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The Observed Effects of Stormwater Infiltration on Groundwater

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Executive Summary

Stormwater infiltration for the purpose of urban stormwater management and watershed protection has become a popular technique to address concerns related to runoff volume, baseflow, peak flow rate and water quality. Significant research has been performed to develop guidance for the design, construction and performance assessment of infiltration features. Many studies have examined the benefits of stormwater infiltration to surface water resources; however less emphasis has been placed upon the impact of infiltration on groundwater resources. Furthermore, among the studies that have considered groundwater; relatively few have involved field-scale investigations. The primary concerns related to stormwater infiltration and groundwater are the potential for aquifer contamination and excessive groundwater mounding.

To address the concerns related to stormwater infiltration and groundwater, this research presents a field-scale case study that aims to observe and analyze some of the impacts of stormwater infiltration on a shallow unconfined aquifer at a bioinfiltration BMP on the campus of Villanova University. The BMP is a vegetated basin that receives runoff from approximately 1.3 acres. The drainage area of the study site is composed of impervious parking areas, roadways and recreational fields with approximately 35% directly connected impervious area. Since its construction in 2001, the BMP has served as a research/demonstration site and has been extensively equipped with several hydrologic and water quality monitoring devices.

The current study analyzes the quality of runoff entering the site, water retained by the site, vadose zone moisture and groundwater surrounding the site. Specifically, the study focuses on the transport of chloride, total phosphorus and conductivity through the

system. The water quality analyses are coupled with hydrologic modeling and estimation of the runoff volume entering the site. In this manner, the transport of contaminants entering the site is observed and compared to the concentration of contaminants in the groundwater. In addition, the study examines the hydrologic impact of infiltration on the shallow aquifer by assessing the extent and general effects of groundwater mounding.

Results indicate that as water passes through the system, concentrations of conductivity and chloride are reduced by the processes involved with infiltration and groundwater flow. Analysis of the fate and transport of total phosphorus is not completely conclusive due to issues related to sorption of phosphorus to soil particles. However, the results suggest that total phosphorus concentrations are reduced during vadose zone transport and that downgradient groundwater shows decreased concentrations with respect to surface water samples. Continuous hydrologic and groundwater monitoring indicate that increased groundwater mounding occurs at the site, but its extent is limited. The extent of groundwater mounding is observed to be related to the infiltration rate and the groundwater temperature. Additionally, it is observed that for storms less than approximately 0.75 inches increased mounding does not occur at the site.

This study illustrates the utility of groundwater monitoring for the purpose of assessing BMP performance. It is suggested that monitor wells be considered for site monitoring plans and as a tool for BMP site selection. For instance, preliminary groundwater monitoring at a future BMP site will demonstrate the hydrologic response of an aquifer to rainfall, which may then be used to design a BMP. In regards to BMP design, it is recommended that subsurface properties such as porosity, hydraulic conductivity, temperature and depth to groundwater be used as site selection criteria.

Additional recommendations are provided for future research related to groundwater temperature, groundwater sampling protocol and sample analyses.

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Chapter 1. Introduction

1.1 Problem Statement

Changes in land use associated with urbanization have been demonstrated to have negative impacts on watersheds both in terms of water quality and quantity (Walsh *et al.* 2005; PADEP 2007). Urban runoff is considered a leading cause of stream, lake and estuarine degradation, therefore stormwater management techniques have evolved to mitigate the impacts of development through the use of structural and non-structural Best Management Practices (BMP) (USEPA 1997; Clar and O'Connor 2004; Muthukrishnan *et al.* 2004; PADEP 2006). In particular, BMP designed to infiltrate runoff have become important tools of stormwater management (Mikkelsen *et al.* 1996; USEPA 2000; Hsieh and Davis 2005; Heasom *et al.* 2006; Schuster *et al.* 2007; Emerson 2008). Existing BMP research has examined many parameters related to design, construction and evaluation; but less emphasis has been placed on the impact to groundwater and subsurface contaminant transport (Mikkelsen *et al.* 1997; Barraud *et al.* 1999; Strecker *et al.* 2001; Akan 2002; Winogradoff 2002; Fischer *et al.* 2003; Birch *et al.* 2005; Dietz and Clausen 2005; M. Clar *et al.* 2007). However, on an annual basis, a major component of total stream flow volume is produced by base-flow, which is derived from groundwater. Since groundwater flow is the link between recharge and base-flow; it is essential to consider the fate of water infiltrating through BMP into the groundwater (Leopold 1974; Lind and Karro 1995; Winter *et al.* 1998; Barraud *et al.* 1999; Birch *et al.* 2005; Weiss *et al.* 2008).

To assess the impact of stormwater infiltration on groundwater, this study considers several aspects of the groundwater system. In a broad sense, the study focuses on quantity and quality considerations; however the two factors are interdependent. With regard to quantity, the following questions are raised:

- What is the extent of groundwater mounding that occurs in response to focused recharge and furthermore,
- What are the impacts of the resultant mounding?

Regarding water quality several additional questions are raised:

- Do the physical, chemical and biological processes involved with infiltration and groundwater flow remove contaminants from influent water?
- Does focused recharge dilute or saturate ambient groundwater conditions?

Ancillary considerations include:

- What pertinent information can be gathered from groundwater monitoring of infiltration BMP?
- Should groundwater monitoring be included with BMP assessment and monitoring and if so, how should it be done?
- What site selection criteria and design parameters should be considered for infiltration BMP to reduce the potential risks to groundwater?

1.2 Research Goals and Objectives

1.2.1 Goals

The over-arching goals of this research consist of the following:

- To expand the understanding of surface/groundwater interactions related to bioinfiltration practices.
- To underscore the importance of groundwater quality as it pertains to stormwater management.
- To provide insight and guidance that enhances the design and performance of bioinfiltration practices.
- To provide a foundation for future research.

1.2.2 Objectives

The particular objectives of this research consist of the following:

- To demonstrate the fate of chloride, conductivity and total phosphorus through an infiltration BMP.

- To assess the extent and impact of groundwater mounding due to bioinfiltration.

1.3 Site Background

1.3.1 Site History

In May 2001, Villanova University received funding from the Pennsylvania Department of Environmental Protection (PADEP) for the construction and monitoring of a stormwater bio-infiltration Best Management Practice (BMP). The BMP was constructed as a retrofit of an existing parking lot traffic island and was designed to accommodate and subsequently infiltrate the runoff produced by a 1 inch storm. To construct the BMP, the existing traffic island was excavated then backfilled with a 1:1 sand/soil mixture, shaped into a basin, planted with appropriate vegetation and configured so as to allow stormwater to enter the basin. The resulting BMP, herein referred to as the site, has been equipped with a variety of hydrologic monitoring equipment and used as a research and demonstration site. To date, the site has been the subject of multiple journal articles, several Master's theses, a Doctoral thesis, multiple tours and ongoing undergraduate education. Furthermore, the site has been shown to successfully handle storms volume up to approximately 1.5 inch, depending upon rainfall intensity, temperature and antecedent conditions. Detailed information concerning site construction and monitoring is provided in the Site Construction Details section of the following chapter. For additional information concerning site history, performance, construction or research the reader is referred to the following referenced documents (Prokop 2003; Ermilio 2005; Heasom *et al.* 2006; Traver *et al.* 2007; Emerson and Traver 2008; Emerson 2008).

1.3.2 Site Location

The site is located in Southeastern Pennsylvania on the campus of Villanova University; a suburban area about 11 miles west of center-city Philadelphia. Villanova's campus is currently home to eight urban stormwater BMP, which compose the Villanova Stormwater BMP Demonstration and Research Park. The site is located in a parking area serving the University's west campus facility; with a total drainage area of approximately 1.3 acres including 45% impervious area of which 35% is directly connected impervious area (Emerson 2008). Figure 1, below shows the site drainage area with topography, general land use and monitor well locations.

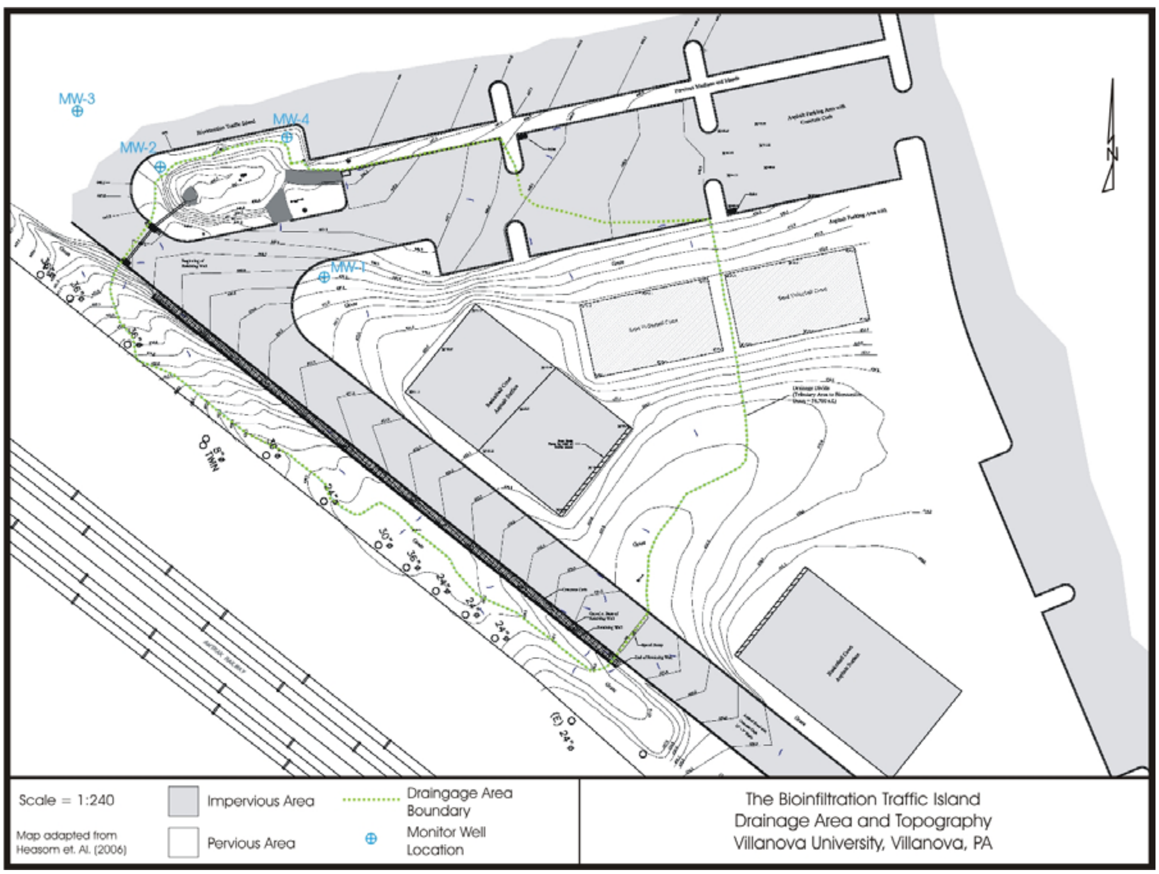

Figure 1: Site Map (adapted from Heasom, *et al.* (2006))

1.3.3 Local Physiography and Climate

Villanova University is located in the Piedmont Upland physiographic province of Pennsylvania. The Piedmont Upland is characterized by rolling hills and valleys with gentle to moderately steep slopes. Altitudes range from 100 feet to 1,200 feet above mean sea level. The study area is underlain by highly metamorphosed Precambrian pyroxene bearing felsic gneiss of the West Chester Massif (Crawford *et al.* 1999; Low *et al.* 2002). The gneiss is highly resistant to weathering and generally has a thin overburden with a brief weathered bedrock zone. The primary minerals include quartz, microcline, hornblendes, pyroxenes and occasionally biotite (Carjan and McCree 1998). USDA maps indicate that the site soils are silt loams of the Chester series. Site investigations indicate that soils have been altered to varying degree by construction and earthwork. The altered soils are a mix of brown sand and silt with occasional clay, construction debris and partially weathered gneiss (Carjan and McCree 1998).

Villanova is located in PADOT region 5 precipitation area and receives an average annual precipitation of about 45 inches (Aron *et al.* 1986). Typically, between 80 to 90% of the average annual precipitation occurs in storms with less than 1 inch of precipitation (Traver 2002). The region experiences distinct seasons characterized by cold winters, moist mild springs, humid and hot summers and wet, mild autumns with mean summer/winter temperatures of 24^{o}C and 0^{o}C (Low *et al.* 2002). Prevailing winds are westerly during winter and southerly during summer. Most weather systems originate in Central US and move eastward across the Appalachians however the region also receives moderate to heavy precipitation from moist weather systems moving northward from the south (Low *et al.* 2002).

Although the region receives uniform precipitation throughout the year, most recharge occurs between late fall and early spring, due to higher evapotranspiration during the remainder of the year. Groundwater flow in the Piedmont Upland is dominated by local flow systems that closely match surface water divides (Low *et al.* 2002). Baseflow is estimated to represent about two thirds of total stream flow in the York County section of the Piedmont Upland (Lloyd and Growitz 1977). Overburden or regolith above the bedrock is typically clayey soil and weathered rock. The regolith is capable of moderate infiltration rates and may store large volumes of water in the available pore space. Groundwater flow within the regolith is generally follows topography but may also be affected by bedrock weathering, fractures and mineral composition of the parent rock (Low *et al.* 2002).

The campus is situated along a local surface drainage divide and contains areas in the headwaters of the Darby-Cobbs Creek and the Schuylkill River watershed. The study area is located within the Ithan Creek watershed which is a tributary of the Darby Creek. The drainage area of the study site consists of approximately 1.3 acres.

Chapter 2. Research Methods

2.1 General Methodology

This project seeks to assess the impacts of stormwater infiltration on groundwater in terms of water quality and groundwater hydrology. The water quality component is addressed through stormwater sampling of 7 storm events. Samples are collected from the influent stormwater, the vadose zone and the groundwater and are analyzed for a variety of common pollutants. Site sample locations include two first-flush samplers, basin grab samples, automated basin samples, lysimeter samples and groundwater samples. During a sampling event, the initial influent water is collected by the first flush samplers. Grab samples are collected from the basin at multiple times to determine the quality of waters infiltrating and/or overflowing the site and to monitor the change in ponded water quality over time. Lysimeter samples are collected to assess the quality of water infiltrating through the vadose zone. Finally, groundwater samples are taken before, during and after a rainfall event to estimate the concentration of pollutants moving through the aquifer.

Assessment of the site surface and groundwater hydrology incorporates a HEC-HMS model developed for the site by Heasom *et al* (2006). A detailed explanation of the site model construction, calibration and performance, is provided in Heasom *et al* (2006). For this study, the HMS model is used to predict the total runoff entering and leaving the site and to estimate the timing of inflow/outflow. The predicted inflow volume is compared to the resulting changes in groundwater elevation and is used to estimate the total pollutant mass entering the site. The fluctuations in groundwater elevation, in response to infiltration, are examined to describe the hydrologic impacts of stormwater infiltration on groundwater. Additionally, several calculations are performed to compare the observed contaminant concentrations to those predicted by general groundwater fate and transport equations. In particular the fate of chloride and total phosphorus in the surface/groundwater system are analyzed.

2.2 Site Monitoring and Sampling Details

2.2.1 Well Installation and Construction

As part of this study, three shallow monitor wells were installed by Thomas Keyes, Inc. on June 6, 2007, using an air rotary drill rig. It was assumed that the groundwater flow direction across the site mimicked the northwesterly surface water flow and so the wells were positioned along this assumed flow path. Prior to this study, one monitor well existed on the site; however a minimum of three wells are required to define the plane of water table and the flow direction. The selected monitor well configuration consists of the three new wells in a line trending approximately northwest-southeast and the existing well located northeast of the line, at the site’s northeast corner. Figure 2, below, displays the site topography and the approximate locations of the wells (adapted from Heasom, *et al* 2006).

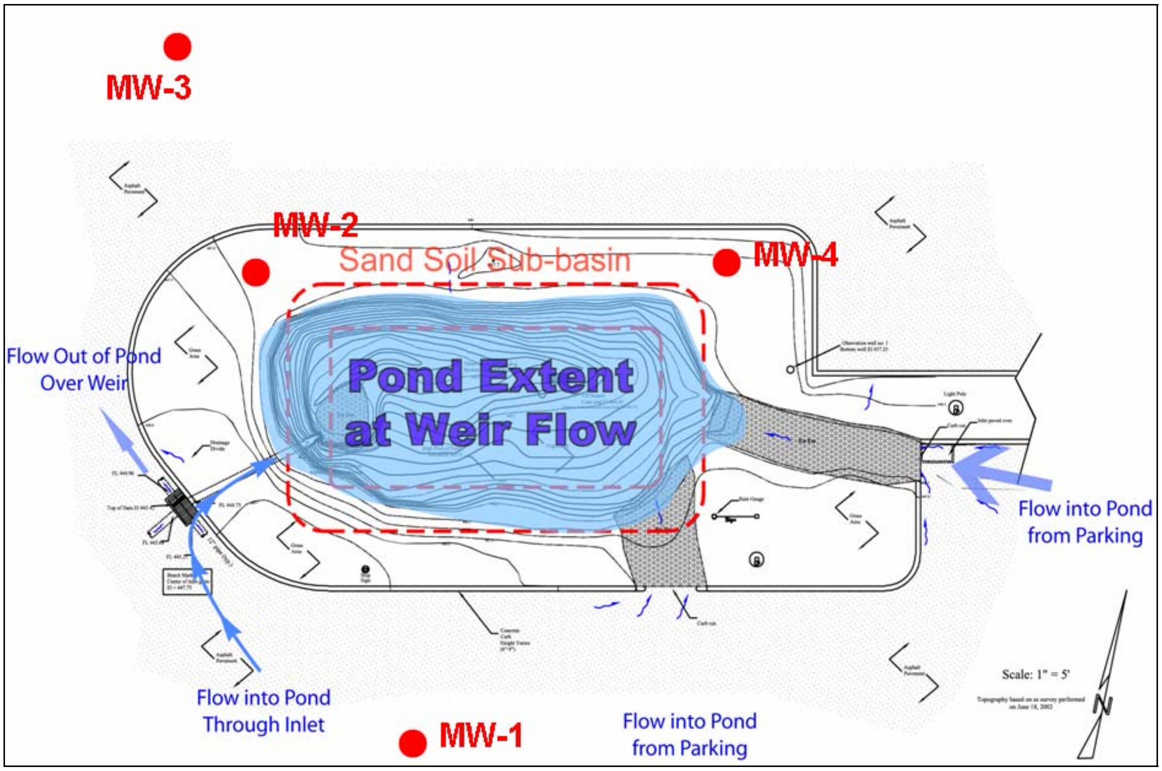

Figure 2. Well Location Map

The existing well (MW-4) was installed in September 2005 using a 6.75 inch hollow stem auger. The well was constructed with about 35 feet (ft) of 1.75 inch O.D. PVC. The bottom of the pipe was sealed with a PVC cap. A screened screen was cut into the lower 20 ft of the PVC with a hacksaw. The total depth of the well is approximately 33.22 ft below the ground surface. The annulus of the borehole was filled with sand to approximately 2 ft above the screened section. The annulus was then sealed with a concrete grout mixture to approximately 0.5 ft. The well was completed with a 4 inch diameter PVC protective stick-up casing and a threaded cap. The protective casing was anchored in grout and a 6 inch diameter concrete collar was emplaced at ground level. The annulus between the concrete collar and protective casing was filled with coarse gravel.

The monitor wells installed for this study are labeled MW-1 through MW-3, with MW-1 located up-gradient, MW-2 located at the northwest corner of the site and MW-3 located down-gradient. Monitor wells 1-3 were installed via air rotary using an 8 inch bit. The boreholes were advanced until adequate water was encountered. The wells are constructed with 2 inch Schedule 40 PVC, with threaded joints and a threaded silt trap. The screened sections consist of pre-slotted 10 slot PVC screens. Total depths of the wells were 36.74, 30.28 and 30.16 ft below ground surface, for MW- 1, MW-2 and MW-3 respectively. MW-1 was constructed with a 25 ft screen section and a 10 ft riser section. MW-2 was constructed with a 20 ft screen section and a 10 ft riser section. MW-3 was constructed with a 20 ft screen section and a 10 ft riser section. The annulus of each well was packed with #01 sand to approximately 2 ft above the screen section, then sealed with a 2 ft bentonite seal and grouted to the surface with a cement/bentonite grout. The wells were then mounted flush with the ground surface with 12 inch diameter steel well vaults set into concrete.

2.2.2 Hydrologic Monitoring

The site hydrology is monitored by a network of devices that record the precipitation, basin water level, groundwater level, outflow level, and temperature. The data collected is used to assess the performance of the site. The following sub-sections document and describe the equipment and methods used to assess the site hydrology.

2.2.2.1 Precipitation

Precipitation is measured by two rain gauges; a Sigma tipping bucket rain gauge and a volumetric rain gauge. The Sigma gauge measures precipitation in 0.01 inch increments and is connected to a Sigma 950 Flow Meter that logs the data in 5 minute intervals. The data recorded is the sum of precipitation for each 5 minute interval. The volumetric rain gauge is an approximately 3.5 inch diameter funnel that is connected to a cylinder with graduated marks corresponding to inches of precipitation. The volumetric gauge can be read visually to approximately 0.1 inch.

2.2.2.2 Basin Water Level

The basin of the site is equipped with a Sigma 75 kHz ultrasonic level sensor which is used to measure the water level during and after a storm. The ultrasonic sensor is mounted on a metal post, upon which is mounted a 3 foot staff gauge that displays measurements by 0.01 ft. Directly below the ultrasonic sensor is a rectangular concrete pad that is used as the base level. The elevation of the concrete pad is 444.43 ft above mean sea level (Heasom *et al.* 2006). The ultrasonic sensor has a precision of 0.001 ft with an accuracy of 0.009 ft. Data from the sensor is logged at a 5 minute interval by the Sigma 950.

2.2.2.3 Outlet Water Level

The water level behind the outlet weir is measured by an Instrumentation Northwest (INW) PT2X pressure transducer. The pressure transducer uses a strain gauge to measure pressure; this pressure is then correlated to the density of water to determine the water depth with an accuracy of 0.01% of the full scale output (FSO). The water depth is recorded at 5 minute intervals using the Sigma 950. As the water level in the basin rises above the crest of the weir, the water level is used to calculate the overflow rate using the rating curve developed by Heasom, *et al* (2006) in general accordance with ASTM D5242 (ASTM 2001).

2.2.2.4 Groundwater Level

Groundwater level is measured at the four wells using pressure transducers. MW-1, MW-2 and MW-3 are equipped with In-Situ Aqua Troll 200 multi-meters. The Aqua Trolls are self-contained data loggers, which log the depth to water, temperature, conductivity and specific conductivity. For the study the Aqua Trolls log data at a 15 minute interval. MW-4 is equipped with an Instrumentation Northwest (INW) PT2X pressure transducer. Data from the INW transducer at MW-4 is logged by the Sigma 950 at 5 minute intervals, similar to the transducer at the outlet.

2.2.2.5 Data Logging

As mentioned above, data from the rain gauge, outlet pressure transducer, ultrasonic sensor and MW-4 pressure transducer are logged by a Sigma 950 flow meter. The 950 is capable of recording data from multiple inputs at various time intervals using a variety of units. The 950 allows the user to calibrate input signals, determine appropriate units, adjust levels, view recorded data, download data and may also be used to facilitate various sampling programs. For this study, the Sigma 950 recorded data at 5 minute intervals.

2.2.2.6 Electronic Data Management

Electronic data from the site are collected by the Sigma 950 and the 3 Aqua Trolls. The Sigma 950 is downloaded with a Sigma Data Transfer Unit (DTU) on a weekly basis. The data are initially saved in a proprietary file format and then exported as a tab delimited text file (.txt) using the Sigma Insight software. The exported text file is saved on a university server. Additionally, the files are saved both in the Insight format and text format on a local hard drive. Next the exported text files are grouped by month and imported to Microsoft Excel files (.xls). The monthly .xls files are used to organize the data, convert measured depths to elevations, to sum precipitation and to create graphs for rapid viewing and analysis of the data.

Data from the Aqua Trolls are downloaded on a monthly basis. Initially data were downloaded more frequently, but the process was noted to disturb the water column and therefore the download procedure and frequency were adjusted. Downloaded files are saved on the data loggers in a proprietary file format. The Win-Situ software program is used to export the files to comma-space delimited text files (.csv). The text files are saved both on a local hard drive and on a university server. Microsoft Excel is then used to import the files, organize the data, convert measured depths to elevations, and to create graphs for rapid viewing and analysis of the data.

2.2.2.7 Field Notes

Observations and notes from site visits are recorded in one or more of several locations. Monthly site reports are created to record and review the operation of site equipment, list maintenance needs, and discuss sampling performance. In addition, a storm sampling report is created for every sampled storm. The storm sampling reports the samples collected, describe the weather, amount of precipitation, discuss the performance of the samplers and provide comments. Additional notes are stored in field notebooks, which are used to compile the site reports and storm sampling reports.

2.2.2.8 QA/QC

To ensure a high level of data quality the VUSP has established a QA/QC plan that outlines sampling protocol, laboratory procedures, field procedures and data management procedures. For details regarding the site, the reader is referred to the VUSP QA/QC plan.

2.2.3 Water Quality Sampling

During storm sampling events, samples are collected from a maximum of 10 locations. The sample locations include the four monitor wells, two first flush samplers, three lysimeters and the basin. Multiple samples are collected from the monitor wells and the basin, while a single sample is collected from the first flush samplers and lysimeters. The VUSP seeks to sample two storm events per month. A storm event is required to produce at least 0.25 inch in 24 hours and to be preceded by a minimum of 24 hours without precipitation. Water quality samples are analyzed for a variety of parameters including:

- pH
- Conductivity
- Temperature
- Total Suspended Solids
- Total Dissolved Solids
- Total Nitrogen
- Total Phosphorus
- Chloride
- Nitrate
- Nitrite
- Orthophosphate

All analyses are performed in the VUSP water resources laboratory by VUSP students. The methods and standard operating procedures for the analyses are described in detail in the VUSP Quality Assurance & Quality Control Plan and in the VUSP Standard Operating Procedures.

2.2.3.1 Lysimeters

Soil moisture is collected from three ceramic cone lysimeters located in the center of the basin at depths of 8 ft, 4 ft and just below surface level. The lysimeters are operated by using a hand pump to place a vacuum on the lysimeters which slowly draws water through the ceramic cone. Later, the pump is used to apply positive pressure to collect the sample. The procedure for collecting a lysimeter sample is to apply a vacuum shortly after the initiation of rainfall and to allow a minimum of 12 hours prior to sample collection. The lysimeters samples are labeled TI LYS0, TI LYS4 and TI LYS8 according to the depth of the lysimeters. The samples are analyzed for all parameters except total suspended solids, because the ceramic cone screens out the suspended solids.

2.2.3.2 Groundwater

Four to five samples are collected per well per storm. The first sample is collected prior to the rainfall, generally within 12 hours of the anticipated start time. The next sample is collected approximately 4-6 hours after the start of the rain, the next two samples are collected at approximately 6-12 hour intervals and the final sample is collected the following day. The actual time of sample collection is highly dependent on the storm timing, accuracy of weather forecasts and sampler availability.

Samples are collected with dedicated bailers, placed in 300 ml plastic bottles and transported to the water resources laboratory for analysis. The samples are labeled TI MW1a through TI MW1e and are analyzed for pH, conductivity, total phosphorus, and chloride. Groundwater samples are collected specifically as part of this thesis research and not are part of the standard VUSP storm sampling routine.

2.2.3.3 First Flush

The first flush samplers are located at the two inlets to the site. The samplers are mounted flush with the ground surface and are constructed with floating stoppers that seal the inlets as the sampler fills with water. In this manner, the sampler is filled with only approximately the first 2 liters of runoff. First flush samples are labeled TI FF01 and TI FF02 and are analyzed for the full suite of parameters.

2.2.3.4 Grab Samples

To assess the quality of water within the basin, grab samples are collected from the ponded water during and after the rainfall. Typically two grab samples, SA1 and SA2 are collected from the basin near the ultrasonic sensor. The first sample, SA1, is collected near the beginning of the storm, generally at the same time that suction is placed on the lysimeters. The second sample is collected after the cessation of precipitation, generally at the same time the lysimeter samples are collected. Grab samples are analyzed for the full suite of parameters.

2.2.3.5 Automated Grab Samples

In January 2008, a Sigma 900 autosampler was installed to collect samples from the basin. The goal of the autosampler is to collect a series of samples throughout the course of the storm to determine the variability of water quality. The autosampler was programmed to collect a total of 8, 500 ml samples in 24 hours. The autosampler is triggered when the water level in the basin reaches 0.3 ft and after being triggered the autosampler collects approximately 250 ml every 1.5 hours. Each sample is therefore composed of two grab samples collected 1.5 hours apart. The intake tube for the autosampler is located near the ultrasonic sensor and in the general vicinity of the grab samples, SA1 and SA2. The samples from the autosampler are labeled TI AS01- TI AS08 and are analyzed for the full suite of parameters.

2.2.3.6 Laboratory Analyses

All laboratory analyses are performed by Villanova University graduate assistants or the water resources laboratory manager. For standard operating procedures and quality assurance, quality control specifications, the reader is referred to the VUSP QA/QC plan and the SOPs.

2.3 Modeling

2.3.1 Surface Water Modeling

Since the amount of runoff entering the site is not directly measured, the HEC-HMS model created by Heasom, *et al* (2006) is used to predict the volume and timing of inflow and outflow. The model accepts precipitation data as the basis for calculations. The model divides the site drainage area into pervious and impervious areas. Runoff produced from the drainage area is routed to the site using the kinematic wave method. The basin itself is modeled as a reservoir, with a diversion to represent infiltration. The model is calibrated by comparing the measured basin water level with the simulated reservoir water level and by comparing the outflow calculated with the weir rating curve to the simulated outflow in the model.

2.3.2 Groundwater Calculations and Analysis

The flow of groundwater through an aquifer is vastly different than open channel flow of surface water. Typical groundwater flow rates are several orders of magnitude less than surface water flow rates (Winter *et al.* 1998). While the flow of water through the unsaturated zone (vadose zone) is similar to groundwater in some aspects there are several key differences. Vadose zone flow, often referred to as infiltration, is a complex and dynamic process that is dependent upon capillary forces (matric potential), gravity, evapotranspiration, vegetation and various soil properties (Ravi and Williams 1998; Williams *et al.* 1998). In contrast, groundwater flow is much more dependent on gravitational forces and aquifer properties. Furthermore, infiltration primarily occurs in the vertical direction, whereas groundwater flow, especially in unconfined aquifers, is generally horizontal.

The fundamental aquifer parameters that effect groundwater flow rate, such as hydraulic conductivity (***K***) and transmissivity (***T)*** may vary significantly and are often difficult to measure within an order of magnitude (Bouwer 1978; Tchobanoglous and Schroeder 1985; Reilly and Pollock 1993; Fetter 1997; Das 1998; Rai *et al.* 1998; Alley *et al.* 2002; Park *et al.* 2006). The concept of average linear velocity is helpful to illustrate the impact of ***K***. Average linear velocity (V_x) is essentially an application of Darcy's Law that accounts for the porosity of the media and is defined by Fetter (1997) as:

$$V_x = -((Kdh)) / (n_e dl) \qquad \textit{Equation (1)}$$

where n_e *= effective porosity and* ***dh/dl*** *= hydraulic gradient*

Emerson (2008) estimated the hydraulic conductivity of the native soil below the site to be between 0.25 and 0.72 ft/day and the porosity to be approximately 40%. Groundwater monitoring indicated an average hydraulic gradient of 0.108 ft/ft between MW-2 and MW-3. Using these values and equation 1, the average linear velocity equation, the time for groundwater to travel the 62.99 ft between MW-2 and MW-3 was estimated. Table 1 below presents calculated travel times for a range of hydraulic conductivity (***K***) and effective porosity (n_e). The shading indicates the range of most likely travel times, with the darker shading indicating the more likely estimates.

Table 1: Estimated Groundwater Travel Time Between MW-2 and MW-3

Porosity	***0.3***	***0.35***	***0.4***	***0.45***
K (ft/day)	**Time (days)**	**Time (days)**	**Time (days)**	**Time (days)**
10	17	20	23	26
5	34	40	46	52
1	174	203	232	261
0.72	242	*282*	*323*	364
0.5	349	*407*	*465*	523
0.48	363	*424*	*484*	545
0.25	698	*814*	*931*	1047
0.1	1745	2036	2327	2619
0.05	3492	4073	4655	5237

As can be seen in Table 1, the estimated travel times are very large in comparison to surface water travel times. Furthermore it can be seen that relatively minor fluctuations in $\boldsymbol{K}$ or $\boldsymbol{n_e}$ result in large variations in travel time.

Aquifer pump tests are generally the most accurate method for determining aquifer properties. The analysis of pump test data is generally more complicated for unconfined aquifers due to the lack of an upper confining surface. Pump test analyses are based on several assumptions and have several requirements. For instance, in unconfined aquifers, the aquifer thickness must be known and pumping wells must be screened across the entire aquifer thickness (Bouwer 1978; Fetter 1997). The accuracy of pump tests at the site is diminished by uncertainty of the aquifer thickness and because the wells are not screened across the entire aquifer thickness. In addition, water levels at the site wells were observed to recovery at a very slow rate; indicating that the wells are only capable of sustaining very low flow rates. The combination of low pumping rates and lack of aquifer thickness information adds significant uncertainty to the accuracy of a pump test. Aside from a pump test, the primary option for the direct determination of $\boldsymbol{K}$ is the slug test. However, slug tests generally provide information applicable only to the area immediately surrounding the well and often exhibit fluctuation between tests

(Bouwer 1978; Fetter 1997). Given the variation of travel time in response to changes in $\boldsymbol{K}$ and $\boldsymbol{n_e}$, an imprecise estimation of these variables is likely to create more confusion than resolution. Thus the limited accuracy of pump tests and slug tests at the site is not likely to provide adequate estimation of the required aquifer properties.

The purpose of the above discourse on groundwater flow is to provide a background on groundwater flow and to underscore the intent of this research, which is to *observe* and *assess* the impacts of stormwater infiltration on groundwater and not to *model* the system. Therefore more emphasis is placed on the observed water quality and water level fluctuations, than on their prediction. Likewise, the intent is to observe the effects of contaminant transport rather than to model and predict their fate and transport. Moreover, the limited ability to accurately define aquifer properties in conjunction with the wide fluctuation of calculated travel times underscores the variability inherent in an attempt to model the system. However, while the purpose of the study is primarily to observe and assess, the study does also compare the observed data to estimates calculated using the average linear velocity and advection-dispersion equations as presented in the following references (Bouwer 1978; Tchobanoglous and Schroeder 1985; Fetter 1997; Das 1998). Additionally, the infiltration studies performed on site by Emerson (2008) and Ermilio (2005) are used in conjunction with current water quality data to discuss the transport of water and contaminants. In particular, the chloride and total phosphorus are used to examine groundwater flow and contaminant transport.

Chapter 3. Results

The sampling and monitoring work of this project consists individual storm sampling and longer duration hydrologic and groundwater monitoring. Due to the unique characteristics of the individual storms and the varying magnitude of contaminant concentrations detected in the individual storms, the results from each storm are presented separately. Each storm is assigned a section, which includes presentation of the results and a brief discussion. Following the individual storm sections, is a section concerning the calculation of total mass of phosphorus and chloride entering the site. The final portion of the results section is a presentation of the longer duration hydrologic and groundwater monitoring.

3.1 Storm Event Sampling

The following sections present the water quality and hydrologic results of 7 storms for which groundwater samples were collected. Storm details including the total rainfall, total inflow, duration, 5 and 30 minute intensity are given for each storm. In addition, the water quality results and hydrologic data are presented in tables and figures.

3.1.1 November 15th 2007

3.1.1.1 Storm Summary

The 11/15/07 storm event produced 0.54 inch of precipitation in 7 hours and 15 minutes. The maximum 5 minute and 30 minute intensity was 0.96 and 0.46 in/hr, respectively. The HEC-HMS simulation indicates a total of 627 ft^3 of runoff entered the site. Observed data show that all runoff entering the BMP was accommodated and either infiltrated or evapotranspired. Figure 3 shows the results of the HEC-HMS model along with the observed rainfall and basin water elevation.

Table 2 lists the results of the 24 samples collected during the 11/15/07 event. Figure 4 and Figure 5 display the results for the conductivity and chloride analyses, while Figure 6 presents a hydrograph of the groundwater elevation during and after the storm. Total phosphorus was not analyzed for the groundwater samples due to a shortage of sampling supplies and sample holding times. In addition, graphs of the temperature and conductivity at MW-1, MW-2 and MW-3 are not provided, because sampling procedures caused disturbances in the readings.

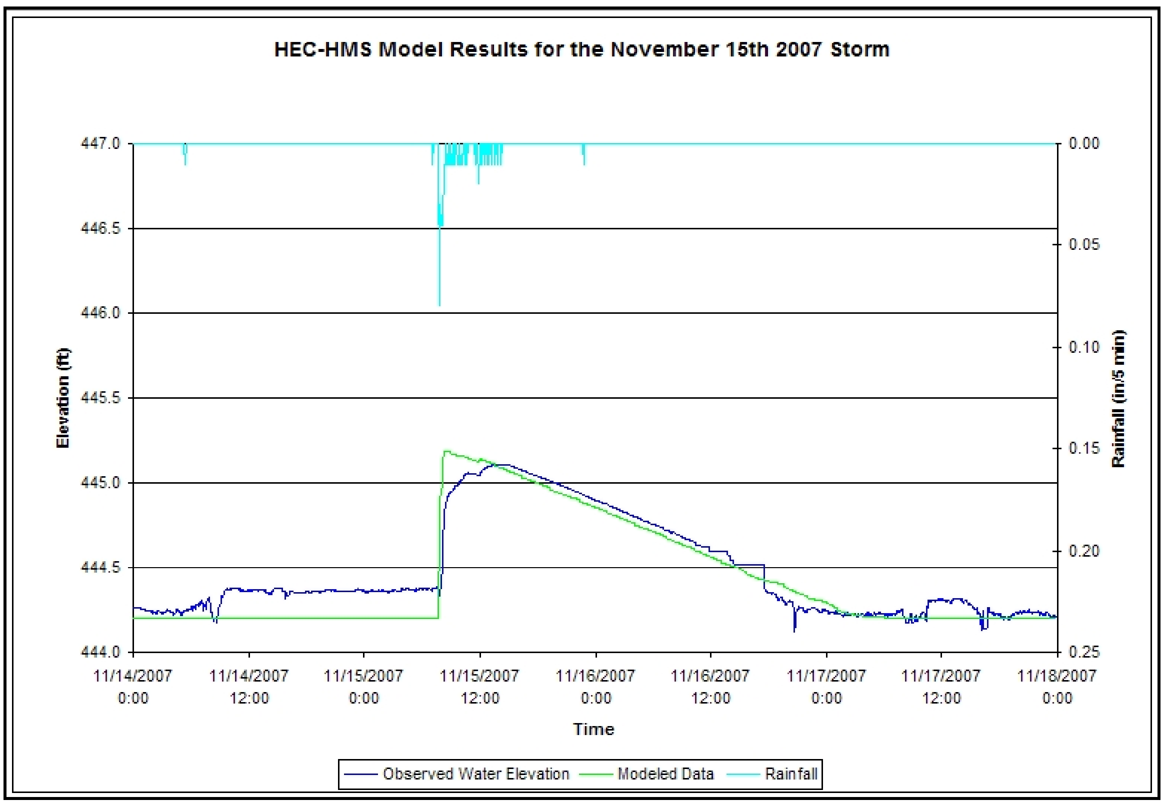

Figure 3: November 15th, 2007 HEC-HMS Results

Table 2: Water Quality Results from the November 15, 2007 Storm Event

Location	Sample Time	pH	Cond	TSS	TDS	TN	NO2	NO3	TP	PO4	Chloride
FF01	-	6.40	171.3	240.2	81.8	7.10	N	N	0.76	N	4.91
FF02	-	7.40	38.4	14.2	27.9	U	0.0739	0.0740	0.68	0.1878	2.76
LYS0	-	6.50	127.5	N	32.2	U	U	U	U	U	6.05
LYS4	-	6.70	369.0	N	176.5	U	U	0.3373	0.28	U	2.89
LYS8	-	6.70	441.0	N	207.3	U	U	1.0560	0.07	U	U
SA01	-	6.80	38.8	13.0	U	N	U	0.4469	0.81	0.1413	1.85
SA02	-	6.90	59.9	12.7	U	N	0.2197	0.0500	0.78	0.1987	4.19
MW1A	11/14/07 15:00	6.70	410.0	N	N	N	N	N	N	N	72.04
MW1B	11/15/07 9:30	5.97	423.0	N	N	N	N	N	N	N	76.47
MW1C	11/15/07 16:30	6.05	416.0	N	N	N	N	N	N	N	71.36
MW1D	11/15/07 21:30	5.76	426.0	N	N	N	N	N	N	N	86.96
MW1e	11/16/07 9:10	6.78	397.0	N	N	N	N	N	N	N	70.28
MW2A	11/14/07 15:45	5.72	205.0	N	N	N	N	N	N	N	4.75
MW2B	11/15/07 16:35	5.48	140.1	N	N	N	N	N	N	N	5.89
MW2C	11/15/07 21:35	3.54	410.0	N	N	N	N	N	N	N	30.73
MW2D	11/16/07 9:15	5.91	124.8	N	N	N	N	N	N	N	56.06
MW3A	11/14/07 16:00	5.92	464.0	N	N	N	N	N	N	N	109.60
MW3B	11/15/07 16:40	5.62	460.0	N	N	N	N	N	N	N	108.13
MW3C	11/15/07 21:40	3.14	837.0	N	N	N	N	N	N	N	111.85
MW3D	11/16/07 9:20	5.81	442.0	N	N	N	N	N	N	N	152.00
MW4A	11/14/07 15:35	6.05	609.0	N	N	N	N	N	N	N	142.01
MW4B	11/15/07 16:45	6.22	611.0	N	N	N	N	N	N	N	138.23
MW4C	11/15/07 21:45	5.45	626.0	N	N	N	N	N	N	N	138.45
MW4D	11/16/07 9:25	5.87	610.0	N	N	N	N	N	N	N	159.77

Notes: **Cond**=Conductivity; **TDS**=Total Dissolved Solids; **NO2**=Nitrite; **TP**=Total Phosphurus; **TSS**=Total Suspended Solids; **TN**=Total Nitrogen; **NO3**=Nitrate; **PO4**=Orthophosphate; **N**=Not Tested; *****All values given in mg/l, except pH and conductivity (uS/cm)

