Novel Modeling Approach to Understand the Fate of Infiltrated Water at Green Stormwater Infrastructure in Philadelphia, PA

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ABSTRACT

Green stormwater infrastructure (GSI) is applied in cities as a means to reduce combined sewer overflows resulting from stormwater runoff. While infiltrating stormwater runoff is beneficial in that regard, there are concerns that the resulting water table mounding may cause infiltration into nearby subsurface infrastructure (e.g., basements). During the planning phases of the Green City, Clean Waters program in Philadelphia, 3-dimensional groundwater models have been applied to help understand the potential for regional and street/neighborhood-level water table rise; however, these models focus on the saturated zone only. The unsaturated zone can also be a concern, particularly in areas with features that may result in preferential pathways leading to adjacent subsurface infrastructure via horizontal flow (rather than mounding of the saturated zone water table). Investigatory work coupled with 2-dimensional unsaturated zone finite element modeling was completed to better understand the mechanisms by which this can occur.

The results of the unsaturated zone simulations indicate that appreciable groundwater table mounding is generally limited to the area within the immediate vicinity of the GSI. With respect to preferential flows within the unsaturated zone, the model results provide guidance on the value of liners, the presence of shallow bedrock, the value of modifying standard tree trench designs utilizing deeper penetrating drainage wells, and the potential for shallow gravel lenses to create conduits of flow in the unsaturated zone. These results have been incorporated into guidance on GSI siting that is applicable to any municipality considering GSI as part of its integrated approach to stormwater management.

KEYWORDS: Green Stormwater Infrastructure, Groundwater Modeling, Unsaturated Zone

BACKGROUND

During the implementation of green stormwater infrastructure (GSI) projects in Philadelphia, PA, two known instances of basement infiltration occurred. While the cause of the infiltration is likely associated with construction-related issues, a potential cause has been hypothesized to be the horizontal flow of infiltrated water from the GSI structure to the building foundation. While these instances have been rare, investigatory work has been conducted to better understand the mechanisms by which this can occur. Specifically, the following questions have been posed:

- Under what conditions would horizontal flow of infiltrated water be expected?
- Does the inclusion of an impermeable liner located between the GSI structure and the building foundation lower the risk of basement infiltration?
- Are drainage wells effective components for GSI?
- How can drainage wells be used in combination with GSI?
- What guidance can be provided when siting and designing GSI controls with respect to the potential for inducing basement infiltration?

To date, three-dimensional numerical models that simulate regional scale and site scale saturated groundwater flow have been used to better understand the potential changes to water table elevations associated with GSI-induced infiltration. These models have been useful tools but are not best suited to answer the questions related to infiltration through the unsaturated zone. This is due to the assumption inherent in saturated flow codes that infiltrated water reaches the water table (saturated zone) instantaneously and directly below the point of application. In addition, a spreadsheet-based tool developed by the USGS to solve the Hantush equation has also been applied at the specific problem areas to evaluate groundwater table mounding, but that also represents saturated conditions only.

METHODOLOGY

To better represent flow through the unsaturated zone, the SWMS_2D code (also included in the commercial package Hydrus 2D), which was developed by the U.S. Salinity Laboratory Agricultural Research Service (U.S. Department of Agriculture) in 1994, was chosen. The SWMS_2D code and users' manual can be downloaded at http://www.ars.usda.gov/services/software/download.htm?softwareid=103. The code can be used to simulate water and solute movement in two-dimensional (horizontal or vertical plane) or axisymmetric (radial symmetry about the vertical axis) variably saturated media. The program uses the finite element method (Galerkin-type) to numerically solve the Richards' equation for saturated-unsaturated water flow and the convection-dispersion equations for solute transport (Simunek et. al. 1994). SWMS_2D can represent irregular boundaries, heterogeneity (including the presence of clay lenses, for example), impermeable boundaries embedded internally in the model domain, sources (infiltration, etc.) and sinks (evapotranspiration, pumping wells, seepage faces, etc.), input time series, prescribed head and flux boundaries, and transport processes (adsorption, degradation, etc.).

