Appendix 4-9: Baseline Tracer Study: STA-2, Cell 3 Final Report

DB Environmental, Inc. and
Milian Swain and Associates, May 2005

BASELINE TRACER STUDY:
STA-2, CELL 3

FINAL REPORT

(C#ML040333)

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Executive Summary

The South Florida Water Management District (District) is continuing efforts to optimize and improve the total phosphorus (TP) removal performance of the Stormwater Treatment Areas (STAs) through the implementation of enhancements described in the Long-Term Plan for Achieving Water Quality Goals. One enhancement recommended for several large STA cells is the construction of an additional levee to improve hydraulic characteristics by redistributing water flow. The District intends to construct such a levee in Cell 3 of STA-2 as soon as possible after flow-through operation of the new Cell 4 commences.

The objective of the current project was to characterize Cell 3's hydraulic residence time (HRT) and internal distribution of flow and P concentrations prior to construction of the levee. A follow-up characterization likely will be performed after levee construction. This document describes the methodology and results of the initial hydraulic characterization of this large (2,220 acre) submerged aquatic vegetation (SAV)-dominated wetland.

DB Environmental, Inc. (DBE) initiated the field component of the tracer study on October 21, 2005, and completed the effort 25 days later. Approximately 8,524 liters of lithium chloride (LiCl) were utilized as the tracer, and this was distributed on a flow-weighted basis among the five Cell 3 inflow culverts. We monitored Cell 3 outflow lithium concentrations at the outflow structure, and we also performed internal monitoring at a network of pre-determined sampling stations to characterize the internal profiles of both lithium and phosphorus. Key findings of this effort are as follows.

Wetland inflows exceeded outflows for much of the study, so Cell 3's stage generally increased during the tracer assessment. We therefore performed a water balance to confirm the accuracy of District inflow and outflow data. Approximately 90% of inflows were accounted for with measured outflows or stage change. The remaining 10% was thought to be due to a combination of seepage and measurement errors.

The lithium tracer reached the outflow structure between 5 and 6 days after tracer injection. The peak outflow lithium concentration (220 μg/L) was observed one day later. Internal monitoring

demonstrated that the tracer proceeded most rapidly along the western and central portions of the cell, regions dominated by submerged aquatic vegetation (SAV). There was a lag in tracer passage through the eastern portion of the cell, which is dominated by cattail and sawgrass. In general, however, both the outflow tracer response curve and the internal tracer profiles depicted relatively efficient hydraulic characteristics.

Internal sampling of water column phosphorus (P) species during the study revealed total P levels exceeding 100 μg/L near the inflow region of the cell, but these dropped markedly in the outflow half of the wetland. Declines in soluble reactive P with distance from the inflow were even more rapid.

Tracer recovery, based on comparing the mass of lithium injected with that recovered at the cell outflow, was 96.6%. Lithium concentrations in the seepage return canal remained near background levels during the study. The measured Cell 3 hydraulic retention time (HRT), based on the tracer data, was determined to be 10.8 days. This was identical to the nominal HRT calculated for the varying flow and stage conditions that prevailed during the study.

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Introduction and Background

The Everglades is an internationally recognized ecosystem and represents the largest subtropical wetland in the United States. During recent decades, the biotic integrity of the Everglades ecosystem has been affected by alterations of the hydrologic and nutrient regimes resulting from agricultural and urban development. Research has shown that both hydrologic improvements and a reduction in the level of total phosphorus (TP) in the runoff from the Everglades Agricultural Area (EAA) and urban areas are a prerequisite to restoring and protecting the remaining Everglades.

The South Florida Water Management District (District) and other parties are aggressively pursuing measures to reduce TP concentrations in EAA runoff. Several measures to reduce TP concentration levels have been implemented and include EAA landowner Best Management Practices (BMPs), and construction and operation of Stormwater Treatment Areas (STAs). These phosphorus control programs have proven very effective at reducing phosphorus concentrations going into the Everglades. In 2003, the Environmental Regulation Commission (ERC) proposed a numeric water quality standard for phosphorus in the Everglades. The proposed rule establishes a phosphorus standard of 10 parts per billion for the entire freshwater area of the Everglades Protection Area (EPA). The District is continuing the efforts to optimize and improve the TP removal performance of the STAs through the implementation of the STA enhancements presented in the Long-Term Plan for Achieving Water Quality Goals (Burn & McDonnell, 2003). Preliminary modeling results presented in the Long-Term Plan have indicated that compartmentalization of some of the STA treatment cells may improve the hydraulics of the wetland by reducing short circuits, thereby increasing the TP removal performance of the treatment system.

The original performance forecast model for the STAs assumed that these systems operated as plug-flow reactors. However, a tracer assessment of the SAV-dominated STA-1W Cell 4 demonstrated that flow patterns may depart widely from ideal plug-flow characteristics and that large short-circuits can exist. These short-circuits result in a portion of the influent water reaching the outflow of the system before the calculated hydraulic residence time (HRT), thereby reducing the TP removal efficiency of the system. These non-ideal flow patterns

typically remain intact until the water is redistributed by structural means, such as an additional levee that partitions the treatment cell into two areas. It is the intention of the District to construct an internal levee within STA 2 Cell 3 as soon as possible after flow-through operation of the new Cell 4 commences. For additional information, refer to the Revised Part 2 of the Long-Term Plan dated November 2004, at http://www.sfwmd.gov/org/erd/Longtermplan/documents.shtml.

This final report summarizes the results of a hydraulic assessment in STA-2 Cell 3 prior to the construction of the internal levee.

Objective

The overall objective of this project is to characterize the wetland hydraulic retention time (HRT), the distribution of flow, and the internal P concentrations prior to the construction of the levee in STA-2 Cell 3. A follow-up characterization likely will be performed after levee construction, which will enable District staff to assess the impacts of levee deployment on STA hydraulic and phosphorus removal performance.

Project Location

STA-2 is located in southern Palm Beach County, adjacent to the southwestern section of Water Conservation Area 2A (WCA-2A). STA-2 is a 6,430 acre treatment wetland, constructed on former agricultural land, consisting of three treatment cells. The tracer study was performed in Cell 3, which is 2,220 acres in size. This cell is maintained as an SAV system dominated by southern naiad (*Najas guadalupensis*), pondweed (*Potamogeton illinoiensis*) and hydrilla (*Hydrilla verticillata*). The expected HRT for this study was 7 days. The wetland contains some navigation hazards such as underwater rocks and agricultural ditches. Water is pumped through the S-6 structure to the inlet canal and then flows through 5 culverts (G-333 A through E), into Cell 3. Water exits Cell 3 through the G-334 outlet structure (Figure 1).

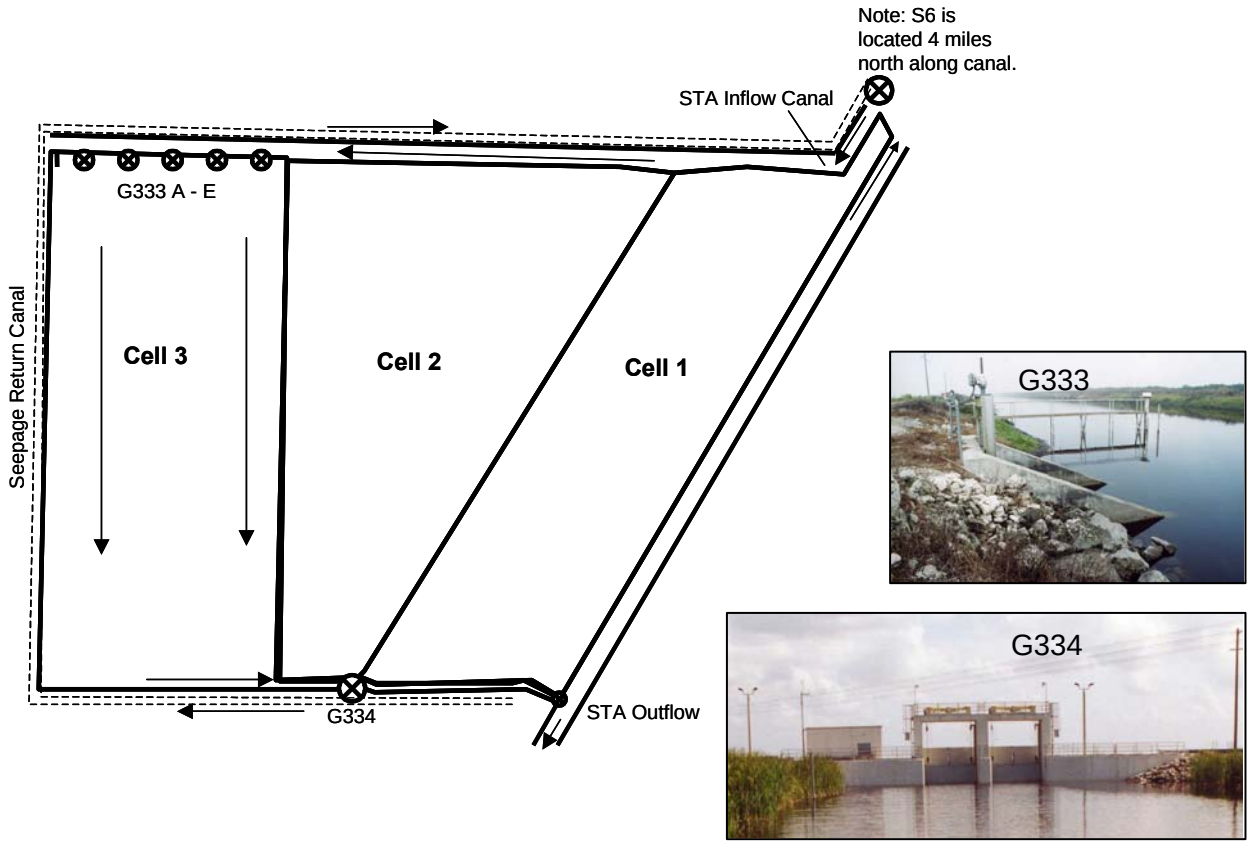


Figure 1. Map depicting flow path and structures within STA2 Cell 3.

Overview of Scope of Work

This project consisted of five tasks that were performed over a 44-week period. These include a Project Work Plan, Kickoff Meeting, Tracer Project, Draft and Final Report, and a Technical Review Meeting to present the findings of the study. This document represents the Final Report for this effort.