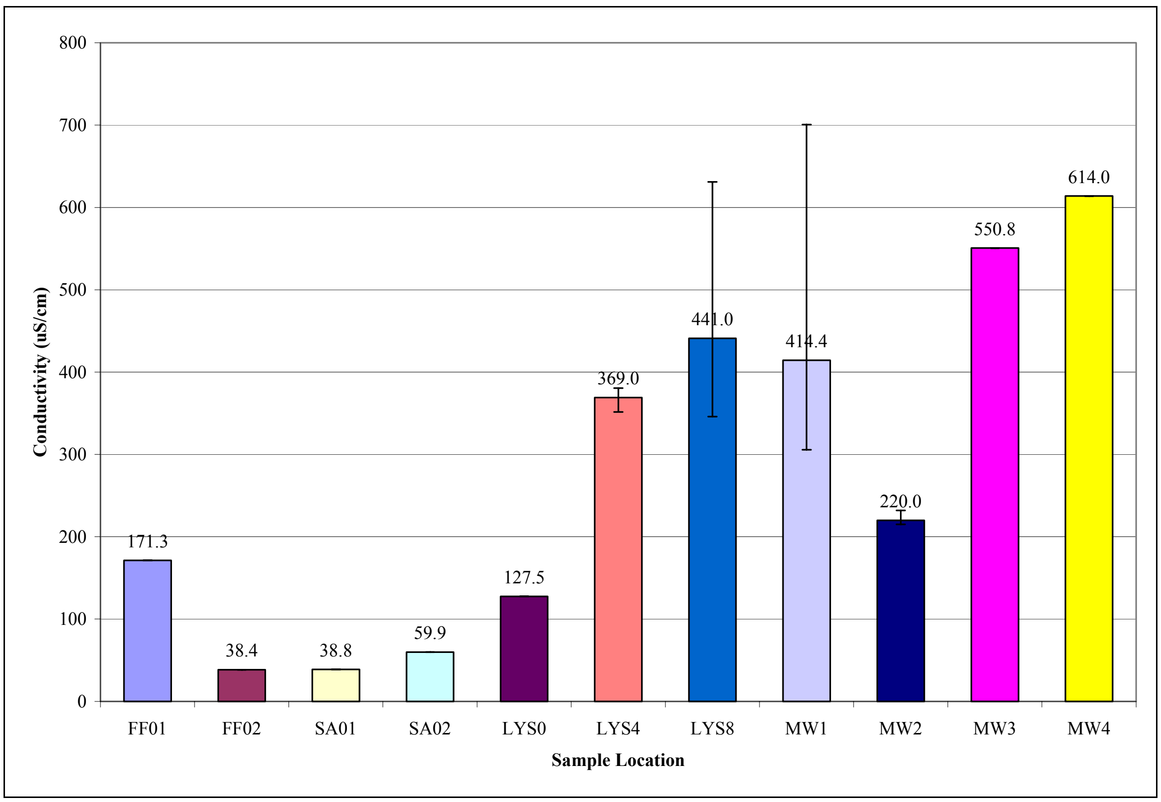

Figure 4: November 15th, 2007 Conductivity Results

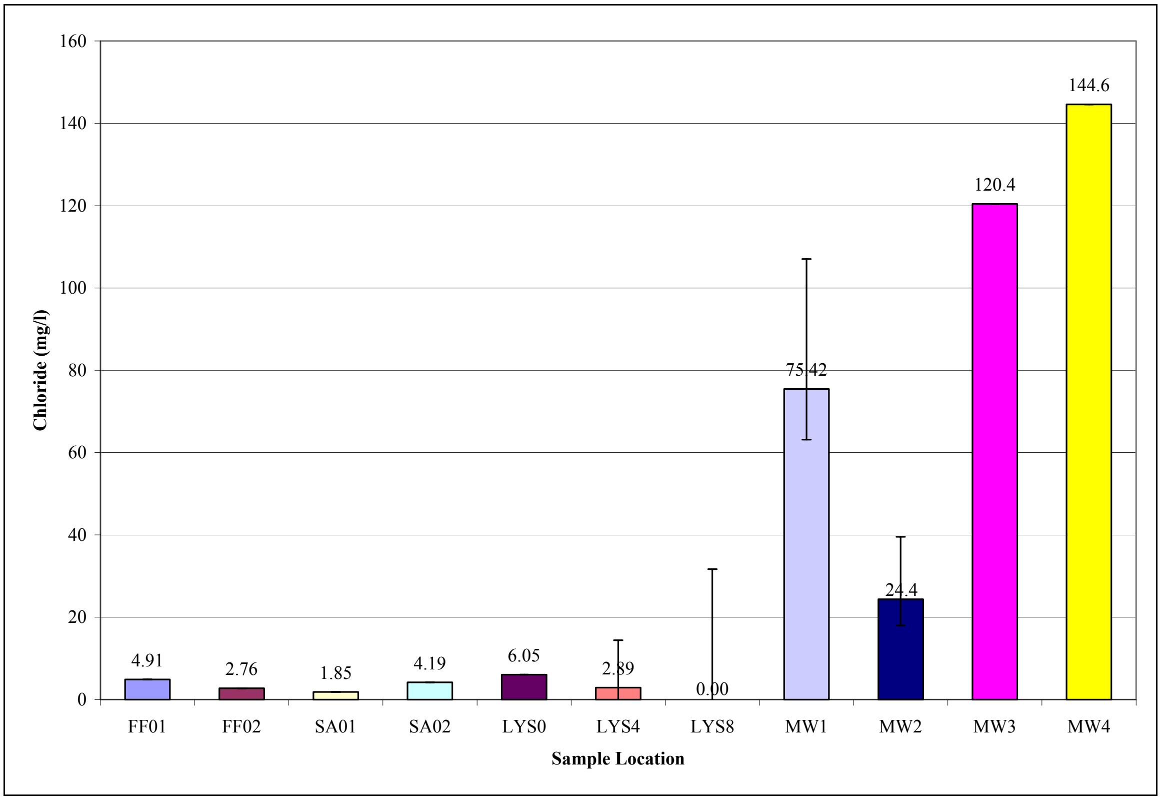

Figure 5: November 15th, 2007 Chloride Results

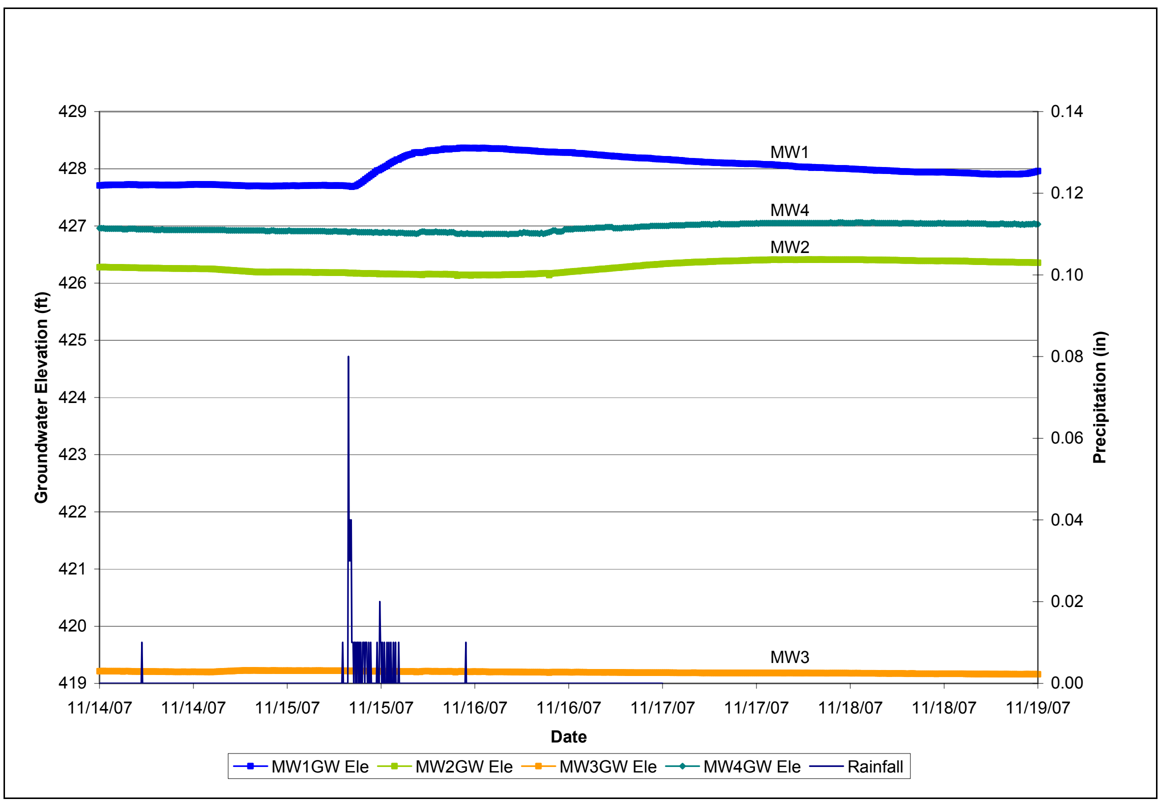

Figure 6: November 15th, 2007 Groundwater Hydrograph

3.1.1.2 Sampling Results

As shown in Figure 3, the HEC-HMS model closely approximates the observed water surface elevation in the BMP. The modeled data has a peak which is sharper and higher than the observed data, which has a more gradual peak at a slightly lower elevation. However, the slopes of the receding limbs for both the modeled and observed data are very similar, with an average recession rate of 0.247 inch/hr. The additional volume represented by the peak of the modeled data is offset by the slightly lower elevation predicted during the recession. In general, the HMS model closely approximates the observed data and therefore it is assumed that the predicted inflow volume is sufficiently accurate.

Figure 4 indicates low conductivity values for the samples representing inflow to the site (i.e. FF01, FF02, SA01) and higher conductivity values for LYS4, LYS8, and the samples from MW-1, MW-3 and MW-4. Three of the four samples from MW-2 are similar to the inflow samples; however MW2C is much higher and is similar to the conductivity at MW-1. Although, MW-1 and MW-4 have, different average conductivities, the four samples collected from each well are similar to each other. The samples from MW-2 and MW-3 display more variance. In order of increasing average conductivity, MW-2 is the lowest followed by MW-1, then MW-3 and MW-4.

The results of the chloride analyses indicate that the surface water and lysimeter samples are relatively similar. The average of these samples is 3.24 mg/l, the maximum is 6.05 mg/l at LYS0 and the minimum is non-detect at LYS8. The first two samples (A and B) from MW-2 are similar to the surface/lysimeter samples with values of 4.75 mg/l and 5.89 mg/l, however samples MW2C and MW2D are several times greater with concentrations of 30.73 mg/l and 56.06 mg/l, respectively. The chloride samples from MW-1 are fairly uniform with an average of 75.42 mg/l and a range of 16.68 mg/l. Chloride samples MW3A-MW3C were similar, ranging between 108.13 mg/l and 111.85 mg/l, but sample MW3D had a higher value of 152.00 mg/l. The samples from MW-4 showed a similar trend to MW-3, the first three samples were similar (138.23-142.01 mg/l), and the final sample spiked up to 159.77 mg/l. For the groundwater samples, MW-2 had the lowest average followed MW-1, MW-3 and then MW-4.

In regards to the conductivity and chloride results, it is also important to consider the total dissolved solids (TDS) results, since these three parameters are generally associated (Hem 1985; Tchobanoglous and Schroeder 1985). It can be seen for samples FF01, FF02, LYS0, LYS4 and LYS8, that increases in TDS generally correspond to higher conductivity values. However, it can also be seen that for these same samples, the higher conductivity values are not apparently derived from chloride concentrations since these sample all have low chloride concentrations. While the well samples were not analyzed for TDS, it can be seen that although variability exists at MW-2, the chloride concentrations are generally consistent with the conductivity values. For example the average chloride concentrations from lowest to highest are MW-2, MW-1, MW-3 and MW-4; which is the same order as the average conductivity concentrations.

The groundwater hydrograph, presented in Figure 6, indicates that MW-1 has a relatively quick response to the rainfall event, while MW-2 and MW-4 have more gradual responses and MW-3 has a relatively imperceptible response. The total change in elevation was 0.67 ft in approximately 14 hours at MW-1, 0.27 ft in 61 hours at MW-2, 0.19 ft in 52 hours at MW-4 and less than 0.02 ft at MW-3. Throughout the storm the groundwater elevation at MW-1 was the highest followed by MW-4 and MW-2 with MW-3 being the lowest elevation. The groundwater elevations indicated a gradient towards the northwest.

3.1.2 December 9th 2007

3.1.2.1 Storm Summary

On 12/9/07 a storm occurred producing 0.18 inch of precipitation in 13 hours and 20 minutes. The maximum 5 minute and 30 minute intensity was 0.60 and 0.20 in/hr, respectively. Storm simulation with HEC-HMS indicates that a total of 426 ft^3 of runoff entered the site. Measured data indicate that runoff was contained by the site and either infiltrated or evapotranspired. Figure 7 shows the results of the HEC-HMS model in addition to the observed rainfall and basin water elevation.

A total of 29 water quality samples were collected during the 12/9/07 storm. Table 3 presents the results of the sampling. Figures 8, 9, and 10 present the results for the conductivity, chloride and total phosphorus analyses. Figure 11 presents a hydrograph of the groundwater elevation during and after the storm.

Table 3: Water Quality Results from the December 9th, 2007 Storm Event

Location	Sample Time	pH	Cond	TSS	TDS	Nitro	NO2	NO3	Phosp	PO4	Chloride
FF01	-	6.80	4600.0	139.6	2229.7	6.40	U	30.6411	1.60	U	3668.37
FF02	-	6.70	1773.0	86.3	875.3	7.70	U	23.1824	0.45	U	1928.93
LYS0	-	6.00	13.3	N	28.0	U	0.3870	U	0.37	U	7.85
LYS4	-	7.00	353.0	N	59.3	U	0.7924	0.2670	0.22	U	1.42
LYS8	-	7.00	405.0	N	51.6	U	0.8544	0.2471	0.07	U	1.53
SA02	-	N	N	172.9	1137.1	6.00	U	5.2569	1.09	U	1464.52
MW1A	12/9/07 16:55	5.95	408.0	N	N	N	N	N	0.12	N	75.38
MW1B	12/10/07 7:55	6.11	347.0	N	N	N	N	N	U	N	48.31
MW1C	12/10/07 12:30	6.02	355.0	N	N	N	N	N	U	N	51.30
MW1D	12/10/07 16:30	5.94	313.0	N	N	N	N	N	U	N	33.93
MW1E	12/10/07 20:25	5.79	332.0	N	N	N	N	N	U	N	43.80
MW1F	12/11/07 9:10	5.78	320.0	N	N	N	N	N	U	N	40.28
MW2A	12/9/07 17:10	6.21	122.2	N	N	N	N	N	2.64	N	3.65
MW2B	12/10/07 8:05	6.12	117.1	N	N	N	N	N	0.56	N	3.29
MW2C	12/10/07 12:35	6.07	118.0	N	N	N	N	N	0.24	N	3.23
MW2D	12/10/07 16:35	6.16	118.7	N	N	N	N	N	0.20	N	3.38
MW2E	12/10/07 20:30	6.13	116.1	N	N	N	N	N	0.42	N	3.19
MW2F	12/11/07 9:15	6.16	119.8	N	N	N	N	N	0.28	N	3.52
MW3A	12/9/07 17:20	5.73	404.0	N	N	N	N	N	0.16	N	84.38
MW3B	12/10/07 8:10	5.71	419.0	N	N	N	N	N	0.12	N	101.79
MW3C	12/10/07 12:40	5.64	406.0	N	N	N	N	N	0.24	N	93.02
MW3D	12/10/07 16:40	5.69	405.0	N	N	N	N	N	0.24	N	93.26
MW3E	12/10/07 20:35	5.73	407.0	N	N	N	N	N	0.22	N	93.26
MW3F	12/11/07 9:30	5.73	418.0	N	N	N	N	N	0.10	N	101.23
MW4B	12/10/07 8:40	5.97	591.0	N	N	N	N	N	0.17	N	136.65
MW4C	12/10/07 12:45	6.28	593.0	N	N	N	N	N	0.08	N	136.76
MW4D	12/10/07 16:45	6.30	592.0	N	N	N	N	N	0.07	N	137.50
MW4E	12/10/07 20:40	6.31	597.0	N	N	N	N	N	0.27	N	138.42
MW4F	12/11/07 9:35	6.34	594.0	N	N	N	N	N	N	N	141.78

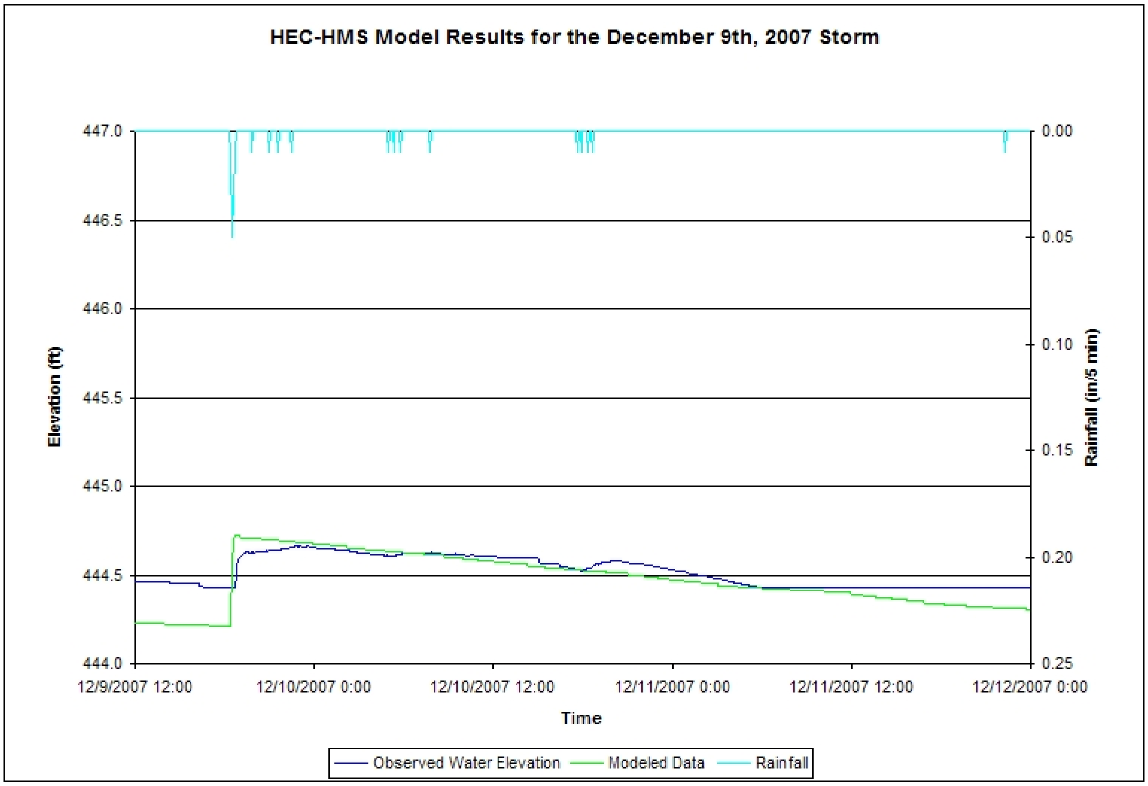

Figure 7: December 9th, 2007 HEC-HMS Model Results

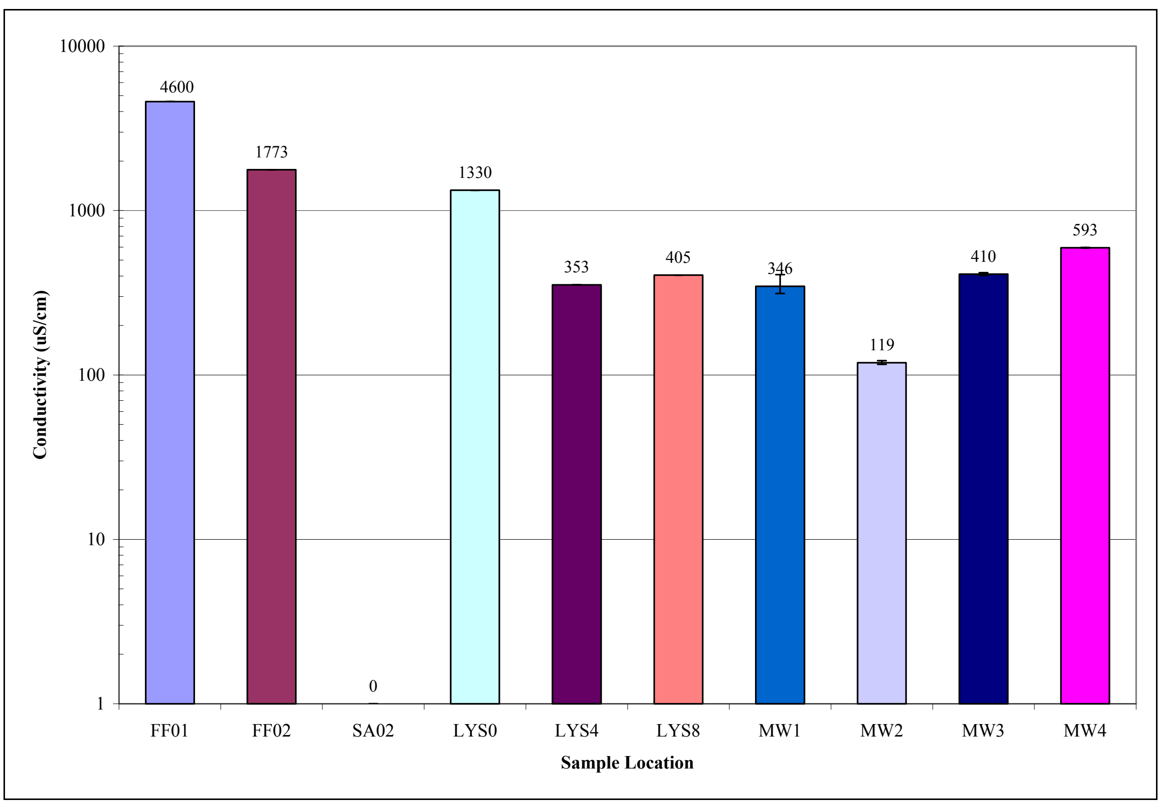

Figure 8: December 9th, 2007 Conductivity Results

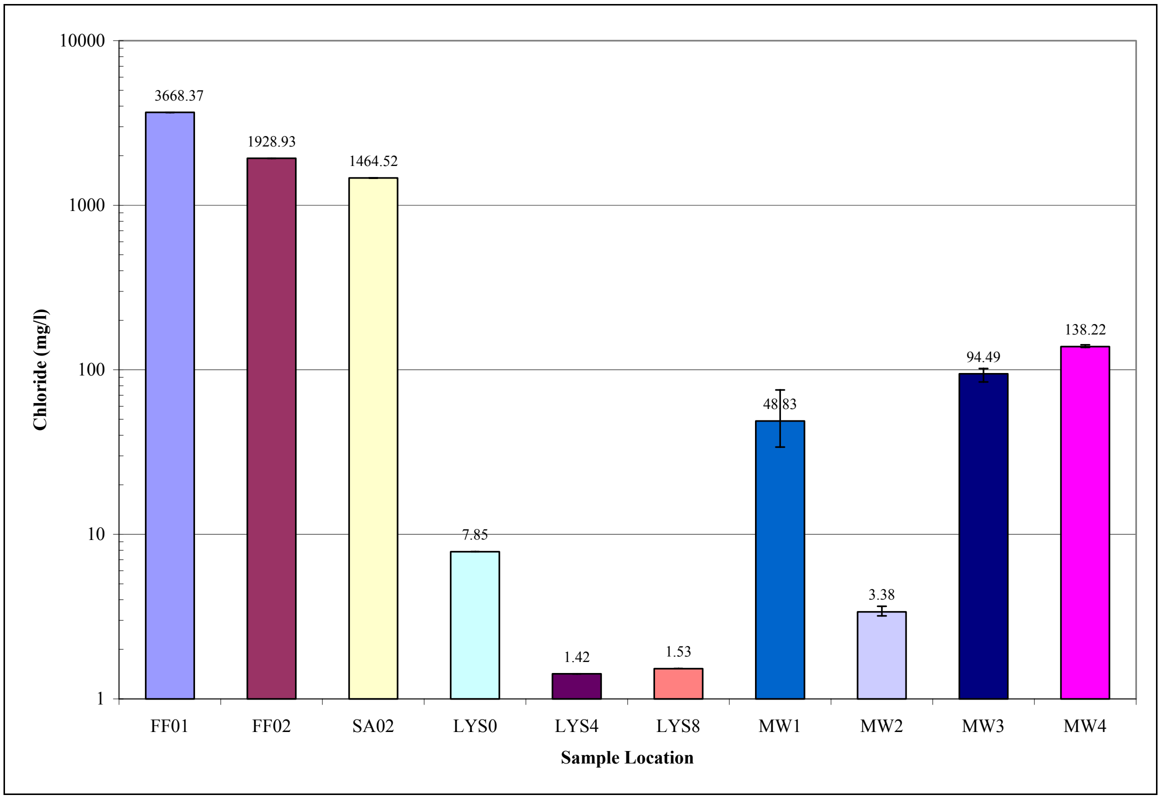

Figure 9: December 9th, 2007 Chloride Results

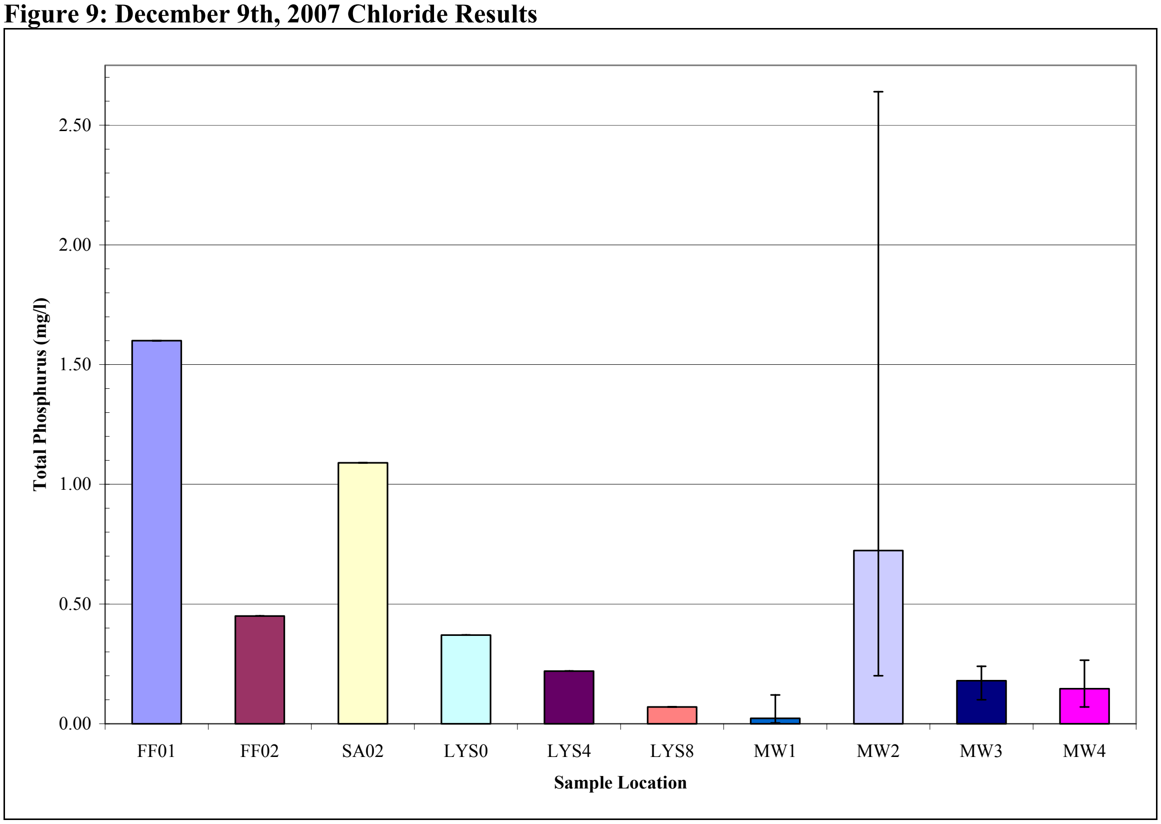

Figure 10: December 9th, 2007 Total Phosphorus Results

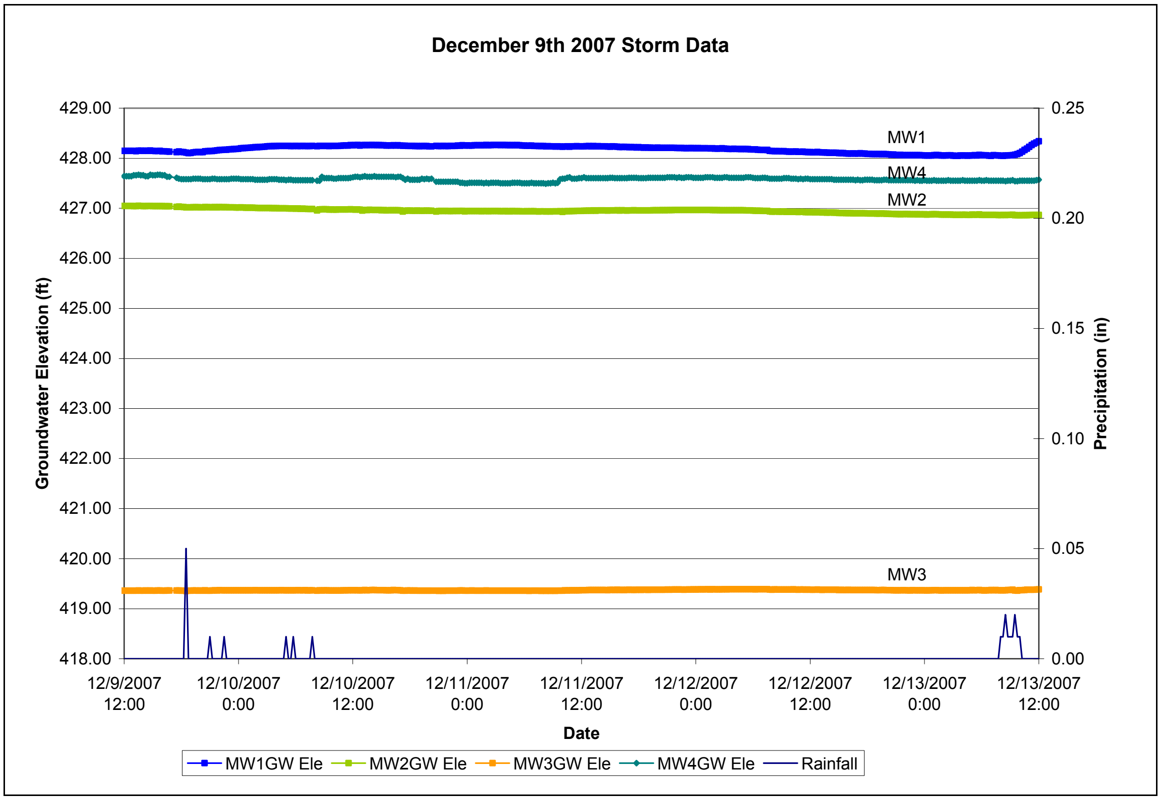

Figure 11: December 9th, 2007 Groundwater Hydrograph

3.1.2.2 Sampling Results

The results of the HEC-HMS simulation presented in Figure 7 closely approximate the observed water surface elevation data. Similar to the previous storm, the modeled data have a sharper and higher peak compared to the observed data, but the slopes of the recession limbs are similar and the total area under the curves are similar. It is therefore assumed that the calculated inflow volume is sufficiently accurate. The average slope of the recession limbs is 0.195 inch/hr.

The conductivity and chloride results display significant variation between the first flush samples, the lysimeters and the groundwater samples (note the logarithmic scale on Figures 8 and 9). The first flush samples have conductivity values and chloride concentrations that are an order of magnitude greater than several of the groundwater samples. Grab sample SA2 was not analyzed for conductivity, but the chloride concentration was similar to the FF02 sample. The lysimeter sample conductivities were relatively variable; ranging from 1330 μS/cm at LYS0 to 353 μS/cm at LYS4 and 405 μS/cm at LYS8. However, the chloride concentrations in the lysimeter samples were low; ranging from 1.42 mg/l at LYS4 to 7.85 mg/l at LYS0. In contrast the samples from the first flush samplers and the wells have relatively stable conductivity and chloride concentrations and the chloride concentrations appear to be linked to the conductivity values. For instance, MW-1 has a lower average conductivity than MW-4 and the chloride concentration at MW-1 is also lower than MW-4. The MW-2 samples had much lower conductivity values and chloride concentrations than the other well samples. The chloride concentrations at MW-2 were similar to the lysimeter samples; however the conductivity was higher than the lysimeter samples. It appears that although variation exists between the wells; the groundwater samples from a given well have relatively stable conductivities and chloride concentrations.

The results of the total phosphorus analysis consist of relatively low concentrations, except at FF01, MW2A and SA02. Phosphorus often exists sorbed to soil particles rather than in solution; thus a water sample with suspended solids may contain more phosphorus than a sample with minimal suspended solids (Hem 1985; Tchobanoglous and Schroeder 1985). It was noted that MW2A was more turbid than the other wells samples; likely due to disturbance of the water column during sampling. The total phosphorus concentrations of the lysimeter samplers display concentrations that decrease at a linear rate with respect to depth; with a concentration of 0.37 mg/l at LYS0, 0.22 mg/l at LYS4 and 0.07 mg/l at LYS8. Phosphorus was only detected in one sample (MW1A) from MW-1. In contrast, MW-2 had an average concentration of 0.72 mg/l, with a maximum of 2.64 mg/l in MW2A and a minimum of 0.2 mg/l in MW2D. MW-3 and MW-4 were fairly similar with average concentrations of 0.18 mg/l and 0.15 mg/l, respectively. Furthermore, MW-3 and MW-4 had minimum and maximum concentrations of 0.12 mg/l (MW3B), 0.07 mg/l (MW4D), 0.24 mg/l (MW3C) and 0.27 mg/l (MW4E), respectively. In summary, MW-1 had the lowest concentrations and MW-2 had the highest concentrations and MW-3 and MW-4 were fairly similar.

The groundwater hydrograph for the 12/9/07 storm indicates minor responses in the wells due to the storm. The lack of response is most likely due to the low volume of rainfall (0.18 in). The total responses observed at the wells were 0.17 ft in 18 hours at MW-1, 0.04 ft in 53 hours at MW-2, 0.03 ft in 55 hours at MW-3 and 0.11 ft in 51 hours at MW-4. Over the course of the storm the hydraulic gradient remains stable with MW-1 at the highest elevation, followed by MW-4, MW-2 and then MW-3. This gradient indicates a northwestern groundwater flow direction, with a steep gradient between MW-2 and MW-3.

3.1.3 January 17th 2008

3.1.3.1 Storm Summary

On 1/17/08, a storm occurred that produced 0.70 inch of precipitation in 11 hours and 30 minutes. The maximum 5 minute and 30 minute intensity was 0.24 and 0.16 in/hr, respectively. The HEC-HMS model indicates that a total of 1344 ft^3 of runoff entered the site. Measured data indicate all runoff was contained by the site and either infiltrated or lost to evapotranspiration. Figure 12 shows the results of the HEC-HMS model in addition to the observed rainfall and basin water elevation.

A total of 33 water quality samples were collected during the 1/17/08 storm. Table 4 presents the results of the sampling. Figures 13, 14 and 15 present the results for the conductivity, chloride, and total phosphorus. Figures 15, 16 and 17 present the groundwater hydrograph, groundwater temperature and conductivity during and after the storm.

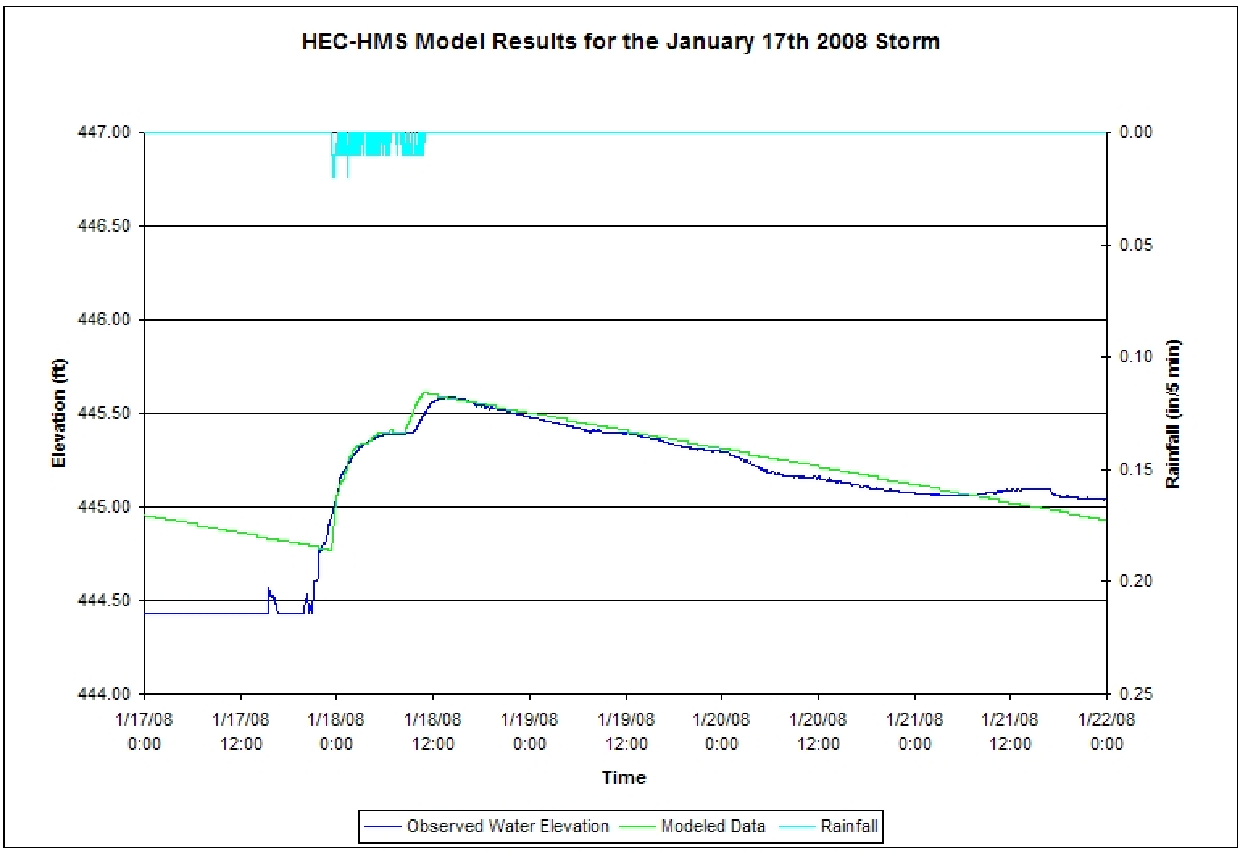

Figure 12: January 17th, 2008 HEC-HMS Model Results

Table 4: Water Quality Results from the January 17th, 2008 Storm Event

Location	Sample Time	pH	Cond	TSS	TDS	TN	NO2	NO3	TP	PO4	Chloride
AS01	1/17/2008 23:22	6.40	2760	26.3	214.2	U	U	3.7852	0.60	U	228.96
AS02	1/18/2008 2:22	6.40	3560	U	950.9	U	U	2.2422	0.11	U	372.00
AS03	1/18/2008 5:22	6.30	4420	U	1044.4	U	U	0.7348	0.27	U	373.15
AS04	1/18/2008 8:22	6.20	4260	2.0	912.2	4.20	U	0.8136	0.21	U	335.06
AS05	1/18/2008 11:22	6.20	3840	U	963.0	U	U	5.0760	1.01	U	410.85
AS06	1/18/2008 14:22	6.30	3590	U	358.1	U	U	0.5947	3.35	U	2,172.86
AS08	1/18/2008 20:22	6.30	3320	U	917.5	U	U	1.0487	1.14	U	3,621.32
FF01	-	6.00	139,600	972.0	12207.4	5.20	U	U	4.00	U	7,921.62
FF02	-	6.68	44,000	57.9	11427.0	2.24	U	U	0.57	U	9,120.41
LYS0	-	6.90	1,279	N	306.3	U	1.9926	U	0.19	U	393.87
LYS4	-	6.90	646	N	83.7	U	U	2.1211	0.18	U	398.12
LYS8	-	6.80	619	N	262.2	U	U	0.4463	0.20	U	439.96
SA02	-	7.70	1,944	U	320.6	2.30	U	0.7754	0.52	U	152.08
MW1A	1/17/08 15:40	5.00	450	N	N	6.00	U	6.0690	0.60	U	87.19
MW1B	1/18/08 10:10	5.40	405	N	N	2.80	U	1.4008	0.20	U	79.57
MW1C	1/18/08 14:00	5.80	407	N	N	N	U	1.3869	0.13	U	79.48
MW1D	1/18/08 19:50	5.90	407	N	N	N	U	1.3795	0.18	U	78.59
MW1e	1/19/08 9:25	5.90	421	N	N	N	U	1.6475	0.16	U	83.47
MW2A	1/17/08 15:40	4.57	300	N	N	11.80	U	9.7474	1.48	U	55.05
MW2B	1/18/08 10:10	5.80	243	N	N	U	U	0.4026	0.32	U	53.10
MW2C	1/18/08 14:00	6.10	245	N	N	N	U	0.4054	0.14	U	53.94
MW2D	1/18/08 19:50	6.20	238	N	N	N	0.0515	0.3527	0.41	U	51.77
MW2e	1/19/08 9:25	6.20	240	N	N	N	U	0.4479	0.32	U	52.60
MW3A	1/17/08 15:40	5.50	361	N	N	4.00	U	3.0533	0.80	U	81.79
MW3B	1/18/08 10:10	5.70	352	N	N	U	U	1.0939	0.45	U	83.02
MW3C	1/18/08 14:00	5.90	357	N	N	N	U	1.0912	0.21	U	85.22
MW3D	1/18/08 19:50	6.10	350	N	N	N	U	0.9377	0.10	U	81.52
MW3e	1/19/08 9:25	6.00	354	N	N	N	U	1.1106	0.23	U	83.94
MW4A	1/17/08 15:40	5.90	588	N	N	5.90	0.2775	3.6595	1.71	U	144.38
MW4B	1/18/08 10:10	5.90	584	N	N	U	U	0.5378	0.19	U	143.52
MW4C	1/18/08 14:00	6.50	590	N	N	N	U	0.4631	0.08	U	146.62
MW4D	1/18/08 19:50	6.50	590	N	N	N	0.3194	0.4459	0.29	U	145.80
MW4e	1/19/08 9:25	6.50	603	N	N	N	U	0.7276	0.25	U	145.81

