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Everglades Nutrient Removal Project Test Cell Research: Optimizing Stormwater Treatment Area Performance – The Importance of Hydrologic Conditions in Maximizing Nutrient Retention by the STAs

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OPTIMIZING STORMWATER TREATMENT AREA PERFORMANCE – THE IMPORTANCE OF HYDROLOGIC CONDITIONS IN MAXIMIZING NUTRIENT RETENTION BY THE STAs

FINAL EXPERIMENT TECHNICAL REPORT

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EXECUTIVE SUMMARY

- The biotic integrity of the Everglades is endangered from a variety of impacts, including nutrient enrichment of the surface water. Reducing the amount of total phosphorus entering the Everglades in agricultural runoff is central to the South Florida Water Management District's (District) restoration program, which includes building a system of large treatment wetlands referred to as Stormwater Treatment Areas (STAs). The Everglades Forever Act requires the District to initiate a research and monitoring program to optimize the nutrient removal performance of the STAs. This research effort includes conducting experiments in the STA-1W test cells.

- Research in the test cells is addressing how hydrology (hydraulic residence time, hydraulic loading rate and water depth) influences STA performance. Modifications to the test cells needed to conduct these experiments were completed in 1998 and research was initiated in May 1999.

- Low- and high hydraulic loading rate experiments were concluded in July 2000. Water depth and pulsed-HLR experiments were initiated in both the south and north test cells in October 2000

- Cotton strip assays indicated that decomposition rates increased as P loads increased in the north test cells. However, at the low inflow TP concentrations observed in the south test cells, decomposition rates were not influenced by changes in P loading rates

- The test cells had similar hydraulic properties. The results of tracer studies indicated that these wetlands can be modeled as plug-flow reactors with a tanks-in-series number ranging from 4.4 to 7.4. Volumetric efficiencies indicated that the test cells were not hydraulically short-circuited.

- Lowering the HLR in test cell experiments to values less than the STA design criteria, and thereby reducing the TP loading, did not significantly improve reduction in mean outflow TP concentrations. The changes in TP loading in these experiments were equivalent to more than doubling the surface area at a constant inflow water volume. These results suggest that increasing surface area in cattail-dominated portions of the STAs would provide little improvement in treatment performance. In addition, none of the low-HLR experiments achieved a mean outflow TP concentration < 30 µg/L, a level of performance that has been exceeded by existing STAs.

- Test cell research identified a range of increased hydraulic loading rates between 4.8 and 10.4 cm/d within which treatment performance in cattail-dominated wetland may be markedly reduced.

1 INTRODUCTION AND RESEARCH OBJECTIVES

The Everglades Protection Area (EPA), which includes the Water Conservation Areas (WCAs) and Everglades National Park, encompasses what remains of a once much larger Everglades ecosystem (**Figure 1**). The biotic integrity of the extant Everglades is endangered as evidenced by undesirable changes in water quality, flora and fauna in portions of the EPA, e.g., establishment of pronounced nutrient gradients, replacement of large areas of sawgrass by cattail, decline in wading bird populations and species shifts in periphyton and macroinvertebrate communities (Swift and Nicholas, 1987; Davis, 1987, 1991, 1994; Belanger et al., 1989; Walker, 1991; Nearhoof, 1992; SFWMD, 1992; Grimshaw et al., 1993, Ogden, 1994). These changes have been attributed to disruption of the system's natural hydroperiod and eutrophication resulting from nutrient-rich runoff from the Everglades Agricultural Area (EAA) entering the EPA (see summaries by Scheidt, 1999, 2001; Chimney and Goforth, 2000). Phosphorus (P) has been identified as the nutrient most responsible for eutrophication of the EPA. The Everglades Forever Act (EFA; Section 373.4592, Florida Statues) enacted by the Florida Legislature in 1994 mandates a series of measures intended to protect and restore the remaining Everglades. These measures include the construction of large treatment wetlands, known as Stormwater Treatment Areas (STAs), that will serve as biological filters and reduce total P (TP) levels in EAA runoff. Furthermore, the EFA requires the South Florida Water Management District (District) to initiate research and monitoring, which, among other things, will seek to modify operation of the STAs to achieve optimum water quality for the benefit of the Everglades. The data summarized in this report were collected as part of the District's STA Optimization Research Program, which is described in Chimney et al. (2000).

The District is conducting research to determine how hydrology influences STA performance; i.e., what water management scenarios will promote maximum TP removal in these systems and conversely, under what operating conditions will performance fail to meet mandated requirements. Experiments to address these questions are being conducted in small wetlands, referred to as "test cells" that are located within the boundaries of STA 1 West (STA-1W) (**Figure 2**). Test cell research is addressing questions related to changes in water depth, hydraulic loading rate (HLR) and hydraulic retention time (HRT):

- Low-HLR experiment: What is the maximum nutrient removal efficiency that can be achieved at low HLRs (and subsequently long HRTs), i.e., what are the limits to TP concentration reduction in the STAs when water is moved slowly through these systems? Lowering the HLR in effect decreases the areal TP load to the test cells.

- High-HLR experiment: At what point along a gradient of increasing higher HLRs (and subsequently shorter HRTs) will TP removal efficiency fall below acceptable levels, i.e., when will STA outflow TP concentrations fail to meet a specified target level when water is flushed rapidly through these systems? Raising the HLR in effect increases the areal TP load to the test cells.

- Pulsed-HLR experiment: How will pulsed flow, i.e., a variable hydraulic loading pattern that simulates the range of flow volumes expected in an STA, affect treatment performance?

- Water depth experiments: How will STA treatment performance be affected by holding the STAs in a deep water condition and conversely, what will be the effect of prolonged low water depths? These situations may occur during severe storm events and droughts, respectively.

Information gained from this research will help the District tailor STA operations to maximize nutrient removal and correspondingly predict situations that may promote poor system performance. The primary focus of our research has been to document TP removal in the test cells. However, as described below, considerable effort has been expended to monitor other aspects of treatment performance.

Small experimental units, such as the test cells, are commonly used in modern ecological research. Small systems afford the researcher with many advantages that include, but are not limited to: (1) comparatively low cost and logistical simplicity relative to large field studies; (2) employing experimental manipulations that cannot be duplicated at full-scale; (3) a level of control over environmental factors and spatial heterogeneity not possible in the field; (4) the ability to replicate treatments and employ experimental designs that are compatible with inferential statistics; and (5) experiments which can be conducted quickly and are easily repeated (Lamberti and Steinman, 1993; Drake et al, 1996; Lawton, 1996). However, use of small systems is predicated on the assumption that they contain sufficient physical and biogeochemical complexity to mimic the functioning of larger ecosystems. Without the context of appropriate field studies, small-scale experiments are suspect as being irrelevant since they may distort or exclude important features of communities and ecosystems (Carpenter, 1996). Indeed, insightful research is likely to consider a range of different scales (Levin, 1992), while the results of small-scale experiments are prompted and verified by results of larger field programs (Frost et al, 1988). We acknowledge that the test cells are not perfect analogs of the STAs. Data collected in our experiments may suffer from effects attributable antecedent soil conditions, vegetation grow-in phenomenon, low water velocities, short duration of the experiments or other factors. The test cells are not unique in this respect, all small experimental systems are potentially subject to scaling and enclosure artifacts. Nevertheless, we feel that the test cells sufficiently duplicate the important nutrient removal processes operating in the STAs that results from these experiments accurately forecast how cattail-dominated portions of the STAs will respond to similar hydraulic manipulations.

The District was awarded a $150,000 matching-funds grant from the U.S. Environmental Protection Agency (EPA Assistance Agreement #X-98464399-0) to partially fund this research. This report is submitted to USEPA in fulfillment of the conditions of this grant. Some of the experiments outlined in the original Scope of Work are still in progress. The HLR experiments were concluded in July 2000 and the major findings are reported in the document; the pulsed-HLR and water depth experiments are scheduled to finish in November 2001. We report on all findings and data analyses completed to-date. As such, this research program must be viewed as work in progress.

2 METHODS

2.1 Study Site

The test cells are small wetlands, 0.2 ha[a] in size. They are arranged into two groups of 15 cells each; one group is situated within Cell 1 of STA-1W and the other group within Cell 3 (**Figure 2**). Ten test cells were assigned to the STA Optimization Research Program (six north test cells and four south test cells); the remaining 20 cells are being used for other District sponsored research projects (**Table 1**). Inflow water for the test cells comes from within STA-1W. Based on historical water quality monitoring data from the old Everglades Nutrient Removal Project (ENRP), it was anticipated that inflow TP concentrations at the north test cells would range between 60 and 150 µg P/L[b] and represent "high" TP conditions, while inflow TP concentrations at the south test cells would range between 30 and 50 µg P/L and represent "low" TP conditions.

The test cells were extensively modified from their original configuration. Changes included (a) installation of a full liner in each test cell to isolate it hydrologically from adjacent test cells and the surrounding STA and allow for independent control of water inflow and depth and (b) a complete rebuilding of the inflow and outflow water distribution system for each group of test cells. Water was first pumped from the surrounding marsh into a water storage cell (**Figure 2**), which was maintained at a stage approximately 0.3-0.6 m[c] above water levels in the test cells. Water from the storage cell gravity flowed into a 76.2-cm[d] diameter feeder pipe and was delivered in parallel fashion to the test cells through 20.3-cm diameter lateral pipes, each fitted with one of several calibrated orifice caps. The end of the feeder pipe was also equipped with an orifice cap, which constantly drained the pipe, and kept the water delivery system well-flushed even when all the test cells were operating at low flow rates or are shut-off altogether. This feature reduced changes in water quality along the length of the feeder pipe due to stagnation. The flow rate into each test cell was regulated by changing the orifice cap. Outflow from each test cell was controlled by an adjustable 90° v-notch weir. Raising or lowering the weir controlled the depth within that cell.

2.2 Start-up Period

All modifications to the north and south test cells described above were completed in June 1998 and November 1998, respectively. Before experiments could be initiated, a number of critical activities had to be completed during a start-up period.

2.2.1 Vegetation establishment

The test cells were operated in flow-through mode at a nominal 0.6 m water depth to promote vegetation growth. Individual test cells had been flooded for varying periods of time to start the grow-in process before the District took custody of each group of test cells from the contractor. Vegetation was established from the native seed bank, roots, shoots and tubers present within the soil that was used to fill each test cell after the liner was installed. This soil was obtained from locations within STA-1W.

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[a] 1 ha = 2.4710 acres
[b] 1 µg P/L = 1 ppb P (part per billion)
[c] 1 m = 3.2808 ft
[d] 1 cm = 0.3937 in

2.2.2 Preliminary water quality evaluation

We assumed that there would be no differences in influent water quality to a group of test cells and that all test cells within a group would have equivalent treatment performance. To confirm these hypotheses, grab sampling of the water storage cell outlet and test cell inlets and outlets was initiated in the north test cells in September 1998 and in the south test cells in November 1998. All test cells were operated at the same HLR (2.7 cm/d) and depth (0.6 m) throughout the start-up period. Water samples were collected and analyzed for temperature, conductivity, pH, dissolved oxygen (DO), TP, ammonia nitrogen (NH_3), nitrate+nitrite nitrogen (NO_x), total Kjeldahl nitrogen (TKN), total organic carbon (TOC), chloride (Cl), total suspended solids (TSS) and alkalinity.

2.2.3 Inflow orifice calibration

Accurate estimates of inflow to the test cells were critical to calculating water and nutrient budgets. Inflow to each test cell was a function of the elevation difference between stage in the water storage cell and the orifice (i.e., head drop) and the size of the orifice. Stage in the water storage cell was recorded to the nearest 0.3 cm on a continuous basis and the data relayed by radio to District computers daily. Individual flow equations were developed for each orifice cap based on the following relationship (Aisenbrey et al., 1978):

$$Q_o = C_o A_o \sqrt{2gH_o} \tag{1}$$

where Q_o is the measured discharge through the orifice cap (cfs), C_o is the orifice discharge coefficient, A_o is the cross-sectional area of the orifice opening (ft^2), g is the acceleration due to gravity (ft/sec^2) and H_o is the head drop on the centerline of the orifice opening (ft).

Flow equations derived for the test cells accounted for 89 to >99% of the variability in the measured flow through the different sized orifices (**Table 2**). Table 2 also provides the range of flow for each orifice based on stage variation within the water storage cell as it filled and drained and the resulting average HLR and HRT. As a check to our calibrations, we independently measured orifice flow using a double-sided tipping bucket similar to a prototype developed at the University of Connecticut and based on the same operating principles as USGS tipping rain gauges (**Figure 3**). Flow measured using this device was within 8% of computed flow through the 0.5-in and 0.75-in diameter orifices. We calibrated orifices greater than 1.0-in diameter only with the tipping bucket. The container used to collect water for manual calibrations (a 5-gal bucket) was unusable at the high flow volumes produced by the large orifices due to excessive water splash-out.

2.2.4 Outflow weir calibration

Flow over the outflow weirs was a function of the stage within each test cell. Test cell stage was measured to the nearest 0.3 cm on a continuous basis by an automated stage recorder and the data relayed by radio to District computers daily. The standard 90° v-notch weir equation (Aisenbrey et al., 1978; Brater and King, 1976) was used to calculate outflow from each test cell:

$$Q_w = C_w H_w^{2.5} \tag{2}$$

where Q_w is the measured discharge over the weir (cfs), C_w is the weir discharge coefficient and H_w is the head on the weir (ft). A discharge coefficient was calculated for each test cell weir.

Three of the north test cells have substantially longer outflow pipes running to their weir-box structures than do the other 12 north test cells (the three test cells in question are adjacent to the old outflow sump area, which was part of the original test cell design; the sump area was filled in when the test cells were modified creating, in effect, a much wider levee through which the outflow pipe from these three cells had to run to reach their weir-box structures). The original design assumption that the longer outflow pipes would not influence flow appears to have been incorrect. The mean discharge coefficient calculated for the three test cells with long outflow pipes (C_o = 2.95) was significantly different from the mean discharge coefficient for the other test cells (C_o = 2.43).

2.3 Test Cell Experiments

The test cells used in STA Optimization Research experiments were all operated initially at a HLR of 2.6 cm/d and a depth of 0.6 m to provide baseline performance data. These starting conditions were within the range of the STA conceptual design criteria (1.6 ≤ HLR ≤ 3.0 cm/d; 0.2 m ≤ operating depth ≤ 1.4 m; Burns & McDonnell, 1994) and operating guidelines currently used for the STAs. Two test cells at each location (north and south groups) were used as controls and maintained at the initial conditions throughout all experiments. We evaluated experimental results from the perspective of whether the hydraulic manipulations described below improved treatment performance relative to "STA baseline" performance in the control test cells.

2.3.1 HLR experiments

Because a limited number of test cells were available for on this project, the HLR in the experimental cells was lowered or raised several times in step-fashion to achieve different TP loading rates, i.e., experiments were conducted sequentially. In the low-HLR experiments, the HLR to two north test cells and one south test cell was decreased by 50 percent in three step changes, one step every 15 weeks, ending with a HLR of 0.3 cm/d (**Table 2**). Concurrently, the HLR in the remaining two north and one south test cells was approximately doubled in three step changes, one step every 15 weeks, ending with a HLR of 18.5 cm/d (high-HLR experiments). Depth was maintained at 0.6 m in all test cells throughout these trials. We measured change in treatment performance as the difference in mean TP concentration between experimental and control test cells. We did not control inflow TP concentrations to the test cells during these experiments.

2.3.2 Water depth and pulsed-HLR experiments

Following completion of the HLR experiments, all test cells were returned to the initial conditions for a period of time before initiating water depth and pulsed-HLR experiments (**Table 3**). Two north test cells and one south test cell were used for water depth experiments (low depth = 0.15 m and high depth = 1.2 m) and operated at a constant HLR (2.6 cm/d). The remaining test cells are assigned to the pulsed-HLR experiment. The HLR in the pulsed-HLR experiment changes weekly and will vary from 0.05 to 15.27 cm/d (**Table 4**). The flow pattern developed for this experiment was based on a 10-yr period of record for the STA-2 basin. Both the water

depth and pulsed-HLR experiments will run for one year. The same four test cells are being used as controls in these experiments as for the HLR experiments.

2.3.3 Water quality

Weekly grab and/or composite water samples were collected at the outlet from the water storage cell (representing inflow water quality to all the test cells) and all test cell outlets. The same suite of water quality parameters was monitored in all experiments (**Table 5**). Particulate phosphorus (PP) was calculated as the difference between TP and total dissolved P (TDP). Dissolved organic phosphorus (DOP) was calculated as the difference between TDP and soluble reactive phosphorus (SRP). Total nitrogen (TN) was calculated as the sum of total Kjeldahl nitrogen (TKN) and nitrate+nitrite-nitrogen (NO_x-N). We considered SRP to be equivalent to dissolved inorganic phosphorus (DIP). However, SRP may include a small fraction of any condensed phosphate present and hydrolyzed during the analytical procedure (APHA, 1989) and therefore may slightly overestimate true DIP concentrations.

2.3.4 Hydraulic tracer studies

Uneven flow patterns through a treatment wetland, i.e. short-circuiting, can result in hydraulic inefficiency and may reduce the system's ability to removal nutrients and other constituents (Reed et al, 1995; Persson et al, 1999). Hydraulic tracer studies are the most effective means to quantify the degree of wetland short-circuiting. We conducted a number of tracer studies using lithium (Li) in five test cells between May 1, 2000, and August 22, 2000 as part of the HLR experiments. The objective was to determine the actual HRT in the test cells during these experiments and compare this value against the nominal HRT computed from the HLR and test cell geometry. Tracer spikes were prepared by diluting lithium chloride (LiCl) brine solution (78,457 mg/L as Li) to an approximate concentration of 350 µg Li/L. The tracer spike was added to each test cell over a period of two minutes by pouring it into the inlet distribution system. Automated samplers were deployed at the outlet of each test cell and programmed to collect 250-mL samples at varying time intervals starting with introduction of the tracer. Samples were preserved with nitric acid to a pH ≤ 2. Test cell outflow rates were measured daily as described in Section 2.2. Time series data of tracer concentrations at the test cell outlets were interpreted using the gamma distribution method summarized by Kadlec (2001).

2.4 Vegetation Monitoring

The development of the vegetation community in the test cells during the start-up period was documented by visually estimating the percent coverage of the dominant species in each cell on a quarterly basis. This effort was supplemented by conducting vegetation line-transect surveys (Bonham, 1937; Browder et al., 1997) in test cells dedicated to the STA Optimization Research Program (**Table 1**) and by inspecting aerial and ground-based photographs of all test cells.

2.5 Additional Research

Additional data has been collected to further characterize conditions within the test cells during these experiments, including water velocity, sediment oxidation-reduction potential (redox), plant stem density, and cellulose decomposition rates. Plant stem density was measured using standard line-transect census methodologies (Bonham, 1937; Brower et al., 1997) along the length and width of each cell. Water velocity was measured using a low-flow Sontech ADV meter at a single depth along length and width transects. Cotton strip frames (Maltby, 1985) and

redox rods (Snoeyink and Jenkins, 1980) were placed in vegetated areas at the inlet and outlet to document the effect of nutrient concentration and HLR on cellulose mineralization rates.

Cotton strip assays were performed using a technique similar to that described in Maltby (1985). A stainless steel frame holding three 12-cm by 30-cm cotton strips was inserted 15 cm into the sediment. Cotton strips were incubated in the test cells for one week during each deployment. When deployed, one-half the cotton strip was within the sediment while the remainder was in the water column to compare decomposition in these environments. Upon retrieval, the cotton strips were cut into 2-cm sections starting 10 cm above and below the soil-water interface. The cotton strips were frayed by hand until a single thread could be removed intact along the length of the cut edge to assure a constant width and avoid measurement bias from weak or torn threads. Each strip was soaked in water and blotted dry to simulate 100 percent humidity before testing. Tensile strength of the strips was measured using a Chatillon TCD-200 tensiometer equipped with a digital force gauge. Force was applied until the strip tore. Tensile strength was adjusted to correct for the loss in tensile strength of a control cotton strip and expressed as an annual rate:

$$CR = \left[(y_0 - y)/y\right]^{1/3} \tag{3}$$

$$CRR = (CR/t) \times 365.25 \tag{4}$$

where CRR is the annual cotton rotting rate (/yr), CR is the dimensionless measure of rottenness, y_0 is the mean tensile strength of control strip (newtons), y is the mean tensile strength of the test strip at a given depth (newtons) and t is the duration of burial (d).

3 RESULTS AND DISCUSSION

3.1 Vegetation Community Development

Nine macrophyte taxa were recorded in the north test cells and eight taxa in the south test cells (**Table 6**). Two species of cattail, *Typha domingensis*, Pers. and *Typha latifolia*, L., were present in both groups of test cells, but were not differentiated from each other for this analysis. The north test cells were largely vegetated by the time the first line-transect survey was conducted in September 1998 (**Figure 4**). All the test cells used in the STA Optimization Research experiments were *Typha* dominated; *Typha* spp. covered at least 70% of test cells 2- through 14-North by March 1999 and *Typha* coverage increased markedly in the south test cells between the time of the first and second vegetation surveys (**Figure 5**). Incidental populations of *Sagittaria latifolia* , submerged aquatic vegetation (SAV), other emergent species and periphyton were interspersed amongst the *Typha*. All macrophyte species that became established in the STA Optimization research test cells did so on a volunteer basis.

We elected to perform this research in *Typha* dominated wetlands that developed naturally because it is anticipated that this community type will also be dominate in the STAs. The District is evaluating treatment efficacy of wetlands dominated by submersed aquatic vegetation and periphyton in other research projects (**Table 1**).

3.2 Preliminary Water Quality Evaluation

There were no substantive differences noted for TP, NH_3, NO_x, TKN, Cl, TOC, alkalinity, conductivity or temperature between the north water storage cell outlet and test cell inlets, nor were any important differences observed among the individual test cell inlets (**Figures 6-9**). Small differences in TSS and pH, and a substantial difference in DO, occurred between the water storage cell and the test cells. A small "down-pipe" decrease in TSS was also evident. The large increase in DO was attributed to aeration of the water as it flowed through the orifice caps into each test cell. The decrease in TSS was assumed to reflect settling out of particles down the length of the inflow feeder pipe. The orifice cap at the end of the inflow feeder pipe was changed from a 1.0 to a 4.0-in diameter orifice to increase flow velocity through the pipe and reduce particle settling.

There were no substantive differences noted for TP, NH_3, TKN, Cl, TOC, alkalinity, conductivity or temperature between the south water storage cell outlet and test cell inlets, nor were any important differences observed among the individual test cell inlets (**Figures 6-9**). Small differences in DO and pH were noted between the water storage cell and the test cells. A small down-pipe decrease in TSS also was evident. The changes in DO and TSS were attributed to the same mechanisms noted above for the north test cells. We increased the diameter of the orifice at the end of the inflow feeder pipe to 4.0-in to increase flow velocity and reduce the loss of TSS.

Mean values for specific conductance, alkalinity, chloride, NH_3, TKN, TP and TOC during the start-up period were somewhat higher at the north test cells compared to the south test cells (1,200 vs. 1,100 µS/cm; 274 vs. 263 mg $CaCO_3$/L; 218 vs. 176 mg/L; 0.244 vs. 0.134 mg N/L; 2.088 vs. 1.879 mg N/L; 0.047 vs. 0.023 mg P/L and 32.87 vs. 30.50 mg C/L, respectively), whereas mean values for DO, pH, NO_x, and TSS were higher at the south test cells (6.35 vs. 4.13 mg/L; 7.71 vs. 7.32; 0.098 vs. 0.027 mg N/L; and 5.8 vs. 1.8 mg/L, respectively) (**Table 7**). Total P concentrations at the north and south test cells were within the range of values expected to occur at these locations based on historic water quality from the ENRP.

An evaluation of test cell treatment performance during the start-up period was based on comparisons of inflow vs. outflow time series data (mean values from all test cells ± 1 SE) (**Figures 10-13**). Concentrations for most water quality parameters at the water storage cell outlet were similar to those at the test cell inlets, indicating little change in water quality within the inflow feeder pipe (note the exception for TSS and NO_x in the south test cells; see discussion above). The test cells were effective at reducing concentrations of TP (north only), NO_x, NH_3 and TSS. Reduced or little treatment was noted for TKN, Cl and TOC. Reductions in alkalinity were also observed in both groups of test cells.

3.3 HLR Experiments

The low- and high-HLR experiments have been concluded (**Table 3**). These data were intended to help answer two questions central to the STA Optimization Research Program: (1) what is the impact of prolonged increases in hydraulic loading on treatment performance, such as may occur after large storm events and (2) what are the limits to STAs treatment performance? The high-HLR experiments directly addressed the first question for cattail-dominated wetlands, while the low-HLR experiments attempted to address the second.

Wetland treatment performance, as measured by outlet TP concentration, is inversely related with TP loading (Kadlec, 1999). Theoretically, decreasing the TP load to a given wetland should result in greater TP concentration reduction until the limit of treatment performance for that wetland (the C* or background concentration) is reached. Given a fixed inflow water volume and fixed inflow TP mass[e], TP loading can be decreased by increasing wetland surface area. Ideally, an experiment designed to investigate the limits of STA treatment performance relative to STA size would employ experimental wetlands of various sizes that simultaneously receive the same inflow water volume. However, the test cells were all the same size and this experiment could not be performed. Our approach instead was to lower the test cell HLR thereby reducing TP loading. We equated the reduction of HLR in the test cells to the corresponding increase in wetland surface area at a fixed HLR that would have the same TP loading. For example, decreasing the test cell HLR by one-half resulted in the same proportionate reduction in TP loading as doubling wetland surface area without changing the inflow water volume.

3.3.1 Low-HLR experiments

Decreasing HLR resulted in, at best, small improvements in TP removal. The mean outflow TP concentrations at the north control and low-HLR test cells were almost identical in the first experiment (35 vs. 31 µg/L, respectively); differences between control and experimental cells in the second experiment were larger (46 vs. 33 µg/L, respectively) (**Figure 14**). However, neither difference in TP concentration was statistically significant. In addition, there was no statistically significant improvement in outflow TP concentrations between north control and lowest-HLR experiment or in any of the experiments conducted at the south test cells. The lowest HLR (0.3 cm/d) was often equal to or less than the daily evapotranspiration rate in the ENRP (annual range approximately 0.1-0.7 cm/d). As a consequence, water was discharged from the test cells at this HLR only when the inflow water volume was augmented by rainfall. We elected not to conduct the 0.3 cm/d HLR experiment in the south test cells because this discharge pattern was judged to be atypical of routine STA operation.

Kadlec (1999) recommends that analyses of P retention in wetlands should not be applied over time periods shorter than three nominal HRTs. This is because a parcel of water entering a wetland can be widely dispersed as it transits the system and discharged at time intervals ranging from < 1 HRT to ≥ 3 HRTs. The first and second low-HLR experiments in the north test cells ran for 102 and 110 d, respectively, at nominal HRTs of approximately 56 and 96 d, respectively. Neither experiment satisfied Kadlec's duration criteria. However, we found that the increase in inflow TP concentration during the second experiment (**Figure 14**) was almost proportionate to the decrease in HLR. As a result, TP loading during both experiments was quite similar (1.150 and 1.126 mg P/m^2/d). We reevaluated both data sets as a single run of 212 d with a mean HRT $\cong$ 71 d. This "combined" experiment met Kadlec's criteria of three HRTs and had flow-weighted outflow TP concentrations from the control and experimental test cells of 41 and 32 µg/L, respectively. Reductions in TP loading to the experimental cells relative to the controls was equivalent to changes that would have resulted by enlarging wetland surface area by a factor of 2.8. It is important to note that the combined experiment did not reduce outflow TP concentrations beyond that observed in the STAs.

[e] The HLRs, and the corresponding TP loads carried in the water, to the STAs can be thought of as being "fixed" in the sense that the volume of water volume delivered to each STA will be dependent upon the amount of rainfall in the drainage basin and independent of the STA's size.

3.3.2 High-HLR experiments

The mean outflow TP concentrations at the north control and high-HLR test cells were almost identical in the first high-HLR experiment (35 vs. 40 µg/L, respectively) in which HLR was increased by a factor of 1.8 (**Figure 14**). The next two step-increases in HLR (10.4 and 18.5 cm/d) resulted in reduced treatment performance, signified by markedly higher mean outflow TP concentrations relative to the controls, although only the difference in the last experiment was statistically significant. However, even at the highest HLR, there was a measurable reduction in TP concentration from inlet to outlet. There were no statistically significant differences in mean outflow TP concentrations between control and high-HLR test cells in any of the experiments conducted at the south test cells. The HLRs in these experiments resulted in nominal HRTs of 14.0, 6.5 and 3.6 d, respectively. The duration of these experiments (15 wk) ranged from approximately 8 to 29 times the HRT and far exceeded Kadlec's (1999) minimum time period recommendation. Nevertheless, our results remain subject to the other scaling and enclosure artifacts discussed previously.