The lithium tracer solution was released into Cell 3 on October 21, 2005, through a flow-weighted distribution at the five G-333 culverts. Monitoring at the G-334 outflow structure began immediately upon release of the tracer. Sampling was conducted for a period of time

estimated to be sufficient to capture the majority of the lithium at the outflow structure, i.e., after the peak concentration passes. Outflow sampling was conducted with time-proportional autosamplers. In addition to routine outflow tracer sampling, grab samples for lithium and phosphorus species were collected at internal locations to help characterize the internal flows and phosphorus concentrations, and to document any short circuiting.

This effort was managed by Ms. Lori Wenkert and Mr. Warren Wagner, Project Managers for the District, and by Mr. Thomas DeBusk, Project Manager for DBE. In addition, personnel from the firm Milian, Swain and Associates (MSA) assisted DBE with field efforts.

Methodology

Tracer Injection

The method of tracer injection is one of the more critical steps in achieving a successful tracer study outcome. Since a pulse of tracer was applied to each inflow culvert, it was essential that each culvert received an amount of tracer mass in proportion to its flow, over an equivalent and relatively short time period.

We determined that a minimum of 8,524 L (2252 gal) of 40% LiCl solution were needed to be injected among the five inflow culverts in Cell 3 to achieve a CSTR concentration of 200 µg/L as Li^+. This calculation, and assumptions upon which it is based, are provided in the Appendix.

Flow measurements were performed the day before the lithium was injected by adding a small amount of Rhodamine-WT™ dye tracer to the inflow end of each culvert. The velocity within each culvert was calculated as the time of transit of the dye cloud through the fixed length of culvert. Flow was then calculated as the product of velocity and the submerged cross-sectional area of the culvert. This measurement was repeated several times for each culvert, and the results averaged to obtain a flow value for each culvert (Table 1).

Based on the flow distribution findings for the inflow culverts, we pumped the appropriate flow-weighted mass of lithium to each inflow culvert (Table 1) from five large reservoirs (ca. 600 gallons), whose inflow points were carefully positioned above the surface of the water

streaming through the culverts (Figure 2a). The lithium chloride was delivered from each reservoir to the upstream side of each inflow culvert by means of an electric pump, which provided a feed rate of approximately 3 gpm (11 L/min.). A gasoline pump (5 hp) also was deployed adjacent to each reservoir (Figure 2b). These pumps were used to inject 100 gpm of dilution water, obtained from the inflow canal, adjacent to the lithium chloride delivery line. The 2" PVC water dilution pipe, along with the injection tubing from the reservoir, were held in place above the inflow culvert using a wooden 4X4 and bracket assembly (Figure 2c).

Table 1. Volumetric flow rate (as determined by rhodamine-WT travel time and cross-sectional area of water in culvert), percentage of the total flow, and the number of gallons of LiCl injected for each of the five inflow culverts (G-333 A-E) at Cell 3 of STA-2. Flow rate measurements were performed one day prior (October 20, 2004) to the injection of LiCl.

Culvert	Rhod-WT Travel (sec)	Flow Rate (cfs)	Percent Total Flow	LiCl Injected (gals)
A	9.8	87.5	19.9	440
B	10.3	98.1	22.3	495
C	10.4	85.2	19.3	412
D	12.9	77.2	17.5	385
E	10.3	92.7	21.0	468
Total		**440.7**	**100.0**	**2200**

Since the specific gravity of lithium (1.25) is higher than that of water (1.00), we were interested in obtaining rapid dilution upon injection to prevent tracer density gradient effects. The dilution provided by the pumped water flow at the point of injection was effectively 33 to 1. This, along with the 96.5 – 98.3 cfs range measured among the five culverts resulted in a further 1: 14,896 dilution. The resulting density increment contributed by the LiCl to the inflow water after mixing therefore was negligible.

We utilized a team of 9 field personnel to inject the tracer, with two persons dedicated to the delivery of tracer at 4 of the culverts; the remaining fifth culvert was manned by one person. We coordinated the commencement (14:30 on October 21) of tracer delivery to each culvert with a phone signal. To ensure adequate mixing of the relatively dense lithium chloride with the inflow waters, we slowly "bled-in" the tracer solution at each culvert for periods ranging in duration from 2 hours and 12 minutes to 2 hours and 37 minutes.

To eliminate the possibility of equipment problems, duplicates of all mechanical equipment, including autosamplers, batteries, and pumps were kept on-site. To minimize other logistical problems we also performed a dry run of all tracer injection methods 48 hours prior to the actual tracer deployment.

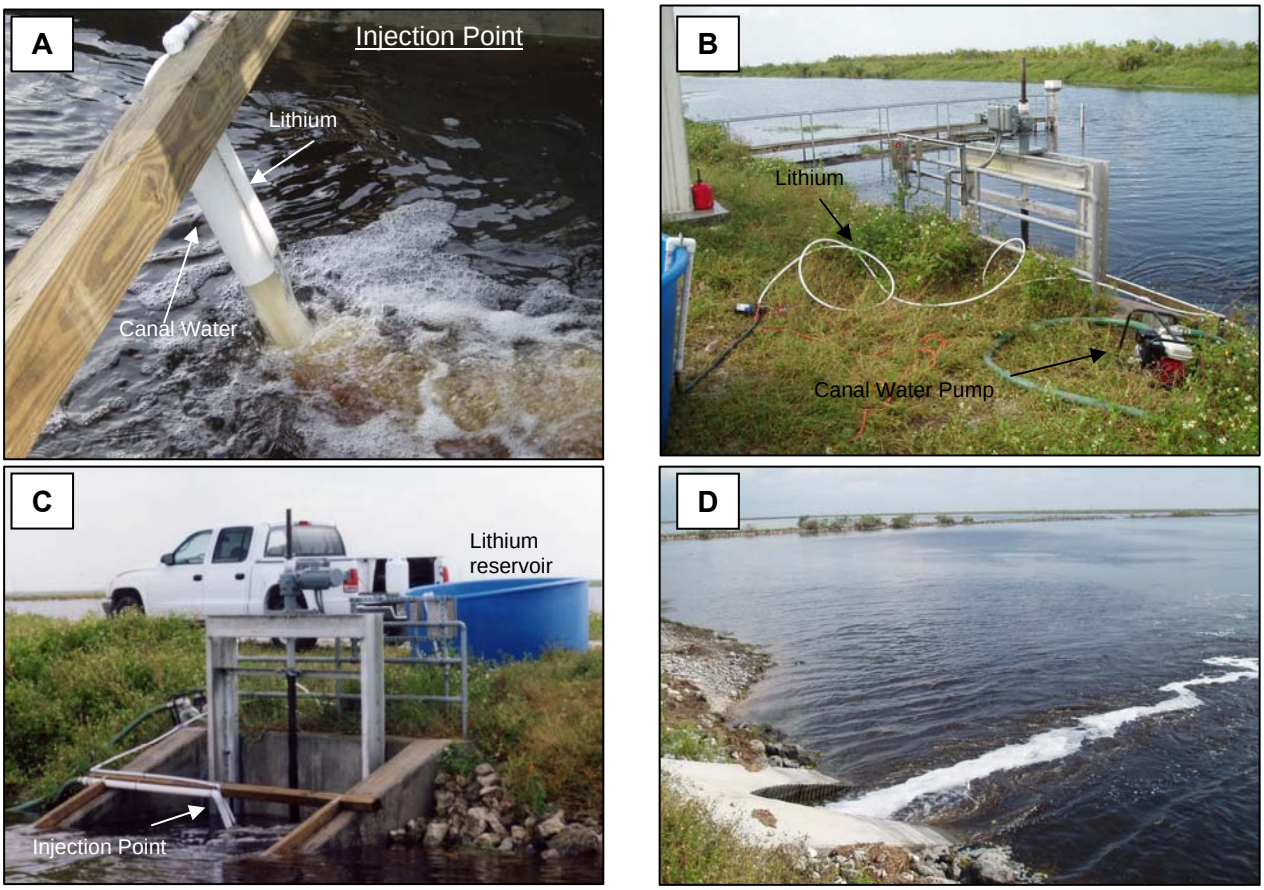


Figure 2. A) Close-up of the injection point at the entrance of a submerged culvert at G-333. **B)** Lithium and canal water pumps and delivery lines at an inflow culvert at G-333 with the supply canal in the background. The lithium reservoir is the tub at the far left. **C)** Lithium and canal water delivery system at an inflow culvert at G-333. The injection period lasted approximately 2.5 hours. **D)** Discharge from an inflow culvert at G-333 into Cell 3 during the lithium injection period.

Inflow and Outflow Monitoring

Once the tracer was injected into the wetland, the collection of samples for lithium analyses commenced at the outflow structure (G-334) using time-proportional autosamplers. The water

passing through this structure was monitored for a maximum of three nominal HRTs, which was estimated to be a sufficient time to capture the majority of the lithium at the outflow structure (G-334) and to allow for the development of an acceptable tracer response curve. Projected inflow into the cell during the tracer study resulted in a nominal HRT of approximately 7 days. The sampling frequency at the outflow structure was every two hours for the first HRT of collection, every four hours for the next HRT, and every eight hours for the remainder of the project.

Monitoring of the inflow stations throughout the project consisted of flow, lithium and phosphorus measurements. Flow was measured on October 14, 19, 20 (two times on this date), and November 2, 2004 at each culvert using the technique described in the Tracer Injection section (i.e., dye tracer), as well as a velocity meter (Swoffer Model 2100). Lithium and phosphorus concentrations were analyzed twice weekly after compositing an equal volume of water from each of the five culverts. We also measured the flow at the outflow structure (G-334) using the Swoffer Model 2100 velocity meter and a second velocity meter (Type AA USGS), on October 31, 2004.

Not every sample collected was analyzed for Li^+; outflow tracer samples analyzed represented 46% percent of the total samples collected. The Li^+ concentration data were depicted as a time series graph and submitted to the District for review. The District, with the assistance of DBE personnel, determined no further lithium analyses were needed.

In addition to collecting flow, tracer and phosphorus data at the inflow and outflow structures, we also periodically collected a surface water sample for Li^+ analysis from the seepage return canal (Figure 3) on the same days that the internal sampling was performed. This sampling station was added to check whether Li^+ in seepage from Cell 3 was significant enough to affect the tracer mass recovery.

