Evaluating Performance of PaveDrain Permeable Pavements in Colmar Manor, MD

Project Final Report

Submitted to:

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Executive Summary

Nitrogen and phosphorous are pollutants of major concern in the Chesapeake Bay watershed due to their high eutrophication potential. Urban stormwater runoff is a significant pathway for transport of nitrogen and phosphorous into the Bay. Urban stormwater can be reduced through stormwater best management practices (BMPs) which promote infiltration. A PaveDrain permeable pavement system was installed in April 2021 at the intersection of 40th Ave and Newark Rd in the town of Colmar Manor, MD. Designed to reduce runoff volumes and pollutant transport to the Chesapeake Bay, the pavement has a 2,305 ft^2 surface area and a subbase storage depth of 4 ft. The pavement site is located in the right-of-way and can withstand loadings from large vehicles, including trucks. The purpose of this study is to analyze the stormwater volumetric and subsurface infiltration performance of the site 2 years following its construction, to gather performance information and to provide recommendations for future PaveDrain implementation. The main parameters of interest are volumes of water entering the system through rainfall and run-on, and leaving the system through subsurface infiltration. Calculated parameters include effective drainage area and run-on ratio, subsurface soil infiltration rate, and reduced pollutant loads.

Sensors monitoring real-time data for rainfall and water storage depth beneath the pavement were used to evaluate site performance. Subsurface infiltration rates were calculated by fitting linear and exponential decay models to water storage depth data. The rates were calculated from the peak of the storage depth during a storm (t=0) to a time t=1, 2, and 4 hours after peak depth. Rainfall data were obtained from a rain gauge located slightly off site (0.6 miles

east in Bladensburg, MD), in addition to data from distance-weighted averages of 4 local rain gauges. Comparisons of the distance-weighted precipitation averages from the 4 local gauges and the study rain gauge data found that the data sets were similar enough to replace the study rain gauge data during offline periods with the weighted averages from local stations.

Data was evaluated from September 22nd, 2021 through March 31st, 2023 and included 50 storms. The largest 24-hr rainfall total measured was 2.41 inches on 8/5/22. The highest water level measured was 23.18 inches on 9/23/22 and no apparent overflow to the mid-drain occurred.

Prior soil boring data revealed a heterogenous soil composition beneath the pavements, including hydrologic soil groups (HSG) A, B, and D soils. The Prince George's County Department of Permitting classifies soils per the lowest HSG (D), which is not recommended for infiltration-based BMPs. Nonetheless, exponential models revealed a mean subsurface infiltration rate of 0.99 ± 1.00 in/hr across 31 storms (geomean = 0.70 in/hr) at the site, which is significantly higher than expected rates for the D soil found on site (0.18 in/hr).

Results of the study predict that the pavement system in Colmar Manor is able to fully capture rainfall from storms up to 4.11 in without reaching overflow into an overdrain (a mid-drain with an upturned elbow), based on static volumetric storage considerations. Using a conservative infiltration rate, due to continuous exfiltration from the storage bed, an additional 0.23 inches can be managed during a 4-hr rainfall event, for a total capture of 4.34 in. Water balances of rainfall depth and change in storage depth reveal that the system receives area from a drainage area of 9400 ft^2, 8% greater than was anticipated in the design stages (8705 ft^2). Based on measured data, the system performed well in managing runoff, even though the underlying soil was classified as HSG D (which precludes stormwater credit in Maryland) and receives run-on from surrounding impervious area. The pavement system is projected to annually reduce total nitrogen by 3.30 lb, total phosphorous by 0.36 lb, and total sediment by 0.09 tons, based on Model 5.3.2 of typical pollutant loads to the Chesapeake Bay from urban impervious sources (Maryland Department of the Environment, 2014).

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Introduction

Background

Urban stormwater runoff is a persistent challenge which frequently leads to public health and environmental risks. Impervious surfaces are the main cause of urban stormwater runoff as they prevent infiltration of rainfall. Runoff disrupts the hydrologic cycle by preventing groundwater recharge, introducing excess nutrients and pollutants into surface waters, and increasing peak flows to surface waters during precipitation events (Selbig, 2019). Runoff that enters surface waters is associated with elevated concentrations of various nutrients and microorganisms that may cause health issues in humans (Gaffield et al., 2003). Nitrogen and phosphorus are two nutrients transported by stormwater which are of major concern to water quality due to their eutrophication potential (Yang and Lusk, 2018). Toxic metals such as copper, zinc, and lead can also be present in urban stormwater due to industrial runoff, construction runoff, and runoff from roads and buildings (Gaffield et al., 2003).

Permeable pavements are a type of stormwater management infrastructure which reduces stormwater runoff by promoting subsurface storage and infiltration. Permeable Articulating Concrete Blocks (P-ACB) are a non-traditional type of permeable pavement which have benefits in both soil erosion control and stormwater infiltration. They are traffic-rated and have a higher loading capacity than similar Permeable Interlocking Concrete Pavers (PICPs), which are a common type of permeable pavement which allows infiltration through void space between the paver blocks (Davis et al, 2022; National Concrete Masonry Association, 2014). Both systems utilize gravel bed storage beneath the permeable blocks, which captures stormwater and allows it to infiltrate slowly into the subgrade soil below. Increased storage and infiltration reduce peak flows and stormwater volume, and filter out pollutants before stormwater enters groundwater or surface flows, thereby protecting water quality.

Various studies have shown permeable pavements to be effective in reducing stormwater volumes when compared to impervious surfaces (Brattebo and Booth, 2003; Morgenroth et al., 2013). A significant limitation of permeable pavements is that they are commonly not designed to support high traffic loads (Davis et al., 2022). However, many low-traffic areas use impervious asphalt and concrete in the United States, such as parking lots, driveways, and low-speed residential roads (Brattebo and Booth, 2003). Permeable pavements can be implemented in these areas to mitigate runoff to local water sources.

Subsurface infiltration rates for permeable pavement subbase systems depend on several factors, including temperature, season, soil type, and soil moisture content (Emerson and Traver, 2008; Davis et al., 2022). Surface infiltration rates are primarily impacted by clogging of pavers (Bean et al., 2007). These factors are variable depending on climate conditions, the engineered design of each individual site, and characteristics of the local environment, including the presence of trees. Due to the variable infiltration performances of different permeable pavement systems, research and studies on the efficiency of permeable pavements are needed across a variety of design elements and locations.

For the state of Maryland, stormwater design criteria are outlined by the Maryland Department of the Environment (MDE) in the *Maryland Stormwater Design Manual*. The manual specifies that for permeable pavements, the Hydraulic Soil Group (HSG) should be A, B, or C (Maryland Department of the Environment, 2000). HSG Group D soil is not recommended for infiltration systems due to its low hydraulic conductivity (Lee et al., 2016). However, several studies performed on infiltration-based stormwater management systems in areas with high clay content have shown a significant reduction in runoff volume and pollutant loads (Alyaseri and Zhou, 2016; Braswell et al., 2018). Further research is needed on how stormwater management soil requirements may be adjusted for heterogenous soil containing clay, and whether disallowing infiltration in HSG D soils may be too conservative.

Project Description and Objectives

The overall goal of this project is to determine the effectiveness of a PaveDrain permeable pavement system at a site in Colmar Manor, Prince George's County, MD, to provide field validation of the stormwater storage and treatment capacity. This validation can allow for greater implementation of PaveDrain throughout the state of Maryland and the Chesapeake Bay Watershed. The site is located on a low-traffic, residential intersection within the right-of-way and can withstand loading from trucks and other heavy vehicles. PaveDrain is manufactured by Ernest Maier, Inc. (EMCO, Bladensburg, MD).

This research is primarily devoted to measuring volumes of stormwater that are collected in the subsurface storage reservoir of the pavement system that will subsequently exfiltrate into surrounding soils over time. The project takes place over approximately 15 months in order to assess stormwater infiltration over various seasons and rainfall characteristics.

Four main objectives guide this research:

1. The first objective is to determine volume collection and infiltration rates of the permeable pavement system. By measuring rainfall depth, change in water storage height, and time we will fit the data to linear and exponential decay models to determine actual subsurface infiltration rates.
2. The second objective of this research is to calculate the run-on ratio for the system. Using a water balance, we will compare volumes of rainwater entering the pavement

storage system with volumes of rain that are measured by nearby rain gauges. This data will allow us to hydrologically determine the drainage area expected for the field system.

3. A third objective is to compare the infiltration performance at the PaveDrain sites to typical infiltration rates expected for the types of soils located at the project site. This comparison will allow us to evaluate how the PaveDrain system performs relative to typical values estimated for these soils. It will also give insight into whether heterogenous soil profiles may perform well despite containing clay.
4. Finally, we aim to compare the results of this study with findings from other permeable pavement/infiltration BMP studies in locations across the United States in order to examine how the system at Colmar Manor performs compared to similar sites with different environmental, weather, and soil conditions.

Methods

Site Information

The pavement site is a low-traffic residential intersection of 40th Ave and Newark Rd located in the town of Colmar Manor in Prince George's County, MD (38.935080, -76.948532, Figures 1 and 2). The pavement system covers an area of 2,350 ft^2 and, per permit drawings, is estimated to receive rainfall from a surrounding area of 8,705 ft^2, creating a run-on ratio of approximately 2.7:1. The permeable blocks overlay a stone storage reservoir approximately 4 ft deep. A mid-drain with an upturned elbow is located approximately 2 feet above the base of the reservoir, which functions hydraulically as an overdrain.

In March 2021 during construction, EMCO hired a geotechnical engineer to collect three soil boring samples at the location of the PaveDrain system. Testing revealed that soil from the samples fell into the categories of HDG A, B, and D. The Prince George's County Department of Permitting and Inspection subsequently classified the soil by the lowest soil group (D).

Figure 1. Photograph of intersection at which PaveDrain site is located (Taken April 2022).

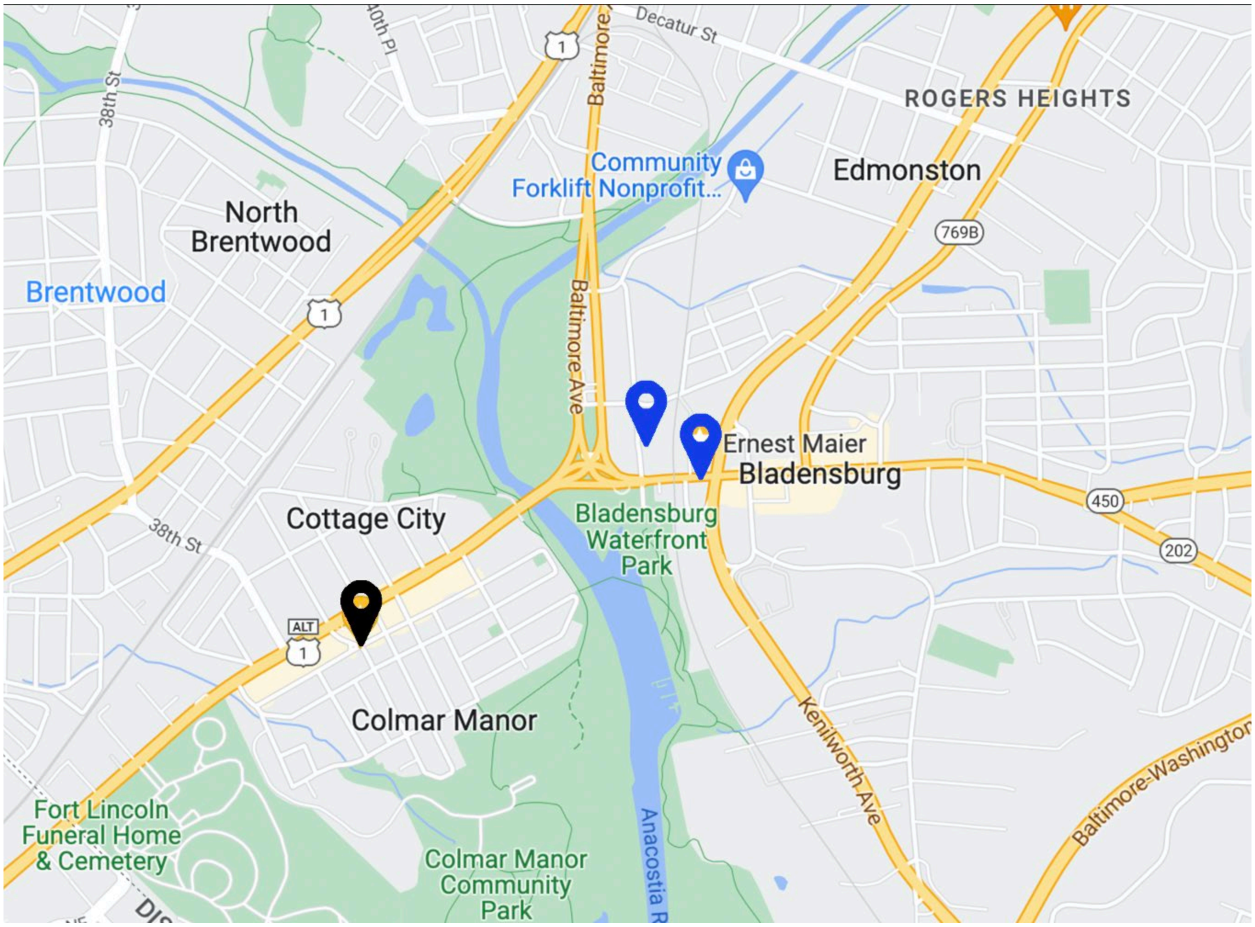


Figure 2. PaveDrain Site (black pin) and EMCO rain gauges (blue pins) on Google Maps.

Data collected from two sensors was used for analysis in this project: an INFIL-Tracker (water depth sensor) and a Rain mX (tipping bucket rain gauge, with sensors for other weather parameters, www.p4i.io). The rain gauge is currently located in Bladensburg, Maryland on 4109 46th Street, 0.6 miles east of the pavement site (Figure 2). Data prior to September 26th, 2022 was collected from a rain gauge located on Ernest Maier's roof (4210 47th St, Bladensburg, MD), 0.7 miles east of the pavement site.