3.3.3 Phosphorus species

Mean concentrations of TP, TDP and SRP were reduced from inlet to outlet in both low- and high-HLR experiments at the north test cells, but not in the south test cells (**Figure 15**). The reduction in TP was inversely proportionate to the HLR, i.e., the greatest concentration decrease occurred at the lowest HLR and became smaller as HLR increased. The data suggest that the same inverse relationship existed for TDP and SRP, although the trend was not as distinct. In addition to concentration reductions, the proportion of P species changed from inlet to outlet in the north test cells. Because most of the SRP had been removed from the water after passage through the test cells (except during the highest HLR experiment in the north test cells), effluent P was largely a mixture of DOP and PP (**Figure 16**), P fractions that are much more resistant to removal by wetlands. The Everglades Nutrient Removal Project processed P in a similar fashion (Chimney et al., 2000). There was little apparent change in the proportion of P species in HLR experiments conducted at the south test cells.

3.3.4 Hydraulic tracer studies

We typically ran each hydraulic tracer study for a time period 3-fold longer than the nominal HRT to ensure adequate recover of the Li spike. However, because relatively little of the tracer was recovered in the time allotted to each of the low-HLR experiments (15 wks; HRTs in these experiments ranged from 46.2 to 201.5 d), only results from the control and the high-HLR experiment test cells were analyzed. The test cells all exhibited similar hydraulic properties and residence time distribution curves (**Table 8**, **Figure 17**). The number of tanks-in-series resulting from this analysis ranged from 4.4 to 7.4, indicating that the test cells can be accurately modeled as plug-flow reactors. In general, the mean HRTs based on the tracer data were larger than nominal HRTs computed using the HLR and test cell geometry. The corresponding volumetric efficiencies (measured HRT/nominal HRT) were greater than 100% indicating that the test cells were not hydraulically short-circuited.

3.4 Water Depth and Pulsed-HLR Experiments

The water depth and pulsed-HLR experiments described in Section 2.3.2 were initiated in both the south and north test cells in October 2000 (**Table 3**). Fieldwork is scheduled for com-

pletion in November 2001. Data analyses and interpretation of results from these experiments will be presented in the District's 2003 Everglades Consolidated Report (the data cannot be analyzed in time for inclusion in the 2002 Everglades Consolidated Report that will be published on January 1, 2002).

3.5 Other Water Quality Parameters

Data for the non-phosphorus water quality parameters monitored during the HLR experiments (**Table 5**) are summarized in **Appendices 1 through 31**. Inorganic N (NH_4-N and NO_3+NO_2-N) concentrations usually declined to levels near their respective analytical detection limits at the outlet. Silica also was reduced consistently at both sites. Total N, TKN and DTKN decreased in the first two experiments at the north site (the magnitude of concentration reduction was inversely proportional to the HLR), but no consistent change was discernible in any of the other experiments. This same pattern of concentration reduction was observed for Cl, conductivity, DOC, Mg, Na, SO_4, TDS and TOC. Most pH values ranged between 7 and 8. Alkalinity generally increased from inlet to outlet at the north site and decreased at the south site, while Ca levels decreased at both sites. Net export of metals (Al, Fe, Mn, Mo and Zn) occurred during one or more of the experiments at both the north and south sites. No consistent treads were detected for DO, K, temperature, TIC or TSS.

3.6 Cellulose Decomposition

A test deployment of cotton strips in the test cells detected no differences in cellulose decomposition rates in the sediment between inlet and outlet areas. However, we did find markedly lower decomposition rates (i.e., decreased loss in tensile strength) in the water column at the outlet compared to the inlet (**Figure 18**). The CRR of cotton strips deployed during the HLR experiments was correlated with increasing HLR at higher inflow P concentrations (north test cells), but there was no apparent response at lower nutrient loads (south test cells) (**Figure 19**). One notable difference between the north and south test cells was the amount of SRP in the inflow water, i.e., the north test cells had substantially higher SRP levels (**Figure 15**). We surmise that microbial activity associated with decomposition is mediated by SRP availability. Other studies in the Everglades also noted an increase in cellulose decomposition with an increase in nutrient loading (Maltby, 1985). Decomposition rates measured within *Typha* stands (mean = 41.3/yr) were similar to rates within SAV beds (mean = 30.6/yr). The use of cotton strip decomposition may prove to be a sensitive indicator of biological activity in wetland sediments (Pankhurst et al., 1995; Smith et al., 1993).

4 MANAGEMENT IMPLICATIONS

Lowering the HLR in the test cells to values less than the STA design criteria (1.6-3.0 cm/d), and thereby reducing the TP loading, did not significantly improve reduction in mean outflow TP concentrations. The changes in TP loading in these experiments were equivalent to more than doubling the surface area at a constant inflow water volume. These results suggest that increasing surface area in cattail-dominated portions of the STAs beyond the current design criteria would provide little improvement in treatment performance. In addition, none of the low-HLR experiments achieved a mean outflow TP concentration < 30 µg/L, a level of performance that has been exceeded by existing STAs. Conversely, an approximate doubling of the test cell baseline HLR (2.6 to 4.8 cm/d) produced relatively little change in mean outflow TP concentrations. However, a marked increase in mean outflow TP levels occurred at a four-fold HLR increase.

The high-HLR experiments identified a region of sustained hydraulic loading between 4.8 and 10.4 cm/d within which treatment performance in cattail-dominated wetlands may be expected to decline. It must be emphasized again that extrapolating from the HLR experiments to the STAs should be restricted to forecasting the performance of cattail-dominated communities.

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Table 1. Assignment of test cells to STA Optimization, Advanced Treatment Technology and Marsh Dry-Out research projects.[a]

Cell #	North Test Cells	South Test Cells
1	SAV/Limerock	*control cell*
2	Managed Wetlands	***STA Optimization***
3	Managed Wetlands	PSTA
4	Managed Wetlands	SAV/Limerock
5	*control cell*	Managed Wetlands
6	***STA Optimization***	Managed Wetlands
7	***STA Optimization***	Managed Wetlands
8	***STA Optimization***	Periphyton-STA
9	***STA Optimization***	SAV/Limerock
10	*control cell*	Periphyton-SAV
11	Low-intensity Chemical Dosing	Periphyton-SAV
12	Low-intensity Chemical Dosing	Periphyton-SAV
13	Low-intensity Chemical Dosing	Periphyton-STA
14	Marsh Dry Out	***STA Optimization***
15	SAV/Limerock	*Control cell*

[a]Advanced Treatment Technology research projects are described in Coffelt et al. (2001).

Table 2. Predictive flow equations for different sized orifice caps, range of flow values, mean hydraulic loading rates and nominal hydraulic retention times for north and south test cells.

Orifice Diameter (in)	Predictive Flow Equation[a]	Flow Range[b] (cfs)	Mean HLR (cm/d)	Nominal HRT (d)
0.25	$0.0002[64\ (\text{Stage - Center Line of Orifice})]^{1/2}$	0.0026-0.0031	0.3	201.5
0.375	$0.0005\ [64\ (\text{Stage - Center Line of Orifice})]^{1/2}$	0.0063-0.0073	0.7	77.4
0.5	$0.0008\ [64\ (\text{Stage - Center Line of Orifice})]^{1/2}$	0.0129-0.0149	1.2	46.2
0.75	$0.0030\ [64\ (\text{Stage - Center Line of Orifice})]^{1/2}$	0.0256-0.0313	2.6	21.0
1.0	$0.0030\ [64\ (\text{Stage - Center Line of Orifice})]^{1/2}$	0.0481-0.0590	4.8	11.6
1.5	$0.0070\ [64\ (\text{Stage - Center Line of Orifice})]^{1/2}$	0.1069-0.1242	10.4	5.3
2.0	$0.0120\ [64\ (\text{Stage - Center Line of Orifice})]^{1/2}$	0.1848-0.2150	18.5	3.0

[a] Predictive flow equations derived from Equation 1 in text.
[b] The range of flow values for each orifice is based on expected stage variation in the storage cell and the corresponding mean HLR to the test cells for different sized orifices.

Table 3. Identification numbers, types, start dates, mean hydraulic loading rates (HLR) and nominal depths for STA Optimization Research experiments conducted in the north and south test cells.

Exp ID	Exp Type[a]	North Test Cells	South Test Cells	HLR (cm/d)			Depth (m)
				Low	Control	High	
1	H/L	May 19, 1999	November 2, 1999	1.2	2.6	4.8	0.60
2	H/L	September 1, 1999	February 14, 2000	0.7	2.6	10.4	0.60
3	H/L	February 14, 2000	July 3, 2000[b]	0.3	2.6	18.5	0.60
4	D	October 2, 2000	October 18, 2000	-	2.6	-	0.15
5	P	October 2, 2000	October 18, 2000	-	Pulsed	-	0.60
6	D	April 1, 2001	April 12, 2001	-	2.6	-	1.20
7	P	April 1, 2001	April 12, 2001		Pulsed		0.60

[a]H/L = high and low HLR experiment; D = depth experiment; P = pulsed-HLR experiment.

[b]The 0.3 cm/d HLR experiment was not conducted in the south test cells. See text for details.

Table 4. Schedule of weekly hydraulic loading rates for the pulsed-HLR experiment conducted in the north and south test cells.

Week #	Low-HLR Pulsing (cm/d)	Week #	High-HLR Pulsing (cm/d)
1	0.05	27	4.04
2	0.05	28	4.04
3	0.74	29	2.09
4	0.74	30	2.09
5	1.03	31	4.82
6	1.03	32	4.82
7	1.62	33	3.22
8	1.62	34	3.22
9	0.52	35	15.27
10	0.52	36	15.27
11	2.75	37	4.18
12	2.75	38	4.18
13	0.13	39	10.85
14	0.13	40	10.85
15	2.57	41	5.59
16	2.57	42	5.59
17	1.53	43	5.93
18	1.53	44	5.93
19	0.05	45	1.76
20	0.05	46	1.76
21	1.30	47	5.10
22	1.30	48	5.10
23	0.58	49	1.05
24	0.58	50	1.05
25	0.32	51	1.99
26	0.32	52	1.99

Table 5. Physical and chemical parameters monitored as part of STA Optimization Research experiments conducted in the north and south test cells.

Nutrients	Physical Parameters	Misc. Chemical Parameters
Total phosphorus (TP)	Dissolved oxygen	Total suspended solids (TSS)
Total dissolved phosphorus (TDP)	Temperature	Total dissolved solids (TDS)
Soluble reactive phosphorus (SRP)	pH	Total organic carbon (TOC)
Dissolved organic phosphorus (DOP)	Conductivity	Dissolved organic carbon (DOC)
Particulate phosphorus (PP)	Stage	Total inorganic carbon (TIC)
Total nitrogen (TN)	Flow	Alkalinity
Total Kjeldahl nitrogen (TKN)		
Dissolved total Kjeldahl nitrogen (DTKN)		
Ammonia-nitrogen (NH_4-N)		
Nitrate+nitrite-nitrogen (NO_3+NO_2-N)		
Silica (Si)	**Other Cations (+)**	
Other Anions (-)	Aluminum (AL)	Calcium (Ca)
Sulfate (SO_4)	Iron (Fe)	Potassium (K)
Chloride (Cl)	Magnesium (Mg)	Sodium (Na)
	Manganese (Mn)	Zinc (Zn)
	Molybdenum (Mo)	

Table 6. Checklist of plant species observed during start-up monitoring of the north and south test cells.

Species	Test Cell Number														
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
North Test Cells															
Typha spp.	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Sagittaria latifolia	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Sagittaria graminea		✓	✓												✓
Cyperus spp.				✓					✓	✓		✓			
Spirodela polyrhiza	✓					✓	✓								
Ludwigia octovalvis						✓	✓	✓	✓	✓	✓	✓		✓	✓
Chara vulgaris	✓	✓	✓	✓	✓	✓	✓	✓	✓		✓	✓	✓		
Najas guadalupensis					✓	✓									
Ceratophyllum demersum												✓			
South Test Cells															
Typha spp.	✓	✓		✓	✓	✓	✓		✓	✓	✓	✓	✓	✓	✓
Sagittaria latifolia		✓		✓	✓	✓	✓		✓	✓	✓	✓		✓	✓
Sagittaria graminea	✓	✓													
Eleocharis cellulosa			✓	✓		✓	✓	✓					✓	✓	
Ludwigia octovalvis	✓			✓	✓	✓	✓							✓	
Chara vulgaris				✓					✓		✓	✓	✓	✓	
Najas guadalupensis			✓												
Hydrilla verticillata	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓

Table 7. Descriptive statistics for water quality parameters monitored at the inlets to the north and south test cells during the test cell start-up period.

Variable	# Samples	Mean[a]	Minimum	Maximum
North Test Cells[b]				
Dissolved oxygen (mg/L)	300	4.13	0.10	6.90
Specific conductance (µS/cm)	300	1220	4	1808
pH	300	7.32	6.83	7.69
Alkalinity (mg $CaCO_3$/L)	280	274	116	3600
Chloride (mg/L)	280	218	11	1400
Total organic carbon (mg/L)	281	32.87	14.81	70.00
Ammonia (mg N/L)	280	0.244	0.019	0.520
Nitrate-nitrite (mg N/L)	280	0.027	0.004	0.100
Total Kjeldahl nitrogen (mg N/L)	281	2.088	0.360	6.700
Total phosphorus (µg P/L)	280	47	23	194
Total suspended solids (mg/L)	278	1.8	0.5	4.4
South Test Cells[c]				
Dissolved oxygen (mg/L)	159	6.35	3.90	9.50
Specific conductance (µS/cm)	159	1100	532	1761
pH	159	7.71	7.40	8.12
Alkalinity (mg $CaCO_3$/L)	117	263	210	290
Chloride (mg/L)	117	176	130	250
Total organic carbon (mg C/L)	114	30.50	28.00	39.70
Ammonia (mg N/L)	117	0.134	0.047	0.310
Nitrate-nitrite (mg N/L)	117	0.098	0.0350	0.190
Total Kjeldahl nitrogen (mg N/L)	117	1.879	1.500	2.400
Total phosphorus (µg P/L)	117	23	14	38
Total suspended solids (mg/L)	117	5.8	2.1	14.0

[a]Mean values are not flow-weighted.

[b]Statistics for the north test cells based on data collected from September 1998 through April 1999.

[c]Statistics for the south test cells based on data collected from November 1998 through April 1999.

Table 8. Hydraulic characteristic of north and south test cells based on analysis of hydraulic tracer study data collected from May 1, 2000 through August 22, 2000.

Parameter	N-Control	S-Control	N-High HLR	S-High HLR
Average volume (m^3)	1449.3	1449.3	1449.3	1449.3
Average flow (m^3/d)	56.2	64.5	474.7	246.0
Nominal HRT (d)	25.8	22.5	3.0	5.9
Mean HRT, τ (d)	33.5	29.6	2.4	7.6
# of tanks in series	6.6	7.4	7.2	4.4
Volumetric efficiency (%)	130	132	80	129
Mass recovery (%)	49	68	93	84

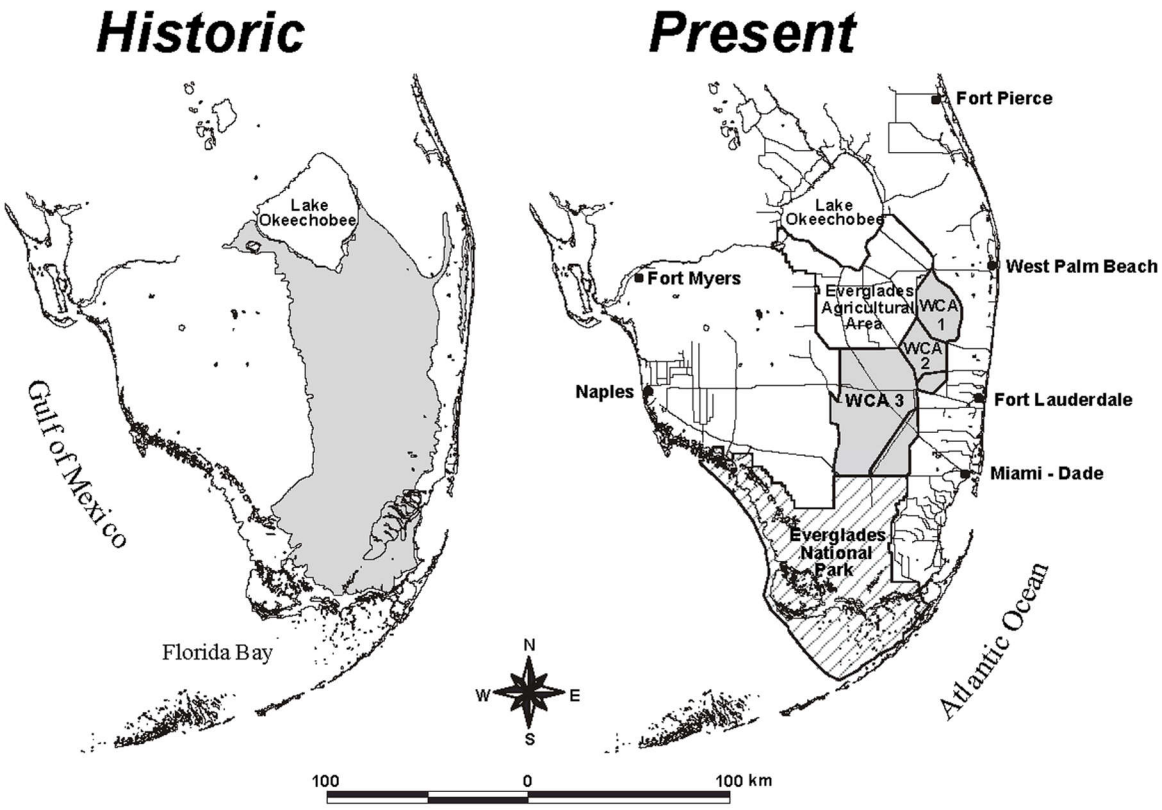


Figure 1. Comparison of areal extent of the historic Everglades with the present-day ecosystem comprised of the Water Conservations Areas and Everglades National Park.

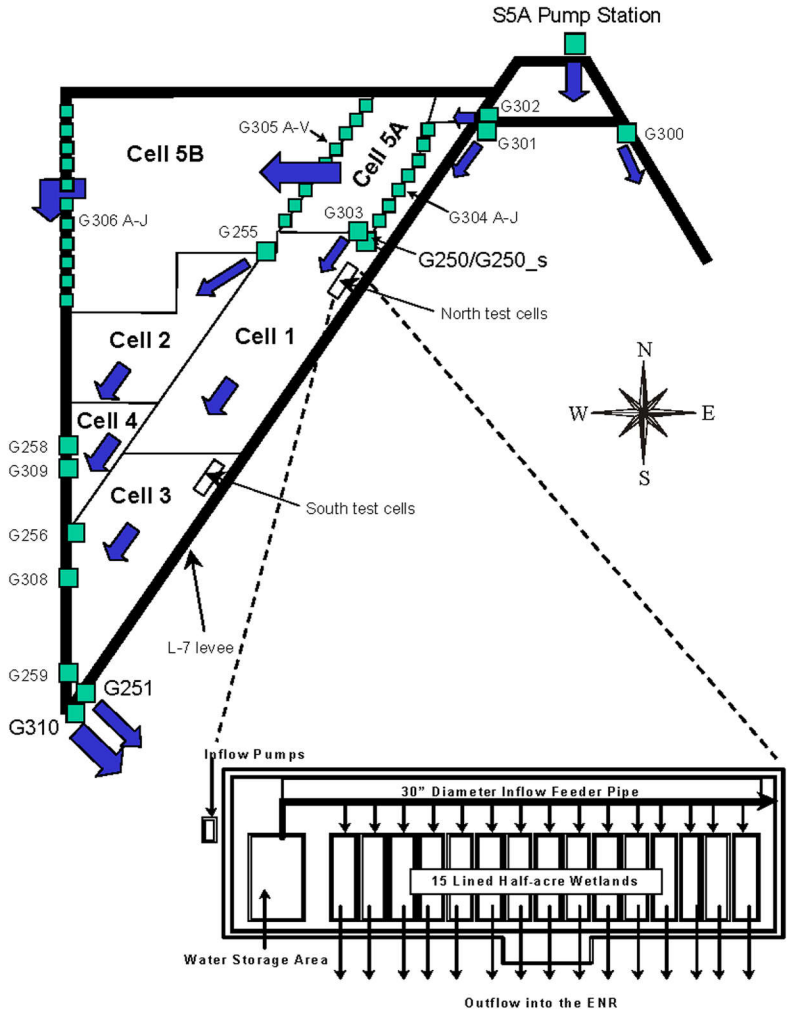


Figure 2. Map of Stormwater Treatment Area 1-W showing location of the north and south test cells. Arrows indicate direction of flow.

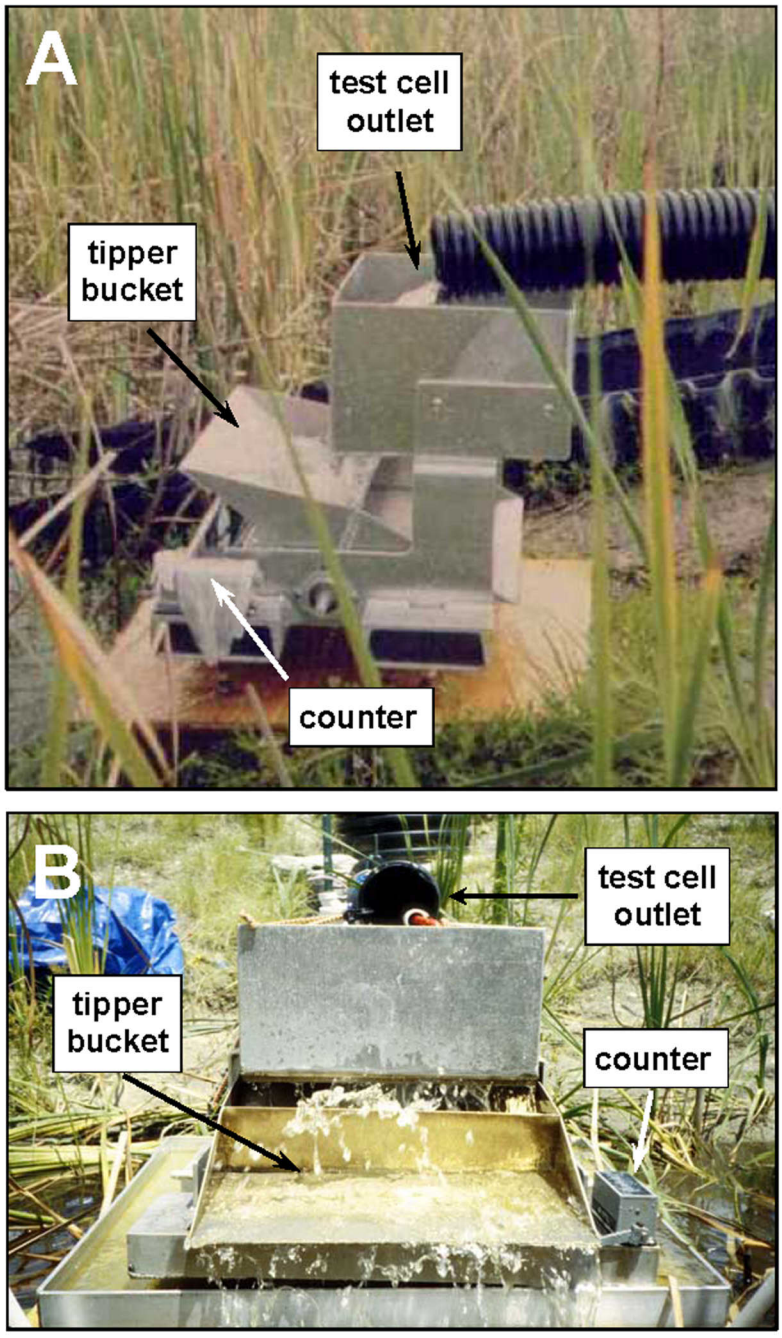


Figure 3. Double-sided tipping bucket used to validate flow calibrations for different sized orifices in the north and south test cells. Panel A: side view of tipping bucket; Panel B: front view of tipping bucket.

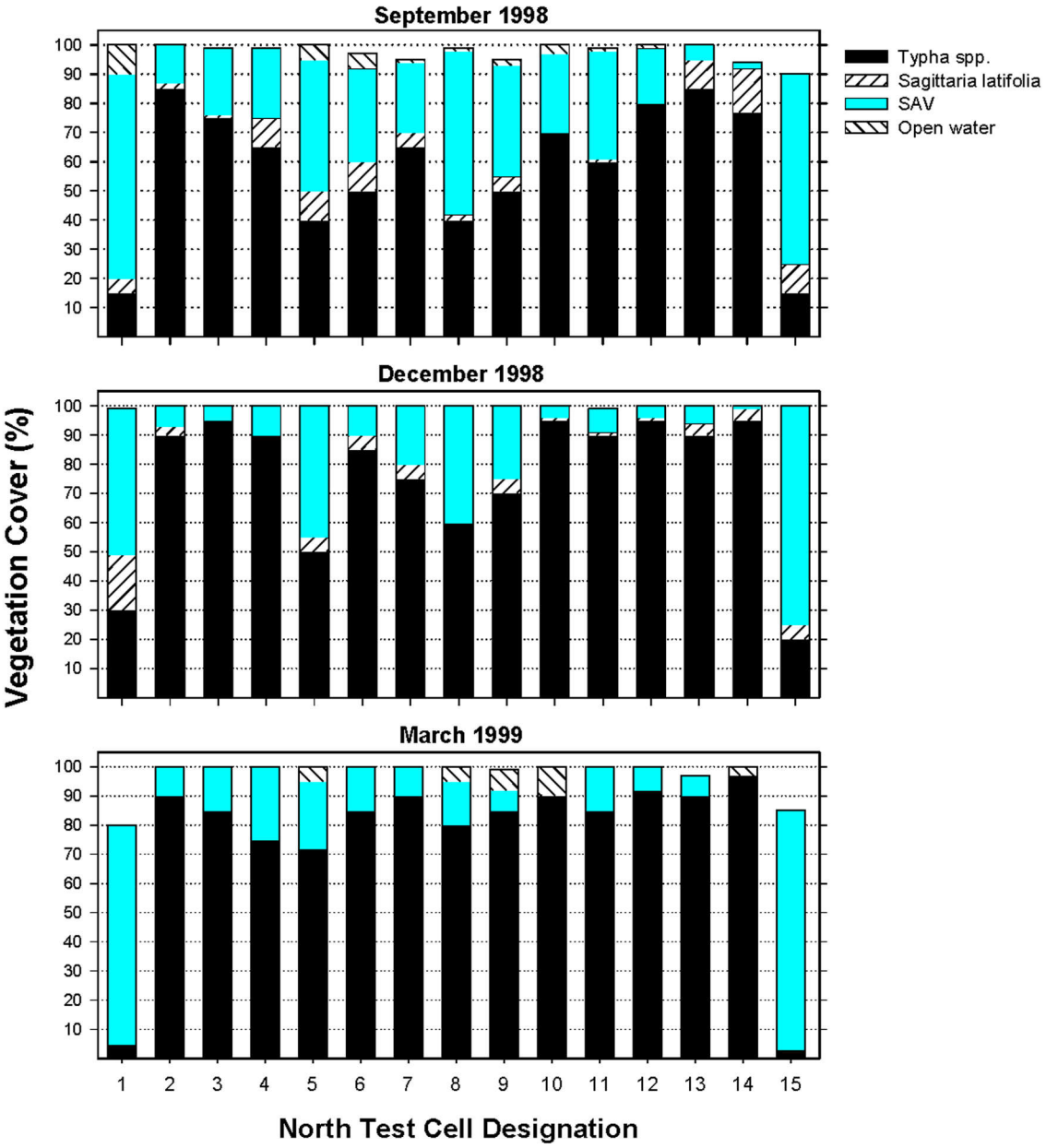


Figure 4. Changes in the percent coverage of emergent (*Typha* spp. and *Sagittaria latifolia*) and submerged aquatic vegetation in the north test cells during the start-up period based on data from vegetation line-transect surveys.