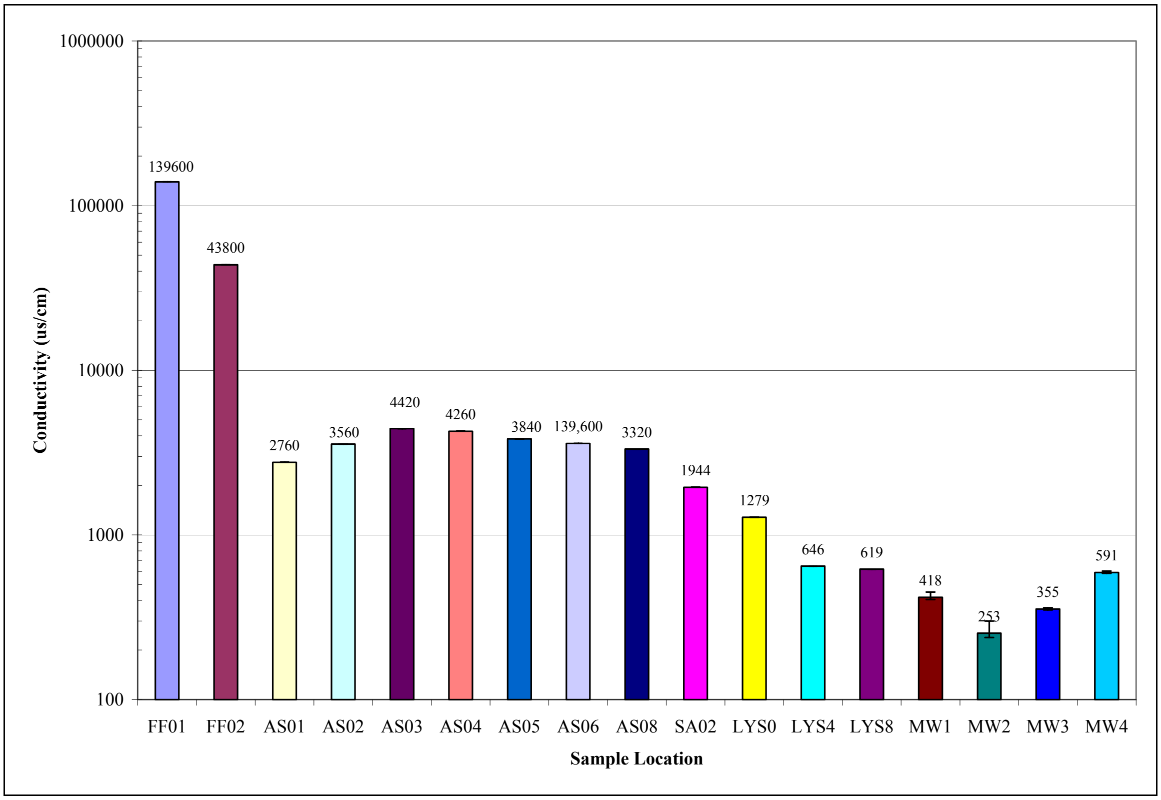

Figure 13: January 17th, 2008 Conductivity Results

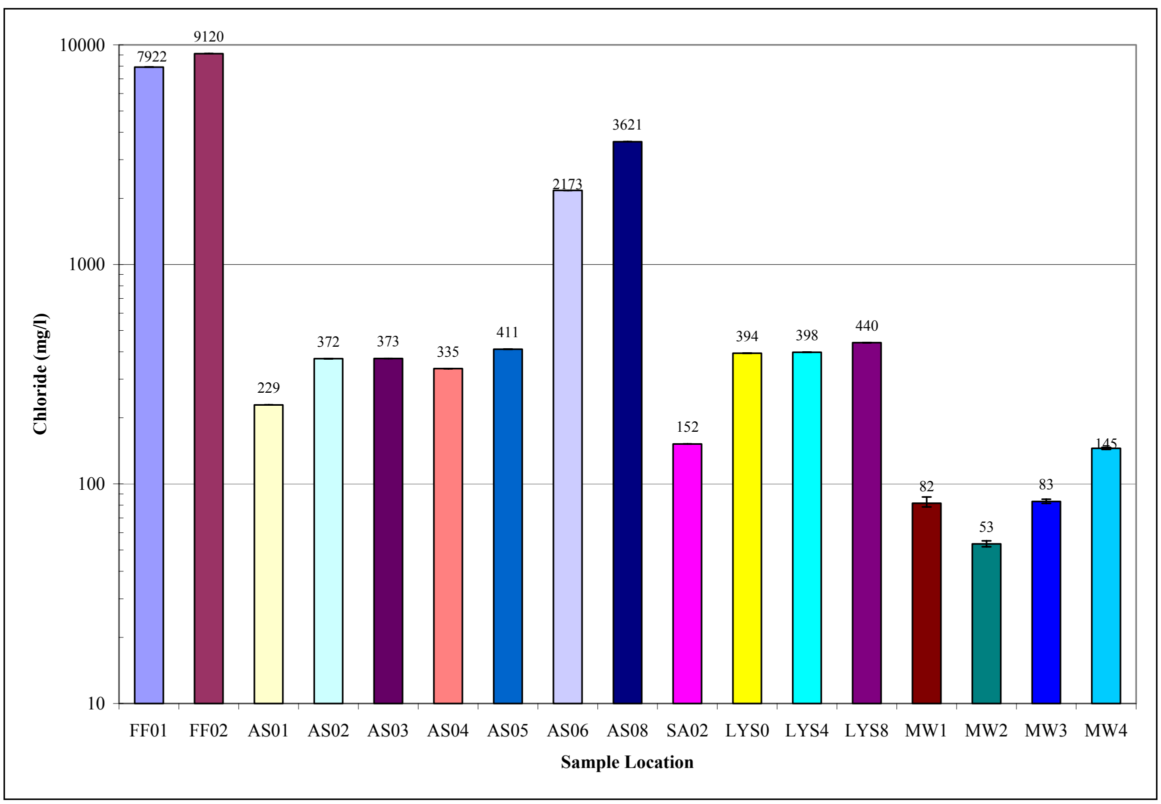

Figure 14: January 17th, 2008 Chloride Results

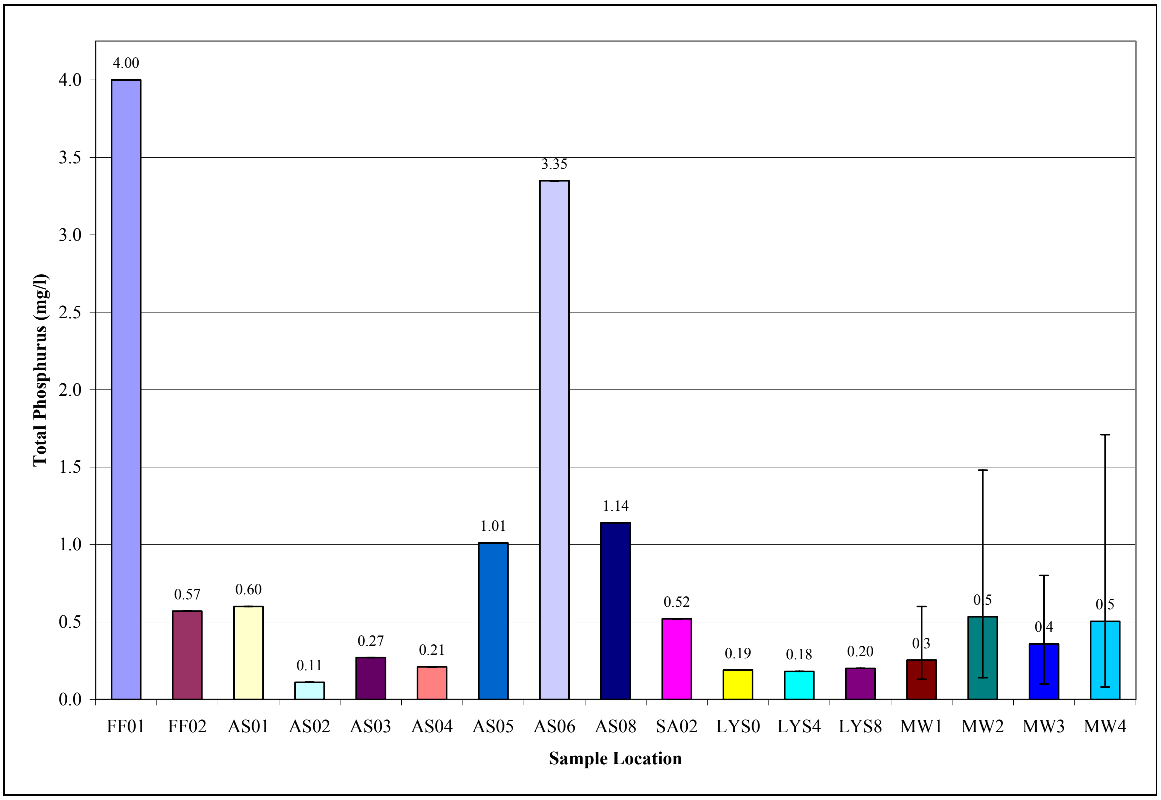

Figure 15: January 17th, 2008 Total Phosphorus Results

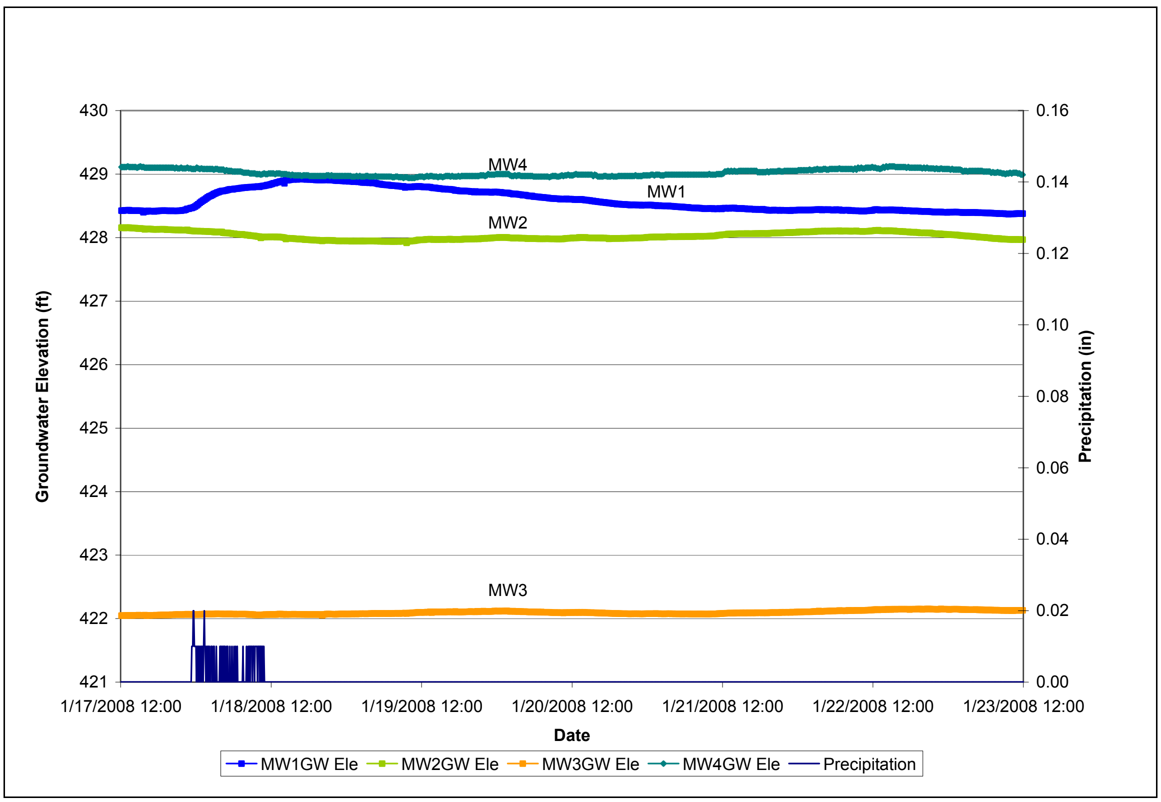

Figure 16: January 17th, 2008 Groundwater Hydrograph

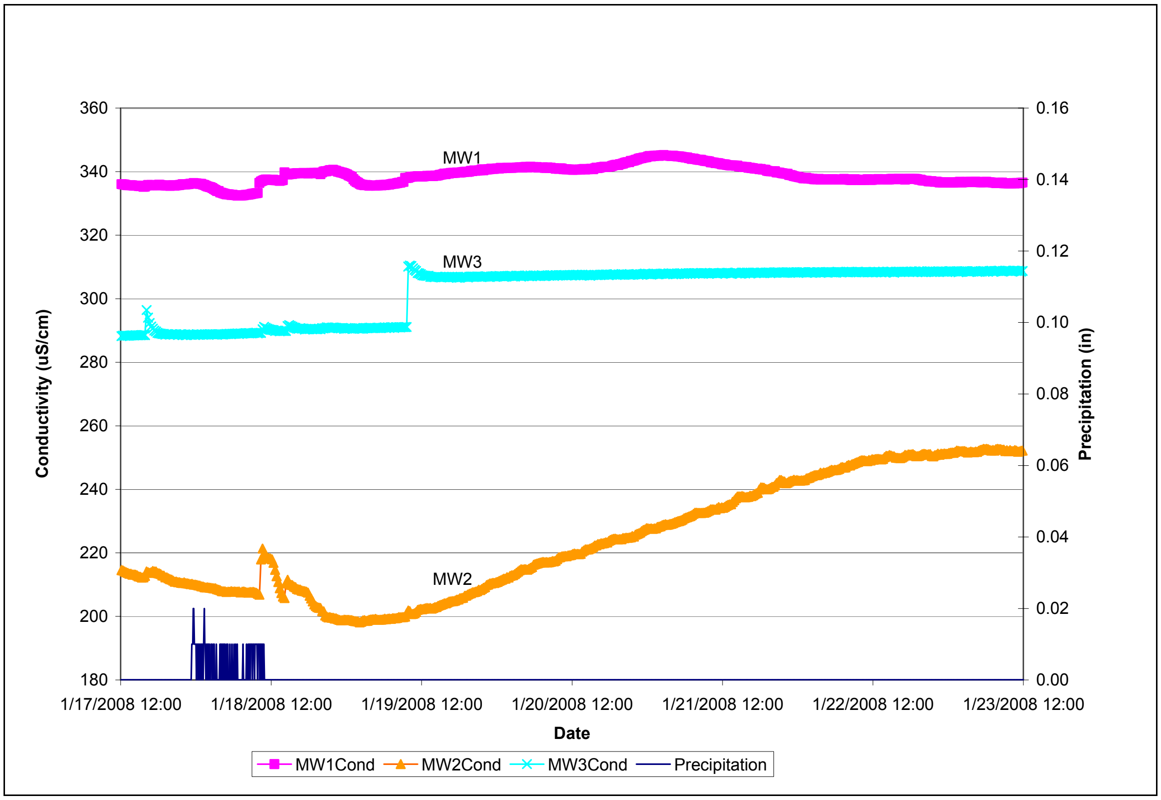

Figure 17: January 17th, 2008 Groundwater Conductivity

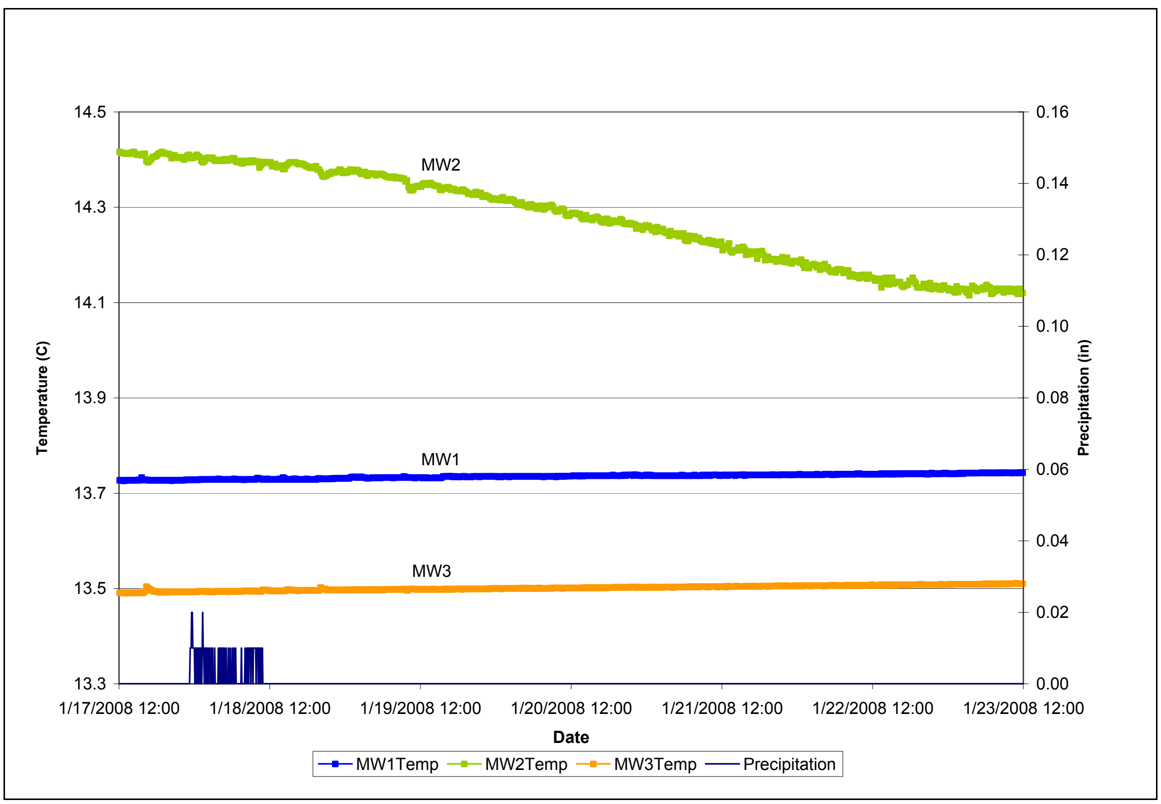

Figure 18: January 17th, 2008 Groundwater Temperature

3.1.3.2 Sampling Results

The HEC-HMS simulation of the storm closely approximates the observed data. The modeled data reaches a peak quicker than the observed data and has a slightly higher peak, but the discrepancy is minor. The slopes recession limbs are very similar, but the observed data exhibits more fluctuation than the modeled data. The average recession rate is 0.111 inch/hr. Overall, the model predicts basin elevations that closely match the observed data and it is therefore assumed that the modeled inflow volume is sufficiently accurate.

Sampling for this storm included 7 samples collected from the basin with a Sigma 900 max autosampler. The samples, AS01-AS06 and AS08, are composed of two discrete samples collected 1.5 hours apart. In this manner the autosamples are meant to record the water quality in the basin over time. The conductivity analysis of the autosamples showed a gradual rise and decline over the duration of sampling. The initial autosample, AS01, had a conductivity of 2760 µS/cm. The conductivity rose to 4420 µS/cm at AS03 and then declined to 3320 µS/cm in AS08. In comparison, grab sample SA02, which was collected around the time of AS06, had a much lower conductivity of 1944 µS/cm, and both AS06 and SA02 had similar TDS values of 358.1 mg/l and 320.6 mg/l, respectively. The first flush samples both had conductivity values much higher than the other samples. FF01 had the highest conductivity of 136,600 µS/cm and FF02 had a conductivity of 43,800 µS/cm. The lysimeter samples displayed declining conductivity with respect to depth; LYS0 was 1279 µS/cm, LYS4 was 649 µS/cm and LYS8 was 619 µS/cm. The well samples were fairly consistent within each well. The average conductivities, in increasing order were 253 µS/cm at MW-2, 355 µS/cm at MW-3, 418 µS/cm at MW-1 and 591 µS/cm at MW-4.

The chloride results of the autosampler started low with AS01 (228.96 mg/l), gradually increased to 410.85 mg/l at AS05, then spiked up to 2,172.86 mg/l and 3,621.32 mg/l at ASO6 and AS08, respectively. The grab sample SA02, was significantly lower than the autosamples, at only 152.08 mg/l. The first flush samples had significantly higher concentrations than the other samples; with concentrations of 7,921.62 mg/l and 9120.41 mg/l at FF01 and FF02. These high chloride concentrations are in line with the high conductivity values recorded for the first flush samples. The lysimeter samples were similar for LYS0 (393.87 mg/l) and LYS4 (398.12 mg/l), but rose to 439.96 mg/l at LYS8. The groundwater samples were uniform within each well with averages as follows: MW-2 was lowest at 53 mg/l, followed by MW-1 at 82 mg/l, then MW-3 at 83 mg/l and finally 145 mg/l at MW-4.

Out of the 33 samples analyzed for total phosphorus, 45% had concentration less than 0.25 mg/l, 67% were less than 0.5 mg/l and 82% were less than 1.0 mg/l. The autosamples displayed a wide range of results, from 0.11 mg/l at AS02 to 3.35 mg/l at AS06. The first autosample had a high concentration of 0.61mg/l, then was followed by three samples with lower concentrations and three samples above 1.10mg/l (AS05, AS06 and AS08). Grab sample SA02 had a concentration of 0.52 mg/l, which is below the average concentration of the autosamples (0.92 mg/l). Sample FF01 was above the method range (>4 mg/l) but FF02 was only 0.57 mg/l. The lysimeter samples had uniform concentrations of 0.19, 0.18 and 0.20 mg/l at LYS0, LYS4 and LYS8. The groundwater samples showed some variation and it is interesting to note that the first sample at each well had the highest concentration and the remaining samples were all below 0.50 mg/l. MW-2 had the highest average concentration of 0.53 mg/l followed by MW-4 with 0.50 mg/l, then MW-3 at 0.36mg/l and MW-1 at 0.25 mg/l. Thus the upgradient well had the lowest concentration, the two wells closest to the BMP had the highest concentrations and the downgradient well contained a moderate concentration.

Groundwater monitoring for the storm shows that MW-1 has a rapid response, that MW-2 and MW-4 have gradual responses and that MW-3 show minimal response. The groundwater elevation at MW-1 rose 0.5 ft in 16.5 hours, while MW-2 and MW-4 rose 0.18 ft in 110 hours and 0.16 ft in 111 hours, respectively. MW-3 rose approximately 0.08 ft in 118 hours. Perhaps the most notable observation from the groundwater monitoring is that the hydraulic head at MW-4 is above that of MW-1, which is a switch from previous storms. The hydraulic gradient of the wells indicates a flow direction to the northwest with a steep gradient between MW-2 and MW-3.

Also presented for this storm are graphs of the groundwater conductivity and temperature during the storm period. The groundwater sample collection procedure was altered to minimize the disturbance to the water column in the well, but the impact is still noticeable. When the bailer is lowered into the well, extreme care was taken not to disturb the water column or the AquaTroll. Although care was taken to minimize the disturbance, effects are still noticeable, but show a significant improvement from previous sampling events. Sampling disturbances aside, several observations can be made from the data. First, MW-2 shows the largest response to the rainfall event, varying by approximately 53 μS/cm. Prior to the storm event, the conductivity at MW-2 declined gradually, but as the groundwater elevation began to rise in response to the storm, the conductivity rose from approximately 198 μS/cm on 1/19 to about 251 μS/cm on 1/23. MW-1 shows a less discernable and more variable response, initially there is a drop in conductivity, but then the conductivity begins to oscillate while gradually increasing. In contrast, MW-3 shows very minor influence and any minor influence is masked by the disturbances caused by sampling. Figure 19, below shows a more detailed graph of the conductivity and groundwater elevation at MW-1 and MW-2.

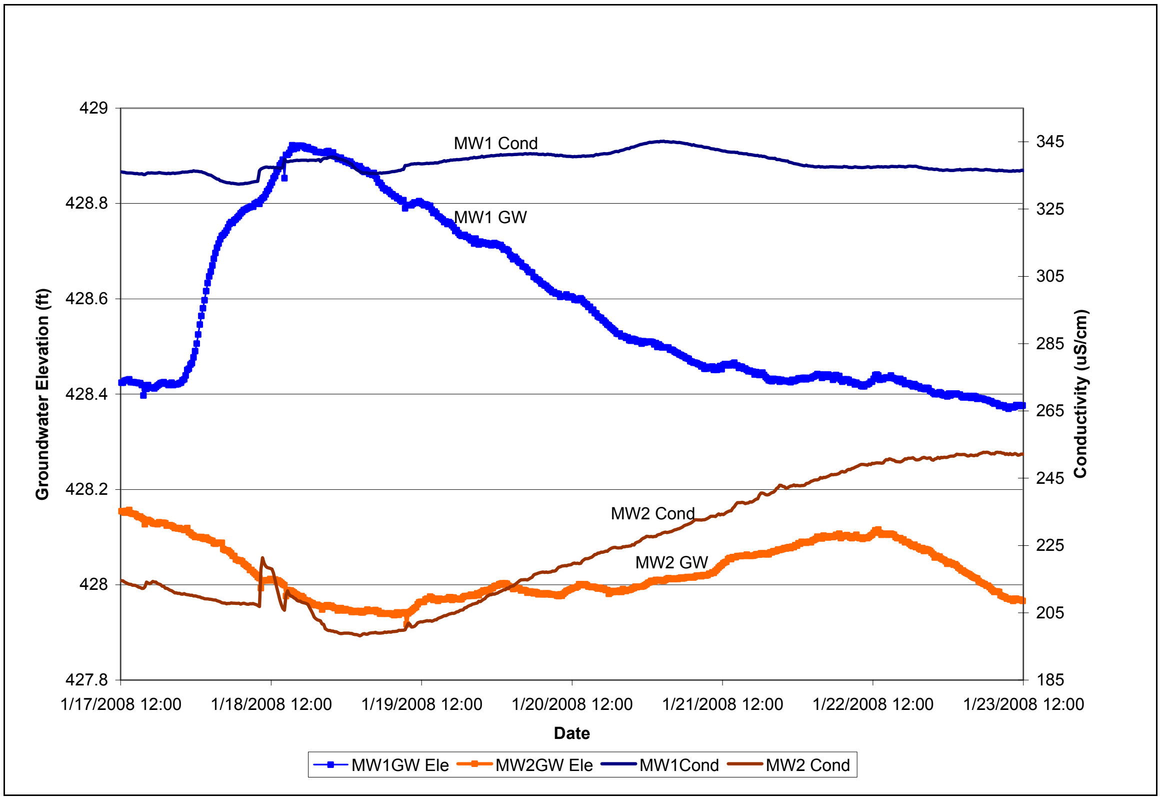

Figure 19: January 17th, 2008 Groundwater Hydrograph and Conductivity for MW-1 & MW-2

The groundwater temperature monitoring was minimally effected by the sampling procedure. The temperature at MW-1 and MW-3 showed no readily discernable response to the storm. In both cases the temperature showed a gradual and steady increase before, during and after the storm, with no observable changes in slope. Between 1/17 and 1/23, MW-1 increased from 13.72 ^{o}C to 13.76 ^{o}C, while MW-3 increased from 13.49 ^{o}C to

13.51 ^{o}C. In contrast, MW-2 displayed a noticeable response to the storm, decreasing in temperature from 14.42 ^{o}C on 1/17 to 14.12 ^{o}C on 1/23. In addition, the temperature curve showed decrease in slope (i.e. more negative) in response to the storm, indicating the infiltration of colder water. From a site-scale perspective, the upgradient (MW-1) and downgradient (MW-3) had similar temperatures, while the well closest to the site had a higher temperature.

3.1.4 March 31st 2008

3.1.4.1 Storm Summary

On 3/31/08, a storm occurred that produced 0.27 inch of precipitation over 24 hours. The maximum 5 minute and 30 minute intensity was 0.24 and 0.06 in/hr, respectively. The HEC-HMS model indicates that a total of 426 ft^3 of runoff entered the site. Measured data indicate that runoff was contained by the site and either infiltrated or lost to evapotranspiration. Figure 20 shows the results of the HEC-HMS model in addition to the observed rainfall and basin water elevation.

A total of 25 water quality samples were collected during the storm. Table 5 presents the results of the sampling. Figures 21, 22 and 23 present the results for the chloride, conductivity and total phosphorus analyses. Figure 24 presents a hydrograph of the groundwater elevations during and after the storm, while Figures 25 and 26 show the fluctuation in temperature and conductivity in MW-1, 2 and 3 over the course of the storm.

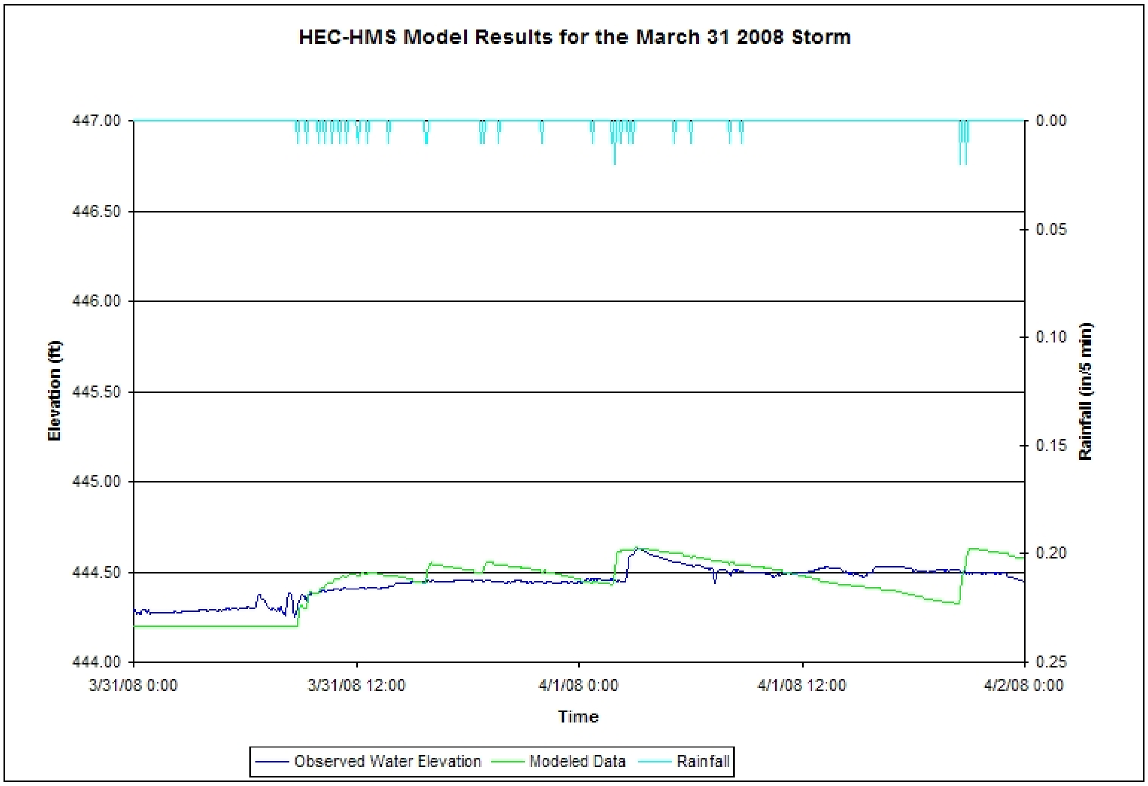

Figure 20: March 31st, 2008 HEC-HMS Model Results

Table 5: Water Quality Results from the March 31st, 2008 Storm Event

Location	Sample Time	pH	Cond	TSS	TDS	Nitro	NO2	NO3	Phosp	PO4	Chloride
FF01	-	6.84	53	1.1	34.1	1.90	0.7970	U	0.18	U	13.80
FF02	-	6.46	247	U	423.0	6.00	1.2120	0.1080	1.41	0.0790	47.25
LYS0	-	7.60	212	N	N	N	0.9000	U	0.56	0.0170	65.21
LYS4	-	6.80	2	N	N	U	0.7970	0.7240	0.20	U	376.32
LYS8	-	6.80	1837	N	N	U	0.9000	U	0.19	U	309.91
MW1A	3/31/08 15:00	5.58	553	N	N	N	N	N	0.48	N	137.21
MW1B	4/1/08 9:30	5.83	U	N	N	N	N	N	0.23	N	130.58
MW1C	4/1/08 13:30	***2.90***	1110	N	N	N	N	N	0.27	N	187.74
MW1D	4/1/08 17:30	5.85	652	N	N	N	N	N	0.95	N	160.95
MW1e	4/2/08 9:45	3.14	1026	N	N	N	N	N	0.98	N	196.02
MW2A	3/31/08 15:00	5.49	1077	N	N	N	N	N	0.16	N	280.66
MW2B	4/1/08 9:30	5.72	1067	N	N	N	N	N	2.33	N	295.98
MW2C	4/1/08 13:30	3.72	1190	N	N	N	N	N	0.26	N	282.59
MW2D	4/1/08 17:30	5.45	1177	N	N	N	N	N	1.10	N	291.15
MW2e	4/2/08 9:45	3.17	1497	N	N	N	N	N	1.01	N	298.47
MW3A	3/31/08 15:00	5.69	334	N	N	N	N	N	0.32	N	64.72
MW3B	4/1/08 9:30	5.78	334	N	N	N	N	N	0.24	N	64.03
MW3C	4/1/08 13:30	5.75	334	N	N	N	N	N	0.20	N	65.83
MW3D	4/1/08 17:30	5.83	334	N	N	N	N	N	0.31	N	64.58
MW3e	4/2/08 9:45	3.03	755	N	N	N	N	N	1.39	N	144.11
MW4A	3/31/08 15:00	6.19	610	N	N	N	N	N	0.11	N	156.40
MW4B	4/1/08 9:30	6.13	601	N	N	N	N	N	0.19	N	147.15
MW4C	4/1/08 13:30	6.19	602	N	N	N	N	N	0.14	N	146.18
MW4D	4/1/08 17:30	6.56	606	N	N	N	N	N	0.20	N	146.73
MW4e	4/2/08 9:45	6.33	619	N	N	N	N	N	0.28	N	148.94