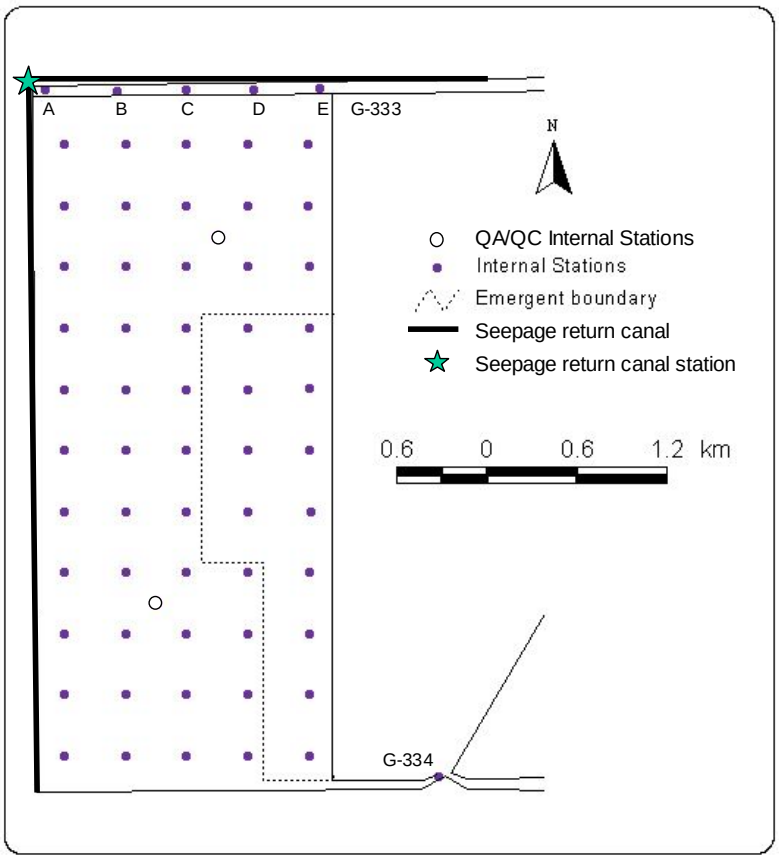


Figure 3. Site map showing the location of the internal stations where lithium and phosphorus samples were collected and vegetation type identified. The distance between nodes is 400m. The area enclosed by the dashed line represents the zone dominated by emergent vegetation (*Typha* and *Cladium*). The single station in the seepage return canal is the location where surface water was occasionally sampled for lithium analysis. Inflow culvert locations are designated A, B, C, D, and E.

Internal Monitoring

During this project we performed internal monitoring at the stations shown in Figure 3 on days 1, 4, 6, 8, 10, 12, 14 and 18 after tracer injection. Except for the two additional internal QA/QC stations depicted in the figure and the eight stations along the easternmost transect within the emergent zone, this grid utilizes coordinates provided by the District. Lithium concentrations were analyzed during every internal monitoring event, while total phosphorus, total dissolved phosphorus, and soluble reactive phosphorus concentrations were analyzed every other event. The presence/absence of vegetation at each location was recorded during the first and last sampling events. To ensure the entire sample grid could be sampled in one day, we utilized two

field crews with airboats for three of the four sampling events that entailed collection of both lithium and P samples.

Computations for Determining Hydraulic Parameters

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 mean tracer residence time, τ_a, is defined as the average time that a tracer particle spends within a basin, and is the first moment of the residence time distribution (RTD) function. The RTD represents the time various fractions of water spend within a basin. 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):

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

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

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

where C(t)=exit tracer concentration (mg/m^3); Q_e = flow rate (m^3/d); t = elapsed time (d); and t_f = total time span of the outflow pulse (d).

Results and Discussion

We terminated the data collection after 25 days (on November 15, 2004) from the date of injection when the Li^+ concentrations at G-334 were only 6 µg/L above the background (13 µg/L) (Table 2). This represented an additional 4 days of data collection beyond the 21 days based on the original estimate of three nominal HRTs.

Table 2. Raw lithium concentrations (µg/L) for samples collected during the tracer study at G334. The lithium tracer was injected on October 21, 2004 at 14:25. The method detection limit was 10 µg/L.

Sample Date/Time	Δ Time	Li^+ (µg/L)	Sample Date/Time	Δ Time	Li^+ (µg/L)
10/21/2004 14:25	0.0	12	11/1/2004 14:25	11.0	75
10/22/2004 00:25	0.4	14	11/1/2004 22:25	11.3	91
10/22/2004 14:25	1.0	14	11/2/2004 06:25	11.7	69
10/22/2004 20:25	1.3	17	11/2/2004 14:25	12.0	71
10/23/2004 14:25	2.0	10	11/2/2004 22:25	12.3	63
10/23/2004 22:25	2.3	13	11/3/2004 06:25	12.7	89
10/24/2004 06:25	2.7	<10	11/3/2004 14:25	13.0	80
10/24/2004 12:25	2.9	16	11/3/2004 18:25	13.2	75
10/24/2004 14:25	3.0	17	11/4/2004 02:25	13.5	70
10/24/2004 22:25	3.3	15	11/4/2004 10:25	13.8	62
10/25/2004 06:25	3.7	<10	11/4/2004 18:25	14.2	73
10/25/2004 14:25	4.0	<10	11/5/2004 02:25	14.5	84
10/25/2004 22:25	4.3	15	11/5/2004 10:25	14.8	87
10/26/2004 06:25	4.7	14	11/5/2004 18:25	15.2	83
10/26/2004 14:25	5.0	12	11/6/2004 02:25	15.5	79
10/26/2004 22:25	5.3	20	11/6/2004 10:25	15.8	55
10/27/2004 06:25	5.7	34	11/6/2004 18:25	16.2	61
10/27/2004 14:25	6.0	60	11/7/2004 02:25	16.5	25
10/27/2004 22:25	6.3	130	11/7/2004 10:25	16.8	46
10/28/2004 00:25	6.4	140	11/7/2004 18:25	17.2	48
10/28/2004 04:25	6.6	140	11/8/2004 02:25	17.5	52
10/28/2004 12:25	6.9	180	11/8/2004 10:25	17.8	39
10/28/2004 14:25	7.0	180	11/8/2004 18:25	18.2	29
10/28/2004 22:25	7.3	220	11/9/2004 02:25	18.5	43
10/29/2004 06:25	7.7	190	11/9/2004 10:25	18.8	55
10/29/2004 14:25	8.0	200	11/9/2004 18:25	19.2	20
10/29/2004 22:25	8.3	200	11/10/2004 02:25	19.5	24
10/30/2004 06:25	8.7	170	11/10/2004 10:25	19.8	18
10/30/2004 14:25	9.0	160	11/10/2004 18:25	20.2	25
10/30/2004 22:25	9.3	160	11/11/2004 02:25	20.5	16
10/31/2004 06:25	9.7	140	11/11/2004 10:25	20.8	25
10/31/2004 14:25	10.0	130	11/13/2004 09:45	22.8	25
10/31/2004 22:25	10.3	120	11/15/2004 11:00	24.9	19
11/1/2004 06:25	10.7	100			

Flow and Hydraulic Conditions

The instantaneous flow measurements performed by DBE personnel at the five inflow culverts at G-333 compared favorably with the calibrated hourly flows reported by the District (Table 3). Differences between DBE and District flows never exceeded 15% for the total inflow into the cell on any day.

Table 3. Instantaneous flow rates measured by DBE using two methodologies (rhodamine-WT dye tracer and Swoffer Model 2100 velocity meter) compared to the hourly flow rates reported by the District at five inflow culverts along the G-333 levee. The lithium tracer was injected on October 21, 2004.

Date	Time	Culvert	Flow Rate (cfs)		
			DBE		District
			Rhod-WT	Swoffer Meter	
Oct. 14	10:00-12:00	A	45.9		44.7
	10:00-12:00	B	46.7		43.1
	10:00-12:00	C	52.0		43.5
	10:00-12:00	D	36.1		42.4
	10:00-12:00	E	40.4		45.9
		Total	**221**		**220**
Oct. 19	12:00-15:00	A	83.3		88.2
	12:00-15:00	B	84.9		89.8
	12:00-15:00	C	89.2		89.0
	12:00-15:00	D	56.0		87.7
	12:00-15:00	E	81.8		87.3
		Total	**395**		**442**
Oct. 20	13:45	A	87.5		88.7
	13:30	B	98.1		90.3
	13:15	C	85.2		89.5
	14:00	D	73.0		85.1
	14:10	E	92.7		84.4
		Total	**436**		**438**
Nov. 2	15:00-17:00	A		61.0	65.3
	15:00-17:00	B		54.0	65.3
	15:00-17:00	C		55.5	64.4
	15:00-17:00	D		51.4	65.6
	15:00-17:00	E		54.6	66.6
		Total		**277**	**327**

We also obtained an instantaneous flow measurement for both gates at G-334 on October 31, 2004 using two separate velocity meters (Swoffer Model 2100 and the Type AA USGS). Agreement between the two meters was excellent. The Swoffer yielded 158 cfs flow at the outflow structure. This flow was 30% lower than the hourly discharge rate (227 cfs) reported by the District.

It is important to note that the inflows at G-333A-C were higher than the outflow at G-334 during the study period (Figure 4) due to a number of factors, including an unforeseen power

outage. There were also periods where G-334 was not flowing. As a consequence, the stage in Cell 3 increased during the study (Figure 4).

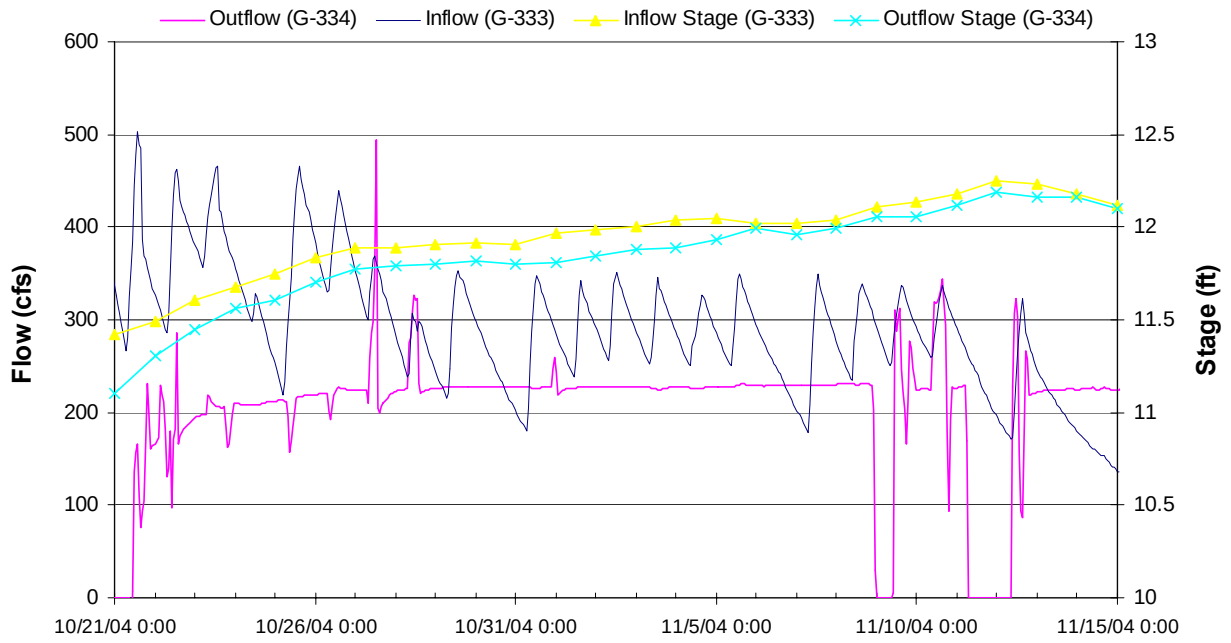


Figure 4. Flow rate and stage for the inflow and outflow of Cell 3 (G-333 and G-334, respectively) during the tracer study (District data).