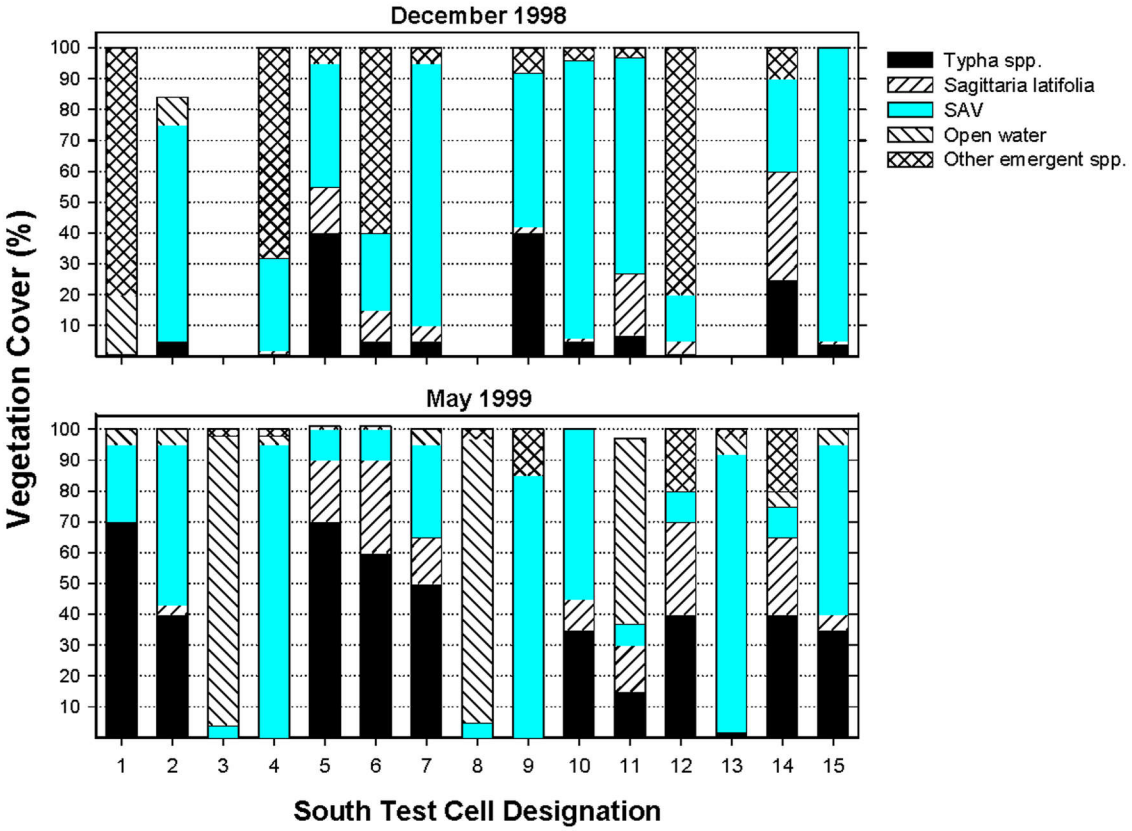


Figure 5. Changes in the percent coverage of emergent (*Typha* spp., *Sagittaria latifolia* and other species) and sub merged aquatic vegetation in the south test cells during the start-up period based on data from vegetation line-transect surveys.

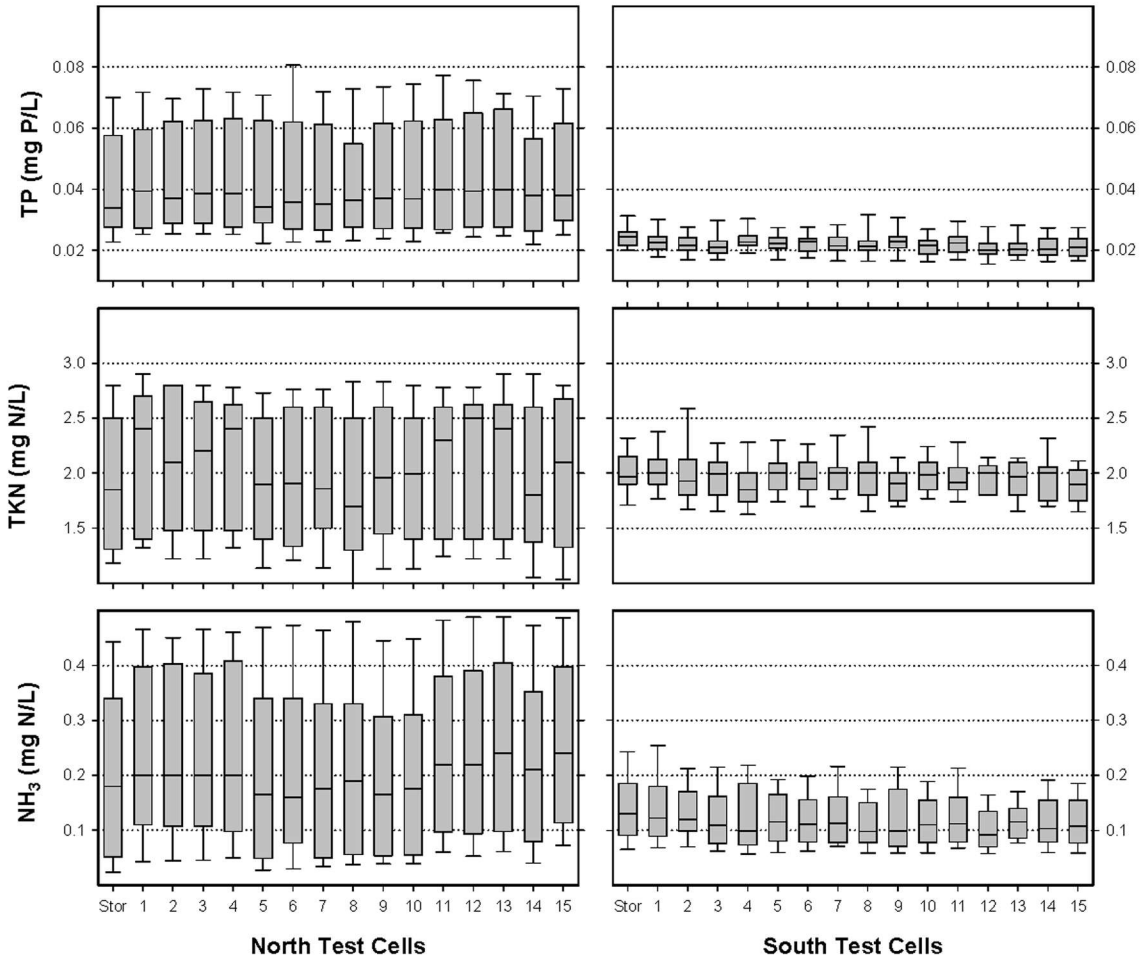


Figure 6. Summary of total phosphorus, total Kjeldahl nitrogen and ammonia-nitrogen measurements at the water storage cell outlet and test cells inlets during start-up of the north test cells (September 1998 through April 1999) and south test cells (November 1998 through April 1999). Description of box plots: top and bottom of box = 75th and 25th percentile of the data distribution, respectively; mid-line in box = 50th percentile; ends of whiskers = 10th and 90th percentiles.

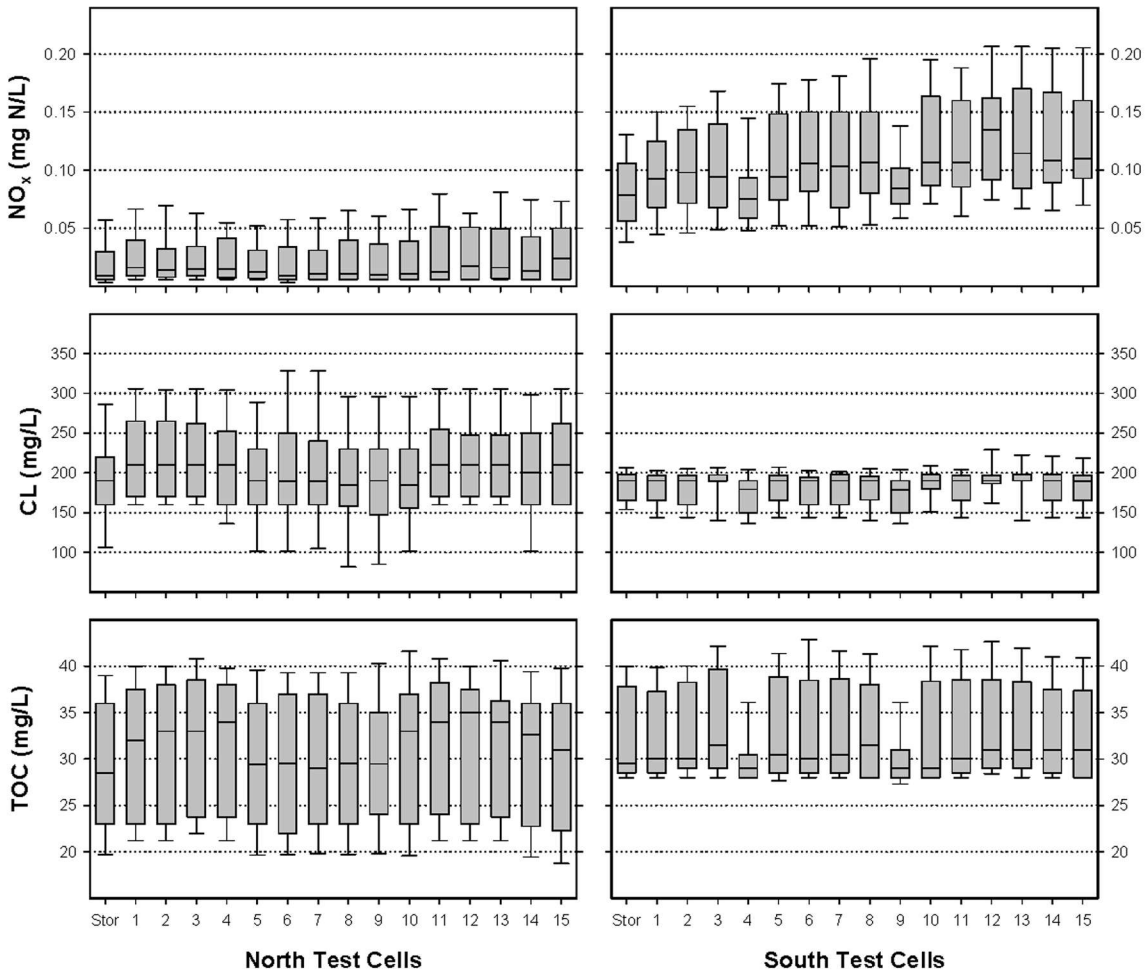


Figure 7. Summary of nitrite+nitrate nitrogen, chloride and total organic carbon measurements at the water storage cell outlet and test cells inlets during start-up of the north test cells (September 1998 through April 1999) and south test cells (November 1998 through April 1999).

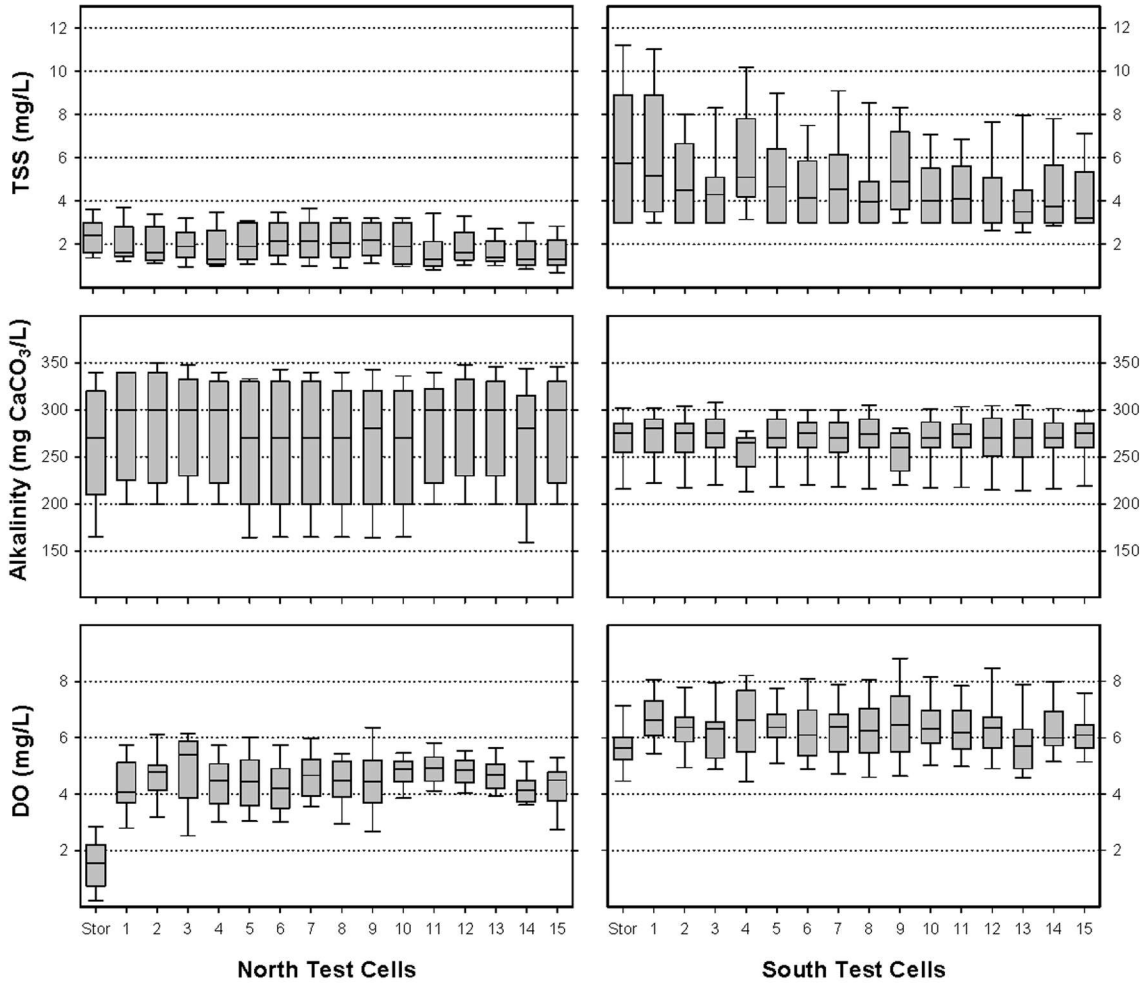


Figure 8. Summary of total suspended solids, alkalinity and dissolved oxygen measurements at the water storage cell outlet and test cells inlets during start-up of the north test cells (September 1998 through April 1999) and south test cells (November 1998 through April 1999).

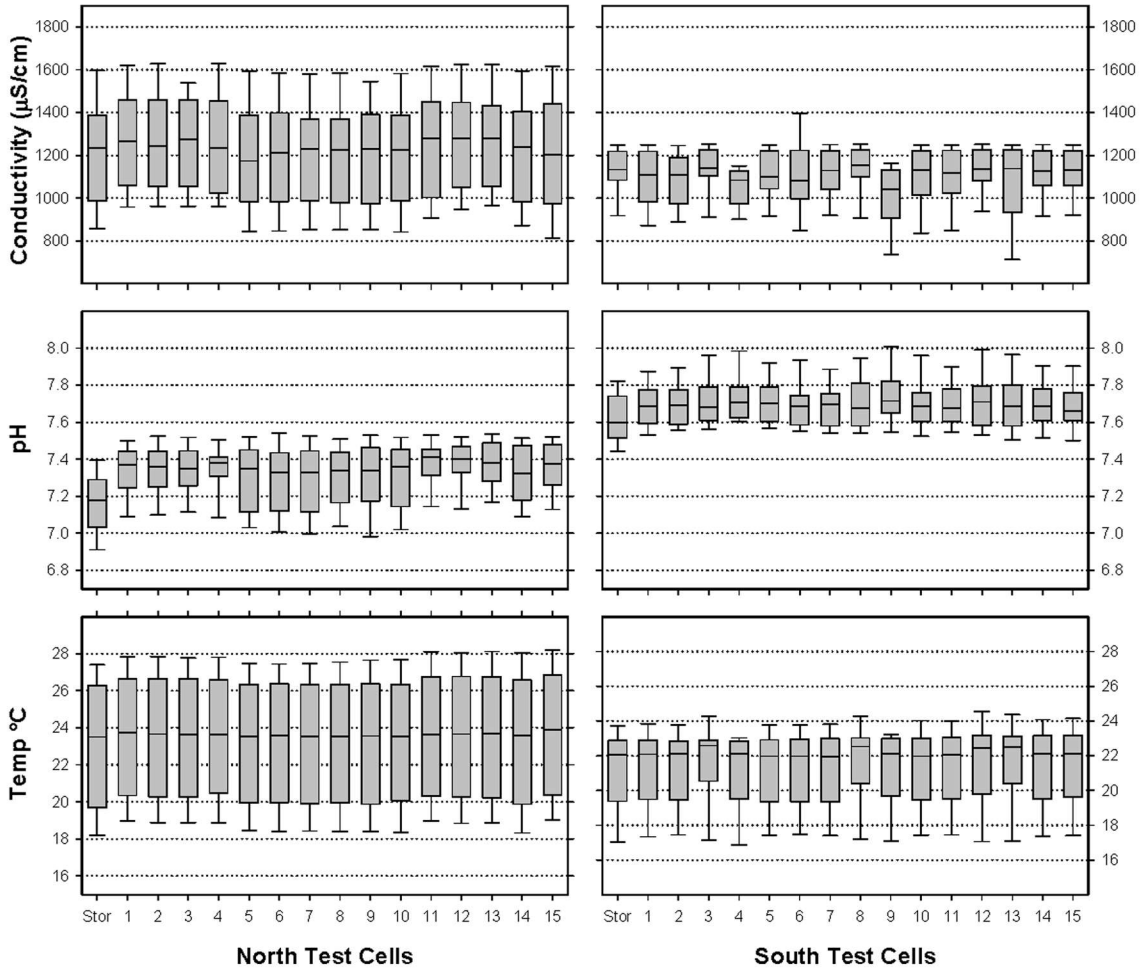


Figure 9. Summary of conductivity, pH and temperature measurements at the storage cell outlet and test cells inlets during start-up of the north test cells (September 1998 through April 1999) and south test cells (November 1998 through April 1999).

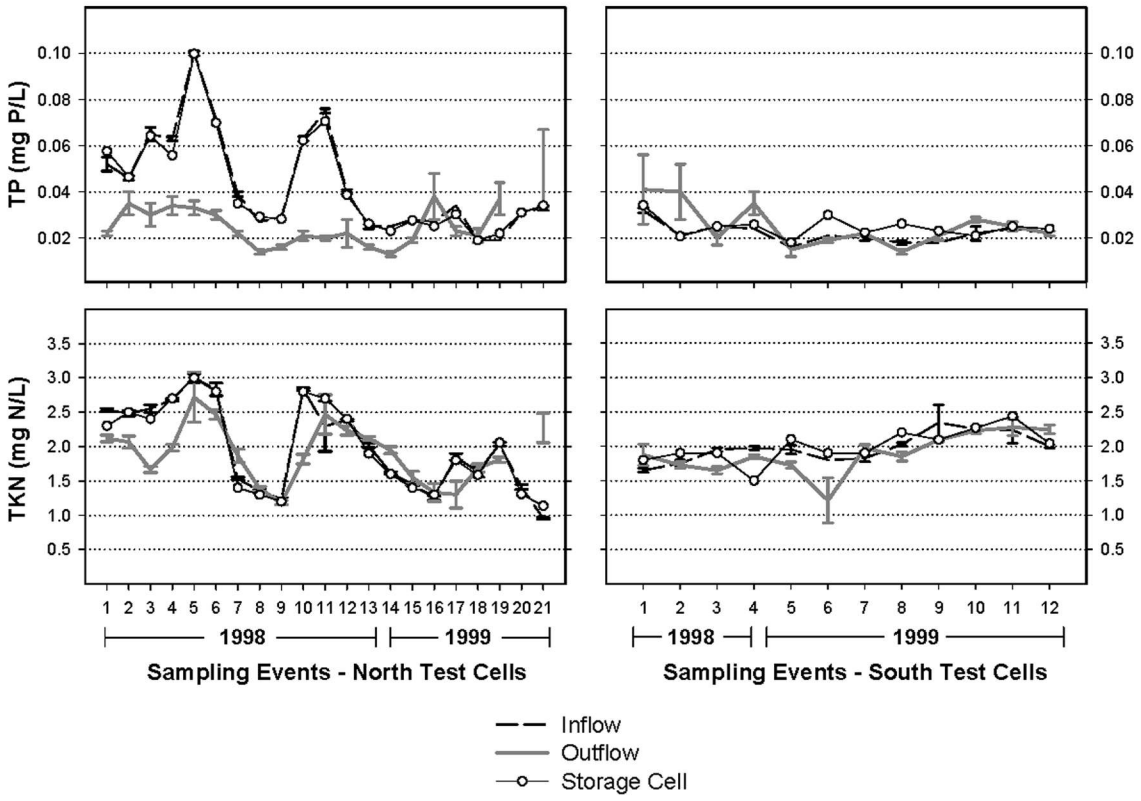


Figure 10. Temporal variation in total phosphorus and total Kjeldahl nitrogen at the water storage cell outlet and the test cell inflows and outflows during start-up of the north test cells (September 1998 through April 1999) and south test cells (November 1998 through April 1999). Values for the test cell inflow and outflow represent the mean for all cells ± 1 standard error.

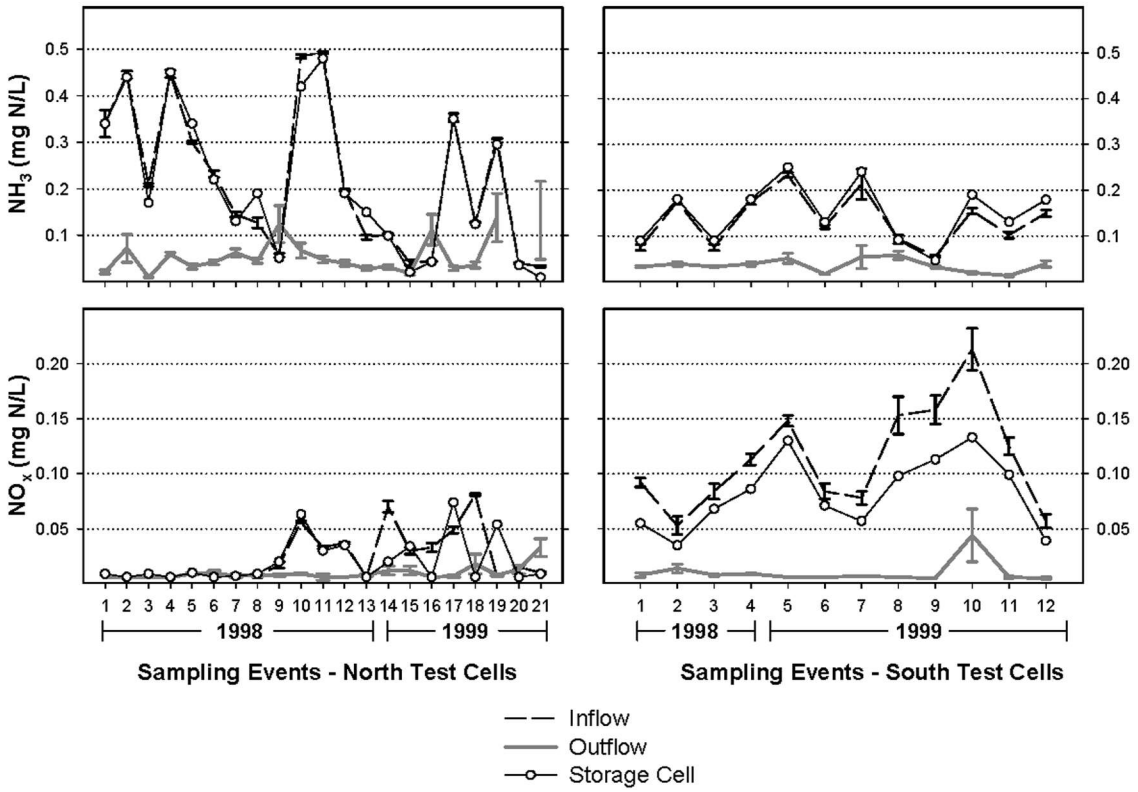


Figure 11. Temporal variation in ammonia-nitrogen and nitrite+nitrate nitrogen at the water storage cell outlet and the test cell inflows and outflows during start-up of the north test cells (September 1998 through April 1999) and south test cells (November 1998 through April 1999). Values for the test cell inflow and outflow represent the mean for all cells ±1 standard error.

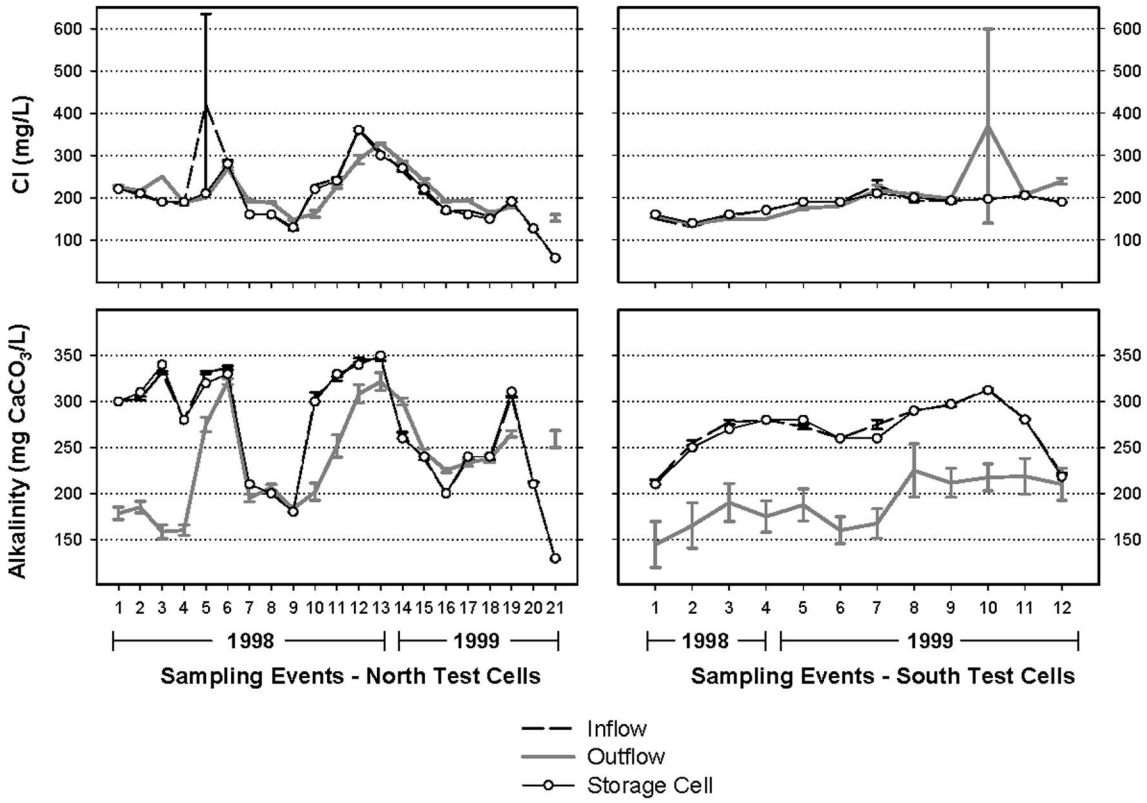


Figure 12. Temporal variation in chloride and alkalinity at the water storage cell outlet and the test cell inflows and outflows during start-up of the north test cells (September 1998 through April 1999) and south test cells (November 1998 through April 1999). Values for the test cell inflow and outflow represent the mean for all cells ±1 standard error.

