WATER LEVEL MONITORING TO ASSESS THE EFFECTIVENESS OF STORMWATER INFILTRATION TRENCHES

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ABSTRACT

Successful stormwater control measures require proper design, monitoring to evaluate effectiveness, and maintenance. To study stormwater runoff mitigation techniques, a row of infiltration trenches with different designs was monitored for 2.5 years. The three trench designs included gravel-filled, gravel-filled with a leaf filter, and sand-filled. Water level loggers in monitoring wells provided low cost monitoring of effectiveness over time and differences between trench designs. In addition, infiltration experiments were conducted. The monitoring showed that the gravel trench tended to have the highest peaks and responded to more storms. These differences were related to uneven water delivery, based on field observations during storms, controlled experiments, and similarity in response for the other two trenches. Thus, any effect of the leaf filter providing maintenance in the center trench was obscured. The first and third trenches in the row drained faster than the center trench both during storms and during the experiments, likely due to extra area for drainage on the sides. The water level recession rate did not decrease over time, indicating that clogging was not a significant factor. Maintenance that consisted of removing fines captured on the top of the sand trench did not significantly change infiltration in that trench. Monitoring with water level loggers was an effective method of determining uneven delivery of water occurred among the three trenches, but there was no decrease in effectiveness of the trenches over the observation period, conclusions that could not be drawn by visual inspection alone.

INTRODUCTION

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. The increased runoff in streams leads to erosion that can cause changes in stream morphology (Smith et al., 2005). In addition, stream ecosystems are impaired by temperature changes and the pollutants brought in by storm runoff (Paul and Meyer, 2001). Just 10% coverage by impervious surfaces causes harmful increases in runoff (Booth and Jackson, 1997). Thus, watershed hydrology is severely impacted by urbanization.

A variety of low impact urban stormwater Best Management Practices (BMPs) have been developed as nonpoint source pollution control measures (US EPA, 1999b). Some experts now prefer the term stormwater control measures (SCMs) (National Research Council, 2008). Infiltration SCMs are relatively small-scale structures that can be installed within existing construction to facilitate infiltration of runoff from rooftops or parking lots (Holman-Dodds et al., 2003). 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 and 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.

An infiltration trench consists of an excavated hole with vertical or gently sloping sides and a level bottom. 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.

Trenches should be monitored to evaluate whether they continue to function for stormwater capture, and in some designs, for water quality filtering.   A number of factors can alter the predicted lifespan of an infiltration trench including flawed prediction of seasonal high water table, errors in infiltration rate calculations, too much compaction and early sediment clogging from construction, poor upkeep of the structure, and lack of sediment removal by a SCM used in conjunction with infiltration (Livingston, 2000). However, once constructed, relatively little monitoring and evaluation of the effectiveness of these systems is conducted (National Research Council, 2008).

Clogging is a concern for both stormwater capture and water quality filtering. In some cases the trenches need to filter sediment, so to some extent, clogging is part of the design. Models are frequently used to estimate the amount of water than can be filtered before clogging occurs (Freni et al., 2009; Siriwardene et al., 2007). Models are also used to assess the appropriate size of trench for the drainage basin (Campisano et al., 2011, Nimmer et al., 2009; Browne et al., 2008). Laboratory studies have been used to evaluate how filter media and sediments flowing into media affect clogging (Siriwardene et al., 2007; Kandra et al., 2014) in addition to evaluating the potential for water quality filtration (Fischer et al., 2003; Hatt et al. 2007). Significant clogging occurs at the interface between the geotextile filter and the surrounding soil (Siriwardene et al., 2007). Relatively few field studies have been conducted, and those that have shown widely differing longevity of trenches. Emerson et al. (2010) found sedimentation and change in recession began immediately, and infiltration declined an order of magnitude the first year. Their study trench was purposely under-designed (capturing more water than design recommendation) to increase failure rate. Brown and Borst (2014) found a decline in infiltration by about a factor of 5 in the first year on one end of an urban stormwater trench, but less change at the other end. The rapid clogging was in part attributed to fine-grained materials used in construction. They also related differences in infiltration rates to heterogeneity of urban soil. Bergman et al. (2011) conducted a long term study of two infiltration basins in Copenhagen and found little change in infiltration after 3 years, but a reduction in hydraulic conductivity of 3.5 in one of the trenches after 15 years. Another study in Copenhagen by Warnaars et al. (2009) found measureable declines in hydraulic conductivity after 2-3 years; declines varied from 30 to 70%. Deschesne et al. (2005) looked at four basins in France aged 10 to 21 years and found little difference between trench infiltration rates and surrounding soil.

