TECHNOLOGY REVIEW OF PERIPHYTON STORMWATER TREATMENT

R. H. Kadlec and W. W. Walker

November 11, 2003

As of December 1, 2003, this article has been revised from the draft version of August 8, 2003 (posted for the August 12, 2003 TOC meeting). All changes pertain to the S332B basin.

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Background

This review has been assembled in support of the continuing investigations of methods of achieving the necessary phosphorus concentrations for discharges to the Everglades. It is occasioned by the need to focus previous knowledge, to guide decisions on potential scaled-up research and demonstration facilities.

Non-emergent wetland systems (NEWS), which include mixtures of submerged aquatic vegetation (SAV) and periphyton in varying proportions, are the only known ecosystems that presently hold out hope for attaining the 10 ppb phosphorus concentration believed necessary to protect Everglades resources. It is appropriate to consider and explore both extremes of the NEWS concept, periphyton and SAV.

Constructed systems dominated by SAV have been successful in closely approaching the 10 ppb goal in small units, and are being studied at all scales from mesocosms up to 2000 acre cells in the stormwater treatment areas (STAs). There is a possibility that SAV wetlands can be improved to produce 10 ppb water.

Natural Everglades periphyton-dominated wetlands exist and function at phosphorus levels below 10 ppb. Constructed wetlands dominated by periphyton, termed periphyton stormwater treatment areas (PSTAs), have also been successful in closely approaching the 10 ppb goal in small units. There is a possibility that PSTA wetlands can produce 10 ppb water. Extensive research at sizes up to five acres has been conducted over the past five years. While some PSTA questions remain that could be addressed in small units, the preponderance of remaining issues can only be addressed in larger systems.

Based upon the available information, which is summarized here, it is suggested that the next incremental step should be a PSTA of approximately 100 acres. That available information contains both positive and negative indicators, which need to be confirmed or resolved, respectively.

Summary of Key Points

The following brief list of key points is derived from the quantitative database as it now exists. Future work may discover processes and techniques that would alter these statements.

1. PSTA is a concept that encompasses several types of algae, emergent and submergent macrophytes, in varying proportions. Test cell and field scale PSTAs have grown to contain more SAV than periphyton. PSTA is perhaps best defined in terms of creating conditions that foster periphyton, such as shallow depth, sparse macrophytes and substrate preparation.
2. Approximately $12 million has been spent investigating PSTA over the past five years, on nine research projects ranging in size from 0.001 to 5 acres. Despite the substantial information gained in these studies, significant uncertainties remain in scaling up these data to full-scale designs.
3. PSTA is not a stand-alone system for treating runoff. Periphyton mats are not sustainable in water of elevated phosphorus concentration. Threshold research indicates eventual disappearance of cyanobacterial mats at or above 10 ppb, and green mats at or above 50 ppb. Either emergents, SAV, or FAV (floating aquatic vegetation, such as water hyacinth) are necessary as an upstream treatment precursor.
4. PSTA has not been successfully established on a peat substrate, possibly due to phosphorus release and recycling that may ultimately foster cattail invasion. Organic soils must be removed, or covered with limerock. The minimum depth of inorganic substrate required to establish and maintain PSTA communities has not been determined, but has a potentially large effect on the cost of constructing full-scale systems.
5. Based upon concentration trends observed in experimental platforms, PSTA system performance startup times range from four months to over a year. Data from that period may not be reflective of sustainable performance. Ecological data are not an acceptable surrogate for phosphorus removal performance. Time frames much longer than those already studied may be required for full development of mat and surface soil conditions representative of long-term sustained operation, under which net phosphorus removal would be controlled by accretion of new soils, as opposed to net mat growth or phosphorus releases from initial substrates.
6. Natural Everglades data indicate that 10 ppb should be reachable in a constructed PSTA. However, no PSTA project to date has shown post-startup, sustained outlet concentrations of 10 ppb or less. That may be related to the fact that virtually none of the research platforms operated under both hydraulic loading and velocity regimes that would be representative of full-scale treatment cells designed to achieve 10 ppb. Most platforms operated at average hydraulic loads well above those likely to occur in a full-

scale cell and above those likely to achieve 10 ppb with typical inflow concentrations of 20-30 ppb.

7. Microcosm studies and theoretical mass-transfer modeling indicate that higher velocities are conducive to better phosphorus removal. A few platforms have achieved high velocities at the cost of introducing other potential experimental artifacts related to recirculation, extremely shallow depths, high aspect (length/width) ratios, and high hydraulic loads. Within the limited range of existing data, however, there is some indication of a positive correlation between velocity and net P removal rate. Larger experimental platforms are needed to study PSTA under full-scale velocity regimes without introducing other artifacts.

8. At concentrations below 20 ppb, updated model calibrations for PSTA generally predict performance levels that are between those predicted by the two calibrations previously used to develop full-scale designs under SFWMD's Basin-Specific Feasibility Studies (NEWS and SAV_C4).

9. The response of PSTA to pulse loadings is unknown. The response to dryout events, while speculatively allowable and possibly beneficial, has not been quantified. If dryout to consolidate sediments is a requirement for sustained operation, additional areas and/or parallel flow paths would be needed to manage PSTA cells without sacrificing overall treatment performance.

10. Once established, PSTA may require moderately intensive vegetation management, in the form of herbiciding cattails and other nuisance invader species.

11. Direct correlations between areal P loads and observed outlet concentrations in PSTA and SAV platforms, as well as model (DMSTA) forecasts, indicate that PSTA inlet loading rates ranging from 0.2 to 0.4 gm/m2•yr would be expected produce an outflow concentration of 10 ppb. Modeling indicates that the upper end of this range (requiring minimum surface area) would be appropriate for hydraulically optimized cells. Results apply to cells with inflow concentrations ranging from 20 to 50 ppb.

12. The size and cost of PSTA cells required to reduce concentrations from 20 to 10 ppb vary by 30-40% or more depending upon choice of model calibration (test-cell vs. field-scale cells). This sensitivity further demonstrates the need for additional data from larger-scale platforms to provide a sufficient basis for model calibration and development of full-scale PSTA designs

13. Economic forecasts for full-scale implementation of PSTA indicate very large costs for construction, ca. $10,000 - $30,000 per acre. There is currently no obvious unexplored mechanism for avoidance of that cost. The SAV option of NEWS carries less cost, and therefore is preferred in those circumstances where either PSTA or SAV is operable.

History

Concepts and Ideas

In December 1991 the Technical Advisory Panel for the design of the ENR conducted a workshop and prepared a report to SFWMD (Kadlec, 1991). The 12 Panel members[1] agreed upon several items, one of them being "The full-scale prototype should contain internal partitioning, and provide for sparse macrophyte algal polishing cells as the final elements." Browder (1991) and Ward (1991) provided detailed and thoughtful comments in that Technical Advisory Panel Report, on what later was termed PSTA. Ward's report included key research questions that required investigation: (1) Will conditions in the polishing cell be amenable to growth of calcite/SRP precipitating periphyton communities? (2) Will the initial precipitation … result in permanent interment of phosphorus in the sediments? (3) Can efficient SRP removing periphyton communities be maintained over the long term under chemical, hydrological, and biological conditions as currently envisioned for the larger P-removing marshes? Browder's recommendation was that "The downstream polishing area should be designed and operated to promote periphyton and the macrophyte communities typical of sites of high periphyton coverage and calcite precipitation."

Cell 4 of the ENR was subsequently managed to exclude emergent macrophytes (cattails). However, Cell 4 underwent self-design to submerged aquatic vegetation (SAV), with sparse periphytic encrustations. It is now generally considered to have been the prototype for full-scale SAV.

In January 1996, Doren and Jones coined the acronym PSTA (Periphyton Stormwater Treatment Area). Doren and Jones (1996) observed that soil and vegetation had been successfully removed, down to bedrock, in the Hole-in-the-Donut (HID) project in Everglades National Park. They also observed that natural periphyton communities of the southern Everglades exist at low phosphorus concentrations (ca. 10 ppb or less). They then concluded that the HID methodology could be directly applied as Phase II methodology in the Everglades Construction Project. A PSTA project in the vicinity of L31W, known as the Frog Pond, was proposed as a demonstration. As a consequence of the Doren and Jones suggestion, the USACOE requested that PSTA be included in the set of Phase II technologies to be investigated (Rice, 1996).

In July 1996, Peer Consultants, P.C./Brown and Caldwell (1996) concluded a Desktop Evaluation of Alternative Technologies for SFWMD. Thirty alternative technologies were examined, and PSTA was one of fourteen that were classified "new." Because of a total lack of data, uncertainties about constructability, and the perception of a lengthy research period, PSTA was eliminated from further consideration.

[1] Drs. Best, Browder, DeBusk, Grace, Johnson, Kadlec (Chair), Maffei, Mitsch, Reddy, Richardson, Snyder and Ward.

Projects

In November 1996, the first of several draft proposals for a Frog Pond PSTA project was issued (USACOE, 1996, 1997, 1998). Because of issues relating to water quality, permitting and threatened and endangered species, these projects did not materialize. However, the need to address C111 water quality issues led to continued planning (USACOE, 2000a,b), and ultimately to a new PSTA facility design, and research project plan (CH2M Hill, 2001a,b). At the time of this writing, the Frog Pond research facilities have not been built, but full-scale scrape down detention basins are in place.

In 1997, SFWMD initiated plans for a demonstration of PSTA for Phase II phosphorus removal from EAA waters (SFWMD, 1997a,b,c; Van der Valk and Crumpton, 1997). SFWMD selected CH2M Hill as their PSTA project contractor, planning and construction began in 1998 (CH2M Hill, 1998a,b,c; 1999a). This CH2M Hill project proceeded in three phases over the period 1999 – 2002, and portions are continuing under a SFWMD initiative.

In 1998, the USACOE began the planning and design of a PSTA pilot study located within the footprint of STA1E (USACOE, 1998, 2000a,b). The facility design was specified by R. D. Jones, and operation is by Florida International University. This facility was structurally completed on February 9, 2000, and became operational in 2002, and reportedly began producing data in 2003.

In 1998, DB Environmental laboratories began a raceway mesocosm study of the use of periphyton for phosphorus removal. This project continued through 2001 under auspices of SFWMD, and continues under funding from the EPD.

In 1999, Florida Atlantic University initiated microcosm studies addressing the issue of water velocity effects on phosphorus uptake by periphyton. (Simmons and Volin, 2000; Simmons, 2001; Simmons et al, 2003).

In 2000, SFWMD instituted a PSTA project under the direction of R.D. Jones. Limerock pads were built into a ten-acre area of STA2, Cell 3. Observations were reported for a one-year period (Jones et al, 2001a,b,c, 2002).

In early 2000, a full-scale, scraped down detention basin in the C111 area was completed and began operation, serving the S332B pump station. This 150-acre USACOE project continues in operation. Inflow and outflow phosphorus data are obtained.

In 2001, studies of periphyton phosphorus uptake were initiated on scraped down patches on the southern rim of the easterly reach of the C111 canal. This ENP-sponsored project produced information over a two-year period (Thomas et al, 2002, 2003).

In 2001, CH2M Hill started an integrated STA project for the Village of Wellington, under the direction of R. D. Jones, which included PSTA cells (CH2M Hill, 2003). Data were acquired from November 2001 through early 2003, at which time the facility was decommissioned.

In 2002, USACOE built two more full-scale, scraped down detention basins in the C111 area. These were completed and began operation in summer 2002, serving the S332C and S332D pump stations. Inflow and outflow phosphorus data are obtained.

In total, nine projects have been conducted over 1998 to present, at a cost of approximately $11.5 million (Table 1).

What is PSTA?

It is becoming apparent that PSTA and SAV are variants on the same theme: shallow submersed aquatic vegetation that supports an active periphyton community (Kadlec, 2000). PSTA envisions sparse vegetation that forms an anchor and a substrate for periphyton. Emergent vegetation must be very sparse, if present at all, to avoid shading of the algal mats which occur on the bottom, as floating mats, and as attached growth on submerged plant parts. Accretion of residuals is needed to make this a passive sustainable process. The benthic mats can access such residuals and recycle accreted phosphorus.

SAV envisions dense submersed vegetation, with periphytic communities restricted to the upper layers because of light limitation. Periphyton exists as crusts on the leaves of the submerged aquatic vegetation. Accretion of residuals is needed to make this a passive sustainable process. For SAV, there are no benthic mats because of light limitation, and phosphorus residuals are recycled by rooted macrophytes.

These two vegetative community structures, PSTA and SAV, are both manifestations of a broader category of wetland ecosystems that contain virtually no emergent plants. This is the category here termed non-emergent wetland systems (NEWS). Everglades slough and wet prairie communities, as well as cell 4 of the ENR project, are examples. In the former, *Utricularia* and *Ludwigia* form a good share of the underwater structure, while *Najas* and *Ceratophyllum* are found in the later. The species composition of a particular NEWS is in part determined by hydrology, soils and water chemistry. It has proven difficult to establish and maintain preconceived assemblages of submerged aquatic vegetation. However, the immersed surface area is an important determinant of the amount of periphyton and its location in the water column, and thus the potential for an algal component of the nutrient cycle that buries phosphorus. It is important to note that it has been relatively easy to prevent the invasion of emergent vegetation in cell 4 ENR. Thus it appears we can select NEWS as an option for a portion of stormwater treatment, but will have difficulty maintaining a specific under-water species composition and relative abundance.

