna and STA performance and outflow TP concentrations. Modified from Vanni (2002).

Overall, these examples are conservative when viewed in the context of biologically productive STAs because they only considered bird effects on P cycling. Recent surveys of the STAs documented large flocks of American coots (*Fulica americana*) and wading birds that use the SAV cells at certain times of the year. In addition, large numbers of fish nests (tilapia) were observed in these areas. Based on the density of these fish, they can have a notable effect on the internal P cycling of this region. As reviewed by Vanni (2002), birds, fish, and macro-crustaceans (e.g., crayfish, grass shrimp) can alter several pathways leading to higher or lower TP concentrations in the water column of aquatic ecosystems (**Figure 5**). The Investigation of the Effects of Abundant Faunal Species on P Cycling in the STAs (Faunal) Study evaluated fluxes of P from fish and invertebrates and found that their contribution to loads through excretion was similar to external loads (Goeke and Dorn 2023b).

### *Sub-question: Wildlife Effects*

*What are direct and indirect effects of wildlife communities at temporal and spatial scales on P cycling (i.e., are they net sinks or sources)?*

In STA cells near outflows, fauna could be major factors in outflow TP levels when concentrations are very low. The STAs host many animal consumers, most conspicuously birds and American alligators (*Alligator mississippiensis*). STAs attract many species of migratory birds, which arrive in large numbers and stay for months at a time during fall and winter (Beck et al. 2013). At the scale of an entire STA, it is unknown whether wildlife interactions will noticeably affect outflow TP concentrations, though they locally influence water column P dynamics. Beck et al. (2013) placed such observations in perspective. They found bird densities in the STAs to be 35 times greater than that found in marshes of WCA-3A averaged over the entire year, but 50 to 120 times greater during fall and winter. Wetland fishes also contribute substantial internal P loading and support high algal growth rates through strong bottom-up influences (Zimmer et al. 2006). Fish can initiate cascading trophic interactions across wetlands like the STAs. Direct and indirect effects (**Figure 5**) associated with faunal predation, grazing, and physical modification of the environment are worthy of further study as they cascade through the marshes near STA outflows and could alter outflow TP concentrations. The Faunal Study evaluated this sub-question and associated questions using field surveys and mesocosm experiments.

Specific study areas can be derived from **Figure 5**:

- Effects of fish on P cycling and other nutrients within the system
- Rates of TP cycling from fish and macro-crustaceans in the STAs
- Contribution of faunal recycling to ambient P turnover
- Form and availability of excreted TP for the dominant faunal components
- Effect of SAV (e.g., *Hydrilla*) grazing on STA functionality
- Effects of herbivory on SAV growth, health, biomass, and TP retention

**Knowledge Gaps**

A few topics are recognized as knowledge gaps and potential areas of further research:

- Effects of wildlife (birds alligators, amphibians) on cycling of P and other nutrients within the system
- Primary diets of waterfowl and submerged aquatic wildlife in the STAs
- Rates of TP cycling from wildlife and insects in the STAs

### <u>Birds</u>

Many avian surveys show the STAs support a relatively diverse and abundant community of birds (Chimney and Gawlik 2007, Beck et al. 2013). More than 160 bird species have been identified in STA-3/4 alone (eBird 2022), and the STAs support more than twice the density of birds in the EAA. Many bird species forage on SAV (e.g., *Hydrilla*), and approximately 90% of birds within the STAs are found in the

SAV areas. By the time spring migration occurs, SAV biomass often is greatly reduced; however, the extent to which this loss is due to herbivory by waterfowl is unknown.

Fish-eating birds, especially wading birds (e.g., herons, ibises, storks), are common in the STAs. Breeding wading birds are potential net exporters of TP from the STAs. Wading birds transfer TP from aquatic habitats to terrestrial breeding colonies and roost sites, largely through feeding their offspring aquatic prey animals and through defecation. The export, import, and recycling of feces may play an important role in P dynamics and STA outflow P concentrations.

Birds protected by the Migratory Bird Treaty Act, such as black-necked stilts (*Himantopus mexicanus*), or the Endangered Species Act, establish a direct link between avian presence in the STAs and operational limitations that can influence STA performance. These birds nest on the ground within drying portions of STA cells. Operational measures implemented to minimize the flooding of nests as part of the *Avian Protection Plan for Black-necked Stilts and burrowing Owls Nesting in the Everglades Agricultural Area Stormwater Treatment Areas* (Pandion Systems 2008) could affect the overall functionality of the treatment wetlands.

**Knowledge Gaps**

A few topics are knowledge gaps:

- Excretion contribution to P content in outflow regions of the FWs
- Effect of predation to reduce fish populations in outflow regions

## Fish

The STAs provide excellent habitat conditions for an abundant and diverse fish community. Evans and Trexler (2018) and Goeke and Dorn (2023b) documented 21 species of small fishes (< 8 centimeters [cm] standard length) in STA-2, and 19 to 20 species of large bodied- fishes (≥ 8 cm standard length) in STA-2, STA-1E, and STA-1W. Mean small-fish density (± standard error) ranged from 25.4 ± 3.6 to 42.4 ± 5.0 individuals per square meter, depending on the season. These densities were 2.3 to 11.3 times higher than those observed in other regions of the Everglades during similar times. The mean catch-per-unit-effort of large-bodied fishes in STA-1W and STA-1E were significantly greater ($p < 0.05$) than those from the Everglades. STA fish are larger and have higher P body content than fish found in the unenriched marshes of the Everglades. Overall estimates of excretion per area of small fishes are in the same range as external loads to the STA FWs (Goeke and Dorn 2023a). Fish also affect SAV through herbivory (Goeke and Dorn 2024a).

**Knowledge Gaps.**

A few topics are knowledge gaps:

- Effect of fish movement from inflow regions to outflow regions of FWs and potential effect on outflow region TP concentrations
- Planting of EAV to reduce fish abundance in outflow regions of the STAs

## Alligators

Alligators are abundant in the STAs, but there have been no quantitative studies of their abundance or their effect on STA performance. Their body mass (approximately 50 kilograms) is huge relative to other organisms in the STAs. When concentrated near outflows, alligators could affect P recycling, and their role in physical disturbance of the soils could influence water column P concentrations substantially. As a result, when working toward very low outflow P concentrations, information on direct and indirect effects of alligators on water column P concentrations would be valuable, particularly near outflows. However, these large animals store more P in their body tissues than smaller animals, and because they are long-lived (beyond 50 years), they function as a nutrient sink.

**Knowledge Gap.** TP content, excretion, and alligator holes contribution to internal P loads and TP concentration in the outflow regions of the FWs have not been investigated.

### Invertebrates

The STAs, as eutrophic to mesotrophic wetlands, provide the food and habitat resources needed to support relatively high densities of macroinvertebrates. Initial surveys indicate high densities of macroinvertebrates and high species richness. While their excretion does contribute to the P loads from fauna, estimates of this flux are much lower than for small fish (Goeke and Dorn 2023b).

### *Sub-question: Wildlife Management*

*What options are there for mitigating or reducing the impacts of fish and wildlife on STA performance through wildlife management or changes in operations?*

Faunal consumers can cause top-down (i.e., predation, herbivory) and bottom-up (i.e., excretion) interactions. Disentangling the consequences of community-level interactions occurring simultaneously in an STA would be difficult, but studies support working in that direction (Wetzel et al. 2005). The Science Plan focused on fish and invertebrates as they are abundant in the STAs, have direct effects on water column TP through excretion and bioturbation, and indirect effects through herbivory of SAV plants. Bird populations in winter breeding season have been surveyed, however their effects through fish and invertebrate predation, plant herbivory, and excretion were not studied in part due to difficulty of tracking and their ephemeral nature. Overall, the challenge is to decide what ecological interactions may be important and conduct the studies necessary to make decisions on potential management and operational means to lower outflow P concentrations through cascading biological interactions.

When birds like Caspian terns (*Hydroprogne caspia*), black skimmers (*Rynchops niger*), or white pelicans (*Pelecanus erythrorhynchos*) gather in specific areas, they may generate nutrient hotspots. Near outflows, such nutrient hotspots could substantially increase TP concentrations, at least for part of the water year (e.g., waterfowl grazing and defecation plus reduction of SAV surface area for periphyton). Quantitative estimates of faunal densities and interactions are needed to ascertain if the hotspots are TP sources or sinks in the STAs. Reliable wildlife information is valuable for monitoring ecosystem performance as well as encouraging public understanding and support for the STAs and Everglades management (Gawlik 2005).

## LIST OF RESEARCH QUESTION KNOWLEDGE GAPS

- What is the effect of wading birds on species and water quality in the STAs, specifically:
  - Fish?
  - SAV?
  - Water column P, retention, removal or addition?
- Are there methods to reduce endangered bird nesting in STA cells?
- What is the effect of alligators on species and water quality in the STAs, specifically:
  - Fish?
  - SAV?
  - Water column P, retention, removal or addition?

- Does turbulent flow increase PP?
- Does laminar flow reduce PP?
- Does laminar flow result in lower TP outflow concentrations?
- Can periphyton enhance marl adhesion?
- How long and under what conditions does marl become rock?
- What is the concentration of P in bulk (upper 5 to 10 cm) soil porewater?
- How deep can marl get before it cannot be colonized by rooted SAV?
- What size/length of PSTA cell is needed to reduce P concentrations from 20 µg/L to the WQBEL?
- What depth of limerock is needed to simulate a PSTA cell?
- Can marl accumulation effectively create a PSTA cell?
- Do fungi provide a significant role in P cycling?
- Can environmental DNA (eDNA) surveys be used to evaluate plant, algae, and fauna communities and can this be related to P retention?
- Does the increase in the partial pressure of carbon dioxide ($pCO_2$) affect P retention, plant growth?
- Can rafts of mussels be used to reduce PP in L-8 FEB and canals?

# GUIDANCE

The information collected over the past three decades has led to numerous potential management options to enhance P retention and achieve the WQBEL in STA discharges (**Table 7**). However, any management strategy must consider the realities of STA operation, i.e., the requirement to provide flood protection for the tributary basins within the SFWMD boundaries and the need to treat large volumes of water each year while trying to minimize major disruptions to STA vegetation including operations associated with extreme weather events such as prolonged drought conditions and high flows and winds associated with tropical cyclones. In addition, the STAs and the individual FWs are different based on history, flow, loads, soils, etc. and the guidance strategies below may not work the same on all FWs. Adaptive management should be applied with any options taken for a given FW.

From the 21 studies included in the Science Plan, 20 management strategies to maximize TP retention were derived (**Table 2**). These strategies may be used, where feasible, considering differences in individual FWs, their history, and the operational realities.

**Table 7.** List of potential management options and references.

| | **Potential Recommendation**<br>(Supporting Evidence) | **References** |
|---|---|---|
| 1 | **Maintain PLRs at or below 1.3 g P/m²/yr or less for each individual FW.**<br>(At this loading rate, annual outflow FWMC are consistently at 19 µg/L or less.) | DB Environmental (2021)<br>Zhao and Piccone (2020) |
| 2 | **Maintain flow rates between 5 and 15 cm/d on a daily basis during flow periods.**<br>(At these rates, outflow TP concentrations are at minimum values.) | Powers et al. (2023a)<br>Villapando et al. (2024)<br>Juston and Kadlec (2019) |
| 3 | **Maintain average annual HLR between 1.7 and 3.5 cm/d.**<br>(Annual TP FWMCs are lower at these HLRs. The lower annual HLR compared to daily flow rates include low or no flow periods allowing the wetland to “rest”.) | Zhao and Piccone (2020) |
| 4 | **To support healthy cattail areas, do not allow water depths to exceed 2.8 ft for more than 8 weeks.**<br>(Plants show signs of stress and elongate in these conditions.) | Diaz et al. (2023) |
| 5 | **If water depths have been kept above 2.8 ft for more than 4 to 6 weeks in cattail regions, avoid rapid water level declines.**<br>(Rapid water level decline can result in cattail lodging, which means they fall over due to elongated leaves.) | Diaz et al. (2023) |
| 6 | **In outflow cells/regions, maintain mixed EAV/SAV communities.**<br>(EAV and SAV are habitat for different periphyton communities that mineralize and retain different types of P forms. Having both EAV and SAV periphyton communities can provide a more complete mineralization of organic P.) | Feeney et al. (2024)<br>Pietro et al. (2023) |
| 7 | **Maintain EAV as windrows in outflow cells to protect SAV communities.**<br>(These windrows have been shown to protect and minimize impacts to SAV, especially during major storm events.) | Field observations<br>Best professional judgement |
| 8 | **Manage EAV in outflow cells to prevent overgrowth into SAV areas.**<br>(Having mixed communities of both EAV and SAV as they help to mineralize different forms of P, providing overall better treatment performance.) | Field observations<br>Best professional judgement |
| 9 | **If further P retention is needed to meet the WQBEL, PSTA (muck removal) may be an option.**<br>(Cells screened as potential candidates for PSTA construction based on outflow TP concentration, soil depth, and soil nutrient status. Costs for potential candidates were estimated. The STA-3/4 PSTA Cell has resulted in annual outflow P concentrations of 13 µg/L or less for the period of record.) | Piccone and Zamorano (2020)<br>Zamorano et al. (2023) |
| 10 | **If PSTA is not feasible, in lieu of muck removal, cap soils with 0.5 to 0.7 ft of limerock at outflow regions of FWs.**<br>(Mesocosm studies using limerock caps found lower TP outflow concentration with SAV in capped soil than SAV and uncapped muck soils.) | Grace et al. (2023) |
| 11 | **Where floating wetlands (formerly known as tussock) formation is observed or imminent, if possible lower water depths below 1.0 ft.**<br>(At these water depths, cattail buoyancy is neutral. Root connectivity affects floating wetland formation.) | Clark (2022) |
| 12 | **Planting deep rooted plants (e.g., spikerush or bulrush) can anchor cattail to prevent tussock formation.** | Field trials and observation<br>Best professional judgement |

**Table 7.** Continued.

| | **Potential Recommendation**<br>(Supporting Evidence) | **References** |
|---|---|---|
| 13 | **Limit fish density and nesting in STA outlet regions through selective EAV planting.**<br>(Small fish abundance was greater in SAV areas than EAV areas.) | Goeke and Dorn (2023a) |
| 14 | **Manage fish populations by reducing water depths to less than 1.5 ft, especially in the dry season.**<br>(Large fish move from the marsh wetlands to concentrate in canals and deeper areas. Lower water depths enhance predation through wading bird feeding. Concentration of fish in deep pools enhances feeding by alligators.) | Goeke and Dorn (2023a)<br>Best professional judgement |
| 15 | **Avoid high P loading to SAV communities.**<br>(High loads result in dense plant biomass leading to low dissolved oxygen and redox at that soil-water interface and potential SAV collapse.) | DB Environmental (2023b) |
| 16 | **Where SAV communities have collapsed, if possible, reduce water depths for a month and then maintain low water depths (1.7 ft) for at least five weeks before returning to normal outflow operations.**<br>(SAV germination and growth is better in consolidated soils. Fish avoid these shallow waters reducing herbivory. Slowly returning to normal outflow operations after SAV established reduces the TP in the outflow) | DB Environmental (2023a)<br>Goeke and Dorn (2024a)<br>Villapando et al. (2024) |
| 17 | **Maintain SAV regions to enhance photolysis.**<br>(DOM from inflow STA waters and leachates from STA vegetation litter are susceptible to photolysis. Photolysis breaks complex molecules into simpler ones that can be further broken down by periphyton exoenzymes. The simpler forms of P can be sequestered by periphyton and other biota.) | Schafer et al. (2023)<br>Morrison et al. (2024) |
| 18 | **SAV ecotopes of *Chara* and naiad should be encouraged at STA outflow regions.**<br>(*Chara* ecotopes produced the lowest TP concentrations during the wet season, mixed *Chara* and naiad produced the next lowest TP concentrations while *Typha* and bare soil ecotopes produced the highest TP concentrations.) | Powers (2024) |
| 19 | **rFAV should be discouraged in outflow regions of the FWs.**<br>(P retention by rFAV is typically less than SAV. These rFAV shade out SAV reducing P retention.) | DB Environmental (2018b) |
| 20 | **After substantial periods of no-flow (weeks to months) introduce low flows gradually to reduce effects of high TP and high flows, which influence the annual FWMC.**<br>(In the P Flux, P Dynamics and Ecotope studies[a], higher TP concentrations, primarily in the form of PP, occurred during no-flow events in outflow regions of STA FWs. Under flow conditions, TP concentrations were lower.) | Herteux et al. (2025)<br>Powers (2025)<br>Villapando et al. (2024) |

a. See **Appendix A**) for full study names.

