MONITORING THE EFFECTIVENESS OF STORMWATER INFILTRATION TRENCHES AT THE PENNYPACK PRESERVE, MONTGOMERY COUNTY, PENNSYLVANIA

A Thesis
Submitted to
the Temple University Graduate Board

In Partial Fulfillment
Of the Requirements for the Degree
MASTER OF SCIENCE

By
Catherine Jedrzejczyk
May 2010

Thesis Approvals:

Laura Toran Thesis Advisor, Department of Earth & Environmental Science
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Dennis O. Terry, Jr., Department of Earth & Environmental Science
Nicholas C. Davatzes, Department of Earth & Environmental Science

ABSTRACT

As a result of urbanization, impermeable surfaces cover about 40% of land area around Pennypack Creek (Philadelphia, PA). The resulting increase in stormwater runoff leads to flooding, bank erosion, and stream habitat degradation. Stormwater Best Management Practices (BMPs) have been constructed in the Pennypack Preserve (Montgomery County, PA) to evaluate the effectiveness of various mitigation techniques.

The BMPs include a row of 3 infiltration trenches constructed in July 2006 to compare different designs. Water level data were recorded in monitoring wells from December 2006 through June 30, 2009, in addition to controlled infiltration experiments. The monitoring wells in the infiltration trenches allowed monitoring of any gradual loss of mitigation effectiveness and for quantitative comparison of the different trench designs. The right and center trenches are filled with gravel, and the left trench is filled with sand. The center trench is distinguished from the right by a leaf filter.

Both seasonal data and controlled experiments showed water in the trenches drained at different rates in the different sections. The right gravel-filled trench tended to have the highest peak water levels followed by the center gravel with filter trench. The center trench showed a slow drainage rate from the beginning of monitoring, thus any effect of the center trench's leaf filter was obscured. The sand-filled trench showed the fastest drainage rate of the 3 trenches.

The drainage rate was uniform within each trench over the 2.5 years of monitoring. The seasonal data showed that the right gravel-filled trench showed the most water level peaks, and the center gravel-filled and left sand-filled trenches responded to

fewer storms over time. However, the uniform drainage rate suggests this decline in response was not due to degradation but rather a change in water delivery.

As of May 2009, water from most storms flowed into only the right gravel trench due to berm erosion. At the end of the study, water level data showed that the trenches continued to receive stormwater without overflowing and drain within 72 hours, the Pennsylvania Department of Environmental Protection recommended design limit. Monitoring water level data in the infiltration BMP showed drainage effectiveness over time but also pointed out how unplanned design differences (water delivery and construction variation) affected trench behavior. Monitoring is the key to developing successful designs, implementation, and maintenance of stormwater BMPs.

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CHAPTER 1

INTRODUCTION

1.1 Background

Land development increases the extent of impermeable surfaces. Paved roads, parking lots, rooftops, and compacted soils all inhibit rainwater from infiltrating into the ground. Thus, watershed hydrology is severely impacted by urbanization. Stormwater in urbanized areas flows over the land, leading to an increase in flow into streams during storms. This stormwater often carries with it sediment and other contaminants. Just 10% coverage by impervious surfaces causes harmful increases in runoff (Booth and Jackson, 1997).

The decrease of permeable surfaces in a watershed reduces infiltration leading to reduced base stream flow, increased volume and velocity of overland runoff, and increased frequency and severity of flooding (Leopold, 1968). The resulting increase in runoff water volume also increases erosion that can cause changes in stream morphology (Smith et al., 2005). The increase in bank erosion and redistribution of stream sediment alter the habitats of stream organisms. Stream bank erosion and amplified flooding damage property and infrastructure, creating financial impetus for developing stormwater control measures. In addition, stream ecosystems are impaired by temperature changes and the pollutants brought in by storm runoff (Paul and Meyer, 2001). These conditions mean that few urban streams resemble their natural state.

Some of the earliest water control measures to reduce stream degradation were attempted in Philadelphia. Late 19th century city engineers used existing streambeds as locations for underground sanitary sewers. The primary goal at the time was to protect public health since the polluted streams contributed to the spread of diseases. Therefore, piping and burying the streams was a practical solution. In addition, using naturally established gravity driven paths for water required less labor (Levine, 2008). Many of the underground sewers that are still used were designed as combined sewers in which stormwater and sanitary sewage is mixed. Initially, stormwater management practices were designed to protect human life and property from flood damage by carrying water away quickly (National Research Council, 2008).

The use of pipes to swiftly deliver stormwater to bodies of water continued into the second half of the 20th century. When it became apparent that stormwater runoff was having a negative effect on streams, lower impact stormwater management methods began to be developed. Early solutions primarily consisted of detention basins or wet ponds to hold piped in stormwater before discharging to streams. The goal became to reduce peak flow rate to streams in addition to addressing flooding. If designed correctly, detention systems slow the velocity of runoff and allow sediment to settle. However, detention does not address the issue of high volumes of urban runoff to streams and reduced groundwater recharge.

Later, engineers developed a category of structural stormwater solutions that included infiltration systems such as porous pavement and infiltration trenches (Urban Land Institute, 1975). These were designed to increase the infiltration capacity of surfaces so that the amount of runoff is decreased (US EPA, 1999a). In particular, infiltration methods address the issue of decreased base flow in streams due to a reduction in groundwater recharge due to urbanization. An early mention of infiltration as a stormwater solution came in 1984. Referred to as a storm water retention and disposal system, the early design resembles the current EPA fact sheet infiltration trench design (US EPA, 1999a). It consists of an excavated hole containing a perforated pipe with gravel backfill and a geotextile liner (Goddard, 1984).

Since then, a variety of low impact urban stormwater Best Management Practices (BMPs) have been developed as nonpoint source pollution control measures. Some experts now prefer the term stormwater control measures (SCMs) (National Research Council, 2008), but most of the current literature uses the term BMPs. The EPA defines a stormwater BMP as a "technique, measure or structural control that is used for a given set of conditions to manage the quantity and improve the quality of stormwater runoff in the most cost-effective manner" (US EPA, 1999b). Specifically, the term BMP refers to not only a structure or set of instructions (Whipple, 1991), but to the entire solution to a problem including construction, maintenance, and monitoring (Barraud et al., 2002).

Infiltration BMPs are an ecologically friendly alternative to more traditional types of stormwater management such as storm drain systems that empty directly into bodies of water (Holman-Dodds et al., 2003). They are relatively small-scale structures that are often used in combination with other stormwater BMPs in larger projects. Individually, they can be installed within existing construction to facilitate infiltration of runoff from rooftops or parking lots. Infiltration trenches are practical in urban areas because the surface of a trench can be reclaimed for use if runoff is delivered to the trench via underground pipe. Another benefit is runoff can be diverted to a group of trenches sized to fit available space. The size of the trench primarily depends on the size of the drainage area, the percentage of impervious surfaces within the drainage area, the infiltration rate of the surrounding soil, and the climate of the region. In Pennsylvania, the maximum recommended infiltration trench size is 8 feet in width and 6 feet in depth (PA DEP, 2006).

An infiltration trench consists of an excavated hole with vertical or gently sloping sides and a level bottom (Figure 1-1). The hole is lined with a geotextile filter layer and filled with sediment with higher hydraulic conductivity than the surrounding soil. Most often the fill medium is gravel. During the excavation, care must be taken to avoid further compaction of the soil within the trench. In addition, sediment control measures must be implemented so that fine sediment from the construction site is not deposited into the trench causing early clogging (US EPA, 1999a). Typically, runoff from impermeable surfaces is piped into the infiltration trench, but sometimes swales and berms are used to direct the water overland.

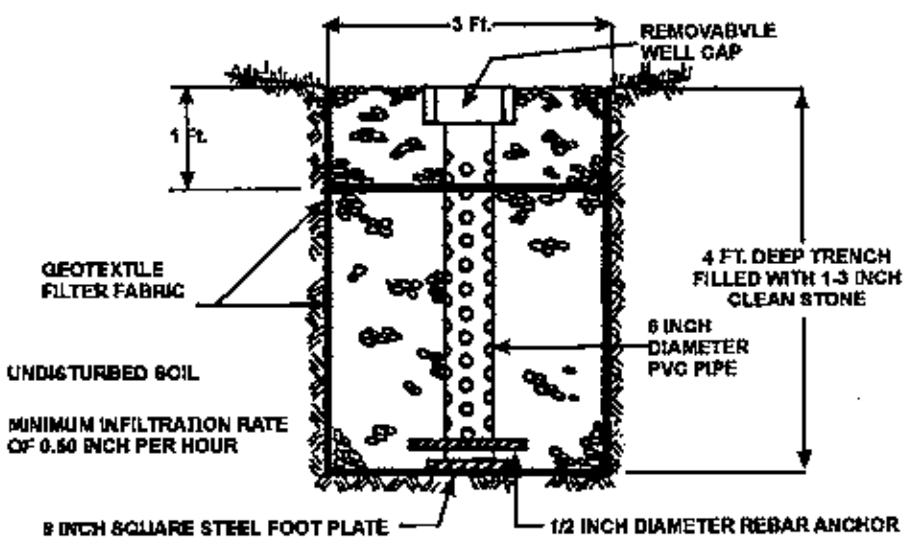

Figure 1-1. Example of infiltration trench design from US EPA (1999a).

Physical clogging of the trench is the primary cause of trenches failing to increase infiltration and reduce excessive runoff. In general, clogging results from fine sediment becoming trapped in the native sediment around the bottom and sides of the trench. As a consequence, hydraulic conductivity decreases, often by orders of magnitude, leading to decay of efficiency in pollutant removal and infiltration rate of a trench. Failure occurs when the trench no longer operates within designated parameters dictated by municipal guidelines. Usually, this means that the trench overflows during an average storm or takes too long to empty. In Pennsylvania, for example, infiltration trenches must be designed to fully drain in 72 hours (PA DEP, 2006).

In the field, a number of factors can alter the predicted lifespan of an infiltration trench. In addition to gradual clogging, mistakes made during design, construction, and maintenance can result in failure. Errors include poor upkeep of the structure, flawed prediction of seasonal high water table, too much compaction caused by construction, flaws in infiltration rate calculations, early sediment clogging from construction, and lack of sediment removal by a BMP used in conjunction with infiltration (Livingston, 2000).

Field studies of trench failure are difficult to summarize because: (1) behavior after construction is not often monitored and reported and (2) differences in design makes direct comparisons difficult. . This is exacerbated by the very small number of studies on small-scale infiltration BMPs. However, laboratory studies show that significant clogging occurs at the interface between the geotextile filter and the surrounding soil. Extremely fine sediment (less than 6 micrometers in diameter) is responsible for this clogging (Siriwardene et al., 2007). To better predict trench efficiency over time, conceptual models are being developed to simulate the clogging of trenches (Freni et al., 2009).

Infiltration is a complicated process that is difficult to evaluate numerically. Freni et al. (2009) conclude that simplified models often underestimate the amount of clogging which leads to inaccurate predictions of trench life spans. Warnaars et al. (1999) refer to a verbal report of 100-year-old infiltration structures; however, there are few studies reporting life spans of trenches in the literature.

Construction of stormwater management projects designed to reduce negative environmental impact is becoming more common. However, once constructed, relatively little monitoring and evaluation of the effectiveness of these systems is conducted (National Research Council, 2008). Warnaars et al. (1999) suggested that reconnecting to a sewer system or replacing a faulty BMP is more cost effective than instituting a monitoring program. The price tag for a new BMP may well be lower than that of monitoring equipment and labor. However, quantifying the efficacy of stormwater management practices would likely improve the implementation of these methods, and determine the circumstances in which they can work at all. Thus, monitoring is the key to achieving and maintaining stormwater management success (Potter, 2006).

