

**Appendix 8:
Submerged Aquatic
Vegetation / Limerock
Treatment System Technology
for Removing Phosphorous
from Everglades Agricultural
Area Waters: Follow-on Study**

Submerged Aquatic Vegetation/Limerock Treatment System Technology for Removing Phosphorus From Everglades Agricultural Area Waters: Follow-on Study

*STA-1W Cell 4 Tracer Study Report
April 19, 2000*

Prepared for:

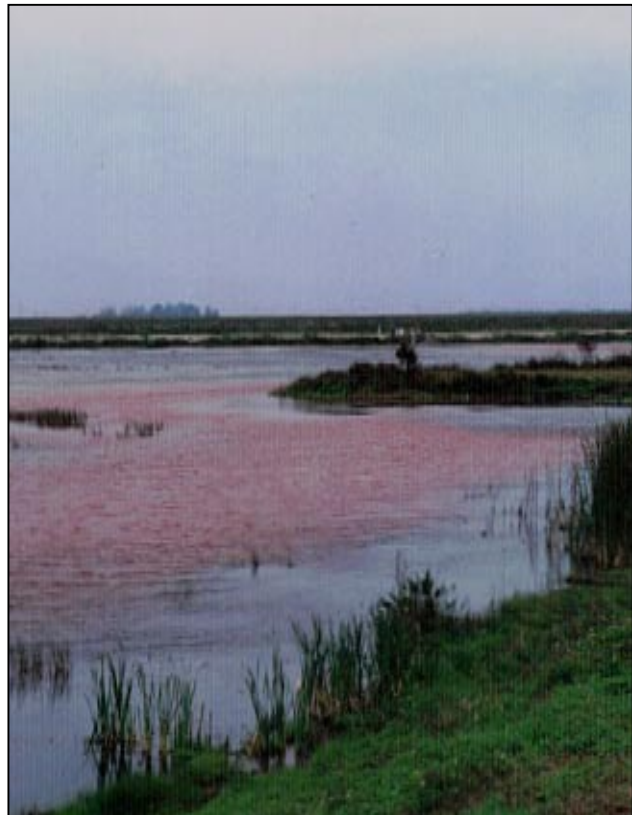
**South Florida Water
Management District
3301 Gun Club Road
West Palm Beach, FL 33306**

and

**Florida Department of Environmental
Protection
Twin Towers Office Building
2600 Blair Stone Road, MS 3560
Tallahassee, FL 32399**

Prepared by:

**DB Environmental Laboratories, Inc.
414 Richard Road, Suite 1
Rockledge, FL 32955**



EXECUTIVE SUMMARY

STA-1W Cell 4, a wetland dominated by submerged aquatic vegetation (SAV), has proven to be the most effective of the original four large “ENR Cells” for phosphorus (P) removal. Despite good historical performance, visual observations of water flow in Cell 4 led DB Environmental Laboratories, Inc. (DBEL) and District investigators to suspect that the wetland’s P removal efficiency may be compromised by internal short-circuiting and dead zones. As part of a larger project designed to evaluate and optimize P removal using SAV-based wetlands, DBEL used a chemical tracer to evaluate the hydraulic efficiency of Cell 4. This report summarizes findings from this tracer study, performed in December 1999 and January 2000. Recommendations on the feasibility of improving Cell 4 hydraulic and P removal performance through engineering modifications will be provided in a subsequent report.

Prior to the tracer study, we performed an evaluation of the water balance, inflow distribution among culverts, and antecedent flow conditions in Cell 4. We selected the dye, Rhodamine-WT, as the appropriate tracer chemical, and injected this into five Cell 4 influent culverts on December 16, 1999. During the next 30 days, we performed periodic sampling for dye and total P concentrations at the inflow, outflow, and 26 internal wetland stations.

Two dimensional, time series plots of the dye concentrations revealed that a disproportionate amount of the tracer flowed along the eastern and western levees of the cell. The tracer response curve developed from Cell 4 outflow data also revealed rapid dye breakthrough, indicative of a prominent short-circuit.

In contrast to the batch-addition of dye, which resulted in transient internal dye plumes, total P loadings to Cell 4 from the upstream wetland (Cell 2) were relatively constant during the study. We therefore observed "steady-state" total P concentrations among the Cell 4 internal and outfall stations for several sampling dates. We segregated the internal P sampling stations into two groups representing areas of Cell 4 lying within and outside of the short-circuits. Based on longitudinal P concentration differences (fractional distance from inflow), we demonstrated that the faster flowing, short-circuit zones that contain little SAV are less effective at reducing total P concentrations than the more densely SAV-occupied areas that characterize most of the wetland.

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Introduction

STA-1W Cell 4 is a submerged aquatic vegetation (SAV)-dominated wetland with a total area of 147 ha (364 acres). The dominant aquatic macrophyte is *Najas. Ceratophyllum* is the next most abundant species, and is usually found near the inflow region. *Potamogeton* is confined to an isolated area along the southwestern levee. The Cell 4 SAV community has performed well, exhibiting a P settling rate substantially higher than that of the other STA-1W cells (Walker 1999; SFWMD, 2000).

Field observations suggest that the existence of relict borrow canals within Cell 4 (particularly along the east and west levees) may result in hydrologic short-circuiting. Not only are these canals deeper than the adjacent wetland, but they also contain less SAV than open water sites. District scientists and other investigators have been concerned that the hydraulic short-circuiting may compromise the efficiency of P removal within the cell.

This report covers the first of two tracer studies within Cell 4 that are to be performed under Task 7 of DBEL's Statement of Work. A second dye study will be performed upon completion of modifications to Cell 4 (to reduce short-circuiting), which is likely to be late spring 2000. Initial deliverables for this study included a Site Visit Report and Data Collection Plan (Appendix A), which were submitted to the District for review on September 27, 1999. These documents included summary tables of hydrologic variables, results of the site visit, tracer injection and field sampling methods, laboratory and data analyses, and an evaluation of the flow partitioning among the five Cell 4 inlet culverts.

Cell 4 Hydrologic and Hydraulic Conditions

We performed an initial review of available hydrology and hydraulic data for Cell 4 in support of the tracer study. The historic water balance in Cell 4 was analyzed to assess pathways for potential tracer loss during the study, such as seepage. Accurate assessments of the relative flow distribution between the five inflow culverts for the week prior to the study were used to flow-weight tracer additions to the culvert flows. Hydrologic parameters of stage and inflow rates were used to determine nominal hydraulic retention times (HRTs) during the study, and Cell 4 outflows were used to flow-weight concentration measurements in mass balance calculations.

Flow Measurement Instrumentation

There are five inlet culvert structures spaced evenly along the northern levee (G254 A-E) and five outflow culverts grouped together at the southern corner of Cell 4 (G256 A-E) (Figure 1). Each culvert is instrumented with ultra-sonic velocity meters (UVMs) to measure flow rate. The District records and stores UVM data at 15-minute intervals. Stage is measured within Cell 4 at four locations. There are two stage recorders located along the northern levee (G254 A/B and G254 D/E), one stage recorder located internally at the ENR401 station, and a stage recorder located in the deep zone in front of the G256 culverts (Figure 1). Stage is recorded by the District at 15-minute intervals.

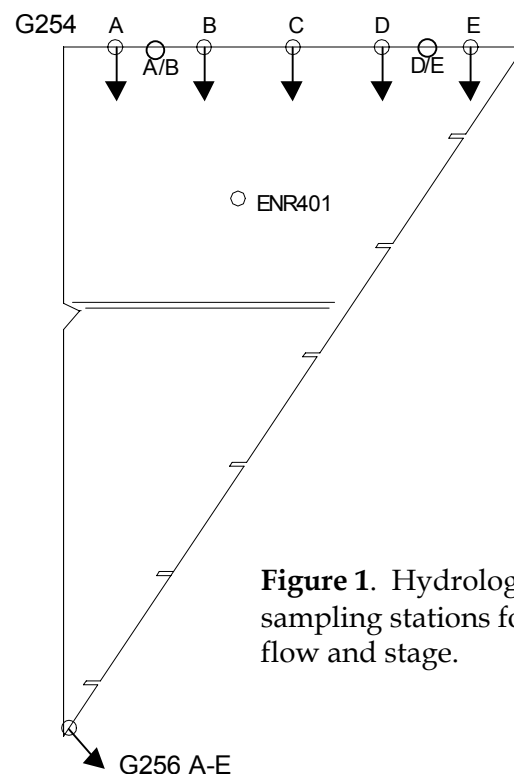


Figure 1. Hydrologic sampling stations for Cell 4 flow and stage.

Historic Water Balance

DBEL obtained and analyzed a District-developed Cell 4 water balance covering the period May 1995 through April 1999. The water budget used measured inflows, measured outflows, measured rain events, District-estimated seepage (through the western levee) and evapotranspiration (ET) losses. The District's water budget closed (inflows equaled outflows) within 3%. Figure 2 summarizes the average percent contributions of Cell 4 water fluxes. Note that average Cell 4 culvert outflow is 92% of culvert inflow and that estimated seepage losses constituted approximately 10% of net Cell 4 outflows. This suggests the potential for a 10% non-recoverable tracer fraction, as tracer additions will leave Cell 4 in concert with both seepage and effluent outflows.

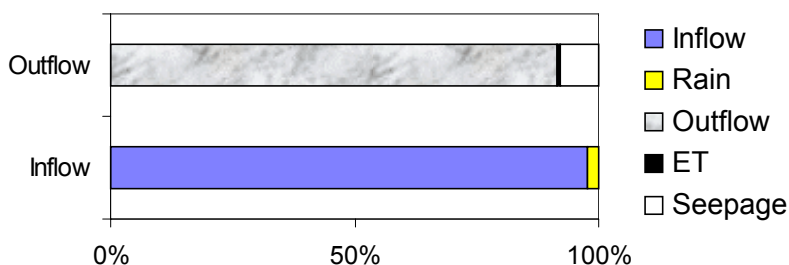


Figure 2. Water balance for Cell 4.

Cell 4 Inflows

Culvert Flow Distributions Before Tracer Injection

We examined the relative balance between culvert inflows to determine if flow-weighting for tracer injection was necessary. Figure 3 shows a time history of culvert inflows for one week prior to tracer injection from District data measured at 15-minute intervals. Note that no data were recorded for culverts G254 D and E for the first and last days of the one week interval. However, based on the average of available culvert flow data, the flow distribution between culverts was within +/- 15%. Based on this analysis, we applied uniform volumes of tracer to each culvert with no flow-weighting.

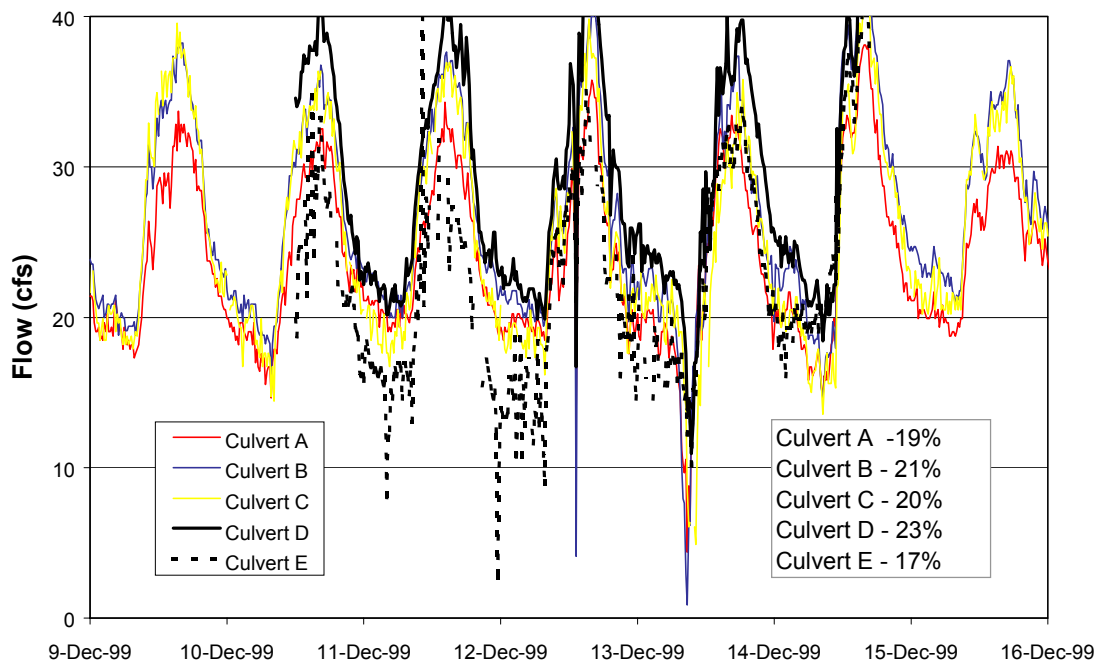


Figure 3. Volumetric flow rate through the five inlet culverts to Cell 4 for a one week period prior to tracer injection.

