THE UNIVERSITY OF CALGARY

Bioretention cell efficacy in cold climates

by

Usman Taqdees Khan

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ABSTRACT

Bioretention cells are an emerging low impact development technology aimed at addressing urban stormwater runoff concerns. The objective of this research was to assess the efficacy of bioretention cells in cold climates. Both hydrologic and water quality performance was measured at the field and laboratory scale.

Experiments demonstrated that the bioretention cell successfully captured the majority of the runoff it received (91.5% on average). It also reduced the peak flow rate and delayed the time to peak. In cold weather conditions, the cell had a reduced capacity to capture runoff for large, high intensity events. Additionally, a frozen surface layer altered the hydrologic regime of the cell. Long term performance experiments demonstrated a significant decrease in saturated hydraulic conductivity over the initial four years of operation due to surface clogging. Saturated hydraulic conductivity decreased between factors of 11.4 to 15.4. Clogging was due to the sediment in the influent and was measured to a depth of 20 cm.

Contaminant mass capture was more than 89% for all contaminants. This was primarily due to the large runoff volume capture rates. Concentration reduction was more variable. Sediment and BOD_5 were significantly reduced in all experiments. Nutrient reduction was highly variable and was dependent on the growing media chemistry. Cold weather conditions did not have a significant impact on water quality performance. The experiments demonstrated that bioretention cells require time to mature before water quality improvement is seen. This varied between 2.7 to 3.6 years for nutrient reduction. The bioretention cell successfully removed 96% of particles larger than 50 μm.

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NOTATION

Symbols

English alphabet

A_B	bioretention cell area (m^2)
A_C	total area of the catchment (ha)
A_{Im}	impervious area (m^2)
C	runoff coefficient for the Rational method
C_i	inlet concentration of a single batch sample or composite sample (mg/L)
C_o	outlet concentration of a single batch sample or composite sample (mg/L)
C_W	weir discharge coefficient
$CaCl_2$	calcium chloride
Cl^-	chloride ion
CR	concentration reduction (%)
d	precipitation depth (m)
d_{annual}	average annual precipitation (m)
DF	peak or centre of mass delay factor
g	gravity acceleration (9.81 m/s^2)
h_1	the head above weir
i	intensity of the event (mm/hr)
I/P	impervious to pervious ratio
k	metric conversion factor for the Rational method
k_h	a constant for the weir discharge equation
KCl	potassium chloride
K_{sat}	saturated hydraulic conductivity
M_i	total mass of contaminant in the influent for an event (kg)
M_o	total mass of contaminant in the effluent for an event (kg)
MR	mass reduction of contaminants (%)
n	number of events
$NaCl$	sodium chloride

NH_3	ammonia
NO_2-NO_3	nitrite and nitrate
PR	peak reduction (%)
$PR^{>50\mu m}$	percent reduction of sediment particles greater than 50 μm (%)
q_{outlet}	flow rate of water in the outlet manhole (m^3/s)
Q_P	peak runoff flow (m^3/s)
Q_{pi}	inlet peak flow rate (L/s/ha)
Q_{po}	outlet peak flow rate (L/s/ha)
Q_W	discharge over weir (m^3/s)
r	radius of storage tanks (m)
S_g	volume of water stored in the growing media (m^3)
t_{pi}	time of peak at the inlet (minutes)
t_{po}	time of peak at the outlet (minutes)
t_s	time at the start of the experiment (minutes)
$TSS^{>50\mu m}{}_{in}$	concentration of inlet TSS particles greater than 50 μm (mg/L)
$TSS^{>50\mu m}{}_{out}$	concentration of outlet TSS particles greater than 50 μm (mg/L)
TSS_{in}	concentration of inlet TSS (mg/L)
TSS_{out}	concentration of inlet TSS (mg/L)
V_{annual}	annual equivalent runoff volume (m^3)
V_{outlet}	volume of water collected in the outlet manhole (m^3)
V_g	representative volume of growing media for each soil moisture sensor (m^3)
V_i	representative volume of inlet flow-weighted composite sample (m^3)
V_o	representative volume of outlet flow-weighted composite sample (m^3)
V_R	volume of runoff (m^3/s)
V_t	volume of water applied to the cell from both tanks (m^3)
V_C	volume of runoff captured in columns (%)
V_M	volume of growing media (m^3)
VR	runoff volume reduction between inlet and outlet (%)

Greek alphabet

α_{in}	fraction of particles in the inlet greater than 50 μm (%)
α_{out}	fraction of particles in the outlet greater than 50 μm (%)
β	average concentration reduction of TSS from field experiments (%)
$\hat{C}_i$	average inlet concentration of all experiments (mg/L)
$\hat{C}_o$	average outlet concentration of all experiments (mg/L)
Δh	initial depth of water – final depth of water in the tanks (m)
Δt	time interval between two flow rate readings (s)
π	3.1415
θ	angle of V-notch in weir (°)
θ_{AP}	soil moisture 12 hours after peak soil moisture (m^3/m^3)
θ_i	initial soil moisture (m^3/m^3)
θ_P	peak soil moisture (m^3/m^3)

Abbreviations

AB	Alberta
BMP	best management practices
BOD	biochemical oxygen demand
BOD_5	Five day biochemical oxygen demand
CoM	centre of mass
DI	de-ionized water
DO	dissolved oxygen
F	fall
IDF	intensity-duration-frequency
LID	low impact development
PAR	photo-synthetically active radiation
PET	potential evapo-transpiration
PSD	particle size distribution
SM	Standard Methods for the Examination of Water and Wastewater
Sp	spring
S	summer
SSC	suspended sediment concentration
TDP	total dissolved phosphorus
TN	total nitrogen
TP	total phosphorus
TSS	total suspended solids
W	winter

CHAPTER 1:INTRODUCTION

1.1 Introduction and problem statement

Urban stormwater runoff is defined as the overland flow that occurs after a precipitation event or after snowmelt. With the increase in urbanization, natural landscapes are replaced with impermeable surfaces such as roads, rooftops and other structures. These surfaces inhibit the landscape's capacity to absorb, store and attenuate runoff; this results in larger quantities of runoff being generated with higher flow rates and the capacity to carry a wide array of contaminants into receiving water bodies.

Uncontrolled, urban stormwater runoff presents a variety of complex environmental concerns. This includes an increased risk of flooding in urban areas due to the high rate and volume of runoff, scouring and eroding downstream water ways due to the high flow rates generated and the potential to carry a variety of contaminants originating from urban areas into these water bodies. This can lead to the destruction of aquatic habitat, pose a threat to potable water supplies and reduce the potential of recreational use of water ways in urban areas. Traditionally, many "end of pipe" treatment methods have been used to address these stormwater runoff concerns. Most of these systems, like curb and sewer networks and retention or detention ponds, focus on reducing the peak flow of urban runoff and conveying runoff to surface waters, but provide minimal improvements to the quality of runoff. However, increasingly, municipalities and stormwater management professionals are focusing their efforts towards Low Impact Development (LID) technologies to address urban stormwater runoff concerns. The purpose of these systems and technologies is to capture and treat stormwater runoff at the source. The aim is to develop urban areas in a way to mimic the pre-development hydrology and water quality characteristics of the site. LIDs focus on increasing infiltration, evapo-transpiration and other natural processes to capture stormwater runoff. Some of the benefits associated with LID is their ability to reduce the total volume of runoff generated, reduce the volume of runoff leaving a site, reduce the peak flow rate during storm events, reduce the total mass and concentration of

stormwater runoff contaminants, recharge groundwater and reduce the cost of urban stormwater runoff infrastructure.

Bioretention cells are a type of LID employed in highly urbanized areas with a large fraction of impermeable surfaces, such as parking lots and traffic islands. Essentially, bioretention cells are densely vegetated infiltration and treatment basins; urban stormwater runoff is routed to the cells, where the water pools on the surface before slowly infiltrating into its highly permeable growing media. As the water passes through the media, it undergoes various physical, chemical and biological reactions that remove contaminants associated with urban runoff. The runoff can then either exit the cell via an under-drain and outlet system, or percolate into the surrounding sub-soils. Considerable research studying bioretention cell performance has been conducted recently, with most research focusing on contaminant capture and transport, design and sizing and hydrologic performance. Unfortunately, most of the research has been done in warm and temperate regions, where regional precipitation patterns and soil conditions limit the applicability of the results to other regions. Before extensive bioretention cell implementation can occur in regions like Calgary, Alberta (AB), in-depth research into bioretention performance in cold climate conditions is necessary. In cold climates, conditions such as low temperatures, frozen soils, repeating freeze-thaw cycles and higher concentrations of sediment and chloride from road de-icing activities can potentially reduce the overall performance of bioretention cells.

In addition to this, many questions on bioretention performance are still unanswered. The short and long term performance of bioretention cells may be dependent on a number of factors that include the design, media type and depth, vegetation type, characteristics of urban stormwater runoff and the type and size of the catchment. All of these factors further affect issues such as maintenance periods and the total lifespan.

Results from regional and climate specific studies are crucial in understanding and determining the level of performance for bioretention cells. This includes determining a bioretention cell's ability in attenuating storm event hydrographs and reducing the mass of contaminants associated with runoff in both small and large events, over a variety of weather conditions. Furthermore, site specific research can help establish design guidelines and appropriate operation and maintenance procedures.

1.2 Thesis objectives

The general objectives of this study are to:

1. Determine a bioretention cell's efficiency at reducing the total volume of runoff and the total mass of pollutants in Calgary's urban runoff in both the short & long term.
2. Determine the effects of Calgary's cold climate on volume reduction, hydrologic performance & pollutant removal.

Both field and laboratory experiments were conducted to achieve these objectives.

1.3 Thesis layout

The thesis consists of seven chapters; Chapter 2 provides an in-depth literature review on urban stormwater runoff issues, bioretention cell performance and the effects of cold climate and weather. Chapter 3 discusses the gaps arising from the literature review and then lists the specific thesis objectives to be achieved. Chapter 4 presents the methods and materials used to conduct both the field and laboratory experiments and the analyses. Chapters 5 and 6 discuss the results from the field and laboratory experiments, respectively. Lastly, Chapter 7 outlines the major conclusions of the project, taking from both the field and laboratory components and ends with recommendations for future research.

CHAPTER 2: LITERATURE REVIEW

2.1 Urban stormwater runoff

As the global population grows, it is expected that a larger fraction of people will inhabit urban areas, potentially leading to uncontrolled and unplanned growth and urban sprawl. Traditional urbanization can adversely affect the environment with urban areas contributing higher pollutant loads to receiving waters, changing microclimates and alter ingthe natural hydrological cycle.

Within the context described above, urban stormwater runoff is an important and abundant natural resource (Hsieh & Davis, 2003). Historically considered a wastewater, the potential to use urban stormwater runoff as a source of water and to contribute to the sustainable vision of water resources is increasing in popularity (Hatt et al., 2007). Simply defined, urban stormwater runoff is the overland flow that occurs after a precipitation event or after snow melt.

As urbanization occurs, natural landscapes get replaced with impervious surfaces. These surfaces inhibit stormwater from infiltrating into the ground and alter the hydrological response and natural water balance of the area, resulting in reduced capacity to absorb, store and attenuate runoff (Marsalek et al., 2001, Davis et al., 2003, Jones at al, 2007). Additionally, the depression storage capacity of impervious surfaces is greatly reduced. Dust, dirt, sediments and pollutants of various kinds, settle from the atmosphere or are generated by urban activities and accumulate on these surfaces between storm events and are washed off by the runoff during subsequent storms. Also, non-impervious surfaces in urban areas are traditionally re-landscaped, covered with grass and sod and treated with fertilizers. Frequently this landscape disturbance increases the overland flow which in turn increases pollutant wash off into receiving water ways creating major and complex environmental concerns (Delleur, 1982, CoC, 2000, Davis, 2008).

Natural channels are either modified (deepened, straightened and lined) or replaced with gutters, storm sewers and drains. Combined with the aforementioned land-use changes, this results in an increase in the volume of runoff generated and in the magnitude of peak flow rates. The peaks also occur sooner due to the higher flow

velocities. The increased velocity and volume of runoff can then carry a large amount of sediment downstream and scour the channels that it leads to. In addition, impervious surfaces can reduce groundwater recharge of aquifers, resulting in a loss of available water and reduced base-flow in streams. Also, infiltration in urban areas poses a risk of carrying contaminants (such as chlorides from road de-icing activities) into groundwater aquifers.

Urbanization can also increase the temperature of coldwater stream environments by transferring heat from solar radiation, captured by pavements, to receiving water bodies through runoff. Snow accumulating in urban areas alongside roads can accumulate high pollutant loads and these can travel to receiving water ways during melt periods. Sediment concentrations have been shown to be significantly higher in urban snowmelt water compared to stormwater runoff (Muthanna et al., 2007a).

Due to these reasons, urban stormwater runoff is considered to be the leading cause of degradation of surface waters (Davis et al., 2003, Hsieh & Davis, 2003, Sharkey & Hunt, 2005, Davis, 2007, Hunt et al., 2008a). The detrimental effects of pollutants in urban runoff are responsible for the degradation of potable water supplies, fish kills, destruction of aquatic ecosystems, as well as a reduced potential for recreational activities (Hunt & Jarrett, 2004).

2.1.1 Conventional urban stormwater runoff contaminants

Urban stormwater runoff contains a large number of contaminants, with varying concentrations, from a variety of sources. The total loadings from urban runoff are comparable with that from wastewater effluent and industrial discharges (AENV, 1999, CoC, 2000). Typical pollutants found in urban runoff are total suspended solids (TSS), biochemical oxygen demand (BOD), nutrients, trace metals and bacteria. The variability in runoff characteristics is dependent on a number of factors including region, land-use type, site and off-site activities, source control practices, traffic volumes, climate, stormwater chemistry and catchment size (Minton, 2005, Hunt et al., 2006). In general, urban runoff quality decreases as the amount of imperviousness increases (AENV, 1999).

TSS, nutrients and BOD are required to be measured by the City of Calgary (mandated by Alberta Environment) as part of its Total Loading Management Plan (CoC,

2000, CoC, 2004). Chloride, a conservative chemical, has been included in this review due to its use in cold climate conditions as a component of de-icing salts. Organic contaminants, trace metals, micro-organisms and pathogens all have significant detrimental effects on receiving waterways, but were not included; the effects of these contaminants are believed to be outweighed by the effects of TSS and nutrients in the Bow and Elbow rivers in Calgary. Table 1 shows the common sources of the aforementioned parameters.

Table 1: Summary of Stormwater runoff contaminant sources (Minton, 2005)

Contaminant	Sources
Sediment	Atmospheric deposition; Transportation vehicles; Pavements, parking lots; Site development, eroded particles;
Nutrients	Atmospheric deposition, precipitation; Landscaping, residential activities, mulch; Building exteriors, wood shingles; Urban wildlife; Litter; Vehicle oil;
Chloride	Pavement de-icing;
BOD	Commercial businesses, litter; Pavement de-icing;

Sediment, in particular, TSS, is considered to be the most important and predominant pollutant associated with urban stormwater runoff. Sediment is often used as an indicator of overall water quality since other pollutants can be carried along with the sediment (CoC, 2000). TSS consists of silts, clays, fine organic and inorganic particles, soluble organic compounds and microscopic organisms. Generally, it is accepted that suspended sediment is the fraction of sediment in a sample that will not pass through a 0.45 μm pore diameter glass fibre filter (CCME, 2002).

Two primary sources of eroded particles are from development or construction activities and particles present on impervious areas (such as parking lots and highways) (Minton, 2005, Li & Davis, 2008). The concentration of TSS in one catchment will vary widely from area to area, depending on land-use type. In the City of Calgary, the annual

TSS loading from stormwater runoff is approximately 10 times higher than wastewater effluent (Bozic, 2007).

Nutrients, such as nitrogen, nitrate, ammonia and phosphorus (in particular ammonia and phosphorus) are controlled substances under the Total Loading Management Plan for the City of Calgary (CoC, 2000). The primary sources of nutrients in urban stormwater runoff are from fertilizers, decaying organic matter (from vegetation and animals) and atmospheric deposition (Davis et al., 2006, CoC, 2000). Nutrient over-enrichment causes excessive plant growth in waterways which often changes the composition of species present and causes eutrophic conditions. Additionally, toxic algae blooms can result, posing a threat to fish (and marine mammals in marine regions).

Dissolved oxygen (DO) is the measure of oxygen (primarily from the atmosphere and aquatic plant photosynthesis) dissolved in surface water. In polluted waters, DO depletion is a serious issue, causing detrimental effects to the aquatic ecosystem. In urban stormwater runoff, organic and bacterial matter that is picked up and transported with runoff into receiving waters is the primary source of DO depleting substances (CCME, 1999, CCME, 2006). BOD is a procedure to measure the depletion of DO over a specified period of time (usually 5 days, indicated as BOD_5). In pristine surface waters, BOD_5 is expected to be below 1 mg/L, up to 10 mg/L in polluted rivers, 20 mg/L for treated wastewater and up to 200 mg/L for sewage (CCME, 2006).

The chloride ion (Cl^-) is the anion found in chloride based salts, such as sodium chloride (NaCl) and calcium chloride ($CaCl_2$). These salts are widely used in cold climate regions as de-icing agents in the winter months. Chlorides get captured by snowmelt or urban runoff from roads and pavements and get transported to receiving waterways (WHO, 2003, CoC, 2000, AENV, 1999).

2.1.2 Runoff characteristics in Calgary, AB

Due to the rapid urbanization in the Calgary area, the Bow River is reaching its assimilative capacity with respect to urban runoff pollutants. The City has been mandated to control the total loading of pollutants in its drainage system (CoC, 2000). Table 2 below shows average City of Calgary urban stormwater runoff characteristics. This data was compiled from a study that sampled 15 sites, between 2001 and 2002, from a mixture

of commercial, industrial, ongoing development and residential catchment areas. Samples were not analyzed for chloride concentrations; however data from a separate study (Vandenberg et al., 2005) have been included for comparison; note that these values represent chloride concentration in the Bow River and not in urban runoff.

Table 2: Average City of Calgary stormwater runoff concentration from 1990 to 2002 (CoC, 2004)

Land-use Type	TSS (mg/L)	NH_3 (mg/L)	NO_2-NO_3 (mg/L)	TP (mg/L)	$Cl^{-(1)}$ (mg/L)	BOD_5 (mg/L)
Commercial	180	0.88	1.2	0.51	-	32.5
Industrial	369	0.73	0.92	0.80	-	34.2
Development	1896	0.45	0.58	2.43	-	17.6
Residential	444	0.62	0.91	0.75	-	26.7
Median	406.5 (2)	0.675	0.915	0.775	2 -3(3) 50 – 70(4)	29.6

1 = Winter concentrations significantly higher than summer concentrations
2 = Mean background base-flow concentration = 24 mg/L (CoC, 2004)
3 = Background chloride concentration in the Bow River; stormwater runoff concentration unavailable (Vandenberg et al., 2005)
4 = Downstream of wastewater treatment plant chloride concentration in the Bow River; runoff concentration unavailable (Vandenberg et al., 2005)

2.2 Managing urban runoff and Low Impact Development

Traditionally, urban stormwater runoff management systems were designed with the aim of protecting urban development from stormwater runoff. The basic principles of urban drainage design consists of flood management; designing and constructing a network of pipes and ditches to carry the anticipated peak flow downstream and into receiving water bodies (streams, rivers, wetland or lakes) (Delleur, 1982, Marsalek et al., 2001). With this design practice, pipes and sewers remain empty for extended periods of time between storm events. During low intensity or low flow events, the network has enough capacity to convey the flow, since they are designed for higher flow events. These higher flow rates or design events are chosen based on a statistically relevant storm event that will minimize surface flooding to an acceptable but infrequent level (Butler & Maksimovic, 2001).

However, with increasing urbanization, these systems require “end-of-pipe” methods to control high flow rates and to prevent flooding. Detention and retention ponds

were introduced into drainage systems to intercept runoff before its release into downstream waterways. The purpose of these ponds is to store large volumes of runoff and to reduce flow rates. This mimics the function of natural landscapes by providing an artificial means of storing and attenuating runoff. These ponds are also designed to release stored water at a controlled rate, based on a less intense design event. Though these release rates reduce the risk of flooding, they still alter the natural flow regimes found in streams and ponds and the overall hydrological cycle (US EPA, 2001). Another issue with the traditional model is that whenever a new development and associated stormwater infrastructure is connected to the older system, it reduces the older systems overall capacity, eventually requiring costly upgrades. The traditional method can also be highly inefficient as the large amount of land required reduces the economic efficiency (Marsalek et al., 2001).

The detrimental impacts of this type of drainage design on the environment have recently emerged. This has introduced the concept of designing stormwater systems to address environmental concerns with respect to water quality improvement as well as traditional flood control and runoff volume management (Delleur, 1982). Though traditional Best Management Practices (BMPs), like the aforementioned detention and retention ponds, provide some level of water quality improvements (in particular for TSS), these large, centralized facilities still contribute in reducing the health of ecosystems (US EPA, 1999, US EPA, 2001).

This has initiated efforts to introduce source controls and natural treatment methods, in particular LID as a means of capturing and treating urban stormwater runoff (Davis et al., 2003). Essentially, LID is a site design strategy; to implement controls and structures on site that allow the post-development hydrology and water quality to maintain (or improve) the pre or undeveloped site conditions (Hsieh & Davis, 2005a, Davis, 2008, Nordberg & Thorolfsson, 2004, Sharkey & Hunt, 2005, US EPA, 2001). The primary aims are to reduce the amount of impervious areas and thus the volume of runoff generated, to capture and treat the runoff on site, and lastly to promote the use of vegetation and natural processes to achieve these goals. This includes introducing technologies that promote infiltration, evapo-transpiration and storage, disconnecting impervious areas and preserving the local water balance, while reducing peak flow rates,

flow lengths and steep grading. Some examples of LIDs are bioretention cells, green roofs, grass swales and porous pavements (Davis et al., 2006, Davis, 2008, Hsieh & Davis, 2005b, Sharkey & Hunt, 2005).

Another advantage of implementing LIDs instead of traditional developments is that they can reduce costs, in terms of construction, maintenance and total lifecycle costs. LIDs promote green spaces in urban areas, thus adding appeal to communities and performing in an aesthetically pleasing way. Also, LID installations require less land disturbance and can be retrofitted. This is especially important in older urban cores, where stormwater infrastructure is eroding and reaching its capacity (US EPA, 2001).

However, some issues still exist that prevent the widespread implementation of LIDs. First, research is still required on many LIDs relating to their suitability in different situations and regions; there is a need to know the accuracy of various LIDs with respect to pollutant removal efficiencies for proper selection and operation (Hunt et al., 2006). Also, public and community perception may hinder the widespread implementation of LIDs. Conventional urban features, such as wide streets, large residential lots, curbs, gutters and other end-of-pipe treatment methods are considered essential, and the reduction and/or removal of these features may be considered undesirable (US EPA, 2001).

2.3 Overview of bioretention cells

Bioretention cells, also known as rain gardens, bio-filtration and infiltration basins, are a type of LID stormwater management technology that are designed to address urban stormwater runoff concerns (Hsieh & Davis, 2005a, Davis et al., 2006). They are small, localized infiltration and treatment basins that capture and treat urban stormwater runoff at the source (Hsieh & Davis, 2003, Hsieh & Davis, 2005b, Winogradoff, 2002). Bioretention cells are simple plant and soil based facilities, consisting of a densely vegetated basin, filled with a highly porous engineered soil media layer that is topped with a vegetated layer and mulch (Hsieh & Davis 2003, Kim et al., 2003). Figure 1 below displays a schematic of a typical bioretention cell showing its different components.

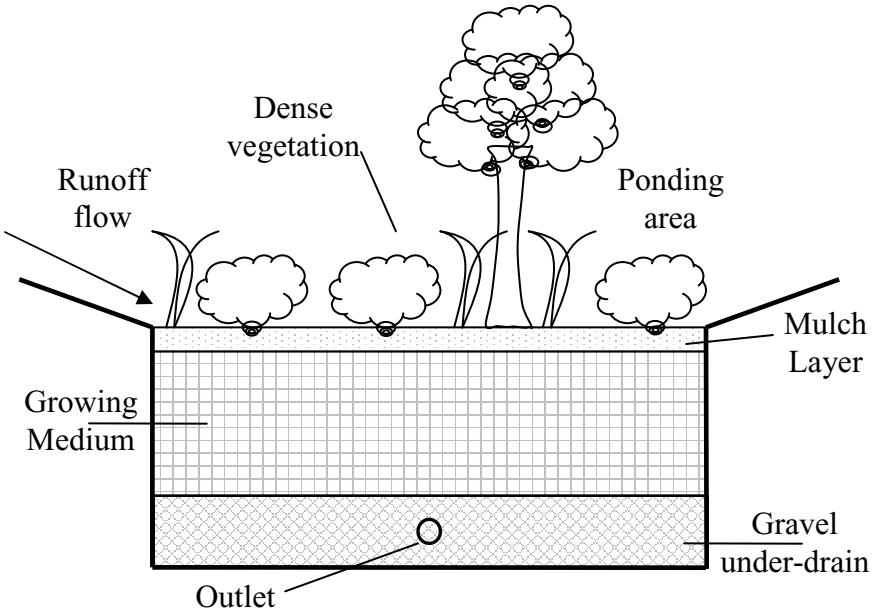

Figure 1: Schematic of a bioretention cell (not to scale)

Stormwater runoff is directed to the cell, where it pools (typically 15 – 30 cm deep) and infiltrates into the media. Vegetation acts to slow incoming stormwater, allowing suspended particles to settle (Hatt et al., 2007). This allows for the attenuation of the peak discharge and time of concentration of the incoming flow (Davis et al., 2006, Hunt et al., 2006). Additionally, the cells have the ability to reduce runoff volumes, recharge ground water and increase evapo-transpiration (Hunt et al., 2008a).

As the ponded water trickles into the soil media, various pollutants are captured via a number of physical, chemical and biological processes, reducing the overall toxicity of the runoff (Hsieh & Davis, 2005a). Pollutant removal and capture occurs on the surface and throughout the media as well (Hunt et al., 2006). The primary treatment media is the fill media, while the mulch layer provides additional filtration (Davis et al., 2006). Removal processes include infiltration, filtration, sedimentation, sorption, adsorption, plant uptake and others (Davis et al., 2003, Davis et al., 2006, Hsieh & Davis, 2005b, Davis, 2007, Muthanna et al., 2007a, Muthanna et al., 2007c Winogradoff, 2002). As the runoff drains to the bottom of the media, it can either percolate into the surrounding sub-soil or exit via an outlet pipe (as shown in the figure above).

Bioretention cells are designed to hold excess runoff in the ponding area if the intensity of stormwater runoff exceeds the infiltration capacity. If the cell is at risk of flooding, excess runoff can be diverted to an overflow drain (Hsieh & Davis, 2005b). The cells are designed to remain dry during storm events; during this time it is expected that numerous chemical and biological reactions take place continuously inside the cell creating a micro-ecosystem (Davis et al., 2006). Overall, bioretention cell technology has the potential to reduce the risk of flooding, peak flow rates and concentrations of most target pollutants from small to midsize storm events and prevent the runoff from discharging into receiving waterways directly (Hunt et al., 2008a, Davis & Li, 2005, Hsieh & Davis, 2003, Hsieh & Davis, 2005b).

2.3.1 Bioretention cell design

Bioretention technology borrows heavily from sand filters and infiltration trenches (Hunt et al., 2003). However, the important distinction between bioretention cells and these technologies is that the former are designed to create a local ecosystem, that matures and self perpetuates (Winogradoff, 2002). The major components of bioretention cells work together to achieve the desired results and to provide complementary roles to each other. These major components are: pre-treatment, inlet, ponding area, vegetation, mulch, growing media and the under-drain. Each component has a specific purpose that helps bioretention cells achieve their intended goals (Winogradoff, 2002).

The pre-treatment component is an option to be used in conjunction with bioretention cells as part of the larger “treatment train” urban runoff management system (Winogradoff, 2002, Lanarc et al., 2005). Pre-treatment options include vegetated buffer strips, swales or fore-bays that allow sediment removal and flow attenuation before the runoff enters the bioretention cell. The primary purpose of a pre-treatment system is to reduce the chances of erosion (due to high flows) at the inlet and to potentially reduce the clogging time of a bioretention cell by the additional sediment removal. A pre-treatment system is dependent on the location of a bioretention cell; retrofitted cells in tight areas may not have this capability. The inlet of a bioretention area is an important component for its overall performance. Ideally, runoff should enter a cell via sheet flow over the entire area; however, in most cases there will be a single inlet point. Thus the inlet has to

be designed to dissipate the influent's energy to protect the bioretention cell from high flows. Additionally, inlets may be clogged from sediment and debris and have to be maintained (Winogradoff, 2002).

The primary purpose of the ponding area in a bioretention cell is to provide storage capacity for when the intensity of runoff exceeds the infiltration capacity of the growing media. The depth of the ponding area is dependent on a number of design factors, including upstream impervious area, soil type and anticipated design hydraulic loading. The ponding area can include an overflow to reduce the risks of flooding, by channelling excess ponded water to a drainage pipe. The mulch layer on the surface of bioretention cells is added to maintain high soil moisture and to prevent the growing media from drying out, prevent the surface layer of the cell from eroding and filter the incoming sediment from runoff (Davis et al., 2006). The mulch layer is responsible for providing an organic medium that promotes biological activity that can lead to the removal of contaminants, such as heavy metals. Too much mulch however, can be detrimental to the vegetation and biological activity, since it can restrict the transfer of oxygen to the soil (Winogradoff, 2002).

The vegetation in a bioretention cell can consist of native or appropriate shrubs and trees that are resistant to environmental stresses. They can range from small plants and shrubs to large trees depending on the size of the cell (Roy-Poirier et al., 2010). The primary purpose of the plants is to provide a protective cover for the growing media, add aesthetics and green spaces to the location and to mimic a natural, undeveloped ecosystem (Davis et al., 2006, Davis, 2008, Le Coustumer et al., 2007). Plants also provide the potential to remove contaminants from urban runoff, especially for nutrient uptake (Davis, 2008, Le Coustumer et al., 2007). Plant roots can also actively adsorb pollutants in non-growing and cold conditions (Muthanna et al., 2007a). Root growth and biological activity can promote infiltration and hydraulic conductivity (by the creation of macro pores), prevent clogging and maintain soil porosity, structure and texture (Davis, 2008, Le Coustumer et al., 2007). Additionally evapo-transpiration by the vegetation can reduce the volume of runoff as well (Davis, 2008). Without plants, a bioretention cell may be a source rather than a sink for some pollutants, particularly nitrogen (Hatt et al., 2007). The presence of vegetation, roots and organic materials encourages small animals

to move through the media. This further increases infiltration rates and the permeability of the cell, improves aeration and allows a higher capacity of water retention. Microbes present in the roots also enhance nutrient uptake and water retention, while bacteria and fungi break down complex organic compounds (Winogradoff, 2002).

The growing media in bioretention cells is the most important component of the system and is an essential parameter for its design (Sharkey & Hunt, 2005). The purpose of the media is to support plant growth by providing water and nutrients and also to retain and detain the incoming stormwater runoff (Winogradoff, 2002). A coarser mix of media, with a high percentage of sand and organic matter is preferred. This is to attain higher hydraulic conductivity and infiltration rates. Lower conductivity or infiltration rates would negate the retention component of bioretention cells and force higher intensity runoff flows to bypass the bioretention media. The use of clays is not recommended as clays swell and are chemically active; even small variations in media size distribution, especially an increase in clay content, can drastically change the overall permeability (Hsieh & Davis, 2005a, Hatt et al., 2007). The physiochemical characteristics of the growing media, such as texture, density, organic matter and nutrient concentration, are important with respect to contaminant capture and removal. Different chemical characteristics will remove different contaminants. Thus, the chemistry can be tailored to target contaminants of interest (Hsieh & Davis, 2005a, Hsieh & Davis, 2005b).

The last component of a bioretention cell is the optional under-drain system. The purpose of the under-drain system is to convey the runoff away from the bioretention cell via a pipe that connects to a storm sewer system. The under-drain system consists of a gravel layer below the bioretention cell, often separated with a non-woven geo-textile or pea-gravel liner. As the runoff moves through the cell, the highly porous under-drain system allows the runoff to drain freely below it, channelling it to a perforated pipe (Davis et al., 2006). An under-drain is only required where local, undisturbed sub-soils have low infiltration rates, if the water table is less than 0.6 m below the bottom of the cell, or if it is located in or near residential areas. Without these restrictions, no under-drain is required and the cell can drain directly into the sub-soils. An under-drain system reduces the risk of groundwater contamination and heaving, allows the runoff in the

bioretention cell to drain faster and reduces the chances of creating anaerobic conditions (Winogradoff, 2002).

2.3.2 Bioretention cell sizing

The sizing and design of a bioretention cell is dependent on a number of factors that preclude any standard design guidelines. To design a bioretention cell the intended purpose and criteria need to be established. This includes determining whether the purpose of the cell is to primarily target runoff capture and reduction, or runoff quality improvement, or both, and to what extent (Muthanna et al., 2007a, Hunt & Jarrett, 2004). Additionally, site constraints (for example, a new development or retrofit application) may factor in what size or type of bioretention cell design is applicable and similarly, whether the bioretention cell is to be online as an individual LID or as a group of technologies in a "treatment train" (Winogradoff, 2002, Lanarc et al., 2005).

The first step in designing a bioretention cell is to determine the impervious area of the drainage area, calculate the anticipated runoff volumes and flow, and then determine the necessary storage volume. The storage volume should be designed to capture 100% of predevelopment runoff volumes and at least 90% of post-development mean annual flow (Lewis et al., 2008). Additional storage capacity can be added based on the desired performance criteria. The water quality event size and the desired water quality performance level should be defined. However, using the water quality event for sizing purposes may oversize the cell since it does not account for infiltration that is occurring during the event (Braga et al., 2007). The Bioretention Manual, published by Prince George's County, USA in 2002 (and revised in 2007) recommends a minimum depth of 0.45 m for the growing media, with an infiltration rate that allows pooled water to drain in 3 to 4 hours (Winogradoff, 2002). However, other studies (Davis, 2008, Nordberg & Thorolfsson, 2004) have shown that the depth of a bioretention cell is related to the anticipated loading rates, i.e. if smaller loading rates are expected, the depth of the cell can be reduced (to up to 0.3 m). Shorter media depths may result in lower hydraulic conductivity rates due to higher relative compaction rates (Le Coustumer et al., 2007). The role of media depth in relation to water quality improvement is quite complex and it can be adjusted for target pollutant capture (Hatt et al., 2007).

The growing media selection is critical for successful design (Sharkey & Hunt, 2005, Hunt et al., 2006). A clay content of less than 5%, a sand content of 50 to 60% and a range of 20 to 30% for both compost and top soil is recommended (Winogradoff, 2002). Additionally, 0.15 to 0.30 m is the recommended ponding depth; while the surface area of the cell (assuming no site constraints) can be adjusted to increase the total storage volume (Davis et al., 2009, Winogradoff, 2002). The rationale behind the minimum size requirements is that these are the minimum dimensions necessary to recreate forest or upland habitats (Winogradoff, 2002). Also, it is preferable to have runoff stored on the upper layer of the soil column rather than in the ponding area, as it gives time for pollutants to sorb to the media, resulting in better water quality performance (Hsieh & Davis, 2005a). While questions regarding bioretention cell design criteria and guidelines still exist; yet considerable runoff reduction and contaminant removal is expected regardless of the design configuration (Sharkey & Hunt, 2005).

The type of facility required has a large influence on bioretention cell design and there are three major types of bioretention cells:

1. An *infiltration and recharge bioretention cell*, allows all the runoff to drain into the sub-soils. This type of cell does not have an under-drain or outlet pipe; the growing media is deepest in these types of cells.
2. A *filtration and recharge bioretention cell*, allows a fraction of the runoff to drain to the outlet while the rest percolates into the sub-soils. This type of cell includes a permeable under-drain, where excess runoff can drain into an outlet pipe, while for smaller, less intense events; the runoff can percolate into the sub-soils.
3. A *filtration-only bioretention cell*, allows all the runoff to drain to the outlet. This type of bioretention cell has an impermeable liner separating the growing media from the native sub-soils and can be relatively shallow; the primary function is to filter the incoming runoff (Winogradoff, 2002, Lanarc et al., 2005).

2.3.3 Bioretention cell application

In many municipalities, regulations require a certain percentage of a new development to be dedicated to green space and park areas. Bioretention, alone or as part of a larger LID system, can be used to fulfil these requirements and add vegetation to

urban environments (Sharkey & Hunt, 2005, Hunt et al., 2005, Muthanna et al., 2007a). Bioretention cells are designed to be employed in highly urbanized small-scale watersheds and drainage areas (Hsieh & Davis, 2003, Sharkey & Hunt, 2005). Some examples of these are residential areas, office complexes and commercial areas, parking lot medians, traffic islands and adjacent to roads, green spaces, playgrounds and golf courses (Le Coustumer & Barraud, 2007, Hunt & Jarrett, 2004, WER, 2007a). In areas that are frequented by high volumes of pedestrian traffic, bioretention cells provide an aesthetically pleasing stormwater treatment technology, making them ideal for residential neighbourhoods as well (Hunt et al., 2003). Furthermore, bioretention cells have been designated a preferred site practice for LEED certification in the United States, thus its widespread use is imminent once suitable performance is demonstrated (Davis et al., 2009).

2.4 Bioretention cell performance

Bioretention cells are assessed based on their ability to capture large volumes of urban runoff, reduce peak flow and increase the time of concentration and time to peak. In addition to this, in terms of hydrologic performance, bioretention cells should have the ability to recharge groundwater and maintain natural base-flow in nearby streams. From a water quality perspective, bioretention cells should reduce the total pollutant loads and reduce the concentration of certain contaminants. Beyond this, bioretention cells provide green spaces to urban areas, encourage the growth of local, small scale ecosystems and improve the landscape (CASQA, 2003). This review focuses on the hydrologic and water quality performance; the following sections discuss performance levels reported in current literature.

2.4.1 Hydrologic Performance

The major hydrological performance indicators of bioretention cell are: total volume captured or reduction of the incoming runoff; the reduction in peak flow rates; the delay or lag time of the outlet hydrograph; and the long term changes to the hydraulic conductivity and surface infiltration rates. The extent of volume reduction in bioretention cells has been poorly documented (WER, 2007a). Table 3 provides a summary of volume

capture rates from various experiments. All experiments were conducted in the field, using real time storm events to calculate the volume of runoff added and released from the cell. In most cases, the bioretention cells were able to contain 100% of the runoff volume from small and medium size events, but for larger events the capture rate ranged between 33% to 80% (Hatt el al, 2009, Traver & Prokop, 2003, Ermilio & Traver, 2006, Davis, 2008). Thus, the volume removed was directly proportional to the inflow volume; the inflow volume capture decreased with storm magnitude (Lewis et al., 2008). Both exfiltration and evapo-transpiration have been noted as important mechanisms of volume capture; in some cases water exfiltrated with the presence of a clay liner (Hunt et al., 2003, Hunt et al., 2006, Dietz & Claussen, 2005). The presence of an internal water storage section or a sump, greatly increased losses via percolation, however the long term impact to groundwater are not known (Hunt et al., 2008b). Volume capture was also seasonally dependent; a statistically significant reduction in capture rates was seen in cold conditions (Hunt et al., 2006).

Table 3: Summary of hydrologic performance from various field experiments

Author	Volume Reduction	Peak Reduction & Delay	Comments
Traver & Prokop, 2003	80%	-	Retrofit project Only small events (1 – 1.5 inches)
Hunt & Jarrett, 2004	Significant reduction of outflow volumes	-	No significant reduction in winter
Dietz & Clausen, 2005	98.8% runoff volume collected	Lower peak flow, increased lag time	Impermeable liner Collected roof runoff only
Sharkey & Hunt, 2005	Considerable	Lined cell: 19.3% Unlined cell: 23.6%	Less water removal in fall and winter
UNHSC, 2005	-	85% peak reduction, 615 minutes lag time	Multiple LIDs tested at field site
Ermilio & Traver, 2006	80% average, 96.6% for an extreme event	-	Back to back events do not significantly affect the performance
Hunt et al., 2006	50% reduction, primarily ET and exfiltration	-	Unlined bioretention cells with clayey soils Lower capture rate in winter
Traver et al., 2007	100% capture for 18% of events; 40-50% reduction of volume; 70% capture of runoff	-	Review from 3 ongoing sites
Davis, 2008	75 – 83% volume captured	44 – 63% peak flow reduction; delay by a factor of 2	Cells had impermeable liners 1/3 to 1/2 of all events had major reductions
Hunt et al., 2008a	-	Peak reduction of 96.5%, 3 hour peak delay. Outlet flow rate significantly lower than inlet flow rate	-

Table 3, continued: Summary of hydrologic performance from various field experiments

Hunt et al., 2008b	"vast majority" infiltrated and did not leave via pipe	Peak reduction at least 96.5% for small and medium sized events	Three cells: 1 cell had no overflow structure, 2 cells had internal sump
Lewis at al, 2008	42% (15 – 83%)	80% peak reduction (45 – 96%)	Fully lined cells, undersized only 1% of catchment. Small and medium intensity events only
Muthanna et al., 2008	-	42% reduction in peak flow ; average lag time of 90 minutes	Two pilot scale bioretention "boxes" All inflow drained to outlet
Hatt et al., 2009	33% reduction of inflow volume	80% reduction of peak flow rates	Different climates tested

Peak flow reduction and delay has been more widely reported than overall volume capture. However, results from various field experiments show great variability in the results. Peak flow reduction ranges from 19% to 96%, while peak delay or lag time varied from 90 minutes to up to 615 minutes. The reasons for the wide variability in results can be attributed to a number of factors; the hydrologic benefits of bioretention cells are dependent on growing media type, design, available storage and pooling volume, site location, catchment characteristics, climate and antecedent conditions, total runoff volumes and the intensity of the monitored events. Peak outflow is strongly correlated with peak inflow rates, but correlation with other parameters, such as rainfall intensity, event duration and antecedent dry weather periods are less significant (Lewis et al., 2008). However in cold weather or snowmelt conditions, both temperature and antecedent dry conditions have a larger effect on hydrological performance; lag time increased with antecedent dry weather periods of 1 day or more (Muthanna et al., 2008). Some impacts of bioretention design have also been reported; the presence of an internal water storage or sump, can delay outflows (i.e. increase lag times) and also reduce flow frequency (Sharkey & Hunt, 2005). The importance of increasing lag time, peak time or time of concentration is that an increase in this duration (from a few minutes to several hours) can decrease the outlet flow rate (Davis et al., 2009, Dietz & Claussen, 2005).

The problem with relying on real time storm events to evaluate the hydrologic performance is the increase in uncertainties. For example, in several experiments (Lewis at al, 2008, Hunt et al., 2008b) the inlet runoff rate exceeded the infiltration rate of the cell, and thus the runoff was routed to an overflow. This overflow volume and thus the total inlet runoff volume could not be calculated in these experiments, hence making it difficult to quantify capture rates.

The hydraulic conductivity and surface infiltration rates of bioretention cells can affect hydrologic performance. Over time, it is expected that due to compaction and clogging, these values will decrease, limiting the effectiveness of the cells. The type of growing media is the factor governing initial hydraulic conductivity; other factors such as the type and amount of vegetation and characteristics of the incoming runoff will govern the decline in conductivity (Le Coustumer et al., 2007). Multiple studies have shown that initially, hydraulic conductivity will rapidly decline (up to a 66% decrease) and then tend

towards a constant value. This is due to the compaction of media and hydraulic loading on the cells. However, after this initial decline, the establishment of vegetation and root growth can maintain or even enhance the hydraulic conductivity (Le Coustumer et al., 2007, Le Coustumer et al., 2008, Lewis et al., 2008, Archer et al., 2002, Li & Davis, 2008). The final value of conductivity is more important than the rate of decline. The bioretention cell should be designed to match this final value as its design conductivity (Le Coustumer et al., 2007).

Clogging, or a decline in infiltration rates, is the main reason for the failure of infiltration based stormwater treatment technologies. Clogging occurs for a number of reasons and is caused by physical, chemical and biological processes (Le Coustumer & Barraud, 2007, Le Coustumer et al., 2007). However, the accumulation of solids (clays are more significant than silt) is the main reason for the reduction in infiltration rates (Hsieh & Davis, 2003, Li & Davis, 2008). High hydraulic loading rates (either an increase in solid concentrations or a decrease in bioretention cell size) will increase the rate of clogging and reduction in hydraulic conductivity and surface infiltration rates (Le Coustumer et al., 2008). Similar results are expected with undersized bioretention cells (Le Coustumer et al., 2007). Over-sizing a bioretention cell can buffer it against variations and decline in hydraulic conductivity (Lewis et al., 2008, Le Coustumer et al., 2008). There is a need to understand the relationship between clogging and sediment deposition (Le Coustumer & Barraud, 2007). Column experiments have shown that both cake filtration and depth filtration occur in bioretention cells; cake filtration is the reason behind decreasing hydraulic performance. Cake filtration causes stratification in the growing media; the incoming solids cannot penetrate beyond the top 5 to 10 cm (up to 20 cm for continuous loading) of the media (Li & Davis, 2008). Suitable maintenance can reduce clogging effects and improve the conductivity and infiltration rates. Some examples include media replacement (for the top 20 cm), the addition of compost and the use of mulch as the top layer (Ermilio & Traver, 2006, Le Coustumer et al., 2008, Hsieh & Davis, 2005a, Li & Davis, 2008). Some reports suggest that back to back events had no effects on infiltration rates, nor did large storm events (Ermilio & Traver, 2006, Hsieh & Davis, 2005b, Traver et al., 2007).

Over the long term, bioretention cells develop unique soil surface and vegetation characteristics that create distinct flow paths. These flow patterns impact retention time and contribute to improving infiltration rates. Plant growth and root systems contribute to reopening pathways, resulting in minimum degradation after several years of operation (Traver et al., 2007). Also, vegetation plays an important role in maintaining the hydrological performance of bioretention cells. Vegetation can improve porosity and reduce clogging on the surface (Traver et al., 2007, Davis et al., 2009). Additionally, some experiments have reported that dense vegetation is better than both sparse and shallow vegetation; dense vegetation reduces the flow rate coming into the cell, increasing lag times (Le Coustumer et al., 2007). Vegetation with shallow or thin and long roots can cause a decrease in overall hydraulic conductivity since they can create a mat effect on the surface of the cell, similar to clogging (Le Coustumer et al., 2008).

2.4.2 Water quality performance

Field and laboratory experiments have shown that bioretention cells can remove TSS, total phosphorus (TP) and nitrogen with varying results. Water quality performance can be expressed as the capture of the total mass of contaminants, which is dependent on both the inflow and outflow volumes. It can also be expressed as the reduction in concentration of the contaminant in the influent and effluent. It is important to look at both these performance parameters, as concentration reduction may be skewed due to runoff characteristics. An increase in influent concentrations with constant effluent concentrations will show a higher concentration reduction or vice versa. Furthermore, on a mass basis, high volume capture rates will show very high mass capture rates as well. Water quality performance is dependent on the size of a storm event, with a higher efficacy occurring during small events (Ermilio & Traver, 2006).

2.4.2.1 Total Suspended Solids

Numerous field and laboratory studies have shown effective reduction of TSS concentrations and capture of total mass. Bioretention cells often exhibited better performance than dry detention basins (Cosgrove & Bergstorm, 2003). TSS removal

efficiencies have been reported between 47 – 100% in numerous studies (UNHSC, 2005, Cosgrove & Bergstorm, 2003, Hatt et al., 2007, Hatt et al, 2008, Hsieh & Davis, 2003, Hsieh & Davis, 2005a, Hsieh & Davis, 2005b and Davis, 2007).

Lower removal rates were attributed to the initial leaching of fines from the growing media and aggregate in the under-drain system, until stabilization occurred (Davis, 2007, Davis et al., 2009, Hatt et al., 2007). Also, the TSS particles in the effluent were believed to originate from the media rather than the runoff (Hsieh & Davis, 2003). Once bioretention cells reach maturity, they provide a buffering effect, where the effluent concentration of TSS is essentially constant, independent of the influent. This can create issues with calculating removal efficiencies as well; higher influent concentrations of TSS will show larger percent reductions while lower influent concretions will show decreased performance (Hatt et al., 2008).

2.4.2.2 Nutrients

Unlike sediment removal, nutrient removal is more complex and dependent on several factors. Physical, chemical and biological processes all contribute to nutrient concentration reduction and capture (Davis et al., 2009). In addition to this, site specific conditions, bioretention cell design and growing media characteristics all influence nutrient reduction (Bratieres et al., 2008). Results of phosphorus and nitrogen removal have varied greatly in previous studies (see Table 4) and the efficacy of bioretention cells to treat nutrient loading is to a large extent, unknown (Kim et al., 2003, Hseih & Davis, 2005b, Hatt et al., 2008). Vegetation is an important component of nutrient removal processes (Davis et al., 2006). Without vegetation soil based filters will act as a source of nutrients rather than a sink (Hatt et al., 2007).

Most studies note that the most effective way of reducing nutrient loads is by focusing on reducing the effluent volumes released from the bioretention cell (Davis, 2007, Davis et al., 2006) since effluent concentrations are typically higher than influent concentrations (Hunt et al., 2006). Also, Wong et al. (2006) and Bratieres et al. (2008) noted that nutrient concentrations in bioretention cell effluent tend to converge to a consistent, background value, providing a buffering effect. However, looking at total

mass reductions, bioretention cells can reach efficacy levels that are higher than dry detention basins (Cosgrove & Bergstorm, 2003).

Variations in phosphorus removal have been noticed in numerous studies and it is understood that the type of growing media used is critical to performance (Davis et al., 2009, Bratieres et al., 2008, Hunt & Jarrett, 2004). There are two reasons for this: the first reason is the phosphorus index (or p-index) of the growing media. If the concentration of phosphorus is low in the growing media, it has a low p-index and a higher concentration means a higher p-index. Results show that a reduction in phosphorus concentration and increase in mass capture is prevalent when the p-index is low. In high p-index soils, the incoming phosphorus (particularly the dissolved fraction) does not have an opportunity to sorb to the media (Traver et al., 2007, Hatt et al., 2008, Hunt & Jarrett, 2004, Hunt et al., 2006, Sharkey & Hunt, 2005). The second reason is the amount of organic matter present in the media; however results based on this hypothesis are conflicting. Bratieres et al. (2008) concluded that low organic matter content (less than 5%) was needed to optimize TP reduction. In contrast, Hseih & Davis (2003, 2005b) concluded that higher organic matter content is directly proportional to TP capture.

Table 4: Summary of nutrient removal performance in bioretention cells

Author	Total phosphorus	Total nitrogen	Ammonia	Nitrate	Comments
Cosgrove & Bergstorm, 2003	70 – 83%	68 – 83%	-	-	-
Hunt et al., 2003		Aerobic: 89% Anaerobic: 86%	Aerobic: 81% Anaerobic: 94%		Laboratory experiments No statistical difference between two configurations
Hunt et al., 2003	-535 – 30%	58 – 89%	-	-	Field experiments
Hsieh & Davis, 2003	37 – 99%	-	5 – 49%	2 – 7%	-
Kim et al., 2003	-	-	-	Up to 80%	Submerged anoxic zone with carbon source in bioretention cell
Hunt & Jarrett, 2004 Hunt et al., 2006	-242% (high p-index) 65% (low p-index)	40%	-	13 – 75%	75% nitrate removal occurred in a cell with an anaerobic zone Anaerobic zone significantly lower TP concentration Significant increase in concentration for most contaminants; up to 30 fold increase of TP and TN
Dietz & Claussen, 2005	-116%	-	85%	No significant reduction	-
Hsieh & Davis, 2005a	37 – 99%	-	2 – 49%	1 – 43%	-
Hsieh & Davis, 2005b	63%	-	13%	-16%	-
Sharkey & Hunt, 2005	Significant decrease	-	Significant increase	Significant decrease	Anaerobic zone and low p-index

Table 4, continued: Summary of nutrient removal performance in bioretention cells

UNHSC, 2005	-	-	-	42%	
Davis et al., 2006	70 – 85%	-	-	Lab <20%, Field 15 – 20%	Large variation in nitrate reduction in laboratory; more consistent in field
Ermilio & Traver, 2006	-3.45	38%	-	19%	-
Davis, 2007	57%	-	-	83%	-
Hatt et al., 2007	Outlet concentration 1.5 – 4 times larger than inlet	29 – 73%	-	-	-
Traver et al., 2007	68%	67%	-	-	More than 50% mass removal
Bratieres et al., 2008	86%	Extremely variable, net increase in concentration	>90%	Extremely variable, net increase in concentration	-
Hatt et al., 2008	-398 – 86%	-7 – 37%	64 – 96%	-17 – 13%	
Hunt et al., 2008a	31%	32%	Significant decrease	Increase	TP reduction insignificant
Hunt et al., 2008b	60%	54%	78 – 88%	33 – 43%	31% TP concentration reduction; significant 32% TN concentration reduction; significant 72% ammonia concentration reduction; significant 4% nitrate concentration reduction; not significant
Davis et al., 2009	0, 73, 81%	-29, 0, 43%	54, 89, 79%	-9, -194, 23%	Lab studies: Upper, middle and lower zones

Similarly, the depth of growing media has been shown to have an effect on TP capture. Some reports conclude that TP removal increases with depth, with higher removal rates occurring at the deeper end (60 to 80 cm) of a bioretention cell (Davis et al., 2009, Davis, 2007, Davis et al., 2006). However, Hatt et al. (2007) concluded that TP reduction occurs in the top 30 cm of the bioretention cell, while Hsieh & Davis (2003) concluded no significant effects of media depth (or texture) were present. The reason for this discrepancy may be due to the characteristics of the urban stormwater runoff. TP exists in both particulate and dissolved forms. The particulate removal will occur in the top region of the cell and is tied to TSS removal (Bratieres et al., 2008). Furthermore, the effluent TP concentration consists largely of the dissolved fraction, originating from the growing media itself (Hatt et al., 2007). Thus, depending on the ratio of particulate to dissolved fraction, the removal of TP will occur at different depths. The design of a bioretention cell has also shown to have an impact on TP removal; the inclusion of anaerobic zone inside the bioretention cell significantly reduced TP concentration in the effluent (Sharkey & Hunt, 2004, Hunt et al., 2004).

Finally, in most studies, TP leaching is significant and consistent (Dietz & Claussen, 2005, Hatt et al., 2008, Hunt et al., 2006). In some cases, the concentration of TP decreases in the effluent over time, as the phosphorus in the soil was flushed out (Dietz & Claussen, 2005, Hatt et al., 2008) and reached a constant value. However, this did not always result in an improvement in TP removal efficacy (Hatt et al., 2007).

Nitrogen reduction in bioretention cell is also variable (Hsieh & Davis, 2005a). Nitrogen can be measured in many different forms, primarily total nitrogen (TN), nitrate and nitrite (individually or as nitrate – nitrite) and ammonia. The primary mechanism of nitrogen removal in bioretention cells is through nitrification and denitrification, i.e. ammonia is converted to nitrate under aerobic conditions, and then nitrate and nitrite are converted to nitrogen gas under anaerobic conditions (Davis et al., 2009). Most bioretention cells should have adequate conditions to undergo nitrification (Hatt et al., 2007), but a submerged saturated zone should be introduced for denitrification. However, results from these systems are still inconclusive and variable (Traver et al., 2007). Other issues include low influent concentrations, where the difference is too slight to see any

significant reduction (Traver et al., 2007); significant reduction is only possible when influent concentrations are high (Wong et al., 2006).

In general, bioretention cells are not effective in reducing the concentration of nitrate; nitrate is very stable and soluble and does not sorb onto soil media, and hence any reduction is a bonus (Kadlec and Knight, 1996, Hsieh & Davis, 2003, Davis et al., 2006, Davis et al., 2009, Hatt et al., 2008). However, most research shows that significant ammonia reduction (through sorption and nitrification) is possible and has the least variability in terms of performance (Davis et al., 2009, Dietz & Claussen, 2005, Bratieres et al., 2008, Hatt et al., 2007, Hatt et al., 2008). TN and nitrate concentrations are typically higher in the effluent than in the influent; it is possible that nitrification is occurring, but instead of continuing to denitrify, the process stops at intermediate products (Hatt et al., 2007, Hatt et al., 2008, Bratieres et al., 2008).

Attempts at using a submerged, anaerobic or anoxic zone in bioretention cells have been inconclusive with respect to encouraging denitrification. Kim et al. (2003), Hunt et al. (2003) and Hunt & Jarrett (2004) noted improved performance with respect to nitrate reduction while using a submerged zone. The significance of this is not clear, as similar reductions were seen in mirrored experiments without the submerged zone (Hunt et al., 2003, Davis, 2007). Additionally, in some cases, introducing an anaerobic zone also contributed to an increase in both ammonia and TN concentrations (Sharkey & Hunt, 2005, Hunt et al., 2006). Dietz & Claussen (2005) propose that there is a possibility that contact time in the growing media (due to high infiltration rates) may be too low for denitrification or that simultaneous nitrification and denitrification may occur, changing the overall mass balance.

Another potential issue with nitrogen removal is that in between events, continuous biological activity will turn nitrogen compounds into nitrate, and this nitrate will then be flushed from the system at the onset of the next event (Davis et al., 2009, Davis et al., 2006). This can increase nitrate concentrations with time. However, decomposing matter from the vegetation can cause similar effects (Hatt et al., 2008, Hatt et al., 2007). Conversely, Hunt et al. (2003) noted an improvement of nitrogen uptake with time, and Bratieres et al. (2008) indicated that vegetation may be the most important component for nitrogen removal in bioretention cells.

2.5 Cold climate issues and performance

Cold climate regions are defined as areas where the mean monthly temperature for any one month is below +1°C; this covers a portion of the world that has a population of more than 1 billion people (Thorolfsson, 2000). Annual temperature fluctuations in these regions are large; low and high temperatures can reach -50°C and 40°C respectively, requiring infrastructure to be designed to withstand both extremes. However, cold climate regions typically follow warm or temperate climate region design guidelines (Bengtsson & Semadeni-Davies, 2000). In cold climate regions, even though snowmelt intensities are much lower than rainfall intensities, melt volumes can be much larger than typical summer events. Altered hydraulic characteristics like these require design guidelines to be adjusted to local climates. However, typically, stormwater infrastructure is designed as it would be for warm or temperate climates (where many design guidelines were developed) (Bengtsson & Semadeni-Davies, 2000). Similarly, holistic, soft engineering approaches like LIDs to address urban runoff concerns cannot be directly transferred from warm to cold climate conditions. As a result, there is a need to research and recommend design guidelines for LIDs in *local* cold climate conditions. The emphasis on local conditions is important to take into account because of the unique freeze-thaw cycles and precipitation patterns. For example, in Calgary, AB, average annual precipitation is 412 mm, of which approximately 28% occurs as snow (Environment Canada, 2010). Also, Calgary experiences westerly winds during the winter, known as Chinook Winds (a type of föhn wind) that can temporarily raise temperatures to above freezing ("Chinook (wind)", 2010). These winds cause Calgary to experience frequent freeze-thaw cycles throughout the cold months, rather than one large spring melt as experienced in other regions.

Issues relating to urban stormwater runoff in cold climates include altered hydrologic flow regimes and resulting design criteria (to account for snowmelt and snow storage) (UNHSC, 2005). Melting snow can significantly increase peak flow rates and runoff quantities, due to the build up of snow throughout the cold season (UNHSC, 2005). Due to this, traditional bioretention sizing criteria cannot be used, since they were developed for temperate coastal areas (like Prince George's County, USA). Using these

design criteria would result in over-designed bioretention cells to account for the large amount of snowmelt at the end of the winter. Designs in cold climate should be derived from both rainfall and snow storage requirements, rather than just rainfall (Muthanna et al., 2007a). Local cold climate characteristics govern the frequency of snow melt events, which are high in Calgary due to Chinook winds and also in many coastal cold climate regions. Designs for these areas differ from inland cold climate areas that experience one large snowmelt event at the end of the season. The relationship between total snow storage volume and required snow storage volume should be derived based on these melt patterns (Muthanna et al., 2007a recommends 25 to 50% of total snow storage volume for areas with intermittent melt periods).

Cold climates also have different mass loading characteristics including higher sediment and chloride concentrations from road de-icing activities (UNHSC, 2005, Muthanna et al., 2007c, Westerlund & Viklander, 2006, Roseen et al., 2006). With the large volume of snowmelt, a large mass of contaminants is mobilized, leading to shock pollutant loadings (Muthanna et al., 2007c). An increase in salinity from salts and low temperatures can lead to a higher rate of availability of certain contaminants (particularly metals) (Warren & Zimmerman, 1994). In cold climate regions, water quality should be addressed by designing for the heaviest polluted area and time. Other issues relating to LID and bioretention use in cold climates include addressing issues related to traffic safety, local flooding and drainage problems that are prevalent in urban areas (Muthanna et al., 2007a).

Generally speaking, various sources assert that LIDs, filter based treatment systems and bioretention cells function suitably in cold weather conditions and that there is minimal effect of frozen media on hydraulic function (UNHSC, 2005, Roseen et al., 2006, Davidson et al., 2008, Roseen et al., 2009). Additionally, a survey of different LIDs has shown that their performance is less variable in cold climate conditions compared to conventional stormwater management devices (Roseen et al., 2009). It is expected that snowmelt and urban runoff in cold conditions can suitably thaw frozen media. However, minimal data has been published on this for bioretention cells.

Infiltration rates and saturated hydraulic conductivity in cold conditions are expected to be lower than warm conditions (Braga et al., 2007, Traver et al., 2007,

Ermilio & Traver, 2006, Davidson et al., 2008). Additionally, impacts on outflow volumes, peak reduction and peak delay have been noted; bioretention performance in cold conditions is characterized by an increase in outflow volumes, an increase in effluent peak flow rates and a longer lag time (Hunt & Jarrett, 2004, Roseen et al., 2009, Muthanna et al., 2008), but these changes (especially peak flow rate and lag time) are not significant (Roseen et al., 2006, Roseen et al., 2009). Some discrepancies exist with these results: Muthanna et al. (2007b, 2008) reported shorter lag times in cold conditions, due to partially frozen media and preferential flow patterns through frozen media. There is also a strong correlation between low temperatures as well as antecedent dry conditions – it decreases lag time (Muthanna et al., 2008). Snowmelt-only events had the shortest lag time when compared to precipitation events or to precipitation combined with snowmelt events (Muthanna et al., 2008). The lower peak flow rates in the outlet of bioretention cells in warm conditions was attributed to a more homogenously distributed soil with less channelization compared to cold conditions, which increased infiltration time (Muthanna et al., 2007b, 2008). Soil temperature is the governing factors for decreasing the hydraulic conductivity (up to 56%) and infiltration rates in cold conditions (Braga et al., 2007, Traver et al., 2007, Ermilio & Traver, 2006, Davidson et al., 2008). A decrease in evapo-transpiration and lower plant water consumption is responsible for a decrease in the total volume of runoff held in bioretention cells (Muthanna et al., 2007b). Although vegetation is inactive in the winter, it is still an important component for bioretention cells in terms of aesthetics and root zone function. Thus there is strong indication towards reduced hydrologic performance and hydraulic capacity, despite the lack of issues relating to frozen media in filter based LIDs.

Water quality performance data for bioretention cells in cold conditions is severely limited. TSS reduction has remained high, even when significant differences in performance between cold and warm conditions have been noted (Muthanna et al., 2007c, Blecken et al., 2007). This is because TSS reduction is a physical process (mechanical filtration) that is not affected by temperature. However, a difference in the particle size distribution (PSD) was noted in the effluent in a cold condition bioretention experiment. The PSD had a higher component of larger particles, most probably originating from organic material from the growing media rather than the influent stormwater runoff

(Muthanna et al., 2007c). TP reduction rates have been reported to be higher in cold conditions and the reduction has improved over time (Blecken et al., 2007). This is attributed to two factors, firstly, there is a higher particulate bound fraction in snowmelt runoff and therefore a higher fraction of TP gets filtered (Muthanna et al., 2007c). Secondly, in lower temperatures, biological activity is lower, which reduces the production or release of TP from the growing media. Similarly, nitrate leaching in cold conditions was lower in some cases (Roseen et al., 2006) while higher leaching was noted in other cases (Hunt et al., 2008b). Ammonia reduction was similar in both cold and warm conditions (Blecken et al., 2007).