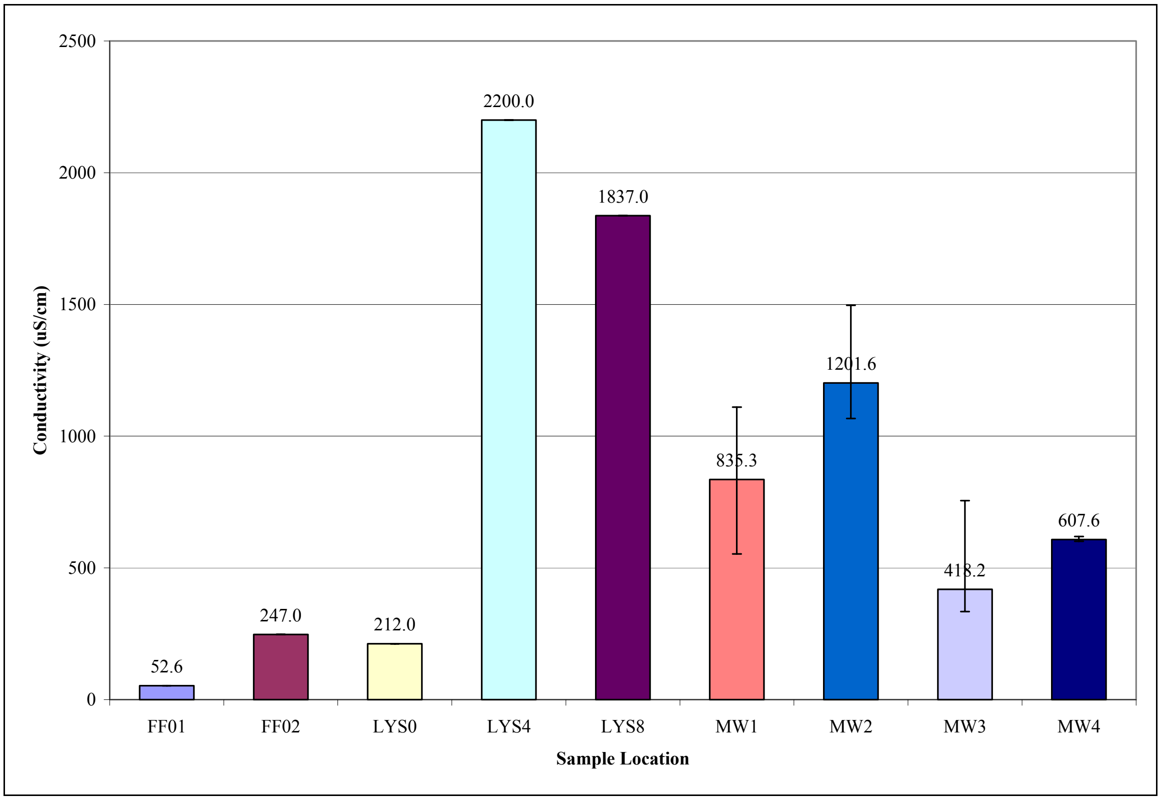

Figure 21: March 31st, 2008 Conductivity Results

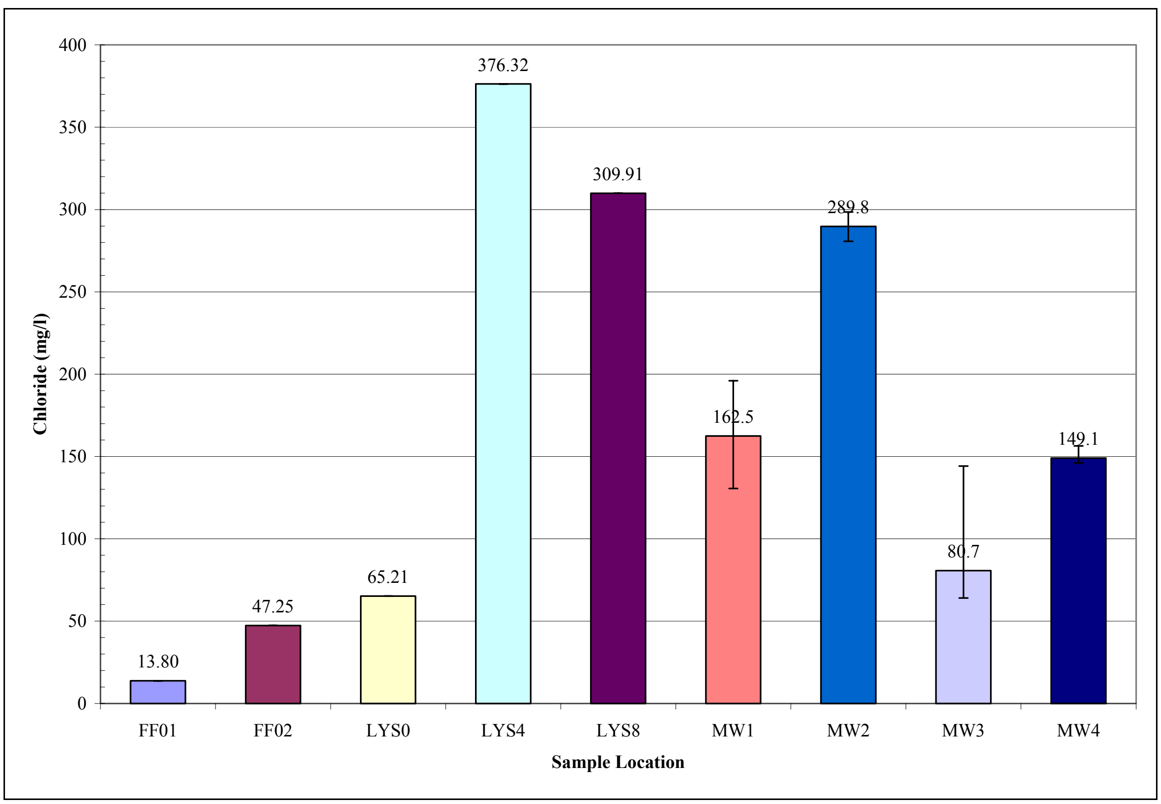

Figure 22: March 31st 2008 Chloride Results

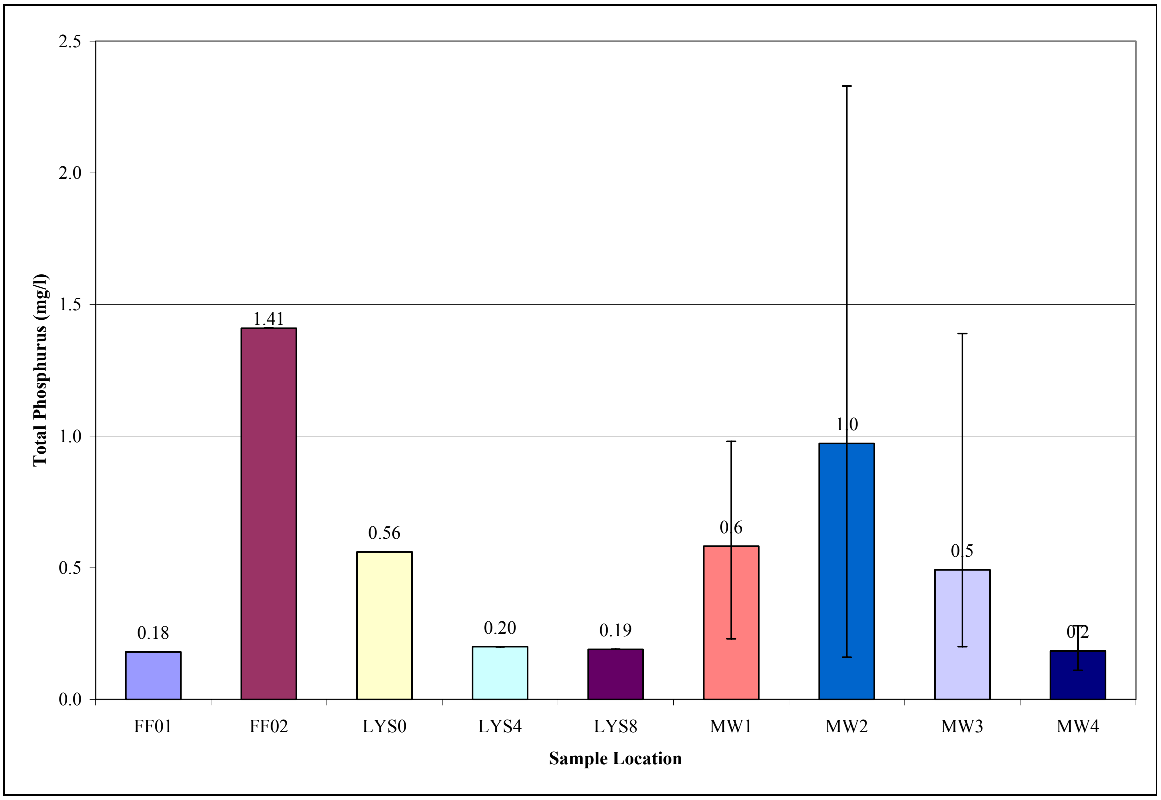

Figure 23: March 31st, 2007 Total Phosphorus Results

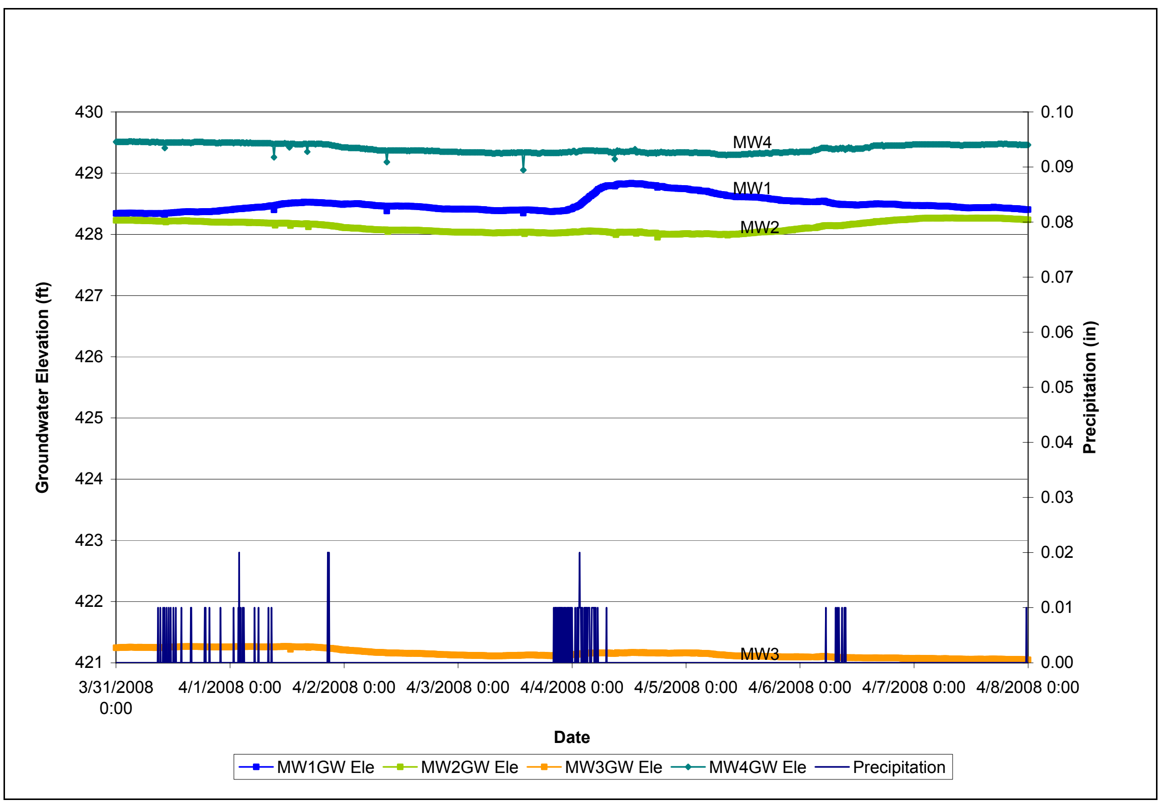

Figure 24: March 31st, 2008 Groundwater Hydrograph

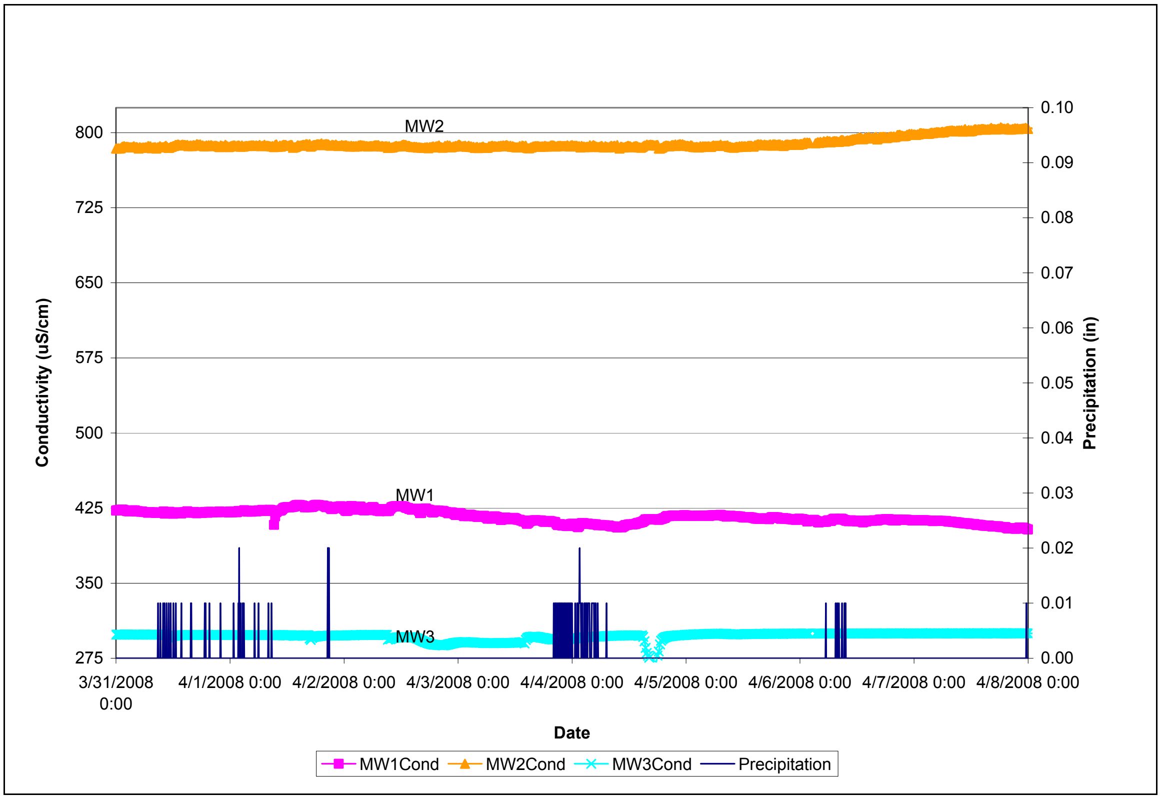

Figure 25: March 31st, 2008 Groundwater Conductivity

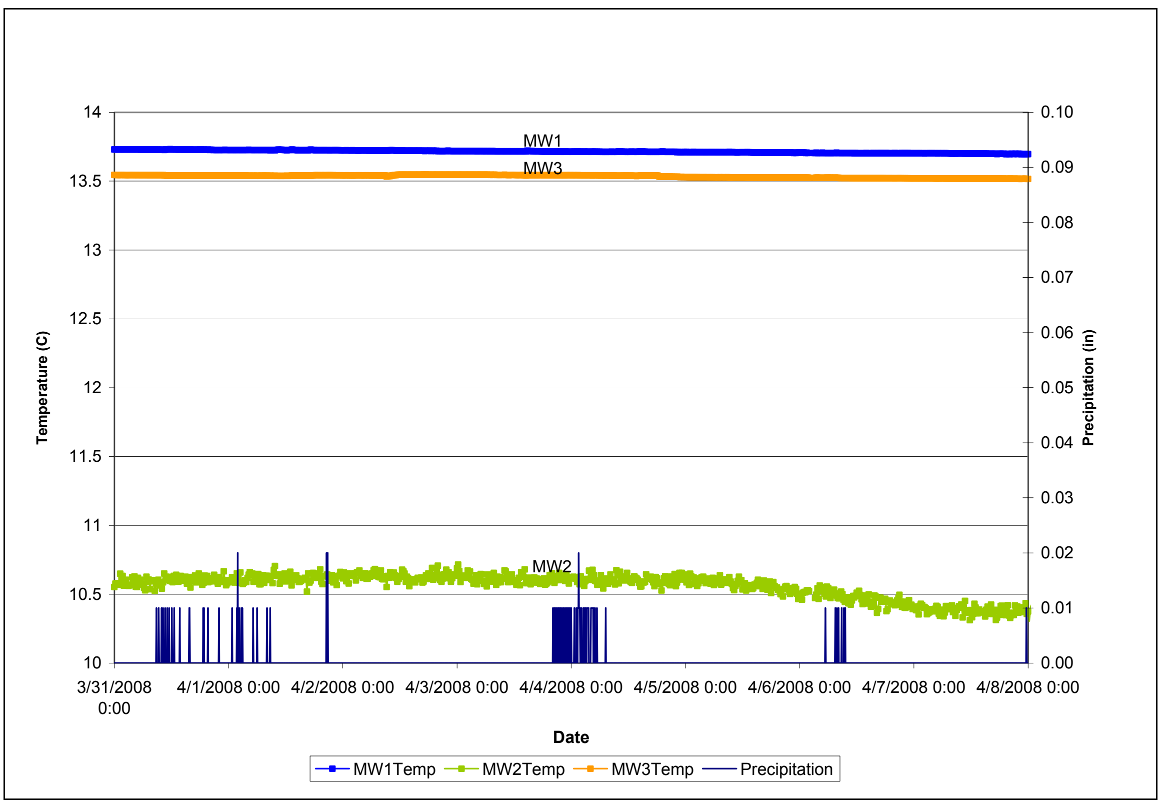

Figure 26: March 31st, 2008 Groundwater Temperature

3.1.4.2 Sampling Results

The event on 3/31/08 was a low intensity, long duration storm that produced a relatively low volume of rainfall. The resulting basin hydrograph is flat with little elevation change and a brief spike occurring late in the storm. The HEC-HMS storm simulation follows the general characteristics of the storm, but does not precisely match the timing or the observed flatness. The HMS simulation has few subtle spikes in response to the rainfall distribution, however the observed data do not show these spikes. The recession limbs of the modeled data generally match the observed data, with an average recession rate of 0.192 inch/hr. The total area under the modeled data curve is similar, but not identical to the observed data. Therefore the inflow volume estimate is assumed to be a reasonable approximation, but may slightly misrepresent the total volume.

The conductivity of the first flush and lysimeter samples had a wide distribution of values. FF01 had the lowest value of 53 μS/cm, while FF02 and LYS04 had similar values of 247 μS/cm and 212 μS/cm. LYS4 and LYS8 had much higher values of 2,200 μS/cm and 1,837μS/cm. The groundwater samples from MW-1 fluctuated from 553 μS/cm at MW1A to 1110 μS/cm at MW1C down to 652 μS/cm at MW1D and back up to 1026 μS/cm at MW1E. MW-2 was slightly more stable with values of 1077 μS/cm and 1067 μS/cm at MW2A and MW2B, rising to 1190 μS/cm and 1177 μS/cm at MW2C and MW2D, then increasing further to 1497 μS/cm in MW2E. MW-3 had a uniform concentration of 334 μS/cm for samples A through D, then rose to 755 μS/cm at sample E. MW-4 remained steady for samples A through E, and had an average concentration of about 607 µS/cm. The average concentrations of the wells are lowest at MW-3, then MW-4, MW-1 and are highest at MW-2.

FF01 had the lowest chloride concentration of 13.80 mg/l, followed by FF02 with a concentration of 47.25 mg/l. The lysimeter samples varied from 65.21 mg/l at LYS0 to 376.32 mg/l at LYS4 and 309.91 mg/l. MW-1 fluctuated from 130.58 mg/l (MW1B) to 196.02 mg/l (MW1E) with an average of 162 mg/l. The samples from MW-2 and MW-4 were uniform with average concentrations of 290 mg/l and 150 mg/l, respectively. MW-3 had a uniform concentration for samples A-D with an average of 65 mg/l, but increased to 144.11 mg/l at MW3E. The general trends and relative magnitudes of the chloride concentrations are similar to those observed in the conductivity values, especially in the well samples. For instance, the average conductivity of the MW-2 samples is higher than that of MW-4 and the same is observed in the chloride concentrations.

Out of 25 samples for total phosphorus, 44% had concentrations less than 0.25 mg/l. 68% were less than 0.5 mg/l and 80% were less than 1.0 mg/l. 8 samples (32%) had concentrations above 0.5 mg/l and 5 (20%) had concentrations above 1 mg/l. 6 of the 8 samples above 0.5 mg/l, were groundwater samples and 4 of the 5 samples above 1 mg/l were groundwater samples. The non-groundwater samples had generally low concentrations except FF02 (1.41 mg/l) and LYS0 (0.56 mg/l). Samples D and E were high for each well, however MW2B was higher and all the samples from MW-4 had low concentrations. No obvious trend was discernable in the groundwater samples, however MW-4 had the lowest average concentration of 0.18 mg/l, MW-1 and MW-3 had average concentrations of 0.58 and 0.49 mg/l, while MW-2 had the highest average of 0.97 mg/l.

Groundwater elevation monitoring for this storm revealed a quick response from MW-1; small and gradual responses from MW-2 and MW-4, and minimal response from MW-3. The groundwater elevation at MW-1 changed a total of 0.18 ft in 31 hours, while the elevation at MW-2 and MW-4 changed by only 0.04 ft over approximately 90 hours. The continuous groundwater conductivity monitoring showed little fluctuation in the wells in response to this storm. MW-2 had the highest conductivity, with an average of 786 μS/cm, followed by MW-1 with an average of 425 μS/cm and MW-3 at 298 μS/cm. MW-1 showed a minor response to the storm increasing from about 419 μS/cm before the storm to 428 μS/cm after the storm. In contrast, the conductivity of MW-2 remained between 784 μS/cm and 789 μS/cm during and after the storm. The conductivity of MW-3 declined slightly from 298 μS/cm during the storm to 288 μS/cm after the storm. Thus the upgradient well saw a minor increase in conductivity, the site well showed little change and the downgradient well decreased slightly. The groundwater temperature at fluctuated by less than 0.1 degree at each well and no discernable effect is noted at any well. The average temperature at MW-1 and MW-3 was 13.7 ^{o}C and 13.5 ^{o}C. MW-2 had an average temperature of 10.6 ^{o}C. Thus the upgradient and downgradient wells were warmer than the site well.

3.1.5 April 3rd 2008

3.1.5.1 Storm Summary

The April 3rd 2008 storm event produced 0.53 inch of precipitation in 11 hours and 10 minutes. The maximum 5 minute and 30 minute intensity was 0.24 and 0.14 in/hr, respectively. The HEC-HMS model indicates that a total of 1146 ft^3 of runoff entered the site. Measured data indicate that runoff was contained by the site and either infiltrated or lost to evapotranspiration. Figure 27 shows the results of the HEC-HMS model in addition to the observed rainfall and basin water elevation.

A total of 30 water quality samples were collected during the storm. Table 6 presents the results of the sampling. Figures 28, 29 and 30 present the results for the conductivity, chloride and total phosphorus analyses. Figure 31 presents a hydrograph of the groundwater elevations during and after the storm, while Figures 32 and 33 show the fluctuation in conductivity and temperature in MW-1, 2 and 3 over the course of the storm.

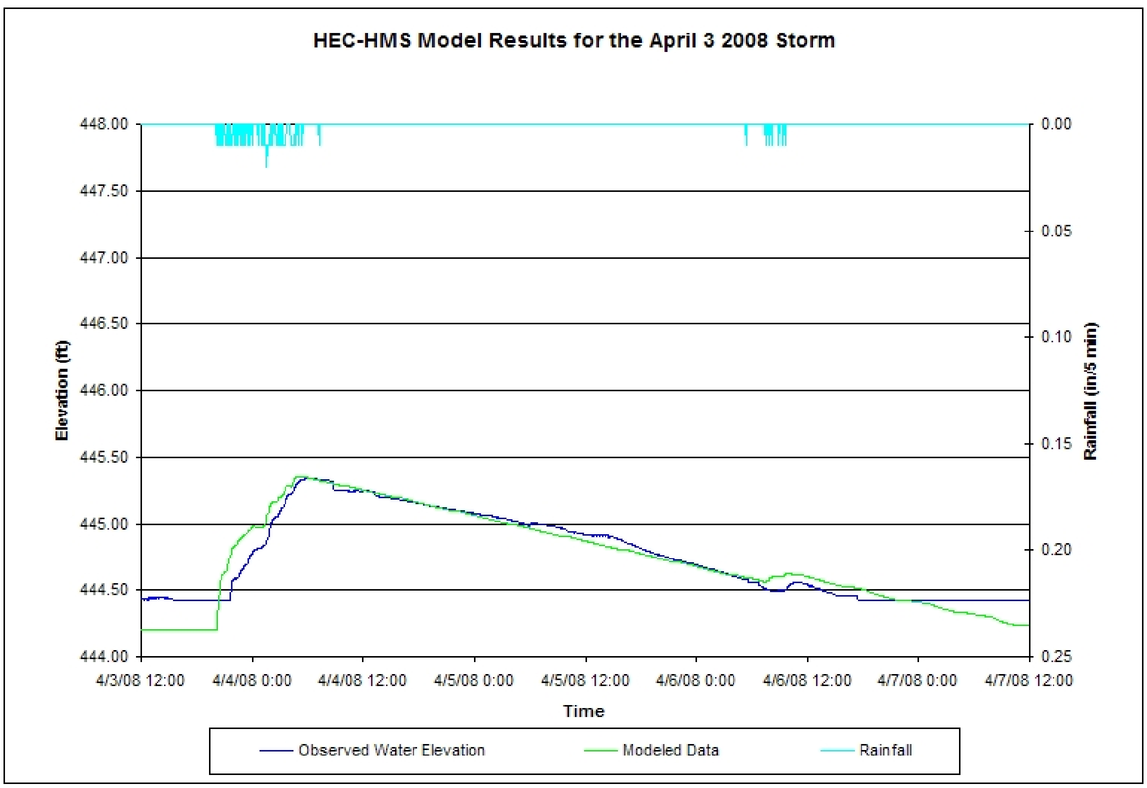

Figure 27: April 3rd, 2008 HEC-HMS Model Results

Table 6: Water Quality Results from the April 3rd, 2008 Storm Event

Location	Sample Time	pH	Cond	TSS	TDS	Nitro	NO2	NO3	Phosp	PO4	Chloride
AS01	4/4/08 2:00	6.20	107	N	N	U	0.6230	U	0.72	2.1380	14.94
AS02	4/4/08 5:00	4.60	89.0	14.5	40.0	U	0.4830	U	0.72	2.1590	22.48
AS03	4/4/08 8:00	4.80	103	12.7	66.9	U	0.4830	U	0.65	1.5400	24.71
AS04	4/4/08 11:00	5.90	36.2	8.8	27.4	U	0.4830	U	0.38	1.5440	5.90
AS05	4/4/08 14:00	6.50	92.4	1.6	62.2	U	0.5530	U	0.56	8.0400	10.32
AS06	4/4/08 17:00	3.70	206	12.6	57.4	2.60	0.5530	U	0.63	7.4900	39.40
FF01	-	6.90	112	U	51.7	U	0.7970	U	0.78	U	10.56
FF02	-	7.20	29.8	U	5.6	U	0.4850	U	0.34	U	2.19
LYS4	-	6.50	2500	N	5.6	U	0.3810	U	0.15	U	381.88
LYS8	-	6.60	1814	N	755.2	U	0.3810	U	0.38	U	364.86
MW1A	4/3/08 15:45	5.70	522	N	N	N	N	N	0.10	N	102.94
MW1B	4/4/08 9:45	5.70	519	N	N	N	N	N	0.18	N	102.94
MW1C	4/4/08 14:15	5.80	527	N	N	N	N	N	0.30	N	119.18
MW1D	4/4/08 16:30	5.80	529	N	N	N	N	N	U	N	117.07
MW1E	4/5/08 12:00	6.30	534	N	N	N	N	N	0.21	N	117.68
MW2A	4/3/08 15:45	5.50	1059	N	N	N	N	N	0.27	N	301.73
MW2B	4/4/08 9:45	5.40	1077	N	N	N	N	N	3.36	N	304.04
MW2C	4/4/08 14:15	5.20	1064	N	N	N	N	N	0.47	N	286.61
MW2D	4/4/08 16:30	4.10	1086	N	N	N	N	N	0.30	N	293.39
MW2E	4/5/08 12:00	5.90	1072	N	N	N	N	N	0.10	N	284.65
MW3A	4/3/08 15:45	6.20	329	N	N	N	N	N	0.35	N	29.35
MW3B	4/4/08 9:45	5.40	330	N	N	N	N	N	0.26	N	100.99
MW3C	4/4/08 14:15	5.70	333	N	N	N	N	N	0.17	N	72.16
MW3D	4/4/08 16:30	5.90	329	N	N	N	N	N	0.12	N	55.29
MW3E	4/5/08 12:00	6.00	329	N	N	N	N	N	U	N	49.71
MW4A	4/3/08 15:45	6.60	613	N	N	N	N	N	0.30	N	138.76
MW4B	4/4/08 9:45	6.20	610	N	N	N	N	N	0.31	N	148.16
MW4C	4/4/08 14:15	6.40	607	N	N	N	N	N	0.26	N	145.71
MW4D	4/4/08 16:30	6.20	610	N	N	N	N	N	0.24	N	144.80
MW4E	4/5/08 12:00	6.10	608	N	N	N	N	N	U	N	143.14

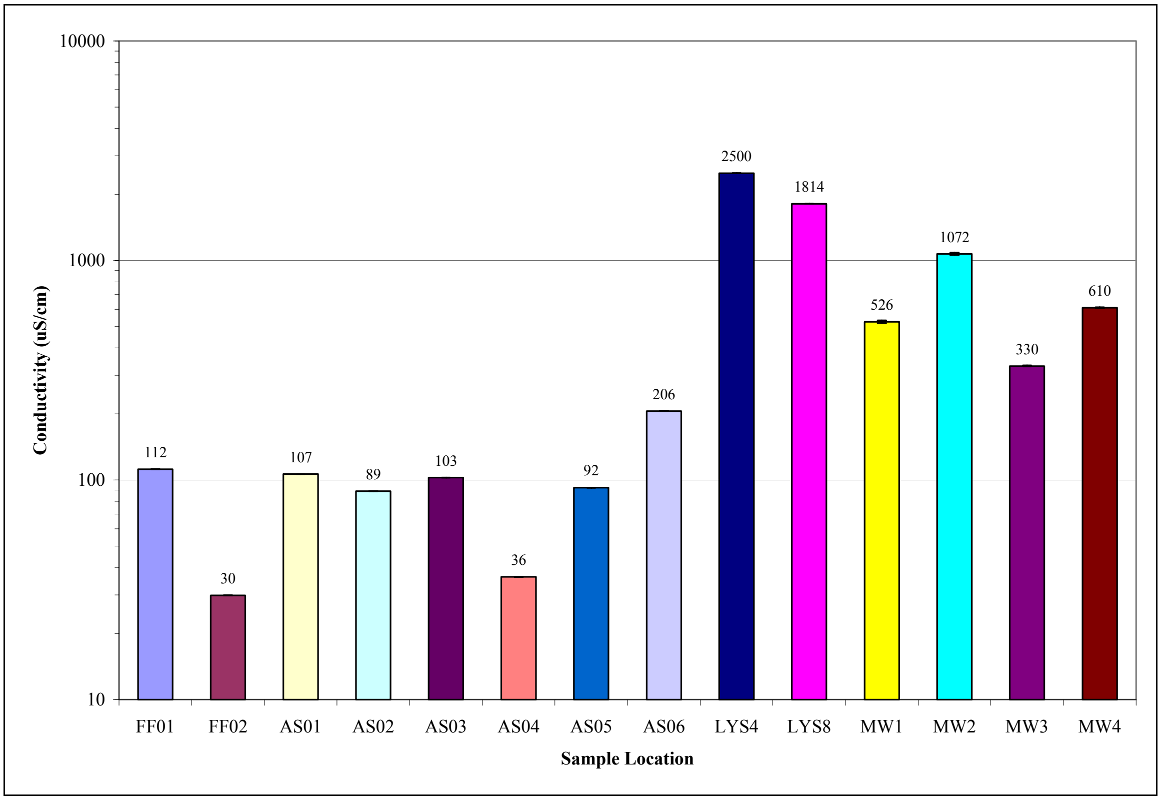

Figure 28: April 3rd, 2008 Conductivity Results

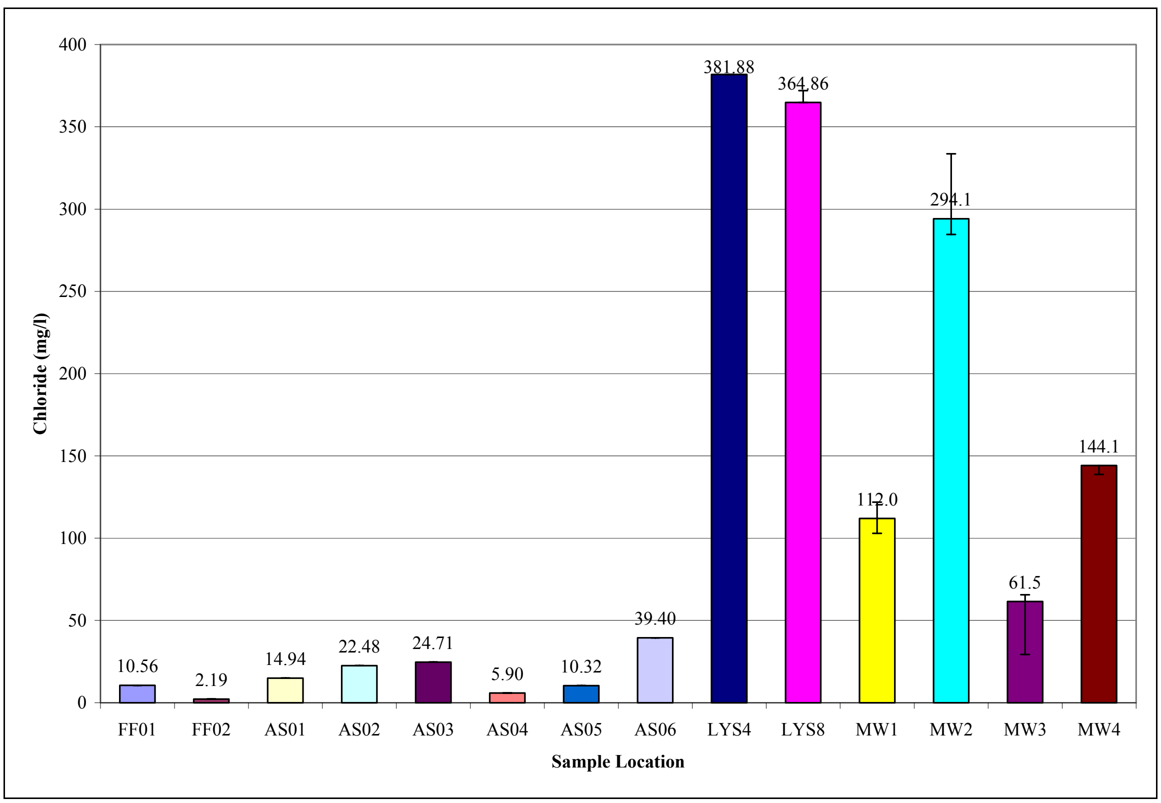

Figure 29: April 3rd, 2008 Chloride Results

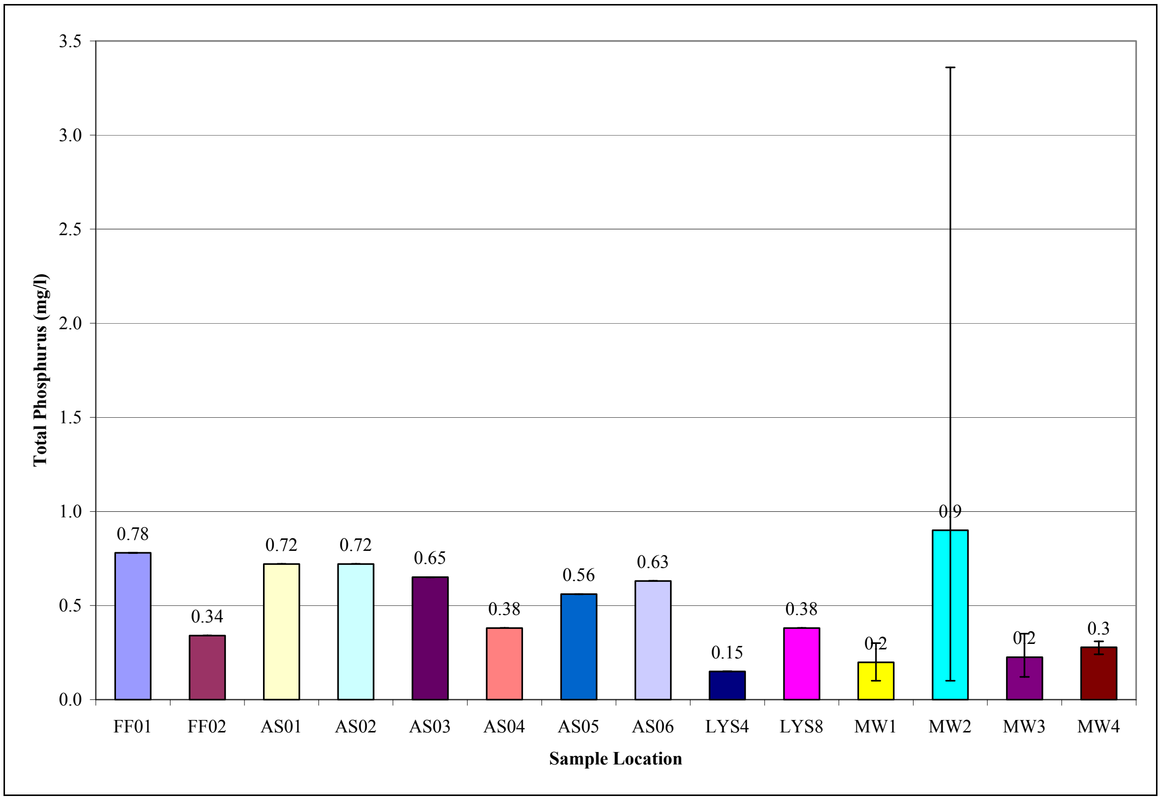

Figure 30: April 3rd, 2008 Total Phosphorus Results

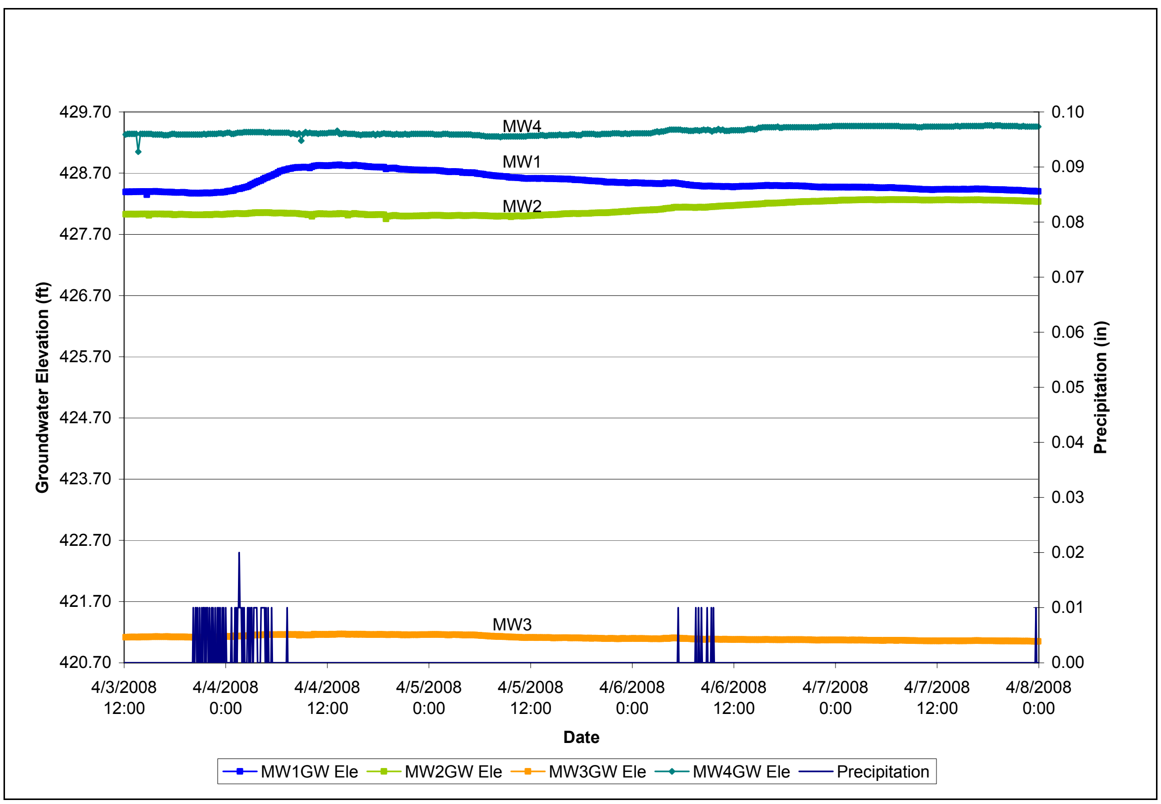

Figure 31: April 3rd, 2008 Groundwater Hydrograph

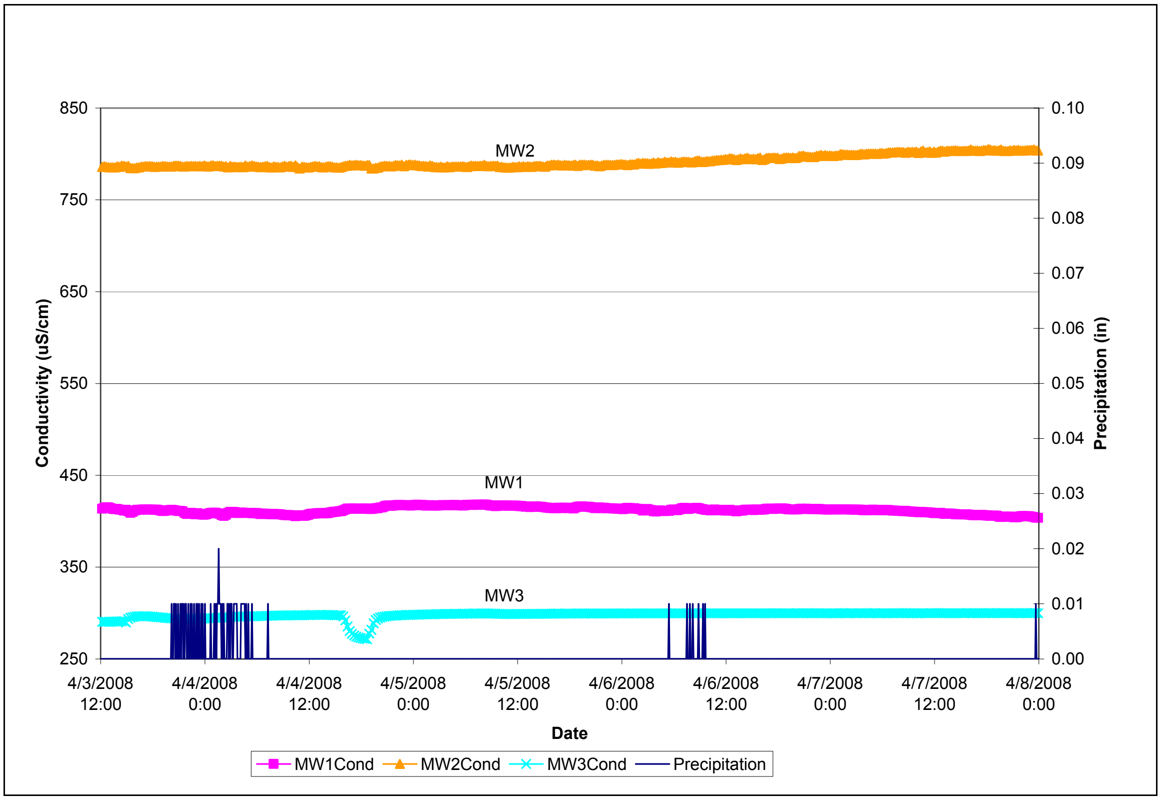

Figure 32: April 3rd, 2008 Groundwater Conductivity

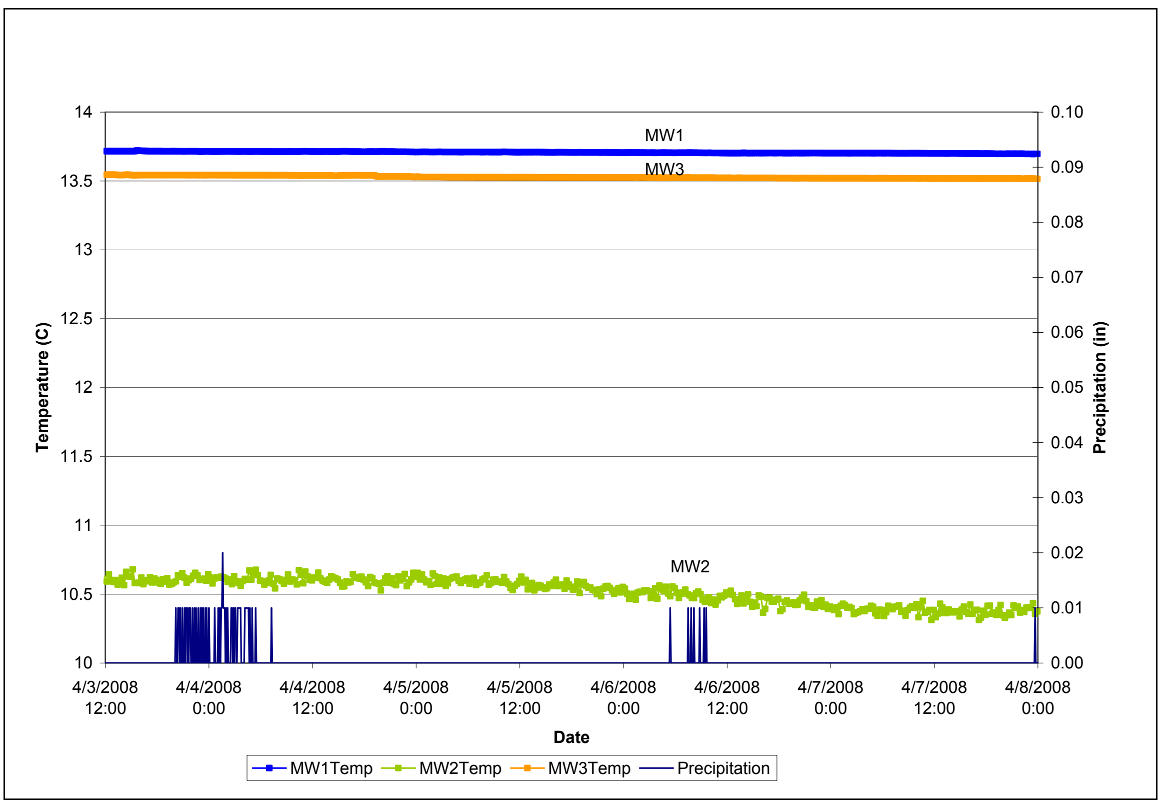

Figure 33: April 3rd, 2008 Groundwater Temperature

3.1.5.2 Sampling Results

The 4/3/08 storm was a well distributed, low intensity, medium duration, center peaking storm. Approximately 50% of the rainfall occurred in the first 5 hours and 20 minutes, while the remaining 50% occurred in 5 hours and 50 minutes. The observed basin hydrograph rises steadily to a peak and recedes at a uniform rate of approximately 0.172 in/hr. The HEC-HMS simulation produced a hydrograph that closes approximates the observed data. The modeled data rises slightly more abruptly, but matches the peak well. The modeled recession rate is nearly identical to the observed data, with a minor exception resulting from a brief slope change in the observed data. Based on the close match of the modeled versus observed data, it is assumed that the total inflow volume predicted is an accurate approximation.

The conductivity analyses for the autosamples indicate variation over the course of the storm. The first three samples were similar, ranging from 89 μS/cm to 107 μS/cm. The fourth sample decreased to 36 μS/cm, the fifth sample then rose to 92 μS/cm and the sixth sample rose abruptly to 206 μS/cm. FF01 was similar to the initial autosamples with a value of 112.1 μS/cm, but FF02 had a lower value of 29.8 μS/cm. The lysimeter samples LYS4 and LYS8 both had high values of 2500 μS/cm and 1814 μS/cm, respectively. The groundwater samples all had uniform concentrations with little variation. The average values for the groundwater samples are as follows: 526 μS/cm at MW-1, 1072 μS/cm at MW-2, 330 μS/cm at MW-3 and 610 μS/cm at MW-4. Thus the wells near the site had the higher values, while the downgradient well had the lowest concentration and the upgradient well had a moderate value.

The chloride results for the autosamples and the first flush samples are all relatively low. To some extent the results correlate to the conductivity results, for instance, AS06 has a higher chloride concentration than the other samples just as the conductivity was higher. Similarly AS04 and FF02 had the lowest chloride concentrations and lowest conductivity values. Additionally AS01-AS03 and FF01 have similar conductivity values and similar chloride values. The lysimeter samples had the highest chloride concentrations of 381.88 mg/l and 364.86 mg/l at LYS4 and LYS8, respectively. The groundwater samples from MW-1, 2, and 4 had uniform chloride results, with averages of 112, 294 and 144 mg/l, respectively. MW-3 had more variation, ranging from 29.35 mg/l in MW3A to 100.99 mg/l in MW3B. Samples C-E decreased from 72.16mg/l to 49.71 mg/l. Review of Figures 28 and 29 show that the general trends observed in the conductivity analyses are also seen in the chloride results, for instance the samples with the highest or lowest conductivity are also the samples with highest or lowest chloride concentrations. The average concentrations of the wells are lowest at MW-3 (61.5 mg/l), followed by MW-1 (112 mg/l), MW-4 (144 mg/l) and MW-2 (294 mg/l).

Out of the 27 total phosphorus samples 30% were below 0.25 mg/l, 74% were below 0.5 mg/l and 96% were below 1.0 mg/l. The total phosphorus concentrations of the autosamples ranged from 0.38 mg/l at AS04 to 0.72 mg/l at both AS01 and AS02, with an average concentration of 0.61 mg/l. The first flush samples had a similar range of 0.78 mg/l at FF01 and 0.34 mg/l at FF02. The lysimeter samples had a lower average with LYS4 containing a concentration of 0.15 mg/l and LYS8 equal to 0.38 mg/l. The groundwater samples had uniformly low concentrations all below 0.5 mg/l, with the exception of MW2B where the concentration was 3.36 mg/l. No trends in total phosphorus concentration were observed in the groundwater samples, except at MW-3, where the low concentration gradually decreased from 0.35 mg/l at MW3A to non-detect at MW3E.

As can be seen in Figure 31, the groundwater elevation at MW-1 rose shortly after the storm. MW-2 and MW-4 had delayed but noticeable elevation changes. The response at MW-3 was less noticeable, however upon scrutiny it can be seen that the groundwater elevation rose approximately 0.05 ft in 18 hours. The groundwater elevation at MW-1 rose 0.46 ft in 17 hours, MW-2 rose 0.27 ft in 83 hours and MW-4 rose 0.18 ft in 94 hours. The overall groundwater hydraulic gradient trends from MW-4 at 429.35 ft to MW-1 at 428.70 ft to MW-2 at 428.20 ft to MW-3 at 421.15 ft. This gradient indicates a flow direction to the northwest with a steep gradient between MW-2 and MW-3.

Review of the groundwater conductivity monitoring indicates a gradual increase at MW-1 and a delayed but gradual increase at MW-2. MW-3 shows a rapid decrease, however it is believed that this abrupt change is due to disturbances caused by groundwater sampling and furthermore that the actual response is a slight increase in conductivity. As an overview, it can be seen that MW-2 has the highest conductivity, approximately twice the value of MW-1 and over twice that of MW-3. Figures 34, 35 and 36, present the conductivity and groundwater elevations at wells at a finer resolution than presented above.