It should be recognized that periphyton treating water of concentration greater than about 10 ppb would not be pristine Everglades periphyton. Extensive research has shown that pristine cyanobacterial mats do not survive at concentrations above that limit. That research shows that at higher concentrations, the periphyton contains a significant proportion of green algae. At some higher P concentration, approximately 50 ppb, the existence of any kind of self-sustaining, algal-dominated system is threatened.

Projects and Results

The nine constructed projects in Table 1, supplemented by three natural system response studies, form an impressively large suite of datasets. A very brief synopsis of results from each are summarized here, but each project addressed many issues. A discussion of those issues, and relevant information obtained, is contained in the following section.

<u>CH2M Hill /SFWMD/FDEP Multi-Scale Studies</u>

The CH2M Hill portion of this project addressed multiple issues at three size scales: mesocosms (6, 18 m^2), test cells (half acre, 2,240 m^2), and field scale (5 acre, 20,790 m^2)(Table 2). The twenty-four mesocosms were operated under a total of nineteen conditions in two phases over a period of 31 months. Three test cells were operated under a total of six conditions in two phases over a period of 27 months. Four field scale systems were operated over a period of 27 months. Data collection is continuing by SFWMD for the test cells and the field scale platforms. Over 5,500 pages of reports and data compilations were produced over the five-year span of the project (see bibliography section).

Those platforms that used peat as a substrate experienced difficulties with vegetation management, despite attempts to control emergents exercised to varying extents. Their behavior was more akin to emergent marshes, and therefore they fall outside even the broadest definition of PSTA.

There were a total of 18 treatments (out of 29) using sand, shellrock, limerock or caprock substrates (Table 3). Depths were 30 or 60 cm, and hydraulic loading rates averaged 8.4 cm/d (range: 3.5 –17.9 cm/d). For inlet concentrations averaging 24.4 ppb (range 19.1 – 28.2 ppb), these produced a global mean outlet of 15.3 ppb (range: 11.4 – 18.8 ppb). The best field scale result was a reduction from 30 to 14 ppb, determined over a one-year period. As compared with the test cell data formerly used as a PSTA prototype for design purposes, recent limited data from larger field-scale cells with ~10-fold higher velocities have net setting rates (phosphorus removal that are about 25% higher.

<u>DBEL/SFWMD Raceways</u>

Three shallow troughs, 0.3 m W x 44 m L, located at the south end of STA1W, were run in either parallel or series over a three-year span. The substrate was 3 cm of crushed limerock, and periphyton was inoculated, providing accelerated colonization. The performance at nine cm depth, including loading rates of 11 and 22 cm/d, reduced phosphorus from 21 ppb to 12 ppb over a 29-month period (DBEL, 2002b). The performance at nine cm depth, at a loading rate of 66 cm/d, reduced phosphorus from 23 ppb to 17 ppb over a six-month period (DBEL, 2002b). For a 19 month period (7/98 – 2/00), at HLR = 11 cm/d, the raceways reduced TP from 18 ppb to 10 ppb (DeBusk et al, 2003).

<u>FIU/SFWMD Limerock Pads</u>

This project involved the placement of two five-acre limerock pads inside the footprint of STA2 Cell3, of thicknesses one and two feet. Data were acquired on periphyton over a period of one year (Jones et al, 2001a,b,c,2002). No significant periphyton growth was noted for three quarters, and there was some development of *Chara* during the fourth quarter. Subsequent episodic surveys have shown a continued absence of periphyton (T. DeBusk, personal communication).

CH2M Hill/FIU Wellington FAV-EAV-SAV-PSTA Studies

The Village of Wellington conducted a pilot study on the use of “green” technologies (Ch2M Hill Constructors, 2003). Facility construction was completed in August 2001, and included two treatment trains. The west train consisted of floating aquatic vegetation (FAV) followed by emergent aquatic vegetation (EAV) followed by PSTA. The east train consisted of EAV followed by SAV followed by PSTA. The 493 m^2 PSTA cells were originally filled with six inches of limerock gravel (57 stone), and an additional one inch of crushed limerock was added in March 2002. Dryout was conducted in January and February of 2002. Cattails were manually removed from the west PSTA cell in May 2002, and replaced with *Eleocharis* transplants. Grow-in occurred through spring 2002, and operation was terminated in spring 2003, following which the system was decommissioned.

Nominal water depth in the PSTA cells was 15 cm. The unlined PSTA cells lost ca. 40% of the inflow to infiltration. The average inlet HLR was 10.4 cm/d for the east PSTA, and 5.4 cm/d for the west. Reductions were from an inlet of 109 ppb to an outlet of 49 ppb in the east PSTA, and from 24 to 23 ppb in the west.

FIU/USACOE Channel Studies

Four concrete channels, ca. 1.5 meter deep, were equipped with a ca. 30 cm layer of highly porous, water filled, artificial substrate, topped by geo-cloth and then a layer of selected substrate. Substrates included peat, limerock and sand. These channels are being operated at an overlying water depth of 15 cm, and a detention time of 14 days, or an HLR of about one cm/d. Phosphorus concentrations are being reduced in three of the channels, to ca. 10 ppb. The fourth channel, with a peat substrate, was invaded by cattails, and data collection was terminated (P. Besrutschko, personal communication).

USACOE S332B Scrape-Down Basin Monitoring

This 160-acre basin was scraped down, and brought into operation in spring, 2000. Pump station 332B delivers water to the basin, with the intent to maximize infiltration and minimize weir overflows to Taylor Slough (ENP). Estimates of the infiltration rate are of the order of 50 - 70 cm/day. There is episodic overflow at a very broad weir on the western boundary. The scrape-down was conducted in the same manner as that for the HID projects; all vegetation and soil was removed down to caprock. Therefore, the system may be regarded as an infiltrating and overflowing PSTA.

Phosphorus concentration data are available for the inflows and internal water at the weir for the basin, and are of acceptable quality (FDEP) for 1/1/01 through 9/30/02 (end of available record). The arithmetic mean of entire period of record inflow values was 11.2 ppb (median 7.0)(2282 samples); the arithmetic mean of values for internal water at the weir was 17.4 ppb (median 9.0)(813 samples). If the data possibly affected by laboratory error are removed from consideration, two year's data remain. For that period, inflow values averaged 6.9 ppb (median 6.0)(1503 samples); the internal water values averaged 16.5 ppb (median 9.0)(439 samples. Outflow weir concentrations were similar to or slightly below inflow concentrations during periods when the basin was thought to be overflowing, although such events were incompletely documented and outflows were not directly measured.

Further understanding of P dynamics and the differences between these project results and those in the C111 natural system data (see below) is needed.

<u>CH2M Hill/USACOE S332D Scrapedown Basin Monitoring</u>

This 800-acre basin, with three compartments, was scraped down, and brought into operation in summer, 2002. Pump station 332D delivers water to the basin, with the intent to maximize infiltration and minimize weir overflows to L31W at the boundary of Taylor Slough (ENP). Estimates of the infiltration rate are of the order of 20 - 40 cm/day. There is episodic overflow at a very broad weir upstream of the southern boundary, which proceeds through a flow-way to the L. The scrape-down of the two primary cells, and part of the flow-way, was conducted in the same manner as that for the HID projects; all vegetation and soil was removed down to caprock. Therefore, the system may be regarded as an infiltrating and overflowing PSTA.

Surface water quality data are available for the very early portion of the startup of this basin. The average inflow concentration was 8.5 ppb, and the average overland outflow averaged 11.7 ppb. This early result, while not encouraging, is undoubtedly within the anticipated startup period.

<u>FIU C111 Scrapedown Patch Studies</u>

The reconfiguration of the spoil mounds along the easterly reach of the C111 canal produced a linear scraped-down (marl over caprock) bench along the canal margin. Canal water flows across this bench into the cutouts, and southerly across relatively pristine Everglades marl prairie, toward ENP. FIU studied the colonization and growth of periphyton on 3.0 cm^2 cores taken from 3x3 m plots on the scraped bench (Thomas et al, 2002,2003). This study focused on the accumulation of phosphorus in the mat, but did not determine water column P mass balances, because of the indeterminate flows that passed over the mat. Mats removed 0.21 – 0.35 $gm/m^2 \bullet yr$, at water concentrations of 9.5 ± 0.5 ppb. These removal rates were based upon harvesting of the mat, at various frequencies, during the wet season. These studies indicate net first-order harvest removal rates of 35 – 60 m/yr, based upon the K/C* model with C* = 4 ppb. Long-term net removal rates would be lower because of the harvesting involved and because the experiments measured the combined phosphorus removal attributed to biomass grow-in and creation of stable residuals.

FAU Mesocosm Velocity Studies

This project investigates the possibility that linear water velocity is a controlling factor in periphyton P removal. Three study platforms have been investigated, using source water at the southern end of STA1W (post-STA):

(1) Small (ca. 1 m^2) periphyton mesocosms (Simmons, 2001; Simmons and Volin, 2000), velocities of 0.1 - 1.0 cm/s
(2) Larger (12 m^2) periphyton mesocosms (Hiaasen et al, 2003; Simmons et al, 2003) , velocities of 0.22 - 2.0 cm/s
(3) Larger (12 m^2) *Ceratophyllum* mesocosms, in progress, velocities of 0.1 - 1.0 cm/s

Periphyton relative growth rates were 20 – 25% faster in the high velocity mesocosms, which was directly correlated with a similar increase in phosphorus uptake. The significance is with respect to large-scale water velocities compared to tank mesocosms and test cells. Typical velocities are: tank mesocosms 0.0001 – 0.001 cm/s; test cells 0.01 – 0.05 cm/s; field scale PSTA 0.07 – 0.22 cm/s; STAs, including full-scale PSTA, 0.1 – 0.5 cm/s; WCAs and ENP 0.5 – 2.0 cm/s.

SFWMD C111 Natural Marsh Studies

SFWMD conducted transect monitoring south of the C111 canal cutouts just north of the easterly extension of ENP. A short easterly transect and a longer westerly transect were monitored. Flows into this system are known as a result of the measurements of flow in the C111 both upstream and downstream of the cutouts. The system is a natural southern Everglades marl prairie, of extreme flatness. Phosphorus concentrations along the transects are below 10 ppb, and display reductions in the flow direction of only 1 – 2 ppb. Calibrations of the DMSTA model have been reported (Walker and Kadlec, 2002).

SFWMD WCA2A Natural Marsh Studies

The interior portions of WCA2A function as an impacted natural system with significant algal components. Flows may be estimated from data on inflows and outflows from the conservation area as a whole. P concentrations form a north-south gradient, ranging down to 10 ppb and below. Data from the southern end of this gradient may be regarded as PSTA on peat – a circumstance not yet replicated in a constructed project. Extensive data collection has occurred along the flow direction, aimed at understanding an appropriate protective P criterion, which also permits calibration of P removal models for this formerly natural and unimpacted area.

Hole-in-the-Donut Restoration Studies

These restoration studies have developed in several phases, starting in 1989 (Resource Management International, Inc., 1998; Everglades Research Group, Inc., 1999, 2000, 2001a, 2001b). These projects collected no quantitative hydrologic or phosphorus removal data. The water depth is dictated by the elevation of the regional water table, via groundwater discharge and recharge processes. There are no phosphorus concentration data.

Issues

Substrate

Natural periphyton assemblages in the Everglades exist on both peat and marl substrates. Because of the calcium requirement for the formation calcareous deposits, it was speculated that calcium-rich substrates would enhance the short and/or long-term existence and performance of periphyton systems. Accordingly, several substrates have been tested in various studies. These have included peat, limerock, shellrock, caprock, sand, and artificial substrates. All except peat involve material handling costs in excess of those for emergent marshes or SAV.

Attempts to establish periphyton systems on peat have not been successful at any scale, presumably in part because of invasion by macrophytes. In contrast, periphyton systems have been successfully established on all other substrates. However, medium to large (test cells, field scale cells, S332B&D) systems have either been on shellrock, limerock or caprock.

Peat Amendments

The potential startup difficulties created by antecedent peat soil phosphorus led to efforts to immobilize this source via soil amendments, with the hope of accelerating the transition to conditions amenable to periphyton dominance. The initial trial was the addition of hydrated lime to Test Cell 13 and mesocosm treatment PP13 in the SFWMD/CH2M Hill study. The anticipated enhancements were not observed. Subsequently, twelve small peat mesocosms were amended with ferric chloride, polyaluminum chloride or calcium hydroxide. No statistically significant benefit was achieved (CH2M Hill, 2003a).

Fate of Removed Phosphorus

The phosphorus removed from the flowing water must appear in ecosystem storages, because there is no other removal mechanism of significance. Two storage locations may be identified, as internal and external to the periphyton communities. Although a mat presumably contains both residuals and active biomass components, there is no known procedure for separating the mat content.

Periphyton P Content

Growth of the algal community represents a major sink for phosphorus. The mat is comprised of both active, living materials as well as inactive residuals. The residuals produced interior to periphyton systems are apparently retained in the mat, for a significant period of time (months and years). Periphyton mats typically contain ca. 200 – 1000 mg/kg. of total P (CH2M Hill, 2003, DeBusk et al, 2003). The lower values are associated with lower water column TP.

Solids concentrations may be combined with information on periphyton biomass standing crop to produce the amount of P contained in the mat. Those standing stocks of periphyton P range from ca. 200 – 700 mgP/m^2. In comparison, the annual areal removal of P from waters flowing through the experimental systems was in the same range, thus indicating that periphyton P storage amounts to about one year's removal.