Three applications were evaluated using the model during this work:

- A sidewalk tree trench site approximated as a two-dimensional vertical plane
- A drainage well site represented axisymmetrically with flow radially outward from the vertical axis
- A combined tree trench/drainage well site also represented axisymmetrically

For each application, finite element grids were developed based on site schematics, including such features as:

- the GSI unit
- shallow fill material
- native aquifer material
- subsurface infrastructure such as a building foundation or subway tunnel
- clay (low permeability) or gravel (high permeability) lenses

SIDEWALK TREE TRENCH SIMULATIONS

Figure 1 depicts a crosssection schematic of the application utilizing a sidewalk tree trench. The scenario, which is based on an actual site, includes the presence of a building with a basement that extends approximately 6 feet below the sidewalk and is located approximately 4 feet away from a 5-foot deep, 8-foot wide, 137-foot long infiltration trench. The trench has a total storage volume of 1,397 cubic feet (ft^3), which captures the first 1.1 inches of runoff from the drainage area. This is the equivalent of 14.5 gpm over 12 hours.

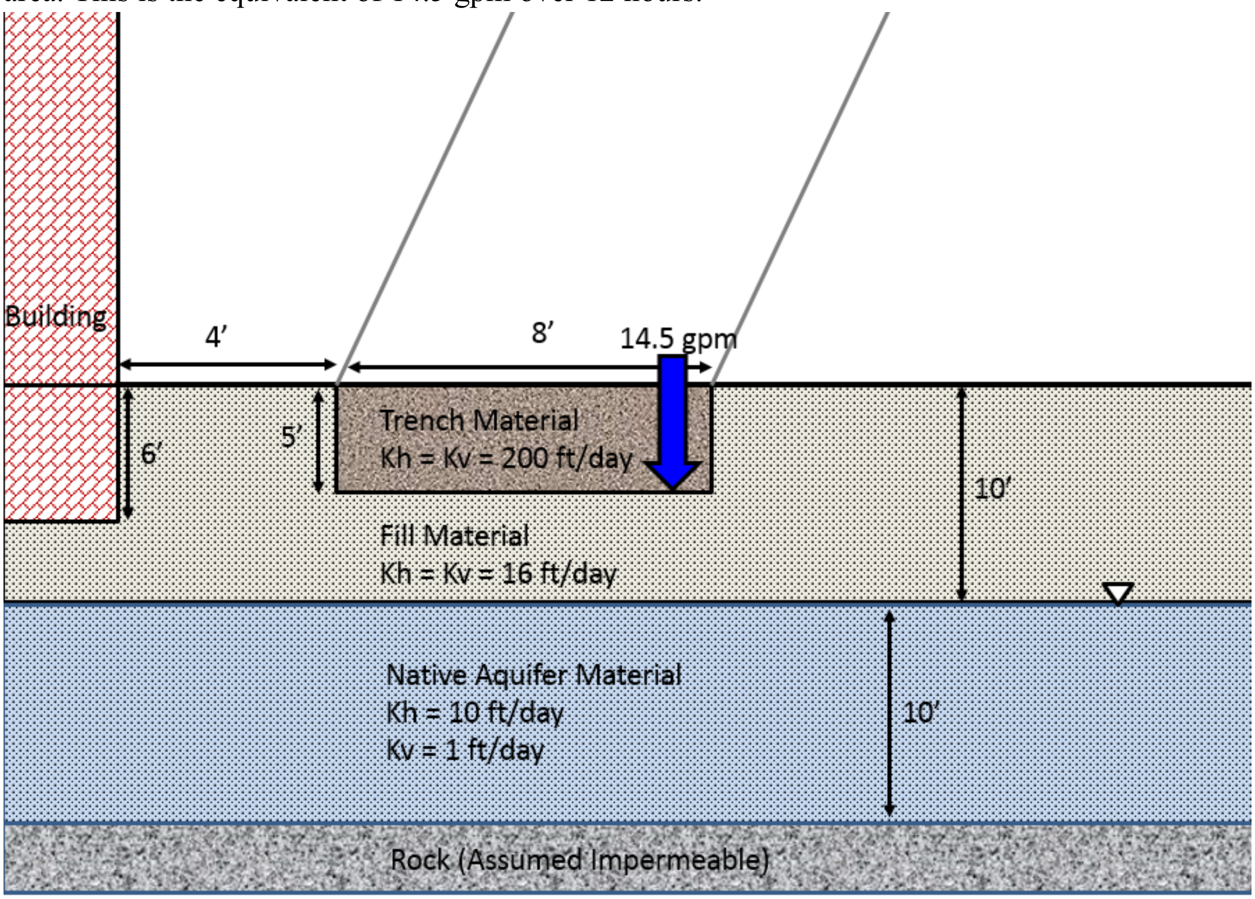

Figure 1 – Sidewalk Tree Trench Schematic (not to scale)