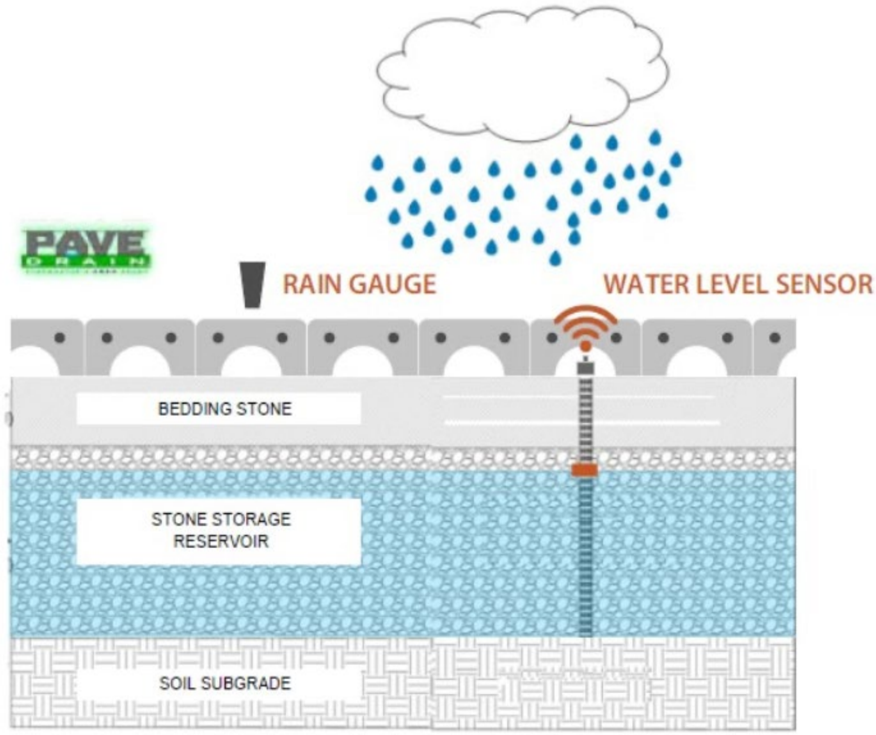


Figure 3. Cross section of site (provided by Ernest Maier).

The INFIL-Tracker system measures the water level in the pavement system's subsurface storage reservoir. The INFIL-Tracker system utilizes a stainless-steel float sensor to measure the water level in the stone storage reservoir (Figure 3). The magnetic float is separate from but encircles and is able to move freely along the cylindrical stainless-steel stem. Inside the stem are Hall effect chips placed to provide 0.25-inch resolution with an overall measuring range of 45.47 inches (Figure 4). The INFIL-Tracker float sensor is located inside a vertical perforated steel pipe and is connected via cord and plug to a P4 solar-powered INFIL-Tracker PaveDrain block which allows wireless sensor communication to the P4 Infrastructure platform. The block above the sensor is partially hollow to allow the block to sit atop the cord without damaging it (Figure 5).

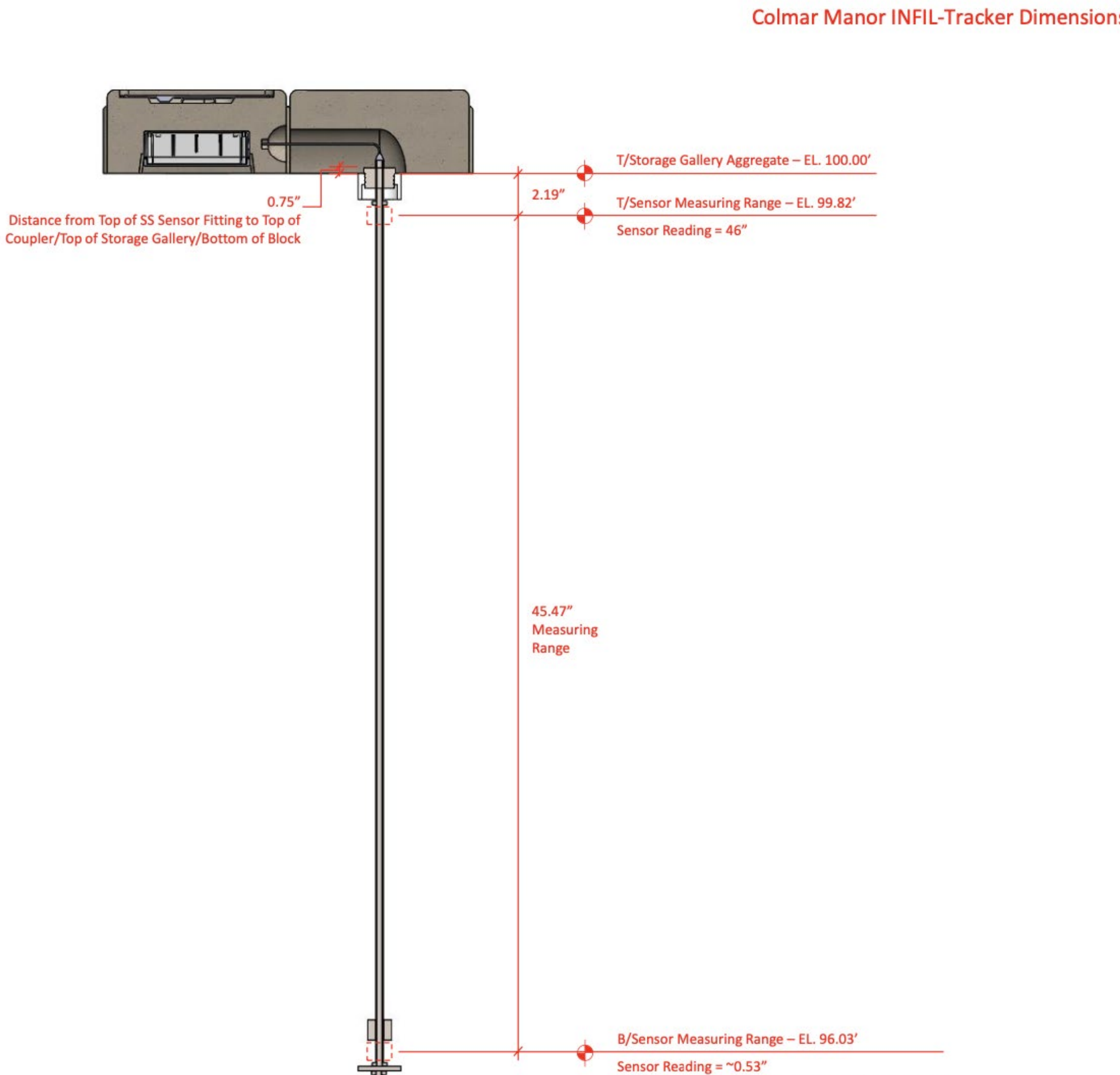


Figure 4. Sensor Dimensions Below Ground (courtesy P4 Infrastructure, Inc).

Figure 5. Solar-powered INFIL-Tracker PaveDrain block (right) connected to underground sensor (left) located beneath adjacent sensor cover block.

Periods of Analysis

Water level sensor and rainfall data were observed for different periods over the course of September 2021 to March 2023 to account for seasonal variation of rainfall and temperature. INFIL-Tracker and rainfall data from September through November 2021 were recorded prior to the start of the study and was provided by EMCO through an Excel spreadsheet. Data from subsequent periods in 2022 were accessed from P4 Infrastructure's online database. Data for both rainfall and water level were reported in intervals of approximately every 10 minutes.

During the project, intermittent maintenance was required for both the INFIL-Tracker sensor and rain gauge. Timelines of the measuring periods are depicted in Figure 6, with periods of sensor interruption shaded in gray. Brief periods of depth sensor interruption occurred from

10/7-10/17 in 2021 and 4/12 - 4/14 in 2022. These instances were verified with EMCO contact Aaron Fisher and did not affect sensor function outside of these periods. Storms that occurred during times of depth sensor interruption were not analyzed. Three periods of missing rainfall data also occurred from 6/8/22 - 7/4/22, 8/23/22 - 10/1/22, and 12/9/22 – 3/31/23; local rain gauge data from Weather Underground (https://www.wunderground.com) was utilized in lieu of the Rain-mX rain gauge data.

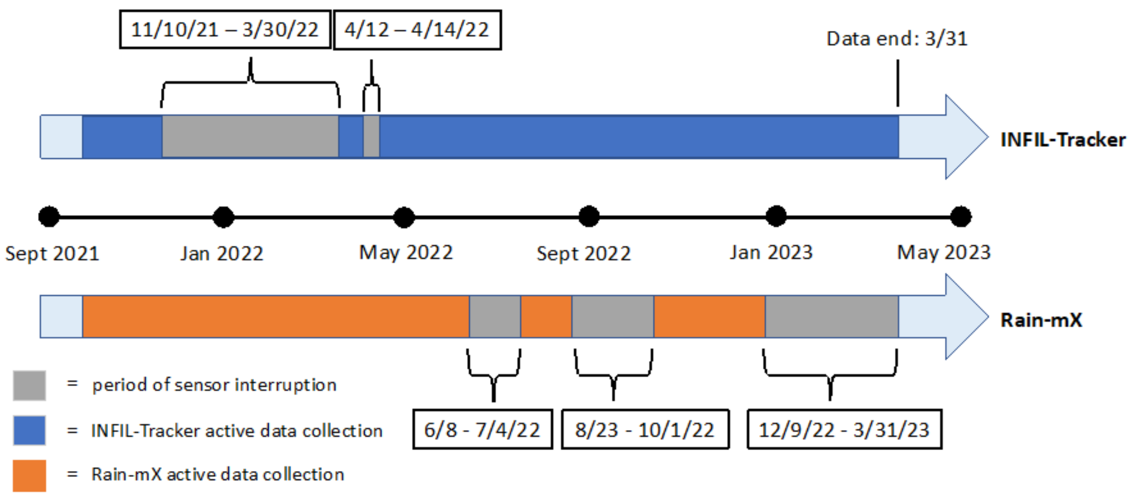


Figure 6. Timeline of Data Collection for PaveDrain Study

Units of Measure

The raw data was transferred from P4 Infrastructure's database to Excel for analysis and modeling by plotting rainfall depth and water storage level (inches) against time. The raw data includes time stamps in the format mm/dd/yyyy hh:mm:ss. Using Excel, the timestamp data was converted into hours since beginning of observation (9/13/21) to ensure continuous time measurements for storms which occur across multiple days. Data were analyzed in detail for individual storm events. Each storm event was defined as a period in which the value of the rain gauge increased from zero inches to a value greater than 0.03 in, and subsequently returned to zero.

Verification of Rain Gauge Data

In order to assess rain gauge accuracy, precipitation data from the EMCO rain gauge was compared with data from four local rain gauges. Using Weather Underground's online precipitation maps (https://www.wunderground.com/wundermap), it was found that the four closest weather stations (Figure 7) within 2 miles of the pavement site were Woodridge (Station ID: KDCWASHI387), Brentwood (KMDBRENT2), Ellaville (KMDHYATT18), and Historic Hyattsville (KMDHYATT28).

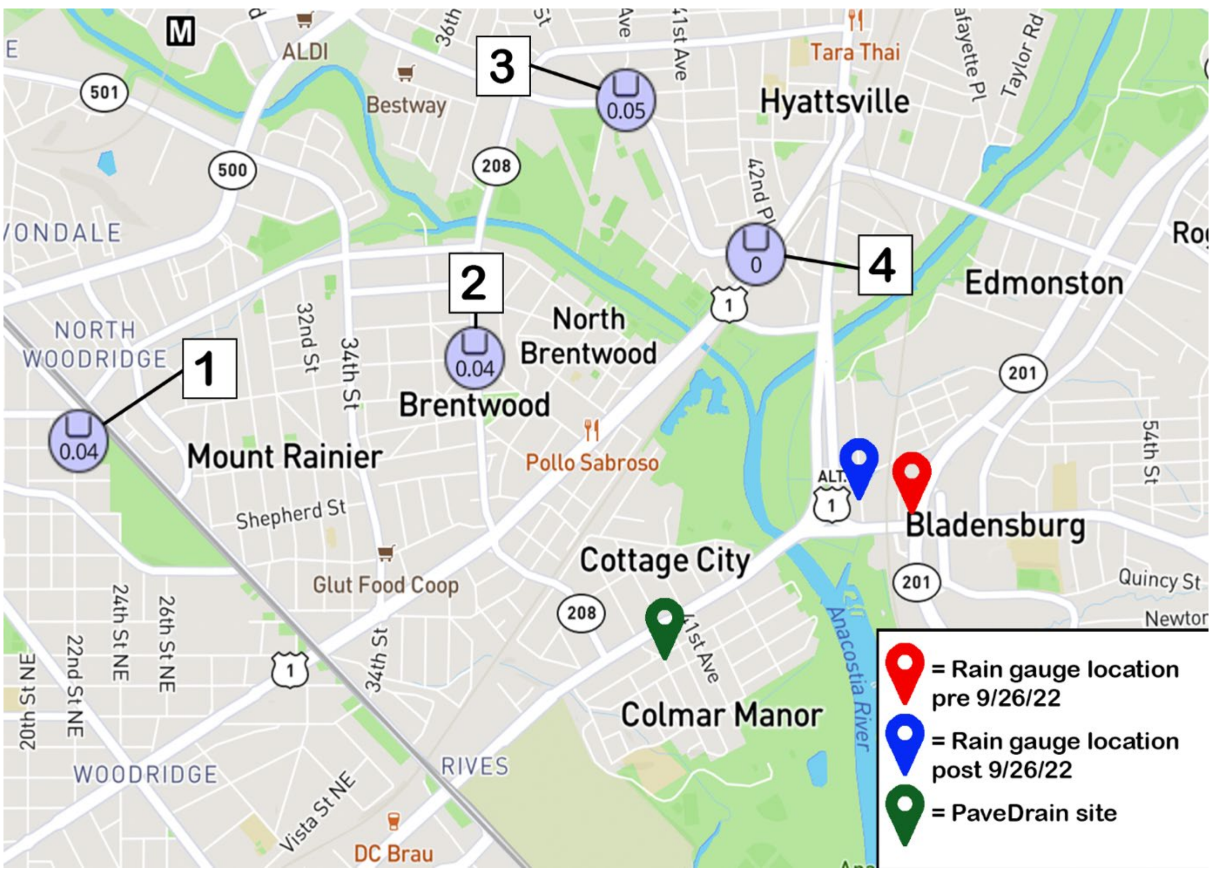


Figure 7. Map of Precipitation Stations (purple circles) from (https://www.wunderground.com/wundermap).1. Woodridge - KDCWASHI387,2. Brentwood - KMDBRENT2,3. Ellaville - KMDHYATT18,4. Historic Hyattsville - KMDHYATT28.