In order to confirm flow data for G333 and G334, we estimated a daily water balance for STA-2 Cell 3 for a 2.5-week period beginning October 20, 2004. The water balance can be expressed as:

$$\Delta S = G333_{\text{inf } low} + \quad rain - \quad G334_{outflow} - \quad ET - \quad seep$$

where ΔS = daily change in wetland water storage (m/d),

$G333_{inflow}$ = daily inflow rate (m/d),

rain = daily rainfall (m/d),

ET = daily evapotranspiration (m/d), and

seep = net daily seepage loss from the cell (m/d).

Measured data for five of the six terms in the water balance were available. Storage change (ΔS) was calculated as the difference in average daily water elevations in the cell from one day's value to the previous day's, where the average daily water elevation was estimated as the average of G333 tailwater stage and G334 headwater stage. Daily values for inflow ($G333_{inflow}$) and outflow ($G334_{outfow}$) were provided to DBE by the District based on their recent calibration efforts. Rain and ET are not measured at STA-2, but data was available for these parameters at STA-1W, which is located approximately 21 km to the north. Seepage (*seep*) is the only parameter that is not directly measured in the balance equation.

Figure 5 depicts the measured data for STA-2 Cell 3 for an 18-day period beginning October 20, 2004. The data are shown in two columns for each day. The first column shows inputs to the water balance and includes daily G333 flows, rain, and the water storage change but only when the change was negative (decreasing stage and storage). The second column shows G334 outflow, ET and water storage change but only when the change was positive (increasing stage and storage). For this 18-day period, water stage increased on all days except for one (October 31), so for the most part the water storage term appears on the second (outflow) column for each day.

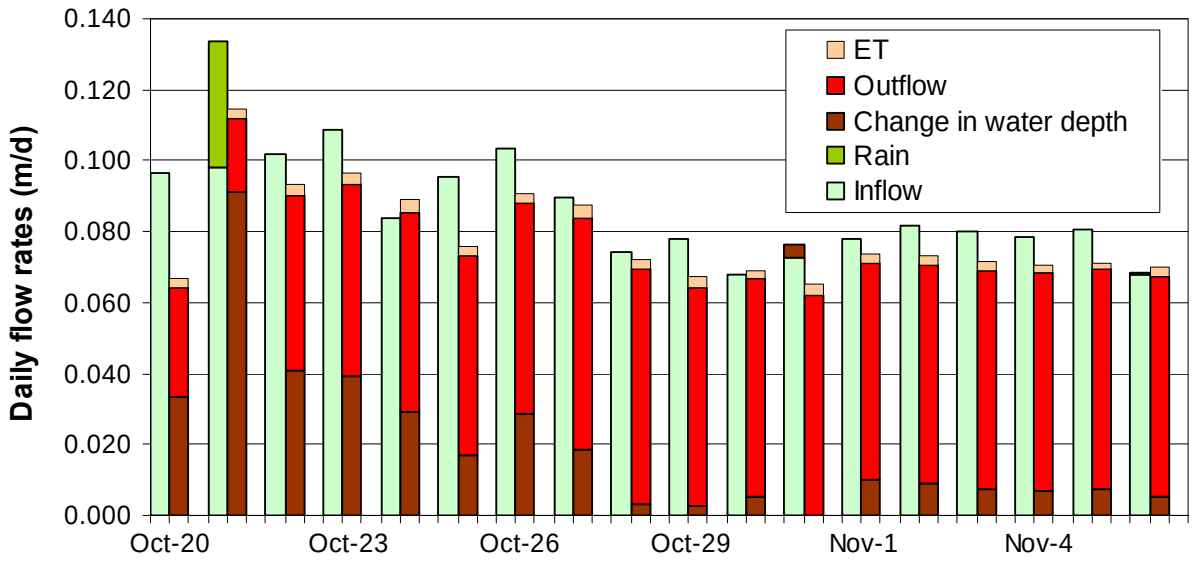


Figure 5. Daily flows in and out of STA-2 Cell 3 during the first 18 days of the tracer study.

On a daily basis, the difference between the two columns (the residual of measured terms in the water balance) in Figure 5 represents a combination of net seepage and measurement errors. Over this 18-day period, approximately 90% of inflows to Cell 3 were accounted for with measured outflows or stage change. The remaining 10% represents an average of 0.009 m/d of unaccounted for outflows from the cell that, as stated above, are due either to net daily seepage losses or to measurement errors.

For an independent assessment of the seepage characteristics of STA-2 Cell 3, we examined a 14-day period in the Cell 3 operational history during which there were zero inflows, zero outflows, and little rain. Therefore, changes in Cell 3 water elevations during this period (April 16 – 30, 2004) could be attributed largely to ET and seepage losses. Figure 6 shows the declining water elevation in Cell 3 during that period as well as a cumulative sum of daily ET estimates (from District ET data measured in STA-1W). Since the largest likely sources for measurement errors are not present during this period (G333 and G334 flows), it is reasonable to assume that the difference between the observed decline in water elevation and the cumulative ET was due to cumulative seepage loss. The estimated seepage loss rate from this analysis during this period was approximately 0.004 m/d (~16 cfs). During this 14-day seepage assessment period, the water level in Cell 3 was between 1.2-1.4 m above the water level in the seepage return canal to the immediate west of the cell. Since this head differential was similar during the October 2004 tracer study period, it is reasonable to assume that seepage loss during the tracer study was also close to 0.004 m/d.

As a result of the 0.009 m/d average residual from measured water balance terms during the tracer study, we estimate that approximately half of that was seepage loss from the cell and the other half measurement errors most likely associated with G333 and G334 flows. Therefore, we estimate measurement error between G333 and G334 flows as approximately 5% during the tracer study period. Similarly, approximately 5% of net inflow during this period left the cell as seepage outflow.

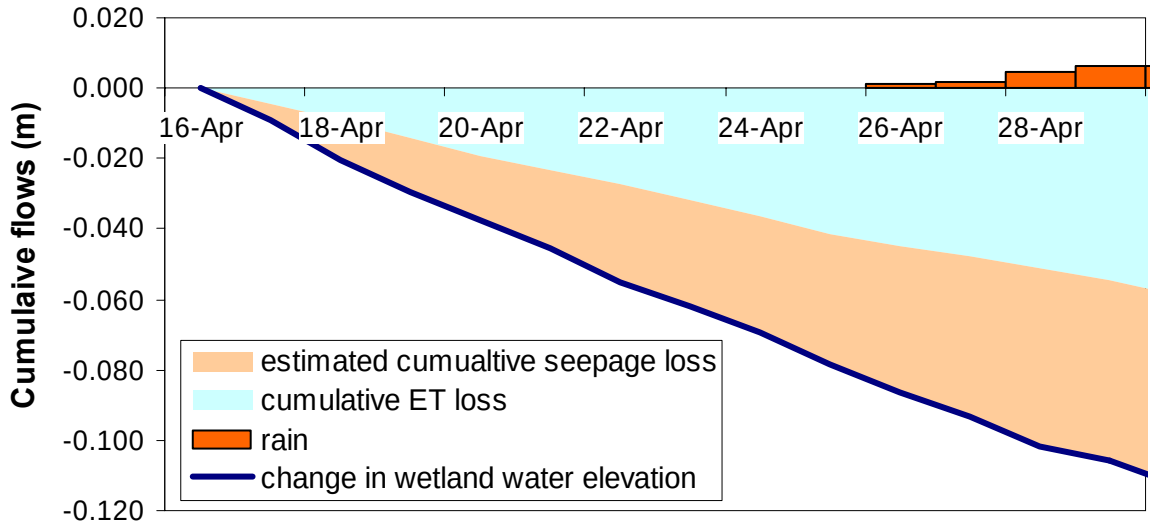


Figure 6. Water balance analysis in STA-2 Cell 3 for a 14-day period in April 2004 with zero inflow and zero outflow.

As a final note, seepage likely plays a larger relative role in the STA-2 Cell 3 water balance over the long-term than it did during the one-month tracer study period. The hydraulic loading rate (HLR) to Cell 3 during the tracer study averaged 0.085 m/d, while the three-year average HLR (2002-2004) was closer to 0.06 m/d. In principal, seepage rates are dependant upon stage (head) differences with surrounding waters and are relatively independent of flow rates. Typically, the head difference between Cell 3 and the adjacent seepage canal is in the same range (1.0-1.6 m) as it was during the 14-day seepage assessment period (1.2-1.4 m), therefore it could be expected that 0.004 m/d is a fairly typical value of seepage in Cell 3 over the long-term also. If this is the case, seepage may comprise closer to 10% of total Cell 3 outflow over the long-term.

Nominal Hydraulic Retention Time

In order to calculate tracer study hydraulic parameters, we sub-divided the tracer-monitoring period into two intervals. The first interval coincided with the first week (October 21-28, 2004) of data collection. During this period the inflow was the highest of the study period, while the outflow at G-334 eventually became constant after initially being closed for 11 hours (0:00 to 11:00) prior to the tracer injection at 14:25 (Figure 4). The second time interval covered the remaining 18 days of the monitoring period (October 28-November 15, 2004), which was

represented by consistent inflow and outflow patterns except for the last 7 days of the interval at the outflow structure (Figure 4).

We calculated the average daily flow rates at G-333 and G-334 during each of these two time intervals. Since the nominal HRT is based on the inflow rate and the standing water volume in the cell (Eq. 1), and the cell volume was changing during the study period (Figure 4), we also calculated the average cell volume for each of the two time intervals (Table 4). We therefore calculated two separate nominal HRTs, each corresponding to one of the two time intervals (Table 4). After weighting each time interval according to the number of weeks associated with each, we calculated a stage- and flow-weighted average nominal HRT of 10.8 days.