2.5.1 Chloride

Studies on bioretention cells have paid little attention to the affects of salting and sanding materials applied onto roads in winter conditions. These materials are picked up by snowmelt runoff and are of concern in cold climate areas. Most BMPs were first introduced in regions that do not deal with road de-icing issues. The environmental effects of salt impact soil, vegetation, infrastructure, physical and chemical water quality processes, and sources of drinking water. Sodium chloride (NaCl), the most commonly used salt, is highly soluble in water and forms sodium and chloride ions when dissolved (Marsalek, 2003). The chloride ions are the principal contaminant of concern when dealing with road salting issues in cold regions.

There is a need to attenuate chloride pulses in LID systems in cold regions (Roseen et al., 2006). Chloride ions are an extremely mobile and do not react with other chemicals nor adsorb onto mineral surfaces in soil (Marsalek, 2003). Removing chloride from runoff is known to be virtually impossible and options for treating chloride-laden water are severely limited (Oberts, 2003). Stormwater containing chloride can have adverse effects on soils, groundwater and surface waters.

Research on chloride removal trends in bioretention cells have been inconclusive and are considered to be complex (Roseen et al., 2006, UNHSC, 2005). Ermilio & Traver (2006) indicated that samples taken 2.5 m below a bioretention cell had elevated chloride levels from snowmelt. Muthanna et al. (2007c) noted that relative to the uncertainties, the concentration of chloride was unchanged when comparing influent and effluent in a

bioretention cell. In some cases, there was an accumulation of chloride in the cell, which was then flushed from the system at the onset of the next event. Therefore, there is a need to study the behaviour of chloride ions in bioretention cells, including potential removal efficiencies, dilution effects in the effluent and any attenuation trends.

2.6 Lifecycle assessment and maintenance

Though there has been considerable effort to define bioretention cell efficacy with respect to reducing the short term event based effects of urban stormwater runoff, the long term lifecycle assessment and necessary maintenance on the cells is unknown. There is very limited data on these issues and this is the major hindrance to the widespread adoption of bioretention cells (Davis et al., 2009). Some of the issues that need to be addressed are the level and rate of decline in performance, the effectiveness of maintenance and the associated costs (Davis et al., 2009). The issue of clogging and resulting decrease in hydraulic conductivity and infiltration rates were presented in Chapter 2.4.1. There is a need to study these affects over the long term and determine the necessary maintenance protocols. It is expected that after several years of operation, maintenance will be required to enhance the hydraulic function to initial levels (Ermilio & Traver, 2006, Lewis et al., 2008). Additionally, the impacts of initial design (especially initial hydraulic conductivity) on long term performance need to be explored (Lewis et al., 2008). Similarly, the potential decline in water quality performance over the long term has not been explored. The long term impacts on contaminant capture in the growing media, effect of percolation and groundwater contamination and heaving also needs to be addressed (Welker et al., 2006).

It is expected that over time, biological activity will encourage ecological transformation and evolution in the bioretention cells; for example, vegetation will grow and mature and organic matter in the growing media will be deposited and recycled. The impacts of this on bioretention efficacy are unknown. This also means that a universal maintenance procedure may be difficult to accomplish, since each cell would have its unique ecosystem, thus affecting the level of maintenance required (Traver et al., 2007). Furthermore, the effectiveness of any maintenance, such as aeration and replacement of growing media, is not known (Cosgrove & Bergstorm, 2003).

CHAPTER 3: THESIS OBJECTIVES

3.1 Gaps in knowledge

A number of questions need to be answered to improve and optimize bioretention cell technology so that it can be used to address urban stormwater runoff concerns in Calgary, AB. The literature review and the needs of the City of Calgary have identified several areas of bioretention cell performance and its applications that need to be addressed. These are outlined below.

3.1.1 Cold climate performance

Most of the research and results presented in Chapter 2 were conducted in warmer regions that are not subject to Chinook conditions. The transferability of these results to cold climate regions, like Calgary, AB, is limited. There is a need to explore the effects of cold climate conditions on all aspects of bioretention cell performance, including volume capture, peak flow rate reduction and delay, hydraulic conductivity and infiltration rates, as well as the overall hydraulic capacity. The influence of lower temperatures on water quality performance, both in terms of concentration reduction and total mass capture also needs to be explored. Results from the research conducted on bioretention cell performance in cold climates are highly variable and severely limited. In addition, the impacts of Chinook-like weather systems on bioretention cell technology are unknown.

3.1.2 Hydrologic performance

In terms of hydrologic performance, there is limited data on the total volume of runoff captured by bioretention cells. There has been a larger focus on looking at peak flow rate reduction and lag time. However, even when looking at peak flow rate reduction and lag or delay times, the impact of design, storm size and intensity have been received limited attention and no uniform performance parameters exist. Limited research on the influence of antecedent moisture conditions on operation exist, with most data presenting extremely variable results.

Most of the research presented data from field experiments, where actual runoff events were used to calculate the performance of bioretention cells. One of the limitations of using this approach is the lack of data collected from infrequent, large and high intensity events. Most research has been conducted on small to midsize events and there is a need to study performance levels of these large events. The different design types used in various experiments limits the transferability of data and performance parameters for use in Calgary.

3.1.3 Water quality performance

Most water quality performance data has focused on mass capture, however more research is required on concentration reduction to understand the different mechanisms of pollutant capture in bioretention cells. Though consistent TSS performance has been well documented, other urban runoff quality parameters, especially nutrients have been highly variable. The usefulness of water quality performance data is limited by the specificity of urban runoff characteristics, location, design and growing media. Limited information regarding the PSD of the captured sediment in a bioretention cell exists. The City of Calgary requires that the stormwater infrastructure in all new developments remove 85% of particulates larger than 50 μm (B. van Duin, personal communication, November 29, 2009). There is also a growing concern over the ability of measured TSS to represent the presence of the larger and smaller ends of the spectrum of stormwater sediment (Clark & Siu, 2008). To tackle this, suspended sediment concentration (SSC) has been proposed as a suitable alternative to measure sediment in stormwater runoff. The impact of the depth of bioretention cells has not been thoroughly researched either.

3.1.4 Long term performance

Bioretention cell performance research has largely been limited to short term studies. The affects of long term operation on performance have not been documented. This information is required to understand the lifecycle and maintenance requirements, as well as to understand potential failure scenarios. Research is needed on the effects of clogging on infiltration and hydraulic conductivity, performance changes with time and maintenance procedures.

3.2 Detailed thesis objectives

3.2.1 Determine the efficacy of bioretention cells in cold climates

The majority of research conducted on bioretention cells has been conducted in warm or temperate regions. The precipitation patterns and resulting hydrologic characteristics and urban runoff quality of these regions do not represent the conditions present in Calgary. The region is semi-arid and thus the total volume of precipitation and urban stormwater runoff is lower than that of north-eastern USA (where most of the original research and early design guidelines were created). Also the underlying soils in Calgary are tight clays, again differing from other areas, and the use of infiltration based practices in these conditions need to be studied. Lastly, the quality of urban stormwater runoff is significantly different than other regions; Calgary has a higher concentration of TSS in its urban runoff, and there are loading limits in Calgary with respect to both TSS and TP. Keeping these issues in mind, there is a need to study the efficacy of bioretention cells in Calgary, taking into account its characteristics.

Studying the efficacy of a bioretention cell includes comparing the efficiencies in hydrologic and water quality performance in both cold and warm weather conditions, looking at the effects of freeze-thaw cycles and antecedent soil moisture conditions.

3.2.2 Investigate the effects of large and high intensity events on efficacy

The performance of bioretention cells with respect to reducing peak flow rates and total runoff volumes have been widely reported, but have focused on small to medium event sizes. There is a need to investigate the efficacy of bioretention cells in capturing large, high intensity events. The purpose of this component is to study any changes in overall efficacy of bioretention cells, in both warm and cold weather conditions. This will help in assessing whether bioretention cells have the capacity to address flooding concerns from these events when compared to conventional stormwater management technologies.

3.2.3 Investigate the impacts of long term operation on efficacy

The long term performance changes and lifecycle of bioretention cells in cold climate regions is unknown. The purpose of this component is to identify failure

scenarios of bioretention cell after long term (i.e. 20 year) performance. The changes in hydraulic conductivity due to clogging will be examined and any potential reduction in efficacy over the long term. The results will help identify maintenance procedures to re-establish the design performance levels.

3.3 Specific research objectives

The specific research objectives are to:

1. Study a bioretention cell's ability to reduce the total volume of runoff, the peak flow rate reduction and delay and drainage efficiency of small and large events.
2. Study a bioretention cell's ability to reduce the total mass and concentration of selected urban runoff contaminants.
3. Compare the performance of a bioretention cell between warm and cold (Chinook) conditions.
4. Study the changes in hydrological and water quality performance levels over the long term.

To achieve the objectives of this research both field and laboratory experiments were conducted. The field study was conducted in southwest Calgary; it investigated the various performance parameters of a bioretention cell at the field scale. These experiments were conducted between May 2008 and August 2010. The laboratory experiments were conducted at the University of Calgary. These studied the long term performance, impact of growing media depth and overall efficacy in both warm and cold conditions. Both sets of experiments are detailed in Chapter 4.

CHAPTER 4: METHODS AND MATERIALS

4.1 Field description and setup

The bioretention cell for the field component was designed by Westhoff Engineering Resources Inc. and it was constructed in 2005 by Canada Lands Company. The cell is designed for testing purposes only and does not receive any stormwater runoff from its drainage area. The City of Calgary conducted performance tests on the bioretention cell in the summer of 2006 and 2007. The site is maintained by Canada Lands Company who performed routine maintenance (weed removal and mowing) on the site.

4.1.1 Location and design

The bioretention cell is located at Hochwald Avenue and Quesnay Wood Drive in south west Calgary, AB (Figure 2). The cell sits in the north east corner of a park, with an elementary school located to the east, an office building to the south, a parking lot to the west and a sediment storage site to the north. The bioretention cell is 8000 mm long and 4000 mm wide. It consists of a 75 mm mulch layer on top, followed by a 300 mm upper rooting zone layer, 900 mm deep rooting zone layer (for a total of 1200 mm growing media depth) and a 300 mm under-drain system at the bottom. The upper rooting zone was designed to consist of a mix of 12 – 30% compost and 70 – 85% growing medium. The growing medium (used for both the upper and deep rooting zone) was designed to consist of sand (50 – 70%), silt (10 – 30%) and clay (7 – 20%); a sandy loam soil classification.

A particle size analysis of the growing media concluded that on average, the cell consists of 43% sand, 49% silt and 8% clay (loam) with an average organic content of 9%. Comparing the upper and deep rooting zones, the top 300 mm layer contains 50% sand, 43% silt and 7% clay (sandy loam) with an organic content of 13% and the lower layer contained 40% sand, 52% silt and 8% clay (silty loam) with an organic content of 6%. The field capacity and wilting point of the growing media, estimated using the Soil Water Characteristics program (Saxton & Rawls, 2006), were 0.275 m^3/m^3 and 0.099

m^3/m^3, respectively. The under-drain system consists of 40 mm drainage rock with a 100 mm diameter sub-drain pipe draining from west to east (along the long axis of the cell) at a slope of 1.0 %. A 1000 mm section of the sub-drain pipe (inside of the east boundary) of the cell is perforated to collect stormwater runoff. The sub-drain pipe leads to a monitoring manhole east of the cell, which connects to the local storm sewer system.

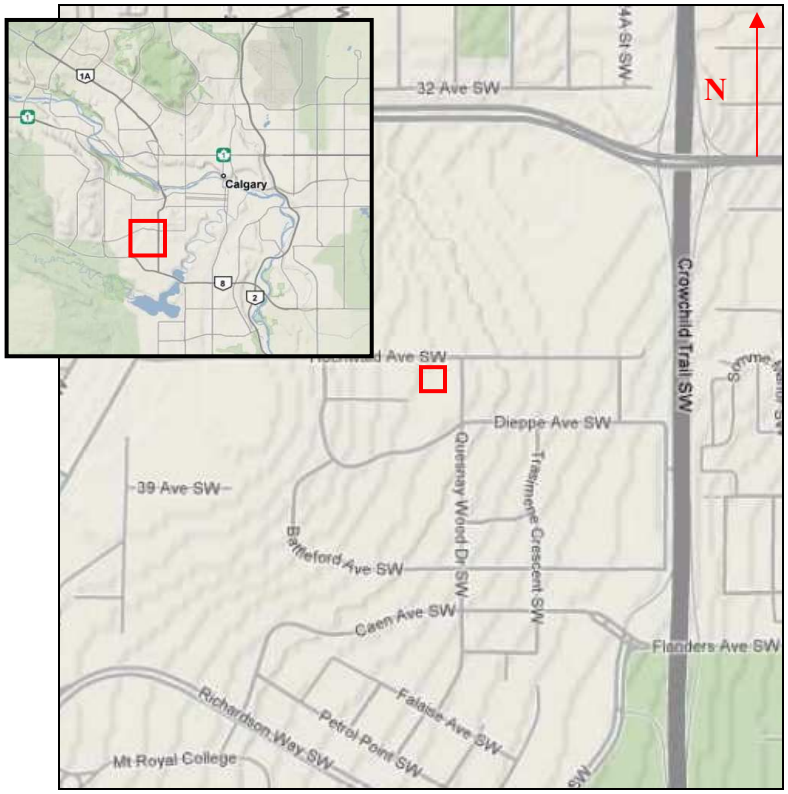

Figure 2: Site Location outlined in red; Insert: Location with respect to City of Calgary limits

The vegetation in the bioretention cell consists of eight trees (four Beaked Sedge: *Salix bebiana* and four Pin Cherry: *Prunus pensylvanica*) and seventy two shrubs (24 Shrubby Cinquefoil: *Potentilla fruticosa*, 24 Prickly Rose: *Rosa acicularis* and 24 Wild Gooseberry: *Ribes oxyacanthoides*). In total there are 80 trees and shrubs in the cell at a density of 2.5 plants/m^2 (see Figure 3). The entire sub-grade of the bioretention cell is enclosed by a non-woven geo-textile. A woven geo-textile separates the under-drain system from the deep rooting zone. The adjacent area to the bioretention cell is landscaped with Kentucky Bluegrass – Fescue Sod. The cell is bounded by a 0.6 m high and 1 m wide berm at a slope of 1:3. A particle size analysis of the surrounding soil

classified it as loam (36% sand, 45% silt and 19% clay), with an organic content of 6%. (to a depth of 1 m). The soil underneath the cell was also classified as loam (34% sand, 46% silt and 20% clay) with an organic content of 2% (to a depth of 0.5 m below the bottom of the gravel layer). See Figure 4 and Figure 5 for detailed design drawings.

Figure 3: Views of the bioretention cell in the summer and winter

4.1.2 Synthetic stormwater distribution system

As mentioned above, this test facility did not receive any natural stormwater runoff, so a stormwater distribution system was set up to simulate different storm events. Two 5 m^3 storage tanks were placed on site in an enclosed compound near the cell. Stormwater was hauled from a City of Calgary stormwater detention pond located on 69th Street south west (the drainage area of the pond is a residential area) and stored in the tanks for the experiments. The water was pumped from the tanks, using a Honda 2 inch (50.8 mm) diameter 4 horsepower pump and a series of 2 inch (50.8 mm) diameter hoses, to a conical 5 m^3 mixing tank.

Sediment was added to the stormwater as it entered the mixing tank. The source of the sediment was material picked up by City of Calgary maintenance crews at the spring of each year, as part of annual road cleaning activities. This material was sieved, using a Sweco vibratory seperator, to less than 250 μm (see Figure 6) representing the fraction of particles carried by runoff during an event (Brown, 2007). The amount of sediment added varied with each experiment, depending on the volume of runoff used; the target TSS concentration was the mean value for residential areas in Calgary, 444 mg/L.

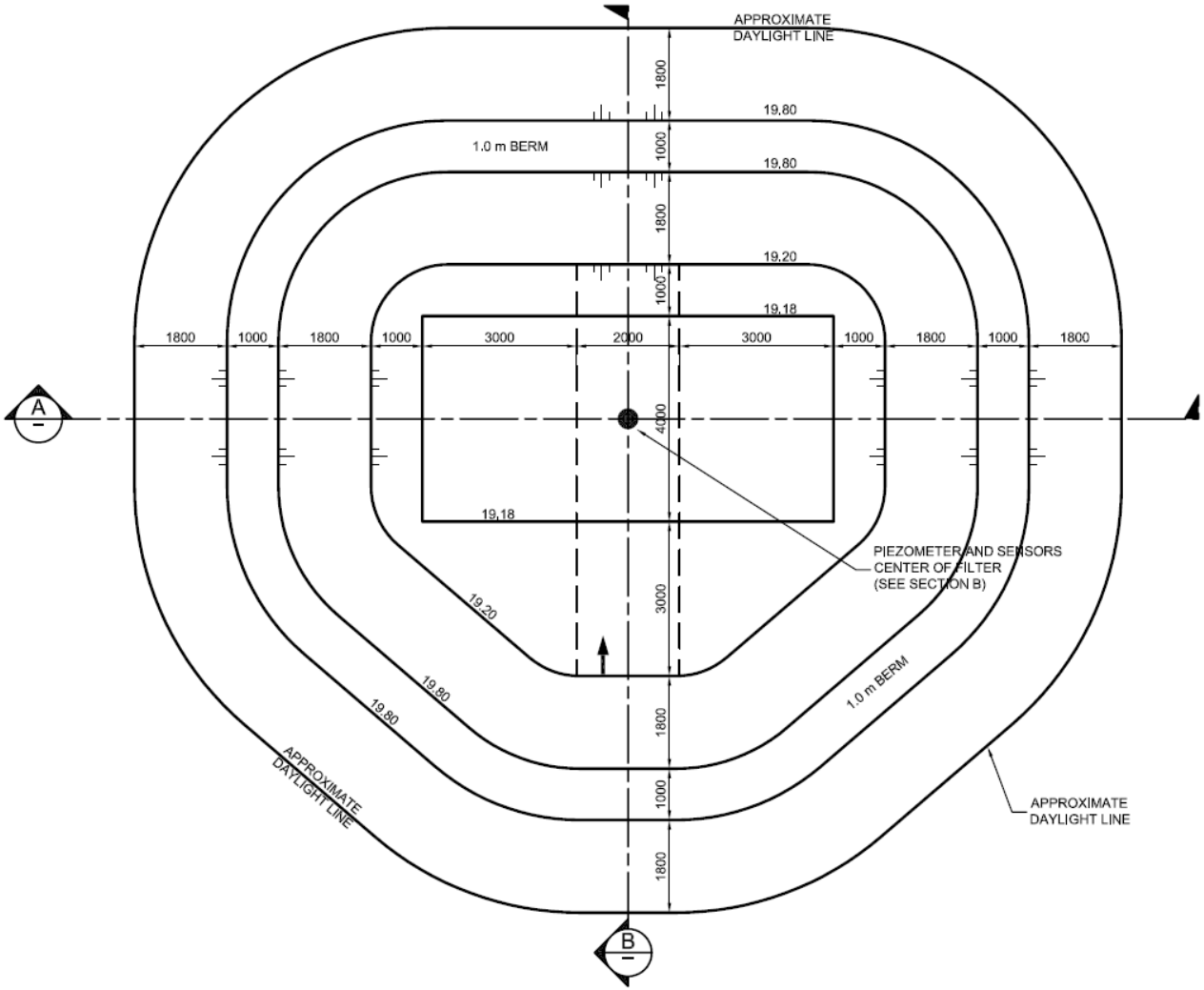

Figure 4: Design drawing of bioretention cell: Plan view (van Duin, 2005)

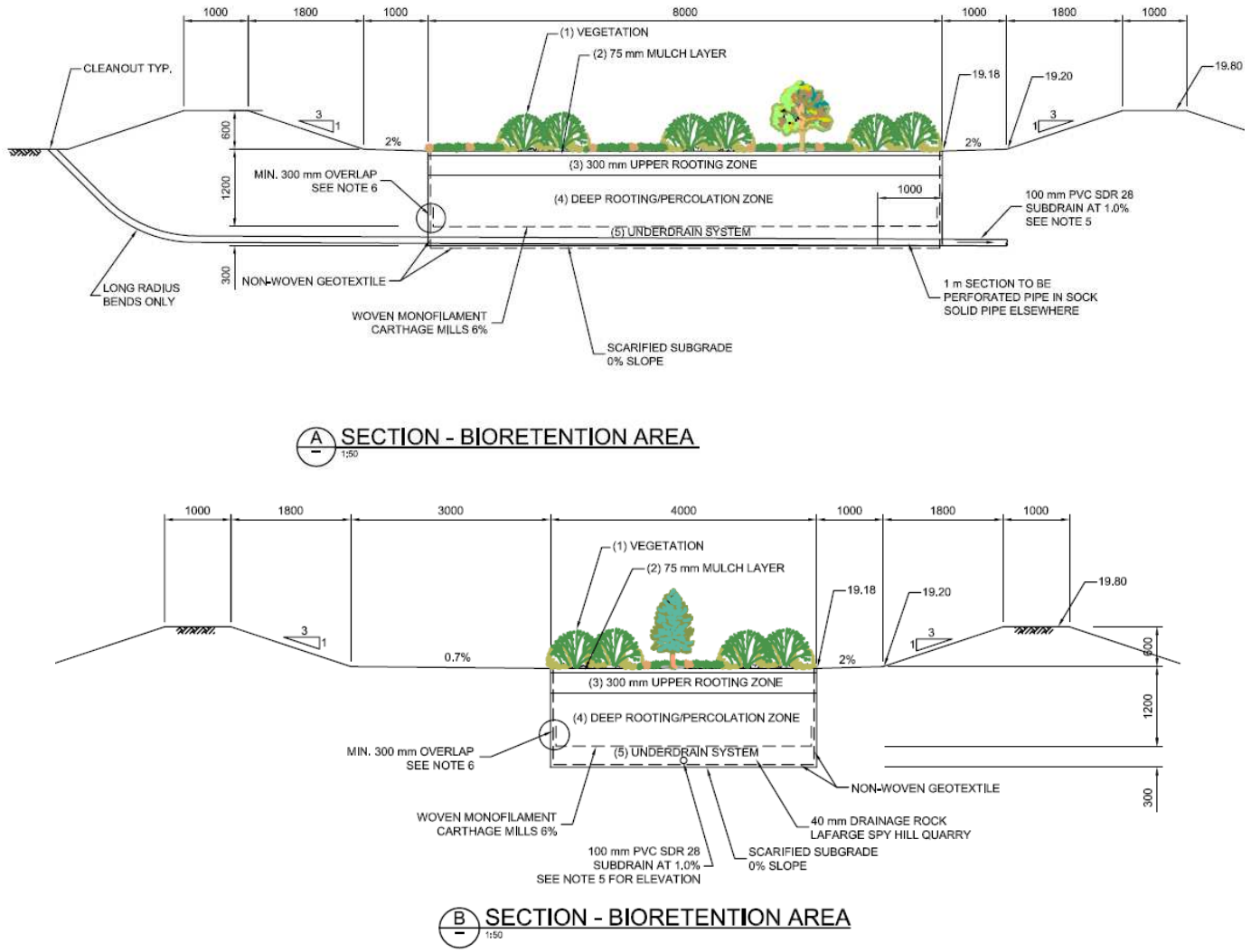

Figure 5: Design drawing of bioretention cell: Profile views of Section A and B (van Duin, 2005)

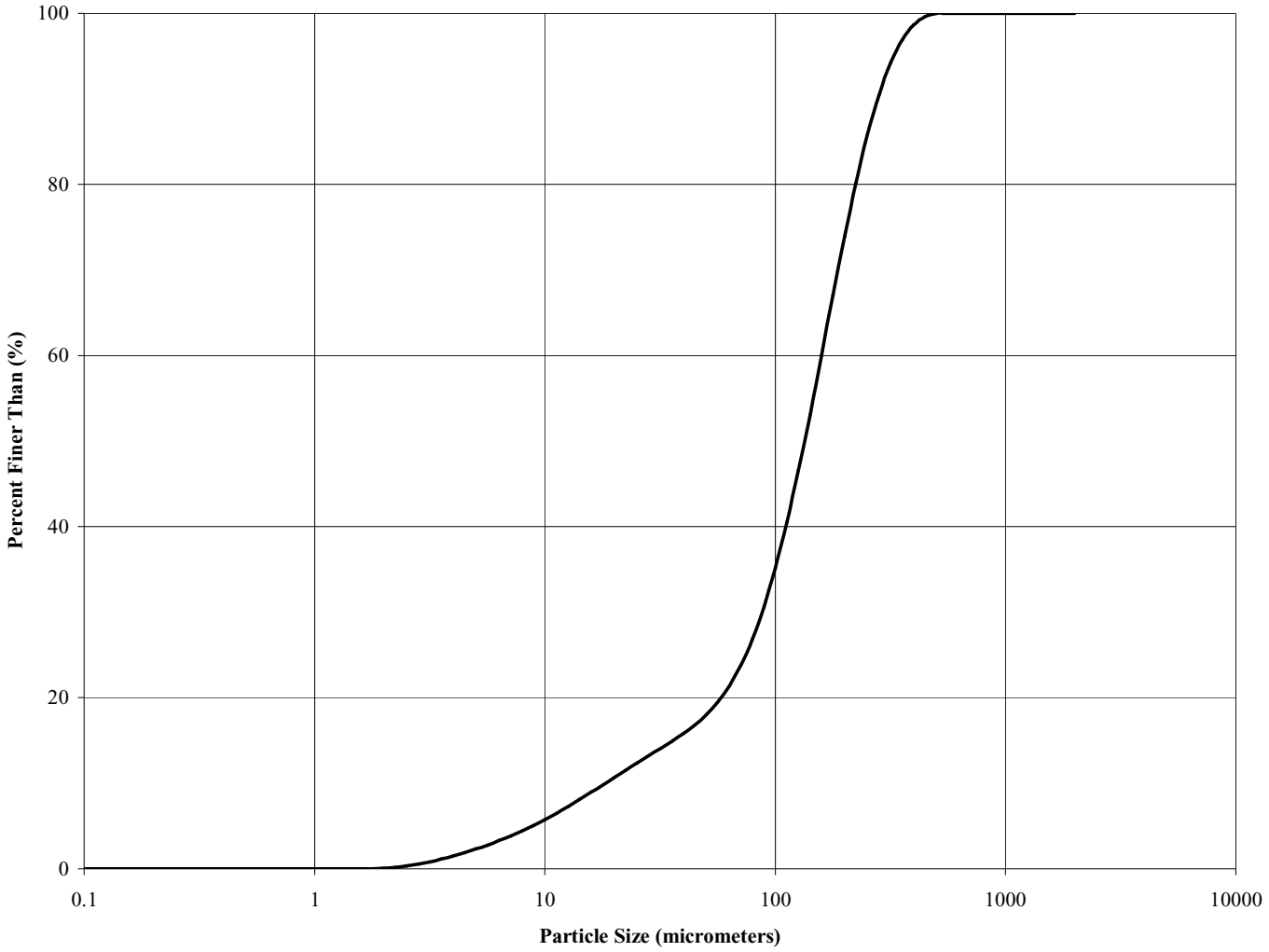

Figure 6: Particle size distribution of sediment added to the synthetic stormwater runoff

Figure 7: Layout of the stormwater runoff distribution system at the field site

After the addition of the sediment, the water drained from the mixing tank through a 4 inch (101.6 mm) diameter Big-O pipe. The outlet of the pipe was placed 1000 mm from the edge of the bioretention cell inlet, allowing the water to flow over a grassed portion, to mimic a pre-treatment device as in an operational bioretention cell. Figure 7 shows the layout of the synthetic stormwater set-up at the field site; the two storage tanks are on the right in the background, the bioretention cell in the centre and the outlet manhole located on the left. Details on the monitoring equipment installed and the experiment procedures are presented in the following sections.

4.2 Laboratory description and setup

Eight miniature versions of the field installation were constructed for the laboratory component of this study. The laboratory experiments were conducted at the University of Calgary in the Civil Engineering Hydraulics Laboratory. The purpose of the laboratory experiments was to test the performance of bioretention cells in a controlled environment. This allowed for the variation of parameters that would not have been possible to do in the field experiments.

4.2.1 Design

Two sets of columns were constructed: six “short” columns which had a depth of 450 mm and two “tall” columns which had a depth of 800 mm (see Figure 8). The surface area of each column was 0.25 m^2, 1/128 the size of the field installation. The field installation had a 1200 mm growing media to 300 mm under-drain depth ratio, or a 4:1 ratio. The same ratio was used to design the columns; the short columns had a growing

media depth of 360 mm and an under-drain depth of 90 mm, while the tall columns had a growing media depth of 640 mm and 160 mm. These depths were picked by consulting recommendations from existing literature and research:

- Davis et al. (2006): 600 to 800 mm depth for TP capture,
- Li & Davis (2008): 200 mm for TSS capture,
- Hunt et al. (2003): 600 mm for nutrient capture,
- Hsieh & Davis (2005a): between 550 and 750 mm, and
- Lanarc (2005): between 450 mm to 1200 mm for overall performance.

Other considerations to determine the size of the columns were constructability, availability and volume of growing media, volume of water required for long term experiments, the ability to support plant growth and mobility.

Figure 8: Relative size of a tall (L) and short column (R)

The columns were assembled with construction lumber (0.75 inch or 20 mm plywood and 2 by 4 inch, or 50 by 100 mm, posts). A 0.75 inch (20 mm) thick perforated steel base plate (with 0.25 inch or 6.4 mm perforations) was installed at the bottom of the columns to support the weight of the material on top. The columns were waterproofed with a wood sealer and lined with a non-woven geo-textile (with the same specification as the field installation). The under-drain consisted of 40 mm drainage rock, which was

thoroughly washed, and was placed directly on top of the perforated steel base plate. A woven geo-textile was then installed as a barrier between the under-drain aggregate and the growing media. Figure 9 shows images of the columns at various stages of construction.

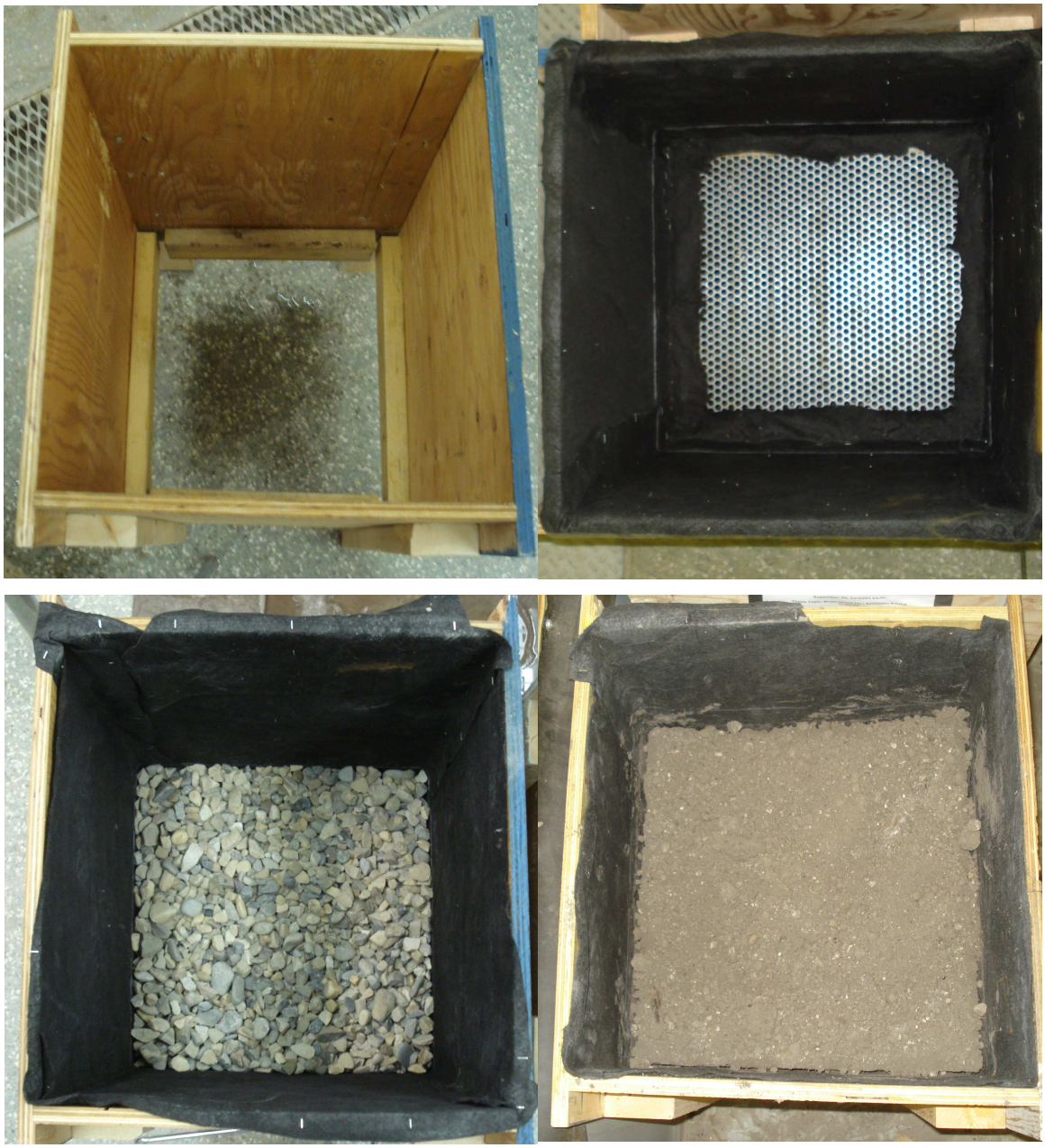

Figure 9: Top row: empty column frame (L) and column with liner and perforated steel base plate (R); Bottom row: column with under-drain aggregate (L) and with growing media (R)

The growing media used for the laboratory columns was the same media used in the field experiments; the media was left over from the construction of the cell. A particle size analysis of the media characterized it as a sandy loam (as opposed to the loam in the field), consisting of 52% sand, 43% silt and 5% clay, with an average organic content of 11%. The growing media was compacted in each column to mimic the compaction levels present in the field. A Dickey-John Compaction Tester was used for measuring the compaction in the field and laboratory. A Proctor Compaction hammer was used to compact the media to the required compaction level at the same moisture levels.

Each column had one shrub installed; four columns had Shrubby Cinquefoil (*Potentilla fruticosa*) and four had Prickly Rose (*Rosa acicularis*), the density was 4 plants/m^2 (Figure 10). The shrubs were kept in a University of Calgary greenhouse facility for six months before use, allowing the vegetation to grow and mature. A 75 mm mulch layer was added on top of each column after the installation of the shrubs. Table 5 summarizes the depth, type of plants and experiments conducted on each column.

Figure 10: Complete column with shrub and mulch installed with a bracket for the stormwater runoff distribution system

Table 5: Summary of laboratory columns and experiments

Column ID	Depth (mm)	Plant type	Experiment
T1	800	Shrubby Cinquefoil	Long term
T2	800	Prickly Rose	Long term
S1	800	Shrubby Cinquefoil	Long term
S2	800	Prickly Rose	Long term
S3	450	Shrubby Cinquefoil	Single event
S4	450	Prickly Rose	Single event
C1	450	Shrubby Cinquefoil	Cold weather
C2	450	Prickly Rose	Cold weather

4.2.2 Synthetic stormwater distribution system

The synthetic stormwater runoff distribution system used for the laboratory experiments was similar to the field system. Stormwater from the same pond (69th Street south west) as the field experiment was stored in the University of Calgary's Civil Engineering Hydraulic Laboratory in a 16 m^3 storage tank. The stormwater was then pumped into a 0.575 m^3 capacity mixing tank using a 0.25 horsepower submersible pump with a one inch (25 mm) diameter hose. The mixing tank (see Figure 11) was constructed out of 0.75 inch (19 mm) thick plywood and was lined with a 0.6 mm thick polyethylene sheet. The tank had four mixing blades that were controlled with a variable speed DC motor which was capable of keeping particles up to 1 mm in size in suspension.

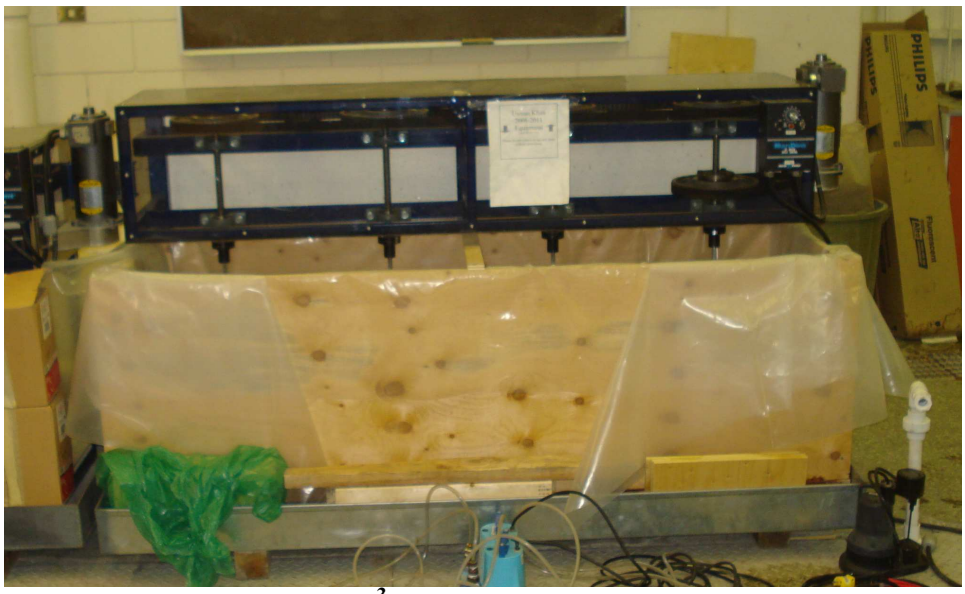

Figure 11: 0.575 m^3 capacity tank with mixing blades

Two 0.25 horsepower submersible pumps were then used to pump the runoff to the columns using 0.18 inch (4.6 mm) diameter clear vinyl tubing. For the experiments, each pump lead to two columns; a Y-connector was used to split the flow evenly. The tubing lead to an ABS pipe reservoir, attached to the columns with a wooden bracket. To distribute the synthetic stormwater runoff evenly across the surface of the columns, twelve 0.18 inch (4.6 mm) diameter clear vinyl tubing sections were connected to the bottom of the ABS reservoir and were attached to a 0.25 inch (6.4 mm) thick Plexiglas sheet. The sheet rested on top of the wooden column frames, 10 inches (254 mm) above the top of the mulch layer (Figure 12). The selection of 0.18 inch (4.6 mm) diameter clear vinyl tubing was to allow the larger component of the sediment to easily flow through, to keep flow rates high and to be able to detect any clogging in the tubes.

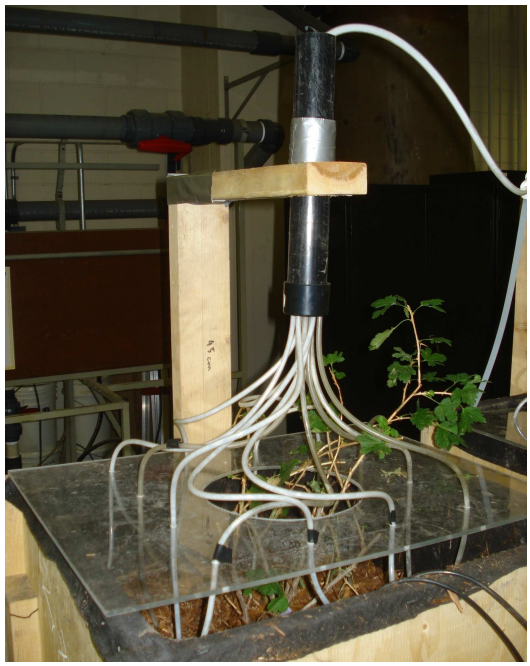

Figure 12: ABS reservoir, vinyl tubing and Plexiglas sheet

As with the field experiments, the amount of sediment added to the mixing tank depended on the volume of water being applied to the columns, which differed for the long term experiments and single event experiments. The sediment was sourced from the same stock as for the field experiment and had the same PSD.

4.3 Hydrologic analysis

4.3.1 Volume and flow rates

For the field experiments, both inlet and outlet flow rates and volumes were measured. The two tanks that stored the stormwater were equipped with Sigma 950 Submerged Pressure sensors that measured the depth of water above the sensor (the sensor was attached to the bottom of the tanks). Sigma 900 MAX auto-sampler data loggers were connected to each pressure sensor to log the depth of water and the time. Thus, the total inlet volume was calculated using the difference between the initial and final depths of the stormwater in the tanks and multiplying it with the cross-sectional area of the tanks. The flow rate was calculated by dividing the difference of two consecutive depth readings with the time difference between the readings.

Water collected from the perforated pipe in the under-drain layer of the bioretention cell drained to a manhole east of the cell. The manhole was equipped with a 100° V-notch weir. Both a Sigma 950 Submerged Pressure sensor and a Sigma 75 KHz ultra-sonic sensor, were installed in the manhole and were used to calculate the depth of the water. Before every experiment, the manhole was filled with water to the bottom of the weir's notch and the two depth sensors were calibrated to zero. An increase in depth of water from the outlet of the bioretention cell would result in water flowing over the weir; the two depth sensors would log the increase in depth of the water. The pressure sensor was connected to a Sigma 900 MAX auto-sampler and the ultra-sonic sensor was connected to a Sigma 950 flow-meter; both systems logged the depth and time-step, and automatically calculated the flow rates using the following equation:

Equation 1: Flow rate equation for V-notch weir (Brown, 2007)

$$Q_W = \frac{8}{15} C_W \sqrt{2g} \tan\left(\frac{\theta}{2}\right)(h_1 + k_h)^{\frac{5}{2}}$$

Q_W = discharge over weir (m^3/s)

C_W = weir discharge coefficient (0.58)

g = gravity acceleration (9.81 m/s^2)

θ = angle of V-notch in weir (100°)

h_1 = the head above weir

k_h = constant (0.0008 m)

The flow rates were used to calculate the total volume released from the cell by multiplying the flow by the time-step. The accuracy of the Submerged Pressure sensor was ± 0.1% and was ± 0.003 m for the ultra-sonic sensor (HACH, 2008). For all field experiments, the inlet level measurements and outlet level and flow rate measurements were programmed to log data every 1 minute.

For the laboratory experiments, the inlet and outlet flow rates were not measured. However, for the inlet, the constant flow rate for the submersible pumps was calculated to be 0.09 L/s or 0.045 L/s per column. The total volume applied to the columns was calculated using the dimensions of the mixing tank. The initial and final levels of water in the tank were measured with a staff gauge and the difference was multiplied by the area of tank. The outlet volume was not calculated.

4.3.2 Soil moisture, temperature and climate station

Four Delta-T SM200 soil moisture sensors were installed in the field bioretention cell. The sensors were installed in the middle of the cell at depths of 100, 300, 500 and 1000 mm from June 2008 to November 2008. The sensors were removed, cleaned and reinstalled in June 2009 at depths of 150, 300, 500 and 1000 mm. The sensors are accurate to ± 3% (Delta-T, 2006). The sensors were programmed to measure continuously, at 1 minute intervals, with the data stored on a Delta-T DL6 Soil Moisture Logger. In addition to these continuous soil moisture sensors, soil moisture was also measured manually using a Delta-T PR2/6 Profile Probe. When the probe is inserted into a 1000 mm long plastic casing, it measured soil moisture at six depths (100, 200, 400, 500, 600 and 1000 mm). Twelve casings were installed across the face of the cell and four casings immediately outside the bioretention cell. A Delta-T HH2 Moisture Meter was used to log the data from the Profile Probe. The accuracy of the Profile Probe is ± 0.06 m^3/m^3 (Delta-T, 2008). The location of the sensors relative to the bioretention cell is illustrated in Figure 13.

For the long term laboratory columns, two Delta-T ThetaProbe ML2x soil moisture sensors were installed in both tall columns at depths of 180 mm and 360 mm from the surface. For the short columns, one Delta-T ThetaProbe ML2x soil moisture sensor was installed at a depth of 130 mm from the surface. For the single event and cold

weather columns, two sensors were installed in each column, both at a depth of 130 mm. The ThetaProbe ML2x soil moisture sensor has an accuracy of ± 1% (Delta-T, 1999). The sensors for all experiments were set to log at 1 minute intervals, continuously, and a Delta-T DL6 Soil Moisture Logger was used for logging the data. The accuracy of all sensors was only true for operating temperatures between 0.1 to 40°C.

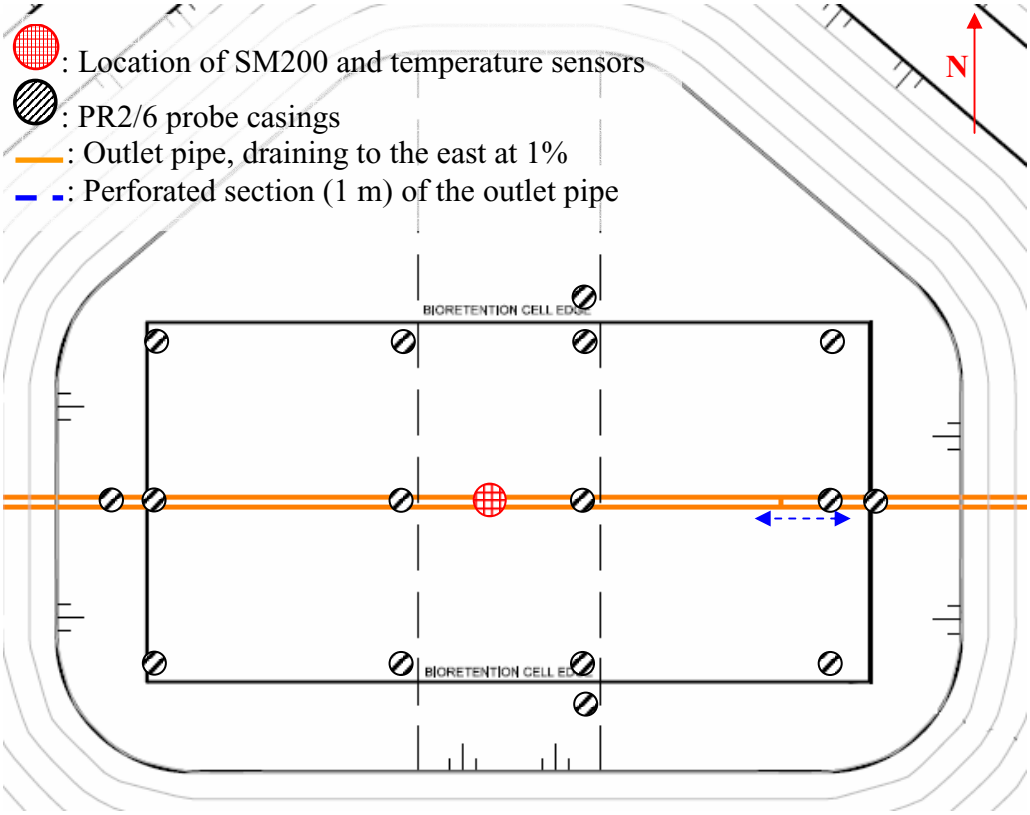

Figure 13: Location of soil moisture and temperature sensors on the field bioretention cell

Two HOBO soil temperature sensors were installed in the field bioretention cell at a depth of 150 and 500 mm. The sensors were programmed to log data every 1 minute for all experiments. Two soil temperature sensors were also installed in each cold weather column at a depth of 130 mm. A HOBO climate station was installed at the field site. The climate station measured rain (mm), pressure (kPa), wind and gust speed (m/s), wind direction, solar and photo-synthetically active (PAR) radiation (µE), temperature and dew point (°C) and relative humidity (%). The climate station was programmed to log data every 1 minute for all experiments.

4.3.3 Depth and intensity of precipitation calculations

To calculate the equivalent depth of precipitation applied in the form of a synthetic stormwater runoff for the experiments, the size of the hypothetical catchment had to be defined. Typically, a bioretention cell should be between 5 – 20% in area of the upstream catchment (Hunt & Jarrett, 2004, Lanarc, 2005). For this project, the bioretention area was defined to be 10% of the total catchment area; the bioretention area of the field site is 32 m^2, meaning the hypothetical catchment area is 320 m^2. A simple method to translate the volume of runoff into precipitation depth is to assume that the volume of runoff is equal to the product of the area of the catchment and the precipitation depth. However, a typical catchment will consist of pervious and impervious areas, and the majority of the runoff will be generated from the impervious fraction. To account for this, a ratio known as the Impervious to Pervious Ratio, or I/P Ratio, was introduced, primarily for use with permeable pavement design (Brown, 2007). The I/P Ratio is the ratio of the upstream impervious area to the area of the pervious LID (bioretention cell in this case) that the runoff drains to. Using this, the relationship between runoff volume and precipitation is:

Equation 2: Relationship between volume of runoff and precipitation depth

$$V_R = dA_B(I/P + 1), \text{ which is reduced to:}$$
$$V_R = d(A_{\text{Im}} + A_B), \text{ since by definition } A_{\text{Im}} = A_B(I/P)$$

V_R = volume of runoff (m^3)

d = precipitation depth (m)

A_B = bioretention cell area (m^2)

I/P = impervious to pervious ratio

A_{Im} = impervious area (m^2)

Equation 2 takes into account the runoff generated from the impervious area in the catchment and also the precipitation that occurs on the bioretention itself. For this project, an I/P ratio of 4 was picked, to represent typical residential areas. Thus, A_{Im} would equal 4 times A_B (32 m^2), or 128 m^2. Over the entire catchment, the impervious area is 40% of the total area (or 128 m^2/320 m^2), and thus the pervious area is 60%. The average intensity is equal to the precipitation depth (d) divided by the duration of the

event. The return period can be estimated using an Intensity-Duration-Frequency (IDF) curves for Calgary (CoC, 2000). The advantage of using this approach is the ease at which changes in scale and in catchment characteristics can be studied.

For comparison purposes, the Rational Method was also used to calculate the intensity and return periods of the experiments. The weighted runoff coefficient, C, for this area would be 0.54 (assuming C = 0.3 for the 60% pervious area and C = 0.9 for the 40% impervious area). Then, the intensity of the applied synthetic stormwater runoff can be calculated using the Rational method:

Equation 3: The Rational method

$$Q_P = kCiA_C$$

Q_P = peak runoff flow (m^3/s)

k = metric conversion factor (1/360)

C = runoff coefficient for the Rational method

i = intensity of the event (mm/hr)

A_C = total area of the catchment (ha)

In Equation 3, Q_P is the peak flow rate observed, calculated using the Sigma Submerged Pressure sensors installed in the tanks. The intensity of the event can then be calculated using C = 0.54 and A_C = 320 m^2 and the return period using the IDF curve for Calgary (CoC, 2000).

4.4 Water quality analysis

Inlet and outlet samples were collected for all field experiments. For each experiment 15 grab samples were taken at the inlet of the bioretention cell using 1 L bottles and a Sigma 900 MAX auto-sampler (Figure 14) was used to collect 24 1 L samples from the outlet. The auto-sampler was located in the manhole east of the bioretention cell. The sampler was level triggered, i.e. when the water level in the manhole increased by 1 mm (measured with the Submerged Pressure sensor), the sampler started collecting samples. It was programmed to collect samples every 3 minutes for the first hour (20 samples) and every 5 minutes for the next 4 samples. For both the inlet and outlet, the samples were reduced to three flow-weighted composite samples for analysis.

For the long term laboratory experiments, one inlet grab sample was taken from every 0.55 m^3 batch of runoff applied to the four columns (see Chapter 4.6.2 for details on experiment procedure). Similarly, one outlet sample was collected from each column for every 0.55 m^3 batch applied to the columns. Approximately, three samples were collected per day; they were then reduced to one volume-weighted composite. For the single event and cold weather experiments, one inlet and outlet grab sample was collected for each event.

Figure 14: A Sigma 900 MAX auto-sampler and Sigma 950 flow-meter

Inlet and outlet samples were analyzed for all field and laboratory experiments. Sediment in the form of TSS and SSC, BOD_5 and phosphorus in the form of TP were analyzed. Also, nitrogen was measured in the form of TN, ammonia – nitrogen, nitrate – nitrogen and nitrite. Lastly, chloride was analyzed as an indicator of road de-icing materials. Table 6 provides a list of the parameters, the methods used and the range and the precision of these methods.

For all of the HACH spectrometer parameters (Figure 15), except for nitrite and TN, a quality control sample was included with the analysis of every set of samples. A standard solution with a concentration of 1.00 mg/L (for the parameter of interest) was analyzed, following the same procedures as for the stormwater runoff samples. The result

of the analysis was compared with the actual value of the standard and this was used to adjust the values of all other samples for that set. No standard solutions were available for TN or nitrite. In addition to this, a duplicate sample was analyzed for every three samples for quality assurance purposes.

Figure 15: A HACH DR2000 Spectrometer, which was used for measuring water quality parameters

For TSS and SSC, the filters were pre-washed with de-ionized (DI) water and the filters were dried and weighed twice before use. The filters were kept in desiccators after drying. For BOD_5 measurements, the dissolved oxygen (DO) probe was calibrated before every use, and the average of two readings for each sample was used for the calculations.

Table 6: List of water quality parameters and associated methods, ranges and errors (adapted from HACH, 1992)

Parameter	Units	Method	Range	Precision
TSS	mg/L – TSS	SM – 2450D: Total Suspended Solids Dried at 103-105^{o}C	Minimum 5 mg/L Scale: 0.01 – 320 g	± 0.001 g
SSC	mg/L – SSC	ASTM D3977 – 97: Standard Test Methods for Determining Sediment Concentration in Water Samples, Test Method B: Filtration	Minimum 5 mg/L Scale: 0.01 – 320 g	± 0.001g
BOD_5	mg/L – BOD_5	SM 5210 – BOD – B: 5 Day BOD Test	DO: 0 – 19.9 mg/L	± 0.1%
TP	mg/L – P	HACH Method 8190, 8048: Standard Method (SM) – 4500 P- E; Ascorbic Acid Method	0 – 0.83 mg/L (P)	± 0.003 mg/L(P)
TN	mg/L – N	HACH Method 10208: Persulfate Digestion Method	1 – 16 mg/L	Not available
Ammonia	mg/L – NH_3-N	HACH Method 8038: SM 4500 – NH_3-N - B & C; Titrimetric Method	0 – 2.50 mg/L	± 0.015 mg/L
Nitrate	mg/L – NO_3^--N	HACH Method 8171: SM 4500 – NO_3^--N – E; Cadmium Reduction Method	0 – 30 mg/L	± 0.8 mg/L
Nitrite	mg/L – NO_2^-	HACH Method 8153	0 – 150 mg/L	± 2.2 mg/L
Chloride	mg/L – Cl^-	HACH Method 8224: SM 4500-Cl – C; Mercuric Nitrate Method HACH Method 8113	500 – 25,000 mg/L 0 – 20 mg/L	Not available ± 0.3 mg/L

4.4.1 Particle size distribution

The PSD analysis of the sediment in the influent and effluent water samples was conducted using a Malvern Mastersizer 2000 Particle Size Analyzer. The samples were first reduced by evaporation in an oven at 105°C. The slurry was collected and separated into sub-samples using a chute-riffler, which allows the sub-samples to maintain the original PSD (Brown, 2007). Once the target mass of 0.5 g was collected, the sediment was soaked in hydrogen peroxide for 24 hours to dissolve any organic matter. Then the sub-sample was soaked in Calgon for another 24 hours to disperse the particles. After preparation, the sediment was fed into the Mastersizer 2000 which uses laser diffraction to analyze the PSD of the sample. Duplicates were analyzed for all samples.

4.5 Growing media analysis

4.5.1 Particle size distribution

The PSD analysis of the bioretention cell media (for both field and laboratory columns) were also conducted using the Malvern Mastersizer 2000 Particle Size Analyzer. The same procedure was carried out as for the runoff samples (Chapter 4.4.1). However, before sub-sampling through the chute-riffler, the soil samples were dried in an oven at 105°C for 24 hours, and then sieved to collect all particles below 2 mm; the upper limit of the Mastersizer 2000 (Mottle, 2007).

4.5.2 Chemical content

Growing media samples from both the field and laboratory experiments were analyzed for chemical content. The parameters measured were total dissolved phosphorus, ammonia – nitrogen, nitrate – nitrogen and nitrite. The cored samples were also measured for water content and organic content. The samples were mixed with 2.0 M potassium chloride (KCl) solution for extraction before undergoing the analyses listed in Table 6. KCl was used as the hydrolysing agent. The concentration values obtained from the water quality analysis were then converted to units of mass of contaminant per mass of soil (mg/kg), by correcting for the water content, mass of sample and the volume of KCl used for extraction.

4.5.3 Saturated hydraulic conductivity

The saturated hydraulic conductivity (K_{sat}) of the growing media was calculated using a Model 2800K1 Guelph Permeameter. It is a constant head permeameter that can measure in-situ K_{sat} (between 10^{-4} to 10^{-8} m/s). The permeameter measures the steady state recharge rate of unsaturated soils, while a constant head is maintained. To measure the conductivity, a bore hole was dug in the media; the permeameter was setup and water from its reservoir was allowed to drain into the soil. The level of water in the permeameter was measured at constant time intervals. This was repeated for two different heads, at two different depths for each location, and the average K_{sat} was calculated. The permeameter is accurate to a factor of 2 (SMEC, 2008).

4.6 Experimental procedure

4.6.1 Field experiments

Figure 16 outlines the experimental procedure of the field experiments. Details are included in below.

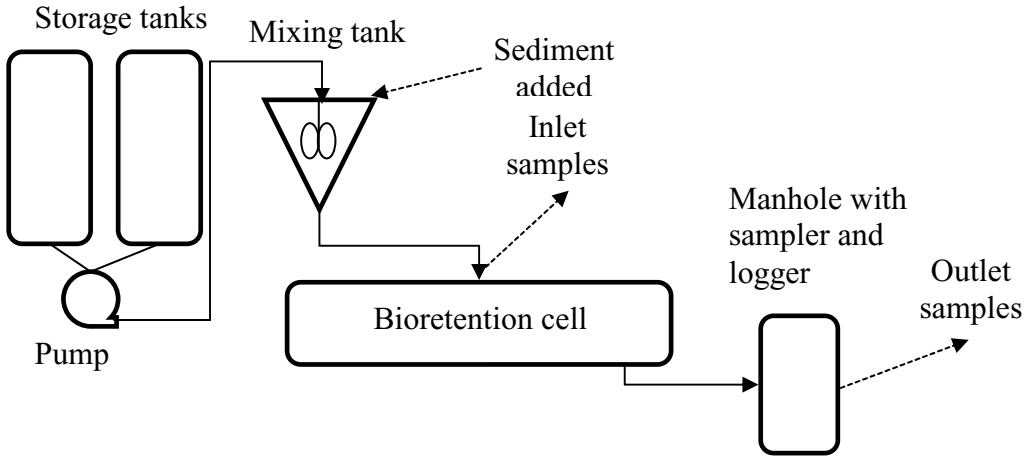

Figure 16: Schematic of field experiments

1. At least one day prior to the scheduled experiment, the soil moisture sensors, soil temperature sensors and climate station were turned on to log every 1 minute.
2. Water from the stormwater pond was hauled to the site, either the day before or the day of the scheduled experiment. The City of Calgary's stormwater monitoring staff contracted Calgary Septic Co. to haul water from the pond using a vacuum truck. The trucks were washed before each visit. The volume of water hauled was 5, 10 or 20 m^3

depending on the requirements for the particular experiment. For more than 10 m^3 two trips to the pond were required. The vacuum trucks pressure filled the stormwater into the two storage tanks.

3. On the day of the experiment, the pressure sensors were lowered into each storage tank. When the water level was steady, the sensors were calibrated by manually measuring the depth of water above the bottom of the tank. The loggers were then activated.
4. Some water from the tanks was used to fill the outlet manhole, so that the water depth inside was level with the bottom of the weir's notch. The ultra-sonic sensor and pressure sensors were permanently attached inside the manhole. Once the water was level, both instruments were calibrated to zero and the loggers and auto-sampler were activated.
5. The storage tanks were connected to the Honda pump using a series of hoses and a single hose connected the pump to the mixing tank. The Big-O pipe was connected to the bottom of the mixing tank and was placed 1000 mm from the edge of the bioretention cell. Figure 17 shows a typical set up of the field experiments.
6. When the pumping started, pre-measured bottles of sediment were poured into the mixing tank as the water from the tanks flowed into it. For example, 30 sediment bottles were prepared for a 10 m^3 30 minute experiment, each weighing approximately 150 g. The sediment was added to the tank at 1 minute intervals. In this case a total of 4500 g of sediment was added for an approximate TSS concentration of 450 mg/L.

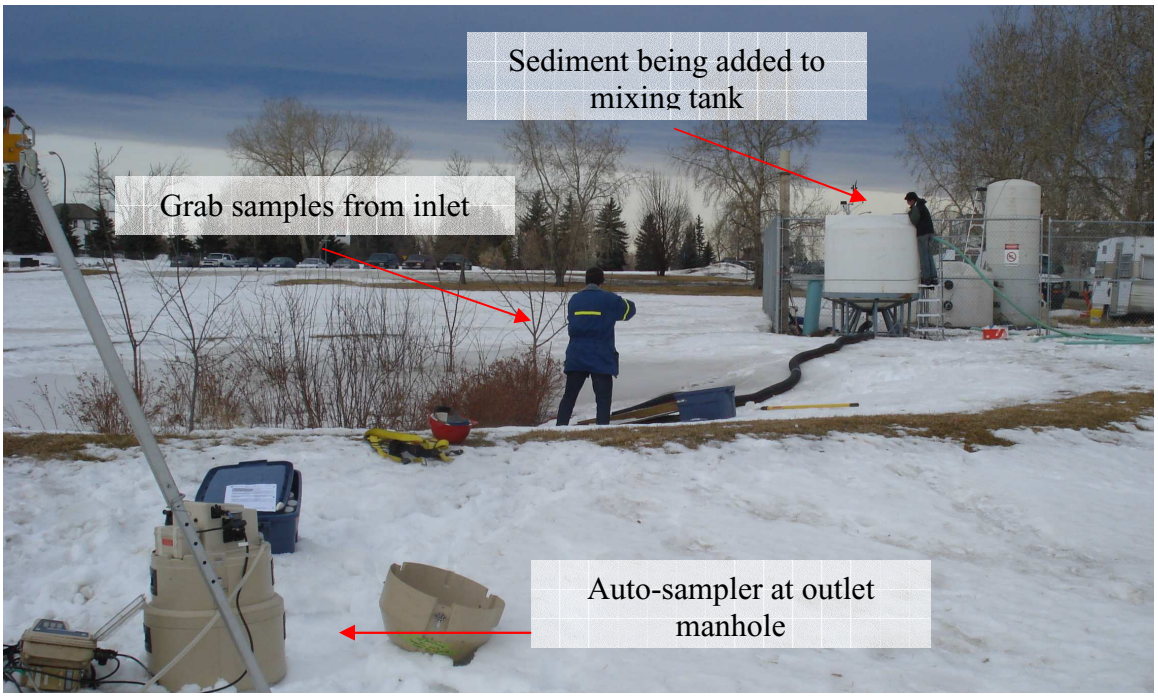

Figure 17: Experiment in progress in snowy conditions

7. As the water drained into the bioretention cell (Figure 18), manual grab samples were taken from the inlet. The pre-washed bottles were rinsed with the stormwater runoff three times before a sample was taken. A sample was taken every 2 minutes; thus for a 30 minute event, 15 inlet samples were taken.

Figure 18: View of inlet of the bioretention cell in cold weather conditions

8. For the experiments where the Delta-T PR2/6 Profile Probe was used to measure instantaneous soil moisture, the readings were taken before starting the experiment,

three times while the water was being pumped onto the bioretention cell, once after the event was complete, and once 24 hours after the event.