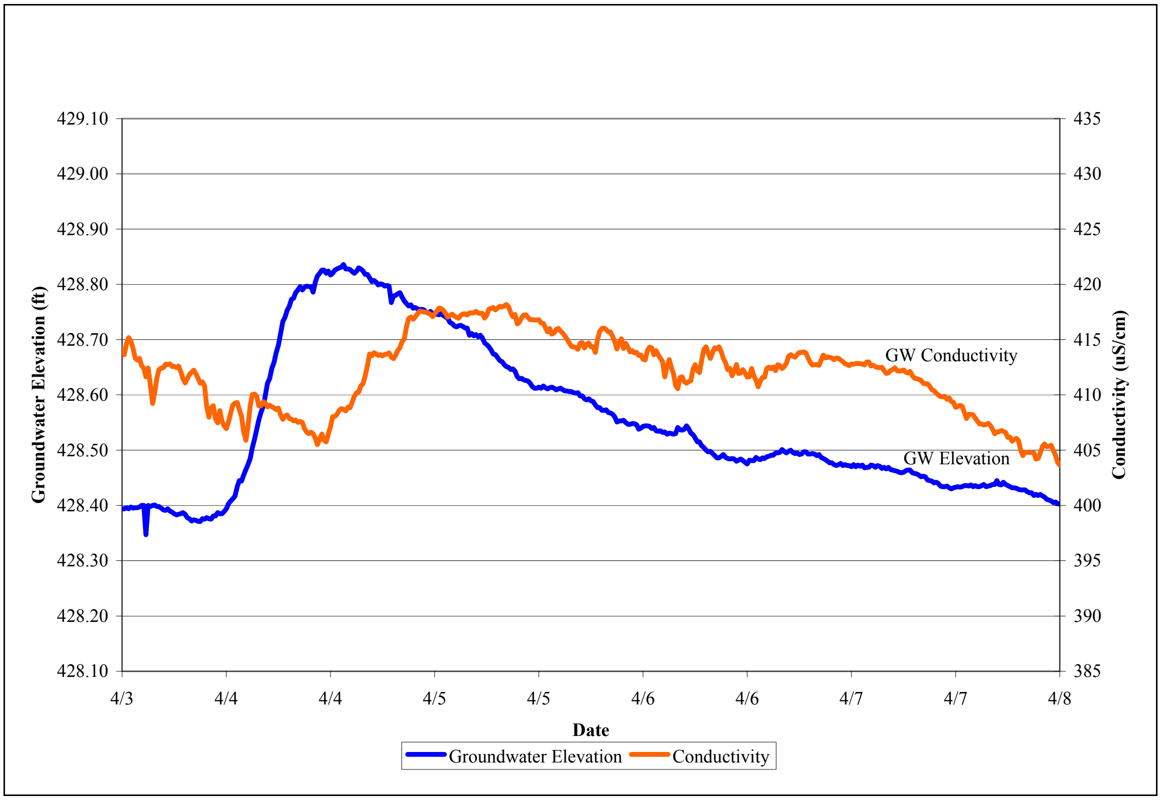

Figure 34: April 3rd, 2008 Groundwater Hydrograph and Conductivity for MW-1

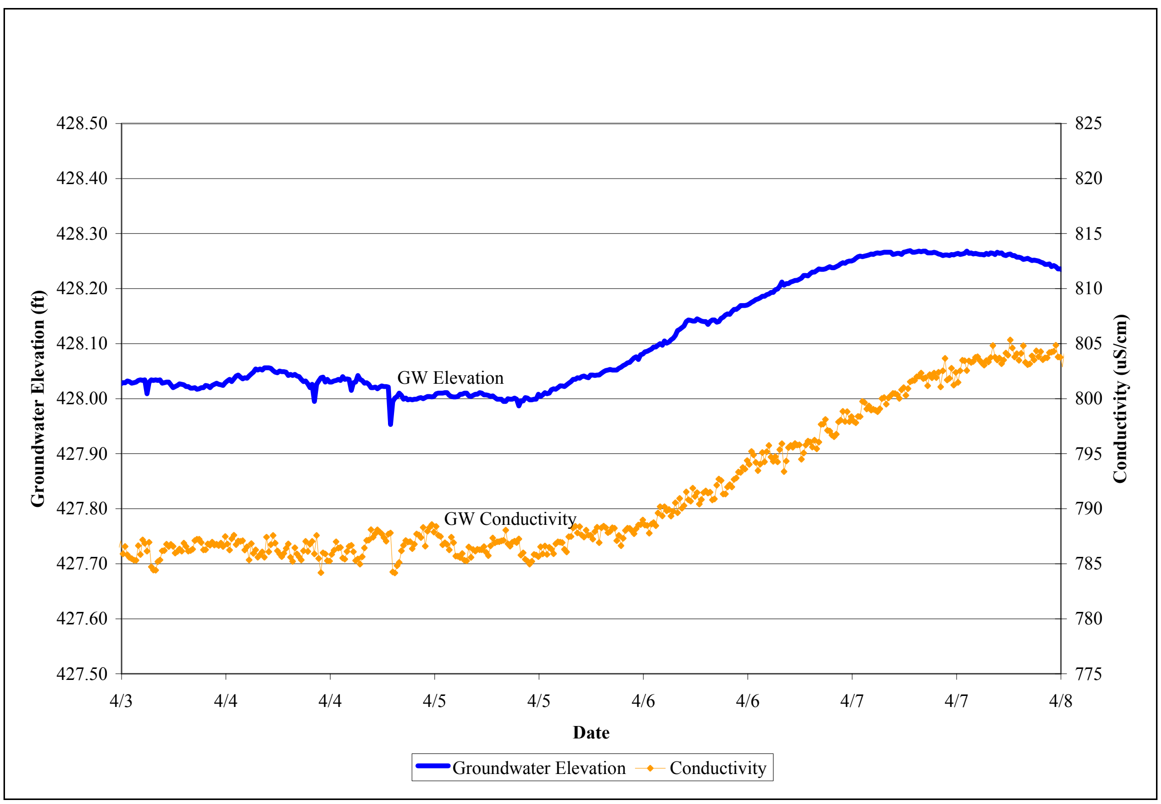

Figure 35: April 3rd, 2008 Groundwater Hydrograph and Conductivity for MW-2

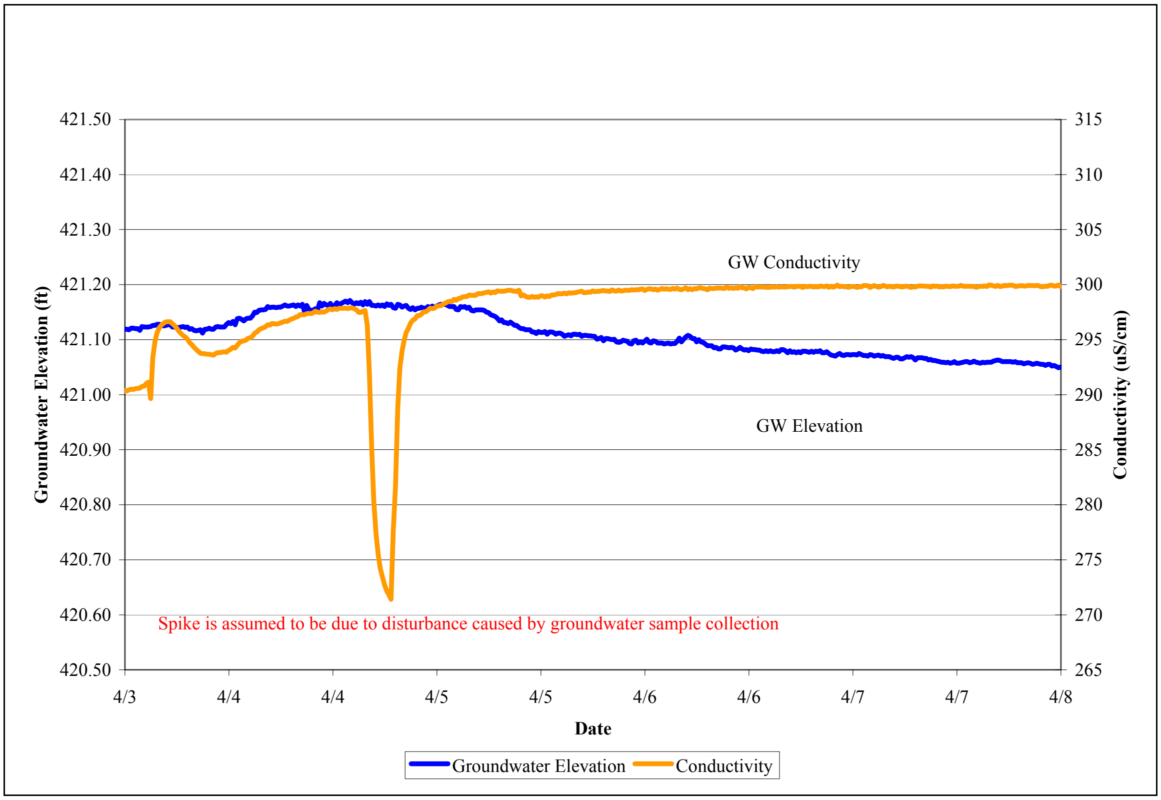

Figure 36: April 3rd, 2008 Groundwater Hydrograph and Conductivity for MW-3

The results of the groundwater temperature monitoring, presented in Figure 33, show minor changes in temperature over the duration of the storm. MW-1 and MW-3 have similar temperatures of 13.71 ^{o}C and 13.51 ^{o}C and remain consistent during and after the storm. MW-2 has an average temperature of approximately 10.53 ^{o}C and exhibits minor fluctuation. Review of the temperature data on a finer scale reveals that MW-1 and MW-3 show no detectable response to the storm, while MW-2 shows a small but noticeable temperature decrease of 0.22 ^{o}C in response to the storm.

3.1.6 April 11th 2008

3.1.6.1 Storm Summary

The 4/11/08 storm produced 0.55 inch of precipitation in 3 hours and 40 minutes. The maximum 5 minute and 30 minute intensity was 0.60 and 0.38 in/hr, respectively. Simulation of the storm with HEC-HMS indicates that a total of 1062 ft^3 of runoff entered the site. Measured data indicate that runoff was contained by the site and either infiltrated or lost to evapotranspiration. Figure 37 shows the results of the HEC-HMS model in addition to the observed rainfall and basin water elevation.

A total of 33 water quality samples were collected during the 4/11/08 storm and their results are presented in Table 7. Figures 38, 39 and 40 present the results for the conductivity, chloride and total phosphorus analyses. Figure 41 presents a hydrograph of the groundwater elevations during and after the storm, while Figures 42 and 43 show the fluctuation in conductivity and temperature in MW-1, 2 and 3 over the course of the storm.

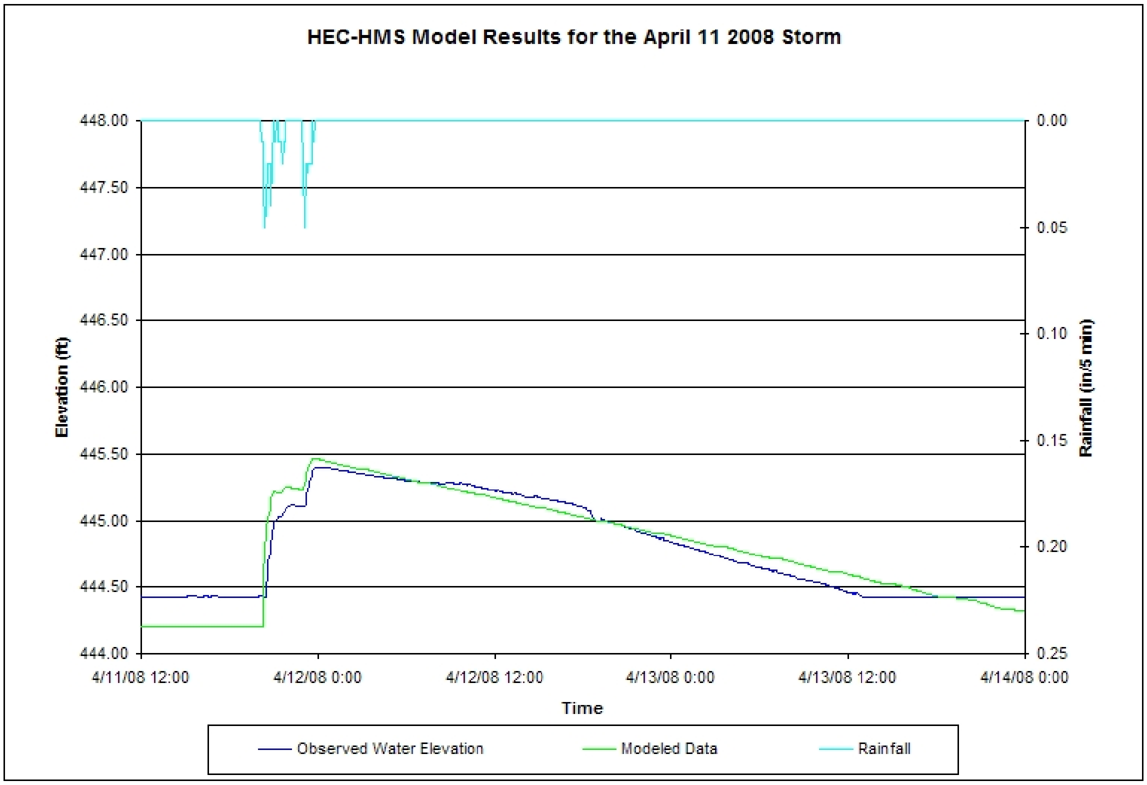

Figure 37: April 11th HEC-HMS Model Results

Table 7: Water Quality Results from the April 11th, 2008 Storm Event

Location	Sample Time	pH	Cond	TSS	TDS	Nitro	NO2	NO3	Phosp	PO4	Chloride
AS01	4/11/08 22:17	6.50	68.2	23.2	83.6	U	0.8800	U	0.55	0.1500	22.29
AS02	4/12/08 1:17	6.50	67.2	3.7	89.1	U	0.8800	U	0.50	0.1210	22.69
AS03	4/12/08 4:17	6.50	75.6	15.7	47.2	U	0.9830	U	0.63	0.1470	22.89
AS04	4/12/08 7:17	3.50	200.0	34.9	93.6	2.40	0.9830	U	0.73	0.1330	54.23
AS05	4/12/08 10:17	4.10	116.3	40.9	65.1	3.00	0.9830	U	0.70	0.0900	49.69
AS06	4/12/08 13:17	5.60	75.8	40.3	94.1	U	1.0860	U	0.65	0.0920	33.37
AS07	4/12/08 16:17	5.70	99.6	54.8	213.0	U	1.0860	U	1.07	0.1440	50.59
AS08	4/12/08 19:17	6.20	91.3	84.4	107.2	U	1.0860	U	0.67	0.0560	50.69
FF01	-	5.40	53.3	645.6	38.1	3.10	0.8800	U	1.08	0.1090	26.12
FF02	-	5.90	106.4	1488.9	68.7	4.00	0.8800	U	2.04	0.1090	21.91
LYS0	-	7.70	100.5	N	94.0	U	1.1900	U	0.52	U	47.36
LYS4	-	6.50	2310.0	N	1344.0	U	1.2930	U	0.16	U	318.55
LYS8	-	5.88	1337.0	N	697.8	U	1.1900	U	0.44	U	325.04
MW1A	4/11/08 16:00	5.80	506.0	N	N	N	N	N	4.00	N	209.29
MW1B	4/12/08 8:45	5.50	505.0	N	N	N	N	N	0.16	N	117.35
MW1C	4/12/08 14:15	5.50	512.0	N	N	N	N	N	0.27	N	127.40
MW1D	4/12/08 19:40	5.60	692.0	N	N	N	N	N	1.68	N	375.90
MW1E	4/13/08 11:00	5.80	N	N	N	N	N	N	0.37	N	117.20
MW2A	4/11/08 16:00	5.10	1153.0	N	N	N	N	N	0.22	N	292.88
MW2B	4/12/08 8:45	5.30	1117.0	N	N	N	N	N	0.16	N	290.61
MW2C	4/12/08 14:15	4.90	1108.0	N	N	N	N	N	0.06	N	225.30
MW2D	4/12/08 19:40	5.00	1103.0	N	N	N	N	N	0.19	N	292.88
MW2E	4/13/08 11:00	5.60	N	N	N	N	N	N	0.30	N	290.61
MW3A	4/11/08 16:00	5.60	356.0	N	N	N	N	N	0.42	N	70.94
MW3B	4/12/08 8:45	5.50	339.0	N	N	N	N	N	0.25	N	70.44
MW3C	4/12/08 14:15	5.43	337.0	N	N	N	N	N	0.24	N	68.72
MW3D	4/12/08 19:40	5.20	332.0	N	N	N	N	N	0.15	N	68.41
MW3E	4/13/08 11:00	5.80	N	N	N	N	N	N	0.20	N	68.82
MW4A	4/11/08 16:00	6.00	613.0	N	N	N	N	N	0.23	N	158.01
MW4B	4/12/08 8:45	5.80	619.0	N	N	N	N	N	0.14	N	158.29
MW4C	4/12/08 14:15	6.00	617.0	N	N	N	N	N	0.15	N	223.03
MW4D	4/12/08 19:40	6.00	614.0	N	N	N	N	N	2.90	N	202.63
MW4E	4/13/08 11:00	6.20	N	N	N	N	N	N	0.39	N	162.68

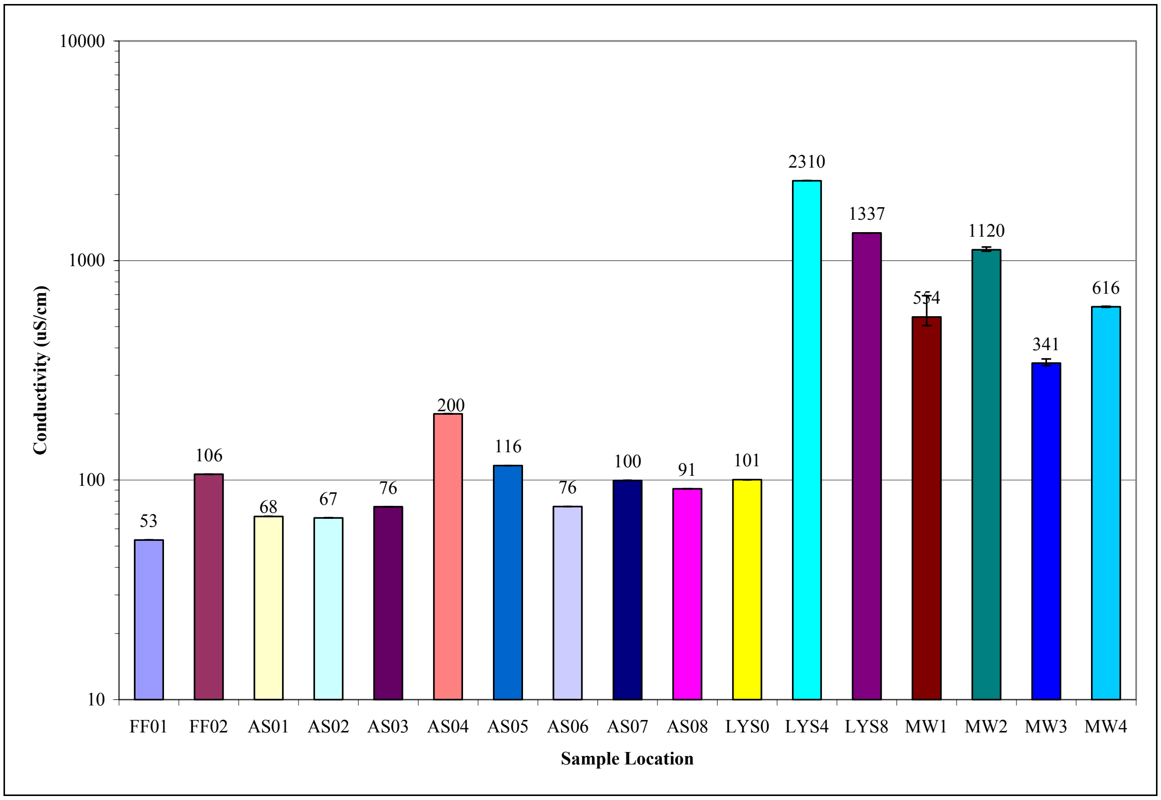

Figure 38: April 11th, 2008 Conductivity Results

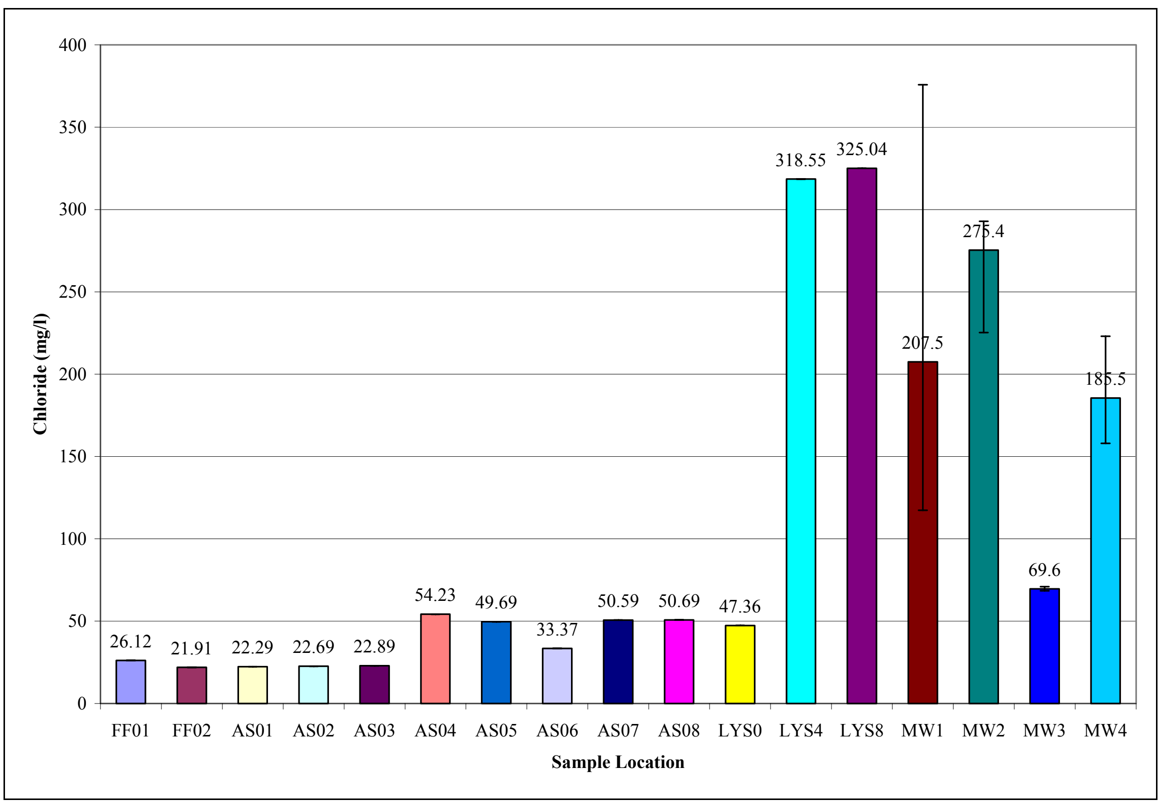

Figure 39: April 11th, 2008 Chloride Results

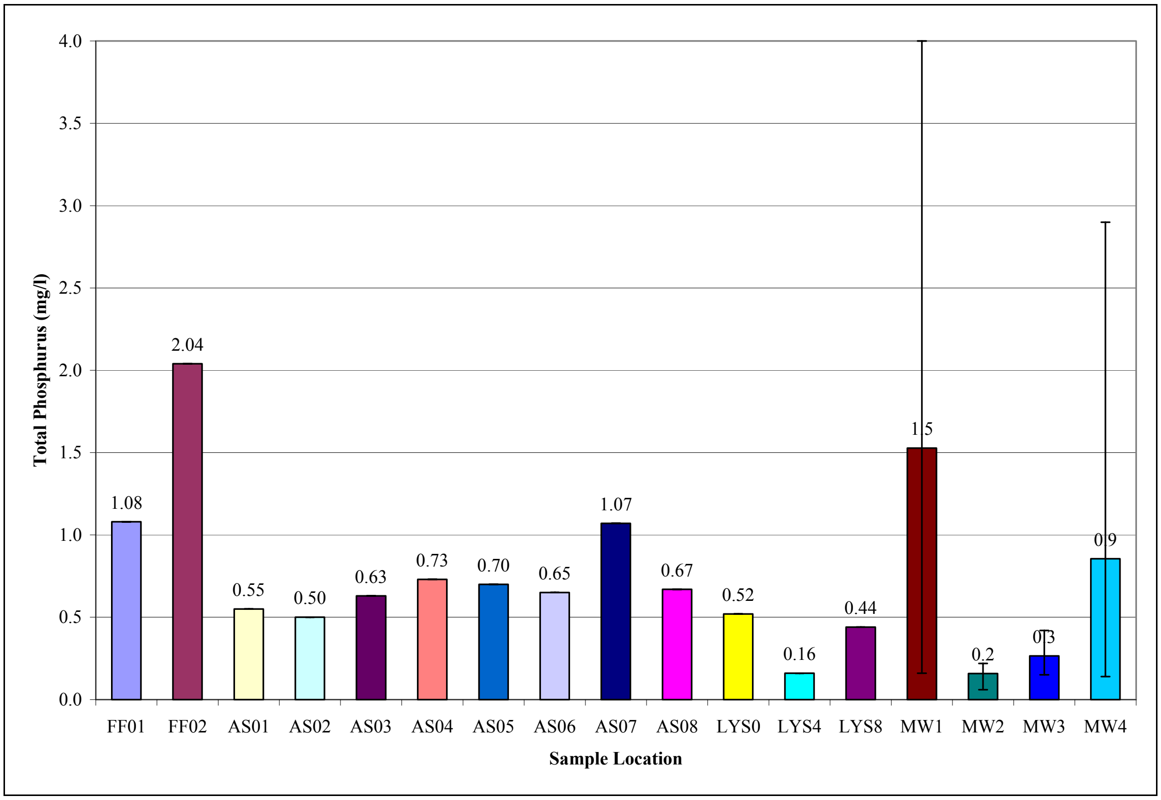

Figure 40: April 11th, 2008 Total Phosphorus Results

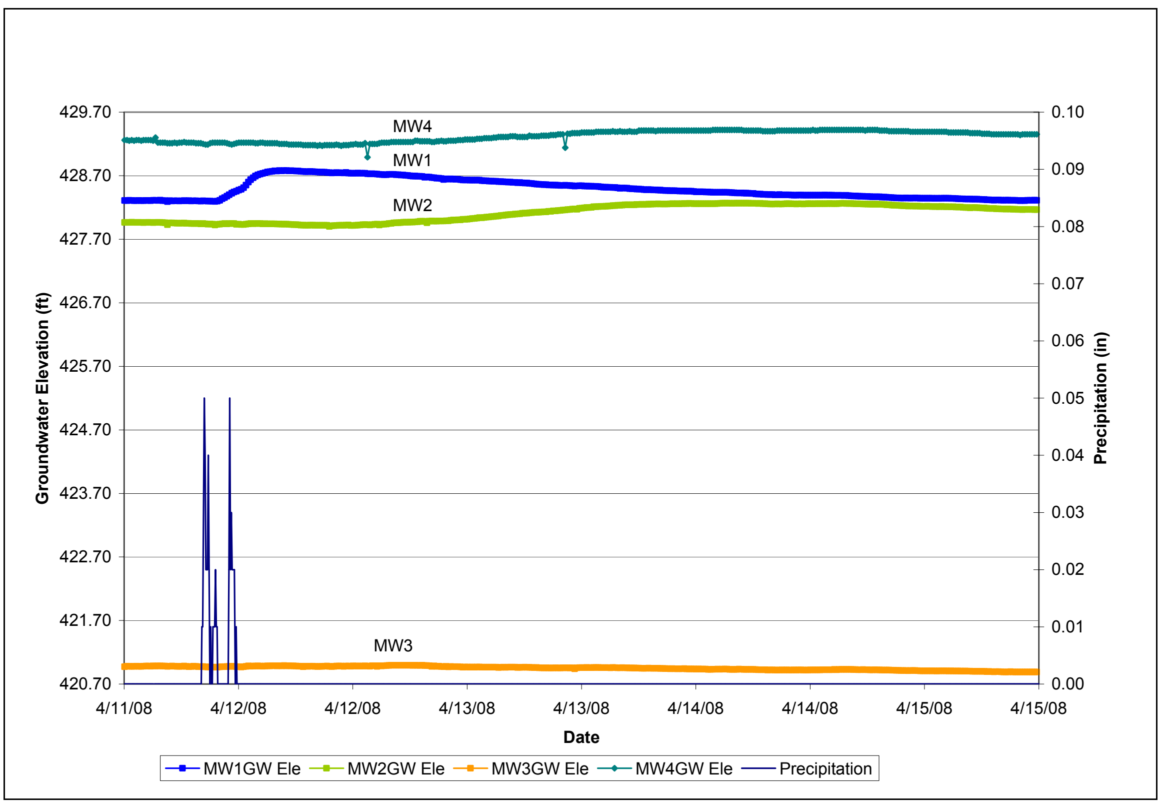

Figure 41: April 11th, 2008 Groundwater Hydrograph

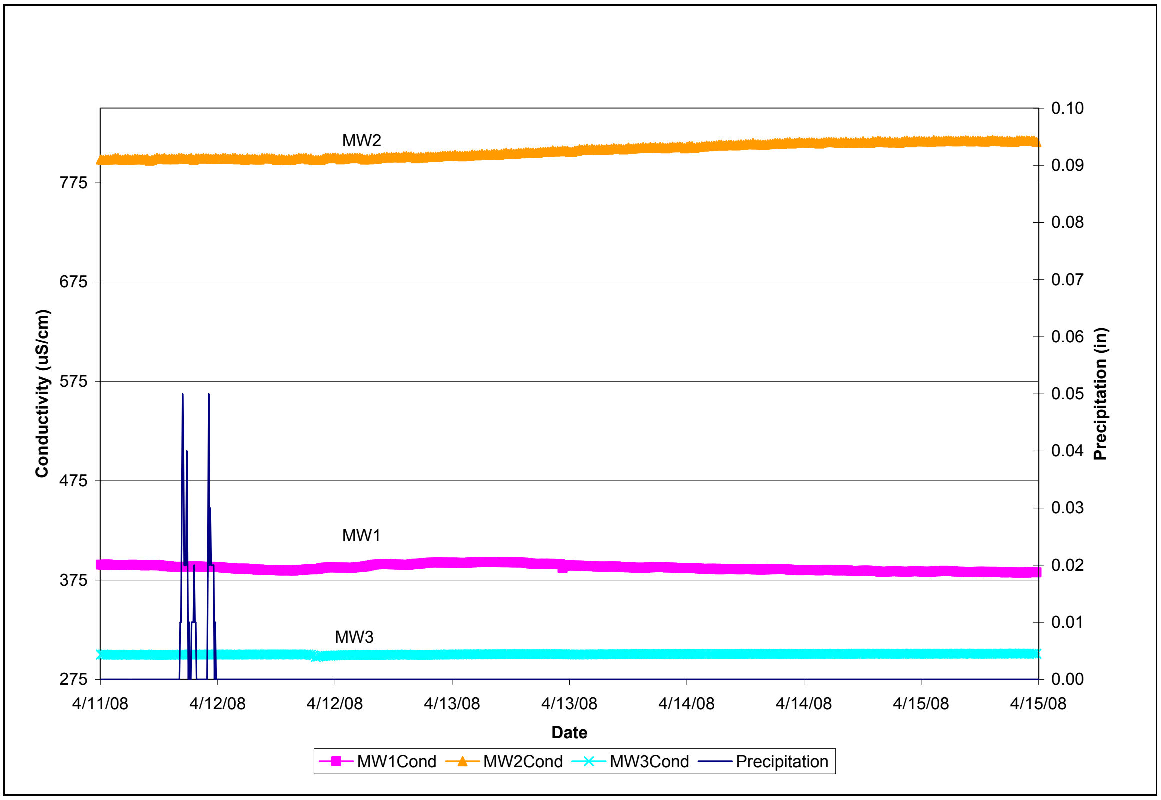

Figure 42: April 11th, 2008 Groundwater Conductivity

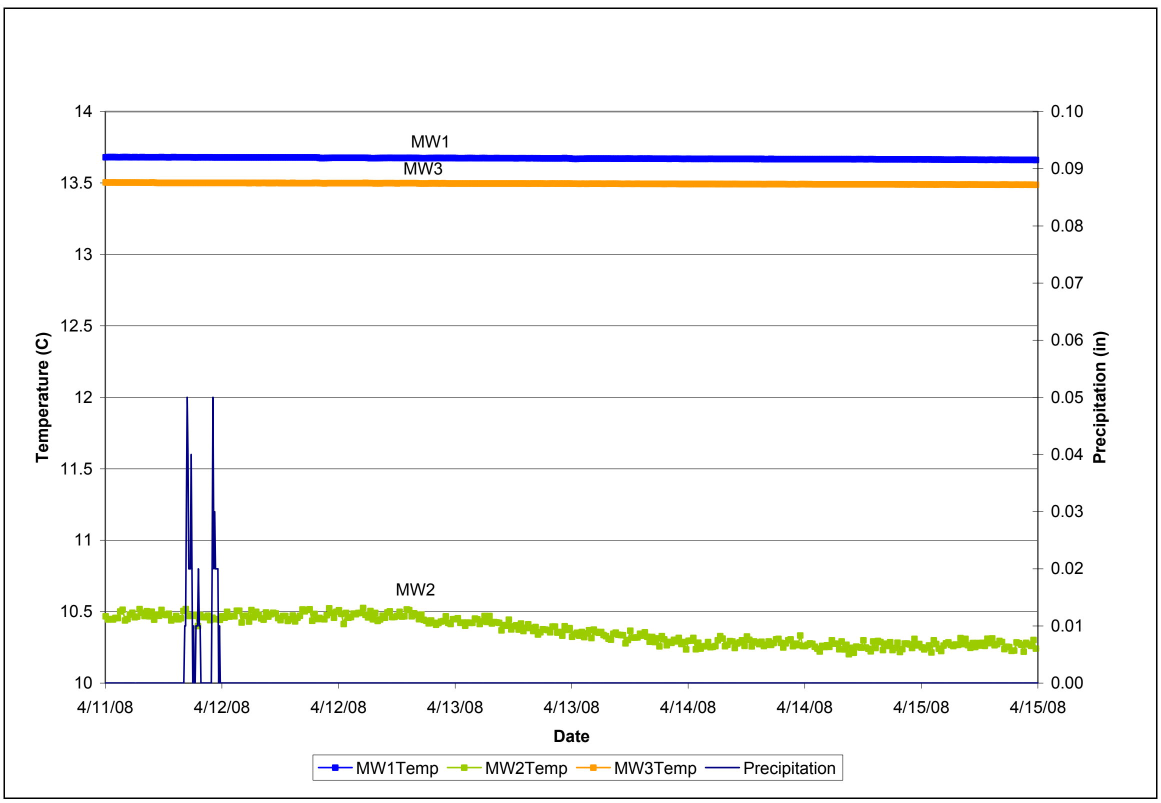

Figure 43: April 11th, 2008 Groundwater Temperature

3.1.6.2 Sampling Results

Compared to the other sampled storms the 4/11/08 event had a short duration with a high intensity. The observed basin hydrograph rose steadily in response to the rain and receded at an average rate of 0.335 in/hr. The HEC-HMS simulation produced a hydrograph that closely matches the observed data. The modeled data slightly overestimates the peak elevation, differs slightly in the timing and has a more linear recession, but overall the model produces a close approximation. Therefore it is assumed that the predicted inflow volume is accurate.

The conductivity of the autosamples was initially low in the first three samples, then rose to a peak in the fourth sample. The remaining autosamples decrease from the peak but are all higher than the initial values. FF01 had a low conductivity of 53.3 μS/cm, while FF02 was approximately twice as high with a value of 106.4 μS/cm. The shallow lysimeter had conductivity of 100.5 μS/cm, which is similar to the average of the autosamples and the first flush samples. The lysimeter samples from 4 and 8 ft had significantly higher conductivity values of 2310 μS/cm and 1337 μS/cm, respectively. Similar to previous events the groundwater samples had uniform values at each well, with the exception of MW-1 where the final sample had a higher conductivity value. The average conductivity at MW-1 was 554 μS/cm, MW-2 was 1120 μS/cm, MW-3 was 341 μS/cm and MW-4 was 616 μS/cm. Thus, for this event MW-2 had significantly higher conductivity than the other wells. MW-3 had the lowest conductivity and MW-1 and MW-4 had similar conductivity, although MW-1 was lower.

The results of the chloride analysis follow the general trends of the conductivity analyses; however the relationship is not directly proportional. The first three autosamples had low concentrations, sample AS04 had the highest autosample concentration, followed by ASO5. The chloride concentration then decreased at AS06 and rose back up in AS07 and AS08. FF01 and FF02 did not follow the conductivity trend, since FF01 had a greater chloride concentration than FF02; however both samples had low concentrations of 26.12 mg/l and 21.91 mg/l, respectively. Similar to the conductivity analysis, LYS0 had a low chloride concentration, while LYS4 and LYS8 had much higher concentrations of 318.55 mg/l and 325.04 mg/l. However, LYS4 had a higher conductivity than LYS8. The chloride results for the groundwater samples had more variability than the conductivity results; but in general the wells had similar values. MW-1 showed the most variability with concentrations of 209.29, 117.35, 127.40, 375.90 and 117.20 mg/l for samples MW1A-MW1E respectively. MW-2 had less variability, samples A,B,D and E were similar with an average concentration of 291.74 mg/l while sample C had a concentration of 225.30 mg/l. MW-3 had uniform concentrations with an average of 69.46 mg/l. Finally, at MW-4 samples A, B and E were similar with an average of 159.66 mg/l, but samples C and D had higher concentrations of 223.03 and 202.63 mg/l.

Of the 33 samples analyzed for total phosphorus, 36% were below 0.25 mg/l, 58% were below 0.5 mg/l and 82% were below 1.0 mg/l. The total phosphorus concentrations of the autosamples were all above 0.50 mg/l, with an average 0.69 mg/l. Sample AS07 had the highest concentration of 1.07 mg/l, the other samples ranged from 0.50 mg/l at AS02 to 0.73 mg/l at AS04. The first flush samples were both above 1mg/l; FF01 was 1.08 mg/l and FF02 had a concentration of 2.04 mg/l. The lysimeter samples varied slightly with a range of 0.52 mg/l at LYS0 to 0.16 mg/l at LYS4. MW-1 had significant variation ranging from >4.0 mg/l at MW1A to 0.16 mg/l at MW1B. Samples MW1C and MW1E were both below 0.5 mg/l, but MW1D was 1.68 mg/l. The samples from MW-2 and MW-3 were all below 0.5 mg/l. Both wells had similar trends, starting with the highest concentrations, decreasing to a minimum, then increasing to a value slightly lower than the initial value. MW-4 had 4 samples with concentrations below 0.4 mg/l, but MW4D contained a concentration of 2.90 mg/l. The average total phosphorus concentrations in the well samples were lowest at MW-2 (0.19 mg/l), then MW-3 (0.25 mg/l), MW-4 (0.76 mg/l) and highest at MW-1 (1.30 mg/l).

Groundwater elevation monitoring for the 4/11/08 shows a quick response from MW-1, slow gradual responses from MW-2 and MW-4 and a slight response from MW-3 occurring between MW-1 and MW-2. The hydraulic gradient ranged from MW-4 to MW-1 to MW-2 to MW-3. MW-1 had a total increase in groundwater elevation of 0.48 ft in 18 hours, MW-2 rose 0.35 ft in 55 hours, MW-3 rose 0.04 in 21 hours and MW-4 increased 0.25 ft in 54 hours. The hydraulic gradient indicates a flow direction to the northwest with a steep gradient between MW-2 and MW-3.

The groundwater conductivity monitoring showed an increase in conductivity at each well in response to the storm. The effects were first noticeable at MW-1, then MW-3 and finally at MW-2. MW-2 showed the greatest fluctuation; increasing from approximately 800 μS/cm to 817 μS/cm. MW-1 increased from 384 μS/cm to 393 μS/cm and MW-3 changed from 300 μS/cm to 301 μS/cm. MW-2 had the highest conductivity, followed by MW-1 then MW-3, which both had similar values.

Groundwater temperature monitoring indicated very minor influence from the storm event. The temperatures at MW-1 and MW-3 showed a constant slope prior to, during and after the storm, thus while both wells have slightly decreasing temperatures, it does not appear that the storm event caused a change in the slope temperature graph. The temperature graph from MW-2 indicates a change in slope in response to the storm. The temperature at MW-2 decreased from 10.47 ^{o}C to 10.25 ^{o}C.

3.1.7 May 27th 2008

3.1.7.1 Storm Summary

The 5/27/08 storm produced 0.27 inch of precipitation in 1 hours and 40 minutes. The maximum 5 minute and 30 minute intensity was 0.84 and 0.30 in/hr, respectively. Simulations with HEC-HMS estimate that 525 ft^3 of runoff entered the site. Measured data indicate that runoff was contained by the site and either infiltrated or lost to evapotranspiration. Figure 44 shows the results of the HEC-HMS model in addition to the observed rainfall and basin water elevation.

A total of 26 water quality samples were collected during the storm. Table 8 presents the results of the sampling. Figures 45, 46, and 47 present the results for the conductivity, chloride, and total phosphorus analyses. Figure 48 presents a hydrograph of the groundwater elevations during and after the storm and Figures 49 and 50 show the fluctuation in conductivity and temperature at MW-1 and 2 over the course of the storm.