Residuals

It is clear that an unharvested periphyton mat cannot be the long-term site of storage of removed phosphorus, else mat growth would need to be unbounded. In the natural Everglades systems, there has been formation of calcitic muds (marl) as a result of mat processes. There are data on the character of SAV residuals, from mesocosms up to full-scale in cell 4 of STA1W. However, to date there is only scant information on the physical and chemical character of PSTA residuals. DeBusk et al (2003) harvested residuals from the raceway inlets, and found 71 – 85% of the accreted non-mat material was "permanently" bound (non-labile). Of the permanently bound fraction, 30 – 33% was calcium bound, and the rest, 67 – 70%, was organically bound. These percentages are not far different from those found in upper layers of accretion along the entire length of the eutrophication gradient in WCA2A (Reddy et al, 1991). However, after eight months, less than one percent of the removed P was found in these sediments; the balance was in the mat.

The CH2M Hill destructive sampling study identified the fate of added P in ten PSTA mesocosms, following 23 months of operation (CH2M Hill, 2001e). Within experimental accuracy, all of the removed phosphorus was found in the periphyton, associated macrophytes, and any stable residuals contained in the harvested mat

Dryout

Natural periphyton systems typically undergo a period of desiccation, which may be a major route for moving residuals from the active mat to the non-mat residuals compartment (Thomas et al, 2002). New periphyton growth upon rewetting proceeds from the desiccated precursor material, but does not necessarily re-incorporate all of the old mat residuals. If a period of desiccation is found to be a necessary or desirable feature of an operational PSTA system, additional design features would likely be required.

<u>Depth</u>

Water depth did not have much of an effect on PSTA performance in the CH2M Hill/SFWMD project platforms, which explored 30 and 60 cm operation. However, the DBEL raceways (9 cm) show the best PSTA performance. DMSTA calibrations (Figure 4) indicate that performance of the Wellington cells (15 cm) through October 2002 was well below that of the raceways and was at the lower end of the range of the 30 – 60 cm CH2MHill/SFWMD platforms operated at similarly low flow velocities. Performance reportedly improved in the final few months of operation (November 2002-March 2003), but model calibration data are not yet available. DMSTA calibrations have been done with no depth effect on k-values. In contrast, SAV and emergent data show better performance with increasing depth, and that effect is included in DMSTA calibrations.

The nine cm water depth of the raceways would be impossible to replicate at field scale, because of hydraulic head loss, and the difficulty of wetland bottom leveling to the required tolerance (see section on scale-up). However, if periphyton performance is truly independent of depth, the raceway results may be applicable to deeper cells operated at similar or higher velocities and extensive leveling may not be required. If the concepts of SAV being better at deep conditions, and PSTA being better at shallower conditions were to be confirmed, there are modeling and design consequences. For instance, separate basin bottom elevations would be implied for SAV and PSTA components.

Velocity

Theory indicates that higher water linear velocities should favor improved phosphorus removal, because of improved mass transfer (Kadlec, 1999a). However, high velocities also increase the potential for sloughing and export. The FAU studies show that such increases are of the order of 20 – 25% for a ten-fold increase in water velocity, up to the velocities anticipated in full-scale PSTAs. Velocities in the DBEL raceways were also higher than for CH2M Hill/SFWMD studies, and performance was very good. Conversely, it should be noted here that a high velocity mesocosm in the CH2M Hill/SFWMD project did not display enhanced P removal.

The best performance in the CH2M Hill/SFWMD field scale studies was for the triple-pass system, with the highest linear velocity. However, other factors were also involved, such as better mixing and large leakage, which are considered in DMSTA modeling.

Velocities were also high in the natural system platforms (WCA2A and C111), and in the scrapedown systems (S332B & S332D basins).

Although it is possible to replicate STA concentrations, depths, hydraulic loads, and hydraulic residence times in small-scale experiments, it is generally not possible to replicate velocities while also providing water residence times sufficient to reduce concentration. For example, a flow path length of 2160 meters would be required to provide both a water residence time of 5 days and a typical full-scale velocity of 0.5 cm/sec. With the exception of shallow raceways, one recirculated mesocosm, and one field-scale cell, none of the experimental PSTA platforms operated within average velocity range expected for full-scale STA cells. None approached the velocities > 1 cm/sec expected under peak flow conditions. This is primarily a consequence of the small spatial scale of the platforms.

Startup

There are several measures of ecosystem startup phenomena, including periphyton (mat) development, macrophyte establishment, and P removal performance. These measures have exhibited different startup periods in the various PSTA study platforms.

A constructed PSTA clearly requires some period during which periphyton becomes established and grows into a fully developed (mat) biomass. Concurrently, SAV and emergent vegetation may also develop, either because these were planted or through natural colonization. The time period for such establishment may be small if large quantities of propagules are used, but that is feasible only for small systems such as the DBEL raceways or CH2M Hill/SFWMD mesocosms. These grow-in processes were observed to require many months in test cell and field scale environments. For example, both periphyton and macrophyte cover in the prototype PSTA test cell 8 displayed a steady increase over the first two years of operation. However, model calibration of P removal stabilized after about six months (CH2M Hill, 2003a), at which time biomass and cover development was only about 25% complete.

Grow-in may or may not be accompanied by improvements or decrements in P removal performance. CH2M Hill/SFWMD test cell data indicated fairly stable performance after four to six months, despite the continued changes in community relative abundance among SAV, emergents and periphyton, for a period of two years (Walker and Kadlec, 2003; CH2M Hill, 2003a). However, performance as measured by model calibration has since dropped considerably, over a subsequent 1.5-year period after the CH2MHill study was complete, possibly in response to lower hydraulic loading and/or flow velocity

Similarly, the DBEL raceway performance stabilized after about three months (DeBusk et al, 2003), as did periphyton grow-in. On the other hand, the S332B scrape down basin continues to export phosphorus three years after startup.

At least two major factors are known to be involved in the determination of the length of the startup period: the amount of labile phosphorus that exists in the antecedent substrate, and the P concentrations to which the system is exposed. Some peats, and some calcitic rock materials, have considerable amounts of available P in them. When these are used as substrates, that phosphorus adds to the external loads, and prolongs the period of startup. If in addition the new PSTA is exposed to fairly low P concentrations (perhaps <25 ppb), the biogeochemical cycle is correspondingly slow, and thus the burial of the antecedent substrate P is also slow. Although it seems reasonable that the initial P load will eventually dissipate, that process may extend over years rather than months.

The PSTA Forecast model and the current DMSTA model capture these effects, and quantify the excessive turnover and burial times involved. Figure 1 shows the predicted stabilization period for each vegetation type as a function of concentration. The stabilization period is defined as the time frame required for phosphorus stored in the biomass to come to 90% of its equilibrium value after a change in concentration in a constant flow and constant depth system. As a consequence of decreased growth rates at lower phosphorus concentrations, PSTA and SAV stabilization periods vary from ~0.5 years at 40 ppb to ~ 2 years at 10 ppb. These long stabilization periods may have important consequences for interpretation of short-term experimental data from platforms operating at low concentration levels.

It is possible that some of the experimental platforms used for calibration and testing had not reached steady-state performance levels. Stabilization effects have been considered in DMSTA modeling, by allowing for a startup period of at least 3 months (where possible, longer than a year) before using the data for calibration purposes.

Trends in outflow concentration and measured biomass are other indicators of stabilization that have been considered in selecting calibration datasets and periods.

Hydraulic Efficiency

Inert tracer testing has been conducted on three PSTA mesocosms, three test cells and three field scale cells in the CH2M Hill/SFWMD studies. Mixing was poorest in the mesocosms (N = 1.5 tanks in series (TIS)), better in test cells (N = 4.0 TIS), and best in field scale wetlands (N = 4 - 25 TIS). However, all these platforms were subjected to bottom leveling except the field scale scrape-down (FS3), for which N=4. Compartmentalization is known to aid in improvement of hydraulics, but no multiple-cell PSTA platforms have been investigated. Because of the apparent scale effect on hydraulic efficiency, direct application of plug flow K/C* model calibrations to full-scale designs would tend to under-estimate performance. More complex models, such as DMSTA, are required to account for variations in hydraulic efficiency, seepage, rainfall, and other factors.

Vegetation Management

Establishment

The community structure of the periphyton is partially controlled by the water column P concentration, and probably cannot be controlled by design. Average water depths and dryout frequencies may also influence community structure. The DBEL raceways developed inlet zone communities characterized by green algae such as *Cladaphora* spp., and outlet zone communities characterized by cyanobacterial mats (DeBusk et al, 2003). Phosphorus removal was achieved primarily in the *Cladaphora* zone, with little further removal in the cyanobacterial zone.

It is likely that sparse macrophyte cover is advantageous for a periphyton system, for two reasons. Firstly, submerged stems and leaves provide attachment sites for periphyton, and therefore enhance the standing crop. Secondly, rooted plants provide anchorage for mats, and to some degree prevent physical washout. However, dense emergent stands shade out the algae, and dense submergent stands limit algal growth to the upper strata of the water column, also due to shading. Localized control of the relative abundance and density of submerged and emergent macrophytes is not within the scope of available technology, but areal control can be practiced to some degree. For instance, macrophyte banding, transverse to flow, has been successfully implemented in the field scale PSTA cells.

Some of the macrophyte species, notably some SAV species, respond negatively to low phosphorus, and will therefore be excluded at the low end of the gradient (DeBusk et al, 2003). Conversely, some species, such as *Typha* spp., are competitive over a wide range of P concentrations, and opportunistic in propagation. Natural periphyton systems have presumably undergone self-design in response to natural hydroperiods and natural phosphorus concentrations and gradients. The anthropogenic conditions of STA flows and P concentrations may not foster the same community structures, and consequently some degree of intercession is likely to be necessary.

Macrophyte Control

The preparative technique of scrape down does not suffice to eliminate nuisance emergents. Cattails have invaded the 332B basin, in copious quantities, over its three-year history. Cattails have also become dominant in the outlet scrapedown flow way of the 332D basins. These areas differ from the HID restorations, in which there is not episodic pumped overland flow, and in which cattail invasion has been considerably less.

The small-scale PSTA mesocosm platforms have not been particularly susceptible to macrophyte invasion, possibly because of their conditions of confinement. However, cattail invasion has occurred to some degree in test cell and field scale systems. Both scrape-down and rock covered systems have been affected. The amount of effort needed to control cattail invasion has been moderate, involving both mechanical removal (pulling) and herbiciding. The frequency of these activities has been on the order of once or twice per year.

<u>Leakage</u>

Many PSTA platforms were built in containers (mesocosms) and therefore did not communicate with groundwater. Similarly, PSTA test cells were lined to prevent leakage. In contrast, some of the SFWMD field scale cells, the Wellington PSTAs, and the S332 basins leaked considerable fractions of incoming water, ranging from 40 – 90%. In the cases of SFWMD field scale cells and the Wellington PSTAs, side-by-side orientation resulted in some unknown degree of “cross-talk” between cells. The effect of leakage is some degree of benefit to treatment of the overland flow waters, depending on the location of the leak. Model calibrations to PSTA experimental platforms partially account for seepage effects inferred from overall water budgets. However, these effects have not been quantified, and therefore contribute to the uncertainty band for model calibrations.

Indications are that most of such leakage is through the confining levees rather than vertically downward to the regional water table. As a consequence, larger systems should be less affected, because of their smaller edge to area ratios. Further, levee leakage is controllable to a large degree by proper levee design.

<u>Harvest</u>

The C111 cutout project investigated the efficacy of periphyton mat harvest at very small scale (Thomas et al, 2002, 2003). The amount of P removed varied from 208 – 354 mgP/m2•yr, depending upon frequency of harvest (0 – 6 times per year). There is currently no information available on techniques or equipment that could be used at full scale to implement harvesting.

<u>Pulse Flow</u>

Nearly all PSTA systems except the S332 basins have been run at steady flow or very gently varied flow. In contrast, runoff events that send water to the Everglades are episodic, with peak-to-mean ratios of as much as 20:1. Inter-flow periods are also forecast to be of widely variable duration, and occur on stochastically variable dates. The effects of such pulse flow characteristics are forecast to be a reduction in performance. However, observed impairment has proven to be minimal for emergent STA experimental platforms (SFWMD, 2003); but substantial for highly loaded SAV experimental platforms (DBEL, 2002b).

PSTA test cell 3, essentially identical to the prototype test cell 8, was operated with slowly varied depth and flow. Its performance was distinctly poorer than the selected prototype, with removals about 25% lower than the steady flow system (TC8)(CH2M Hill, 2003a).

Phosphorus Speciation

It is known that the rate of P removal in STA systems in general depends upon the forms of phosphorus in the feed water. Analytical procedures distinguish between soluble reactive P (SRP), dissolved organic P (DOP), and particulate P (PP). Removal and regeneration mechanisms differ across these forms. Particulate P may be physically settled or resuspended, SRP may be metabolized, and DOP may be produced by decomposition or enzymatically converted. Typically, waters reaching a PSTA system would be nearly devoid of SRP, and contain variable amounts of DOP and PP.

There are currently no calibrated periphyton models to describe speciation. The lumped concentration measure of total phosphorus has thus far been exclusively utilized. As a consequence, variations in speciation form part of the variability in model calibrations.

Calcium

Formation of stable calcium phosphate residuals in and below periphyton mats may be an important factor contributing to sustainable phosphorus removal in PSTA cells. It is possible that this process is controlled to some degree by the calcium content and alkalinity of the inflowing waters, which vary considerably in regional source waters (EAA sources being generally more calcitic than Lake Okeechobee, western basins, and urban basins). The effects of variations in inflow calcium content on P removal performance have not been studied. Since nearly all of the experimental platforms have used water directly or indirectly from the EAA, model calibrations may over-estimate P-removal performance in other basins with less calcitic waters.