9. Once water started draining into the outlet manhole (Figure 19), it triggered the auto-sampler. The sampler was programmed to sample every 3 minutes for the first hour and then every 5 minutes for the next 20 minutes, for a total of 24 samples. This distribution was selected so that the entire or the majority of the effluent could be captured by the sampler. It was programmed to rinse the sampling line three times before taking a sample.

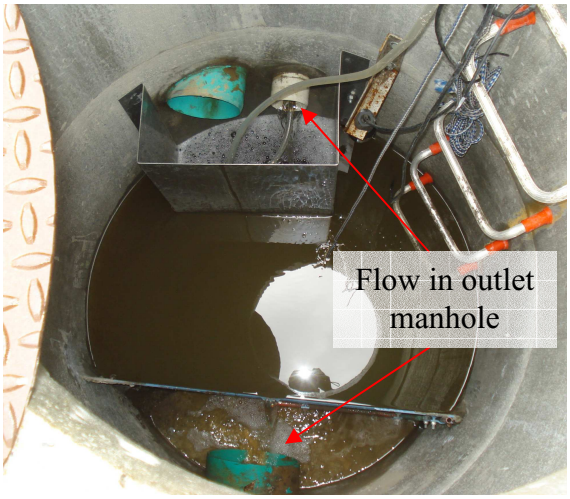

Figure 19: Flow in outlet manhole during an experiment

10. When the event was completed (Figure 20), data from the pressure sensors in the storage tanks was downloaded. The pressure sensor and ultra-sonic sensor in the outlet manhole, the soil moisture and temperature sensors and the climate station continued to log for more than 24 hours after the end of the event. The inlet and outlet water samples were taken to the University of Calgary and analyzed within 24 hours for all water quality parameters.

Figure 20: Ponding on the surface of the bioretention cell after an event

4.6.2 Long term performance column experiments

For the long term performance experiments on the columns, the equivalent of 20 years of runoff was applied in a relatively short duration of time. The annual equivalent runoff volume is given by:

Equation 4: Annual equivalent runoff (Brown, 2007)

$$V_{annual} = d_{annual} A_B (I/P + 1)$$

V_{annual} = annual equivalent runoff volume (m^3)

d_{annual} = average annual precipitation (m)

A_B = bioretention cell area (m^2)

I/P = impervious to pervious ratio

With d_{annual} = 412 mm, the average annual precipitation in Calgary, I/P = 4, the same as the field experiments and AB = 0.25 m^2, the area of the 500 x 500 mm columns, the annual equivalent runoff volume (V_{annual}) equates to approximately 0.5 m^3. For a 20 year period, this means that the equivalent runoff to be applied to the columns is 10 m^3. This volume of runoff was applied onto the columns in batches, over a period of 31 days. Figure 21 shows a schematic of the experiment procedure which is outlined below.

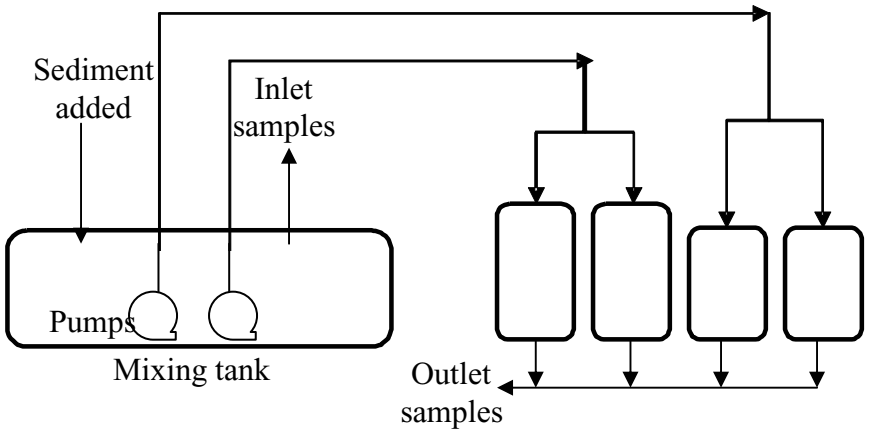

Figure 21: Schematic of long term experiments

1. Stormwater from the 69th Street south west pond was hauled to the site by Calgary Septic Co.; five 10 m^3 deliveries were required and were delivered weekly. The water was stored in a 16 m^3 tank in the Hydraulic Laboratory at the University of Calgary. Two short (450 mm depth) columns and two tall (800 mm depth) columns were used for the long term experiments; the columns were placed in a metal reservoir that would capture the effluent from the columns.
2. A volume of 0.55 m^3 of stormwater was pumped via a submersible pump from the storage tank to the 0.575 m^3 capacity mixing tank. Then 250 g of sediment was added to the mixing tank for a target TSS concentration of 444 mg/L. The mixing blades were turned on at 60 rpm to keep the sediment in suspension (Figure 22).
3. Two 0.25 horsepower submersible pumps pumped the synthetic stormwater runoff to the four columns via 0.18 inch (4.6 mm) diameter clear vinyl tubing. Each pump lead to two columns and the flow was split using a Y-connector. One batch of 0.55 m^3 took approximately 90 minutes using two pumps. After 0.55 m^3 was pumped onto the columns, the mixing tank was refilled with more stormwater from the storage tank, the effluent draining out of the columns was pumped into a sanitary drain in the laboratory and the columns were allowed to drain; this was a 60 minute process. Once the mixing tank was full again, the synthetic stormwater runoff was pumped to the columns again. The submersible pumps were switched between the tall and short columns after each batch to make sure each set of columns received equivalent runoff

volumes. Approximately three batches were conducted per day. This process was continued until each column had received 10 m^3 of runoff, which took 31 days.

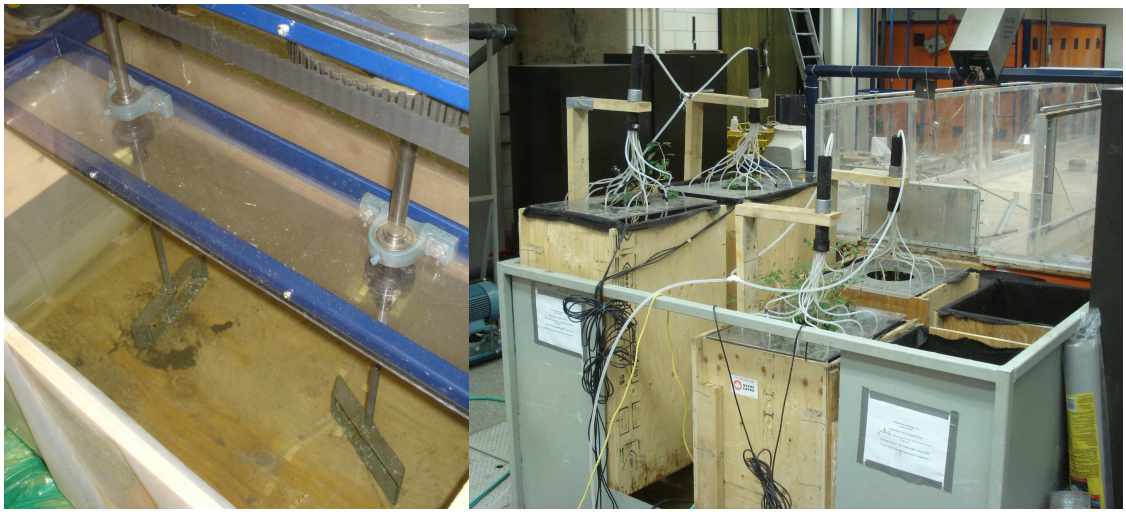

Figure 22: Blades in the mixing tank (L) and the four long term performance columns with runoff distribution system

4. One inlet sample and one outlet sample from each batch of stormwater runoff applied was taken. The outlet samples were collected in plastic trays placed below the columns to collect the effluent. For the first three days, or the equivalent of 0.83 years per column in terms of runoff application, each sample was analyzed separately. For the remainder of the 20 year testing period, three inlet samples and three outlet samples from each column, were reduced into one volume-weighted composite sample each. That is, each day, samples from three batches were combined into one sample. The samples were analyzed within 24 hours.
5. Initial saturated hydraulic conductivity was measured using a Guelph Permeameter. This was continued during the experiment, sampling twice a week for the remainder of the experiment (Figure 23).
6. Initial soil samples were taken and analyzed for chemistry and PSD. This was continued during the experiment, sampling twice a week for the remainder of the experiment.

Figure 23: Bore hole for hydraulic conductivity measurement (L) and growing media samples (R)

7. Continuous soil moisture at 1 minute intervals was measured throughout the 30 day testing period.

4.6.3 Single event warm and cold weather column experiments

The purpose of the single event column experiments was to be able to compare bioretention cell performance in both cold and warm weather conditions with the field experiments. To do this, the event size of the synthetic stormwater runoff applied to the columns has to be proportionally equivalent to the field experiments. Thus, the ratio of the field and laboratory columns' area was used to calculate the equivalent volume of stormwater runoff required. Thus a 10 m^3 event with a 60 minute duration in the field is equivalent to 78 L with 60 minutes on the laboratory columns (0.25 m^2 / 32 m^2).

The warm weather experiments were conducted in the Hydraulics Laboratory at the University of Calgary, using the same runoff distribution system used for the long term performance experiments. The cold weather experiments were conducted at the compound adjacent to the field site. Two laboratory columns were transported to the site in September 2009 and tested the following winter.

For both set of experiments, approximately 78 L of synthetic stormwater runoff, with a target TSS concentration of 444 mg/L (or 35 g of sediment) was pumped onto the columns using one submersible pump over 60 minutes. Soil moisture and soil temperature were continuously measured at 1 minute intervals. One inlet sample and one outlet sample from each column was collected and analyzed for all water quality parameters. Initial soil chemistry and saturated hydraulic conductivity were also measured.

In addition to this, for the warm weather experiments, the influent concentrations were altered after the first three experiments. The TSS was increased from 511 – 1360 mg/L and the nutrient concentrations were also increased. For the cold weather experiments, there was no mixing tank at the field location, so manual agitation was used to keep the sediment in suspension, making sure that all the sediment was pumped onto the columns. Also, the cold weather columns were left at the field location through the winter and spring, and were also tested in warm weather conditions in June 2010.

CHAPTER 5: FIELD EXPERIMENTS RESULTS AND DISCUSSION

5.1 Summary of experiments

A total of 24 experiments were conducted on the field bioretention cell site. A summary of the experiments is provided in Table 7. The experiments were conducted in the spring (Sp), summer (S), fall (F) and winter (W). Eight of the experiments were conducted in cold weather conditions, during or proceeding Chinook conditions, where the mean air temperature was between -5 to +5 °C, to simulate snowmelt conditions. The cold weather experiments in chronological order were conducted as follows: F3, W1, Sp1, F4, W2, W3, W4 and W5.

The equivalent precipitation depth of the synthetic stormwater runoff applied varied from 23.23 to 112.47 mm. The intensities of the events varied from 25.88 to 134.29 mm/hr and the return periods were evaluated to be 25, 50, 100 and 200 year events (see Chapter 4.3.3 for the calculation procedure). To calculate these storm event parameters, it was assumed that the bioretention cell's area (32 m^2) was 10% of the total hypothetical catchment area (320 m^2) and that the impervious area in the catchment was four times the area of the bioretention cell (128 m^2). Intensities calculated using the Rational method are presented in Appendix A.

Over the two year testing period (July 2008 to July 2010), approximately 180 m^3 of synthetic runoff and 107 kg of sediment was applied to the cell. This was the equivalent of 2.7 years (or 1124 mm) of precipitation.

Table 7: Summary of field experiments with cold weather experiments highlighted

ID	Event	Volume of runoff	Precipitation depth	Duration	Intensity	Return Period
		(L)	(mm)	(minutes)	(mm/hr)	(years)
S1	7/17/2008	8004	50.03	116	25.88	100
S2	8/6/2008	7520	47.00	21	134.29	100
S3	8/15/2008	7736	48.35	36	80.58	100
S4	8/27/2008	7943	49.64	31	96.08	100
F1	10/7/2008	8230	51.44	34	90.77	100
F2	10/24/2008	8120	50.75	32	95.16	100
F3	11/4/2008	4739	29.62	28	63.47	50
W1	2/3/2009	3919	24.49	19	77.35	25
Sp1	5/20/2009	3866	24.16	21	69.04	25
Sp2	6/9/2009	8601	53.76	27	119.46	100
Sp3	6/16/2009	3877	24.23	14	103.85	50
S5	7/8/2009	8395	52.47	34	92.59	100
S6	7/22/2009	7842	49.01	36	81.69	100
S7	8/12/2009	4848	30.30	17	106.94	50
S8	8/26/2009	4857	30.36	16	113.84	50
S9	8/27/2009	3717	23.23	21	116.16	50
S10	9/2/2009	17995	112.47	88	76.68	200
F4	12/2/2009	8840	55.25	61	54.34	100
W2	1/12/2010	8398	52.49	62	50.79	100
W3	1/14/2010	9014	56.34	68	49.71	100
W4	2/19/2010	8951	55.94	69	48.65	100
W5	3/3/2010	8581	53.63	64	50.28	100
S11	7/8/2010	6922	43.26	67	38.74	100
S12	7/13/2010	8868	55.43	67	49.63	100

5.2 Hydrological performance

5.2.1 Volume reduction and mass balance

The inlet volumes were calculated by measuring the difference between the initial and final depth in the two 5 m^3 storage tanks using the Submersible Pressure sensor and multiplying it by the area of the tank:

Equation 5: Volume of water used for the experiments

$$V_t = \Sigma(\pi r^2 \Delta h)$$

V_t = volume of water applied to the cell from both tanks (m^3)

π = 3.1415

r = radius of tank (m); r = 1.12 m for the short tank and r = 0.637 m for the tall tank

Δh = initial depth of water – final depth of water in the tanks (m)

The outlet volumes were calculated by multiplying the flow rates logged by the ultra-sonic sensor with the time interval (1 minute) and then adding these values for the entire event:

Equation 6: Volume of water collected in the outlet manhole

$$V_{outlet} = \Sigma(q_{outlet} \Delta t)$$

V_{outlet} = volume of water collected in the outlet manhole (m^3)

q_{outlet} = flow rate of water in the outlet manhole (m^3/s)

Δt = 60 seconds; time interval between two flow rate readings (s)

The volume reduction was defined as the percentage of volume released from the bioretention cell to the outlet manhole via the under-drain pipe relative to the volume applied:

Equation 7: Volume reduction calculation

$$VR = 1 - \frac{V_{outlet}}{V_t} \times 100\%$$

VR = volume reduction between inlet and outlet (%)

V_{outlet} = volume of water collected in the outlet manhole (m^3)

V_t = volume of water applied to the cell from both tanks (m^3)

The volume reduction for all experiments is shown in Figure 24; the average reduction was 91.5%. For 7 experiments that had a precipitation depth of 30.36 mm or less, the volume reduction was 99.9%. Apart from F3 (*VR* = 99.9%) and Sp3 (*VR* = 99.8%), no outflow was seen in the outlet manhole. In Calgary, 96% of all precipitation events are smaller than 32 mm (WER, 2007b). This demonstrates that this particular bioretention cell can capture the vast majority of precipitation and resulting runoff in Calgary, when sized to 10% of the catchment area.

The average volume reduction for warm conditions was 93.5% and the reduction in cold conditions was 87.5%. This difference was not significant (at the 95% confidence level). However, if all events smaller than 32 mm are excluded from the analysis (i.e. events that do not produce any outflow) there is a statistically significant difference ($p = 0.006$) between the warm and cold weather condition volume reduction rates (91% vs. 80% respectively). Thus, in cold weather conditions, there is reduced capacity to capture the volume of runoff from large events. A summary of all statistical analyses for the field experiments is included in Appendix B.

There is a relationship between the volume of runoff added to the cell and the resulting *VR*. The *VR* decreases with an increase in applied volume. The *VR* was 100% for events smaller than 32 mm and this decreased to 81.9% for the extremely large event S10 that had a precipitation depth of 112 mm. However, this trend was not significant at the 95% confidence level.

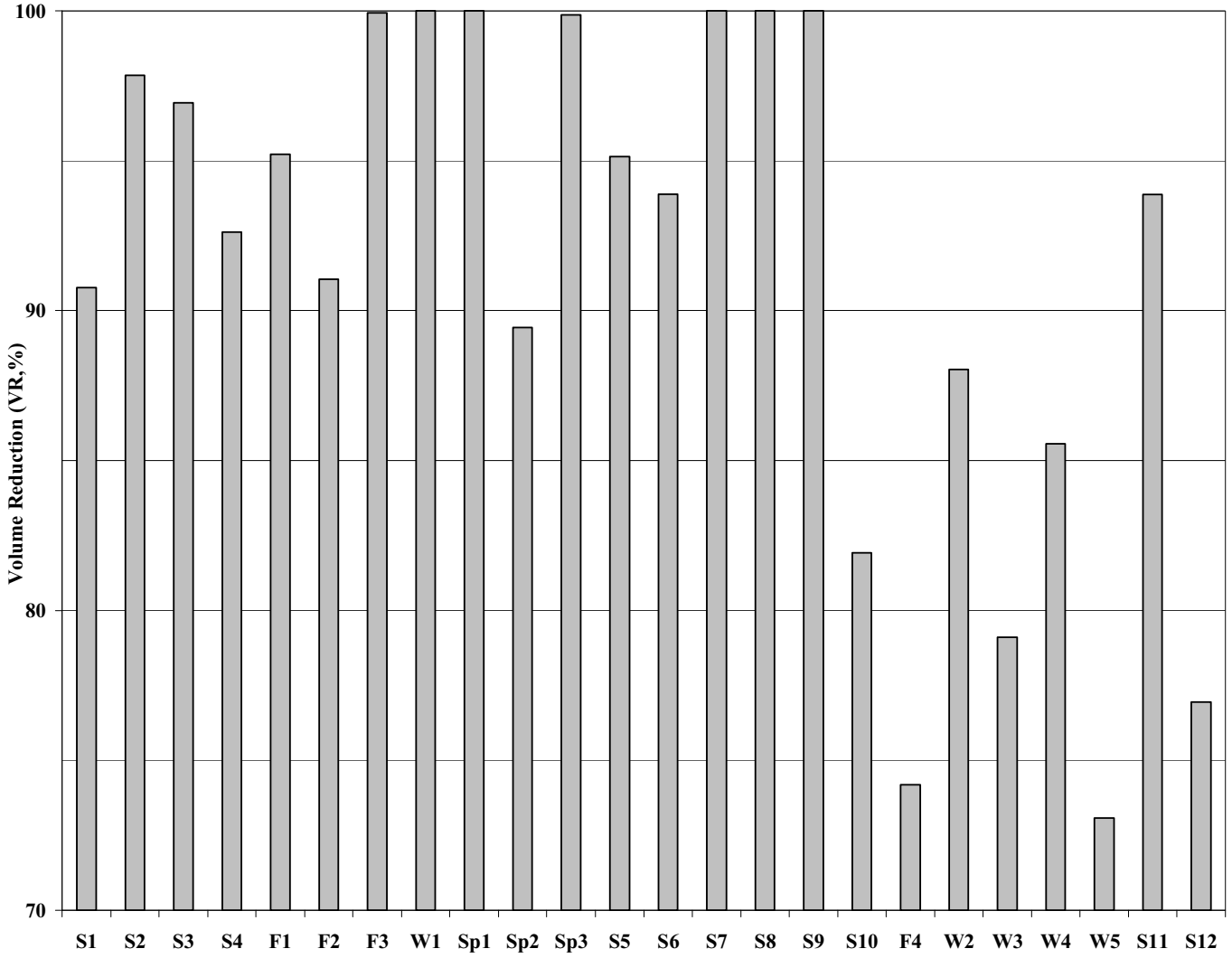

Figure 24: Volume reduction of runoff between inlet and outlet of the cell in the field experiments

For the experiments Sp2 and S12, the *VR* was lower than the average. This is attributed to the fact that for both experiments, there was heavy precipitation before the events, 12.4 mm for Sp2 (in the 48 hours leading up to the event and 2 mm the day of the event) and 21 mm for S12 (in the 72 hours leading up to the event and 19 mm the day of the event). There is no soil moisture data available for Sp2, but for S12 the four continuous soil moisture sensors indicate a 33% increase in intial soil moisture for all sensors when compared to the average. This indicates that the increase in soil moisture due to precipitation reduced the capacity of the bioretention cell to store the incoming runoff.

However, precipitation also occurred 24 hours prior to Sp3, S5 and S7 (13.6, 2.4 and 1 mm, respectively). The precipitation had no impact on volume capture for Sp3 and S7 due to the fact that the event sizes were small and that the initial soil moisture prior to the start of the experiments was equivalent to the average initial soil moisture for all experiments. S5 was a larger event and this did not impact the volume reduction capacity to the same extent as similarly sized Sp2 and S12. And unlike Sp2 and S12, for these three experiments, high temperatures (>20°C) and photo-synthetically active radiation (PAR) rates (2000 μE vs. 900 μE) contributed to decreasing the initial soil moisture in the media and thus negating the effects of precipitation prior to the experiments.

S8 and S9 were conducted within 24 hours of each other. This did not impact the volume capture rates as both experiments had a 100% reduction. This can be attributed to the fact that both events were small and when comparing the soil moisture for both events, the moisture had nearly receded to its initial value within 24 hours (i.e. before the start of S9) allowing the cell to have the same capacity to capture runoff. However, if larger events had been tested, the reduction in soil moisture may not have occurred so rapidly.

The mass balance of the runoff was calculated using:

Equation 8: Mass balance of runoff

$$V_t = V_{outlet} + S_g + L$$

V_t = volume of water from tanks (m^3)

V_{outlet} = volume of water collected in the outlet manhole (m^3)

S_g = volume of water stored in growing media 12 hours after peak soil moisture (m^3)

L = other losses (m^3)

S_g is a measure of the volume of water held in the growing media. It is defined as the difference between the initial volume of water and the "final" volume of water held in the growing media. The final volume moisture is defined as the moisture 12 hours after the peak soil moisture. L represents the combined losses from evapo-transpiration and percolation into the soil surrounding the bioretention cell.

Equation 9: Volume of water stored in growing media

$$S_g = \left[\sum_{1}^{4} \left(\theta_{AP} V_g \right) - \sum_{1}^{4} \left(\theta_i V_g \right) \right]$$

θ_{AP} = soil moisture 12 hours after peak soil moisture (m^3/m^3)

θ_i = initial soil moisture prior to event (m^3/m^3)

V_g = representative volume of growing media for each soil moisture sensor (m^3)

V_g was calculated by multiplying the representative depth of each soil moisture sensor with the area of the bioretention cell. The representative depths for each sensor were 0 – 200, 200 – 400, 400 – 750 and 750 – 1200 mm for the sensors 150, 300, 500 and 1000 mm, respectively, below the surface of the bioretention cell.

A summary of the results from the mass balance analysis is shown in Table 8 below. The table shows each component of the mass balance equation (Equation 8) as a fraction of the inlet volume. Soil moisture data was not logged for 5 events, W1 through S5, so these events were excluded from the analysis. For all experiments, approximately 59% of the runoff was left the cell via other losses (L) and 31% was held in the growing media (S_g). This indicates that, if this bioretention cell was constructed with an impermeable liner, the volume of runoff leaving the site could increase to up to 69%, reducing the overall volume and pollutant mass removal efficiencies.

Comparing warm and cold weather conditions, there was a statistically significant difference between the volumes of runoff leaving the outlet ($p = 0.035$) and also between the volumes of runoff stored in the growing media ($p = 0.043$). The amount of water lost via other losses was not significantly different between warm and cold conditions. Thus, in cold conditions, less runoff volume is being held in the growing media and the fraction of volume leaving via the outlet pipe is larger.

Table 8: Summary of mass balance for the field experiments

	V_{outlet}/V_t (%)	S_g/V_t (%)	L/V_t (%)
All experiments	9.97	30.82	59.21
Warm only	6.87	36.48	56.65
Cold only	16.68	18.56	64.76

Soil moisture readings from the PR2/6 Profile Probe (for Sp1 – S7) show that the water is not moving uniformly through the bioretention cell. The water appears to move towards the northeast corner of the cell and collects at the bottom. Readings from immediately outside the cell show that water does not move into the surrounding soils (up to a depth of 1000 mm), indicating that it percolates into the under-drain layer, bypassing the outlet pipe and moving into the sub-soils. The south west corner of the cell does not receive any runoff due to preferential flow paths and remains dry during the experiments.

5.2.2 Flow rate reduction and delay

For the field experiments the average inlet peak flow rate was 237 L/s/ha (or 7.61 L/s for a 320 m^2 catchment area) and the average outlet flow rate was 8.80 L/s/ha (0.282 L/s). The inlet peak flow rate varied from 82 to 407 L/s/ha, with a standard deviation of 95 L/s/ha. The outlet peak flow rate varied from 0.028 L/s/ha to 24.7 L/s/ha, with a standard deviation of 1.09 L/s/ha. The peak flow rates, peak reduction and delay, and the time of concentration are summarized in Table 9. The peak reduction was calculated using the following equation:

Equation 10: Peak flow rate reduction between inlet and outlet

$$PR = 1 - \frac{Q_{po}}{Q_{pi}} \times 100\%$$

PR = peak reduction (%)

Q_{po} = outlet peak flow rate (L/s/ha)

Q_{pi} = inlet peak flow rate (L/s/ha)

On average, the peak flow rate reduction for all the experiments was 95.3% (i.e. for experiments where outflow occurred). The peak reduction is dependent on the inlet peak flow rates, since the outlet flow rates have a low deviation. The cell buffers the

incoming flow to a particular magnitude in the effluent. The outlet flow rates are independent of the inlet flow rates. Peak flow rate reduction in cold weather conditions was lower on average than warm conditions (93.5% vs. 96.2%); this difference was not statistically significant ($p = 0.203$). There was also no significant difference in inlet and outlet flow rates between cold and warm conditions ($p = 0.138$ and 0.188, respectively).

Table 9: Summary of peak flow rates for field experiments

ID	Time of concentration	Inlet peak	Outlet peak	Peak reduction	Peak delay	Peak delay factor
	(min)	(L/s/ha)	(L/s/ha)	(%)	(min)	
S1	38	82.0	9.1	88.9	31	1.38
S2	31	407.6	4.2	99.0	15	1.75
S3	31	360.1	5.1	98.6	30	2.30
S4	36	275.8	9.5	96.5	22	2.29
F1	34	368.5	5.3	98.6	23	2.35
F2	28	330.9	7.2	97.8	30	1.45
F3	90	194.3	$8.5E10^{-4}$	100.0	90	11.00
W1	-	201.0	No flow	-	-	-
Sp1	-	219.5	No flow	-	-	-
Sp2	26	355.3	9.1	97.4	26	2.44
Sp3	-	302.1	0.2	99.9	76	11.29
S5	32	197.0	6.3	96.8	12	1.32
S6	37	232.8	6.4	97.2	34	2.89
S7	-	204.2	No flow	-	-	-
S8	-	189.2	No flow	-	-	-
S9	-	227.6	No flow	-	-	-
S10	29	259.2	24.7	90.5	46	1.43
F4	32	104.6	15.9	84.8	46	5.18
W2	26	251.0	8.8	96.5	61	7.78
W3	26	170.8	11.8	93.1	69	18.25
W4	36	303.0	10.2	96.6	31	1.66
W5	37	161.9	16.4	89.9	38	2.03
S11	31	149.7	5.0	96.6	38	2.83
S12	44	158.6	12.1	92.4	71	19.50
Averages						
All	32	237.8	8.8	95.3	42	5.22
Warm	33	256.3	8.0	96.2	35	4.10
Cold	31	200.8	10.5	93.5	55	7.65

The average delay in peak flow rate (i.e. the difference between the times at which peak flow rates occurred) was 42 minutes; with a shorter lag in warm conditions compared to cold conditions (35 vs. 55 minutes). This was a statistically significant result ($p = 0.039$). However, analyzing the delay in peak without considering the start time of the event can be misleading, so a peak delay factor was defined, which took the ratio of the time to peak of the outlet hydrograph and the time to peak of the inlet hydrograph:

Equation 11: Calculating the peak delay factor

$$DF = \frac{t_{po} - t_s}{t_{pi} - t_s}$$

DF = delay factor

t_{po} = time of peak at the outlet

t_{pi} = time of peak at the inlet

t_s = time at the start of the experiment

The average DF for all experiments is 5.22, with 4.10 in warm conditions and 7.65 in cold conditions. This essentially supports the results from looking at the peak delay, where there is a longer delay in cold weather conditions but this was not a significant difference for DF ($p = 0.188$). The time of concentration was defined as the interval between the end of the inlet flow and the inflection point of the receding limb of the outlet hydrograph. The average time of concentration was 32 minutes for all the experiments. There was no statistically significant difference in time of concentration between the warm and cold conditions. Thus, to summarize, a bioretention cell can successfully reduce the peak flow rate and delay the peak time of the effluent. The difference in peak reduction and time of concentration between cold and warm conditions is not significant; the peak delay is not significant when the time from the start of the experiment is accounted for.

Figure 25 shows the inlet and outlet hydrograph for S6. Though the outlet hydrograph is a fairly representative hydrograph with a defined peak, the inlet hydrographs were very variable, consisting of multiple peaks. Thus, it was important to look at the centre of mass (CoM) of both the inlet and outlet hydrographs and their respective reduction and delay (see Table 10), as was done for the peak flow rates above.

Results from analyzing the centre of mass flow rates support the results from the peak flow rate analysis. Outlet CoM flow rates are higher in cold conditions and the reduction in the CoM flow rates is lower in these conditions, but these are not statistically significant ($p = 0.202$ and $p = 0.271$). There is a larger delay in CoM in cold conditions ($p = 0.049$) but the CoM delay factor does not show a significant difference ($p = 0.861$).

Table 10: Summary of centre of mass flow rates for field experiments

ID	Inlet CoM	Outlet CoM	CoM reduction	CoM delay	CoM delay factor
	(L/s/ha)	(L/s/ha)	(%)	(min)	
S1	34.6	2.2	93.6	57	1.95
S2	127.6	0.9	99.3	28	3.33
S3	103.4	1.1	98.9	38	3.11
S4	147.7	1.8	98.8	41	3.41
F1	125.5	0.9	99.3	43	3.69
F2	135.6	1.0	99.3	50	3.27
F3	72.9	$3.0E10^{-4}$	100.0	112	9.00
W1	104.6	No flow	-	-	-
Sp1	69.8	No flow	-	-	-
Sp2	140.2	1.3	99.1	51	4.64
Sp3	102.5	0.0	100.0	72	11.29
S5	106.1	2.2	98.0	41	2.58
S6	133.8	1.5	98.9	48	3.67
S7	150.2	No flow	-	-	-
S8	121.5	No flow	-	-	-
S9	150.4	No flow	-	-	-
S10	59.6	4.5	92.5	90	2.17
F4	72.7	2.1	97.1	52	2.86
W2	58.7	1.7	97.1	62	3.21
W3	47.2	2.5	94.8	73	3.81
W4	90.5	2.2	97.6	66	3.00
W5	50.7	2.7	94.6	70	3.12
S11	32.2	0.8	97.5	60	3.61
S12	53.5	2.0	96.2	75	3.78
Averages					
All	95.5	1.7	97.5	59	3.97
Warm	107.8	1.6	97.8	53	3.88
Cold	70.9	1.9	96.8	73	4.17

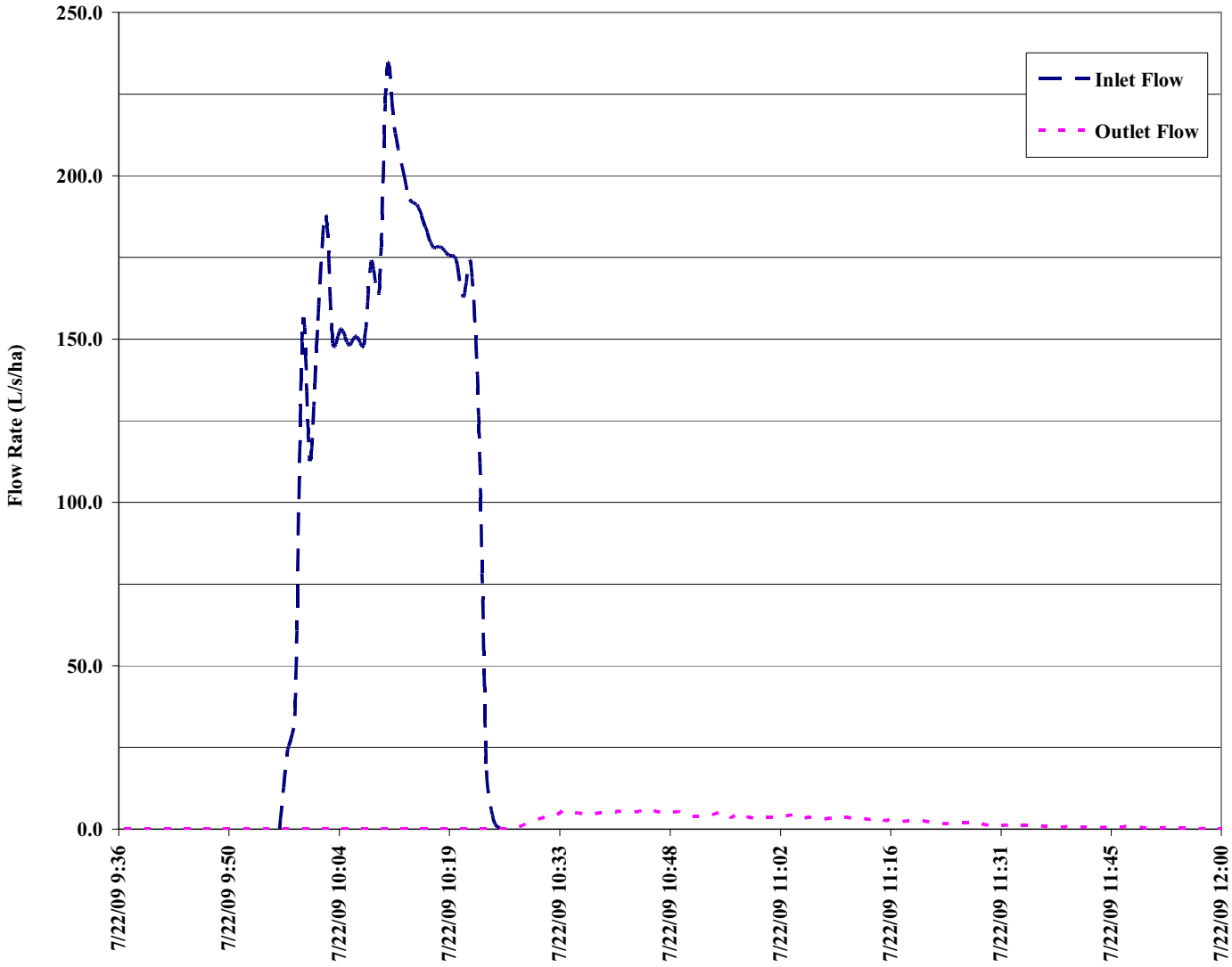

Figure 25: Inlet and outlet flow hydrograph for S6

5.2.3 Soil moisture trends

Soil moisture was measured at four depths for all field experiments except for W1, Sp1, Sp2, Sp2 and S5. The purpose of measuring soil moisture was to see the difference in how well the bioretention cell drains, between warm and cold conditions, and also in each layer. A summary of the initial (θ_i), peak (θ_P) and 12 hours after peak (θ_{AP}) soil moisture for each sensor at depths of 150, 300, 500 and 1000 mm is presented in Appendix A; sensor errors or errors due to freezing soil conditions have been indicated where applicable.

Figure 26 shows a typical soil moisture hydrograph for field experiment S6, with all four sensors. It is interesting to note that there is no lag between the different sensors as to when the soil moisture increases at the start of the event. Once the peak value is reached the soil moisture plateaus before it starts to recede. As expected, the moisture levels recede sequentially, starting with the top layer and proceeding with depth. The chart also indicates that as the water moves downwards, it accumulates in the bottom layer (before progressing to the under-drain layer); since the receding limb of the deepest sensor takes the longest time to approach the initial soil moisture.

Comparing soil moisture data between warm and cold conditions, there was no statistical difference between initial soil moisture in the growing media at all depths. This indicates that the amount of available storage capacity was unchanged in the two climatic conditions. However, the peak soil moisture was statistically significantly higher in warm conditions compared to cold conditions for the sensor 150 mm below the surface ($p = 0.020$). Thus in cold weather conditions, even though the initial soil moisture was similar, the maximum amount of volume held was lower near the surface (i.e. the same layer that was initially frozen). Also, soil moisture readings 12 hours after the peak soil moisture ("final soil moisture"), the moisture levels at the 150 mm and 1000 mm deep sensors were significantly higher in warm conditions ($p = 0.046$ and $p = 0.021$). This means that either a larger volume of runoff is held at these locations in warm conditions or that these locations are receiving less total runoff (thus resulting in lower soil moisture values) in cold conditions. It is also important to note that there are no significant differences in moisture values for the 300 mm and 500 mm deep sensors.

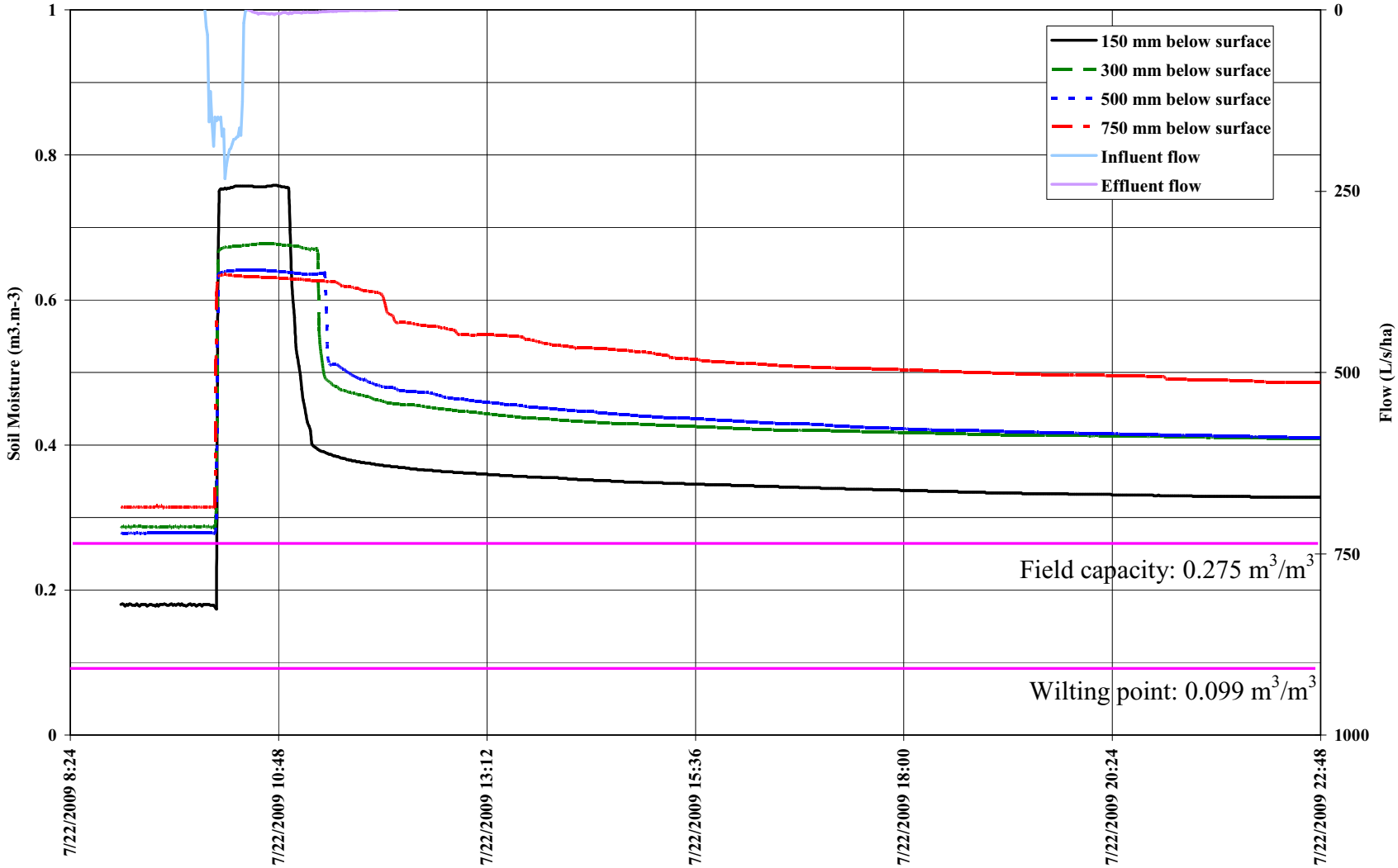

Figure 26: Soil moisture hydrograph for S6

The 1000 mm deep sensor approached the initial soil moisture value faster in cold weather conditions. Along with this, the higher peak flow rates, higher effluent volumes, and lower S_g in cold weather conditions indicate that the partially frozen top layer (depth of 150 mm) is altering the flow path of the runoff. The runoff is short circuiting and travelling through preferential flow paths and macro-pores to the outlet pipe, bypassing or not fully utilizing the available media mass in the deeper areas of the cell.

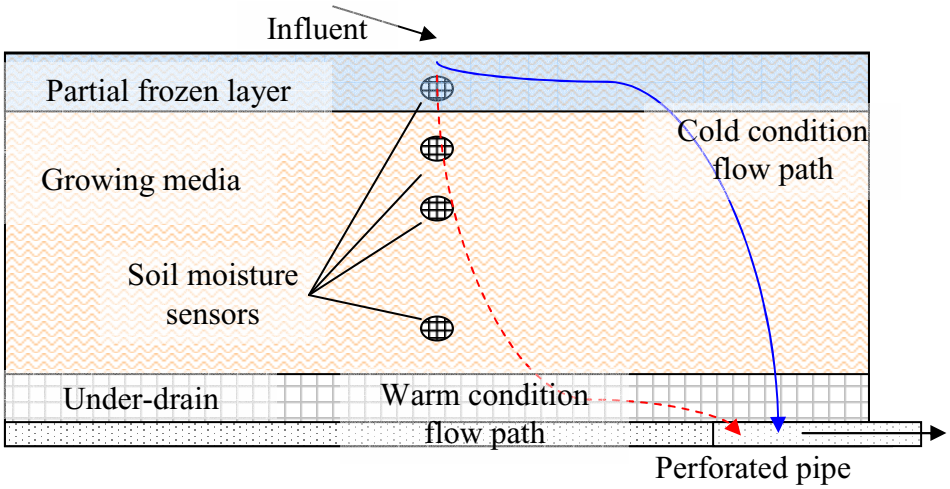

Figure 27: Comparison of warm and cold condition flow paths; the partial frozen layer was measured to a depth of 150 mm

As the runoff is applied to the cell (Figure 27), in cold conditions the frozen top layer does not allow the water to penetrate the soil as it does in warm conditions. The runoff does not disperse and tends to travel laterally, before finding a route towards the perforated section of the pipe. This explains the higher peak flow rate (since the runoff is wetting a lower volume of soil), longer peak delays (due to the larger travel path) and the lower volume held in the growing media (bypassing effect). It is important to note that since the 300 and 500 mm deep sensors do not show any difference between warm and cold conditions, the bioretention media itself is not altering the hydrologic response in cold weather conditions. Rather the boundary affects, primarily the surface boundary (that is subject to freezing conditions) appears to affect the flow paths.

5.3 Water quality performance

5.3.1 Mass capture

Mass capture refers to the reduction in the total mass of contaminants between the inlet and outlet streams through the bioretention cell. This was calculated by multiplying the flow rates with the concentration of the contaminants for both the influent and effluent. For the influent, where 3 composite samples were taken for each experiment, the total influent mass is given by:

Equation 12: Mass of contaminant in influent

$$M_i = \sum_{1}^{3} (V_i C_i)$$

M_i = total mass of contaminant in the influent for an event (kg)

V_i = representative volume of inlet flow-weighted composite sample (m^3)

C_i = the concentration of the contaminant in an influent composite sample (mg/L)

For each experiment, 15 inlet grab samples were reduced to 3 flow-weighted composite samples. For each sample, the flow rates at the time of the grab sample was multiplied by the time interval (2 minutes) to calculate the representative volume (V_i) of runoff applied. This volume was multiplied by the concentration of the contaminant in the sample (C_i) to obtain the mass of the contaminant in each sample. The sum of the masses for the three composite samples represents the total inlet mass of the contaminant (M_i). Similarly, 24 outlet samples were reduced to 3 flow-weighted composite samples. The first 20 samples were reduced to 2 composite samples (10 samples in each), and the remaining 4 samples for the third composite. The representative volume (V_o) of each sample was calculated by multiplying the flow rate by the time interval (3 minutes for the first 20 samples and 10 minutes for the last 4 samples). This volume was then multiplied by the concentration of the contaminant (C_o) in the sample to obtain the mass of the contaminant in the sample. The sum of the masses for the three composite samples was the total mass of contaminant in the effluent, as shown in Equation 13:

Equation 13: Mass of contaminant in effluent

$$M_o = \sum_{1}^{3} (V_o C_o)$$

M_o = total mass of contaminant in the effluent for an event (kg)

V_o = representative volume of outlet flow-weighted composite sample (m^3)

C_o = the concentration of the contaminant in an effluent composite sample (mg/L)

The mass reduction through the bioretention cell was then calculated:

Equation 14: Mass reduction of contaminants

$$MR = \frac{M_i - M_o}{M_i} \times 100\%$$

MR = mass reduction (%) of contaminant

M_i = total mass of contaminant in the influent for an event (kg)

M_o = total mass of contaminant in the effluent for an event (kg)

Table 11 lists the summary of mass reduction for all contaminants measured. The first three rows show average results from all field experiments and also separate results for warm and cold weather conditions. However, this includes results from experiments that had a 100% *VR* and thus a 100% *MR*. This skews the data to higher averages. Thus, the second set of rows list results from only the experiments where outflow was seen. The second set of results shows a more conservative estimate for mass removal parameters. Figure 28 shows the results of mass capture for the outflow-only experiments.

Table 11: Summary of mass removal of contaminants

	TSS	**SSC**	**BOD_5**	**TN**	**NO_3^--N**	**NO_2^-**	**NH_3^+-N**	**TP**	**Cl^-**
All	99.63	99.72	92.77	92.35	92.62	89.96	93.50	94.10	88.15
Warm	99.50	99.62	91.94	96.06	94.00	84.19	91.28	93.37	88.59
Cold	99.89	99.99	93.80	86.79	90.38	97.18	97.11	95.54	87.28
Outflow	99.51	99.61	91.32	89.08	89.67	84.95	90.90	91.15	83.59
Warm	99.34	99.52	91.05	94.10	91.34	73.65	87.41	90.06	82.88
Cold	99.86	99.99	91.73	82.39	87.17	96.24	96.15	93.31	84.73

On average, both sediment parameters, TSS and SSC exhibited the highest mass removals, in both warm and cold conditions, averaging greater than 99% removal (ranging from 96 to 100%). Nutrient mass removal was high but varied:

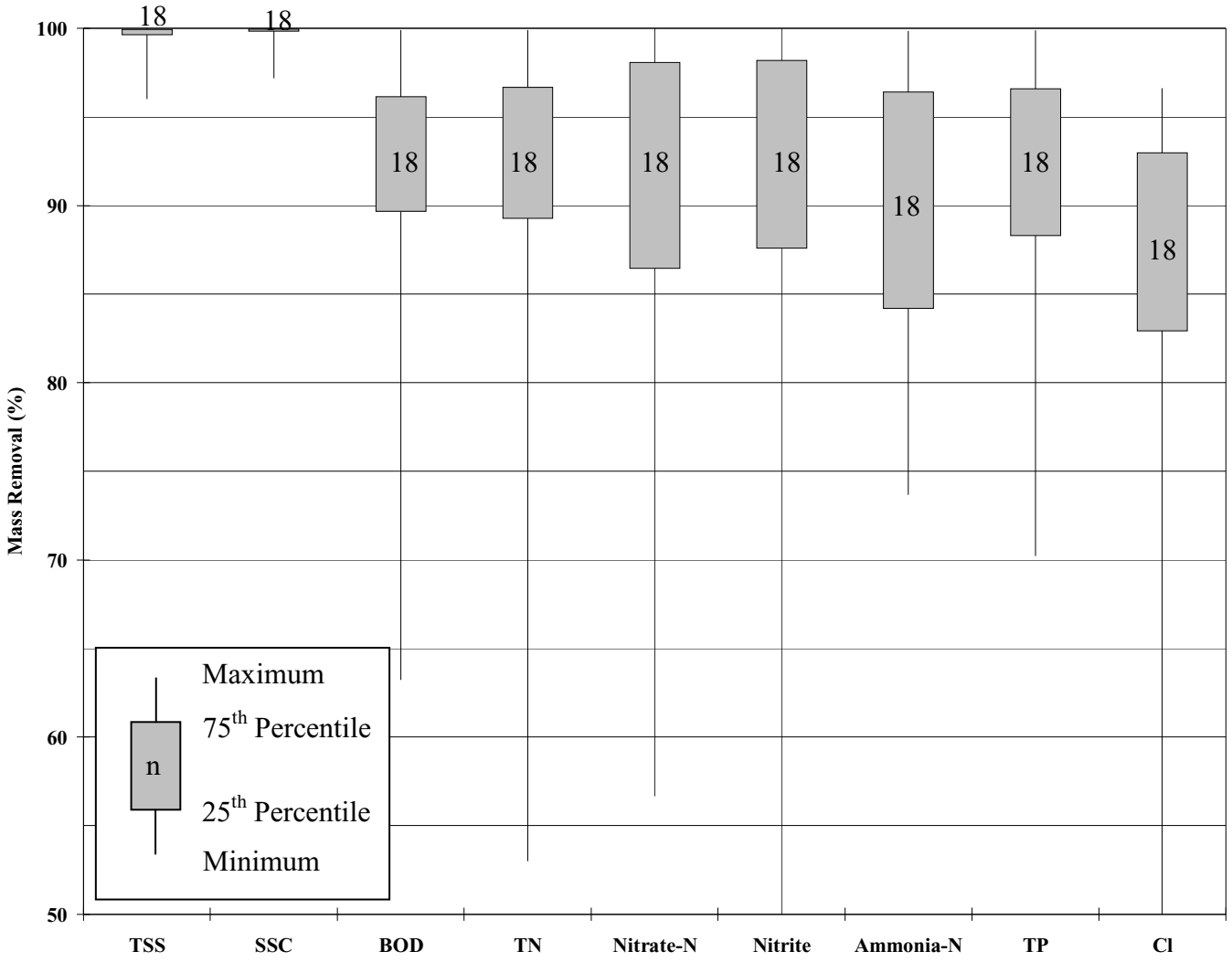

Figure 28: Mass removal rates of all contaminants through the bioretention cell

- TN ranged from 53.00 to 99.91%
- Nitrate ranged from 56.66 to 100%
- Nitrite ranged from 6.78 to 100%
- Ammonia ranged from 73.67 to 99.86%
- TP ranged from 70.22 to 99.88%

BOD_5 removal rates were high in both warm and cold conditions, and varied between 63.23 to 99.92%. Chloride averaged more than 80% for all conditions and varied between 41.62 to 96.62%.

Comparing warm and cold condition removal rates, only SSC and ammonia have a significant difference between the two weather conditions. For both, the removal rates were significantly higher in cold conditions ($p = 0.044$ for SSC and $p = 0.034$ for ammonia). These results are interesting because in cold weather conditions, there was a significant increase in the volume of runoff leaving the cell via the outlet (which should reduce the mass removal rates). However, both SSC and ammonia had higher influent concentrations in cold weather conditions and thus, the greater reduction in concentration compensated for the lower volume capture, resulting in the higher reduction of mass. The concentration reduction is discussed in the following section.

5.3.2 Concentration reduction

Since mass removal rates are dependent on both the runoff volume and concentration of the contaminant, it is important to look at concentration reduction when evaluating bioretention cell performance with respect to water quality. For all the field experiments, the inlet and outlet concentrations of all contaminants were compared independently for the entire data set: TSS, SSC, nitrate and TP had significant differences between the influent and effluent. TSS, SSC and TP were significantly reduced ($p = 0.000$, 0.000 and 0.027 respectively), while nitrate significantly increased ($p = 0.039$). Table 12 shows the average inlet and outlet concentrations of all contaminants for all the field experiments, negative percent reduction indicates leaching. The average concentration reduction (using Equation 15) is shown for all contaminants; again only TSS, SSC, nitrate and TP are significant.

Table 12: Average influent and effluent concentration (mg/L) of contaminants

	TSS	**SSC**	**BOD_5**	**TN**	**NO_3^--N**	**NO_2^-**	**NH_3^+-N**	**TP**	**Cl^-**
Influent	414.17	889.69	4.68	3.03	1.94	9.88	0.65	0.36	215.77
Effluent	13.85	19.95	4.08	3.07	2.49	7.03	0.50	0.20	262.76
Reduction (%)	**96.65**	**97.76**	12.93	-1.58	**-28.60**	28.85	23.36	**43.26**	-21.78

Equation 15: Average concentration reduction of contaminants

$$CR = \frac{\hat{C}_i - \hat{C}_o}{\hat{C}_i} \times 100\%$$

CR = concentration reduction (%)

$\hat{C}_i$ = average inlet concentration of all experiments (mg/L)

$\hat{C}_o$ = average outlet concentration of all experiments (mg/L)

However, looking at each experiment individually paints a slightly different picture in terms of average concentration reduction. Table 13 lists the average concentration reductions for each parameter calculated by averaging the individual reduction from each event. For this case, paired comparisons were conducted between the inlet and outlet concentration of each parameter for each experiment (Equation 16).

Table 13: Comparison of concentration reduction (%) in different weather conditions

	TSS	**SSC**	**BOD_5**	**TN**	**NO_3^--N**	**NO_2^-**	**NH_3^+-N**	**TP**	**Cl^-**
All	**96.10**	**95.80**	**7.87**	-7.78	-32.25	-126.05	-18.74	**0.60**	-6.70
Warm	96.51	94.80	3.81	25.95	-21.86	-270.99	-52.97	-9.59	-7.63
Cold	95.42	99.77	13.95	-52.75	-50.96	18.90	32.62	20.98	-5.20

Equation 16: Average concentration reduction (individual experiment basis)

$$CR = \frac{\sum^{n} \frac{C_i - C_o}{C_i}}{n} \times 100\%$$

CR = concentration reduction (%)

C_i = influent concentration of a single experiment (mg/L)

C_o = effluent concentration of a single experiment (mg/L)

n = number of events

Figure 29 shows the range of concentration reduction for all parameters for all experiments where there was outflow. TSS, SSC, BOD_5 and TP were found to have a significant difference between the inlet and outlet, on an experiment by experiment basis ($p = 0.000$, 0.005, 0.038 and 0.05 respectively). The significance of this approach is that it shows us that for BOD_5, the reduction in outlet concentration is dependent on the inlet concentration. Similarly, the first analysis shows that nitrate concentration in the effluent was statistically higher overall but on a case by case basis, there is no statistical difference. Thus effluent nitrate concentrations are not dependent on inlet concentrations. For TSS, SSC and TP, this is not true since a reduction was seen in both analyses.

Comparing performance between warm and cold conditions, a significant change in performance was noted for both TN and ammonia. In warm conditions, TN concentration was reduced by 25.95% and this changed to an increase in concentration by 52.75% ($p = 0.015$) in cold conditions. Ammonia leached at a rate of 52.97% in warm conditions, to a reduction of 32.62% in cold conditions ($p = 0.018$). However, the actual change between inlet and outlet concentrations for both of these parameters was not significant. Chloride concentrations were not significantly different between the inlet and outlet, in either analyses or in warm and cold conditions.

To summarize, on an event basis, the bioretention cell successfully reduced the concentration of sediment (TSS and SSC) by more than 95%. BOD_5 and TP reduction were also significant; however reduction rates were lower, 7.87 and 0.6%, respectively. Over the course of the 2 year testing period, the bioretention cell successfully removed a large percentage (85% or higher) of mass for all contaminants.

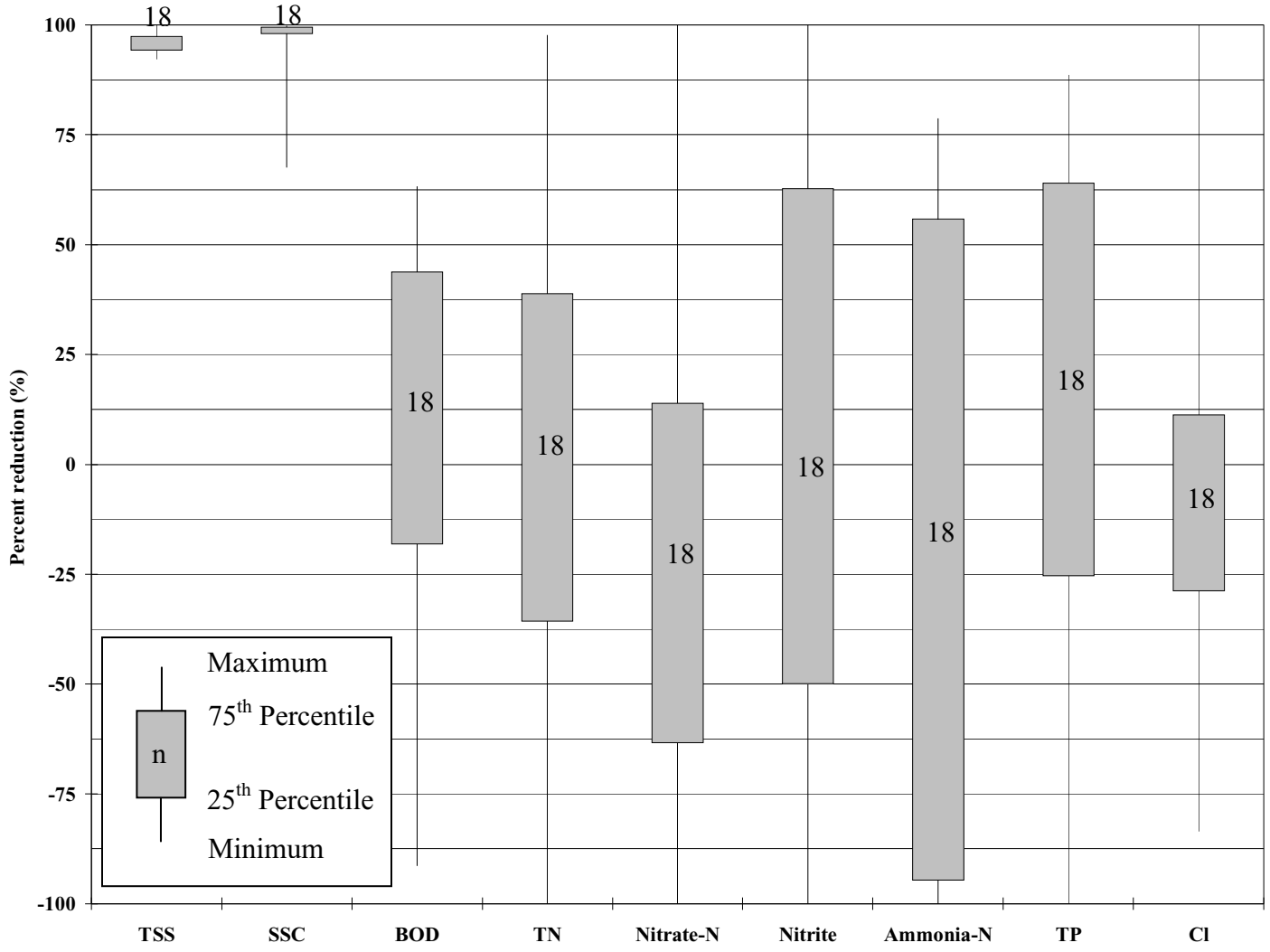

Figure 29: Range of concentration reduction for all field experiments (with outflow)

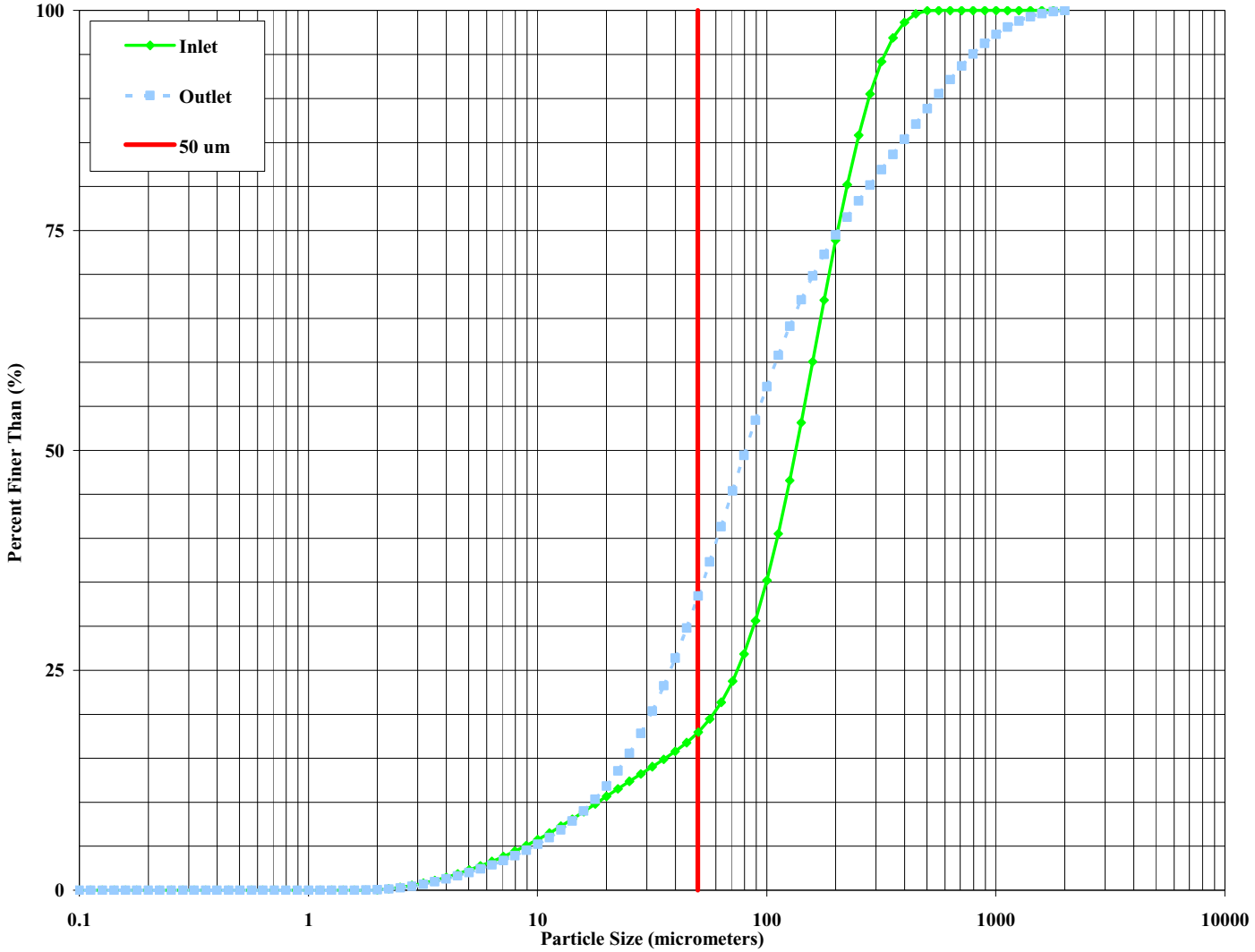

Figure 30: Particle size distribution of sediment in the influent and effluent

5.3.3 Particle size distribution

The PSD of the sediment in the influent and effluent was analyzed using a Malvern Mastersizer 2000 laser diffraction particle size analyzer. The average results from the analysis for the field experiments are illustrated in Figure 30. The City of Calgary requires all stormwater BMPs to remove 85% of particles larger than 50 μm.

On average, the influent has 82% of its particles greater than 50 μm, while the effluent has 68% of its particles greater than 50 μm. To calculate the amount of solids removed, a relationship between the TSS and particle size is defined (see Equation 17). Using this relationship, the bioretention cell demonstrated 96.68% removal of particles greater than 50 μm from the influent runoff.