Distance-weighted averages of rain depth for the four local rain gauges were calculated for each storm event by using distance from the Colmar Manor pavement site as a weighting factor. Distances were squared to more heavily weight rain gauges that were closest to the pavement site. Means for the four stations were compared to the Colmar Manor rain gage values for each observed storm event to verify if rainfall depths were similar. The equation to calculate distance-weighted rainfall depth is:

$$P_w = \frac{\sum_{i=1}^{n}(\frac{1}{D_i^2} * P_i)}{\sum_{i=1}^{n}(\frac{1}{D_i^2})} \quad \text{(Eq. 1)}$$

P_w = distance-weighted precipitation
D_i = distance of rain gauge i from measuring point
P_i = 24-hour total rain for rain gauge i
n = number of rain gauges (changes depending on how many of the four local rain gauges had available data for a given storm)

During periods of EMCO rain gauge cell-signal interruption (Figure 6), rainfall depths are reported as the weighted mean of the 24-hour maximum total daily rain reported by the four nearby local rain gages based on Eq. 1.

Removing Noise and Outlier Points

Raw depth sensor data during some periods was not usable for analysis due to outlier points in the data set. We assume that extreme outlier points are a result of sensor noise and/or signal interruption. The sensor level should never read zero because of the physical thickness of the disk float, and water level values at and close to zero indicate sensor malfunction. For high outliers, if no rainfall occurred at the time of the data point, we also assume that sensor malfunction occurred. No outlier points were observed in the rain gauge data.

In order to remove assumed inaccurate values from the INFIL-tracker data, the averages of the surrounding ten values from each individual data point were calculated. The difference between the mean of the surrounding ten values and the current data point was calculated by subtracting each water level reading from its corresponding mean value. If the difference was >0.2 inches, the data point was deemed unreliable and the point was removed. In data series with several undesirable points, data points which differed from the mean by the highest amount were removed first to avoid removing viable points which were skewed by the mean of the outliers.

Water storage level readings during a rainfall event were exempt from the point removal criteria. Due to the rapid increase that occurs in water storage level during rainfall events, the point removal criterion described above was not suitable. The periods of increase were identified by noting the time of storm events in the rainfall data and boxing these periods in Excel to mark them as exempt from point removal (Appendix A).

Data Presentation

Data across storms is presented by plotting water level recorded by the INFIL-Tracker sensor on a primary axis and 24-hour rainfall total on a secondary axis, both as a function of time. Both water level and rainfall are measured in inches. Water storage level is depicted by a blue curve, while rainfall is depicted by an orange curve (Figure 9). Plots were created in 1-2-month periods to allow for greater visibility of individual storms.

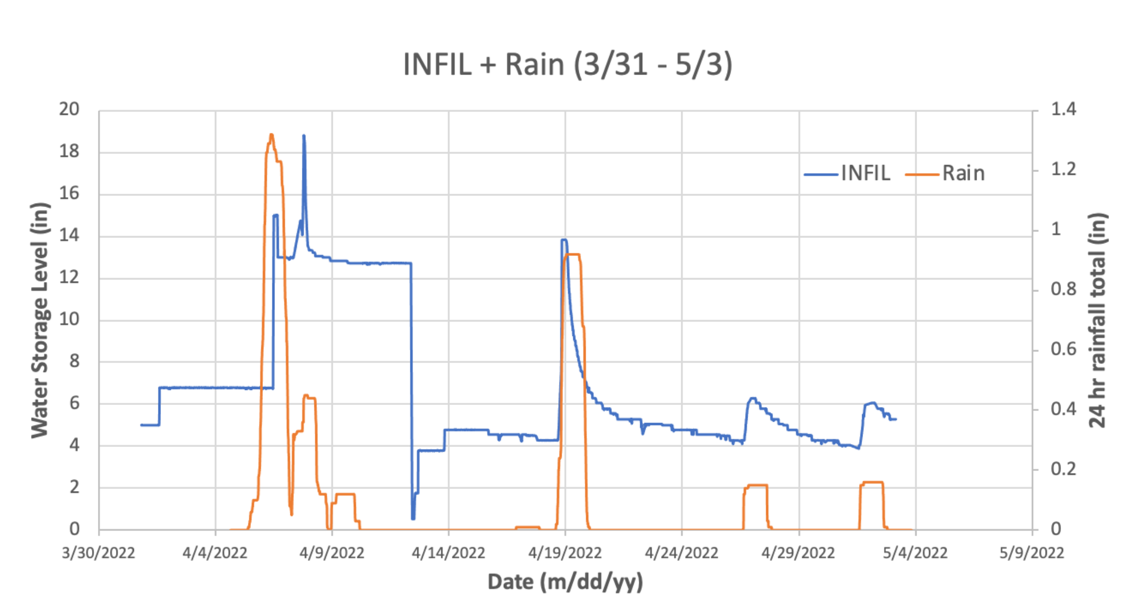


Figure 9. Sample INFIL-tracker and rain gauge graph from 31 March to 03 May 2022 (including sensor signal interruption 4/12-4/14).

Calculating Infiltration Rates

Storage depth data for each storm event was plotted from the time at peak water storage level until the time at which water level ceased to decrease by increments over 0.01 inches per hour. Smaller subplots of data were created for 1, 2, and 4-hour periods after the peak water storage level (Appendix B). These times were selected in order to compare infiltration rates across each individual storm event and see how they differ depending on time. A tolerance of 0.1 hr (6 minutes) was established due to availability of data, as readings did not always occur exactly 1, 2, or 4 hours after the peak water level.

The water level data was fitted in Excel using linear and exponential trendlines in order to calculate infiltration rates. These models were selected because rainfall that exceeds infiltration capacity will infiltrate following an exponential decay model due to the falling head, but in the immediate hours after peak rainfall the curve is more linear (Viessman and Lewis, 2003). For linear trendlines, the slope of the line provided an infiltration rate in the units [in/hr]. For exponential trendlines, the exponential coefficient of the curve provided a value in the units [hrs^{-1}]. The exponential coefficient was converted to an infiltration rate when multiplied by the depth of the underlying saturated soil (assumed default value of 12 inches). These equations and coefficients were tabulated in Excel for each storm event.

The increase in water level during a rain event was calculated by subtracting a baseline value from the peak water storage level. The baseline value represents the consistent point at which the water level sensor measured prior to the increase in water level for a specific storm event, typically after recession from a previous event. No universal baseline was noted due to fluctuations resulting from sensor maintenance and variance of natural conditions, and a unique baseline value was used for each storm event. The peak water storage level represents the highest value for water storage level per storm event.

Calculated infiltration rates were plotted against the difference in baseline values to examine any correlation between rate of infiltration and increase in water level. Linear and exponential plots were created for one-, two-, and four-hour rates for each event and tabulated (Appendix A). Storms with over two hours of missing data near the peak were omitted from infiltration rate calculations due to lack of available data on when the peak water storage level occurred.

Statistical Analysis

Statistical analysis was performed on the depth sensor data and rain data. Means of data are reported as unweighted averages unless otherwise specified. Standard deviations are calculated to report the variation of different statistics, such as infiltration rates. R^2 values were calculated by Excel for all regressions. Comparisons between data sets were made using the Student's t-test with the level of significance set at 5% ($p \leq 0.05$).

Results

Overview of Sensor Data Analysis

The baseline value (i.e., the INFIL-Tracker level with no recent rainfall) varied slightly over seasons and storm events. Over the entire course of the study, the baseline for storage depth ranged from approximately 2.5 to 4.5 inches. The baseline value from September to November 2021 and from March to May 2022 remained at approximately 4.0 ± 0.5 in. In the summer and early fall months (July – Oct 2022), the baseline reduced to 3.5 ± 0.75 in. From Oct 2022 to March 2023, the baseline reduced further to 3.0 ± 0.5 in. In total, 50 storms were analyzed over the course of this study.

The location of the vertical standpipe extending from the base of the mid-drain corresponds to a height 1.35 inches below the base of the paver blocks, which is 0.84 inches above the maximum sensor depth reading of 45.47 in., assuming that the pavement is flat. The highest recorded water storage level across all storm events was 23.33 inches on 9/21/21 during a rain event of magnitude of 1.32 inches (24-hr total). The PaveDrain system at Colmar Manor is predicted to store volumes of water from 10-year storms or less without reaching overflow, as discussed below. Since no overflow was recorded in this study (maximum recorded 24-hour rainfall total of 2.41 in.), no observations may be made for a typical overflow event for this PaveDrain system.

Figures 10 and 11 show the INFIL-Tracker and rain data for two periods over the course of the study. For both graphs, the blue line represents the INFIL-Tracker data and the orange line plotted on the secondary axis represents rainfall. The brief periods of depth sensor inconsistency/interruption from 10/7-10/17/21 are shown (Figure 10), as well as the gap in rainfall data from 6/8-7/4/22 (Figure 11).

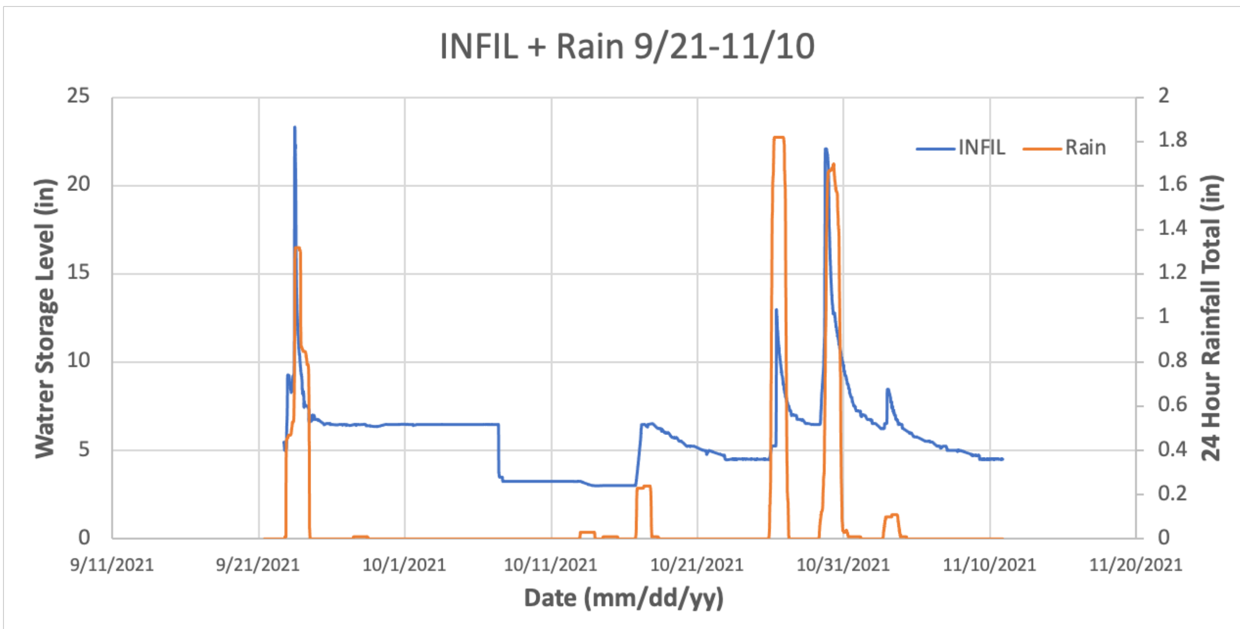


Figure 10. Water depth and rainfall data from 21 September to 10 November 2021.

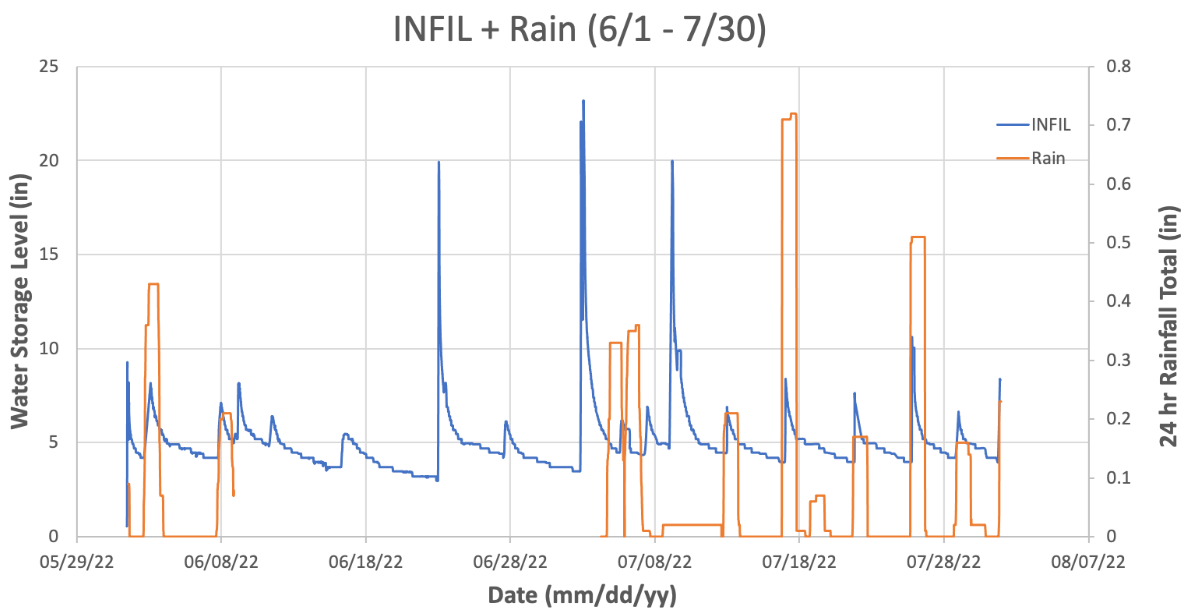


Figure 11. Water depth and rainfall data from 1 June 2022 to 30 July 2022.

Rain Gauge Verification

Figure 12 shows the relationship between the EMCO gauge recorded rainfall depths and the distance-weighted average of the local gauges. An approximate linear relationship results. A slope of 0.8193 with an R^2 of 0.8791 was found (forcing the line through the origin), indicating that the weighted average of the nearby gauges was a strong predictor of the EMCO rain gauge value. A slope of one would represent perfect agreement. This slope of the relationship in Figure 12 indicates that for storms with data available for at least 2 local gauges and the EMCO rain gauge, the weighted means of the local gauges were, on average, 81.9% of the EMCO values. This correlation provides a reasonable level of confidence in the EMCO rainfall data. Also, in events where EMCO data are not available, local gauge averages are used in the water balance analyses.