Figure 2 shows the numerical model mesh representation of the schematic as a two-dimensional vertical plane with the assumption that the trench and building foundation extend infinitely into the paper. For these purposes, this assumption is appropriate as the length of the trench is significantly longer than the width, which is explicitly represented. Nodal spacing varied from 9 cm in the infiltration trench to 66 cm further away from the area of interest. The grid spans approximately 3,600 cm (approximately 118 feet) in the x direction, with the center at the rightmost edge of the building foundation. In the vertical direction the grid spans approximately 614 cm (20 feet), with material distributions to match the schematic in Figure 1 (top 10 feet assigns hydraulic conductivity at 16 ft/day, water table down 10 feet from ground surface, etc.).

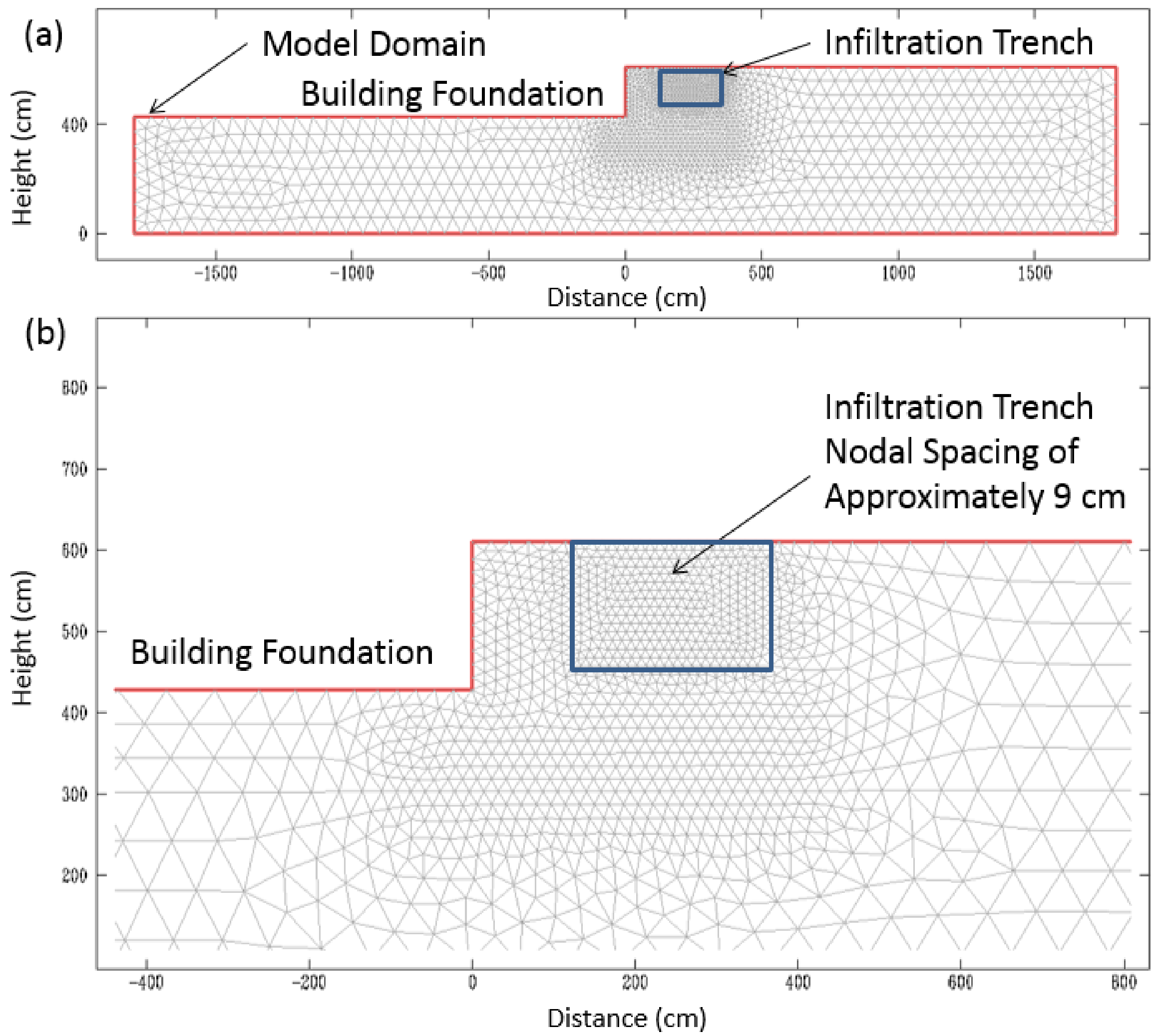

Figure 2 – Tree Trench Site Model Grid

The actual depth to the water table is unknown at this site, so the 10foot depth represents an assumption. Geotechnical evaluations were limited to 4.5 feet beneath the surface (the water table was not encountered). The value of hydraulic conductivity is based on a double ring infiltrometer test conducted at the site, which resulted in a calculated infiltration rate of 8.46 in/hr (16.92 ft/day). Isotropic conditions were assumed for initial simulations. Initial simulations also assumed that the saturated portion of the overburden has a hydraulic conductivity of 10 ft/day in the horizontal direction and 1 ft/day in the vertical. As mentioned above, the geotechnical data were limited to 4.5 feet below grade; therefore, the properties of the deeper sediments and the depth to bedrock are currently unknown.

Water content, fluid flux and pressure head are solved for each time step at every node in the model, which are each assigned values for the following parameters:

- saturated hydraulic conductivity
- residual water content
- maximum water content
- and van Genuchten water retention parameters α and N

Figure 3 (a, b, and c) shows the starting, 12-, and 24-hour water contents, respectively, as filled contours. All properties modeled in this scenario had a residual water content of 0.05 (or 5%) and a maximum water content of 0.43 (or 43%), so the filled contour (bright green) representing a water content of 0.43 indicates the presence of the saturated zone. Only saturated pores are likely to convey water that would cause infiltration into subsurface infrastructure. These figures indicate that the soil within the trench is initially fully drained (at residual water content) and that initial water contents in the native soil vary from around 20% near the ground surface to fully