# DATA MANAGEMENT

A vast amount of data and information have been gathered from the field, the SFWMD laboratory, and from contractors. All data and information have been stored in the proper repository, in accordance with the SFWMD's Scientific Data Management Policy (SFWMD 2007) and standard operating procedures (SOPs) for data management (SFWMD 2012a,c). The policy elements are supported by quality assurance/quality control manuals, including SOPs for field sampling, laboratory analyses, data review, and data management. Data management SOPs define roles and responsibilities for project staff and guide the complete data lifecycle from establishment of a study through its data distribution.

Standardized metadata are necessary to achieve these objectives and support data structure heterogeneity. Water quality monitoring metadata follow requirements defined by FDEP (2014). Hydrologic monitoring metadata are based on United States Geological Survey practices. Ecological monitoring and research metadata conform to the Ecological Metadata Language standard.

## DATA REPOSITORIES

SFWMD maintains a scientific data management system consisting of three databases: DBHYDRO (http://www.sfwmd.gov/dbhydro), DataOne, and Everglades Research Database Product (ERDP). DBHYDRO is primarily for water quality and hydrologic monitoring data, whereas DataOne and ERDP are primarily for metadata and ecological monitoring and research data (**Table 8**).

**Table 8.** Restoration Strategies Science Plan data type and process for storage.

| Data Type | Process and Database |
|---|---|
| Water Quality | Data generated in the field and in the laboratory are verified and validated by following a standard review process then archived in DBHYDRO. Data not meeting all quality criteria are assigned standard qualifier codes. When applicable, data from outside contractors should be delivered in Adapt format for validation and loading to the DBHYDRO database. |
| Hydrologic | Stage and rainfall data from STA structures are remotely acquired via telemetry. Localized measurements are included in some field studies (e.g., using pressure transducers, velocity meters, or measuring sticks). Data, including calculated flow data, are reviewed according to SOPs, which could vary depending on the criticality of the hydrologic information. Critical information (e.g., for permit reporting) undergoes additional quality assurance and is stored as preferred data. All structure data are archived in DBHYDRO, while study measurements are stored in ERDP or DataOne databases. |
| Ecological Research | Other ecological measurements or experimental data are validated by research team technical leads and stored in the DataOne and ERDP databases. |

# GLOSSARY

**Abiotic:** Non-living chemical and physical parts of the environment that affect living organisms and the functioning of ecosystems.

**Accretion**: Increase in size because of accumulation. Soil accretion results in accumulation of particles and plant material.

**Acre-foot or acre-feet (ac-ft):** Volume of liquid required to cover 1 acre to a depth of 1 foot, commonly used to express large amounts of water (1 acre-foot = 43,560 cubic feet).

**Adsorption:** The process by which a solid holds molecules of a gas or liquid or solute as a thin film.

**Advection (advective)**: A transport mechanism of a substance or conserved property by a fluid due to the fluid's bulk motion.

**Alkalinity**: Capability of water to neutralize an acid.

**Amalgam**: A mixture or blend.

**Amorphous:** Without a clearly defined shape or form.

**Anaearobic:** In the absence of oxygen.

**Anoxia:** Depravation of oxygen supply of such severity as to result in permanent damage.

**Asymptote:** A line that a curve approaches but never quite touches.

**Benthic**: Relating to the bottom region of a water body (e.g., ocean or lake), which includes the soil surface and some sub-surface layers.

**Biogeochemistry**: Study of the chemical, physical, geological, and biological processes and reactions that govern the composition of the natural environment (including the biosphere, hydrosphere, pedosphere, atmosphere, and lithosphere), and the cycles of matter and energy that transport the Earth's chemical components in time and space.

**Biomass**: Weight of living material in a sample, population, or area, usually measured as dry weight.

**Biotic**: Relating to or resulting from living things especially in their ecological relations.

**Bioturbation**: Disturbances caused by living organisms.

**Bulk density**: Mass of soil per unit volume.

**Calcareous:** Containing calcium.

**Cationic:** Something that is of, relating to, or being a cation, which is a positively charged ion formed when an atom or molecule loses one or more electrons.

**Chlorosis:** Abnormal reduction or loss of the normal green coloration of leaves of plants, typically caused by iron deficiency in lime-rich soils or by disease or lack of light.

**Conductivity:** A measure of the ability of water to pass an electrical current. Because dissolved salts and other inorganic chemicals conduct electrical current, conductivity increases as salinity increases. Conductivity is also affected by temperature: the warmer the water, the higher the conductivity.

**Consolidated soil:** The mechanical process by which soil changes volume gradually in response to a change in pressure. This happens because soil is a two-phase material, comprising soil grains and pore fluid, usually groundwater.

**Constructed wetlands**: Man-made wetlands created by surrounding areas with earthen levees or berms to contain areas inundated by water. Water movement through the wetlands is usually controlled by water control structures, such as pump stations or culverts.

**DBHYDRO**: SFWMD's environmental database that contains water quality and hydrological data.

**Decomposition**: Action of microorganisms breaking down organic compounds into simpler ones, resulting in the release of energy.

**Desorption**: Physical process where a previously adsorbed, or deposited on the surface, substance is released from the surface.

**Detritus:** Organic matter produced by the decomposition of organisms.

**Diagenesis:** The physical and chemical changes occurring during the conversion of sediment to sedimentary rock.

**Diel**: The daily (24-hour) cycle, primarily related to animal and plant physiology.

**Diffusion**: Transport of mass of material in response to a chemical concentration gradient.

**Discharge:** Release water from a facility via a water control structure see outflow.

**Dissolved inorganic phosphorus (DIP):** A form of phosphorus associated in a water sample that has been passed through a 0.45-micrometer membrane filter, primarily in the form of phosphate ($PO_4$).

**Dissolved organic phosphorus (DOP)**: A form of phosphorus associated with organic matter in a water sample that has been passed through a 0.45-micrometer membrane filter; usually calculated as DOP = total dissolved phosphorus - soluble reactive phosphorus.

**Diurnal**: Recurring every day or having a daily cycle (e.g., diurnal animals are active during the day rather than at night; diurnal flowers open during the day and close at night).

**Drawdown**: Lowering of the water level in a reservoir or other body of water.

**Drought**: Extended period of low rainfall, below-normal streamflow, and depleted surface and subsurface storage.

**Dryout**: Condition in which the water level within the STA cells falls below the average ground elevation.

**Ecosystem**: Biological communities together with their environment, functioning as a unit.

**Ecotope**: Plant communities and their environment.

**Effective treatment area**: Area within an stormwater treatment area that is hydrated under normal operational conditions and functions to remove phosphorus from the receiving water. The effective treatment area usually does not include levees or water control structures.

**Efficacy:** The ability to produce a desired or intended result.

**Emergent aquatic vegetation (EAV)**: Wetland plants that extend above the water surface (e.g., cattail, bulrush, sawgrass).

**Entrainment:** Entrapment of one substance (like liquid droplets or solid particulates) by another (like a flowing gas or liquid).

**Environmental DNA (eDNA):** Deoxyribonucleic acid (DNA) that is collected from a variety of environmental samples such as soil, seawater, or even air rather than directly sampled from an individual organism.

**Enzyme**: Complex protein that speeds up (catalyzes) specific biochemical reactions.

**Enzyme activity**: A measure of the amount of substrate converted to product per unit time under specific reaction conditions catalyzed by an enzyme.

**Epiphyton:** Periphyton growing on plants.

**Equilibrium phosphorus concentration**: The critical concentration of phosphorus when net phosphorus adsorption equals zero, i.e., adsorption equals desorption and the system is at equilibrium. At this point, the soil exhibits maximum capacity for buffering phosphorus in soil pore water (Reddy and DeLaune 2008).

**Eutrophic:** (Of a body of water) rich in nutrients.

**Evapotranspiration:** The loss of water from soil by evaporation and transpiration from the plants growing within it.

**Everglades Forever Act (EFA)**: A 1994 Florida law (Section 373.4592, Florida Statutes), amended in 2003 and 2013, to promote Everglades restoration and protection. This will be achieved through comprehensive and innovative solutions to issues of water quality, water quantity, hydroperiod, and invasion of nonindigenous species to the Everglades ecosystem. The EFA establishes the plan, the enforceable schedule, and the funding for the various components of the Everglades Program.

**Everglades Forever Act (EFA) permit**: Stormwater treatment area permit issued in accordance with the Everglades Forever Act (Section 373.4592, Florida Statutes) authorizing construction, operation, and maintenance activities for the stormwater treatment areas.

**Everglades Protection Area (EPA)**: As defined in the Everglades Forever Act, the EPA includes Water Conservation Area (WCA) 1 (Arthur R. Marshall Loxahatchee National Wildlife Refuge), WCA-2A, WCA-2B, WCA-3A, WCA-3B, and Everglades National Park.

**Everglades Stormwater Treatment Areas (STAs)**: Large freshwater treatment wetlands situated south of Lake Okeechobee, constructed to reduce TP concentration from runoff water prior to entering the Everglades Protection Area. Currently, the Everglades STAs (STA-1W, STA-1E, STA-2, STA-3/4, and STA-5/6) cover approximately 68,000 acres, including 57,000 acres of effective treatment area.

**Exoenzyme:** An enzyme that is secreted by a cell and functions outside that cell.

**Fauna**: All animal life associated with a given habitat.

**Floating aquatic vegetation (FAV)**: Wetland plants that have portions floating near or at the water surface (e.g., water lettuce, water hyacinth, water lily).

**Floc**: A fluffy mass of materials formed in wetlands through settling, precipitation, or aggregation of suspended particles and decomposing plants and detritus; this may be comprised of inorganic and organic material.

**Flora**: All plant life associated with a given habitat.

**Flow equalization basin (FEB)**: Impoundment areas that serve to store or distribute water to stormwater treatment areas to modulate treatment area inflows for vegetation health, optimal water depths, and phosphorus reduction efficiency.

**Flow path**: Planning-level delineation of source basins that are tributary to the existing stormwater treatment areas developed during preparation of the *Restoration Strategies Regional Water Quality Plan* (SFWMD 2012). The Eastern Flow Path contains STA-1E and STA-1W, the Central Flow Path contains STA-2 (including Compartment B) and STA-3/4, and the Western Flow Path contains STA-5/6 (including Compartment C).

**Flow-way (FW)**: Area within an stormwater treatment area that consists of one or more treatment cells, separated with levees and has one or more inflow and outflow structures.

**Flow-weighted mean concentration (FWMC)**: Average concentration of a substance in water, corrected for volume of water flow at the time of sampling. Samples taken when flow is high are given greater weight in the average. FWMCs are used to calculate mass loading at a particular location.

**Germination:** The process by which a seed or spore develops into a new plant or organism, typically after a period of dormancy, under favorable conditions of water, oxygen, and temperature.

**Herbivory:** The state or condition of feeding on plants.

**Hydraulic loading rate (HLR)**: Amount of water received by a stormwater treatment area divided by the amount of effective treatment area, typically expressed as centimeters per day.

**Hydraulic residence (or retention) time**: Length of time that water resides in a specified area, usually measured as days. Hydraulic residence (or retention) time is estimated by dividing the average depth by hydraulic loading rate (inflow volume divided by effective treatment area acreage).

**Hydraulic(s)**: Pertaining to the movement (flow) or effects (pressure) of liquids such as water.

**Hydrology**: Scientific study of the properties, distribution, and effects of water on the Earth's surface, in the soil and underlying rocks, and in the atmosphere.

**Hydropattern**: Water depth, duration, timing, and distribution of fresh water in a specified area. A consistent hydropattern is critical for maintaining various ecological communities in wetlands and other ecosystems.

**Hydroperiod**: Duration and frequency of inundation in a wetland area.

**In situ:** In the natural or original position or place. For environmental monitoring, this indicates measurements taken directly at the sampling site, as opposed to samples collected at a site and analyzed at a different location.

**Inflow**: Movement of water into a facility or area. In stormwater treatment areas, inflow is water flow at the beginning or top of a cell, flow-way, or stormwater treatment area. Inflow may also refer to the structure or location where untreated water enters a cell, flow-way, or stormwater treatment area.

**Inoculation**: The act of introducing a biological organism into a suitable situation for growth. In the stormwater treatment areas, inoculation is used as a management tool to accelerate submerged aquatic vegetation recruitment in areas converted from emergent aquatic vegetation to submerged aquatic vegetation or in submerged aquatic vegetation cells undergoing rehabilitation.

**Inorganic**: Composed of minerals rather than material from living organisms.

**Kinetics:** The rates of chemical or biochemical reaction.

**Labile**: Readily or continually undergoing chemical, physical, or biological change or breakdown.

**Laminar**: (Of a flow) taking place along constant streamlines; not turbulent.

**Leachate:** A liquid that has percolated through a solid and leached out some of the constituents.

**Litter**: Plant material that is suspended in the water column or deposited on the soil surface.

**Loading (hydraulic or mass loading)**: Amount of a substance carried into a specified area expressed as mass per unit of time or volume per unit of time. Total phosphorus loading is typically reported in metric tons per year, hydraulic loading is typically reported in acre-feet per year.

**Lodge:** When a plant falls over because of an inability to support its weight.

**Macrophytes**: Visible (non-microscopic) plants found in aquatic environments.

**Marl**: A naturally occurring fine crumbly mixture of clay and limestone, often containing shell fragments and sometimes other minerals.

**Marsh**: Area of soft, wet, low-lying land, characterized by grassy vegetation and often forming a transition zone between water and land.

**Mesocosm**: Experimental units or enclosures larger than microcosms but smaller than macrocosms that are used to provide a limited amount of the natural environment under controlled conditions.

**Mesotrophic:** Moderate nutrient conditions.

**Microbial:** Relating to or characteristic of microbes.

**Microcosm:** A study regarded as encapsulating in miniature the characteristic qualities or features of a much larger community.

**Mineralization**: Decomposition or oxidation of the chemical compounds in organic matter releasing the nutrients contained in those compounds into soluble inorganic forms that may be plant accessible.

**Muck**: Dark, organic soil derived from well-decomposed plant biomass.

**National Pollutant Discharge Elimination System (NPDES) permit**: A wastewater facility permit required under the Clean Water Act that authorizes discharge to waters of the United States. The permit specifies limits on what can be discharged, monitoring and reporting requirements, and other provisions to ensure that the discharge does not impact water quality or human health. For the stormwater treatment areas, an NPDES permit was issued under the provision of Chapter 403, Florida Statutes, and applicable rules of the Florida Administrative Code.

**Necromass:** The mass of dead organic matter, including dead plant material, timber, and dead microbial biomass, found in ecosystems, particularly in soil.

**Nutrients**: Organic or inorganic compounds essential for survival of an organism. In aquatic environments, nitrogen and phosphorus are key nutrients that affect the growth rate of plants.

**Oligotrophic**: Aquatic environment depleted of nutrients, resulting in low plant productivity.

**Optimization**: Action or goal to improve the effectiveness and/or efficiency of a method, process, or mechanism.

**Organic**: Relating to, derived from, or characteristic of living things.

**Outflow**: Movement of water out of an area, discharge. In stormwater treatment areas, outflow occurs at the end of a cell, flow-way, or stormwater treatment area. Outflow may also refer to the structure where treated water exists a cell, flow-way, or stormwater treatment area.

**Parameter**: Variable or constant representing a characteristic of interest. For example, pH is a water quality parameter. Use of this term is highly subjective and varies greatly across disciplines.

**Particle impaction**: Occurs when particles in the water column hit a surface (in stormwater treatment areas, typically plants, soil, or rock) and stick to that surface rather than being swept around by the current.

**Particle interception**: Occurs when particles in the water column contact and stick to a boundary (such as a plant stem) as they pass by in the current.

**Particulate**: Relating to or in the form of minute separate particles.

**Particulate phosphorus (PP)**: Particulate-bound phosphorus, not passing through a 0.45-micrometer filter, that can include both organic and inorganic forms; usually a calculated value: PP = total phosphorus - total soluble phosphorus.

**Peat**: Soils that contain partially decayed plant material. Peat is formed under anaerobic conditions found in inundated wetlands, is rich in humus, and known as a histosol.

**Periphyton**: The biological community of microscopic plants and animals attached to surfaces in aquatic environments, including bacteria, fungi, and algae—the primary component in these assemblages.

**Periphyton-based stormwater treatment area (PSTA)**: Wetland area where periphyton assemblages are a major component. Soil may be scraped away to reduce the amount of phosphorus released into the water column from the soil or porewater. Emergent or submerged aquatic vegetation are also typically present.

**pH**: Dimensionless quantity that ranges from 1 to 14. It is measured on a scale that is a negative logarithmic representation of the quantity of hydrogen ions in the solution. A value below 7 is considered acidic, above 7 is alkaline.

**Phosphorus (P)**: Element that is essential for life. In freshwater aquatic environments, phosphorus is often in short supply; increased levels can promote the growth of algae and other plants. The Everglades Stormwater Treatment Areas were constructed to remove excess phosphorus from surface waters before they enter into the Everglades Protection Area.