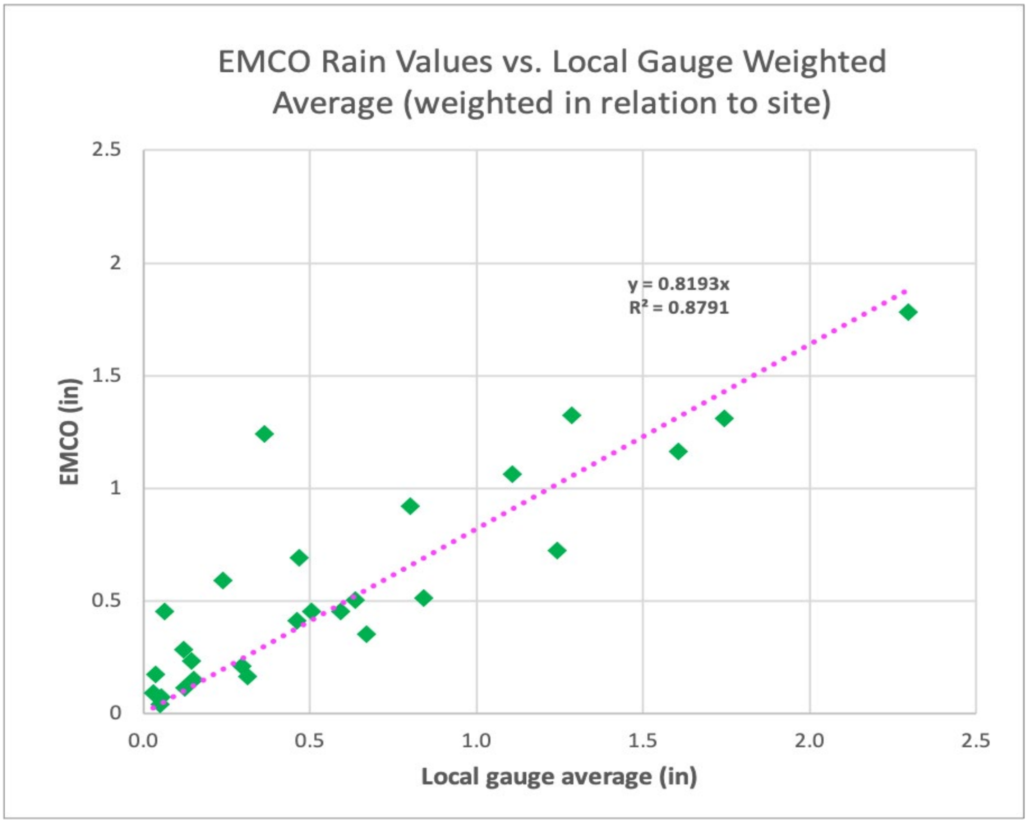


Figure 12. Scatter plot comparing EMCO rain values to distance-weighted average of 4 local rain stations

Water Balance Calculations

Increase in subsurface water storage was found to vary for rain events of similar sizes (Figures 10-11), in which events with similar rainfall depths (orange) show different amounts of water storage (blue) increase.

A water balance was completed to compare the volume of water entering the pavement system through rainfall/run-on and the increase in water volume in the pavement storage system. Figure 13 shows the relationship between water storage level increase and depth of rainfall for 44 storm events. Data from the local gauges were used in 20 events where EMCO data were not available. The data from the pavement system exhibited a mostly linear relationship, with some outliers. Possible explanations for outlier values in the data may be natural hydrologic variation such as change in soil moisture conditions, varied amounts of run-on from the drainage area, and/or sloping of roadways/gutters. The plot was fit to a linear trendline with the equation y=11.26x. The intercept for this fit was set to zero because only positive values for change in water storage are possible for a given rainfall. This linear relationship indicates an approximate 11.26-inch increase in water storage level per every inch of rainfall.

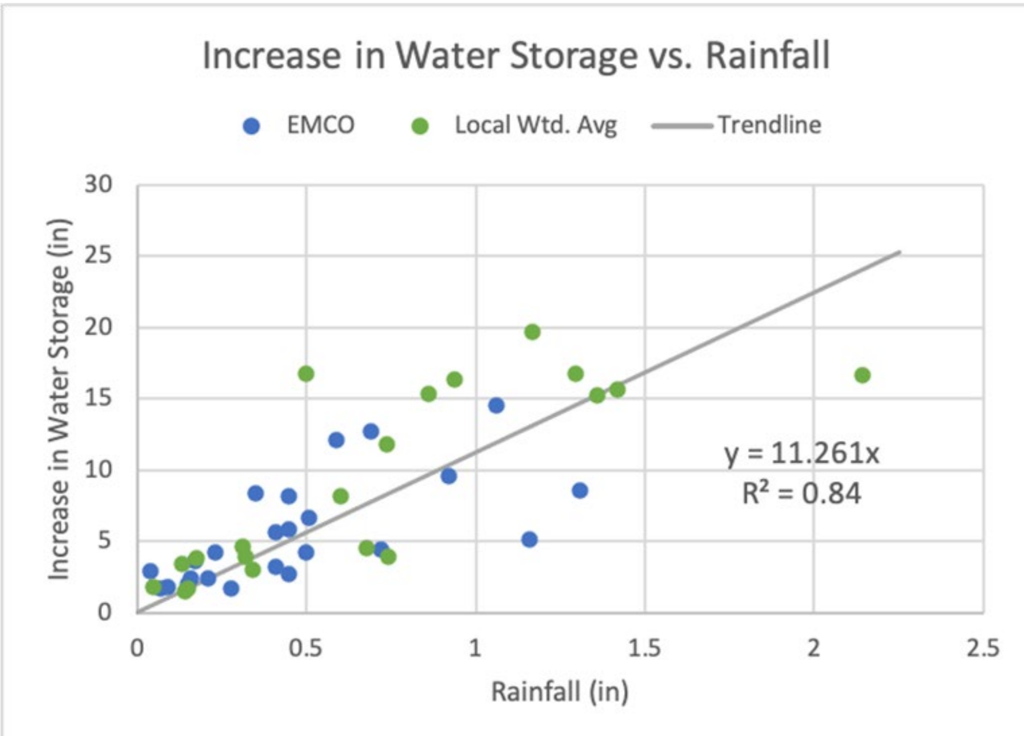


Figure 13. - Plot of correlation between rainfall and increase in water storage

To calculate the increase in the volume of water received by the pavement system, the area of the pavement site, A_p (2350 ft^2), was multiplied by the change in water level, d_s, and by the porosity of the infiltration media, ε. Due to the variable thickness of stone in the storage reservoir, we assumed a value for porosity of 0.4 based on design criteria found in the Maryland Stormwater Manual (Maryland Department of the Environment, 2000). A plot of water volume stored as a function of rainfall depth, d_r, will give a slope equal to the total drainage area, A_d.

$$d_s\, A_p\, \varepsilon = (\, A_d)\;\, d_r \qquad \text{(Eq. 2a)}$$

The run-on area, A_{ro}, is the difference between the total drainage area and the pervious pavement area.

$$A_{ro} = A_d - A_p \qquad \text{(Eq. 2b)}$$

The run-on ratio is given by:

$$Run - on\ ratio\ = \frac{A_{ro}}{A_p} \qquad \text{(Eq. 2c)}$$

Figure 14 shows the results of volumetric water balance calculations for each storm event comparing rainfall depth and storage volume. Each point represents an individual storm event. The slope is 783 ft^3/in or 9400 ft^2, equal to total drainage area A_d. With the pavement area, A_p, equal to 2350 ft^2, the run-on area is calculated as 7050 ft^2 and the run-on ratio is 3.00. This value is 10.9% greater than the 6355 ft^2 of run-on area estimated during the facility design, although some of this variation may be a result of the porosity assumption.

Figure 15 shows a similar figure of estimated rainfall volume (calculated as the rainfall depth over the total area of 8,705 ft^2 (estimated during design) and storage volume. A linear trendline was fit to the water balance data and a slope of 1.08 was calculated, with an R^2 value of 0.82, (Figure 15). According to slope, approximately 108% percent of rainfall measured over the drainage area enters the permeable pavement system, or that the area is 7% greater than the design estimate. Increasing the total area by 8% to 9401 ft^2 agrees with the analysis above.

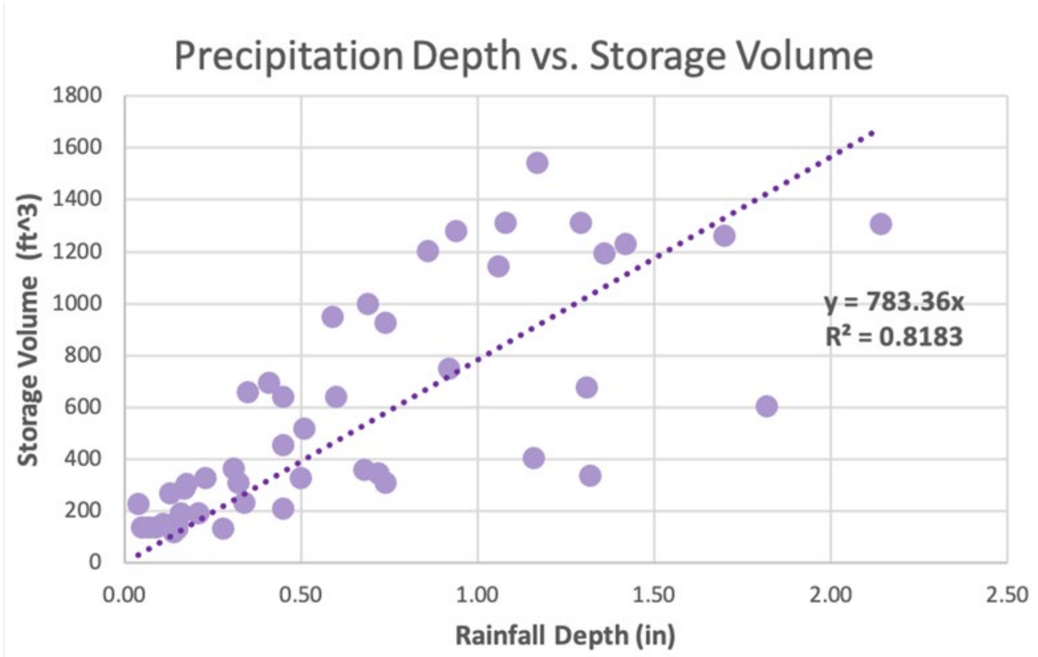


Figure 14. Plot of precipitation depth vs storage volume per storm event

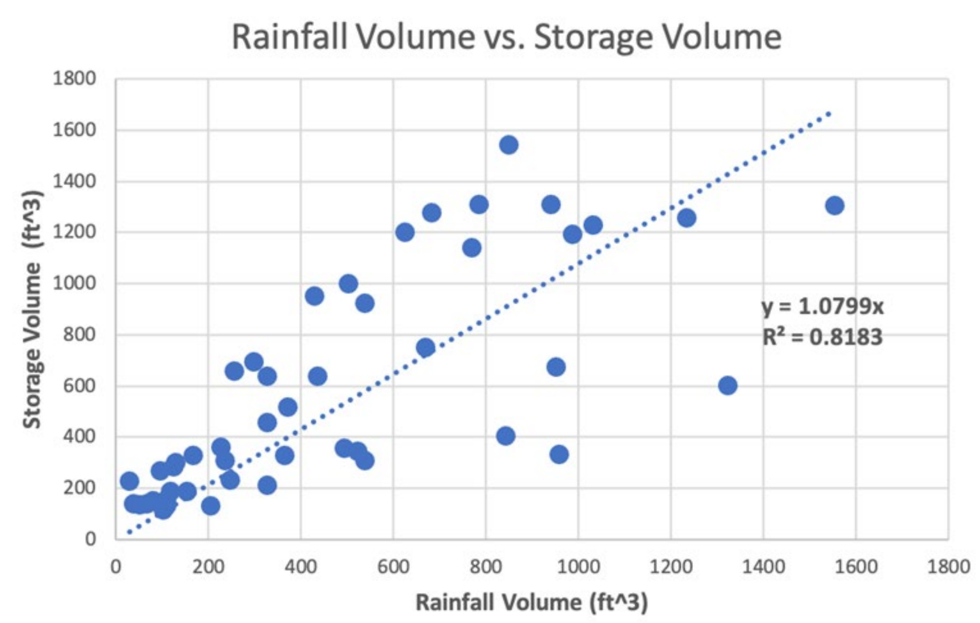


Figure 15. Volumetric water balance of water entering pavement system through rainfall and water draining from storage per storm event.

Since all the water volume entering the pavement system exits the storage reservoir through infiltration to the underlying soils, the PaveDrain system performs very well from a stormwater management perspective. The total storage volume at the site is approximately 3630 ft^3 based on the available depth, area of 2350 ft^3 and a porosity of 0.4.

According to the observed 11.26-in increase in storage depth per every inch of rainfall, it would take 4.11 inches of rainfall to reach the height of overflow, corresponding to a depth sensor reading of 46.31. Based on data from the NOAA Precipitation Frequency Data Server, using the 90th percentile to account for climate change, this magnitude of rainfall is approximated as a 4-yr (24-hr) storm for the site. *This analysis assumes static storage only and infiltration over the course of a long duration storm would increase the storm size that is fully captured, as discussed below.* Over the course of the study, the largest 24-hr rain total measured 2.41 in, which corresponds to a return period of less than 1 year.

Table 1 is created examining the probability of exceeding the static volumetric capacity of the site, which corresponds to 4.11 inches of rainfall over the entire drainage area. NOAA Atlas 14 rainfall data are used, employing the 90-percentile value to account for predicted climate change impacts. Rainfall durations from 1 to 24 hours are examined, with the return periods extrapolated from standard return period data. Results show the low probability of exceeding the static volumetric capacity for short duration events (high return periods). Higher probability is found for longer durations, but these events will also include volume recovered from infiltration that occurs during the event, as discussed below.

Table 1. Estimated return periods (NOAA Atlas 14) for rainfall events exceeding 4.11 inches of rainfall over the entire drainage area at Colmar Manor, MD. The 90-percentile rainfall value is used to account for climate change.

Rainfall Duration (hrs)	Approximate Return Period for 4.11 in. Rainfall (yrs)
24	3.8
12	6.5
6	18
3	50
2	86
1	360

* Return period is equal to the *average* time interval in which an event of this magnitude will occur. That is, a 3.8-year return period corresponds to an event that is expected, on average, to occur once every 3.8 years.