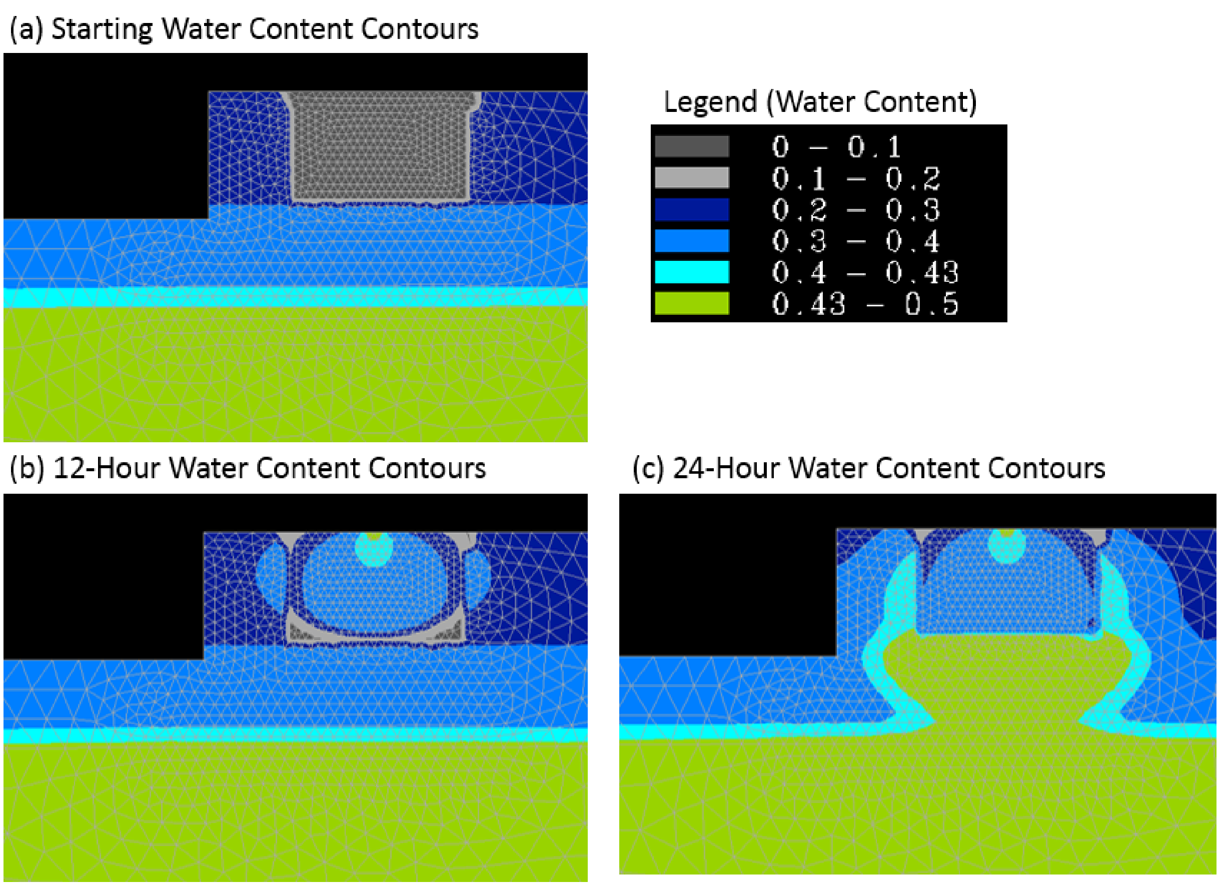

Figure 3 – Simulated Water Content Contours, Tree Trench Site Basecase

saturated at a depth of 10 feet from the ground surface (assumed depth of the water table). After 12 hours of infiltration, the unlined trench box has begun to approach fully saturated but breakthrough has not yet occurred beneath the trench. After 24 hours of infiltration (24 hours of continuous application of 14.5 gpm, which represents twice the storage volume), the saturated zone has become continuous between the bottom of the trench and the starting water table, though the water table farther away from the trench has not been impacted. Water content of the soil adjacent to the building foundation has increased over the course of the simulation, but the saturation zone does not reach it.

A second scenario was modeled to understand how different this base case scenario would look if an impermeable liner was in place on the left and right side of the trench, as well as the building-side portion of the bottom of the trench (similar to actual conditions). **Figure 4 (a, b, and c)** shows the simulated starting, 12- and 24-hour water contents, respectively, for this variant. With an impermeable liner in place, infiltrated water can exit the trench in a limited zone restricting flow, increasing water content in the trench and ultimately directing the saturated zone below the trench away from the building foundation. This variant of the base case (all other parameters were held constant from the base case) indicates that the use of a liner can limit water content increases in the vicinity of the building and subsequently lessen the potential for basement infiltration.