1.2 Site Description

The studied infiltration trenches are located on the grounds of the Pennypack Preserve of the Pennypack Ecological Restoration Trust (PERT) headquartered in Huntingdon Valley, Montgomery County in Southeastern Pennsylvania. This nonprofit land trust owns the 720-acre (291ha) Pennypack Preserve located within the Upper Pennypack Creek Watershed (Figure 1-2). The Pennypack Preserve consists of public trails through forests and meadows interspersed with privately owned properties. This

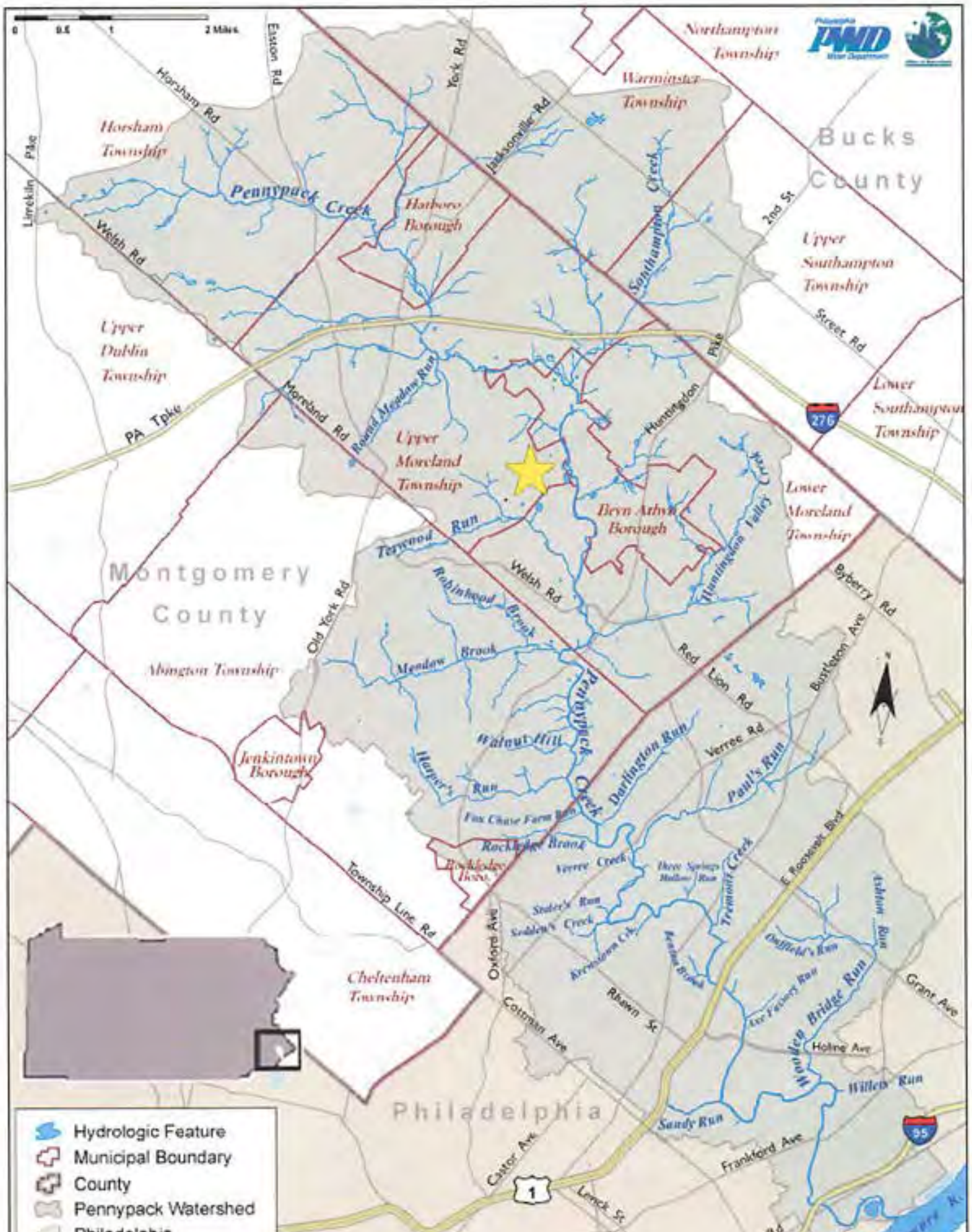

Figure 1-2. Map of Pennypack Creek watershed showing location of study site as yellow star (Adapted from PWD, 2003).

suburban area is located within the Piedmont Uplands physiographic province north of the city of Philadelphia. The region typically experiences 110 cm of rain per year (Cianfrani et al., 2006).

The Pennypack Creek watershed spans the following counties in southeastern Pennsylvania: Montgomery County (56%), Philadelphia County (32%), and Bucks County (12%). The Pennypack Creek is a tributary to the Delaware River. The creek consists of 127 km (79 miles) surface water streams. The watershed covers 145.8 km^2 (56.3 sq miles) of land. There are approximately 2 km^2 (502 acres) of wetlands within the watershed. The elevations range from less than 10 feet above Mean Sea Level to 436 feet (Center for Sustainable Communities, 2006).

Land use in the watershed has evolved from small-scale farms and industry to residential over the last 200 years. Prior to the Industrial Revolution, there were many mills on Pennypack Creek (Levine, 2008). Farms dominated the landscape in the upper reaches of the Pennypack. As of 2000, more than 300,000 people live in the Pennypack Creek watershed. Today, land use is mostly residential with single-family houses as the predominant home type. Wooded areas are the second highest percentage land use. Most of the suburban development within the watershed occurred after World War II. In the upper part of the watershed surrounding the study site, development has continued to the present. However, in this time there has been no new development in the capture area of the specific BMP being studied from 2006-2009.

Land development has had a significant impact on the streams located in the Pennypack Creek watershed. Of these, 82% are considered to be impaired by the PA DEP (Philadelphia Water Department, 2003). Most of the streams do not resemble their natural state because they are cut off from their original floodplains. This, coupled with the large amount of impervious cover in their capture areas, causes the stream banks to be steep and to experience high rates of erosion. A large amount of sedimentation occurs along point bars as a result of the increase in erosion and from sediment-laden overland flow.

1.3 Study History

At the Pennypack Preserve, the Temple-Villanova Sustainable Stormwater Initiative (T-VSSI), a partnership between the Temple-Ambler Center for Sustainable Communities and the Villanova Urban Stormwater Partnership is studying methods of reducing the impact of urbanization on watersheds. This location was chosen due to ease of access for installing BMPs and for holding educational workshops on stormwater management practices. Several types of stormwater BMPS, including an infiltration gallery under a partially porous paved parking lot, 3 infiltration trenches with differing characteristics (Figure 1-3), and a riparian stormwater wetland, were constructed on site. In addition to the desired positive impact on the local stream (Terwood Run), goals for the BMPs included acting as an accessible demonstration to the local community and industry as well as an experimental study site (Temple-Villanova Sustainable Stormwater Initiative, 2006).

Figure 1-3. Photograph of infiltration trench excavation.

CHAPTER 2

METHODS

2.1 Description of Infiltration Best Management Practices

In July 2006, an infiltration gallery was constructed under the parking lot of the PERT Visitor Center. To create storage, this subsurface infiltration gallery was constructed by excavating a trench, laying approximately 1-m-diameter stormwater Recharger® devices at the bottom, and surrounding them with gravel (Figure 2-1). Upon this base, a portion of the parking lot was paved with porous asphalt to allow infiltration of rainwater, and the remainder was paved with conventional asphalt. The parking lot was graded so that runoff would be directed toward the porous pavement. A monitoring well was installed in this parking lot, but the data are not discussed in this study.

Figure 2-1. Photograph of excavation of infiltration gallery under the porous pavement parking lot. Monitoring wells were installed in this BMP, however the data are not discussed in this study.

A row of 3 infiltration trenches down slope from the parking area and up slope from a pond was constructed as an additional BMP. Overland flow not captured by the parking lot infiltration gallery continues down a driveway and is directed to a buried 8 inch PVC pipe that drains onto a hill slope above the trenches and pond below (Figure 2-2).

Figure 2-2. Photographs of stormwater overland flow on driveway within trench capture area (taken on May 16, 2008). Right photo shows drainage to the buried pipe.

The drainage area is approximately 3 acres (1.2 ha) consisting of lawns, forests, and pavement (Figure 2-3), with an estimated 50% impervious surface (Temple-Villanova Sustainable Stormwater Initiative, 2006). The bedrock beneath the trenches is felsic gneiss (Pennsylvania Bureau of Topographic and Geologic Survey, 2001). Within the Pennypack Preserve study site, the soil is classified as silt loam (United States Department of Agriculture, 2005). To estimate infiltration rates for the trench subsurface, percolation tests were performed prior to filling the trenches. On the left side of the hill slope, the average infiltration rate from two tests was 1.3 cm/min and on the right side 0.6

cm/min (Derron LaBrake, Wetlands & Ecology, Inc, personal communication, January 27, 2010).

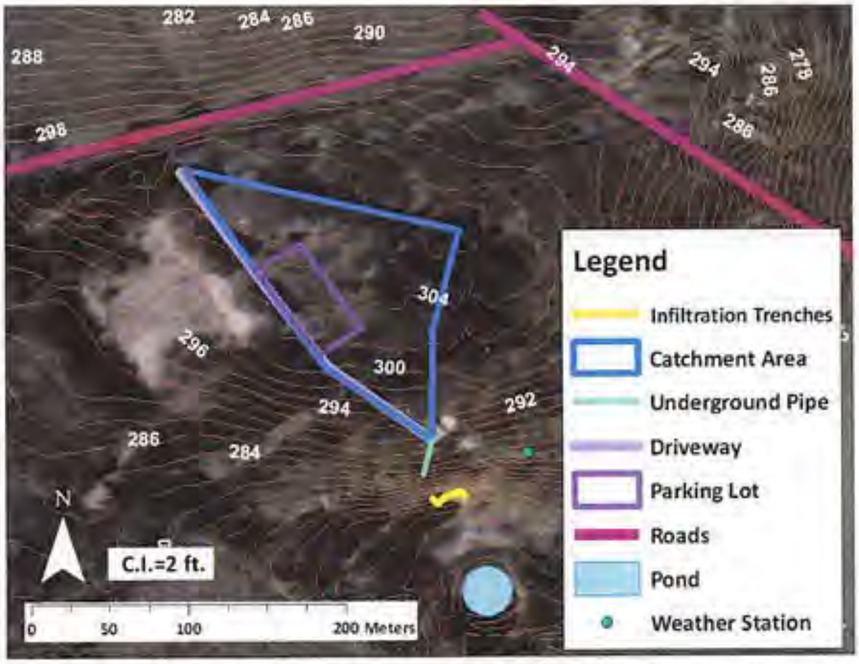

Figure 2-3. Map of infiltration trench location showing catchment area of infiltration trenches and topographic contours.

The infiltration trenches were designed to compare maintenance requirements and performance of 3 different designs. The right and center trenches were filled with 5 to 10 cm-sized gravel. The designations "left trench" and "right trench" are determined by looking down slope toward the pond (Figure 2-4). The center trench inflow pipe was screened with a filter to catch leaves (Figure 2-5); the right trench was unscreened. The purpose of leaving one gravel trench unfiltered was to reproduce a scenario in which no maintenance was performed on the trench.

The left trench was filled with medium-grained sand and was not equipped with a leaf filter. Each trench is 4 feet deep, 5 feet wide, and 10 feet long (1.5m x 3m x 1.2m).

The bottom and sides of each of the trenches were lined with a geotextile filter fabric. The geotextile lining prevents fines from moving upward into the sand or gravel but allows water to flow through.

Figure 2-4. Labeled photograph of infiltration trenches taken prior to July 2007.


Figure 2-5. Photograph of leaf filter with foot for scale (top view) and side view with hose.

During rain events, stormwater runoff from the capture area flows both over land and through pipes to reach the trenches (Figure 2-6). Overland flow enters a pipe at the bottom of the paved area and flows to the top of the slope on which the trenches were constructed. The outlet of this uppermost pipe is located uphill and toward the right side of the row of trenches. The water flows down the slope to a swale, which was designed to spread the water to each of the trenches. They were each outfitted with a separate inflow pipe (Figure 2-7).

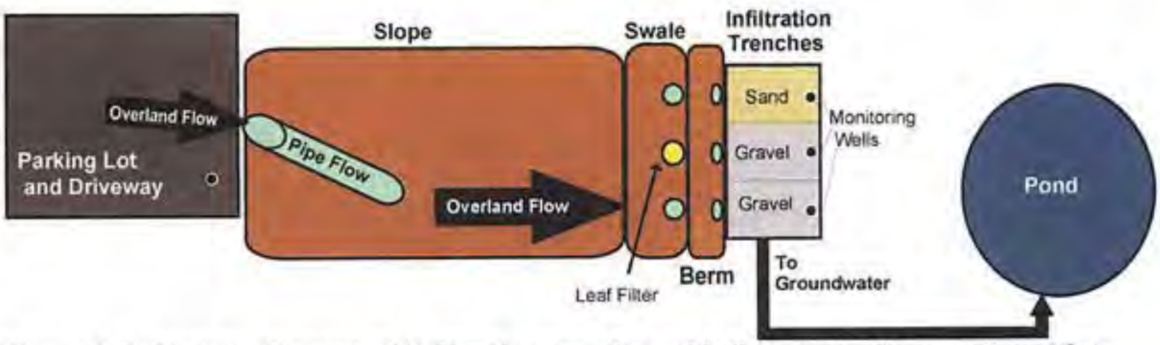

Figure 2-6. Sketch of layout of infiltration trenches with flow path of stormwater. Note that this figure is not drawn to scale.

Figure 2-7. Photograph of water flowing from upper pipe that delivers water from the paved area to the slope above the trenches (left photo). The water flows down the slope to the pipes that lead to each of the trenches as shown in the right photo.

The outlets of these pipes are located above the ground and allow the water to flow onto the surface of the trenches. Native ornamental vegetation was planted on the slope, which developed some weeds over the growing season. However, some exposed soil was always visible on the slope, swale, and berm.

2.2 Monitoring

2.2.1 Setup

Collection of the data presented in this thesis began in December 2006 and continued until the spring of 2009. Each trench was outfitted with a monitoring well that housed a pressure transducer to measure the water level. The pressure transducer was placed at the bottom of the trench. These data provide the basis to compare water levels before, during, and after rain events. Thus trench response including its ability to accept water and subsequent drainage rates could be measured. In between storms, the trenches were typically dry.

HOBO Water Level Loggers were installed in the trench monitoring wells on December 18, 2006. HOBO Water Level Loggers recorded pressure and temperature in the wells. The recording interval of the HOBO loggers was set to 15 minutes with the exception of short periods of experimentation during June, July, and August of 2008. The loggers can store approximately 6 months of data at this interval, but data were downloaded more frequently. Files stored on the HOBO loggers were downloaded onto a cordless waterproof shuttle to be transferred later to a computer or with a USB shuttle connected to a laptop on site. To change the recording interval, synchronize time, or clear the memory, the transducer must be connected to the computer using the shuttle.

The pressure readings must have atmospheric pressure subtracted from them to generate water levels. The Barometric Compensation Assistant (BCA) included in the

HOBO software automated this process. Initially, atmospheric pressure data were obtained from the on-site weather station. Since the files had to be formatted prior to input into the BCA, a HOBO logger was installed that records atmospheric pressure to streamline the process.