**Phosphorus co-precipitation**: The formation of amorphous particles as phosphorus reacts with metallic cations such as calcium (Ca), magnesium (Mg), iron (Fe), and aluminum (Al). This is an important phosphorus reduction mechanism in aquatic environments.

**Phosphorus cycling**: The transformation and exchange of P, mediated by biological, chemical, and physical processes, from the environment through one or more organisms and back to the environment.

**Phosphorus flux**: The movement of phosphorus between a source and a sink such as soil and overlying water column or from one physical or chemical state to another. The dimensions of flux are $M/L^2/T$, where M is mass of material transferred by flux, L is the distance or length, and T is the time. The processes associated with flux are advection (movement of phosphorus with water flow), diffusion (movement between the soil and water column), and dispersion. Diffusive and advective flux between soil and overlying water and elemental uptake by rooted wetland vegetation are the major transport mechanism in which nutrients, metals, and toxic organic compounds are removed from the soil and water column. Flux can be between the solid phase and porewater of soils.

**Phosphorus loading rate (PLR)**: Amount of total phosphorus received by a stormwater treatment area divided by the amount of effective treatment area. Phosphorus loading rate is usually expressed as grams of total phosphorus per area per year.

**Photolytic degradation (photolysis)**: The breakdown of compounds by light.

**Photosynthesis:** The process by which green plants and some other organisms use sunlight to synthesize foods from carbon dioxide and water. Photosynthesis in plants generally involves the green pigment chlorophyll and generates oxygen as a byproduct.

**Physiochemical:** Relating to physics and chemistry.

**Phytoplankton:** Periphyton floating free in the water.

**Polyphosphate:** A salt or ester of similar anions containing oxygen atoms formed from a structure where a central atom is bonded to four other atoms, arranged at the corners of a tetrahedral (three-dimensional shape with four triangular faces) phosphate ($PO_4$) structural units linked together by sharing oxygen atoms.

**Porewater**: Water contained within the spaces between particles within soils.

**Ramet:** A single, physically separate individual within a group of genetically identical organisms arising from a single ancestor.

**Recalcitrant (or refractory):** Resistant to chemical, physical, or biological change or breakdown.

**Redox potential**: Measure of the oxidation-reduction potential (electron activity) of components in the soil, as measured using platinum electrodes.

**Refractory (or recalcitrant)**: Resistant to chemical, physical, or biological change or breakdown.

**Rhizome:** A continuously growing horizontal underground stem which puts out lateral shoots and adventitious roots at intervals.

**Rhizosphere:** The region of soil in the vicinity of plant roots in which the chemistry and microbiology is influenced by their growth, respiration, and nutrient exchange.

**Rooted floating aquatic vegetation (rFAV)**: Floating wetland plants that have extensive belowground rhizomes.

**Recently accreted soil (RAS)**: Particulate organic material along with inorganic soils that has accumulated between the floc and pre-STA soil layers since the STA became operational.

**Senesce:** (Of a living organism) deteriorate with age.

**Senescence:** The gradual deterioration of vegetation or soil over time.

**Seepage**: Water moving into or out of the wetland through the ground, levees, or areas surrounding the water control structures.

**Sequestration:** In a biological context, the capture and storage of carbon dioxide ($CO_2$) from the atmosphere by living organisms, primarily plants, and its subsequent storage in biomass (like trees and plants) and soils.

**Sheetflow:** An overland flow or downslope movement of water taking the form of a thin, continuous film over relatively smooth soil or rock surfaces and not concentrated into a small stream.

**Short circuit:** A situation in which part of the influent water exits a stormwater treatment area too quickly.

**Slough**: Depression associated with swamps and marshlands as part of a bayou, inlet, or backwater; it contains areas of slightly deeper water and a slow current, and can be thought of as the broad, shallow rivers of the Everglades.

**Soil amendment**: Addition or alteration used to improve the ability of soil to capture and bind pollutants (e.g., soil amendments for phosphorus treatment include lime, coagulants, and carbon sources).

**Soil management**: Process of managing soil to achieve desired phosphorus reduction results. Management includes but is not limited to preventing dryout conditions, removing soils high in nutrient concentrations, adding amendments, and tilling.

**Soluble reactive phosphorus (SRP)**: The dissolved form of phosphorus measured in a water sample after being filtered through a 0.45-micrometer membrane filter; generally represents the most readily available form of phosphorus. Similar to dissolved inorganic phosphorus but includes inorganic and sometimes simple dissolved organic phosphorus compounds.

**Sorption**: Taking in or holding of something, either by absorption or adsorption.

**Stage**: Height of a water surface above an established reference point (datum or elevation). This vertical control measurement is usually expressed as feet National Geodetic Vertical Datum of 1929 or feet North American Vertical Datum of 1988.

**Structure**: Man-made pump stations, reservoirs, canals, and levees. Region-wide water management is accomplished by the agency's operation and maintenance of over 2,800 miles of canals and levees, over 1,300 water control structures, and 69 pump stations.

**Submerged aquatic vegetation (SAV)**: Wetland plants that exist below the water surface (e.g., *Hydrilla*, *Chara*, southern naiad).

**Sustainability**: In relation to the Everglades Stormwater Treatment Areas, sustainability is the maintenance of phosphorus reduction efficiency and vegetation communities over time.

**Synoptic:** Of or relating to data obtained nearly simultaneously over a large area.

**Topography:** The arrangement of the natural and artificial physical features of an area.

**Total phosphorus (TP):** Total amount of phosphorus in a system or in an environmental sample, includes both organic and inorganic forms of phosphorus.

**Total soluble phosphorus**: Total phosphorus in water sample filtered through a 0.45-micrometer membrane filter and analyzed after sample digestion process; may include soluble reactive phosphorus and dissolved organic phosphorus.

**Transect**: A traverse path through an area along which ecological measurements are made.

**Transpiration**: To lose water vapor from a plant surface, especially through leaf stomata.

**Translocation**: The movement of soluble materials within plants (i.e., the movement of food materials from leaves to the roots or the movement of dissolved minerals upwards from the roots to the leaves).

**Tussocks**: A floating mass of live and dead vegetation.

**Treatment cell**: Area within a stormwater treatment area that functions to remove phosphorus from the receiving water; treatment cells are demarcated by levees.

**Turbidity**: The measure of light scattered by particles in solution and reported in nephelometric turbidity units (NTUs).

**Vegetation conversion**: Process of changing the dominant vegetation within a treatment cell through herbicide application of undesired plants, water depth manipulation, or inoculations. In the Everglades Stormwater Treatment Areas, large-scale vegetation conversions have occurred to convert areas dominated by emergent aquatic vegetation to submerged aquatic vegetation.

**Vegetation resistance:** Friction created by plants as water moves through the stormwater treatment area. The amount of vegetation resistance is determined by plant species, height, and density.

**Water column:** Conceptual column of water from the surface of a water body to the bottom sediment.

**Water Conservation Areas (WCAs)**: Diked areas of the remnant Everglades that are hydrologically controlled for flood control and water supply purposes. These are one of the primary targets of Everglades restoration and major components of the Everglades Protection Area.

**Water quality**: Physical, chemical, and biological condition of water as applied to a specific use, typically propagation of fish and wildlife, public water supply, industry, or recreation.

**Water Year (WY)**: Period from May 1 through April 30, during which water quality and other data are collected and reported in South Florida Water Management District reports.

**Water quality based effluent limit (WQBEL)**: Per Chapter 62-650, Florida Administrative Code, the WQBEL is an effluent limitation (discharge limit), which may be more stringent than a technology based effluent limitation, that has been determined necessary by the Florida Department of Environmental Protection to ensure that water quality standards in a receiving body of water will not be violated. Under the proposed WQBEL for stormwater treatment area discharge into the Everglades Protection Area, total phosphorus concentrations in the discharge from each stormwater treatment area may not exceed either 13 micrograms per liter (µg/L) as an annual flow-weighted mean in more than three out of five years or 19 µg/L as an annual flow-weighted mean.

**Waterfowl:** Birds that frequent water, specifically herons, egrets, ibis, ducks and geese.

**Wetland**: Area that is inundated or saturated by surface water or groundwater with vegetation adapted for life under those soil conditions (for example, swamps, bogs, and marshes).

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# APPENDIX A: RESTORATION STRATEGIES SCIENCE PLAN STUDIES LIST

**Table A-1.** Restoration Strategies Science Plan studies (short title in parentheses).

| Study Title/Description/References | Initiation and Status |
|---|---|
| **Investigation of STA-3/4 Periphyton-Based Stormwater Treatment Area Performance, Design and Operational Factors (PSTA Study)** – assess the chemical, biological, design, and operational factors of the PSTA Cell that contribute to the superior performance of this technology | 2013 [a]<br>Completed in 2018 (inflow and outflow monitoring continue) |
| **Development of Operational Guidance for FEBs and STA Regional Operation Plans (Operation Study)** – create tools and methodologies to provide operational guidance for FEBs and STAs. | 2013 [a]<br>Completed in 2017 |
| **Evaluation of the Influence of Canal Conveyance Features on Stormwater Treatment Area and Flow Equalization Basin Inflow and Outflow Phosphorus Concentrations (Canal Study)** – determine if and how conveyance through STA inflow or outflow canals alters TP concentrations or loads. | 2013 [a]<br>Completed in 2017 |
| **Remote Environmental Sampling Technology: Evaluation of Sampling Methods for Total Phosphorus (Sampling Study)** – identify factors that may bias water quality monitoring results leading to improved sampling procedures for the STAs. | 2013 [a]<br>Completed in 2017 |
| **Investigation of Rooted Floating Aquatic Vegetation in Stormwater Treatment Areas (rFAV Study)** – assess the ability of rFAV to further enhance low-level P reduction performance of SAV communities. | 2016 [a]<br>Completed in 2018 |
| **Evaluate Phosphorus Sources, Forms, Flux and Transformation Processes in the Everglades Stormwater Treatment Areas (P Flux Study)** – increase understanding of the mechanisms and factors that affect P reduction in the STAs, particularly in the outflow regions of well performing FWs. | 2013 [a]<br>Completed in 2019 |
| **Stormwater Treatment Area Water and Phosphorus Budget Improvements (Water and P Budget Study**) – develop more accurate annual estimates of STA water and P budgets of treatment cells to improve understanding and assessment of STA P retention. | 2013 [a]<br>Completed in 2020 |
| **Evaluation of Inundation Depth and Duration Threshold for Cattail Sustainability (Cattail Study)** – evaluate cattail health under different inundation depths and durations to identify thresholds for cattail sustainability in the STAs | 2013 [a]<br>Completed in 2021 |
| **Evaluation of Factors Contributing to the Formation of Floating Wetlands (formerly Tussocks) in the Stormwater Treatment Areas (Tussock Study) –** determine the causes of floating wetlands and cattail tussocks and the probability of their formation in STAs. Identify floating wetlands with unmanned aircraft systems. | 2018 [b]<br>Completed in 2022 |
| **Improving Resilience of Submerged Aquatic Vegetation in the Stormwater Treatment Areas (SAV Resilience Study)** – investigate the effects of operational and natural environmental conditions on SAV health in the STAs. | 2018 [b]<br>Completed in 2022 |
| **The Effect of Vertical Advective Transport (Positive Seepage) on Total Phosphorus Concentrations in the STAs. (Advective Transport Study)** – examine potential for advective transport from groundwater to influence TP concentrations in the outflow regions of the STAs. | 2022 [c]<br>Completed 2022 |
| **Use of Soil Amendments or Soil Management to Control Phosphorus Flux (Soil Management Study) –** investigate the benefits of soil amendment applications and/or soil management techniques to reduce internal loading of P in the STAs. | 2013 [a]<br>Ended in 2022 |
| **Assess Feasibility and Benefits of Consolidating Accrued Marl in the Everglades Stormwater Treatment Areas (Marl Study)** – evaluate the technical feasibility of consolidating marl (an amalgam of $CaCO_3$ solids that include organic material as well as P). Determine if consolidation or improved aggregation of marl can lower the water column P concentration in the outflow regions of the Everglades STAs. | 2021 [c]<br>Completed in 2023 |

**Table A-1.** Continued.

| Study Title/Description/References | Initiation and Status |
|---|---|
| **Quantifying the Recalcitrance and Lability of Phosphorus Within Stormwater Treatment Areas (Biomarker Study)** – evaluate relationships between organic matter and P that capture the sources and potential turnover of P within the STAs. | 2020 [c] |
| **Investigation of the Effects of Abundant Faunal Species on Phosphorus Cycling in the Everglades Stormwater Treatment Areas (Faunal Study)** – evaluate faunal processes and factors that affect P retention in STAs at low TP concentrations. | 2018 [b]<br>Completed in 2024 |
| **P Removal Performance of Ecotopes in the STAs (Ecotope Study)** – examine water quality at inflow and outflow regions of 5 ecotopes—*Typha domingensis* (southern cattail), *Chara* spp. (muskgrass), *Chara*-naiad Mix, naiad, and bare soil) commonly found in the STAs to compare their ability to retain P. | 2021 [d]<br>Completed in 2024 |
| **Phosphorus Dynamics in the STAs (P Dynamics Study)** – evaluate biogeochemical factors and mechanisms influencing P reduction in underperforming FWs. | 2020 [c]<br>Completed in 2024 |
| **Quantifying Phosphorus Uptake and Release from Periphyton and Phytoplankton Communities (Periphyton Study)** – determine the genetic composition and functional diversity of the periphyton community and estimate P uptake and release rates from periphyton in downstream STA treatment FWs to determine their influence on the P cycle and TP discharge from STAs. | 2019 [c]<br>Completed in 2024 |
| **L-8 FEB and STA Operational Guidance (L-8 FEBOG Study)** – provide guidance for FEB operations to moderate TP in discharge as potentially affected by stage, flow, and groundwater. | 2019 [c]<br>Completed in 2024 |
| **Sustainable Landscape and Treatment in a Stormwater Treatment Area Study (Landscape Study)** – use flumes to evaluate flow, water depth, and plant density on P mixing and retention in STAs. | 2022 [c]<br>To be completed 2024 |
| **Data Integration and Analysis Study (Data Integration Study)** – Integrate STA and Science Plan data, research, and reports to support management decision making and provide a guidance document. | 2020 [d]<br>To be completed 2024 |

a. Studies included in the original *Restoration Strategies Science Plan* (SFWMD 2013).

b. Studies added after the original and before the 2018 *Restoration Strategies Science Plan* update (SFWMD 2018).

c. Studies added in the 2018 *Restoration Strategies Science Plan* update (SFWMD 2018).

d. Studies added after the 2018 *Restoration Strategies Science Plan* update (SFWMD 2018) was published.

# APPENDIX B: STUDY SUMMARIES

## DEVELOPMENT OF OPERATIONAL GUIDANCE FOR FEBS AND STA REGIONAL OPERATION PLANS


Management of inflow and outflow waters of the STAs is key to optimize their performance and maintain their health. This study developed tools and methods to support regional operation plans and guidance to optimize the use of FEBs and distribution of flow to the STAs to achieve the WQBEL for TP.

The study included three tasks:

1. Evaluate relevant STA data and conduct field tests to evaluate hydraulics and water quality.
2. Define model parameter values to simulate STA hydraulics, hydrology and operational control.
3. Develop local (STAs/FEBs) and regional operating strategies and rules and application of system optimization tools.

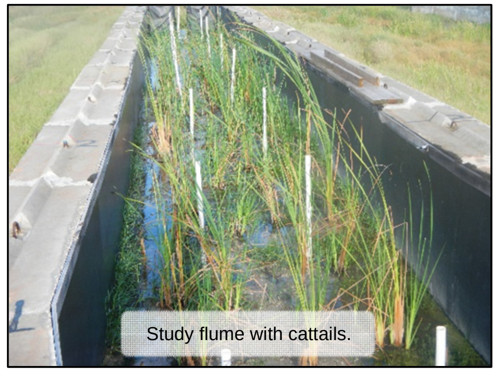
### Results

Waves generated by varying inflow discharges into STA cells at various flow rates and water depths were measured over distance improving water depth estimates, hydrologic resistance of flow, and residence times. These measurements improved accuracy of physically-based models of the STAs (Lal et al. 2015, Lal 2017). The patterns of hydrologic resistance calculated by these models reflect the general patterns of the vegetation distribution. The applications estimated flow based on vegetation, topography, blockages, short-circuiting and turbulent behaviors. This information assists project planning, design, and vegetation management. Modeled flow behaves either as porous-media flow or short-circuiting stream flow depending on conditions.

An inverse model (iModel) for Restoration Strategies Operational Protocol (RSOP) was developed to optimize flow rates along the Central Flow Path for proper flow attenuation (Ali 2015) and treatment with and without the FEB (Ali 2018). Scenarios were run of different FEB and Lake Okeechobee water delivery configurations to optimize TP removal and outflow TP concentrations. The iModel predicted lower TP concentration in discharge for all the scenarios compared to observed values. While the results are encouraging, the difficulty to obtain accurate statistical prediction of outflow TP concentrations was found. This difficulty has been seen in multiple statistical and modeling studies of the STAs, which is likely related to the difficulty in predicting TP at ultra-low concentrations.