The wide variation in performance points to the need for additional monitoring to improve stormwater management success. Potter (2006) highlights that small-scale stormwater control projects are particularly subject to uncertainty because of variations in local conditions. This study compared different types of material in a field application of infiltration trenches using low cost monitoring techniques.

Site Description

The infiltration trenches in this study were on the grounds of the Pennypack Preserve of the Pennypack Ecological Restoration Trust (PERT) in Southeastern Pennsylvania. The Pennypack Preserve is located within the Upper Pennypack Creek Watershed. Land development has impaired the streams located in the Pennypack Creek watershed, with 79% considered to be impaired (Philadelphia Water Department, 2009). About 33% of the watershed has impervious surface and development is primarily residential. A row of three infiltration trenches were installed on PERT property to provide an accessible demonstration to the local community and industry as well as an experimental study site.

The infiltration trenches were constructed using three different designs to compare maintenance requirements and performance. 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 1). The center trench inflow pipe was screened with a filter to catch leaves; the right trench was unscreened. The leaf filter was intended to simulate maintenance to remove organic material that could break down and clog the trench. 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. Medium-grained sand was used to test whether fines would be captured at the top rather than the bottom of the trench. Each trench was 1.2 m deep, 1.5 m wide, and 3 m long (Figure 2). 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.

During rain events, stormwater runoff was directed from the capture area to a swale, which was designed to spread the water to each of the trenches. The infiltration trenches were down slope from a parking area and up slope from a pond. Water from the parking lot flowed down a driveway and was directed to a buried 8-inch PVC pipe that moved stormwater beneath a hill slope onto the swale above the trenches (Figure 1). Each trench was outfitted with a separate pipe receiving water from swale. The outlets of these pipes allowed stormwater to flow onto the surface of the separate trenches. The trenches were intended to increase infiltration to groundwater, which discharges to the pond or becomes part of a larger flow system.

The drainage area is approximately 3 acres (1.2 ha) consisting of lawns, wooded areas, and pavement, with an estimated 50% impervious surface. To estimate infiltration rates for the trenches, percolation tests were performed prior to construction. 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 (LaBrake, 2010, personal communication).

METHODS

Monitoring

Each trench was outfitted with a monitoring well (Figure 1) that housed a pressure transducer to measure the water level response to rain events. HOBO water level loggers were placed at the bottom of the trench and set to log at 15 minute intervals. Data were recorded from December 2006 through the June 2009. In between storms, the trenches were typically dry.

The sand trench logger’s recording depth was changed in June 2007 after the monitoring well 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 removed to download data. The well was pulled out, then a 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). Data were collected during the plugged phase. However, the baseline increased after the new well was installed. Only storm responses higher than 30 cm were recorded after June 2007. In addition to water level monitoring, a tipping bucket rain gauge was installed on site to record precipitation at 15-minute intervals.

Water level data from the trenches were plotted and compared over the 2.5 year period to look for changes in the hydraulic behavior of the 3 different trench designs. To assess storm response, the number of storms that created a response in each trench was recorded. The response was calculated as a percent of the total number of storms to compare periods with similar precipitation. 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.

In addition, recession rate or drainage rate was approximated 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 result in significant overland flow with wet antecedent conditions. These events were included when there was a sufficient water level increase to identify a recession.

Controlled Infiltration Experiments

A series of experiments with controlled delivery of water were designed with two goals: 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 natural storm events may be uneven, and does not necessarily provide equal stress to each trench. A garden hose outfitted with a flow splitter was used to control the delivery of water to the trenches. A graduated cylinder and a timer were used to measure the rate of flow through the splitters to each trench.