Scaleup

As the emergent marsh and SAV platforms have been scaled up to the 2000+ acre sizes, new phenomena have been observed. These relate to wind, waves, animal use, topography, high-energy point discharges, flow velocities, emergent vegetation control, and other driving forces that are not captured at mesocosm or test cell scales. Therefore, mid-size systems are a prudent step in evaluation of PSTA. An appropriate increase factor might be 20, thus moving from 5 acres to 100 acres. The remaining step to full scale would then also be of the order of 20, from 100 acres to 2000 acres. Issues of scaleup include availability of source water, the ability to convey the anticipated flow, substrate acquisition and installation, and hydropattern control.

Source Water and Siting

The average flow requirement for a 100-acre project would be of the order of 50,000 m^3/d (ca. 20 cfs), with pulses of ten times that value. The pretreatment requirement would be for ca. 20 ppb water, in order to provide assurance of the survivability of periphyton. The only sources of such water are the STAs. Consequently, siting would of necessity be at the downstream end of an existing or planned STA. Construction in an existing STA would require curtailed use of the STA, and significant dewatering activities. Siting in STA3/4 and/or STA1E, during current construction would avoid those retrofitting difficulties.

Headloss/Conveyance

The feasibility of implementing shallow depths, while maintaining the ability to pass large episodic flows, is limited by hydraulic constraints. The overland flow resistance of periphyton wetlands is not well quantified, although there are ongoing efforts by USGS to provide such quantitative information for natural Everglades systems, for Northeast Shark River Slough (Bolster and Saiers, 2002), and for central WCA2A (Choi et al, 2003). Based upon these overland flow coefficients, and the average STSOC flow conditions, a flow-path terminal PSTA would be depth-controlled by the PSTA wetland and not the outflow structure. Figure 2 provides an example of this constraint, based upon the Bolster and Saiers (2002) information. It serves to illustrate the need for data on overland flow resistance in constructed periphyton systems.

Conveyance of the maximum flow episodes would require large depths, as is the case with other STA communities.

Substrate Considerations

Two categories of substrates have been identified as feasible alternatives: soil removal to caprock, and over-layering of peats with crushed rock or possibly sand. Data acquired from the SFWMD field scale systems suggest that caprock and limerock overlays are about equally promising. Appropriate substrate choices would depend upon availability, cost, and labile phosphorus content.

The potential southern STA3/4 site currently has about 1.25 feet of soil over caprock. The logical option at that site would be the removal of that soil, some portion of which might be usable for the containment levees. The underlying caprock is reportedly uneven, with micro-topographical relief of as much as a foot or two. The acceptability of that unevenness is a further issue.

The potential southwestern STA1E sites have deeper peats. The logical option there would be over-layering of that soil, with one of the several locally available rock materials. The thickness and composition of that overlayer is a further issue.

Hydropattern Control

Water depth, and its response to event driven flows, may be a significant factor in the performance of PSTA (see previous discussion). The vertical positioning of the PSTA cell bottom with respect to upstream pretreatment cells, and with respect to downstream receiving waters, places constraints on ability to achieve the desired depth regimes by gravity flow. It is possible that an outlet pump will be required to avoid such constraints.

Models and Calibration

In order of increasing complexity, the available models for organizing PSTA data and providing a means of performance forecasting are:

1. The STA design model (one parameter: k_1, the "settling rate")
2. The k-C* model (two parameters: k and C*)
3. DMSTA (three parameters: k and C_0 = C* plus a storage capacity C_1)
4. PSTA Forecast Model (seven parameters)
5. HydroQual/SFWMD Wetland Water Quality Model (209 parameters)

Each of these has played some role in the PSTA evaluation process.

The STA Design Model

For a considerable period, the basis for STA design was a model that presumes steady state, plug flow through the STA, and first order removal (Walker, 1995). The model was calibrated to a 26-year period of record from a ~25,000 acre region of WCA-2A and successfully applied in designing emergent macrophyte STAs to achieve average outflow concentrations of 50 ppb. The model is constrained to be applied to long-term average wetland performance, however. Flow dynamics (pulsing) must be considered in extrapolating small-scale experimental data on other vegetation communities collected under relatively steady flows to full-scale designs for achieving lower outflow concentrations under dynamic flow conditions. Attempts to apply it to a dynamic time series of Everglades Agricultural Area (EAA) flows and concentrations were not successful. Further, it contained no built-in constraint on the lower limit of effluent P concentrations. Because this model may be calibrated with great ease to point information on HLR, TP_i and TP_o, it has been extensively exercised, particularly in the CH2M Hill project reports. However, this model is known to be overly sensitive to hydraulic load variations (Kadlec and Knight, 1996; Kadlec, 1999), and therefore is of use only in interpolations on calibration sets.

The k-C* Model

A modified version of the steady state, first order, areal model, containing a lower limit on the achievable P concentration, was proposed by Kadlec and Knight (1996). That modification was subsequently adopted for design of STA3/4 (B&M, 1999). Because this model may be calibrated with relative ease, using the Excel™ Solver routine, to sets of information on HLR, TP_i and TP_o, it has been extensively exercised, particularly in the CH2M Hill project reports. It applies to long-term average wetland performance. While useful for comparing research results across platforms, the model has limited applicability to full-scale designs because it does not account for differences between experimental platforms and full-scale STAs with respect to flow and depth dynamics, hydraulic efficiencies, seepage, and other factors. It is, however, a dangerous model for extrapolations (Kadlec, 1999).

DMSTA

A major constraint on these early models was their inability to deal with the actual, pulse driven sequences of runoff that have historically occurred in both agricultural and urban basins in south Florida. Therefore, a model was needed to deal with those dynamic conditions. The goal of further modeling work was to develop and calibrate the simplest, highly aggregated model that could mimic the major features of event driven behavior of treatment wetlands in the runoff environment. There are also design needs for consideration of variations in seepage, hydraulic efficiency, atmospheric deposition, and simulation of treatment areas consisting of multiple cells in series and/or parallel with different vegetation communities.

A simple extension of the STA and k-C* design models is the addition of P storage in the biota of the wetland ecosystem. During periods of high phosphorus availability, that storage will increase, and in periods of P-famine, the storage will decrease. At all times, the ecosystem produces the residual sediments containing unavailable P, that characterized the WCA2A calibration data of the STA design model (Walker, 1995). This extension has been named the Dynamic STA Design Model (DMSTA). DMSTA is an unsteady state model that removes phosphorus to permanent burial in proportion to the amount of labile P in storage (Walker and Kadlec, 2002). There is an implied labile pool of phosphorus, in addition to the permanently buried P. That labile pool is presumed to be drawn down by a return flux, or bleed-back. Temporal variations in the water budget (flows, rainfall, evapotranspiration, seepage, storage) are also simulated. Additionally, DMSTA has a bookkeeping structure that can account for seepage losses, different internal arrangements of cells, different internal hydraulics and mixing, as well as potential depth dependences.

The parent rate constants calibrated to this event driven model are intrinsically different from those of the other models. However, those parent constants may be rearranged to match k and C* in the earlier model, with an additional storage parameter (C_1) (Walker and Kadlec, 2002).

DMSTA represents the simplest option for PSTA forecasting. Initial calibrations to emergent, PSTA, and SAV communities were developed in early 2002 using data from one prototype platform in each category, selected based upon platform size and dataset duration. A generalized calibration for non-emergent vegetation (NEWS, non-emergent wetland system) simulates the transition from SAV-dominated to periphyton-dominated communities expected to occur along of gradient of decreasing phosphorus concentrations. The prototype calibrations have been tested against other datasets in each category. Ongoing work involves modifications to the model structure and calibration to data from new experimental platforms and full-scale STA cells. Potential structural enhancements include addition of phosphorus speciation and a soil compartment.

Net removal rates predicted by initial DMSTA calibrations to each vegetation type are shown as function of concentration and water depth in Figure 3. Results vary with depth because the emergent and SAV models are depth-dependent, whereas the PSTA model is not. This distinction is related to fact that SAV and emergent biomass is distributed throughout the water column, whereas PSTA communities generally develop as floating or bottom mats. At depths >= 60 cm, PSTA has the highest removal rate at P concentrations <15 ppb and SAV, at concentrations >15 ppb. As water depths decrease from 60 cm to 30 cm, the transition point increases from 15 to 35 ppb. While PSTA is clearly superior at shallow depths, there is some uncertainty as to whether full-scale cells can be operated in this depth range at high flows because of hydraulic constraints. The test-cell PSTA calibration indicates that net removal rates would range from 0.50 - 0.15 g/m^2-yr in a PSTA cell operating at steady flows in a concentration range of 25 to 10 ppb.

DMSTA Update (2003)

The PSTA calibrations used in the Brown and Caldwell BSFS covered operational results through March 2001. Since that time, there have been significant additional PSTA data acquired, both from old existing platforms (test cells), and from new facilities including the SFWMD Field-Scale, Wellington, and USACOE C111 projects. Other data from the USACOE STA1E (FIU) project are not yet available. The additional data are being incorporated into the larger DMSTA database (Walker and Kadlec 2003). A detailed presentation of the updated PSTA calibrations is given at http://www.wwwalker.net/dmsta. Current results are summarized below.

Recent DMSTA calibration results for PSTA platforms are summarized in Figure 4. New data from field-scale (5-acre) PSTA cells studied by CH2MHill for SFWMD are included. These are important additions because they are about 10-fold larger than the test cells used to develop the initial PSTA calibration. Larger platforms are desirable for a variety of reasons, as discussed above.

An estimate of the first-order net removal rate at steady state (K (C* = 4), m/yr) is shown for each platform, based upon least-squares fits of log-transformed outflow concentration data collected after startup periods ranging from 3 to more than 12 months. Higher K values reflect higher net removal rates per unit area at a given concentration. The prototype PSTA calibration was previously based upon data collected by CH2MHill at the ENR Project South Test Cell 8, which had a K (C* = 4) value of 24 m/yr and achieved an average outflow concentration of 12 ppb for the period 2/99 – 3/01. Monitoring of TC8 has continued at a lower hydraulic loading rate. For the period 1/02 – 11/02 the hydraulic load was reduced from 6 to 3 cm/day, TC8 achieved 15 ppb, and the value of K (C* = 4) was 8 m/yr.

K (C* = 4) values for the other PSTA platforms range from ~10 m/yr (shellrock TC3) to ~40 m/yr (raceways, sand, aquamat). Variations in K across platforms reflect any residual effects of startup, other experimental artifacts, other factors not considered directly in the model, and random sampling/analytical errors. These contribute to uncertainty in predicting the performance of full-scale treatment areas. Despite variations in the optimal K values, the model explains 84% of the outflow concentration variance in other PSTA platforms when run using the prototype TC2 calibration (K = 24 m/yr).

Experimental platforms with flow velocities exceeding 0.1 cm/sec (raceways and field-scale PSTA) had K values in the range of 25 – 45 m/yr (Figure 5), as compared with the test cell PSTA prototype (K = 24 m/yr, velocity = 0.02 cm/sec). K values for the high velocity platforms overlap with the 35-60 m/yr range estimated above based upon FIU harvested patch studies in the C111 region. Lines in Figure 5 show velocities that would occur in platforms designed to reduce concentrations from 25 to 10 ppb at a water depth of 30 cm for various length/width ratios. Some design conditions are excluded because of headloss considerations. These calculations are based upon steady-state solution of DMSTA with K = 30 m/yr (calibrated to field-scale cells) and other model parameters listed in Figure 5. The hydraulic load required to produce a 10 ppb outflow concentration under these conditions is 5 cm/day (independent of area). For example, a 100-acre (~405,000 m^2) cell expected to reduce concentration from 25 ppb to 10 ppb (based upon the field-scale calibration) would have velocities ranging from 0.13 to 0.37 cm/sec for aspect ratios (L/W) ranging from 1 to 8 and for depth of 30 cm.

The fact that no PSTA project to date has shown post-startup, sustained outlet concentrations of 10 ppb or less may be related to the fact that virtually none of the research platforms operated under both hydraulic loading and velocity regimes that would be representative of full-scale treatment cells designed to achieve 10 ppb (Figure 6). Most platforms operated at average hydraulic loads well above those likely to occur in a full-scale cell and above those likely to achieve 10 ppb with typical inflow concentrations of 20-30 ppb, based upon existing model calibrations and K values in the range of 10 to 40 m/yr. Platforms operating at lower hydraulic loads have generally had flow velocities only 1-10% of those expected for full-scale cells and been more susceptible to experimental artifacts related to phosphorus releases from initial substrates and short duration.

New field-scale (5-acre) PSTA results for limerock and caprock substrates indicate K values of 25-35 m/yr (Figure 4), based upon the most recent 8 months of data (after startup and dryout). This improved performance relative to the test cell prototype (K = 24 m/yr) may be due to the effects of higher velocity, which would suggest use of a higher K for full-scale systems. Of the existing PSTA platforms, PSTA-FSC2 (K = 35 m/yr) comes closest to replicating a full-scale system with respect to size and velocity because if its high L/W ratio. This facility was operated at a hydraulic load of 15 cm/day, which would be typical of a full-scale treatment cell in an STA operated at an average hydraulic load of 2.5 cm/day and divided into 6 cells in series. Testing on a larger spatial scale is needed to provide hydraulic load and velocity regimes that are more representative of full-scale STAs and reduce the risks associated with extrapolating the model calibrations.