Inflow History Throughout Tracer Study

Figure 4 shows the history of net G254 culvert flow for the tracer study duration. Net flow is the summed flow of the five culvert stations. As noted above, occasionally the UVM database had missing records or records indicating negative (i.e. reverse) flow for one or more culverts. On days with missing or negative data, net flow was calculated by averaging only positive culvert data and multiplying this average by the total number of culverts (i.e., five). No data were available around January 1, 2000 due to District shutdowns to avoid potential Y2K problems. The cyclical pattern of G254 inflow is a result of high head conditions created upstream by the S5A pumping schedule.

The heavy line in Figure 4 shows a 24-hour rolling average (12 hours before, 12 after) of G254 inflows. Average G254 flow throughout the tracer study duration was 123 cubic feet per second (cfs); this corresponds to a Cell 4 hydraulic loading rate of 20.5 cm/day. The average tracer

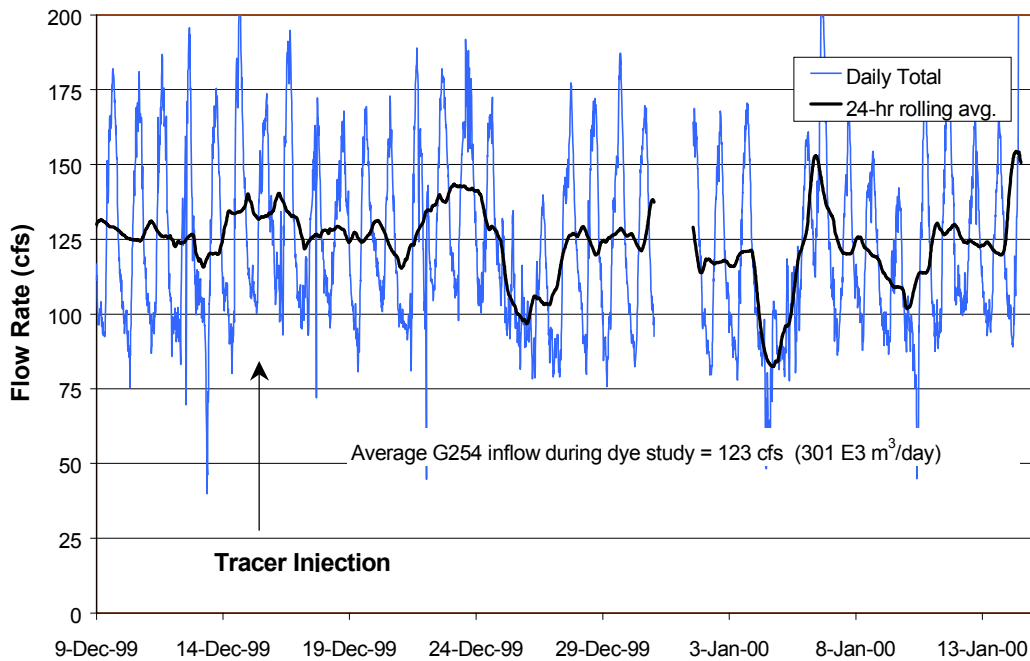


Figure 4. Net volumetric flow rate through the five inlet culverts to Cell 4 for one week prior and four weeks subsequent to tracer injection.

study flow and loading was 31% greater than the historic averages, which were 94 cfs and 15.7 cm/day, respectively, between January 1995 and April 1999. The average tracer study flow was also 67% greater than the average Cell 4 inflow measured over the previous year (May 1998 – April 1999), which was approximately 74 cfs. Throughout the tracer study, the rolling average of inflow varied within +/- 30% of the average flow. However, flow was relatively steady during the first week of the study, which is when peak tracer concentrations were recorded.

Cell 4 Outflows

The G256 outflows exhibited the same cyclical pattern as G254 inflows, but with lower amplitude in variations (cf. Figure 4 and Figure 5). Water volume and vegetation density in Cell 4 tended to dampen the influent oscillations. The heavy line in Figure 5 shows a 24-hour rolling average (12 hours before, 12 after) for Cell 4 outflows. The average G256 flow during the tracer study was 122 cfs, which was 99% of measured inflow.

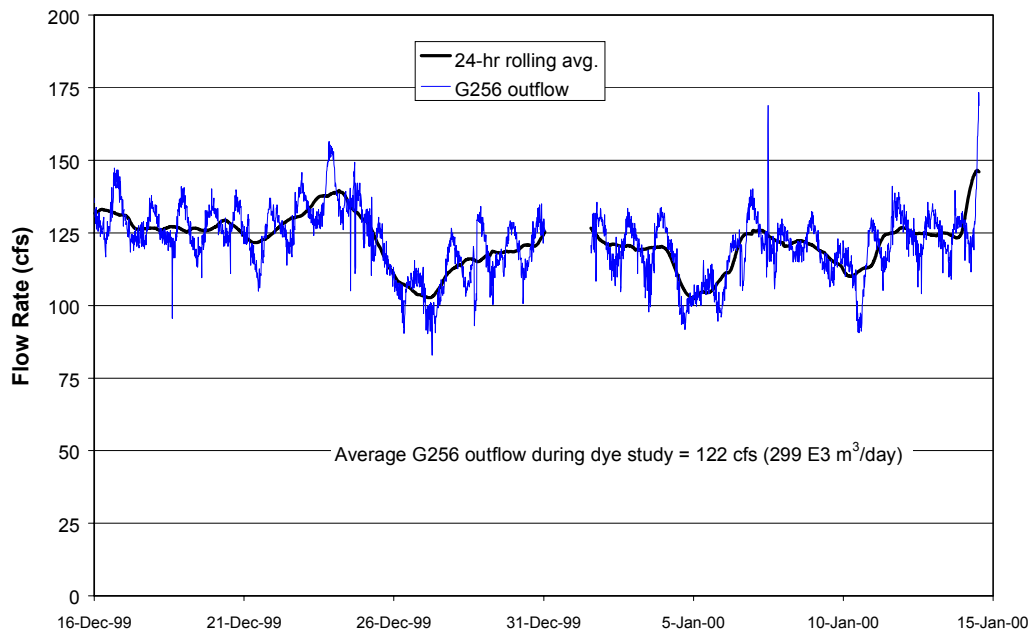


Figure 5. Volumetric outflow rate from Cell 4 during the tracer study period.

Cell 4 Stage

Figure 6 shows the history of Cell 4 stage measured at G254 and G256 structures for the tracer study duration. The stage reported at G254 is averaged from data at two stations (G254 A/B and D/E) along the northern levee. Note that Cell 4 stage also demonstrates cyclical behavior in response to the S5A pump schedule. Based on the combined 24- hour rolling average of G254 and G256 stage data, the mean Cell 4 stage throughout the tracer study was 12.09'. Assuming an average Cell 4 ground elevation of 9.66', this corresponds to an average Cell 4 depth of 0.74 m throughout the tracer study.

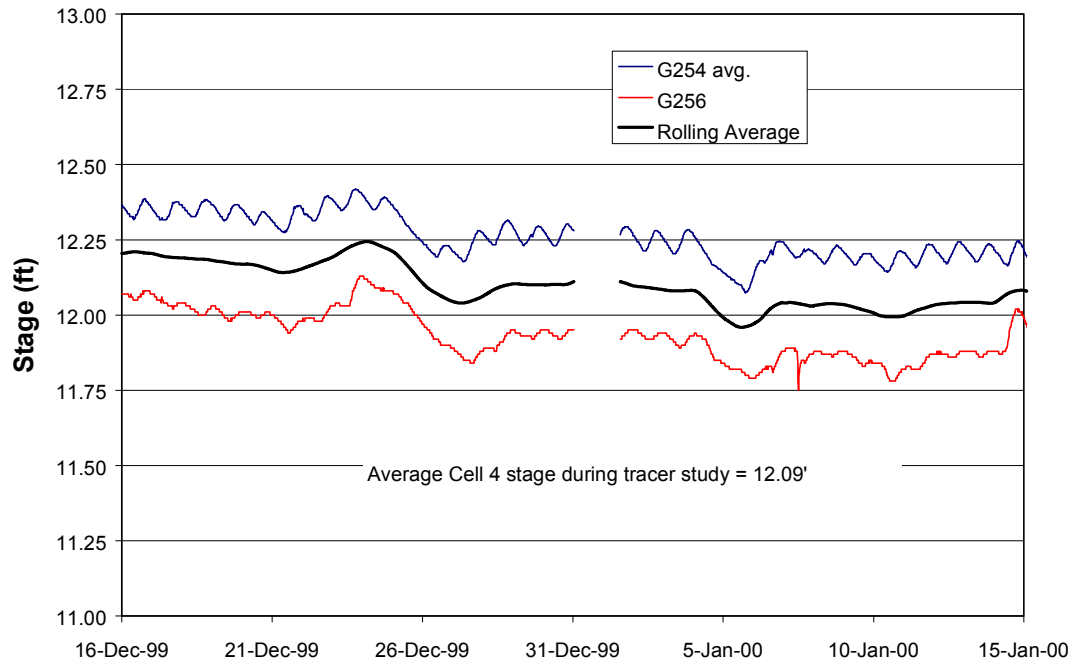


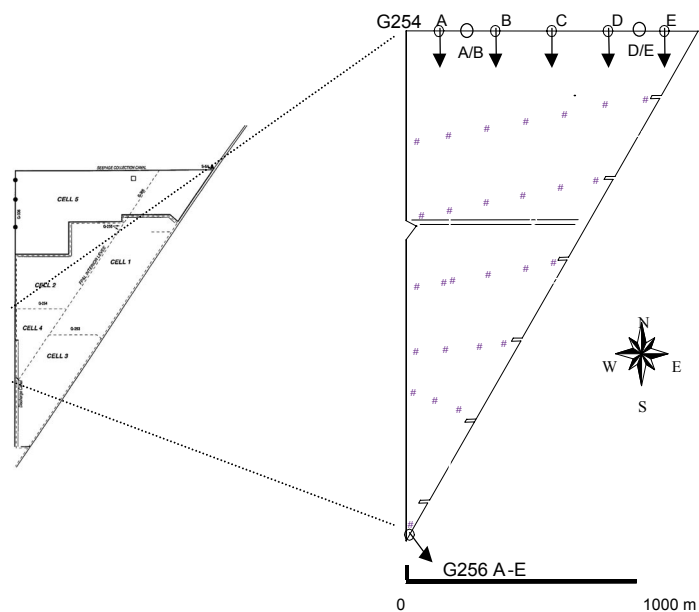
Figure 6. Stage fluctuations in Cell 4 during the tracer study period.

Tracer Study Methodology

Internal Sampling Locations

Following District approval of the Site Visit Report and Data Collection Plan, we established a 5-transect sampling grid within Cell 4. The transects, which were approximately normal to the flow path within the cell, were 402 m (1/4-mi) apart. From 3 to 7 sampling locations, each separated by approximately 125-187 m (depending on transect location), were "visually" marked off along each transect, yielding a total of 26 internal sampling stations (Figure 7). Each of the internal sampling stations was marked by a stake. Precise coordinates of these stations were later obtained by use of differential GPS.

Figure 7. Locations of the internal tracer and phosphorus sampling stations within Cell 4. The small projections along the east levee are pads constructed by FP&L for their power lines. The transverse canal near the middle of the cell is a relict channel which routes some of the short-circuited flow.



Tracer Injection

We added 227 kg (53.5 gallons) of 20% Rhodamine-WT (45.5 kg active ingredient) into Cell 4 on December 16, 1999. The dye delivery system consisted of five 55 gallon drums equipped with outflow valves in the bottom. The concentrated dye was subdivided into five equal parts (i.e., 10.7 gallons), and each 10.7 gallon aliquot was poured into one of the five 55 gallon drums, and mixed with site water to a volume of 53.5 gallons (1:5 dilution). The valves for all five of the dispensing drums were then opened at the same time, allowing the contents of the drums to enter the flow

paths of the five major inflow culverts in a synchronous manner. The delivery time was 35 minutes for each drum.