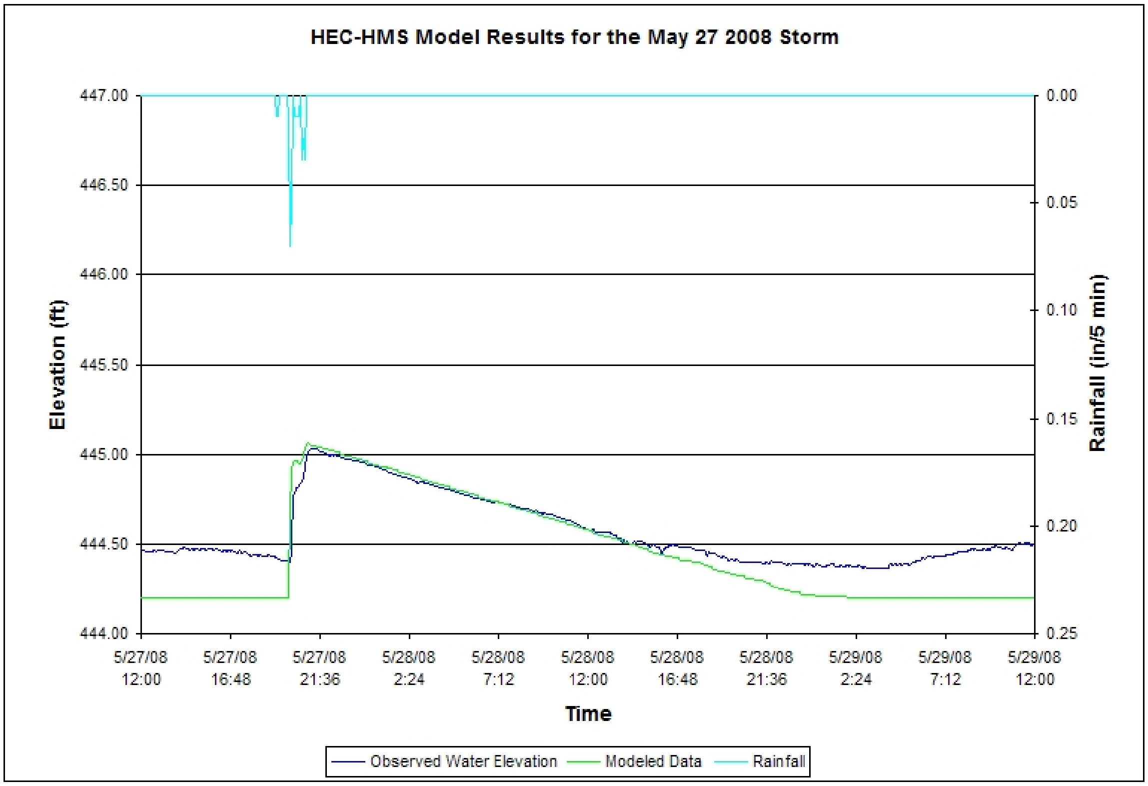

Figure 44: May 27th, 2008 HEC-HMS Model Results

Table 8: Water Quality Results from the May 27th, 2008 Storm Event

Location	Sample Time	pH	Cond	TSS	TDS	Nitro	NO2	NO3	Phosp	PO4	Chloride
AS01	5/27/08 13:29	6.30	56	9.2	13.2	2.10	0.5510	1.1800	0.59	0.0080	U
AS02	5/27/08 16:29	6.20	62	10.7	19.4	2.10	0.6460	1.0290	0.58	0.0200	U
AS03	5/27/08 19:29	6.20	65	U	12.2	2.80	0.8360	0.7980	0.53	0.0720	U
AS04	5/27/08 22:29	6.30	69	7.9	23.4	2.50	0.6460	0.7300	0.78	0.0950	U
AS05	5/28/08 1:29	6.70	274	N	N	U	1.0270	0.5830	4.00	2.2730	83.47
FF01	-	6.10	69	108.6	5.4	3.70	0.4560	1.4010	2.28	U	U
FF02	-	6.90	68	342.3	2.9	3.80	0.7410	1.3090	0.86	U	U
LYS0	-	7.20	101	N	N	2.40	0.7410	0.4370	0.21	U	9.20
LYS4	-	7.30	774	N	577.4	U	0.8360	0.3760	0.20	U	158.98
LYS8	-	7.60	476	N	185.2	3.50	0.7410	0.2360	0.14	U	34.45
MW1A	5/27/08 12:00	5.60	539	N	N	N	N	N	0.17	N	116.88
MW1B	5/28/08 10:00	5.80	420	N	N	N	N	N	0.23	N	117.40
MW1C	5/28/08 16:00	6.00	616	N	N	N	N	N	2.10	N	155.31
MW1D	5/28/08 8:50	5.80	690	N	N	N	N	N	0.13	N	116.46
MW2A	5/27/08 12:00	5.50	535	N	N	N	N	N	0.28	N	69.01
MW2B	5/28/08 10:00	5.70	410	N	N	N	N	N	0.08	N	151.33
MW2C	5/28/08 16:00	5.60	314	N	N	N	N	N	0.09	N	96.56
MW2D	5/28/08 8:50	6.50	483	N	N	N	N	N	0.52	N	97.71
MW3A	5/27/08 12:00	5.80	281	N	N	N	N	N	0.34	N	89.65
MW3B	5/28/08 10:00	6.40	617	N	N	N	N	N	0.10	N	91.43
MW3C	5/28/08 16:00	5.40	399	N	N	N	N	N	0.20	N	90.90
MW3D	5/28/08 8:50	5.90	520	N	N	N	N	N	0.11	N	91.22
MW4A	5/27/08 12:00	5.70	363	N	N	N	N	N	0.24	N	138.24
MW4B	5/28/08 10:00	6.30	616	N	N	N	N	N	0.20	N	137.19
MW4C	5/28/08 16:00	6.30	614	N	N	N	N	N	0.16	N	138.03
MW4D	5/28/08 8:50	6.80	806	N	N	N	N	N	0.14	N	139.50

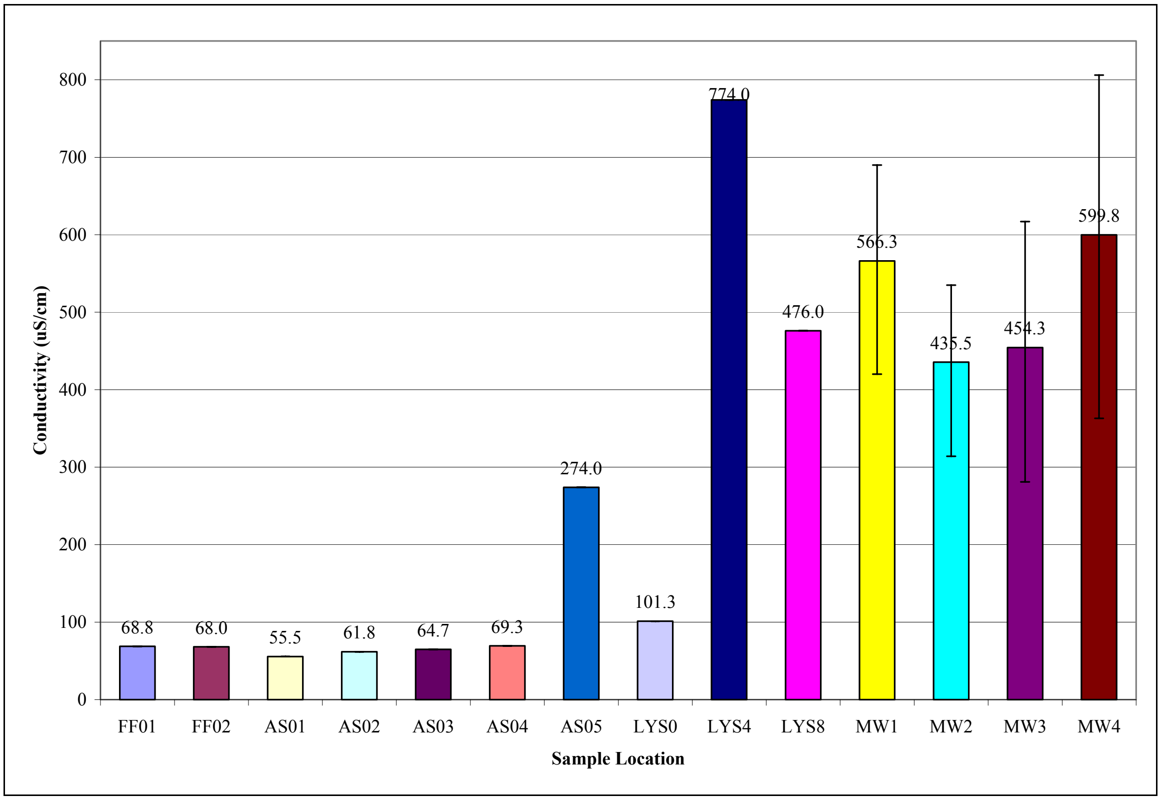

Figure 45: May 27th, 2008 Conductivity Results

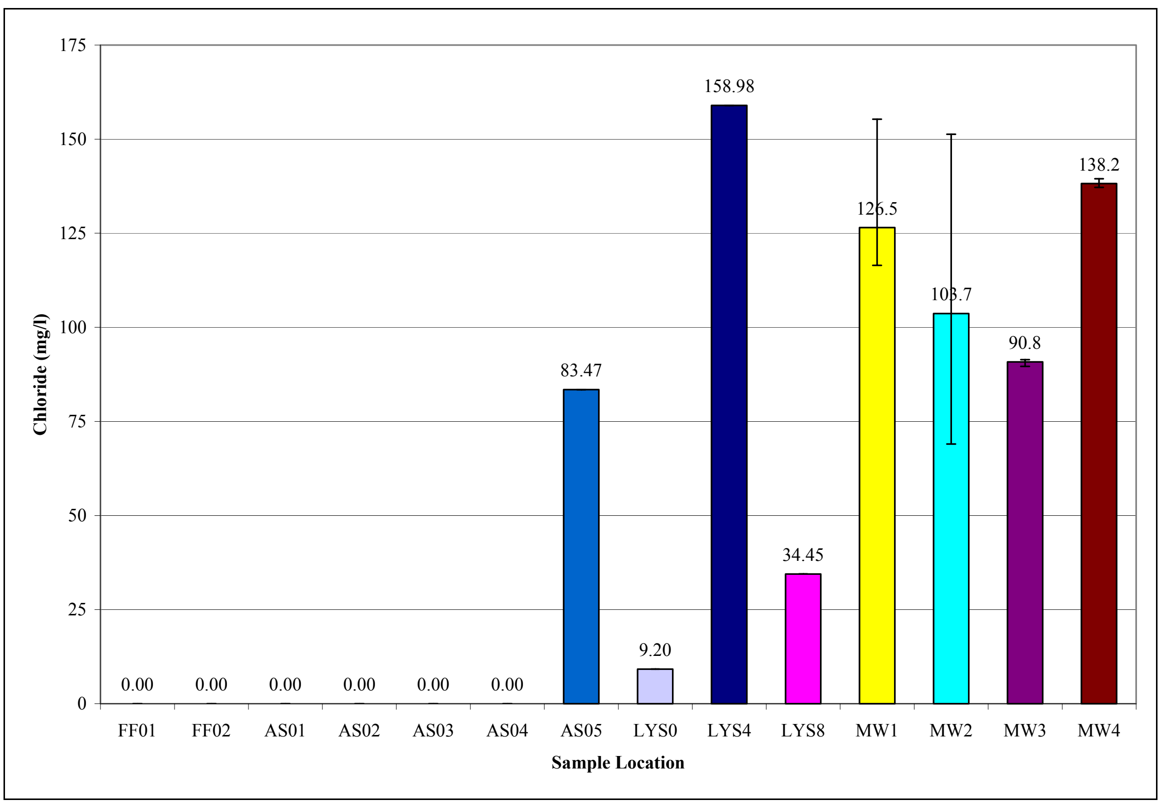

Figure 46: May 27th, 2008 Chloride Results

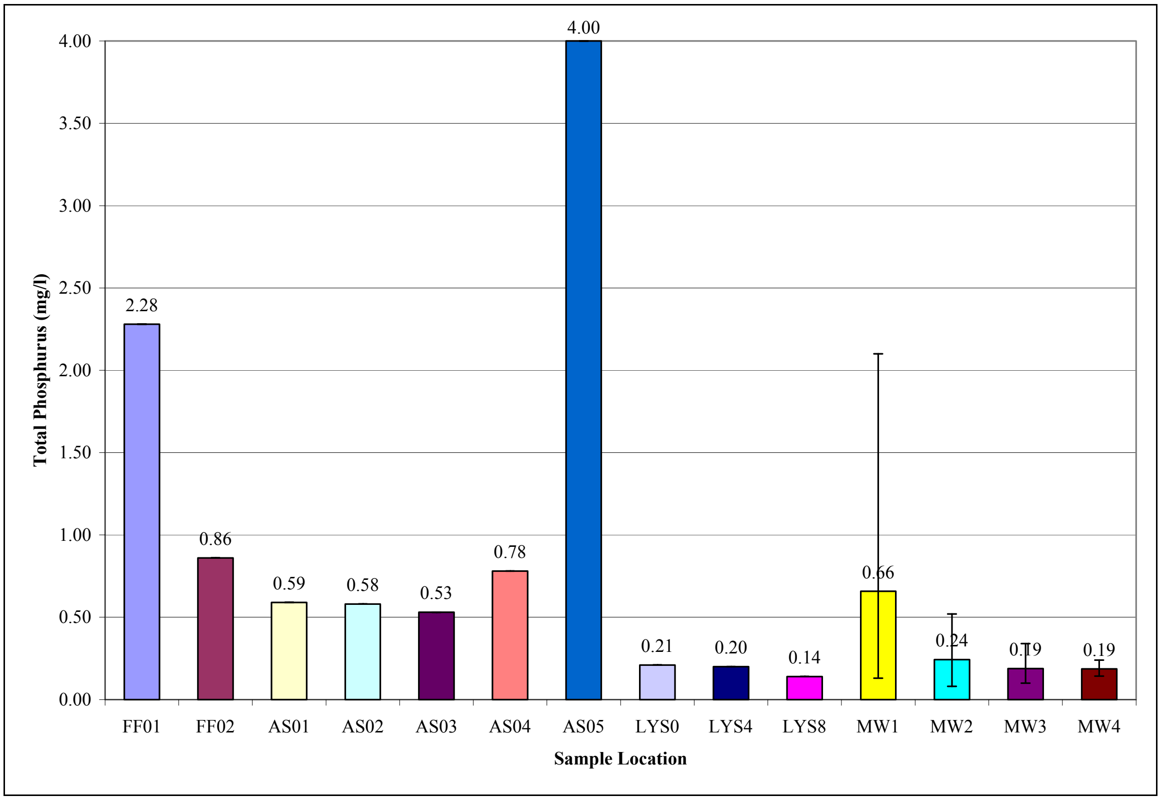

Figure 47: May 27th, 2008 Total Phosphorus Results

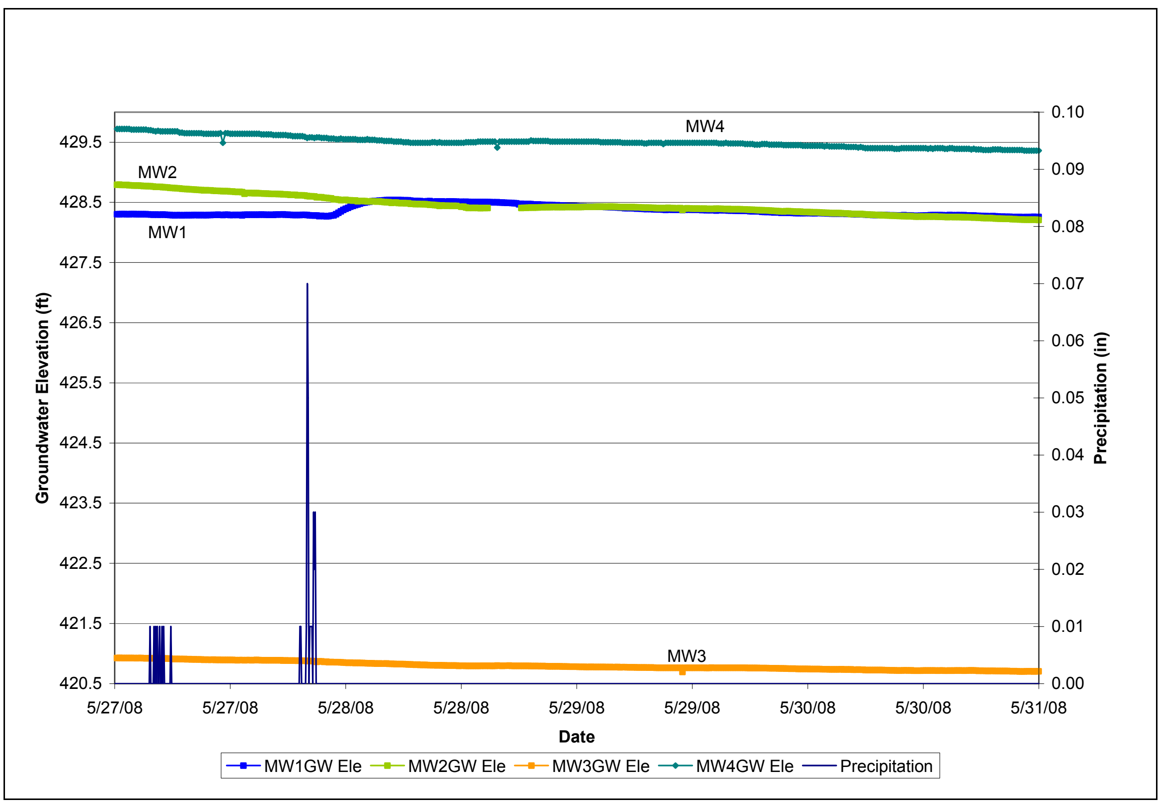

Figure 48: May 27th, 2008 Groundwater Hydrograph

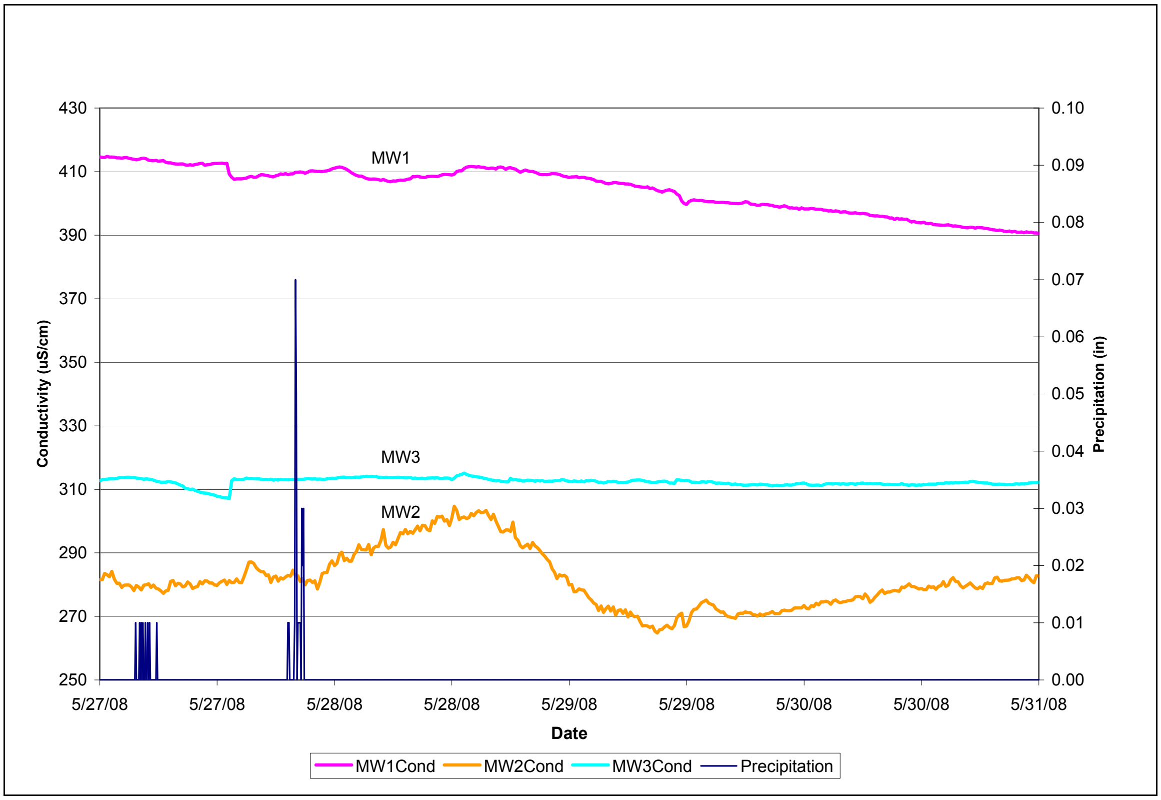

Figure 49: May 27th, 2008 Groundwater Conductivity

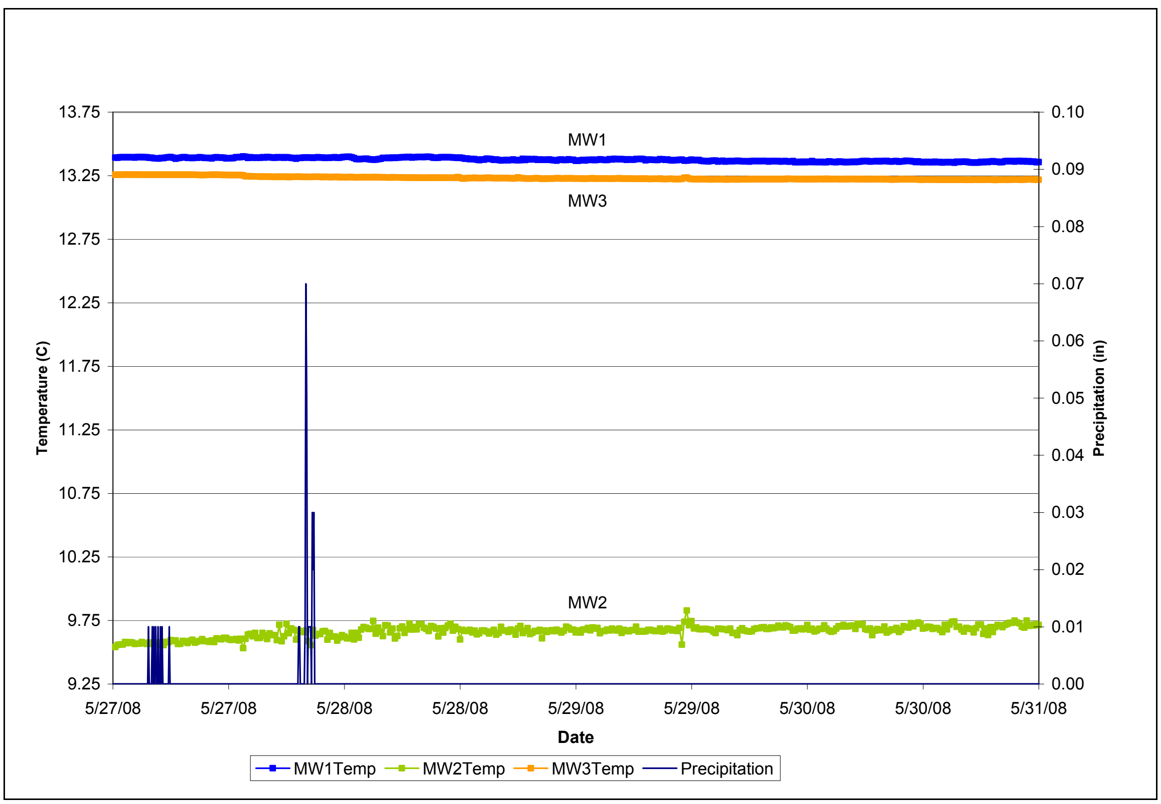

Figure 50: May 27th, 2008 Groundwater Temperature

3.1.7.2 Sampling Results

The 5/27/08 event was the shortest storm sampled and also had the greatest average intensity, of 0.16 inch/hr. The observed basin hydrograph rose steadily in response to the rain and receded at an average rate of 0.334 in/hr. The HEC-HMS simulation produced a hydrograph that closely matches the observed data. The modeled data slightly overestimated the peak elevation and differed slightly in the timing, but closely matched the observed recession rate. It is assumed that the predicted inflow volume is accurate.

The conductivity of the samples ranged from 55.5 μS/cm at AS01 to over 800 μS/cm at MW4D. The conductivity of the first four autosamples increased gradually from 55.5 μS/cm at AS01 to 69.3 μS/cm at AS04. AS05 had a much higher conductivity of 274 μS/cm. Both first flush samples had similar conductivity values of 68.8 and 68.0 μS/cm, respectively. The lysimeter samples had a wide variation of conductivity, from 101.3 μS/cm at LYS0, to 774 μS/cm at LYS4 and 476 μS/cm at LYS8. The groundwater samples also varied widely, ranging from 281 μS/cm at MW3A to 806 μS/cm at MW4D. The fluctuation in conductivity of the groundwater samples shows no discernable trend.

The results of the chloride analysis correlated to the conductivity results for the surface water and lysimeter samples; however, the groundwater samples did not show as strong of a correlation. Samples AS01 through AS04, FF01 and FF02 all had low conductivity values and all contained no detectable chloride, whereas AS05 had a high conductivity and contained 83.47 mg/l of chloride. LYS0 had a slightly higher conductivity value than the first flush and autosamples and also contained 9.20 mg/l. Lysimeter samples LYS4 and LYS8, both had high conductivity values and had chloride concentrations of 158.98 mg/l and 34.45 mg/l, respectively. If the relationship between conductivity and chloride were directly proportional, then LYS8 would have contained a higher chloride concentration, thus the conductivity value must be derived from ions other than chloride. It should be noted that LYS4 had a significantly higher concentration of total dissolved solids than the other surface water and vadose zone samples. Thus it may be that the high conductivity value is derived from the dissolved solids in the sample. The groundwater samples from MW-3 and MW-4 contained uniform chloride concentrations with averages of 90.80 mg/l and 138.24 mg/l, respectively. MW-1 and MW-2, both exhibited a fluctuation in chloride concentration. MW-1 had similar concentrations at samples A, B and D, with an average of 116.91 mg/l, but sample MW1C had a concentration of 155.31 mg/l. The samples from MW-2 ranged from 69.01 mg/l to 151.33 mg/l at samples A and B. Samples MW2C and MW2D were similar with an average concentration of 97.13 mg/l. The average chloride concentration in the wells was lowest at MW-3, then MW-2, MW-1 and MW-4.

Out of the 26 total phosphorus samples, 58% were less than 0.25 mg/l, 65% were less than 0.5 mg/l and 88% were less than 1 mg/l. Autosamples AS01-AS03 had concentrations similar to each other with an average of 0.57 mg/l. AS04 had a slightly higher concentration of 0.78 mg/l and AS05 had the highest concentration of 4 mg/l. FF01 had the second highest concentration of 2.28 mg/l, but FF02 had a concentration of only 0.86 mg/l. The lysimeter samples all had low concentrations, ranging from 0.21 mg/l at LYS0 to 0.14 mg/l at LYS8. The groundwater samples had mostly low concentrations below 0.25mg/l; only MW1C and MW2D were above 0.5 mg/l, the remaining samples were all below 0.35 mg/l and had an average concentration of 0.18 mg/l. The average well concentrations were lowest at MW-3 and MW-4 (both 0.19 mg/l), followed closely by MW-2 (0.24 mg/l) and were highest at MW-1 (0.66 mg/l).

Groundwater elevation monitoring for this storm indicated minor water level responses from MW-2, 3, and 4. MW-1 had a clearly discernable response of 0.27 ft in approximately 10 hours, however MW-2 and MW-4 increased by only 0.03 and 0.04 ft over approximately 27 hours. MW-3 increased had a total response of 0.01 ft over 21 hours. The groundwater elevations indicate a hydraulic gradient to the northwest with a steep gradient between MW-2 and MW-3.

The conductivity of the groundwater was highest at MW-1 and lowest at MW-2. MW-1 and MW-2 both showed changes in conductivity in response to the storm; however the response is better discerned at a finer resolution as presented in Figures 51 and 52 below. MW-1 showed a sharp decrease in conductivity in response to the storm followed by brief increase then a general declining trend. In contrast, MW-2 had a net increase in conductivity, but showed a sharp decline in response to the storm, before resuming the general increasing trend. MW-3 shows no discernable response to the storm. Overall, the lowest conductivity was at MW-2 followed closely by MW-3 and MW-1 had the highest conductivity.

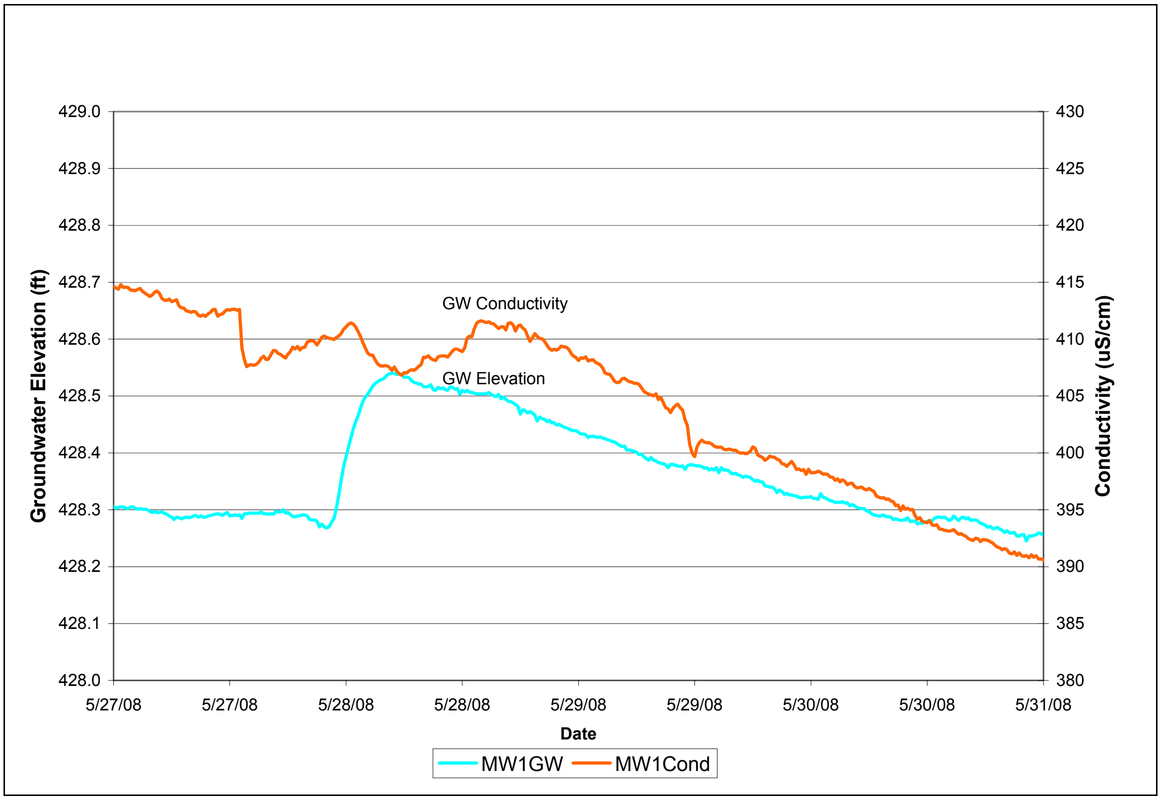

Figure 51: May 27th, 2008 Groundwater Hydrograph and Conductivity for MW-1

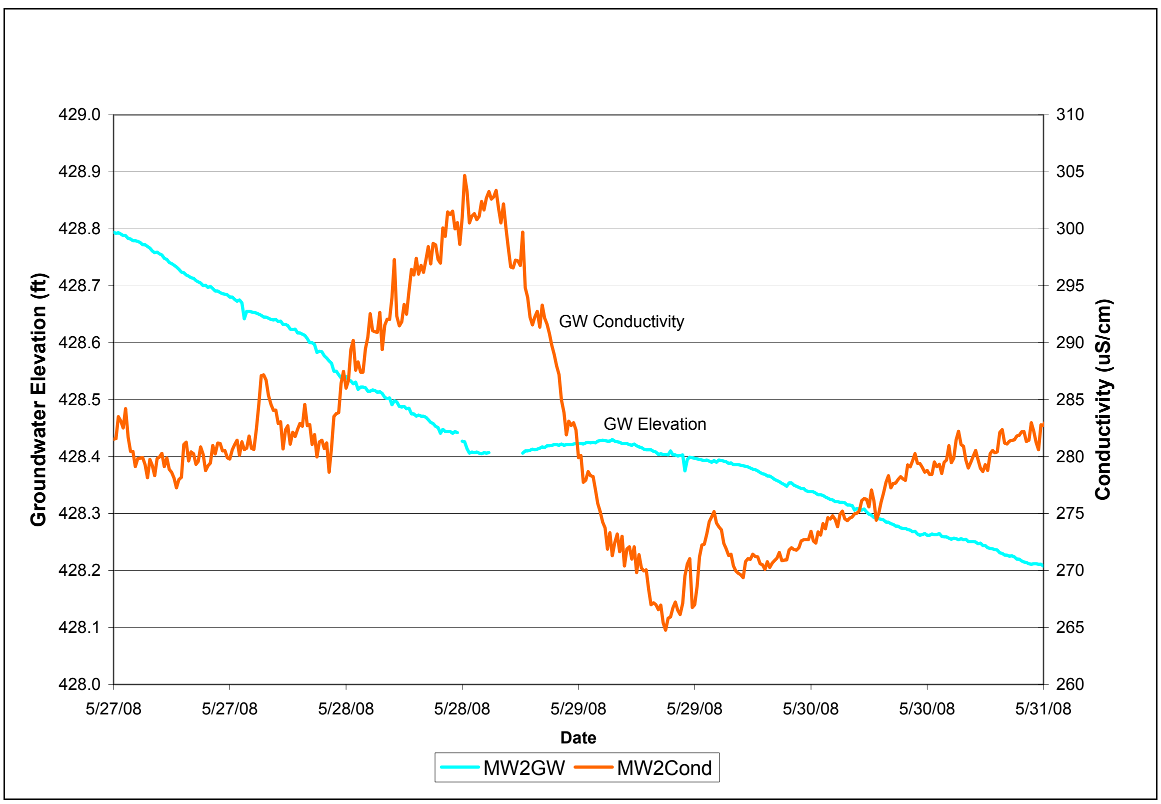

Figure 52: May 27th, 2008 Groundwater Hydrograph and Conductivity for MW-2

The groundwater temperature remained fairly stable at each of the wells over the storm monitoring period. MW-1 had the highest average temperature of 13.3 ^{o}C, followed closely by MW-3 at 13.2 ^{o}C and MW-2 had the lowest average temperature of 9.6 ^{o}C. Closer review of the data indicates that MW-2 had a slight and brief decrease in temperature after the storm, but quickly returned to the prior ambient temperature.

3.2 Continuous Groundwater Monitoring

In addition to monitoring the site hydrology and groundwater during sampled storm events, this study also examines the fluctuations in groundwater elevation, temperature and conductivity over an extended period of time. At monitor wells MW-1, 2 and 3 In-Situ AquaTroll 200 data loggers recorded the groundwater elevation, conductivity and temperature, while at MW-4 an INW PT2X pressure transducer measured the groundwater elevation.

3.2.1 Groundwater Elevation

Figure 53 below presents the groundwater elevations in the wells over the study period from November 2007 to August 2008. During this time, there was a total of approximately 31.20 inch of rainfall. The majority of this precipitation occurred in storms less than 1 inch and the great majority of the runoff was infiltrated by the site. It can be seen that significant fluctuations in groundwater elevation were observed at each well. Wells MW-1, 2 and 4 showed similar general trends and fluctuations. For most of the period MW-4 had the highest elevation, followed by MW-1 then MW-2; however at times MW-1 had the highest elevation and at times MW-2 surpassed MW-1. MW-3 remained the lowest elevation over the entire period and in general showed more gradual longer-term fluctuations. The hydraulic gradient resulting from the recorded groundwater elevations indicates a relatively flat water table in the vicinity of the MW-1, 2 and 4, with a fairly steep downward gradient towards MW-3. This gradient changes slightly over the study period, but remains fairly steep. Over the study period, the water table is highest from mid-January to mid-May and lowest towards the end of summer and beginning of winter.

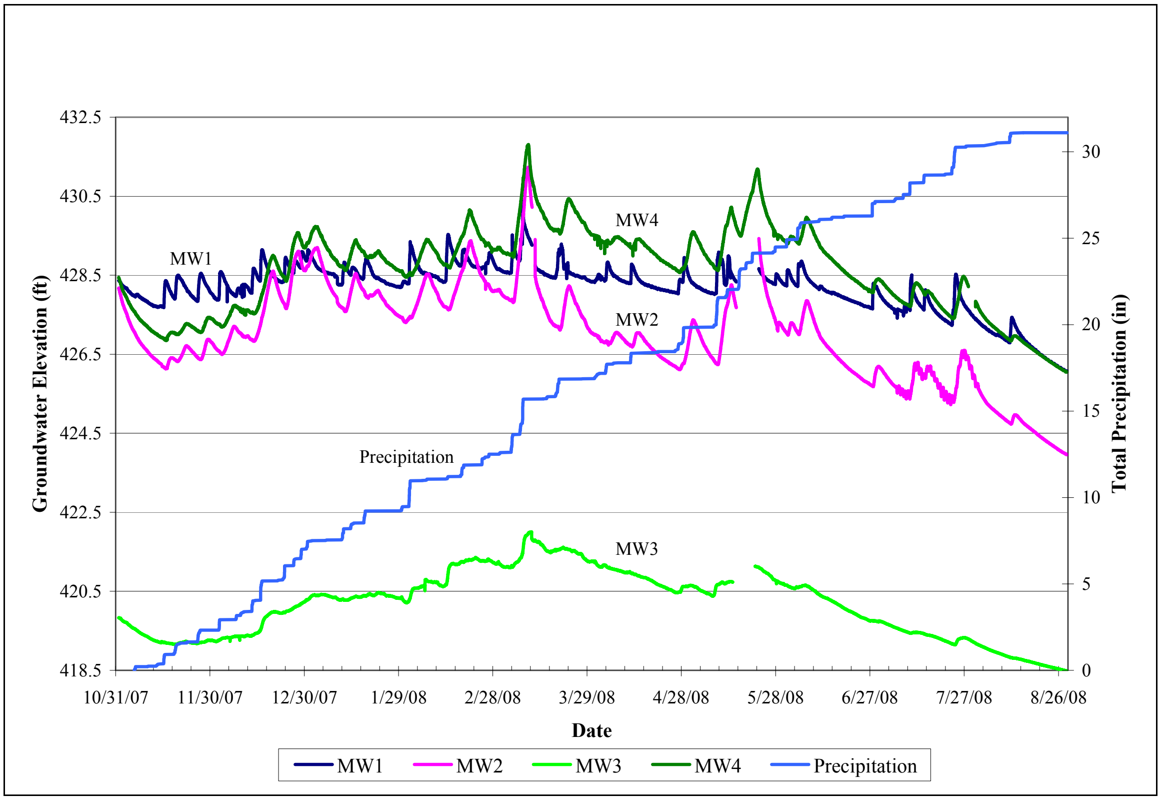

Figure 53: Groundwater Hydrograph for the Study Period

Over the entire monitoring period, the range between the maximum and minimum water level was 4.32 ft at MW-1, 7.28 ft at MW-2, 3.53 ft at MW-3 and 5.76 ft at MW-4. For the individual storms that were sampled, MW-1 showed the most change in water level with a maximum fluctuation of 0.67 ft. MW-3 had the least fluctuation with a maximum of 0.08ft, while MW-2 and MW-4 showed similar changes in groundwater elevation with maximum responses of 0.35 and 0.25 ft, respectively. The largest fluctuation in groundwater elevation occurred following the storms between 3/4/08 and 3/7/08, which had a combined total rainfall of 3.09 inch and an estimated inflow volume of 6554 ft^3. During this period, the elevation at MW-1 rose 1.83 ft, MW-2 rose 3.421ft, MW-3 rose 0.905ft and MW-4 rose 2.85 ft.

3.2.2 Conductivity Monitoring

The conductivity values observed at MW-1, MW-2 and MW-3 vary significantly between wells; therefore it is necessary to plot the results in separate figures to obtain sufficient resolution. For this reason, the scales on the figures should be noted, lest the reader assume similar ranges for each well. For instance, the conductivity range at MW-3 is approximately 270 to 370 μS/cm; whereas at MW-2 the range is about 75 to 875 μS/cm.

It is also important to note that disturbances in the well column were noted to have significant effects on the conductivity. For the first groundwater sampling event, bailers were used to collect samples and the data loggers were raised in the water column during sample collection. When the data were downloaded for this period it was noted that the temperature and groundwater elevation quickly returned to their previous readings but the conductivity required a long duration to return to previous values. For the next sampling event, the bailers were lowered with caution to minimize disturbance, however due to their manner of attachment the data loggers were still required to be moved slightly. While the disruption of the conductivity was decreased, significant disturbance was still caused.

In addition to disturbances caused by the sampling procedure, similar effects were noted during data download periods if the data loggers were raised in the water column.

To alleviate the issues caused by the downloading, the data loggers were secured in a manner that allowed for access to the data cable without any disturbance to the water column. Also data downloading was performed on a monthly basis rather than a weekly or bi-weekly timeframe.

To address issues caused by sampling disturbances, significant care was used when lowering and raising the bailers from the well. In general, the disturbance to the water column were minimized, however in some cases the effects were still noted. In other cases, it appears that significant impacts were noted to the conductivity and are believed to be the sole result of the storm event. In cases where it was believed that sampling or data downloading caused disturbances, the data has been omitted from the figures, in cases where the cause for the disturbance is not known the data are included. It should also be noted that the loggers were removed from the wells for the period 5/15/08 to 5/22/08 for downloading, extended calibration and remounting purposes. Figures 54, 55 and 56 below present the conductivity and groundwater elevation at MW-1, MW-2 and MW-3 over the study period. The groundwater elevation is included in the figures as an indication of when infiltrated waters reached the wells.

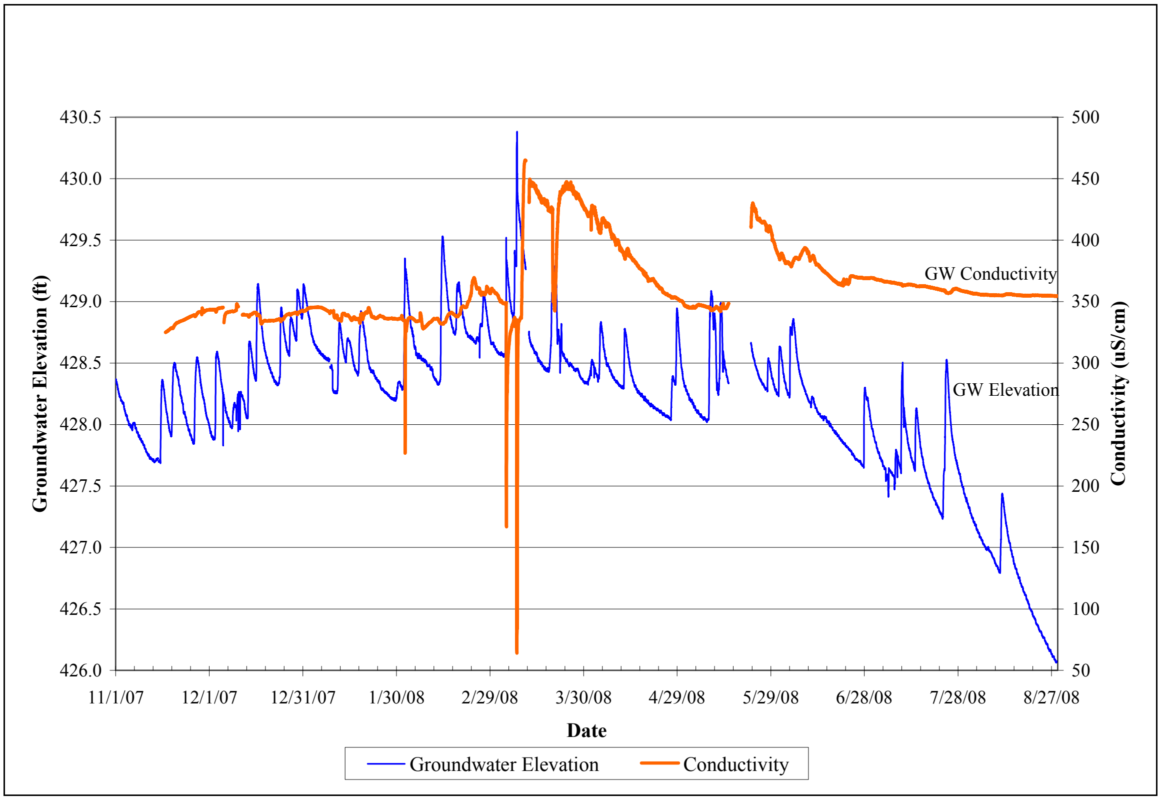

Figure 54: Groundwater Hydrograph and Conductivity of MW-1 for the Study Period

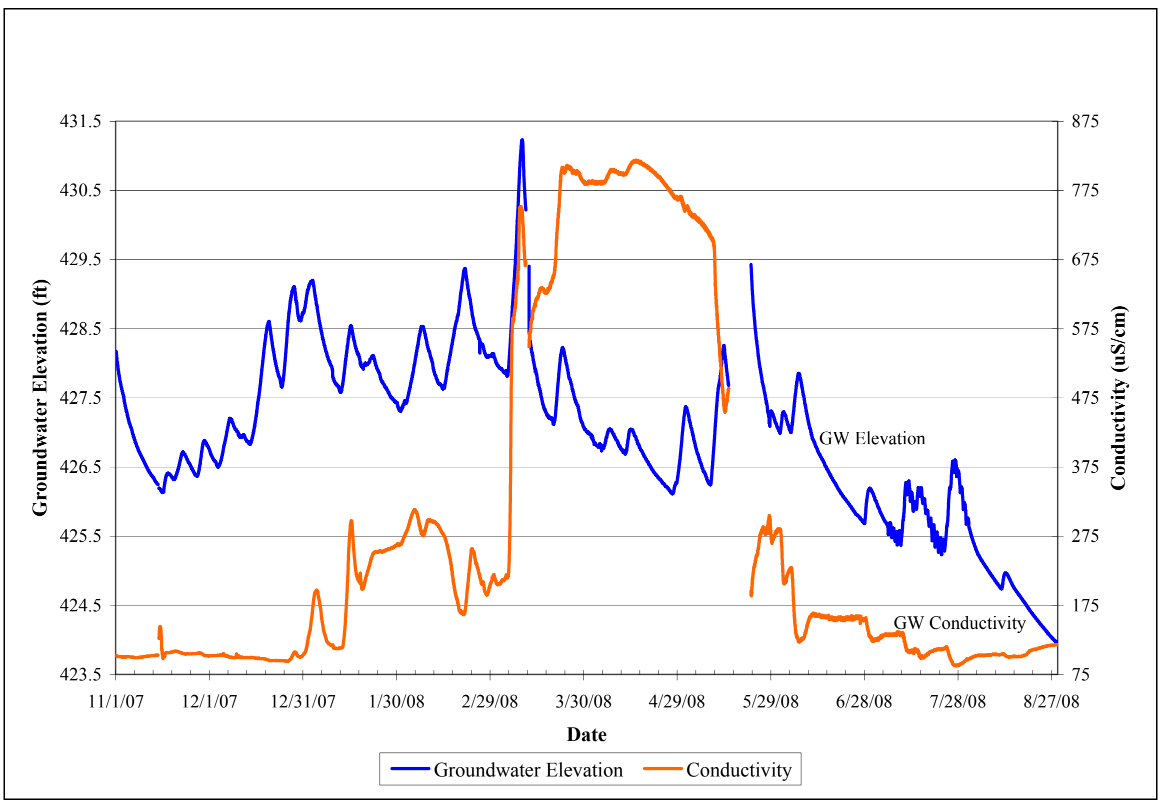

Figure 55: Groundwater Hydrograph and Conductivity of MW-2 for the Study Period

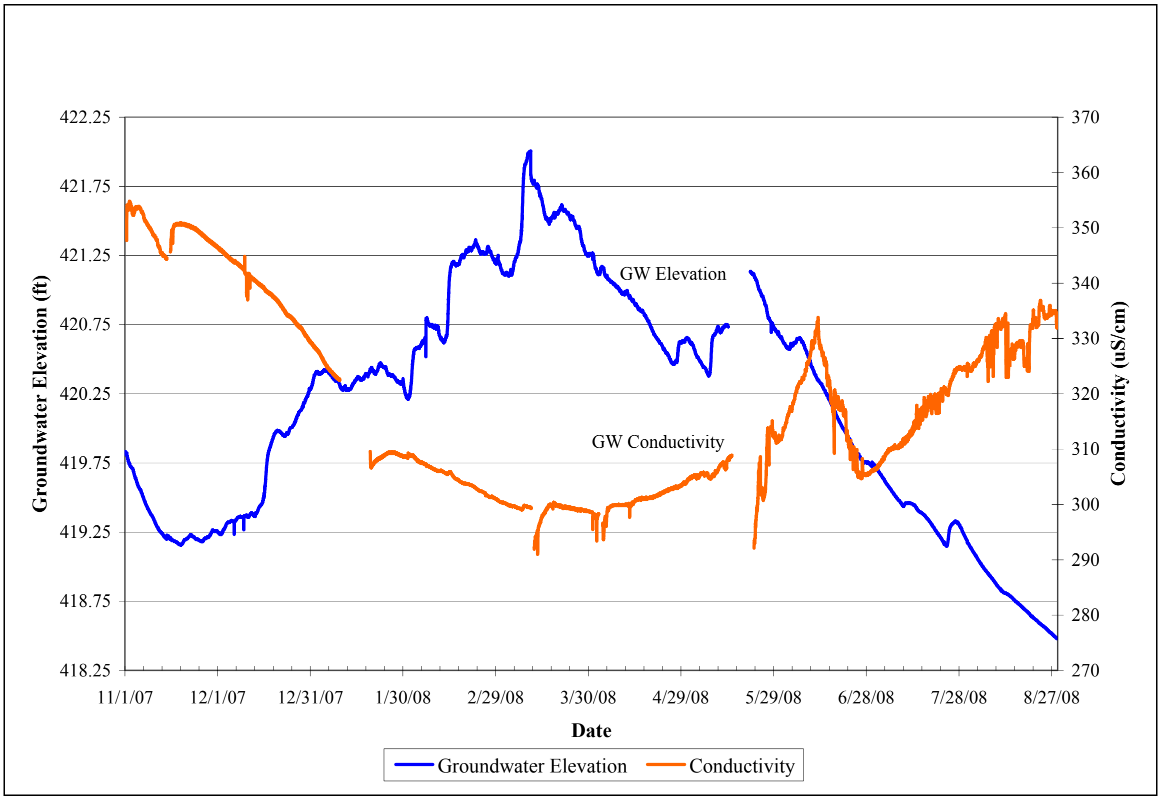

Figure 56: Groundwater Hydrograph and Conductivity of MW-3 for the Study Period

As shown in Figure 54, MW-1 shows a wide range of conductivity with major decreases in February and early March. Other than these fluctuations, the conductivity remained between approximately 320 and 360 µS/cm. Upon closer inspection, it can be seen that the sharp decrease in conductivity in early February corresponds with a storm event that produced 1.5 inch in just over 11 hours. Likewise the sharp decrease on 3/5/08 corresponds to a storm event with 1 inch over 12 hours and the decrease on 3/8/08 corresponds to a storm which produced 2.05 inch over 27 hours including 1.41 inch in the final 10 hours. Similarly, the decrease observed on 3/20/08 also corresponds to an event with 1.02 inch in 26 hours, with 0.77 inch in the final 13 hours. Although the conductivity graph is highly variable and exhibits constant fluctuation, the general trend at MW-1 is an overall increase from November 2007 to March 2008, followed by an overall decrease from April to August. While precise trends are difficult to discern, it appears that intense storms tend to cause a rapid decrease in conductivity, but after the storm the groundwater continues the more gradual overall conductivity trend. For instance, from November 2007 to March 2008, although the conductivity fluctuates there is a net increase. During this period storm events caused an initial decrease in conductivity that appears related to the storm intensity, but after the initial decrease the conductivity curve returned to the prior increasing trend. During the period April 2008 to August 2008, storm events caused similar decreases, but the overall trend was a net decrease.