<u>PSTA Forecast Model</u>

This dynamic model is similar in structure to DMSTA (CH2M Hill, 2003a). It uses a different uptake calculation, based on biomass growth rate. It adds a dependence on solar radiation, and a specification of “bleed-back” of antecedent soil P. It presumes a hydraulic pattern of one well-mixed unit. This model was used in support of the PSTA STSOC forecast calculations (Ch2M Hill, 2001g, 2003a). DMSTA and the PSTA Forecast Model have been cross-compared, and found to yield similar results in situations where both may be used. The additional complexities of the PSTA Forecast Model, together with its inherent restrictions, give it no advantage over DMSTA.

<u>Wetland Water Quality Model</u>

HydroQual, working in cooperation with SFWMD, developed a water quality-based model for STAs (HydroQual, 1998). The Wetland Water Quality Model (WWQM) relies upon a very detailed hydrodynamic component that computes a two-dimensional dynamic depth and flow net. The water chemistry and biology are also very complex, involving 72 state variables. As a result, the combination is exceedingly computationally cumbersome, and requires inordinate amounts of workstation time to simulate just a relatively brief real time period (ca. 2 workstation-days for a one year simulation). Most of the over 200 coefficients must be estimated, because of insufficient calibration data.

As evidence of the apparent confusion concerning SAV, PASTA and NEWS, HydroQual (1998) considered their calibration to ENR Cell 4, generally regarded as the premiere SAV prototype, to be a PSTA calibration.

SFWMD discontinued utilization of the WWQM a few years ago, but it is the current model of choice by USACOE in connection with STA1E.

Historical Full-Scale Area and Cost Estimates

As PSTA research achieved long-term operating data from the small-scale platforms (mesocosms and test cells) it became possible to formulate conceptual full-scale designs, and to evaluate area requirements and costs for such potential projects. Three major efforts have produced considerable perspective on these two challenges for PSTA implementation. Two other analyses have been conducted for purposes of this summary, and results are given in the next section.

PSTA in Accelerated Implementation Planning (1999)

A comprehensive examination of alternatives for improving the performance of STAs was summarized in the document: Accelerating Implementation of Phase 2 of the Everglades Forever Act (Department of Environmental Protection, 1999). A conceptual design and cost estimate for implementing PSTA in STA3/4 was performed, as part of this broader planning effort, by Burns and McDonnell (1999a, 1999b). The calculations were based upon the k-C* Model presented in Kadlec and Knight (1996). The analysis presumed that 6,000 acres of the total of 16,660 acres of STA3/4 would be converted to PSTA, by removing 1.25 feet of soil (measured), down to caprock. The target outflow concentration was assumed to be 10 ppb. The required performance of that 6,000 acres was then determined to be represented by a settling rate of 63.5 m/yr (C* = 3ppb). The cost of the modifications was estimated to be $76.6 million for STA works, plus $49 million for an additional pump station (required for the extra 1.25 ft lift), for a total capital cost of about $125 million. The unit capital cost of this PSTA alternative was therefore $21,000 per acre. The required time, following conceptual design, to achieve final design and complete the construction, was estimated to be three years. An additional period of startup and stabilization would be required, independently estimated to be not less than one year.

Supplemental Technology Standard of Comparison (2001)

The evaluation of the various candidate technologies for achieving Phase 2 Everglades protection was based in large part upon conceptual designs and costs established from research results, under a Supplemental Technology Standard of Comparison (STSOC) protocol (Peer Consultants P.C./Brown and Caldwell, 1998 & 1999). The common basis was a synthetic data set scaled to the flows and concentrations expected from STA2, which represents approximately 15% of the flow, and 16% of the area, of the total of all the STAs. The SFWMD PSTA project, conducted by CH2M Hill, exercised this STSOC conceptual design, with the goal of reducing phosphorus from 50 ppb to 12 ppb (the lowest demonstrated outflow concentration). The calculations were based upon the PSTA Forecast Model developed by CH2M Hill (CH2M Hill, 2001d, 2003a), and calibrated to 24 months of data from half-acre test cells. A two-foot thick cover of shellrock was selected, based upon field constructability data collected by SFWMD during the construction of the FIU limerock pads. The mean water depth was 1.14 ft (35 cm). The hydraulic loading rate to the proposed PSTA cells was 0.86 cm/d, with event hydraulic loadings of twelve times that mean loading. During the 31 period of record simulation, dry conditions existed only 4.3% of the time.

The required area was 15,300 additional acres, at an additional capital cost of $844 million (50 year present worth of $889 million). However, this total included two feet of limerock addition. If that were reduced to one foot, the 50-year present worth was reduced to $561 million. The unit capital cost of this later alternative was PSTA was therefore $34,000 per acre. The estimated time to implement the project was six years.

PSTA in the Basin Specific Feasibility Studies (2002)

The Basin Specific Feasibility Studies (BSFS) were carried out by SFWMD with assistance from their Contractors, Brown and Caldwell (B&C) and Burns and McDonnell (B&M) during 2001-2002. Through a public review process, the best candidate technologies were selected for detailed examination. Forty-one alternatives were examined for the twelve tributary basins to the Everglades Protection Area (EPA)(Brown and Caldwell, 2002; Burns & McDonnell, 2002). One of those proposed alternatives, for the L28 Basin, contained a 50% periphyton component to a 1088-acre STA. The calculations were based upon the DMSTA model developed by Walker and Kadlec (2002), and calibrated to 1.3 – 6.0 years of data from 27 different PSTA platforms (mesocosms, test cells, natural field systems).

Soil preparation was presumed to be an on-site rearrangement of the top six inches of soil, and the S140 pump station was assumed to be available as the outflow pump. The hydraulic loading rate to the combined two proposed PSTA cells was 12.5 cm/d, with event hydraulic loadings of eight times that mean loading. The PSTA cells were predicted to reduce the P concentration from 14 ppb to 12 ppb. Water depth in the PSTA cells was assumed to be 69 cm (2.3 ft). During the 31 period of record simulation, predicted water depths were less than 15 cm (6 inches) only 1.3% of the time. This alternative had a 50-year present worth of $43 million ($37 million capital), and was estimated to require 8.5 years to stable operation. The unit capital cost of this PSTA alternative was therefore $34,000 per acre.

Updated Full-Scale Area and Cost Estimates

Two procedures have been used to forecast land areas needed to reach 10 ppb in a full-scale prototype system. The first and simpler approach is to examine the concentration – load response of the available data. The second and more involved approach is to use DMSTA. While the former has the advantage of simplicity, the latter is thought to account for a wider variety of factors that contribute to variations across platforms, such as hydraulic efficiency, flow and depth dynamics, seepage, dataset duration, and atmospheric deposition. The basis for these is the STSOC dataset (Peer Consultants P.C./Brown and Caldwell, 1998), which was constructed to match forecasts for flows and loads reaching STA2, subsequently pretreated to 50 ppb in STA2. The average flow for that simulated STA2 dataset is 140 mgd (531,000 m^3/d).

Load Response Forecast

The phosphorus concentration produced in an STA depends upon three primary variables (area, water flow and inlet concentration), as well as numerous secondary variables (vegetation type, internal hydraulics, depth, event patterns and others). It is presumed that the area effect may be combined with flow as the hydraulic loading rate (flow per unit area), since two side-by-side STAs with double the flow should produce the same result as one STA. Therefore, two primary variables are often considered: hydraulic loading rate (HLR) and inlet concentration (TP_i). Both mass removal models (e.g., the k-C* model) and performance regressions are based upon these two variables (Kadlec and Knight, 1996).

An equivalent approach is to rearrange the primary variables, without loss of generality, by using phosphorus loading rate (PLR = HLR • TP_i) and concentration (TP_i). Thus it is expected that the phosphorus concentration produced (TP_o) will depend upon PLR and TP_i. A graphical display has often been adopted in the literature (Kadlec and Knight, 1996; USEPA, 2000). In the broad context, multiple datasets are represented by trends that show decreasing TP_o with decreasing PLR, with a different trend line associated with each inlet concentration (Figure 7).

The load response data for PSTA and SAV span a much narrower range of inlet concentrations, but display the same trend of increasing TP_o with increasing PLR (Figure 8). Scatter is presumably due to secondary variable differences, such as the relative proportions of SAV, PSTA and sparse emergents, hydraulic efficiencies, and other factors. It is seen that at low phosphorus loadings, the outlet concentration trend crosses the 10 ppb horizon. However, the lowest points are for the natural marsh. Nonetheless, the loading needed to achieve 10 ppb is located approximately at PLR = 0.18 – 0.35 gm/m2•yr.

This loading range may then be used to calculate the required areas for various pretreatment levels (upstream of PSTA). The allowable HLR is derived from the inlet TP_i and the PLR; then the area is derived from the HLR and the incoming flow. The pretreatment levels are presumed to be in the range of 20 – 50 ppb, so as not to jeopardize the existence of PSTA. The resultant required additional acreages are from 2,700 to 13,300 acres (Table 4).

If the approximate unit cost for PSTA is taken as $30,000 per acre (mean of the three previous analyses), Table 4 shows that the incremental capital cost for the STSOC prototype PSTA would range from $80 million to $160 million for a 20 ppb pretreatment. If pretreatment is to only 50 ppb, capital costs for the STSOC prototype PSTA would range from $205 million to $400 million. As discussed below, DMSTA indicates that costs for hydraulically optimized cells would be at the lower ends of these ranges.

It is noted that these estimates of allowable inlet load are more optimistic than those of the CH2M Hill STSOC and more pessimistic than those of the Brown and Caldwell BSFS for the L28 basin.

The estimates are reasonably consistent with steady-state solutions of DMSTA. Using the PSTA calibration (K = 24 m/yr), DMSTA predicts that an inlet loading rate of 0.35 gm/m2•yr would produce an outflow concentration of 10 ppb in a treatment cell with 3 tanks in series (favorable hydraulics), steady flows, and an inflow concentration of 25 ppb. With 1 TIS (poor hydraulics), the allowable inlet load decreases to 0.21 gm/m2•yr (Figure 8). Results are insensitive to inflow concentration ranging from 20 to 50 ppb. Corresponding results using the updated PSTA calibration (field-scale cells, K = 30 m/yr) are 0.44 and 0.27 gm/m2•yr for TIS = 3 and 1, respectively. These results are reasonably consistent with the direct loading correlations in Figure 8, given that most of the experimental platforms represented in Figure 8 had low hydraulic efficiencies (only 1-2 TIS). Sensitivity to TIS demonstrates the importance of optimizing the hydraulic efficiency of treatment cells to achieve a 10 ppb outlet concentration with minimum surface area. Measures such as internal levels, limerock berms, transverse deep zones, and transverse emergent macrophyte bands have been suggested for this purpose, although their effects on PSTA performance have not been experimentally demonstrated. Results also demonstrate the danger of extrapolating areal removal rates measured in small-scale platforms with poor hydraulics to full-scale cells designed to provide good hydraulics.

DMSTA Design and Cost Implications

Potential design implications of alternative PSTA calibrations can be explored by comparing them with the initial calibrations used to project the performance of optimized designs for the STAs developed under SFWMD' s Basin-Specific Feasibility Studies (BSFS). Figure 9 shows predicted outflow concentrations for a hypothetical STA cell with an inflow concentration of 20 ppb using alternative DMSTA calibrations.

The range of PSTA calibrations is reflected by PSTA (calibrated to ENRP South Test Cell 8, K = 24 m/yr) and PSTA_H (calibrated to DBEL raceways, the best-performing PSTA platforms, K = 40 m/yr). The raceway platforms (9 cm deep) are used here only to reflect the extreme upper bound of performance based upon existing data (not as a central estimate). Existing datasets do not provide a basis for determining whether this level of performance can be sustained at depths and velocities representative of full-scale cells. NEWS_H is an alternative version of NEWS that links the SAV and PSTA_H calibrations. STA_H is calibrated to the best-performing full-scale platforms (other then ENRP Cell 4), including STA-6, STA-2, and the center of WCA-2A.

The SAV_C4 calibration still gives the most optimistic forecast, but only by extrapolating well below the performance range of the calibration dataset (ENRP Cell 4, outflow = 22 ppb on average, and 14 ppb in its optimal performance period). This calibration also under-predicts outflow concentrations in other SAV platforms with outflow concentrations < 20 ppb. Generally, results for the updated calibrations (PSTA_H, NEWS_H, STA_H) are similar fall and between the results for the SAV_C4 and NEWS calibrations used in the BSFS..

One possible design concept is to sequence emergent (EAV), SAV, and PSTA cells. Table 5 lists simulation results for this concept applied to STA-2 (total area = 6,300 acres). In the interest of simplicity, this illustration does not explore the known ranges of emergent marshland SAV behavior. This analysis assumes that the ENRP-Cell4 community can be replicated in the submergent cell and is effective down to a flow-weighted mean concentration of ~20 ppb and ignores data from other SAV platforms. Areas would be higher if other SAV platforms are considered.

Results for the PSTA cell are shown using alternative platforms for calibration. If the 0.5-acre ENRP South Test Cell 8 platform is used, this EAV-SAV-PSTA combination example requires expansion of the STA2 footprint by 700 acres of PSTA, and conversion of 2300 existing STA2 acres to PSTA. The cost associated with constructing the additional acres is assumed to be $16,000 per acre, and the PSTA unit cost is assumed to be $30,000. Therefore, the total capital cost is estimated as $101 million (700x46,000 + 2300x30,000). If the 5-acre Field-Scale cells on limerock or caprock platform are used for design, no additional land would be required, approximately 2,100 acres of PSTA would be constructed within the existing footprint, and the estimated total capital cost would be $63 million. The sensitivity of the PSTA area (2,100 – 3,000 acres) and cost ($63 – $101 million) to the assumed calibration platform further demonstrates the need for additional data from larger-scale platforms to provide a sufficient basis for model calibration and development of full-scale PSTA designs. Costs are also sensitive to the assumed substrate and depth of application, both of which are candidates for additional investigation and optimization.