Sampling Frequency

We performed sampling of the dye tracer at the Cell 4 outfall at an intensive frequency, particularly during the first few days of the study (Table 1). In addition, we included internal wetland surface water stations in our sampling program in order to gain an understanding of the extent and exact locations of dead zones and short-circuiting areas. Compared to the outfall station, the 26 internal stations were sampled at a reduced frequency (at elapsed times of 3 and 7 hours on the first day of dye injection, then at 27, 51, 99 and 147 hours). On two occasions (27 and 99 hours), we also collected samples for analysis of total P concentrations coincident with the dye sampling at the internal stations.

Table 1. Number of samples collected at the Cell 4 outfall structure each day after injecting Rhodamine-WT into the wetland.

Day	1	2	3	4	5	6	7	8	9	10	11	12
Sample Numbers	3	6	6	5	3	3	2	2	2	2	2	1
Day	13	14	15	16	18	19	20	21	22	23	26	30
Sample Numbers	1	1	1	1	1	1	1	1	1	1	1	1

Variations in Tracer Concentrations with Water Depth

Simultaneous surface (0.1 m) and bottom (0.6 m) dye samples were collected at the 26 internal stations on December 17, twenty-seven hours after tracer injection. The presence or absence of SAV beds at each station was noted at the time of sample collection.

Laboratory Analysis of Dye Tracer

Rhodamine-WT concentrations were measured on a Turner Designs Model 10-AU-005-CE fluorometer with excitation and emission filters of 550 and > 570 nm, respectively (Wilson et al. 1986). The emission filter consisted of an orange sharp-cut filter. A reference filter (>535 nm) reduced baseline drift and instrument noise by filtering out scattered light. The light source was

a clear quartz lamp. The standard curve was linear to 80 mg/L and the method detection limit was 0.1 µg/L. Since Rhodamine-WT fluorescence is sensitive to temperature, both standards and samples were analyzed at room temperature (20-27 °C). Background fluorescence (from dissolved organic matter) was subtracted from each of the sample fluorescence readings. Prior to analysis, all water samples were stored in amber-colored bottles.

Computations for Determining Hydraulic Parameters

Calculations for determining selected hydraulic parameters for Cell 4, based on the tracer data, were performed as follows.

The nominal HRT, τ , is the volume of water in the treatment wetland (V) divided by the volumetric inflow rate of water (Q):

$$\tau = V/Q \quad (1)$$

The tracer residence time, τ_a , is defined as the average time that a tracer particle spends in Cell 4, and is the first moment of the residence time distribution (RTD) function. The RTD represents the time various fractions of water spend in Cell 4. It is the contact time distribution for the system and defines the key parameters that characterize the actual detention time (Kadlec 1994). Levenspiel (1989) uses the RTD in the analysis of reactor behavior.

The mean residence time, τ_a , was calculated by dividing Eq. 4 of the tracer flow distribution, by Eq. 3, both of which are based on mean outflow rates and tracer concentrations (Kadlec 1994):

$$\tau_a = M_1/M_0 \quad (2)$$

$$M_0 = \int_0^{t_f} Q_e(t) C(t) dt \quad (3)$$

$$M_1 = \int_0^{t_f} t Q_e(t) C(t) dt \quad (4)$$

where $C(t)$ =exit tracer concentration (mg/m³); Q_e = flow rate (m³/day); t = elapsed time (days); and t_f = total time span of the outflow pulse (days).

To find the RTD, the concentration response curve (experimental $C(t)$ vs. t curve) is converted to an E_t curve by changing the concentration scale so that the area under the response curve is

unity (Levenspiel 1989). This is accomplished by multiplying the concentration readings by the volumetric flow rate divided by the mass (M) of injected tracer:

$$E_t = C(Q_e/M) \quad (5)$$

where E_t = RTD function in reciprocal time units.

The RTD function is normalized when it is expressed in terms of the dimensionless time scale by multiplying the Y-axis (i.e., the E_t function) units by τ (the nominal HRT):

$$E_\Theta = \tau E_t \quad (6)$$

where E_Θ = dimensionless RTD function,

and dividing the time units of the X-axis by τ :

$$\Theta = t/\tau \quad (7)$$

where Θ = dimensionless time scale and represents the number of mean HRTs.

This changes the X and Y axes so that the area under the curve is still equal to one, but the Y and X axes are normalized to τ (Levenspiel 1972). The purpose of creating the normalized distribution function, E_Θ , is to be able to compare the flow performance among wetlands of different sizes and containing different plant communities and densities.

Whereas τ_a represents the centroid of the distribution and is the first moment of the RTD, the variance (σ^2) is the square of the spread of the distribution, or a measure of the dispersive processes, and is expressed in units of (time)²:

$$\sigma^2 = \frac{\int_0^{t_f} t^2 Q_e(t) C(t) dt}{\int_0^{t_f} Q_e(t) C(t) dt} - \tau_a^2 \quad (8)$$

The variance, which is the second moment of the RTD, is particularly useful for matching experimental curves to one of a family of theoretical curves (Levenspiel 1972).

The variance can be rendered unitless by dividing by the square of the tracer detention time:

$$\sigma_\Theta^2 = \frac{\sigma^2}{\tau_a^2} \quad (9)$$

where σ_Θ^2 is the dimensionless variance of the tracer pulse.

Two common one-parameter models used to characterize non-ideal flows are the tank-in-series (TIS) and dispersion models (Levenspiel 1972). The TIS model views flow through a series of equal-size ideal stirred tanks, and the one parameter in this model is the number of tanks (N) in the chain. The number of constantly stirred tanks in the series that best matches the tracer response curve is given by N, which is determined by:

$$\sigma_{\theta}^2 = \frac{1}{N} \quad (10)$$

To construct an idealized dimensionless tracer response curve for N = 1, 2, etc.:

$$E_{\theta} = \frac{N}{(N-1)!} \left(N \frac{t}{\tau_a}\right)^{N-1} e^{-N \frac{t}{\tau_a}} \quad (11)$$

The second model is a dispersed plug flow, or dispersion model, which draws on an analogy between mixing in actual flow and a diffusional process. Here the dispersion process is superimposed on a plug flow model, and mixing is presumed to follow a diffusion equation (Kadlec and Knight 1996). For boundary conditions that are closed-closed, the following relation for the dimensionless variance has been found (Fogler 1992):

$$\sigma_{\theta}^2 = \frac{2}{Pe} - \frac{2}{Pe^2} (1 - e^{-Pe}) \quad (12)$$

where Pe is the Peclet number, dimensionless.

Eq (12) can be converted to the wetland dispersion number ($\mathcal{D}$, dimensionless) by utilizing:

$$\mathcal{D} = \frac{D}{uL} = \frac{1}{Pe} \quad (13)$$

where L = distance from inlet to outlet, m

u = superficial velocity, m/day

D = dispersion constant, m²/day

Combining Eqs. (12) and (13) yields:

$$\sigma_{\theta}^2 = 2\mathcal{D} - 2\mathcal{D}^2 (1 - e^{-\frac{1}{\mathcal{D}}}) \quad (14)$$

RESULTS

Tracer Response Curve for Cell 4

The tracer concentration response curve for Cell 4 illustrates the non-ideal flow distributions, where neither plug flow reactor (PFR) nor constantly stirred tank reactor (CSTR) flow patterns exist. The tracer concentration curve more closely mimicked a well-mixed reactor, however, than a plug flow reactor (Figure 8). Due to short-circuiting, the dye appeared at the effluent region of Cell 4 within 16-20 hours after tracer addition. After the lag period, the ascending limb of the tracer curve peaked close to the maximum concentration ($40\text{ }\mu\text{g/L}$) expected for CSTR behavior (Figure 8). The resemblance of the tracer response to a well-mixed system is also indicated by the shape of descending limb, which was coincident with that of the idealized CSTR during the post-nominal HRT period.

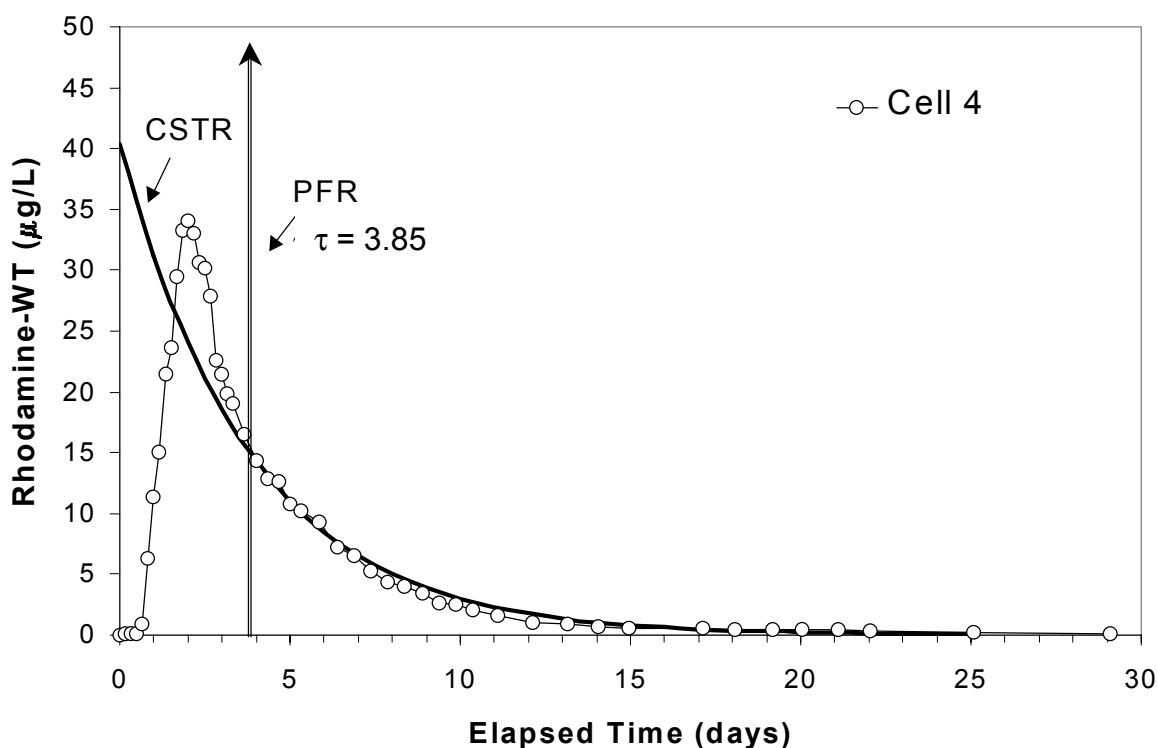


Figure 8. Tracer response curve of Rhodamine-WT dye applied to Cell 4 on December 16, 1999. Responses to ideal well-mixed (CSTR) and plug flow (PFR) conditions are represented by the exponential decay and vertical (coinciding with the nominal HRT, τ) lines.

Tracer Mass Balance

The Rhodamine-WT mass balance was calculated by comparing the added mass to the tracer mass recovered at the effluent. The total mass of tracer exiting Cell 4 is given in Eq. 3. A comparison of the recovered tracer mass and the amount added to Cell 4 demonstrates a 85% recovery for Rhodamine-WT. Some of the unaccounted tracer may have left Cell 4 as seepage, which may constitute as much as 10% of the net outflow from the cell (see Historic Water Balance section of this report.)

Tracer Detention Time

The nominal Cell 4 HRT for the tracer study period can be calculated in two ways, each yielding slightly different results. The average Cell 4 depth (0.74 m) can be divided by average loading (20.5 cm/day) to yield a nominal 3.6-day HRT. A more accurate approach calculates HRT on an instantaneous basis using the 15-minute interval flow data set and averaged over the study duration; this approach yields a nominal HRT of 3.85 days

Our data show that the tracer detention time ($\tau_a=4.7$ days) is longer than the nominal HRT ($\tau=3.8$ days). This inequality has been observed in all tracer studies that we have performed on SAV “platforms” at STA-1W (mesocosms, test cells, and Cell 4). Microtopographical variations, internal recirculation, and the density distribution of the SAV biomass may contribute to this discrepancy.

Two-Dimensional Time Series Plots of Tracer Concentrations

The two-dimensional time series plots for the dye concentrations were produced in Arcview GIS (Version 3.1). The Spline/Tension interpolator in the Arcview program fitted a minimum-curvature surface through the input concentrations.

The appearance of the dye at the Cell 4 outflow soon after tracer study injection suggests that this wetland exhibits a prominent short-circuit. The internal samples proved useful in identifying the locations of both short-circuits and dead zones.