The first experiment was designed to assess interaction between the trenches. Water was added only to the center trench (gravel with leaf filter trench) and the water level was observed in the other trenches to determine whether the trenches are draining into each other. The second 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 four hours, and pressure was recorded on the transducers at a 5-minute interval. When no rise in water level was observed in the sand trench after the 4 hours (because of the higher elevation of the logger), 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 45 minutes. The water levels were logged at 5 minute intervals during the experiments.

The average drainage rate can be calculated for the infilling period during these experiments. The volume of water in the trench can be calculated from the peak water level multiplied by an assumed porosity of 30% porosity (typical of unconsolidated sediment). The peak water level is multiplied by the area of the trench or 1.5 by 3 m. The amount drained was the injection volume water subtracted by the water volume at peak saturation. If a constant drainage rate is assumed (not correct, but an approximation for comparison purposes), the infiltration rate is the difference in water volume divided by the infiltration time. For the sand trench the rate was calculated assuming that the trench filled to just below detection during the phase of the experiment when flow was to all three trenches or 0.3 m. This steady state drainage rate provides a comparison between the three trenches.

Sand trench scraping

The use of sand to fill one of the trenches was intended to test whether fines would accumulate at the surface and result in clogging. If clogging occurred at the top, the layer of finer material could be scraped off to return the trench to a higher infiltration rate. The surface of the sand trench was scraped on two occasions, March 2008 (18 months after construction) and May 2009 (another 15 months later). First, a core was taken to determine the depth of the fine layer (Figure 3). Then the top layer of fines was removed with a trowel. The scraped sediment was sieved to quantify grain size distribution and hydraulic conductivity was calculated using the Hazen method. The layer below the fines (presumably original trench material) was also sieved. A Hazen coefficient of 60 to 80 was used based on the amount of fines in the sample.

RESULTS AND DISCUSSION

Controlled flow trench experiments

The experiment with flow directed into the center trench was conducted to determine if the trenches were draining into each other. For this experiment, the water level rose 0.41 cm in the center trench. The water level did not rise in the other two trenches. A sufficient volume of water was added to the center trench to rise above the sensor in the sand trench even though it was 0.3 m above the base of the 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 material 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.

The purpose of adding water to all 3 trenches simultaneously was to observe the drainage rates of the trenches under controlled conditions with approximately the same flow rate into each trench (80 to 100 mL/s). The water level in the right gravel trench increased more gradually than the water level in the center trench (gravel-filled with leaf filter configuration) (Figure 4). This shallower slope resulted in a lower maximum water level in the gravel trench. Since the porosity and water input rate was approximately the same in these two trenches, it was expected that the water level rise would be the same. Since the water level in the right gravel trench did not increase as quickly or reach the same height, water must have been exiting faster from this trench than from the center gravel with filter trench. After the water was turned off, the water level in the right gravel trench decreased rapidly. The gravel with filter trench took 3.5 hours longer to empty. Thus, the gravel with filter trench had a higher peak and stored water longer.

The sand trench did not show a response for the first 4 hours of the experiment. The flow rate in the sand trench was increased to 265 mL/min after the flow to the other trenches was stopped. The water level rose above the 0.3 m baseline within 5 minutes, indicating that 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 of the trench). The sand trench both filled and drained faster than the either of the gravel trenches.

The three trenches had distinct responses to the controlled fill experiment. In particular, they did not drain at the same rate, based on both the slopes but also on the volume of water added and the observed peaks. Based on the steady state drainage assumption described in the methods, the drainage rates were 2.7 L/min in the gravel with filter trench, 3.9 L/ min in the gravel trench, and 4.4 L/min for the sand trench (Table 1). The two trenches on the ends of the row had higher drainage rates than the middle trench. The lower drainage rate in the middle trench was also observed after storms early in the observation period (Figure 5), therefore the slower drainage is unlikely to be due to clogging over time. Because the lower rate was observed from the beginning of the available data, the effect of leaf filter on reducing maintenance was difficult to evaluate. The middle trench could have a lower infiltration rate due to restricted horizontal drainage out the sides or due to smearing during construction.