Equation 17: Relationship between TSS and sediment capture (Brown, 2007)

$$PR^{>50\mu m} = \frac{TSS_{in}^{>50\mu m} - TSS_{out}^{>50\mu m}}{TSS_{in}^{>50\mu m}} \times 100\%$$

$$PR^{>50\mu m} = \frac{TSS_{in}(\alpha_{in}) - TSS_{out}(\alpha_{out})}{TSS_{in}(\alpha_{in})} \times 100\%$$

$$PR^{>50\mu m} = \frac{TSS_{in}[\alpha_{in} - (1-\beta)\alpha_{out}]}{TSS_{in}(\alpha_{in})} \times 100\%$$

$$PR^{>50\mu m} = \frac{[\alpha_{in} - (1-\beta)\alpha_{out}]}{(\alpha_{in})} \times 100\%$$

$PR^{>50\mu m}$ = percent reduction of sediment particles greater than 50 μm (%)

$TSS^{>50\mu m}_{in}$ = concentration of inlet TSS particles greater than 50 μm (mg/L)

$TSS^{>50\mu m}_{out}$ = concentration of outlet TSS particles greater than 50 μm (mg/L)

TSS_{in} = concentration of inlet TSS (mg/L)

TSS_{out} = concentration of inlet TSS (mg/L)

α_{in} = fraction of particles in the inlet greater than 50 μm (%): 82%

α_{out} = fraction of particles in the outlet greater than 50 μm (%): 68%

β = average concentration reduction of TSS from field experiments (%): 96.10%

5.4 Summary of field experiments

From a hydrologic point of view, the field experiments demonstrated that the bioretention cell can successfully reduce the total volume of runoff, peak flow rates and

increase the peak lag. It can also reduce the total mass of contaminants; 99% for sediment and more than 85% for all other parameters tested. Also, the cell can significantly reduce the concentration of TSS, SSC, BOD_5 and TP. Overall, the field component of this study demonstrated that in terms of both water quantity and quality, bioretention cells can operate at a high performance level in Chinook conditions.

CHAPTER 6: LABORATORY EXPERIMENT RESULTS AND DISCUSSION

6.1 Long term performance experiments

To test the long term performance of bioretention cells, the equivalent of 20 years of runoff was applied to four columns (i.e., two tall columns and two short columns). The equivalent runoff volume for each column was 10 m^3 (for I/P = 4) which was applied over the course of 31 days in batches. A total of 72 batches of synthetic stormwater runoff were applied, with an average volume of 0.139 m^3 per batch per column. The average duration of each batch was 96 minutes. The amount of sediment applied on each column (for a target TSS concentration of 444 mg/L) was 5 kg or approximately 0.070 kg per batch per column. Figure 31 shows the cumulative volume of runoff (4 x 10 m^3) and sediment (4 x 5 kg) applied to all four columns.

6.1.1 Hydrologic performance

Saturated hydraulic conductivity was measured using a Guelph Permeameter for each column; initial conductivity was measured before the experiments started (0 equivalent years) and after 3.8, 9.2, 15.6 and 20 equivalent years. Two readings of conductivity were taken on each location; with a head of 10 cm and 15 cm. The chart below (Figure 32) shows the averaged results for the tall and short columns along with maximum and minimum results for each time step (red high-low bars) and the associated upper and lower errors (dotted grey lines). Over the testing period, the tall columns' saturated hydraulic conductivity decreased from 2.25 x 10^{-5} to 1.98 x 10^{-6} m/s (or 3.2 to 0.28 in/hr), a reduction by a factor of 11.4 or 91.2% ($p = 0.017$). The short columns decreased from 1.91 x 10^{-5} to 1.24 x 10^{-6} m/s (or 2.7 to 0.18 in/hr) a reduction by a factor of 15.4 or 93.3% ($p = 0.015$). A summary of laboratory results and statistical analyses is included in Appendix C and D, respectively.

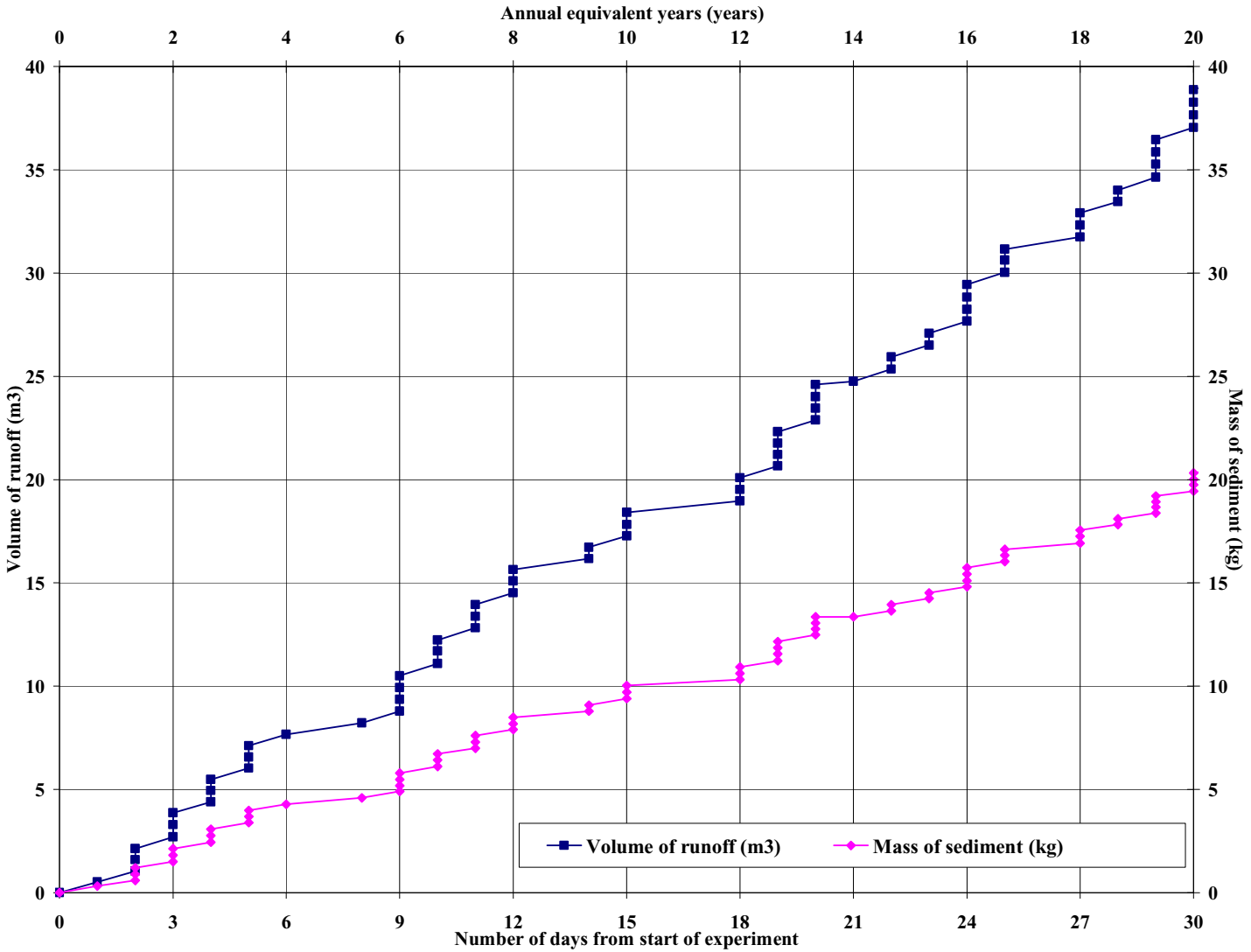

Figure 31: Cumulative volume of runoff and mass of sediment applied to the four columns

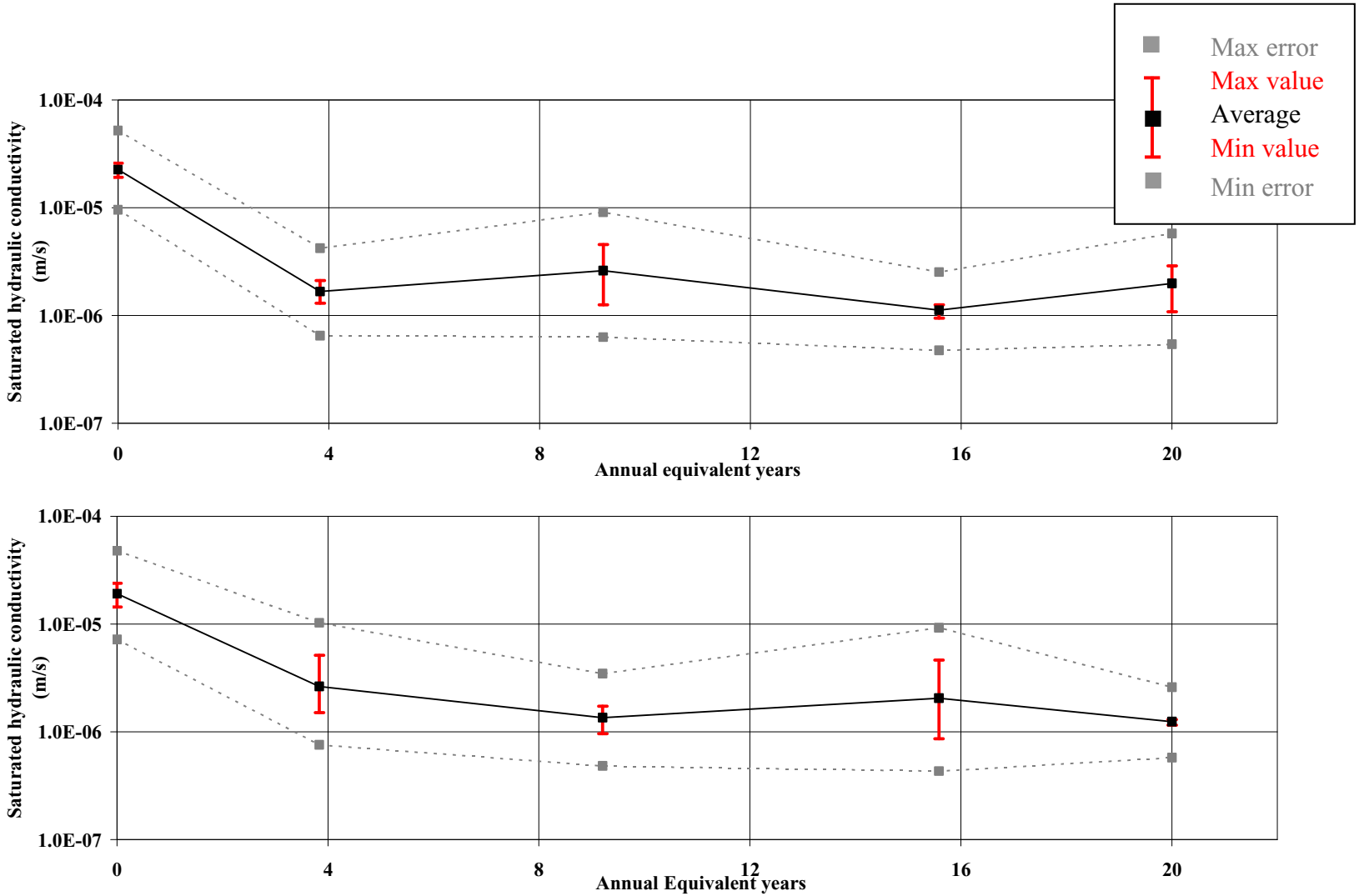

Figure 32: Saturated hydraulic conductivity (on log scale) trends for the tall (top) and short (bottom) columns with the corresponding upper and lower bound values and instrument error (n = 4)

For both sets of columns, the conductivity decreased rapidly over the first 4 equivalent years of runoff application. After this point, the conductivity exhibited a slower rate of decline, but was effectively a constant value after accounting for instrument accuracy. This is similar to results discussed in the literature review; the conductivity initially drops due a combination of additional compaction from the application of runoff and initial clogging. Plant growth and macro-pore generation then keeps the conductivity relatively constant.

The PSD of the growing media was analyzed throughout the experiment duration. Media samples were taken from 2 depths for the short columns (0 – 0.18 m and 0.18 to 0.36m) and 3 depths for the tall columns (0 to 0.20 m, 0.20 – 0.4 m and 0.4 to 0.64 m) at 5 intervals (0, 3.8, 9.2, 15.6 and 20 equivalent years). The analysis concluded that:

1. There was effectively no change to the distribution below 0.20 m for all columns.
2. For the 0 – 0.20 m layer, no changes to the PSD were apparent for particles below 0.1 μm and larger than 200 μm for all columns.
3. The fraction of particles between 50 to 200 μm increased by 50% (45% compared to 30%) between the initial and final analysis with respect to the overall distribution.
4. The fraction of particles between 0.1 and 50 μm were reduced by 50% (24% compared to 48%) between the initial and final analysis with respect to the overall distribution.

Thus, the sediment from the synthetic stormwater runoff (the majority of which is between 50 and 200 μm) was primarily captured in the top 20 cm for all columns. The capture of the sediment is due to surface filtration; as additional depth did not have any impact on particle capture (depth filtration). The capture of these particles on the surface is also responsible for the overall reduction in saturated hydraulic conductivity of the columns.

The hydrological results from the long term performance experiments point toward two major conclusions:

1. A rapid decrease in the saturated hydraulic conductivity occurs over the first 4 years of operation.

2. The decrease in saturated hydraulic conductivity is due to surface clogging (top 20 cm) on the bioretention cell which occurs because of the deposition of sediment from stormwater runoff.

It is important to note that the rate of decrease in conductivity and sediment capture in this experiment is accelerated compared to what might be experienced on a field scale. There was no maintenance conducted on the columns and the plants did not mature at the same rate as the runoff application. As a result, the effects of the root function are not fully accounted for as in the field experiments. Similarly, the effects of micro and macro organisms, and the resulting ecosystem are also not represented here. Thus, this procedure gives a conservative estimate in terms of hydrologic performance.

6.1.2 Water quality performance

Inlet samples for water quality analysis were taken from each batch of synthetic runoff that was applied to all four columns. One outlet sample was taken from each column per batch for analysis as well. For the first 0.83 equivalent years, each batch sample was analyzed individually for both influent and effluent, and for the rest of the experiments, three batches were combined into one volume-weighted composite and analyzed. The concentration reduction was calculated using Equation 18:

Equation 18: Concentration reduction of contaminants

$$CR = \frac{C_i - C_o}{C_i} \times 100\%$$

CR = concentration reduction (%)
C_i = inlet concentration of a single batch sample or composite sample (mg/L)
C_o = outlet concentration of a single batch sample or composite sample (mg/L)

For TSS, the average influent concentration was 420 mg/L for all batches, while the average outlet concentration was 13 mg/L for both the tall and short columns. This was a significant reduction for all columns ($p = 0.000$), with an average reduction rate of 97%. Additionally, there was no difference between the effluent concentrations of TSS between the tall and short columns (Figure 34). The concentration reduction did not vary

with time. Thus, over the long term, bioretention cells consistently had a very high rate of sediment capture and the depth of the columns did not have an effect on this. Comparing the influent and effluent PSD (see Figure 33), there is no significant difference between the distributions of the tall and short columns. Additionally, both set of columns removed 97.7% of particles larger than 50 μm for an average TSS reduction of 97%.

The average influent concentration of BOD_5 was 8.88 mg/L, while the average effluent concentrations of the tall columns was 5.56 mg/L and 5.50 mg/L for the short columns (this was not statistically different at the 95% confidence level). Significant concentration reduction was seen for both sets of columns, 37% for the tall columns ($p = 0.000$) and 35% for the short columns ($p = 0.000$). Reduction rates improved from an average of 16% over the first 2.7 equivalent years to 45.7% for the remainder of the experiment (see Figure 34 and Figure 35).

TP significantly leached from all columns throughout the testing period ($p = 0.000$); average influent concentrations were 0.15 mg/L and effluent concentrations were 0.48 and 0.60 mg/L from the tall and short columns (the difference between the two set of columns was not significant). The effluent concentrations decreased from an average of 0.7 mg/L over the first 6.9 years, to 0.53 mg/L after 13.8 years and to 0.26 mg/L at the end of the testing period (Figure 36). There are a number of possible reasons for the lack of TP concentration reduction. The influent concentration of TP (0.15 mg/L) is a fifth of typical values in Calgary (0.75 mg/L); this results in a lower *CR*. If the mean Calgary TP concentration was used for the *CR* analysis, a reduction of TP would have been seen for the majority of the 20 year equivalent testing period. In addition to this, the organic matter content of the media was high (11%) and according to Bratieres et al. (2008), TP reduction is optimal when the organic content is less than 5%. Since there are no significant differences between the two depths, it cannot be concluded whether or not this had an effect on the potential to reduce TP.

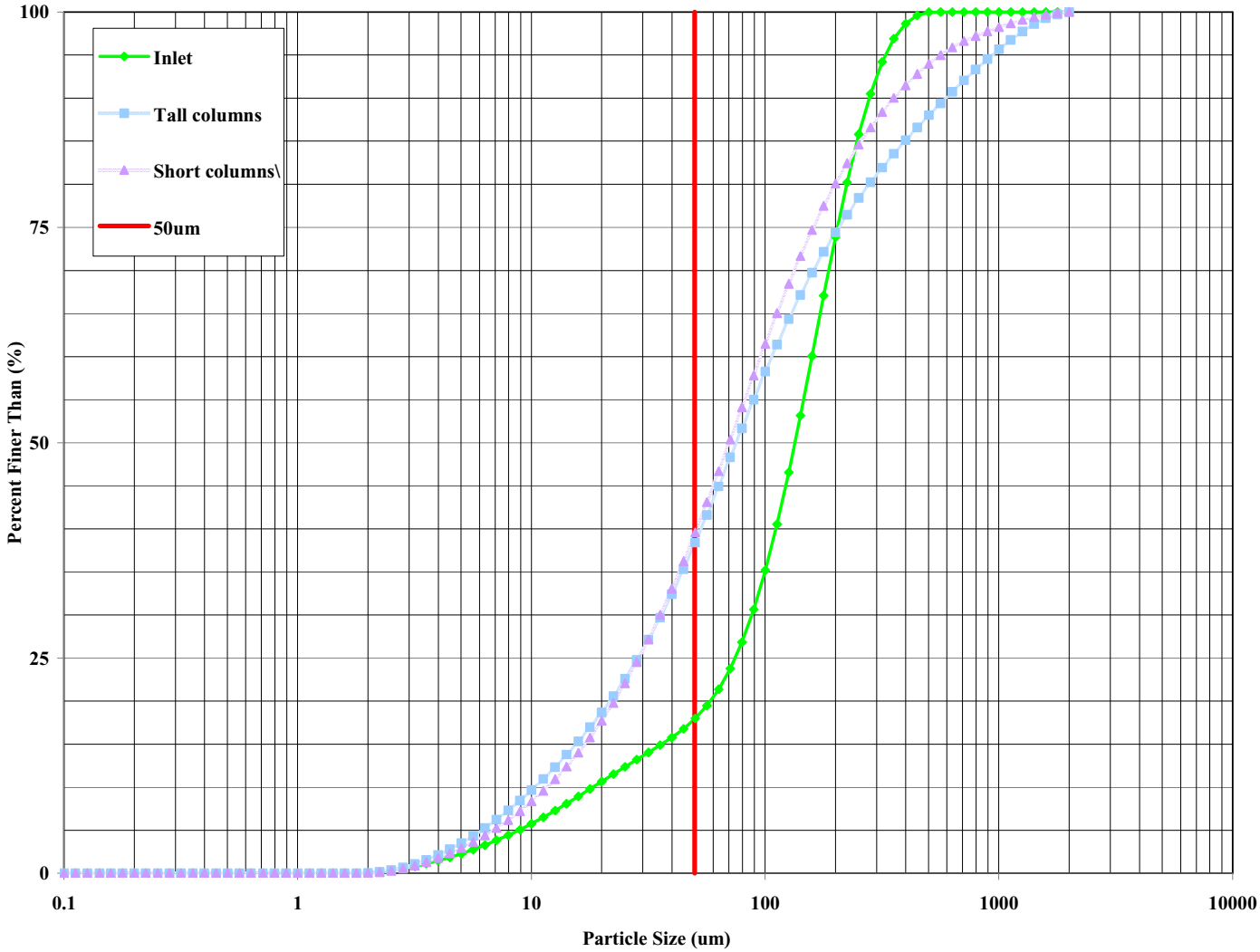

Figure 33: Comparison of inlet and outlet PSD of sediment

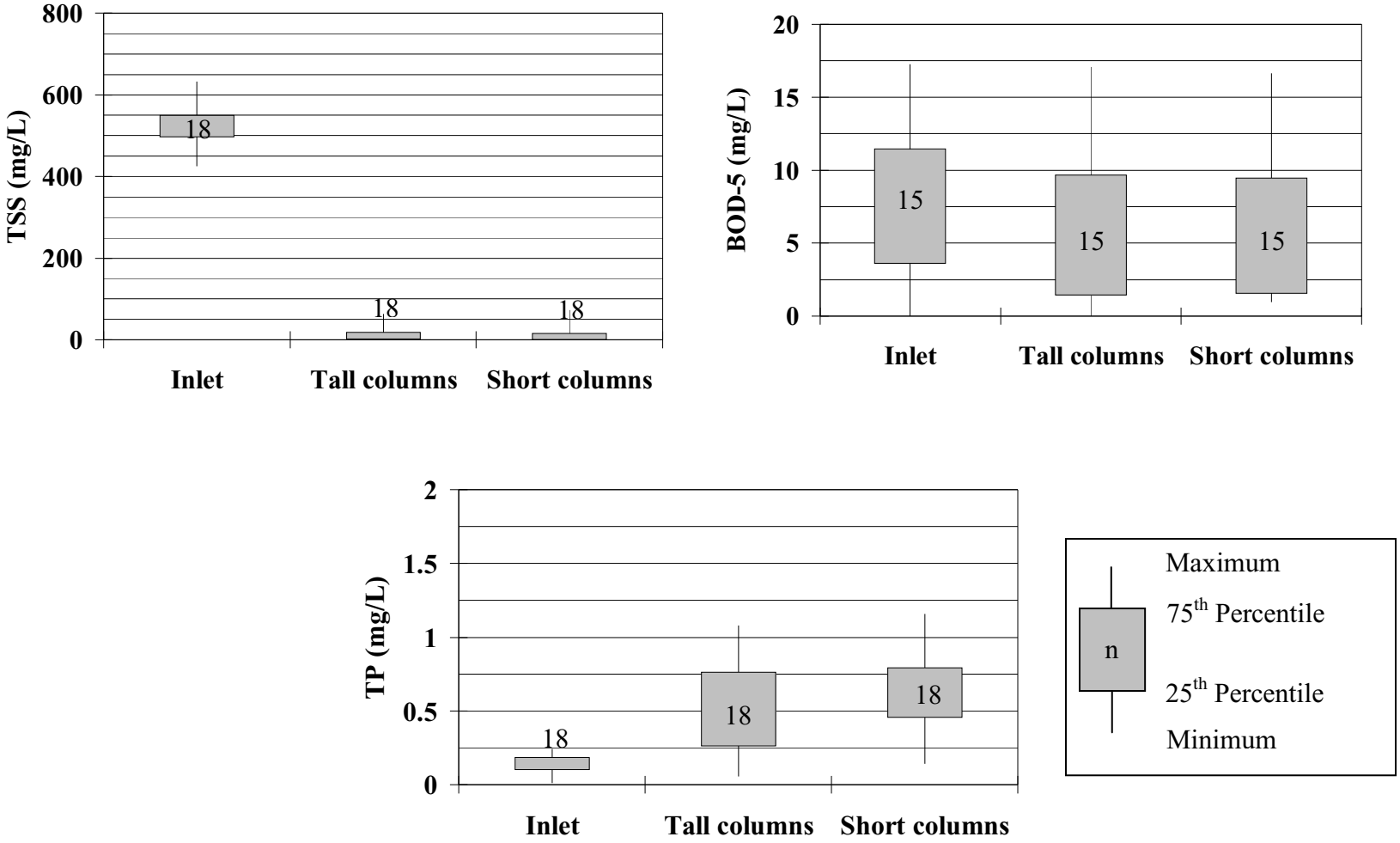

Figure 34: Inlet and outlet concentrations of (clockwise from top left) TSS, BOD_5 and TP from the tall and short columns for the long term experiments

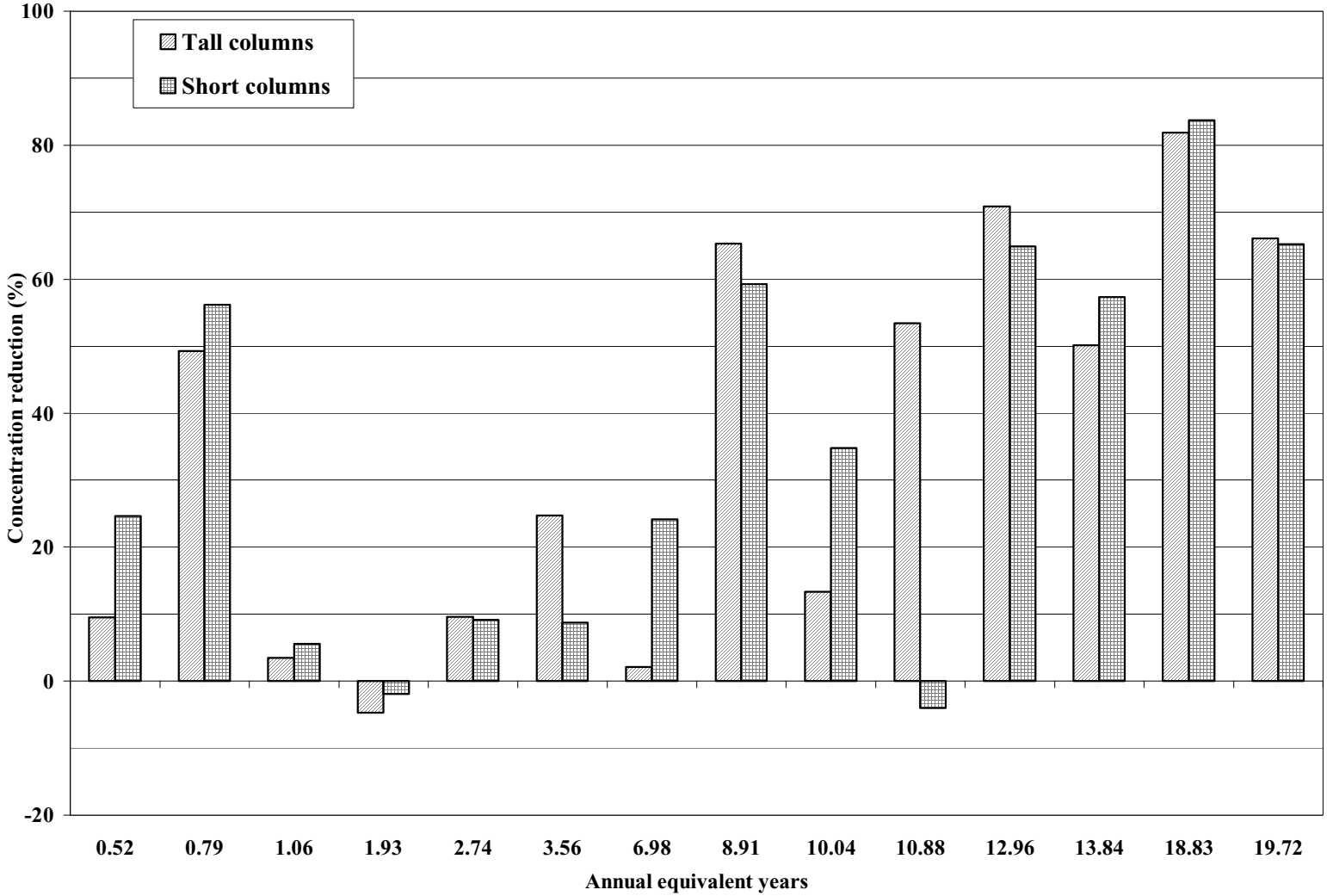

Figure 35: BOD_5 concentration reduction changes over the experiment

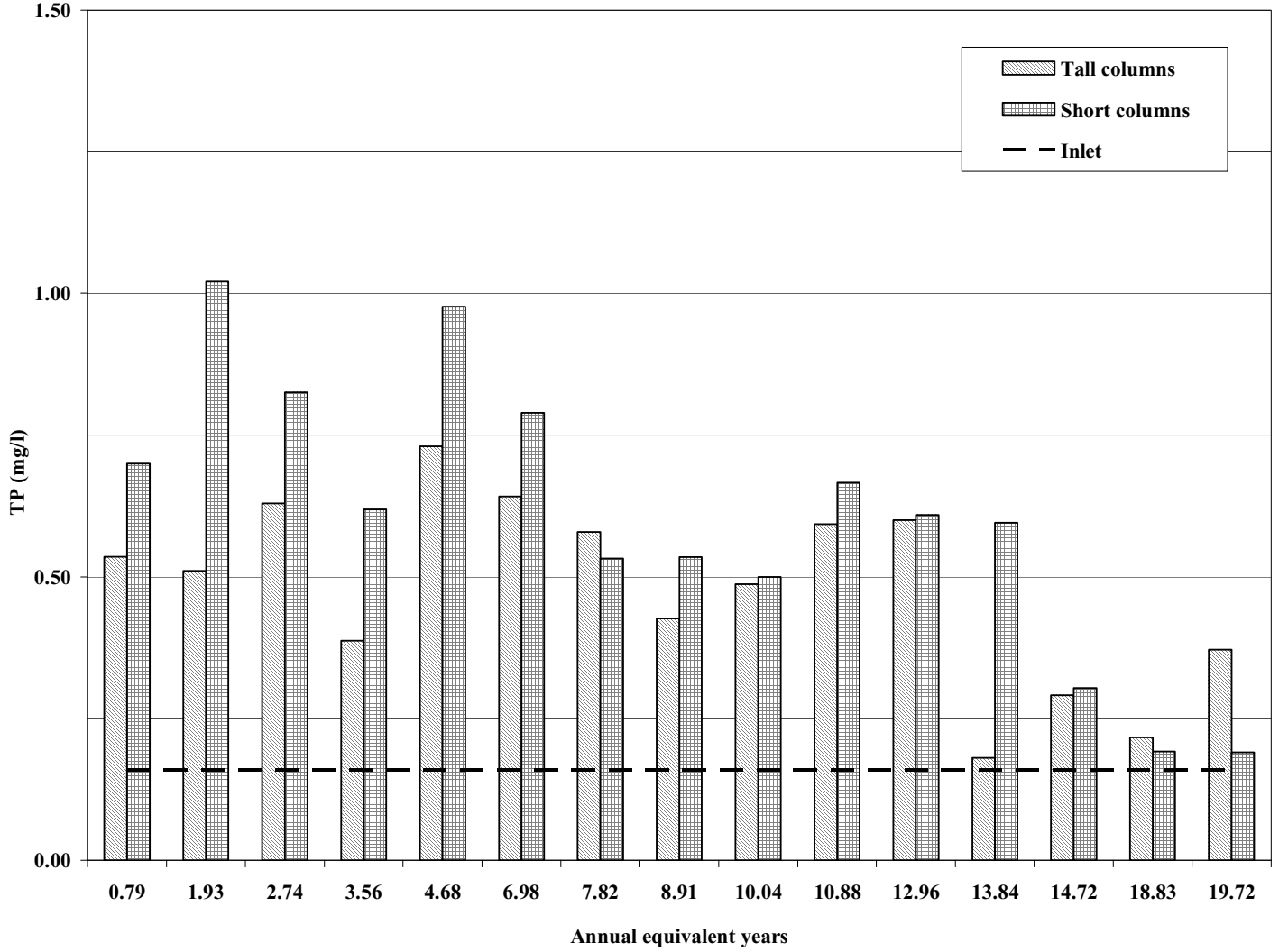

Figure 36: Outlet concentration of TP from both columns with average inlet concentration

The TDP of the soil was measured and was relatively low (<10 mg/kg) for all columns. Though this is not directly transferable to the p-index, it shows that the columns had a high theoretical capacity to capture phosphorus. This shows that the concentration of TP in the effluent was not dependent on the influent phosphorus concentration and likely dependent on the concentration in the growing media. The effluent concentration decreases over time as the TP gets flushed from the system. The most likely reason for the lack of TP reduction was the low influent concentration.

The average inlet concentration of TN was 4.05 mg/L and the outlet concentration of the tall columns was 7.02 mg/L and 5.35 mg/L for the short tanks (Figure 37). There was no significant reduction of TN in either set of columns. TN concentrations were significantly higher in the outlet for the tall columns ($p = 0.001$), while the effluent from the short columns was not significantly different from the influent concentration (at the 95% confidence level). On average the effluent concentrations from the tall columns were 77% higher than the influent concentrations and 33% higher in the short columns. For both sets of columns, the effluent concentration decreased after 3.6 years of runoff application; for the tall columns the concentrations decreased from an average of 14.53 mg/L to 4.20 mg/L, while the concentration of the short columns decreased from 10.70 mg/L to 3.34 mg/L. Figure 38 shows the decrease of effluent concentration with time. It clearly shows effluent concentration decreasing over time, as the TN gets flushed from the system, to a relatively constant value (after 6.9 years) which is equivalent to the influent concentration.

For nitrate, there was a significant ($p = 0.002$) reduction in concentration in the short columns but no difference in the tall columns. On average for the tall columns the effluent concentration was 15% higher than the influent, while the short column's effluent concentration was reduced by 15%. The average influent concentration was 2.4 mg/L (NO_3^- – N) and the outlet concentration was 2.8 mg/L (NO_3^- – N) for the tall columns and 2.0 mg/L (NO_3^- – N) for the short columns (Figure 37). For the tall columns, the effluent concentrations were 100% higher on average till 3.6 years, after which there was a reduction of 28%. For the short columns, the effluent concentrations were 40% higher until 3.6 years and were reduced by 36% thereafter. Similar to TN, Figure 39 shows the decrease in effluent concentration over time, indicating nitrate leaching from

the soil. However, after 10 years, an increase in nitrate concentration is seen, after which it buffers to a relatively constant value. A possible reason for this, as described in Chapter 2.4.2.2, is that biological activity will convert nitrogen compounds into nitrates, which will be subsequently flushed from the system at the onset of the next event.

Average influent concentrations for nitrite were 7 mg/L, while the effluent from the tall columns had a concentration of 10 mg/L and the short columns had 12 mg/L. The difference between the influent and effluent concentrations was not significant, nor was the increase in effluent concentration (at the 95% confidence level). Nitrite reduction was not seen in either column until after 4.7 equivalent years; the reduction rate for the tall and short columns after this point was 31.87%.

For ammonia, the average influent concentration was 0.26 mg/L (NH_3 – N) while the effluent concentration was 0.60 mg/L (NH_3 – N) for the tall columns and 0.67 mg/L (NH_3 – N) for the short columns (Figure 37) (this was not significantly different between the two sets of columns). This was a significant increase in concentration in all columns ($p = 0.000$). Throughout the testing period, no concentration reduction was seen. However, Figure 40 shows the effluent concentration from both sets of columns, which clearly indicates a decrease over time. The concentration decreased over the first 3.6 years from an average of 1.18 mg/L to 0.31 mg/L (NH_3 – N) in the tall columns and from 1.38 mg/L to 0.34 mg/L (NH_3 – N) in the short columns. This indicates that ammonia is flushed from the media to a relatively constant value. Also, similar to TP, the ammonia concentration is relatively low compared to the average City of Calgary runoff concentration: 0.62 mg/L vs. 0.32 mg/L (NH_3). Thus the lack of ammonia capture is due to lower influent concentrations (when compared to actual runoff) and also because of the high rates of flushing that occurred from the columns.

The average influent concentration for chloride was 75.6 mg/L while the effluent concentration was 74.8 mg/L for the tall and 66.1 mg/L for the short columns. The reduction in concentration was not significant for either set of columns. There was no statistical difference between the effluent concentrations between the tall and short columns. The concentration reduction varied widely over the entire testing period and did not improve with time. This shows that the bioretention columns were not effective in controlling chloride pulses in stormwater runoff.

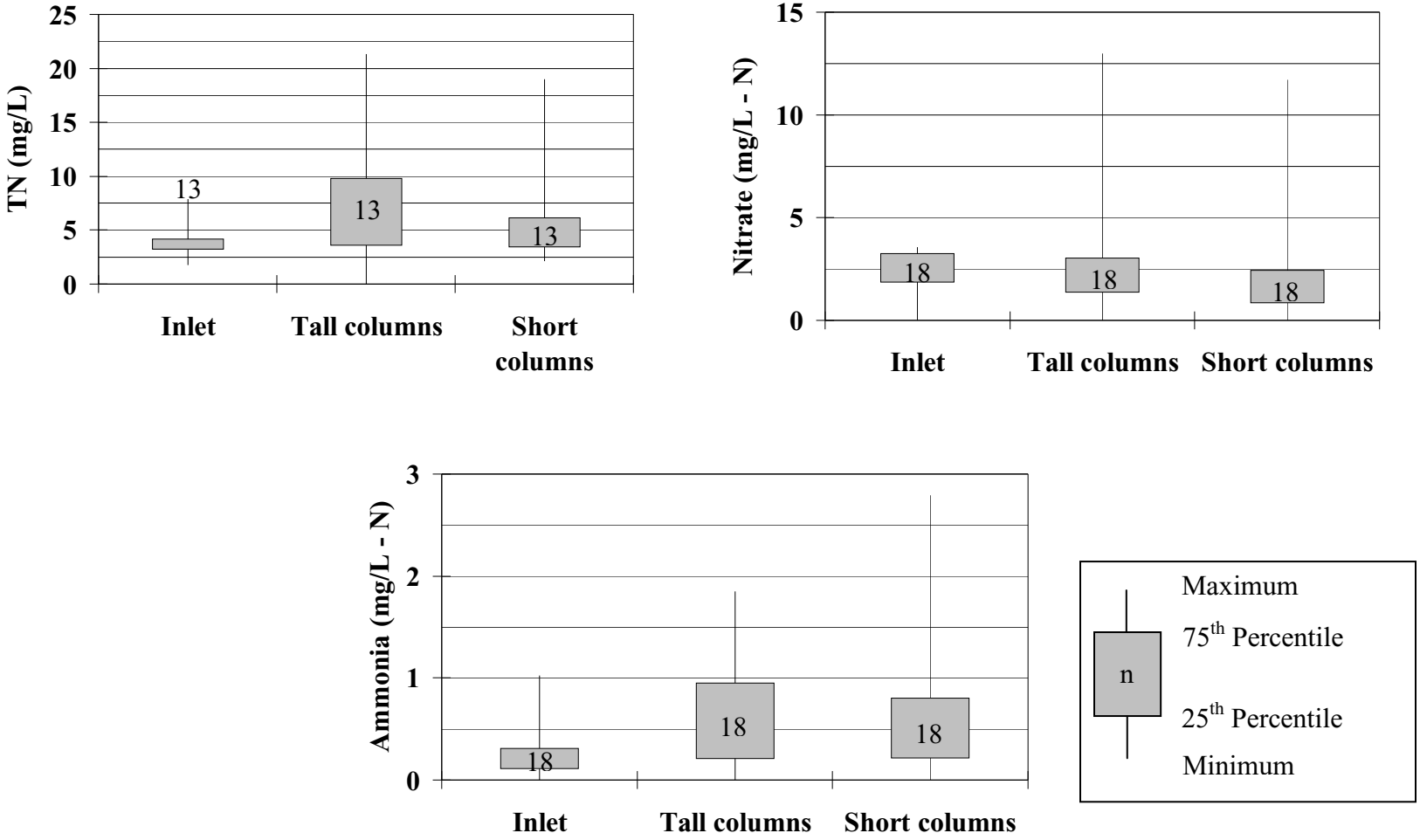

Figure 37: Inlet and outlet concentration of (clockwise from top left) TN, nitrate and ammonia from the tall and short columns for the long term experiments

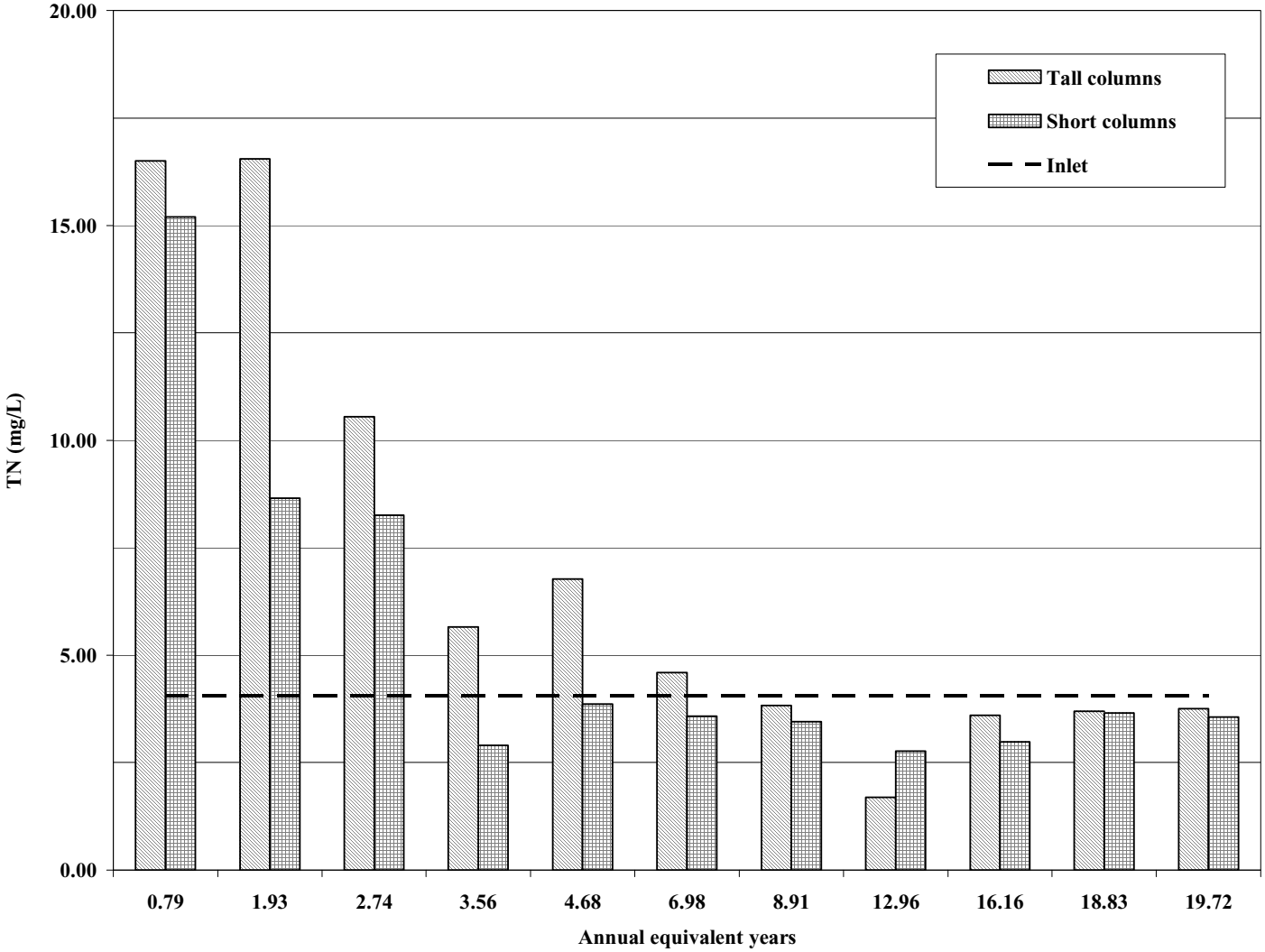

Figure 38: Outlet concentration of TN from both set of columns with average inlet concentration

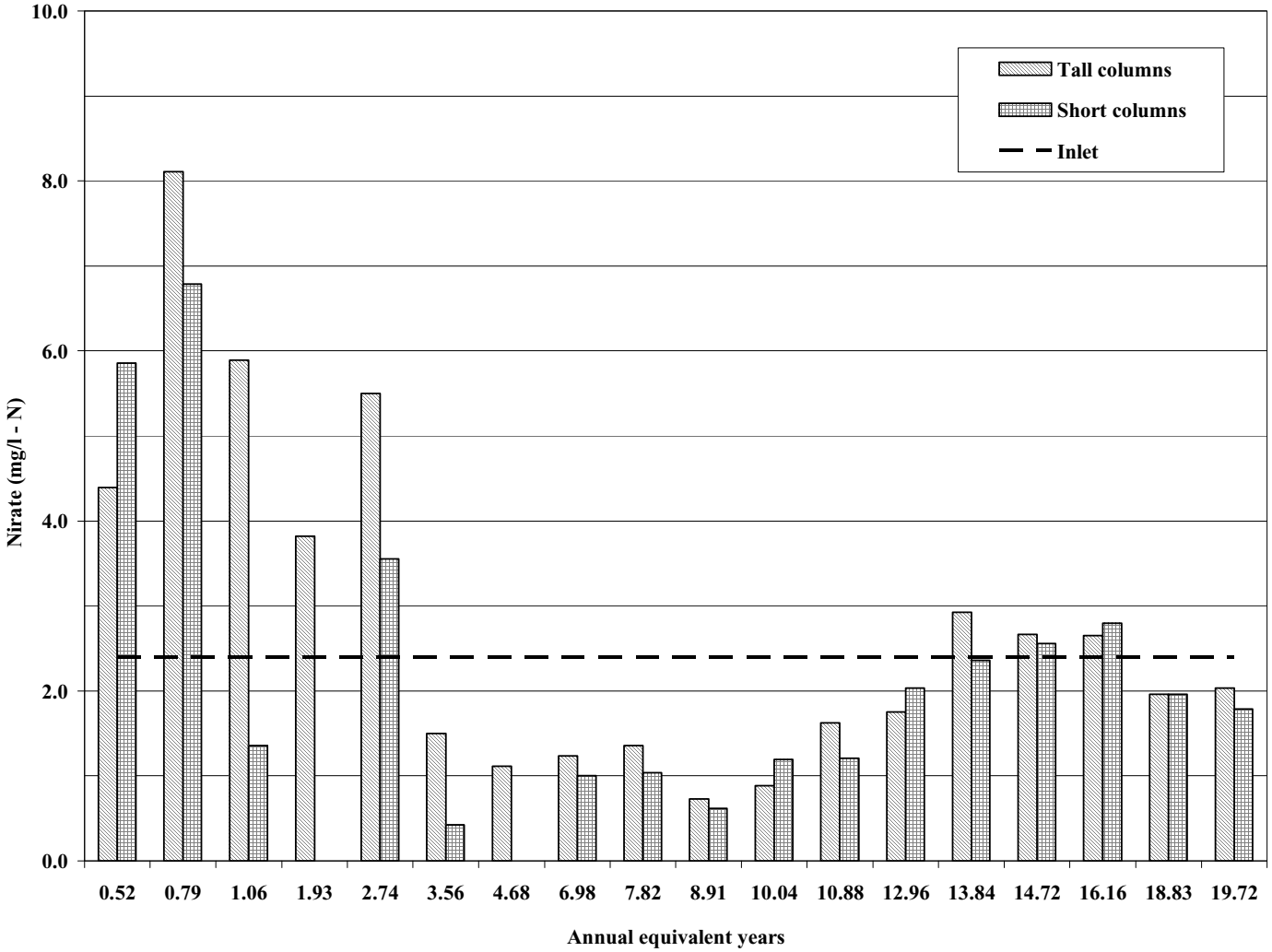

Figure 39: Outlet concentration of nitrate from both set of columns with average inlet concentration

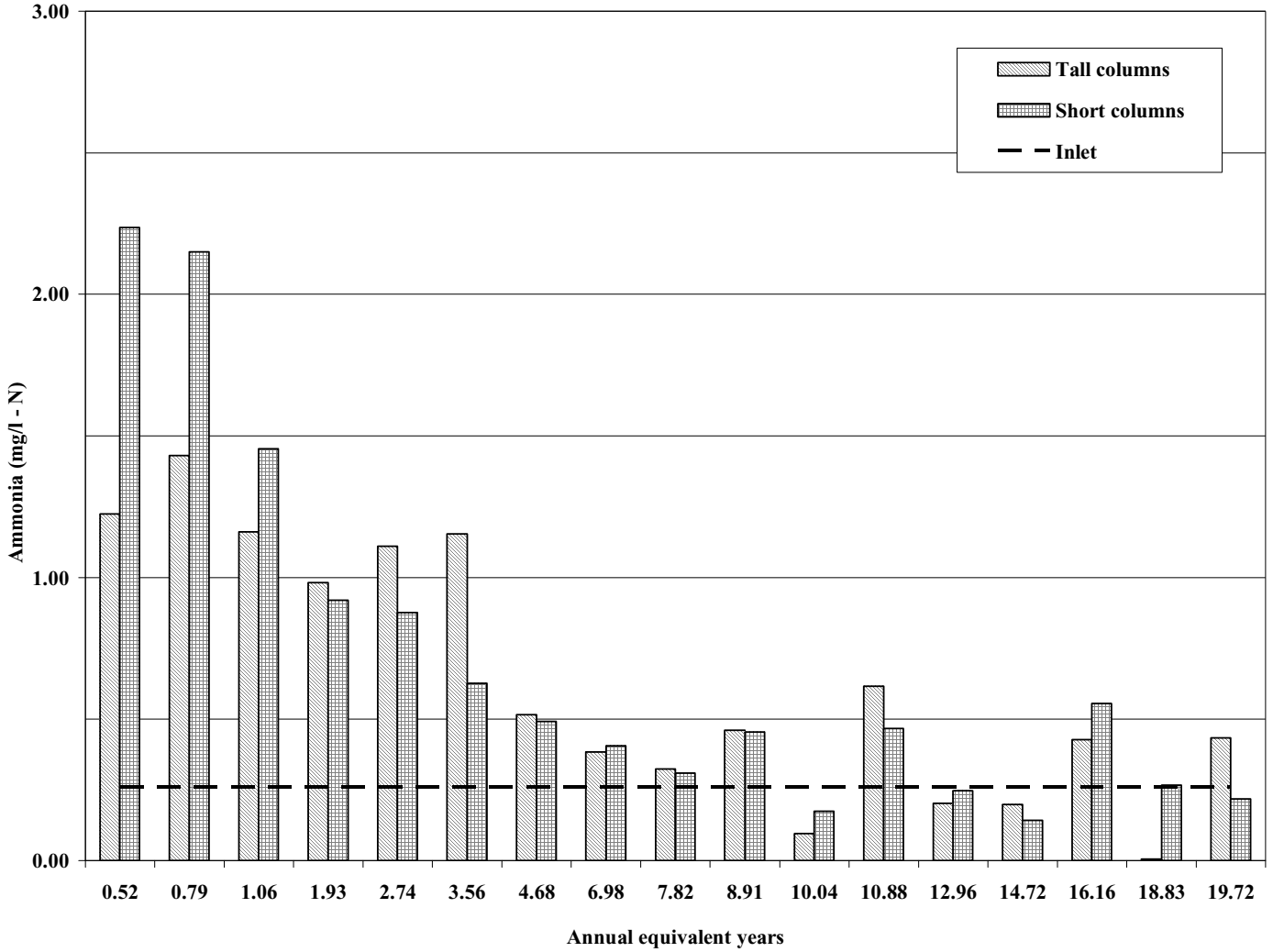

Figure 40: Outlet concentration of ammonia from both set of columns with average inlet concentration

6.2 Single event column experiments

6.2.1 Cold weather columns

Two columns, C1 and C2 were taken to the bioretention field compound for cold weather condition experiments. The columns were set up in September 2009, and tested in February and March, 2010 for cold conditions (experiments number 1, 2 and 3) and then in July 2010 for warm condition experiments (number 4, 5, 6 and 7). In total, 7 events were conducted on each column and these are summarised in Table 14. The target TSS concentration was 444 mg/L for all experiments, except for event 3, where the target concentration was 900 mg/L. The equivalent precipitation depths were calculated assuming that the bioretention cell was 10% of the total hypothetical catchment, with 40% being impervious (i.e. an I/P ratio of 4).

Table 14: Summary of cold weather column experiments

Experiment No.	ID	Runoff Volume	Precipitation depth	Duration	TSS concentration
		(L)	(mm)	(minutes)	(mg/L)
1	C1	75	60	57	427
	C2	75	60	57	427
2	C1	75	60	57	533
	C2	75	60	57	533
3	C1	75	60	52	1067
	C2	75	60	52	1067
4	C1	76	60	44	530
	C2	76	60	44	530
5	C1	81	65	48	496
	C2	81	65	48	496
6	C1	81	65	52	496
	C2	81	65	52	496
7	C1	81	65	55	496
	C2	81	65	55	496

For the hydrologic performance of the columns, the percent of synthetic runoff held in the growing media after the event was calculated and compared between warm and cold conditions. The volume of runoff stored was calculated by taking the difference between initial and final soil moisture and was multiplied by the volume of the growing

media. This was divided by the volume of runoff applied to each cell. Soil moisture values for frozen conditions were ignored for this analysis.

Equation 19: Volume capture by bioretention columns

$$V_C = \frac{(\theta_{AP} - \theta_i)V_M}{V_R} \times 100\%$$

V_C = Volume captured (%)

θ_{AP} = Soil moisture 12 hours after peak soil moisture (m^3/m^3)

θ_i = Initial soil moisture (m^3/m^3)

V_M = Volume of growing media (m^3); 0.5 x 0.5 x 0.36 m = 0.09 m^3

V_R = Volume of runoff applied to each column (m^3)

The average V_C for cold weather conditions was 12% and it was 4% for warm conditions. However, this was not a statistically significant difference (p = 0.061). The soil temperature sensors indicated that for all cold weather condition experiments, the growing media was initially frozen. Thus the initial soil moisture values cannot be compared due to sensor reading error, and this also creates an error for the V_C calculations. Comparing the peak soil moisture for the two climatic conditions, there was a significant difference (p = 0.000). The average peak soil moisture for warm conditions was 0.511 m^3/m^3 compared to 0.297 m^3/m^3 for cold conditions. The final soil moisture was significantly higher in warm conditions (p = 0.013); 0.396 m^3/m^3 in warm conditions versus 0.304 m^3/m^3 for cold conditions. This shows that in warm conditions, the columns are able to store more runoff (higher peak soil moisture) and are able to retain water better than cold conditions (higher final soil moisture). This is due to the frozen soil in cold conditions. As in the field experiments, the frozen layer did not allow the water to travel through the column as in warm conditions. It is suspected that the runoff flowed through preferential flow paths and macro-pores (formed because of the partially frozen soil) and drained from the columns, bypassing the sensors.

Comparing influent and effluent contaminant concentrations of both columns (Figure 41), TSS and BOD_5 were both significantly reduced (p = 0.000 and 0.008 respectively). TN and TP significantly leached (p = 0.000, 0.007). No decrease in TP concentrations in the effluent was seen over time, but the average influent concentration

was low (0.29 mg/L) compared to average Calgary runoff concentration (0.75 mg/L). Comparing warm and cold conditions (Table 15), there was a significant difference in concentration reduction for TN, nitrate and ammonia (p = 0.012, 0.004 and 0.008 respectively). For TN the amount of leaching decreases in warm conditions. This is because of a significant decrease in outlet concentrations in warm conditions (from 30 mg/L to 8 mg/L, p = 0.004), whereas the influent concentration does not change. Similarly, the nitrate concentrations in the effluent are reduced from 17 mg/L to 0.35 mg/l (p = 0.045) between cold and warm conditions, with steady influent concentrations. The decrease in effluent concentration for TN and nitrate are probably due to the flushing of nutrients from the media rather than the effects of lower temperatures, as was seen in the long term experiments (Figure 42). However for ammonia, the increase in leaching from 15% to 201% is due to the fact that the influent concentration is significantly reduced from 1.2 mg/L to 0.6 mg/L (p = 0.039), while the effluent concentration remains constant.

Table 15: Concentration reduction rates (%) in cold weather columns

	TSS	**BOD_5**	**TN**	**Nitrate**	**Ammonia**	**TP**	**Cl^-**
Cold	88	30	**-1061**	**-542**	**-15**	-143	10
Warm	91	32	**-157**	**52**	**-201**	-330	-921

To summarize the water quality performance of columns C1 and C2:

- TSS and BOD_5 are significantly reduced and weather conditions did not have an effect on the reduction.
- TP significantly leached from the columns and weather conditions did not have an effect on this. However, low influent concentrations contributed to the lack of concentration reduction.
- TN significantly leached from the columns; the rate of leaching was significantly higher in cold conditions. This is attributed to the higher effluent concentrations in cold conditions compared to warm conditions. However, this was not due to lower temperatures. Rather it was a function of the age of the columns; the cold condition experiments were conducted prior to the warm condition experiments. Thus, the columns experienced higher rates of nutrient flushing initially and this rate decreased over time to when the warm condition experiments were conducted.

- Nitrate was not significantly different between influent and effluent concentrations overall. However, effluent concentrations were significantly lower in warm conditions, resulting in a net decrease of concentration. This is likely due to the same reason discussed for TN above.
- Ammonia was not significantly different between influent and effluent concentrations overall. However, inlet concentrations were significantly lower in warm conditions, resulting in a significantly higher rate of leaching in warm conditions. Thus, the seemingly higher rate of leaching is due to lower influent concentrations, rather than higher effluent concentrations in warm conditions.

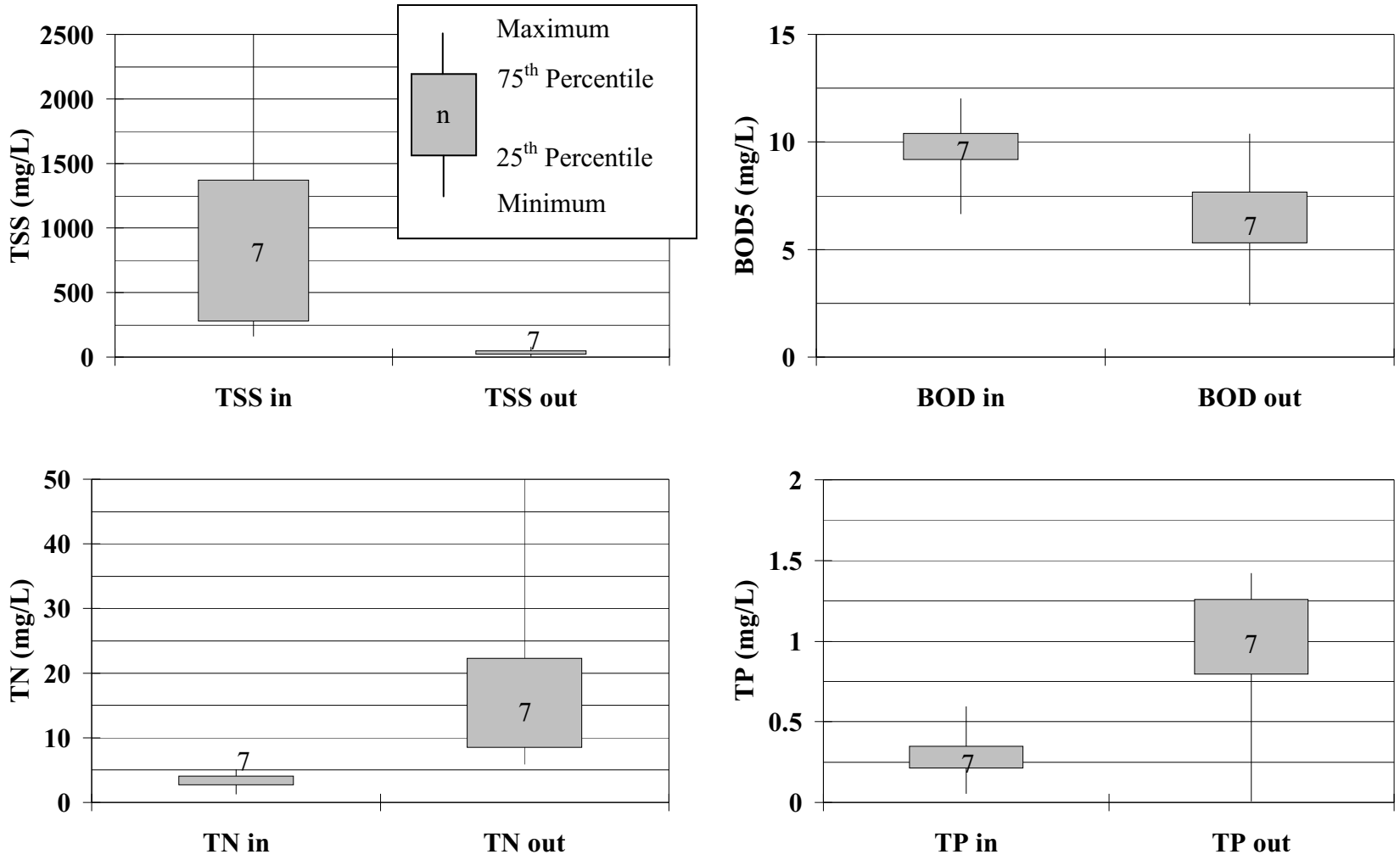

Figure 41: Inlet and outlet concentrations for C1 and C2 for (clockwise from top left) TSS, BOD_5, TP and TN, under both cold and warm weather conditions

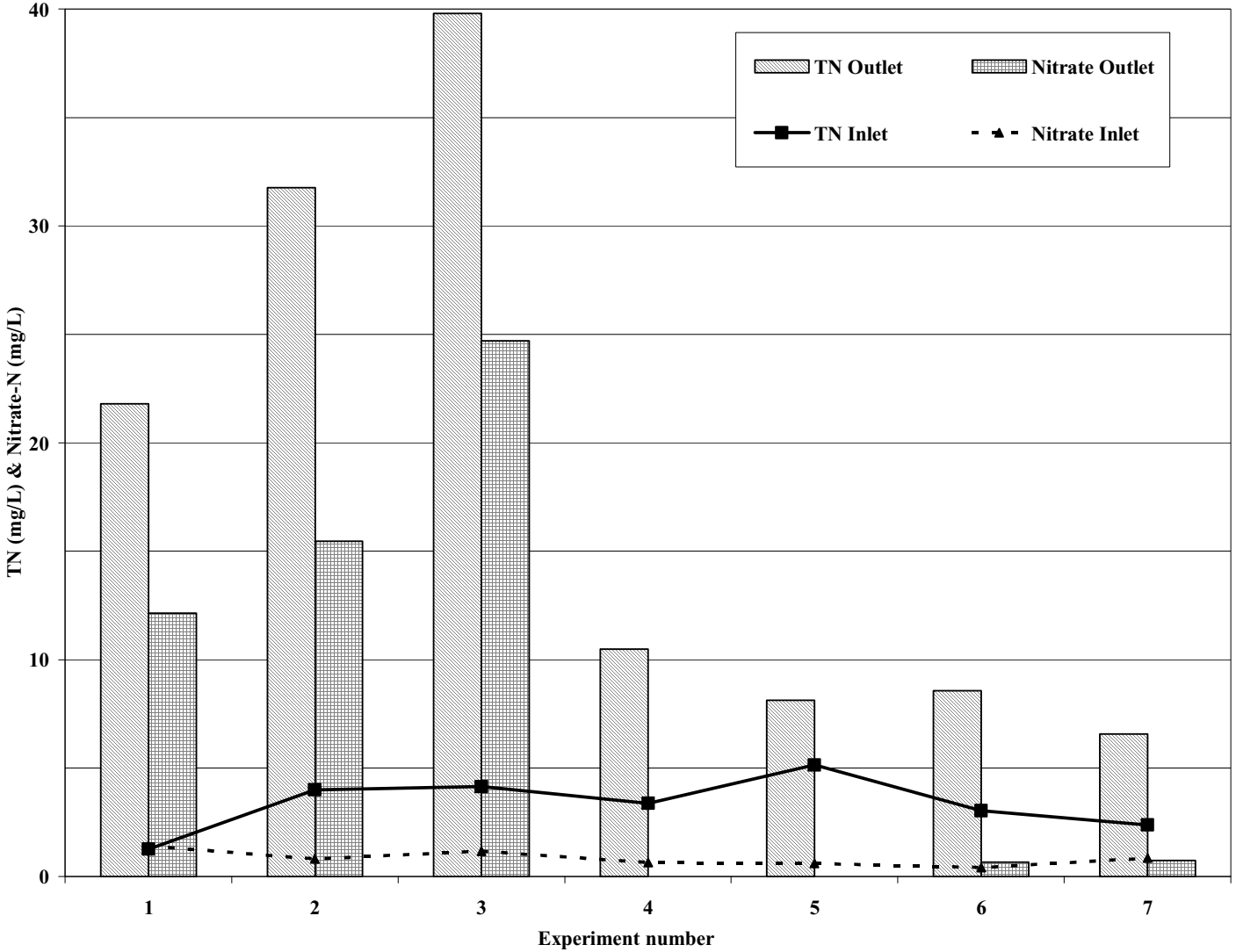

Figure 42: Change of TN and nitrate effluent concentration with time versus inlet concentrations

6.2.2 Temperate weather columns

Two columns, S3 and S4 were tested at the University of Calgary's Hydraulic Laboratory for single event experiments. In total, 9 experiments were conducted during July and August, 2010 and these are summarized in Table 16. The target TSS concentration varied between 471 mg/L (3 experiments), 511 mg/L (3 experiments), 786 mg/L (1 experiment) and 1370 mg/L (1 experiment). The precipitation depths were calculated assuming that the bioretention cell was 10% of the catchment, with an I/P = 4).