The spatial resolution of the dye tracer plume during the first two internal collection times (3 and 7 hours) was limited because our first monitoring transect was located 0.40-km south of the 5 tracer injection points. This was too great of a distance from the inlets for the dye to reach all the stations along the first transect within the first 7 hours. We therefore estimated the extent of dye plumes surrounding the injection points during the 3 and 7 hour collection times. These estimates were based on visual observations and photographs taken from both the ground and the air.

Pronounced short circuits along the eastern and western levees are readily observed in the 3 and 7 hour elapsed time sequences (Figure 9). Dye concentrations in these areas remained high through several subsequent collection times. Since the short-circuited areas exhibited higher velocities (122 - 149 m/hr) and sparser SAV than the central area of Cell 4, they also provided a conduit for transport of the dye from the more hydraulically isolated central area of the cell at the end of the dye retention period (99 hr). The short-circuiting apparent in Figure 9 provides a level of detail that aids in the discussion of the hydraulic parameters (e.g., measured HRT, tanks-in-series number, wetland dispersion number) in the following sections of this report.

Variations in Tracer Concentrations with Water Depth

The dye was more evenly distributed throughout the water column for those stations when SAV was absent than when it was present (Figure 10). However, even in SAV beds we frequently found equal concentrations of dye at the surface and at a 0.6 m depth. In general, these data indicate that dye molecules can readily penetrate SAV beds.

Hydraulic Efficiency of Cell 4

We compared the hydraulic characteristics of Cell 4 to the STA-1W test cells, on the basis of the normalized residence time distribution (RTD) function (E_θ), expressed in dimensionless units. The data for the SAV-dominated test cells were obtained under more "idealized" flow conditions: the test cells are smaller (0.26-0.28 ha), have calibrated influent manifolds and do not exhibit obvious short-circuits. The tracer study on the test cells was performed from October 26-November 30, 1999. The hydraulic parameters (HRT, variance, TIS and wetland dispersion numbers) obtained

under the more "idealized" conditions of the test cells may represent a reasonable "target" for the optimization of Cell 4.

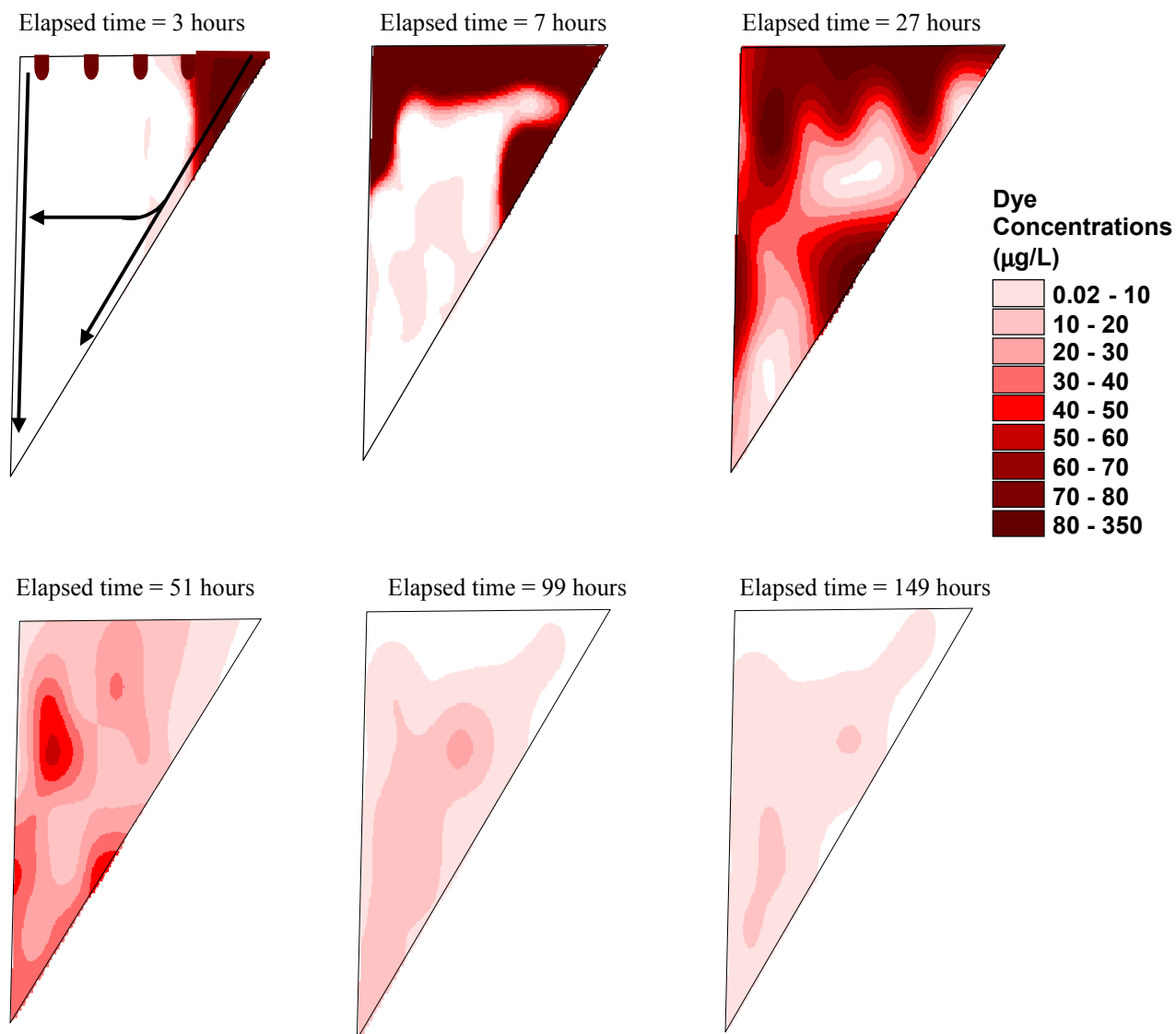


Figure 9. Time series showing the progression of the Rhodamine-WT dye through Cell 4. The arrows inserted in the 3-hour elapsed time panel depicts the approximate locations of the short circuited areas. For elapsed times of 3 and 7 hours, the extent of the dye plume was estimated by the interpolation algorithm of Arcview and by visual observations and photographs taken from both the ground and the air. Dye concentrations for all other elapsed times (27, 51, 99 and 149 hours) were estimated solely by the interpolation algorithm of Arcview.

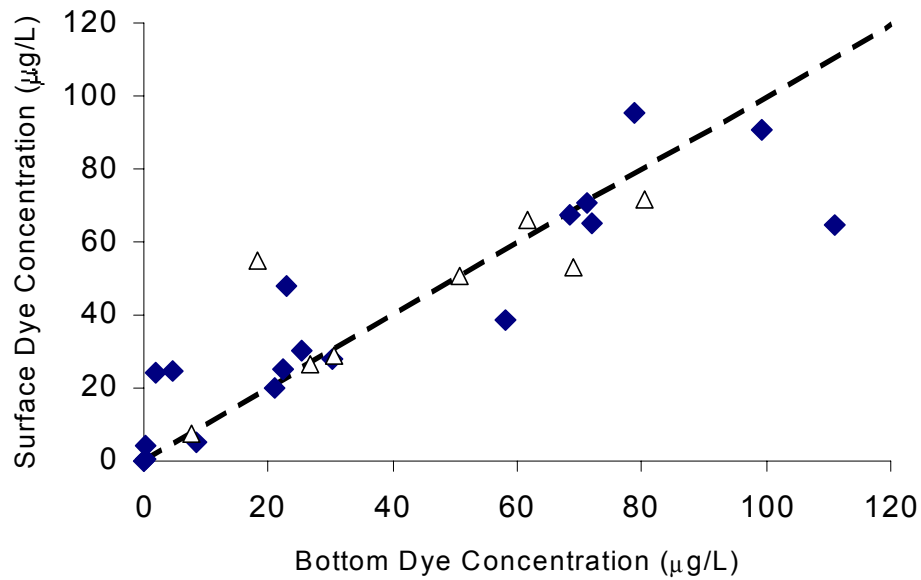


Figure 10. Cell 4 surface (0.1m) and bottom (0.6m) Rhodamine-WT dye concentrations 27 hours after injection. Samples were collected from 18 stations with SAV (closed markers) and 8 stations without (open markers) on December 17, 1999. The dashed line represents equal concentrations at surface and bottom.

The HLR for Cell 4 was about twice as high as the test cell HLRs during their respective dye study periods. This resulted in differing values for some of the pertinent hydrologic variables (HLR, water column depth, HRT) among the test cells and Cell 4 (Table 2). Theoretical flow velocities ranged from 10 - 12 m/day for the deeper test cells (NTC-1 and STC-9) and 19 - 22 m/day for the shallower test cells (NTC-15 and STC-4). Because of its larger size, the theoretical flow velocity in Cell 4 was 591 m/day.

Table 2. Key hydrologic variables present during tracer studies in the test cells and Cell 4.

Wetland Cell Designation	Dominant SAV	Depth (m)	HLR (cm/day)	Nominal HRT (τ , days)
NTC-1	<i>Chara</i>	0.91	10	7.6
STC-9	<i>Hydrilla</i>	0.79	11	6.3
NTC-15	<i>Chara</i>	0.49	13	3.6
STC-4	<i>Hydrilla</i>	0.51	12	4.1
Cell 4	<i>Najas</i>	0.74	21	3.85

Figure 11 and Figure 12 compare the dimensionless RTD functions of Cell 4 to those of the two test cells (NTC-1 and STC-9) that were maintained at water depths similar to Cell 4, and to two test cells (NTC-15 and STC-4) that had nominal HRTs (τ) comparable to Cell 4 (Table 2). In both sets of figures, the response curve for Cell 4 begins to peak before those of either of the paired test cells.

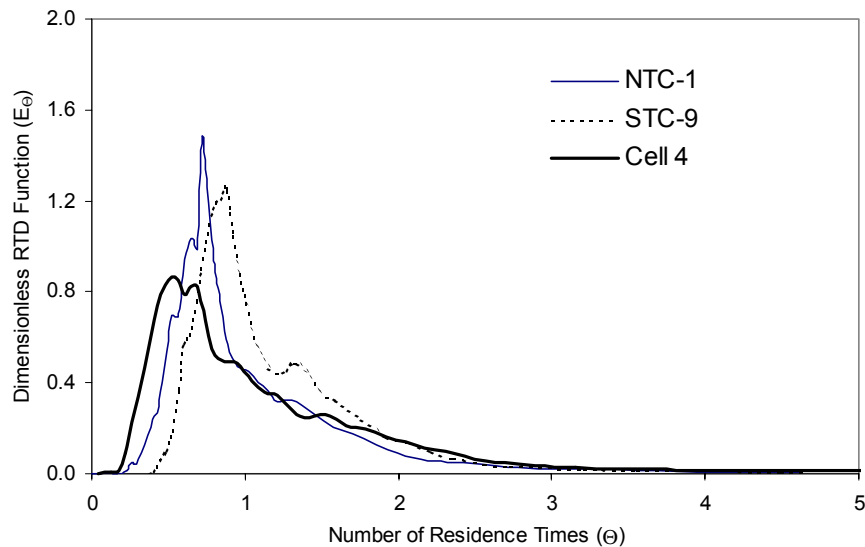


Figure 11. Dimensionless residence time distribution (RTD) functions for two test cells and Cell 4 at similar water depths (0.74 - 0.91 m).

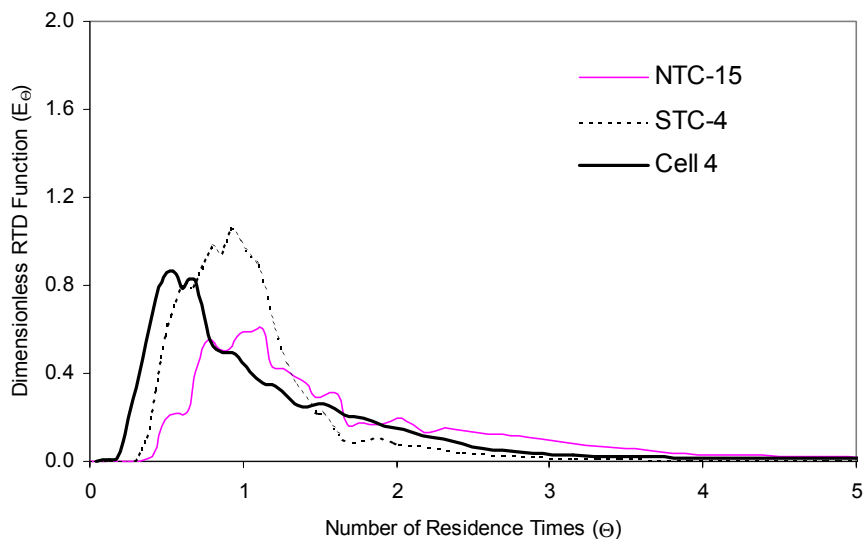


Figure 12. Dimensionless residence time distribution (RTD) functions for two test cells and Cell 4 at similar nominal hydraulic retention times (3.6 - 4.1 days).