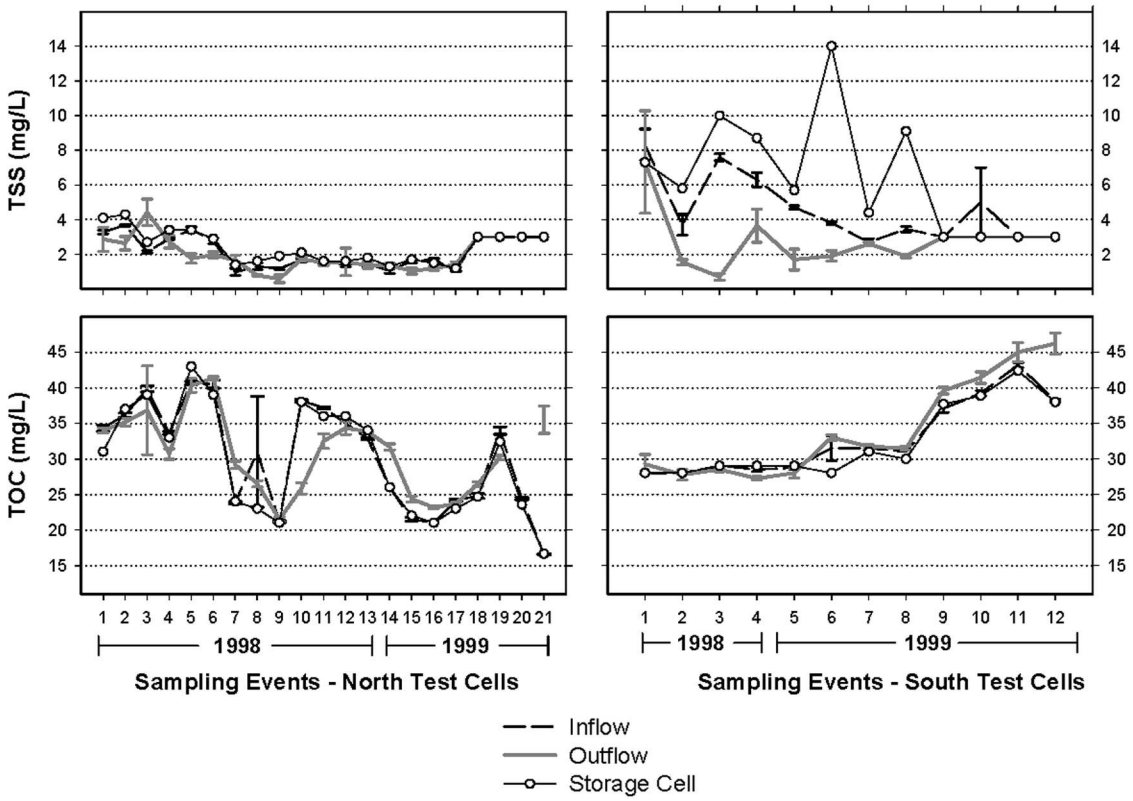


Figure 13. Temporal variation in total suspended solids and total organic carbon at the water storage cell outlet and the test cell inflows and outflows during start-up of the north test cells (September 1998 through April 1999) and south test cells (November 1998 through April 1999). Values for the test cell inflow and outflow represent the mean for all cells ± 1 standard error.

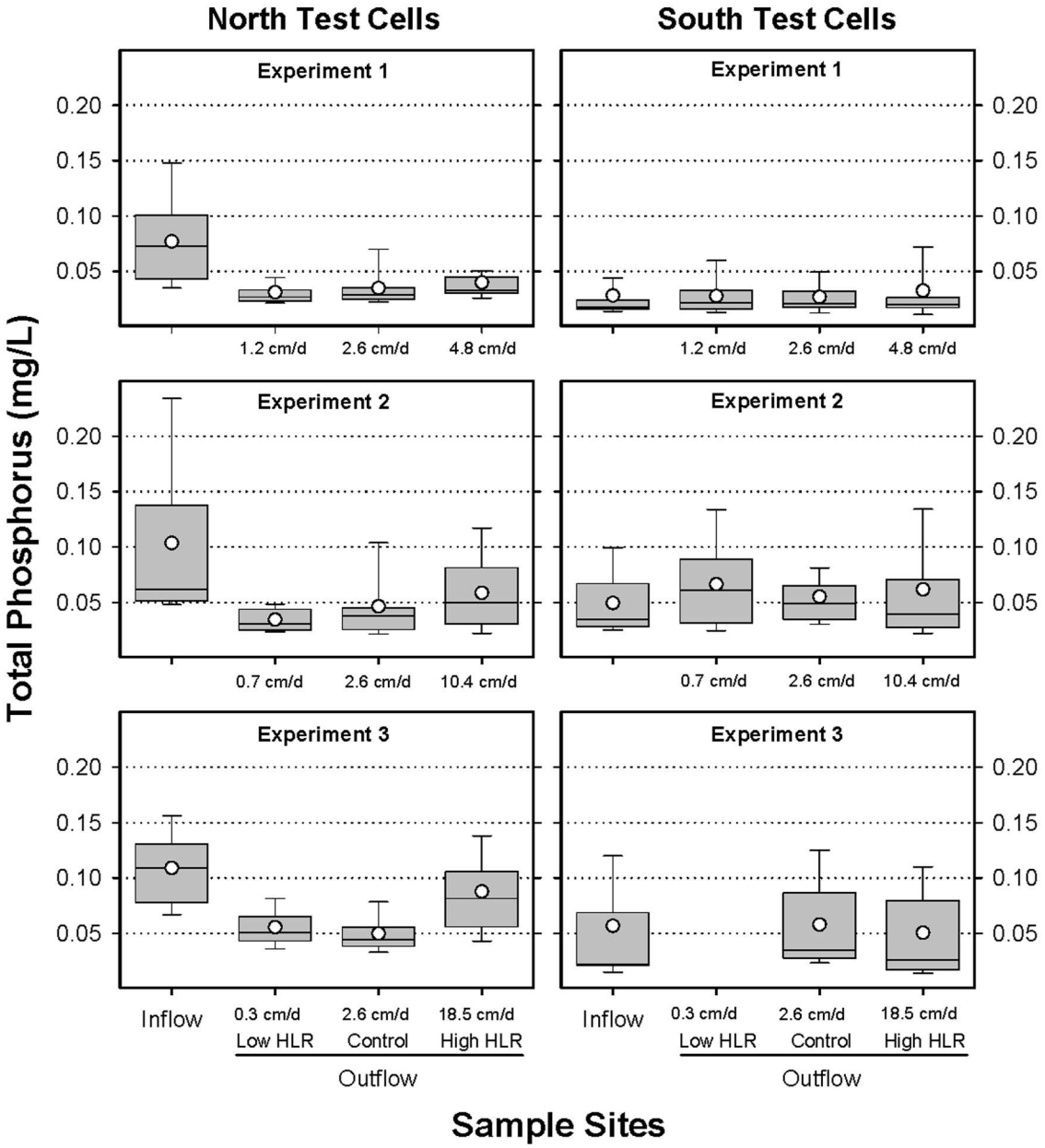


Figure 14. Summary of weekly inflow and outflow total phosphorus concentrations during hydraulic loading rate experiments conducted in the north and south test cells. Open circles represent mean values. The 0.3cm/d HLR experiment was not conducted in the south test cells. See text for details.

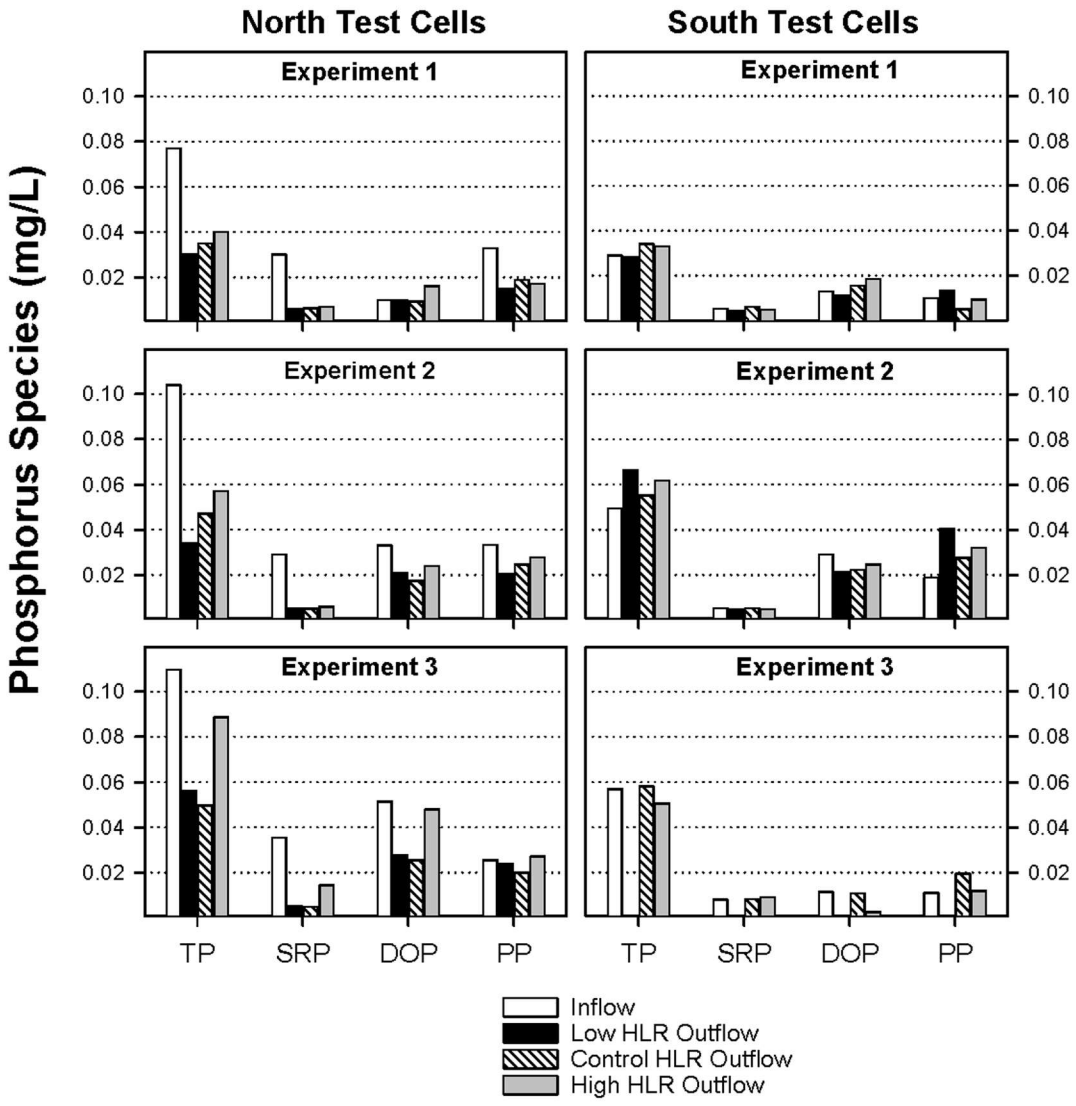


Figure 15. Mean concentrations of total phosphorus, soluble reactive phosphorus, dissolved organic phosphorus and particulate phosphorus measured in the inflow and outflow at the north and south test cells during hydraulic loading rate (HLR) experiments. The 0.3cm/d HLR experiment was not conducted in the south test cells. See text for details.

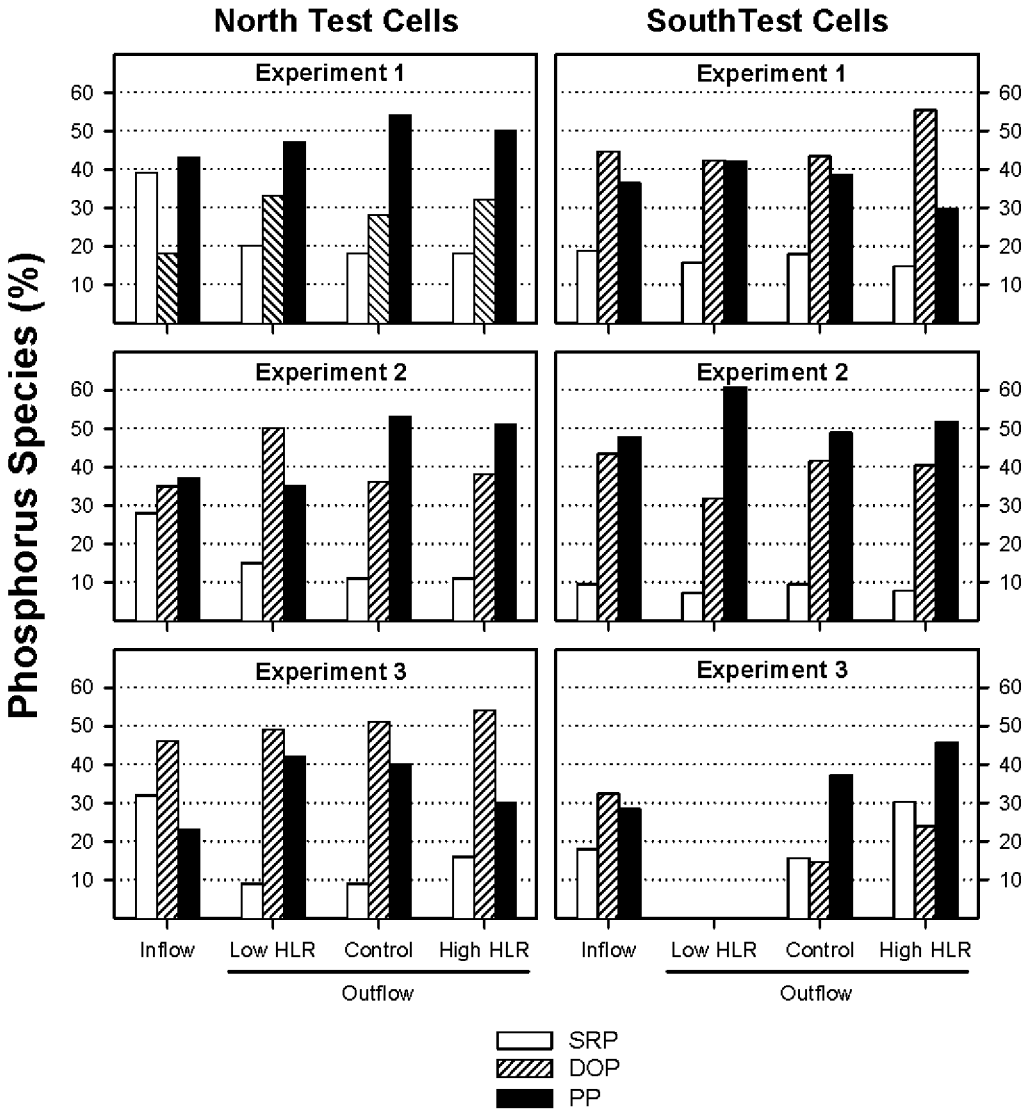


Figure 16. Proportion of phosphorus species measured in inflow and outflow at the north and south test cells during hydraulic loading rate (HLR) experiments. SRP = soluble reactive phosphorus; DOP = dissolved organic phosphorus; PP = particulate phosphorus. The 0.3cm/d HLR experiment was not conducted in the south test cells. See text for details.

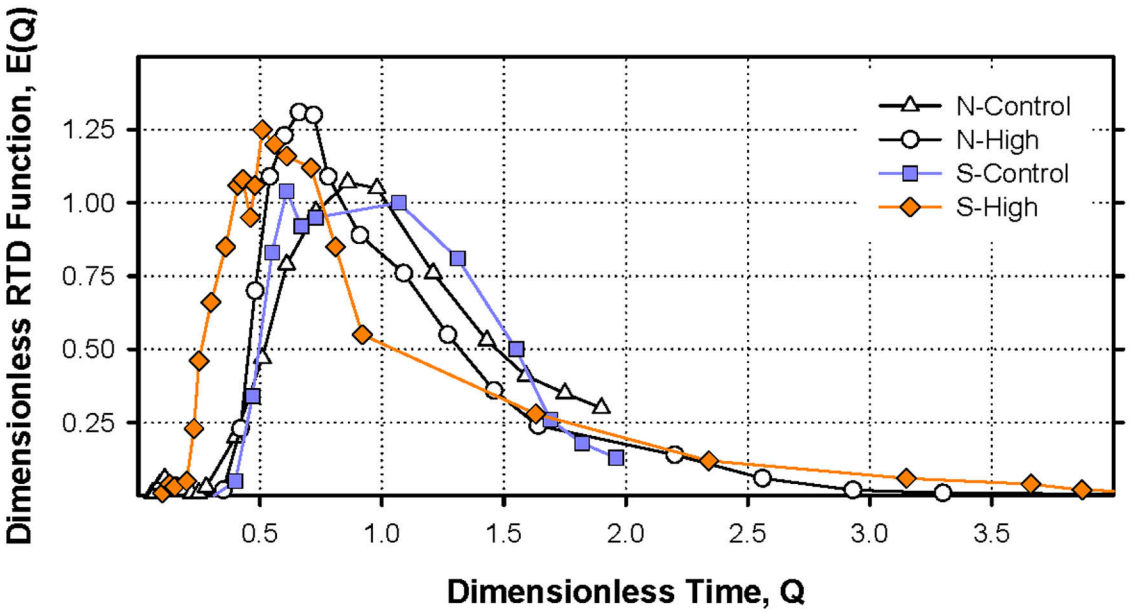


Figure 17. Residence time distribution curves for the north and south test cells generated using the Gamma distribution method. Tracer data were collected during HLR experiments conducted from May 1, 2000 through August 22, 2000.

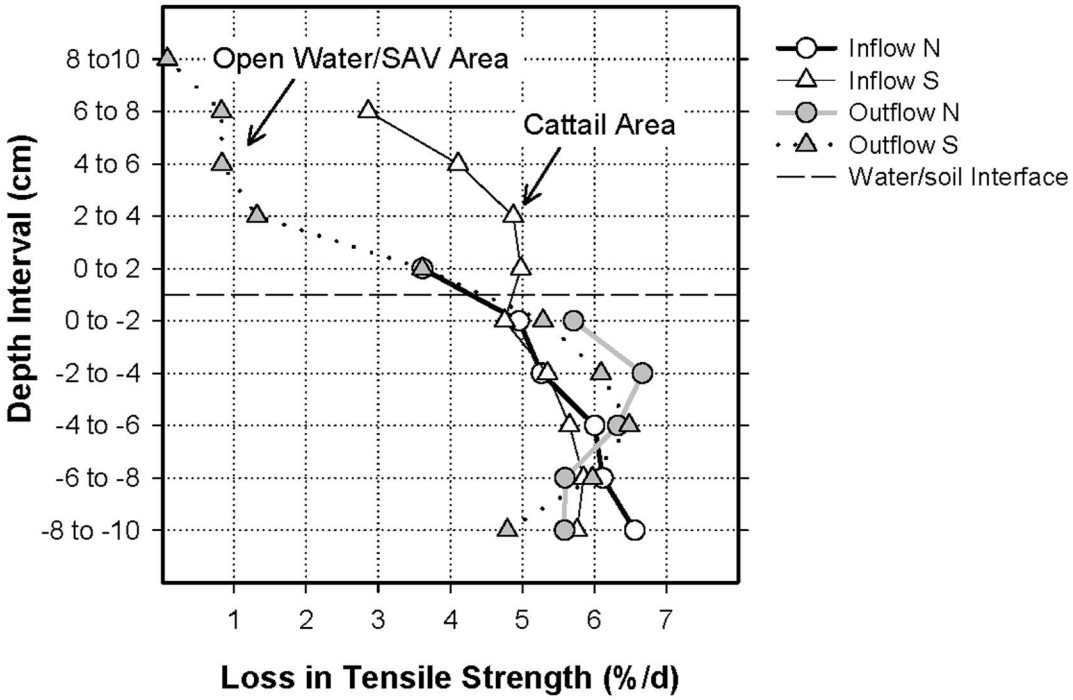


Figure 18. Loss of tensile strength in a one-week test deployment of cotton strips at inlet and outlet areas of north and south test cells.

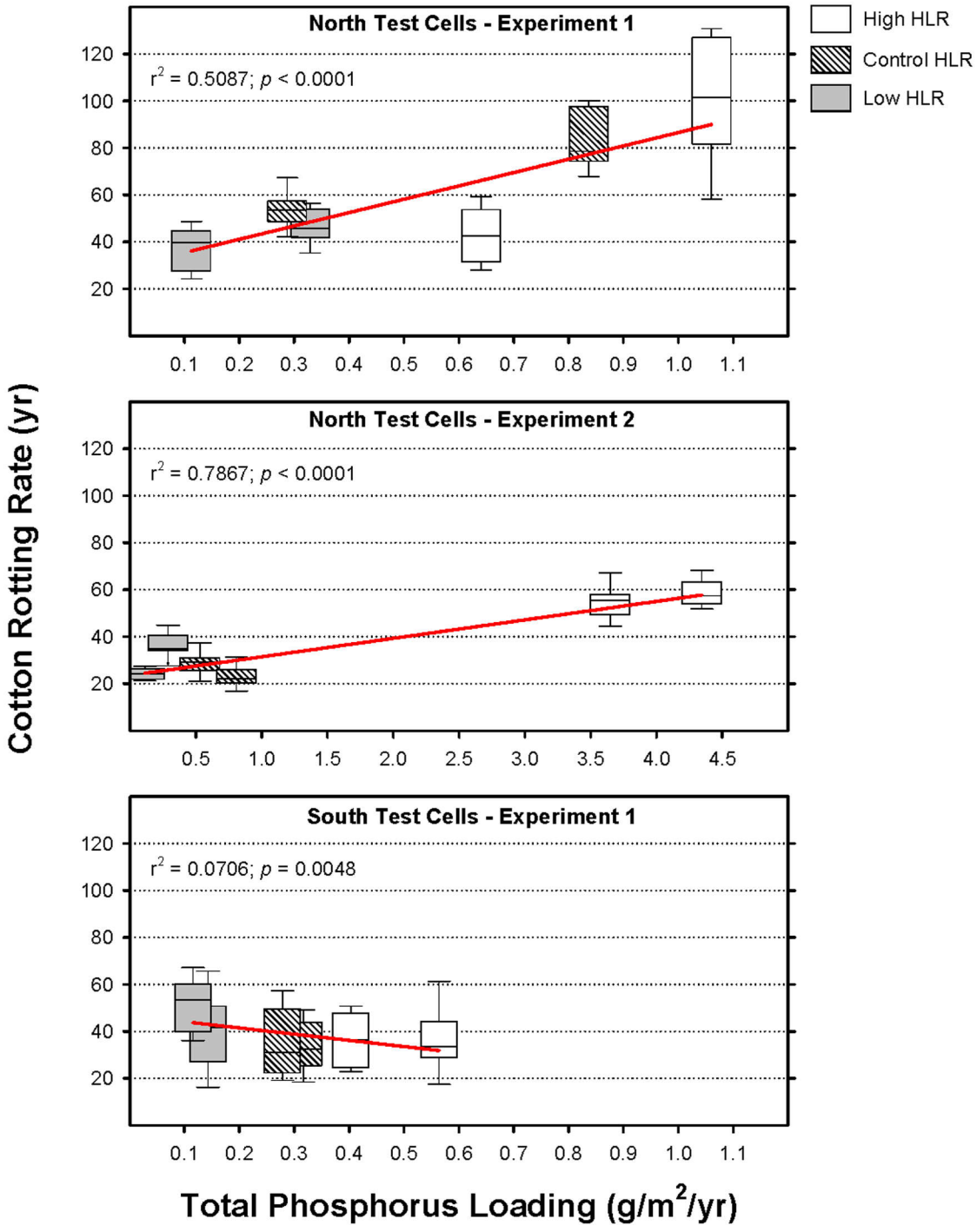
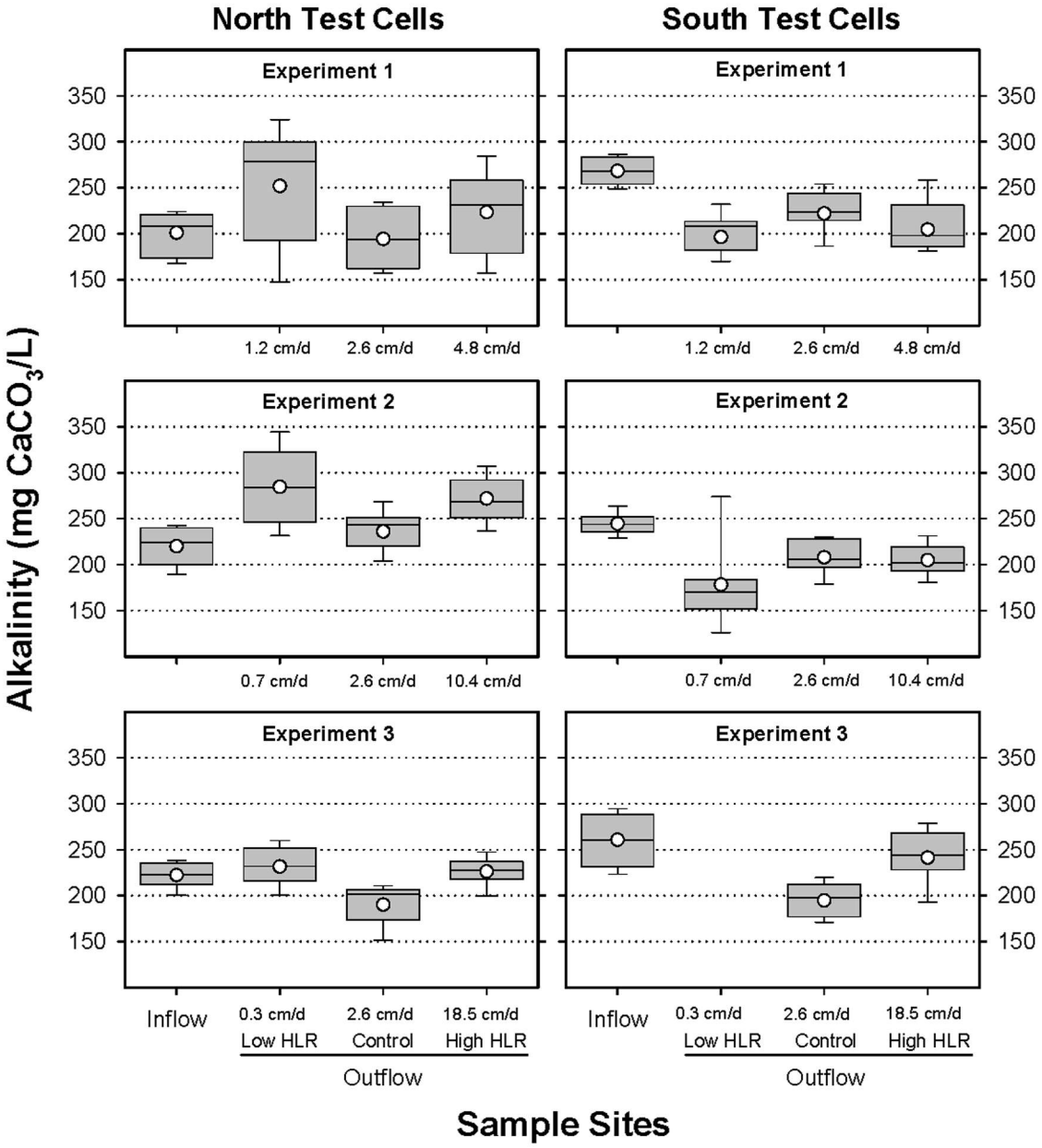
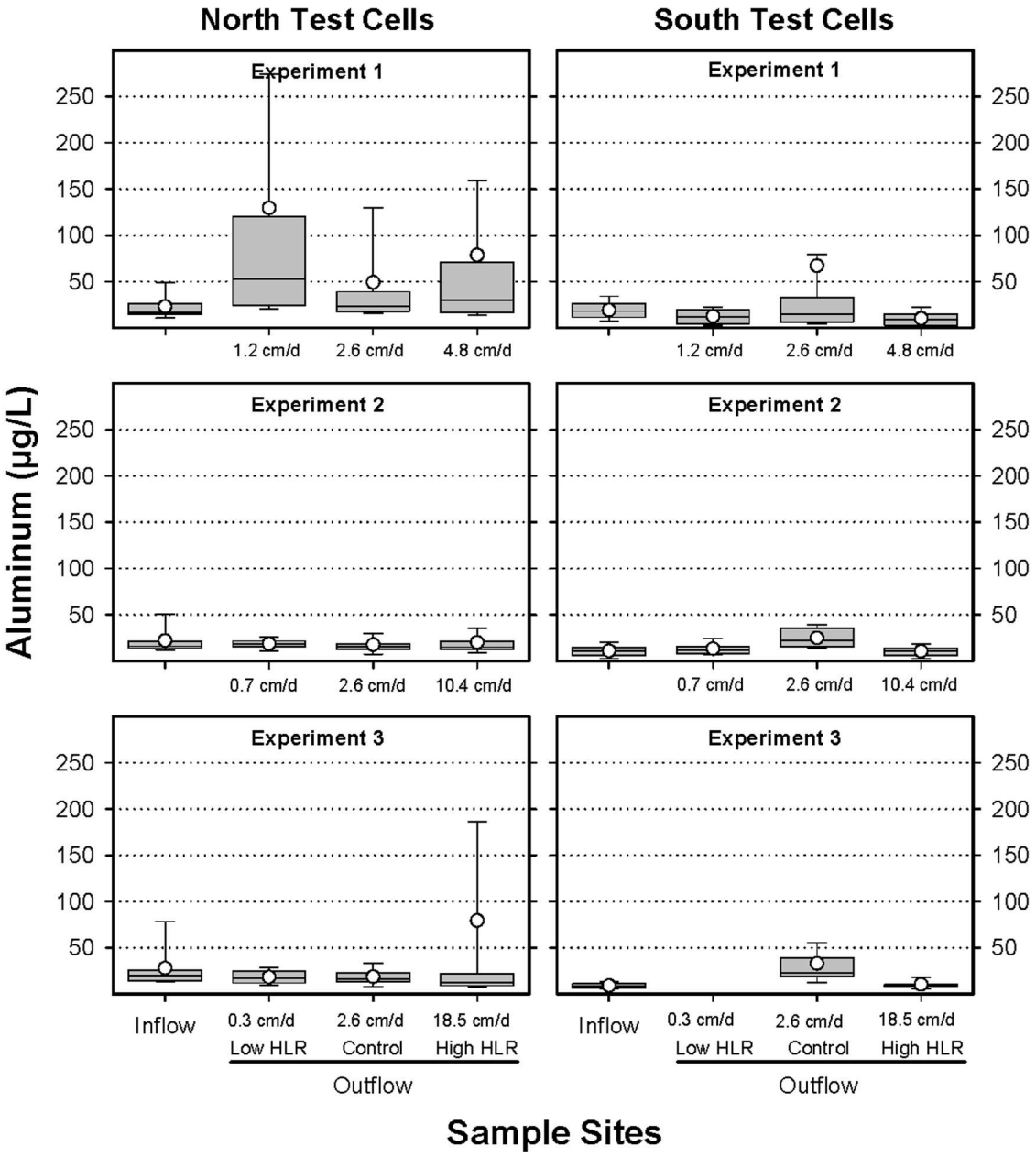


Figure 19. Cotton rotting rates relative to total phosphorus loading during hydraulic loading rate (HLR) experiments conducted in the north and south test cells. Rotting rates were based on one-week incubations at test cell inlets and outlets.