Infiltration Rates

Absolute values of linear and exponential subsurface infiltration rates were determined from depth sensor readings. Plots were created for 1-, 2-, and 4-hour periods. Figure 16 shows an example of a graphical infiltration analysis for an individual storm, in which linear and exponential trendlines are fit to the INFIL-Tracker sensor data from the peak storage depth (t=0) until the storage depth at time t = 1, 2, or 4 hours.

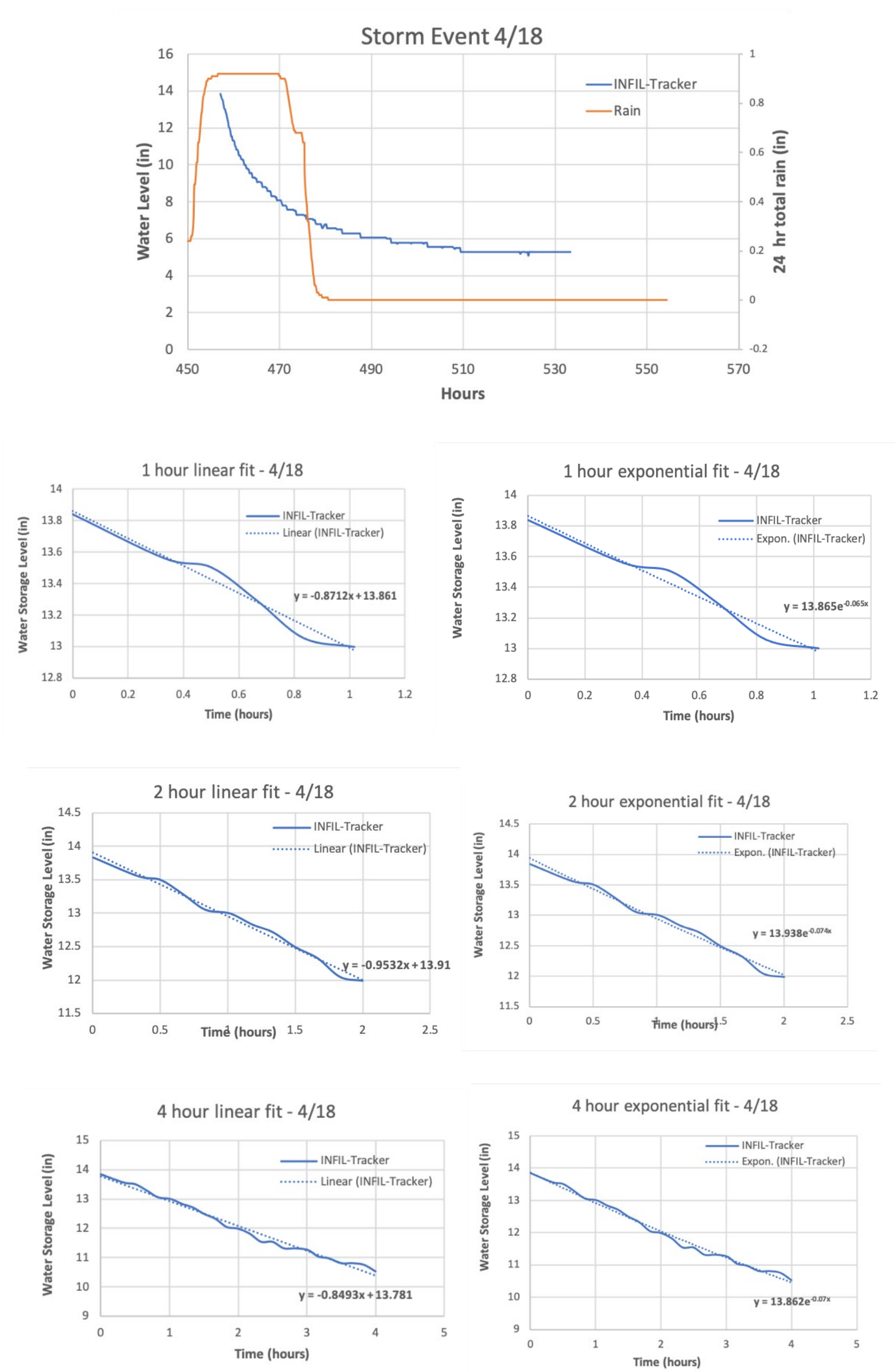


Figure 16. Example Storm Event Infiltration Rate Analysis – 18 April 2022. Linear and exponential curves are fit over 1-, 2-, and 4-hour infiltration times.

Surface infiltration rates through the permeable blocks were not measured for this study. Based on water storage depth data, the storage reservoir filled quickly for all storms. If any clogging did occur over the study, it was not significant enough to impact water depth data and surface infiltration rates. No maintenance specific to permeable pavement systems was performed since the facility was installed; the permeable pavement area was exposed to identical impacts and treatments as the surrounding pavement area.

Table 2. Linear and Exponential Infiltration Rates summarized over All 50 Storms

Linear and Exponential Infiltration Rates (in/hr)					
	Range	**Mean**	**Median**	**25th percentile**	**75th percentile**
Linear					
1-hr rates	0.12 - 5.34	1.04	0.50	0.23	1.57
2-hr rates	0.10 - 5.05	1.21	0.53	0.20	1.99
4-hr rates	0.08 - 3.00	0.89	0.78	0.18	1.08
Exponential					
1-hr rates	0.12 - 3.70	0.99	0.66	0.34	1.11
2-hr rates	0.10 - 3.89	1.13	0.59	0.34	1.78
4-hr rates	0.10 - 2.35	0.92	0.58	0.33	1.45

Table 2 shows summary data for linear and exponential infiltration rates across all rainfall events. The Maryland Stormwater Manual specifies that infiltration rates for stormwater BMPs should be at least 0.52 in/hr (Maryland Department of the Environment, 2000). The mean and median rates for both the linear and exponential models are all higher than this MDE value, indicating that the soil infiltration at the Colmar Manor site is satisfactory for compliance with Maryland stormwater design standards. Two studies of infiltration-based BMPs in other states found infiltration rates with rates comparable to the PaveDrain 1-hr exponential rates. Another PaveDrain study in Cudahy, Wisconsin reported an average infiltration rate of 1.34±1.07 in/hr across three storm events, and a Philadelphia infiltration trench study reported an average infiltration rate of 3.36±1.16 in/hr (Diekfuss and Foley, 2021; Ebrahimian et al, 2022). These studies are under various soil conditions and design specifications, and therefore would need greater analysis for formal statistical comparison.

Saturated hydraulic conductivity values are affected by season, with higher conductivity in the warmer months due to decreased water viscosity (Ebrahimian et al, 2022). This trend was evaluated within the PaveDrain data. Warmer months (May through September) reported a mean 1-hr exponential infiltration rate of 1.04 ± 1.06 in/hr, while colder months (October – April) reported a mean rate of 0.90 ± 0.96 in/hr. However, a student's t-test of the means indicated that the difference in rates were not statistically significant at a 5% confidence level, due to the large variation in rates.

Correlations were also examined between infiltration rates and increase in storage depth per each rainfall; increased rates are expected due to the greater hydraulic head. Plots of the per-storm increase in storage depth read by the INFIL-Tracker sensor and infiltration rates were created; separate plots were developed for linear and exponential model rates, as well as for different time intervals (t) used to calculate the rates. Figure 18 shows the plot for 1-hour linear infiltration rates. Storms that were missing data within 0.10 hours of the time t (for this sample plot t = 1 hr) after the peak storage depth were excluded from this analysis so only 30 out of 50 storms were analyzed. R^2 values were slightly higher for calculated linear rates compared to exponential rates (Table 3). The Horton equation has been used to describe rainfall infiltration into watersheds and it is reasonable to assume a similar relationship in the site subsurface where the soils are saturated during rain events (Horton 1940, Ren et al, 2020). The Horton equation predicts exponential decay in infiltration rate over time; therefore, final infiltration values were selected using the exponential model.

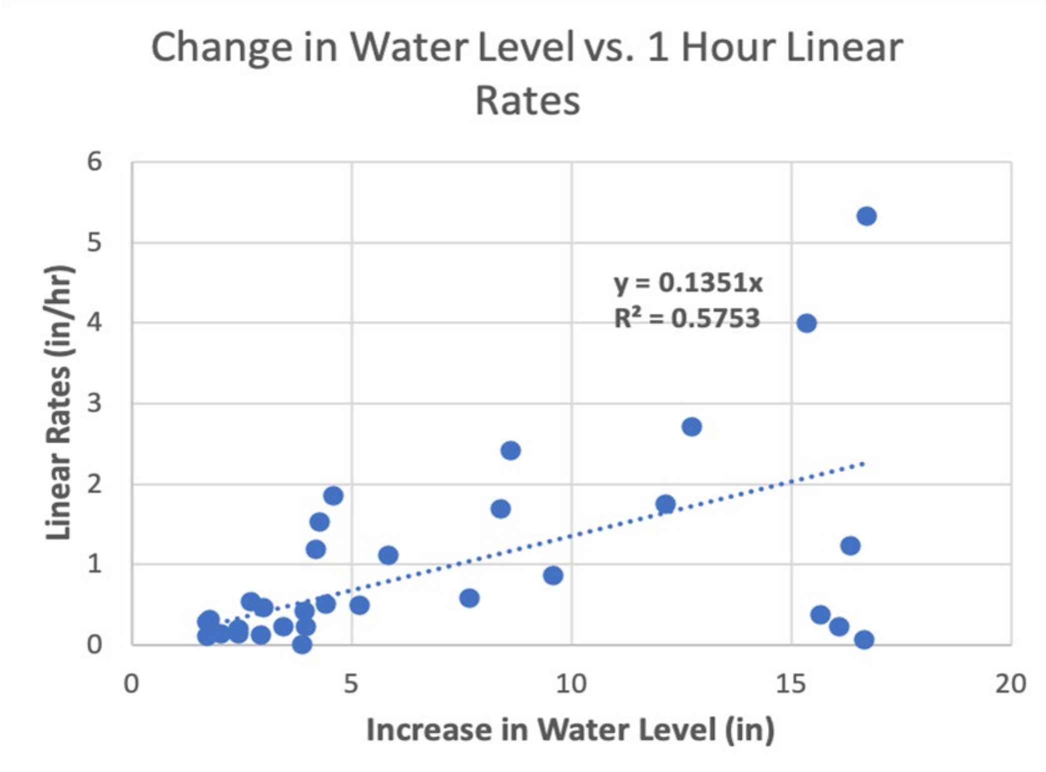


Figure 17. Plot of correlation between water storage increase and infiltration rates derived from 1-hour linear fit.

Table 3. Comparison of R^2 values for linear and exponential infiltration models.

	1-hour	**2-hour**	**4-hour**
Linear model R^2	0.5753	0.6457	0.6655
Exponential model R^2	0.5164	0.5838	0.5650

Soil Hydraulic Conductivity and Infiltration Rates

Subsurface infiltration rates depend on the hydraulic conductivity of the soil. Saturated hydraulic conductivity is a fundamental property of the media whereas infiltration rates can vary depending on hydraulic gradient; they are equal at a hydraulic gradient of 1. Saturated hydraulic conductivity, K_{sat}, values for each soil group noted in the soil borings were estimated using the USDA *SPAW Soil and Water Characteristics tool* (Saxton & Rawls, 2009) to compare to measured infiltration rates. K_{sat} values retrieved from the Soil Water Characteristics tool based on the compositions of soil found through the three soil borings collected during construction are 0.18 in/hr, 0.26 in/hr, and 3.85 in/hr, for silty clay (D), silty clay loam (B), and loamy sand (A) soil types, respectively, with a mean value of 1.43 in/hr (geomean 0.56 in/hr). The exact composition and distributions of the underlying soils is unknown.

Table 4. Soil Boring Data and Hydraulic Conductivity (K) values

Sample	Depth [ft]	%Gravel	%Sand	%Silt	%Clay	Classification	USDA	K
1	1.5	0	14.6	54.6	30.8	Gray Silt	Silty Clay Loam	0.26 in/hr
2	2	0.2	86.7	7.2	5.9	Brown Silty Sand	Loamy Sand	3.85 in/hr
3	1	0	11.1	49.4	39.5	Gray Lean Clay	Silty Clay	0.18 in/hr

The mean 1-hr exponential infiltration rate across the 31 storms was found to be 0.99 +/- 1.00 in/hr. This rate falls within the range of K_{sat} values for the types of soil identified on site. The mean saturated hydraulic conductivity of the 3 soils types is 1.43 in/hr and the geometric mean is 0.56 in/hr. The observed mean 1-hr exponential infiltration rate of 0.99 in/hr is 0.44 in/hr less than the mean and 0.33 in/hr greater than the geomean. Though the subsurface soil was classified based on the lowest hydrologic group (D for soil at the PaveDrain site), it is recommended that for stormwater BMP site selection that soil borings are analyzed to reflect the infiltration potentials for all types of soils found on site.

It is important to note that this study only considers vertical infiltration. Several studies on infiltration-based systems consider sidewall infiltration, or horizontal infiltration through the sides of the subsurface infiltration media (Finch et al, 2008). For simplicity of calculations, all infiltration was assumed to be vertical in this study, although it may be noted that sidewall infiltration is possible.

Dynamic Storage

The continuous exfiltration from the subbase storage acts to regenerate a portion of the available storage volume (i.e., filling a leaky bucket). Infiltration rates will be highest at the point of the greatest hydraulic head and slow as the head in the subsurface decreases. Using a conservative value measured for the infiltration, the 4-hr exponential rate of 0.58 in/hr, a volumetric infiltration rate is calculated based on the infiltration area and the porosity:

$$0.58\ \frac{in}{hr}(2350\ ft^2)(0.4)\frac{1\ ft}{12\ in} = 45.4\ \frac{ft^3}{hr}$$

This value is divided by the total drainage area to translate the flow rate into a rainfall intensity that is continuously being infiltrated through the subbase:

$$\frac{45.4\ \frac{ft^3}{hr}}{9400\ ft^2} = 0.0048\ \frac{ft}{hr} = 0.058\ \frac{in}{hr}$$

A rainfall intensity of 0.058 in/hr over the entire drainage area corresponds to an additional 0.23 inches of rainfall storage and management over a four-hour rainfall duration. This value is particularly impactful on long duration events where the volume is continuously being regenerated. This exfiltration and loss of 0.23 inches in a 4-hour period can be added to the static volume that can be stored at the site.

Considering this additional exfiltration, Table 5 is created as a modification of Table 1. In Table 5, the exfiltration rate of 0.058 in/hr is included during the storm duration, producing an additional volume management. Therefore, the event return periods in Table 5 are larger than those in Table 1, which does not account for dynamic storage.