For the data sets collected at nearly identical depths (but different HRTs and HLRs), the earlier Cell 4 peak had a less elongated RTD function than the test cell peaks (Figure 11). The tail of the Cell 4 response curve is also somewhat more gradual than those for the test cells. The dimensionless RTD functions for Cell 4 and the pair of test cells that had similar τ values (but different water depths and HLRs) are considerably different than the prior comparison (cf. Figure 11 and Figure 12). Here the peaks for NTC-15 and STC-4 occur at $E_{\theta}=1$ (where $t=\tau$), but considerably more dye is exiting from Cell 4 at an earlier time than from either of the two test cells (Figure 12).

Since τ equals the storage volume divided by the volumetric flow rate (Eq. 1), if water depth is halved (thereby decreasing the storage volume by two) and the HLR is also halved (resulting in a two-fold decrease in the volumetric flow rate), the τ remains the same. This is essentially what accounts for the similar τ values in Table 2 for the two shallow depth test cells (NTC-15 and STC-4) and Cell 4. Assuming that a change in depth offset by a comparable change in HLR (such that the τ remains the same) does not affect the RTD function (although it may affect the P removal rate), then Figure 12 is a more valid direct comparison between Cell 4 and the test cells than Figure 11. From this comparison, it appears that the short-circuiting within Cell 4 is the leading contributory factor to a less than optimum flow regime. This in turn could result in reduced P removal efficiency, relative to a wetland with more ideal hydraulic characteristics.

One technique for assessing potential improvements in the hydraulic efficiency for Cell 4, assuming that correcting the short-circuiting results in a RTD function more typical of the test cells in Figure 12, may be to integrate that portion of the ascending limb of Cell 4 curve that is excluded from the ascending limbs of either of the test cells. The integrated area represents the portion of water leaving Cell 4 prematurely relative to the more idealized RTD function of the test cells. Dividing that area by the total area of the Cell 4 RTD function yields the percentage of the water volume in Cell 4 (17 - 33%) that could be contained within the cell for a longer period of time under more ideal hydraulic conditions.

Another technique for evaluating the hydraulic efficiency of Cell 4 is to compare the dimensionless RTD function (E_{θ}) of the cell with the theoretical RTD functions of increasing tanks-in-series (TIS) according to Eq. 11. Special cases of the TIS are the single CSTR ($N=1$) and the PFR ($N=\infty$). In other

words, the higher N that a wetland represents, the closer it resembles a PFR and less of a CSTR. Hydraulic characteristics of a PFR are more conducive to more efficient treatment of P since the average time that inflow water is retained in the wetland more closely approaches the HRT; or alternatively, a lesser proportion of the inflow water leaves the wetland early.

Compared to the dimensionless RTD function of 1, 2, and 3 TIS, the RTD function for Cell 4 lies between 1 and 2 (Figure 13) with an $N=1.3$ according to Eq 10. This number is very low for a treatment wetland since most surface flow wetlands have reported $2 < N < 8$ (Kadlec and Knight 1996). When compared to the more hydraulically efficient, SAV-dominated test cells (i.e., without obvious short-circuiting) the $N=1.3$ for Cell 4 is lower than the TIS values of the former ($1.7 < N < 3.3$) (Table 3).

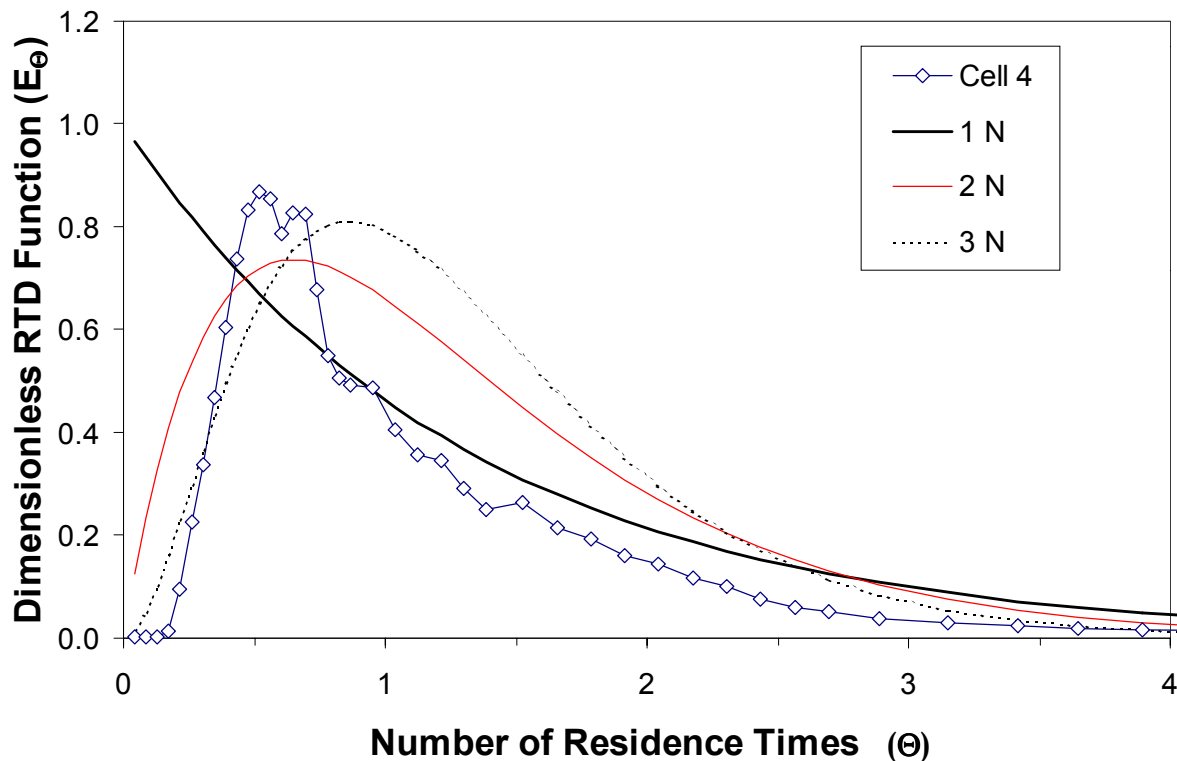


Figure 13. Dimensionless residence time distribution (RTD) function for Cell 4. Also shown are theoretical RTDs for 1, 2, and 3 (N) well-mixed (CSTR) "tanks-in-series".

Table 3. Comparison of key hydraulic parameters among four test cells and Cell 4.

Wetland Cell Designation	Nominal HRT τ , days	Measured HRT τ_a , days	Variance σ^2 , day ²	Dimensionless Variance σ_θ^2	Tanks-in-Series N	Wetland Dispersion Number $\mathcal{D}$	Peclet Number Pe
NTC-1	7.6	8.2	25.2	0.37	2.5	0.24	4.17
STC-9	6.3	7.7	16.6	0.28	3.3	0.17	5.88
NTC-15	3.6	6.6	24.9	0.57	1.7	0.51	1.96
STC-4	4.1	4.5	7.4	0.37	2.6	0.24	4.17
Cell 4	3.85	4.7	17.2	0.78	1.3	1.25	0.80

Besides the TIS model, the other commonly deployed one-parameter model for evaluating flows through wetlands is the dispersion number, $\mathcal{D}$, which is equal to the dispersion coefficient divided by the product of the superficial velocity and length of the wetland ($D/[uL]$ in Eq. 13). Kadlec (1999) states that values of $\mathcal{D}$ range from 0.2 to 0.4 in wetlands (predominantly emergent macrophyte wetlands), which places them in the "large amount of dispersion" category. The $\mathcal{D}$ values obtained for the four SAV-dominated test cells are mostly within that range (Table 3). However, we observed a $\mathcal{D}$ of 1.25 for Cell 4, indicating that it is hydraulically atypical of surface-flow treatment wetlands.

The inverse of $\mathcal{D}$, the Peclet number (Pe), describes the ratio of the rate of tracer transport by convection (bulk flow) to the rate of transport by diffusion or dispersion (uL/D). The comparison of the Pe values for the test cells with that of Cell 4 in Table 3 indicates that Cell 4 transport is dominated by diffusion and dispersion ($Pe < 1$), whereas the transport within all the test cells was controlled mainly by bulk flow ($Pe > 1$). Considering that hydraulic efficiency in treatment wetlands is thought to be enhanced by plug flow rather than dispersive or diffusive flow processes, then the test cells perform better than Cell 4 from a hydraulic perspective.

Two-Dimensional Time Series Plots of Total P Concentrations

The rapidly changing spatial profiles for dye concentrations in Cell 4 were a result of the batch-addition, or the transient nature of the dye pulse (Figure 9). By contrast, Cell 4 was essentially at a "steady-state" with respect to TP levels during the study, as indicated by the comparable spatial TP

profiles at 27 and 99 hours (Figure 14) and the consistent inflow and outflow TP concentrations (Table 4).

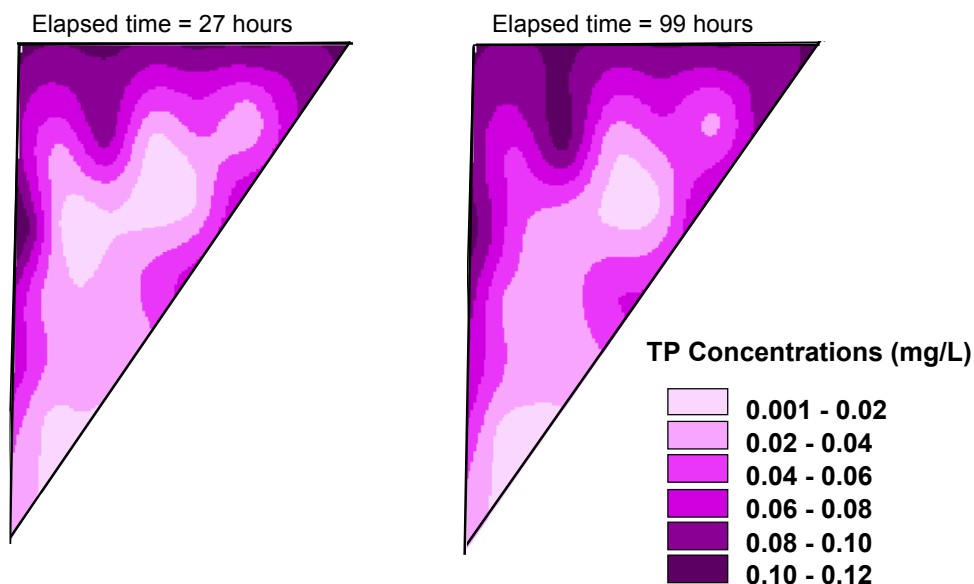


Figure 14. The distribution of total phosphorus concentrations (mg/L) within Cell 4 at 27 and 99 hours following tracer injection.

Table 4. Total P concentrations in the inflows and outflows of Cell 4 during ten days surrounding the onset of the dye tracer study. Rhodamine-WT was injected on December 16, 1999.

Date	Elapsed Time (days)	Inflow* (µg/L)	Outflow** (µg/L)
Dec. 15, 1999	-1	91	30
Dec. 20, 1999	4	100	28
Dec. 25, 1999	9	96	26
Mean		96	28

* Composite of grab samples from Culverts A,C, and E at G-254.

** Composite of grab samples from Culverts A,B,C,D, and E at G-256.

The Phosphorus Removal Efficiency of Cell 4

It is well known that treatment wetlands exhibit spatial variations in vegetation density that affect treatment efficiency (DBEL 1999; Kadlec 1999). When sparse vegetation dominates within a flow

path, the removal efficiency is lower because of higher velocities and more dispersion compared to the slower flow paths through dense biomass.

In the case of short-circuiting, a portion of the incoming water travels rapidly through the wetland with only partial treatment. This can lead to the illusion of a high background concentration (C_b), when in reality a lower C_b may be attainable. Based on our dye study, we have located the short-circuiting areas of the wetland (Figure 9), which facilitates the following analysis of the P removal characteristics of Cell 4.