Table 16: Summary of temperate weather column experiments

Experiment No.	ID	Runoff Volume	Precipitation depth	Duration	TSS concentration
		(L)	(mm)	(minutes)	(mg/L)
1	S3	76	61	58	471
	S4	76	61	58	471
2	S3	76	61	53	471
	S4	76	61	53	471
3	S3	76	61	55	471
	S4	76	61	55	471
4	S3	76	61	48	511
	S4	76	61	48	511
5	S3	76	61	43	511
	S4	76	61	43	511
6	S3	76	61	50	511
	S4	76	61	50	511
7	S3	76	61	50	786
	S4	76	61	50	786
8	S3	76	61	52	1370
	S4	76	61	52	1370
9	S3	76	61	61	1370
	S4	76	61	61	1370

The average V_C rate (Equation 19) for S3 and S4 was low compared to both the warm and cold weather conditions analysis of C1 and C2. S3 and S4 averaged a V_C of 0.23%. Essentially showing that over the 12 hour period, the bioretention filled and drained very rapidly. The peak soil moisture, on average was 0.426 m^3/m^3, which was significantly higher than the cold weather peak soil moisture for C1 and C2 ($p = 0.000$),

but was also lower than the warm weather peak soil moisture for C1 and C2 ($p = 0.000$). Thus, though the temperate weather columns are exhibiting different results than the cold condition experiments, they do not mimic the warm weather column results either (on C1 and C2). The only variable between these two sets of columns was the level of maturity of the vegetation. This could have had an effect on how much runoff was retained. C1 and C2 were stored outdoors at the field compound and may have had the opportunity to mature at a faster rate during the spring and summer (2010), compared to S3 and S4 that were stored indoors at the University's Hydraulic Laboratory.

Table 17: Average influent and effluent concentrations for S3 and S4

	TSS	Nitrate	Ammonia	TP	Cl^-
	(mg/L)	(mg/L-N)	(mg/L-N)	(mg/L)	(mg/L)
Influent	566	0.8	0.42	1.16	67.88
Effluent	28	3.5	1.27	1.41	84.96

Average influent and effluent concentration of contaminants are listed in Table 17. Both columns significantly ($p = 0.000$) reduced TSS concentrations; the average concentration reduction was 93% (Figure 43). Ammonia significantly leached ($p = 0.000$) from both columns for all experiments and on average the effluent concentrations were three times higher than the influent (Figure 44). All other parameters (BOD_5, TN and nitrite were not measured for these experiments) were not significantly different between the influent and effluent; the paired statistical analysis for these results insured that the increasing inlet concentration would be accounted for.

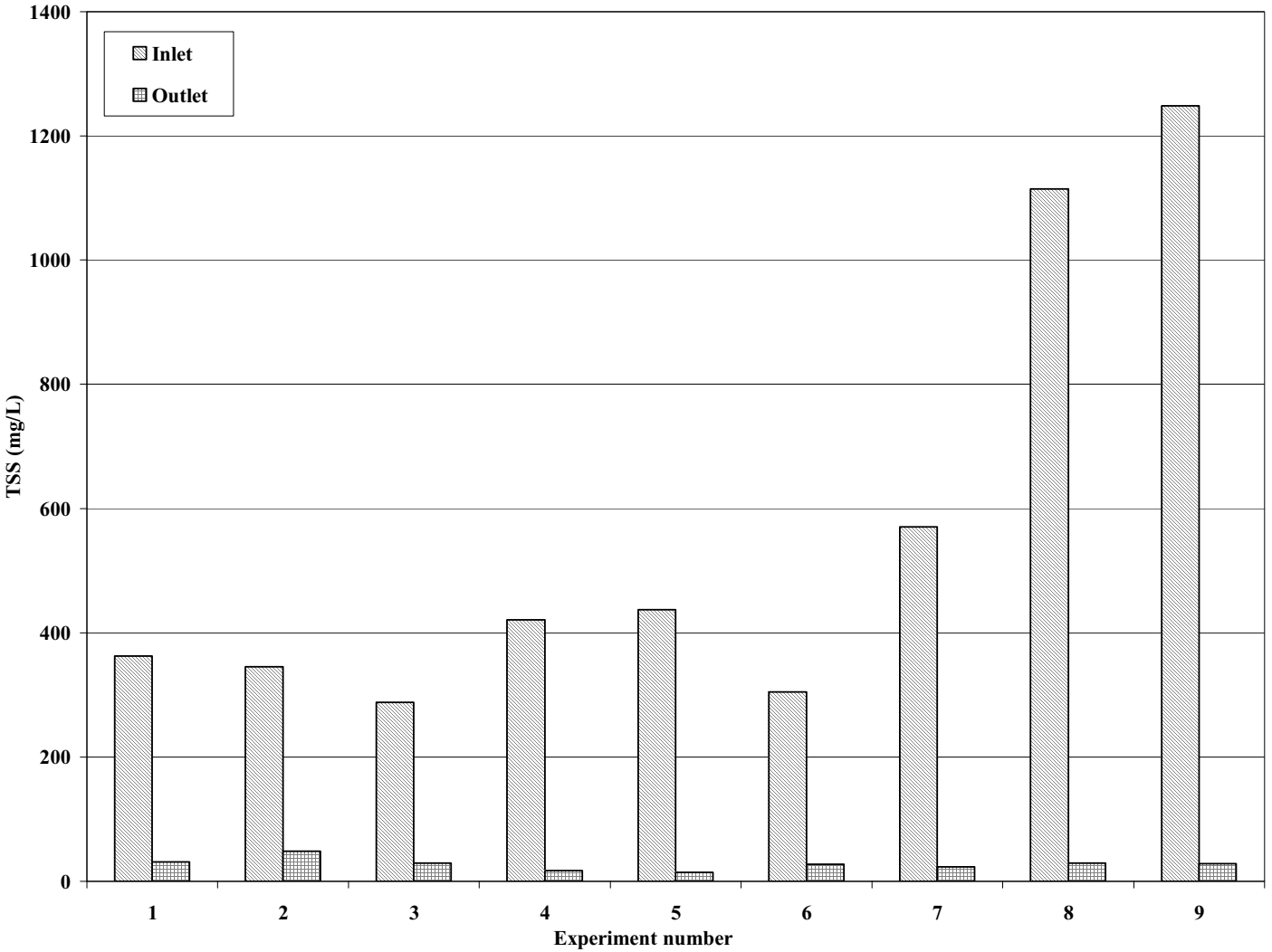

Figure 43: Influent and effluent TSS concentration for S3 and S4

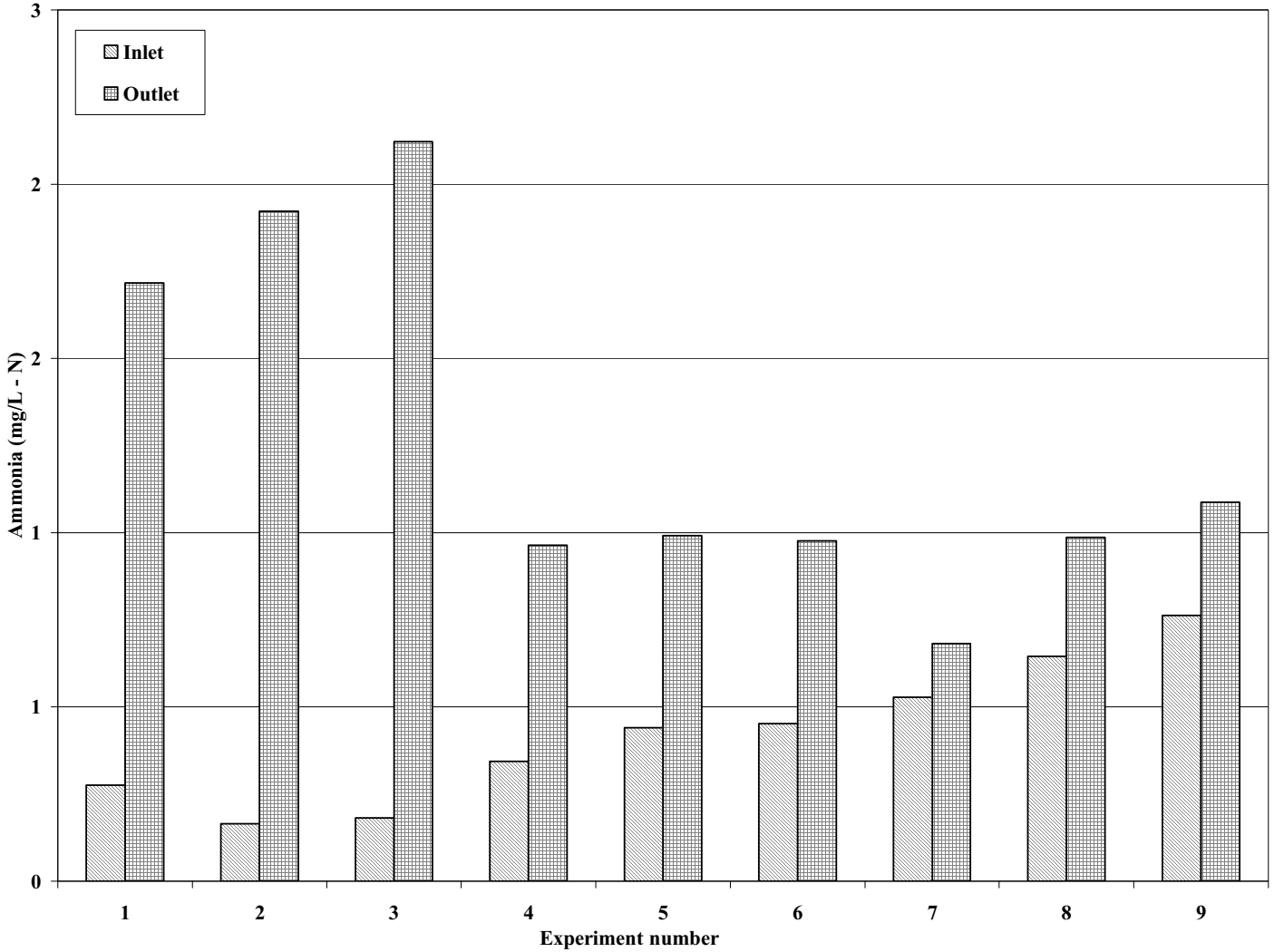

Figure 44: Influent and effluent ammonia concentration for S3 and S4

In the 9 events tested, TSS concentrations were increased by a factor of 4, nitrate by 12, ammonia by 5, TP by 8 and chloride by 20. No correlation was found between increasing influent concentrations and the resulting effluent concentrations (at the 95% confidence level) for any parameter. Figure 43 and Figure 44 show the increasing influent concentration of TSS and ammonia and the resulting effluent concentrations. For ammonia, the effluent concentration significantly decreased after the first 3 events ($p = 0.007$). This decrease in concentration can be attributed to the initial flushing of ammonia from the media, as seen in the long term experiments. This decrease, along with the increase in influent concentration improved the overall concentration reduction rate, from -890% to -90%. It is important to note that influent concentration for ammonia for the first three experiments was 0.21 mg mg/L ($NH_3 – N$) or 0.25 mg/L (NH_3), which is 40% less than average City of Calgary runoff concentration (0.62 mg/L NH_3).

6.3 Water quality performance comparison of all column experiments

TSS was significantly reduced in all column experiments. The depth of the columns, weather conditions or increasing influent concentrations did not have an effect in all three (long term, cold weather and temperate weather) experiments. BOD_5 was significantly reduced in the long term and cold weather column experiments (it was not measured for the temperate weather conditions) and the depth of the media did not impact performance.

Effluent TP concentrations were significantly higher in both tall and short columns in the long term experiments, as well as the cold weather columns experiments (in both climatic conditions). However, there was no statistical difference between influent and effluent concentration in the temperate weather column experiments. The leaching of TP is attributed to the low inlet concentrations (as compared to average City of Calgary runoff concentrations) rather than the generation of TP in the columns. A decrease in TP concentrations over time was noted in the long term experiments.

Significant TN leaching was noted in the tall columns only for the long term experiments, and from both cold weather columns as well. The effluent concentration reduced with time, indicating that TN was being flushed from the columns. Significant

nitrate reduction was seen in the short columns only for the long term experiments, while there was no significant difference for the cold weather or temperate weather columns. However, a significant decrease in effluent concentration was noted with time for the long term and cold weather column experiments. Again, indicating flushing of the nutrient from the system. Nitrite concentrations were not measured for the cold weather and temperate weather columns, and no significant difference between the inlet and outlet was noted for the long term experiments. Ammonia significantly leached from the long term columns as well as the temperate weather columns and there was no significant difference for the cold weather columns. The leaching was due to the fact that influent concentrations were low, rather than ammonia generation in the media. Indications of ammonia flushing from the media were seen from the long term and temperate weather columns; effluent concentrations significantly decreased with time. Inlet and outlet chloride concentrations were not significantly different in all column experiments.

6.4 Contaminant removal mechanisms in bioretention cells

The primary mechanisms for contaminant removal in bioretention cells include sedimentation, filtration, sorptive processes, precipitation and ion exchange. These processes target the major contaminants in urban stormwater runoff such as sediment, BOD, TP and nitrogen compounds.

Sedimentation is a process to separate solids and liquids from a mixture (in this case sediment from the runoff), using gravitational settlement (Reynolds & Richards, 1996). In bioretention cells, sedimentation occurs when the influent runoff ponds on the surface of the cell. As the runoff infiltrates, the larger particles in the sediment settle onto the top layer. A number of factors affect the process of sedimentation, but the underlying phenomena is dependent on the settling velocity of the particles present. The settling velocity is a function of particle size, shape, specific gravity and water temperature. In general, settleable solids are larger than 100 μm but particles as small as 0.5 μm can undergo sedimentation. Larger hydraulic residence time or detention time can allow the smaller fraction to settle as well. In urban stormwater runoff the coarse material (>50 μm) settles quickly as discrete particles, while silts (5 – 50 μm) flocculate and settle collectively. Clays (<5 μm) tend to take a long time to settle, i.e. longer than the ponding

time in a bioretention cell, and thus may not settle in bioretention cells. The amount of organic content in the influent sediment will determine the effectiveness of sedimentation; larger organic content will be lighter (or have a lower specific gravity) than inorganic content and will settle more slowly (Minton, 2005). TSS and SSC are the primary pollutants removed via sedimentation in bioretention cells, while particulate-bound TP and BOD may also be removed via sedimentation.

Filtration is a solid-liquid separating process in which the influent passes through a porous medium which removes suspended solids. Often, as in bioretention cells, filtration processes include numerous layers. Bioretention cells have two layers: mulch and the growing media (Reynolds & Richards, 1996). There are two common types of filtration processes that can occur in bioretention cells: (1) inert media filtration in which a filter media (such as coarse sands) removes suspended solids from the influent, and (2) sorptive media filtration, in which dissolved particles are removed by attachment to the filter media. In bioretention cells, incoming suspended sediment can be captured by cake filtration (filtration at the top layer) and depth filtration (filtration throughout the depth of the media); both of which are examples of inert media filtration (Li & Davis, 2008, Minton, 2005).

Filtration is a function of the size of the incoming solids, the water chemistry (e.g. electrostatic relationship) and the type, size and porosity of the filtering media. In general, physical processes (straining and sedimentation) are good at removing bulk sediment (especially larger particles), whereas the chemical and biological mechanisms deal with removing particular pollutants (e.g. nitrification and denitrification via biological processes and phosphorous) (Minton, 2005). In bioretention cells, influent particles can not significantly penetrate the bioretention media and are captured in the upper 5 to 20 cm of the cell (primarily cake filtration and surface straining). The filtration mechanism allows media stratification in the cell (i.e. larger particles filtered on top and smaller particles penetrate deeper) (Li & Davis, 2008).

Sorption is defined as the combination of adsorption and absorption, processes that frequently occur simultaneously. Adsorption is defined as when a substance is collected onto the surface of an adsorbent (bioretention media in this case), and absorption is the penetration of the collected substance onto the solid (Reynolds &

Richards, 1996). Sorptive processes in filtration are a function of the type of media, its characteristics and the affect of water chemistry on these characteristics (Minton, 2005). Two types of sorptive processes can occur: physical and chemical. Physical sorptive processes are due to van der Waals forces and are a reversible. Chemical sorptive processes include a chemical reaction between the incoming solid (in the influent) and the adsorbed solute (the media); generally these reactions are irreversible (Reynolds & Richards, 1996). In addition to sedimentation, adsorption and microbial metabolism are the primary methods of removing BOD from urban runoff. It is anticipated that the microbial metabolism occurred on the surface of the plant roots (Karathanasis et al., 2003).

Precipitation is a process in which inorganic dissolved species in a solution chemically combine to form settleable or filterable solids, which can be easily removed (through sedimentation or filtration). Natural precipitation occurs in bioretention cells; chemical reactions and mixing (in the aqueous phase) allow for the formation of larger particles with higher settling velocities (Minton, 2005). Ion exchange is a process by which dissolved pollutants in the influent runoff chemically react with solid phase particles (in the media). Ions from the liquid phase are preferentially sorbed by the solid media and ions from the media replace the ions in the liquid phase. Traditionally, sand has been used as the net negative solid media that can sorb cations (such as Mg^{+2} and N^{+}) from the influent runoff. In bioretention cells, ion exchange can also remove ammonium (replaced with K^{+}, H^{+} or Na^{+}) if proper media conditions are present (Davis, 2003, Reynolds & Richards, 1996).

Phosphorous is primarily removed from stormwater runoff by sorption and precipitation in the soil media. The removal of phosphorous through these processes is dependent on the pH of the soil with the least amount of removal occurring when the pH is neutral. Although it is primarily an inorganic process, organic matter can assist in phosphorous removal. Sorption and precipitation of phosphorous can occur under both aerobic and anaerobic conditions, but anaerobic conditions can cause reduced removal rates. In saturated and acidic conditions, inorganic phosphates sorb with iron, aluminium and manganese oxides and is then precipitated in the form of metal-phosphate-complex.

The governing equations for sorption and natural precipitation are shown below in Equation 20; the ability of these reactions to proceed is dependent on the amount of iron, aluminium and calcium present in the media. The reactions occur on the surface of the sand in the filter media, which acts as the nuclei (Minton, 2005).

Equation 20: Typical TP removal mechanism equations

$$Fe^{3+} + H_nPO_4^{3-n} \leftrightarrow FePO_4 + nH^{+;}$$

$$Al^{3+} + H_nPO_4^{3-n} \leftrightarrow AlPO_4 + nH^{+}$$

$$10Ca^{2+} + 6PO_4^{3-} + 2OH^{-} \leftrightarrow Ca_{10}(PO_4)*6(OH)_2$$

Biological processes refer to the action of bacteria and plants in bioretention cells. The primary role of biological processes is removing nitrogen and nitrogen compounds and degrading organic compounds in the influent runoff (Minton, 2005). The mechanism for removing nitrogen from urban runoff in bioretention cells follows two major biological processes: biochemical action under aerobic and anaerobic conditions. Under aerobic conditions, biochemical action converts carbonaceous and organic nitrogen matter to ammonia, which eventually nitrifies to nitrite then nitrate (nitrification), as shown in Equation 21. For nitrification, aerobic autotrophic bacteria are used for the conversion from ammonia to nitrite (*Nitrosomonas*) and from nitrite to nitrate (*Nitrobacter*).

Equation 21: Governing equations for nitrification

$$2NH_3 + 3O_2 + \textit{Nitrosomonas} \rightarrow 2NO_2^{-} + 2H_2O + 2H^{+}$$

$$2NO_2^{-} + O_2 + \textit{Nitrobacter} \rightarrow 2NO_3^{-}$$

Biochemical action (under anaerobic conditions) converts nitrate to nitrogen gas (denitrification). A number of facultative heterotrophic bacteria are used to convert nitrate to nitrogen gas including *Pseudomonas*, *Micococcus*, and *Bacillus*. The addition of a supplemental carbon source is required, as well as an artificially induced anaerobic condition for denitrification (Minton, 2005, Reynolds & Richards, 1996).

Equation 22: Governing equation for denitrification

$$2NO_3^{-} + 10e^{-} + 12H^{+} \rightarrow N_2 + 6H_2O$$

CHAPTER 7: CONCLUSIONS AND RECOMMENDATIONS

This research investigated the ability of bioretention cells to address urban stormwater runoff concerns in cold climates. The focus of the research was to study the hydrologic and water quality performance of bioretention cells and the affects of cold weather on the performance in both the short and long term.

7.1 Hydrologic performance

The field component of this study showed that the bioretention cell studied can successfully capture the majority of runoff that it receives, when sized to 10% of the catchment and with loamy surrounding soils. The cell captured a 100% of the runoff resulting from events smaller than 32 mm and captured 91.5% of runoff from all events, including events with long return periods (1 in 25, 50 and 100 year events). The majority of the applied runoff (60%) left the cell via percolation into the sub-soils. The bioretention cell was able to reduce the peak and CoM flow rate of the inlet hydrograph by 95.3% and 97.5%, respectively. The time to peak and centre of mass were delayed by a factor of 5.22 and 3.98, respectively.

Cold weather conditions reduced the ability to capture the total volume of runoff for large events only; on average, the reduction in cold weather conditions was 80% compared to 91% in warm weather conditions. There was no significant difference in peak and CoM flow rate reduction or in the time to peak and time to CoM in cold weather conditions. A significant reduction of the volume of water retained in the bioretention cell was noted in cold weather conditions. This was due to the effects of a frozen layer on the surface of the cell, which channelled a higher percentage of runoff to the outlet of the cell. This was noted in both the field and laboratory experiments.

This research showed that bioretention cells are capable of performing at high efficiencies in both warm and cold conditions in terms of hydrologic performance. Although some differences in cold weather performance were noted, bioretention cells are still capable of addressing urban stormwater runoff concerns in cold climates.

7.2 Water quality performance

The bioretention cell tested in the field demonstrated a very high mass capture rate for all contaminants tested, which was primarily a function of the high runoff volume capture rate. On average, the cell captured more than 99% of sediment (both TSS and SSC), 91% of BOD_5, more than 89% for all nitrogen components tested (TN, nitrate, nitrite and ammonia), 91% of TP and 83% of chloride. No significant difference was noted in mass capture rates between warm and cold weather conditions. In addition to this, the bioretention cell was able to capture more than 96% of particles that are larger than 50 μm in the influent.

Concentration reduction was more variable in the bioretention cell and columns. The field experiments significantly reduced the concentration of TSS, SSC, BOD_5 and TP. The single event laboratory column experiments showed a significant reduction in TSS and BOD_5. However, a significant increase in TP, TN and ammonia was noted. This was due to a combination of two factors: (1) the influent concentration of these contaminants was low compared to average Calgary runoff concentrations and (2) these contaminants initially leached at high rates from the growing media before reducing to levels seen in the field experiments. This shows that for nutrient removal, bioretention cells require time to mature before any concentration reduction is seen. Also, the concentration reduction is dependent on the influent concentration. This was mirrored in the long term performance experiments.

Comparing the performance in cold weather conditions, there was a significant difference in effluent concentrations for both TN (increase) and ammonia (decrease) in the field experiments. However these differences were not significant when compared to inlet concentrations. The cold weather column experiments indicated a difference in performance in cold and warm conditions, but these differences were not due to temperature differences, rather a function of the media chemistry. Chloride concentrations were not significantly reduced in the field or laboratory experiments and no difference was noted between warm and cold weather conditions.

To summarize, bioretention cells can perform at a high level in both warm and cold weather conditions with respect to water quality improvement. However, nutrient

reduction is highly variable and dependent on media selection and the cells do not provide any improvement to chloride concentrations.

7.3 Long term performance

The long term performance column experiments showed that saturated hydraulic conductivity of the columns reduced significantly over the 20 year testing period. The conductivity decreased by a factor of 11.4 for the tall columns and by a factor of 15.4 for the short columns. For both sets of columns, the major reduction in conductivity was seen after 4 years of runoff application, after which it remained relatively constant. A PSD analysis of the growing media indicated that the majority of the stormwater runoff sediment accumulated in the top 20 cm. These results can be used to determine appropriate maintenance procedures for bioretention cells. The conductivity data shows that the conductivity needs to be renewed after four years, particularly for the top 20 cm layer.

TSS and BOD_5 were significantly reduced by long term experiment columns. TSS reduction was high throughout the testing period, while BOD_5 concentration reduction improved from 16% over the first 2.7 years to 45% after, on average. TP significantly leached throughout the 20 year period; this was due to the low inlet concentrations of TP. Also, a reduction in effluent TP concentration was noted, indicating that TP was flushed from the columns, eventually reaching a steady value. No significant difference between the tall and short columns was noted.

The columns also demonstrated that TN, nitrate and ammonia get flushed from the columns before a constant value is established. Any concentration reduction is then dependent on the magnitude of the influent concentration. For these three parameters this reduction occurred after 3.6 years of runoff application. Effluent chloride concentration was not significantly different from the influent concentration.

Water quality performance results from both the single event and long term experiments show that bioretention cell's capability to reduce effluent concentrations are highly dependent on media properties rather than influent runoff characteristics. This means that if a bioretention cell is designed to target nutrient reduction, the media

selection, in particular, the initial media chemistry is the key parameter for water quality performance.

7.4 Recommendations for future research

One of the major limitations of this project was the inability to mimic snowmelt events and the resulting hydrological performance of a bioretention cell. In addition, the methodology used to calculate the intensities of the synthetic storm events did not account for the time of concentration. Both these issues make it difficult to mimic actual storm events. Thus, a system to measure both these issues should be developed for future research using a synthetic stormwater runoff distribution system.

The bioretention cell used for the field experiments did not have an impermeable liner separating the cell from the sub-soils, making it difficult to conduct a mass balance on the runoff applied. This hindered the ability to quantify the role of the vegetation in up-taking the runoff. Future field studies should have an impermeable liner so that a more sensitive mass balance can be conducted. Also, the fate of the water percolating into the subsoil needs to be identified.

Future laboratory experiments should be conducted with a variety of media types, particularly the nutrient concentration. This would allow for a better understanding of nutrient reduction that occurs in bioretention cells. Additionally, the potential use of additives to the growing media to encourage nutrient removal needs to be studied. A new method of reporting nutrient removal efficiencies, particularly for concentration changes, needs to be developed that will not be affected or skewed by low influent concentrations.

Maintenance procedures need to be identified to target the clogging seen in the long term experiments. The suitability of different maintenance procedures also need to be explored. Lastly, the changes in performance levels due to different I/P ratios need to be analyzed.

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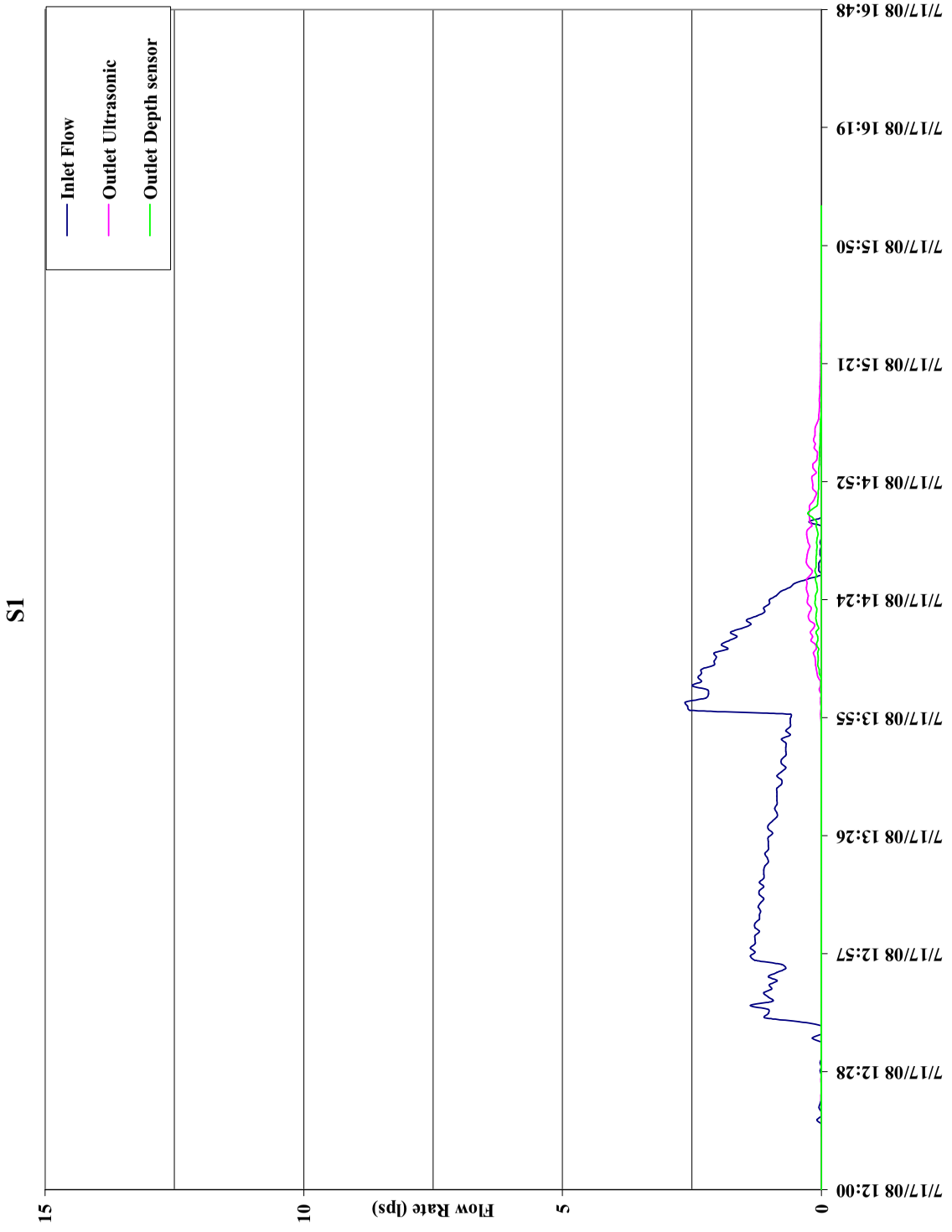
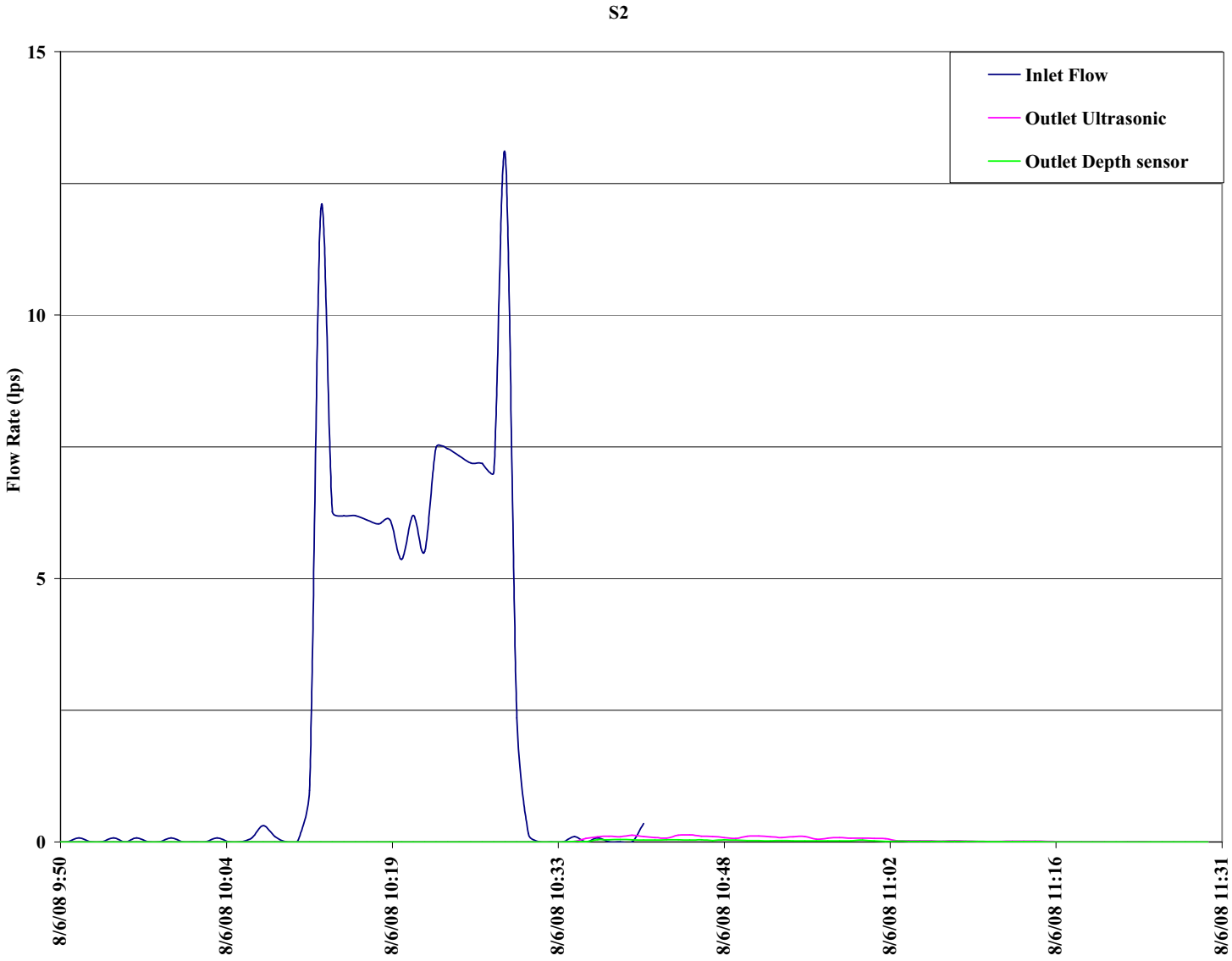
APPENDIX A: Field experiment results

Table 18: Precipitation depth, duration and intensities calculated using the Rational method

ID	Event	Volume of runoff	Precipitation depth	Duration	Intensity
		(L)	(mm)	(minutes)	(mm/hr)
S1	7/17/2008	8004	50.03	116	54.67
S2	8/6/2008	7520	47.00	21	271.71
S3	8/15/2008	7736	48.35	36	240.08
S4	8/27/2008	7943	49.64	31	183.90
F1	10/7/2008	8230	51.44	34	245.69
F2	10/24/2008	8120	50.75	32	220.60
F3	11/4/2008	4739	29.62	28	129.56
W1	2/3/2009	3919	24.49	19	134.00
Sp1	5/20/2009	3866	24.16	21	146.35
Sp2	6/9/2009	8601	53.76	27	236.85
Sp3	6/16/2009	3877	24.23	14	201.40
S5	7/8/2009	8395	52.47	34	131.31
S6	7/22/2009	7842	49.01	36	155.19
S7	8/12/2009	4848	30.30	17	136.13
S8	8/26/2009	4857	30.36	16	126.15
S9	8/27/2009	3717	23.23	21	151.71
S10	9/2/2009	17995	112.47	88	172.81
F4	12/2/2009	8840	55.25	61	69.75
W2	1/12/2010	8398	52.49	62	167.33
W3	1/14/2010	9014	56.34	68	113.83
W4	2/19/2010	8951	55.94	69	202.02
W5	3/3/2010	8581	53.63	64	107.92
S11	7/8/2010	6922	43.26	67	99.77
S12	7/13/2010	8868	55.43	67	105.73