The sand trench logger's recording depth was changed when the monitoring well of the sand trench became clogged. The bottom of the well should have been plugged, but was not, so sand moved up into the well and surrounded the transducer. As a result, the HOBO logger inside the well could not be extracted. However, the transducer continued to record the water level in the trench. Because of the limited storage capacity, the logger had to be dug up by removing the entire well. The well was pulled out on July 2, 2006. Data were recorded from December 2006 until June 6, 2007, resulting in about a 1-month gap in the data set. The monitoring well with bottom plug and side screen was driven back into the sand trench to a level 30 cm higher than the original setup (because of infilling of the hole during removal and reinstallation).

Figure 2-8. Photograph of laptop connected to weather station console (left) and weather station rain gauge (right).

A Davis Vantage Pro2 weather station was installed on site to record temperature, barometric pressure, humidity, wind, and precipitation at 15-minute intervals (Figure 2-8). Precipitation was recorded with a tipping bucket rain gauge. When set to a 15-minute recording interval, the weather station could store 23 days of data, which required frequent downloading. The weather station files were stored as two formats: 15-minute interval files and daily summary files. For each file type, files consisted of one month's worth of data. Later, the months were organized into larger files that contained 3-month periods referred to as "seasons."

2.2.2 Controlled Infiltration Experiments

A series of experiments with controlled delivery of water were designed to ensure that the trenches were not hydrologically connected and to compare the trench response under identical conditions. Delivery of water to the trenches during storm events may be uneven, and does not necessarily provide equal stress to each trench. Transducers were placed in each of the 3 delivery pipes just above the trench to attempt to evaluate the volume of water each trench received during storms. However, the flow rate was too low to be measured with a flow-meter or a water level logger.

To compare the behavior of the trenches, a constant delivery rate was needed. Because this could not be provided in natural storm events, I used a garden hose, which allowed us to control the delivery of water to the trenches. The hose was outfitted with a flow splitter with 4 outlets, each with a flow regulation switch. A graduated cylinder and a timer were used to measure the rate of flow to each trench (Figure 2-9).

Figure 2-9. Photograph of flow splitter and hoses used to deliver water to the trenches during experiments (left) and photograph depicting timed filling of a graduated cylinder to measure flow rate during trench experiments (right).

The first experiment was designed to assess interaction between the trenches. By adding water only to the center trench (gravel with leaf filter trench) and observing the water level in the other trenches, I could determine whether the trenches are draining into each other. To monitor water level in these trenches, I used water level tape as well as recording water depth with pressure transducers set to record at a 15-minute interval. The second trench experiment was designed to measure response in the left sand trench by adding water only to that trench.

The third trench experiment was designed to provide even delivery of water to all 3 trenches. Water was delivered at approximately 100 ml/min to each trench with the flow splitter for two hours, and pressure was recorded on the transducers at a 15-minute interval.

The fourth experiment was also designed to provide even delivery of water to all 3 trenches. However, after water was added to all 3 trenches, the flow was redirected to only the sand trench to determine how fast a response could be produced at a higher water input rate. Water was delivered to all 3 trenches for 4 hours, and the data-recording interval was reduced to 5 minutes. When no rise in water level was observed in the sand trench after the 4 hours, the valves to the two gravel trenches were shut off, and the water to the sand trench thus increased. The sand trench received the higher rate of flow for about an hour.

2.3 Evaluation of trench data

Water level data from the trenches was plotted and compared over the 2.25 year period to look for changes in the hydraulic behavior of the 3 different trench designs. I tested for several distinct behaviors likely to result from clogging of the different trenches due to fines. If the gravel trenches become clogged at the bottom, drainage may be slowed. If the sand trench becomes clogged, it is more likely to occur at the top, which may restrict infiltration. Changes may appear in how often storm response is recorded in the trenches and the rate of water flow out of the trench through infiltration (the recession of water level).

To assess these behaviors, first, the number of storms with a response in each trench was recorded. The percentage of response for each season was calculated to compare periods with similar precipitation. Second, the slope of the response was calculated by assuming a straight-line slope between the peak and the return to baseline. The rise in water level was divided by the time to recovery. Each storm greater than 0.5

cm was evaluated for response in each of the trenches. Based on observation of water levels in the trenches, smaller storms do not typically lead to sufficient overland flow to create a water level response in the trenches. Storms that had multiple peaks were sometimes difficult to evaluate, because small increases in rain intensity can sometimes accumulate significant overland flow with wet antecedent conditions. These events were included when there was a response (water level increase) in the trenches.

The top layer of the sand trench was scraped after about a year to see if fines were accumulating. Dark-colored, fine sediment was noted on the surface of the sand trench as early as July 27, 2007, approximately one year after construction. The top layer of the sand trench was scraped on two occasions, March 29, 2008 and May 2009. First, a core was taken to determine the sampling depth (Figure 2-10). Both times, the scraped sediment was sieved to quantify grain size distribution and hydraulic conductivity was calculated using the Hazen method (Bair and Lahm, 2006).

Several field checks aided the interpretation of results. Rain events were observed on several occasions (May 16, 2008, January 7, 2009, June 5, 2009, June 9, 2009, and June 20, 2009) to look for how water distributed across the swale above the trenches and to verify flow to the individual pipes. These data provide a picture of how the trenches have behaved over time and how the behavior varies between the different trench designs.

Figure 2-10. Photograph of sand trench core taken March 29, 2008. Meter stick added for scale.

CHAPTER 3
RESULTS

3.1 Experiments in Trenches

3.1.1 Communication between Trenches

The purpose of adding water to the center trench was to determine if the trenches were draining into each other. The water level in gravel with filter center trench rose 0.41 cm. The HOBO sensors did not detect a response in the other two trenches. Since the well in the sand trench was set 30 cm above the base of the trench, there would only be a response if the water level rose above 30 cm. A sufficient volume of water was added to the center trench to rise above the sensor in the sand trench. Furthermore, it is unlikely that water would flow at a significant rate from the gravel-filled trench to the lower hydraulic conductivity sand-filled trench. Although the two gravel trenches contain the same fill with presumably the same conductivity, the geotextile-lined earthen barrier between the trenches seems to inhibit flow. Thus, the response of each trench to water level increase can be interpreted independently of the adjacent trench.

3.1.2 Three Trench Experiment

The purpose of adding water to all 3 trenches simultaneously was to observe the drainage rates of the trenches under controlled conditions. The experiment was first performed on July 17, 2008 and was repeated on August 29, 2008. Initially, I planned to add water to each of the trenches at the same rate. Due to the limitations of the flow splitter, the flow rates were not equal. On July 17, the average discharge to the gravel, gravel with filter, and sand trench was 90 mL/s, 101 mL/s, and 96 mL/s, respectively. On August 29, the average discharge to the gravel, gravel with filter, and sand trench was 85 mL/s, 79 mL/s, and 101 mL/s, respectively. For the repeat experiment, the flow rate was higher in the gravel trench rather than the gravel with filter trench to make sure that differences in response were not due to the difference in delivery.

On July 17, there was no response in the sand trench after adding water for two hours (Figure 3-1). Although there appears to be an upward shift of the sand trench data point that corresponds with the peak in the gravel with filter trench, a water level meter did not detect water in the sand trench. Initially, the gravel and gravel with filter trenches appear to fill at a similar rate. After 30 minutes, the gravel trench's rate of filling decreased, resulting in a 0.12 m lower peak. This was lower than can be explained by the 11% lower volume of water that reached the gravel trench. The area under the response curve is approximately 60% lower, so the water must be exiting the gravel trench faster than the gravel with filter trench. After the water was turned off, the gravel trench drained at a higher rate than the gravel with filter trench.

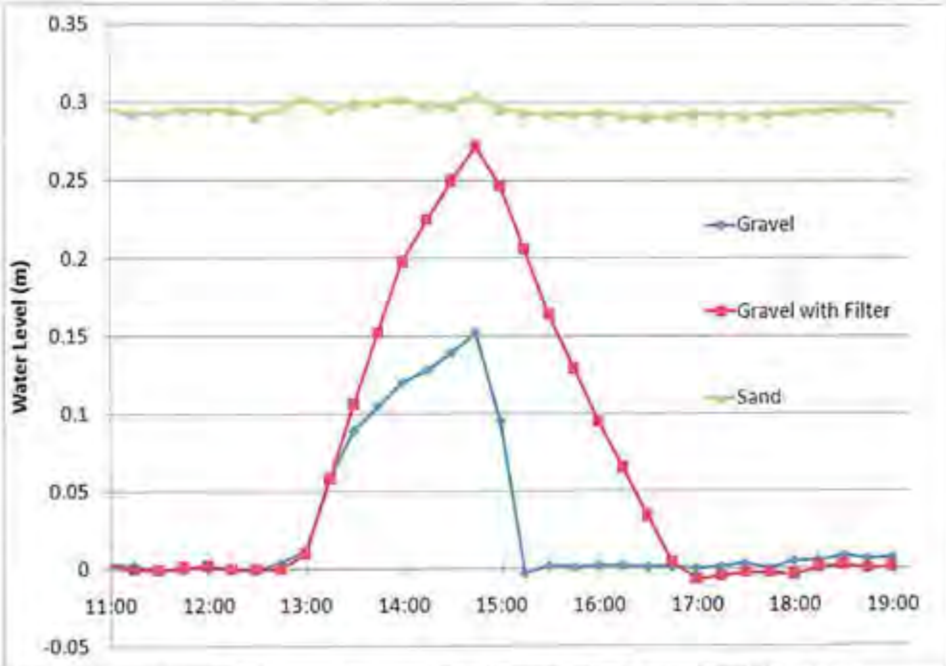

Figure 3-1. Plot of 3-trench experiment performed on July 17, 2008.
The gravel trench drained faster than the gravel with filter trench. The peak water level was higher in the gravel with filter trench. There was no response in the sand trench.

For the August 29, 2008 experiment, each pressure logger was set to record at a 5-minute interval to increase the number of data points. The water level in the gravel trench increased faster than the water level in the gravel with filter trench for the first 5 minutes (Figure 3-2). Then, the water level rise flattened to a rate lower than that of the gravel with filter trench. This resulted in a lower maximum water level in the gravel trench. Again, since water input was verified to be approximately the same rate in these two trenches, the water must have been exiting the gravel trench faster than the gravel with filter trench, so it did not fill as quickly or as high. Although the gravel with filter trench received about 6% less water, it had a higher peak. After the water was turned off, the rate of water level fall in the gravel trench was higher than that of the gravel with filter trench, taking 3.5 hours longer to empty. The flow rate to the sand trench was about 20% higher throughout the experiment. In spite of this, the sand trench did not show a response (Figure 3-2).

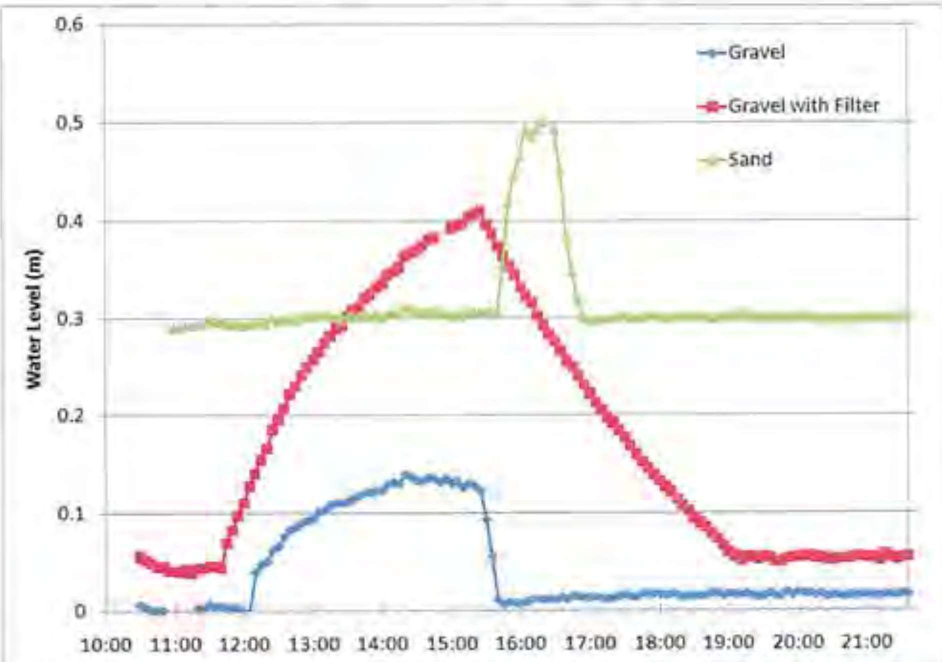

Figure 3-2. Plot of second 3-trench injection experiment from August 29, 2008. The peak in the sand trench occurred after the valves to the other 2 trenches were shut off.

Over the course of the experiment, the gravel with filter trench received approximately 1143 L of water, which resulted in a 0.365 m water level increase. Based on a 30% porosity estimate (typical of unconsolidated sediment), the amount of water needed to fill the gravel with filter trench to 0.365 m is 493 L. The difference between these values represents the volume of water that drained as the trench was filling. In the gravel with filter trench, 650 L of water drained during the 240-minute experiment, resulting in an average drainage rate estimate of 2.71 L/min. In contrast, the gravel trench experienced a 4.34 L/ min average drainage rate during the experiment. Approximately 1129 L of water was added to the gravel trench to achieve a 0.139 m increase in water level. Had the trench not been draining, it would require only 188 L of water to increase the level to 0.139 m, resulting in a 1041 L difference.

The 3 trenches had distinct responses so there does not appear to be leaking or communication between the trenches. Later sections will show that the behavior of the trenches during the experiments corresponds with the behavior of the trenches during natural rain events.