Table 4. Determination of nominal hydraulic retention time (HRT) by separating the data collection period into two intervals (October 21-28 and October 28 –November 15, 2004) because of unequal inflows and outflows, and a changing water volume within the cell (Figure 4).

Time Interval	Mean Volume (x 10^6 m^3)	Mean Inflow (x 10^5 m^3/day)	Mean HRT (days)	Weighted HRT (days)
Oct. 21-28	6.3575	8.485	7.5	
Oct. 28-Nov. 15	7.7645	6.41	12.1	
Oct. 21-Nov. 15				**10.8**

Tracer Response Curve

The tracer reached the outflow structure between 5 and 6 days after tracer injection (Table 2; Figure 7). The peak concentration of 220 µg/L was attained one day thereafter, followed by a slow recession limb interrupted several times by small secondary peaks. Uneven flows and changing stage levels probably contributed to the appearance of the secondary peaks.

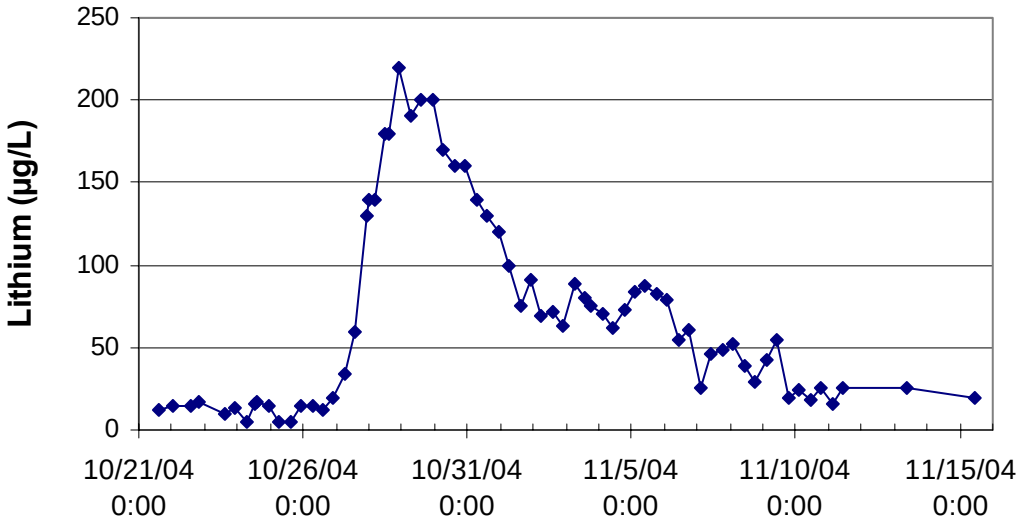


Figure 7. Tracer response curve for G334. The data collection period was October 21 – November 15, 2004.

Spatial Distribution of Emergent and Submerged Aquatic Vegetation (SAV)

The distribution of the major aquatic plant communities within Cell 3 are presented in Figure 8. The dominant genera at each location are provided in Appendix B. Vegetation surveys were performed at the beginning and the end of the internal sampling of the cell for tracer and water quality parameters, and the survey locations coincided with the sample stations where water samples were collected (Figure 3). The cell primarily contains SAV communities, with emergent vegetation dominating along the eastern levee (Figure 8). For a few locations, our initial and final surveys provided differing vegetation types. This primarily was due to greater "topping out" of SAV on the final measurement date (perhaps due to weather conditions), as well as different orientation of the airboat between survey dates.

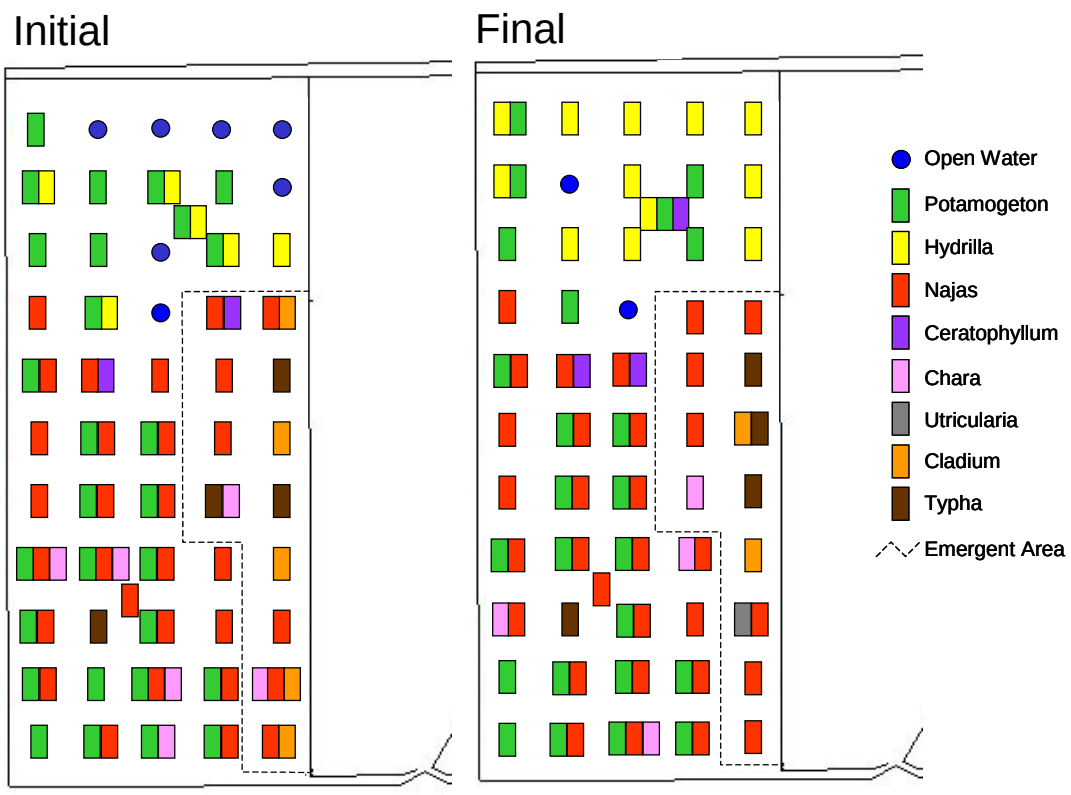


Figure 8. Two-dimensional spatial vegetation coverage in Cell 3 of STA-2. The initial data were collected on October 22, 2004, one day after tracer injection. The final data were collected on October 31 and November 8, 2004. The locations of the sampling sites coincided with those for lithium and phosphorus analyses. The distance between nodes was 400m. The area enclosed by the dashed line represents the zone dominated by emergent vegetation (*Typha* and *Cladium*).

Verification of ArcView Interpolation Algorithm

To check the interpolation algorithm (Spline/Tension interpolator) that was utilized in ArcView, we removed the concentration data collected from the two QA/QC stations in Figure 3, and then ran the algorithm. We then compared the lithium, DOP, PP, SRP, and TP concentrations interpolated by the algorithm with the respective measured concentrations at each of the two stations. In most instances there was good agreement between the interpolated and measured values (Table 5), indicating that the appropriate interpolation model was used and the sampling grid was sufficiently resolute.

Table 5. Comparison of the measured with the ArcView-interpolated (Spline/Tension algorithm) concentration for lithium, dissolved organic phosphorus (DOP), particulate phosphorus (PP), soluble reactive phosphorus (SRP), and total phosphorus (TP) at two QA/QC stations within Cell 3 of STA-2. See Figure 3 for station locations.

		North Station		South Station	
Sample Date	**Parameter**	**Measured**	**Interpolated**	**Measured**	**Interpolated**
10/22/2004	Lithium	19	<10	<10	13
10/25/2004	Lithium	92	102	150	209
10/27/2004	Lithium	93	28	250	279
10/29/2004	Lithium	48	20	180	106
10/31/2004	Lithium	26	15	92	61
11/2/2004	Lithium	30	21	63	40
11/4/2004	Lithium	21	19	31	32
11/8/2004	Lithium	23	17	<10	17
10/22/2004	DOP	11	10	15	11
10/27/2004	DOP	17	11	8	9
10/31/2004	DOP	15	18	8	8
11/4/2004	DOP	19	27	10	12
10/22/2004	PP	59	41	22	24
10/27/2004	PP	58	32	13	13
10/31/2004	PP	48	28	10	14
11/4/2004	PP	47	27	9	10
10/22/2004	SRP	9	4	<2	<2
10/27/2004	SRP	7	10	<2	<2
10/31/2004	SRP	11	23	<2	3
11/4/2004	SRP	18	22	<2	2
10/22/2004	TP	79	55	23	35
10/27/2004	TP	82	52	22	23
10/31/2004	TP	74	69	19	24
11/4/2004	TP	84	76	20	24

Time Series Progression of Tracer Movement

Figure 9 depicts the progression of lithium through Cell 3 over the course of the study. These maps were developed using the GIS mapping program ArcView Spatial Analyst. The Li^+ concentration isopleths for the first day after tracer injection indicate that the tracer was present in high concentrations at the front third of the cell, and by day 4 the tracer plume had traveled to nearly the full length of the cell. Note that we did not perform an internal monitoring event between days 1 and 4, because immediately after injection of the tracer it became clear that aberrations in the inflow/outflow rates would result in a longer than anticipated HRT.

We noted an exclusion zone in the days 4 and 6 tracer profiles, which corresponds to an area of emergent vegetation (*Typha* and *Cladium*) outlined by the dashed line in the figure. Eventually the tracer penetrated this emergent zone as indicated by the tracer progression from days 6 through 18. As a result, there was a considerable lag between the time that the tracer exited the SAV portion of the cell and when it exited the emergent zone (Figure 9).

Time Series Progression of Phosphorus Movement

Total P, SRP, PP, and DOP concentrations were higher in the first half of the cell near the inflow region compared to the last half on all four days when internal P sampling was performed (Figures 10 – 12). For total P and SRP, the concentrations increased within the cell over the four progressive time steps (Figure 10), which reflected the rising stage and the resumption of inflow and outflow rates to values more typical of the study period (i.e., 288 cfs). Flow out of the cell did not occur for 4 of the 8 days prior to tracer injection, and was less than 122 cfs on the other four days. Even with an average flow rate of 288 cfs, corresponding to a HLR of 7.7 cm/day, the TP concentrations in the back-end of the cell rarely exceeded 30 µg/L, while highest SRP levels were within the 5-10 µg/L range (Figures 10 and 12). Particulate P concentrations were highest on the first day after tracer injection, and generally decreased throughout the remainder of the monitoring period (Figure 11). The emergent zone along the eastern levee contained higher concentrations of DOP than did SAV regions at comparable distance down the flow path (Figure 11). The higher DOP concentrations within the emergent zone consequently contributed to the higher TP concentrations relative to SAV communities the same distance from the inflow levee (Figure 11).