The conductivity graph for MW-2 exhibits a high degree of fluctuation with a range of about 80 to 800 μS/cm. In addition, the curve shows several opposing trends during the observation period. From November 2007 to late December 2007, there is very little variation in conductivity, even with the varying water level. However in late December through late January 2008, changes in water level are directly proportional to changes in conductivity. Then from approximately 1/22/08 to 1/31/08, while the groundwater elevation decreased, the conductivity continued to increase. Beginning 2/1/08, the groundwater elevation began to rise steadily from approximately 427.3 ft to 428.5 ft by 2/7/08. During this same period, the conductivity rose from 264 μS/cm to 312 μS/cm on 2/5/08 and then dropped to 278 μS/cm by 2/7/08. Thus, for this period the conductivity was initially directly proportional to the water level, then inversely proportional.

The following interval from 2/7/08 until about 3/5/08 is characterized by an inverse relationship between the groundwater elevation and the conductivity. On 3/5/08, an intense storm occurred producing 1 inch in 12 hours. This event led to an abrupt increase in conductivity, from 225 μS/cm to 745 μS/cm; the largest increase detected over the entire study period. As the groundwater elevation receded from the 3/5/08 event, the conductivity also decreased, but as the groundwater recession rate began to slow, the conductivity began to increase. This inverse relationship continued until the 3/20/08 storm event at which point the conductivity began to rise with the groundwater.

After 3/20/08, as the groundwater receded, the conductivity remained high, between 750 and 810 μS/cm. During three storm events in April 2008, the conductivity rose with the groundwater elevation, but overall the conductivity had a net declining trend. Then between 5/8-5/9, approximately 1.73 inch of precipitation occurred which caused the groundwater elevation to rise about 2 ft. Concurrently the conductivity abruptly decreased from 700 to 460 μS/cm. Following this event on 5/15/08, the data loggers were removed from the wells for data downloading, inspection and calibration, then re-installed on 5/22/08. After 5/22/08, the groundwater decreased while the conductivity rose. Then on 6/1/08 and 6/6/08, the groundwater elevation and conductivity exhibited an inverse relationship, with the conductivity decreasing sharply as the groundwater elevation rose. After the event on 6/6/08, while the groundwater elevation receded the conductivity rose from 120 to 160 μS/cm. Then for the remainder of the study period, the conductivity followed an inverse relationship with the groundwater elevation and remained in the range of 85 to 160 μS/cm.

Overall the conductivity at MW-2 remained between 75 and 310 μS/cm between 11/1/07 to 3/6/08 and from 5/22/08 to 8/28/08. However, between 3/6/08 and 5/15/08 the conductivity had an average value of 730 μS/cm with a range of 465 to 820 μS/cm. The relationship between the groundwater elevation and conductivity varied between a direct relationship and an inverse relationship.

The conductivity and groundwater elevation at MW-3 exhibited less short-term volatility than both MW-1 and MW-2. Over the entire study period, the groundwater elevation ranged from 418.5 ft in August 2008 to 422 ft in March 2008 and the conductivity varied from 290 in March 2008 to 355 µS/cm in November 2007. The most readily observable trend is the opposing relationship between the conductivity and the groundwater elevation. From November 2007 until 3/11/08, the groundwater elevation follows a net increasing trend and the conductivity follows a net decreasing trend, then from 3/8/08 until 8/28/08 the groundwater elevation decreases while the conductivity increases. Two notable exceptions to this trend occurred between 6/12/08 and 6/27/08 and 7/25/08 and 7/28/08 when the conductivity and groundwater elevation both followed decreasing trends. Both of these exceptions occurred in late spring/early summer and following storm events of 1 inch and 1.5 inch.

3.2.3 Temperature Monitoring

The groundwater temperature at the site wells is presented in Figure 57 below. MW-1 and MW-3 had very similar gradual trends and maintained temperature difference of about 0.2 ^{o}C over the study period. In contrast, MW-2 had a highly variable temperature and followed a very different trend. While MW-1 and MW-3 had a range of less than 1 ^{o}C, MW-2 had a range of over 6.2 ^{o}C. The temperature curves at MW-1 and MW-3 were smooth and gradual, while MW-2 had a variable curve with many fluctuations.

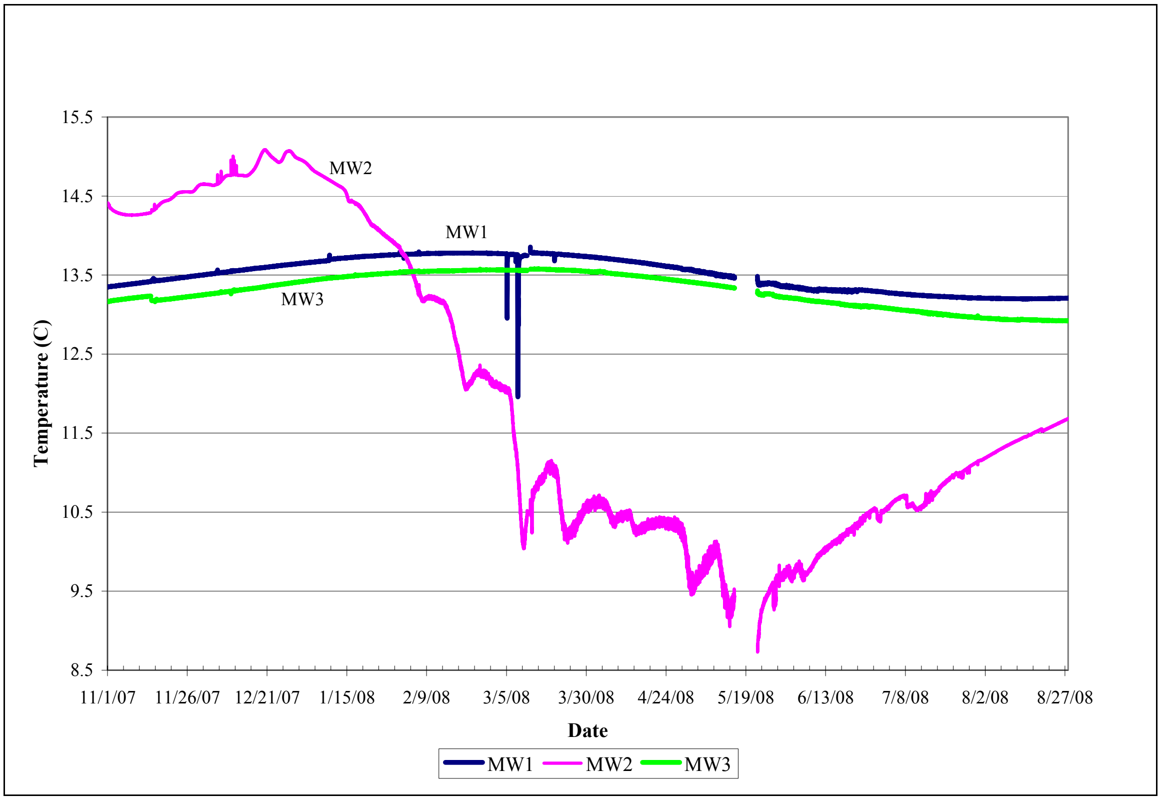

Figure 57: Groundwater Temperature for the Study Period

In November 2007, MW-1 and MW-3 had temperatures of 13.35 and 13.16 °C, respectively. The temperatures rose gradually to 13.76 and 13.56 °C, respectively, by early March and then proceeded to gradually decline to 13.20 and 12.98 °C by August 2008. MW-1 had two large temperature decreases in March 2008, both occurring immediately after storm events. The first event occurred around 3/5/08 when a storm produced 1.04 inch in 12.5 hours and the second event occurred 3/8/08 after a storm of 2.05 inch in 27 hours.

In November 2007, MW-2 began with a temperature of 14.41 °C and increased to 15.05 °C by the end of December 2007. From January 2008 until late May 2008, the temperature at MW-2 decreased from 15.05 °C to 8.77 °C and then from 5/22/08 until the end of the study period in 8/28/08, the temperature rose steadily to 11.68 °C with only minor variations.

For review, the temperature curve at MW-2 may be divided into four distinct sections. The first section ranges from 11/1/07 to 12/29/07 and is characterized by a gradual temperature increase from 14.25^{o}C to 15.08^{o}C. During this first section, the temperature has minor fluctuations that correspond and are proportional to the groundwater elevation. Generally when the groundwater elevation rises the temperature also rises and when the groundwater elevation declines, the temperature either declines or remains constant. The second section of the temperature curve lasts from 12/30/07 until 3/6/08 and is characterized by a general decline with two steeper declines. The two steep declines correspond to storm events on 1/29-2/1/08 and 2/13/08. After each storm event the temperature stabilized and slightly increased.

The third section of the temperature curve is from 3/6 to 5/22/08. This section has an overall decline in temperature, but includes several large temperature swings. The initial temperature swing is an abrupt decline from 11.95 ^{o}C to 10.06 ^{o}C and occurs in conjunction with the 1.04 inch storm event that occurred between late 3/4 to 3/5/08. After this storm event the temperature rises to 11.15 ^{o}C, but then continues to rise and fall in response to various storm events. Two large temperature decreases follow the storms on 3/19/08 and 4/27/08. The fourth and final section of the temperature curve occurs between 5/22/08 and 8/28/08. This final section involves a steady increase in temperature from 8.74 ^{o}C to 11.69 ^{o}C with several minor fluctuations. The fluctuations consist of minor temperature decreases in response to storm events and are typically variations of less than 0.20 ^{o}C. Throughout the entire study period it is interesting to note that the highest temperature occurred on 12/20/07 and the lowest temperature occurred on 5/22/08.

Chapter 4. Discussions

4.1 Water Quality

This section discusses the significance of the water quality sampling results and examines the variations observed among the sample locations. For each storm, the first flush sample results varied from the lysimeter and well samples. Also, for each storm there was a unique variance amongst the samples and the trends observed at one storm were not necessarily observed at another storm. However, when the results are examined over the entire study period, certain trends become apparent. Furthermore, additional insight is gained when the results are viewed in the context of contaminant transport through the BMP.

The following sections present graphs of the sample results over the entire study period and discuss the trends observed in the conductivity, chloride and total phosphorus results. Results are compared to regional values and applicable regulatory criteria. The values presented for the wells are the average of all the samples collected from each well for each storm. Since the wells typically displayed minimal variation between the samples for a given storm and due to the slow rate of infiltration and groundwater flow in comparison to the sampling interval, it is assumed that averaging the sample values provides a reliable estimate of the actual concentration. The values used for the basin are the average of the grab samples and the autosamples collected for a given storm. Although the basin samples displayed variation, it is assumed that the variation was sufficiently low so as to be accurately represented by an average value.

4.1.1 Conductivity

Conductivity or specific conductance is a measure of the ability of a substance to conduct an electric current and to conduct a current the solution must contain charged ionic species. (Hem 1985; Low *et al.* 2002). In natural waters the most prevalent ions contributing to conductivity include: Ca^{2+}, Mg^{2+}, Na^{+}, K^{+}, CO_3^{2-}, SO_4^{2-} and Cl^{-} (Ludlow and Loper 2004). Due to a lack of ionic species, pure water has very low conductivity; likewise rain water also has low conductivity. As ionic species dissolve and dissociation into water the conductivity rises, therefore measurement of conductivity also serves as a proxy to the amount of total dissolved solids (TDS) in a fluid. In fact, TDS, in mg/l, is generally between 55% to 75% of the conductivity, in µS/cm (Hem 1985). Because conductivity is a rapid and simplistic measurement it is a common analysis used to evaluate the water quality and to monitor changes in water quality.

For the purpose of this research, conductivity is a useful measurement to track the movement and change in quality of stormwater entering and infiltrating through the BMP. In addition, the relationship between conductivity and TDS is particularly useful for estimating the TDS of the groundwater. While there is no regulatory criterion for conductivity, the United States Environmental Protection Agency (EPA) has established a Secondary Maximum Contaminant Level (SMCL) of 500 mg/l for TDS (Low *et al.* 2002). Assuming an average coefficient of 0.65, groundwater samples with conductivity greater than 769 µS/cm are likely to exceed the 500 mg/l TDS SCML. Concentrations above the SMCL indicate that the water is not suitable for drinking, due to taste or appearance and may not be suitable for industrial, agricultural, or commercial purposes (Sloto and McManus 1996).

The figures below present the conductivity results from the first flush samples, lysimeter, basin samples and well samples over the entire study period. Figure 58 presents the values for the first flush, lysimeter and basin samples, while Figure 59 presents the lysimeter and groundwater samples and Figure 60 presents only the groundwater samples.

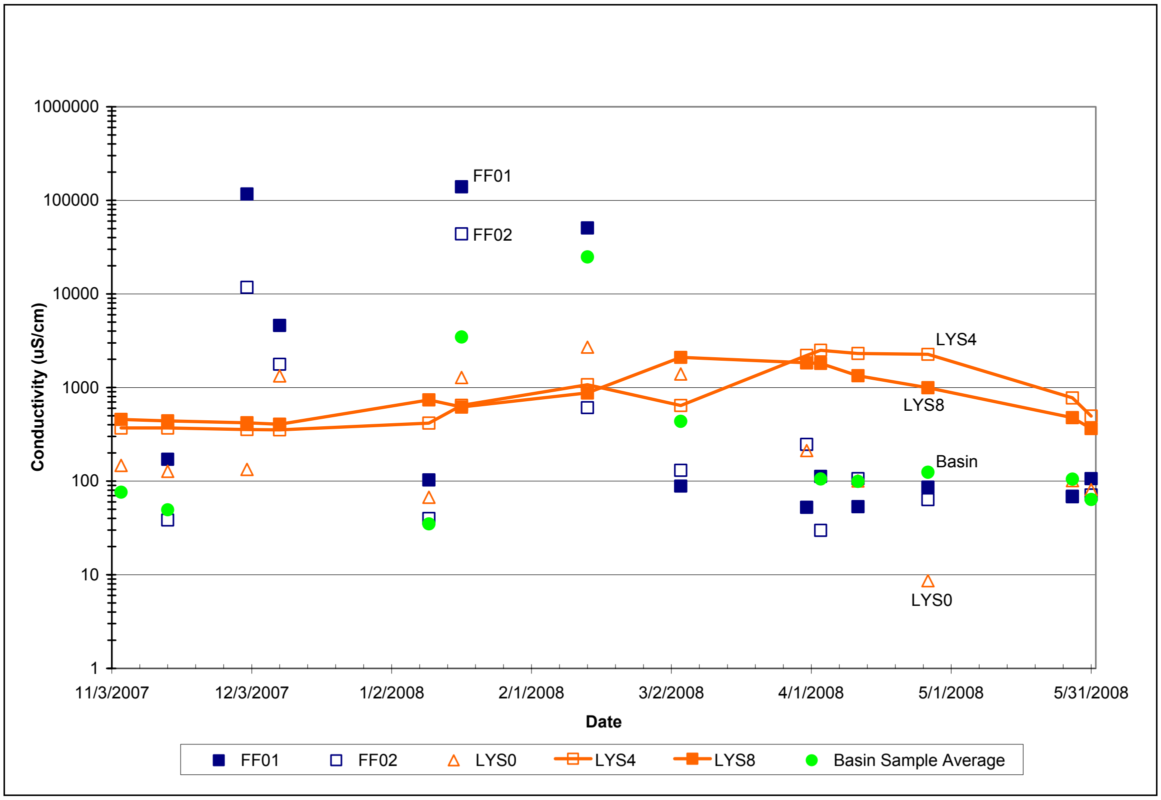

Figure 58: Conductivity Comparison of First Flush, Lysimeter and Basin Samples

Over the study period, the first flush, basin and lysimeter sample LYS0 vary significantly (note the logarithmic scale). The first flush samples contain the overall highest and lowest conductivity samples. The basin sample average and LYS0 follow a trend similar to the first flush samples, but with less range. In contrast, the lysimeter samples from four feet and eight feet below ground surface, LYS4 and LYS8, exhibit much less fluctuation and remain within a narrower range of conductivity values. These results indicate that the influent water quality varies widely over the course of the year, likely in response to the application of de-icing salts. The lower values and range of the basin samples, compared to the first flush samples, is likely due to a combination of dilution and mixing in the basin and particle settling. The similarity between the basin samples and LYS0 indicates that water which has infiltrated approximately 8-12 inch to the lysimeter undergoes little change in conductivity. However, the relative stability of conductivity at LYS4 and LYS8 indicates that infiltration affects the water conductivity. Furthermore it appears that the ions which create the conductivity are retained in the subsurface thus allowing the conductivity to remain relatively constant over the study period. This is illustrated by the high conductivity of LYS4 and LYS8 during the last several storms, when the conductivity in the remaining samples is lower than LYS4 and LYS8. If the soil did not have the capacity to retain ionic species, then these samples would have values similar to the influent waters. Although the subsurface near LYS8 never reaches saturation (Emerson 2008), moisture is still retained in the vadose zone. It is likely that the water and soil particles in the vadose zone retain ions and during subsequent storms these ions are dissolved into infiltrating water thus producing the conductivity observed in LYS4 and LYS8. The result is that while the lysimeters never attain the extreme concentrations observed in the first flush and basin samples, they maintain a steady concentration of relatively high values throughout the study period.

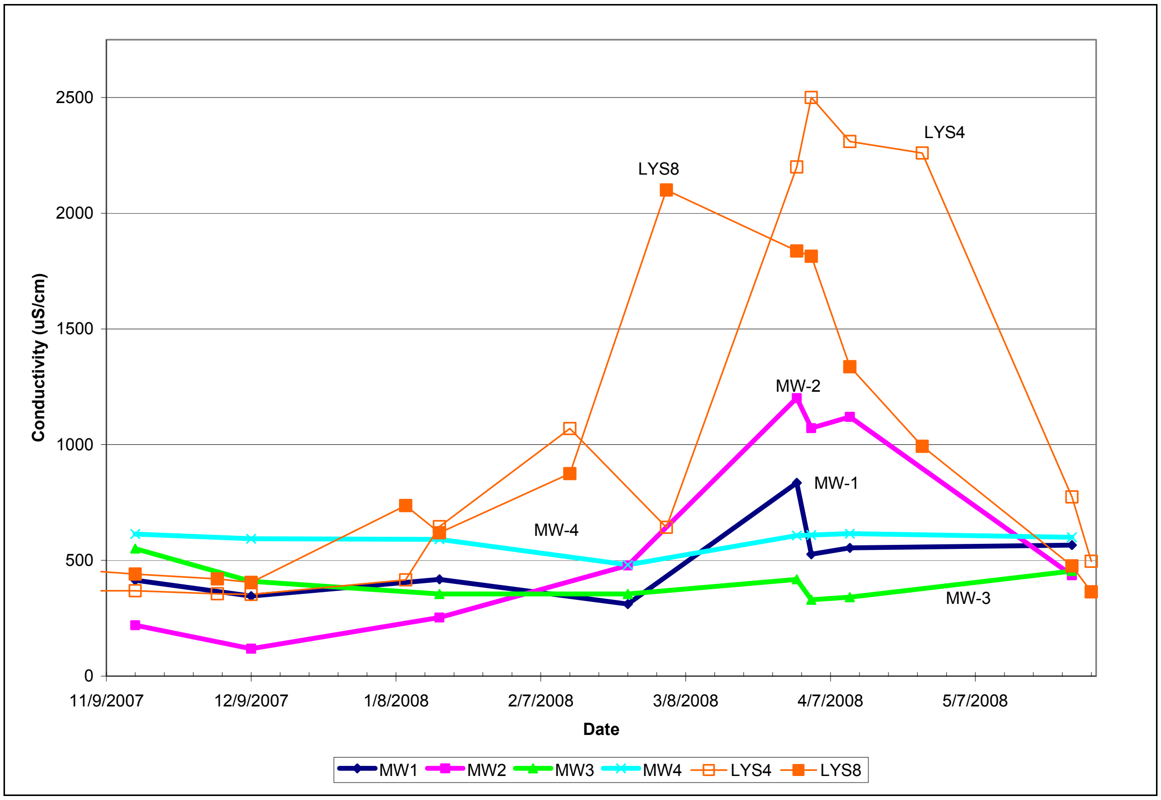

Figure 59: Conductivity Comparison of Lysimeter and Groundwater Samples

As illustrated in Figure 59 above, comparison of conductivity in lysimeters to the groundwater reveals that the wells are more stable and have a lower range. Over the study period, the wells do not reach conductivities as high as those encountered in the lysimeters. MW-2 follows a trend very similar to LYS4 and LYS8, but with conductivity values much lower than the lysimeters. MW-1 displays a spike in conductivity on 3/31/08, but in general remains stable. MW-3 and MW-4 remain relatively constant throughout the study period and do not exhibit large fluctuations. The conductivity at MW-2 indicates the impact of the infiltrated groundwater and suggests that the high conductivity water infiltrating past LYS4 and LYS8 is attenuated or diluted during transport to the groundwater at MW-2.

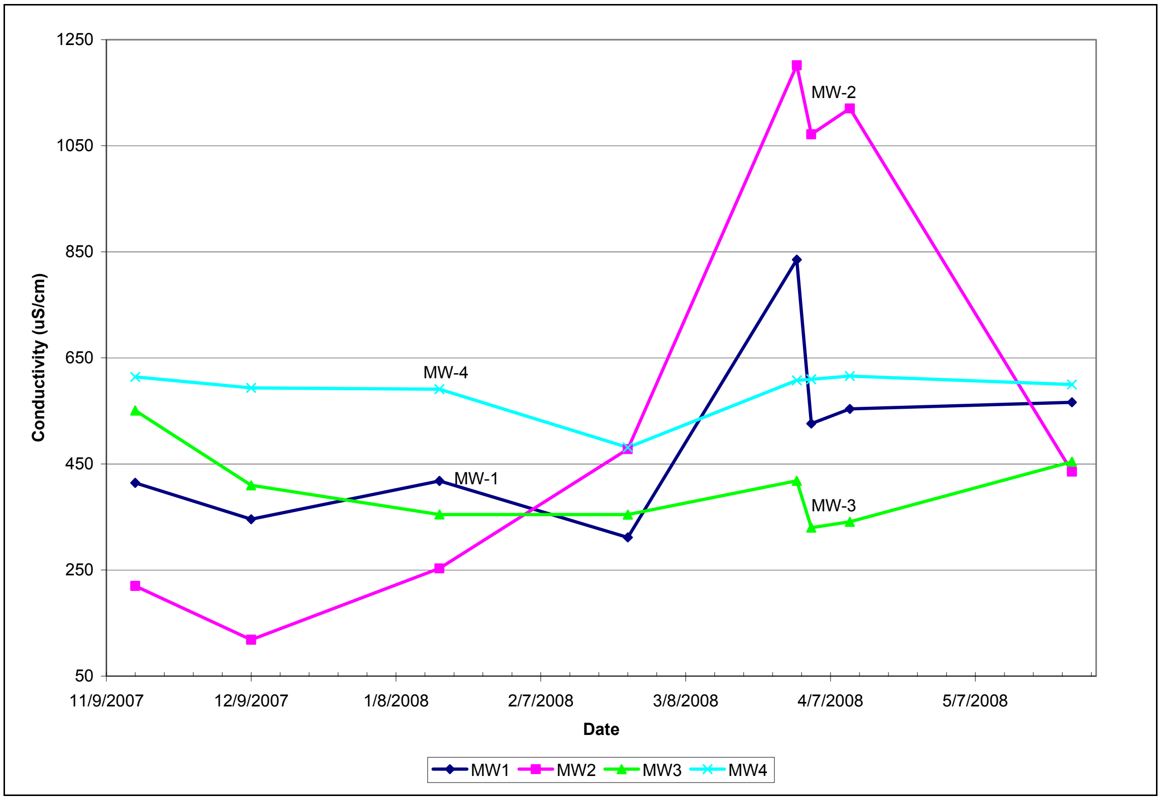

Figure 60: Conductivity Comparison of the Groundwater Samples

As shown in Figure 59 and 60, MW-3 and MW-4 remain relatively stable throughout the study period. MW-4 has a range of 135 µS/cm with a standard deviation of 44.58 µS/cm, while MW-3 has a range of 221 µS/cm and a standard deviation of 74 µS/cm. Compared to MW-2 with a range of 1083 µS/cm and a standard deviation of 446 µS/cm. The stability of MW-3 and MW-4 indicates that they receive waters of similar quality throughout the study period, whereas MW-2 receives water with varying quality. MW-1 also displays variation in conductivity, particularly the high value of 835 µS/cm recorded on 3/31/08. The high value on 3/31/08 is likely related snowmelt and the rapid groundwater elevation response to rainfall observed at MW-1. The rapid response indicates that infiltrating water reaches the groundwater relatively quickly, thus on 3/31/08 rainfall and snowmelt would rapidly infiltrate to the groundwater with little opportunity for attenuation. Overall, the conductivity results show that MW-2 varies widely in response to infiltrated stormwater, with low conductivity values through much of the year and high conductivity values related to the winter season when road salt is applied. However, the high and low conductivity at MW-2 appears to be attenuated downgradient at MW-3, which is approximately 63 ft away.

As mentioned previously, conductivity indicates the amount of solids dissolved in water and is a proxy to the overall water quality. The relationship between conductivity and TDS suggests that conductivity values greater than 769 μS/cm are likely to exceed the 500 mg/l TDS SCML. Thus the samples from MW-2 on 3/31/08 (1,201 μS/cm), 4/3/08 (1,071 μS/cm) and 4/11/08 (1,120 μS/cm) and from MW-1 on 3/31/08 (835 μS/cm) all likely exceed the SMCL. These findings suggest that the high conductivity/TDS water infiltrated through the BMP degrades groundwater quality and cause an exceedance of the TDS MCL. However, it is important to note that the upgradient well, MW-1 also exceeds the MCL. The area above MW-1 is landscaped and grass covered, but fairly close to a road and parking lot. The primary sources of conductivity for the area contributing to recharge at MW-1 include: stockpiled snowmelt, fertilizers, soil particles, plant and animal waste and litter. The recharge area for MW-2 is much larger due to infiltration at the BMP and therefore the MW-2 recharge area has the same potential sources in addition to a multitude of sources related to the roadway and parking areas. So the impact of focused recharge at the BMP may not be substantially different from the recharge occurring at nearby turf covered areas. Finally, it is imperative to note that the SMCL is exceeded for a short duration and that the downgradient water at MW-3 is significantly below the SMCL. Therefore the overall impact of the high conductivity is limited both temporally and spatially.

In their study of groundwater in Chester County, PA, Ludlow and Loper (2004) determined minimum, median and maximum conductivities for wells in gneiss to be 50 μS/cm, 218 μS/cm and 750 μS/cm, with 75% of the wells less 317 μS/cm. Low, *et al*. (2002) determined median and maximum conductivities for wells completed in gneiss in the Piedmont Upland province of Pennsylvania to be 190 μS/cm and 1,500 μS/cm. In addition, Low *et al*. determined median and maximum TDS concentrations of 145 mg/l and 929 mg/l for wells completed in gneiss. While the wells used for the studies mentioned above are completed entirely in gneiss bedrock and are all generally much deeper than the monitor wells used for the study, it is still useful to compare the values. For instance, the median concentrations are both lower than the median concentrations observed in this study and the maximum concentration observed by Low *et al*. is similar to that observed at MW-2. Since the wells used by Low *et al*. and Ludlow and Loper are generally much deeper and are completed solely in bedrock, the surface water recharging these wells has traveled a farther distance and had more potential for attenuation. Thus the discrepancy between the regional averages and the current study may likely be due to the well depth.

4.1.2 Chloride

The chloride concentrations of the first flush and basin samples show a trend similar to the conductivity results. Both the chloride and conductivity at these locations have the highest concentrations and exhibit the widest range in concentration (see Figure 61, below). In contrast, the chloride concentrations of the lysimeter samples differ slightly from the conductivity results. Unlike the trend observed with the conductivity, the chloride concentration at LYS0 does not closely follow the concentration of the basin sample. Also the chloride concentrations at LYS4 and LYS8 exhibit more of a range in concentration than is observed with the conductivity results. However, similar to the conductivity, the lysimeter samples do not reach concentrations as high as those detected in the first flush samples. Rather, the lysimeter samples (particularly LYS4 and LYS8) maintain a relatively high concentration during the early spring, when the other samples have lower concentrations.

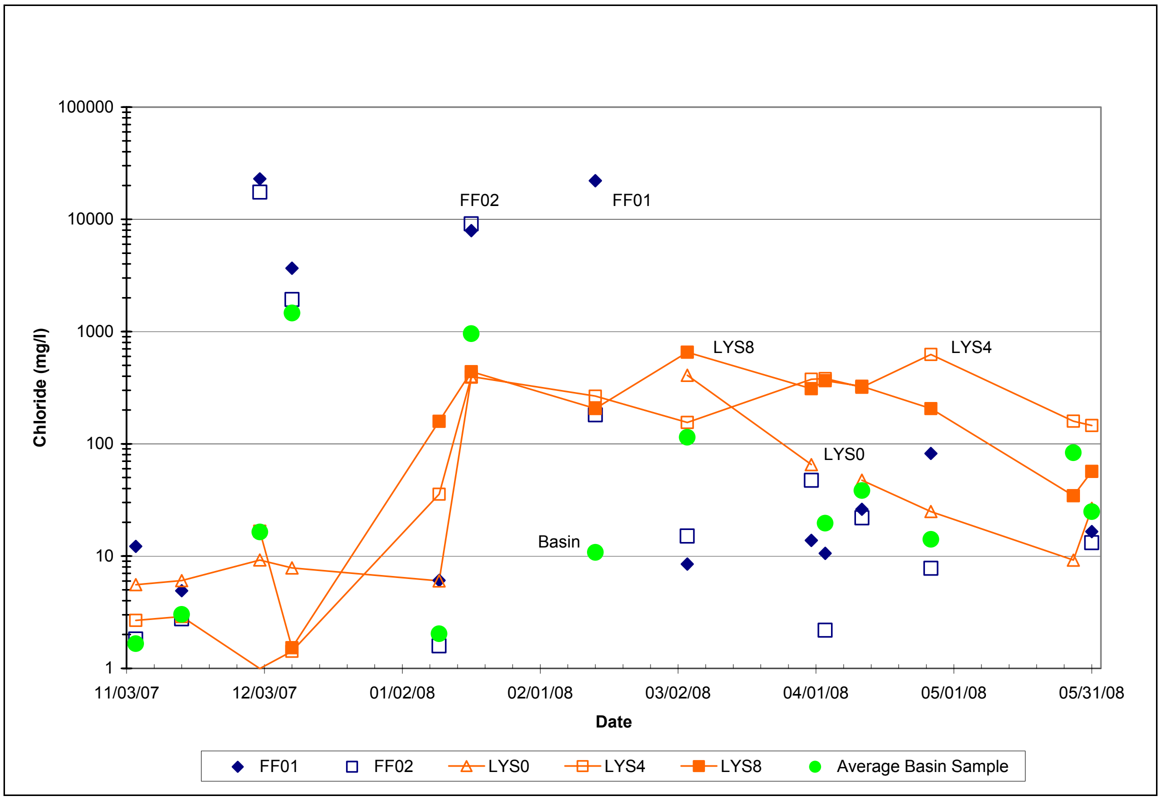

Figure 61: Chloride Comparison of First Flush, Lysimeter and Basin Samples

These results indicate that the high chloride concentration observed in the first flush and basin samples is attenuated during infiltration to the depth of the lysimeters. Additionally, it is apparent that the vadose zone retains chloride mass and that this mass is transported through the subsurface at a rate slower than infiltration. This is shown in November and December when the lysimeters have low chloride concentrations and the basin has high concentrations and later in the spring, when the basin samples have low concentrations but the lysimeters maintain higher concentrations. Thus the BMP appears to retain chloride and release lower concentrations over a longer time period. It is likely that during the spring, evapotranspiration may reduce the volume of water passing through the vadose zone, hence increasing the chloride concentration. However, the lysimeter concentrations are an order of magnitude greater than the first flush and basin samples. Thus it is unlikely that evapotranspiration is solely responsible for the increased concentrations. Since the influent water in the spring has lower chloride concentrations than the vadose zone concentrations, there must be a source of chloride in the subsurface and this source is assumed to be derived from chloride retention from prior infiltration of high chloride water.

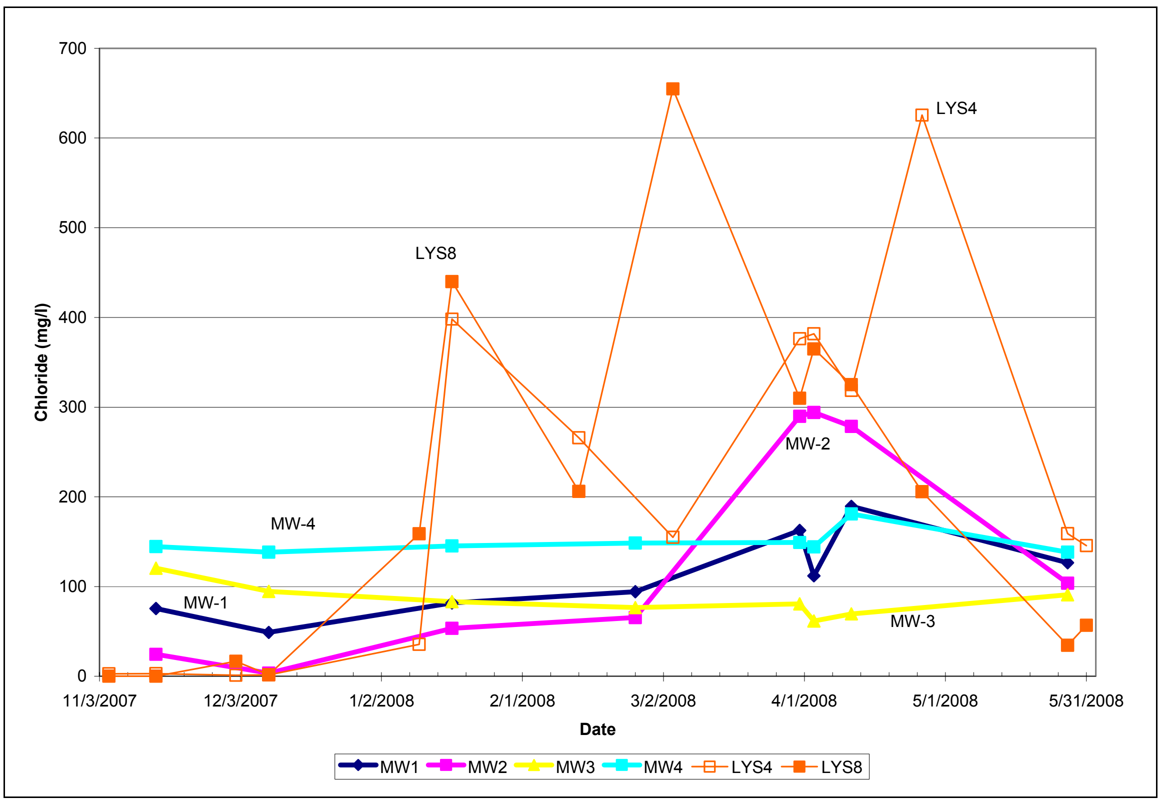

Figure 62: Chloride Comparison of Lysimeter and Groundwater Samples

Figure 62, above illustrates that the lysimeter samples have a much larger variation in chloride concentration over the study period than the groundwater samples. Wells MW-1, MW-3 and MW-4 vary little over the study period. MW-3 and MW-4 both have a range of approximately 50 mg/l while MW-1 has a range of about 140 mg/l. In contrast, MW-2 has a range of about 290 mg/l and has the highest and lowest chloride concentration of all the groundwater samples. While high concentrations are detected at MW-2, the concentrations are still less than the maximum concentrations detected at the lysimeters. Thus it is apparent that the chloride concentration is attenuated during infiltration and groundwater transport. The attenuation is likely due to a combination of dilution in groundwater and chloride retention in the vadose zone.

Chloride is generally unreactive and tends to remain in solution, and thus is readily transported (Hem 1985). In fact, a study by Pitt *et al*. (1999) indicates that salt concentrations increase as water travels through soil due to leaching. Conversely, chloride may be retained by clay particles and shale, however the site soils contain very little clay (Hem 1985; Carjan and McCree 1998). The cause of the chloride attenuation observed at the site is likely due to a combination of processes including evapotranspiration, dilution and soil retention. While the exact process or mechanism for attenuation is not certain, it can be seen that the maximum chloride concentration at MW-2 is lower than the maximum concentration in the lysimeters and furthermore that the maximum concentration in the lysimeters is less than the maximum concentration detected in the basin sample.

Although the chloride concentration may be attenuated during infiltration to groundwater, three samples from MW-2 exceeded the EPA SCML of 250 mg/l. In general, concentrations above 250 mg/l are not suitable for public supply and concentrations above 350 mg/l are objectionable for irrigation and some industrial uses; furthermore higher concentrations increase the corrosiveness of water (Low *et al.* 2002; Ludlow and Loper 2004). For comparison, only one out of the 440 wells included in a study of groundwater in Chester County, contained a chloride concentration above 250 mg/l and this well was located adjacent to the Pennsylvania Turnpike (Ludlow and Loper 2004). Ludlow and Loper determined the median chloride concentration in 'service areas' in Chester County to be 32.5 mg/l and 11.5 mg/l in low-medium density residential areas. In a study of groundwater in Southeastern Pennsylvania, Low *et al*.(2002) found median and maximum chloride concentrations of 12 mg/l and 1,800 mg/l for wells completed in gneiss of the Piedmont Upland. Review of Figure 62 shows that the median chloride concentration for each well is substantially higher than the median values reported in regional studies. As mentioned in the discussion of conductivity, this discrepancy may be due to the difference in well depth. Finally, while three samples from MW-2 exceeded the chloride SMCL, the downgradient concentrations at MW-3 remained stable and had a maximum concentration of 120 mg/l.

4.1.3 Total Phosphorus

Phosphorus is naturally derived from plant material, animal waste, igneous and sedimentary rocks and soils. Anthropogenic sources of phosphorus include: fertilizers, detergents, animal waste, sewage, organic chemicals and motor oils (Hem 1985; Tchobanoglous and Schroeder 1985; Pitt *et al.* 1999; Low *et al.* 2002). Most forms of phosphorus have a low solubility and therefore phosphorus tends to remain sorbed to particles, precipitated or associated with biota. Dissolved concentrations of phosphorus are generally less than 0.4 mg/l and the most common dissolved species of phosphorus is orthophosphate (Hem 1985). Orthophosphate is also the most biologically available form of phosphorus for aquatic life (USEPA 1999). Maintaining low phosphorus concentrations in natural waters is essential, since excess phosphorus may cause algal blooms and lead to reduced dissolved oxygen and increased biological oxygen demand (Tchobanoglous and Schroeder 1985; Mihelcic 1999). Measurement of total phosphorus includes the dissolved forms as well as suspended forms and is generally not indicative of solution composition (Hem 1985). However, the test for total phosphorus is significantly less complicated and labor intensive, therefore total phosphorus was used for this study as a comparative tool rather than a precise analysis.

Figure 63, below presents a comparison of the total phosphorus results for the first flush, basin and lysimeter samples over the study period. The first flush samples, especially FF1 show significant variation. The basin sample average, which is a composite of several samples, shows less variation and the lysimeter samples, which are collected through ceramic cones, show the least variation. Variations aside, the first flush and basin samples have higher concentrations than the lysimeters and LYS4 and LYS8 typically have lower concentrations than LYS0 and the basin samples. The lower lysimeter values are likely a result of filtration through the ceramic cone of the lysimeter, but they may also be representative of total phosphorus removal by the physical, chemical and biological processes involved with infiltration.