## SUSTAINABLE LANDSCAPE AND TREATMENT IN A STORMWATER TREATMENT AREA STUDY

As evaluated in the Development of Operational Guidance for FEBs and STA Regional Operation Plans study, plant resistance to flow can affect the movement and mixing of water within an STA cell. To understand the relationships of plant density water depth and flow, more controlled conditions were used in this current study. This study measured transport and dispersion of salt and P within a cattail community in a controlled (flume) environment to determine the flow volumes and velocities that optimize mixing based on water depth and plant densities. The effects of constant flow and pulsed flow on transport and dispersion also were measured.


Study flume with cattails.

Flow tests were carried out in two flumes, a V-shaped flume and a straight flume as a control. The flow velocity of water discharged at the top of the V-shaped flume decreases along the flume as the flume widens. This allows the measurement of multiple flow velocities at once on mixing.

Two tests were included in this study:

1. Steady state flow – when flow in is equal to flow out, a specified amount of salt and P was added and measured along the flumes pathway to determine mixing and removal, respectively.
2. Wave tests – Wave and tracer/salt experiments were successfully completed for two pulse conditions at two water depths (0.5 and 1.25 ft). Data from the waves created within the flumes were used to measure vegetation resistance of flow within the flume. Added salt and TP were measured to determine mixing and removal.

These tests were repeated three times over a year: first with no plants as a baseline, second after cattail were planted and grew in for three months, and the third six months after planting of cattail resulting in higher densities of cattail. Thus, the repeated experiments can compare results under different resistance regimes.

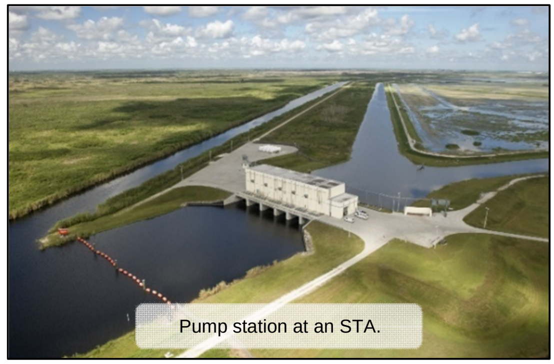
### Results

Low flow rates (below 50%) combined with shallow water were more effective in mixing of waters than high flow high water depths (South Florida Engineering and Consulting LLC 2024).

Pulsed waves at higher plant density and increased vegetation resistance resulted in higher transmissivity surface water slope and increase mixing. Further investigation of pulsing flows at the STA level should be evaluated.

## EVALUATION OF THE INFLUENCE OF CANAL CONVEYANCE FEATURES ON STORMWATER TREATMENT AREA AND FLOW EQUALIZATION BASIN INFLOW AND OUTFLOW PHOSPHORUS CONCENTRATIONS

Canals collect and convey agricultural and urban stormwater runoff water to the FEBs and STAs as well as from the STAs into the Everglades Protection Area. TP in the water of these canals can increase due to resuspension of underlying sediments or decrease due to settling. This study evaluated the change in TP concentrations as water is conveyed along STA canals and estimated the amount of TP load exported from or accumulated in canals for a given period.


Pump station at an STA.

Six STA canals—STA-1 Inflow Basin Canal, STA-1W Discharge Canal, STA-2 Supply/Inflow Canal, STA-2 Discharge Canal, STA-3/4 Supply/Inflow Canal, and STA-1E Discharge Canal—were included in this study (Zhao et al. 2015a). Measurements of TP, SRP, PP, DOP, chlorine (Cl) and total suspended solids (TSS) were evaluated for each canal along with flow. The sediment in the STA-2 Supply/Inflow Canal was also measured to find zones of deposition and scouring.

### Results

The STA-1 Inflow Basin Canal was a source of TP during peak flows, primarily in the form of PP. With the implementation of the upstream L-8 FEB, these peak flows are expected to decrease, reducing the potential for sediment resuspension and transport (Zhao et al. 2016).

The STA-1W Discharge Canal was a sink for TP, with much of it being deposited as PP. After the STA-1W expansion is constructed, the STA-1W Discharge Canal will no longer serve as the discharge canal for the STA (since completed with the writing of this report). Therefore, no further evaluation is recommended.

The STA-2 Supply/Inflow Canal receives water from the S-6 pump station and G-328 pump station, with relatively high TP concentrations from stormwater runoff, and G-337, with relatively low TP concentrations from STA seepage water. When S-6 flows dominated, the canal behaved as a TP sink. When G-337/G-328 flows dominated, the canal behaved as a TP source (Zhao et al. 2017). A canal survey indicated sediment buildup in the canal bottom and notable erosion from canal side-slope areas. Future canal surveys (e.g., every three to five years) are recommended.

This study showed that in general the canals act as sinks during low flow and potential sources during high flow. Also, canals that experience inflow waters with both high and low TP concentration may alternate from being a sink with high concentration inflow TP waters and a source at low concentration inflow TP waters.

## L-8 FEB AND STA OPERATIONAL GUIDANCE


L-8 FEB.

The L-8 FEB is 950 acres in size and can store approximately 45,000 ac-ft of water. This FEB is used to reduce peak stormwater flows, temporarily store stormwater runoff, and improve water delivery to STA-1E and STA-1W. Improved water delivery should enhance STA performance to achieve state water quality standards in the Everglades.

In Water Year 2018 (WY2018: May 1, 2017, to April 30, 2018), the FWMC of TP in outflow from the L-8 FEB was higher than inflow. Potential sources for this excess TP included groundwater, levee soil erosion, sediment resuspension, and P release from aquatic plants and animals. The objective of this study was to determine the potential sources of this excess TP and to provide operational guidance to limit the occurrence of higher TP outflow compared to TP inflow.

### Results

Samples of groundwater from wells surrounding the L-8 FEB had TP concentrations lower than observed in L-8 surface water samples, indicating that groundwater did not contribute to the intermittent high TP concentrations at the outflow site (DB Environmental 2019). PP constituted the major fraction of TP in the surface water suggesting that resuspension, or introduction of sediments may be the source of PP in the FEB surface water.

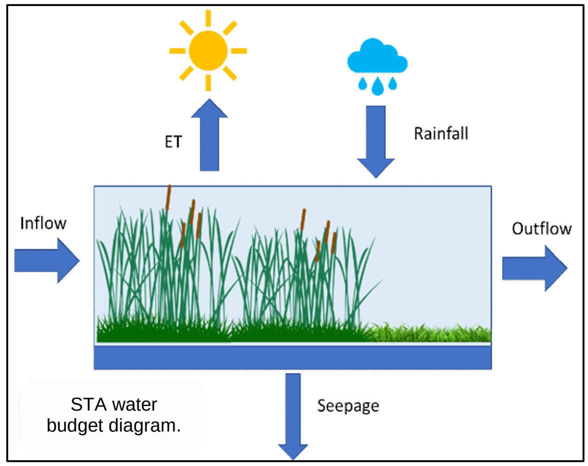
Surface water quality was sampled monthly for one year and sediment and soils in and around the FEB were sampled once. Soils from the FEB banks had low TP content compared to benthic sediments suggesting benthic sediments likely contributed to TP in the water column (DB Environmental 2020b). Large flows of water at the inflow structure added significant nutrient loads and suspended materials into the FEB. Additionally, these large flow events caused benthic sediments to resuspend into the water column DB Environmental 2021a). These suspended particulates release dissolved P into the water column, which can then be converted into algal biomass resulting in temporarily elevated TP in the water column.

A multiple regression model using SRP and turbidity was developed to predict TP to develop near real-time estimates of TP at the outflow of the FEB, using in situ sensors of SRP and turbidity. This estimate can be used to make operational recommendations about the timing of water discharge from the FEB.

An alum feasibility study was carried out to determine the methods and costs of installing an alum addition treatment system to remove TP. Total cost over 10 years is estimated at $600 to $800 per pound of P removed (J Tech 2024).

## STORMWATER TREATMENT AREA WATER AND PHOSPHORUS BUDGET IMPROVEMENTS

Water and P budgets are important tools that can be used to understand the treatment performance of STAs. Accurate water budgets are critical to develop accurate P budgets. The objective of this study is to improve the annual water and P budgets for selected STA treatment cells and associated FWs for STA-3/4 and STA-2. The performance of each STA FW was evaluated based on these improved budgets.



STA water budget diagram.

### Results

Flows were improved for the FWs of both STA-3/4 and STA-2. For STA-3/4 Cells 3A/3B, small differences in water levels across large culverts at mid-levees were the main source of error in annual cell-by-cell water budgets (Polatel et al. 2014, Zhao and Piccone (2019). The budgets were greatly improved by updating flows between the upper and lower portions of the FW. Annual errors for the water budgets were reduced to 8% or less. Flows of STA-2 FWs 1 to 3 were improved through enhanced quality assurance/quality control and improvements in flow rating curves, and stage resulting in average annual water budget residuals of 1 to 8% (annual budget residuals originally ranged from -27 to +24%) (Zhao and Piccone 2018). Rainfall, evapotranspiration, change in storage, and seepage were minor contributors to these cells' annual water budgets.

These efforts resulted in more reliable water and P budgets and other performance estimates including annual and long-term average annual hydraulic retention times, HLRs, PLRs, and P reduction efficiency. For the six FWs studied, a higher frequency of low-level outflow TP annual FWMC was found when the annual hydraulic residence time was longer than 14 days, annual HLR was less than or equal to 3.5 cm/d, the annual water depth was shallower than or equal to 0.65 meter, the annual PLR was smaller than or equal to 1.2 g P/m$^2$/yr, or the annual inflow TP FWMC was less than or equal to 100 µg/L (Zhao and Piccone 2020). This study demonstrated that TP settling rate alone was not adequate to evaluate STA treatment performance especially when HLRs differ. This study also helped improve understanding of the factors that affect the treatment performance of large-scale constructed wetland FWs which consistently retained TP and reduced TP concentrations over a long-term operational period.

## REMOTE ENVIRONMENTAL SAMPLING TECHNOLOGY: EVALUATION OF SAMPLING METHODS FOR TOTAL PHOSPHORUS

To assure the accuracy of the sampling and monitoring being used to evaluate TP concentrations, particularly in STA discharge, sampling and monitoring techniques must meet stringent requirements of quality assurance and quality control. These include potential biotic, physical, or other activities that can skew the results. This study evaluated various field sampling methods and made recommendations on improving the monitoring of TP.


P sampling location.

Various sampling methods were evaluated (Rawlik 2017). Cameras were used to observe physical and biological disturbances that could affect sample quality. Methods were compared based on analytical results and sampling efficiency. Sample sets using different methods, including, grab sampling, flow-proportional composite autosamplers (ACF) and discrete autosamplers based on time (ADT), were collected. These sets were compared to measurements from a remote P analyzer (RPA), which collected and measured water samples every few hours for several months at a time. Additionally, water quality sondes were deployed to measure conductivity, pH, and turbidity.

### Results

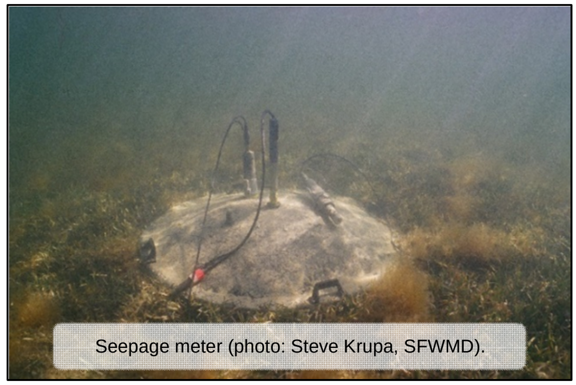
Data comparisons suggested grab and ADT collection methods were more reliable than ACF methods (Rawlik 2017). Under some conditions, the ACF method could be biased and not meet the completeness (percent of acceptable samples collected based on planned number of samples to be collected) target of 90%. Completeness estimates differed, depending on whether they were based on time coverage and/or flow representation. Reverse, low, or poorly defined flows interfered with ACF sampling and could lead to non-representative samples, particularly at sites with small water level differences from up to downstream. Data from the RPA method indicated a mid-day peak in TP concentrations.

Wildlife found congregating around infrastructure and on levees could be potential sources of TP Rawlik 2017). Some animals such as anhingas and turtles were observed interfering directly with sampling systems. Accumulation of large amounts of SAV were often observed at sample intake screens, but the influence of these events on TP results was not clear.

It is recommended that flow proportionality of autosamplers and comparison of ACF versus ADT at multiple locations be further investigated (Rawlik 2017). The use of ACF method at structures with small water level differences from up to downstream should be discouraged. Evaluating the completeness of collection should be based on the amount of flow represented, rather than time. Also, methods for limiting wildlife impacts on surface water sampling should be studied further.

## THE EFFECT OF VERTICAL ADVECTIVE TRANSPORT (POSITIVE SEEPAGE) ON TOTAL PHOSPHORUS CONCENTRATIONS IN THE STAS.

Vertical advection, primarily groundwater seepage, could potentially transport TP into an STA cell, increasing the water column TP concentration. Such a process could affect the TP outflow concentration and reduce P retention in an STA FW. This study evaluated if it was feasible to quantify the relative magnitude of vertical advection (positive seepage) and associated P loading across the soil-water interface of outflow STA cells.



Seepage meter (photo: Steve Krupa, SFWMD).

### Results

A literature review of seepage in wetlands (WSP Inc. 2022a) found seepage accounts for less than 6% of a given wetland water budget. The same review indicated that longitudinal (through levees) and vertical (groundwater) sources could not be differentiated.

Data on flow, rainfall, evaporation, lateral seepage, water depths, TP, and Cl for STA-1W Eastern FW, STA-2 FW-3, and STA-3/4 Cell 2B were compiled to develop water budgets and P budgets (WSP Inc. 2022b). Various methods and statistical analyses were run to determine if seepage effects could be determined.  None of the analyses found any substantial effect based on residuals.

A steady state version of the LPWEM model was used to evaluate the potential effect of vertical advection on STA P retention (Juston and Kadlec 2019, WSP Inc. and Dynamic Solutions 2022). A vertical advection component was added to the model to allow variation of advective flow and TP concentration carried along with the flow. Results showed only minor effects (1 µg/L increase per 50 µg/L) in the advected water. These analyses demonstrated that vertical advection was not a major factor in STA P retention (Blair and James 2024).

## EVALUATE PHOSPHORUS SOURCES, FORMS, FLUX AND TRANSFORMATION PROCESSES IN THE EVERGLADES STORMWATER TREATMENT AREAS

To understand how P is processed and removed within well performing STAs, this multi-component study evaluated mechanisms and factors affecting P reduction from the water column particularly in the outflow regions of the STAs. The study measured FW water quality, internal phosphorus loads, soil, microbial enzymes, vegetation, particulate transport and settling, fauna, and organic P speciation. In addition, these data were synthesized to explain factors and processes influencing STA performance and will serve as the basis to develop or improve management options to reduce TP discharge concentrations from the STAs.


In vivo mesocosm.

### Results

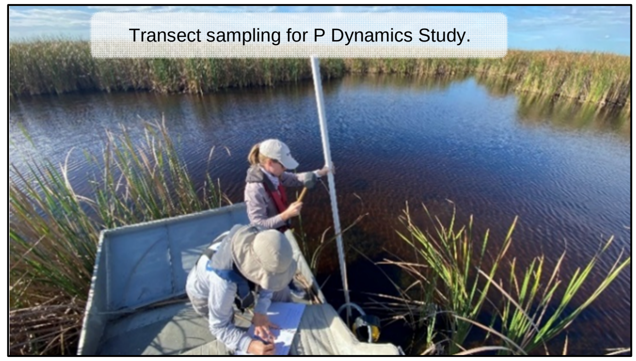
Many consistent patterns were observed in this study (Villapando et al. 2024). Removal of P in EAV dominated areas was primarily biotic resulting in accretion of organic material in the soil. In SAV dominated areas a coupled biotic chemical process occurred resulting in the production of particulate inorganic compounds that settled out removing P with it. This inorganic material accumulated as mineral floc in the soil. Distinct declines of TP were found in water column, plants, floc, soil, and soil flux measurements along the pathway of each cell. P removal from the water column, primarily as SRP in EAV areas and PP in SAV areas, was greater for EAV areas than SAV areas and the amount of reduction was higher at moderate flow rates (94 and 73% for EAV and SAV regions, respectively) than low flow (88 and 71%, respectively). Under no flow conditions, there was an increase in DOP and PP in SAV areas, attributed to in situ production of PP potential through phytoplankton growth, periphyton sloughing, litter fragmentation, and/or resuspension via entrainment or bioturbation. PP and DOP comprised the residual P pool at the outflow region.