Inlet and outlet hydrographs

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Outlet Ultrasonic
Outlet Depth sensor
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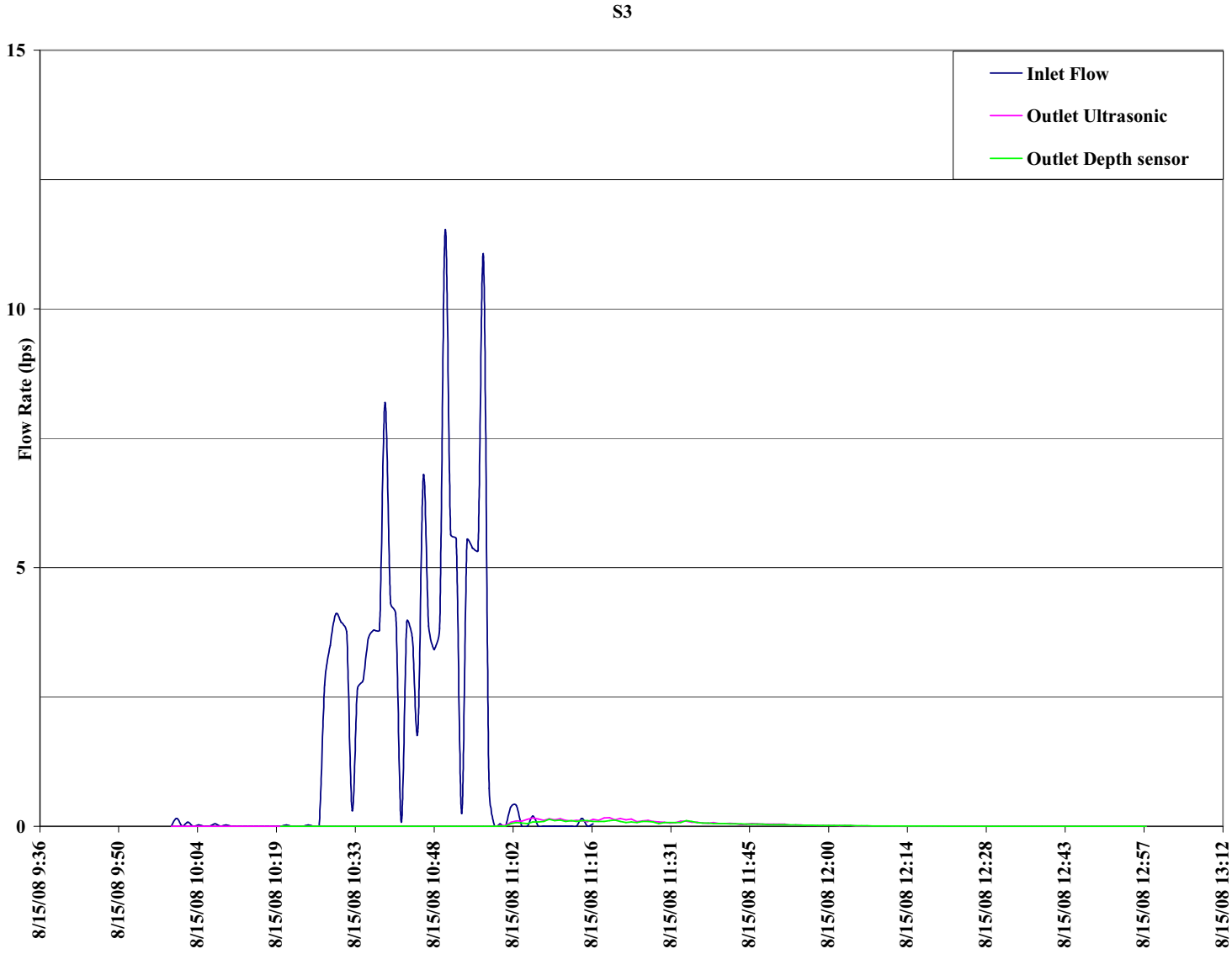
8/6/08 10:48
8/6/08 11:02
8/6/08 11:16
8/6/08 11:31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Outlet Depth sensor
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8/15/08 10:33
8/15/08 10:48
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8/15/08 11:45
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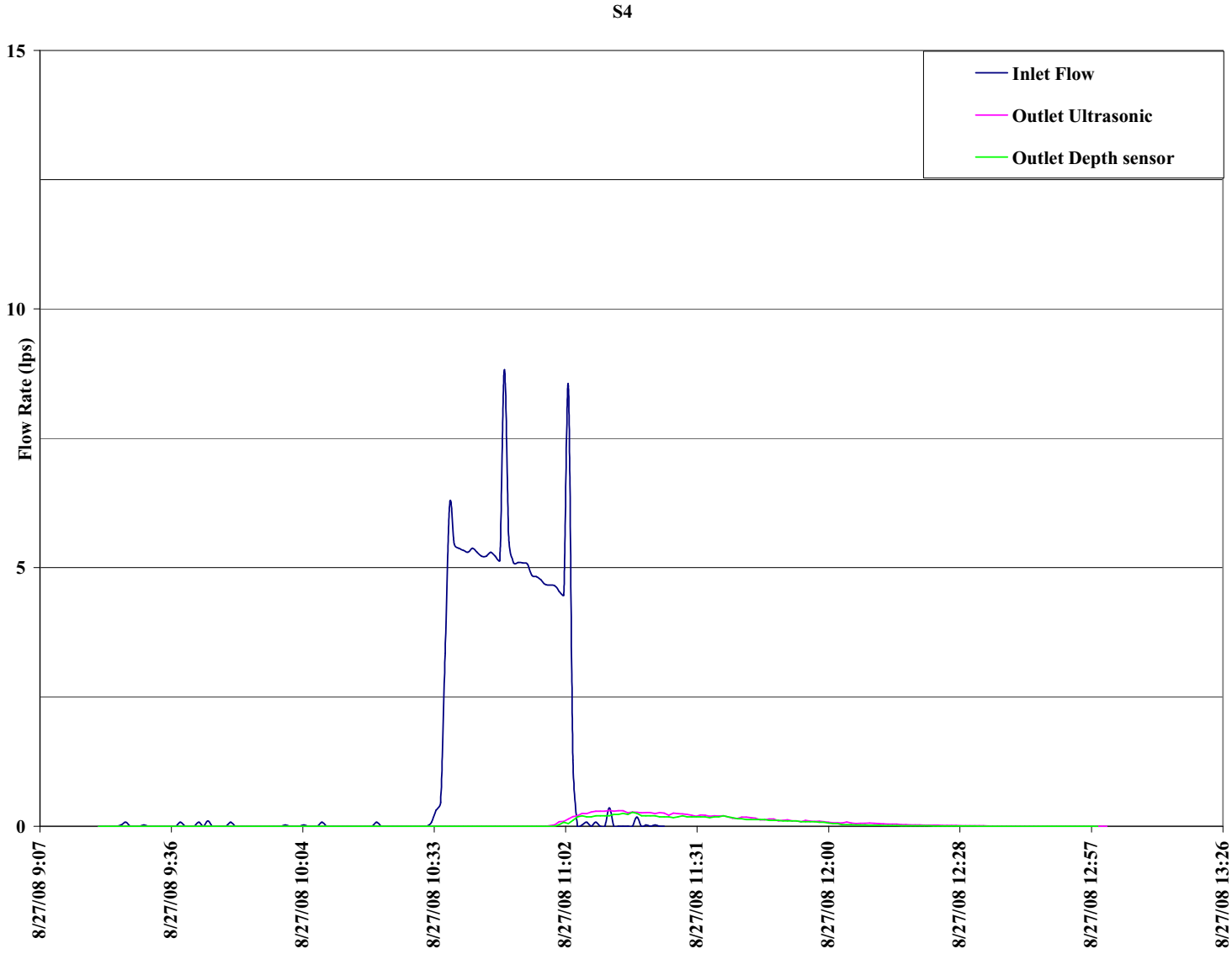
8/15/08 13:12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Outlet Depth sensor
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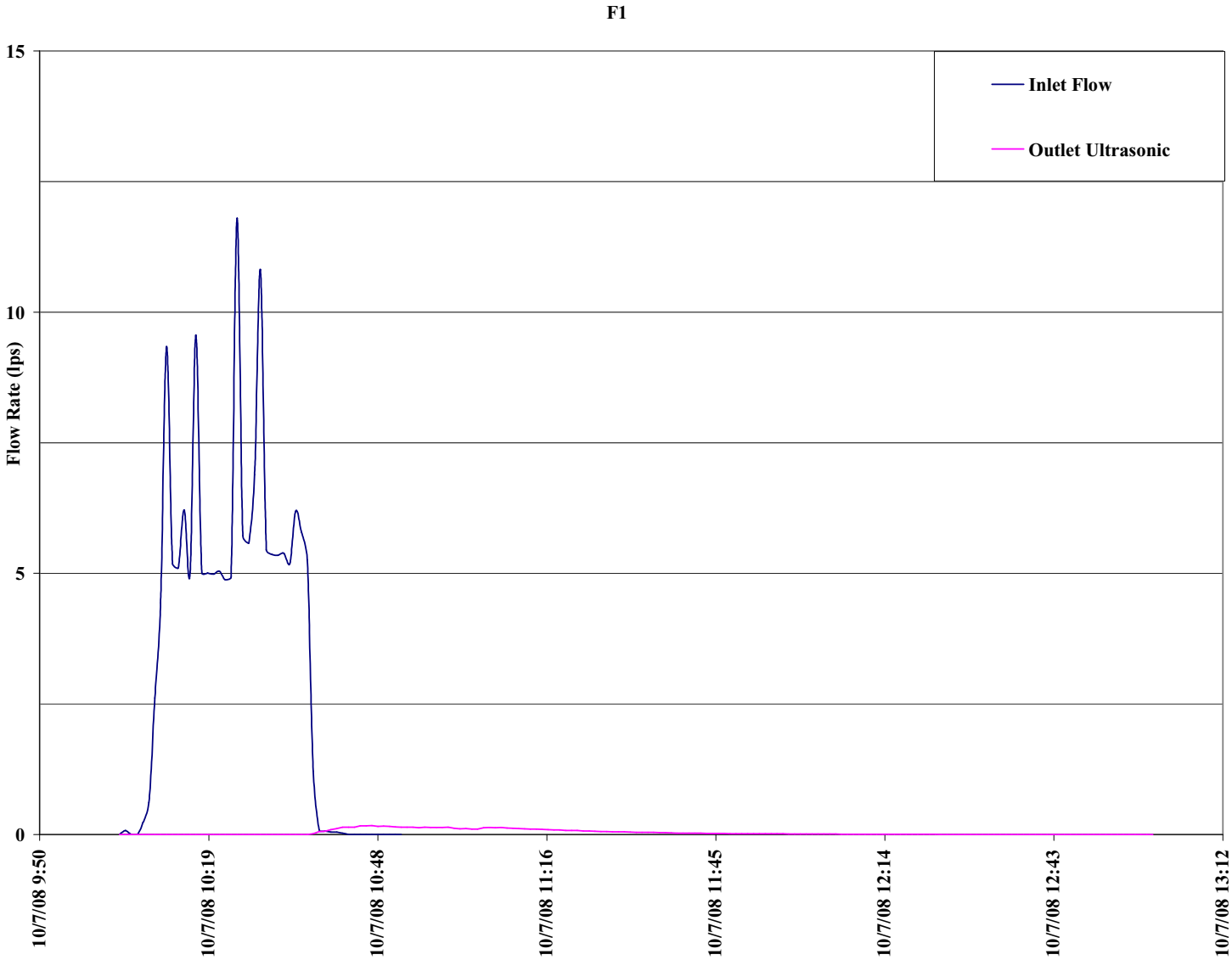
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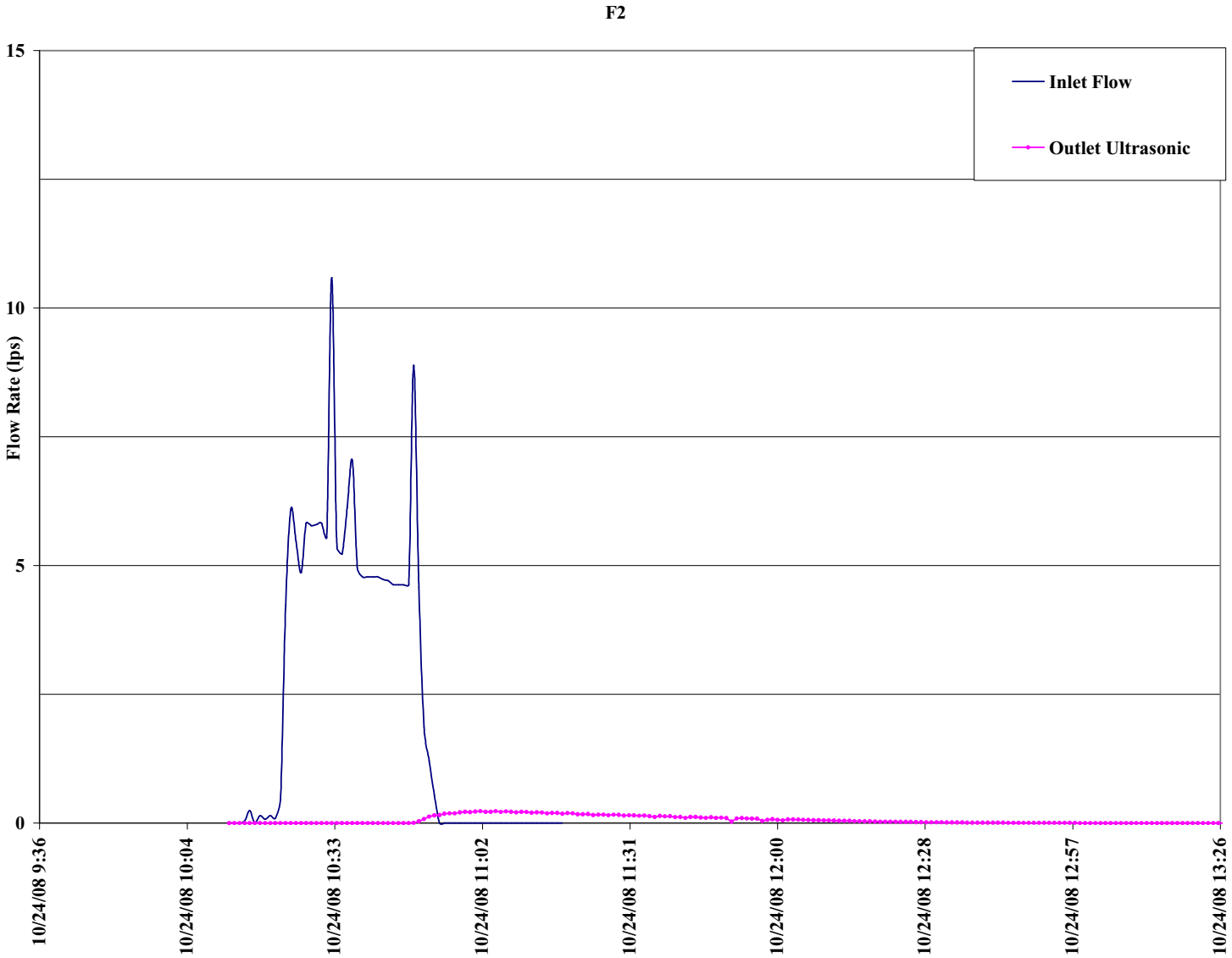
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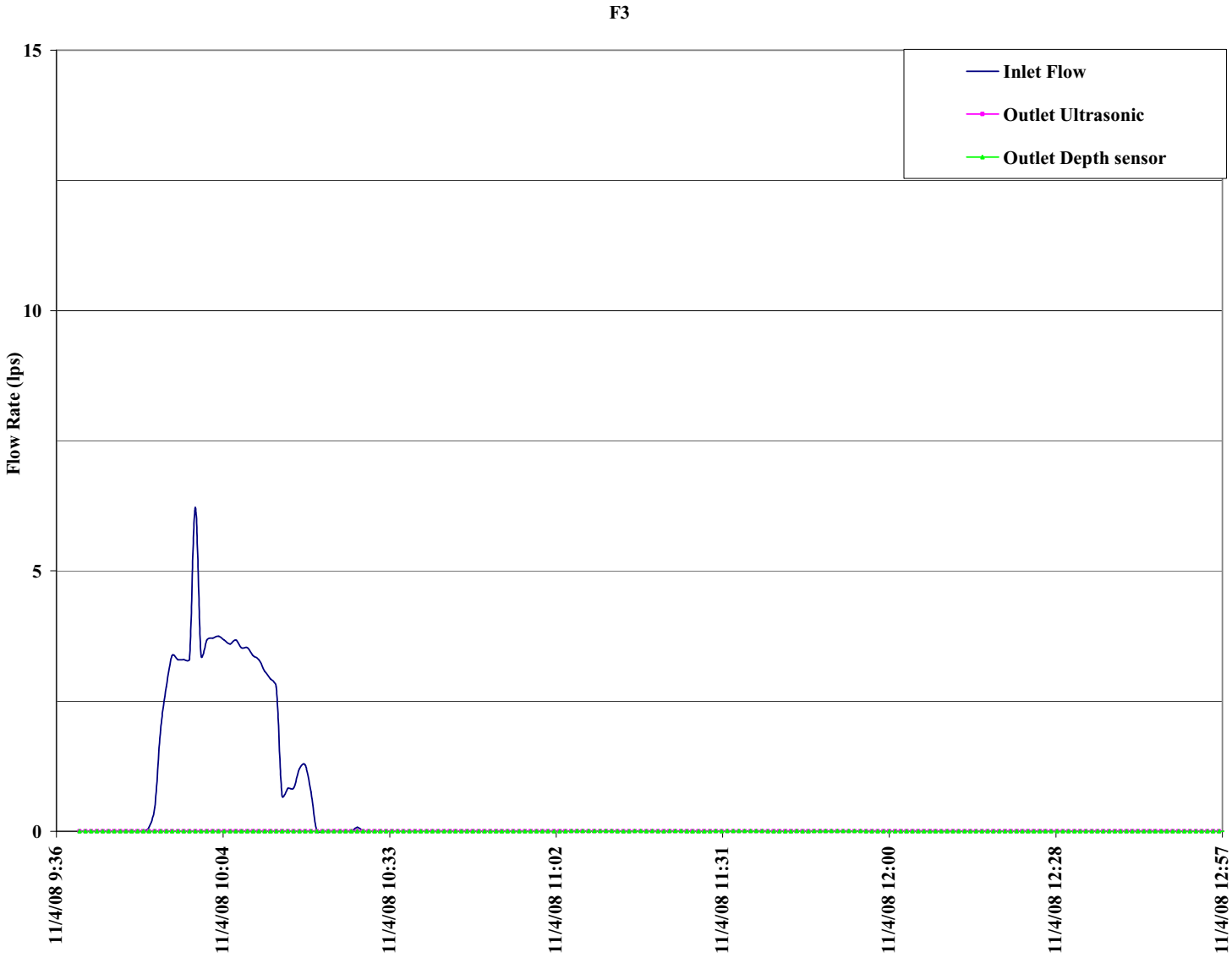
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Outlet Depth sensor
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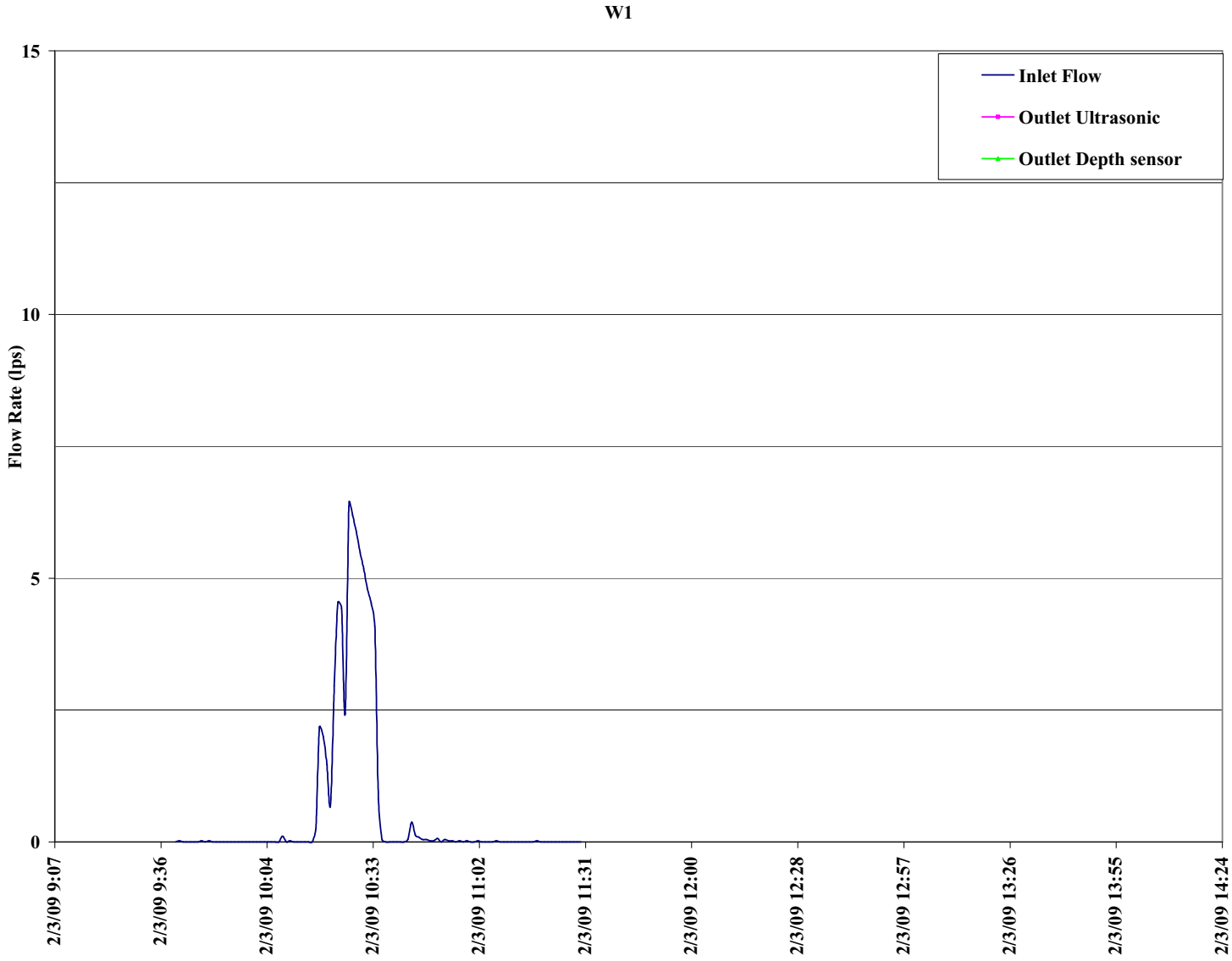
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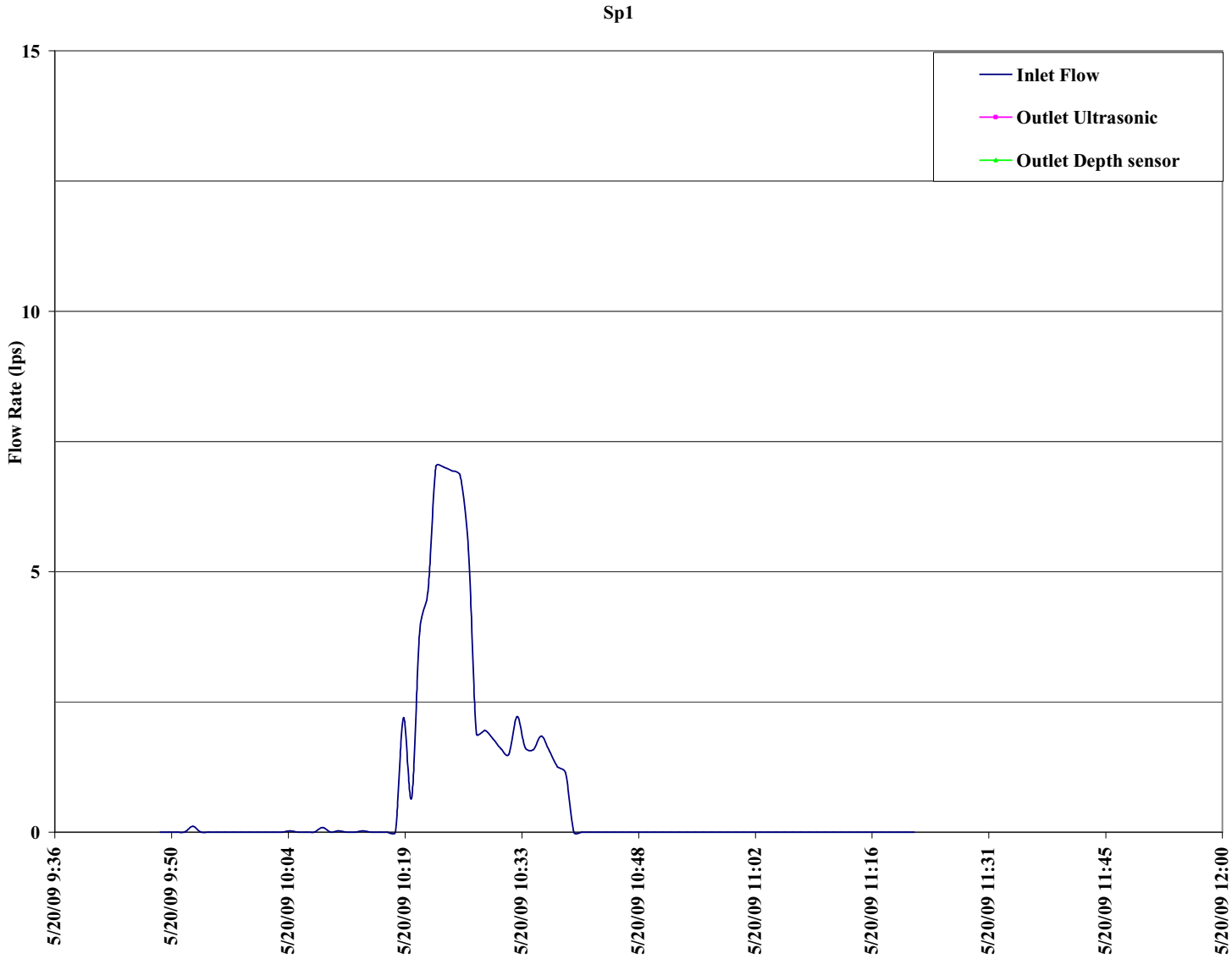
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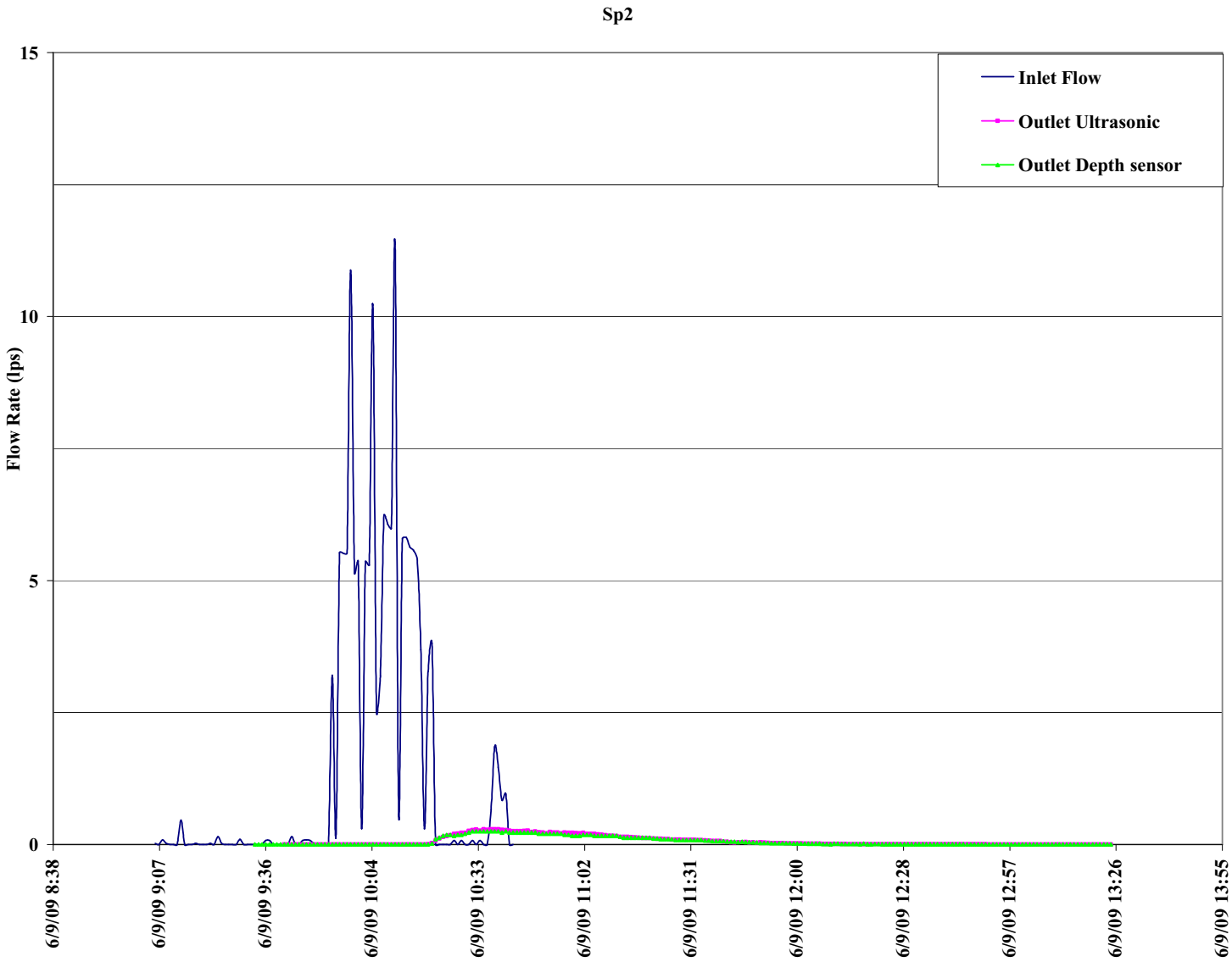
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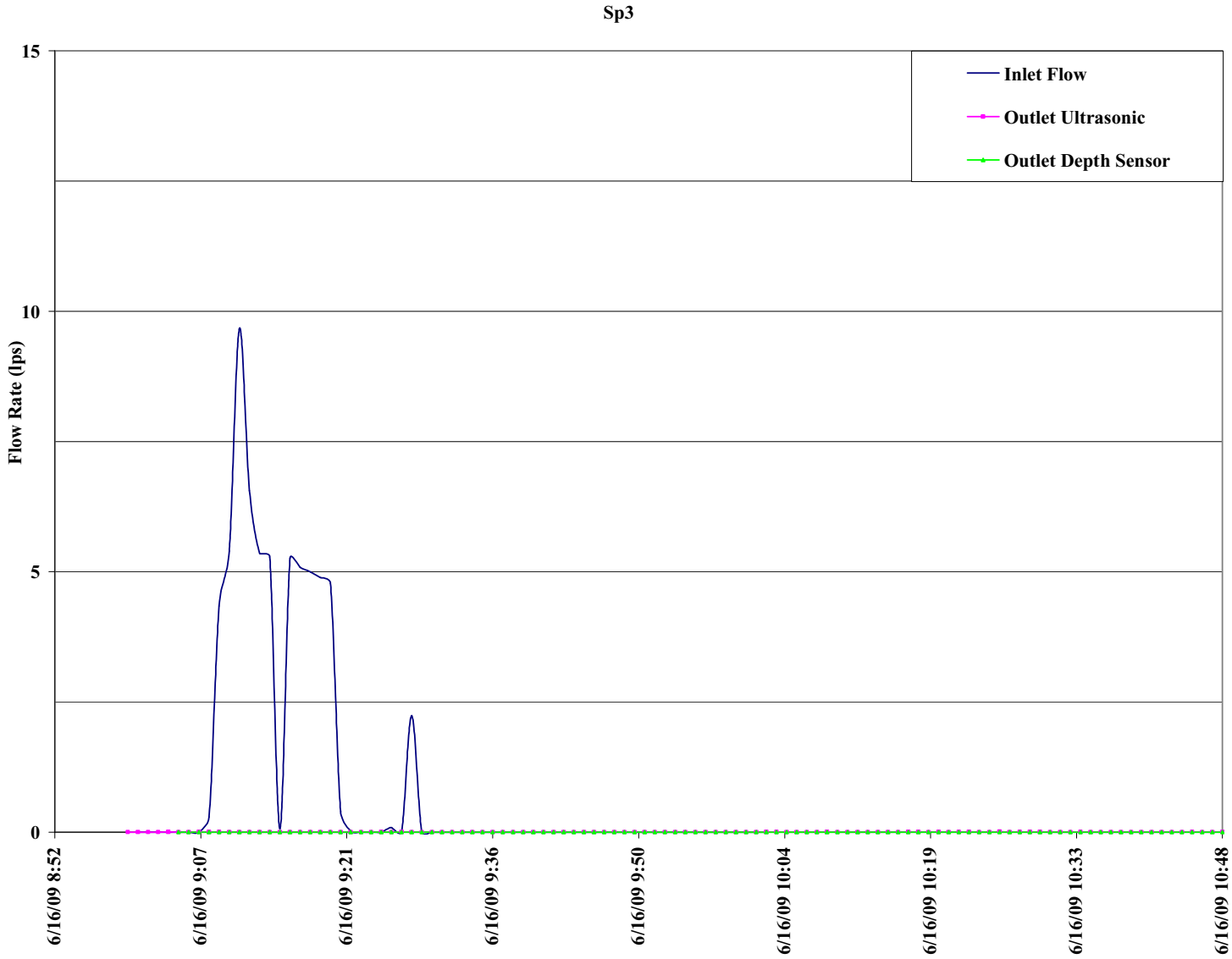
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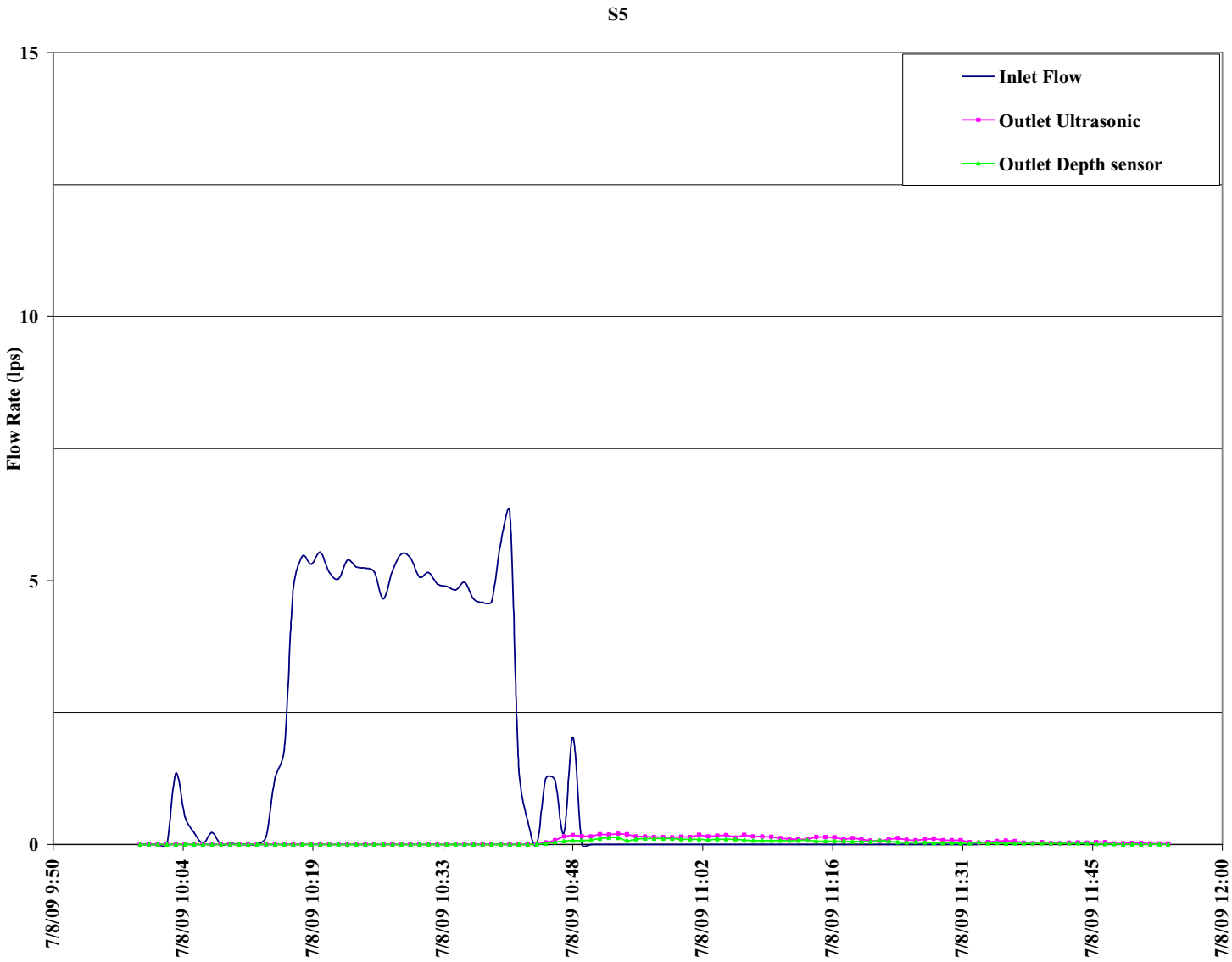
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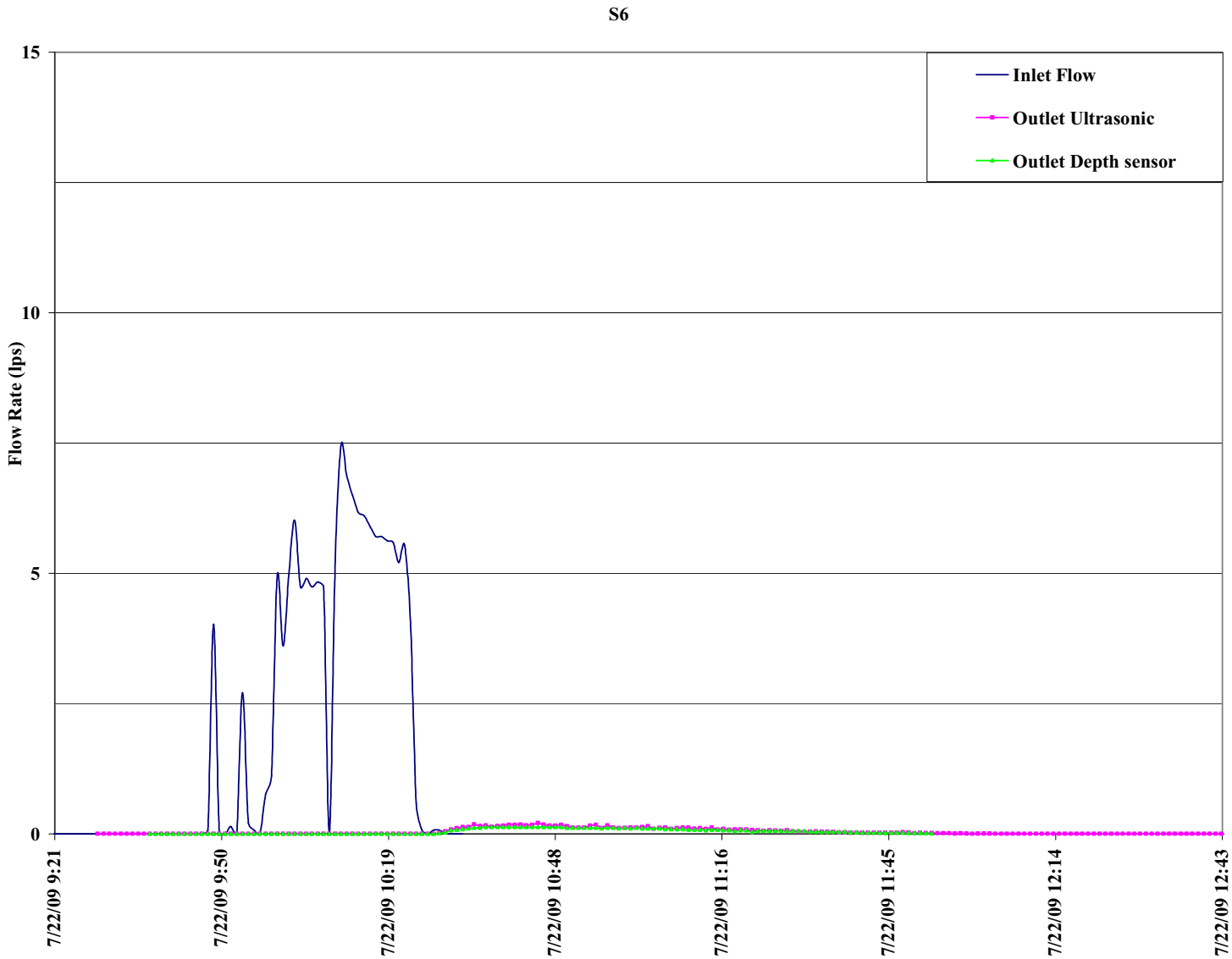
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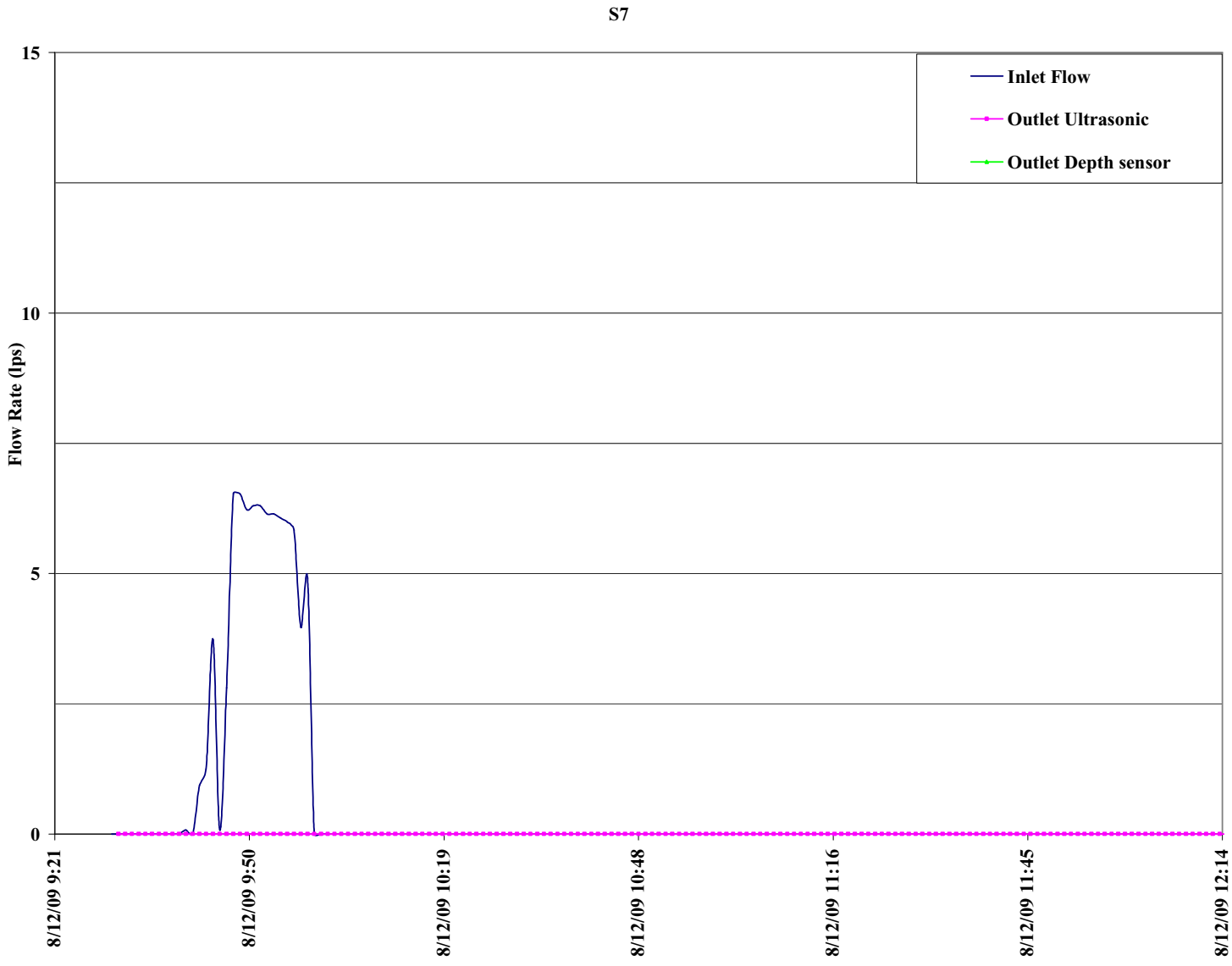
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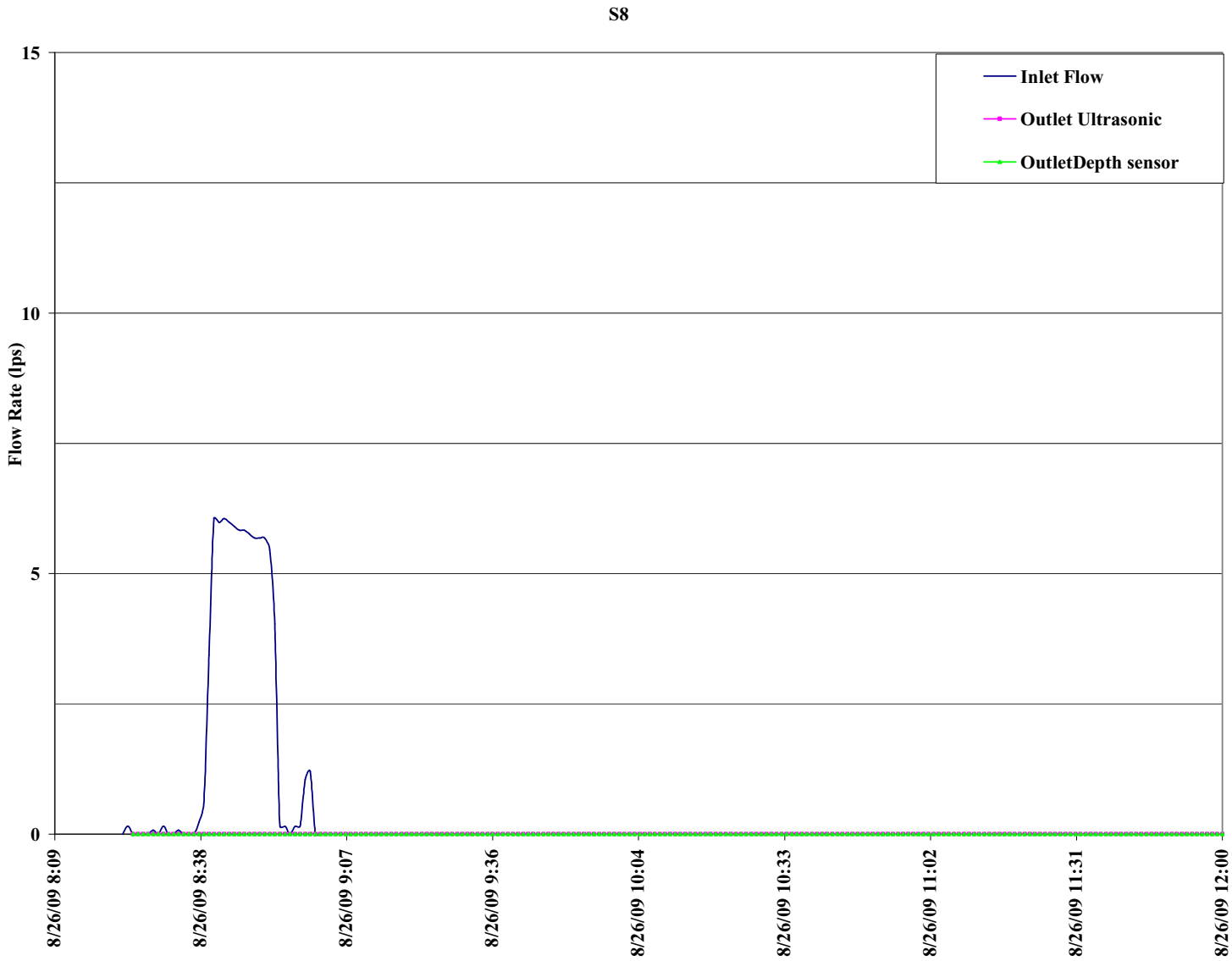
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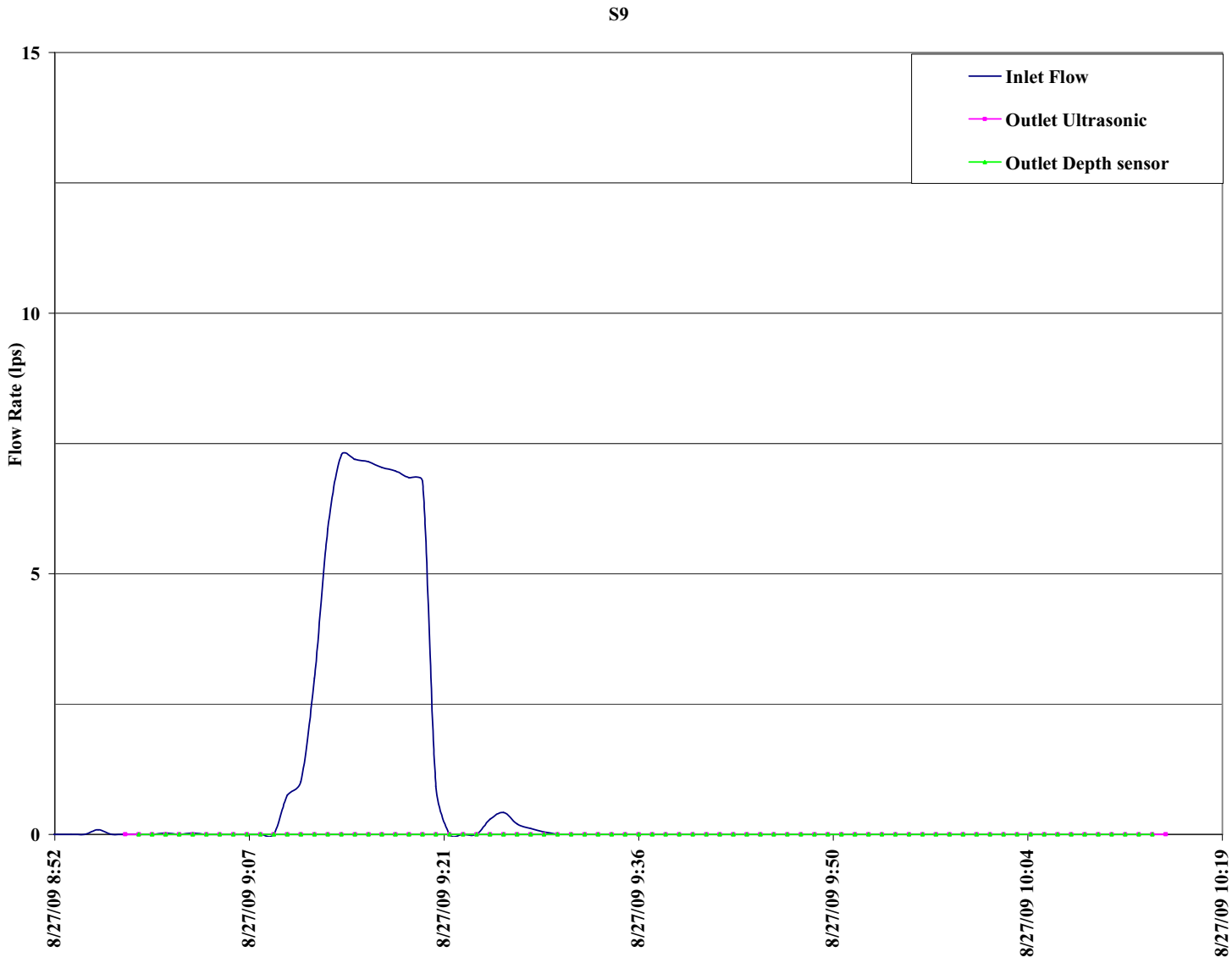
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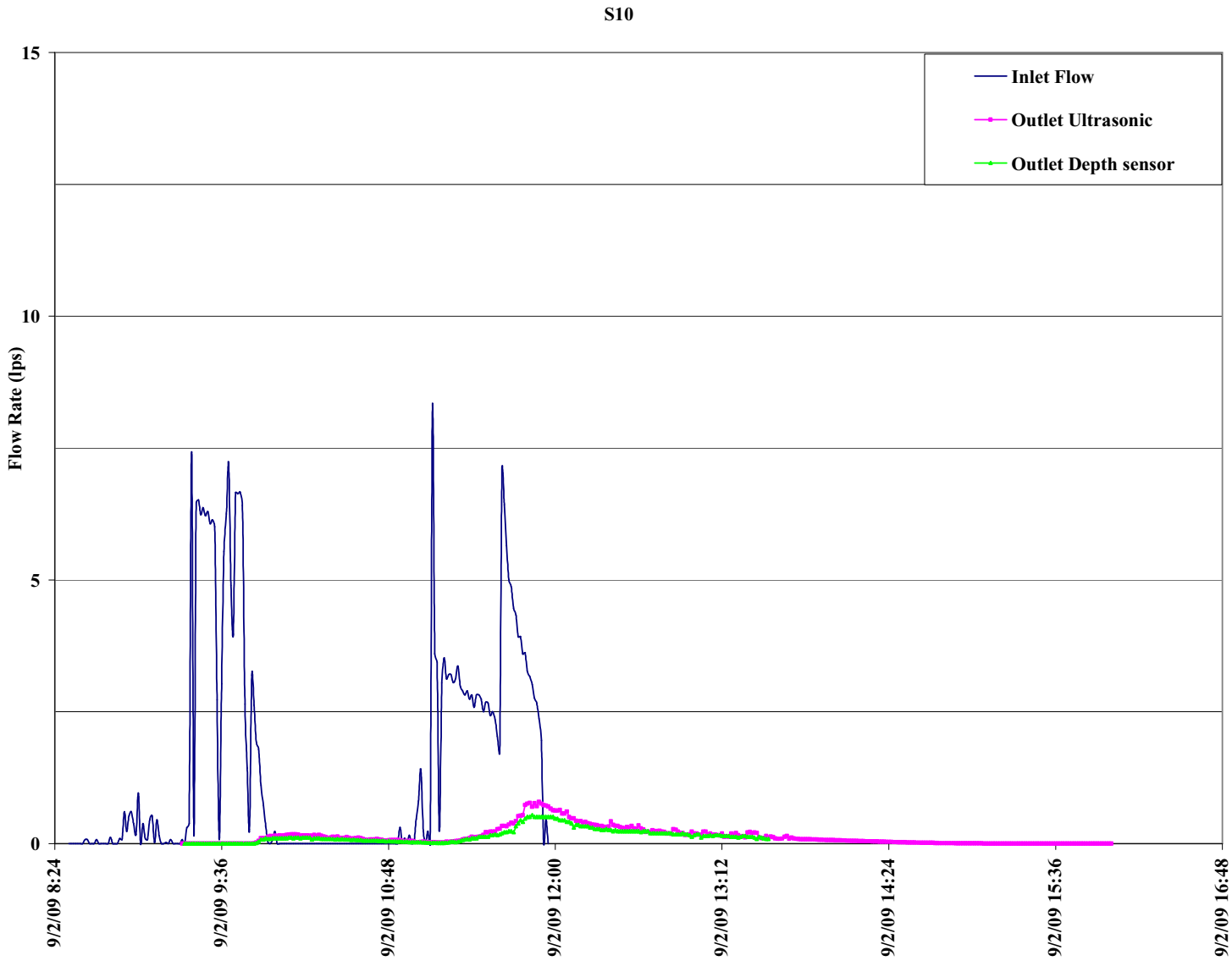
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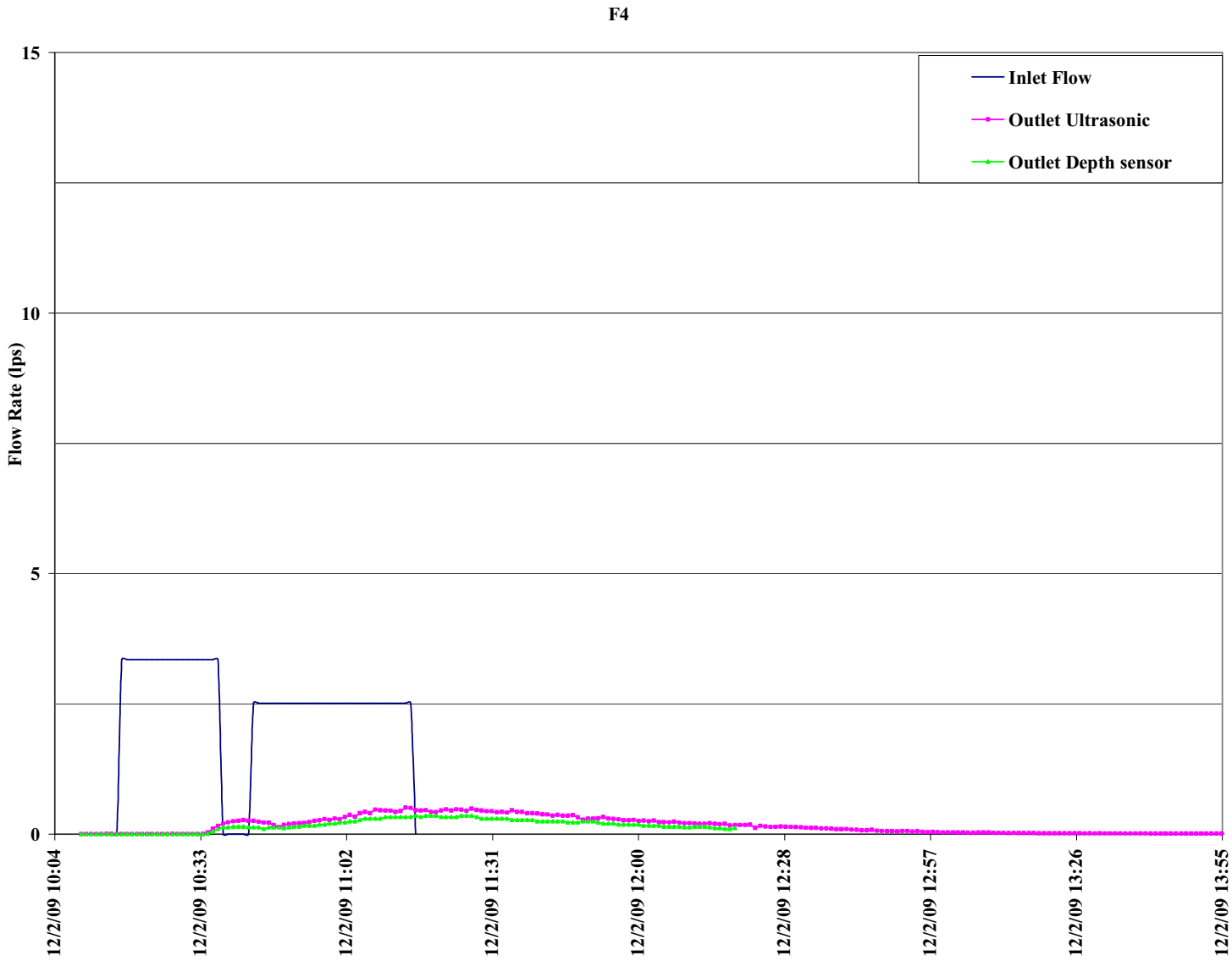
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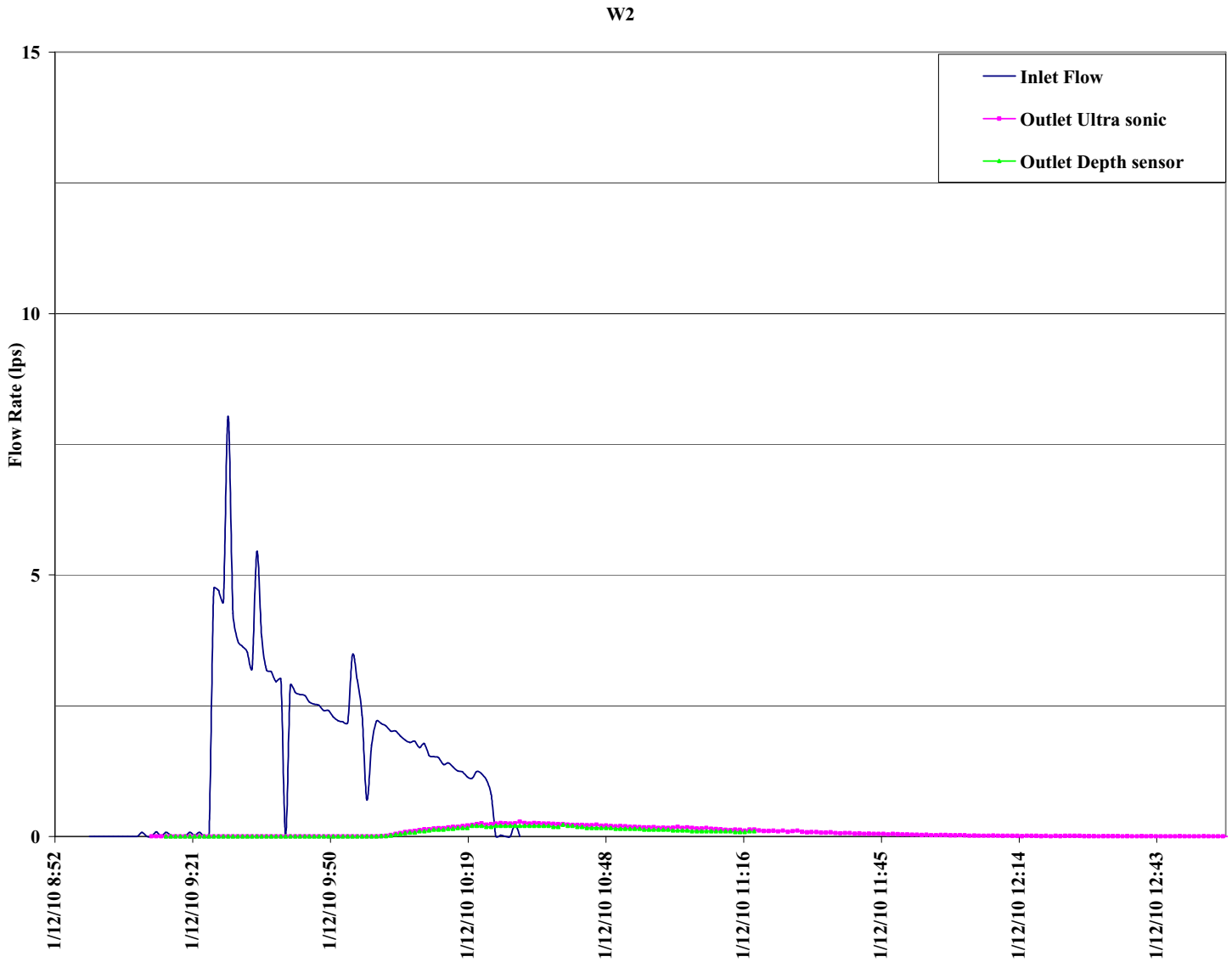
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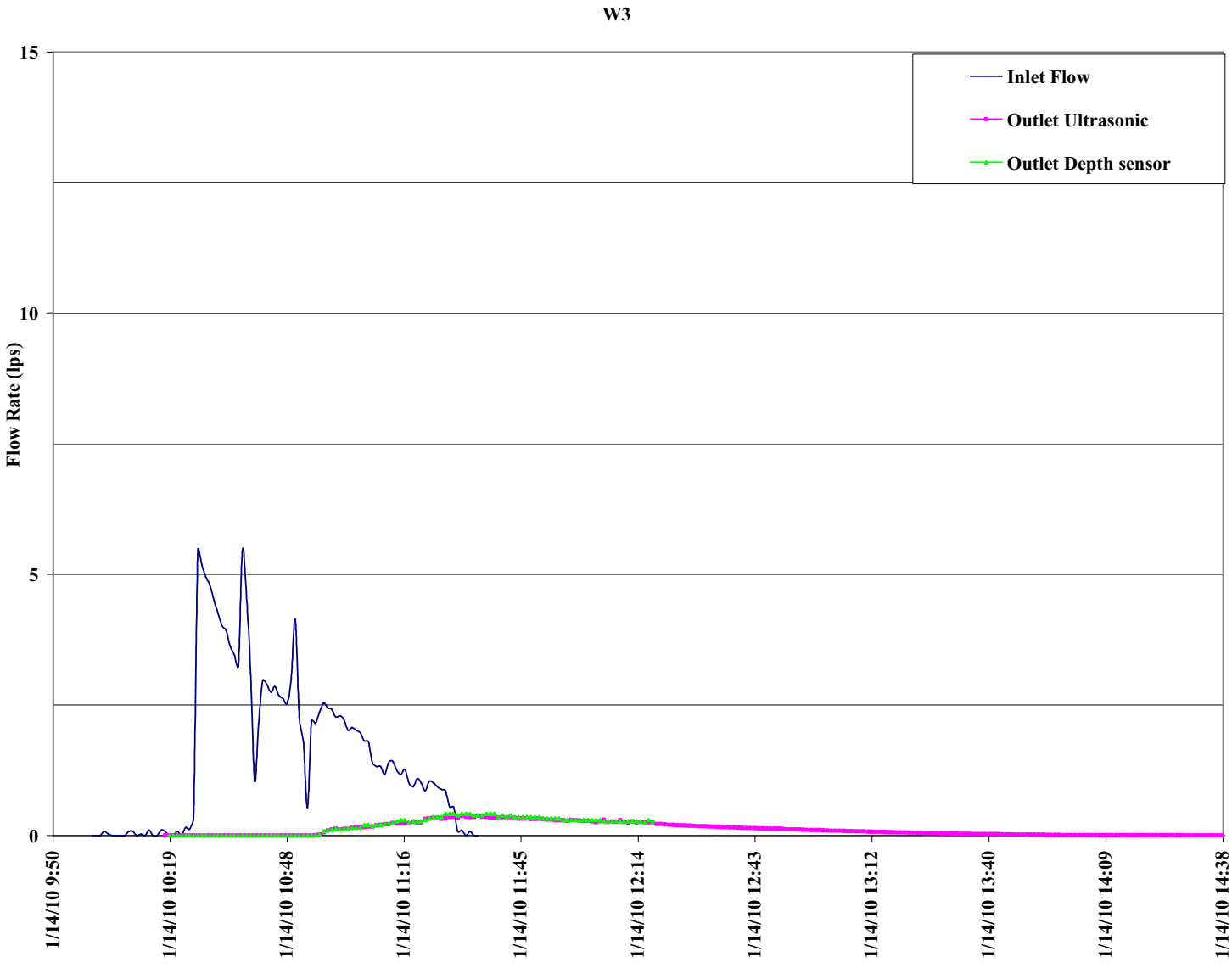
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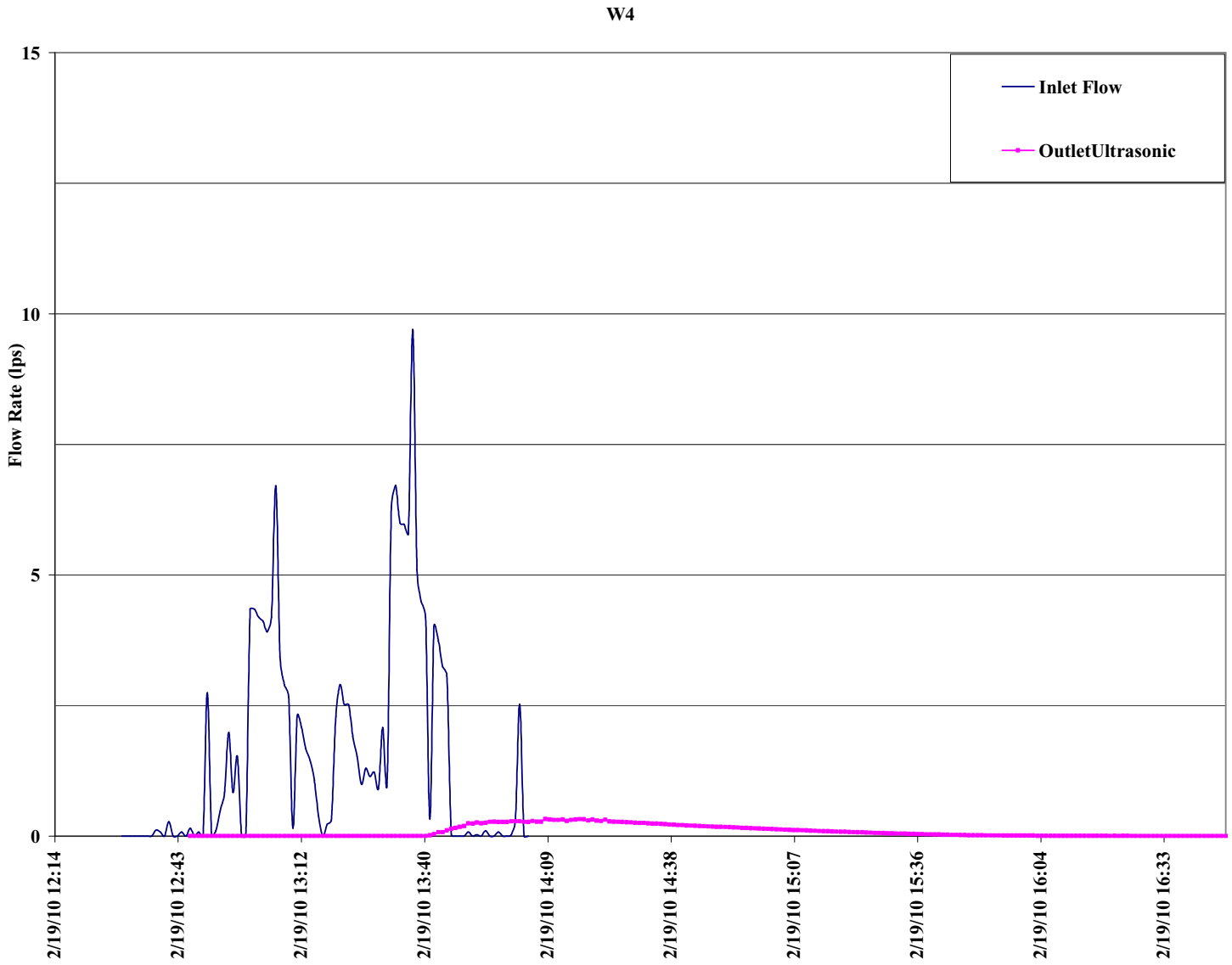
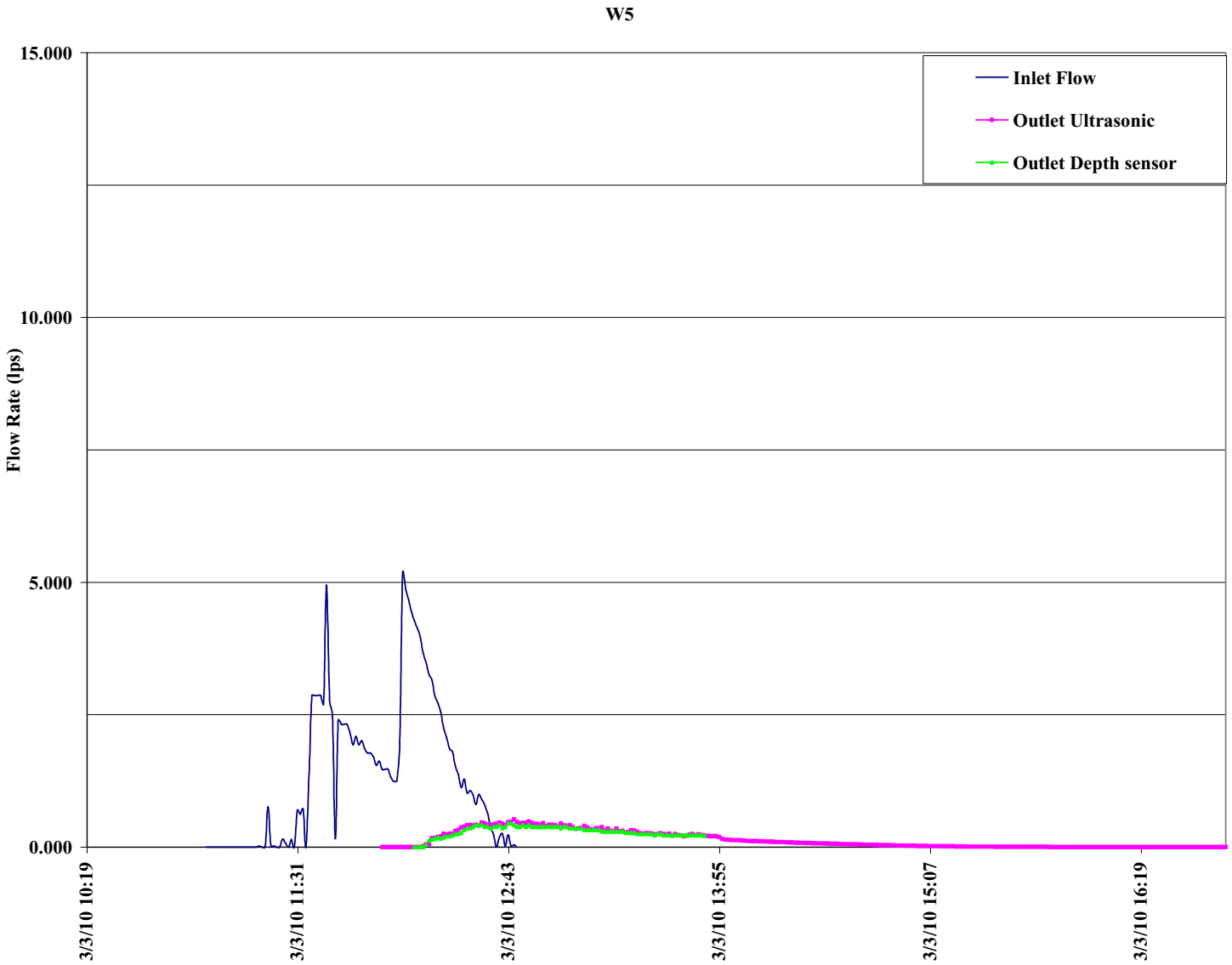
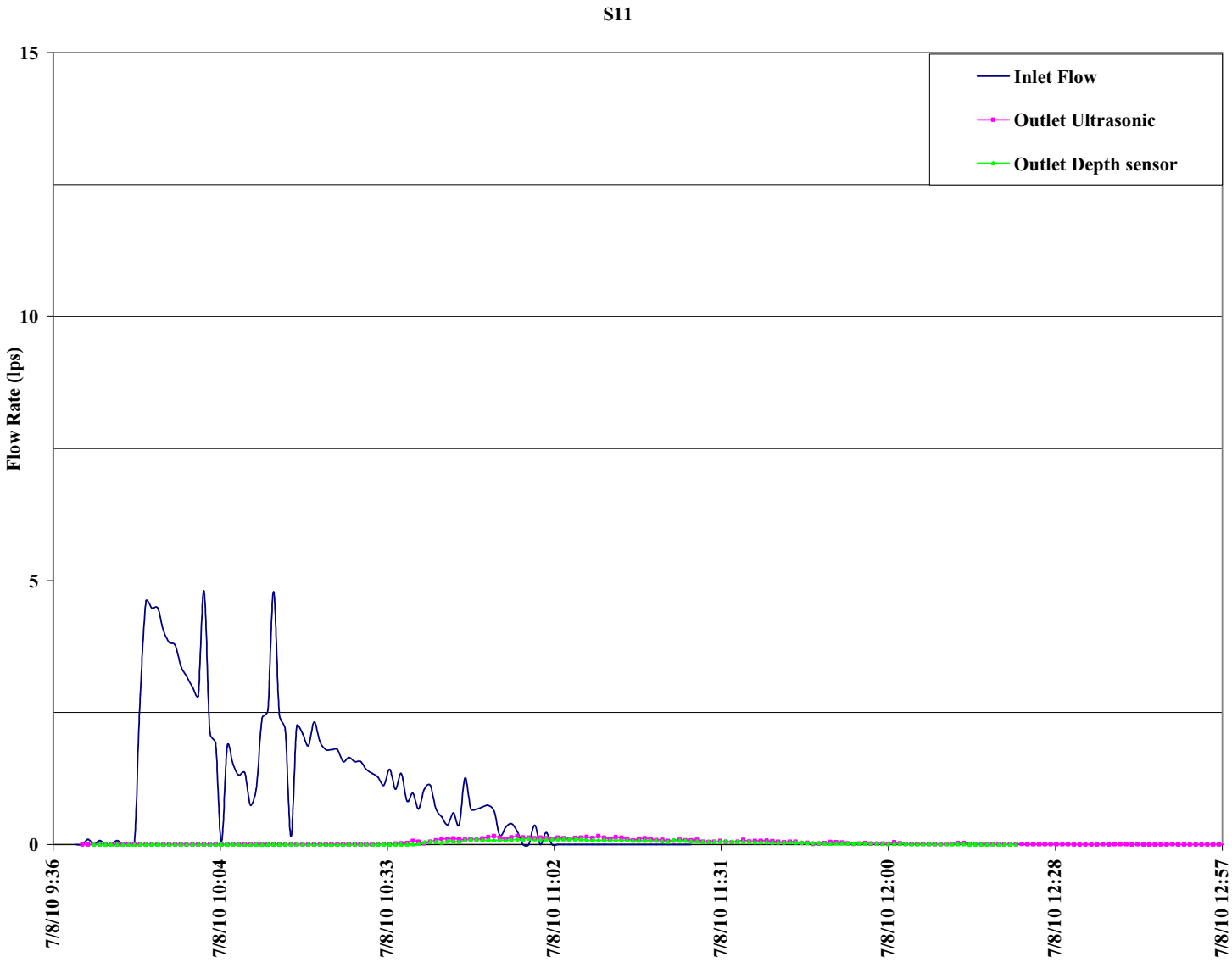
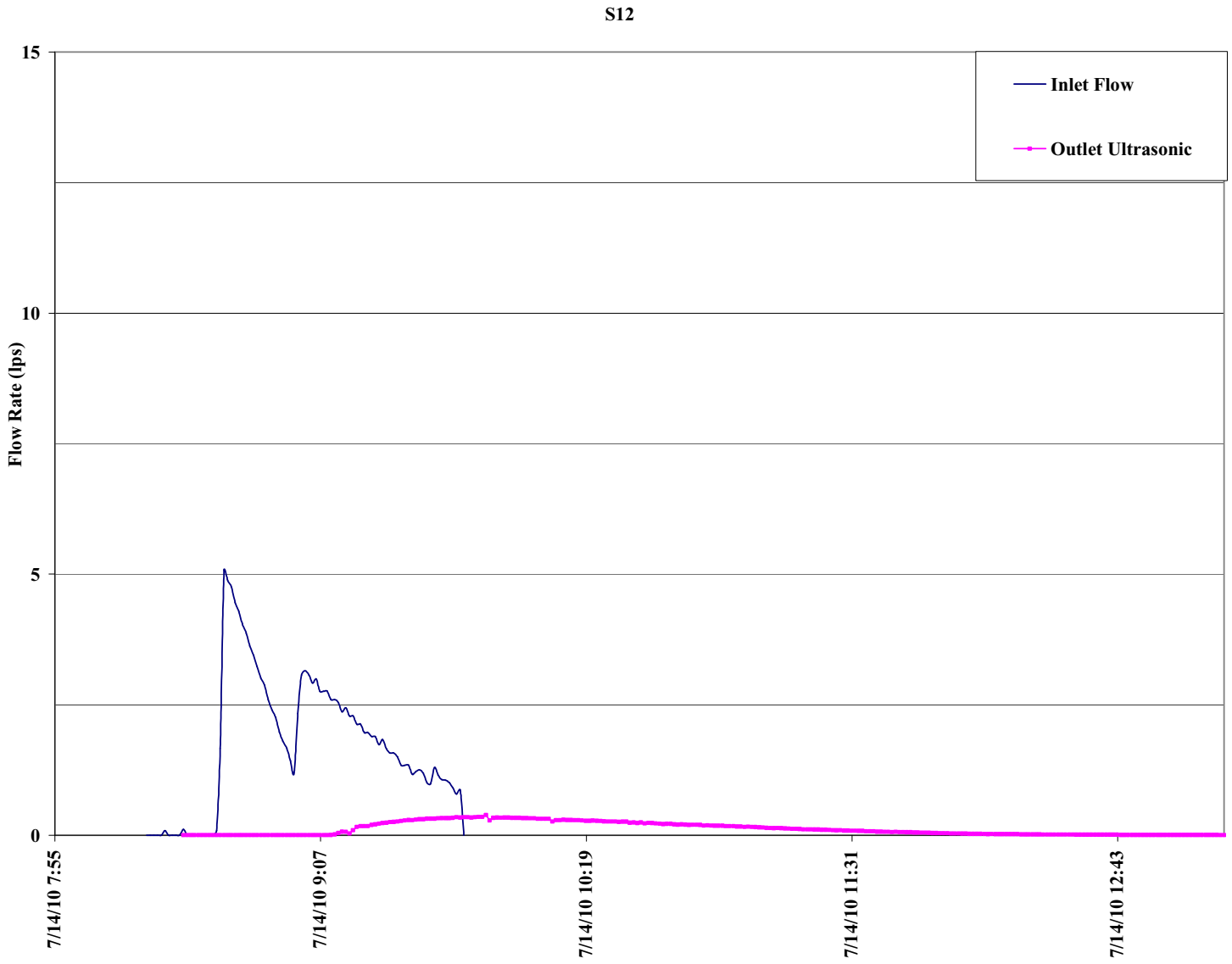
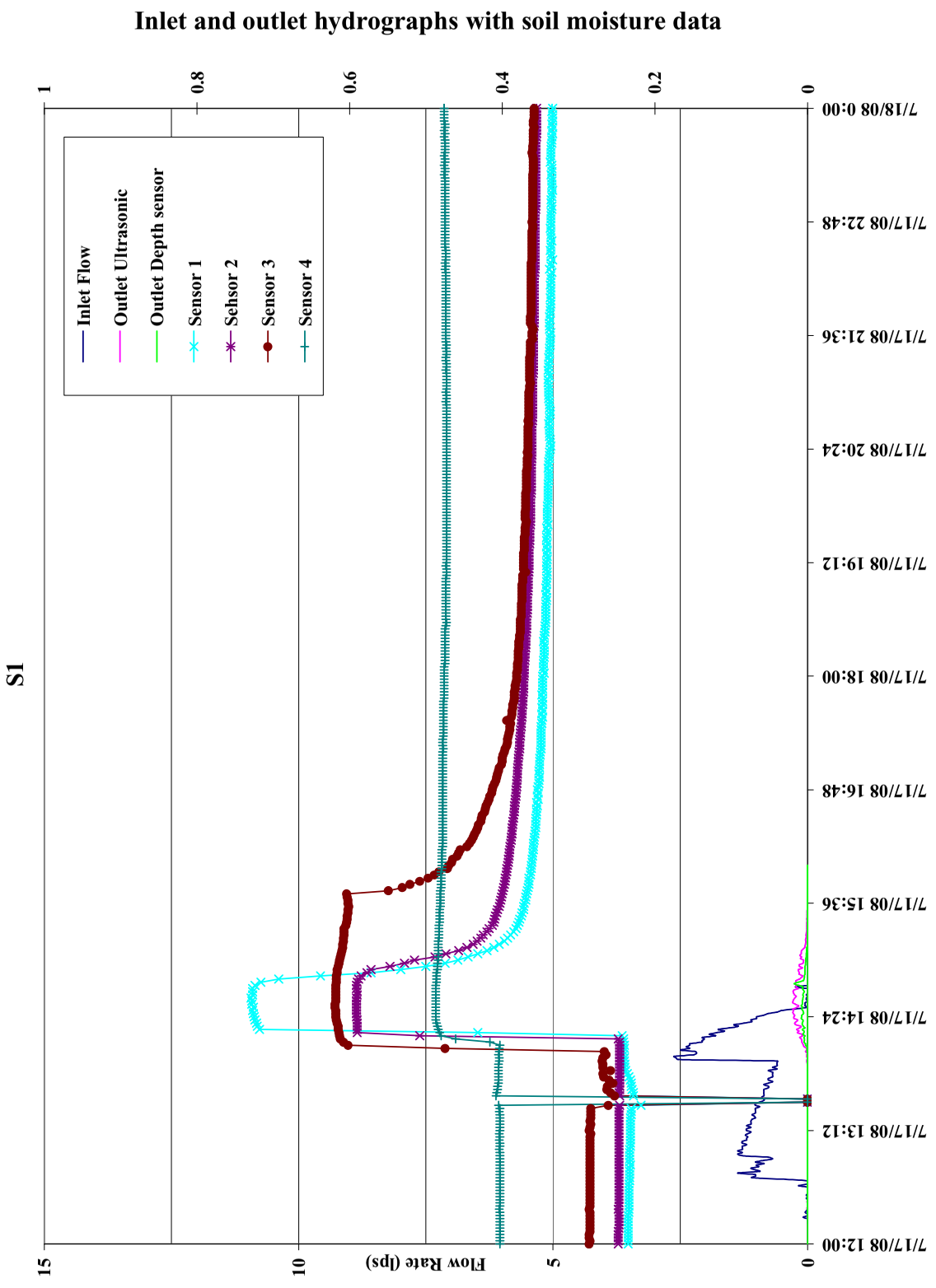
1/14/10 14:09
1/14/10 14:38

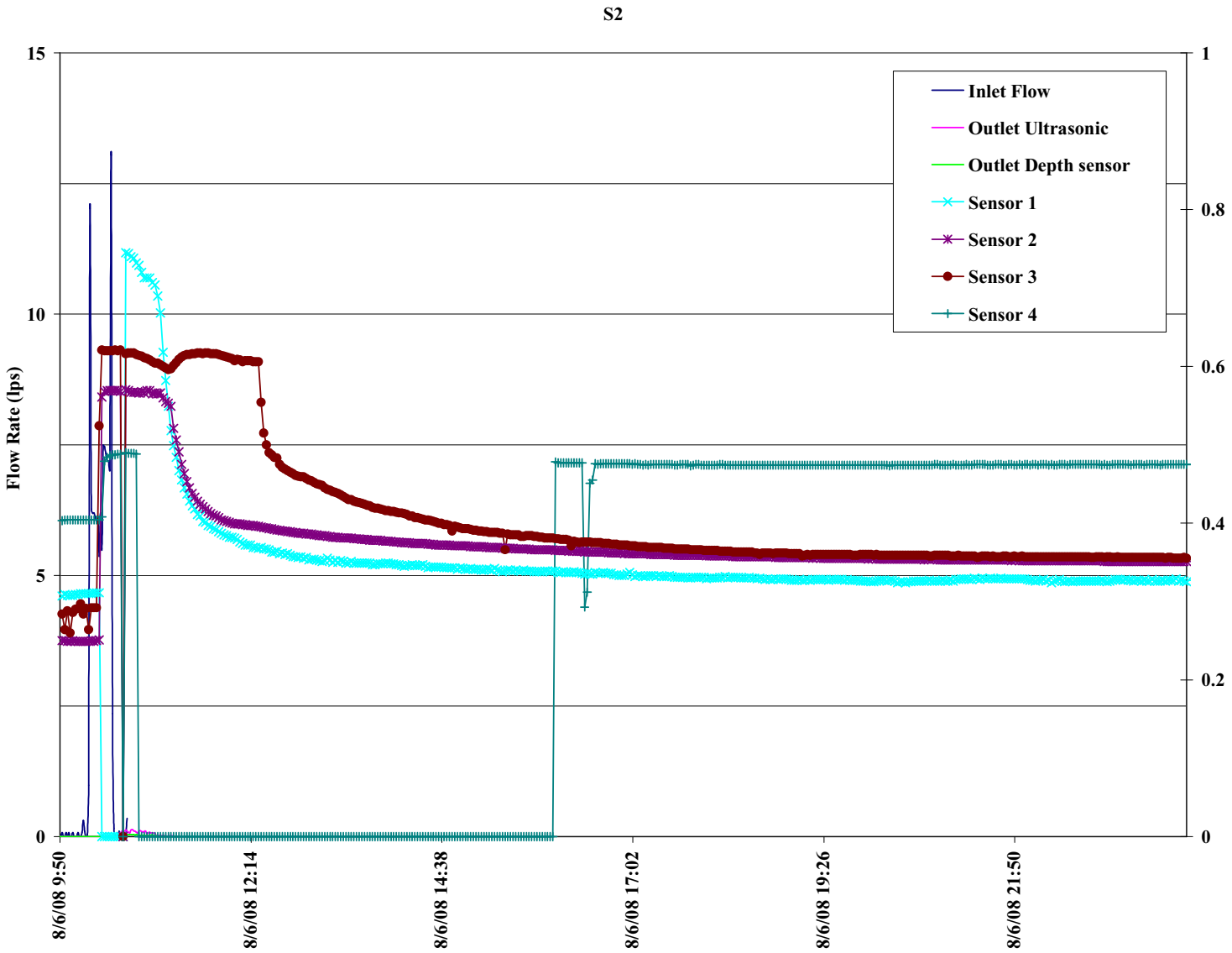

W4
15
10
5
0
Flow Rate (lps)
Inlet Flow
OutletUltrasonic
2/19/10 12:14
2/19/10 12:43
2/19/10 13:12
2/19/10 13:40
2/19/10 14:09
2/19/10 14:38
2/19/10 15:07
2/19/10 15:36
2/19/10 16:04
2/19/10 16:33