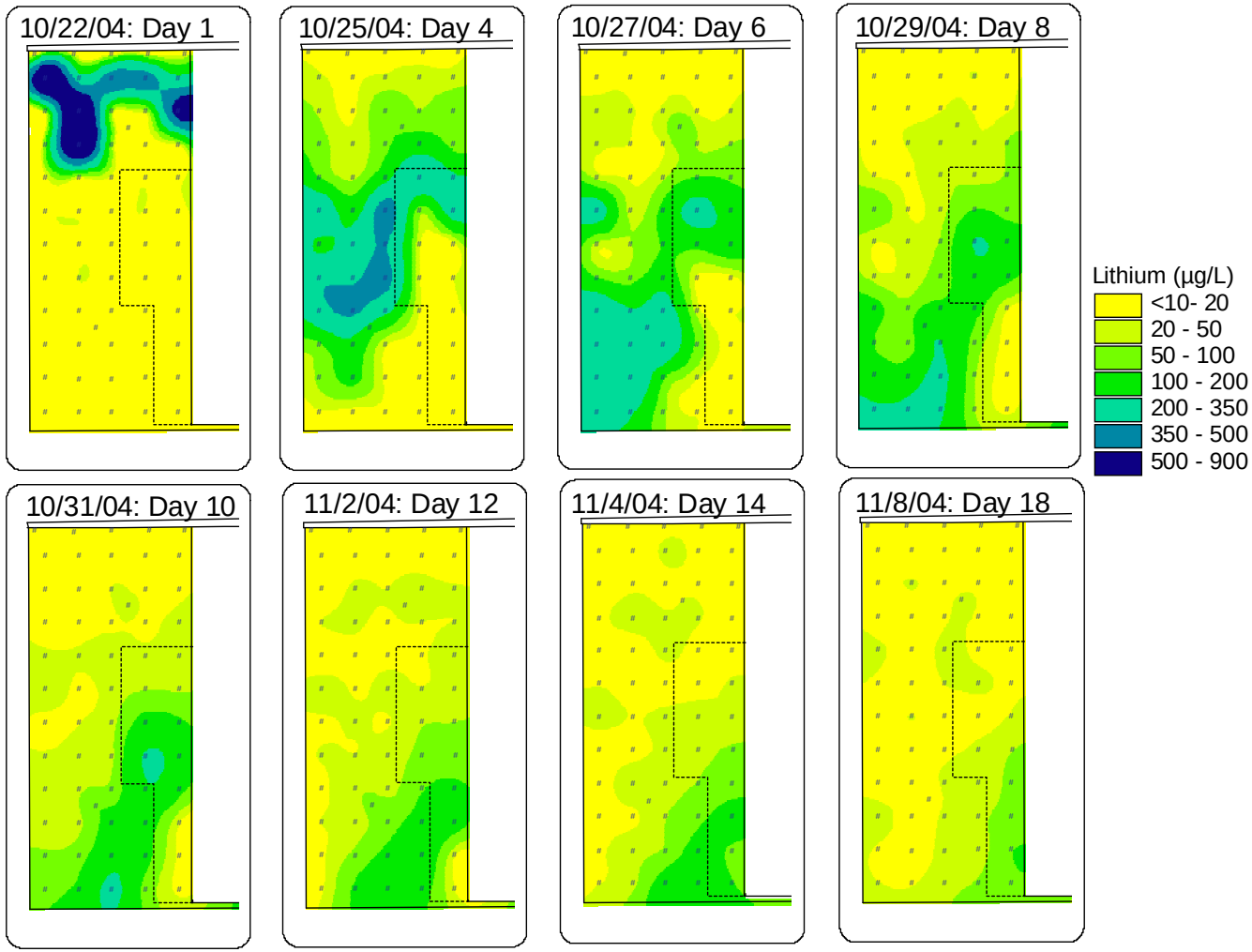


Figure 9. Two-dimensional spatial lithium concentration gradients in the water column on one, four, six, eight, ten, twelve, fourteen, and eighteen days after injecting LiCl into Cell 3 of STA-2 through 5 culverts at G-333. The area enclosed by the dashed line represents the zone dominated by emergent vegetation (*Typha* and *Cladium*)

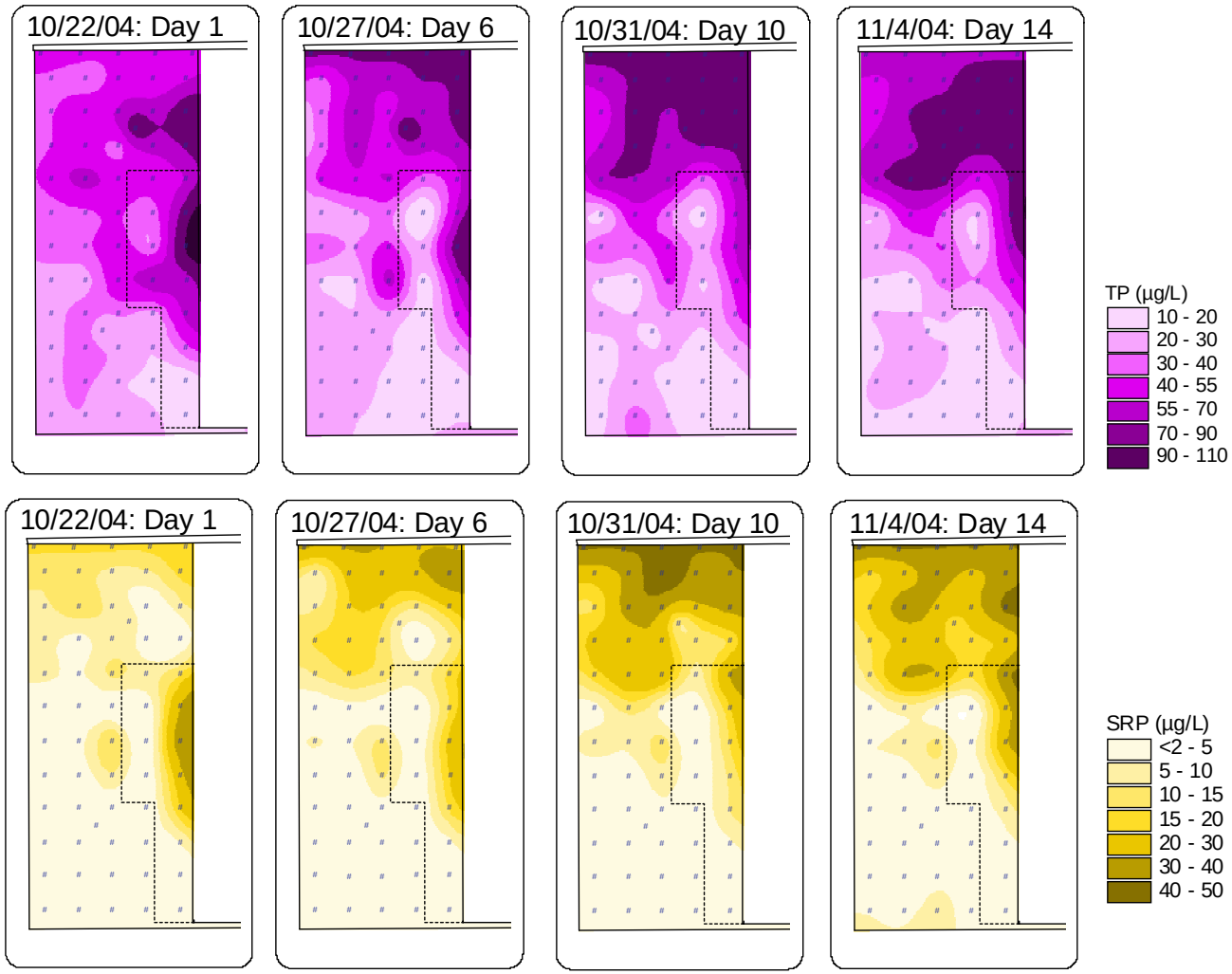


Figure 10. Two-dimensional spatial TP and SRP concentration gradients in the water column on one, six, ten and fourteen days after injecting LiCl into Cell 3 of STA-2 through 5 culverts at G-333. The area enclosed by the dashed line represents the zone dominated by emergent vegetation (*Typha* and *Cladium*).