Seasonal storm response and effects of sand trench scraping

The seasonal plots and storm hydrographs typically showed the right side gravel trench experienced the highest water level peaks in response to storms, followed by the center gravel trench, and then the sand trench (Figures 5-7). A storm hydrograph from within the first year showed these distinct responses between the trenches (Figure 5). Although the sand trench sensor was positioned higher than the other two sensors after June 2007, the sand trench typically exhibited a response during storms that resulted in a water level increase above 30 cm in the gravel with filter trench (Figures 6). There are variations to this pattern of higher response in the gravel trench when the gravel with filter trench had higher responses (late Spring 2009, Figure 7). There were also periods when storm response was nearly absent in the sand and center gravel trench (early Spring 2009, Figure 7). Similar observations are apparent for other seasons (Jedrzejczyk, 2010).

The height of the peak water levels during storms differed from the controlled experiment. For the controlled experiment, the gravel trench had the lowest peak, which based on calculations was due to faster drainage. During storms, the gravel trench typically had a higher peak than the other two trenches. This higher storm response in the right gravel trench suggests there were differences in the amount of water delivered to each trench rather than differences in drainage rates.

The number of precipitation events and number of water level responses was catalogued for each trench for 10 seasons (Figure 8). In general, precipitation events less than 0.5 cm did not show a response. Not all storms show a response in each well, and the number of responses per season varies over time. Spring 2007 had the greatest percent storm response in each of the trenches. The lowest number of storm responses occurred during Winter 2009, when neither the gravel with filter nor the sand trench had any storm response. The gravel trench had the highest response rate except for Winter 2008 when it was equal to the gravel with filter trench and Summer 2008 when the gravel with filter trench response rate was slightly higher. The sand trench had the lowest response rate. Although the sensor was raised at the end of Spring 2007, the Summer 2007 season had a similar response rate so it is not clear that the sensor elevation caused changes in the response rate. Furthermore, when the sand trench had lower response, the gravel with filter trench nearly always had lower response as well. The similarity in response for the center and left trenches suggests increased delivery of water to the right trench caused the change.

The response rate did not vary consistently from one season to another over the 2.5 years of study (Figure 8). Spring had the highest response rates in 2007, but not in 2008 or 2009. The lowest response rate in the gravel trench was in Summer 2009, but in the sand and gravel with filter trench the lowest response was Winter 2009.

The top layer of the sand trench was scraped off two times during the study. The top 1-2 cm was removed and grain size analysis was conducted on this layer and the layer just below the surface. The top layer of sediment from the March 2008 (18 months after construction) showed a hydraulic conductivity of $2.2\text{x}10^{-4}$ cm/s. The 1 cm layer below that had a hydraulic conductivity of $3.4\text{x}10^{-2}$ cm/s. Thus, the finer material accumulated at the surface of the sand and decreased the hydraulic conductivity by 2 orders of magnitude. From the May 2009 scraping, the top 1 cm of sediment was calculated to have a hydraulic conductivity of $9.8\text{x}10^{-3}$ cm/s. The hydraulic conductivity of the 3 cm layer below (from 1 to 4 cm below surface) was $3.5\text{x}10^{-2}$

cm/s. In 13 months, 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. However, the seasonal storm data did not show any distinguishable increase in response after scraping the sand trench (Figure 8), and the hydrograph response in Spring 2009 (Figure 7) showed an increase late in the season for both the sand and the gravel with filter trench. Any effect of removing the layer of fine sediment seems obscured by water delivery inconsistences.

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. If clogging was significant, the drainage rate should decrease and there should be a greater number of storm responses recorded. However, except for the gravel trench, the response rate decreased rather than increased over time (Figure 9). The higher response rate in the gravel trench over time was attributed to increased water delivery based on the controlled experiment, observed decay of the berm on that side, and decreased responses in the sand and gravel with filter trenches.

Storm Recession

The recession rate, or drainage rate, of the trenches, is the slope of the recession limb of the water level peaks. A decrease in drainage rate over time can be an indication of clogging. 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 three trenches, and experienced the largest range of recession rate values (Figure 9).