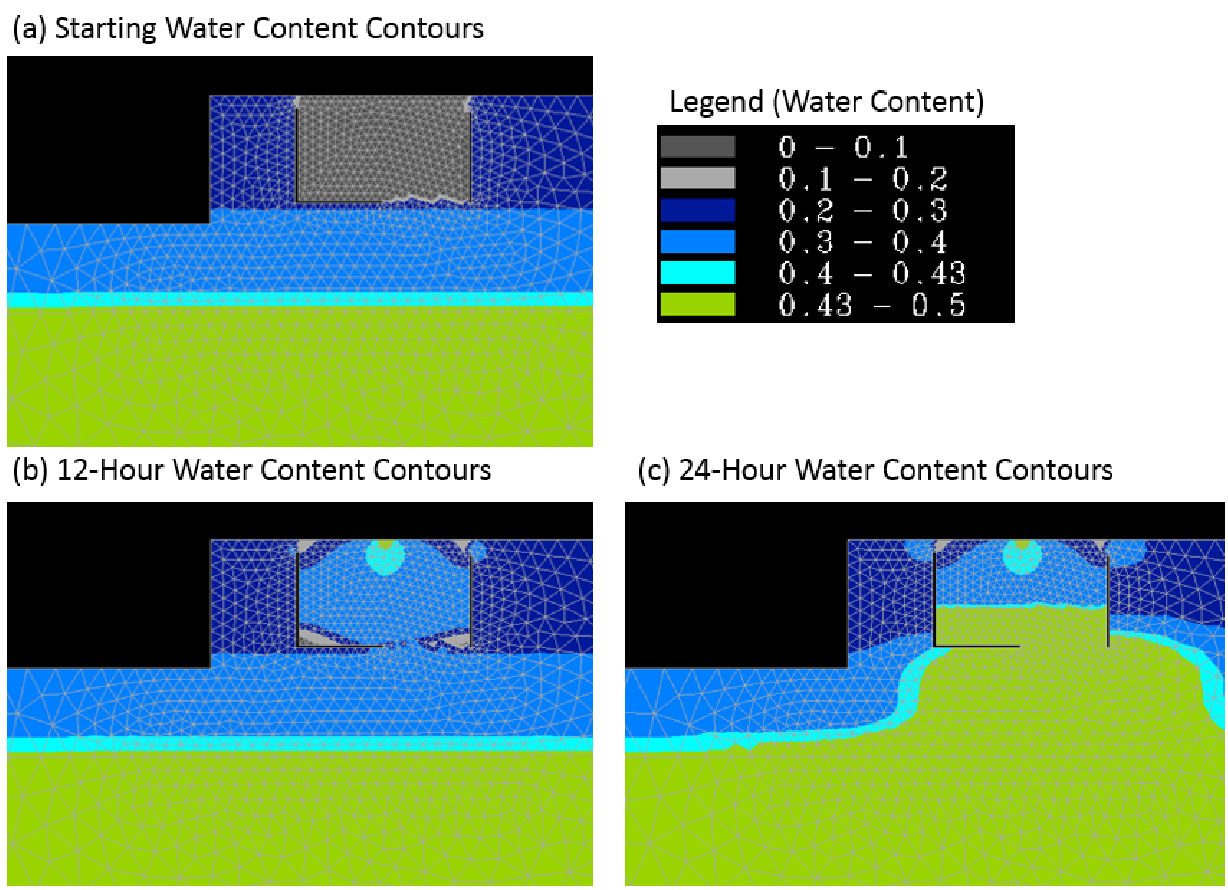

Figure 4 – Simulated Water Content Contours, Tree Trench Site With Liner

While the presence of a liner likely decreases the potential for basement infiltration, additional scenarios were modeled to determine which conditions were more likely to generate basement infiltration at the tree trench site. As part of this analysis, the following model inputs were varied:

- hydraulic conductivities and unsaturated zone parameters of the soils included in the infiltration trench, the top layer of 'fill' and the underlying native strata
- water table depth from ground surface
- the presence of shallow bedrock
- the presence of clay or gravel lenses between the unlined trench and the basement foundation
- the presence of an extremely high degree of heterogeneity in the native soils

As expected, the depth to water table and the permeability of the soils are inversely related to water table mounding; however, more mounding does not directly correlate with lateral flow and basement infiltration under base case conditions. The two conditions simulated that had the biggest influence on the potential for basement infiltration were depth to bedrock and the