Table 5. Estimated return periods (NOAA Atlas 14) for rainfall events exceeding 4.11 inches of rainfall over the entire drainage area with exfiltration at Colmar Manor, MD. The 90-percentile rainfall value is used to account for climate change.

Rainfall Duration (hrs)	Exfiltration (in)	Total Rainfall Depth Managed (in)	Approximate Return Period (yr)
24	1.39	5.50	11.4
12	0.70	4.81	12.8
6	0.35	4.46	25
3	0.17	4.28	65
2	0.12	4.23	100
1	0.06	4.17	390

Pollutant Load Reductions

Data for pollutant load reductions were sourced from the 2014 MDE *Guidance for NPDES Stormwater Permits* based on two Chesapeake Bay Watershed models: 5.3.0 and 5.3.2 (Figure 21). Version 5.3.2 has updated pollutant load data when compared to the previous Model 5.3.0, though the MDE considers both models to remain accurate (Maryland Department of the Environment, 2014). Data from the models were converted from lb/acre/yr to lb/yr, multiplying the model values by the calculated drainage area of 9,400 ft^2 to obtain load reductions for the PaveDrain site, converted to acres. This calculation assumes complete capture of all runoff due to having no occurrences of overflow during this study, with overflow only expected for a 10-yr precipitation event or greater. Table 6 shows the annual load reductions to the PaveDrain system for total nitrogen and phosphorus (measured in lb/yr) as well as total sediment (measured in tons/yr). Similar nutrient reduction calculations can be made for other PaveDrain sites, assuming similar designs with significant run-on from nearby pervious area.

Table 6. Pollutant Load Reductions estimated for the PaveDrain System

Loads for PaveDrain System		
Chesapeake Annual Pollutant Loads for Urban Impervious Surfaces Versions 5.3.0 and 5.3.2		
	5.3.0	5.3.2
Total Nitrogen (lb/yr)	2.33	3.28
Total Phosphorous (lb/yr)	0.44	0.36
Total Sediment (tons/yr)	0.10	0.09

Estimates of the cost for nutrients removal for Maryland stormwater BMPs have recently been provided by Wainger et al. (2023). Although in some cases data were limited (in the case of permeable pavements, inadequate data were available), the median annual cost for N removal was $1558/lb and that for P was $9,639/lb. Therefore, using the removals for the PaveDrain facility in Table 4, the value of N and P reductions are given in Table 7.

Table 7. Value of Pollutant Load Reductions estimated for the PaveDrain System

Annual Value of Nutrients Removal by the PaveDrain System		
	5.3.0	5.3.2
Total Nitrogen ($/yr)	$3646	$5141
Total Phosphorus ($/yr)	$4241	$3470
Total N & P ($/yr)	$73887	$8611

Conclusions

This 1.5-year study examined the hydrologic performance of a recently constructed permeable pavement system. The main goals of this research were to: 1) assess stormwater volume collection potential and infiltration rates of the pavement system, 2) evaluate the run-on ratio for the facility, 3) compare infiltration performance to expected rates for soils found on site, and 4) compare the site's performance to other permeable pavement systems and Maryland stormwater BMP requirements. The site was designed to reduce runoff volumes from a drainage area of 8,705 ft^2, as well as to reduce pollutant loadings to the Chesapeake Bay. The underlying soils were classified as HSG D; many jurisdictions will not provide stormwater management credit to permeable pavements installed over HSG D soils.

Specific findings from this study include:

- The PaveDrain system in Colmar Manor, MD was designed to capture runoff from a drainage area that is 2.7 times larger than the pavement area. A water balance comparing rainfall volumes to volumes of stormwater infiltrated into the underlying soil revealed that on average, the drainage area is 9,400 ft^2, compared to that of 8705 ft^2 estimated by PG County Department of Permitting Inspection and Enforcements (DPIE) (108%). The run-on ratio of the site is 2.98.
- Based on static volumetric capture, the system is expected to hold and infiltrate all storm events up to a 10-year, 24-hr storm. Consideration of additional infiltration occurring during the event (dynamic storage) allows for capture of larger events.
- Exponential models fit to depth sensor data revealed a mean subsurface infiltration rate of 0.99 in/hr, which is substantially greater than the infiltration rate expected for a HSG D soil (0.18 in/hr).

- The system in Colmar Manor is reducing annual TN, TP, and TS loads to the Chesapeake Bay.
- Use of in-situ sensors for permeable pavements allows engineers and manufacturers to efficiently verify site performance, improving permit compliance, and potentially reducing inspection costs
- The PaveDrain system demonstrated significant performance despite having no cleaning or maintenance, with no clogging observed over the course of the study. Therefore, alternative types of low-maintenance permeable pavement systems should be considered for modified stormwater BMP credit due to their reduced potential for clogging.

The results of this study show the PaveDrain system in Colmar Manor reduces runoff volumes and pollutant loads to the Chesapeake Bay at values greater than expected in design stages, thereby promoting water quality improvement. It is recommended that storage depth and rainfall depth continue to be examined for this site, and that sensors be installed in future PaveDrain facilities to further verify the results of this study and the performance of PaveDrain in various environments and climates.

Appendices

Appendix A

Figure A1 shows a set of data which at first follows a smooth curve then becomes dominated with noise and becomes unreadable. Extreme outliers can be observed toward the end of the data. Figure A1.1 shows the same set of data, with noise removed according to our point removal criterion.

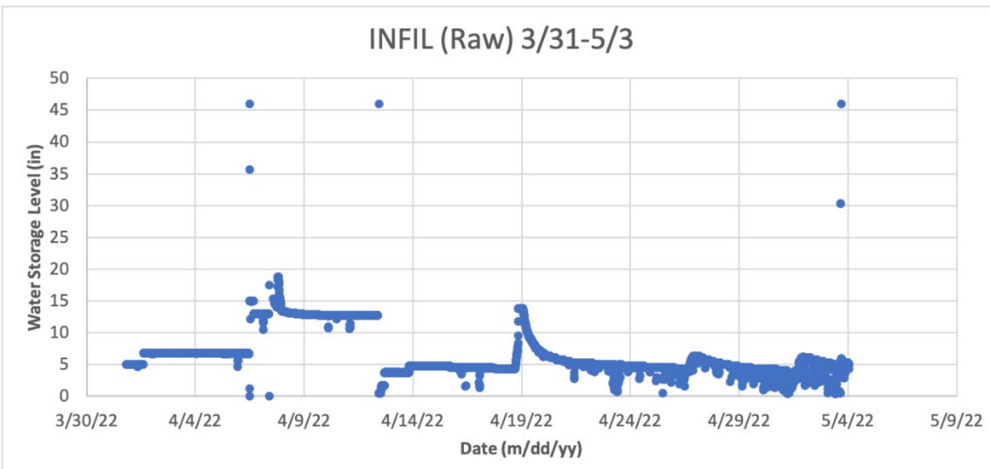


Figure A1: Raw INFIL-tracker Data from 3/30 to 5/4

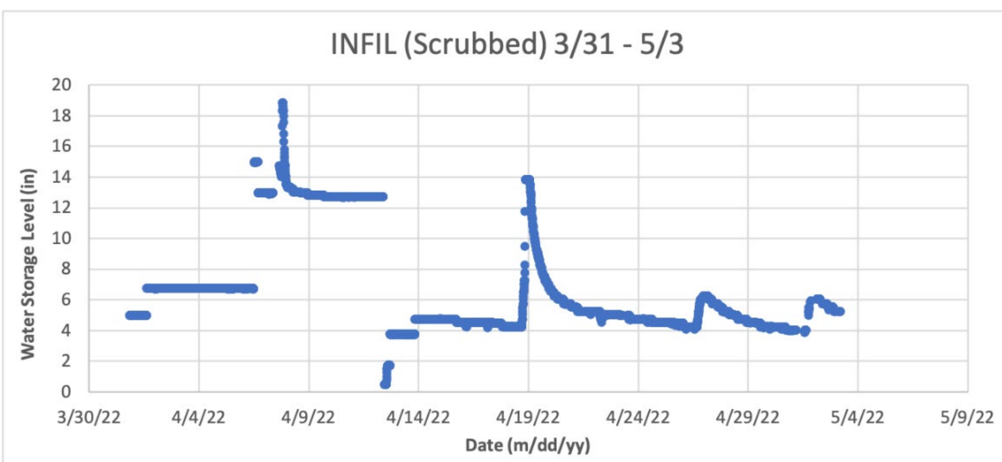
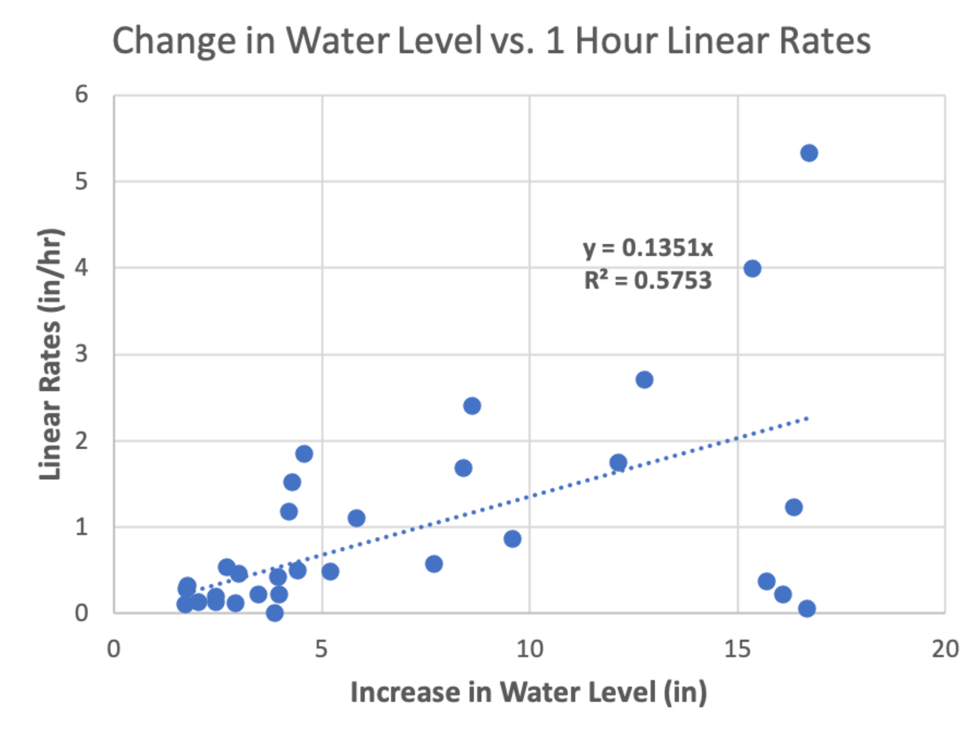
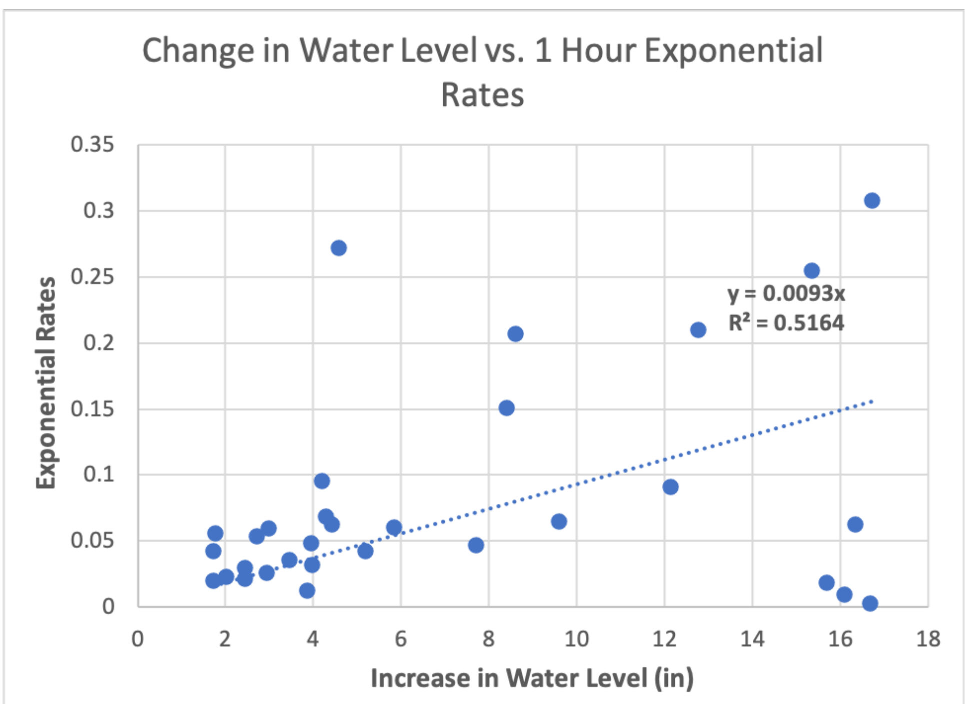
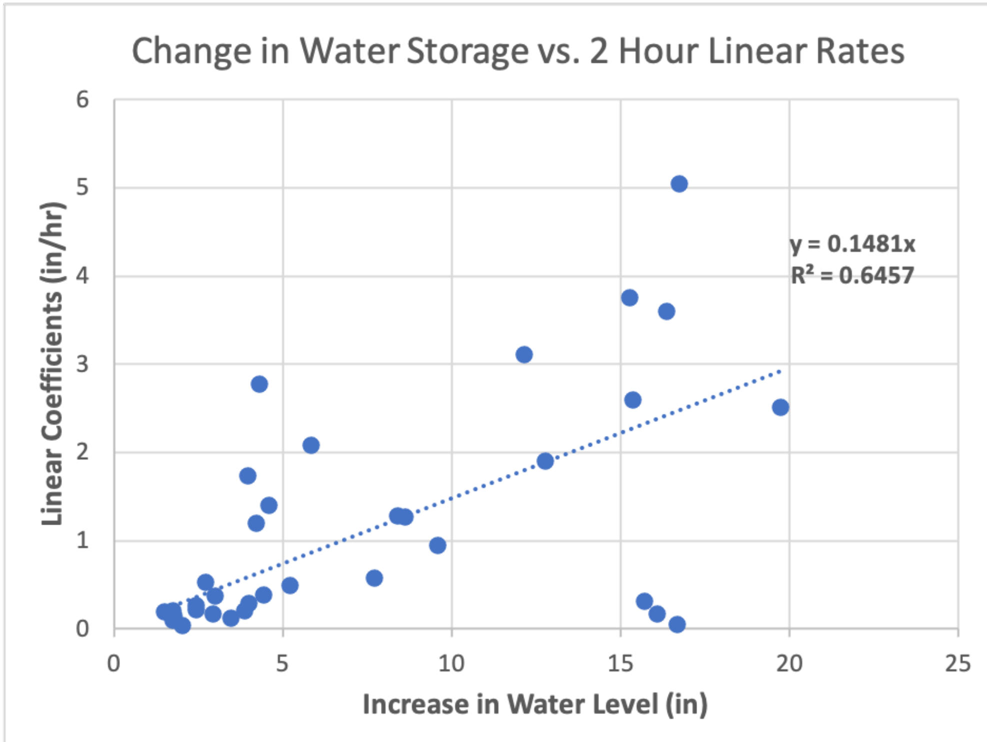