Near the outflow region of the cells, water column P concentration reached an equilibrium between removal and internal loads. These internal loads must be considered as they can affect P concentrations in the outflow (Jerauld et al. 2020).

Additional sub studies were initiated from this study including the Biomarker, Periphyton, Faunal, and Data Integration studies[9], which are presented below.

[9] The full study names are provided in Appendix A.

## PHOSPHORUS DYNAMICS IN THE STAS




This study followed the Phosphorus Flux Study[10] by investigating factors and mechanisms that affect treatment performance in underperforming STAs, particularly key drivers affecting TP concentrations at the lower reaches of the treatment FWs. This study evaluated water, vegetation, soils, ultra-fine particulates, and microbially-mediated processes to understand factors and processes influencing STA performance in underperforming STA cells and in comparison to well performing STAs. The goal was to improve management options to reduce TP discharge concentrations from the STAs.

### Results

Historical analyses (DB Environmental 2024) found that for the three years after FWs experienced some major form of disturbance (construction, dryout, or major vegetation declines) annual P outflow FWMCs consistently exceed 19 µg/L. When disturbance free for more than three years and PLR outflow was less than or equal to 1.3 g P/m$^2$/yr, P FWMCs were consistently at or below 19 µg/L. This analysis and the data collected in this study did not find any significant differences between well performing and underperforming FWs other than disturbance and PLR. However, three STAs that were not overloaded in the past decade had the best properties for P retention kinetics in the soils (UF-WBL 2024). All other major factors evaluated including transect trends of water column, floc, plant, soil P, and major P species (PP, DOP, SRP) were consistent between well performing and underperforming FWs. One difference was observed for wet season measurements of ultra-fine particulate SRP (between 3 kDaltons and 0.45 microns [µm] in size). In well performing FWs, the percentage of < 0.45-µm SRP present as ultrafine particulate SRP increased up to 100% as the distance from the inflow increased and the amount of truly dissolved SRP was very low (Buchanan et al. 2023).

[10] The full study name is available in Appendix A.

## QUANTIFYING THE RECALCITRANCE AND LABILITY OF PHOSPHORUS WITHIN STORMWATER TREATMENT AREAS

P can come in many forms, some of which is associated with particles (particulate P) and organic matter (organic P). These forms of P may be stored in the soils and vegetation in the STA, consumed by organisms like fish and microorganisms and then recycled into other P forms (internal cycling), or exported to the Everglades.

To evaluate these P forms, this study used several sophisticated techniques (X-ray diffraction, P-31 nuclear magnetic resonance or $^{31}$P-NMR, ultrafiltration, and mass spectrometry) to determine their lability. A pilot study initiated under the P Flux Study[11] indicated that this approach could provide information on P sources and sinks within the STAs (Morrison et al. 2020). Inflow and transects along two FWs were sampled for various organic carbon and P molecules using these specialized techniques. Photolysis and extraction of DOM from litter bag experiments were also carried out.

Litter bags deployed in an STA.

### Results

The study found that inflow water DOM varied among the tributary watersheds (Morrison et al. 2024). Much of this DOM can be mineralized by the microbial community. Exposure to ultra-violet light (UV) and sunlight also breaks down this DOM and associated DOP through a process called photolysis. The microbial community can enhance the degradation of this photolyzed material. Polyphosphates and pyrophosphates, inorganic chains of P that are storage molecules created by the microbial community, were found in soils of the STAs. This finding demonstrated the importance of the microbial community in the retention of P within these STAs. Litter bags that contained fresh plant material released DOM quickly. SAV litter not only released dissolved material faster but also released more orthophosphate than EAV litter. EAV did release more P over time, thus, the DOM (and DOP) in STAs is primarily from litter decomposition of vascular plants (largely EAV).

[11] The full study name is provided in Appendix A.

## INVESTIGATION OF STA-3/4 PERIPHYTON-BASED STORMWATER TREATMENT AREA PERFORMANCE, DESIGN AND OPERATIONAL FACTORS

A 100-acre PSTA Cell was constructed in STA-3/4 as a pilot demonstration to evaluate the ability of this project to achieve ultra-low outflow TP concentrations.


PSTA Cell at STA-3/4.

This study included monitoring and surveys within the cell, as well as mesocosm and microcosm experiments that supplemented these studies. Inflow and outflow locations of the cell were monitored regularly for TP.

Inflow and outflow concentrations of TP and flows into and out of the cell have been monitored continuously (Dombrowski and Piccone 2024). Surface water grab samples taken at the structures were analyzed for various P species (Zamorano et al. 2023). Other data measured periodically within the PSTA Cell included conductivity, pH, temperature, dissolved oxygen, chlorophyll a, turbidity, water depth, light, and ion concentrations. Effects of pulse flows, season, time of day, water depth, inflow P concentration, flow rate, and seepage on cell performance were evaluated. Enzyme assays were also conducted to evaluate the role of microbial activity. Sediment accrual and vegetation nutrient contents were also analyzed. Reports and manuscripts have been completed. Final analyses were reported in Zamorano et al. (2018).

### Results

The PSTA Cell achieved annual outflow TP FWMCs between 8 and 13 µg/L for the period of record (WY2008–WY2023) (Dombrowski and Piccone 2024). Pulse flow events and associated higher P loads had no adverse effect on treatment performance (Zamorano et al. 2018). Outflow TP concentrations were not affected by two different operational water depths (average of 0.39 and 0.55 meters) the time of day (James 2015), or longer periods of constant moderate flow (James 2017). Generally, lower outflow TP FWMCs were observed during the wet season. The optimal inflow TP concentrations to the PSTA Cell was 22 µg/L or less, which achieved outflow concentration of 13 µg/L or lower (DB Environmental 2024). Lateral seepage through the levee between the Lower SAV Cell and the PSTA Cell was the major source of seepage (Zamorano 2017, Zhao et al. 2015b). The accumulated sediment in the cell is low in P (Zamorano et al. 2023), which sustains the effective treatment performance.

## USE OF SOIL AMENDMENTS OR SOIL MANAGEMENT TO CONTROL PHOSPHORUS FLUX

The STAs have been constructed to a large extent on former agricultural lands. Once the STA cells are flooded, P in the soils can be released (flux) into the water column. This study was intended to screen methods that could reduce P flux from the flooded soil by application of soil amendments and/or management techniques. Effective methods may be useful at appropriate locations within the STAs to reduce outflow P concentrations.


Inverting soil in a STA.

Technologies to reduce soil P flux in wetlands or lakes were reviewed from the literature and past SFWMD projects. The available technologies and soil amendments indicated that many potentially could lower P flux from flooded soils (Chimney 2015).

### Results

Soils in the STA-1W Expansion Area #1 Cell 7 were inverted as a remedial action to bury high copper concentrations that resulted from past agricultural practices. Soils in the adjacent Cell 8 were not inverted and were used as a control. Prior to flooding these cells, soils were collected and incubated to determine the amount of soluble P that could be released (Josan et al. 2018). P release from inverted soils was less than non-inverted soils. All STA-1W Expansion Area #1 cells were flooded and the facility began treating water on a restricted basis in late June 2021. Weekly monitoring of P concentrations at Cell 7 and 8 inflow and outflow sites began in July 2021. Surveys of these wetland cells have shown similar soil TP concentrations, overlapping TP water concentrations, and differences in the type and distribution of plant (Chimney 2022).

While inversion appeared successful in laboratory studies, there were too many confounding conditions to determine if it was successful at the field scale.

# ASSESS FEASIBILITY AND BENEFITS OF CONSOLIDATING ACCRUED MARL IN THE EVERGLADES STORMWATER TREATMENT AREAS

Marl is the primary soil type in SAV dominated systems. It is produced when carbon dioxide ($CO_2$) is removed from calcium rich water by photosynthetic activity of both algae and aquatic macrophytes, resulting in the formation of particulate ($CaCO_3$), which accumulates in soils as a primary component of marl. Some STA marl soils are physically unstable, allowing rooted macrophytes to be dislodged by wind/wave energy, while resuspension, bioturbation, and movement of unconsolidated marl material may increase water column turbidity and discharge TP concentrations. This study used sediment cores in laboratory experiments to measure erodibility of marl and organic soils and methods to enhance stability of these soils, which could lead to lower TP and turbidity in the water column.

Measuring marl in a sediment core.

## Results

Marl soils had a wide range of organic matter, TP content, and physical stability across the STAs (DB Environmental 2023a). Organic soils from the STAs were less stable than marl soils. TP and turbidity typically increased in the water column after a suspension test to a greater degree in organic soils than marl. Consolidation of marl soils by drying increased stability. However, this stability lasted no more than 12 weeks after rehydration. In addition, P flux increased in these dried soils after rehydration as compared to non-dried soils. The consolidation did have a benefit, it provided opportunity for faster SAV germination and regrowth.

Marl soils are likely not as ‘problematic’ for STA P retention as initially hypothesized, as they typically exhibit higher physical and chemical stability than more organic soils. These results suggest reducing or limiting the coverage of emergent plants (such as cattail) near STA outflows may improve soil stability and reduce internal loading, both critical factors in achieving ultra-low water column TP concentrations.

## EVALUATION OF INUNDATION DEPTH AND DURATION THRESHOLD FOR CATTAIL SUSTAINABILITY

Cattail (*Typha* spp.) communities are an important component of STAs. They remove PP by reducing water turbulence allowing the particles to settle or by colliding with and adhering to plant leaves. Soluble P is removed by periphyton attached to cattail leaves.

Cattail study site.

Areas of cattail growing throughout STAs reduce water flow velocity and block the effects of winds from major storm events, thereby supporting aquatic vegetation. Cattails are hardy plants but were found to decline or die if water depths are too deep for a long period especially during the wet season in areas where water depths are greater than three ft (91 cm) for long periods of time (Diaz and Vaughan 2019).

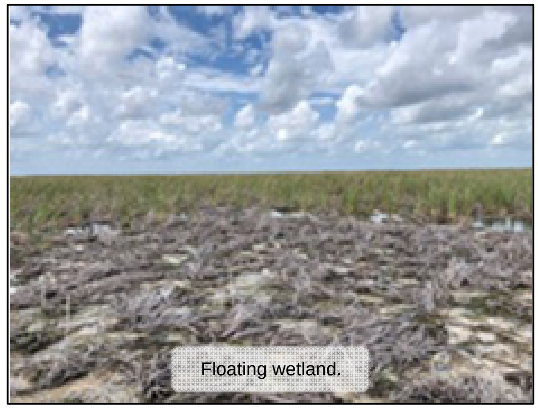
Water depth experiments were carried out in 15 0.2-hetare test cells in STA-1W North (Diaz et al. 2023). Cattails were grown from seed and seedlings into fully matured plants. Water depth experiments began with 3 replicate test cells of 5 different water depths 40 cm, 61 cm, 84 cm, 104 cm, and 124 cm.

### Results

All outflow P species except DOP were significantly less than inflow P species for all treatments except the 40-cm control cells (Diaz et al. 2023). This exception is attributed to a lower amount of SAV and attached algae in the control cells due to the lower water depths. These lower water depths resulted in faster turnover of the water, compared to other treatments, reducing the ability of control cells to retain P.

Cattails responded to increased water depths by increasing leaf length allowing plants to maintain photosynthesis and activities related to gas exchange (Diaz et al. 2023). However, there was a reduction in vegetative reproduction, and a significant decline in juvenile density with increasing water depths. When water depths were lowered at the end of the study in the deep water treatments, the cattails collapsed (lodging) because of the low structural support for the long leaves. Overall, cattail demonstrated tolerance at constant water depths ≥ 84 cm for 10 months; however, reduced juvenile densities could result in declining overall cattail density, which should be considered in the overall management of these systems.

# EVALUATION OF FACTORS CONTRIBUTING TO THE FORMATION OF FLOATING WETLANDS[12] (FORMERLY KNOWN AS TUSSOCKS) IN THE STAS


Floating wetland.

Floating wetlands in STAs can scour EAV, shade out SAV, increase turbidity, block gates and other water control structures, and create short circuits. All these actions can reduce STA treatment performance. This study evaluates factors that cause the formation of floating wetland areas in STAs and methods to determine current coverage of these floating areas.

## Results

A review of the literature found a consistent terminology to describe the various types of floating vegetation does not exist. A nomenclature was developed (Clark 2019) based on floating substrate presence or absence, horizontal connectivity, and dominant vegetation to define floating emergent plant communities in the STAs.

An unmanned aircraft system (UAS; drone) carrying a multispectral camera was used to survey EAV cells for floating wetland communities (Clark et al. 2022). *Typha* floating wetlands were found that were not observed in satellite imagery. Floating wetlands were identified based on observed flattened vegetation (lodging), presence of fern seedlings, and nearby open seams.

Historical data from the STAs were analyzed to identify significant predictors of floating wetland communities across EAV cells (Clark and Glodzik 2020). Results suggested a higher potential for floating vegetation occurs (1) if land had been farmed a short time before the STA was constructed, (2) if TP in the soil was low, and (3) if water depths were exceedingly high (greater than 90% of the daily observed water depths).

A buoyancy model was then developed to evaluate the effect of water depths and various plant and soil conditions on the probability that floating wetlands will occur (Clark 2022).

[12] Formerly known as tussocks.

## INVESTIGATION OF ROOTED FLOATING AQUATIC VEGETATION IN STORMWATER TREATMENT AREAS

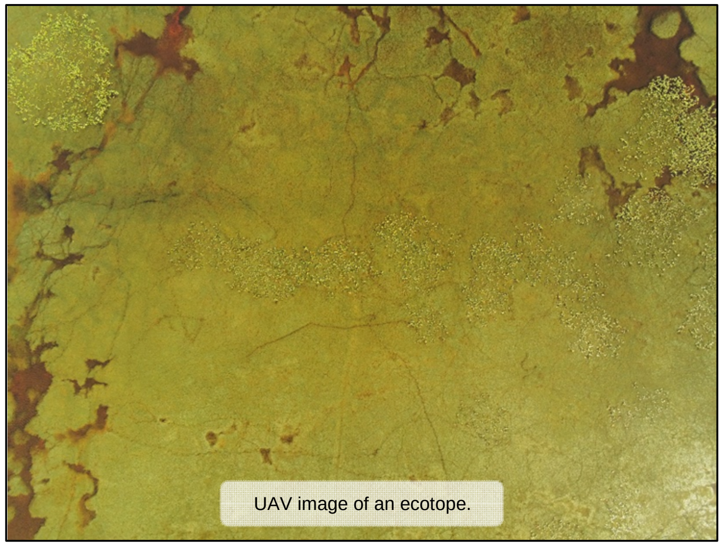

rFAV can make up a substantial amount of the vegetation in STAs. They could be a valuable method of removing P as they can grow in deep areas where EAV and SAV cannot. This study was to determine if rFAV enhance low-level P removal in back-end SAV communities of STAs.

### Results

Water column P concentrations were different for two of three patches of rFAV plant species compared to nearby SAV patches (Powers 2018, 2019). Water column P concentrations in white water lily (*Nymphaea odorata*) and American lotus (*Nelumbo lutea*) patches were higher than in the nearby SAV patch, while water column P concentrations in a spatterdock (*Nuphar advena*) patch were not significantly different from the nearby SAV patch. Soils in white water lily patches had lower bulk density, higher organic content, and lower Ca content compared to its paired SAV patch. These low bulk density soils may be prone to resuspension and could contribute to higher PP concentrations in the water column. Dissolved oxygen and pH indicated greater aquatic metabolism in the SAV patch relative to the rFAV patch. Greater aquatic metabolism resulted from increased photosynthesis in the water column, which led to higher pH during the daylight hours. This higher pH may enhance co-precipitation of P with calcium resulting in more P removal. The soil from American lotus patches has a higher organic content than SAV patches but were similar otherwise.

# P REMOVAL PERFORMANCE OF ECOTOPES IN THE STAS

Wetland ecotopes are contiguous homogenous vegetation communities with similar physical and chemical environments. Water quality monitoring at the ecotope scale captures the effects of these smaller areas that are obscured at the larger landscape scale. These ecotopes include key ecological features present in the STAs that are not found in finer scale mesocosm research. Four different ecotopes in the outflow regions of STA-3/4 Central FW were monitored for water quality, physico-chemical properties, and soil characteristics over two years. Ecotope types included a dominant *Chara spp*. ecotope, a dominant *Typha domingensis* ecotope, a codominant *Najas guadalupensis* and *Chara* spp. ecotope, and an open-water/bare ecotope.



UAV image of an ecotope.