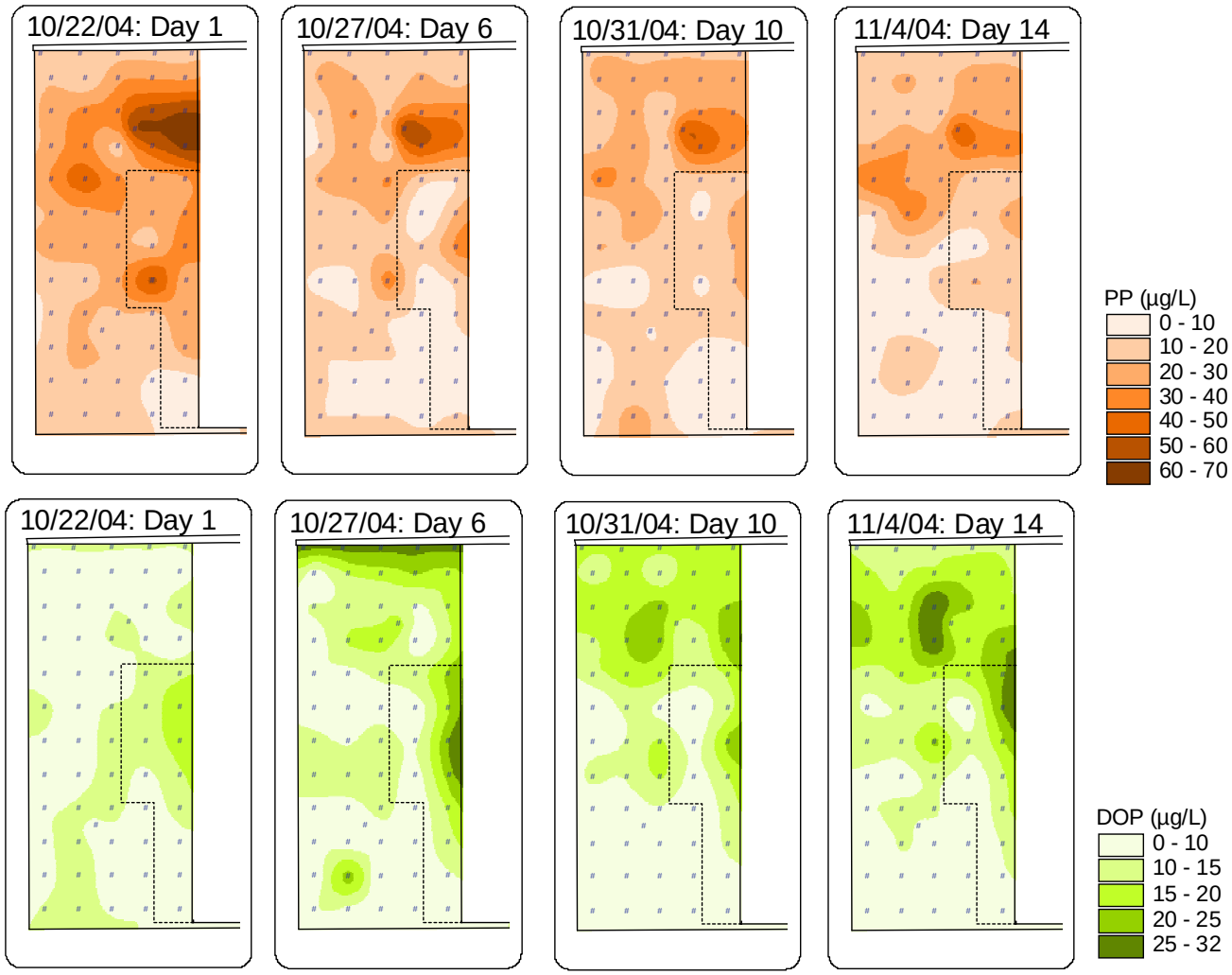
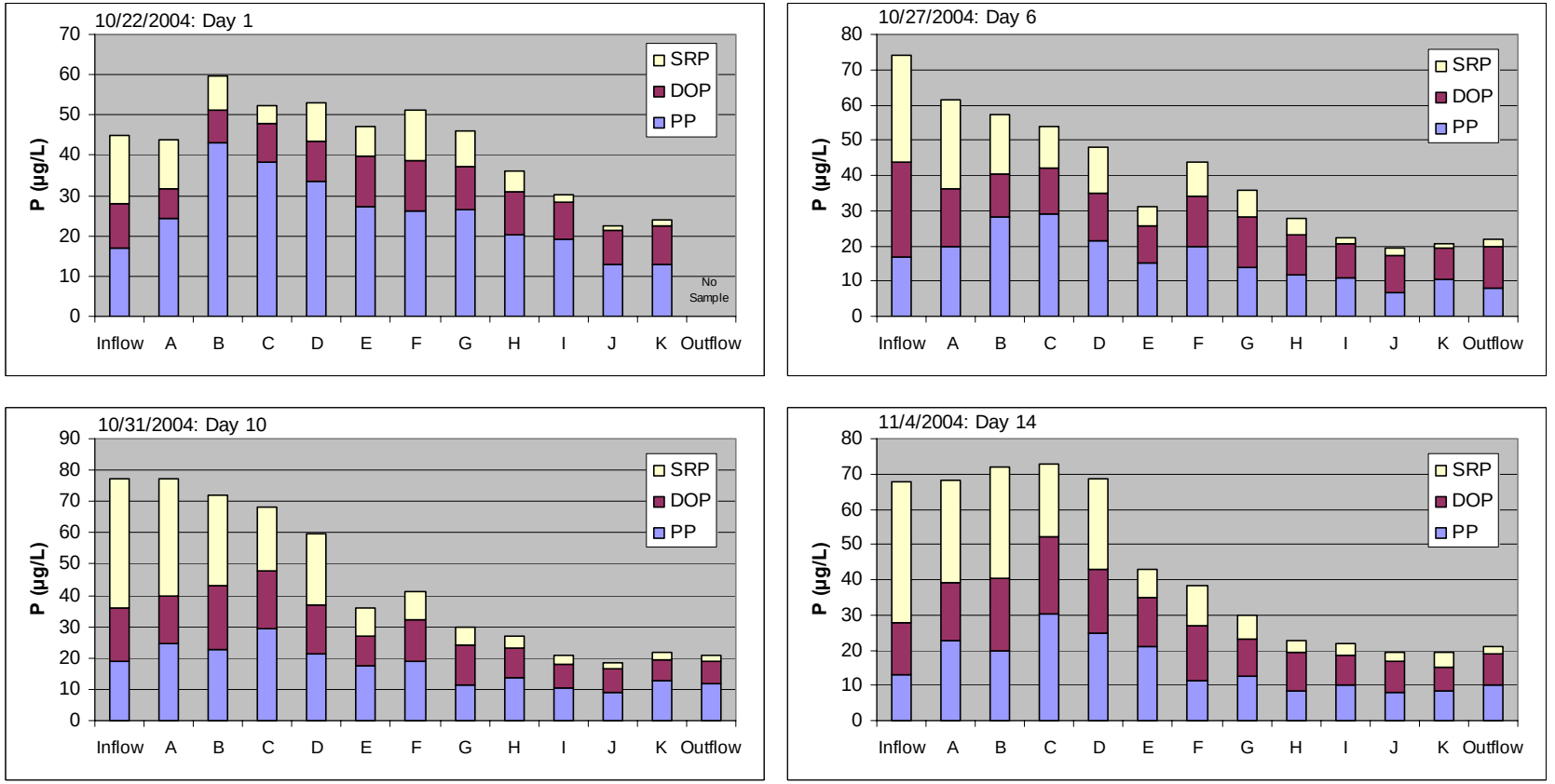


Figure 11. Two-dimensional spatial PP and DOP concentration gradients in the water column on one, six, ten and fourteen days after injecting LiCl into Cell 3 of STA-2 through 5 culverts at G-333. The area enclosed by the dashed line represents the zone dominated by emergent vegetation (*Typha* and *Cladium*)



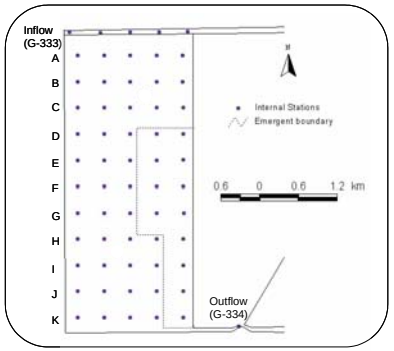


Figure 12. Internal phosphorus gradients along the flow path of Cell 3 on days one, six, ten and fourteen days after injecting LiCl into Cell 3 of STA-2 through 5 culverts at G-333. The map to the left depicts the sampling locations within the cell. The inflow represents a field composite of the five culverts at G-333. A – K each represent the average of the five samples collected along that east-west transect.

Tracer Mass Balance

We injected a total lithium mass of 692 kg at G-333, and based on G-334 flow and Li^+ concentration data, retrieved 668.5 kg, resulting in a 96.6% recovery. Seepage did occur from the cell into the seepage return canal at a calculated rate of 5% of net inflow during the study. The low seepage rates were confirmed by the lack of an elevated Li^+ concentration in the seepage return canal surface water during the course of the study (Appendix D; Raw Data Report).

Tracer Hydraulic Retention Time (HRT) and Tanks In Series (TIS)

The measured HRT for Cell 3 according to Eq. 2 was 10.8 days, which coincided with the nominal HRT (Table 4). This indicates that "on average", the entire wetland volume was being utilized for treatment. The calculated TIS value was 5.5.

References

Burns and McDonnell. Long-Term Plan for Achieving Water Quality Goals: Final Report. October 2003.

Appendices

Appendix A

LiCl injection calculation

Appendix B

Raw flow data from the two velocity meters used at G-334 on October 31, 2004

Appendix C

Vegetation present at internal locations

Appendix D

Field Notes – electronic copy located on the CD

Appendix E (electronic copy only)

C3TracerDataForAnalysisDistrictFormat.xls

ML040333 Cell 3 Tracer library.zip: ADaPT Library for this project

ML040333 STA02 Cell 3.txt: Raw data for this project

ML040333 STA-2 Cell 3_ErrorLog.txt: Error Log produced by ADaPT for this project

Case Narrative.doc: Case narrative describing the overall quality of the data

Appendix A

Calculations to determine the amount of LiCl to be injected into Cell 3 of STA-2 at a target concentration of 200 µg Li/L

Area is 898 ha (5.65 km x 2.04 km) and water depth estimated as 0.38 m.

Volume of Cell 3 = $(8.98 \times 10^6\ m^2)$ (0.38 m) = $3.42 \times 10^6\ m^3$

Table of comparisons between Li tracer study in STA-1W Cells 1 and 2 with the tracer study in Cell 3 of STA -2.

	STA-1W			STA-2
	Cell 1	Cell 2	Combined Cells	Cell 3
Flow (cfs)	78.9	119.5	198.4	200
Volume ($x10^6\ m^3$)	3.25	3.14	6.39	3.42
Nom. HRT (days)	17.5	11.8	-	7
Inflow Culvert No.	None	7	7	5
Outflow Culvert No.	10	9	19	1
Target [Li] (µg/L)	200	200	200	200
Injected Li Mass (kg)	-	-	1321.3	599
Injected Volume (gal)	-	-	4180	1971
Delivery Time (min)	-	-	65	-
Range of peak [Li] at outflows (µg/L)	75-420	175-470	75-470	-

Li = 6.941 g/mol
LiCl=42.394 g/mol
The LiCl is 40.9±1-2% and there is 225 lb of LiCl per 55 gallon drum

$$\frac{[(225\ lb\ LiCl/2.205\ lb/kg) \times 1000 g/kg)][6.94\ g\ Li/mol]}{(55\ gal)(3.785\ L/gal)(42.394\ g\ LiCl/mol)} = \mathbf{80.242\ g\ Li/L\ of\ solution}$$

Target Li concentration is **200 µg/L:**
Mass needed: $(0.200\ mg\ Li/L)(3.42 \times x10^6\ m^3)(10^{-6} kg/mg)(10^3 L/m^3)$ = **684 kg Li**
Volume needed: (684 kg Li)/(0.08024 kg Li/L of solution) = **8,524 L LiCl solution**
No. of 55-gal barrels required: (8,524 L)/[(55gal/barrel)(3.785 L/gal)] = **41 barrels**

Appendix B

Raw data collected using two separate velocity meters (Swoffer Model 2100 and the Type AA USGS) on October 31, 2004 at the North gate of G-334.