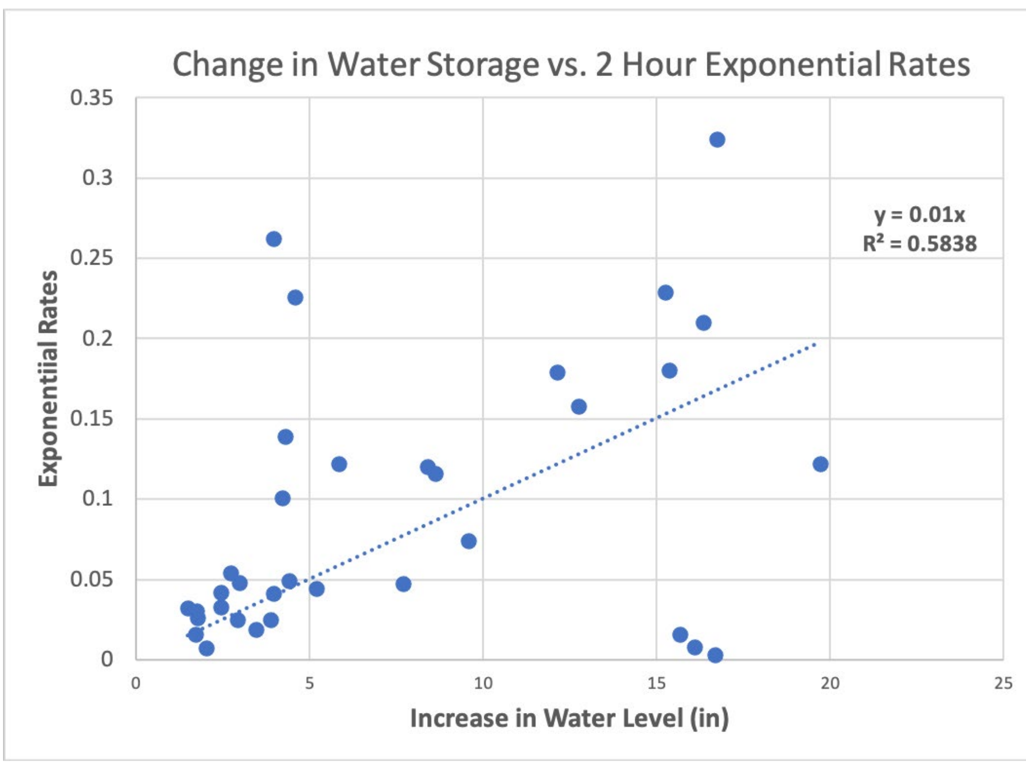
Figure A1.1: Scrubbed INFIL-Tracker Data from 3/30 to 5/4

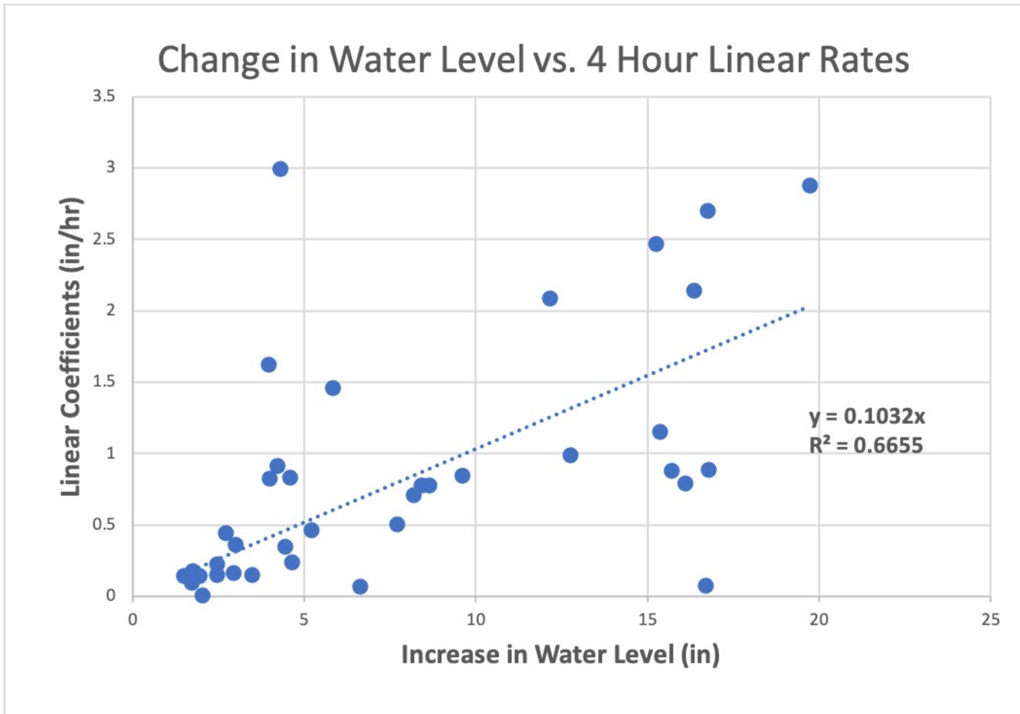
Appendix B

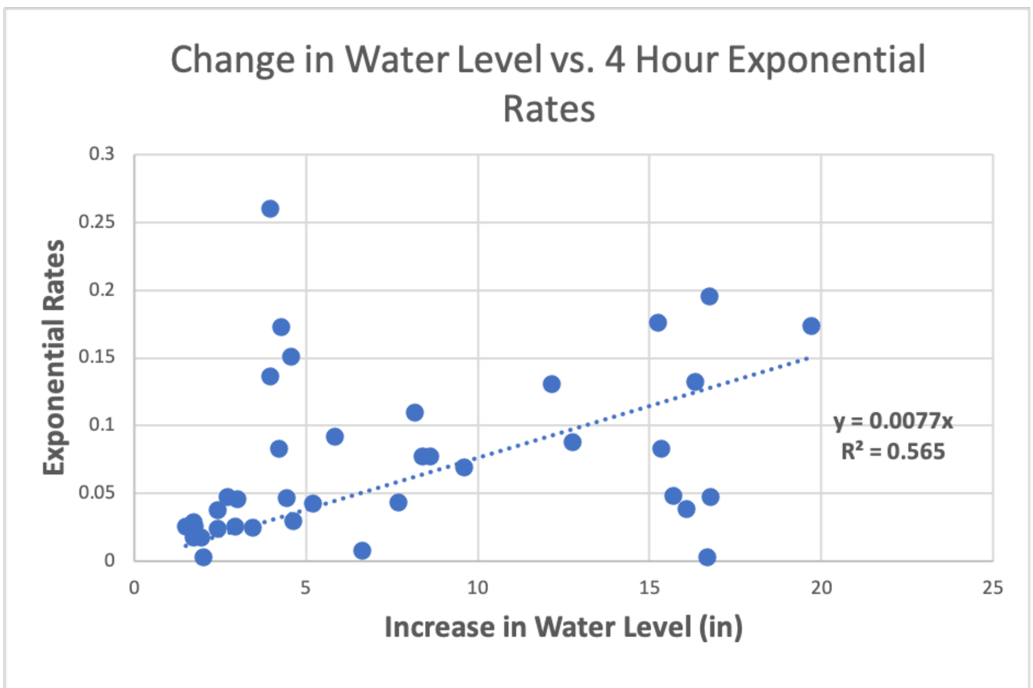

Change in Water Level vs. 1 Hour Linear Rates
Linear Rates (in/hr)
Increase in Water Level (in)
y = 0.1351x
R^2 = 0.5753
0
1
2
3
4
5
6
0
5
10
15
20


Change in Water Level vs. 1 Hour Exponential Rates
Exponential Rates
Increase in Water Level (in)
y = 0.0093x
R^2 = 0.5164
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
0
2
4
6
8
10
12
14
16
18


Change in Water Storage vs. 2 Hour Linear Rates
Linear Coefficients (in/hr)
Increase in Water Level (in)
y = 0.1481x
R² = 0.6457
0
1
2
3
4
5
6
0
5
10
15
20
25


Change in Water Storage vs. 2 Hour Exponential Rates
Exponential Rates
Increase in Water Level (in)
y = 0.01x
R² = 0.5838
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
0
5
10
15
20
25


Change in Water Level vs. 4 Hour Linear Rates
Linear Coefficients (in/hr)
Increase in Water Level (in)
y = 0.1032x
R² = 0.6655
0
0.5
1
1.5
2
2.5
3
3.5
0
5
10
15
20
25


Change in Water Level vs. 4 Hour Exponential Rates
Exponential Rates
Increase in Water Level (in)
y = 0.0077x
R² = 0.565
0
0.05
0.1
0.15
0.2
0.25
0.3
0
5
10
15
20
25

Appendix C

Storm Event	24 hour total rain	Distance from EMCO gauge 1 to local gauge (mi)	Distance from EMCO gauge 2 to local gauge (mi)	Distance from site to local gauge (mi)	Average	Weighted Average 1 (related to EMCO pre Sept 2022)	Weighted Average 2 (related to EMCO post Sept 2022)	Weighted Average 3 (in relation to PaveDrain Site)	24 hour total rain: EMCO data
STORM EVENT 9/23					1.27	1.28	1.28	1.29	1.32
Brentwood - KMDBRENT2	1.31	1.20	1.11	0.70					
Woodridge - KDCWASHI387	1.22	1.74	1.65	1.20					
Ellaville - KMDHYATT18		0.98	0.89	1.03					
Orban - KMDHYATT28		1.42	1.38	1.78					
STORM EVENT 10/26					1.82				1.82
Brentwood - KMDBRENT2		1.20	1.11	0.70					
Woodridge - KDCWASHI387	1.82	1.74	1.65	1.20					
Ellaville - KMDHYATT18		0.98	0.89	1.03					
Orban - KMDHYATT28		1.42	1.38	1.78					
STORM EVENT 10/29					1.10	0.75	0.73	0.62	1.7
Brentwood - KMDBRENT2	0.11	1.20	1.11	0.70					
Woodridge - KDCWASHI387	2.09	1.74	1.65	1.20					
Ellaville - KMDHYATT18		0.98	0.89	1.03					
Orban - KMDHYATT28		1.42	1.38	1.78					
STORM EVENT 11/2					0.12	0.12	0.12	0.12	0.11
Brentwood - KMDBRENT2	0.13	1.20	1.11	0.70					
Woodridge - KDCWASHI387	0.1	1.74	1.65	1.20					
Ellaville - KMDHYATT18		0.98	0.89	1.03					
Orban - KMDHYATT28		1.42	1.38	1.78					
STORM EVENT 4/7					0.49	0.49	0.49	0.50	0.45
Brentwood - KMDBRENT2	0.52	1.20	1.11	0.70					
Woodridge - KDCWASHI387	0.46	1.74	1.65	1.20					
Ellaville - KMDHYATT18		0.98	0.89	1.03					
Orban - KMDHYATT28	0.48	1.42	1.38	1.78					
STORM EVENT 4/18					0.72	0.85	0.85	0.80	0.92
Brentwood - KMDBRENT2	1.07	1.20	1.11	0.70					
Woodridge - KDCWASHI387	0.01	1.74	1.65	1.20					
Ellaville - KMDHYATT18		0.98	0.89	1.03					
Orban - KMDHYATT28	1.09	1.42	1.38	1.78					
STORM EVENT 4/26					0.15	0.15	0.15	0.15	0.15
Brentwood - KMDBRENT2	0.16	1.20	1.11	0.70					
Woodridge - KDCWASHI387	0.14	1.74	1.65	1.20					
Ellaville - KMDHYATT18		0.98	0.89	1.03					
Orban - KMDHYATT28	0.15	1.42	1.38	1.78					
STORM EVENT 6/8					0.05	0.05	0.05	0.05	0.04
Brentwood - KMDBRENT2	0.05	1.20	1.11	0.70					
Woodridge - KDCWASHI387	0.06	1.74	1.65	1.20					
Ellaville - KMDHYATT18		0.98	0.89	1.03					
Orban - KMDHYATT28	0.05	1.42	1.38	1.78					
STORM EVENT 6/9					0.36	0.34	0.34	0.33	
Brentwood - KMDBRENT2	0.3	1.20	1.11	0.70					
Woodridge - KDCWASHI387	0.43	1.74	1.65	1.20					
Ellaville - KMDHYATT18		0.98	0.89	1.03					
Orban - KMDHYATT28	0.35	1.42	1.38	1.78					
STORM EVENT 6/11					0.14	0.14		0.13	
Brentwood - KMDBRENT2	0.12	1.20	1.11	0.70					
Woodridge - KDCWASHI387	0.15	1.74	1.65	1.20					
Ellaville - KMDHYATT18		0.98	0.89	1.03					
Orban - KMDHYATT28	0.15	1.42	1.38	1.78					
STORM EVENT 6/16					0.10	0.09		0.09	
Brentwood - KMDBRENT2	0.06	1.20	1.11	0.70					
Woodridge - KDCWASHI387	0.16	1.74	1.65	1.20					
Ellaville - KMDHYATT18		0.98	0.89	1.03					
Orban - KMDHYATT28	0.07	1.42	1.38	1.78					
STORM EVENT 6/23					1.09	1.07		1.20	
Brentwood - KMDBRENT2	1.16	1.20	1.11	0.70					
Woodridge - KDCWASHI387	1.3	1.74	1.65	1.20					
Ellaville - KMDHYATT18		0.98	0.89	1.03					
Orban - KMDHYATT28	0.8	1.42	1.38	1.78					
STORM EVENT 6/27					0.15	0.15		0.17	
Brentwood - KMDBRENT2	0.18	1.20	1.11	0.70					
Woodridge - KDCWASHI387	0.15	1.74	1.65	1.20					
Ellaville - KMDHYATT18		0.98	0.89	1.03					
Orban - KMDHYATT28	0.11	1.42	1.38	1.78					
STORM EVENT 7/2					1.18	1.16		1.25	
Brentwood - KMDBRENT2	1.21	1.20	1.11	0.70					
Woodridge - KDCWASHI387	1.36	1.74	1.65	1.20					
Ellaville - KMDHYATT18		0.98	0.89	1.03					
Orban - KMDHYATT28	0.97	1.42	1.38	1.78					