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. Linear regression fitting showed no significant trends and higher values were observed at later time for the gravel trenches. For example, the gravel trench experienced recession rates greater than 0.6 cm/s in both 2007 and 2009. In addition, the trenches experienced recession rate values below 0.1 cm/min both at the beginning and the end of the recorded period. Clearly, no progressive change to indicate clogging was detectable from the calculated recession rates. It should be noted that a lack of storm response in the gravel with filter and sand trenches between October 2008 and March 2009 limits the detectability of a trend.

The observed variation in recession rates can be explained by different size storm events. Regression between recession and water level showed a linear relationship with R^2 of 0.7 for all three trenches (Table 2). As the height of the water level peak increases, the recession rate increases. This relationship can be explained in part by the change in the hydraulic gradient (difference in water level inside and outside the trench) and in part by the increase in trench wall area through which the water can drain. This linear relationship would be less strong if clogging occurred to reduce drainage over time. The maximum recession rates (Table 2) are higher in the right gravel trench than in the left sand trench (0.86 and 0.39 cm/min, respectively), just as the rates measured at the top of the soil during trench design were higher on the right than the left (1.3 and 0.6 cm/min, respectively). The rates are 1.5 times lower than the pre-construction rates, but the difference could be due to soil compaction at depth rather than clogging over time.

CONCLUSIONS

Differences in infiltration were observed between the trenches, both rate of infiltration and rate of response to storm events. Although the trenches behaved differently, the behavior can be attributed to design factors rather variations in trench longevity. First, the center trench had a lower infiltration rate than the two side trenches. It also had restricted flow because the side trenches had one more side for outflow than the center trench. Second, the berm directing the water to the piping system eroded over time and more water was delivered to the right side trench. Thus, the right side gravel trench had a higher response rate to storms. Occasionally higher rainfall rates could still spread the water across all three trenches but preferential flow to the right side was directly observed in some storms.

Temporal changes in clogging were not observed in these trenches over the 2.5 year study. This conclusion is based on the scatter in recession rates observed in the three trenches, with both high and low values at the beginning and end of the monitoring period. Furthermore, the lower recession rate observed in the center trench was observed both in initial storms and in a later controlled experiment when the same amount of water was delivered to all three trenches. Finally, no change in recession rate was observed in the sand trench after fines were scraped off the top.

Although the differences in trench design did not result in apparent changes in behavior between the trenches, the study pointed out several issues with stormwater monitoring. Even with a piping system designed to split the flow of water, it is difficult to deliver an even flow of water across a 9 m length of trenches. Erosion of the berm caused water to bypass the piping system. Controlled experiments can be used in place of storm events to test response to a measured flow rate and to observe different responses among different trenches. Nonetheless, a simple monitoring network of a single well in each trench readily showed the breakdown in the berm which caused a water delivery problem and showed the similarity in the sand and gravel trench responses when they both received the same amount of water. This type of monitoring can point out where maintenance is and is not needed. Without the water level loggers installed in the trenches, it would not have difficult to determine whether the trenches were receiving water, not overflowing, and still draining in a reasonable amount of time. Thus, monitoring should continue to play a role in effective stormwater control.