3.1.3 Sand Trench Experiment

The purpose of adding water to only the sand trench was to determine what conditions would be necessary to create a detectable water level in the sand trench. Since the first 3-trench experiment did not result in a detectable water level in the sand trench, it was decided that water should be added to the sand trench individually. On August 6, 2008, the first attempt at this experiment resulted in a 0.142 m increase after 165 minutes at a 19.0 L/min average flow rate (Figure 3-3). The total increase from the base of the trench was 0.442 m. Since the sand trench well was planted 0.3 m above the base of the trench, water below this level is not detectable. For the second attempt at this experiment, the flow rate in the sand trench was increased immediately after the 3-trench experiment on August 29, 2008 (Figure 3-3). To create a peak in the sand trench so that the drainage rate could be observed, the flow rate to the sand trench was increased to 15.9 L/min after the flow to the other trenches was stopped. The water level rose above the 0.3 m baseline within 5 minutes, indicating the sand trench was close to the detectable water level at the start of the experiment. The increase in flow rate resulted in a 0.2 m increase in water level after 45 minutes at the higher rate (or 0.5 m increase from base). Prior to the increase, water had been added at an average of 6.1 L/min for 240 minutes. The total volume of water added was 2491 L. Again assuming 30% porosity, the trench would require 675 L to fill to 0.5 m. Thus, 675 L drained at an average rate of 1.2 L/m. This rate would not be constant in any of the experiments, particularly in this trench since the inflow rate changed. The water level increased faster during the second experiment. The sand trench both filled and drained faster than the either of the gravel trenches.

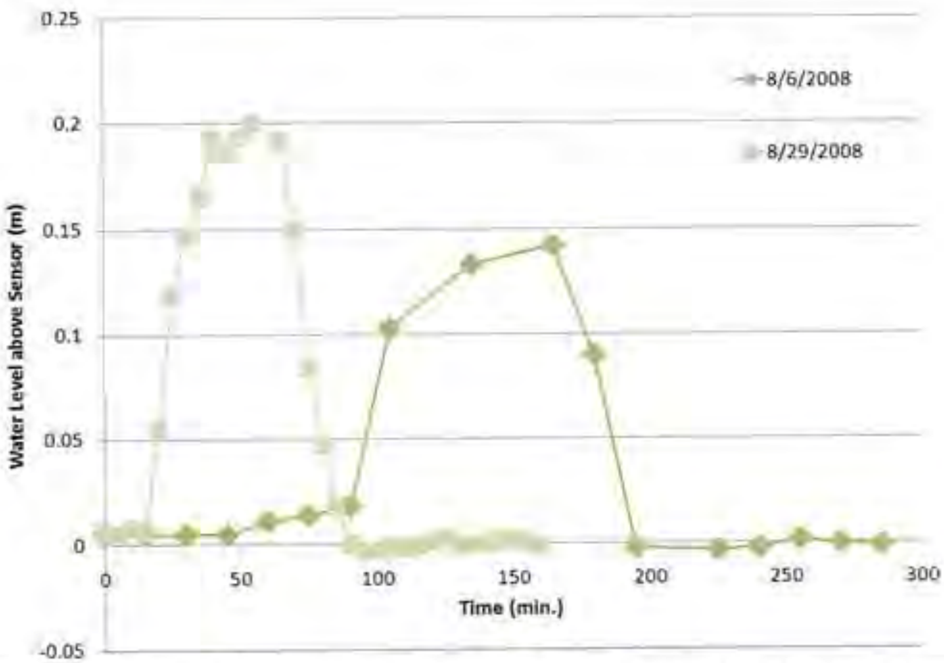

Figure 3-3. Plot of sand trench experiments from August 6, 2008 and August 29, 2008.

3.2 Sand Trench Scraping

The top 1 cm layer of sediment from the March 2008 scraping was calculated to have a hydraulic conductivity of 2.2×10^{-4} cm/s using a Hazen's coefficient, C, of 60. The 1 cm layer below that had a hydraulic conductivity of 3.4×10^{-2} cm/s (Hazen's C=80). Thus, the finer material accumulated at the surface of the sand and appears to have decreased the hydraulic conductivity by 2 orders of magnitude (Figure 3-4).

From the May 2009 scraping, the top 1 cm of sediment was calculated to have a hydraulic conductivity of 9.8×10^{-3} cm/s using a Hazen's coefficient of 80. The hydraulic conductivity of the 3 cm layer below (from 1 to 4 cm below surface) was found to be 3.5×10^{-2} cm/s using a Hazen's coefficient of 80. In 1 year and 1 month's time, fine sediment again accumulated at the surface of the sand trench, although the grain size and conductivity difference was not as great as the previous sampling (Figure 3-5).

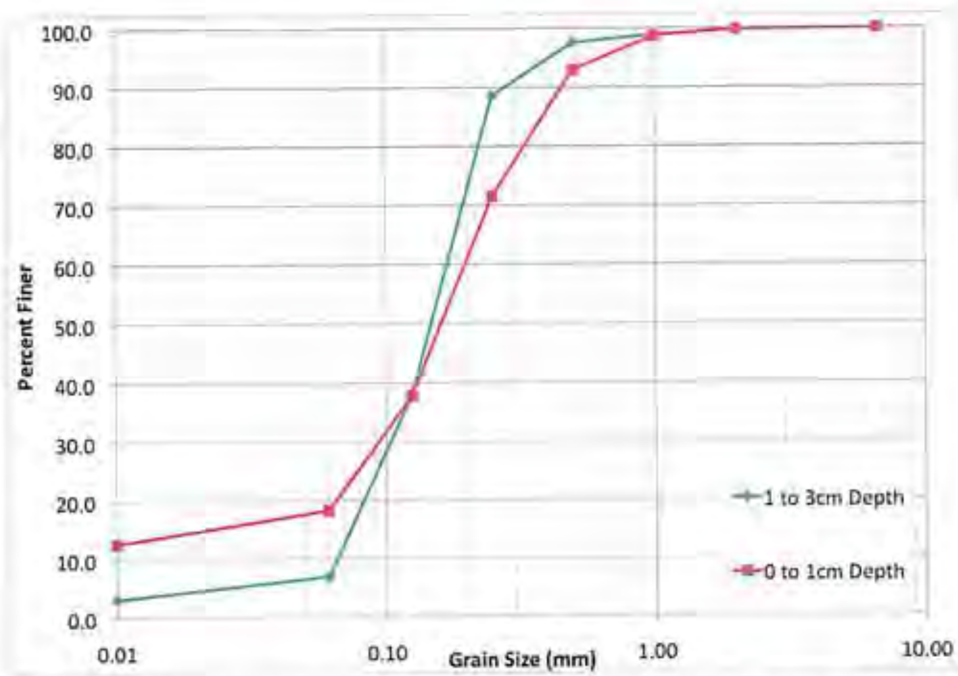

Figure 3-4. Grain size chart for March 29, 2008 scraping showing percent finer grains versus grain size for the top 1 cm layer and the 2 cm layer below that.

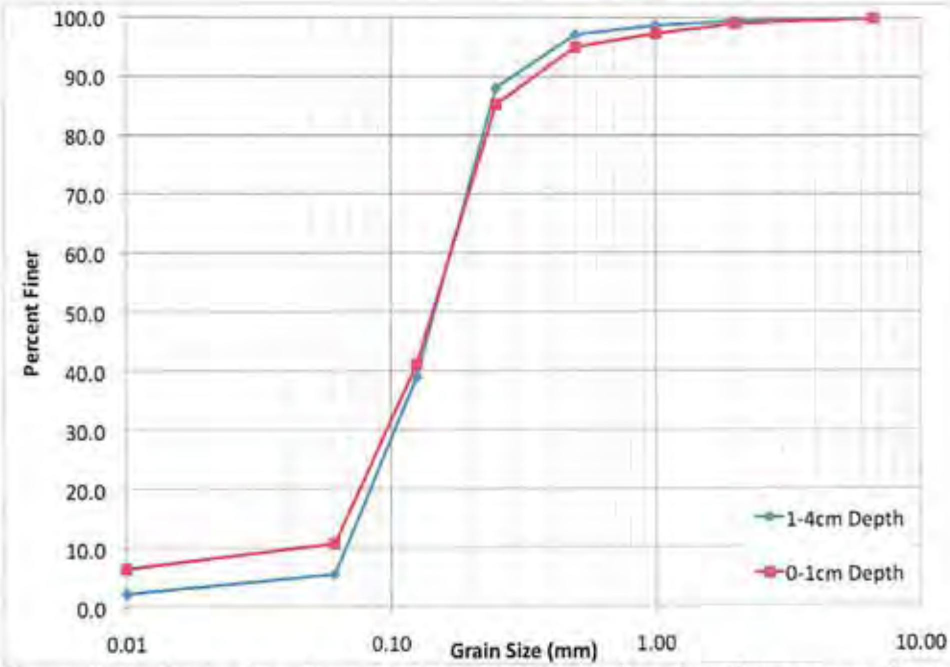

Figure 3-5. Grain size chart for May 2009 scraping showing percent finer grains versus grain size for the top 1 cm layer of the trench and the 3 cm layer below that.

The storm data as described in the following section does not show any distinguishable change after scraping. Any effect of scraping seems obscured by water delivery issues as described in Section 2.2.2 and Chapter 4. Even after the scraping, water was observed to pool on the sand trench during site inspections (Figure 3-6), yet trench infiltration continued to occur.


Figure 3-6. Photograph of water pooled on sand trench surface during storm.

3.3 Seasonal Trench Data

Storm response in the trenches is shown for 10 seasons from Winter 2007 through Spring 2009. For the purpose of data organization during this study, the term Winter refers to the period from January 1 to March 31. Spring is designated as April 1 to June 30, Summer is July 1 to September 30, and Winter is October 1 to December 31. In this study, the term season always refers to these periods as opposed to standard calendar seasons. The data are presented as plots and as a summary table (Table 3-1 and Figures 3-7 through 3-17). Each plot consists of the water level data for all 3 trenches over a 3-month period.

These plots show comparison of trench behavior over all of the recorded storm events. Individual storms are examined in more detail in a following section. The seasonal plots show typical storm response in the trenches (for example, Spring 2008), where the right side gravel trench shows the highest response, followed by the center gravel trench, and the sand trench shows the lowest (Figure 3-13). There are variations to this pattern such as the Summer 2007 and Spring 2008 when the sand trench had some high responses (Figures 3-10 and 3-13). There is also a period when storm response was nearly absent in the sand and center gravel trench (starts Fall 2008 to Spring 2009) and a subsequent return to response in all 3 trenches (Spring 2009) (Figure 3-17), and examples of rain events without trench responses (Fall 2007) (Figure 3-11). Additional examples of exceptions to typical behavior are discussed in section 3.3.

Table 3-1. Summary table of percentage of storm responses in the infiltration trenches for each season based on season-scale water level versus time plots. Note that the sand trench transducer is shifted up 30 cm from the base of the trench starting Summer 2007.

Season	Daily Rain	Gravel Trench		Gravel with Filter Trench		Sand Trench	
	Days with 0.5cm or greater	Peaks >1cm	Response %	Peaks >1cm	Response %	Peaks >1cm	Response %
Winter 2007	15	6	40	4	27	1	7
Spring 2007	11	13	118*	8	73	5	45
Summer 2007	10	8	80	4	40	5	50
Fall 2007	16	14	88	5	31	3	19
Winter 2008	12	6	50	6	50	5	42
Spring 2008	12	8	67	5	42	5	42
Summer 2008	13	4	31	5	38	0	0
Fall 2008	13	8	62	0	0	1	8
Winter 2009	4	4	100	0	0	0	0
Spring 2009	23	19	83	5	22	2	9

*Includes response when rain gauge may have been blocked.

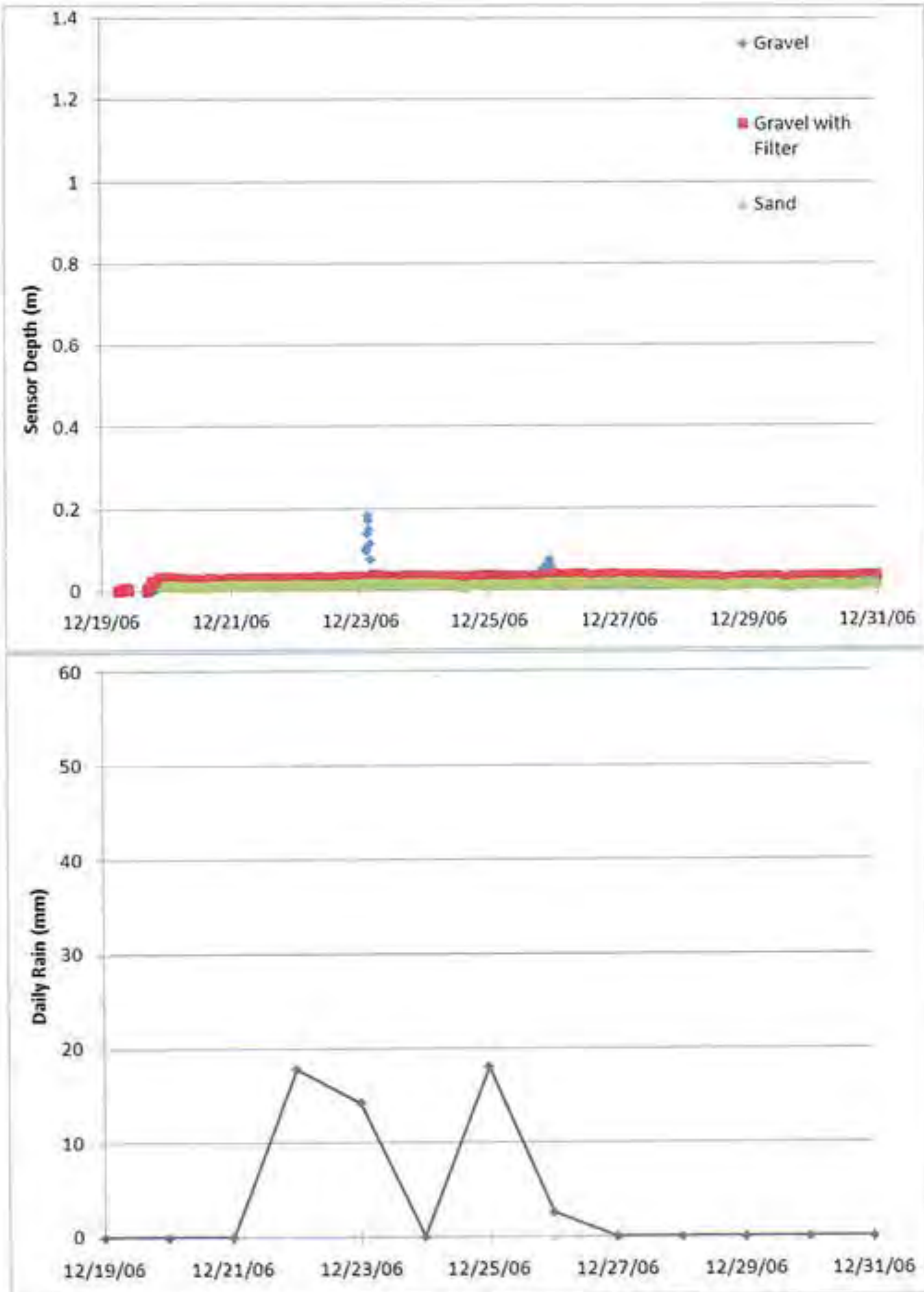

Figure 3-7. Water level data for trenches from December 19, 2006 to December 31, 2006. Note that all 3 trenches are plotted on the same scale.