Closure

At considerable effort and expense, a very large body of knowledge has been assembled concerning periphyton-rich, non-emergent wetland treatment systems. The observed performance in phosphorus removal has been quite variable, extending from the rates in emergent macrophyte systems up to the low end of rates for SAV systems. The minimum achievable P concentration has not been actively sought, but indications are that it might be lower than the 10 ppb criterion, despite the fact that 10 ppb has not been sustainably demonstrated.

Periphyton systems, in common with other wetland treatment systems for Everglades protection, are slow to startup, and slow to respond to changes. Further work should recognize this important feature, and develop study schedules that acknowledge it. The slow response is exacerbated by antecedent labile phosphorus in the soils or substrates.

There are many aspects of periphyton systems that have not been definitively resolved. Some, such as substrate, loading and depth, have been investigated, but not fully resolved. Others, such as pulse flow and flow resistance, have not been adequately investigated. Consideration of the remaining areas of uncertainty strongly indicates the need for a demonstration scale project. Scale-up from tanks and small channels appears very risky, because of the perceived effects operating in a landscape setting.

If the prognosis of periphyton systems producing 10 ppb effluent is correct, the current forecasts are for considerable expense, in money and quite possibly in additional land, to implement the systems. While it may be hoped that further investigation will discover new economies, the currently anticipated costs dictate the need to focus on finding them.

Tables

Table 1. Investment in PSTA research work related to flow-through phosphorus removal.

	Sponsors	Investigators	Duration (years)	Cost*
EAA	SFWMD FDEP ENP	CH2M Hill SFWMD	5	$4,500,000
EAA	SFWMD EPD	DBEL	3	$200,000
STA2**	SFWMD	FIU SFWMD	1	$1,000,000
Wellington	Wellington FDEP	CH2M Hill FIU	2	$700,000
STA1E	USACOE	FIU	3	$2,000,000
S332B**	USACOE	USACOE	1	$300,000
S332D**	USACOE	CH2M Hill USACOE	3	$2,000,000
C111	ENP USACOE	FIU	2	$600,000
Micro Channels	ENP	FAU	2	$200,000
Total				$11,500,000

* Approximate. Includes estimates of sponsor and reviewer time.

** Exclusive of construction cost.

Table 2. SFWMD + CH2M Hill Project Platforms.

PHASE	SITE_TREATMENT	SITE	TREATMENT	CELL	SCALE	SIZE	DEPTH (cm)	Substrate	Biomass	OTHER
1	STC-3	STC	3	3	Test Cell	28 x 80 m	0-60	shellrock	yes	Ź
2	STC-6	STC	6	3	Test Cell	28 x 80 m	0-60	shellrock	yes	Ź
1	STC-2	STC	2	8	Test Cell	28 x 80 m	60	shellrock	yes	Ź
2	STC-5	STC	5	8	Test Cell	28 x 80 m	60	shellrock	yes	Ź
1	STC-1	STC	1	13	Test Cell	28 x 80 m	60	peat	yes	Ź
1	STC-1b	STC	1b	13b	Test Cell	28 x 80 m	60	peat	yes	1/10/00 - 3/15/00
2	STC-4	STC	4	13	Test Cell	28 x 80 m	60	peat + CaOH	yes	Ź
1, 2	PP-7	PORTA	7	19	Porta-PSTA	1 x 6 m	P1: 60 , P2: 30	sand	yes	Ź
1	PP-8	PORTA	8	20	Porta-PSTA	1 x 6 m	30	sand	yes	Ź
1	PP-8b	PORTA	8b	20b	Porta-PSTA	1 x 6 m	30	sand	yes	1/10/00 - 3/15/00
2	PP-17	PORTA	17	20	Porta-PSTA	1 x 6 m	30	acid washed sand	yes	Ź
1	PP-9	PORTA	9	21	Porta-PSTA	1 x 6 m	60	peat	no	aquashade
2	PP-18	PORTA	18	21	Porta-PSTA	1 x 6 m	30	none	no	Ź
1	PP-10	PORTA	10	22	Porta-PSTA	1 x 6 m	60	shellrock	no	aquashade
2	PP-19	PORTA	19	22	Porta-PSTA	1 x 6 m	30	none	no	aquamat
1, 2	PP-11	PORTA	11	23	Porta-PSTA	1 x 6 m	30	shellrock	yes	Ź
1, 2	PP-12	PORTA	12	24	Porta-PSTA	1 x 6 m	30	peat	yes	Ź
1	PP-6	PORTA	6	1, 6, 15	Porta-PSTA	1 x 6 m	0-60	shellrock	yes	variable
2	PP-16	PORTA	16	1, 6, 15	Porta-PSTA	1 x 6 m	0-30	shellrock	yes	variable
1, 2	PP-3	PORTA	3	12, 14, 17	Porta-PSTA	1 x 6 m	30	peat	yes	Ź
1	PP-5	PORTA	5	2, 13, 16	Porta-PSTA	1 x 6 m	60	shellrock	yes	Ź
2	PP-15	PORTA	15	2, 13, 16	Porta-PSTA	1 x 6 m	30	shellrock	yes	recirculated
1, 2	PP-4	PORTA	4	3, 5, 10	Porta-PSTA	1 x 6 m	30	shellrock	yes	Ź
1	PP-2	PORTA	2	4, 7, 8	Porta-PSTA	1 x 6 m	60	shellrock	yes	Ź
1	PP-2b	PORTA	2b	4b, 7b, 8b	Porta-PSTA	1 x 6 m	60	shellrock	yes	1/10/00 - 3/15/00
2	PP-14	PORTA	14	4, 7, 8	Porta-PSTA	1 x 6 m	30	lime-rock	yes	Ź
1	PP-1	PORTA	1	9, 11, 18	Porta-PSTA	1 x 6 m	60	peat	yes	Ź
2	PP-13	PORTA	13	9, 11, 18	Porta-PSTA	1 x 6 m	30	peat + CaOH	yes	Ź
1	PP-1b	PORTA	1b	9b, 11b, 18b	Porta-PSTA	1 x 6 m	60	peat	yes	1/10/00 - 3/15/00
3	1	FS		1	Field Scale	61 x 317 m	30	limerock	yes	
3	2	FS		2	Field Scale	61 x 317 m	30	limerock	yes	
3	3	FS		3	Field Scale	61 x 317 m	30	limerock	yes	
3	4	FS		4	Field Scale	21 x 951 m	30	peat	yes	

Phase 1: 2/1/99 - 3/31/00
Phase 2: 4/1/00 - 3/31/01
Phase 3: 8/1/01 - 9/30/02

Table 3. Performance of the CH2M Hill PSTA Platforms.

Platform	Treatment	HLR	TP In	TP Out
		cm/d	ppb	ppb
FS	1	8.5	27.2	18.2
FS	2	10.7	26.6	15.3
FS	3	8.1	26.1	16.1
PP	2	7.6	19.1	13.0
PP	4	8.3	28.2	14.6
PP	6	4.6	24.1	14.5
PP	7	8.2	27.8	15.2
PP	8	7.7	19.3	16.1
PP	11	8.6	28.1	17.8
PP	14	8.6	23.1	14.5
PP	15	7.8	23.1	14.6
PP	17	7.6	22.9	11.4
STC	2	4.1	25.1	13.3
STC	5	5.5	22.1	11.7
PP	16	16.8	23.1	17.0
PP	5	17.9	25.0	16.4
STC	3	3.5	25.1	17.1
STC	6	6.9	23.7	18.8
min		3.5	19.1	11.4
max		17.9	28.2	18.8
mean		8.4	24.4	15.3

Table 4. Additional area (acres) required to reach 10 ppb for different inlet concentrations, and for low and high allowable phosphorus loading limits. Those limits are estimated as the range of intercepts at 10 ppb from the data trends in Figure 8.

TP In ppb	TP Load 0.18 gm/m2•yr	TP Load 0.35 gm/m2•yr
50	13,298	6,839
40	10,638	5,471
30	7,979	4,103
20	5,319	2,736

Table 5. Three-stage STA analysis, using DMSTA applied to 31-year hydrologic time series for STA-2 (future conditions, with CERP). A first unit emergent marsh is presumed to reduce TP to a geometric mean of 78 ppb. A second unit SAV is presumed to further reduce TP to a geometric mean of 14 ppb. A third and final unit PSTA is presumed to further reduce TP to a geometric mean of 10 ppb.

Vegetation	Emergent	Submergent	Periphyton	Total
Calibrations	Boney Marsh	ENRP Cell4 Entire Pd.	ENRP STC-8 / Field-Scale Cell 2	-
C0 (ppb)	4	4	4	
K (m/yr)	4	68	23 – 30	
Area (1000 acres)	1.0	3.0	3.0 – 2.1	7.0 – 6.1
Flow-Wtd P (ppb)	82	21	15	15
Geo Mean (ppb)	78	14	10	10

Figures

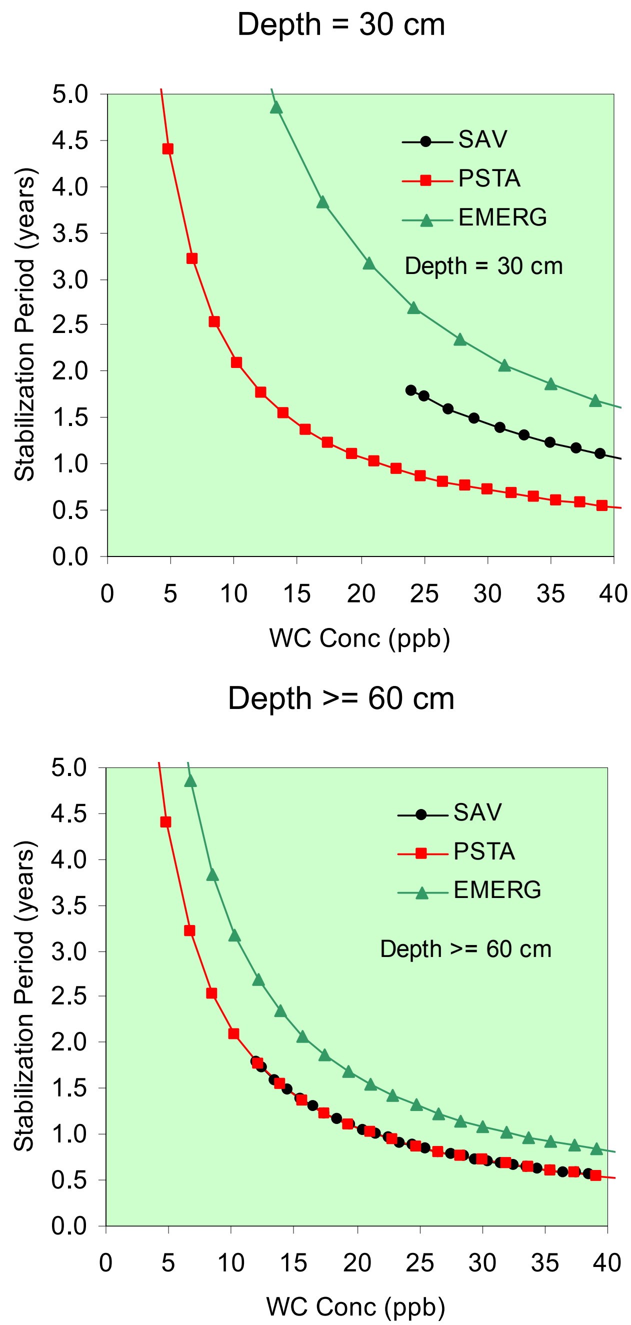


Figure 1. Phosphorus removal stabilization times for each vegetation type. Derived from steady-state solutions of DMSTA for water depths 30 and 60 cm using each calibration. Stabilization time = time for phosphorus stored in biomass to reach 90% of its equilibrium value in a steady-flow and constant depth system.