To better describe the impact of short-circuiting on P removal within Cell 4, we divided internal sampling data into two groups: "inside" and "outside" the short-circuited areas. Flow partitioning between the two groups of stations is approximately equal according to our simple HEC-RAS model (DBEL, 2000). The data set representing the stations within the sparsely SAV-populated, deeper, short-circuited areas (i.e., "inside" stations) consistently had higher total P concentrations for a given distance down the wetland length than the data set for the more densely vegetated, shallower areas of Cell 4 (i.e., "outside" stations) (Figure 15). Although Kadlec (1999) advises using long-term averages to avoid synoptic error and stochastic variability, we still were able to achieve significant linear and exponential fits to the two sets of data based on only the average of two grab samples a few days apart. Because of the short-term nature of the data set, the outlier in the "outside" data (Figure 15) could not be "averaged out" with longer-term data. Deleting the outlier from the data set would increase the r^2 -value for the exponential function from 0.61 to 0.84.

Not only is there a distinct difference in P concentrations between the two data sets, but there is also a difference in their respective P removal responses with distance from the inflow (Figure 15). For the stations "inside" the short-circuited areas, the decrease in P concentration with distance was a linear function, while that of the "outside" stations followed a more exponential decay. The asymptote for these latter stations, which can be considered an apparent background concentration (C^*) under the hydraulic and P loading conditions during the dye study, was 23 $\mu\text{g/L}$. Because of the effects of short-circuiting and higher-than-normal hydraulic loading, this C^* may be higher than what the wetland could potentially achieve.

For the hydrologic conditions that existed during the dye study, the effects of the short-circuiting may be estimated to some degree by the difference between the flow-weighted outflow concentration (28 µg/L) and some of the lower P concentrations within the internal "outside" stations (e.g., 15-20 µg/L). At first glance it appears that reduced removal efficiency associated with the short-circuiting may have contributed an extra 8-13 µg/L of P to the final outfall concentration of Cell 4 under the prevailing loading conditions during the dye study. If short-circuiting within the cell were eliminated, however, this improvement might not be as dramatic since it would result in a more even distribution of the hydraulic and P loading to all areas (both "inside" and "outside" zones).

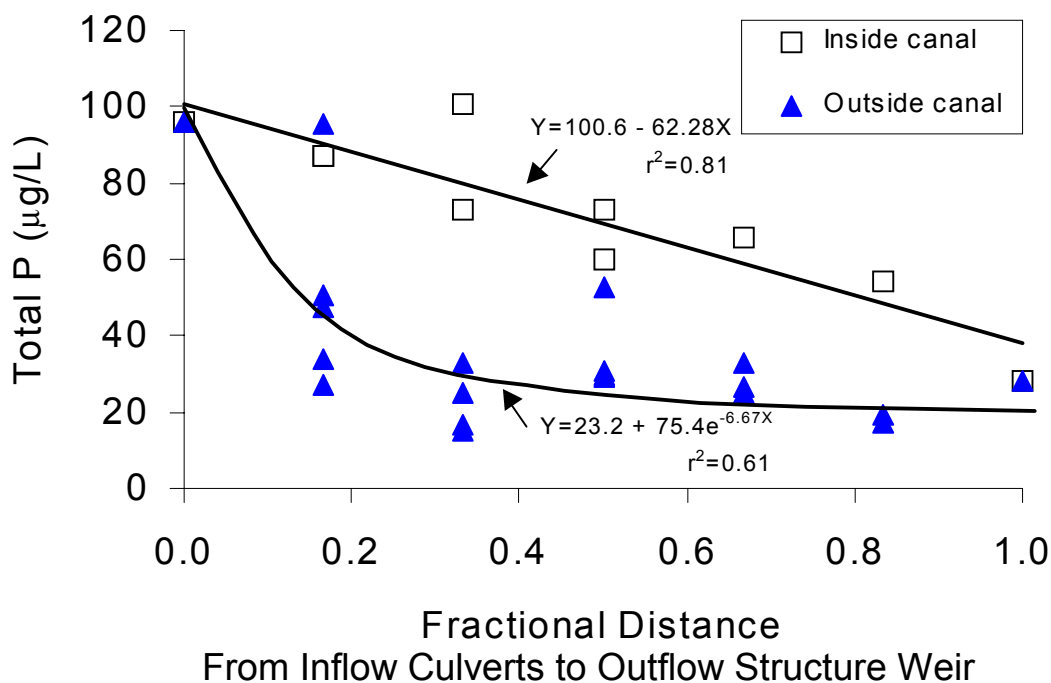


Figure 15. Mean total phosphorus concentration profiles (n=2) along two flow paths within Cell 4 on December 17 and 20, 1999. The open boxes and closed triangles, respectively, represent stations located inside and outside the relict borrow canals.

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Appendix A

Demonstration of Submerged Aquatic Vegetation/Limerock Treatment Technology for Phosphorus Removal From Everglades Agricultural Water Follow-On Study

**STA-1W Cell 4 Site Visit Report and Data Collection Plan
December 13, 1999**

Introduction

Cell 4 of STA-1W is an SAV-dominated wetland with a total area of 147 hectares (364 acres). A stable, diverse submerged plant community has developed and persisted in Cell 4 for four years. Field observations indicate that the dominant aquatic macrophyte is *Najas*. *Ceratophyllum* is the next most abundant species, and usually is found near the inflow region. *Potamogeton* is confined to an isolated area along the southwestern levee. The Cell 4 SAV community has performed well, exhibiting a P settling rate substantially higher than that of the other STA-1W Cells (Walker 1999; SFWMD, 2000).

Despite the good P removal performance of this Cell 4, there is visual evidence of short-circuiting, which could be impairing treatment performance (e.g., limiting the minimum achievable effluent P concentration) of the wetland. There are two borrow canals along the west and east levees with water depths approximately 2 ft deeper than the open water area. Aquatic macrophyte abundance is considerably lower in these canals than the open water area. We have observed high water velocities in these canals, which suggest water is short-circuiting in this region.

As part of Task 7 of the SAV/LR Follow-On contract, DBEL is preparing to conduct a tracer study using the fluorescent dye, Rhodamine WT, to quantify the area and degree of Cell 4 hydrologic short-circuiting. The intent is to quantify the hydraulic performance of the system under historically 'typical' conditions. This document reports on the pre-study site visit and the experimental data collection plan for the dye study.

Review of Historic Data

Cell 4 has been operating continuously since August 1994. The District provided DBEL with spreadsheet data of historic Cell 4 hydrologic parameters; the file contained complete data from January 1995 through April 1999. The District also supplied a separate spreadsheet with historic culvert flows between January 1995 and July 1999.

Figures A1-A3 depict time histories of mean monthly depth, hydraulic loading rate and

retention time, respectively, in Cell 4. Table 1 summarizes means, standard deviations, and ranges for these parameters for the entire period of record and for the last year of record. Over the life of the system, water depth varied consistently around a 0.63 m mean depth (stage = 11.75' NVGD). However, hydraulic loading showed considerably greater fluctuation during the first two years than during the most recent three years.

From 1994-1999, inflow from Cell 2 into Cell 4 was provided through five culverts; in the near future, that number will be increased to nine culverts. We summarized means, standard deviations, and fraction of total flow for each culvert for the entire period of record and for the last year of record (Table 2). We also prepared a time history of fraction of total flow through each culvert into Cell 4 (Fig. A-4). Two significant factors can be extracted from the culvert data. First, inflow is not equally distributed between culverts. Second, there was no historical correlation between flow fractions in the culverts; for example, culvert 254-B has supplied both the maximal and minimal flow fractions over the period of record.

To facilitate interpretation of Cell 4 performance data from 1994-1999, it is important to conduct the dye study under 'typical' historic conditions. From our review of historic data, we make the following recommendations regarding the dye study:

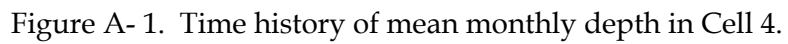
- Water depth in Cell 4 during the study should be approximately 0.63m; this is equivalent to a Cell 4 stage reading of approximately 11.7 feet.
- Throughout the duration of the dye study, SFWMD should make efforts to maintain total culvert inflow to Cell 4 as close as is possible to 94 cfs. This flow rate represents the mean historic flow into Cell 4 over the last five years. The most meaningful test results will be achieved with flow maintained at or near this value, with minimal fluctuations.
- It may be desirable to conduct an additional dye study at some point in the future at flow and stage representative of future operating conditions.
- Addition of dye will be flow-weighted to culvert inflow rates, since culvert flows are not equal.
- Flow-weighting dye should be based on most recent available culvert flow data, since there is no historical correlation between culvert flows.

Table 1. Summary Table for Cell 4 Hydrologic Parameters

Parameter	Units	Mean Values		Std. Dev		Range	
		1/95 - 4/99	5/98 - 4/99	1/95 - 4/99	5/98 - 4/99	1/95 - 4/99	5/98 - 4/99
Water Depth	(m)	0.63	0.63	0.1	0.1	0.43 - 0.81	0.43 - 0.77
Retention Time	(days)	5.11	5.99	2.68	2.98	1.78 - 14.8	3.52 - 14.8
Loading Rate	(hm ³ /day)	0.23	0.18	0.12	0.07	0.04 - 0.60	0.04 - 0.34
	(cfs)	94	73.6	49	29	16.3 - 245	16.3 - 139
	(cm/d)	15.7	12.5	7.9	4.8	2.90 - 40.9	2.90 - 23.2

Table 2. Summary of Cell 4 Culvert Inflows

Culvert	Mean Flow (m ³ /d)		Flow Range (m ³ /d)		Fraction of Total	
	1/95 - 7/99	8/98 - 7/99	1/95 - 7/99	8/98 - 7/99	1/95 - 7/99	8/98 - 7/99
254 A E	40276	31079	0-120600	7500-48800	0.18	0.19
254 B	36980	22961	0-142000	7600-45000	0.17	0.14
254 C	44253	28708	8600-121500	8600-47600	0.20	0.17
254 D ↓	46843	38416	11500-116000	11500-55900	0.21	0.23
254 E W	55142	44123	12500-110600	15800-57800	0.25	0.27
Totals	223500	165300	68500-601000	68500-219200	1	1



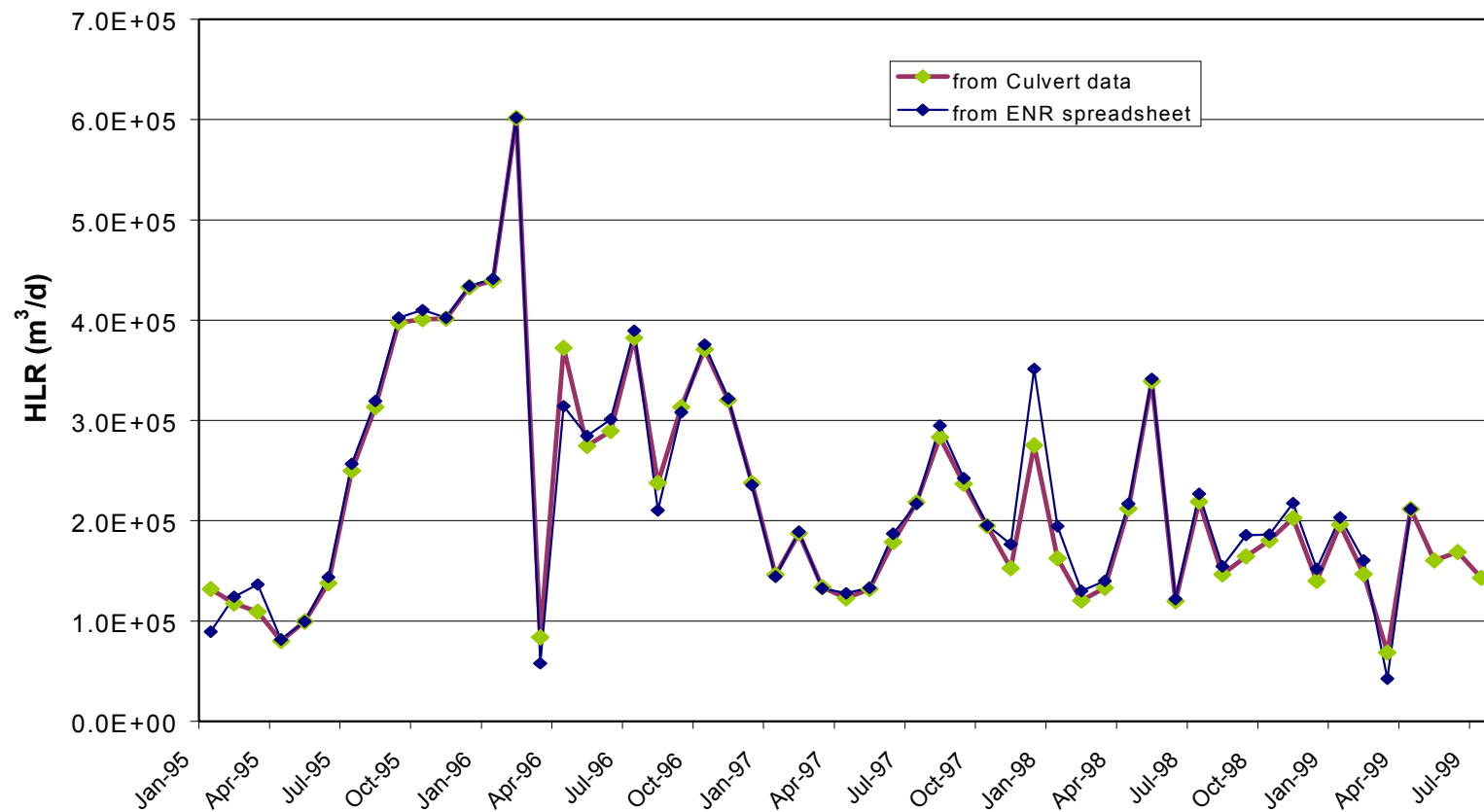


Figure A- 2. Time history of hydraulic loading rate in Cell 4. Loading rate showed more variation in earlier years than in most recent years.