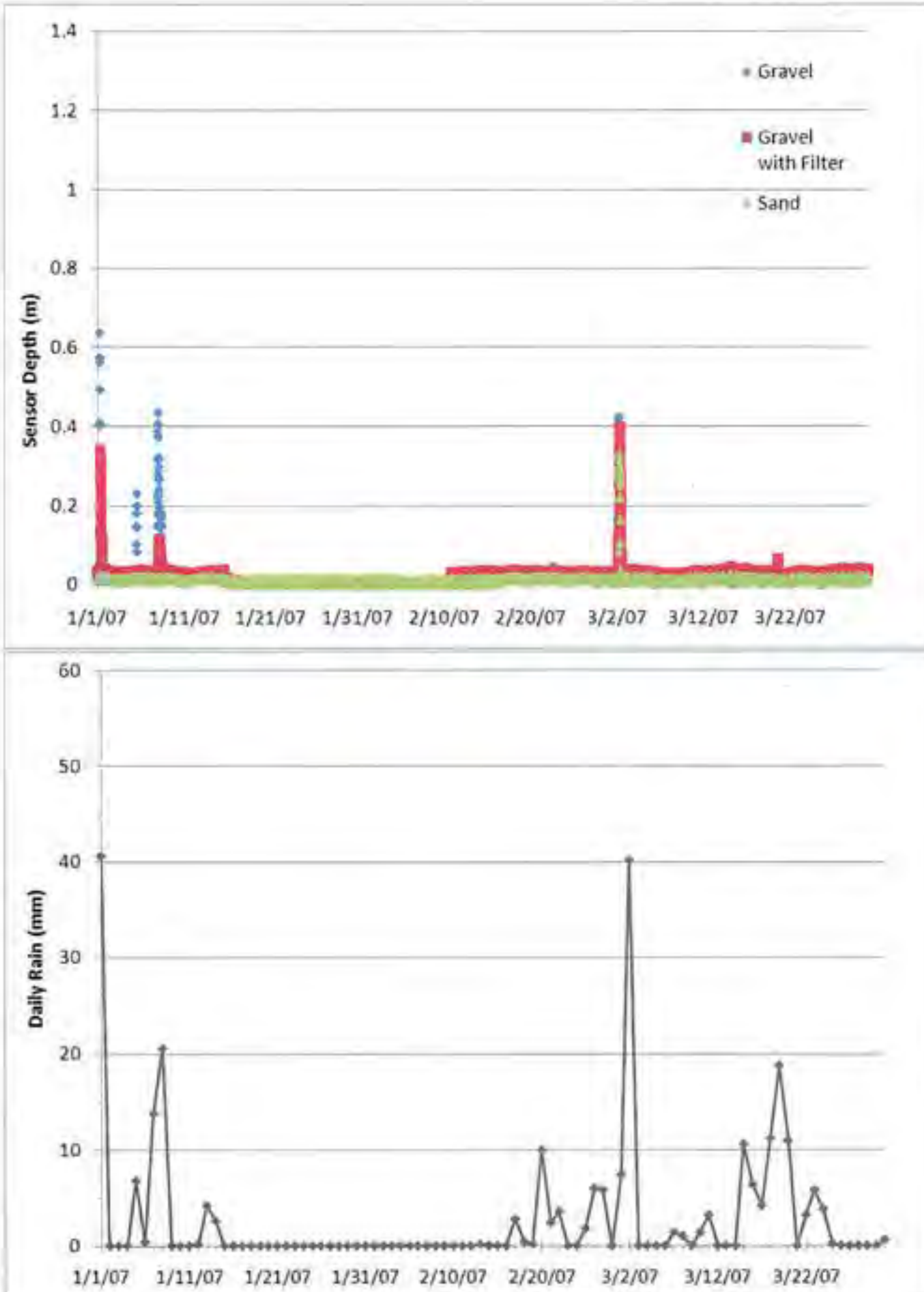

Figure 3-8. Water level for trenches and daily rain data from Winter 2007 (January 1, 2007 to March 30, 2007). Note that all 3 trenches are plotted on the same scale. The gravel trench shows the largest storm response and the sand trench shows the smallest response. Using weather data from a different station resulted in the slight water level offset from January 15 to February 10.

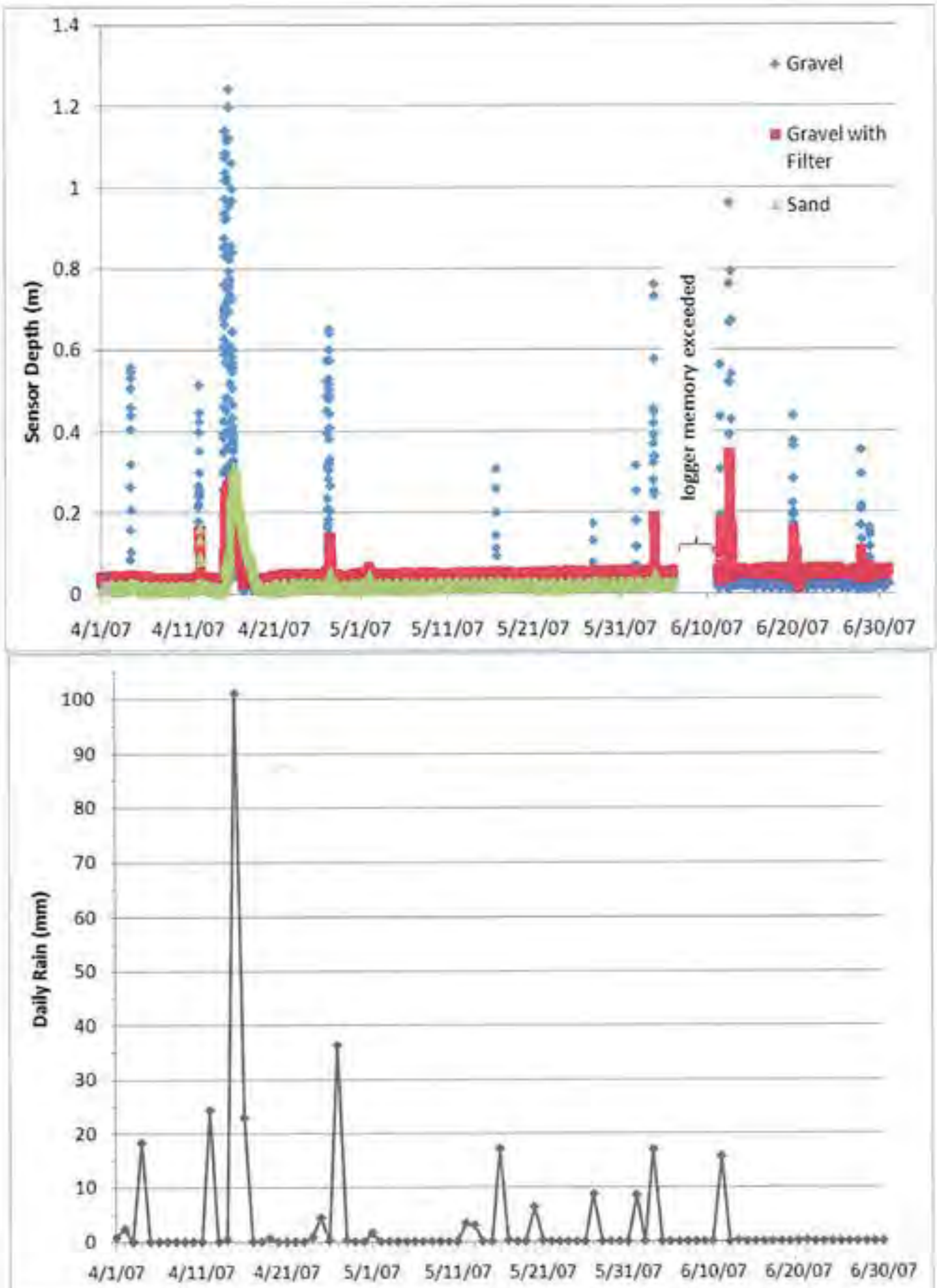

Figure 3-9. Water level for trenches and daily rain data from Spring 2007 (April 1, 2007 to June 30, 2007). Note that all 3 trenches are plotted on the same scale. The storm responses are higher than those of Winter 2007, but the response was still highest for the gravel trench and lowest for the sand trench. The logger in the sand trench ran out of memory June 7, 2007. Unlike the rest of the daily rain plots, the y-axis maximum is 105 mm corresponding to the highest recorded rain per day of 101.2 mm on April 15, 2007.

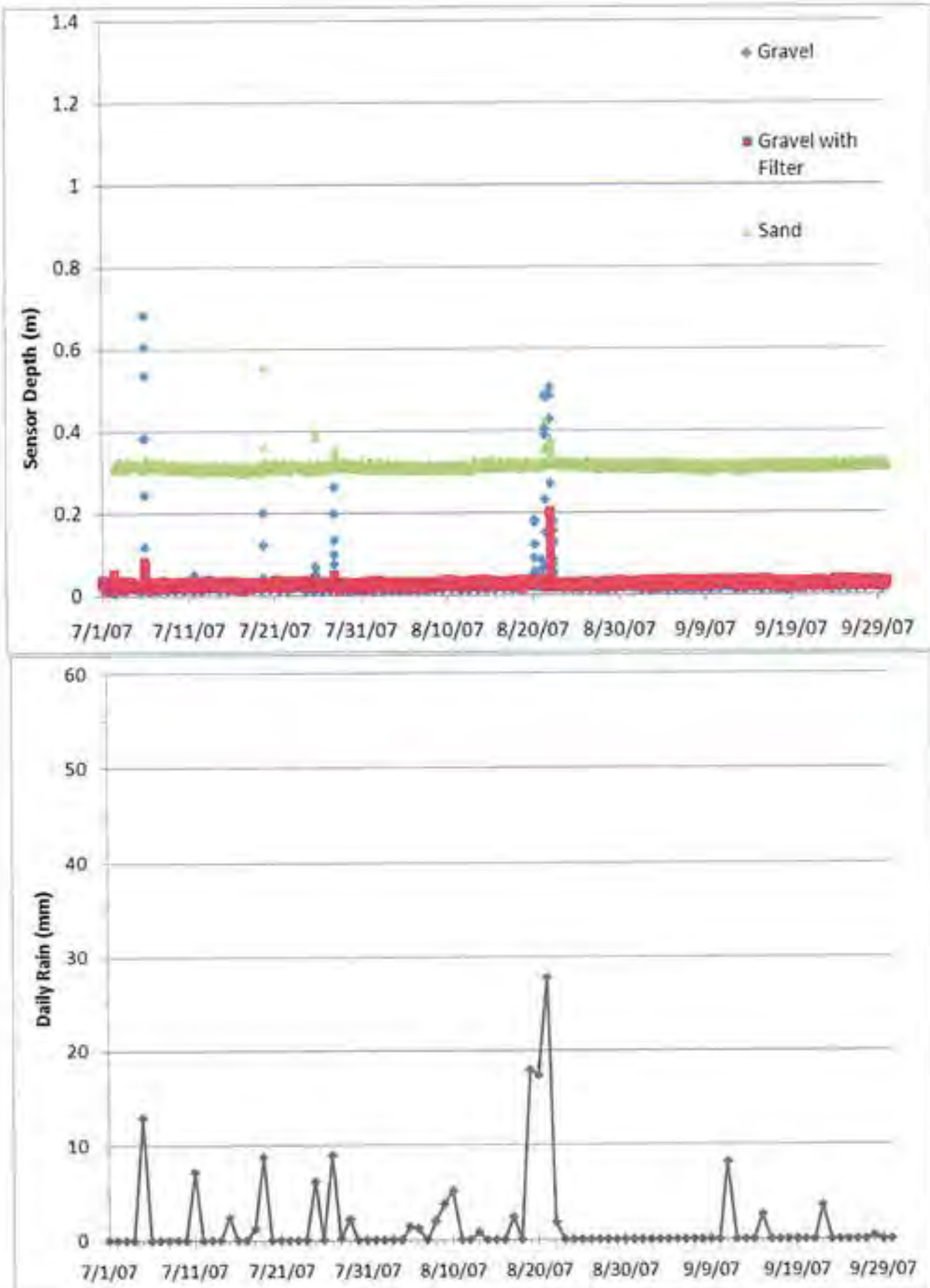

Figure 3-10. Water level data for trenches and daily rain data from Summer 2007 (July 1, 2007 to September 30, 2007). Storm response was highest in the gravel trench except for two July storms when the sand trench had unusually high responses. The highest recorded water level in the sand trench occurred during this period. The gravel with filter trench's storm responses were low except for one storm in August. The water level logger in the sand trench is raised 0.3 m due to replanting of the well on July 1, 2007.