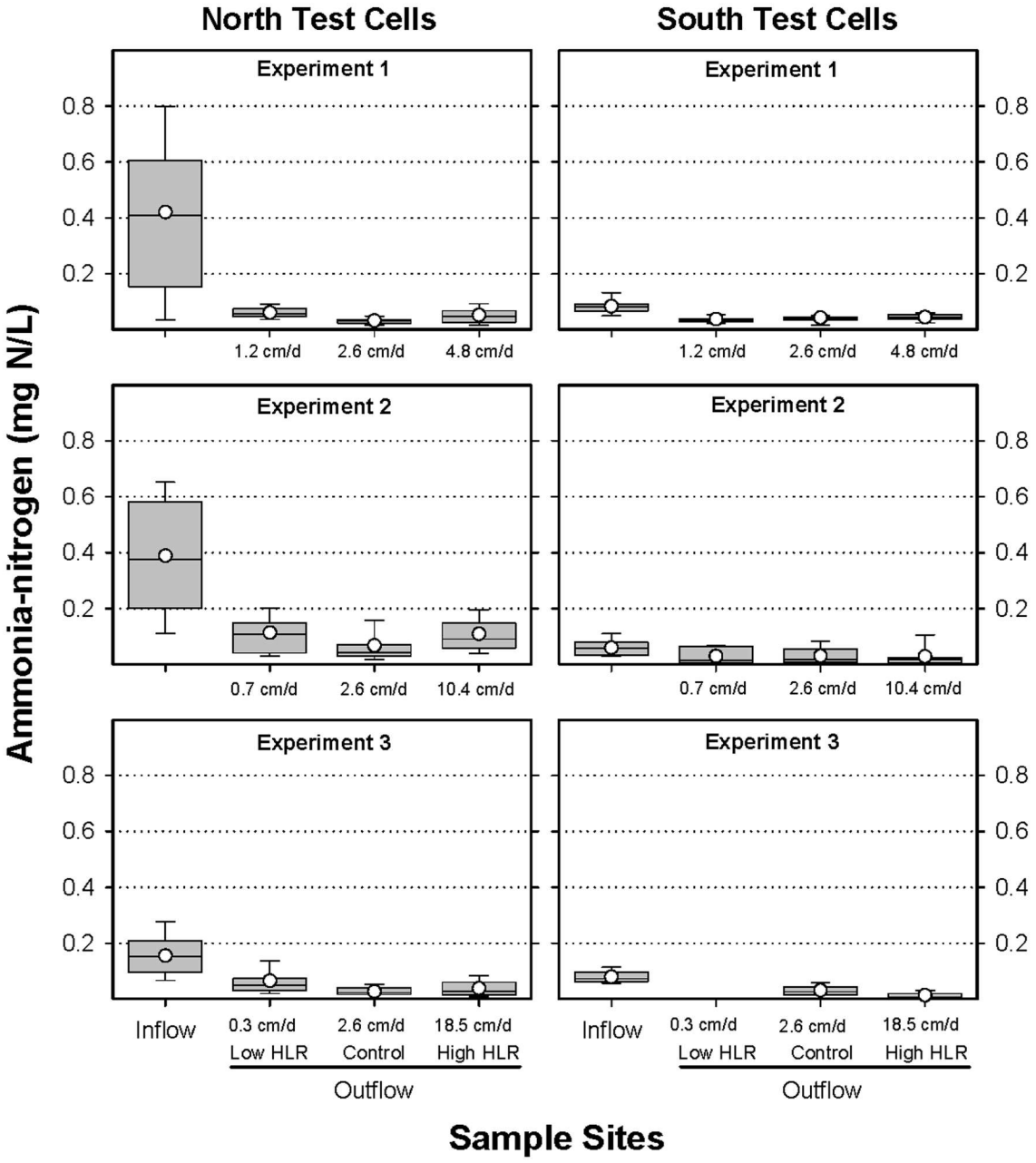
Appendicies



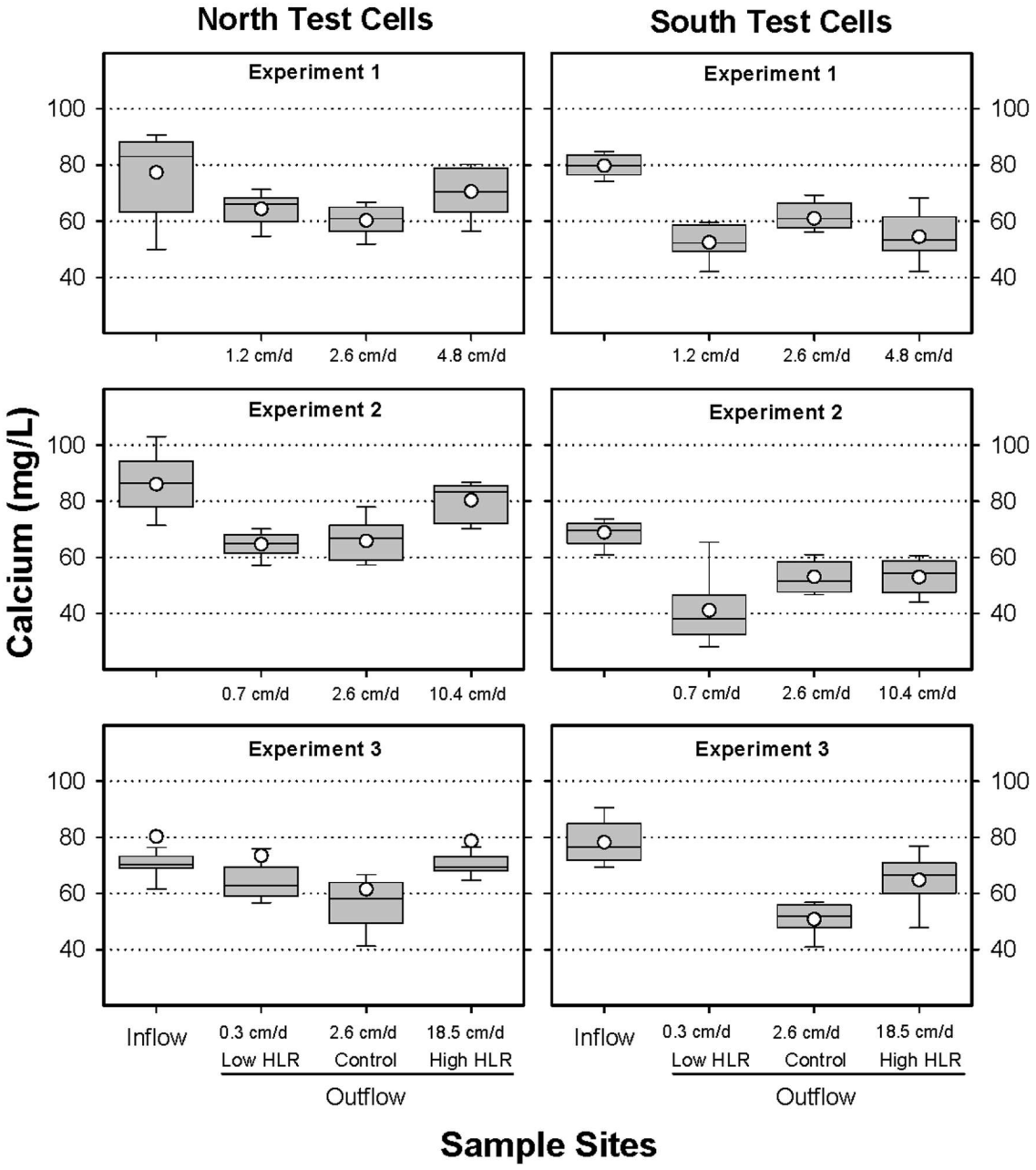
Appendix 1. Summary of weekly inflow and outflow alkalinity during hydraulic loading rate experiments conducted in the north and south test cells. Open circles represent mean values. The 0.3 cm/d HLR experiment was not conducted in the south test cells. See text for details. Description of box plots: top and bottom of box = 75th and 25th percentile of the data distribution, respectively; mid-line in box = 50th percentile; ends of whiskers = 10th and 90th percentiles.



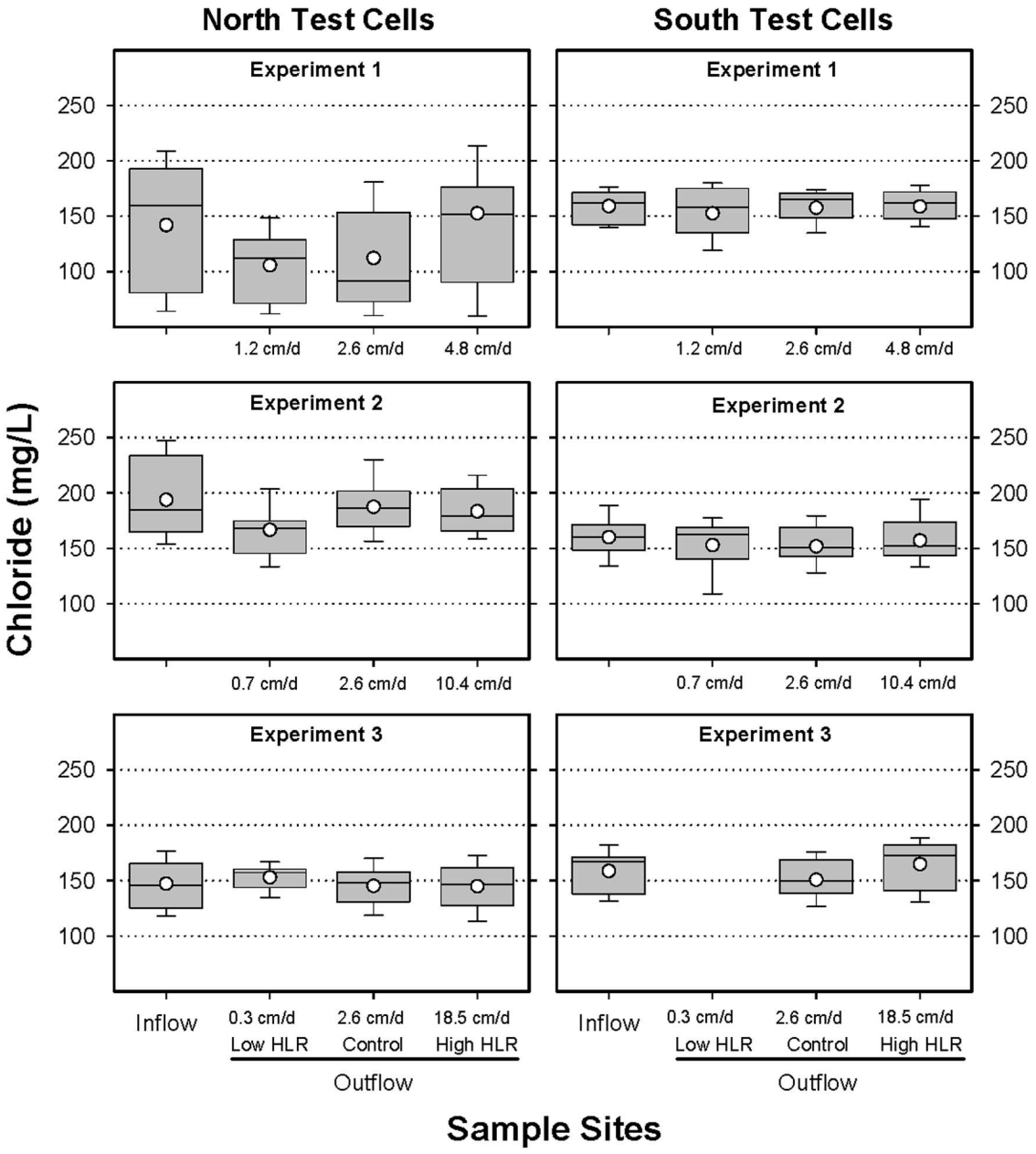
Appendix 2. Summary of weekly inflow and outflow aluminum concentrations during hydraulic loading rate experiments conducted in the north and south test cells.



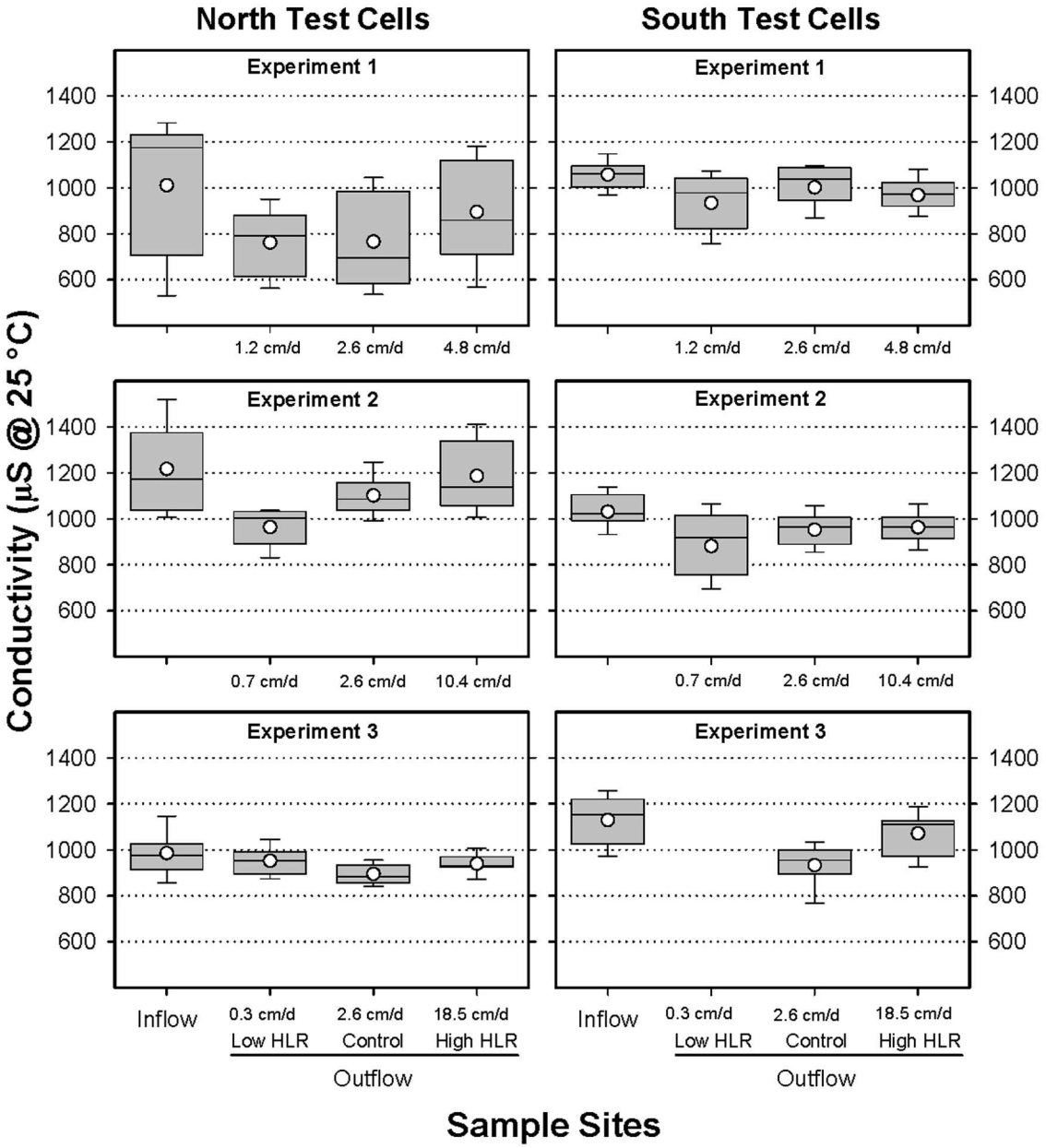
Appendix 3. Summary of weekly inflow and outflow ammonia-nitrogen concentrations during hydraulic loading rate experiments conducted in the north and south test cells.



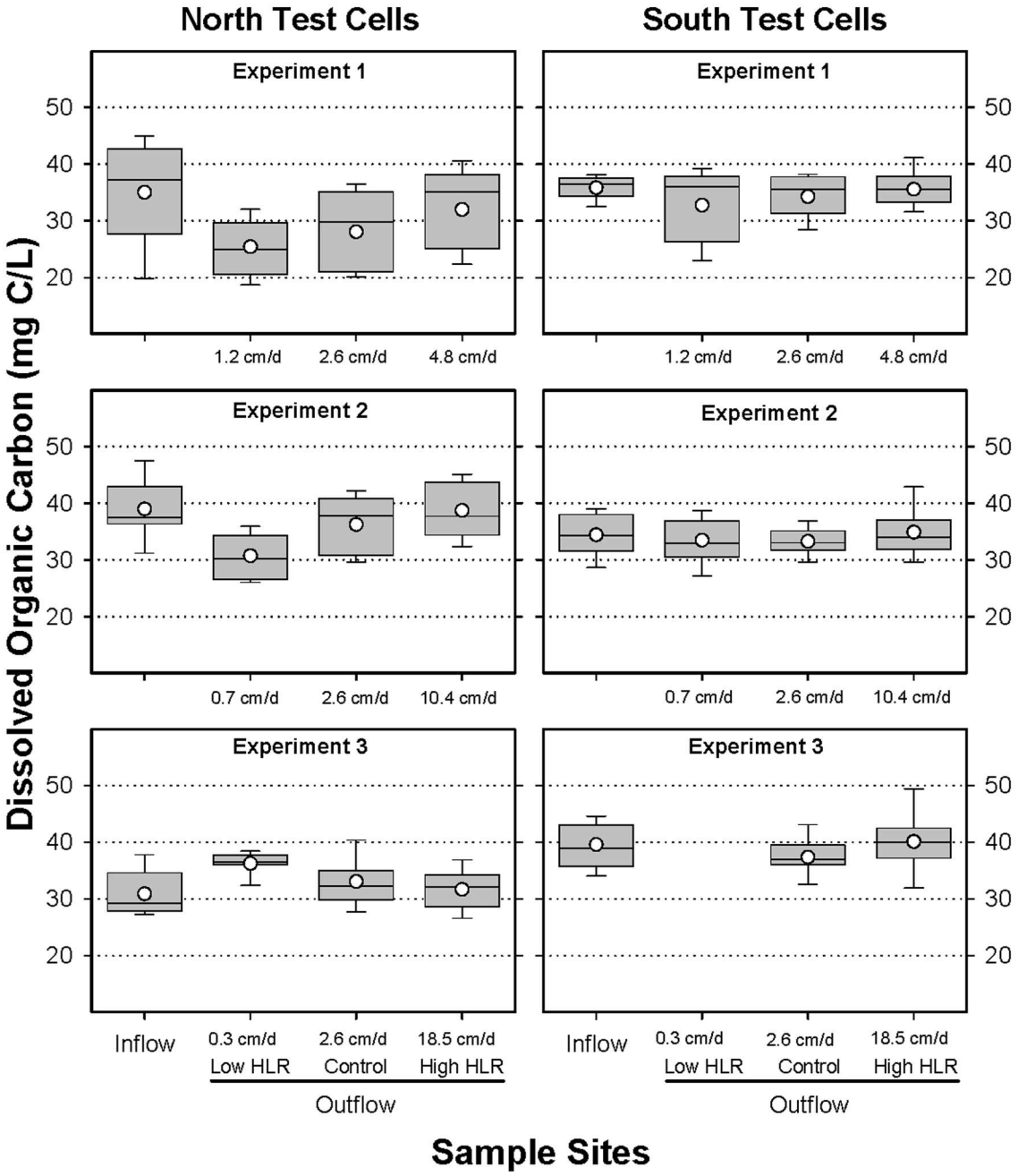
Appendix 4. Summary of weekly inflow and outflow calcium concentrations during hydraulic loading rate experiments conducted in the north and south test cells.



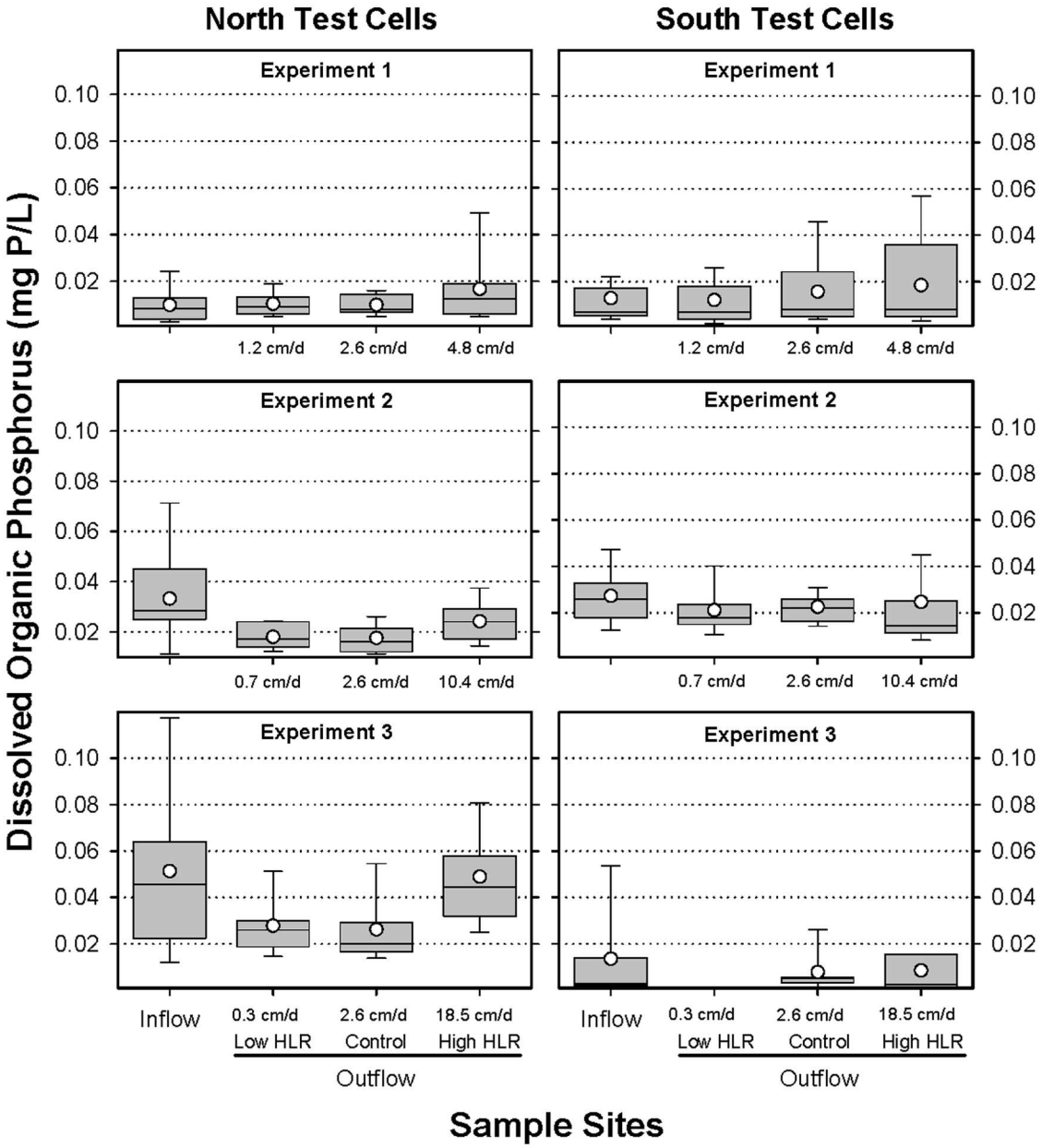
Appendix 5. Summary of weekly inflow and outflow chloride concentrations during hydraulic loading rate experiments conducted in the north and south test cells.



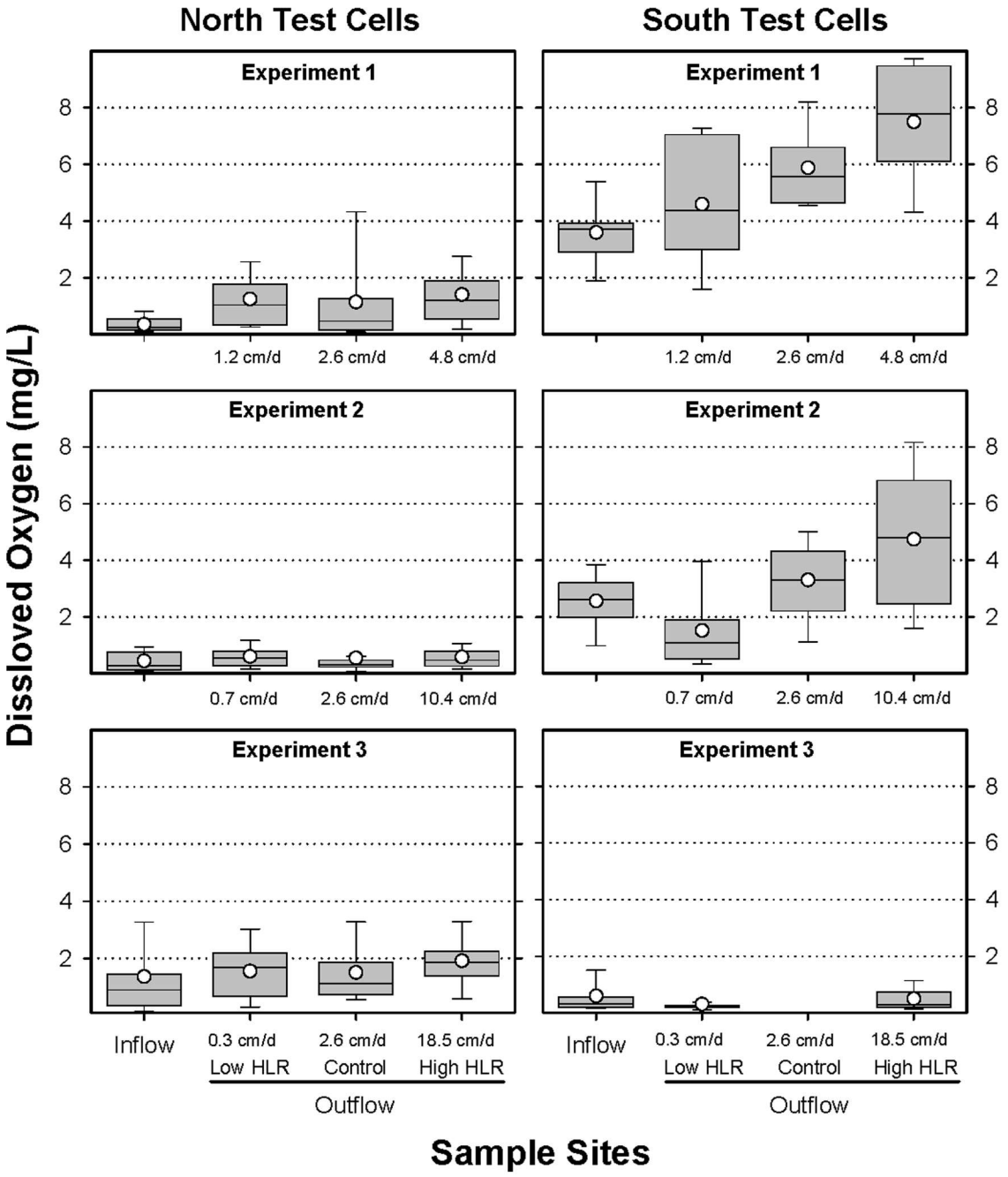
Appendix 6. Summary of weekly inflow and outflow conductivity during hydraulic loading rate experiments conducted in the north and south test cells.