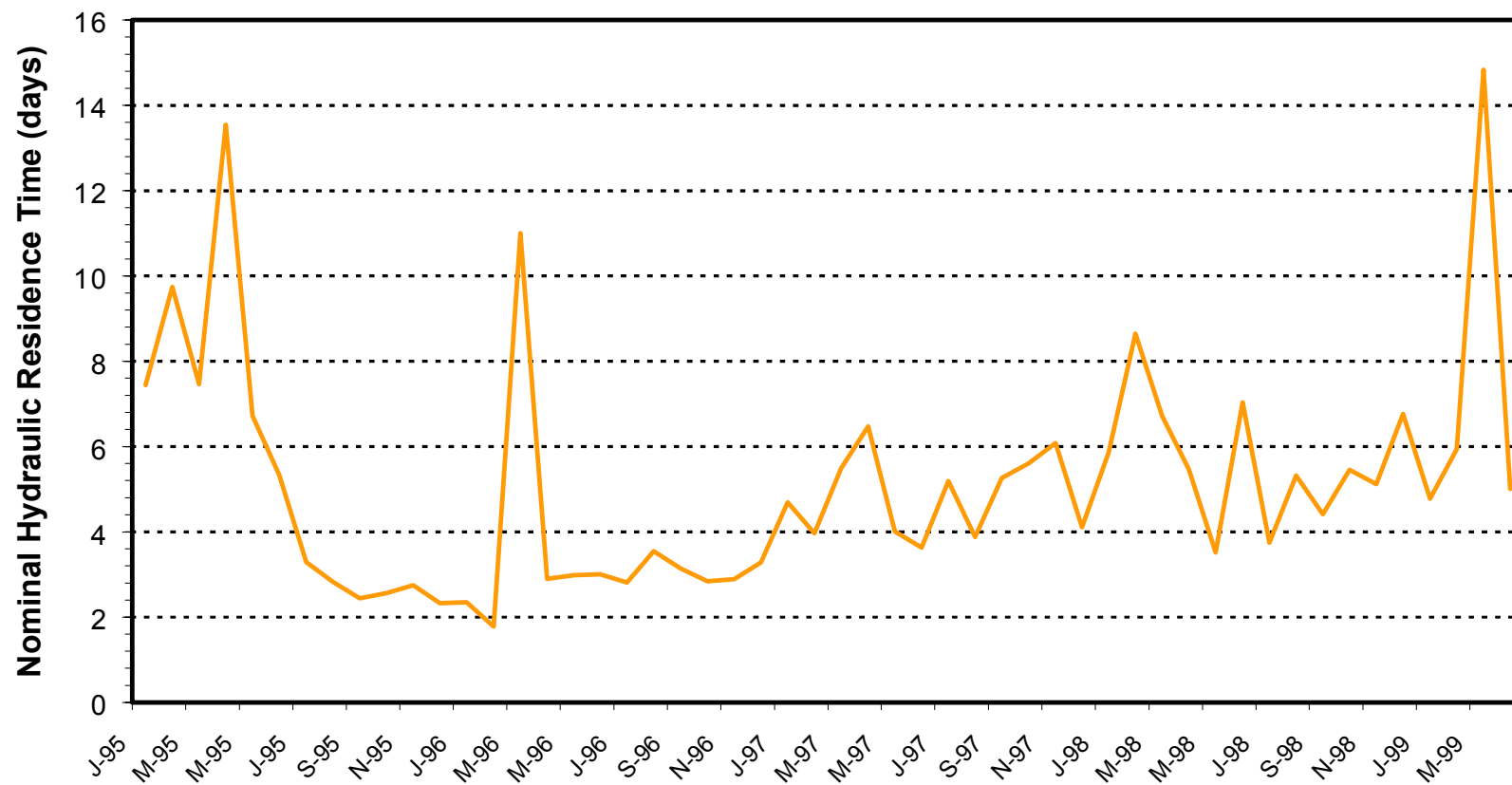


Figure A- 3. Monthly average hydraulic residence time in Cell 4 since commencing operation.

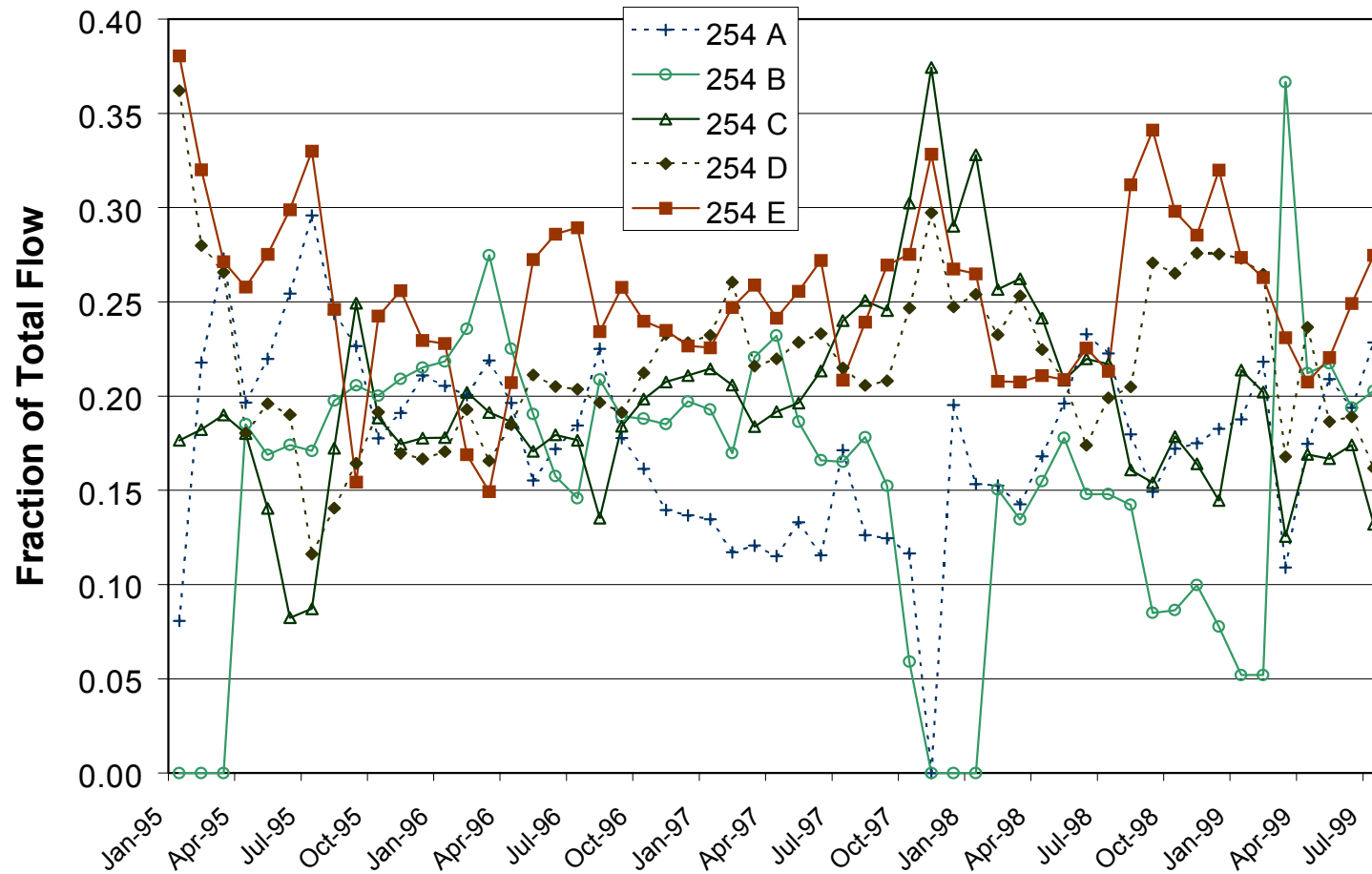


Figure A-4. Flow partitioning among the five (5) Cell 4 inlet culverts. There is no historical relationship between flow partitioning in the five Cell 4 inlet culverts.

Results of Site Visit

A site visit of Cell 4 was conducted on September 27, 1999, by DBEL's Site Project Manager. During the visit, he inspected stage, culvert flows, and the elevation of the outflow structure. The following observations are pertinent to this tracer study:

- There are nine culverts between Cell 2 and Cell 4, only five of which were flowing. SFWMD has indicated to DBEL that the five flowing culverts are the same culverts that have been operating historically.
- The stage in Cell 4 measured around 12.7 feet and was approximately 1' deeper than usual. The SAV canopy, which is often topped out, was submerged by 6" of water.
- Water velocity in the short-circuit area along the eastern berm seemed appreciably lower under these flooded conditions than normal conditions.

These observations have the following impact on our study:

- Since we wish to mimic historic inflow patterns, the four new culverts should remain closed for the study duration.
- Since we wish the study to mimic historic stage and flow patterns within the wetland, the dye study should be conducted during a period when Cell 4 is managed for normal stage and normal loading rates. For meaningful experimental results, continuation of 'normal' steady-state conditions should be guaranteed for 4 - 6 weeks after the tracer injection date.

Tracer Study Methods

Field Methods

Tracer Dosage

Rhodamine WT is an organic compound belonging to the xanthene dye family with color index name of acid red 388. We selected this dye as a tracer for the Cell 4 study based on its cost effectiveness, and the following successful past experiences with this chemical.

- Rhodamine WT was successfully used as a tracer in four SAV-dominated ENR test cells during a November 1999 study (DBEL, results to-appear in Follow-On Study 1st quarterly report). Dye recovery in the four test cell studies was good, ranging from approximately 78-90%.
- Rhodamine WT was successfully used as a tracer in the buffer cell of the ENR in 1994 (M. Chimney, unpublished documents);
- Rhodamine WT was successfully used as a tracer in SAV mesocosms in Phase 1 of this study;
- Rhodamine WT has a visible trace at concentrations as low as 30 µg/L;
- Rhodamine WT is not hygroscopic;
- Rhodamine WT does not react exothermically when added to water;
- Rhodamine WT is not readily absorbed via plant uptake in SAV communities. Turner et al. (1991) reported 95% of initial dye remained in *Hydrilla*-containing aquaria 96 hours after dosage.

There are at least two methods for calculating dye dosage volume for a wetland tracer study. The first is based on a plug-flow assumption and uses the following empirical equation developed by Kilpatrick (1970) for natural streams:

$$V_s = 3.4 \times 10^{-4} (QL/v)^{0.94} C_p \quad (1)$$

Where C_p is the peak concentration at the sampling site, in µg/L;

L is the distance to the downstream site, in miles;

Q is the discharge, in ft³/sec;

V_s is the volume of Rhodamine-WT dye (20%), in L

v is the mean-stream velocity, in ft/sec.