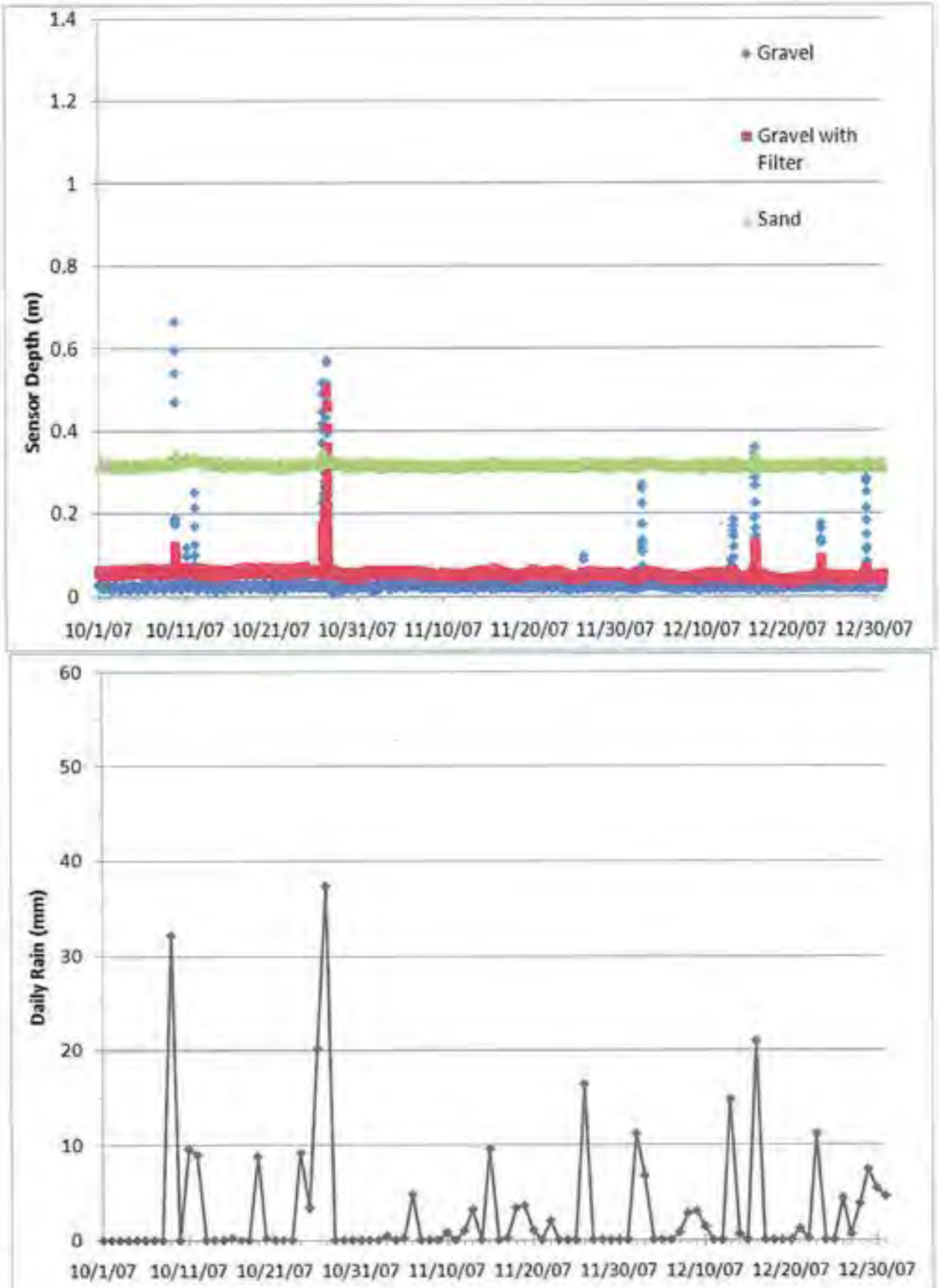

Figure 3-11. Water level for trenches and daily rain data from Fall 2007 (October 1, 2007 to December 31, 2007). The water level logger in the sand trench is raised 0.3m due to replanting of the well. Of the 3 trenches, the gravel trench had the highest water level for all of the storms during this period. Except for one storm, the gravel with filter trench water level was one third or less than of the gravel trench. Early November provides several examples of small rain events with no response in the trenches.

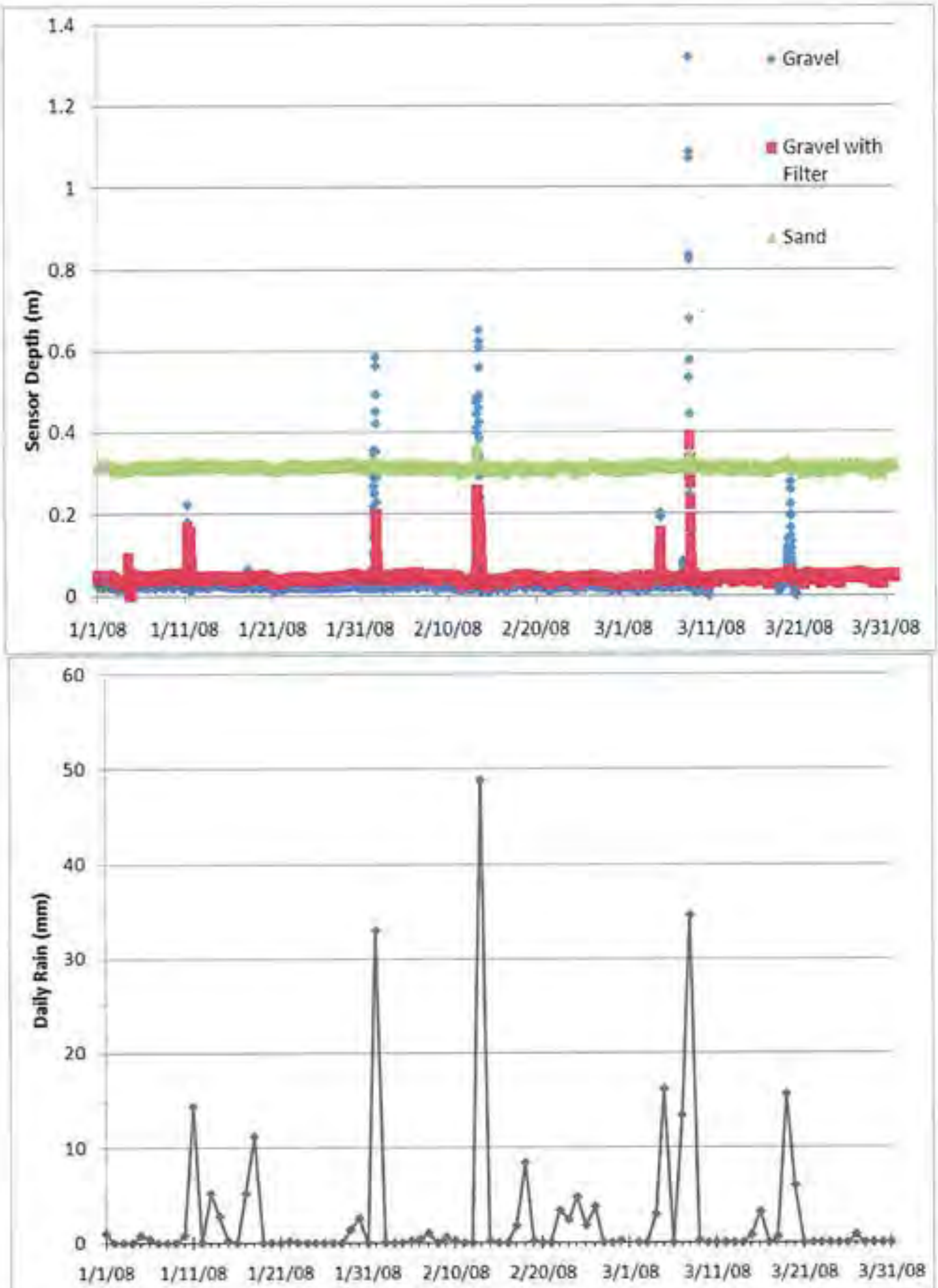

Figure 3-12. Water level for trenches and daily rain data from Winter 2008 (January 1, 2008 to March 31, 2008). The water level logger in the sand trench is raised 0.3m due to replanting of the well. The highest observed water level in the gravel trench occurred on March 8, 2008. Most of the storm responses during this period follow the typical gravel-trench-highest pattern.

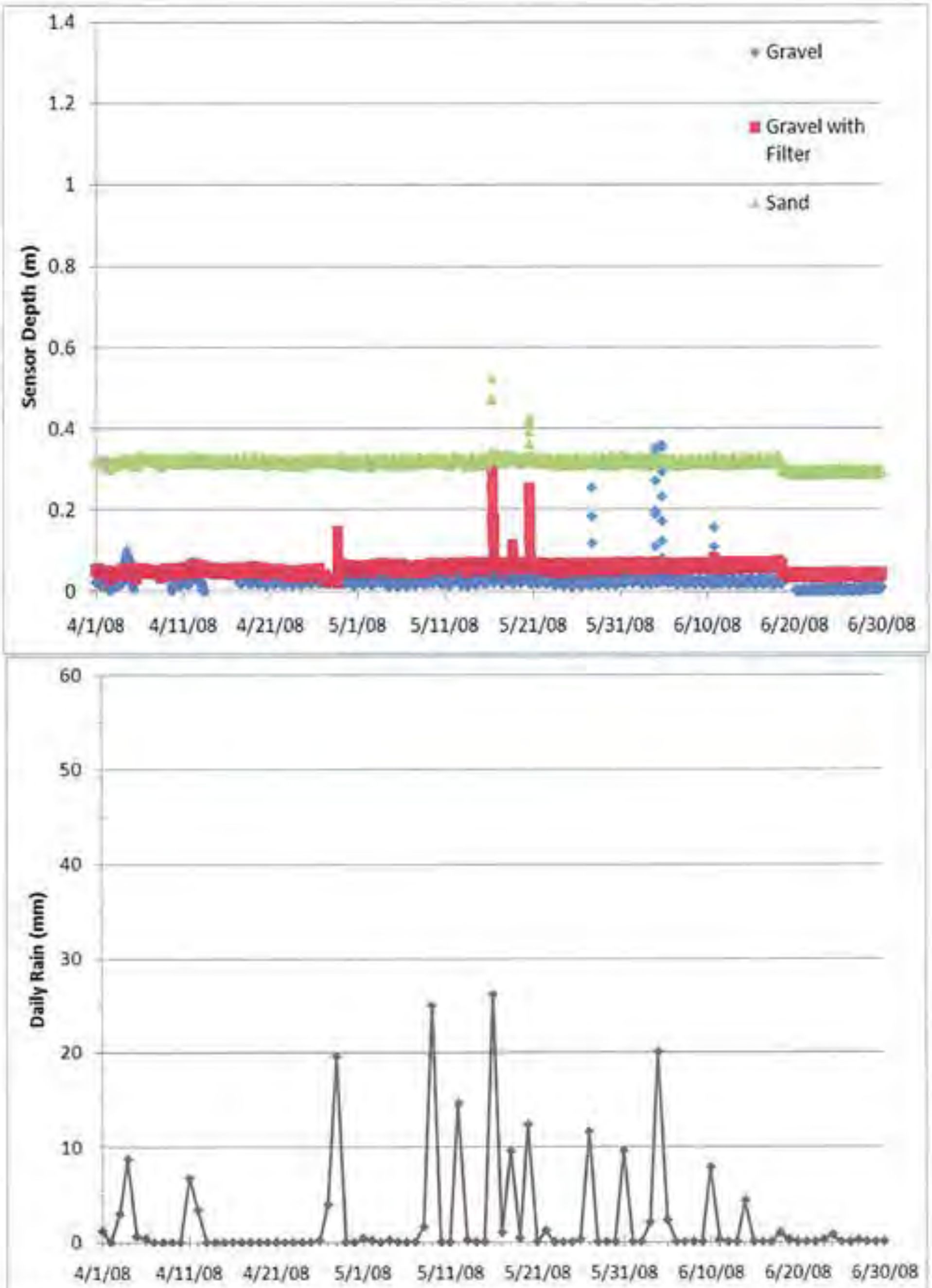

Figure 3-13. Water level for trenches and daily rain data from Spring 2008 (April 1, 2008 to June 30, 2008). The water level logger in the sand trench is raised 0.3m due to replanting of the well. The storm response in the trenches is unusual during this period. The gravel trench does not have the highest peak during several storms. In fact, the rarely responding sand trench had the highest water level of the 3 trenches for two storms.