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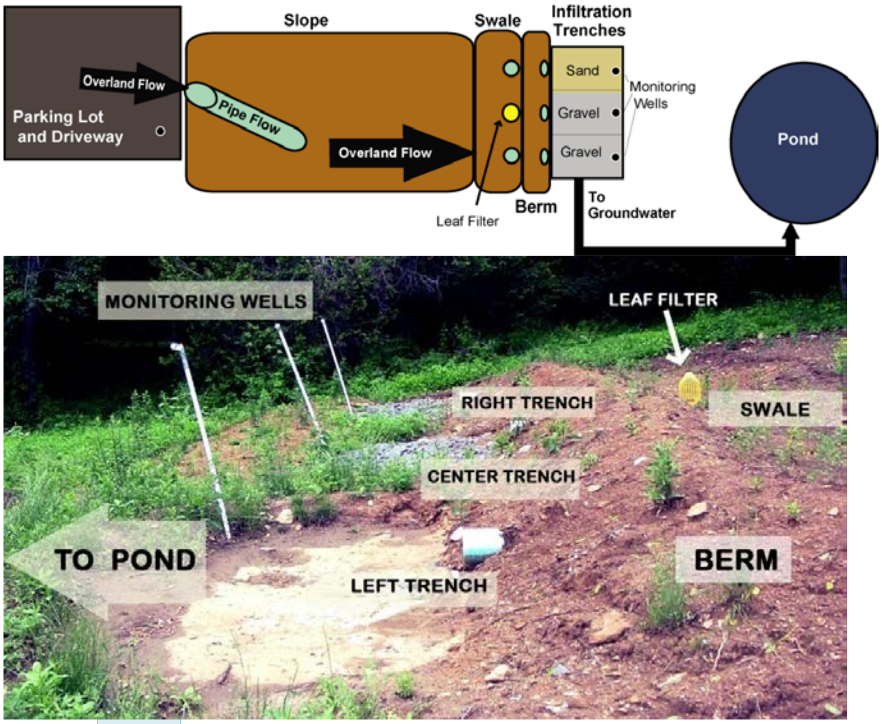

Figure 1: Diagram and photograph showing layout of piping to direct water to the three infiltration trenches. The differing trench material (gravel versus sand) can be seen. Monitoring wells in trenches are shown in photograph before they were trimmed to the level of the ground surface. [Need to switch orientation on one of these figures.]

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Figure 2: Photograph of trench excavation.

Figure 3: Photograph of core taken from sand trench 18 months after construction showing a layer of fines in the top 2 cm of dark sediment.

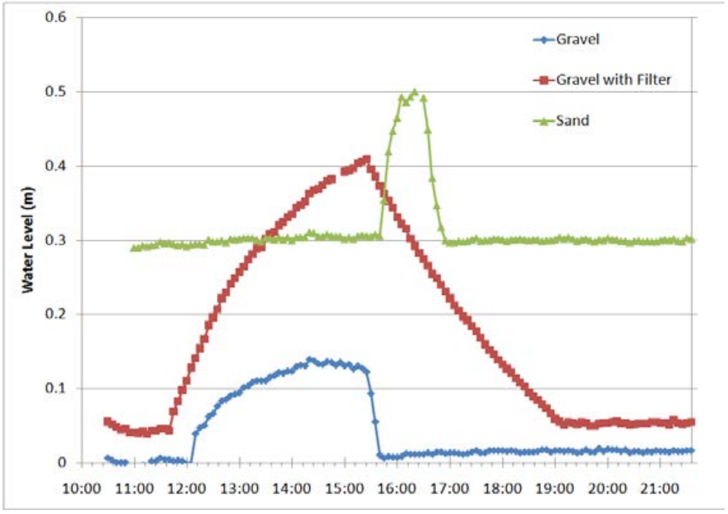

Figure 4: Water level increases observed from controlled experiment injecting about 100 mL/s into each trench. The water level in the sand trench can only be observed above 0.3 m because the sensor was raised above the base of the trench during repair of the well. The sand trench sensor did not show an increase until the water in the other trenches was shut off at 15:30 and all water was directed into the sand trench. The water level then rose immediately, suggesting the prior water level was just below the 0.3 m detection limit.