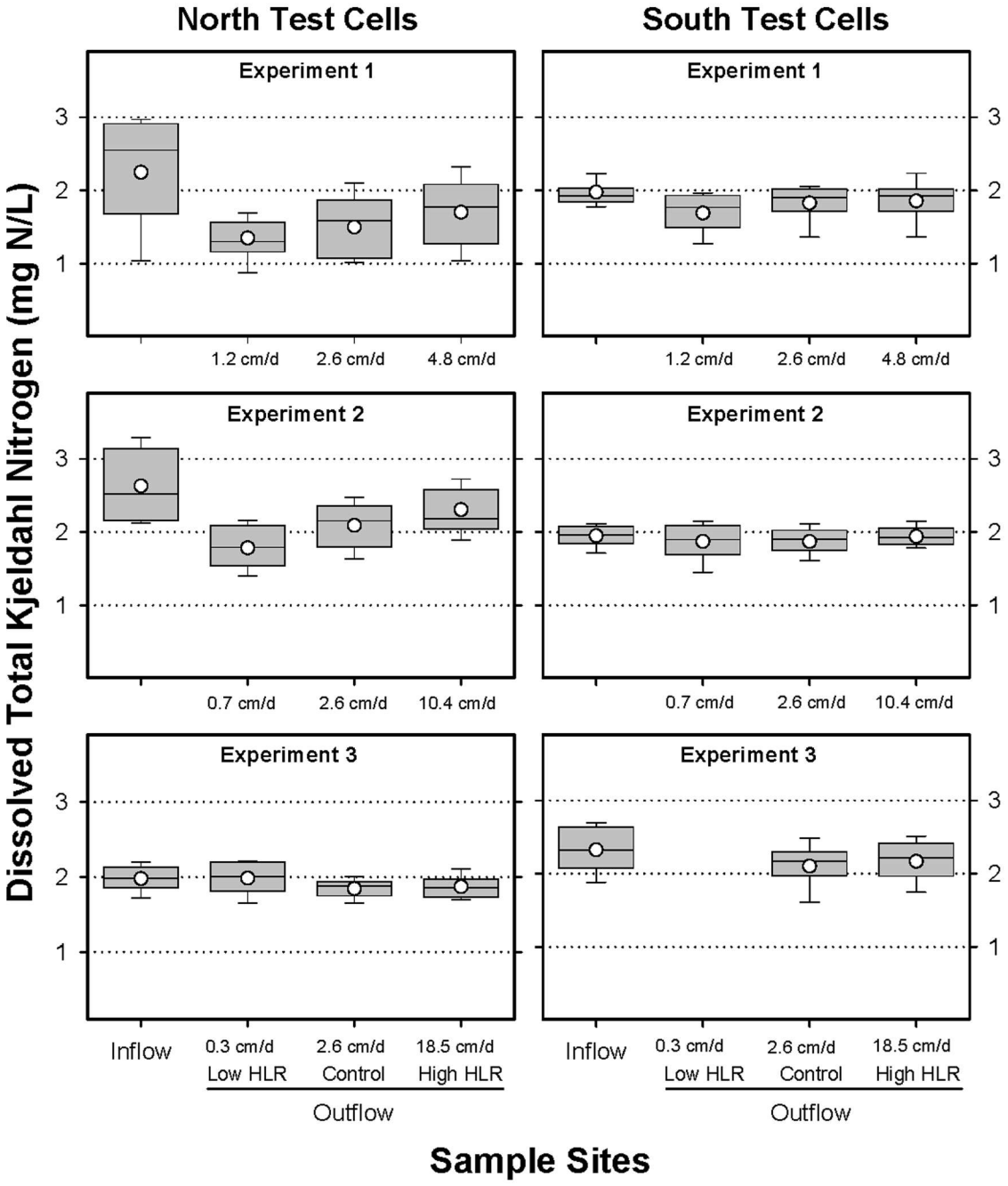
Appendix 7. Summary of weekly inflow and outflow dissolved organic carbon concentrations during hydraulic loading rate experiments conducted in the north and south test cells.



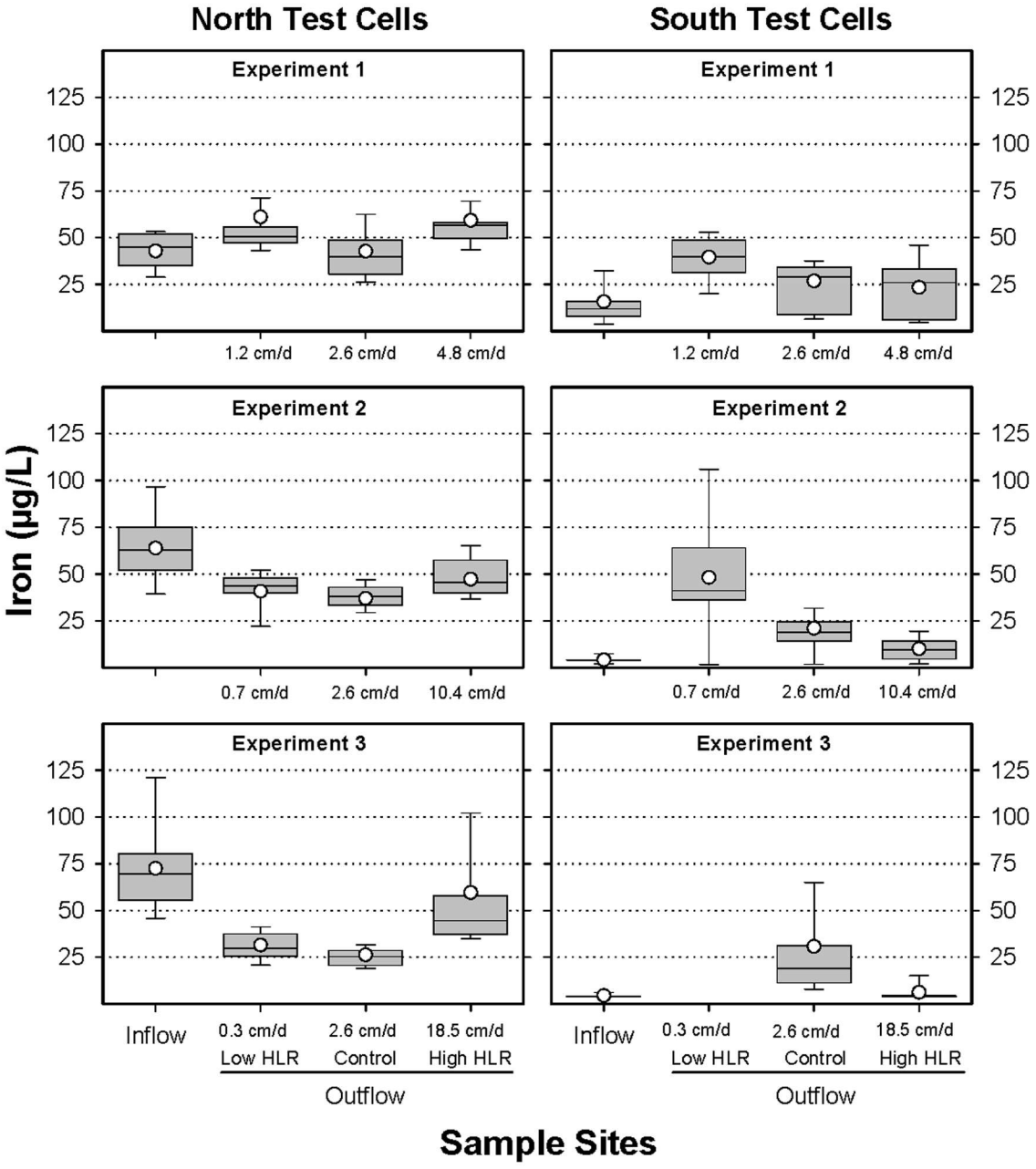
Appendix 8. Summary of weekly inflow and outflow dissolved organic phosphorus concentrations during hydraulic loading rate experiments conducted in the north and south test cells.



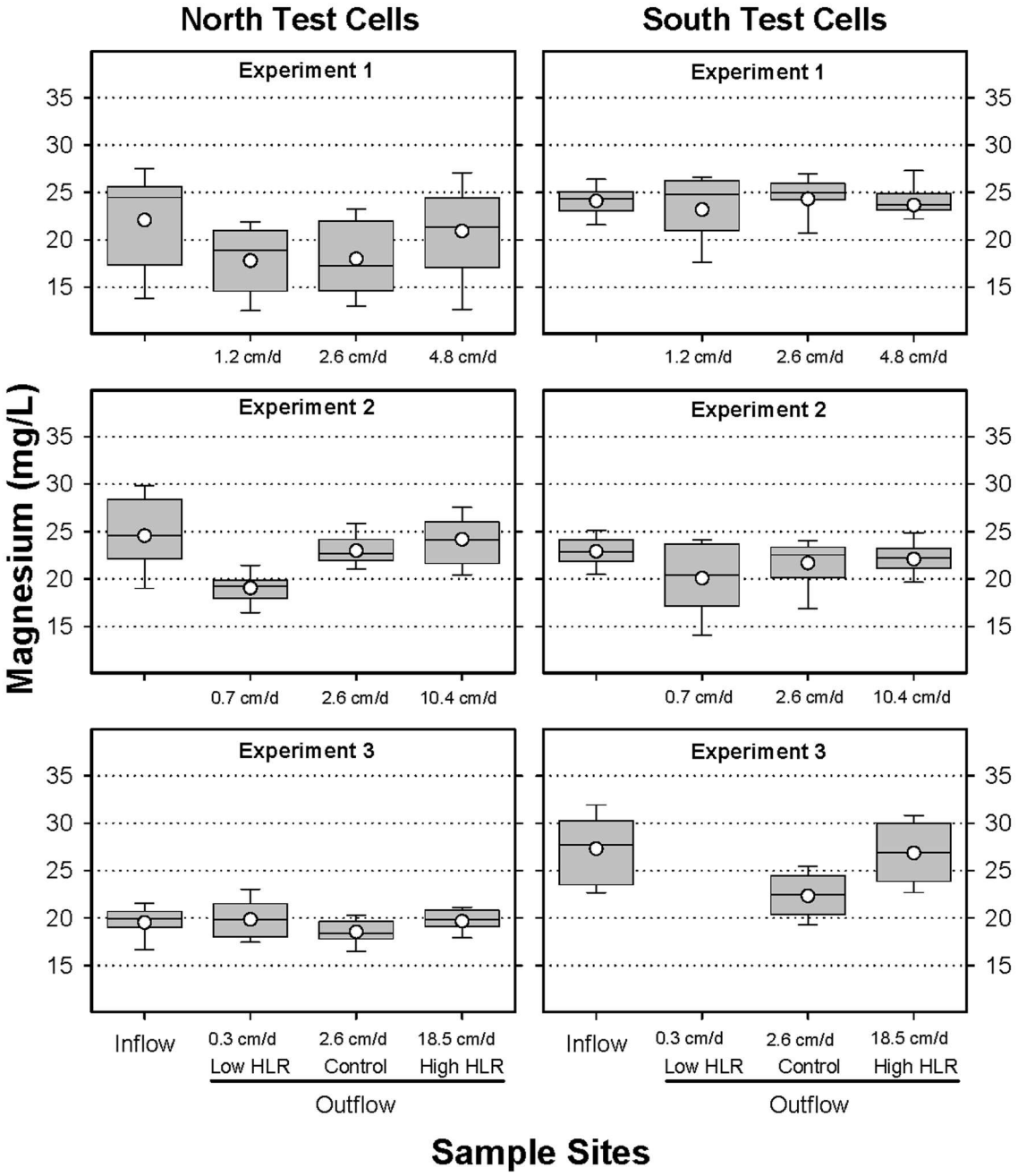
Appendix 9. Summary of weekly inflow and outflow dissolved oxygen concentrations during hydraulic loading rate experiments conducted in the north and south test cells.



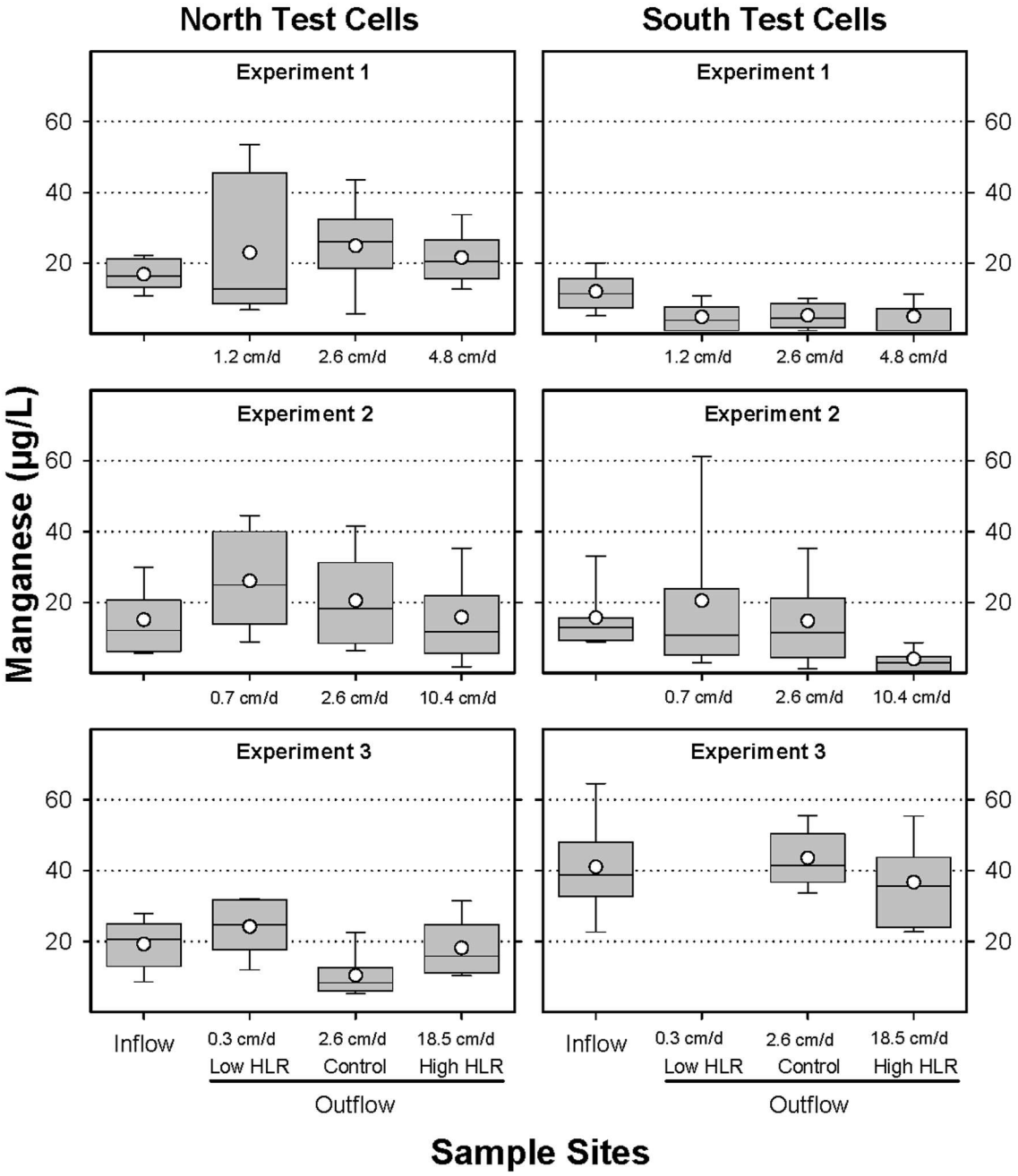
Appendix 10. Summary of weekly inflow and outflow total dissolved total Kjeldahl nitrogen concentrations during hydraulic loading rate experiments conducted in the north and south test cells.



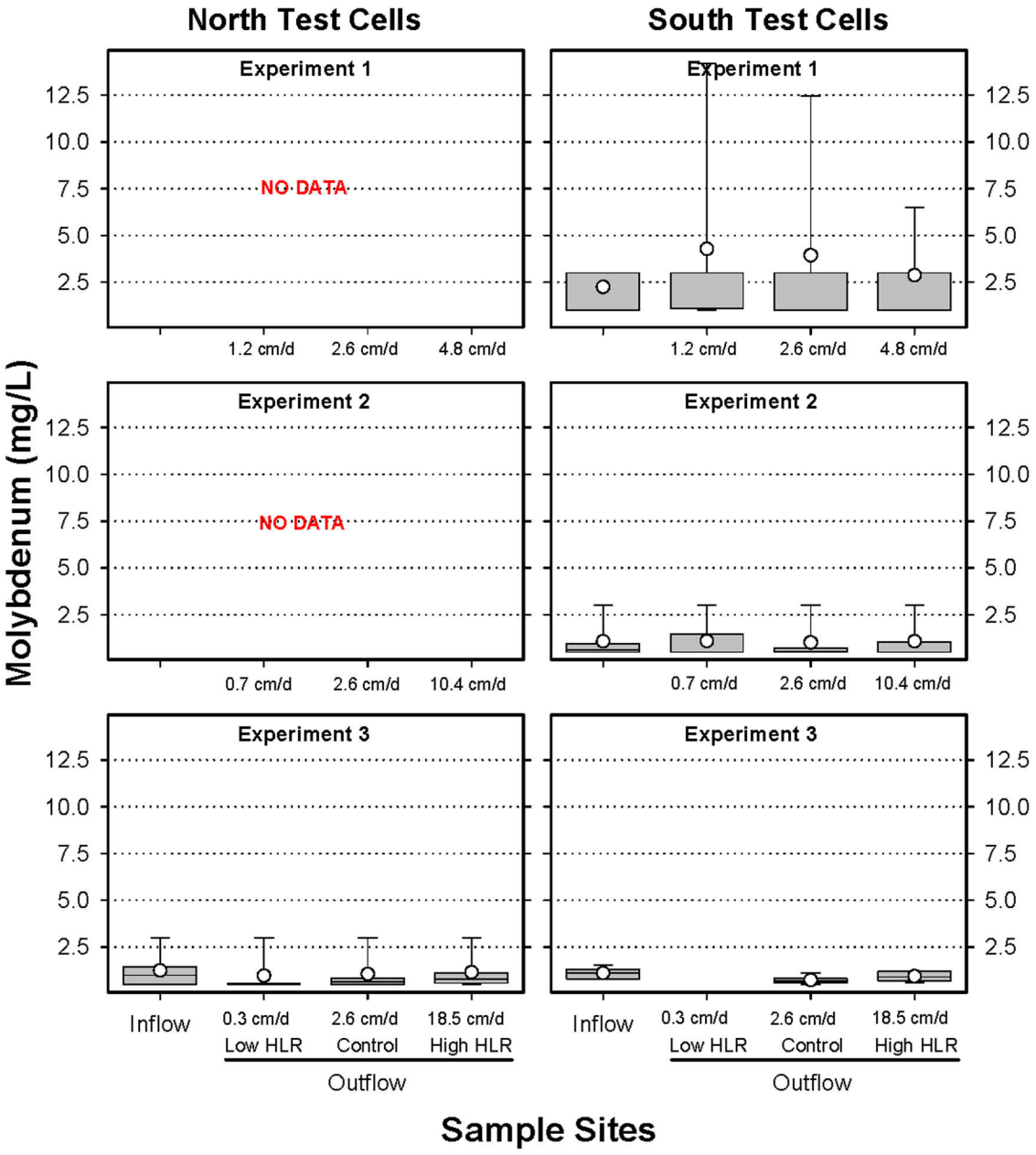
Appendix 11. Summary of weekly inflow and outflow iron concentrations during hydraulic loading rate experiments conducted in the north and south test cells.



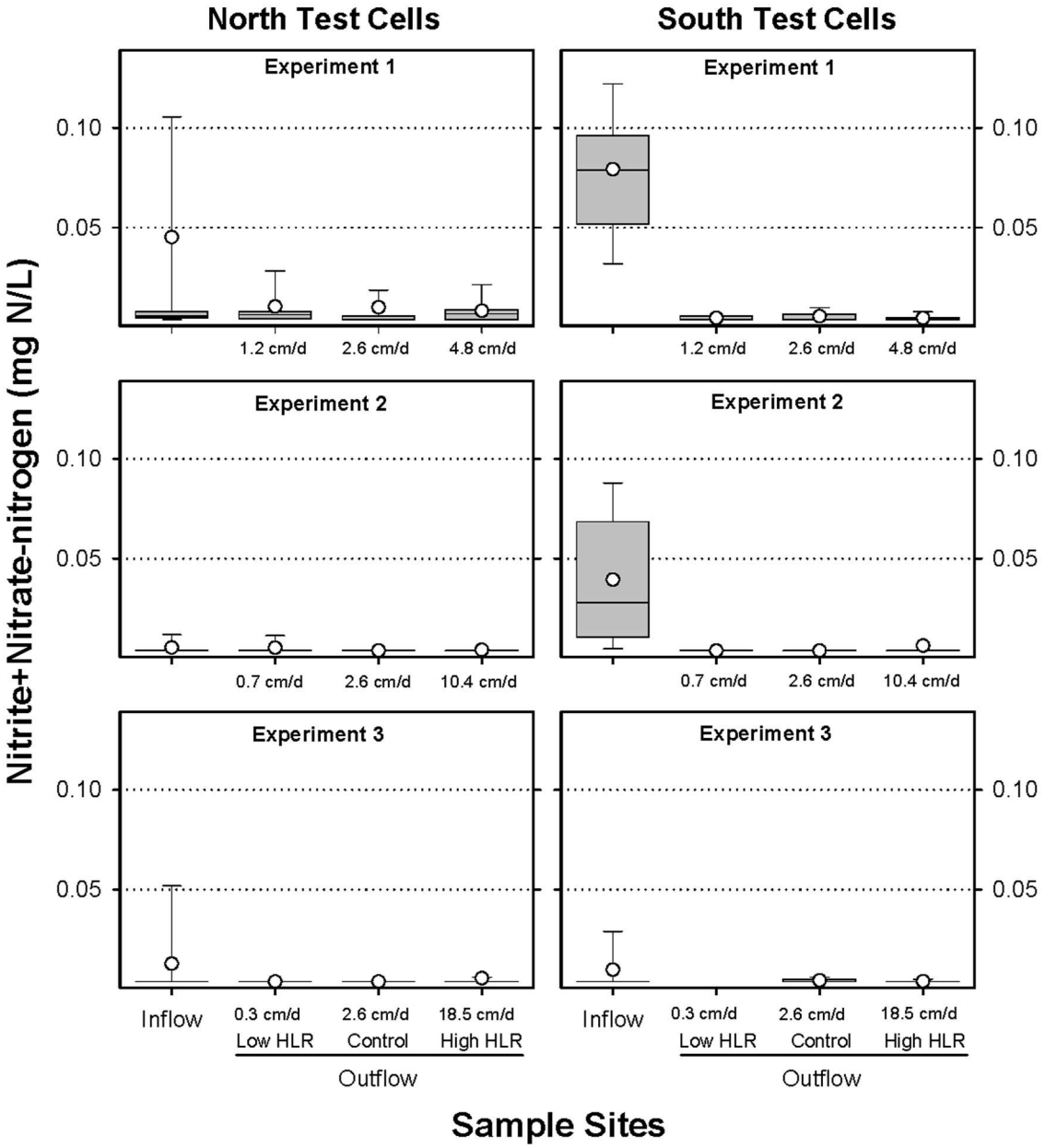
Appendix 12. Summary of weekly inflow and outflow magnesium concentrations during hydraulic loading rate experiments conducted in the north and south test cells.



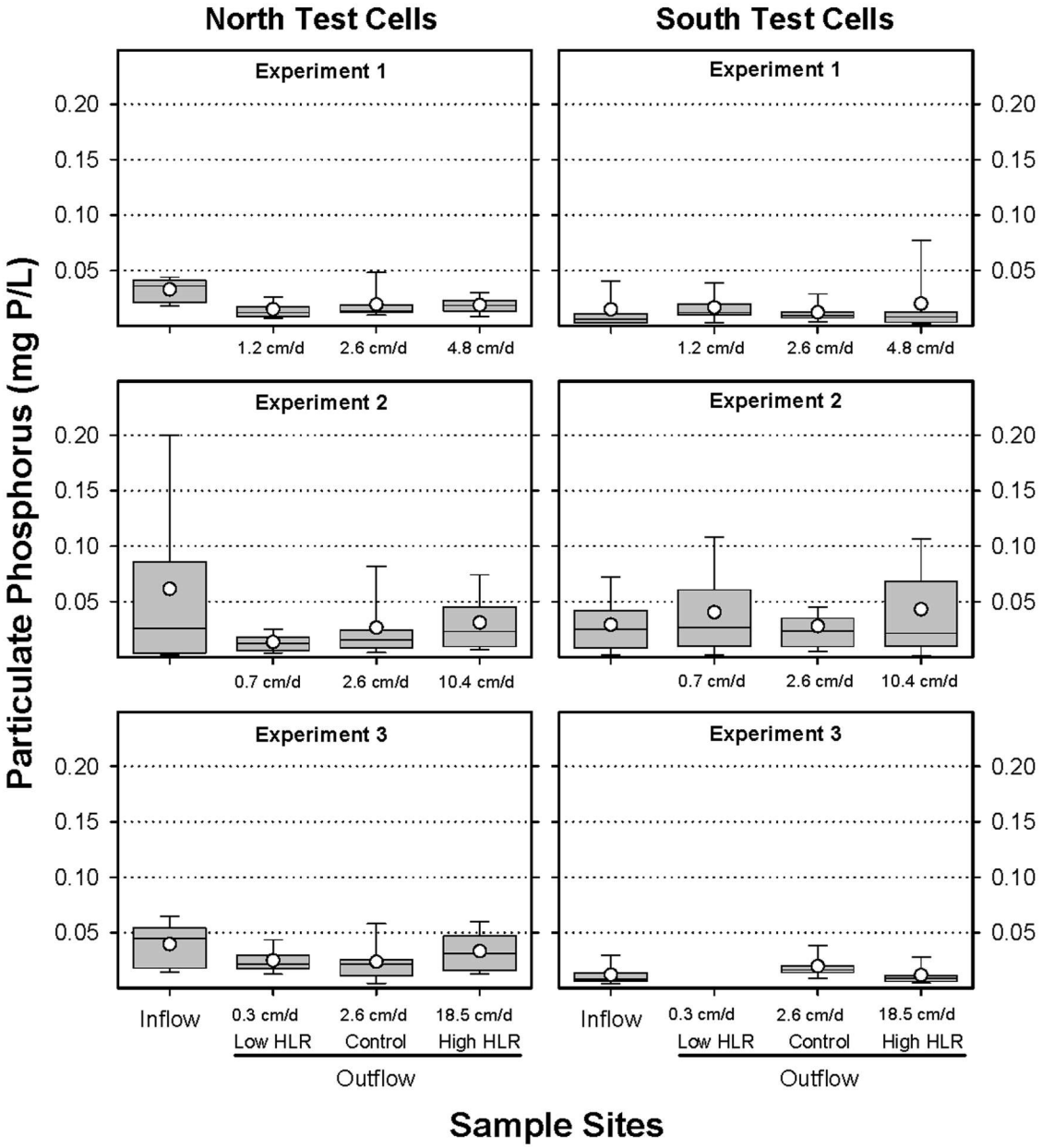
Appendix 13. Summary of weekly inflow and outflow manganese concentrations during hydraulic loading rate experiments conducted in the north and south test cells.