STORM EVENT 7/9					**1.40**	**1.37**		**1.40**	
Brentwood - KMDBRENT2	1.38	1.20	1.11	0.70					
Woodridge - KDCWASHI387	1.46	1.74	1.65	1.20					
Ellaville - KMDHYATT18	1.28	0.98	0.89	1.03					
Orban - KMDHYATT28	1.46	1.42	1.38	1.78					
STORM EVENT 7/12					**0.28**	**0.27**	**0.26**	**0.29**	**0.21**
Brentwood - KMDBRENT2	0.34	1.20	1.11	0.70					
Woodridge - KDCWASHI387	0.29	1.74	1.65	1.20					
Ellaville - KMDHYATT18	0.21	0.98	0.89	1.03					
Orban - KMDHYATT28	0.26	1.42	1.38	1.78					
STORM EVENT 7/16					**1.30**	**1.25**	**1.25**	**1.24**	**0.72**
Brentwood - KMDBRENT2	1.19	1.20	1.11	0.70					
Woodridge - KDCWASHI387	1.43	1.74	1.65	1.20					
Ellaville - KMDHYATT18	1.17	0.98	0.89	1.03					
Orban - KMDHYATT28	1.4	1.42	1.38	1.78					
STORM EVENT 7/21					**0.06**	**0.03**	**0.03**	**0.04**	**0.17**
Brentwood - KMDBRENT2	0	1.20	1.11	0.70					
Woodridge - KDCWASHI387	0.19	1.74	1.65	1.20					
Ellaville - KMDHYATT18	0	0.98	0.89	1.03					
Orban - KMDHYATT28	0.04	1.42	1.38	1.78					
STORM EVENT 7/25					**0.73**	**0.71**	**0.72**	**0.84**	**0.51**
Brentwood - KMDBRENT2	0.97	1.20	1.11	0.70					
Woodridge - KDCWASHI387	0.97	1.74	1.65	1.20					
Ellaville - KMDHYATT18	0.63	0.98	0.89	1.03					
Orban - KMDHYATT28	0.35	1.42	1.38	1.78					
STORM EVENT 7/28					**0.31**	**0.30**	**0.30**	**0.31**	**0.16**
Brentwood - KMDBRENT2		1.20	1.11	0.70					
Woodridge - KDCWASHI387	0.35	1.74	1.65	1.20					
Ellaville - KMDHYATT18	0.29	0.98	0.89	1.03					
Orban - KMDHYATT28	0.29	1.42	1.38	1.78					
STORM EVENT 7/31					**0.18**	**0.12**	**0.12**	**0.14**	**0.23**
Brentwood - KMDBRENT2		1.20	1.11	0.70					
Woodridge - KDCWASHI387	0.27	1.74	1.65	1.20					
Ellaville - KMDHYATT18	0.01	0.98	0.89	1.03					
Orban - KMDHYATT28	0.26	1.42	1.38	1.78					
STORM EVENT 8/2					**0.05**	**0.03**	**0.03**	**0.05**	**0.07**
Brentwood - KMDBRENT2		1.20	1.11	0.70					
Woodridge - KDCWASHI387	0.14	1.74	1.65	1.20					
Ellaville - KMDHYATT18	0	0.98	0.89	1.03					
Orban - KMDHYATT28	0.02	1.42	1.38	1.78					
STORM EVENT 8/4					**1.83**	**1.71**	**1.69**	**1.74**	**1.31**
Brentwood - KMDBRENT2		1.20	1.11	0.70					
Woodridge - KDCWASHI387	2.01	1.74	1.65	1.20					
Ellaville - KMDHYATT18	1.45	0.98	0.89	1.03					
Orban - KMDHYATT28	2.04	1.42	1.38	1.78					
STORM EVENT 8/5					**1.43**	**1.56**	**1.59**	**1.61**	**1.16**
Brentwood - KMDBRENT2		1.20	1.11	0.70					
Woodridge - KDCWASHI387	1.53	1.74	1.65	1.20					
Ellaville - KMDHYATT18	1.91	0.98	0.89	1.03					
Orban - KMDHYATT28	0.86	1.42	1.38	1.78					
STORM EVENT 8/8					**0.48**	**0.41**	**0.40**	**0.36**	**1.24**
Brentwood - KMDBRENT2		1.20	1.11	0.70					
Woodridge - KDCWASHI387	0.33	1.74	1.65	1.20					
Ellaville - KMDHYATT18	0.21	0.98	0.89	1.03					
Orban - KMDHYATT28	0.89	1.42	1.38	1.78					
STORM EVENT 8/10					**2.16**	**2.26**	**2.28**	**2.29**	**1.78**
Brentwood - KMDBRENT2		1.20	1.11	0.70					
Woodridge - KDCWASHI387	2.25	1.74	1.65	1.20					
Ellaville - KMDHYATT18	2.52	0.98	0.89	1.03					
Orban - KMDHYATT28	1.72	1.42	1.38	1.78					
STORM EVENT 8/15					**0.04**	**0.03**	**0.02**	**0.03**	**0.09**
Brentwood - KMDBRENT2		1.20	1.11	0.70					
Woodridge - KDCWASHI387	0.06	1.74	1.65	1.20					
Ellaville - KMDHYATT18	0	0.98	0.89	1.03					
Orban - KMDHYATT28	0.06	1.42	1.38	1.78					
STORM EVENT 8/17					**0.60**	**0.52**	**0.51**	**0.59**	**0.45**
Brentwood - KMDBRENT2		1.20	1.11	0.70					
Woodridge - KDCWASHI387	0.88	1.74	1.65	1.20					
Ellaville - KMDHYATT18	0.41	0.98	0.89	1.03					
Orban - KMDHYATT28	0.51	1.42	1.38	1.78					
STORM EVENT 8/21					**1.11**	**1.02**	**1.01**	**1.11**	**1.06**
Brentwood - KMDBRENT2		1.20	1.11	0.70					
Woodridge - KDCWASHI387	1.45	1.74	1.65	1.20					
Ellaville - KMDHYATT18	0.9	0.98	0.89	1.03					
Orban - KMDHYATT28	0.97	1.42	1.38	1.78					

RAIN GAUGE MOVE									
STORM EVENT 9/6					0.79	0.74	0.74	0.75	
Brentwood - KMDBRENT2		1.20	1.11	0.70					
Woodridge - KDCWASHI387	0.84	1.74	1.65	1.20					
Ellaville - KMDHYATT18	0.64	0.98	0.89	1.03					
Orban - KMDHYATT28	0.9	1.42	1.38	1.78					
STORM EVENT 9/11					0.99	0.94	0.94	0.97	
Brentwood - KMDBRENT2		1.20	1.11	0.70					
Woodridge - KDCWASHI387	1.09	1.74	1.65	1.20					
Ellaville - KMDHYATT18	0.86	0.98	0.89	1.03					
Orban - KMDHYATT28	1.02	1.42	1.38	1.78					
STORM EVENT 10/1					0.59	0.56	0.37	0.47	0.69
Brentwood - KMDBRENT2		1.20	1.11	0.70					
Woodridge - KDCWASHI387	0.76	1.74	1.65	1.20					
Ellaville - KMDHYATT18	0.41	0.98	0.89	1.03					
Orban - KMDHYATT28		1.42	1.38	1.78					
STORM EVENT 10/2 (1)					0.45	0.43	0.29	0.46	0.41
Brentwood - KMDBRENT2		1.20	1.11	0.70					
Woodridge - KDCWASHI387	0.58	1.74	1.65	1.20					
Ellaville - KMDHYATT18	0.32	0.98	0.89	1.03					
Orban - KMDHYATT28		1.42	1.38	1.78					
STORM EVENT 10/2 (2)									
Brentwood - KMDBRENT2		1.20	1.11	0.70					
Woodridge - KDCWASHI387		1.74	1.65	1.20					
Ellaville - KMDHYATT18		0.98	0.89	1.03					
Orban - KMDHYATT28		1.42	1.38	1.78					
STORM EVENT 10/3					0.48	0.43	0.46	0.63	0.5
Brentwood - KMDBRENT2		1.20	1.11	0.70					
Woodridge - KDCWASHI387	0.69	1.74	1.65	1.20					
Ellaville - KMDHYATT18	0.27	0.98	0.89	1.03					
Orban - KMDHYATT28		1.42	1.38	1.78					
STORM EVENT 10/4					0.18	0.17	0.18	0.24	0.59
Brentwood - KMDBRENT2		1.20	1.11	0.70					
Woodridge - KDCWASHI387	0.25	1.74	1.65	1.20					
Ellaville - KMDHYATT18	0.11	0.98	0.89	1.03					
Orban - KMDHYATT28		1.42	1.38	1.78					
STORM EVENT 10/5					0.09	0.08	0.08	0.12	0.28
Brentwood - KMDBRENT2		1.20	1.11	0.70					
Woodridge - KDCWASHI387	0.14	1.74	1.65	1.20					
Ellaville - KMDHYATT18	0.04	0.98	0.89	1.03					
Orban - KMDHYATT28		1.42	1.38	1.78					
STORM EVENT 10/13					0.51	0.48	0.51	0.67	0.35
Brentwood - KMDBRENT2		1.20	1.11	0.70					
Woodridge - KDCWASHI387	0.68	1.74	1.65	1.20					
Ellaville - KMDHYATT18	0.34	0.98	0.89	1.03					
Orban - KMDHYATT28		1.42	1.38	1.78					
STORM EVENT 10/14					0.05	0.05	0.05	0.06	0.45
Brentwood - KMDBRENT2		1.20	1.11	0.70					
Woodridge - KDCWASHI387	0.06	1.74	1.65	1.20					
Ellaville - KMDHYATT18	0.04	0.98	0.89	1.03					
Orban - KMDHYATT28		1.42	1.38	1.78					
STORM EVENT 11/11					0.69	0.65	0.65	0.68	
Brentwood - KMDBRENT2		1.20	1.11	0.70					
Woodridge - KDCWASHI387	0.81	1.74	1.65	1.20					
Ellaville - KMDHYATT18	0.58	0.98	0.89	1.03					
Orban - KMDHYATT28	0.69	1.42	1.38	1.78					
STORM EVENT 11/15					1.37	1.42	1.43	1.42	
Brentwood - KMDBRENT2		1.20	1.11	0.70					
Woodridge - KDCWASHI387	1.34	1.74	1.65	1.20					
Ellaville - KMDHYATT18	1.55	0.98	0.89	1.03					
Orban - KMDHYATT28	1.21	1.42	1.38	1.78					
STORM EVENT 11/25					0.16	0.13	0.13	0.13	
Brentwood - KMDBRENT2		1.20	1.11	0.70					
Woodridge - KDCWASHI387	0.17	1.74	1.65	1.20					
Ellaville - KMDHYATT18	0.07	0.98	0.89	1.03					
Orban - KMDHYATT28	0.23	1.42	1.38	1.78					
STORM EVENT 11/30					0.32	0.31	0.31	0.32	
Brentwood - KMDBRENT2		1.20	1.11	0.70					
Woodridge - KDCWASHI387	0.35	1.74	1.65	1.20					
Ellaville - KMDHYATT18	0.31	0.98	0.89	1.03					
Orban - KMDHYATT28	0.3	1.42	1.38	1.78					
STORM EVENT 12/15					2.10	2.14	2.15	2.14	
Brentwood - KMDBRENT2	2.13	1.20	1.11	0.70					
Woodridge - KDCWASHI387	2.11	1.74	1.65	1.20					
Ellaville - KMDHYATT18	2.27	0.98	0.89	1.03					
Orban - KMDHYATT28	1.9	1.42	1.38	1.78					

STORM EVENT 12/22					**1.31**	**1.32**	**1.32**	**1.29**	
Brentwood - KMDBRENT2	1.26	1.20	1.11	0.70					
Woodridge - KDCWASHI387	1.27	1.74	1.65	1.20					
Ellaville - KMDHYATT18	1.38	0.98	0.89	1.03					
Orban - KMDHYATT28	1.32	1.42	1.38	1.78					
STORM EVENT 1/1					**0.76**	**0.58**	**0.58**	**0.74**	
Brentwood - KMDBRENT2	0.68	1.20	1.11	0.70					
Woodridge - KDCWASHI387	1.75	1.74	1.65	1.20					
Ellaville - KMDHYATT18	0.26	0.98	0.89	1.03					
Orban - KMDHYATT28	0.35	1.42	1.38	1.78					
STORM EVENT 1/22					**0.26**	**0.25**	**0.25**	**0.31**	
Brentwood - KMDBRENT2		1.20	1.11	0.70					
Woodridge - KDCWASHI387	0.48	1.74	1.65	1.20					
Ellaville - KMDHYATT18	0.29	0.98	0.89	1.03					
Orban - KMDHYATT28	0	1.42	1.38	1.78					
STORM EVENT 1/26					**0.59**	**0.60**	**0.60**	**0.60**	
Brentwood - KMDBRENT2		1.20	1.11	0.70					
Woodridge - KDCWASHI387	0.59	1.74	1.65	1.20					
Ellaville - KMDHYATT18	0.62	0.98	0.89	1.03					
Orban - KMDHYATT28	0.56	1.42	1.38	1.78					
STORM EVENT 2/13					**0.86**	**0.86**	**0.86**	**0.86**	
Brentwood - KMDBRENT2		1.20	1.11	0.70					
Woodridge - KDCWASHI387	0.87	1.74	1.65	1.20					
Ellaville - KMDHYATT18	0.85	0.98	0.89	1.03					
Orban - KMDHYATT28	0.87	1.42	1.38	1.78					
STORM EVENT 2/16					**0.19**	**0.23**	**0.23**	**0.18**	
Brentwood - KMDBRENT2		1.20	1.11	0.70					
Woodridge - KDCWASHI387	0	1.74	1.65	1.20					
Ellaville - KMDHYATT18	0.26	0.98	0.89	1.03					
Orban - KMDHYATT28	0.31	1.42	1.38	1.78					

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