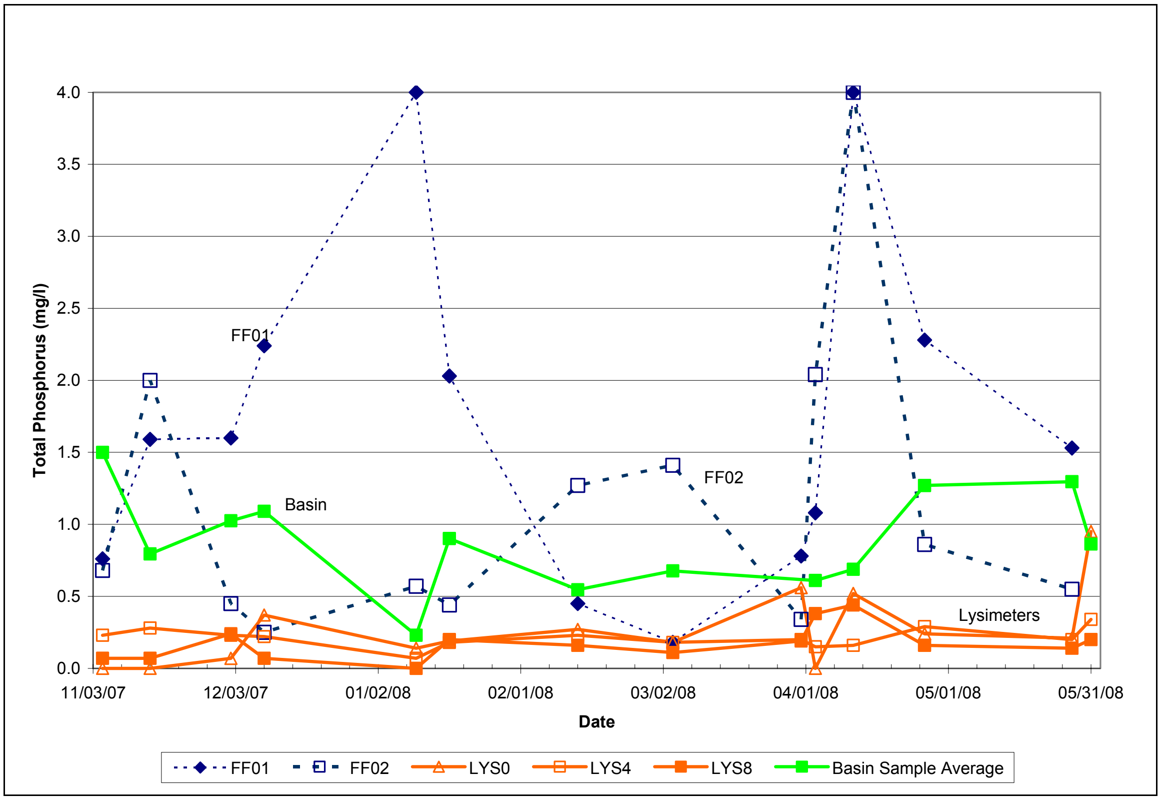

Figure 63: Total Phosphorus Comparison of First Flush, Lysimeter and Basin Samples

Figure 64, below compares the total phosphorus results of the basin samples to the groundwater samples. The concentrations of the groundwater samples are variable and generally higher than the lysimeters, therefore they are compared to the basin samples. MW-3 has the lowest average concentration of all the wells and never exceeds 0.5 mg/l. MW-4 had the next lowest average and did not exceed 0.8 mg/l.

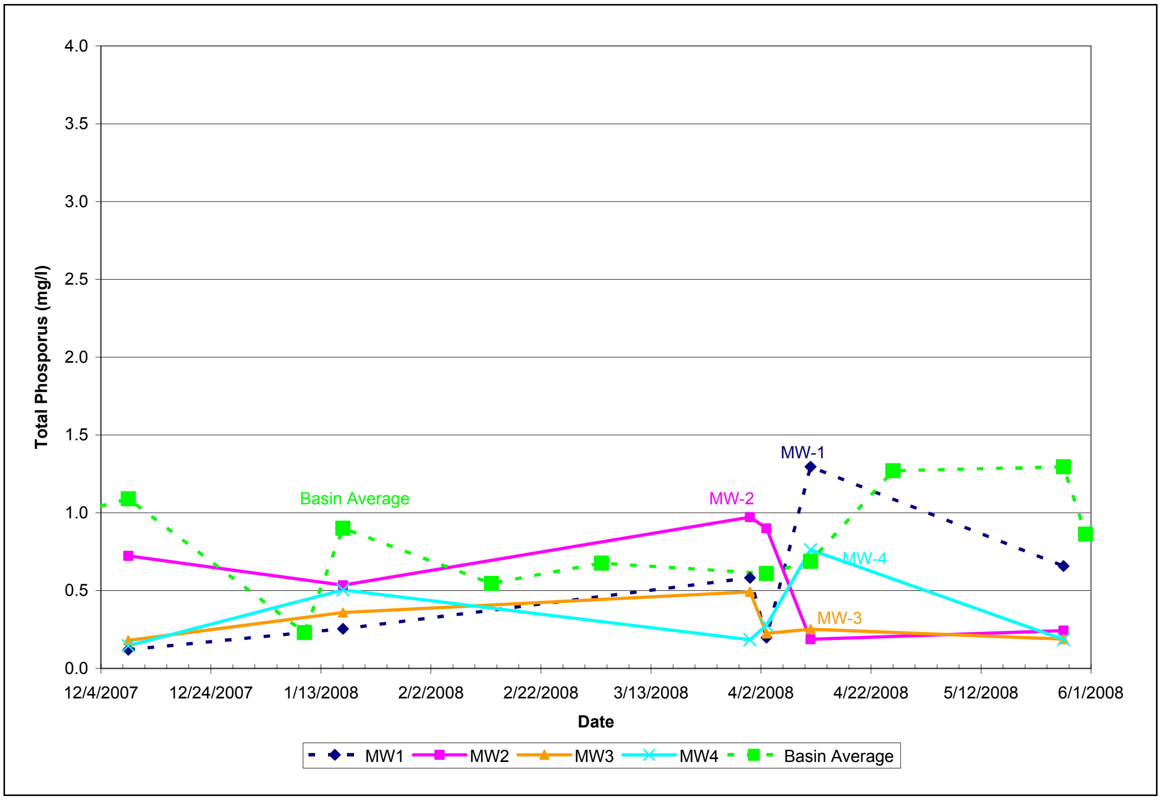

Figure 64: Total Phosphorus Comparison of Basin and Groundwater Samples

Figure 64 shows that the basin samples are variable and generally higher than the most of the groundwater samples. On several occasions MW-1 and MW-2 had concentrations higher than the basin samples, but MW-3 consistently had concentrations lower than the basin samples. The source of the phosphorus at MW-1 may be related to the soil and bedrock geochemistry or it may be a result of surface water infiltration. The area above MW-1 was observed to be a favored spot of migrating Canadian geese that frequently left reminders of their presence. It is possible that water infiltrating to MW-1 transports phosphorus from the surface to the groundwater; however it is also likely that the phosphorus is derived from the natural composition of the soil and bedrock of the aquifer. It was noted during sampling and analysis that the total phosphorus results appear to be linked to the amount of turbidity in the sample; thus it is likely that the soil and bedrock contain phosphorus that may be suspended in the sample due to mixing caused by sample collection. The source of phosphorus at MW-2 may also be related to the subsurface geochemistry, however given its proximity to the basin, it is also likely that phosphorus is transported through the BMP to the groundwater. Although the precise origin of the detected phosphorus is not known, it is imperative to note that the phosphorus concentrations at MW-3 are lower than at MW-1 and MW-2. Assuming that the phosphorus concentration at MW-2 is a result of infiltration through the BMP and that groundwater flows from MW-2 to MW-3, then the lower concentrations at MW-3 indicate that phosphorus is either removed, degraded or diluted by the time it reaches MW-3. The relationship of total phosphorus concentration and sample turbidity make the determination of phosphorus transport uncertain; however, if phosphorus is retained by the BMP and not transported to the groundwater, then the soil and bedrock of the aquifer must contain sufficient phosphorus to create the concentrations detected in the wells.

4.2 Continuous Groundwater Monitoring

4.2.1 Groundwater Conductivity

The following discussion of groundwater conductivity is based upon the values recorded in-situ by the Aqua Troll 200 meters. It should be noted the Aqua Troll conductivity values are generally less than the conductivity measured in the well samples. When groundwater samples are collected, the sample is exposed to the atmosphere, placed in a bottle, transported to the laboratory and again exposed to the atmosphere. Since each instrument is calibrated and maintained appropriately, it is assumed that the associated variations in temperature and environmental conditions are responsible for the variation between the laboratory and in-situ measurements.

The infiltration of stormwater at the BMP is observed to significantly effect the conductivity at MW-2. During warm periods when de-icing salt is not applied, the groundwater has low conductivity, but in winter and early spring when snow accumulates and salt is applied, the conductivity rises. Precipitation naturally has low conductivity due to the lack of dissolved solids, but as runoff travels across the land it acquires dissolved solids, such as the chloride ions derived from de-icing salt. Therefore, it is intuitive that the conductivity at MW-2 is low during warm periods and higher during colder periods, when de-icing salt is applied.

As mentioned previously, the EPA SMCL for TDS is 500 mg/l. In general TDS concentrations range from 55% to 75% of the conductivity (Hem 1985; Low *et al.* 2002). Therefore, assuming an average coefficient of 0.65, conductivity levels greater than 769 μS/cm may indicate exceedance of the SCML for TDS. As shown in Figure 55, the conductivity at MW-2 remained above 769 μS/cm from 3/22/08 to 4/27/08, potentially indicating exceedance of the TDS SCML.

Although the conductivity at MW-2 displays a wide variation, the wide fluctuation is attenuated by the time it reaches MW-3. However, the conductivity at MW-3 is generally lower than at MW-1 and this may be due to dilution caused by infiltration at the site. Thus it appears that the net effect of the basin is to slightly lower the ambient groundwater conductivity. Still, the difference in conductivity between MW-1 and MW-3 is relatively small and likely represents an inconsequential impact, if any. Furthermore, the potential TDS SCML exceedance is observed to be of short duration and limited extent.

4.2.2 Groundwater Temperature

As can be seen in Figure 57, stormwater infiltration has a significant effect on groundwater temperature in the immediate vicinity of the site, but the effect is sufficiently reduced within a relatively short distance. Although MW-2 is observed to have a significant fluctuation in temperature in response to stormwater infiltration, MW-1 and MW-3 remained relatively stable. While MW-3 has a slightly lower temperature than MW-1 the difference is rather small and most likely inconsequential. The observed results indicate that the travel time between the site and MW-3 is sufficiently large to restore the groundwater to ambient conditions.

The implications of the temperature monitoring suggest that there is minimal downstream impact related to stormwater infiltration. However, given the relationship between temperature and hydraulic conductivity (Bouwer 1978; Fetter 1997; Emerson 2008), the colder temperatures observed at MW-2 translate into slower infiltration and groundwater flow, which may likely increase the extent of groundwater mounding. This may be a factor contributing to the observed groundwater mounding after the 10/26/07 and 3/4/08 storm events. The 10/26/07 event produced 3.76 inch of precipitation over 24 hours while the 3/4/08 event produced 3.09 inch of precipitation over 4 days, but the groundwater rose 3.33 ft after the 3/4/08 event and only 1.961 ft following the 10/26/07 event. The groundwater temperature on 10/26/07 ranged from 14.06^{o}C to 14.54 ^{o}C, while on 3/4/08 the range was 10.14 ^{o}C to 12.06 ^{o}C. Therefore, the relationship between groundwater mounding and rainfall is also likely to be heavily dependent upon the temperature of the water. For instance, three storms listed in Table 9, 2/1/08, 5/9/08 and 7/23/08 had similar rainfall volume, but MW-2 had a different response for each storm. The 5/9/08 storm had the largest response and the lowest temperature, while the 2/1/08 storm had the smallest response and warmest temperature. While there are many factors involved with infiltration and groundwater mounding, it is apparent that water temperature plays a large role and that lower temperatures generally lead to increased mounding due to slower infiltration and groundwater flow rate.

4.2.3 Groundwater Mounding

The infiltration of water to an unconfined aquifer naturally causes the groundwater elevation to rise, thus water level fluctuations observed at the monitor wells are to be expected. Infiltration BMP focus recharge in a specific area rather allowing rainfall to infiltrate over a dispersed area. The question thus arises, how does focused recharge effect the change in groundwater elevation? Groundwater monitoring for this study shows that for storms smaller than approximately 0.75 inch, the wells closest to the site display less change in groundwater elevation compared to the other wells. However for storms greater than 0.75 inch the reverse is observed. Table 9 presents a summary of the groundwater elevation increases following several storms. In addition, Figure 65 plots the change in groundwater elevation versus total rainfall.

Table 9: Groundwater Elevation Fluctuation in Response to Precipitation

Storm Date	Total Rainfall (in)	Total Inflow (ft^3)	Elevation Change (ft)			
			MW1	MW2	MW3	MW4
12/09/07	0.18	426	0.170	0.040	0.030	0.110
11/06/07	0.21	273	0.030	0.000	0.000	0.000
02/25/08	0.25	1173	0.400	0.020	0.050	0.040
03/31/08	0.27	426	0.180	0.040	0.060	0.020
05/27/08	0.27	525	0.270	0.030	0.010	0.040
07/14/08	0.45	1046	0.490	0.310	0.020	0.100
04/03/08	0.53	1146	0.480	0.350	0.040	0.250
11/15/07	0.54	627	0.670	0.270	0.000	0.190
08/10/08	0.54	1202	0.648	0.232	0.001	0.130
04/11/08	0.55	1062	0.480	0.350	0.040	0.250
09/11/07	0.68	1451	0.660	0.330	0.001	0.180
08/09/07	0.70	1488	0.760	0.600	0.015	0.360
01/17/08	0.70	1344	0.500	0.180	0.080	0.160
06/27/08	0.73	1541	0.650	0.511	0.006	0.350
12/23/07	0.83	1626	0.610	1.300	0.135	1.120
06/04/08	0.97	1958	0.590	0.830	0.060	0.660
12/16/07	1.12	2280	0.740	1.100	0.535	1.360
02/01/08	1.50	3155	0.930	1.100	0.350	0.890
07/23/08	1.55	3136	1.280	1.310	0.180	1.040
05/09/08	1.58	3199	1.040	1.500	0.320	1.150
10/10/07	2.51	5593	2.010	2.006	0.291	1.520
03/04/08	3.09	6554	1.770	3.330	0.900	2.830
08/19/07	3.15	6876	1.780	3.650	0.768	2.730
10/26/07	3.76	8832	1.584	1.961	0.929	1.630
R^2 Value			0.863	0.837	0.847	0.818
Correlation Coefficient			0.929	0.915	0.920	0.904

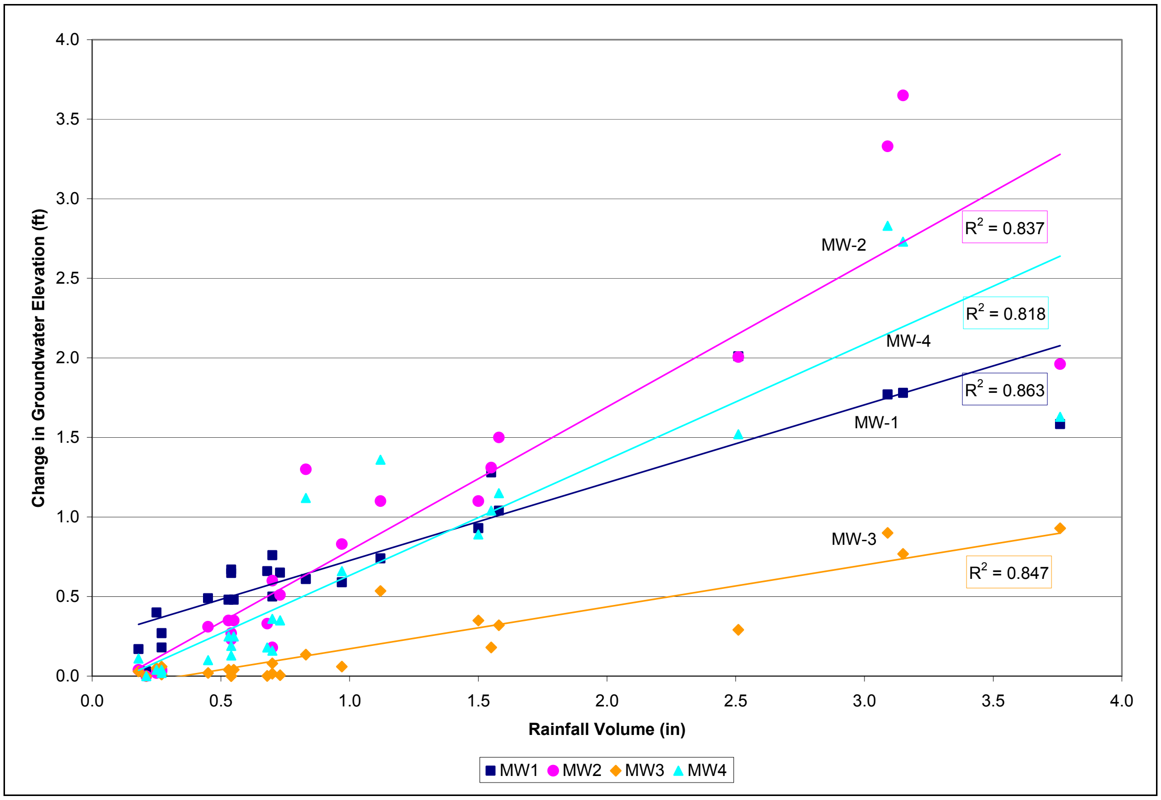

Figure 65: Groundwater Mounding Comparison

Based on the changes in groundwater elevation, it is concluded that for storms less than 0.75 inch the site does not significantly increase the magnitude of groundwater mounding. As shown in Figure 65, for storms less than approximately 0.75 inch, MW-1, which is upgradient of the site, displays a larger increase in groundwater elevation than MW-2. For larger storms MW-2 displays a larger increase in groundwater elevation. However, the groundwater elevation changes at MW-3 demonstrate that the increased mounding observed at MW-2 is attenuated prior to reaching MW-3.

It is believed that the infiltration rate is a primary factor affecting the extent of groundwater mounding. As an analogy, it is proposed that the subsurface below the site is similar to a retention basin and that the infiltration rate is equivalent to an outlet control structure. Expanding upon this analogy, it is observed that the infiltration rate at MW-1 is more rapid than at MW-2 and MW-4; as can be seen by the rapid rise in groundwater elevation at MW-1 after a storm. For a given storm less than 0.75 inch, rain rapidly infiltrates near MW-1 causing a quick increase in groundwater elevation. At MW-2, a slower infiltration rate requires a longer duration for water to reach the groundwater. Thus in a given time period, less volume of water is delivered, resulting in a lower rise in groundwater elevation. However, due to the BMP, more total volume of water is infiltrated near MW-2 and this larger volume is conveyed to the groundwater over a longer period of time. Therefore the hydrograph at MW-2 has slow gradual changes in elevation that are sustained for a longer duration. Returning to the retention basin analogy, just as a retention basin stores a volume of water and releases it at constant rate based on the outlet control structure; the infiltration rate at MW-2 restricts the release of water to the aquifer at a low rate over a long duration.

Continuing with the retention basin analogy, it appears that for storms smaller than 0.75 inch, the infiltration rate is sufficiently low to allow water to be stored in the vadose zone without causing a large increase in groundwater elevation. However, for larger storms, infiltration occurs over a sufficient duration to produce larger increases in groundwater elevation. Also for larger more intense storms the basin is maintained at capacity for longer durations and the surface soil of the drainage area may become saturated so that rainfall produces runoff rather than infiltration and this runoff flows into the basin rather than the groundwater near MW-1.

Although larger storms lead to increased mounding at MW-2 and MW-4, the hydrographs from MW-3 indicate that the mounding does not extend far downgradient. In addition, the mounding near the site remains at a significant depth below the basin. The maximum groundwater elevation observed at MW-2 occurred on 3/10/08 in response to 3.09 inch precipitation and was still 12 ft below the bottom of the basin. Thus substantial storage volume exists in the vadose zone to accommodate larger runoff events.

An interesting observation regarding groundwater fluctuations is that the observed rise in groundwater elevation does not correlate well with the amount of precipitation. Table 9, previously, presents R^2 values and correlation coefficients for the volume of precipitation and the associated rise in groundwater elevation. MW-1 has the highest R^2 value and correlation coefficient of 0.863 and 0.929, while MW-4 has the lowest values of 0.818 and 0.904. These statistics indicate that the values are related, but that there is not a strict correlation solely between the rainfall volume and rise in groundwater elevation. This implies that other factors, such as rainfall intensity, temperature, antecedent moisture content and evapotranspiration play a significant role in the magnitude of groundwater mounding.

4.2.4 Groundwater Velocity and Contaminant Transport

Groundwater flow is dependent upon hydraulic gradient to provide the head to create movement. A steep gradient causes faster flow than a shallow gradient. For example, with all other aquifer properties equal; the steep hydraulic gradient observed between MW-2 and MW-3 generates a faster flow rate than the shallower gradient between MW-1 and MW-2. However the hydraulic gradient fluctuates based on precipitation and as discussed above, larger storms increase the mounding near the basin. The question arises: how does increased mounding effect the groundwater flow rate?

To evaluate the effect of mounding on groundwater flow rate, the following calculation is presented. Using Equation 1 and assuming a hydraulic conductivity of 0.5

ft/day, an effective porosity of 0.4, and the minimum, average and maximum observed hydraulic gradients the following average linear velocities are calculated: 0.11, 0.14 and 0.18 ft/day. While these values appear relatively similar, when they are used to calculate the travel time between MW-2 and MW-3 the results are: 573, 450 and 350 days. So the result of groundwater mounding may have a significant impact on the transport of groundwater. Because the groundwater elevation is rather stable at MW-3, the hydraulic gradient is primarily dependent on the groundwater elevation at MW-2. The hydrographs of MW-2 show that the groundwater generally recedes to pre-storm elevation within five to eleven days; thus the maximum gradient is not applied over a long period of time. Thus the gradient and flow rate will constantly vary but will trend toward an average over the course of several days.

Variations in groundwater velocity affect the transport of any dissolved contaminants. The transport of conservative, non-reactive contaminants, such as chloride may be estimated with advection-dispersion equations based on Fick's Laws (Bouwer 1978; Tchobanoglous and Schroeder 1985; Fetter 1997; Vance 1997). The advection-dispersion equation as presented in Fetter (1997) is written as:

$$C = 0.5C_o * \{erfc[(L-v_xt)/(2\sqrt{(D_Lt)})] + exp(v_xL/D_L) * erfc[(L+v_xt)/(2\sqrt{(D_Lt)})]\} \quad \textbf{Equation (2)}$$

In this equation the concentration (***C***) at a given location is dependent upon average linear velocity ($\boldsymbol{v_x}$), initial contaminant concentration ($\boldsymbol{C_o}$), the flow path length (***L***), time (***t***) and longitudinal dispersion ($\boldsymbol{D_L}$). While the dispersion coefficient is not known for the site, assuming an average value within the range of $1*10^{-9}$ to $2*10^{-8}$ m^2/s as presented in Tchobanoglous (1985) allows for comparison of transport time in response to variations in groundwater velocity. Since the complimentary error function (***erfc***) is infinitely small for values greater than 3, the latter part of the advection-dispersion equation is negligible given the estimated site parameters. For the latter half of the equation to be valid, the $\boldsymbol{D_L}$ would have to be two orders of magnitude larger than the estimated value, but the $\boldsymbol{D_L}$ range for the site aquifer soil texture does not include values this large. Therefore the equation simplifies to:

$$C = C_o/2*(erfc[(L-v_x t)/(2\sqrt{(D_L t)})) \qquad \textbf{\textit{Equation (3)}}$$

Using this equation, the estimated transport times are presented in Table 10, below.

Table 10: Estimated Chloride Transport Time

Estimated Chloride Transport Time				
	Ratio: C_{MW3}/C_{MW2}			
Gradient	**1%**	**10%**	**25%**	**50%**
Minimum	506 days	535 days	553 days	573 days
Average	403 days	424 days	436 days	450 days
Maximum	318 days	332 days	340 days	350 days

Since the **erfc** function has a maximum value of 1 and because the latter part of the full advection-dispersion equation is negligible given the assumed site parameters; the maximum predicted downstream concentration is 50% of the initial concentration. Thus the equation predicts that the effects of dispersion, advection and dilution will significantly attenuate the downgradient chloride concentration.

Table 10 demonstrates the effects of advection and diffusion with respect to chloride transport. When advective-diffusive factors are considered it is estimated that chloride will begin reaching MW-3 approximately 1 to 2 months sooner than estimates made with only average linear velocity. For example, as presented above assuming the maximum gradient and using Equation 1 the travel time is 350 days whereas Equation 3 predicts chloride will begin reaching MW-3 after only 318 days. However, the accelerated transit time also entails lower concentration due to dispersion. For instance the advection-diffusion equation (Equation 3) predicts that the maximum concentration will be approximately half of the initial concentration. So while the same mass of chloride is transported, it is spread over a larger volume both longitudinally and laterally (Vance 1997; Heath 2004). The resulting spatial concentration distribution is referred to as a contaminant plume (Fetter 1997; Winter *et al.* 1998).

Due to the long travel time, fluctuating gradient and the variable chloride concentrations observed at MW-2, it is difficult to accurately determine the significance of the chloride concentration at MW-3. For instance, the concentration observed at MW-3 may be the result of water that passed through the BMP over a year ago. Given the large variation in groundwater velocity with respect to small variations in hydraulic conductivity, the accuracy of such calculations becomes more uncertain. Perhaps the most important observation is that after over seven years of BMP operation, the concentration at MW-3 shows low variation and is generally less than observed at MW-1 and MW-2, and always less than the concentration at MW-4. In fact, the concentration at MW-3 ranges from 50% to 65% of the concentration at MW-4.

Chapter 5. Conclusions

5.1 Water Quality

5.1.1 Conductivity

The conductivity of influent and ponded water was observed to vary widely over the course of the year, likely in response to the application of de-icing salts. In contrast, the conductivity of the deeper lysimeters and the groundwater had much less variation. The observed results indicate that the processes associated with infiltration stabilize the conductivity, by reducing the peak conductivity and maintaining a higher minimum value. It is therefore concluded that the subsurface has the capacity to retain dissolved solids and to slowly release ions during subsequent storms thus producing the stable conductivity observed in the vadose zone and groundwater. The net affect is that the groundwater is able to maintain relatively stable conductivity, which is lower than the vadose zone and significantly lower than the influent and ponded water.

Although, the BMP was observed to attenuate the high conductivity of the influent water, the groundwater at MW2 likely exceeds the EPA SMCL for TDS (500mg/l) during certain periods of the year. Thus the BMP does degrade the groundwater quality. However the duration of the impact is limited to a period of several weeks and the full extent of impact does not reach the downgradient well (MW-3). Still the average conductivity at MW-3 is higher than the average and median conductivity values for groundwater in similar geological settings as reported in the regional studies by Ludlow and Loper (2004) and Low *et al (2002)*. As mentioned previously, the wells utilized in the studies mentioned above are generally much deeper and are completed solely in bedrock. Therefore, the surface water recharging these wells has traveled a farther distance and had more potential for attenuation. Thus the discrepancy between the regional averages and the current study may likely be due to the well depth. Furthermore, the upgradient well (MW-1), considered to represent background conditions also had a sample in exceedance of the SMCL. So it is likely that in general, the local shallow groundwater has higher than average conductivity. While the values at MW-2 were higher than MW-1, the results suggest that the impacts of BMP may not be substantially different than turf covered areas adjacent to paved areas.

5.1.2 Chloride

Results of this study indicate that the site is effective at attenuating the concentration of chloride as influent water passes through the site and into the groundwater. This finding is contrary to the typical conservative behavior of chloride and to the findings of Pitt *et al*. (1999). During periods when the influent and vadose zone water had high chloride concentrations, the groundwater concentrations were observed to be lower than both the vadose zone and basin concentrations. However, when the influent concentrations declined, the vadose zone and groundwater chloride concentrations remained relatively stable. It is apparent that the processes involved with infiltration, dilution and groundwater flow serve to attenuate high chloride concentrations. Similar to the results of the conductivity analyses, it is inferred that the attenuation of chloride is largely a result vadose zone retention, prolonged release and dilution of chloride in the groundwater. It is assumed that approximately the same total mass of chloride is transported through the system, but the chloride is transported slower than the infiltrating water due to retention, dilution and evapotranspiration in the basin and vadose zone.

Similar to the conductivity results, the chloride concentration at MW-2 exceeded the EPA SMCL of 250 mg/l. However, the exceedance lasted for a short duration and the extent of groundwater degradation is limited to MW-2 since the downgradient well (MW-3) maintained a stable concentration between 61 mg/l and 120 mg/l. While the chloride concentrations at MW-3 are two to ten times greater than the average regional values reported by Ludlow and Loper (2004) and Low *et al (2002)*, the concentrations at MW-3 are generally lower than the concentrations at MW-1. Therefore, it is likely that the BMP dilutes and/or attenuates the chloride concentration. Overall the chloride results indicate that the impact of the BMP has a limited extent and duration.

5.1.3 Phosphorus

Precise conclusions with respect to total phosphorus are hindered by the relationship of total phosphorus and sample turbidity. Phosphorus is known to become sorbed to soil particles and organic material; therefore sample turbidity may increase the resulting total phosphorus concentration. Accurate determination of phosphorus transport requires additional testing and may require a different sampling protocol. Aside from the inherent limitations of the employed sampling methodology, results indicate that infiltration processes reduce the total phosphorus concentration of influent water during transport to the groundwater. Groundwater results indicate total phosphorus concentrations higher than those observed in vadose zone samples; however this is likely due to sampling methodology. On average the groundwater samples contained lower phosphorus concentrations than influent water, indicating potential reduction. Furthermore, although MW-2 generally had higher concentrations than the upgradient well (MW-1), the concentrations in the downgradient well (MW-3) remained consistently less than both wells and the influent water. Thus it is concluded that the BMP and the processes associated with infiltration and groundwater transport serve to reduce the total phosphorus concentration in downgradient groundwater.

5.2 Groundwater Monitoring

5.2.1 Mounding

The formation of a groundwater mound is a natural occurrence associated with recharge to an unconfined aquifer. When the downward infiltration of water through the vadose zone exceeds the lateral flow rate of the unconfined aquifer, the result is an increase in groundwater elevation, or a groundwater mound. Continuous monitoring at the site wells indicates increased groundwater mounding occurs near the BMP in response to storms greater than 0.75 inch. The increased mounding appears to be limited to a relatively small area adjacent the site and is assumed to be predominantly vertical with minimal lateral extent. This assumption is supported by the lack of mounding observed at the downgradient site well (MW-3). Although increased mounding is observed following larger storms, the groundwater remains at sufficient depth below the site (12 ft). Given the extent and duration of groundwater mounding observed, it is concluded that sufficient storage capacity exists in the vadose zone to accommodate much larger storms without adversely affecting the local subsurface. Furthermore, it is concluded that for smaller storms, the BMP produces lesser groundwater mounding, as measured by the overall increase in groundwater elevation, than the turf covered area near MW-1. The difference in groundwater mounding is concluded to be related to the difference in infiltration rate between the area near the BMP and MW-1.

The rate of infiltration is observed to be a primary factor affecting groundwater mounding and further, temperature is observed to influence the infiltration rate and the resulting mound. As analogy, the infiltration rate is similar to an outlet control structure of a retention basin. Just as the control structure limits flow and maintains a steady release rate, so to does the infiltration rate control limit recharge to the unconfined aquifer. For storms less than 0.75 inch, the infiltration rate sufficiently slows the downward flow of water through the vadose zone and allows lateral groundwater flow to dissipate the influent water. However, for storms larger than 0.75 inch, infiltration occurs over a sufficiently long duration to form a groundwater mound. Regarding temperature, the infiltration rate is dependent on hydraulic conductivity, which is a partial function of temperature. As the temperature decreases so does the hydraulic conductivity and infiltration rate of the groundwater and vadose zone and observations indicate that lower temperatures correlate with increased groundwater mounding.

5.2.2 Groundwater Velocity and Contaminant Transport

The observed mounding related to stormwater infiltration affect the rate of groundwater flow and subsequent contaminant transport. The uncertainty in aquifer properties, such as effective porosity and hydraulic conductivity, adds considerable uncertainty to estimates of groundwater velocity and contaminant transport. Based on the best available estimates, groundwater travel time and contaminant transport rates across the site are on the order of several hundred days. Due to the long duration and inherent uncertainties, it is difficult to precisely conclude the nature of contaminant transport from the site to the downgradient well. However, the observed data indicate that sufficient attenuation occurs between the site and the downgradient well. These observations indicate that the site and local groundwater system adequately reduce the concentrations of the sampled parameters during transport to the downgradient well. Hence it is concluded that at the point of surface water discharge, the impact of the BMP is negligible.

5.2.3 Groundwater Temperature and Conductivity

Continuous monitoring of the groundwater temperature and conductivity via the In-Situ Aqua Troll 200 meters, indicate that infiltration at the BMP causes significant fluctuations near the site but that these fluctuations are attenuated downgradient. The temperature and conductivity at MW-1 and MW-3 are similar, indicating that infiltration through the site does not significantly impact the downgradient water. However, stormwater infiltration is observed to significantly alter the groundwater temperature and conductivity at MW-2 for prolonged periods. Decreases in temperature are observed to be related to increased groundwater mounding, thus while the downgradient temperature may not be effected variations in temperature effect the performance of the system.

5.2.4 Comparison of MW1 and MW2

MW-1 is topographically and hydraulically upgradient from MW-2 is intended to represent background conditions. MW-2 is located adjacent to the BMP. The area above MW-1 is a grass field located near the local surface water drainage divide. MW-1 receives recharge from a relatively small grassy area whereas MW-2 receives recharge from a proportionately larger area, including a roadway and parking area. The hydrograph at MW-1 is very flashy, showing a quick response to storms with rapid groundwater elevation rise and decline. In contrast, the hydrograph at MW-2 shows a delayed but prolonged response to precipitation with slow groundwater elevation changes occurring over an extended period. Water quality monitoring shows minimal variation in temperature, conductivity and chloride at MW-1, except after large storms and snowmelt. Monitoring at MW-2 shows a significant impact of infiltration with large fluctuations in temperature, conductivity and chloride concentration. Based on these results, it is concluded that the BMP significantly affects the local hydrology and water quality, however based on downgradient monitoring it is further concluded that the net affect of the BMP is negligible, particularly with respect to the larger watershed quality and hydrology. For example, although the water quality varies at MW-2, such changes are not observed at MW-3. Likewise, the increased mounding at MW-2 has minimal downgradient impact. Therefore the groundwater quality and hydrology is not significantly affected and the local surface water is not impacted as it would be using conventional stormwater management practices.

5.3 Review of Key Questions

As presented in the Problem Statement (Chapter 1.1) the primary questions of this study are:

- What is the extent of groundwater mounding that occurs in response to focused recharge and furthermore,
- What are the impacts of the resultant mounding?
- Do the physical, chemical and biological processes involved with infiltration and groundwater flow remove contaminants from influent water?
- Does focused recharge dilute or saturate ambient groundwater conditions?
- What pertinent information can be gathered from groundwater monitoring of infiltration BMP?
- Should groundwater monitoring be included with BMP assessment and monitoring and if so, how should it be done?

- What site selection criteria and design parameters should be considered for infiltration BMP to reduce the potential risks to groundwater?

This study indicates that the extent of groundwater mounding near the site is minimal in response to storms less than 0.75 inch, but increased for larger storms. The mounding is generally restricted to the area near the site and does not extent to the downgradient well. The groundwater remains at a sufficient depth below the ground surface and the mounding is concluded to have minimal impact on the overall groundwater flow and contaminant transport. Water quality sampling and monitoring indicate that contaminant concentrations are significantly attenuated during infiltration and groundwater flow. Although groundwater is observed to exceed the SMCL for chloride and TDS, the exceedance occurs for a limited duration and is generally limited to the area near the BMP. Furthermore downgradient sampling and monitoring indicates that concentrations are returned to background conditions during groundwater transport. The observed attenuation is concluded to be due to a combination of dilution, retention, evapotranspiration and dispersion. This study demonstrates the utility of groundwater monitoring for evaluating BMP performance and contaminant transport. The following chapter presents several recommendations for the use of groundwater monitoring for BMP design and assessment.

Chapter 6. Recommendations

6.1 Design Considerations

6.1.1 Subsurface Storage

The findings of this study offer insight to the design of infiltration BMP. Specifically, the observed groundwater mounding underscores the importance of ensuring that adequate capacity exists at a site to accommodate infiltrated volumes. At the study site, increased groundwater mounding occurs in response to storms greater than 0.75 inch, but groundwater depth did not rise above 12 ft below the basin. However, the groundwater depth ranged from 12 to 20 ft, therefore it is important to consider the season and recent rainfall conditions when estimating the depth to groundwater for site design. Groundwater monitoring is a very useful tool for determining existing capacity of a site to accommodate stormwater infiltration. Utilizing a monitor well as a pre-design tool will provide information about the depth to groundwater, soil properties, aquifer properties and hydrologic performance.

Determination of subsurface storage capacity must consider the depth to groundwater, but equally as vital is the estimation of vadose and saturated zone effective porosity and hydraulic conductivity. The porosity and hydraulic conductivity are key factors for estimating the subsurface storage volume and the rate at which mounding will dissipate. In addition, study observations demonstrate the influence of temperature on groundwater mounding, with lower temperatures leading to increased mounding. Furthermore, it was observed that infiltration led to a significantly larger temperature range near the site and that lower temperatures persisted well into the summer season. Since decreased temperature is also observed to cause increased mounding by lowering the infiltration rate, it is recommended that BMP designs consider the impact of temperature when estimating BMP size and performance.

6.1.2 Water Quality

While study results indicate concentration reduction of chloride, conductivity and total phosphorus it is important to note that transport still occurs. BMP design must consider the land use of the drainage area, the quality of the influent water, the soil properties related to contaminant fate and transport, ambient groundwater quality and downgradient receptors. Furthermore, design should consider the transport times related to infiltration and groundwater flow. For instance, assessment of site performance with respect to groundwater quality must factor the time required for transport to occur.

6.1.3 Pervious Surfaces

Groundwater monitoring at MW-1 indicates rapid response of the groundwater elevation following storm events. These observations demonstrate that the grass covered pervious area surrounding MW-1 has a good ability to infiltrate stormwater over a short duration. It is therefore recommended that site design seek to maximize the amount of grass covered pervious area, wherever feasible. Furthermore it may be beneficial to line inflow channels with grass or similar pervious cover to maximize the area conducive to infiltration.

6.1.4 Design Storms

This study demonstrates the effectiveness of the BMP for handling storms less than 0.75 inch. For small storms, it is observed that the extent of groundwater mounding at the BMP is similar to upgradient conditions. In addition, water quality sampling and monitoring indicate that contaminant concentrations are significantly reduced during infiltration and are sufficiently attenuated during groundwater flow to the downgradient well. These findings are particularly relevant since over 80% of the annual precipitation in the region occurs during small storms. Thus it is recommended that similar BMP are considered for stormwater management in regions with similar design requirements.

6.2 Future Investigations

6.2.1 Total Phosphorus Analysis

The total phosphorus analysis was noted to be sensitive to the presence of suspended and dissolved solids. Phosphorus has an affinity to sorb to various soil particles or colloidal particles and thus turbidity in samples may significantly increase the total phosphorus concentration, while not actually representing the amount of phosphorus dissolved in the water (Hem 1985; Massoudieh *et al.* 2007). While total phosphorus is often a valuable analysis for studies of biological availability of nutrients, it may not be the most appropriate analysis for groundwater transport studies. Two possible alternatives would be to either filter the samples prior to analysis or to switch analyses. Sample filtration is already conducted as part of the metals and total solids procedures and therefore would not require significant changes to the current sampling protocol. Switching analyses may be a fruitful endeavor and it is recommended that the interested research consider analysis of orthophosphate, however this analysis may require additional time and labor.

6.2.2 Groundwater Sampling Protocol

It is recommended that future groundwater sampling be conducted on a monthly basis rather than a storm by storm basis. Given the estimated travel time between wells and infiltration rate, it is sufficient to extend the sampling interval. Furthermore, the number of samples collected from each well could be reduced to one per well or two samples used as an average. These changes would significantly reduce the sampling effort and might perhaps allow for an expanded suite of analyses, such as solids and orthophosphate.

6.2.3 Long-Term Groundwater Monitoring

The data collected from the AquaTroll 200 meters proved to be very valuable and it is therefore recommended that an additional meter be installed at MW-4. An AquaTroll at MW-4 would significantly expand monitoring and analysis of groundwater conductivity and temperature. Given MW-4s location next to the site it is of interest to assess the impact of infiltration on the temperature and conductivity. Furthermore the additional AquaTroll would provide uniformity in the groundwater data collection method which would be beneficial for data management and analysis. Regardless of the additional meter, it is recommended that the monitoring frequency be reduced from a 15 minute interval to a 30 minute interval. Such a reduction, would significantly reduce the required storage space, speed up the download time and conserve the battery life, all without a detrimental effect to the data quality.

Another potential for expansion of the groundwater monitoring and analysis would be the installation of additional monitor wells. Although the site is constrained by the roads, utilities, curbs and other fixtures, there are potential well locations that would yield valuable information. For instance a well between MW-1 and MW-2 on the grass area adjacent the site would provide insight into the shape, extent and duration of the resulting groundwater mound. Such a location would also provide insight into the flow and transport of contaminants in the subsurface. Another potential location would be adjacent to the retaining wall across the street from the site. This location would provide further delineation of the groundwater table and the resulting mound. The monitoring network created by this suggested configuration would provide a good framework for future groundwater modeling with programs such as MODFLOW.

6.2.4 Temperature Monitoring

Based on the observed relationship between groundwater temperature and mounding, future research is warranted. Such research should consider the observed groundwater temperature and subsequent temperature variations in conjunction with the volume of infiltration, storm duration, basin ponding duration and the resulting groundwater mounding. Knowledge of this relationship will likely be useful for the design of infiltration BMP and performance prediction.

6.2.5 Total Suspended/Dissolved Solids

Due to limited sampling equipment and associated labor-time, TSS and TDS analyses were not performed on the groundwater samples. For future investigations it is recommended that all groundwater samples be analyzed for both TSS and TDS to assess the relationship between solids, conductivity, chloride and phosphorus concentrations. Several interesting questions remain to be answered, such as what is the relative contribution of chloride to the conductivity. If chloride is not the primary ion related to conductivity, what is? Along these lines, what other ions are present and what are their relative contribution to TDS and conductivity? Another important question to address is what is the relationship between TSS/TDS and total phosphorus? A possible goal of these investigations would be to determine the relationship between dissolved solids and the conductivity. If the various species contributing to conductivity and their relative proportions were known and found to be relatively constant, then the conductivity analysis could be used as an indicator for the general composition of the water. Conductivity analyses are far easier to conduct than most other analyses, thus if it were found to be a reliable proxy to other parameters, significant time and expense could be saved while increasing the suite of parameters evaluated. Hem (1985) provides an excellent discussion of water chemistry, sampling and analysis in relation to conductivity.

6.2.6 Cumulative Water Quality Impacts

Study observations indicate that certain contaminant concentrations are reduced during the conveyance to groundwater. However, the reduced concentrations exist for long durations. Thus while the concentration is reduced it is present for a long duration. A potential topic for future research is a watershed-scale study of the cumulative effect of infiltration BMP. An analogy is made to the observed cumulative effect of retention basins. While retention basins serve to reduce local peak flows, an observed side effect is the increased duration of peak flow and flow rate at a watershed-scale (Emerson 2008). Application of this concept to bioinfiltration prompts the question of the cumulative effect that many infiltration BMP may have across an entire watershed. Specifically, what is the impact of long duration transport of low concentrations on baseflow? Further, if the baseflow is altered, what is the impact to local streams and is there an observable difference between bioinfiltration BMP and non-vegetated infiltration BMP?

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