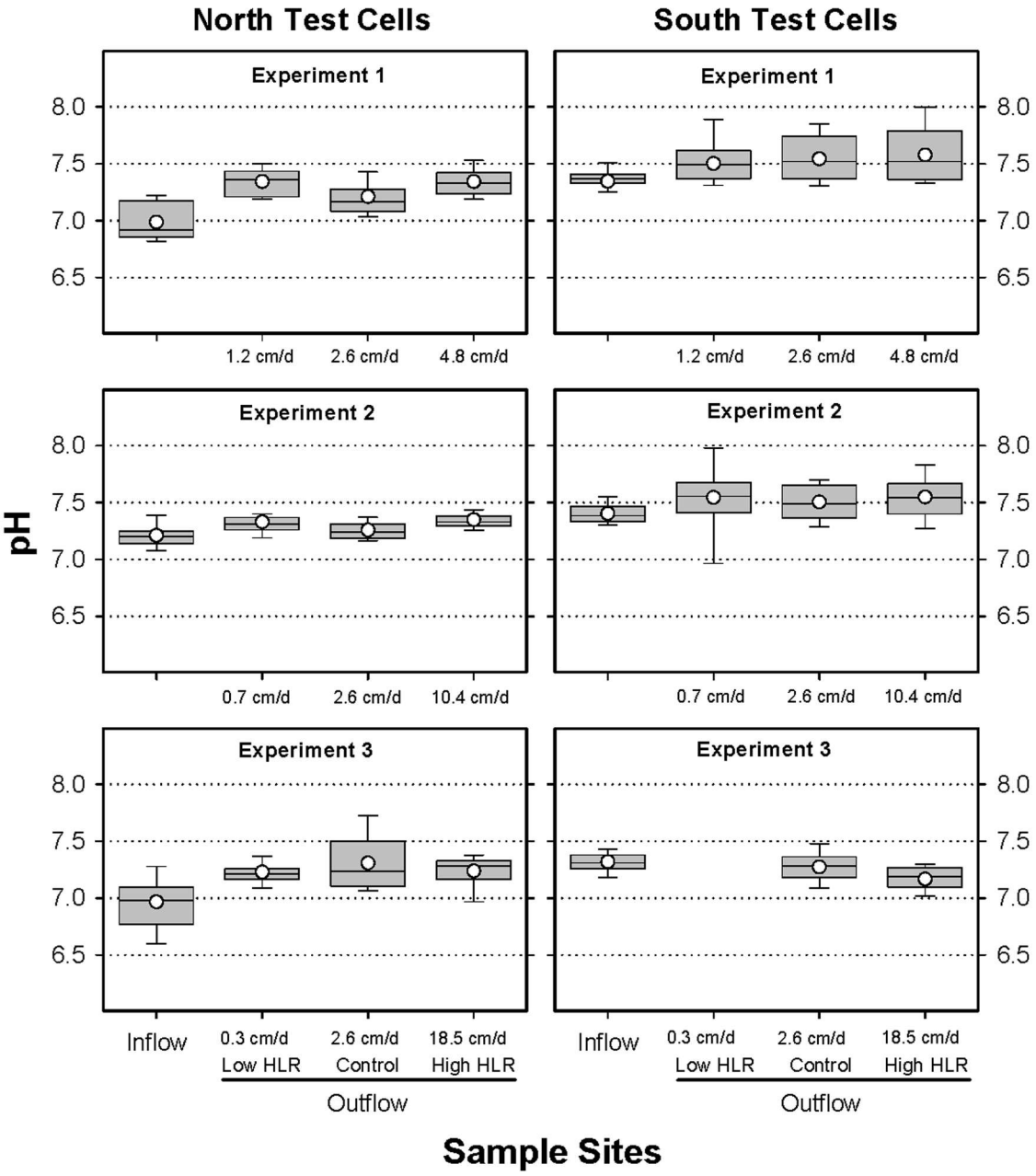
Appendix 14. Summary of weekly inflow and outflow molybdenum concentrations during hydraulic loading rate experiments conducted in the north and south test cells.



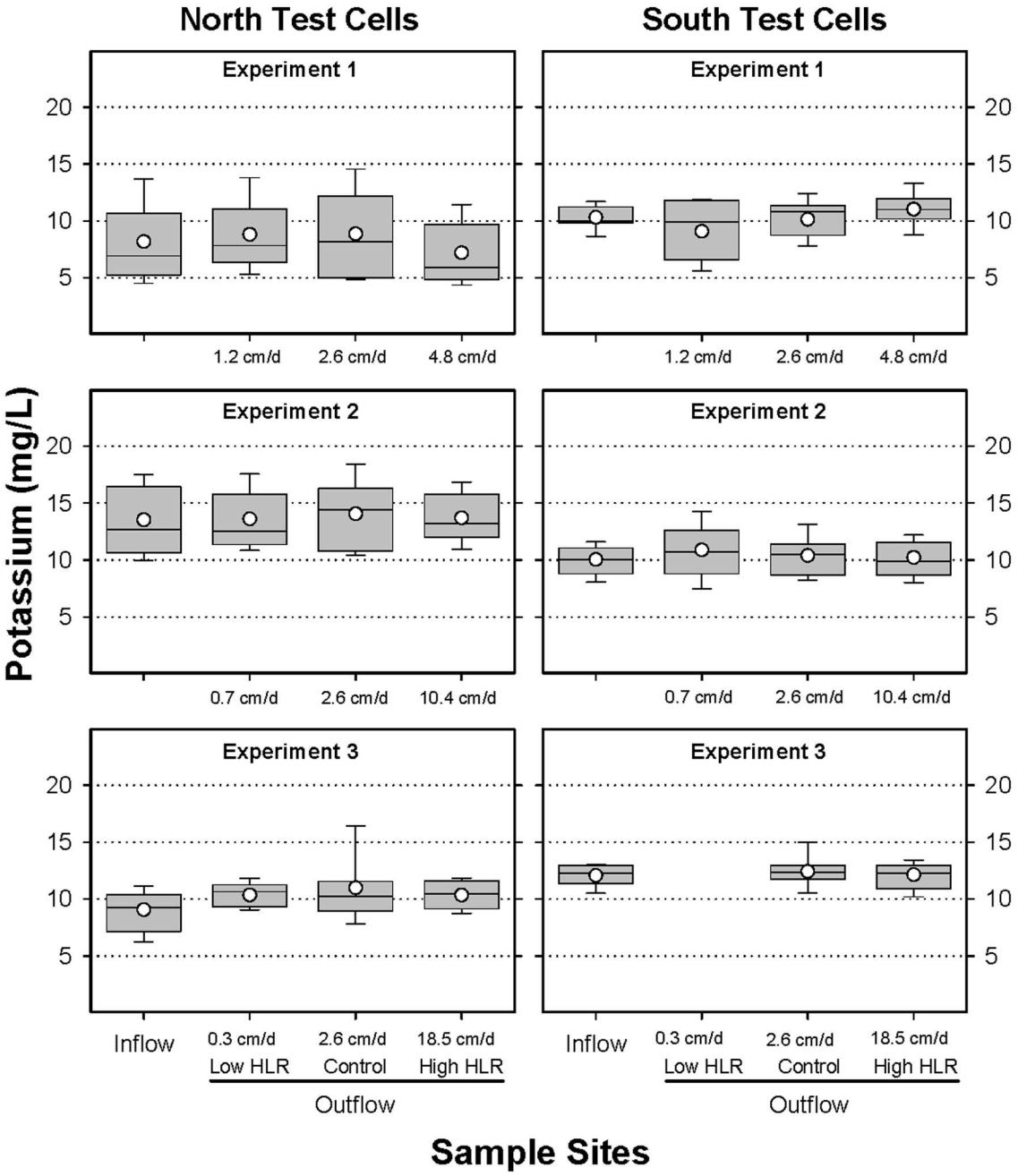
Appendix 15. Summary of weekly inflow and outflow nitrate+nitrite-nitrogen concentrations during hydraulic loading rate experiments conducted in the north and south test cells.



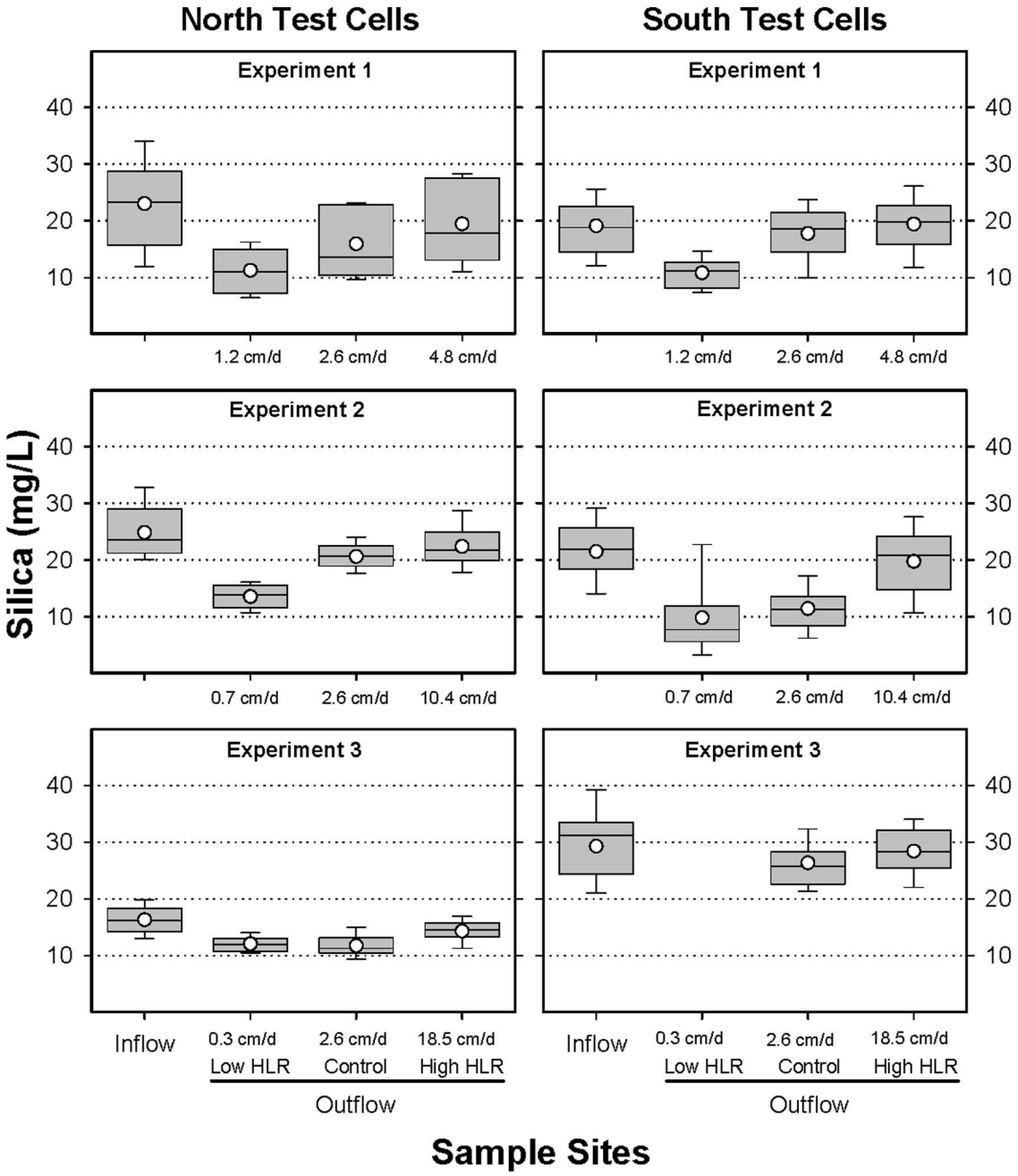
Appendix 16. Summary of weekly inflow and outflow particulate phosphorus concentrations during hydraulic loading rate experiments conducted in the north and south test cells.



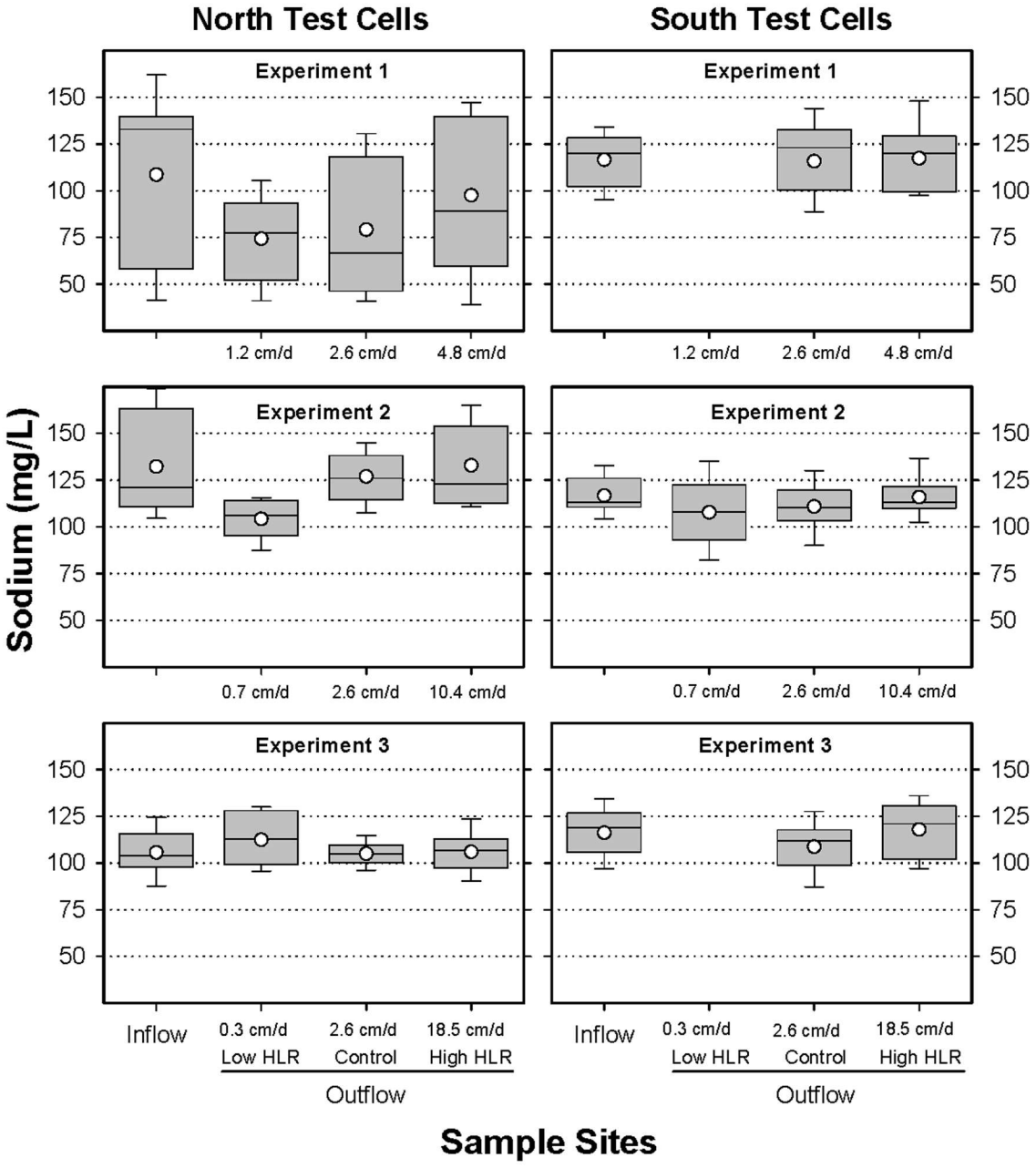
Appendix 17. Summary of weekly inflow and outflow pH during hydraulic loading rate experiments conducted in the north and south test cells.



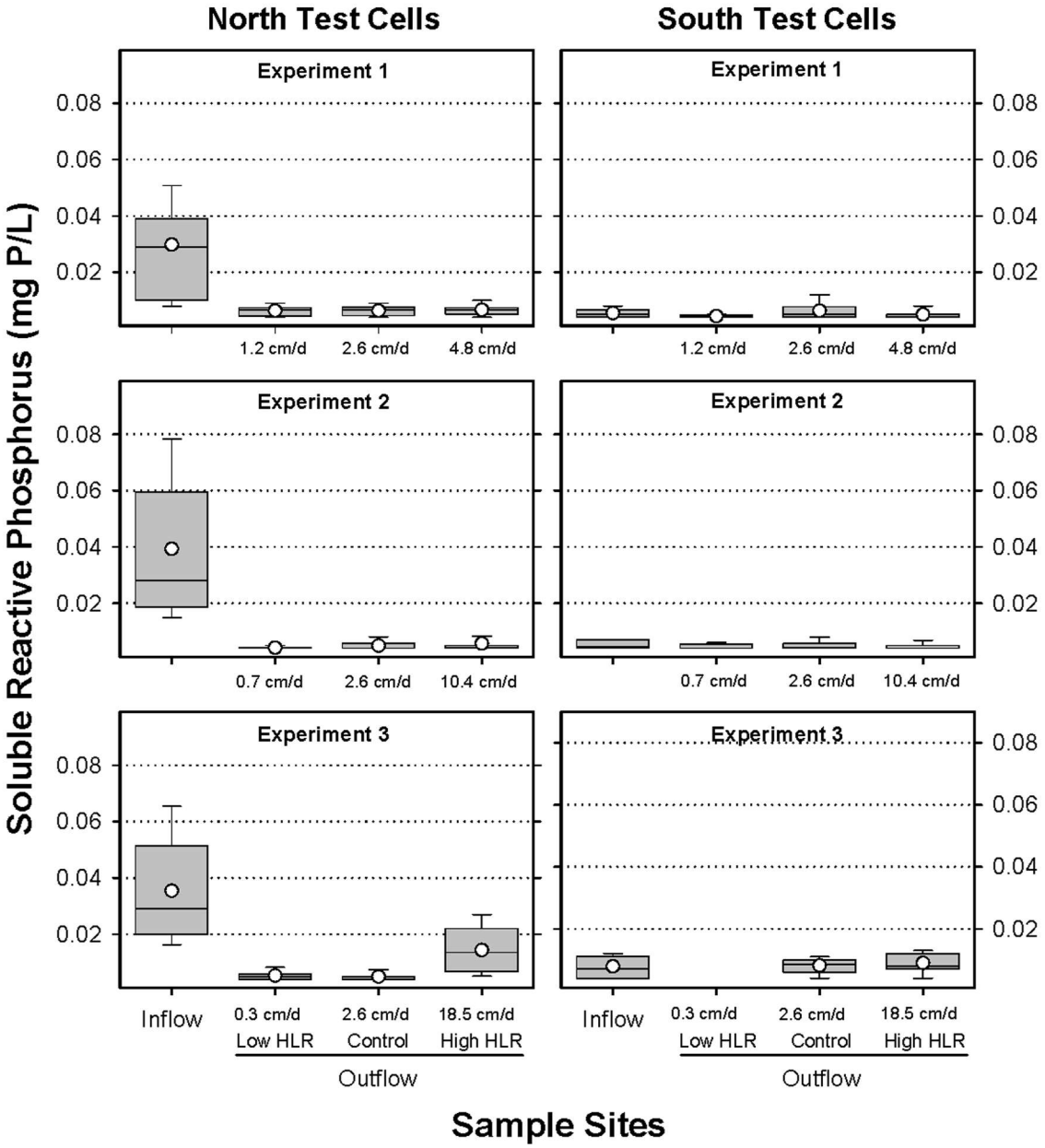
Appendix 18. Summary of weekly inflow and outflow potassium concentrations during hydraulic loading rate experiments conducted in the north and south test cells.



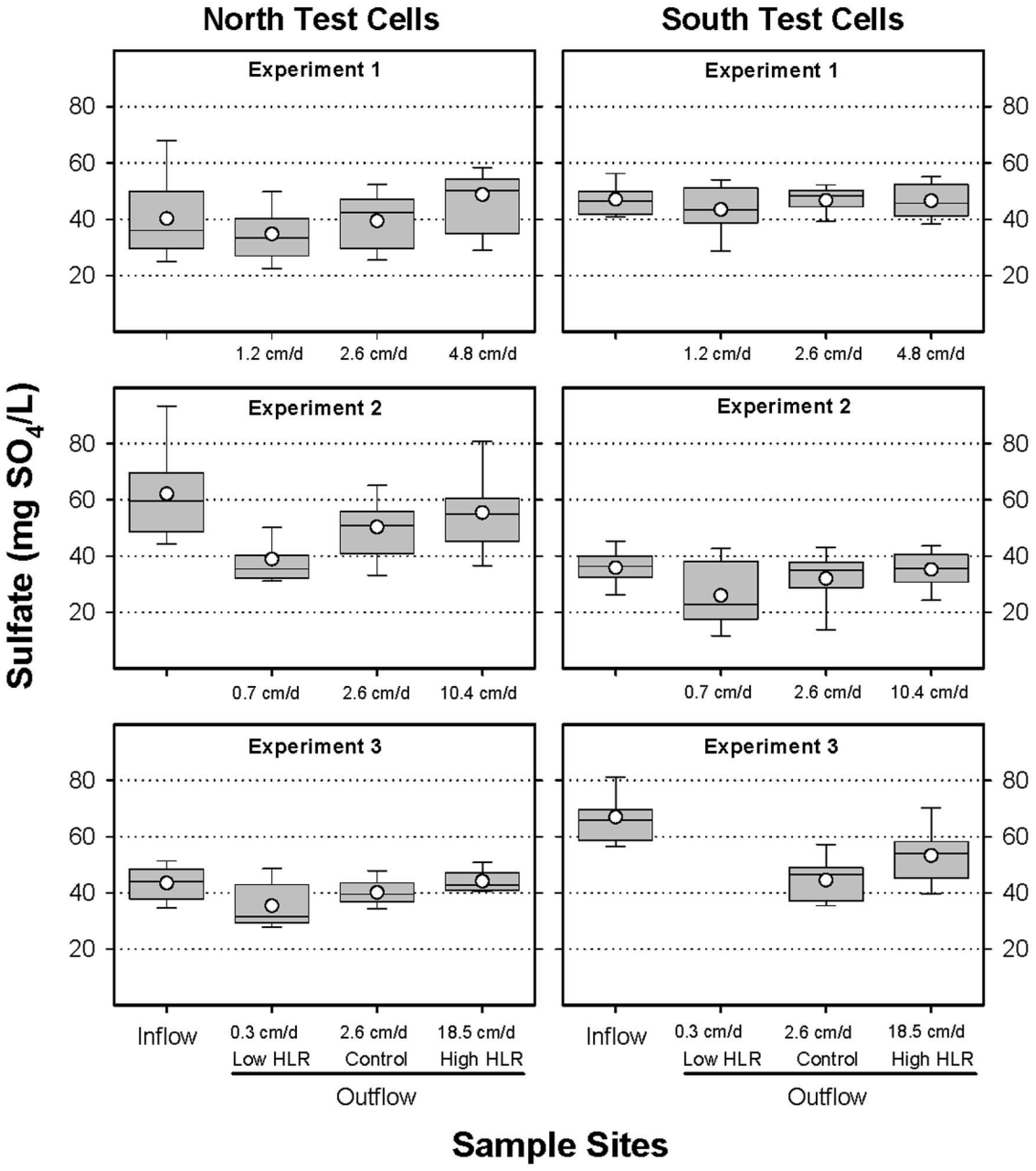
Appendix 19. Summary of weekly inflow and outflow silica concentrations during hydraulic loading rate experiments conducted in the north and south test cells.



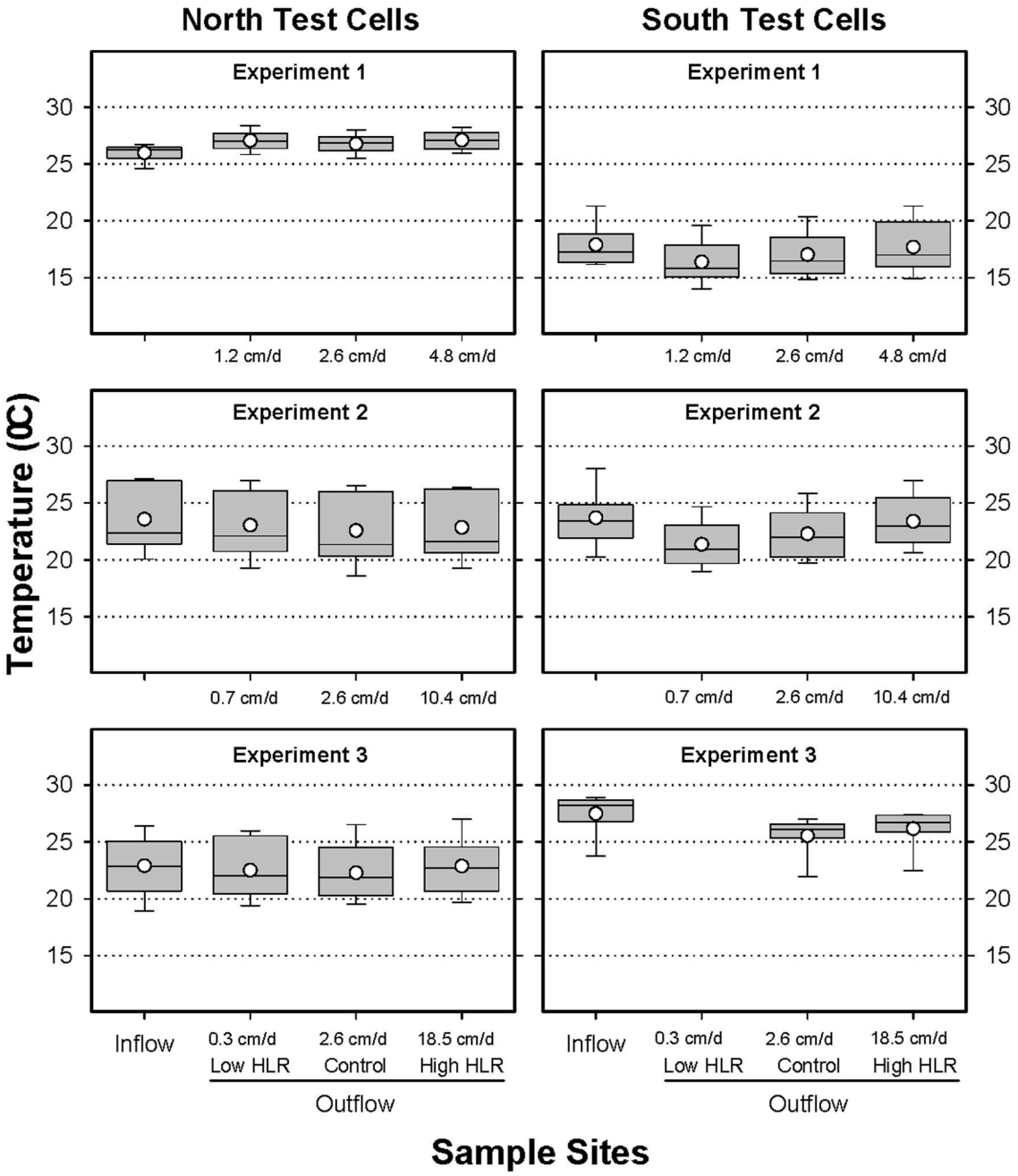
Appendix 20. Summary of weekly inflow and outflow sodium concentrations during hydraulic loading rate experiments conducted in the north and south test cells.