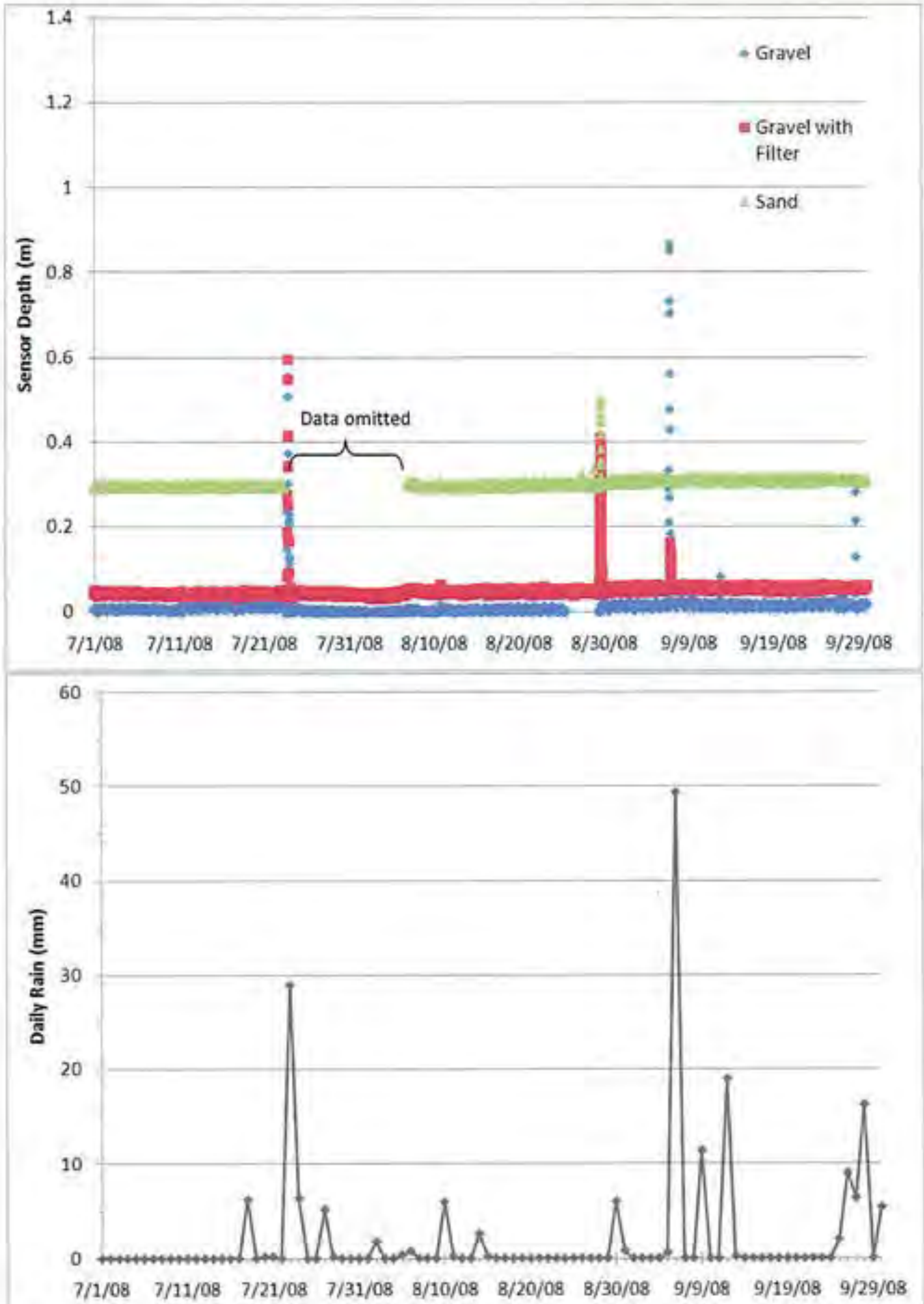

Figure 3-14. Water level for trenches and daily rain data from Summer 2008 (July 1, 2008 to September 30, 2008). The water level logger in the sand trench is raised 0.3m due to replanting of the well. Some data are omitted because the controlled injection experiments were conducted during this season.

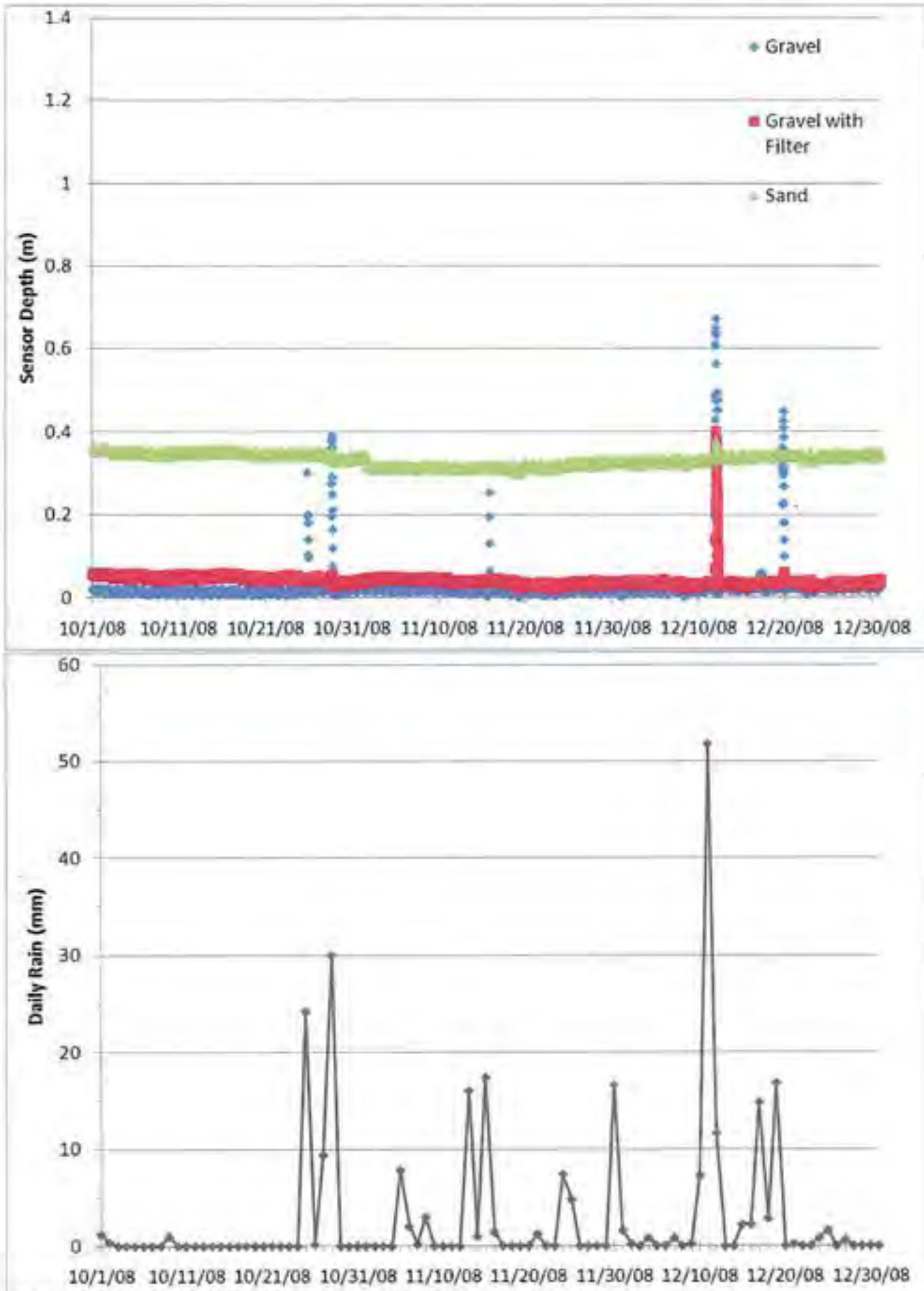

Figure 3-15. Water level data for trenches and daily rain data from Fall 2008 (October 1, 2008 to December 31, 2008). The water level logger in the sand trench is raised 0.3 m due to replanting of the well. The response for the gravel with filter trench on December 18, 2008 marks the beginning of a gap in this trench's response that lasts until Spring 2009.

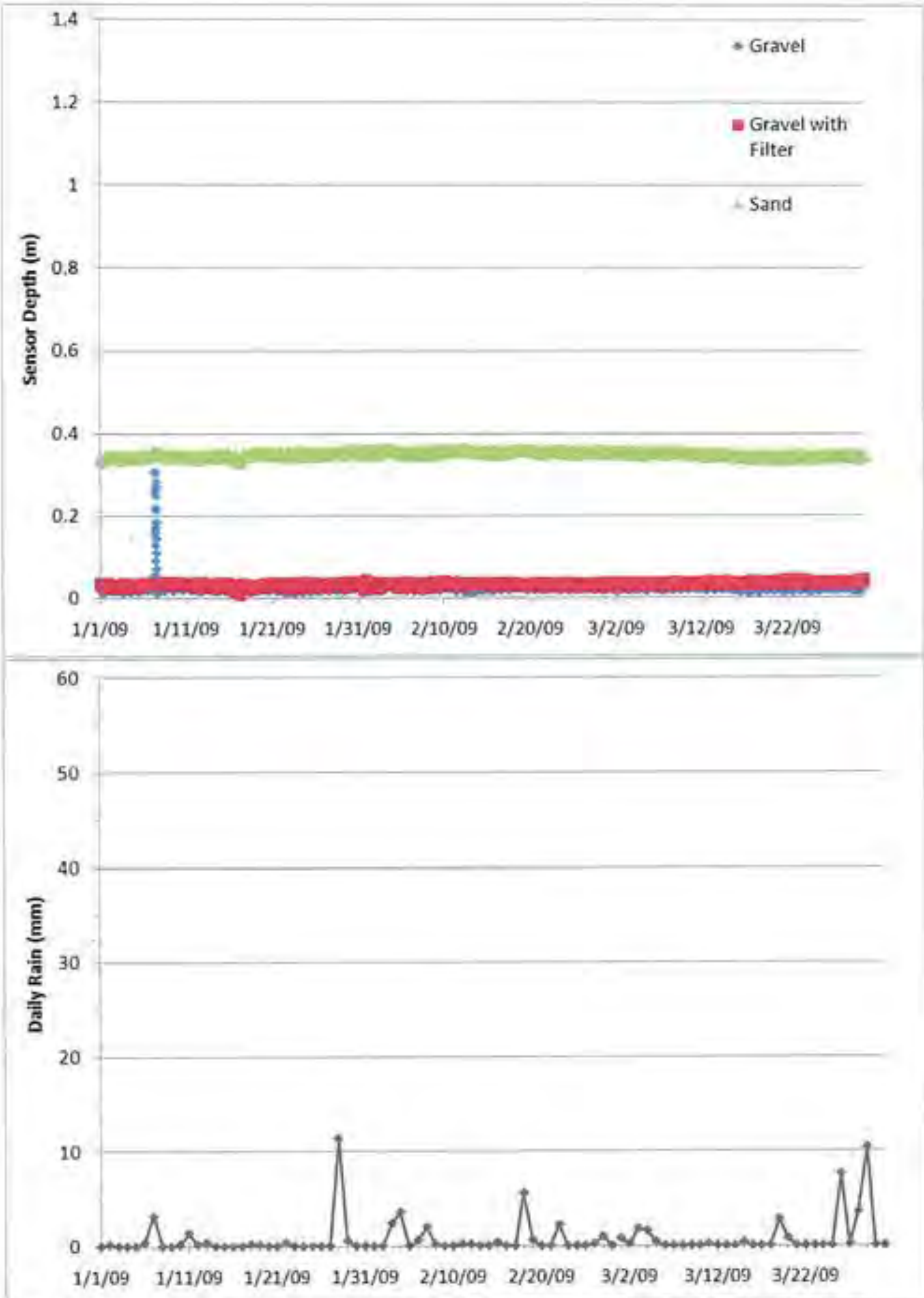

Figure 3-16. Water level for trenches and daily rain data from Winter 2009 (January 1, 2009 to March 31, 2009). The water level logger in the sand trench is raised 0.3m due to replanting of the well. Only the gravel trench responds to the one storm that occurs during this period. The lack of response appears to be a result of the low daily rain totals during this season.