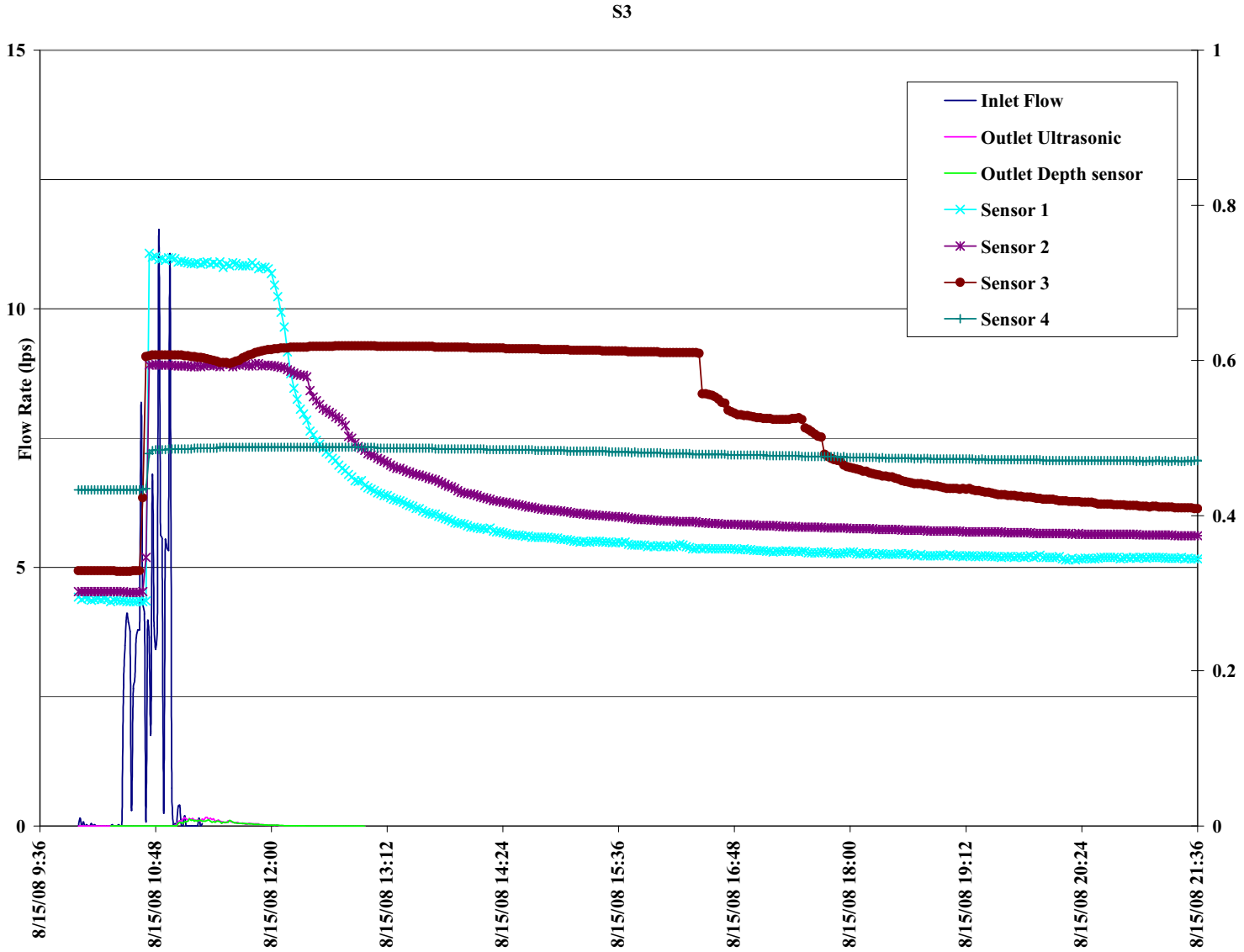

W5
15.000
10.000
5.000
0.000
Flow Rate (lps)
Inlet Flow
Outlet Ultrasonic
Outlet Depth sensor
3/3/10 10:19
3/3/10 11:31
3/3/10 12:43
3/3/10 13:55
3/3/10 15:07
3/3/10 16:19

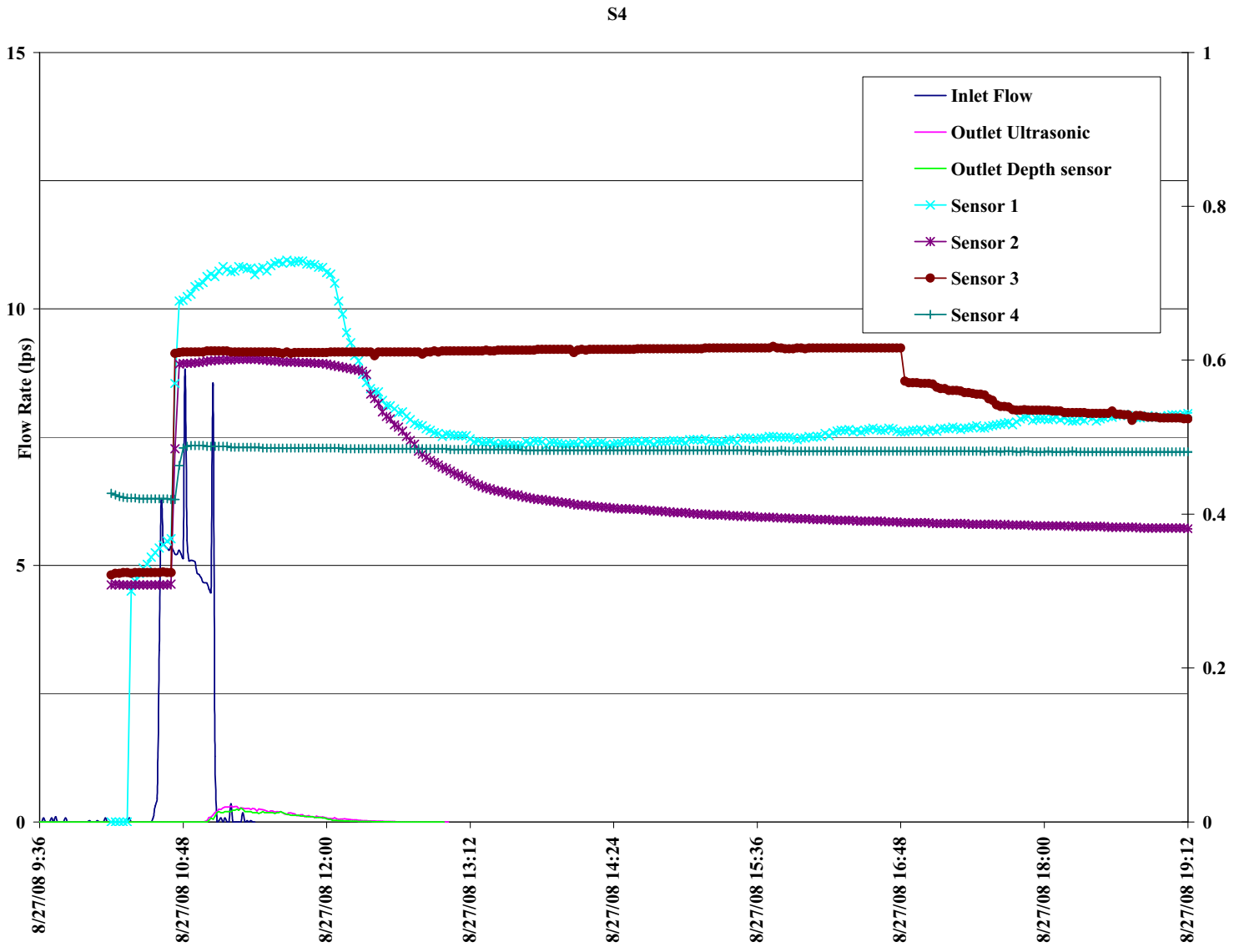

S11
15
10
5
0
Flow Rate (lps)
Inlet Flow
Outlet Ultrasonic
Outlet Depth sensor
7/8/10 9:36
7/8/10 10:04
7/8/10 10:33
7/8/10 11:02
7/8/10 11:31
7/8/10 12:00
7/8/10 12:28
7/8/10 12:57

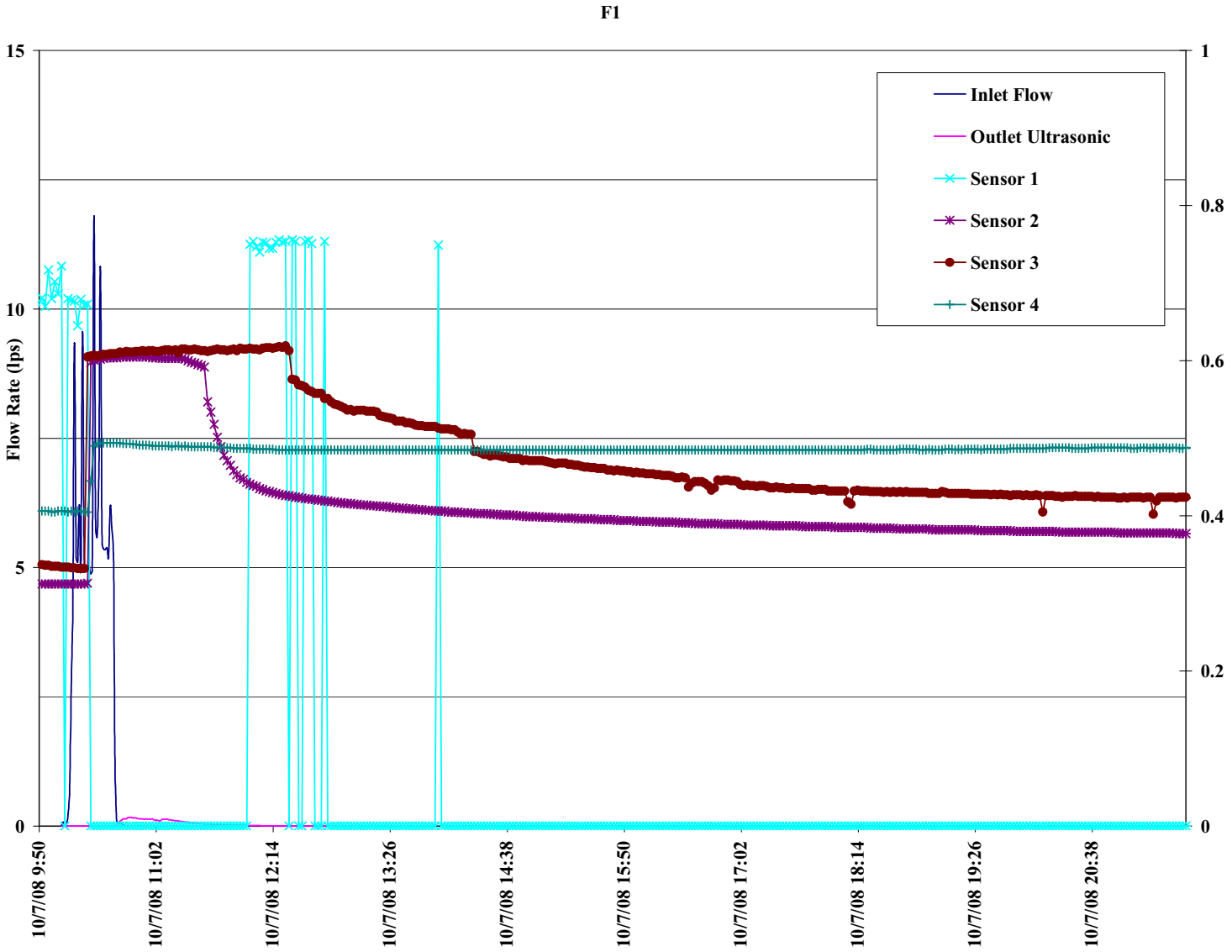

S12
15
10
5
0
Flow Rate (lps)
Inlet Flow
Outlet Ultrasonic
7/14/10 7:55
7/14/10 9:07
7/14/10 10:19
7/14/10 11:31
7/14/10 12:43

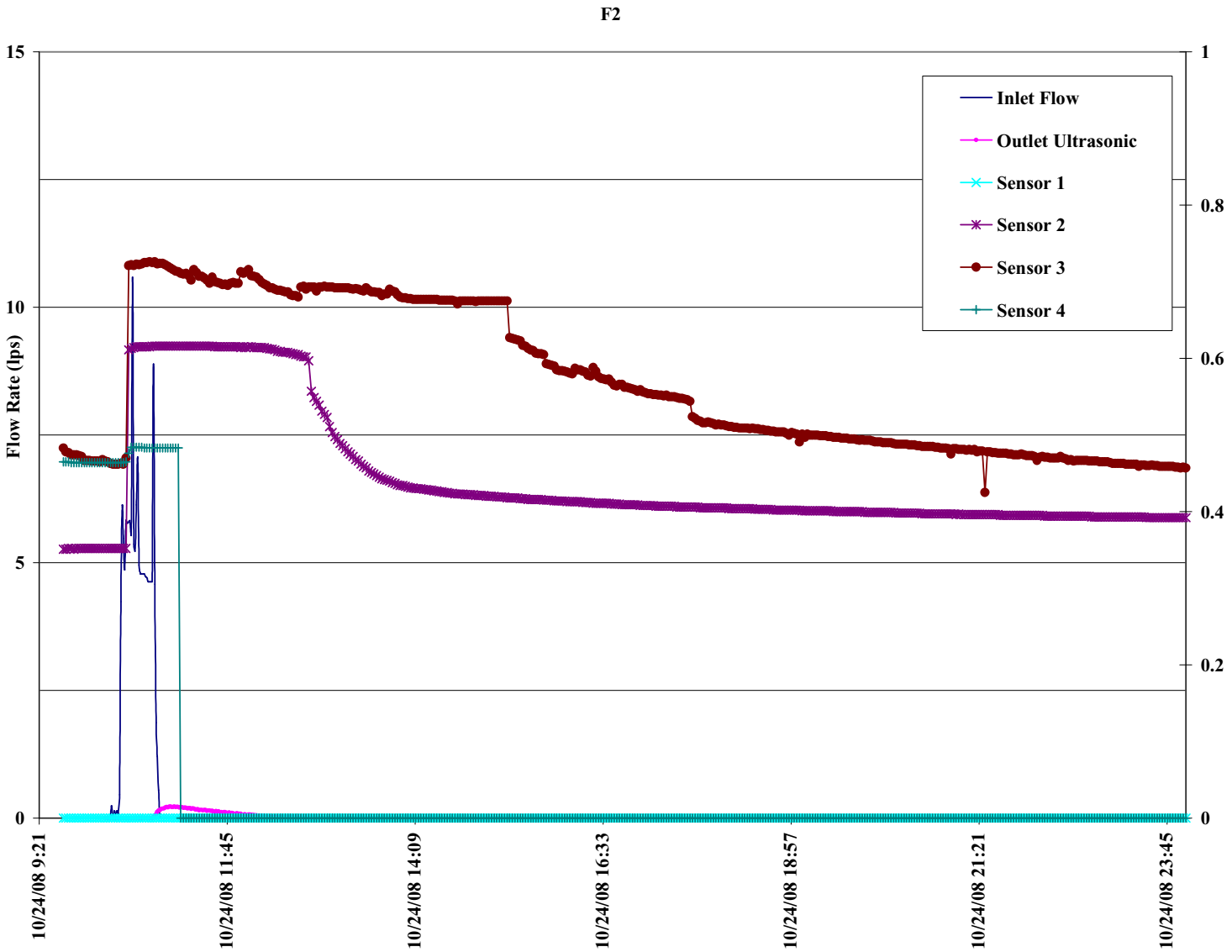

Inlet and outlet hydrographs with soil moisture data
S1
Flow Rate (lps)
Inlet Flow
Outlet Ultrasonic
Outlet Depth sensor
Sensor 1
Sehsor 2
Sensor 3
Sensor 4
0
5
10
15
0
0.2
0.4
0.6
0.8
1
7/18/08 0:00
7/17/08 22:48
7/17/08 21:36
7/17/08 20:24
7/17/08 19:12
7/17/08 18:00
7/17/08 16:48
7/17/08 15:36
7/17/08 14:24
7/17/08 13:12
7/17/08 12:00

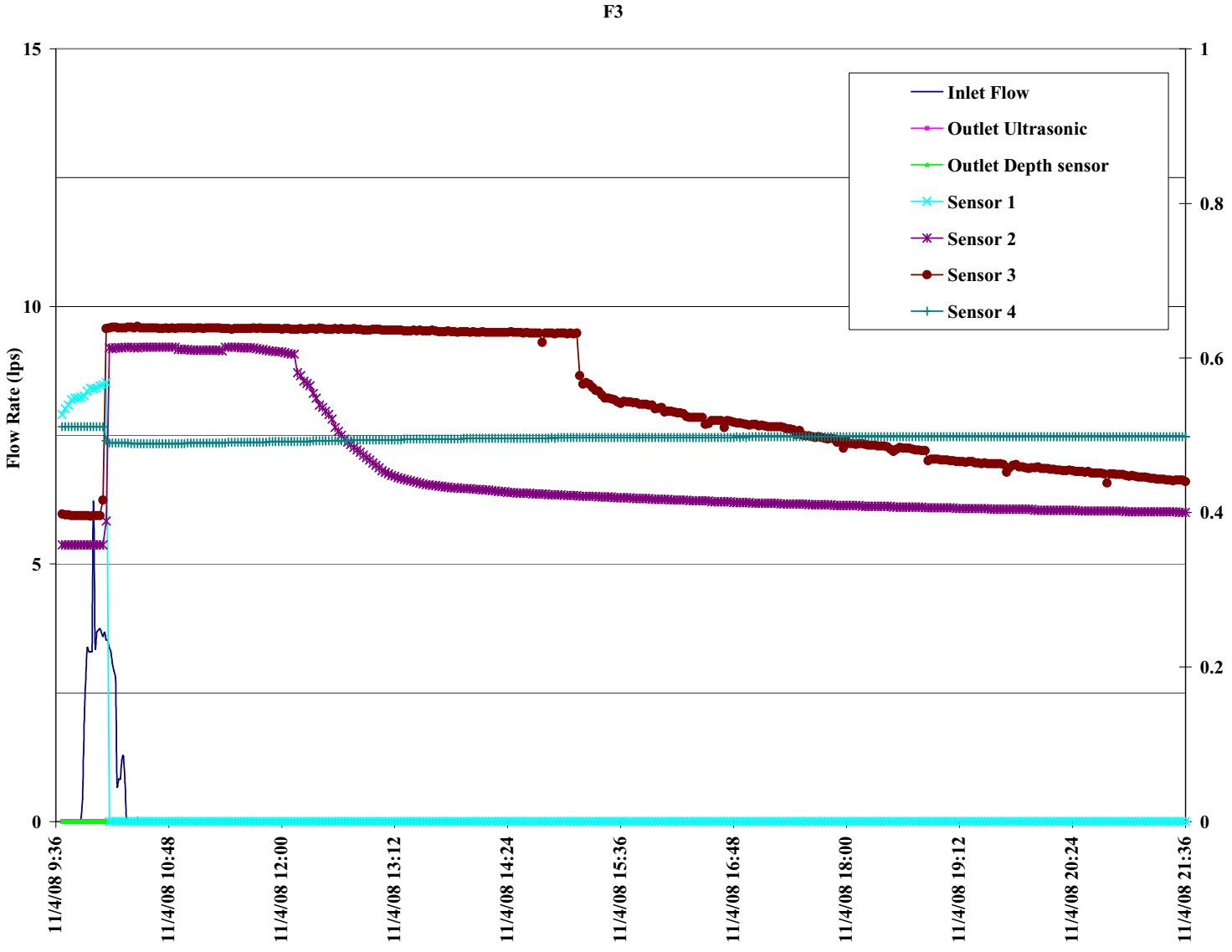

S2
Flow Rate (lps)
15
10
5
0
1
0.8
0.6
0.4
0.2
0
Inlet Flow
Outlet Ultrasonic
Outlet Depth sensor
Sensor 1
Sensor 2
Sensor 3
Sensor 4
8/6/08 9:50
8/6/08 12:14
8/6/08 14:38
8/6/08 17:02
8/6/08 19:26
8/6/08 21:50

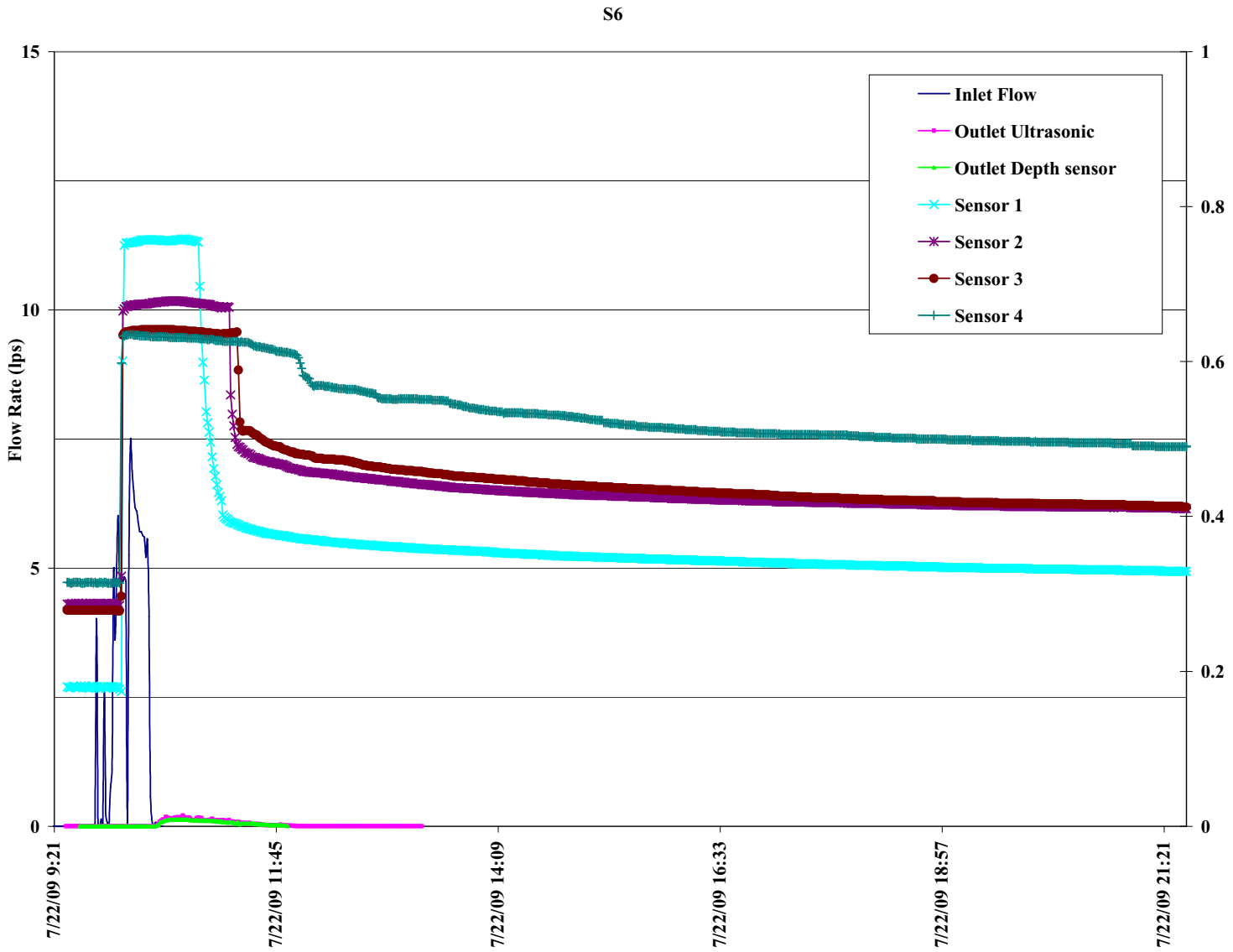

S3
Flow Rate (lps)
15
10
5
0
1
0.8
0.6
0.4
0.2
0
Inlet Flow
Outlet Ultrasonic
Outlet Depth sensor
Sensor 1
Sensor 2
Sensor 3
Sensor 4
8/15/08 9:36
8/15/08 10:48
8/15/08 12:00
8/15/08 13:12
8/15/08 14:24
8/15/08 15:36
8/15/08 16:48
8/15/08 18:00
8/15/08 19:12
8/15/08 20:24
8/15/08 21:36

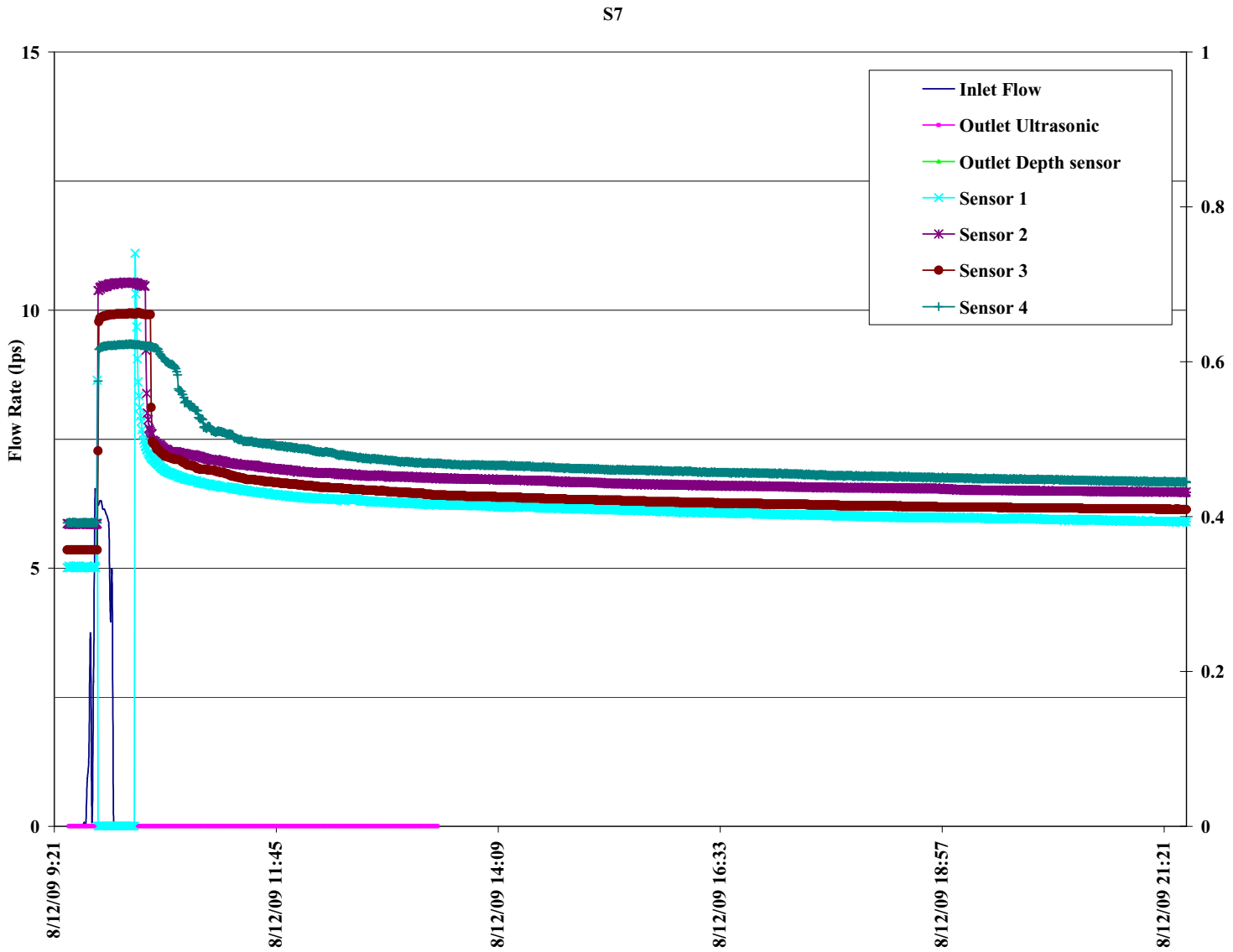

S4
15
10
5
0
1
0.8
0.6
0.4
0.2
0
Flow Rate (lps)
Inlet Flow
Outlet Ultrasonic
Outlet Depth sensor
Sensor 1
Sensor 2
Sensor 3
Sensor 4
8/27/08 9:36
8/27/08 10:48
8/27/08 12:00
8/27/08 13:12
8/27/08 14:24
8/27/08 15:36
8/27/08 16:48
8/27/08 18:00
8/27/08 19:12

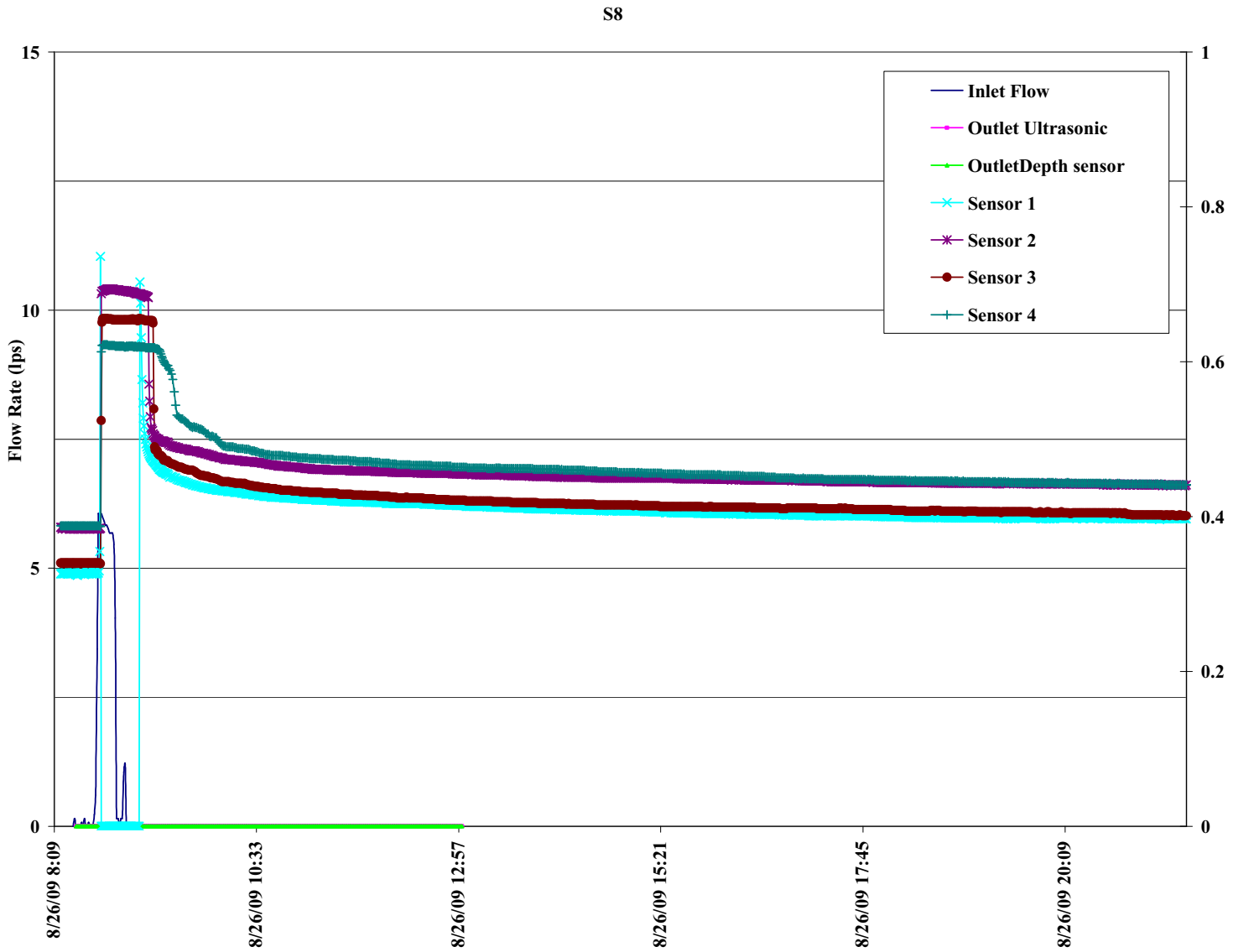

F1
Flow Rate (lps)
15
10
5
0
1
0.8
0.6
0.4
0.2
0
Inlet Flow
Outlet Ultrasonic
Sensor 1
Sensor 2
Sensor 3
Sensor 4
10/7/08 9:50
10/7/08 11:02
10/7/08 12:14
10/7/08 13:26
10/7/08 14:38
10/7/08 15:50
10/7/08 17:02
10/7/08 18:14
10/7/08 19:26
10/7/08 20:38

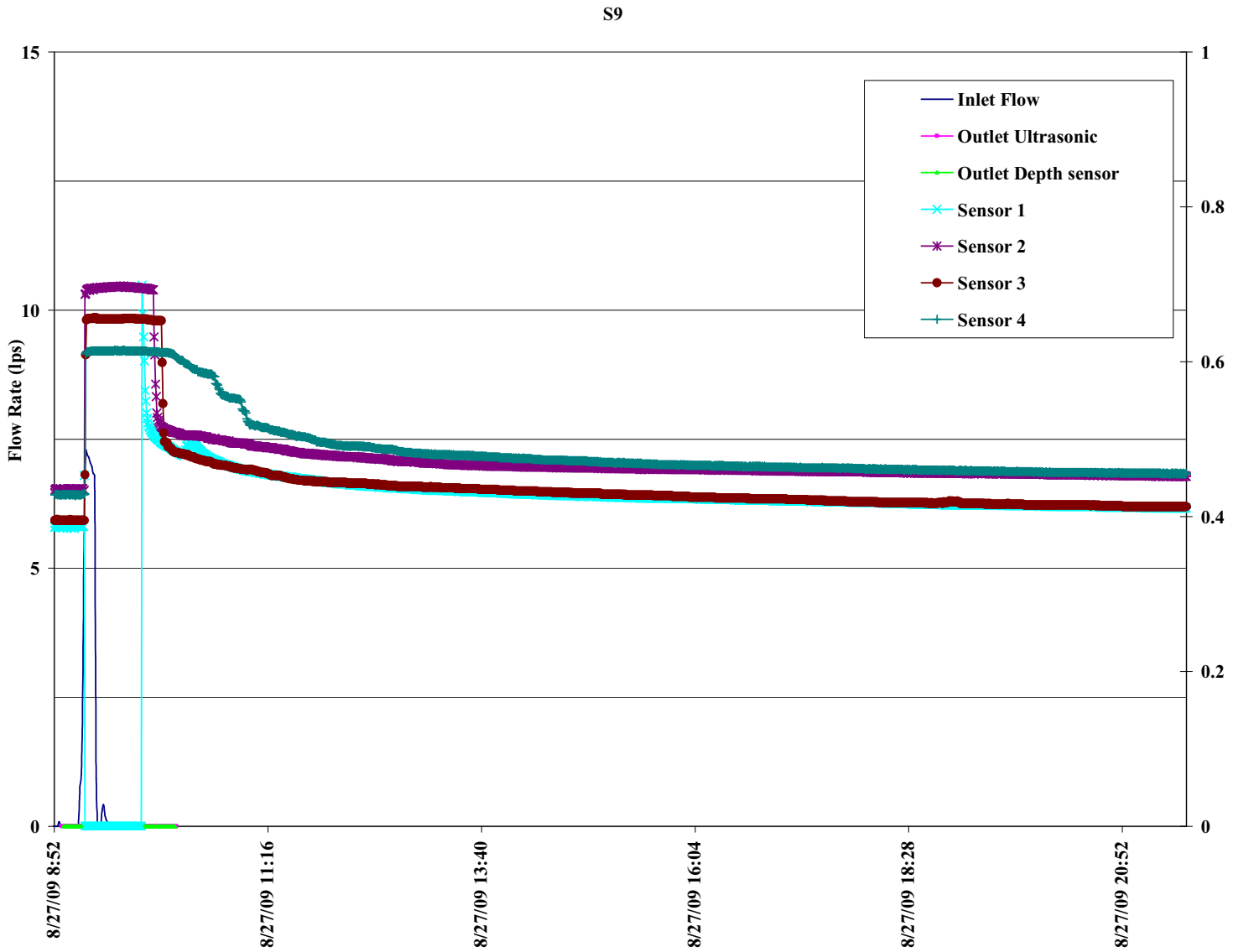

F2
Flow Rate (lps)
15
10
5
0
1
0.8
0.6
0.4
0.2
0
Inlet Flow
Outlet Ultrasonic
Sensor 1
Sensor 2
Sensor 3
Sensor 4
10/24/08 9:21
10/24/08 11:45
10/24/08 14:09
10/24/08 16:33
10/24/08 18:57
10/24/08 21:21
10/24/08 23:45

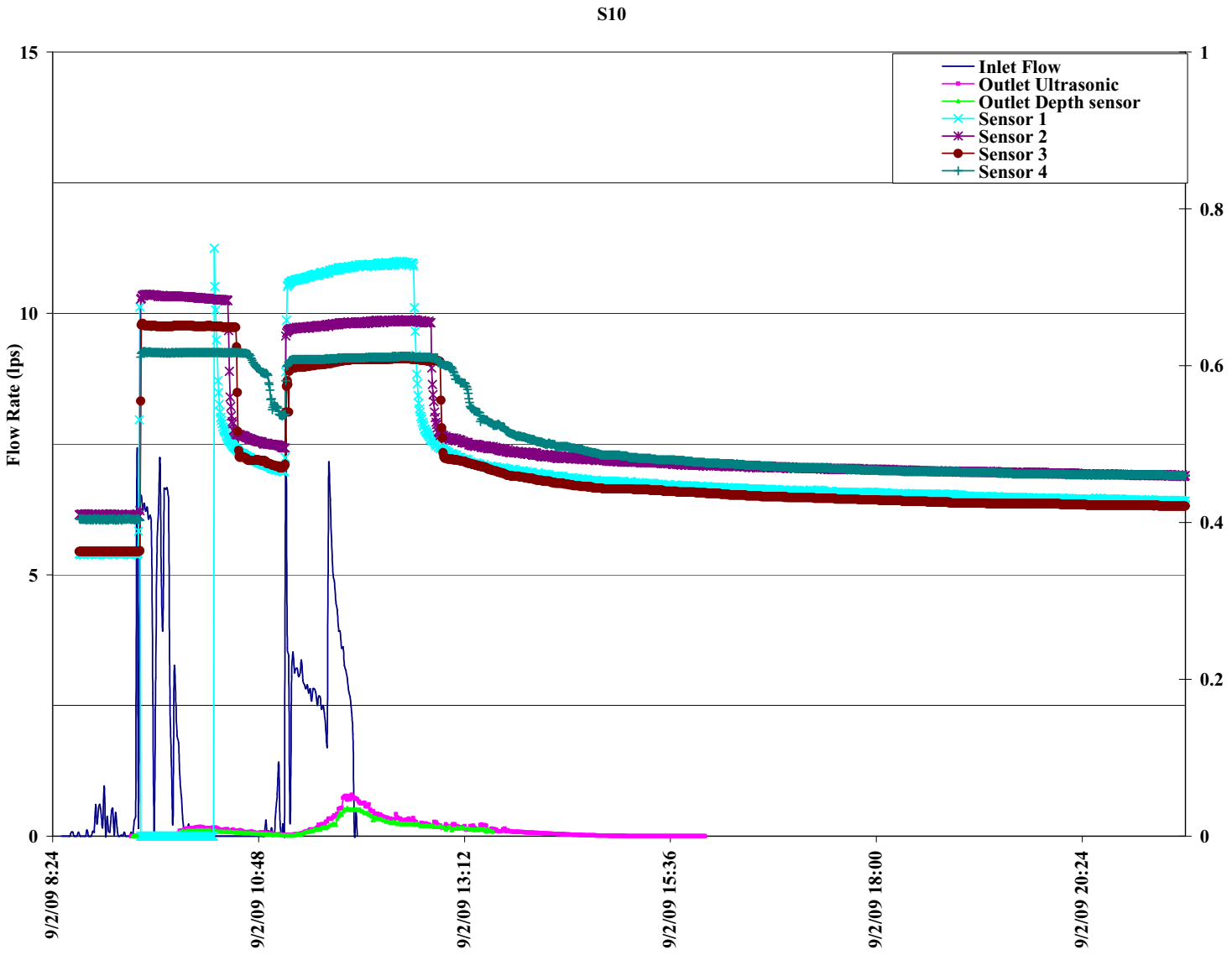

F3
Flow Rate (lps)
15
10
5
0
1
0.8
0.6
0.4
0.2
0
Inlet Flow
Outlet Ultrasonic
Outlet Depth sensor
Sensor 1
Sensor 2
Sensor 3
Sensor 4
11/4/08 9:36
11/4/08 10:48
11/4/08 12:00
11/4/08 13:12
11/4/08 14:24
11/4/08 15:36
11/4/08 16:48
11/4/08 18:00
11/4/08 19:12
11/4/08 20:24
11/4/08 21:36

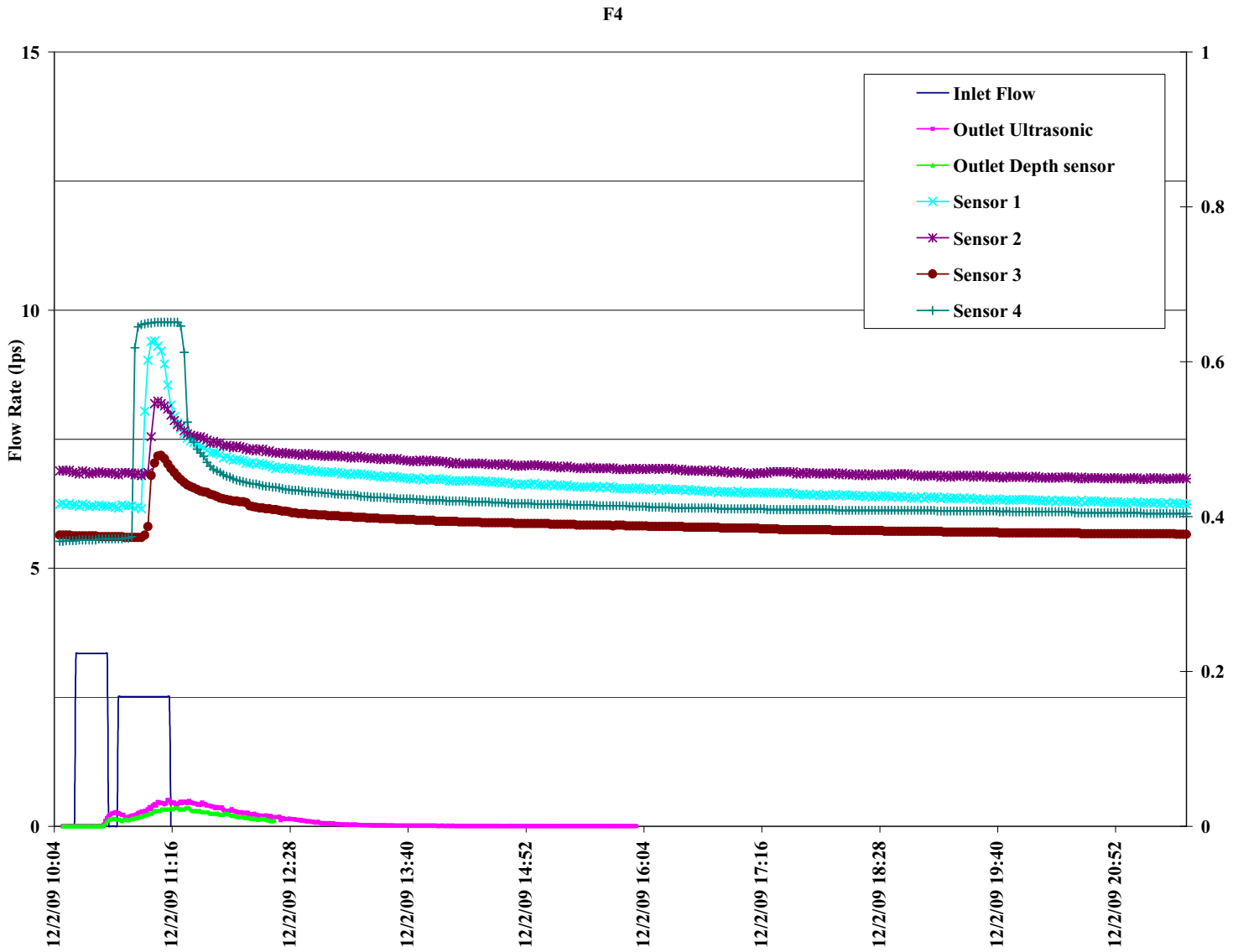

S6
Flow Rate (lps)
15
10
5
0
1
0.8
0.6
0.4
0.2
0
Inlet Flow
Outlet Ultrasonic
Outlet Depth sensor
Sensor 1
Sensor 2
Sensor 3
Sensor 4
7/22/09 9:21
7/22/09 11:45
7/22/09 14:09
7/22/09 16:33
7/22/09 18:57
7/22/09 21:21

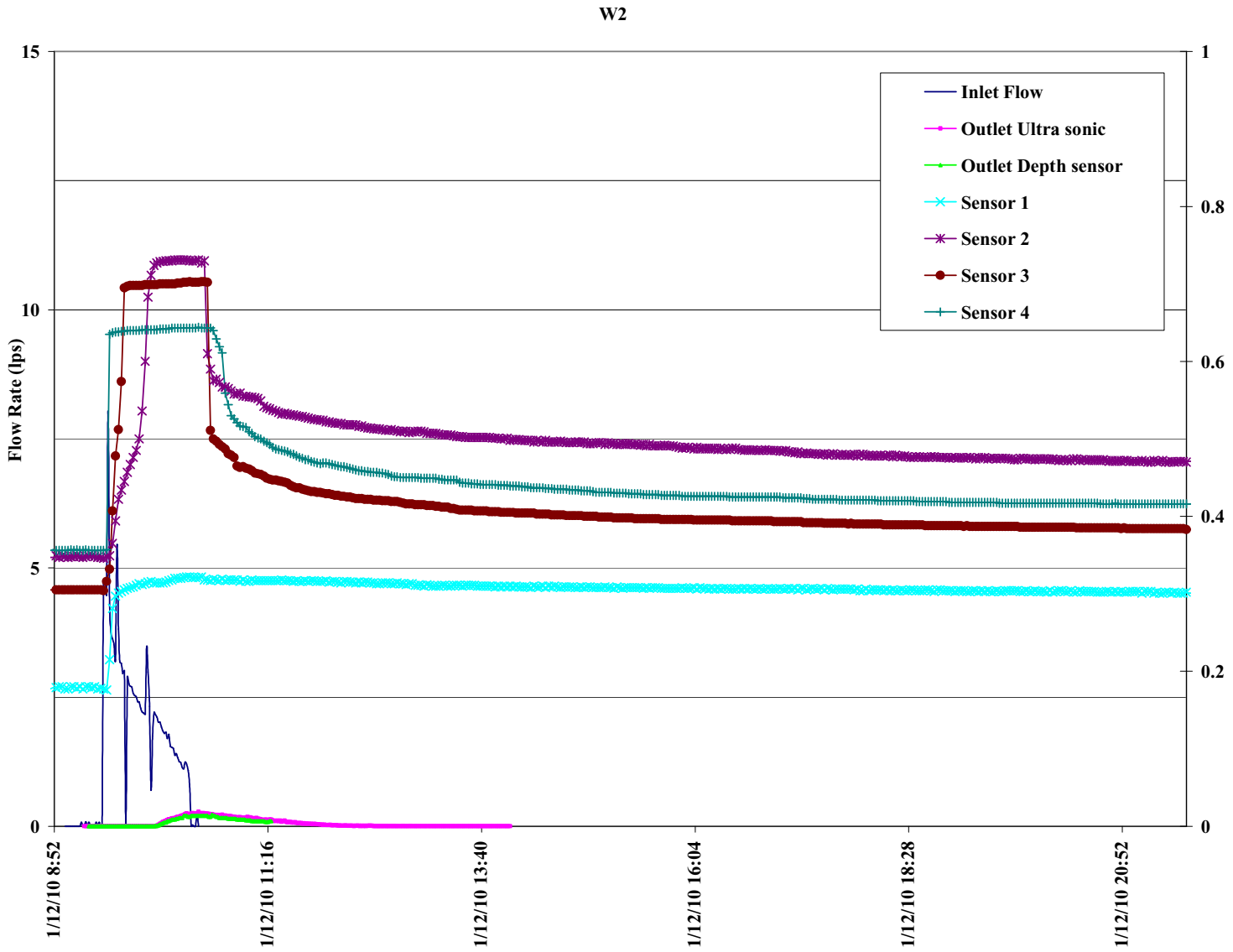

S7
Flow Rate (lps)
15
10
5
0
1
0.8
0.6
0.4
0.2
0
Inlet Flow
Outlet Ultrasonic
Outlet Depth sensor
Sensor 1
Sensor 2
Sensor 3
Sensor 4
8/12/09 9:21
8/12/09 11:45
8/12/09 14:09
8/12/09 16:33
8/12/09 18:57
8/12/09 21:21

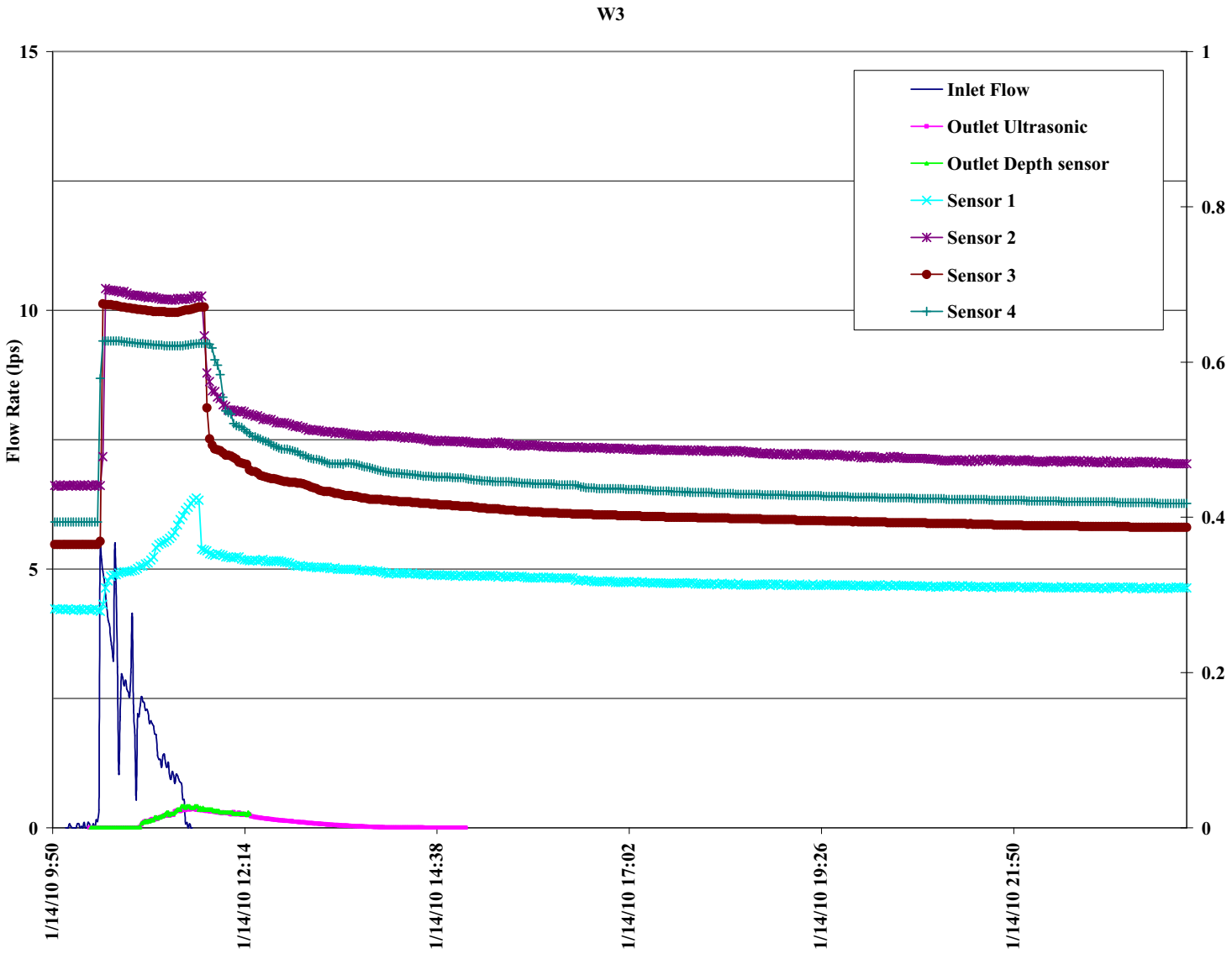

S8
Flow Rate (lps)
15
10
5
0
1
0.8
0.6
0.4
0.2
0
8/26/09 8:09
8/26/09 10:33
8/26/09 12:57
8/26/09 15:21
8/26/09 17:45
8/26/09 20:09
Inlet Flow
Outlet Ultrasonic
OutletDepth sensor
Sensor 1
Sensor 2
Sensor 3
Sensor 4

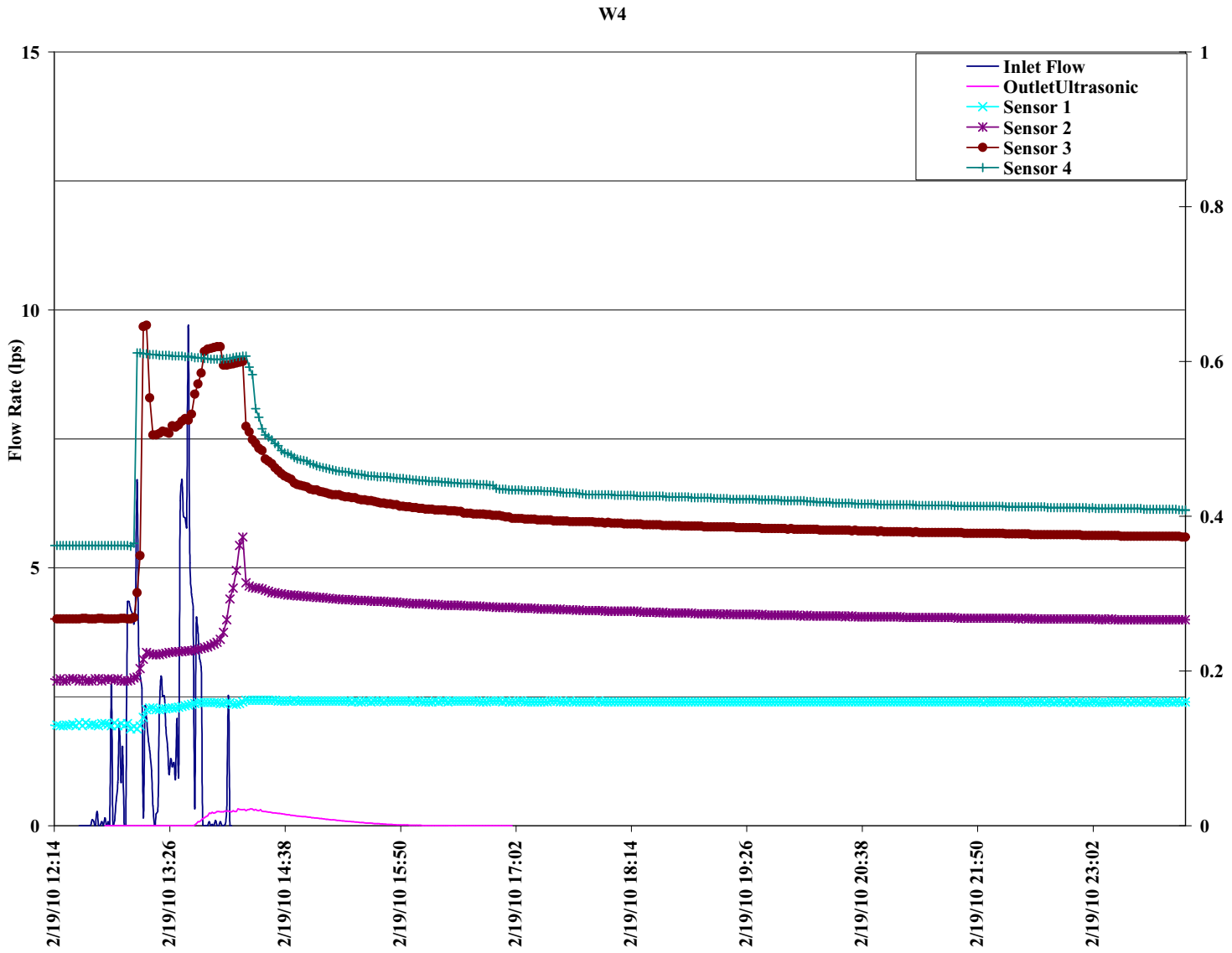

S9
Flow Rate (lps)
15
10
5
0
1
0.8
0.6
0.4
0.2
0
Inlet Flow
Outlet Ultrasonic
Outlet Depth sensor
Sensor 1
Sensor 2
Sensor 3
Sensor 4
8/27/09 8:52
8/27/09 11:16
8/27/09 13:40
8/27/09 16:04
8/27/09 18:28
8/27/09 20:52

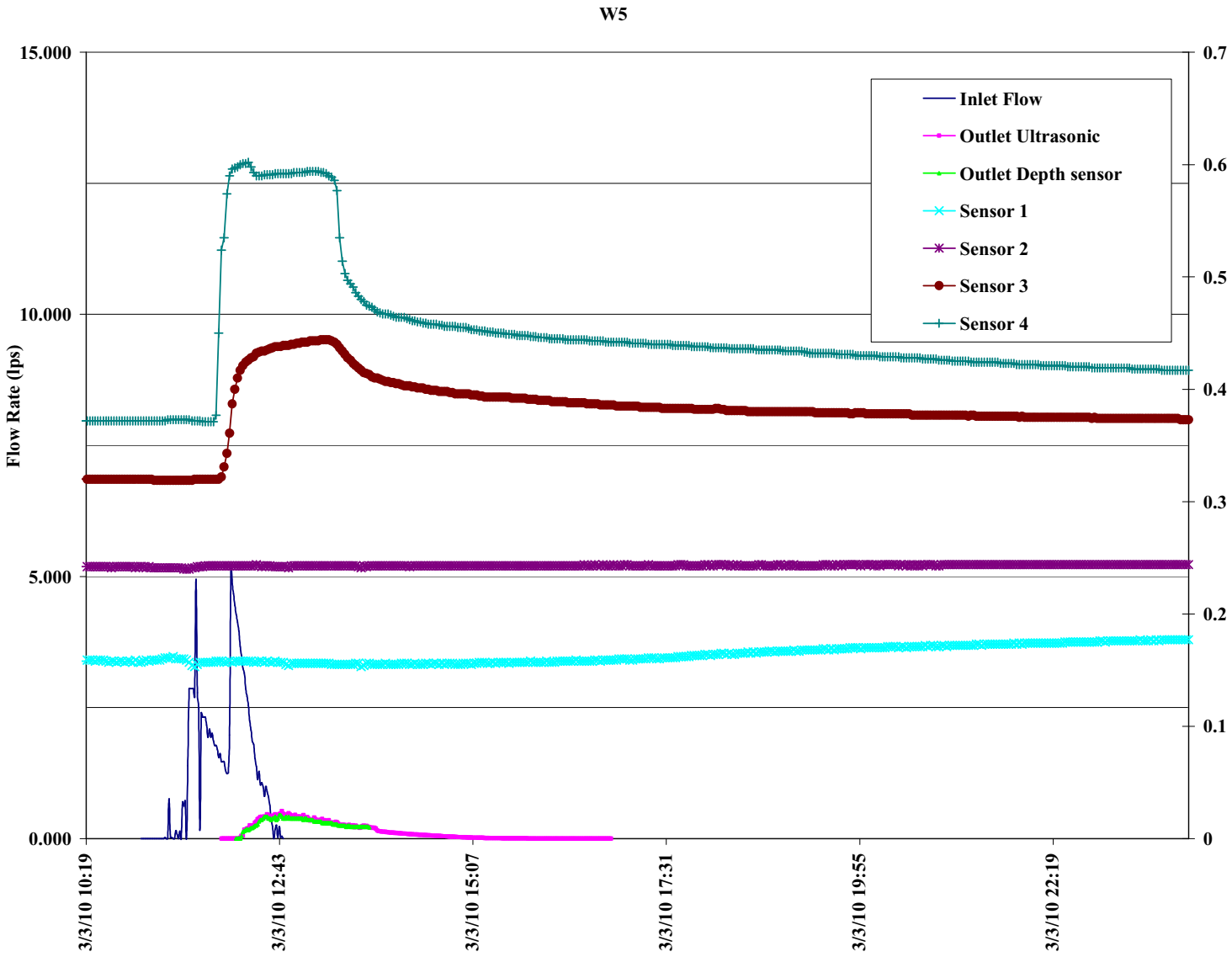

S10
Inlet Flow
Outlet Ultrasonic
Outlet Depth sensor
Sensor 1
Sensor 2
Sensor 3
Sensor 4
Flow Rate (lps)
15
10
5
0
1
0.8
0.6
0.4
0.2
0
9/2/09 8:24
9/2/09 10:48
9/2/09 13:12
9/2/09 15:36
9/2/09 18:00
9/2/09 20:24

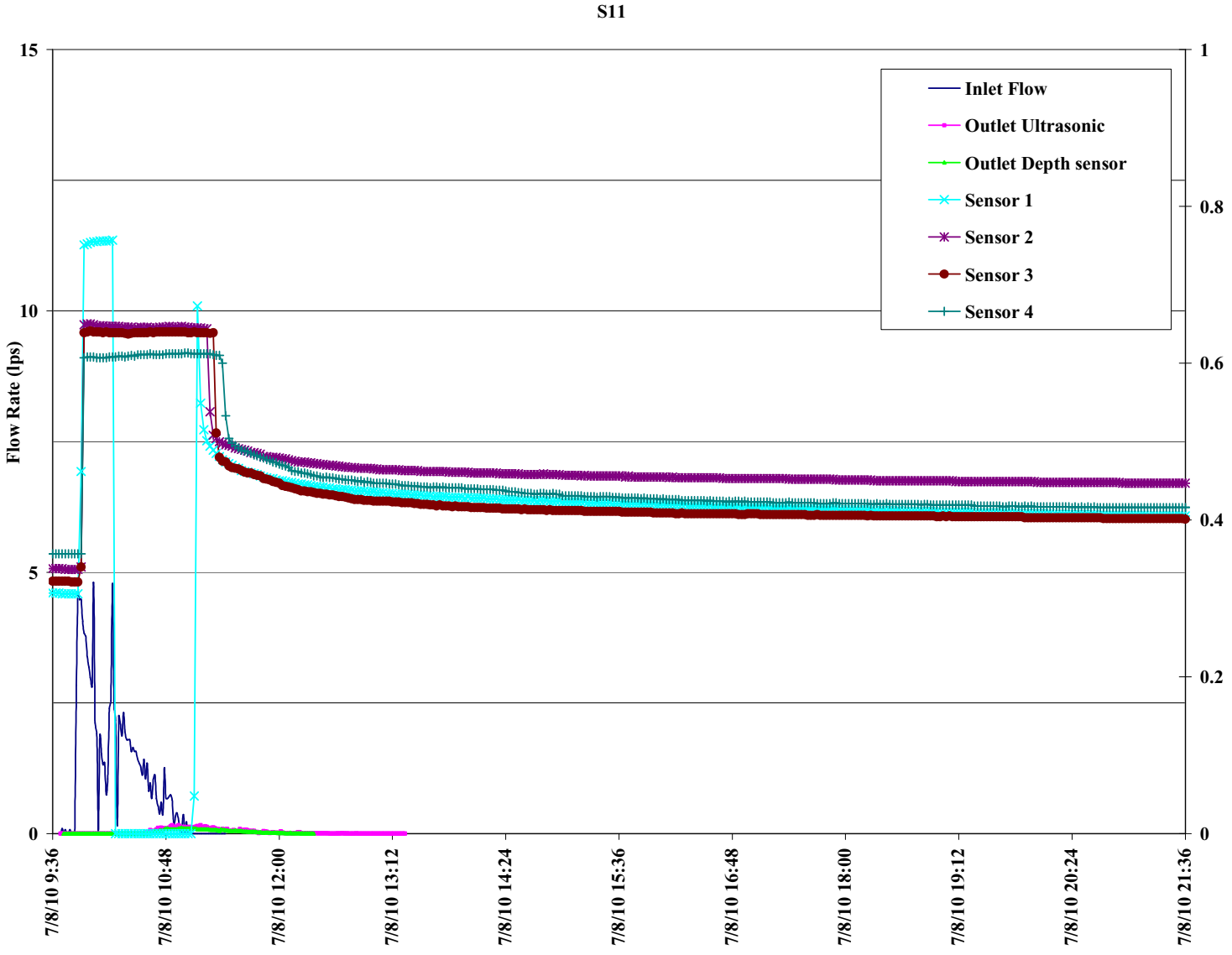

F4
Flow Rate (lps)
15
10
5
0
1
0.8
0.6
0.4
0.2
0
Inlet Flow
Outlet Ultrasonic
Outlet Depth sensor
Sensor 1
Sensor 2
Sensor 3
Sensor 4
12/2/09 10:04
12/2/09 11:16
12/2/09 12:28
12/2/09 13:40
12/2/09 14:52
12/2/09 16:04
12/2/09 17:16
12/2/09 18:28
12/2/09 19:40
12/2/09 20:52


W2
Flow Rate (lps)
15
10
5
0
1
0.8
0.6
0.4
0.2
0
Inlet Flow
Outlet Ultra sonic
Outlet Depth sensor
Sensor 1
Sensor 2
Sensor 3
Sensor 4
1/12/10 8:52
1/12/10 11:16
1/12/10 13:40
1/12/10 16:04
1/12/10 18:28
1/12/10 20:52