## Results

The *Chara* ecotope had the lowest wet season mean TP in both years of the study (Powers 2024, 2025). Differences between the ecotopes mean wet season TP concentration were not large (typically less than 3 µg/L between all ecotopes), this could affect meeting WQBEL criteria for STAs with TP discharges near compliance limits. All ecotopes had wet season means below 13 µg/L except the mixed ecotope in Year 2. TP concentrations were higher in the dry season than the wet season. Because the dry season discharge is less, these higher dry season concentrations contribute less to the annual FWMC calculation than the wet season concentrations. Flow rate and water depth also affect wet season TP concentration. TP concentrations were reduced 5 µg/L as flow increased from 0 to 300 cubic feet per second (cfs), no further reduction was found above 300 cfs.

## IMPROVING RESILIENCE OF SUBMERGED AQUATIC VEGETATION IN THE STORMWATER TREATMENT AREAS

SAV communities in the STAs are important components of P retention. As $CO_2$ is removed from the water column during photosynthesis, a chemical reaction occurs to form particulate $CaCO_3$, which removes P from the water as a co-precipitant.


This study investigated SAV biology, water chemistry, soil chemistry, soil physical characteristics, herbivory, and their interactions to understand SAV species distribution, persistence, colonization, and recovery in STAs. Field surveys and experiments using mesocosms or enclosures evaluated the effects of marl, muck, and aged muck soils; hydraulic and P loading rates; drying out wetland soils; and fish herbivory (DB Environmental 2023b).

### Results

Literature and data analyses found a number of factors can affect SAV growth, persistence, and sustainability. This included P and nitrogen loading, turbidity, Ca concentrations, water depth, sediment accretion, dry down/reflood events, wind/wave disturbance events, herbivory, and physiological senescence.

Results of SAV surveys found (1) P content in SAV decreased from inflow to outflow along STA FWs, (2) FAV encroachment into SAV areas, followed by herbicide treatment of FAV biomass, could reduce SAV densities and P removal performance, and (3) extreme environmental events (e.g., high flows, drawdown, or cold temperatures) could change SAV community distribution (DB Environmental 2023b).

Mesocosm experiments found that SAV grew well in muck, aged muck, and marl soils (DB Environmental 2023b). Plants grown on aged muck had the lowest plant tissue P suggesting reduced nutrient availability as soils in the STA age. SAV (*Chara*) did not grow as well with low P inputs than modest or high P inputs. Additionally, soils with high P content provided internal P inputs and *Chara* grew well even with low external P inputs. Additionally, on the high P content soils, less P is retained, and the outflow P concentrations were higher than for similar mesocosms grown on low P content soils.

Given high external or internal nutrient loads, *Chara* concentrates its biomass near the water surface, creating anoxic conditions in bottom waters. This anoxia could stress the SAV community and reduce P removal efficiency (DB Environmental 2023b).

Germination and growth rates of SAV were higher than on soils previously dried than those that remained hydrated (DB Environmental 2023b). Shallow rooted SAV grew faster than deep rooted SAV in field enclosures (DB Environmental 2023b). Deeply rooted SAV grew faster in mixed plant communities than monocultures. Exotic nuisance fish (blue tilapia [*Oreochromis aureus*]) significantly reduced SAV growth.

## QUANTIFYING PHOSPHORUS UPTAKE AND RELEASE FROM PERIPHYTON AND PHYTOPLANKTON COMMUNITIES

Periphyton (microbial communities of bacteria, algae, and fungi) grow on submerged aquatic plants surfaces or soils (epiphyton), or float free in the water column (phytoplankton) (Laughinghouse et al. 2019). These communities play an important role in P cycling within the Everglades STAs through nutrient uptake, cellular growth, and senescence. The degree of periphyton nutrient cycling can affect P reduction in STAs, especially in outflow regions of the STAs where P concentrations are very low (≤ 19 μg/L) (DB Environmental 2021b).

Periphyton.

### Results

This study began as a sub-study of the P Flux Study[13] measuring enzyme activity in periphyton, floc, soils, and water column under various flow conditions and for EAV and SAV communities (Pietro et al. 2023). Phosphatase and N-acquisition enzymes were most active, while carbon (C)-acquisition enzymes were least active. Phosphatase activity increased along the nutrient gradient. When DOP in the surface water was above 10 μg/L, the phosphatase rates were low, suggesting P was not limiting. When DOP concentrations were < 10 μg/L, phosphatase rates were greatly increased. Both N- and P-limitation were found at the inflow and midflow sites. P-limitation only occurred at the outflows in all treatment cells. There were also indications that nutrient cycling differs between periphyton from the EAV and SAV communities under low-P conditions, suggesting optimal P retention in a mixed marsh community.

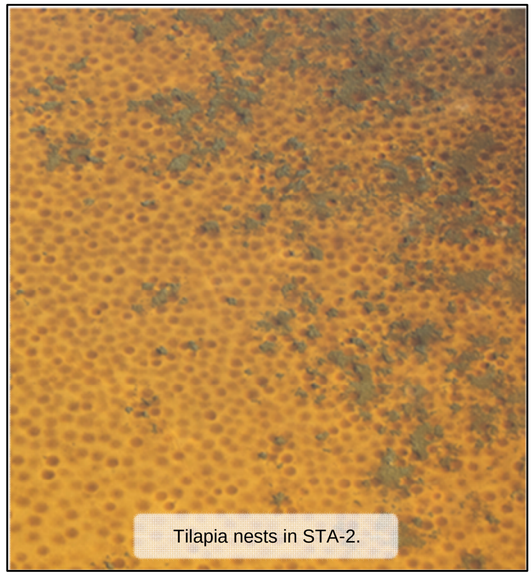
Two literature reviews evaluated methodologies and results of periphyton studies with a focus on South Florida and the STAs (Laughinghouse et al. 2019, DB Environmental 2021b). These reviews found light intensity, temperature, and nutrient availability affect periphyton community structure. A few published rates on photosynthesis and growth, applicable to subtropical systems, were also found. Approaches to measure periphyton community structure, productivity, decomposition, senescence, and nutrient uptake rates were reviewed. Information from these literature reviews were used to develop and implement additional study efforts.

The study proceeded with a pilot followed by a field scale study to evaluate the use of metagenomics (which identifies the DNA of microbial species) and metatranscriptomics (quantifies active genes in microbes) to measure periphyton processes involved in P dynamics. The pilot study determined that metagenomics can be used to measure periphyton genera and physiological processes (enzyme production, nutrient uptake, etc.) (Feeney and Rosen 2022). This study found an SAV site had a significantly greater relative abundance of genes involved in P metabolism compared to a nearby EAV site. The field-scale study used these techniques to evaluate periphyton responses to spatial and seasonal changes in water column nutrients and hydrology (Feeney et al. 2024). P metabolism gene abundances were highest in the SAV community at an outflow site of STA-2 Cell 4 compared to a nearby EAV site and an SAV site near the midflow region of the cell. Higher densities of algal cells and greater overall phosphatase enzyme activity were found in SAV and its associated periphyton compared to EAV. Thus, SAV periphyton was generally better at removing organic P from the water column than EAV periphyton. Measurements of RNA transcripts showed that SAV periphyton was more adapted to use inorganic P, where EAV periphyton was more adapted to use less abundant organic P forms (phosphonates).

[13] The full study name is provided in Appendix A.

# INVESTIGATION OF THE EFFECTS OF ABUNDANT FAUNAL SPECIES ON PHOSPHORUS CYCLING IN THE EVERGLADES STORMWATER TREATMENT AREAS

Aquatic fauna, fish, and large invertebrates such as crayfish, may significantly affect P cycling within STAs. This study evaluates the potential of aquatic fauna to affect TP reduction in STA surface waters.



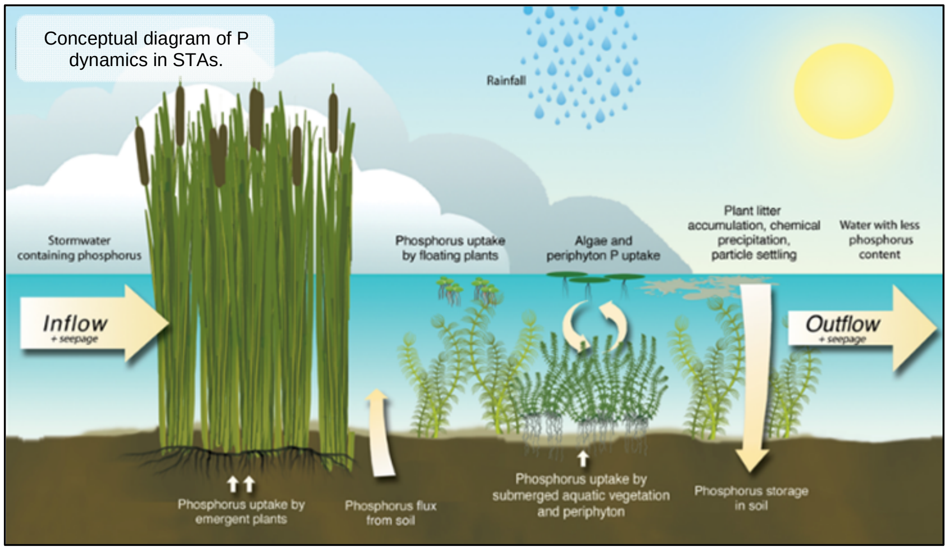
Tilapia nests in STA-2.

## Results

The STAs support a high biomass of fish and macroinvertebrates (Goeke and Dorn 2023). By comparison, the biomass per unit area was approximately 2 to 15 times higher than in other Everglades regions.

Ten of the most abundant fish species in STA-2 stored 1.0 metric ton of P and 3.7 metric tons of N within their body tissues and excreted > 0.63 kilogram (kg) of P per hour and > 3.90 kg of N per hour (Barton et al. 2023). Moreover, bioturbation by large fish was found to quickly and substantially increases the TP content of enclosures by 2 to 3 times (Goeke et al. 2023). Fish in the STAs also affect SAV growth, especially in bare regions where the SAV is regrowing (Goeke and Dorn (2024).

## DATA INTEGRATION AND ANALYSIS STUDY




The purpose of this study was to synthesize and summarize results from the Science Plan (SFWMD 2018) studies and other STA scientific activities. This synthesis included reviews of Science Plan study documents and the key questions and sub-questions from the Science Plan that they answered, a review of the fire project, historical water quality of the STAs, development of biogeochemical models. The final guidance and gap analysis will provide a comprehensive understanding of P dynamics within the Everglades STAs that affects P retention within these constructed wetlands. This synthesis will support STA management and the *Restoration Strategies Regional Water Quality Plan* (SFWMD 2012) to meet the WQBEL.

### Data Analyses

Comparing plant P and soil P and TP concentrations in water of outflow cells found that the lowest water column TP concentration occurred when moderate to high densities of musk grass (*Chara* spp.) were present (DB Environmental 2020a). Relationships of plant and soil P content to water column TP concentration were not as strong, however in studies using mesocosms (typically 1 meter diameter containers that include soils, plants, and inflowing and outflowing STA water) soil and plant tissue P content was related to outflow TP concentration.

Data compiled for each FW was analyzed over the period of record to determine annual outflow P FWMCs in relation to major disturbances (dryout/reflood, loss of vegetation, construction) and PLR (DB Environmental 2024). Outflow P concentrations were higher in years with disturbances than in years without disturbance. Furthermore, during years with no disturbance, when PLR was less than 1.3 g P/m$^2$/yr, outflow P concentrations were consistently less than 19 µg/L, while when PLR was greater than 1.3 g P/m$^2$/yr outflow P concentrations ranged above 19 µg/L.

### Microbial Research Review

The microbial research in STAs with specific focus on periphyton (attached algae), processes, biomass, and enzyme activity were reviewed. Reduced mineralization in soils and enhanced enzyme activity in water column promoted lower TP outflow concentrations (DB Environmental 2021b).

### STA Evaluation

Monthly observed data for each STA for the period of record was compiled and this data was used to develop statistical structural equation models [SEMs] (Hu et al. 2023). These models were used to determine if outflow TP concentrations were related to any of the 81+ monthly measurements taken in the STAs. Relationships varied among the STAs. There were no consistent relationships between inflow and outflow TP concentration among the STAs. Inflow TN concentration was positively correlated with the TP retention rate in STA-1W, and outflow TP concentration in STA-2. The relationship between Ca and P in STA-3/4 suggests the removal of P through co-precipitation with Ca.

### Biogeochemical (BGC) and Comprehensive Aquatic Ecosystem Model (CASM) Models

STA data and research from STA-2 FW1 was used to develop conceptual models—Biogeochemical (BGC) and Comprehensive Aquatic Ecosystem Model (CASM)—that represent P cycling in the STAs. While outflow TP was somewhat affected by external TP loads, internal flux from the soil to the water column had the greatest effect on outflow TP for the BGC model. P cycling was substantially influenced by periphyton. Optimal P removal occurred in the BGC model when water depth was 0.5 meter, PLR was 0.5 milligrams P per square meter per year (mg $P/m^2/yr$). and HLR was 0.03 cm/d. This internal flux and precipitation of P were the dominate factors in the CASM.

### Fire Project Review

The Fire Project was a 6-year study undertaken to evaluate accelerated (by fire) and natural recovery of a wetland affected by high nutrient surface water loading resulting in a community shift from historic ridge and slough to cattail-dominated marshes.

### Final Report and Knowledge Gap Analyses

This current document is a compilation of studies carried out under the Science Plan. It was developed based on interviews with study leads, reviews of the major documents and results of each study, a tabulation of study answers to key questions and subquestions, and any additional findings. Knowledge gaps were discussed with the study leads and others involved in the review of study results. Finally, a table of potential options is included to provide guidance for management of the STAs.