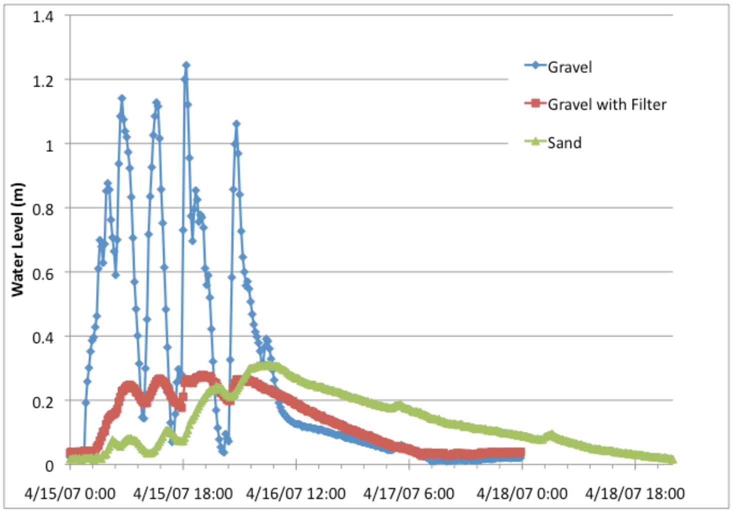

Figure 5: Water level increases observed in an early storm, before the sensor was raised in the sand trench. Data recorded at 15 minute intervals shows multiple peaks as the rain starts and stops. The highest and most rapid response is observed in the gravel trench. A more graduate recovery is observed in the sand and gravel with filter trench.

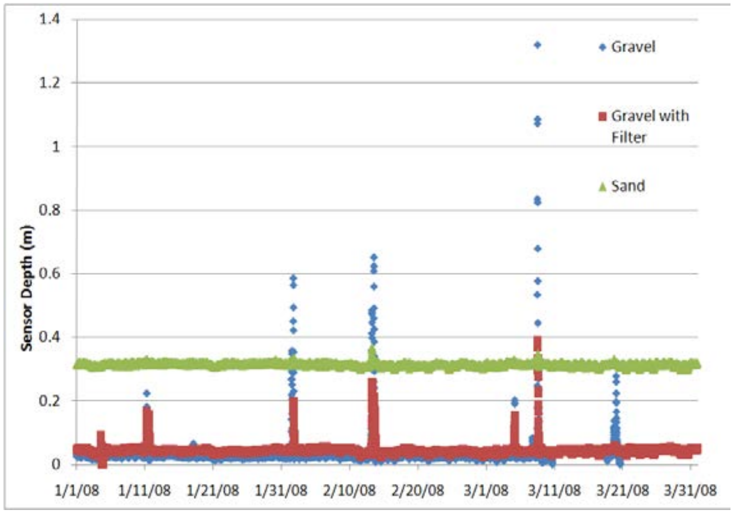

Figure 6: Typical storm response showed higher water levels in the gravel trench (right side) and response in the sand trench only when the gravel with filter trench was at least 0.3 m. The baseline for the sand trench was 30 cm above the other trenches for these periods and does not indicate a water filled trench.

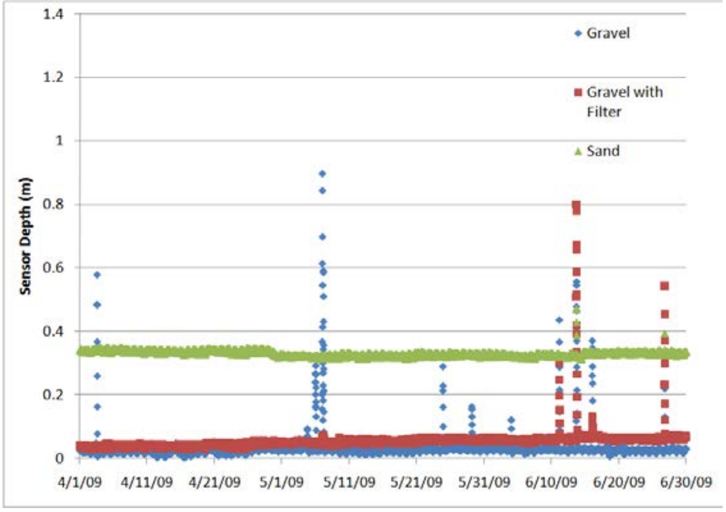

Figure 7: Typical storm response is higher in the gravel trench but in late spring the gravel with filter trench had a higher response and in early spring there was no storm response in the sand or gravel with filter trench. These changes may reflect water delivery issues. The baseline for the sand trench was 30 cm above the other trenches for these periods and does not indicate a water filled trench. Only storm responses greater than 30 cm are recorded in this trench.