Using a peak dye concentration of 50 $\mu\text{g/L}$ at the discharge point and the following values derived for average conditions in Cell 4 during the May 1998 to April 1999 period:

$$Q=73.6 \text{ ft}^3/\text{sec}$$

$$L=1.3 \text{ miles}$$

$$v=Q/A \text{ where } A \text{ is the cross-sectional area } [2.07 \text{ ft deep} \times 2461 \text{ ft wide}] = 0.01444 \text{ ft/sec}$$

we obtained a V_s of 66.4 L of 20% Rhodamine dye from Eq (1).

The second method for estimating the volume of 20% Rhodamine-WT to be added to Cell 4 is to assume a more liberal mixing regime (i.e., constantly stirred tank reactor [CSTR]). Based on the area and average depth of Cell 4 (146 ha and 0.63 m), 57.8 gallons (219 L) of Rhodamine-WT dye will be required to achieve an initial concentration of 50 $\mu\text{g/L}$. A 50 $\mu\text{g/L}$ target concentration results from tradeoff considerations between resolution in dye concentration measurement and dye cost, which is appreciable at this scale. DBEL's Phase 1 mesocosm dye studies were conducted with a target CSTR concentration of 100 $\mu\text{g/L}$.

DBEL has more confidence in the simple dilution calculation for a CSTR than the calculation based on Eq (1) for the following reasons:

- dye tracer studies performed in the SAV mesocosms during Phase I of the SAV/LR investigations indicated a mixing regime that more closely resembled a CSTR than plug flow,
- those tracer studies yielded peak effluent dye concentrations approximately equal to the calculated concentrations, which had been based on the CSTR dilution assumption,
- the presence of SAV, the relatively slow velocities, and the short-circuiting within Cell 4 creates conditions that are outside the boundaries established for the application of Eq. (1), and

- review of the buffer cell dye study in 1994, in which a Rhodamine-WT application of 10 gallons yielded peak effluent concentrations of 70 µg/L. This ratio of applied dye to peak outflow dye concentrations is approximately equivalent to our proposed 58 gallon dye application, when differences (buffer cell vs. Cell 4) in volumes and discharges are considered.

Tracer Injection

The date of dye injection will be coordinated with SFWMD. Ideally, on the dye injection date, steady-state hydraulic conditions (e.g., average water depth and discharge) will have been maintained within Cell 4 for at least a week and the continuation of those steady-state conditions should be promising for at least 2-5 weeks after the injection date.

Since the discharge rates differ among the five culverts (Table 2), the amount of dye placed in each of the 55-gallon drums (one drum per each of the five culverts) will be proportionate to the respective discharge rates through the culverts from Cell 2 to Cell 4. For example, the discharge through Culvert B was one-half that of Culvert E during the August 1998 to July 1999 period (Table 2); therefore, twice as much Rhodamine-WT dye would be injected into Culvert E than Culvert B. For this study, DBEL will use the most recently available culvert flow data for flow proportioning dye among culverts.

After placing the appropriate amounts of the concentrated dye into each drum, approximately 44 gallons of site water will be pumped into each of the five drums to dilute the concentrated dye roughly five-fold. After mixing the site water with the concentrated dye in each drum, the contents will be delivered to the end of each of the five culverts that connect Cell 2 to Cell 4. The dye delivery rate will be metered (by the appropriate valve setting) to empty the contents of each 55-gallon drum within a 10 - 30 minute interval. By both diluting the concentrated dye within each drum five-fold and metering the injection into each discharge stream passing through the culverts from Cell 2 to Cell 4, the density of the concentrated dye (1.14) will be reduced to that of water (1.00). Therefore, any possibility of the dye not mixing thoroughly with the inflow stream through the culverts because of density differences will be reduced.

Sample Monitoring Grid

In addition to the single sampling station at the outfall weir from Cell 4, five east-west transects will be established perpendicular to the general flow direction (Fig. A-5). Between three and seven equidistant sampling stations will be located on each transect. The locations of the sampling stations will be established by compass headings, local landmarks (e.g., power lines, platforms), and a hip chain. GPS coordinates will later be obtained for each station.

Sampling Frequency

Historically, the average residence time of Cell 4 has been 5 to 6 days. Considering the likelihood that short-circuiting occurs within the cell, we expect the frontal edge of the dye peak at the discharge weir to likely occur within the first day after dye injection. We therefore propose to sample at the outfall weir every 3-6 hours during the first 4-5 days. Thereafter, we will sample once per day for several days, segueing to an every-other day sampling frequency until the dye concentrations are reduced to approximately 5% of their peak concentrations. Final decision on sampling frequency at the outflow weir will be made in the field based on the developing history of measured dye concentrations.

Stations along the transects will be sampled on approximately six occasions. The internal sampling locations and times will depend on our initial observations of dye dispersion through the wetland, as well as how quickly it reaches the Cell 4 outflow weir. At most sampling locations, dye will be collected approximately several centimeters below the water surface. At selected stations and times, we will collect both surface (2.5 cm deep) and bottom (~10 cm above sediment) samples for dye analysis, as well as samples for analysis of P species. Cell 4 is relatively shallow (~0.6m) and samples collected at these two depths will further help to characterize its internal flow patterns.

Laboratory and Data Analyses

Fluorometric Analysis

Sampled waters will be stored in amber glass containers at room temperature until analyzed with a Turner Model 10-AU-005-CE fluorometer. Excitation and emission filter wavelengths are 545 and > 570 nm, respectively (Wilson et al. 1986). Since Rhodamine-WT fluorescence is sensitive to temperature, both standards and samples will be analyzed at room temperature. Field replicates will be collected at a 10% frequency. Prior to dye injection, background fluorescence of Cell 4 water will also be measured.

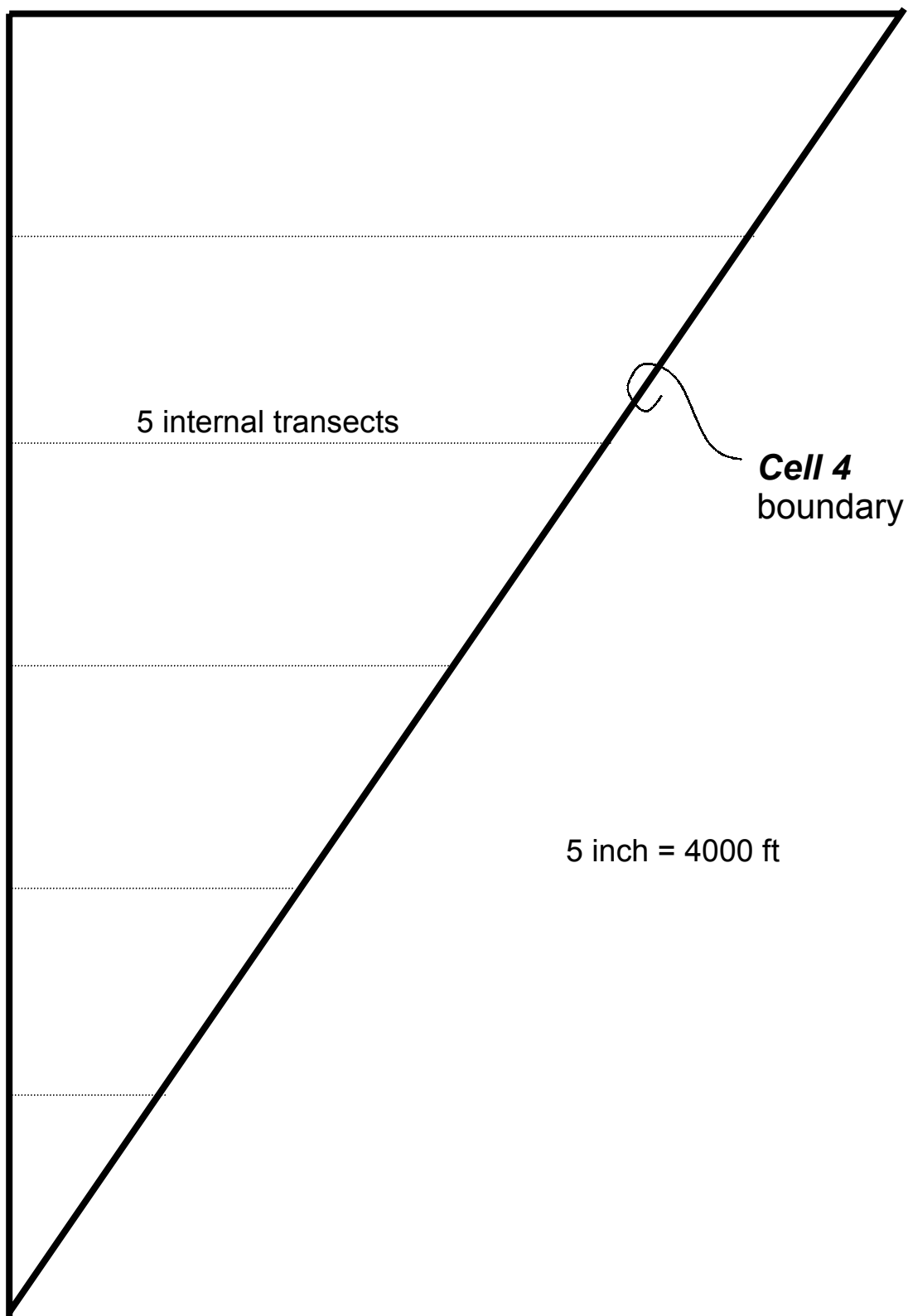


Figure A- 5. Transect locations for sampling sites in the Cell 4 dye study.

Data Analyses

Data collected during the study will be used to calculate the mean residence time, the residence time distribution, and dispersion coefficients for Cell 4. The spatial samples will enable us to pinpoint the locations of short-circuits and dead zones, and provide insight into the internal mixing patterns of the wetland. Data from this study will help guide optimization efforts on Cell 4, as well as improve the accuracy of existing performance forecast models that have been developed using Cell 4 data.

It is important to note that reduced data will be most useful for understanding Cell 4 hydraulic characteristics if inflow conditions are maintained steady or near-steady throughout test duration. Near-steady conditions are most essential during the initial 7 days of the study; during this period, the pulse of peak dye concentration should be recorded in Cell 4 effluent. After that period, variations of 10-15% are probably acceptable and should still allow for meaningful calculation of important hydraulic parameters, and hence meaningful information regarding historic Cell 4 hydraulic performance. Stochastic rain events are impossible to manage for in this study, but by conducting the dye study during the dry season, the likelihood of a major storm event should be low.

We propose to analyze the tracer data for the following hydraulic characteristics of Cell 4:

Hydraulic Residence Time (HRT)

The tracer residence time, defined as the average time that a tracer particle spends in Cell 4, will be calculated by dividing the first moment of the tracer flow distribution by the zeroth moment, both of which are based on mean outflow rates and tracer concentrations (Kadlec 1994).

Residence Time Distribution (RTD)

The RTD represents the time various fractions of water spend in Cell 4. It is the contact time distribution for the system (Kadlec 1994). To find the RTD, the concentration response

curve is converted to an E_t curve by changing the concentration scale so that the area under the response curve is unity (Levenspiel 1989). This is done by multiplying the concentration readings by the volumetric flow rate divided by the mass of injected tracer.

Time-of-Travel

Time-of-travel measurements represent the velocity. It is calculated by dividing the time of arrival of the dye cloud as measured by the peak concentration or centroid mass into the distance from the point of injection (Kilpatrick and Wilson 1989). We intend to measure the time-of-travel at the weir outfall station as a means of determining the velocity of the water flow within Cell 4.

Longitudinal Dispersion Coefficient (Optional)

Dispersion coefficients are often required in hydraulic mixing models. They are usually determined using tracer data either by the slope method or the variance method. The slope method relies on the first derivative of the RTD function at time equal to the average residence time. The variance method relies on using the variance of the concentration-time response to the pulse input of the dye (Hill 1977). Since the calculations rely on steady-state hydraulic conditions, invariant mass flow, and evenly spaced time increments, we will decide on whether to proceed with calculating longitudinal dispersion coefficients (for outfall structure data only) after we have examined the tracer data.

Spatial/Temporal Mixing Characteristics

A time history of spatial concentration fronts will be produced with data collected along internal transects. GPS coordinates for transect collection points will allow data to be linked to GIS maps. Spatial Analyst, a feature within the ArcView platform, will produce interpolated contour maps from measured concentrations on the collection grid. The time-history of spatial concentrations should provide strong evidence for location and severity of hydraulic short-circuiting.

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