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# APPENDIX C: SCHEMATIC MAPS OF THE STAS AND FEBS

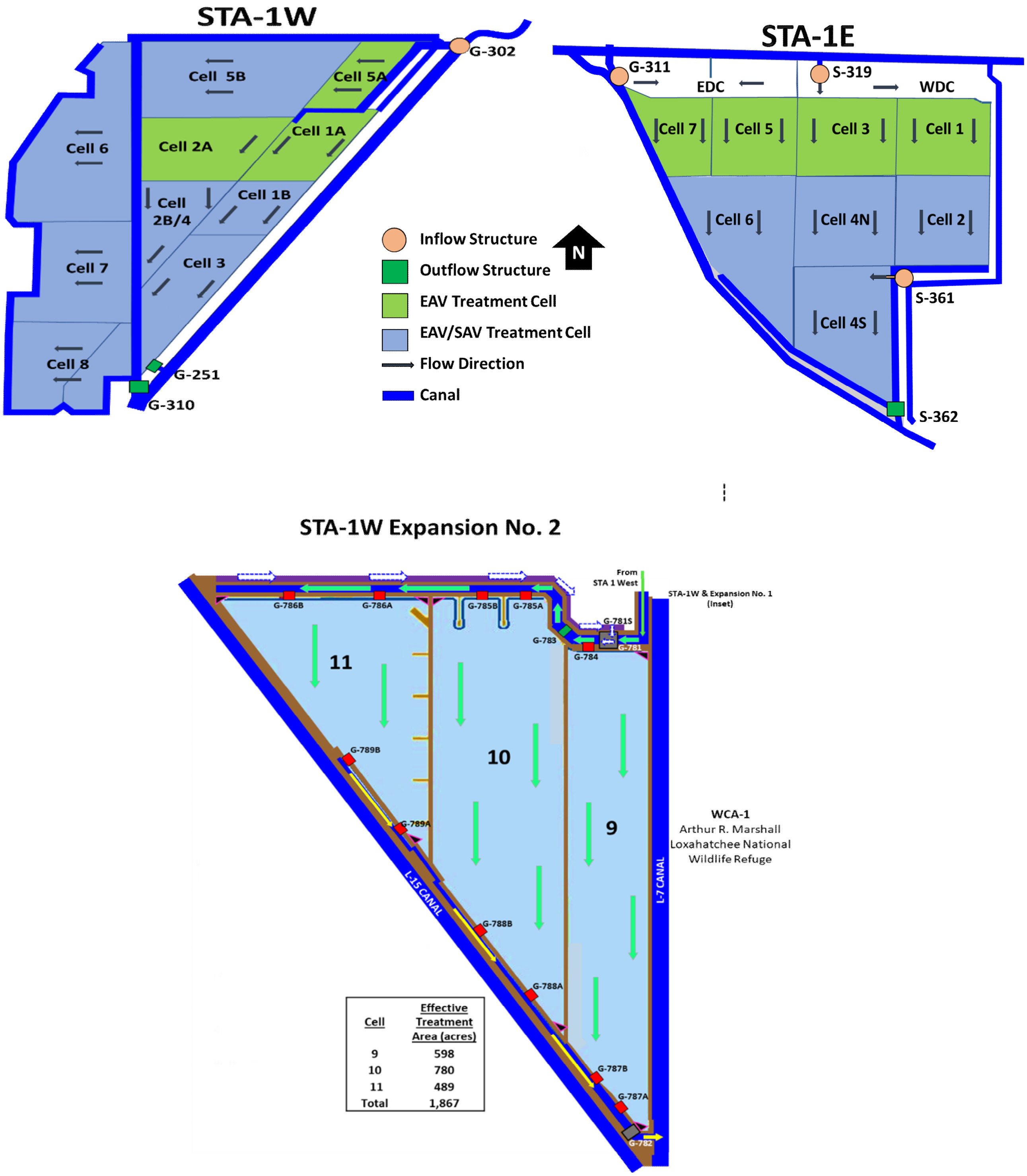


**Figure C-1.** Schematic maps of STA-1W and STA-1E including the STA-1W Expansion #2.

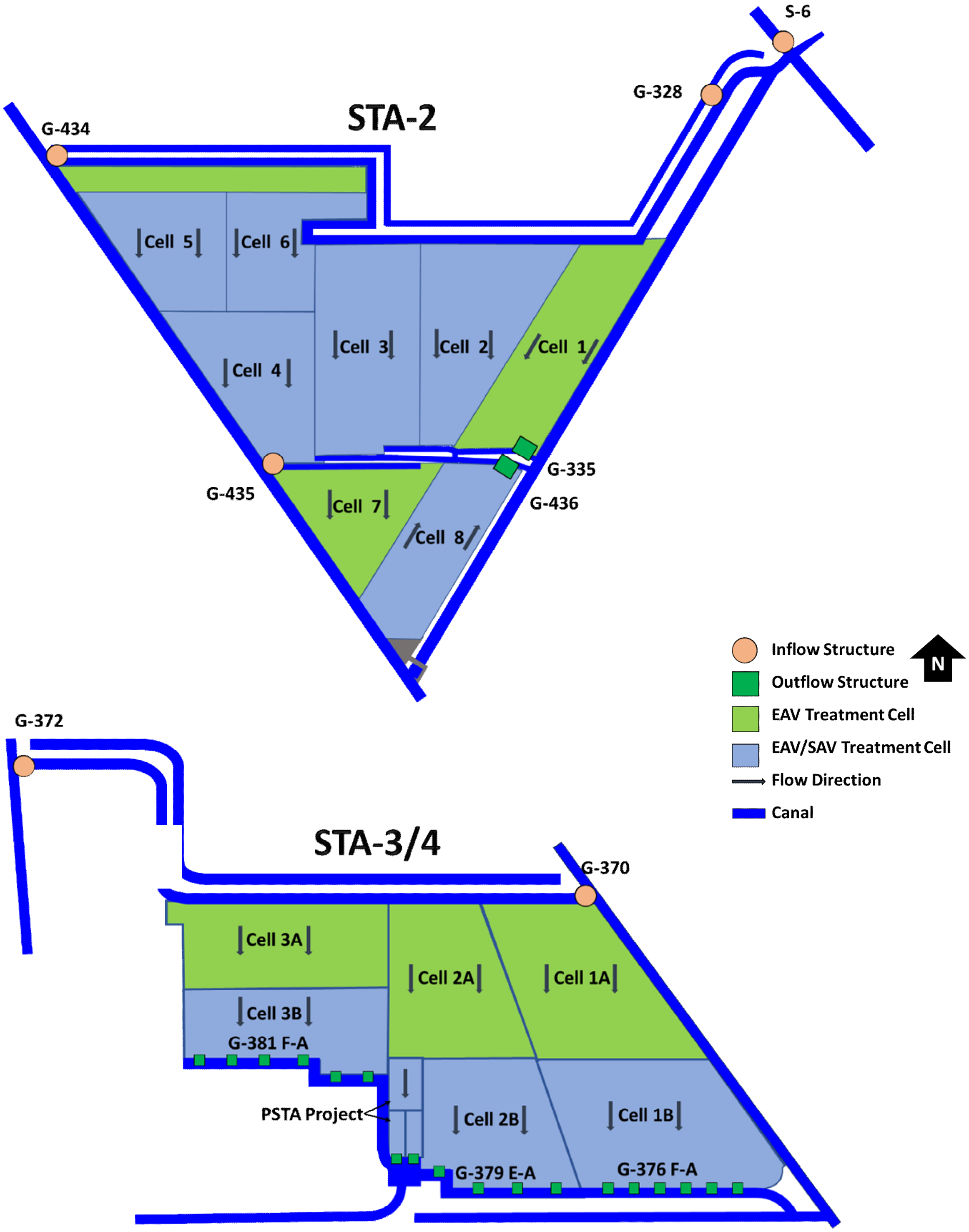


**Figure C-2.** Schematic maps of STA-2 and STA-3/4.

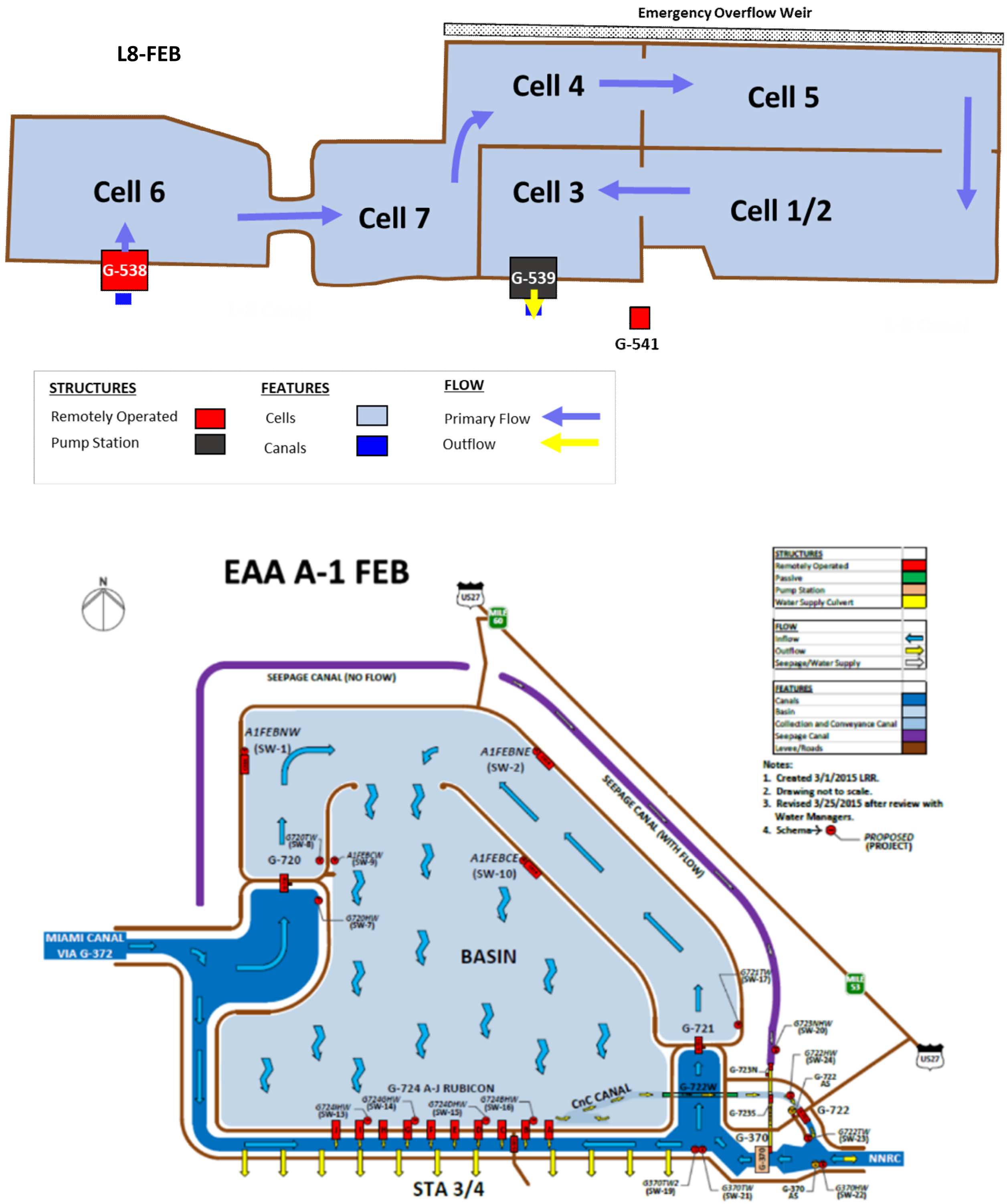


**Figure C-3.** Schematic maps of the L-8 and EAA A-1 FEBs.

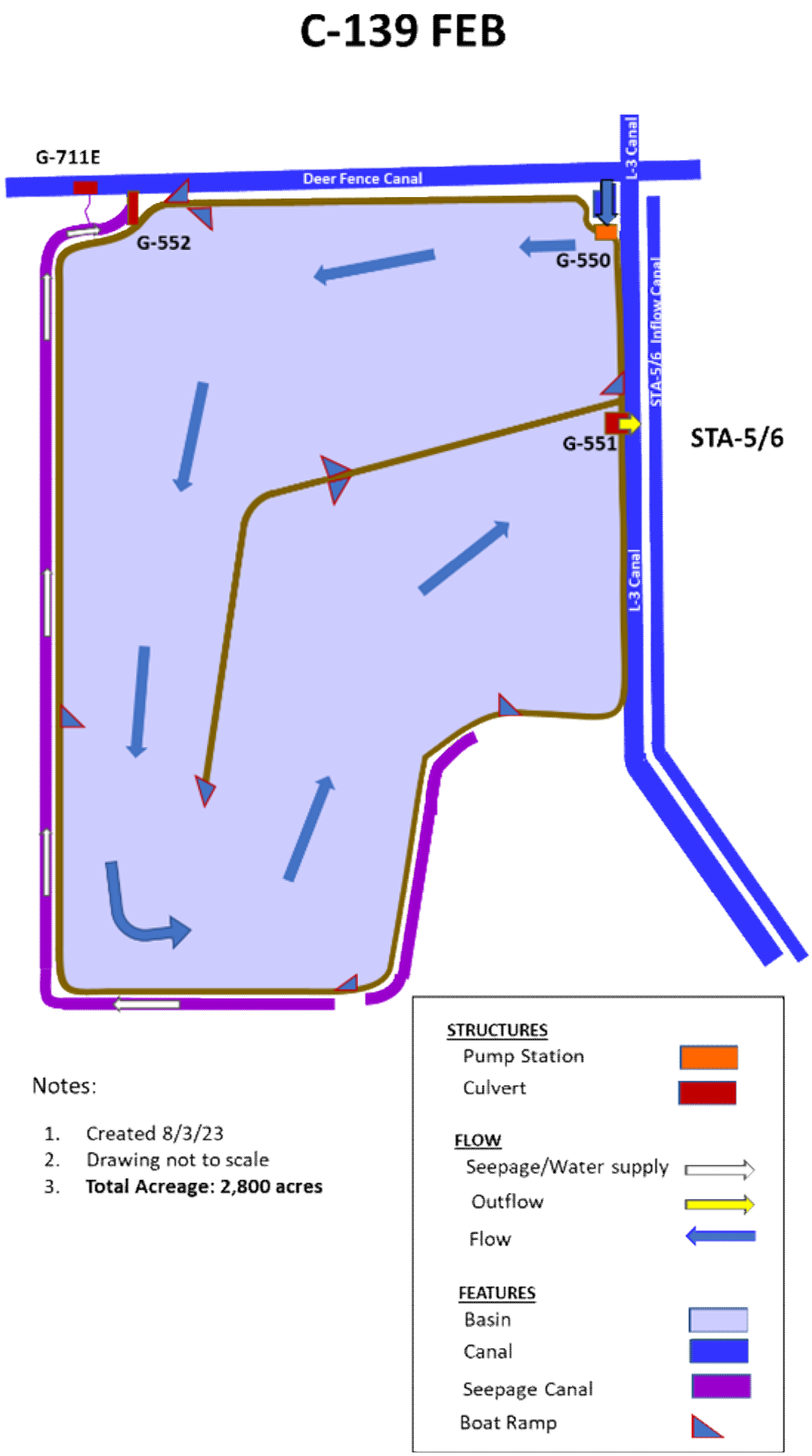


**Figure C-4.** Schematic map of the C-139 FEB.

# APPENDIX D: SUB-QUESTIONS ARCHIVED BUT CLARIFIED IN NEW OR REVISED QUESTIONS IN THE 2018 *RESTORATION STRATEGIES SCIENCE PLAN*

**Table D-1.** Sub-questions archived but clarified in new or revised questions in the 2018 Science Plan (SFWMD 2018).

| Original Question | Rationale for Archiving |
|---|---|
| Should littoral zones be established in the shallow FEBs to reduce flow impedance? | The question, as stated in the original plan, was unclear. Vegetation is establishing naturally and planted in strategic areas (e.g., upstream of outflow structures). |
| How does water depth affect sustainability of dominant vegetation? | Included in new, more general sub-questions:<br>What key factors affect and what management strategies could improve system resilience of SAV communities?<br>What key factors affect and what management strategies could improve system resilience of EAV communities? |
| How do water depths and soil characteristics affect sustainability of dominant vegetation: is the formation of floating mats and tussocks determined by water depth and duration regimes and soil characteristics? | Included in a new, more general sub-question:<br>What key factors affect and what management strategies could improve system resilience of EAV communities? |
| Can STA performance and sustainability be improved with increased plant species diversity or relative coverage of vegetation types: can fire flag *(Thalia geniculata),* knotweed *(Ploygonum densiflorum*), and giant bulrush *(Schoenoplectus californicus)* provide similar P uptake and reduction potential as cattail? | Included in new and revised sub-questions:<br>What are the differences in long-term P reduction between pure SAV communities and mixed SAV/EAV communities?<br>Can various vegetation types (subtypes) enhance P uptake and reduction in SAV cells?<br>What are the relative short-term and long-term P reduction capacities of the dominant and alternative vegetation species in the STAs? |
| What factors determine spatial and temporal variability of SAV community structure (species composition, cover, density): will sediment deposition and nutrient loadings lead to a decline in the sustainability and P uptake performance of SAV cells? | Included in a new, more general sub-question:<br>What are the differences in long-term P reduction between pure SAV communities and mixed SAV/EAV communities? |
| How do water depths and soil characteristics affect sustainability of dominant vegetation: will lowered stages during the dry season enhance sustainability and associated P uptake performance of *Hydrilla* (and other dominant SAV species)? | Included in new, more general sub-questions:<br>What key factors affect and what management strategies could improve system resilience of SAV communities?<br>What key factors affect and what management strategies could improve system resilience of EAV communities? |
| Do dry-outs result in changes in the relative cover of musk grass (*Chara* spp.) and southern naiad (*Najas guadalupensis*)? | Included in a new, more general sub-question:<br>What key factors affect and what management strategies could improve system resilience of SAV communities? |
| What are the impacts and potential benefits of dry-outs and drawdowns on STA performance and sustainability: are the rates of reestablishment of cover and associated P uptake processes of dominant SAV species (*Chara* spp. and *Najas guadalupensis*) dependent on the duration and intensity (water table depth) of dryout events? | Included in a new, more general sub-question:<br>What key factors affect and what management strategies could improve system resilience of SAV communities? |

**Table D-1.** Continued.

| Original Question | Rationale for Archiving |
|---|---|
| Can STA performance and sustainability be improved with increased plant species diversity or relative coverage of vegetation types: what is the appropriate relative cover of emergent vegetation in the SAV cells? | Included in new, more general sub-questions:<br>What key factors affect and what management strategies could improve system resilience of SAV communities? |
| Can STA performance and sustainability be improved with increased plant species diversity or relative coverage of vegetation types: will rotation of SAV and emergent vegetation cover enhance sustainability of SAV cells? | Included in new, more general sub-questions:<br>What key factors affect and what management strategies could improve system resilience of SAV communities?<br>What key factors affect and what management strategies could improve system resilience of EAV communities?<br>What are the differences in long-term P reduction between pure SAV communities and mixed SAV/EAV communities? |
| Can STA performance and sustainability be improved with increased plant species diversity or relative coverage of vegetation types: can *Potamogeton illinoensis, Vallisneria americana*, and floating leaved species, such as *Nelumbo lutea* and *Nuphar lutea,* survive in deeper portions of SAV cells and complement P uptake by dominant SAV species? | Included in new and revised sub-questions:<br>What key factors affect and what management strategies could improve system resilience of SAV communities?<br>Can various vegetation types (subtypes) enhance P uptake and reduction in SAV cells?<br>What are the relative short-term and long-term P reduction capacities of the dominant and alternative vegetation species in the STAs? |
| Can STA performance and sustainability be improved with increased plant species diversity or relative coverage of vegetation types: what is the effect of the size and distribution of emergent vegetation strips on SAV sustainability? | Studying the effects of size and distribution of vegetation strips will be difficult to study.<br>Included in new, more general sub-questions:<br>What are the differences in long-term P reduction between pure SAV communities and mixed SAV/EAV communities?<br>What are the relative short-term and long-term P reduction capacities of the dominant and alternative vegetation species in the STAs?<br>Can various vegetation types (subtypes) enhance P uptake and reduction in SAV cells? |
| What are the impacts and potential benefits of dry-outs and drawdowns on STA performance and sustainability: will P uptake processes in EAV cells be reestablished within one month of reflooding after a controlled drawdown? | Second part of the question regarding reestablishment is already known through years of STA observation.<br>Included in new, more general sub-questions:<br>What key factors affect and what management strategies could improve system resilience of SAV communities?<br>What key factors affect and what management strategies could improve system resilience of EAV communities? |
| What design or operational changes can be implemented to reduce PP and DOP at the outfall of the STA? | Two similar sub-questions were combined into one revised sub-question:<br>Are there design or operational changes that can be implemented in the STAs to reduce PP and DOP in the water column? |
| Does pumping at lower STA inflow and outflow rates over 16 or 24 hours in a day, versus 8-hour day shifts, improve STA performance? | While this question has not been directly studied, the implementation of FEBs upstream of STAs is intended to address the issue of peak flow impacts on STA performance. |