W3
Flow Rate (lps)
15
10
5
0
1
0.8
0.6
0.4
0.2
0
Inlet Flow
Outlet Ultrasonic
Outlet Depth sensor
Sensor 1
Sensor 2
Sensor 3
Sensor 4
1/14/10 9:50
1/14/10 12:14
1/14/10 14:38
1/14/10 17:02
1/14/10 19:26
1/14/10 21:50


W4
Inlet Flow
OutletUltrasonic
Sensor 1
Sensor 2
Sensor 3
Sensor 4
Flow Rate (lps)
15
10
5
0
1
0.8
0.6
0.4
0.2
0
2/19/10 12:14
2/19/10 13:26
2/19/10 14:38
2/19/10 15:50
2/19/10 17:02
2/19/10 18:14
2/19/10 19:26
2/19/10 20:38
2/19/10 21:50
2/19/10 23:02


W5
15.000
10.000
5.000
0.000
Flow Rate (lps)
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
Inlet Flow
Outlet Ultrasonic
Outlet Depth sensor
Sensor 1
Sensor 2
Sensor 3
Sensor 4
3/3/10 10:19
3/3/10 12:43
3/3/10 15:07
3/3/10 17:31
3/3/10 19:55
3/3/10 22:19


S11
Flow Rate (lps)
15
10
5
0
1
0.8
0.6
0.4
0.2
0
Inlet Flow
Outlet Ultrasonic
Outlet Depth sensor
Sensor 1
Sensor 2
Sensor 3
Sensor 4
7/8/10 9:36
7/8/10 10:48
7/8/10 12:00
7/8/10 13:12
7/8/10 14:24
7/8/10 15:36
7/8/10 16:48
7/8/10 18:00
7/8/10 19:12
7/8/10 20:24
7/8/10 21:36

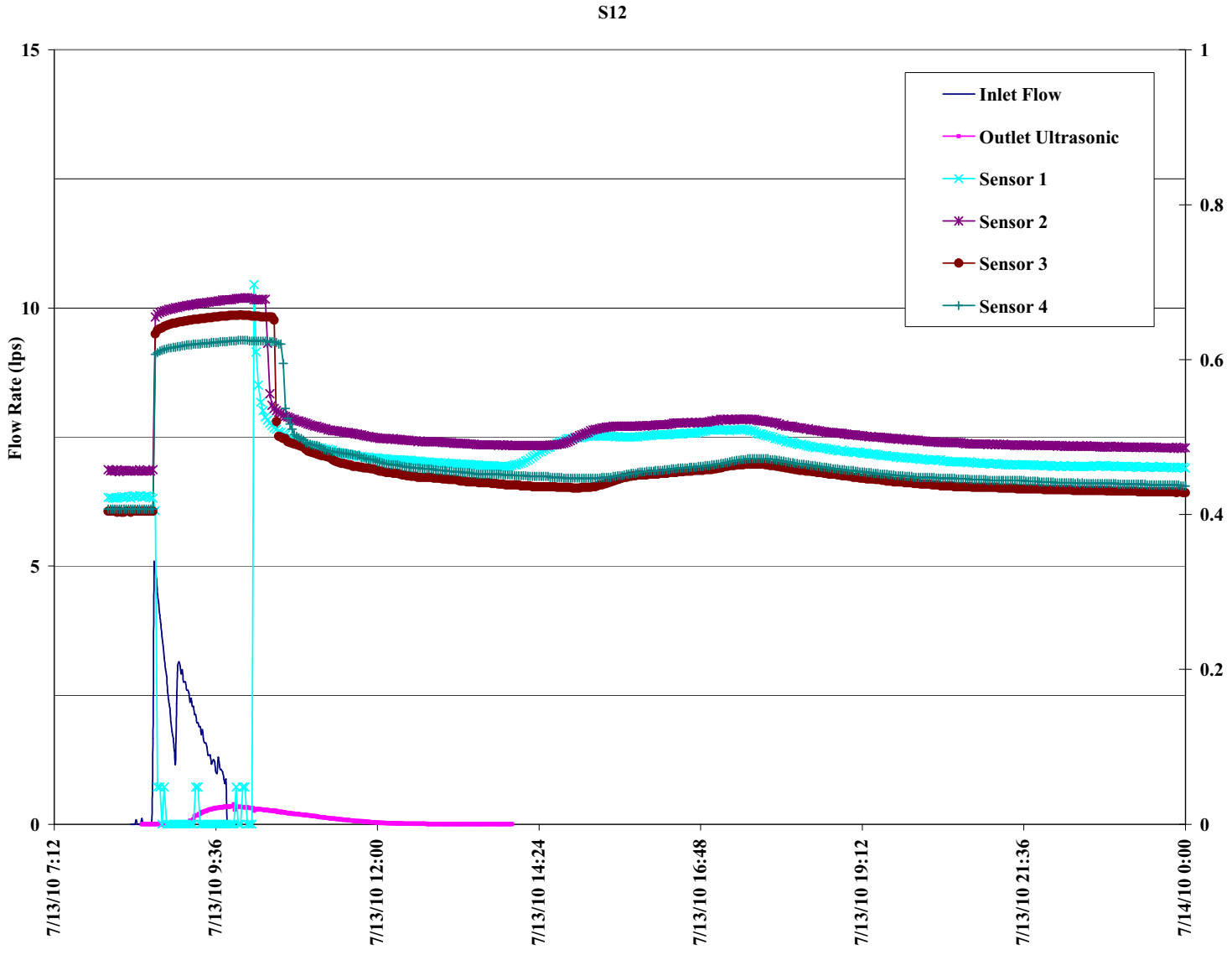

S12
Flow Rate (lps)
15
10
5
0
1
0.8
0.6
0.4
0.2
0
Inlet Flow
Outlet Ultrasonic
Sensor 1
Sensor 2
Sensor 3
Sensor 4
7/13/10 7:12
7/13/10 9:36
7/13/10 12:00
7/13/10 14:24
7/13/10 16:48
7/13/10 19:12
7/13/10 21:36
7/14/10 0:00

Table 19: Inlet and outlet water quality data for field experiments

		Median Flow	Volume	TSS	SSC	BOD	TN	Nitrate	Nitrite	Ammonia	TP	Cl
		L/s	L	mg/L	mg/L	mg/L	mg/L N	mg/L NO_3^--N	mg/L NO_2^-	mg/L NH_3-N	mg/L P	mg/L
S1	Inlet	0.898	1012.9	2.00	-	3.23	-	-	-	-	-	-
	Inlet	0.955	3505.2	2.00	-	4.74	-	-	-	-	-	-
	Inlet	1.504	3541.5	3.00	-	3.88	-	-	-	-	-	-
	Outlet	0.062	106.5	5.00	-	5.19	-	-	-	-	-	-
	Outlet	0.046	249.6	1.00	-	4.38	-	-	-	-	-	-
S2	Inlet	5.776	6371.7	0.00	-	-	-	-	-	-	-	-
	Inlet	2.358	933.3	33.00	-	-	-	-	-	-	-	-
	Outlet	0.033	24.0	26.00	-	-	-	-	-	-	-	-
	Outlet	0.025	27.9	2.00	-	-	-	-	-	-	-	-
S3	Inlet	3.716	3776.4	279.00	-	-	-	-	-	-	-	-
	Inlet	4.705	2264.4	466.00	-	-	-	-	-	-	-	-
	Inlet	5.375	1301.9	13.00	-	-	-	-	-	-	-	-
	Outlet	0.087	86.9	17.50	-	-	-	-	-	-	-	-
	Outlet	0.092	81.5	15.00	-	-	-	-	-	-	-	-
	Outlet	0.043	82.2	12.50	-	-	-	-	-	-	-	-
S4	Inlet	5.296	2887.6	159.00	-	1.36	-	2.2	-	0.12	-	-
	Inlet	5.080	3611.3	242.00	-	2.70	-	2.4	-	0.18	-	-
	Inlet	4.507	1128.0	790.00	-	3.92	-	3.2	-	0.30	-	-
	Outlet	0.201	206.6	24.00	-	2.28	-	4.7	-	0.65	-	-
	Outlet	0.181	166.5	13.00	-	2.62	-	3.9	-	0.68	-	-
	Outlet	0.098	193.2	8.00	-	3.06	-	4.1	-	0.52	-	-

F1	Inlet	5.188	3648.4	303.00	793.43	8.38	3.38	4.8	18	0.33	0.74	50.0
	Inlet	5.448	3362.9	279.00	903.92	6.95	3.89	3.4	11	0.17	0.29	90.0
	Inlet	5.267	2030.1	305.00	390.19	5.97	4.18	3.1	10	0.19	0.24	90.0
	Outlet	0.114	72.9	18.00	28.50	4.00	7.36	4.3	12	0.42	0.20	90.0
	Outlet	0.136	100.3	22.00	15.92	3.68	3.05	4.2	12	0.45	0.30	160.0
F2	Inlet	5.558	3362.3	29.00	164.31	2.01	5.47	2.9	0	0.18	0.05	100.0
	Inlet	4.805	3045.2	243.00	648.63	2.47	4.25	2.8	2	0.18	0.57	125.0
	Inlet	4.605	1913.6	44.00	219.12	2.58	5.02	2.8	0	0.16	0.00	100.0
	Outlet	0.217	267.9	17.00	30.66	2.56	4.86	5.8	11	0.45	0.45	100.0
	Outlet	0.170	247.5	2.00	298.75	0.91	3.45	4.9	8	0.33	0.47	100.0
	Outlet	0.104	150.0	0.00	5.10	1.29	4.57	4.0	5	0.26	0.17	100.0
F3	Inlet	3.335	1780.5	402.00	596.45	2.15	5.02	1.6	3	0.16	0.11	-
	Inlet	3.634	1744.5	132.00	344.71	1.84	3.39	1.4	1	0.11	0.07	-
	Inlet	3.073	1106.1	261.00	971.04	2.56	6.37	1.2	2	0.09	0.08	-
	Outlet	0.000	3.2	10.00	-	2.51	6.84	1.8	6	0.26	0.14	-
W1	Inlet	5.488	2583.0	540.00	508.57	4.21	4.85	1.9	2	0.48	0.00	237.5
	Inlet	4.808	1404.1	327.00	1386.40	5.68	4.85	1.8	2	0.44	0.00	300.0
	Inlet	0.812	194.9	446.00	675.90	5.03	4.85	1.9	1	0.43	0.00	300.0
	Outlet	0.000	0.0	-	-	-	-	-	-	-	-	-
Sp1	Inlet	6.191	2281.4	209.00	475.20	2.31	2.41	1.4	4	1.71	0.39	-
	Inlet	1.779	441.3	81.00	118.90	2.42	1.70	1.3	6	1.72	0.33	-
	Inlet	1.136	298.0	2077.00	4990.10	3.96	4.95	1.3	9	1.89	0.65	-
	Outlet	0.000	0.0	-	-	-	-	-	-	-	-	-
Sp2	Inlet	5.366	3272.4	1788.00	2723.68	6.54	3.24	2.0	13	1.15	0.48	262.5
	Inlet	6.075	4396.1	2290.00	2819.12	10.96	5.36	2.1	15	2.27	0.55	425.0
	Inlet	3.801	2258.5	2016.00	3296.24	11.98	1.51	2.0	10	2.19	0.69	475.0

	Outlet	0.257	386.5	24.00	23.20	8.14	0.51	2.4	5	0.73	0.24	325.0
	Outlet	0.206	347.6	18.00	11.68	7.63	2.81	2.0	9	0.89	0.31	340.0
	Outlet	0.096	116.7	14.00	7.04	7.27	0.27	1.9	9	0.88	0.26	350.0
Sp3	Inlet	5.392	1878.1	323.00	376.50	4.88	1.25	1.1	1	0.16	0.13	130.0
	Inlet	5.261	1553.9	233.00	611.40	2.30	2.90	1.2	2	0.17	0.13	120.0
	Inlet	2.587	605.0	77.00	220.80	5.04	1.27	1.1	2	0.17	0.10	125.0
	Outlet	0.000	0.0	-	-	-	-	-	-	-	-	-
S5	Inlet	5.160	2602.6	1843.00	3243.50	8.64	1.89	1.0	7	0.34	0.38	150.0
	Inlet	5.066	3047.3	1439.00	3041.20	4.91	1.42	2.2	11	0.65	1.78	162.5
	Inlet	4.650	2498.4	729.00	914.60	4.49	1.40	1.5	1	0.50	0.49	150.0
	Outlet	0.152	176.0	12.00	17.60	3.15	<0	2.8	3	0.60	0.30	162.5
	Outlet	0.118	156.6	3.00	8.60	3.92	<0.049	2.5	4	0.52	0.00	200.0
	Outlet	0.050	56.0	3.00	4.70	3.30	<0.061	2.3	1	0.51	0.00	195.0
S6	Inlet	4.830	2455.7	680.00	249.08	3.11	1.08	1.2	2	0.28	0.06	102.5
	Inlet	6.105	3764.5	2062.00	131.08	2.09	1.35	1.8	2	0.33	0.06	102.5
	Inlet	0.575	1196.5	48.00	1022.75	1.64	2.38	1.5	1	0.28	0.03	117.5
	Outlet	0.080	160.0	16.00	5.83	5.96	1.95	4.3	13	0.70	0.23	125.0
	Outlet	0.080	160.0	19.00	6.42	3.18	1.53	4.0	13	0.70	0.15	142.5
	Outlet	0.080	160.0	21.00	5.67	3.93	2.95	4.2	12	0.71	0.15	137.5
S7	Inlet	6.300	1703.5	996.00	122.83	-	2.17	2.8	10	0.61	0.27	112.5
	Inlet	6.144	1838.7	3250.00	624.00	-	2.70	3.0	23	1.09	0.32	125.0
	Inlet	3.967	961.4	3920.00	415.75	-	3.17	3.1	15	0.83	0.30	132.5
	Outlet	0.000	0.0	-	-	-	-	-	-	-	-	-
S8	Inlet	5.980	1757.6	709.00	-	-	2.46	1.6	14	0.26	0.52	122.5
	Inlet	5.756	1726.7	745.00	-	-	1.77	1.5	10	0.32	0.32	100.0
	Inlet	4.037	928.4	396.00	-	-	1.44	1.3	9	0.38	0.42	112.5

	Outlet	0.000	0.0	-	-	-	-	-	-	-	-	-
S9	Inlet	7.095	2234.7	240.00	-	-	<0.918	2.0	7	0.38	0.20	110.0
	Inlet	6.842	1032.2	489.00	-	-	1.16	1.4	9	0.48	0.91	120.0
	Inlet	0.920	258.5	205.00	-	-	1.38	1.3	6	0.25	0.10	125.0
	Outlet	0.000	0.0	-	-	-	-	-	-	-	-	-
S10	Inlet	6.239	2902.6	1804.00	1199.50	-	1.97	1.9	14	0.26	0.60	140.0
	Inlet	4.893	2765.8	2230.00	890.30	-	1.98	2.0	10	0.23	0.83	-
	Inlet	4.651	2111.4	2143.00	668.10	-	2.18	3.1	10	0.28	0.41	-
	Inlet	2.761	9876.0	1274.00	-	-	1.44	2.4	12	0.56	0.69	-
	Outlet	0.151	239.9	0.00	13.80	-	<0.461	2.3	10	0.45	0.10	125.0
	Outlet	0.114	213.3	0.00	3.50	-	<0.623	2.0	7	0.39	0.09	-
	Outlet	0.036	105.9	-3.00	3.70	-	<0.742	1.9	9	0.41	0.00	-
	Outlet	0.559	1260.6	-6.00	4.00	-	<0.748	1.6	9	0.43	0.19	120.0
	Outlet	0.292	730.5	-1.00	2.60	-	1.95	1.7	7	0.39	0.21	-
	Outlet	0.179	438.9	-1.00	2.10	-	1.30	1.8	7	0.43	0.22	127.5
F4	Inlet	3.348	4017.0	5255.00	-	6.74	3.68	2.9	23	0.43	0.43	67.31
	Inlet	2.512	4822.0	1343.00	-	9.11	3.9	3.4	66	1.24	0.51	50.00
	Outlet	0.212	707.3	10.00	-	4.12	3.42	1.9	7	0.15	0.13	73.08
	Outlet	0.332	1107.7	15.00	-	5.75	3.71	2.1	7	0.00	0.19	76.92
	Outlet	0.140	467.1	19.00	-	2.41	3.51	2.4	7	0.38	0.16	76.92
W2	Inlet	4.268	2442.5	1761.00	3453.55	5.46	4.48	2.7	25	1.19	-	575.9
	Inlet	3.009	1869.2	1345.00	2266.82	4.56	3.68	2.4	17	1.04	-	535.7
	Inlet	2.457	1163.5	13.00	13.45	1.92	3.56	1.9	5	0.78	-	544.6
	Outlet	0.163	264.24	18.00	6.00	3.40	4.22	2.0	6	0.34	-	575.9
	Outlet	0.217	656.4	34.00	2.36	3.61	-	2.3	5	0.40	-	482.1
	Outlet	0.154	182.4	19.00	4.45	3.79	10.80	2.9	4	0.35	-	361.6

W3	Inlet	4.4970	2706.72	3366.00	2748	2.95	7.45	2.3	29	1.50	-	1022.3
	Inlet	2.9690	1753.56	2225.00	1563	3.94	2.75	1.5	24	1.40	-	875.0
	Inlet	2.5990	1334.16	30.00	10	4.59	2.74	1.2	6	1.06	-	122.8
	Outlet	0.1775	316.8	13.00	3	4.42	5.46	2.4	9	0.59	-	843.8
	Outlet	0.3475	614.88	7.00	3	5.14	5.01	2.6	6	0.57	-	964.3
	Outlet	0.2895	345	14.00	3	5.80	4.71	2.8	8	0.58	-	794.6
W4	Inlet	2.183	8951.0	1174	-	5.93	3.46	1.1	8	1.49	0.33	488.00
	Outlet	0.104	1293.0	35	-	4.17	4.41	3.4	8	0.61	0.25	436.00
W5	Inlet	1.894	8581.0	3833	-	10.90	2.23	0.0	4	1.33	0.55	444.44
	Outlet	0.2885	487.08	67	-	5.52	-	0.9	0	0.76	0.23	444.44
	Outlet	0.4260	766.44	14	-	6.36	-	0.2	0	0.53	0.18	344.44
	Outlet	0.3125	378.6	11	-	6.03	5.51	0.0	0	0.47	-	452.78
S11	Inlet	2.837	3366.788	1027	1234	5.50	3.82	0.0	-	0.41	0.24	11.24
	Inlet	1.122	3631.961	7156		10.02	4.3	3.0	-	0.99	0.46	27.39
	Outlet	0.065	413.340	20	12	2.91	3.97	0.4	-	0.58	0.27	22.94
	Outlet	0.002	9.420	13		2.80	3.62	0.2	-	0.48	0.40	29.03
S12	Inlet	2.731	4015.083	5047	1074	1.27	2.7	0.7	-	0.81	0.31	15.45
	Inlet	1.968	4532.009	672		2.29	3.3	0.0	-	0.33	0.20	14.51
	Outlet	0.28	1500.24	38	24	2.68	1.51	0.0	-	0.51	0.34	20.83
	Outlet	0.019	556.02	13		2.99	1.63	0.0	-	0.44	0.22	34.18

Table 20: Initial, peak, and 12 hour after peak (AP) soil moisture for all four sensor locations

ID		150 mm	300 mm	500 mm	1000 mm	ID		150 mm	300 mm	500 mm	1000 mm
S1	θ_i	0.230	0.249	0.282	0.402	S9	θ_i	0.389	0.434	0.395	0.429
	θ_P	0.729	0.591	0.619	0.487		θ_P	0.699	0.698	0.657	0.615
	θ_{AP}	0.330	0.353	0.353	0.478		θ_{AP}	0.410	0.452	0.413	0.455
S2	θ_i	0.307	0.250	0.284	0.403	S10	θ_i	0.364	0.414	0.368	0.405
	θ_P	-[+]	0.570	0.621	-[+]		θ_P	0.750	0.691	0.654	0.618
	θ_{AP}	0.326	0.352	0.357	-[+]		θ_{AP}	0.425	0.459	0.421	0.460
S3	θ_i	0.299	0.302	0.328	0.433	F4	θ_i	0.417	0.460	0.376	0.368
	θ_P	0.738	0.596	0.619	0.488		θ_P	0.627	0.549	0.479	0.651
	θ_{AP}	0.340	0.371	0.400	0.470		θ_{AP}	0.414	0.447	0.376	0.402
S4	θ_i	0.313	0.308	0.324	0.421	W2	θ_i	-[*]	0.347	0.306	0.356
	θ_P	0.730	0.601	0.618	0.489		θ_P	0.321	0.731	0.703	0.644
	θ_{AP}	-[+]	0.373	0.398	0.480		θ_{AP}	0.301	0.470	0.383	0.415
F1	θ_i	-[+]	0.312	0.179	0.410	W3	θ_i	-[*]	0.454	0.372	0.404
	θ_P	-[+]	0.606	0.619	0.494		θ_P	0.425	0.695	0.675	0.627
	θ_{AP}	-[+]	0.375	0.418	0.488		θ_{AP}	0.309	0.472	0.389	0.420
F2	θ_i	-[+]	0.351	0.482	-[+]	W4	θ_i	-[*]	0.189	0.267	0.362
	θ_P	-[+]	0.616	0.726	-[+]		θ_P	-[*]	0.373	0.647	0.611
	θ_{AP}	-[+]	0.393	0.466	-[+]		θ_{AP}	-[*]	0.264	0.371	0.407

F3	θ_i	-[+]	0.358	0.399	0.513	W5	θ_i	-[*]	0.242	0.320	0.372
	θ_P	-[+]	0.614	0.641	0.513		θ_P	-[*]	-[+]	0.444	0.602
	θ_{AP}	-[+]	0.399	0.433	0.498		θ_{AP}	-[*]	-[+]	0.372	0.416
S6	θ_i	0.181	0.286	0.278	0.314	S11	θ_i	0.306	0.338	0.322	0.357
	θ_P	0.758	0.678	0.641	0.635		θ_P	0.757	0.650	0.641	0.613
	θ_{AP}	0.328	0.409	0.411	0.487		θ_{AP}	0.404	0.446	0.401	0.415
S7	θ_i	0.335	0.391	0.357	0.392	S12	θ_i	0.422	0.456	0.404	0.407
	θ_P	0.740	0.703	0.664	0.623		θ_P	0.697	0.680	0.658	0.625
	θ_{AP}	0.393	0.431	0.409	0.443		θ_{AP}	0.462	0.489	0.432	0.442
S8	θ_i	0.326	0.385	0.340	0.388	[*]Frozen soil, sensor did not function					
	θ_P	0.736	0.694	0.656	0.622	[+]Sensor error					
	θ_{AP}	0.397	0.442	0.405	0.442						

APPENDIX B: Summary of statistical analysis (field experiments)

Normality was tested using the Shaprio-Wilk (SW) test. The sample set was normal if the significance was greater than 0.05. Independent non-parametric sample sets were compared using the Mann-Whitney (MW) test. An independent t-test (TT) was conducted for parametric sample sets. Equal variances were assumed if Levene's Test significance was greater than 0.05. Wilcoxon Signed (WS) Rank test was conducted for non-parametric paired comparisons while paired t-test (PT) was conducted for parametric sample sets.

Hydrological performance

Table 21: Statistical significance: hydrologic performance for field experiments

Volume reduction		**SW**	**MW**	**TT**
All Data	Warm	0.022	0.32	-
	Cold	0.122		
Large events	Warm	0.032	0.006	
	Cold	0.436		
Mass balance		**SW**	**MW**	**TT**
Outlet	Warm	0.03	0.035	-
	Cold	0.555		
Storage	Warm	0.734	-	0.043
	Cold	0.74		
Other Losses	Warm	0.545	-	0.28
	Cold	0.879		
Peak Flow		**SW**	**MW**	**TT**
Inlet	Warm	0.725	-	0.138
	Cold	0.904		
Outlet	Warm	0.006	0.188	-
	Cold	0.371		
Reduction	Warm	0.015	0.203	-
	Cold	0.781		
Delay	Warm	0.039	0.039	-
	Cold	0.811		
Delay Factor	Warm	0	0.188	-
	Cold	0.454		
CoM		**SW**	**MW**	**TT**
Inlet	Warm	0.054	-	0.007
	Cold	0.628		

Outlet	Warm	0.035	0.202	-
	Cold	0.076		
Reduction	Warm	0.003	0.271	-
	Cold	0.452		
Delay	Warm	0.525	-	0.049
	Cold	0.098		
Delay Factor	Warm	0	0.861	-
	Cold	0.001		

Soil Moisture		**SW**	**MW**	**TT**
Initial				
Sensor 1	Warm	0.135	-	0.269
	Cold	0.276		
Sensor 2	Warm	0.463	-	0.949
	Cold	0.476		
Sensor 3	Warm	0.373	-	0.861
	Cold	0.347		
Sensor 4	Warm	0.032	0.254	-
	Cold	0.009		
Peak				
Sensor 1	Warm	0.035	0.02	-
	Cold	0.53		
Sensor 2	Warm	0.063	0.38	-
	Cold	0.532		
Sensor 3	Warm	0.008	0.86	-
	Cold	0.118		
Sensor 4	Warm	0.001	0.136	-
	Cold	0.1		
12AP				
Sensor 1	Warm	0.103	-	0.046
	Cold	0.691		
Sensor 2	Warm	0.3	0.503	-
	Cold	0.018		
Sensor 3	Warm	0.043	0.152	-
	Cold	0.908		
Sensor 4	Warm	0.478	-	0.021
	Cold	0.827		

Water quality performance

Table 22: Statistical significance: water quality performance field experiments

Mass Removal		SW	MW	TT
TSS	Warm	0.000	0.453	-
	Cold	0.008		
SSC	Warm	0.000	0.044	-
	Cold	0.024		
BOD5	Warm	0.001	0.480	-
	Cold	0.182		
TN	Warm	0.014	0.156	-
	Cold	0.059		
Nitrate	Warm	0.014	0.953	-
	Cold	0.004		
Nitrite	Warm	0.000	0.109	-
	Cold	0.001		
Ammonia	Warm	0.029	0.034	-
	Cold	0.241		
TP	Warm	0.002	0.865	-
	Cold	0.079		
Cl	Warm	0.000	0.884	-
	Cold	0.478		

Concentration		SW	MW	TT
TSS	Influent	0.000	0.000	-
	Effluent	0.000		
SSC	Influent	0.000	0.000	-
	Effluent	0.000		
BOD5	Influent	0.001	0.722	-
	Effluent	0.159		
TN	Influent	0.018	0.205	-
	Effluent	0.068		
Nitrate	Influent	0.105	-	0.039
	Effluent	0.101		
Nitrite	Influent	0.000	0.457	-
	Effluent	0.161		
Ammonia	Influent	0.000	0.465	-
	Effluent	0.665		
TP	Influent	0.000	0.027	-
	Effluent	0.403		
Cl	Influent	0.000	0.373	-
	Effluent	0.000		

Concentration		SW	WS	PT
TSS	Influent	0.000	0.000	-
	Effluent	0.973		
SSC	Influent	0.503	0.005	-
	Effluent	0.000		
BOD5	Influent	0.164	-	0.038
	Effluent	0.342		
TN	Influent	0.179	-	0.436
	Effluent	0.729		
Nitrate	Influent	0.954	-	0.066
	Effluent	0.371		
Nitrite	Influent	0.007	0.266	-
	Effluent	0.426		
Ammonia	Influent	0.104	-	0.092
	Effluent	0.997		
TP	Influent	0.968	-	0.05
	Effluent	0.860		
Cl	Influent	0.036	0.807	-
	Effluent	0.031		

Concentration		SW	MW	TT
TSS	Warm	0.000	0.964	-
	Cold	0.000		
SSC	Warm	0.000	0.964	-
	Cold	0.000		
BOD5	Warm	0.001	-	0.681
	Cold	0.159		
TN	Warm	0.018	-	0.015
	Cold	0.068		
Nitrate	Warm	0.105	-	0.557
	Cold	0.101		
Nitrite	Warm	0.000	0.109	-
	Cold	0.161		
Ammonia	Warm	0.000	0.018	-
	Cold	0.665		
TP	Warm	0.000	-	0.629
	Cold	0.403		
Cl	Warm	0.000	1.000	-
	Cold	0.000		

APPENDIX C: Laboratory experiment results

Table 23: Water quality data for cold weather column experiments

Exp No	Source	TSS	BOD_5	TN	Nitrate	Ammonia	TP	Cl⁻
		(mg/L)	(mg/L)	(mg/L)	(mg/L-N)	(mg/L-N)	(mg/L)	(mg/L)
1	Inlet	1369	6.65	1.26	1.9	1.42	0.33	366.0
	C1	23	7.13	20.80	13.4	0.65	0.78	432.0
	C2	14	5.85	22.80	10.9	0.70	0.71	374.0
2	Inlet	160	10.98	4.00	0.0	0.81	0.36	405.5
	C1	42	2.88	37.20	19.5	1.35	1.42	773.1
	C2	49	9.48	26.30	11.4	1.57	0.83	222.2
3	Inlet	1377	12.02	4.15	3.9	1.17	0.60	629.4
	C1	56	6.02	17.10	13.0	1.38	1.21	191.9
	C2	80	7.62	62.50	36.4	1.37	1.11	285.7
4	Inlet	372	9.52	3.37	0.1	0.64	0.05	1.3
	C1	52	10.21	9.57	0.0	2.37	0.03	20.0
	C2	3	6.61	11.40	0.0	2.26	0.01	54.4
5	Inlet	391	9.81	5.14	1.2	0.60	0.24	10.7
	C1	38	7.72	9.32	0.0	2.45	1.37	30.5
	C2	6	10.38	6.95	0.0	2.08	1.39	17.8
6	Inlet	184	8.82	3.04	1.9	0.41	0.24	16.7
	C1	42	5.94	8.42	0.4	1.46	1.05	11.7
	C2	34	5.10	8.71	0.9	1.38	1.01	12.5
7	Inlet	2751	9.83	2.38	0.5	0.85	0.18	-
	C1	18	2.41	5.85	0.2	1.02	1.28	8.4
	C2	62	2.87	7.29	1.3	1.01	1.20	10.5

Table 24: Water quality data for temperate weather column experiments

Exp No	Source	TSS	Nitrate	Ammonia	TP	Cl-
		(mg/L)	(mg/L-N)	(mg/L-N)	(mg/L)	(mg/L)
1	Inlet	362.66	0.6	0.28	0.31	131.58
	S3	0	4.9	0.91	0.40	136.51
	S4	63	13.8	2.52	0.67	143.09
2	Inlet	345.66	0.0	0.17	0.35	95.39
	S3	38	15.9	2.08	0.41	166.12
	S4	59	0.0	1.76	0.39	210.53
3	Inlet	288.16	0.5	0.18	1.73	172.70
	S3	28	9.1	2.04	3.70	125.00
	S4	31	0.0	2.20	1.79	157.89
4	Inlet	421.30	0.3	0.34	2.45	107.27
	S3	25	1.3	1.16	1.35	29.55
	S4	10	0.1	0.77	1.67	100.45
5	Inlet	436.80	0.4	0.44	0.98	23.86
	S3	10	1.3	0.90	1.92	71.82
	S4	19	0.2	1.08	1.64	58.64
6	Inlet	304.80	1.4	0.45	-	7.95
	S3	23	5.0	0.91	-	73.64
	S4	31	4.1	1.04	-	56.82
7	Inlet	570.26	3.5	0.53	2.32	11.36
	S3	19	4.4	0.65	2.12	28.36
	S4	27	3.4	0.72	2.67	14.32
8	Inlet	1114.25	0.0	0.65	2.54	32.39
	S3	18	0.0	0.94	2.20	78.07
	S4	40	0.0	1.04	1.73	33.52
9	Inlet	1248.25	0.0	0.76	3.36	28.38
	S3	40	0.4	1.02	2.07	21.35
	S4	17	0.0	1.15	2.18	23.65

Table 25: Summary of volume and sediment applied to the four long term performance columns

Day	Sampling Date	Testing Date	Run No	Total Runs	Water Depth (cm)	Volume (L)	Sediment (g)	Target TSS Conc. (mg/L)	Start Time	End Time	Del-t	Volume (m3)
1	11/10/2009	11/11/2009	1	1	50	509.21	322	632.35	13:48	15:23	1:35	0.51
2	11/11/2009	11/11/2009	1	2	52	529.58	274	517.39	9:55	11:26	1:31	1.04
2	11/11/2009	11/11/2009	2	3	54	549.95	293	532.78	12:30	14:01	1:31	1.59
2	11/11/2009	11/12/2009	3	4	53	539.77	308	570.62	16:11	17:59	1:48	2.13
3	11/12/2009	11/12/2009	1	5	56	570.32	303	531.28	10:28	12:30	2:02	2.70
3	11/12/2009	11/12/2009	2	6	58	590.69	313	529.89	14:13	16:00	1:47	3.29
3	11/12/2009	11/13/2009	3	7	56	570.32	314	550.57	17:16	19:00	1:44	3.86
4	11/13/2009	11/13/2009	1	8	53	539.77	323	598.41	10:21	11:55	1:34	4.40
4	11/13/2009	11/13/2009	2	9	53	539.77	312	578.03	13:22	15:00	1:38	4.94
4	11/13/2009	11/14/2009	3	10	53	539.77	303	561.36	16:06	17:36	1:30	5.48
5	11/14/2009	11/14/2009	1	11	54	549.95	318	578.23	10:30	12:05	1:35	6.03
5	11/14/2009	11/14/2009	2	12	52	529.58	308	581.59	13:01	14:34	1:33	6.56
5	11/14/2009	Not Tested	3	13	55	560.13	294	524.87	15:33	17:10	1:37	7.12
6	11/15/2009	Not Tested	1	14	54	549.95	298	541.87	14:15	15:53	1:38	7.67
7	11/17/2009	11/18/2009	1	15	54	549.95	313	569.14	14:43	16:20	1:37	8.22
8	11/18/2009	11/18/2009	1	16	56	570.32	301	527.78	8:40	10:30	1:50	8.79
8	11/18/2009	11/18/2009	2	17	56	570.32	290	508.49	11:31	13:11	1:40	9.36
8	11/18/2009	Not Tested	3	18	56	570.32	296	519.01	14:12	15:50	1:38	9.93
8	11/18/2009	Not Tested	4	19	56	570.32	307	538.30	17:20	18:55	1:35	10.50
9	11/19/2009	Not Tested	1	20	57	580.50	314	540.91	9:58	12:00	2:02	11.08
9	11/19/2009	Not Tested	2	21	60	611.06	310	507.32	13:08	14:54	1:46	11.69
9	11/19/2009	Not Tested	3	22	53	539.77	295	546.53	15:57	17:33	1:36	12.23

10	11/20/2009	11/21/2009	1	23	58	590.69	290	490.95	9:51	11:39	1:48	12.82
10	11/20/2009	11/21/2009	2	24	55	560.13	296	528.45	12:43	14:19	1:36	13.38
10	11/20/2009	11/21/2009	3	25	56	570.32	315	552.32	15:21	17:00	1:39	13.95
11	11/21/2009	11/23/2009	1	26	56	570.32	285	499.72	13:21	15:00	1:39	14.52
11	11/21/2009	11/23/2009	2	27	56	570.32	287	503.23	16:00	17:36	1:36	15.09
11	11/21/2009	11/23/2009	3	28	53	539.77	309	572.47	18:31	20:05	1:34	15.63
12	11/23/2009	11/24/2009	1	29	53	539.77	298	552.09	9:59	11:38	1:39	16.17
12	11/23/2009	11/24/2009	2	30	53	539.77	296	548.39	14:00	15:45	1:45	16.71
13	11/24/2009	11/24/2009	1	31	55	560.13	303	540.94	10:45	12:20	1:35	17.27
13	11/24/2009	Not Tested	2	32	54	549.95	322	585.51	14:37	16:15	1:38	17.82
13	11/24/2009	Not Tested	3	33	58	590.69	314	531.58	17:30	19:05	1:35	18.41
14	11/27/2009	11/28/2009	1	34	55	560.13	290	517.73	9:50	11:26	1:36	18.97
14	11/27/2009	11/28/2009	2	35	53	539.77	304	563.21	12:28	13:56	1:28	19.51
14	11/27/2009	11/28/2009	3	36	56	570.32	314	550.57	14:51	16:25	1:34	20.08
15	11/28/2009	11/29/2009	1	37	56	570.32	302	529.53	11:18	12:56	1:38	20.65
15	11/28/2009	11/29/2009	2	38	54	549.95	336	610.97	13:49	15:21	1:32	21.20
15	11/28/2009	11/29/2009	3	39	55	560.13	284	507.02	16:15	17:49	1:34	21.76
15	11/28/2009	Not Tested	4	40	55	560.13	305	544.51	18:47	20:20	1:33	22.32
16	11/29/2009	Not Tested	1	41	55	560.13	319	569.51	9:56	11:28	1:32	22.88
16	11/29/2009	Not Tested	2	42	56	570.32	283	496.21	12:27	13:58	1:31	23.45
16	11/29/2009	Not Tested	3	43	55	560.13	302	539.16	14:49	16:26	1:37	24.01
16	11/29/2009	Not Tested	4	44	57	580.50	288	496.12	17:24	19:07	1:43	24.59
17	11/30/2009	Not Tested	1	45	16	162.95	0	0.00	11:12	11:32	0:20	24.76
18	12/1/2009	Not Tested	1	46	57	580.50	302	520.24	13:32	15:13	1:41	25.34
18	12/1/2009	12/2/2009	2	47	58	590.69	296	501.11	16:12	17:52	1:40	25.93
19	12/2/2009	12/3/2009	1	48	57	580.50	293	504.74	13:34	15:13	1:39	26.51

19	12/2/2009	12/3/2009	2	49	56	570.32	282	494.46	16:09	17:45	1:36	27.08
20	12/3/2009	12/3/2009	1	50	58	590.69	281	475.72	9:41	11:21	1:40	27.67
20	12/3/2009	12/4/2009	2	51	57	580.50	310	534.02	12:17	13:55	1:38	28.25
20	12/3/2009	12/4/2009	3	52	58	590.69	315	533.28	14:54	16:35	1:41	28.84
20	12/3/2009	12/4/2009	4	53	59	600.87	309	514.25	17:33	19:16	1:43	29.44
21	12/4/2009	Not Tested	1	54	59	600.87	297	494.28	9:55	11:36	1:41	30.04
21	12/4/2009	Not Tested	2	55	58	590.69	290	490.95	12:34	15:05	1:39	30.63
21	12/4/2009	Not Tested	3	56	52	529.58	297	560.82	15:57	17:29	1:32	31.16
22	12/6/2009	12/7/2009	1	57	57	580.50	301	518.52	13:16	14:55	1:39	31.74
22	12/6/2009	12/7/2009	2	58	57	580.50	328	565.03	15:55	17:33	1:38	32.32
22	12/6/2009	12/7/2009	3	59	58	590.69	298	504.50	18:49	20:27	1:38	32.92
23	12/7/2009	Not Tested	1	60	54	549.95	271	492.77	10:09	11:49	1:40	33.47
23	12/7/2009	Not Tested	2	61	53	539.77	272	503.92	13:16	14:53	1:37	34.01
24	12/8/2009	Not Tested	1	62	62	631.42	292	462.45	12:34	14:22	1:48	34.64
24	12/8/2009	Not Tested	2	63	62	631.42	279	441.86	15:22	17:08	1:46	35.27
24	12/8/2009	12/9/2009	3	64	58	590.69	257	435.09	17:58	19:40	1:42	35.86
24	12/8/2009	12/9/2009	4	65	59	600.87	274	456.00	20:10	21:54	1:44	36.46
25	12/9/2009	12/9/2009	1	66	58	590.69	251	424.93	9:36	11:20	1:44	37.05
25	12/9/2009	12/9/2009	2	67	60	611.06	299	489.32	12:19	14:06	1:47	37.66
25	12/9/2009	12/10/2009	3	68	59	600.87	271	451.01	15:05	16:47	1:42	38.26
26	12/9/2009	12/10/2009	4	69	60	611.06	300	490.95	17:44	19:26	1:42	38.87
26	12/10/2009	12/10/2009	1	70	56	570.32	278	487.45	9:27	11:08	1:41	39.44
26	12/10/2009	Not Tested	2	71	39.6	403.30	272	485.60	12:07	13:12	1:05	39.85
26	12/10/2009	Not Tested	3	72	15.4	156.84	0	485.60	13:12	13:43	0:31	40.00

Table 26: List of long term performance composite samples

Sample ID	Sampling Date	Testing Date	Run	Source	Sample ID	Sampling Date	Testing Date	Run	Source
L1	11/10/2009	11/12/2009	1	Inlet	L18	11/11/2009	11/12/2009	3	T2
L2	11/10/2009	11/12/2009	1	T1		11/12/2009	11/12/2009	1	T2
L3	11/10/2009	11/12/2009	1	T2		11/12/2009	11/12/2009	2	T2
L4	11/10/2009	11/12/2009	1	S1	L19	11/11/2009	11/12/2009	3	S1
L5	11/10/2009	11/12/2009	1	S2		11/12/2009	11/12/2009	1	S1
L6	11/11/2009	11/12/2009	1	Inlet		11/12/2009	11/12/2009	2	S1
L7	11/11/2009	11/12/2009	1	T1	L20	11/11/2009	11/12/2009	3	S2
L8	11/11/2009	11/12/2009	1	T2		11/12/2009	11/12/2009	1	S2
L9	11/11/2009	11/12/2009	1	S1		11/12/2009	11/12/2009	2	S2
L10	11/11/2009	11/12/2009	1	S2	L21	11/12/2009	11/13/2009	3	Inlet
L11	11/11/2009	11/12/2009	2	Inlet		11/13/2009	11/13/2009	1	Inlet
L12	11/11/2009	11/12/2009	2	T1		11/13/2009	11/13/2009	2	Inlet
L13	11/11/2009	11/12/2009	2	T2	L22	11/12/2009	11/13/2009	3	T1
L14	11/11/2009	11/12/2009	2	S1		11/13/2009	11/13/2009	1	T1
L15	11/11/2009	11/12/2009	2	S2		11/13/2009	11/13/2009	2	T1
L16	11/11/2009	11/12/2009	3	Inlet	L23	11/12/2009	11/13/2009	3	T2
	11/12/2009	11/12/2009	1	Inlet		11/13/2009	11/13/2009	1	T2
	11/12/2009	11/12/2009	2	Inlet		11/13/2009	11/13/2009	2	T2
L17	11/11/2009	11/12/2009	3	T1	L24	11/12/2009	11/13/2009	3	S1
	11/12/2009	11/12/2009	1	T1		11/13/2009	11/13/2009	1	S1
	11/12/2009	11/12/2009	2	T1		11/13/2009	11/13/2009	2	S1

L25	11/12/2009	11/13/2009	3	S2	L33	11/17/2009	11/18/2009	3	T2
	11/13/2009	11/13/2009	1	S2		11/18/2009	11/18/2009	1	T2
	11/13/2009	11/13/2009	2	S2		11/18/2009	11/18/2009	2	T2
L26	11/13/2009	11/14/2009	3	Inlet	L34	11/17/2009	11/18/2009	3	S1
	11/14/2009	11/14/2009	1	Inlet		11/18/2009	11/18/2009	1	S1
	11/14/2009	11/14/2009	2	Inlet		11/18/2009	11/18/2009	2	S1
L27	11/13/2009	11/14/2009	3	T1	L35	11/17/2009	11/18/2009	3	S2
	11/14/2009	11/14/2009	1	T1		11/18/2009	11/18/2009	1	S2
	11/14/2009	11/14/2009	2	T1		11/18/2009	11/18/2009	2	S2
L28	11/13/2009	11/14/2009	3	T2	L36	11/20/2009	11/21/2009	1	Inlet
	11/14/2009	11/14/2009	1	T2		11/20/2009	11/21/2009	2	Inlet
	11/14/2009	11/14/2009	2	T2		11/20/2009	11/21/2009	3	Inlet
L29	11/13/2009	11/14/2009	3	S1	L37	11/20/2009	11/21/2009	1	T1
	11/14/2009	11/14/2009	1	S1		11/20/2009	11/21/2009	2	T1
	11/14/2009	11/14/2009	2	S1		11/20/2009	11/21/2009	3	T1
L30	11/13/2009	11/14/2009	3	S2	L38	11/20/2009	11/21/2009	1	T2
	11/14/2009	11/14/2009	1	S2		11/20/2009	11/21/2009	2	T2
	11/14/2009	11/14/2009	2	S2		11/20/2009	11/21/2009	3	T2
L31	11/17/2009	11/18/2009	3	Inlet	L39	11/20/2009	11/21/2009	1	S1
	11/18/2009	11/18/2009	1	Inlet		11/20/2009	11/21/2009	2	S1
	11/18/2009	11/18/2009	2	Inlet		11/20/2009	11/21/2009	3	S1
L32	11/17/2009	11/18/2009	3	T1	L40	11/20/2009	11/21/2009	1	S2
	11/18/2009	11/18/2009	1	T1		11/20/2009	11/21/2009	2	S2
	11/18/2009	11/18/2009	2	T1		11/20/2009	11/21/2009	3	S2

L41	11/21/2009	11/23/2009	1	Inlet	L49	11/23/2009	11/24/2009	1	S1
	11/21/2009	11/23/2009	2	Inlet		11/23/2009	11/24/2009	2	S1
	11/21/2009	11/23/2009	3	Inlet		11/24/2009	11/24/2009	1	S1
L42	11/21/2009	11/23/2009	1	T1	L50	11/23/2009	11/24/2009	1	S2
	11/21/2009	11/23/2009	2	T1		11/23/2009	11/24/2009	2	S2
	11/21/2009	11/23/2009	3	T1		11/24/2009	11/24/2009	1	S2
L43	11/21/2009	11/23/2009	1	T2	L51	11/27/2009	11/28/2009	1	Inlet
	11/21/2009	11/23/2009	2	T2		11/27/2009	11/28/2009	2	Inlet
	11/21/2009	11/23/2009	3	T2		11/27/2009	11/28/2009	3	Inlet
L44	11/21/2009	11/23/2009	1	S1	L52	11/27/2009	11/28/2009	1	T1
	11/21/2009	11/23/2009	2	S1		11/27/2009	11/28/2009	2	T1
	11/21/2009	11/23/2009	3	S1		11/27/2009	11/28/2009	3	T1
L45	11/21/2009	11/23/2009	1	S2	L53	11/27/2009	11/28/2009	1	T2
	11/21/2009	11/23/2009	2	S2		11/27/2009	11/28/2009	2	T2
	11/21/2009	11/23/2009	3	S2		11/27/2009	11/28/2009	3	T2
L46	11/23/2009	11/24/2009	1	Inlet	L54	11/27/2009	11/28/2009	1	S1
	11/23/2009	11/24/2009	2	Inlet		11/27/2009	11/28/2009	2	S1
	11/24/2009	11/24/2009	1	Inlet		11/27/2009	11/28/2009	3	S1
L47	11/23/2009	11/24/2009	1	T1	L55	11/27/2009	11/28/2009	1	S2
	11/23/2009	11/24/2009	2	T1		11/27/2009	11/28/2009	2	S2
	11/24/2009	11/24/2009	1	T1		11/27/2009	11/28/2009	3	S2
L48	11/23/2009	11/24/2009	1	T2	L56	11/28/2009	11/29/2009	1	Inlet
	11/23/2009	11/24/2009	2	T2		11/28/2009	11/29/2009	2	Inlet
	11/24/2009	11/24/2009	1	T2		11/28/2009	11/29/2009	3	Inlet

L57	11/28/2009	11/29/2009	1	T1	L68	12/2/2009	12/3/2009	1	T2
	11/28/2009	11/29/2009	2	T1		12/2/2009	12/3/2009	2	T2
	11/28/2009	11/29/2009	3	T1		12/3/2009	12/3/2009	1	T2
L58	11/28/2009	11/29/2009	1	T2	L69	12/2/2009	12/3/2009	1	S1
	11/28/2009	11/29/2009	2	T2		12/2/2009	12/3/2009	2	S1
	11/28/2009	11/29/2009	3	T2		12/3/2009	12/3/2009	1	S1
L59	11/28/2009	11/29/2009	1	S1	L70	12/2/2009	12/3/2009	1	S2
	11/28/2009	11/29/2009	2	S1		12/2/2009	12/3/2009	2	S2
	11/28/2009	11/29/2009	3	S1		12/3/2009	12/3/2009	1	S2
L60	11/28/2009	11/29/2009	1	S2	L71	12/3/2009	12/4/2009	2	Inlet
	11/28/2009	11/29/2009	2	S2		12/3/2009	12/4/2009	3	Inlet
	11/28/2009	11/29/2009	3	S2		12/3/2009	12/4/2009	4	Inlet
L61	12/1/2009	12/2/2009	2	Inlet	L72	12/3/2009	12/4/2009	2	T1
L62	12/1/2009	12/2/2009	2	T1		12/3/2009	12/4/2009	3	T1
L63	12/1/2009	12/2/2009	2	T2		12/3/2009	12/4/2009	4	T1
L64	12/1/2009	12/2/2009	2	S1	L73	12/3/2009	12/4/2009	2	T2
L65	12/1/2009	12/2/2009	2	S2		12/3/2009	12/4/2009	3	T2
L66	12/2/2009	12/3/2009	1	Inlet		12/3/2009	12/4/2009	4	T2
	12/2/2009	12/3/2009	2	Inlet	L74	12/3/2009	12/4/2009	2	S1
	12/3/2009	12/3/2009	1	Inlet		12/3/2009	12/4/2009	3	S1
L67	12/2/2009	12/3/2009	1	T1		12/3/2009	12/4/2009	4	S1
	12/2/2009	12/3/2009	2	T1	L75	12/3/2009	12/4/2009	2	S2
	12/3/2009	12/3/2009	1	T1		12/3/2009	12/4/2009	3	S2
						12/3/2009	12/4/2009	4	S2

L76	12/6/2009	12/7/2009	1	Inlet	L83	12/9/2009	12/9/2009	1	T2
	12/6/2009	12/7/2009	2	Inlet		12/9/2009	12/9/2009	2	T2
	12/6/2009	12/7/2009	3	Inlet	L84	12/8/2009	12/9/2009	3	S1
L77	12/6/2009	12/7/2009	1	T1		12/8/2009	12/9/2009	4	S1
	12/6/2009	12/7/2009	2	T1		12/9/2009	12/9/2009	1	S1
	12/6/2009	12/7/2009	3	T1		12/9/2009	12/9/2009	2	S1
L78	12/6/2009	12/7/2009	1	T2	L85	12/8/2009	12/9/2009	3	S2
	12/6/2009	12/7/2009	2	T2		12/8/2009	12/9/2009	4	S2
	12/6/2009	12/7/2009	3	T2		12/9/2009	12/9/2009	1	S2
L79	12/6/2009	12/7/2009	1	S1		12/9/2009	12/9/2009	2	S2
	12/6/2009	12/7/2009	2	S1	L86	12/9/2009	12/10/2009	3	Inlet
	12/6/2009	12/7/2009	3	S1		12/9/2009	12/10/2009	4	Inlet
L80	12/6/2009	12/7/2009	1	S2		12/10/2009	12/10/2009	1	Inlet
	12/6/2009	12/7/2009	2	S2	L87	12/9/2009	12/10/2009	3	T1
	12/6/2009	12/7/2009	3	S2		12/9/2009	12/10/2009	4	T1
L81	12/8/2009	12/9/2009	3	Inlet		12/10/2009	12/10/2009	1	T1
	12/8/2009	12/9/2009	4	Inlet	L88	12/9/2009	12/10/2009	3	T2
	12/9/2009	12/9/2009	1	Inlet		12/9/2009	12/10/2009	4	T2
	12/9/2009	12/9/2009	2	Inlet		12/10/2009	12/10/2009	1	T2
L82	12/8/2009	12/9/2009	3	T1	L89	12/9/2009	12/10/2009	3	S1
	12/8/2009	12/9/2009	4	T1		12/9/2009	12/10/2009	4	S1
	12/9/2009	12/9/2009	1	T1		12/10/2009	12/10/2009	1	S1
	12/9/2009	12/9/2009	2	T1	L90	12/9/2009	12/10/2009	3	S2
L83	12/8/2009	12/9/2009	3	T2		12/9/2009	12/10/2009	4	S2
	12/8/2009	12/9/2009	4	T2		12/10/2009	12/10/2009	1	S2

Table 27: Long term experiments water quality data

ID	TSS (mg/L)	BOD_5 (mg/L)	TN (mg/L)	Ammonia (mg/L - N)	Nitrate (mg/L - N)	Nitrite (mg/L - N)	TP (mg/L)	Cl- (mg/L)
L1	681	17.15	1.76	0.36	2.3	2.7	0.13	0.13
L2	46	13.95	13.00	1.38	3.3	2.1	0.25	0.25
L3	18	17.09	>20.00	1.07	5.5	7.8	0.82	0.82
L4	58	16.63	19.00	2.02	7.5	20.1	0.75	0.75
L5	61	9.23	11.40	2.45	4.2	9.6	0.65	0.65
L6	674	17.27	1.76	0.36	2.3	2.4	0.13	0.13
L7	16	10.01	13.00	1.01	3.2	1.5	0.25	0.25
L8	46	7.53	>20.00	1.85	13.0	11.1	0.82	0.82
L9	23	5.25	19.00	2.79	11.7	11.7	0.75	0.75
L10	36	9.89	11.40	1.51	1.9	4.2	0.65	0.65
L11	289	15.85	1.76	0.29	3.6	2.4	0.13	0.13
L12	16	16.43	13.00	0.85	3.4	0	0.25	0.25
L13	12	14.17	>20.00	1.47	8.4	7.8	0.82	0.82
L14	13	15.51	19.00	1.71	1.9	12.9	0.75	0.75
L15	17	14.43	11.40	1.20	0.9	0	0.65	0.65
L16	128	9.18	7.89	0.31	3.1	3	0.11	7.1
L17	19	9.77	11.80	0.79	1.5	6.3	0.17	12.8
L18	27	9.46	21.30	1.17	6.1	9.6	0.85	15.3
L19	17	9.48	10.50	0.95	0.0	5.7	0.88	10.1
L20	16	9.24	6.80	0.89	0.0	7.5	1.16	13.4
L21	88	11.45	7.34	0.44	3.3	0.3	0.18	44.1
L22	-3	11.39	9.99	0.95	4.3	1.5	0.25	57.7
L23	11	9.32	11.10	1.27	6.7	7.2	1.01	66.7
L24	6	9.43	9.15	1.14	3.3	7.2	0.78	61.1
L25	11	11.38	7.37	0.62	3.8	1.2	0.87	55.4
L26	202	11.52	3.30	1.02	0.0	0.6	0.15	687.5
L27	14	9.86	4.72	0.97	1.2	1.2	0.16	762.5
L28	9	7.50	6.60	1.34	1.8	2.4	0.62	750.0
L29	4	10.28	3.29	0.78	0.8	0.6	0.87	-
L30	11	10.76	2.52	0.47	0.1	0.6	0.37	-
L31	346	-0.47	4.87	-	1.8	1.2	0.01	59.9
L32	33	-0.98	4.09	0.18	0.0	2.4	0.38	54.8
L33	-3	0.64	9.46	0.85	2.2	4.5	1.08	137.0

L34	-1	1.48	4.18	0.65	0.0	7.5	0.94	75.3
L35	-1	1.42	3.55	0.34	0.0	4.8	1.02	47.9
L36	387	4.35	3.47	0.16	2.1	1.8	0.15	99.3
L37	12	3.77	4.70	0.24	1.0	0.3	0.41	65.1
L38	9	4.75	4.48	0.53	1.5	1.2	0.87	71.9
L39	14	2.95	2.96	0.46	0.8	0.9	0.83	80.5
L40	73	3.65	4.19	0.35	1.2	0.6	0.75	73.6
L41	133	-	-	0.22	1.6	0.9	0.22	66.8
L42	22	-	-	0.30	1.4	1.2	0.37	113.9
L43	-1	-	-	0.35	1.4	2.1	0.79	106.4
L44	-4	-	-	0.28	0.9	1.2	0.46	106.4
L45	0	-	-	0.34	1.2	1.5	0.60	84.2
L46	554	5.23	3.29	0.26	1.8	2.7	0.16	-
L47	2	1.42	3.22	0.24	0.4	0	0.28	-
L48	3	2.21	4.45	0.68	1.1	0.9	0.57	-
L49	-5	2.36	3.40	0.48	0.5	1.2	0.59	-
L50	-3	1.90	3.50	0.43	0.7	0.9	0.48	-
L51	207	1.73	-	0.06	1.0	-	0.24	45.6
L52	8	1.20	-	0.00	0.5	-	0.28	57.4
L53	2	1.79	-	0.19	1.2	-	0.69	45.6
L54	-6	0.96	-	0.17	1.4	-	0.55	55.9
L55	-4	1.29	-	0.18	1.0	-	0.45	47.1
L56	1067	1.67	-	0.29	2.2		0.24	63.9
L57	-3	0.67	-	0.40	1.2	-	0.37	53.0
L58	13	0.89	-	0.83	2.1	-	0.81	50.3
L59	2	1.10	-	0.71	1.1	-	0.79	66.6
L60	33	2.38	-	0.22	1.3	-	0.54	63.9
L61	179	5.68	2.88	0.05	2.7	2.4	0.19	76.9
L62	0	1.63	3.38	0.27	1.5	1.5	0.34	82.7
L63	2	1.69	-	0.14	2.0	2.1	0.86	61.5
L64	-23	1.99	3.44	0.46	1.9	2.4	0.58	57.7
L65	-9	2.00	2.10	0.04	2.1	1.8	0.64	82.7
L66	247	2.82	-	0.00	3.3	-	0.18	-
L67	0	1.39	-	0.00	2.9	-	0.30	-
L68	11	1.42	-	0.00	3.0	-	0.06	-
L69	16	1.14	-	0.00	2.3	-	0.70	-
L70	45	1.27	-	0.00	2.4	-	0.49	-
L71	120	-	-	0.09	3.6	-	0.09	-
L72	-15	-	-	0.12	2.6	-	0.23	-

L73	20	-	-	0.27	2.8	-	0.35	-
L74	-180	-	-	0.15	2.4	-	0.29	-
L75	15	-	-	0.13	2.7	-	0.32	-
L76	58	-	3.37	0.21	3.5	2.1	0.09	84.2
L77	64	-	2.97	0.47	2.3	1.5	0.13	63.9
L78	-30	-	4.22	0.39	3.0	2.4	0.30	100.5
L79	-14	-	2.57	0.56	2.8	1.5	0.21	87.0
L80	3	-	3.39	0.56	2.8	1.2	0.18	69.3
L81	188	9.44	3.17	0.16	3.2	3.3	0.09	70.9
L82	7	2.19	3.40	0.00	1.9	0.9	0.12	51.2
L83	6	1.23	3.99	0.01	2.0	1.2	0.62	65.1
L84	-5	1.31	3.80	0.52	1.7	1.2	0.24	44.2
L85	2	1.77	3.51	0.01	2.3	1.8	0.14	59.3
L86	213	6.77	3.23	0.31	2.2	1.5	-	82.9
L87	18	2.67	3.35	0.66	1.9	0.9	-	88.1
L88	-1	1.92	4.15	0.21	1.9	2.4	-	71.2
L89	-6	2.01	3.61	0.27	1.6	0.9	-	102.3
L90	-1	2.70	3.50	0.16	1.9	1.5	-	111.4

APPENDIX D: Summary of statistical analysis (laboratory experiments)

Long term column experiments

Table 28: Statistical significance: hydrologic performance long term experiments

K_sat		SW	MW	TT
Tall	Initial	0.000	0.017	-
	Final	0.000		
Short	Warm	0.000	0.015	-
	Cold	0.000		

Table 29: Statistical significance: water quality performance long term experiments

Long Term WQ		SW	WS	PT
TSS i	In	0.292		
TSS T1	Tall	0.358	0.000	-
TSS T2		0.004		
TSS S1	Short	0.001	0.000	-
TSS S1		0.011		
BOD5 i	In	0.166		
BOD5 T1	Tall	0.241	-	0.000
BOD5 T2		0.230		
BOD5 S1	Short	0.060	-	0.000
BOD5 S2		0.081		
TN i	In	0.021		
TN T1	Tall	0.002	0.001	-
TN T2		0.030		
TN S1	Short	0.001	0.426	-
TN S2		0.010		
Nitrate i	In	0.769		
Nitrate T1	Tall	0.182	0.540	-
Nitrate T2		0.015		
Nitrate S1	Short	0.002	0.002	-
Nitrate S2		0.044		
Nitrite i	In	0.104		
Nitrite T1	Tall	0.272	0.279	-
Nitrite T2		0.149		
Nitrite S1	Short	0.071	0.122	-
Nitrite S2		0.008		
Ammonia i	In	0.033		
Ammonia T1	Tall	0.183	0.000	-
Ammonia T2		0.937		
Ammonia S1	Short	0.141	0.000	-

Ammonia S2		0.008		
TP i	In	0.315		
TP T1	Tall	0.498	-	0.000
TP T2		0.724		
TP S1	Short	0.557	-	0.000
TP S2		0.344		
Cl i	In	0.787		
Cl T1	Tall	0.027	0.158	-
Cl T2		0.654		
Cl S1	Short	0.488	0.136	-
Cl S2		0.524		

Cold weather column experiments

Table 30: Statistical significance: hydrologic performance cold weather column experiments

Volume Captured		SW	MW	TT
C1+C2	Warm	0.02	0.016	-
	Cold	0.203		
Peak soil moisture				
C1+C2	Warm	0.07	0	-
	Cold	0.895		
Final soil moisture				
C1+C2	Warm	0.375	-	0.013
	Cold	0.357		

Table 31: Statistical significance: water quality performance cold weather column experiments

Concentration		SW	MW	TT
TSS	Influent	0.065	0	-
	Effluent	0.927		
BOD5	Influent	0.764	-	0.008
	Effluent	0.432		
TN	Influent	0.986	0	-
	Effluent	0.001		
Nitrate	Influent	0.308	0.389	-
	Effluent	0.001		
Ammonia	Influent	0.722	-	0.013
	Effluent	0.227		
TP	Influent	0.717	0.007	-
	Effluent	0.017		
Cl	Influent	0.033	0.689	-

	Effluent	0.002		

Concentration		SW	MW	TT
TSS	Warm	0.59	-	0.643
	Cold	0.601		
BOD5	Warm	0.223	-	0.871
	Cold	0.825		
TN	Warm	0.338	-	0.012
	Cold	0.11		
Nitrate	Warm	0.006	0.004	-
	Cold	0.989		
Ammonia	Warm	0.256	0.008	-
	Cold	0.044		
TP	Warm	0.114	-	0.091
	Cold	0.955		
Cl	Warm	0.007	0.093	-
	Cold	0.383		

Effluent Concentration		SW	MW	TT
TSS	Warm	0.535	-	0.045
	Cold	0.065		
BOD5	Warm	0.632	-	0.96
	Cold	0.764		
TN	Warm	0.1	-	0.004
	Cold	0.986		
Nitrate	Warm	0.045	-	0.045
	Cold	0.308		
Ammonia	Warm	0.419	-	0.039
	Cold	0.722		
TP	Warm	0.066	-	0.818
	Cold	0.717		
Cl	Warm	0.043	-	0.041
	Cold	0.032		

Temperate weather columns

Table 32: Statistical significance: hydrologic performance warm weather column experiments

Soil Moisture		SW	MW	TT
Peak	S3 S4	0.014	-	0.000
	C1 C2 cold	0.07		
Peak	S3 S4	0.895	0.000	-
	C1 C2 warm	0.002		

Table 33: Statistical significance: water quality performance warm weather column experiments

Concentration		SW	MW	TT
TSS	Influent	0.005	0	-
	Effluent	0.422		
Nitrate	Influent	0.001	0.031	-
	Effluent	0		
Ammonia	Influent	0.748	0	-
	Effluent	0.003		
TP	Influent	0.047	0.548	-
	Effluent	0.014		
Cl	Influent	0.134	0.689	-
	Effluent	0.124		
Ammonia	Effluent 1 -3	0.299	-	0.007
	Effluent 4 -9	0.461		