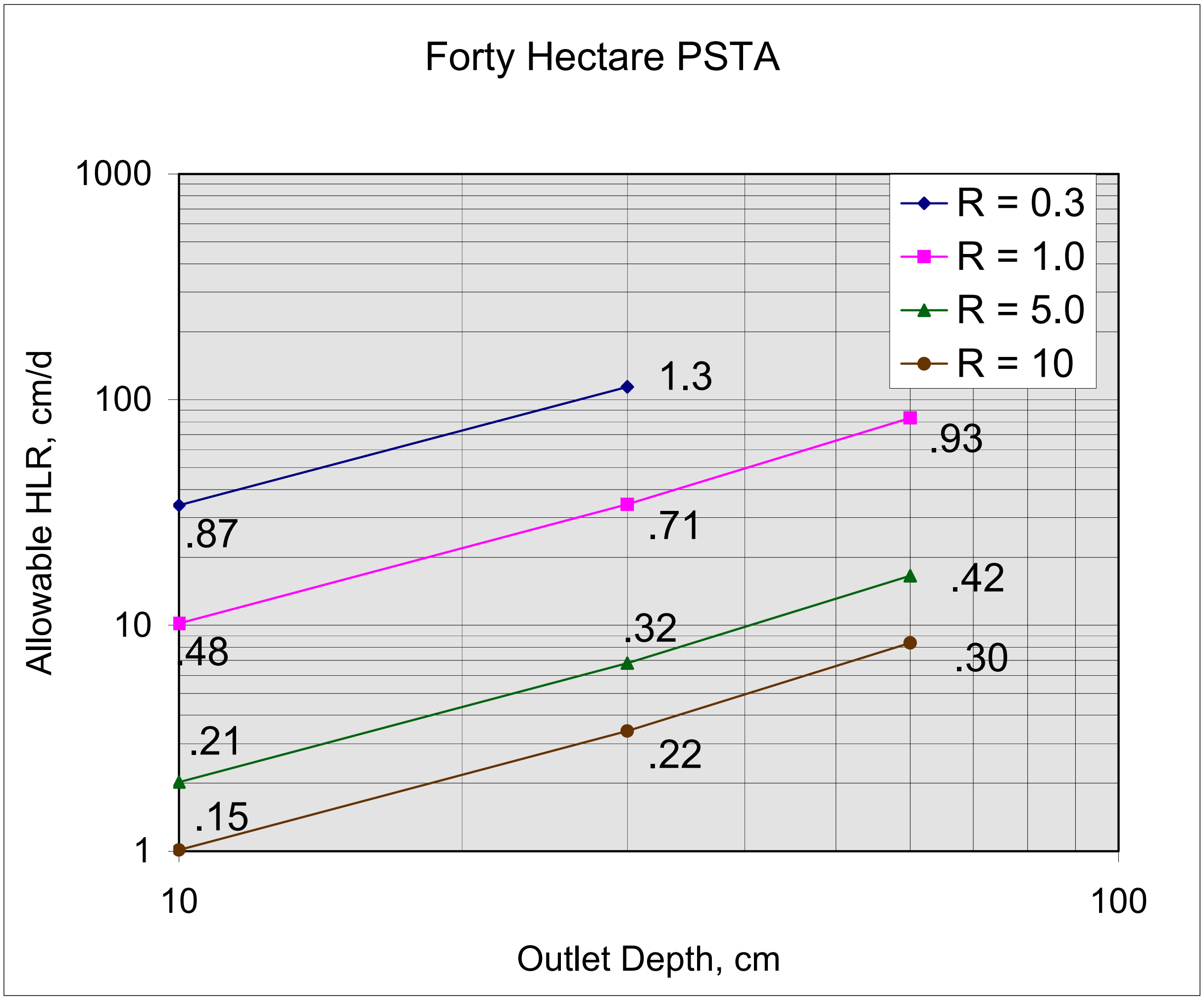


Figure 2. Hydraulic constraints on a 40-hectare (100 acre) PSTA with a flat bottom. Overland flow resistance is computed using the Bolster and Saiers (2002) calibration for NE Shark River Slough. The constraint is a 10 cm maximum allowable headloss for conditions of long-term average flow. Outlet depths are presumed to be fixed, by a weir setting or equivalent. Shallow depths require either low aspect ratio (R = length:width) or low HLR. Linear velocities are shown for each computed point (cm/s).

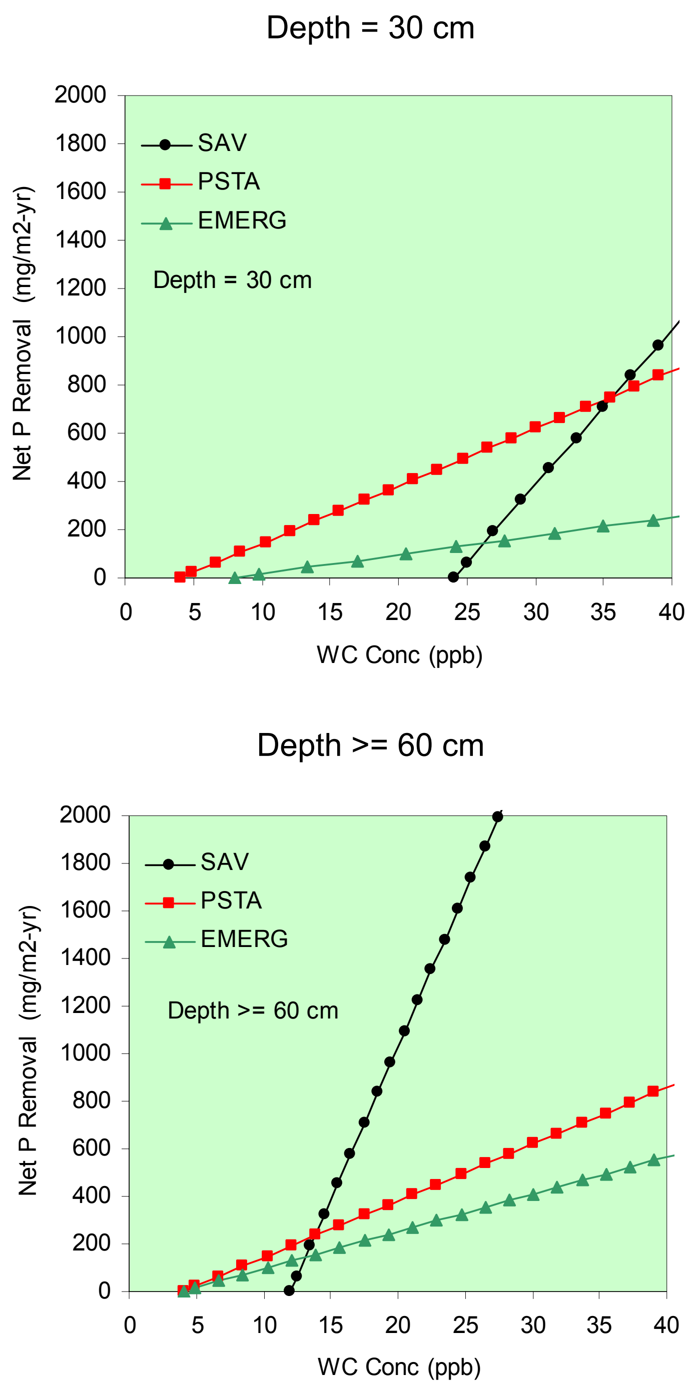


Figure 3. Phosphorus removal rates for each vegetation type. Derived from steady-state solutions of DMSTA for water depths >=60 cm (bottom) and 30 cm (top) using each calibration.

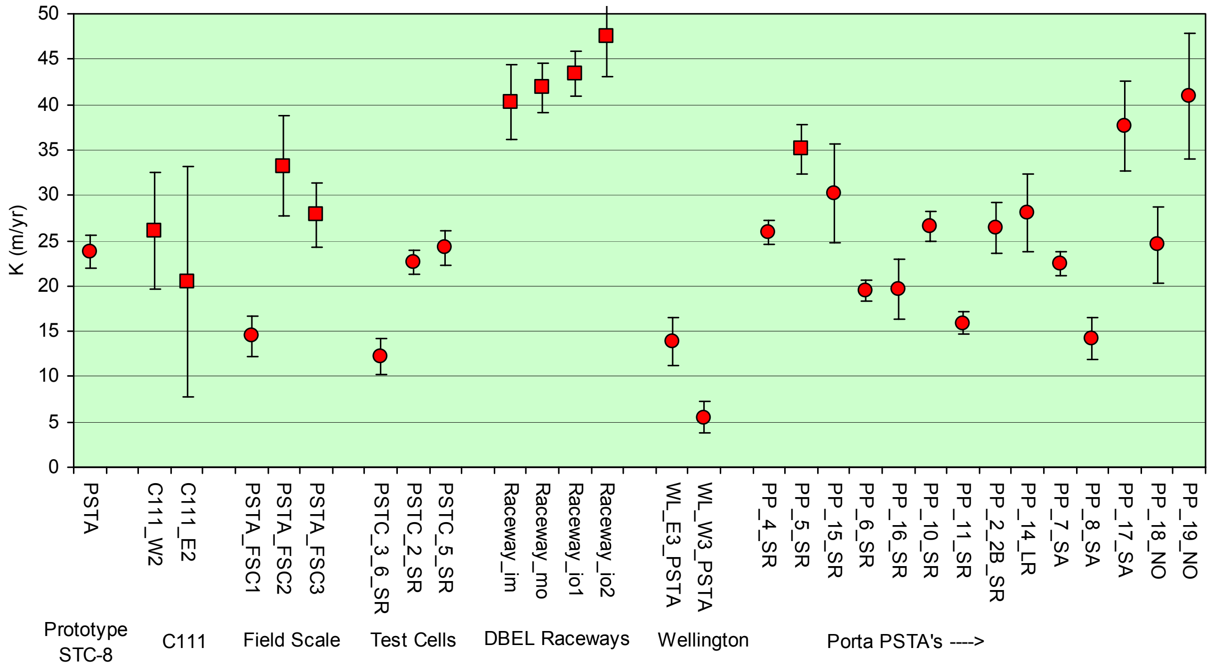
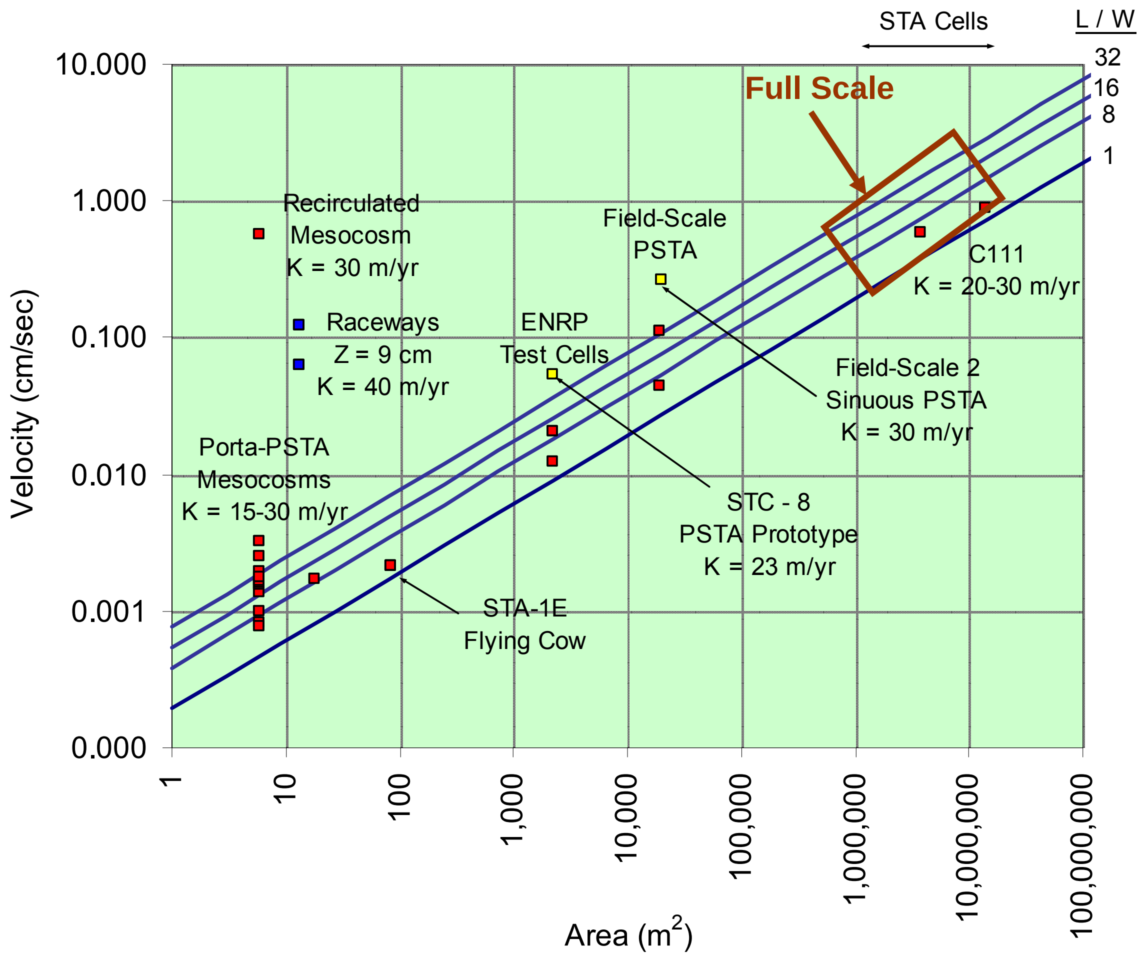


Figure 4. K values calibrated to PSTA platforms. Mean ± 1 Standard Error. Other DMSTA parameters: $C0 = C^* = 4$ ppb, $C1 = 22$ ppb. Estimated from least-squares fits of log-transformed outflow concentration data after stabilization.



Depth	30	cm	K	30	m/yr
Hydr Load	5	cm/day	C*	4	ppb
Cin	25	ppb	TIS	3	
Cout	10	ppb	HRT	6	days

Figure 5. Scale effects in PSTA experimental and full scale design. Points show values for PSTA platforms. Lines show mean velocity vs. surface area for various length/width ratios in hypothetical platforms designed to achieve 10 ppb outflow concentration for a mean depth of 30 cm, an inflow concentration of 25 ppb, k(C* = 4) = 30 m/yr, and other model parameters listed above. The hydraulic load (5 cm/day) is determined by the outflow concentration constraint and other model parameters. The velocity is computed from the hydraulic load, depth, and length. Area ranges for full-scale STA cells are from DMSTA model results for SFWMD Basin-Specific Feasibility Studies.