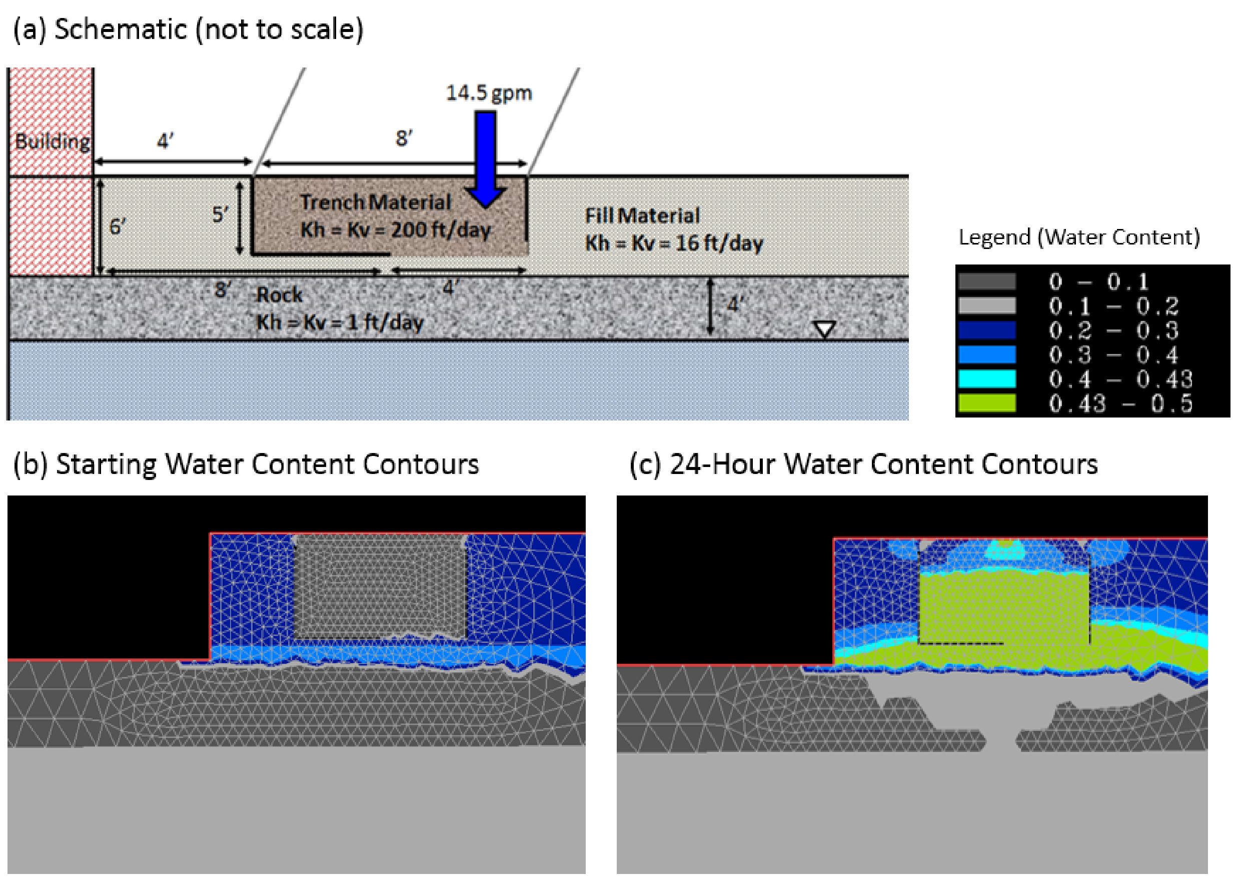

Figure 5 – Simulated Water Content Contours, Tree Trench Site With Shallow Rock and Liner

presence of gravel or other highly conductive material between the (unlined) trench and the basement foundation.

Figure 5 (b and c) shows simulated starting and 24-hour water contents for a scenario where the base of the building foundation is at the top of the bedrock (schematic included as Figure 5 (a)). The depth to water and properties of the materials overlying the bedrock (both in and surrounding the trench) were kept the same as the base case (with and without liner). In this case, the rock is represented as having a much narrower range of water contents, with a 5% residual water content and a 10% maximum water content. Because of this, the top of the rock becomes fully saturated (represented as light grey in **Figure 5 (b)**) very quickly, while portions of the rock just below this top zone of saturation can be fully drained. This scenario results in significant lateral spreading to the basement foundation, even with a liner in place.

Figure 6 (a) depicts the representation of a gravel or very transmissive lens (brick, rubble, etc.)