North Gate

Swoffer Meter				**USGS**					
Time	**Depth**	**Velocity (ft/sec)**		**Time**	**Depth**	**Revolutions**	**Seconds**	**R = rev/sec**	**Velocity (ft/sec)**
15:40	Surface	0.57		16:00	Surface	11	45	0.2444	0.55
15:40	Surface	0.51		16:00	Surface	11	46	0.2391	0.54
15:40	Surface	0.55							
15:40	Surface	0.53							
15:40	Surface	0.52							
15:40	Surface	0.51							
	Average	**0.53**							**0.54**
15:45	Middle	0.54		16:05	Mid	11	46	0.2391	0.54
15:45	Middle	0.52		16:05	Mid	11	46	0.2391	0.54
15:45	Middle	0.48							
15:45	Middle	0.56							
15:45	Middle	0.54							
15:45	Middle	0.54							
	Average	**0.53**							**0.54**
15:35	Bottom	0.30							
15:35	Bottom	0.24							
15:35	Bottom	0.26							
15:35	Bottom	0.33							
15:35	Bottom	0.30							
15:35	Bottom	0.34							
	Average	**0.30**							

Raw data collected using a Swoffer Model 2100 on October 31, 2004 at the South gate of G-334.

South Gate

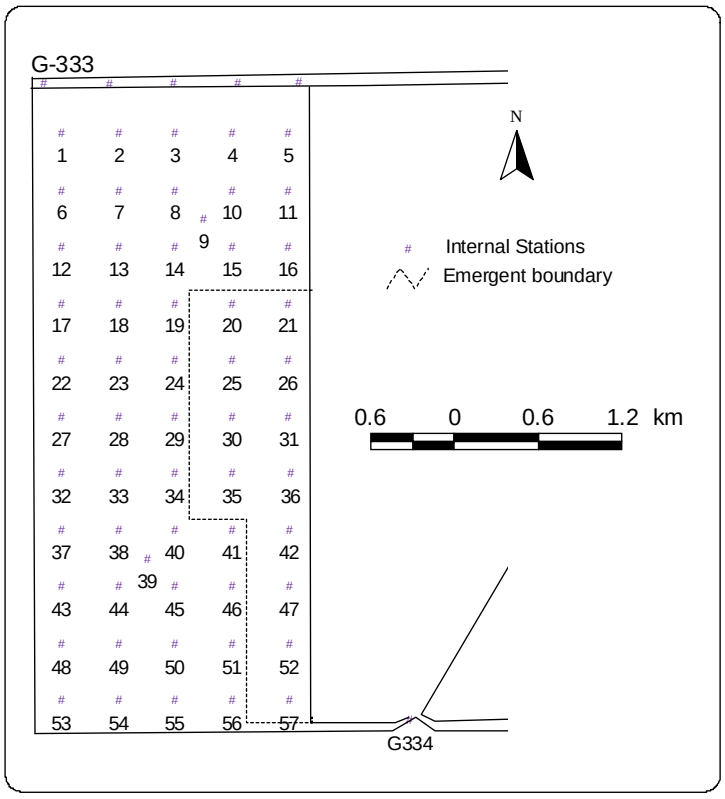
Swoffer Meter		
Time	**Depth**	**Velocity (ft/sec)**
16:35	Surface	0.50
16:35	Surface	0.48
16:35	Surface	0.49
16:35	Surface	0.49
16:35	Surface	0.46
16:35	Surface	0.46
	Average	**0.48**
16:30	Middle	0.49
16:30	Middle	0.49
16:30	Middle	0.50
16:30	Middle	0.48
16:30	Middle	0.50
16:30	Middle	0.50
	Average	**0.49**
16:25	Bottom	0.39
16:25	Bottom	0.43
16:25	Bottom	0.47
16:25	Bottom	0.49
16:25	Bottom	0.47
16:25	Bottom	0.44
	Average	**0.45**

Appendix C

Vegetation observed at each of the 57 internal sampling nodes either 1 (10/22/04), 10 (10/31/04), or 18 (11/8/04) days after tracer injection. Open water denoted the absence of vegetation. A map depicting the station locations is provided on the following page.

	Day 1			Day 10 or 18		
Station	Observation Date	Vegetation	Veg Type	Observation Date	Vegetation	Veg Type
1	10/22/2004	*Potamogeton*	SAV	11/8/2004	*Hydrilla/Potamogeton*	SAV
2	10/22/2004	Open Water	None	11/8/2004	*Hydrilla*	SAV
3	10/22/2004	Open Water	None	11/8/2004	*Hydrilla*	SAV
4	10/22/2004	Open Water	None	11/8/2004	*Hydrilla*	SAV
5	10/22/2004	Open Water	None	11/8/2004	*Hydrilla*	SAV
6	10/22/2004	*Potamogeton/Hydrilla*	SAV	11/8/2004	*Hydrilla/Potamogeton*	SAV
7	10/22/2004	*Potamogeton*	SAV	11/8/2004	Open Water	None
8	10/22/2004	*Potamogeton/Hydrilla*	SAV	11/8/2004	*Hydrilla*	SAV
9	10/22/2004	*Potamogeton/Hydrilla*	SAV	11/8/2004	*Hydrilla/Potamogeton/ Ceratophyllum*	SAV
10	10/22/2004	*Potamogeton*	SAV	11/8/2004	*Potamogeton*	SAV
11	10/22/2004	Open Water	None	11/8/2004	*Hydrilla*	SAV
12	10/22/2004	*Potamogeton*	SAV	11/8/2004	*Potamogeton*	SAV
13	10/22/2004	*Potamogeton*	SAV	11/8/2004	*Hydrilla*	SAV
14	10/22/2004	Open Water	None	11/8/2004	*Hydrilla*	SAV
15	10/22/2004	*Potamogeton/Hydrilla*	SAV	11/8/2004	*Potamogeton*	SAV
16	10/22/2004	*Hydrilla*	SAV	11/8/2004	*Hydrilla*	SAV
17	10/22/2004	*Najas*	SAV	11/8/2004	*Najas*	SAV
18	10/22/2004	*Potamogeton/Hydrilla*	SAV	11/8/2004	*Potamogeton*	SAV
19	10/22/2004	Open Water	None	11/8/2004	Open Water	None
20	10/22/2004	*Najas/Ceratophyllum*	SAV	10/31/2004	*Najas*	SAV
21	10/22/2004	*Najas/Cladium*	SAV & Emergent	10/31/2004	*Najas*	SAV
22	10/22/2004	*Potamogeton/Najas*	SAV	11/8/2004	*Potamogeton/Najas*	SAV
23	10/22/2004	*Najas/Ceratophyllum*	SAV	11/8/2004	*Najas/Ceratophyllum*	SAV
24	10/22/2004	*Najas*	SAV	11/8/2004	*Najas/Ceratophyllum*	SAV
25	10/22/2004	*Najas*	SAV	10/31/2004	*Najas*	SAV
26	10/22/2004	*Typha*	Emergent	10/31/2004	*Typha*	Emergent
27	10/22/2004	*Najas*	SAV	11/8/2004	*Najas*	SAV
28	10/22/2004	*Potamogeton/Najas*	SAV	11/8/2004	*Potamogeton/Najas*	SAV
29	10/22/2004	*Potamogeton/Najas*	SAV	11/8/2004	*Potamogeton/Najas*	SAV
30	10/22/2004	*Najas*	SAV	10/31/2004	*Najas*	SAV
31	10/22/2004	*Cladium*	Emergent	10/31/2004	*Cladium / Typha*	Emergent
32	10/22/2004	*Najas*	SAV	11/8/2004	*Najas*	SAV
33	10/22/2004	*Potamogeton/Najas*	SAV	11/8/2004	*Potamogeton/Najas*	SAV
34	10/22/2004	*Potamogeton/Najas*	SAV	11/8/2004	*Potamogeton/Najas*	SAV
35	10/22/2004	*Typha /Chara*	SAV & Emergent	10/31/2004	*Chara*	SAV
36	10/22/2004	*Typha*	Emergent	10/31/2004	*Typha*	Emergent
37	10/22/2004	*Potamogeton/Chara/Najas*	SAV	11/8/2004	*Potamogeton/Najas*	SAV
38	10/22/2004	*Potamogeton/Chara/Najas*	SAV	11/8/2004	*Potamogeton/Najas*	SAV
39	10/22/2004	*Najas*	SAV	11/8/2004	*Najas*	SAV
40	10/22/2004	*Potamogeton/Najas*	SAV	11/8/2004	*Potamogeton/Najas*	SAV

Station	Day 1 Observation Date	Vegetation	Veg Type	Day 10 or 18 Observation Date	Vegetation	Veg Type
41	10/22/2004	*Najas*	SAV	11/8/2004	*Najas/Chara*	SAV
42	10/22/2004	*Cladium*	Emergent	10/31/2004	*Cladium*	Emergent
43	10/22/2004	*Potamogeton/Najas*	SAV	11/8/2004	*Chara/Najas*	SAV
44	10/22/2004	*Typha*	Emergent	11/8/2004	*Typha*	Emergent
45	10/22/2004	*Potamogeton/Najas*	SAV	11/8/2004	*Potamogeton/Najas*	SAV
46	10/22/2004	*Najas*	SAV	11/8/2004	*Najas*	SAV
47	10/22/2004	*Najas*	SAV	10/31/2004	*Najas/Utricularia*	SAV
48	10/22/2004	*Potamogeton/Najas*	SAV	11/8/2004	*Potamogeton*	SAV
49	10/22/2004	*Potamogeton*	SAV	11/8/2004	*Potamogeton/Najas*	SAV
50	10/22/2004	*Potamogeton/Chara/Najas*	SAV	11/8/2004	*Potamogeton/Najas*	SAV
51	10/22/2004	*Potamogeton/Najas*	SAV	11/8/2004	*Potamogeton/Najas*	SAV
52	10/22/2004	*Chara/Najas/Cladium*	SAV & Emergent	10/31/2004	*Najas*	SAV
53	10/22/2004	*Potamogeton*	SAV	11/8/2004	*Potamogeton*	SAV
54	10/22/2004	*Potamogeton/Najas*	SAV	11/8/2004	*Potamogeton/Najas*	SAV
55	10/22/2004	*Potamogeton/Chara*	SAV	11/8/2004	*Potamogeton/Najas/Chara*	SAV
56	10/22/2004	*Potamogeton/Najas*	SAV	11/8/2004	*Potamogeton/Najas*	SAV
57	10/22/2004	*Najas/ Cladium*	SAV & Emergent	10/31/2004	*Najas*	SAV



Appendix D: Field logs