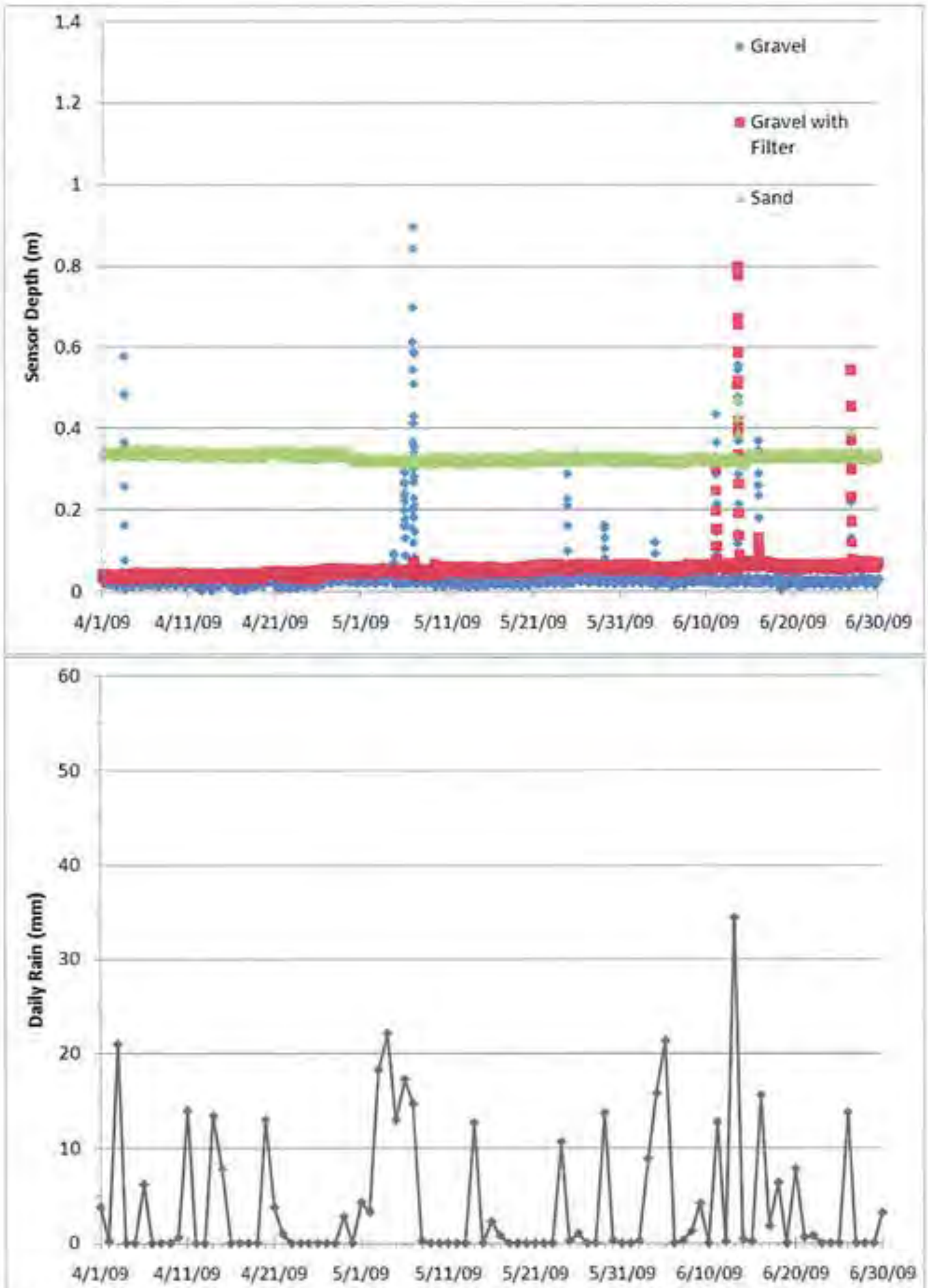

Figure 3-17. Water level for trenches and daily rain data from Spring 2009 (April 1, 2009 to June 30, 2009). The water level logger in the sand trench is raised 0.3m due to replanting of the well. Heavy summer rains bring return of response in the center (formerly gravel with filter) and sand trenches. The maximum recorded water level in the gravel with filter trench occurs during this period.

The number of precipitation events and number of water level responses was catalogued for each trench for each season (Table 3-1). Not all storms show a response in each well, and the number of responses per season varies over time. In general, precipitation events less than 0.5 cm did not show a response. Spring 2007 had the greatest number of storm responses. The lowest number of storm responses occurred during Winter 2009.

The sand trench showed the least number of storm responses, partly due to the position of the transducer 30 cm above the other two. The gravel trench consistently showed the most frequent and greatest magnitude responses although there are several exceptions. For example, during May 2008 there are 3 examples of rain events with peaks in the gravel with filter and sand trenches and unusually low responses in the gravel trench (Figure 3-13). Additional examples of exceptions to typical behavior are discussed in section 3.3.

Comparing responses of one particular season over different years provides a sense of whether responses are changing, because each season is likely to have similar antecedent conditions. In the spring of 2007, there were 13 storms recorded with daily precipitation greater than 0.5 cm (Figure 3-9). All but one of these storms showed a response in the gravel trench. There was one small storm (less than 1 cm) that did not show a response plus one small storm (around 0.5 cm) that did show a response, so the trench had an overall response approaching 100% (Table 3-1). The gravel with filter trench showed a response for only 60% of the storms. Forty percent of storms created a response in the sand trench. The sand trench responded to 5 storms or 45%. During this season, the sand trench transducer ran out of memory when it became stuck in the monitoring well, making this the last season that recorded the sand trench water level from the bottom. After Spring 2007, the transducer was shifted up 30 cm from the bottom of the sand trench. At the end of the month, the rain gauge did not record rain events but there were storm responses. The bucket may have been blocked. The greatest number of storm responses per season on record occurred during this season.

In the spring of 2008, there were 12 days with daily precipitation greater than 0.5 cm (Table 3-1). Eight of these storms showed a response in the gravel trench (dropping to 67%). The gravel with filter trench and the sand trench each showed a response for only 5 of the storms (42%, which was a drop for the gravel with filter trench and about the same for the sand trench). There were several rain events with daily accumulation greater than 0.15 cm that did not result in a gravel trench response. This season was unusual because the gravel with filter and sand trenches had higher peaks than the gravel trench for two storms (Figure 3-13).

In the spring of 2009, there were 23 days with daily precipitation greater than 0.5 cm, the highest number of rainy days per season on record (Table 3-1). Spring 2009 is the last season reviewed in this study. The gravel trench experienced 19 peaks, the highest number of storm responses per season for an 83% response rate. Over the same period, the gravel with filter trench shows a 22% response and the sand trench had a 9% response rate. These response rates were lower than previous spring seasons, but higher than the preceding fall and winter (Figure 3-17). The return of responsiveness in the sand and gravel with filter trenches was somewhat unexpected since by this time the berm had eroded significantly above the gravel trench creating a preferential flow path to the gravel trench. This recovery of responsiveness could be explained by the black pipe located closer to the sand and gravel with filter trenches contributing water or that ground saturation lead to increased overland flow.

In the summer of 2007, there were 10 days with at least 0.5 cm of rain (Table 3-1). This was the smallest number on record until Winter 2009. There were 8 responses in the gravel trench (80%), and 4 responses in the gravel with filter trench (40%). The sand trench responded 5 times, or 50% of the time, the highest percentage on record in spite of the transducer being raised 30 cm from the bottom of the trench.

In the summer of 2008, there were 13 days with at least 0.5 cm of rain (Table 3-1). This season was the first with no sand trench responses greater than 1 cm. The gravel with filter trench responded one more time than did the gravel trench, with a 38% and 31% response, respectively. This response rate was lower than the previous summer. This was the only season on record during which the gravel with filter trench had the highest number of peaks of the 3 trenches (Figure 3-14).

In the fall of 2007, there were 16 days with at least 0.5 cm of rain (Table 3-1). This season was the rainiest on record until the spring of 2009. The gravel trench responded 88% of the time, similar to previous seasons, but the responses were lower in the gravel with filter trench (31%) and sand trench (19%). The relatively low percentage of responses in the center and left trenches can be partly explained by the small size of the rain events during this season (Figure 3-11). During smaller rain events during which the soil was not saturated, water had been observed to flow directly toward the right side gravel trench.

In the fall of 2008, there were 13 days with at least 0.5 cm of rain (Table 3-1). Eight of these 13 days, or 62%, created a response in the gravel trench. This was the first season with no response in the gravel with filter trench. The water level increased greater than 1 cm in the sand trench only one time. Due to the offset, this indicates that the sand trench water level actually reached at least 31 cm (Figure 3-15). Compared with Fall 2007, there were fewer responses in the trenches during Fall 2008.

In the winter of 2007, there were 15 days with at least 0.5 cm of rain (Table 3-1). This is the first complete 3 month season on record. The percentages of responses in the trenches were relatively low, less than 50% for all 3 trenches. The sand trench responded only one time (Figure 3-8). This was prior to the transducer being shifted up 30 cm, so the full trench depth was monitored.

In the winter of 2008, there were 12 days with at least 0.5 cm of rain (Table 3-1). Both the gravel and gravel with filter trenches experienced a 50% response. The highest observed water level in any of the trenches occurred during this season (Figure 3-12).

In the winter of 2009, there were 4 days with at least 0.5 cm of rain (Table 3-1). This is the fewest number of rainy days per season on record. Some of the precipitation that occurred during this period might have fallen as snow, which is not measured by the weather station. Snowfall would not have an immediate impact on the infiltration trench water levels. All 4 of the recorded daily rain totals greater than or equal to 0.5 cm resulted in peaks in the gravel trench. During this season, there were no peaks in the gravel with filter and sand trenches. Winter 2009 is the only season during which neither the gravel with filter nor the sand trench experienced a recorded increase in water level (Figure 3-16).

The observed magnitude and frequency of storm response over time must be interpreted not only in terms of trench degradation but also by considering water delivery and drainage rate estimates. For example, higher numbers and magnitudes of peaks in the gravel trench could be interpreted as a decrease in the drainage rate (i.e. clogging). The next section shows that this interpretation is inconsistent with drainage rate estimates over time (which showed no trend).

The observed decrease in magnitude and frequency of storm response over time in the sand and gravel with filter trenches may have been due to a delivery problem rather than trench degradation. There were two factors identified during site inspections: an additional drainage pipe and erosion of the berm. Based on my observation of water flowing directly toward the right side of the trenches where the gravel trench is located and extensive berm erosion on that side, it is plausible that the gravel trench receives the most water of the 3 trenches. Exceptions to this might indicate a high rainfall rate resulting in water spreading across the swale as intended or flow from a second pipe contributing water to the sand and gravel with filter trenches.

According to the design, the only piped source of water to the trenches was to be a PVC pipe at the end of the paved area. However, during a storm in May 2008, a second pipe delivering water to the trenches was discovered (Figure 3-18). This 6-inch diameter tarpaper pipe is thought to be part of the parking lot's previous drainage system. These pipes were supposed to be disconnected during construction of the infiltration gallery, but it appears that this might be a source of the additional water. Thus, temporal trends are less likely to be related to trench degradation.


Figure 3-18. Photograph of intermittently flowing black tarpaper pipe. Taken on May 16, 2008.

The inlet of this second pipe has not been locatable via smoke testing and water injection; therefore I have been unable to ascertain the area that is drained by the black pipe. Furthermore, field visits during storm events showed that this pipe was not observed to be flowing during each storm observation. This suggests that a variety of factors influence the behavior of this pipe, and thus water delivery to each of the trenches is uneven and unpredictable.

3.4 Recession through Time

The recession rate, or drainage rate, of the trenches, is the slope of the recession limb of the water level peaks calculated by dividing the change in water level by the duration of drainage. The change in water level was found by subtracting the base level after drainage from the maximum height of the peak. Analyses of the recession rates for the different trenches reveal that the gravel trench responded to the most storms, had the highest recession rate of the 3 trenches, and experienced the largest range of recession rate values (Figure 3-19).

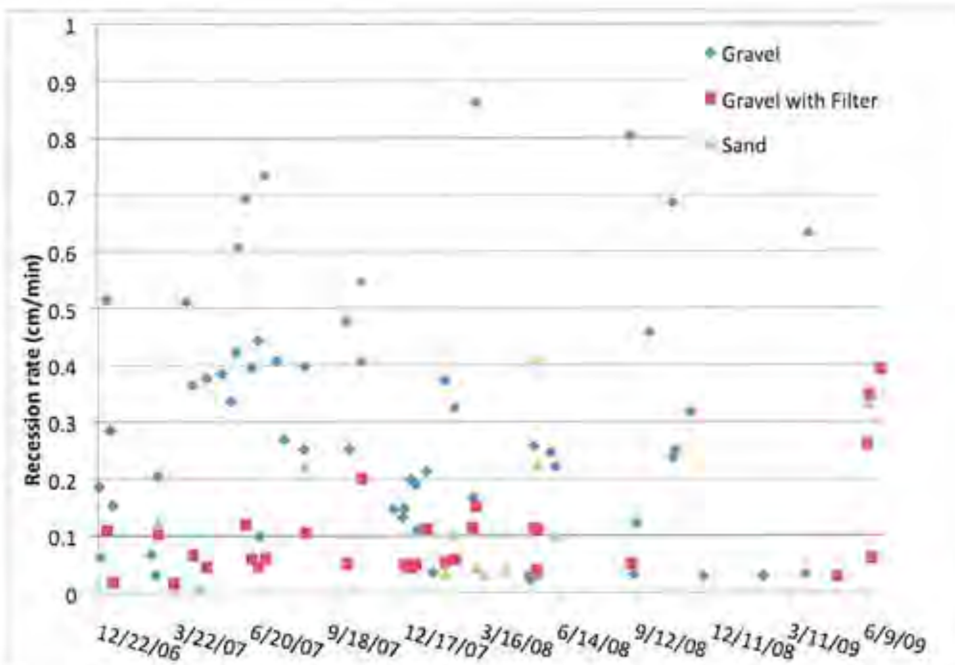

Figure 3-19. Plot of recession rate over time for all 3 trenches.

The data points are highly scattered, and there does not appear to be a significant change in the recession rate over time for any of the trenches (Figures 3-20, 3-21, and 3-22). Linear fitting showed R^2 values of less than 0.33 for all 3 trenches. The sand trench had R^2 of 0.01, the center gravel with filter trench had a positive slope (increase in rate rather than decrease) with R^2 of 0.29, and the right gravel trench had a positive slope with an R^2 of 0.33. The range of values at the beginning and end of the recorded period are similar. For example, the gravel trench experienced recession rates greater than 0.6 cm/s in both 2007 and 2009. In addition, all 3 trenches experienced recession rate values below 0.1 cm/min during the recorded period. The gravel with filter trench had the highest recession rates at the end of the recorded period. Clearly, no progressive change is detectable from the calculated recession rates, which would indicate clogging. It should