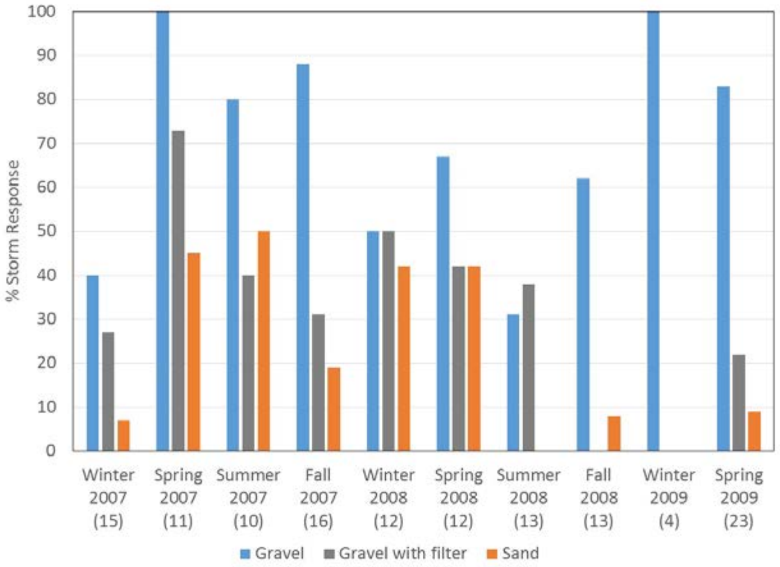

Figure 8: Percent storm response shown for each season. The number of storms greater than 0.5 cm is given in parentheses after the season name. Both the gravel with filter and sand trench showed a decline in response, but likely due to water delivery issues rather than clogging. The gravel trench varied both up and down. There was not a distinct change in the sand trench response after the logger was raised (summer 2007), or after the top layer was scraped off (spring 2008).

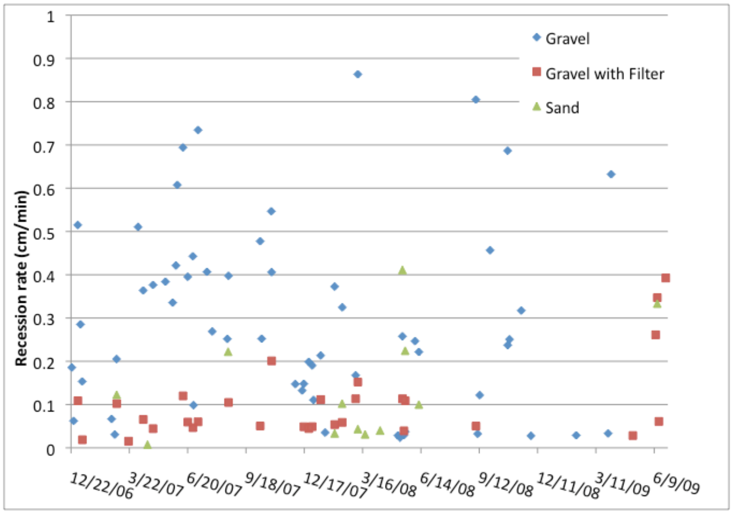

Figure 9: Recession rates for the three trenches does not show a significant decrease over time. The gravel trench experienced the highest rates, but they were similar at the beginning and end of the monitoring period.

Table 1: Infiltration rates during experiments for rising limb of response. Time to peak response is 240 minutes. Volume remaining in trench calculated from area, peak height and assuming 30% porosity. Amount drained is injected minus volume remaining in trench. Drainage rate is amount drained divided by 240 minutes.

	Volume injected, L	Water level at peak, m	Volume Remaining, L	Drainage rate L/min
Gravel	1129	0.139	188	3.9
Gravel with filter	1143	0.365	493	2.7
Sand	1454	0.3 (approximate*)	391	4.4

*For the sand trench the rate was calculated assuming that the trench filled to just below detection during the phase of the experiment when flow was to all three trenches or 0.3 m, based on the rapid response of the trench once the inflow was increased.

Table 2: Regression between water level and storm recession rate

Trench	R^2	Slope	Max rate cm/min
Gravel	0.73	0.82	0.86
Gravel with filter	0.73	0.45	0.42
Sand	0.71	1.95	0.39