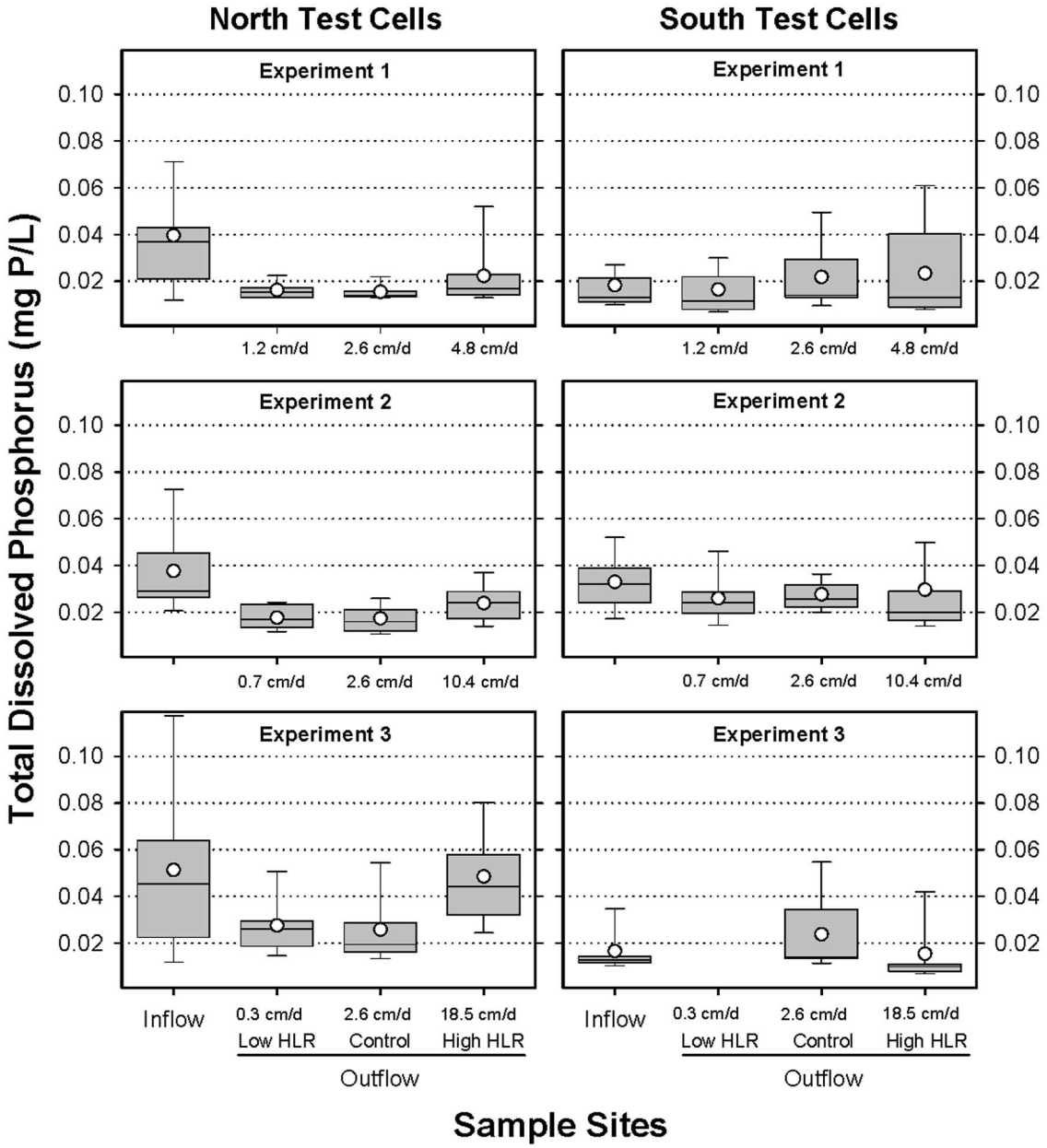
Appendix 21. Summary of weekly inflow and outflow soluble reactive phosphorus concentrations during hydraulic loading rate experiments conducted in the north and south test cells



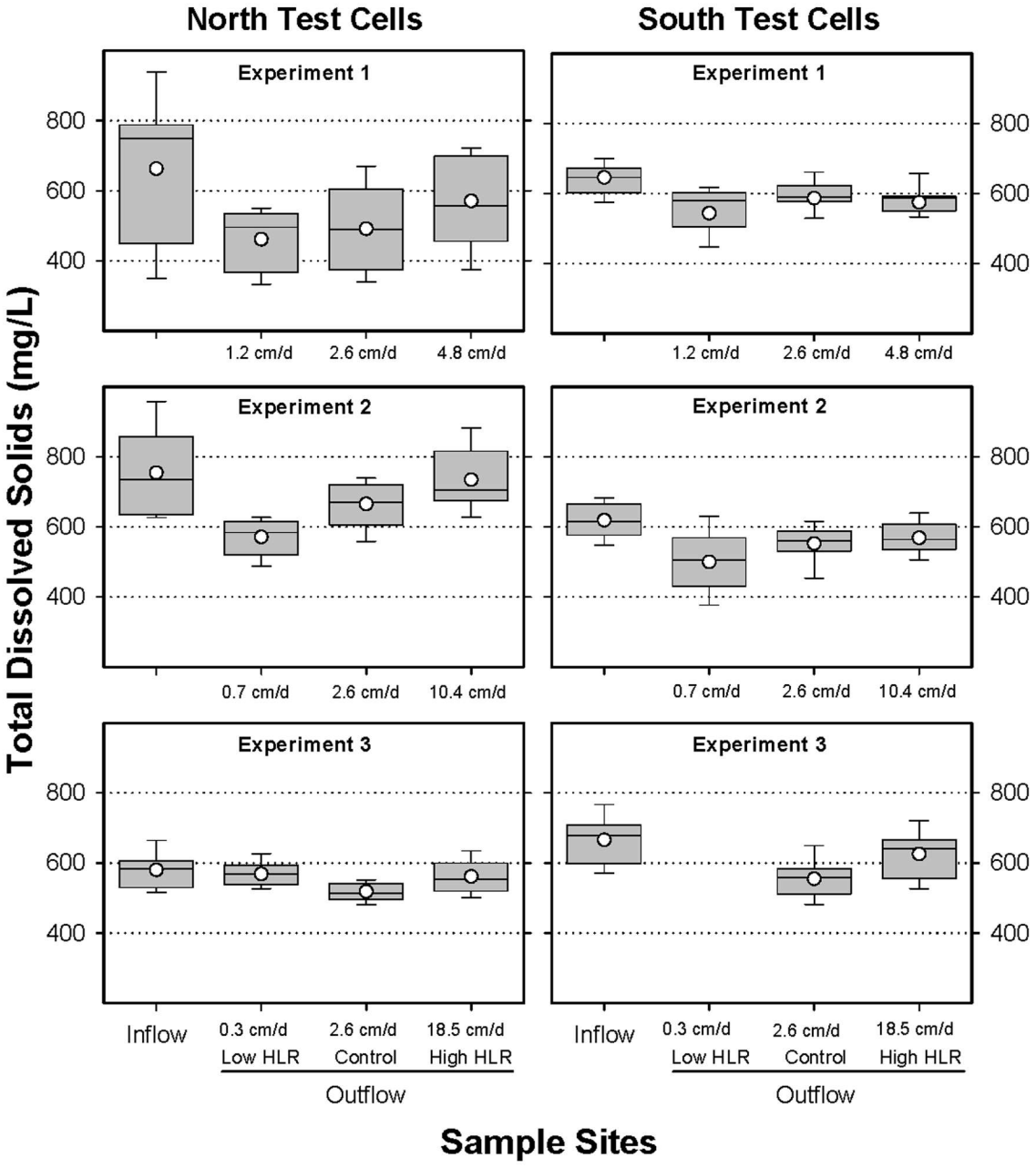
Appendix 22. Summary of weekly inflow and outflow sulfate concentrations during hydraulic loading rate experiments conducted in the north and south test cells.



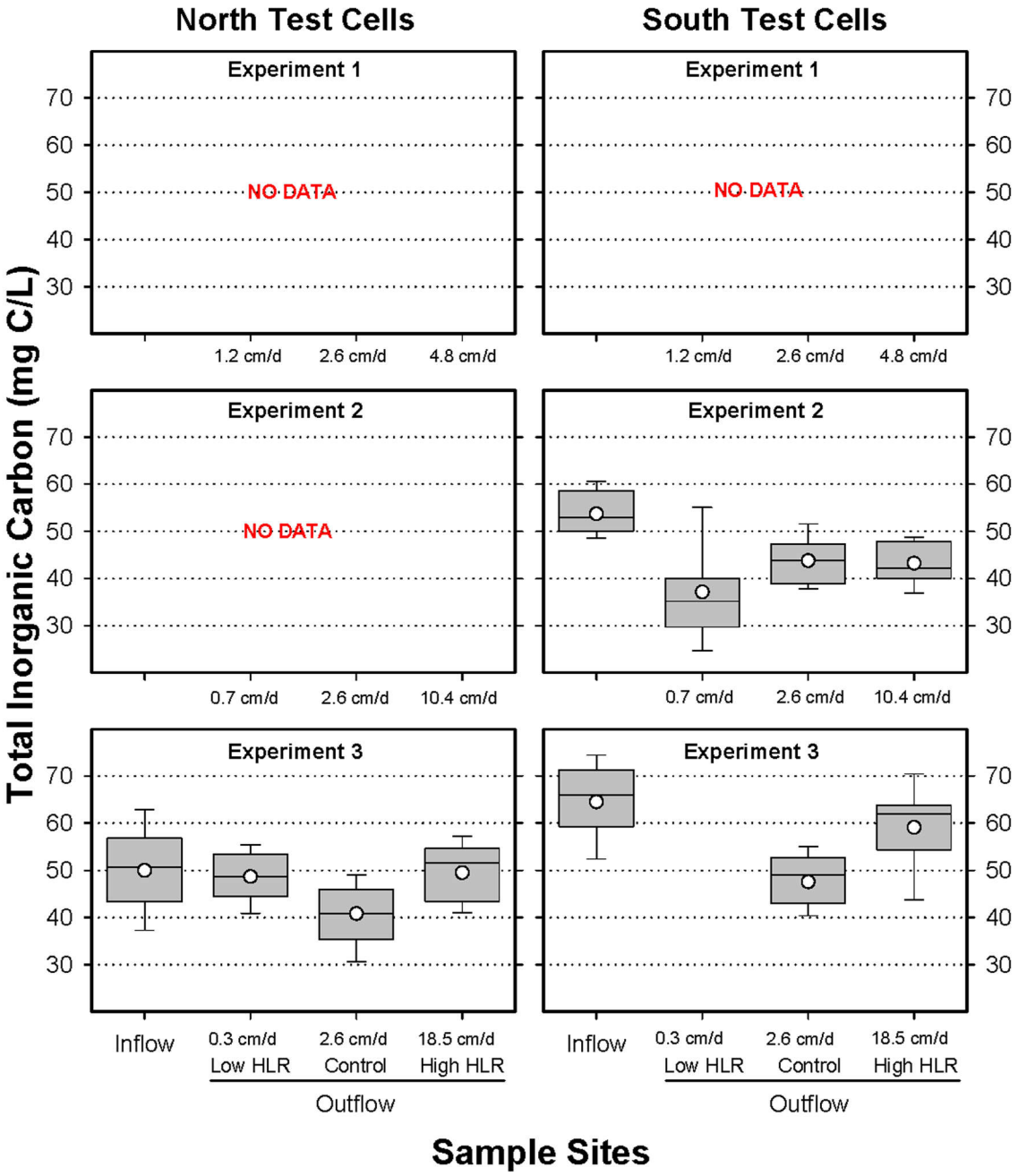
Appendix 23. Summary of weekly inflow and outflow water temperature during hydraulic loading rate experiments conducted in the north and south test cells.



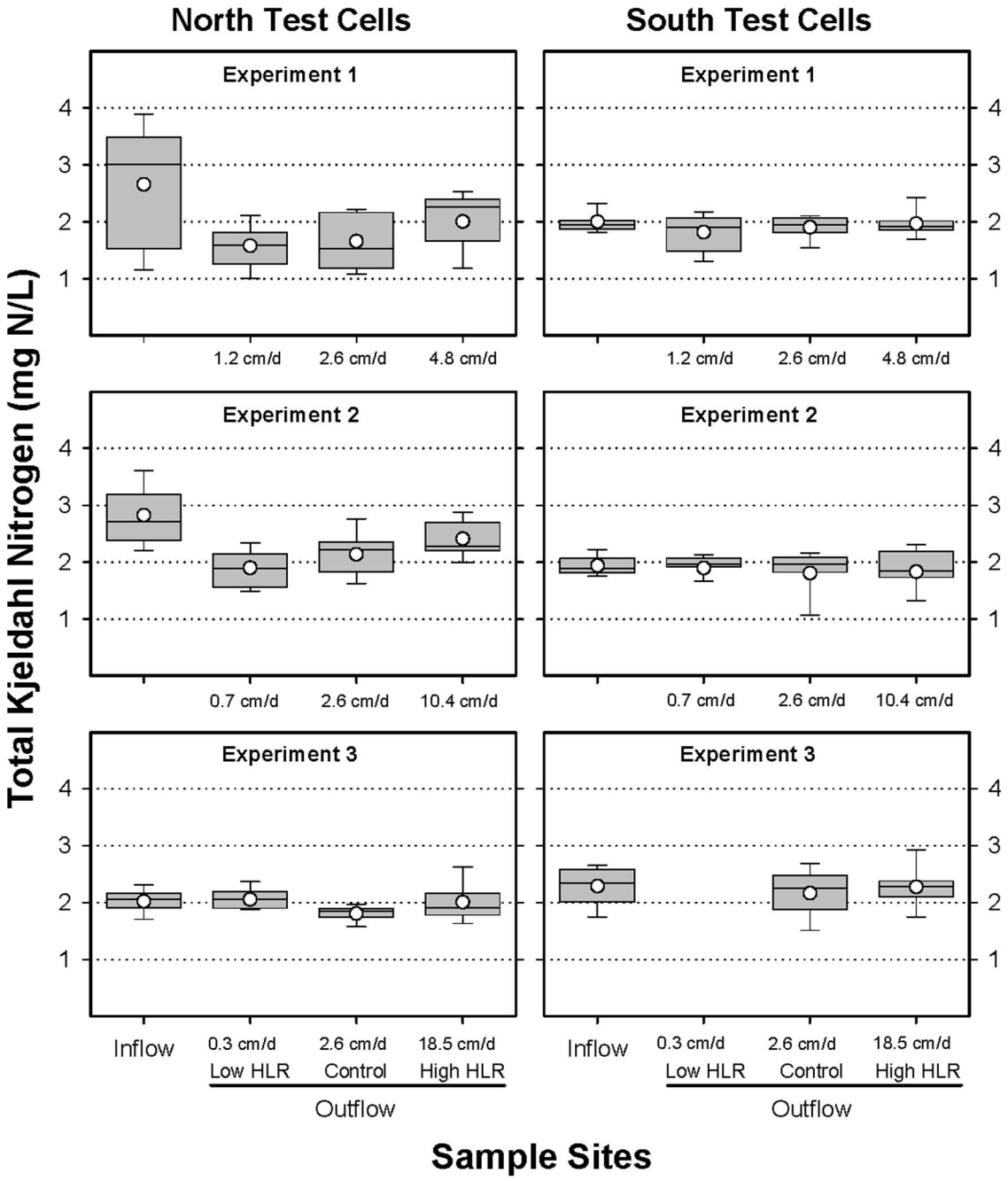
Appendix 24. Summary of weekly inflow and outflow total dissolved phosphorus concentrations during hydraulic loading rate experiments conducted in the north and south test cells.



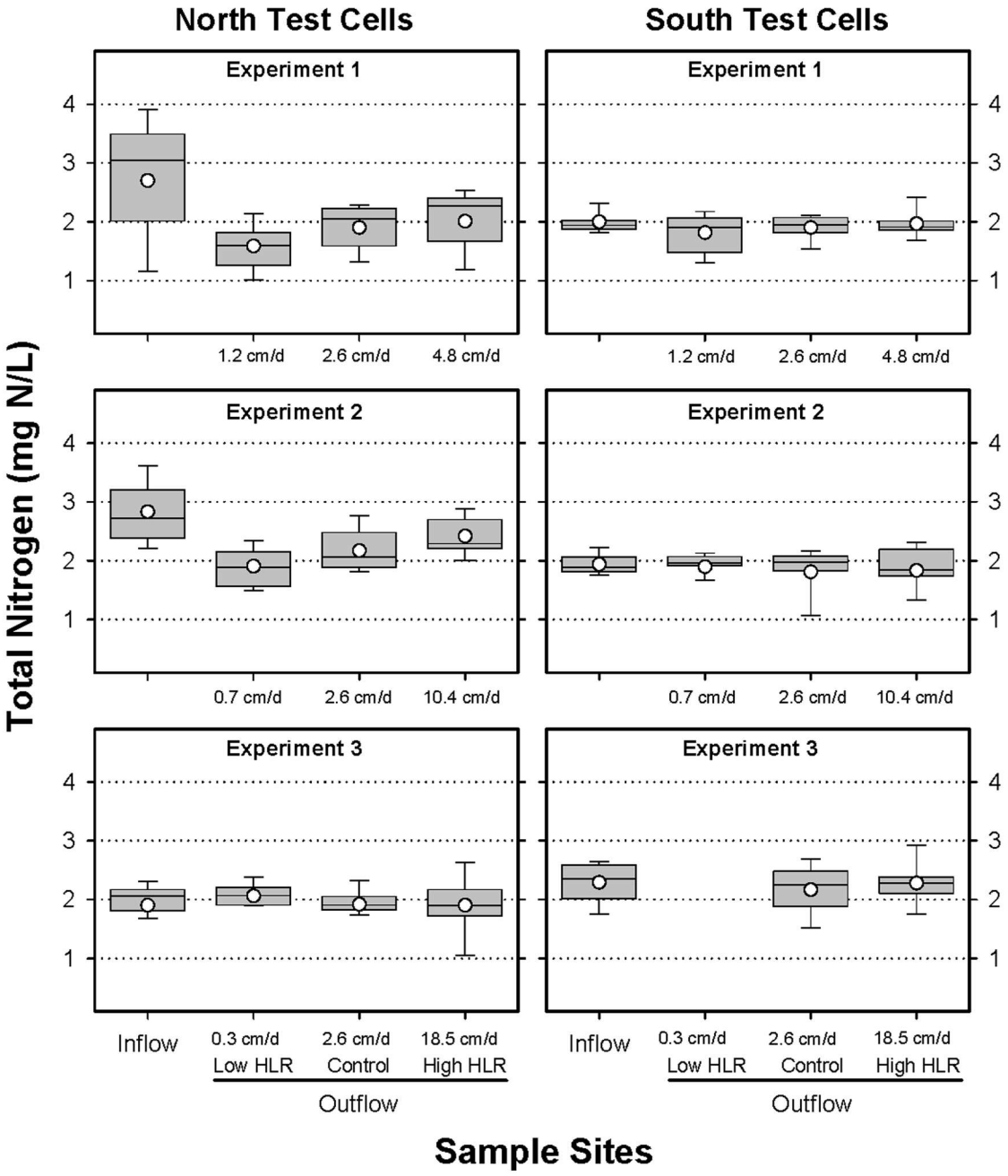
Appendix 25. Summary of weekly inflow and outflow total dissolved solids concentrations during hydraulic loading rate experiments conducted in the north and south test cells.



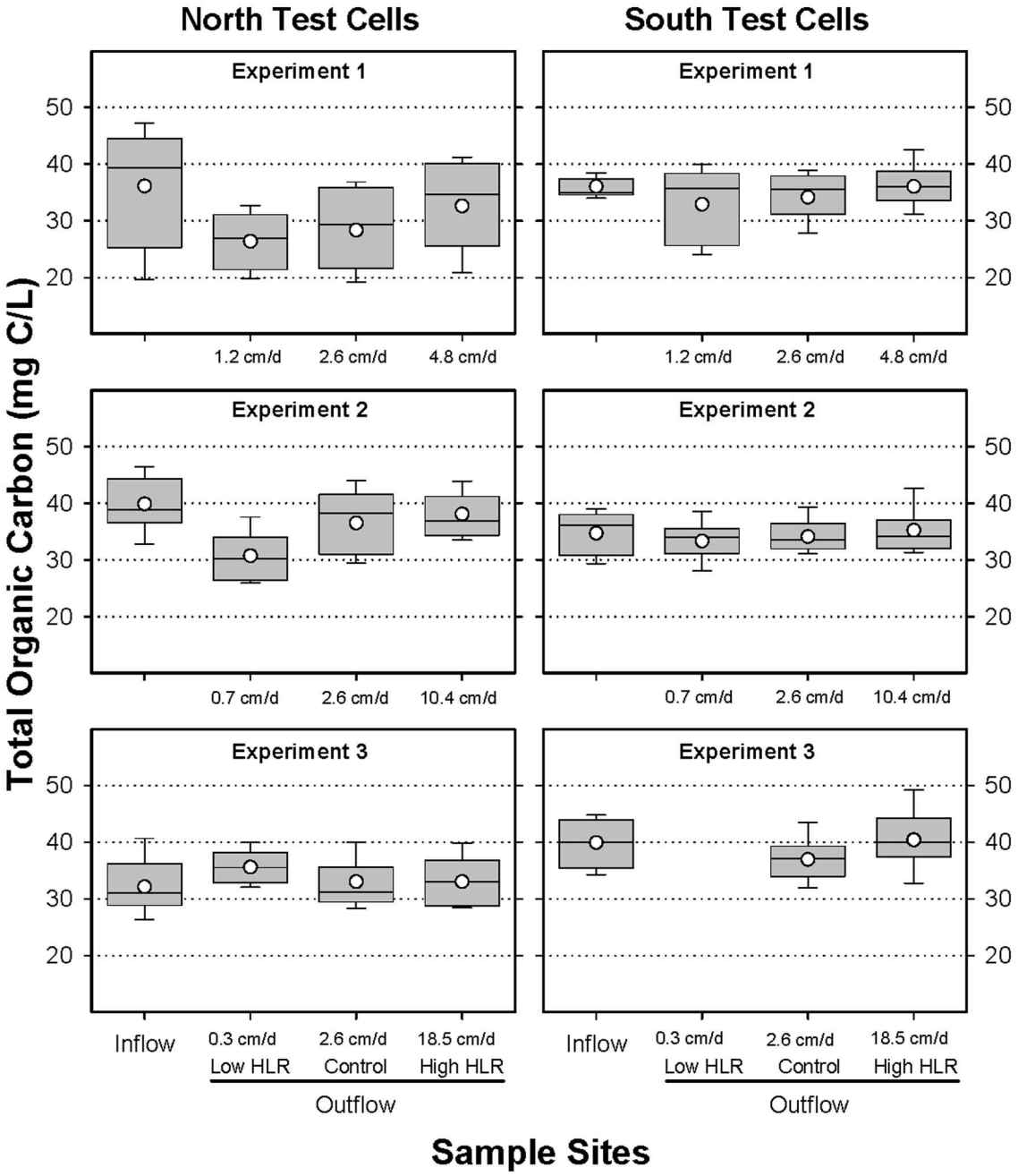
Appendix 26. Summary of weekly inflow and outflow total inorganic carbon concentrations during hydraulic loading rate experiments conducted in the north and south test cells.



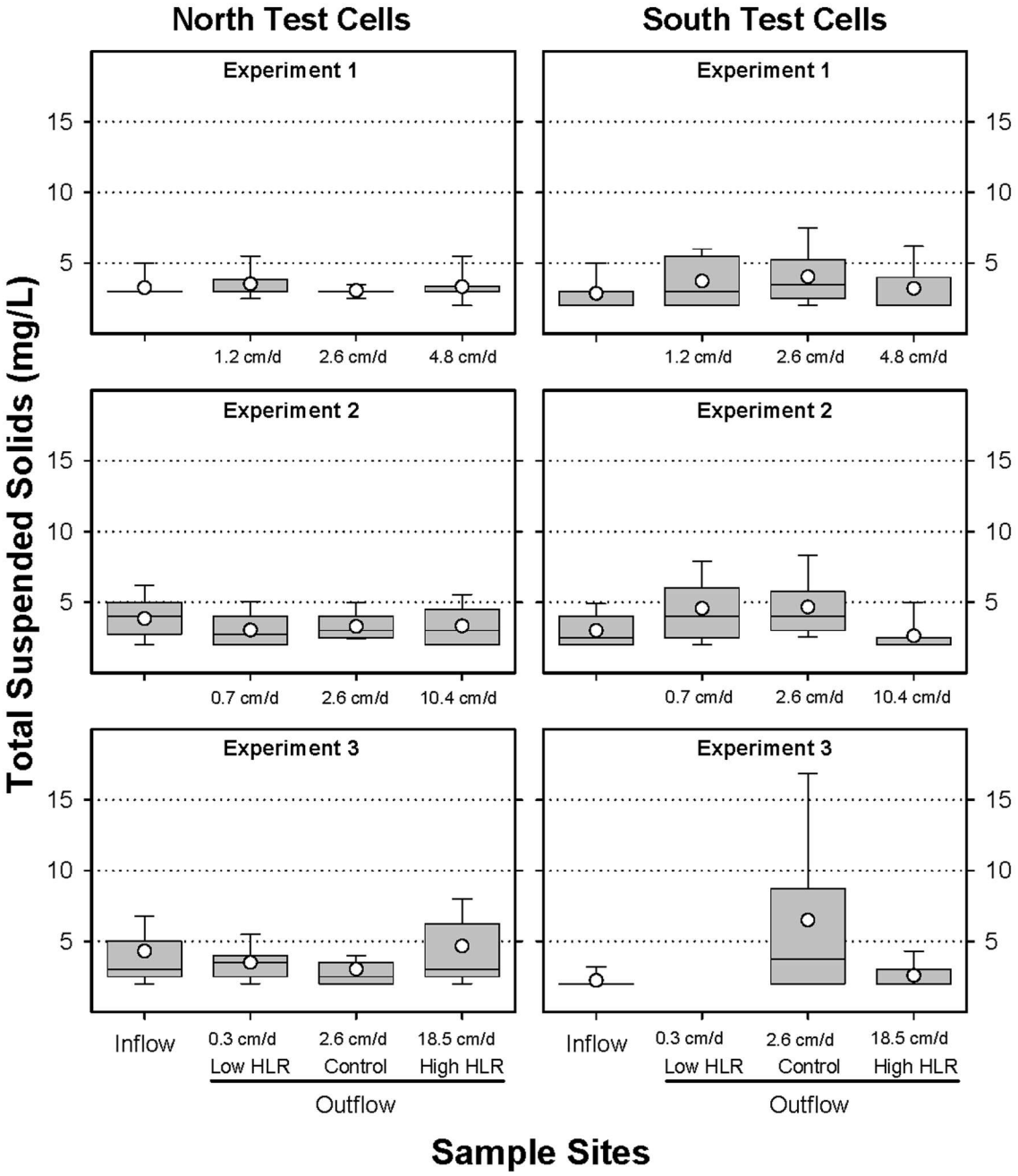
Appendix 27. Summary of weekly inflow and outflow total Kjeldahl nitrogen concentrations during hydraulic loading rate experiments conducted in the north and south test cells.



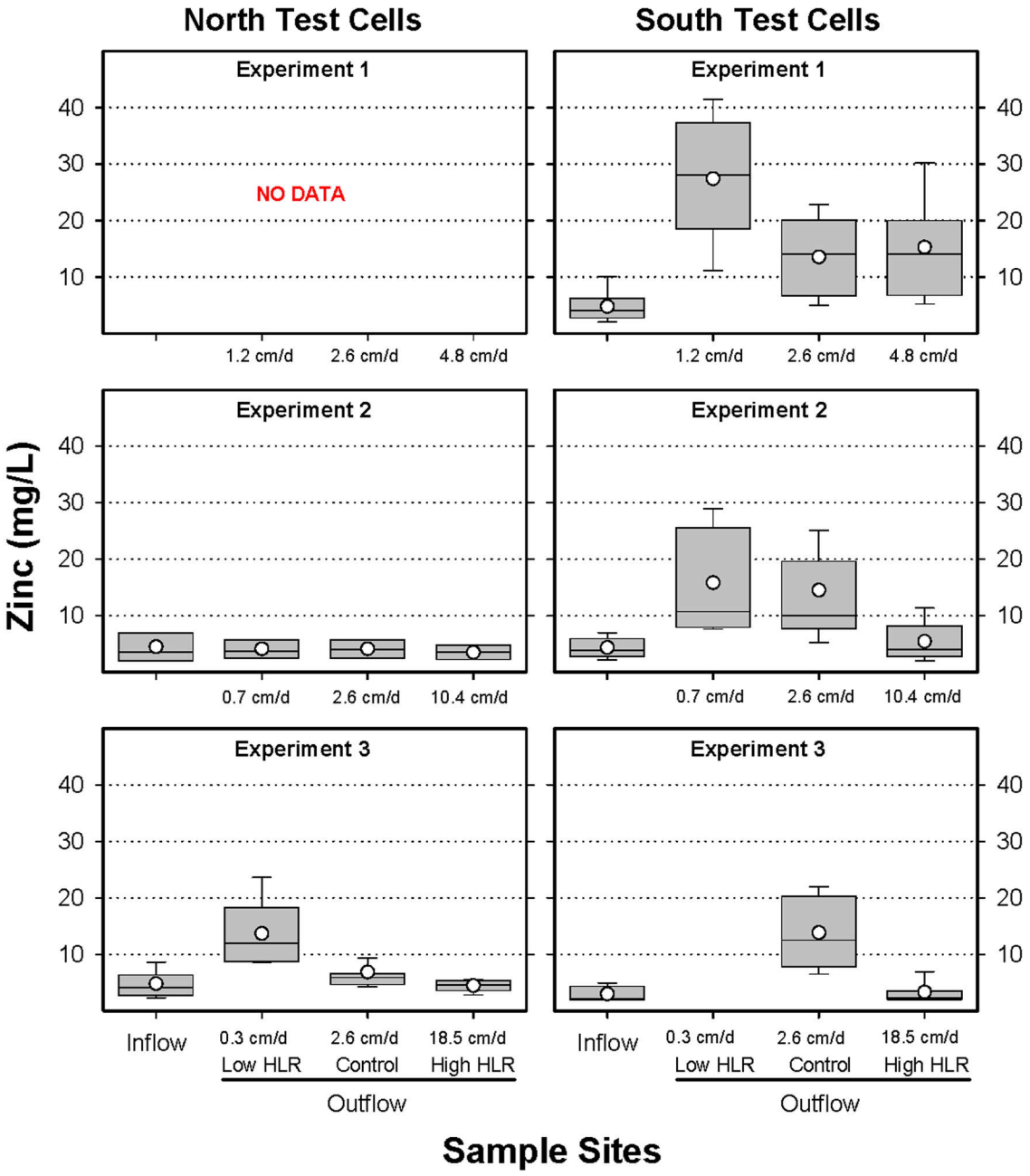
Appendix 28. Summary of weekly inflow and outflow total nitrogen concentrations during hydraulic loading rate experiments conducted in the north and south test cells.



Appendix 29. Summary of weekly inflow and outflow total organic carbon concentrations during hydraulic loading rate experiments conducted in the north and south test cells.



Appendix 30. Summary of weekly inflow and outflow total suspended solids concentrations during hydraulic loading rate experiments conducted in the north and south test cells.



Appendix 31. Weekly inflow and outflow zinc concentrations during hydraulic loading rate experiments conducted in the north and south test cells.