**Table D-1.** Continued.

| Original Question | Rationale for Archiving |
| --- | --- |
| What factors determine spatial and temporal variability of SAV community structure (species, composition, cover and density): what are the short and long-term impacts of herbivory by wintering waterfowl on SAV cover, community structure, and sustainability or P uptake of SAV cells? | Included in new subquestions:<br>What are the direct and indirect effects of wildlife communities at temporal and spatial scales on P cycling (e.g., are they net sinks or sources)?<br>What key factors affect and what management strategies could improve system resilience of SAV communities? |
| What options are there for mitigating or reducing the impacts of fish and wildlife on STA performance through wildlife management or change in operations? | Included in a new, more general sub-question:<br>What are the direct and indirect effects of wildlife communities at temporal and spatial scales on P cycling (e.g., are they net sinks or sources)? |
| What are the direct and indirect effects on alligators on water column P concentrations in the downstream cells of the STAs? | Included in a different sub-question:<br>What are the direct and indirect effects of wildlife communities at temporal and spatial scales on P cycling (e.g., are they net sinks or sources)? |
| Can the outfall areas of the STAs be designed or operated in a manner to discourage congregations of birds, alligators, or other fauna? | Included in a more general sub-question:<br>What are the direct and indirect effects of wildlife communities at temporal and spatial scales on P cycling (e.g., are they net sinks or sources)? |
| Should the establishment of FAV be promoted in the L-8 FEB? | SFWMD has no plans to promote FAV in the L-8 FEB at this time. |
| If FAV is promoted in the L-8 FEB, is mechanical harvesting beneficial or feasible? | SFWMD has no plans to promote FAV in the L-8 FEB at this time. |

# APPENDIX E: QUESTIONS FROM THE DATA INTEGRATION AND ANALYSIS STUDY

**Table E-1.** Questions from the Data Integration and Analysis Study.

| Questions | Studies[a]/Approaches Relevant to the Question | Comments and Results |
|---|---|---|
| A. What are the sources, forms, and transformation mechanisms controlling the residual P pools within the different STAs and are they comparable to those observed in the natural system? | Biomarker Study<br>Marl Study<br>P Flux Study<br>P Dynamics Study<br>Data integration Study | Inflow DOM (DOP) was primarily derived from terrestrial and vascular plants. Most of the inflow TP ends up as particulate organic or inorganic P in the soils (80%). |
| 1. How do forms and distribution of P in the water column change from inflow to outflow and across cell types? | P Flux Study<br>P Dynamics Study<br>Biomarker Study | FW water quality assessment.<br>There is a significant downward trend of P and P forms with the exception of DOP which likely is transformed over the length of each FW. |
| 2. How is the distribution of P species in the water column affected by flow conditions? | Water and P Budget Study<br>Remote Environmental Sampling Test (REST) data (RPA analyses)<br>P Flux Study<br>P Dynamics Study<br>Periphyton (flume) Study<br>Ecotope Study | FW water quality assessment. When waters are flowing, outflow TP concentrations are at a minimum when HLR is between 5 and 15 cm/d. On an annual basis, TP concentrations are a minimum when average annual HLR is between 1.7 and 3.5 cm/d. |
| 3. What are the sources and composition of DOP and PP observed at the outflow region of the FWs? How much of these were generated internally? | Biomarker Study | Primarily mineralization of litter, microbial decomposition, and photolysis of DOM. |
| B. What are the key physical and biogeochemical factors influencing P cycling at very low concentrations? | Fauna Study<br>Biomarker Study<br>P Dynamics Study<br>Periphyton Study<br>SAV Study<br>Ecotope Study | $CaCO_3$ production, settling, and marl accumulation, enzyme activity and uptake by SAV, periphyton, internal loadings, resuspension, bioturbation, and fauna excretion. |
| 1. What is the C* (lowest P concentration attainable) for each STA FW? At what spatial point does TP concentration reach background(C*)? | P Flux Study<br>P Dynamics Study<br>Juston and Kadlec (2019) | Approximately 2/3 of the way down a FW, the concentrations level off, and retention ≈ internal loads. |
| 2. Where is the “moving front” of P enrichment, spatially and temporally (annual and decadal), for all study FWs? | P sorption/desorption<br>Spatial soil sampling | P Flux and P Dynamic soil analyses. |
| 3. What is the optimum treatment area to achieve the WQBEL? | P Flux Study<br>P Dynamics Study<br>Modeling<br>Data integration Study | See figures above approximately 3000 to 4000 acres and 4000 to 5000 meters |

**Table E-1.** Continued.

| Questions | Studies[a]/Approaches Relevant to the Question | Comments and Results |
|---|---|---|
| 4. What is the optimum HLR and PLR to achieve the WQBEL? | Modeling<br>Data mining<br>Zhao and Piccone (2020) | Annual PLR ≤ 1.3 g P/$m^2$/yr and HLR < 3.5 average annual cm/d. |
| 5. How does the difference in vegetation type (EAV, SAV) influence water column TP concentrations and reductions? | Ecotope Study<br>rFAV Study<br>P Dynamics Study<br>P Flux Study | EAV – at the inflow, PP is reduced and DIP is removed.<br>SAV – near the outflow, removes DIP indirectly through photosynthesis that causes $CaCO_3$ to form and P removal through co-precipitation.<br>Periphyton and open areas can break down organic P to inorganic P, which is quickly removed either biotically or chemically (precipitation). |
| 6. How does litter decomposition affect the concentration and distribution of P species in the overlying water column? | Biomarker Study<br>Chimney and Pietro (2006) | Both biomarker and litterbag studies demonstrated rapid P removal from dead (fresh) plant material, which is incorporated into the water column and then broken down either through enzymes or photolysis. |
| a. What are the magnitudes of litter decomposition rates? | P Flux Study<br>Biomarker Study<br>Chimney and Pietro (2006)<br>UF-WBL (2019) | *Najas*/*Ceratophyllum* (0.0568/day ) > *Pistia* (0.0508/day) > *Eichornia* (0.0191/day) > submerged *Typha* (0.0059/day ) > aerial *Typha* (0.0008/day). |
| b. What is the rate of release of P from SAV? | Biomarker Study<br>P Flux Study<br>Chimney et al. (2006) | P content decreased by 36 to 54% in first week and then stable after mass% of P, N, C, Ca, and K remaining in the litter mirrored the loss of dried material. |
| c. What is the rate of release of P from EAV? | Chimney et al. (2006) | P content wet *Typha* declined by only 7% by day 7.<br>Mass% of P, N, C, Ca, and K remaining in the litter mirrored the loss of dried material. |
| d. What is the relationship between decomposition rate of organic materials and remobilization of P from the sediments? | Biomarker Study<br>P Flux Study<br>Mesocosms studies<br>P Dynamics Study | When SAV decomposes it releases a pulse of SRP. EAV decomposes much slower, often the content of P in the EAV increases with decomposition as organic P is more recalcitrant. |
| 7. What data is needed to determine key limiting factors to achieve WQBELs for each STA? | This question is very broad in scope. Information from science plan studies will collectively help answer this question. | Each FW is different and factors that affect P retention and the ability to achieve the WQBEL must be evaluated independently for each FW. |
| 8. How much is the P net accretion in soil for each FW on a long-term basis? | Reddy et al. (2020)<br>UF-WBL (2019) | 25 to 30% highly reactive.<br>15 to 20% non-reactive.<br>50 to 60% moderately reactive in RAS. |
| a. What are the magnitudes of particulate settling? | Particulates<br>Fugate et al. (2021) | Highest at inflow, declines as TP declines along the FW. |

**Table E-1.** Continued.

| Questions | Studies[a]/Approaches Relevant to the Question | Comments and Results |
|---|---|---|
| b. What are the magnitudes of diffusion and resuspension at the different regions of the FW? | P Flux Study<br>P Dynamics Study<br>Jerauld et al. (2020)<br>Fugate et al. (2021) | In situ P flux chamber studies. These fluxes decline from the inflow to the outflow regions of a FW. |
| 9. What is the magnitude of influence of soil P forms and concentration on water column P? | P Dynamics Study<br>P Flux Study<br>Reddy et al. (2020) | Soil P fractionation; water quality data from transect and benchmark soil samplings.<br>25 to 30% highly reactive.<br>15 to 20% non-reactive.<br>50 to 60% moderately reactive in RAS. |
| a. What is the effect of recently accreted soil and floc P concentrations in the water column for EAV versus SAV dominated systems? | P Flux Study<br>P Dynamics Study<br>SAV Study | P sorption/desorption; P dosing long-term SAV mesocosm studies. For SAV, the accumulated marl can affect SAV germination and persistence. Consolidating the marl can enhance germination.<br>Organic soil found in EAV regions is easily resuspended and may affect floating wetland (tussock) formation. |
| b. How does soil nutrient concentration affect water column P spatially and temporally along the inflow-outflow gradient? | P Flux Study<br>P Dynamics Study<br>PSTA Study<br>SAV Study | Spatial soil sampling; FW water quality assessment. There is some relationship between soil content and TP in mesocosm studies. The relationship is muted in the outflow regions of FWs. Where soil content is minimal (e.g., PSTA cell), overlying water column TP is below 13 µg/L. |
| 10. How does P mining by macrophytes influence water column P? | P Flux Study<br>P Dynamics Study<br>PSTA Study (mesocosms) | TP concentrations in mesocosms with rooted plants are higher than similar mesocosms without rooted plants.<br>Major source of internal P load.<br>Soil nutrient profile from transect and benchmark soil samplings; vegetation dynamics. |
| 11. What are the effects of other elements (C, N, S, Ca, etc.) on P cycling? | FW water quality assessment; PSTA<br>Jerauld et al. (2024)<br>Bhomia (2013)<br>Bhomia et al. (2015)<br>Reddy et al. (2021)) | Ca is the primary component that has been evaluated both in non-Science Plan and Science Plan studies. |
| 12. How do soil depth and stored P affect water column P concentrations through seepage and advection? | PSTA Study<br>Soil Management Study<br>WSP Inc. (2022)<br>WSP Inc. and Dynamic Solutions (2022) | Advection is not a major concern.<br>PSTA limerock cap studies.<br>Soil management flipping studies (soil core P flux) indicate that burying high P soils can reduce P flux and thereby result in lower P concentrations in the water column. This has not been verified at the field scale. |

**Table E-1.** Continued.

| Questions | Studies[a]/Approaches Relevant to the Question | Comments and Results |
|---|---|---|
| 13. How do loading rate, cumulative load, vegetation type, and density affect equilibrium P concentration (EPC)? | P Flux Study<br>P Dynamics Study | P sorption/desorption; P dosing EPC tends to be lower in FWs that have experienced lower PLR. |
| 14. How does EPC vary along the treatment FW? | P Flux Study<br>P Dynamics Study | P sorption/desorption; P dosing<br>experiments have found EPC is higher in inflow regions and lower in outflow regions. |
| 15. What are the differences in magnitude of influence between microbial versus sorption and coprecipitation on SRP reduction along the FW gradient? | Periphyton Study<br>P Flux Study<br>Data Integration Study | Periphyton mesocosm studies.<br>Enzyme activity net settling analyses from from the P Flux and P Dynamics studies.<br>BGC model sensitivity analyses suggest that periphyton cycling is a dominant process affecting TP concentrations in the STA. The co-precipitation process was a dominant factor in the CASM model. |
| 16. How do water depths affect P concentrations in the STAs? | PSTA<br>Cattail Study<br>Ecotope Study<br>RPA analyses<br>Powers et al. (2023) | PSTA showed little effect of different water depths.<br>Short-term cattail (10 months) did not observe difference in outflow concentrations from control to very deep. |
| 17. Can we predict the effects of deeper water in SAV cell, assuming SAV depth stays constant? (i.e., effects of water movement over SAV canopy; lack of contact with SAV). | SAV sustainability | SAV was unaffected by changes in water depth. |
| 18. What mechanisms and factors are helping STA-2 FW 1 achieve very low outflow TP concentrations? Is exchange with WCA-2A water a factor? | Water and P budget analysis<br>P Flux Study | Initial soils were not farmed. Maintained healthy cattail community. |
| 19. What is the effect of vegetation on floc transport? | P Flux Study<br>Periphyton Study<br>Fugate et al. (2021)<br>Fugate and Thomas (2024) | |
| 20. How do key P cycling rates differ between the lower reaches of the STAs and the WCAs? What are the key influencing factors for the differences? | Will need collective information from various Science Plan studies to address this question. | Knowledge gap. |
| 21. What is the pattern for carbon sources for microbial activities along the gradient? What is the relative distribution of available versus resistant carbon sources? | Periphyton Study<br>Pietro et al. (2023) | Carbon enzyme activity was the lowest and least variable DOM created within the STA FW. |

**Table E-1.** Continued.

| Questions | Studies[a]/Approaches Relevant to the Question | Comments and Results |
|---|---|---|
| 22. What is the actual role of enzymes in P cycling and what are the factors affecting enzyme activities in the STAs? | Periphyton Study<br>Pietro et al. (2023) | Enzymes are effective at mineralizing DOP. P enzymes occur where P is limited. |
| 23. What are the effects (contributions to P loading) of the different animal communities (i.e., fishes and macroinvertebrates and birds) on water quality and vegetation in the STAs? | Fauna Study<br>Goeke and Dorn (2023) | Faunal cycling and bioturbation indicate that small fish recycle as much P as loaded to FW. Bioturbation is order of magnitude less but under certain circumstances (nesting near outflow) could affect both the amount of P in the water column and disturb SAV. |
| 24. What are the factors influencing residual TP (mainly PP and DOP) concentrations in the STAs? | Biomarker Study<br>P Flux Study<br>P Dynamics Study | Enzymes, photolysis, microbial uptake, and $CaCO_3$ co-precipitation. |
| 25. Is there an optimal hydraulic retention time for the different STAs that can effectively minimize PP and DOP, especially at the back end of the FW? | Water and P budgets<br>Zhao and Piccone (2020)<br>Powers et al. (2023) | FW water quality assessment (partly); historical inflow-outflow water quality and flow data. |
| 26. Is abiotic mineralization of organic P via photolysis a significant process in P cycling in the STAs? | P Flux Study<br>Schafer et al. (2023) | Yes. |
| 27. What is the relative photolytic reactivity of DOM from dominant vegetation types in the STAs? | Schafer et al. (2023) | Abiotic degradation of DOM through photolysis does occur with the greatest effect in mid-FW regions of SAV. |
| C. Are there things that can be done in the STAs to enhance settling, filtering, and treatment of DOP and PP in the water column? | Rafts of oysters and clams<br>Sticky materials<br>Geo tubes | Knowledge gaps. |
| 1. How can we optimize biotic transformations of residual DOP and PP by increasing vegetation and microbial activity? | Periphyton Study<br>Feeney et al. (2024) | Recommendations are to maintain SAV/EAV communities with open areas near the outflows to promote distinct SAV/EAV periphyton communities and open areas to allow photodegradation. |
| 2. What are the effects of specific operational or environmental conditions (e.g., change in flow operation, vegetation community structure, presence of vegetation strips, and presence of deep areas) in altering particle resuspension and transport processes? | Periphyton Study<br>Fugate and Thomas (2024)<br>P Flux Study<br>Fugate et al. (2021)<br>Operation Study<br>Lal (2017) | Particulates are primarily sloughed off plants into the water column at low shear stress. Shallower water may cause soil resuspension.<br>Flow can be turbulent or laminar, which may affect resuspension. |
| a. If water depths are shown to influence water column P concentrations, could we manage depths to optimize stages before and after flow events? | P Flux Study<br>P Dynamics Study<br>Data Integration Study<br>Landscape Study | Water depth is easier to control for no-flow conditions and these have been set to provide optimal growth for plants. Analyses have not found significant relationships between water depth and TP concentrations as flow is a confounding parameter. |

a. Full names for studies are provided in Appendix A.

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