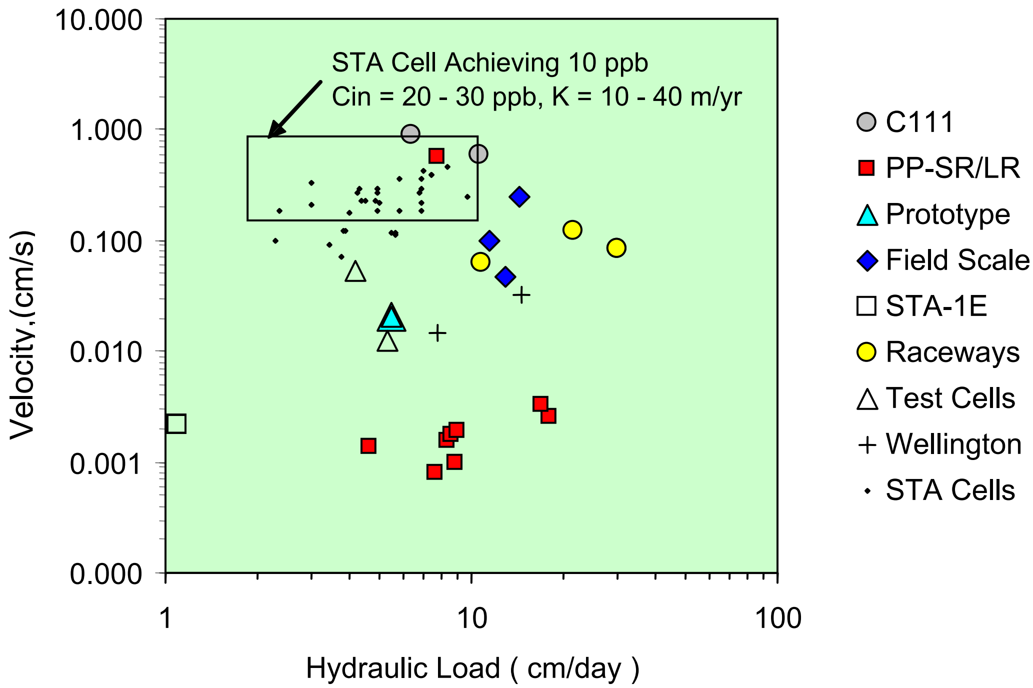


Figure 6. Hydraulic properties of PSTA platforms and optimized full-scale cells. Boxed = predicted ranges for optimized full-scale STA cells designed to achieve 10 ppb outflow concentrations with inflow concentrations of 20–30 ppb and K values of 10-40 m/yr. Hydraulic load ranges computed from steady-state tanks-in-series model with C* = 4 ppb and TIS = 3.

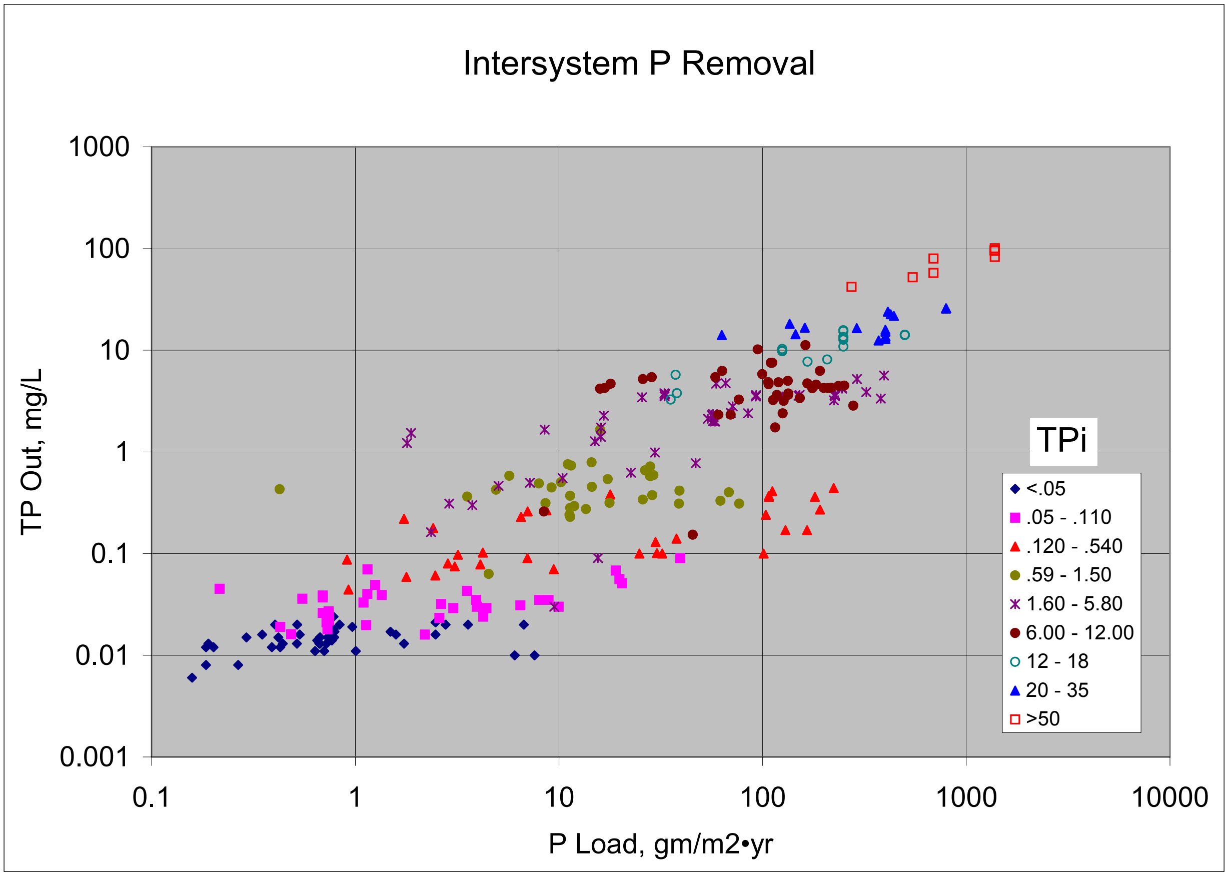


Figure 7. Intersystem phosphorus responses for treatment marshes. Data span four orders of magnitude in both inlet and outlet concentrations and P loading, for the entire period of record for 283 individual systems. Data groups are coded in nine ranges to illustrate the effect of inlet concentration on the trends. Only the two lowest groups are relevant for Everglades protection systems.

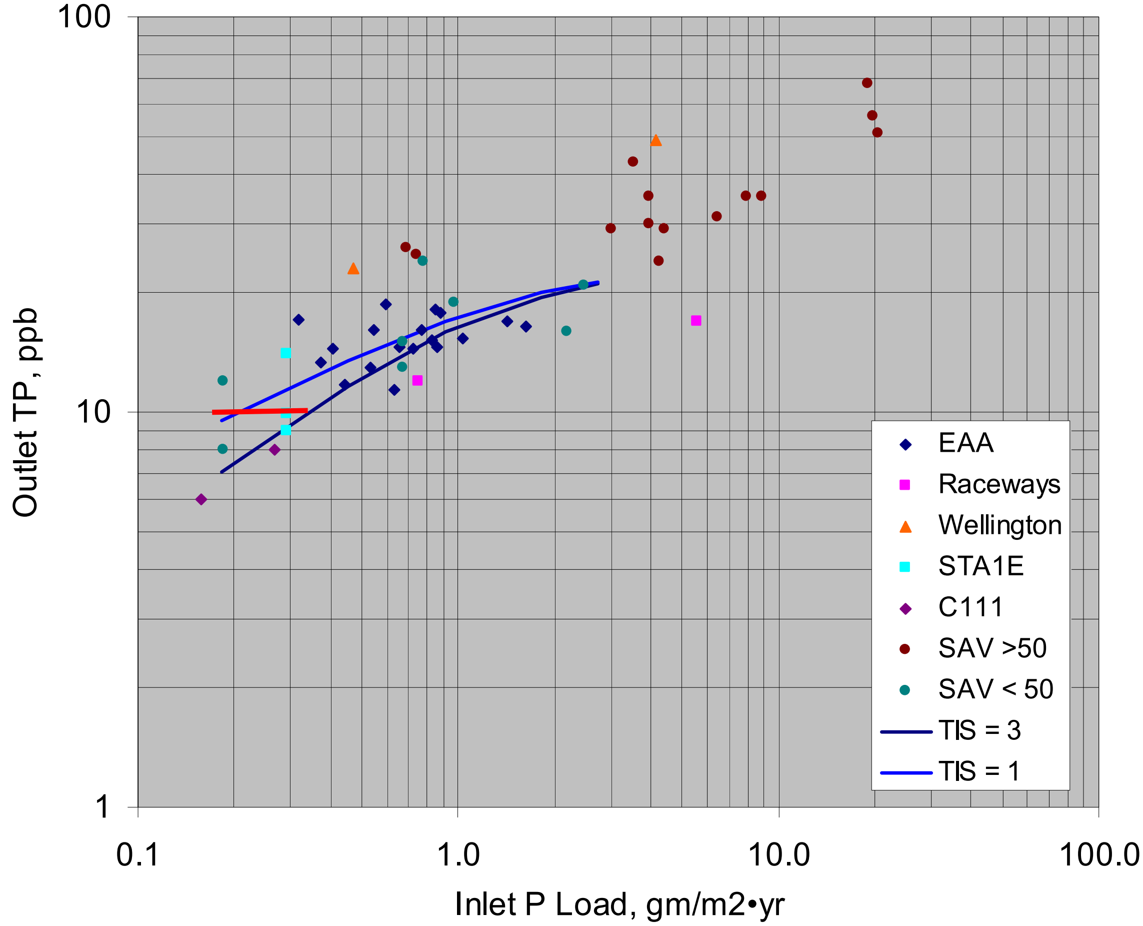


Figure 8. Response of PSTA and SAV platforms to increased phosphorus loads. Symbols = results from various platforms. Lines = predicted outlet concentrations based upon steady-state solution of DMSTA using the PSTA calibration (K = 24 m/yr, C0 = 4 ppb) for an inflow P concentration of 25 ppb and 1 or 3 tanks in series.

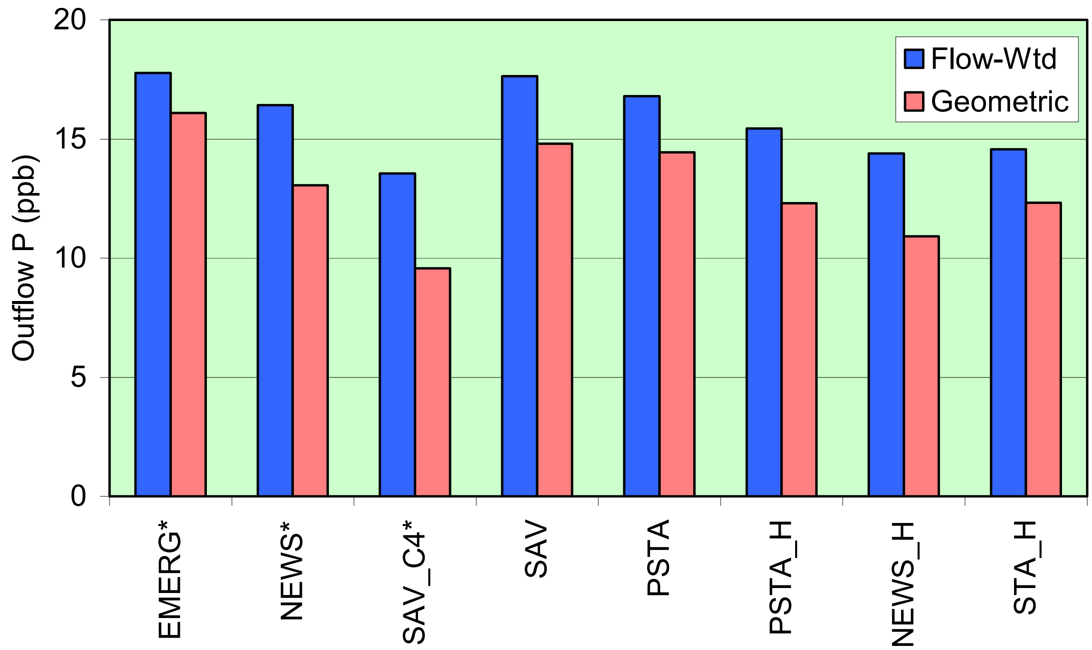


Figure 9. Simulation of a hypothetical STA polishing cell with alternative DMSTA calibrations

Based upon 31-Year hydrologic time series for STA-2, adjusted to inflow conc. = 20 ppb
Mean Hydraulic Load = 17 cm/day, corresponding to 312 ha (771 acres).

Legend	Description	C0 (ppb)	K (m/yr)
EMERG	Emergent – Boney Marsh	4	16
NEWS	Non-Emergent (All SAV & PSTA Platforms)	12 / 4	129 / 24
SAV_C4	SAV - STA-1W Cell 4 – Optimal Perf Pd	4	80
SAV	SAV Community – All SAV Platforms	12	129
PSTA	Periphyton - ENRP South Test Cell 8	4	24
PSTA_H	Periphyton – Best Platforms (DBEL Raceways)	4	40
NEWS_H	Non-Emergent (SAV -→ PSTA_H)	12 / 4	129 / 40
STA_H	Best-Performing Full-Scale Platforms (Excluding STA1W Cell-4) - STA-6, STA-2, Center of WCA-2A	2	35

* Calibrations used in SFWMD Basin Feasibility Studies

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