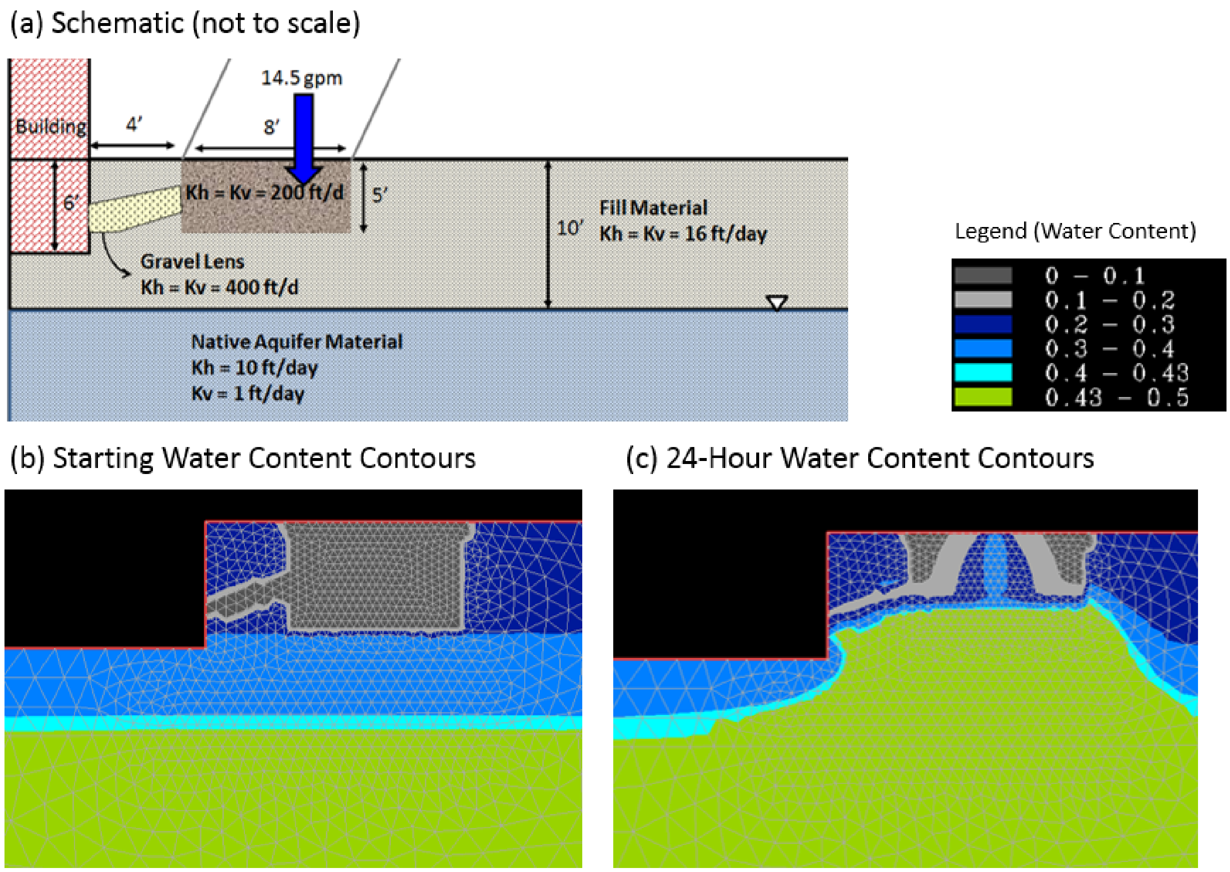

Figure 6 – Simulated Water Content Contours, Tree Trench Site With Gravel Lens

between the unlined trench and the basement foundation. Simulation results indicate that if the saturated zone extends vertically to the elevation of the lens, water can potentially flow along the highly permeable conduit to the basement as depicted in **Figure 6 (c)**. This phenomenon is further evidence that in similar scenarios, an impermeable liner should be used. Furthermore, an infiltration trench may perform as designed for a period of time before fouling reduces the permeability of the trench material. At that point, without a liner in place, the subsequent decrease in drainage rates through the trench could elevate the zone of saturation within the trench to strata that are much more permeable and could serve as a new conduit of flow.

DRAINAGE WELL SIMULATIONS

The second GSI site simulated was the axisymmetric representation of a drainage well, as depicted schematically in **Figure 7**. The associated model grid is shown in **Figure 8**. The center of the well represents the vertical axis of symmetry and is located at zero on the x axis. Nodal spacing ranges from 20 cm in the drainage well to 60 cm at the extremities. A flow rate of 1,000 ft^3/day was applied constantly to the nodes located at the top of the drainage well for 24 hours. This flow rate represents calculated infiltration into a potential drainage well of similar dimensions and a drainage area of slightly more than 7,400 square feet for 1.6 inches of rain. As shown in the schematic and represented in the model, the drainage well is cased down three feet from ground surface and an open borehole with gravel pack exists from 3 to 22 feet below ground. The base case scenario had an initial depth to the water table of 32 feet.

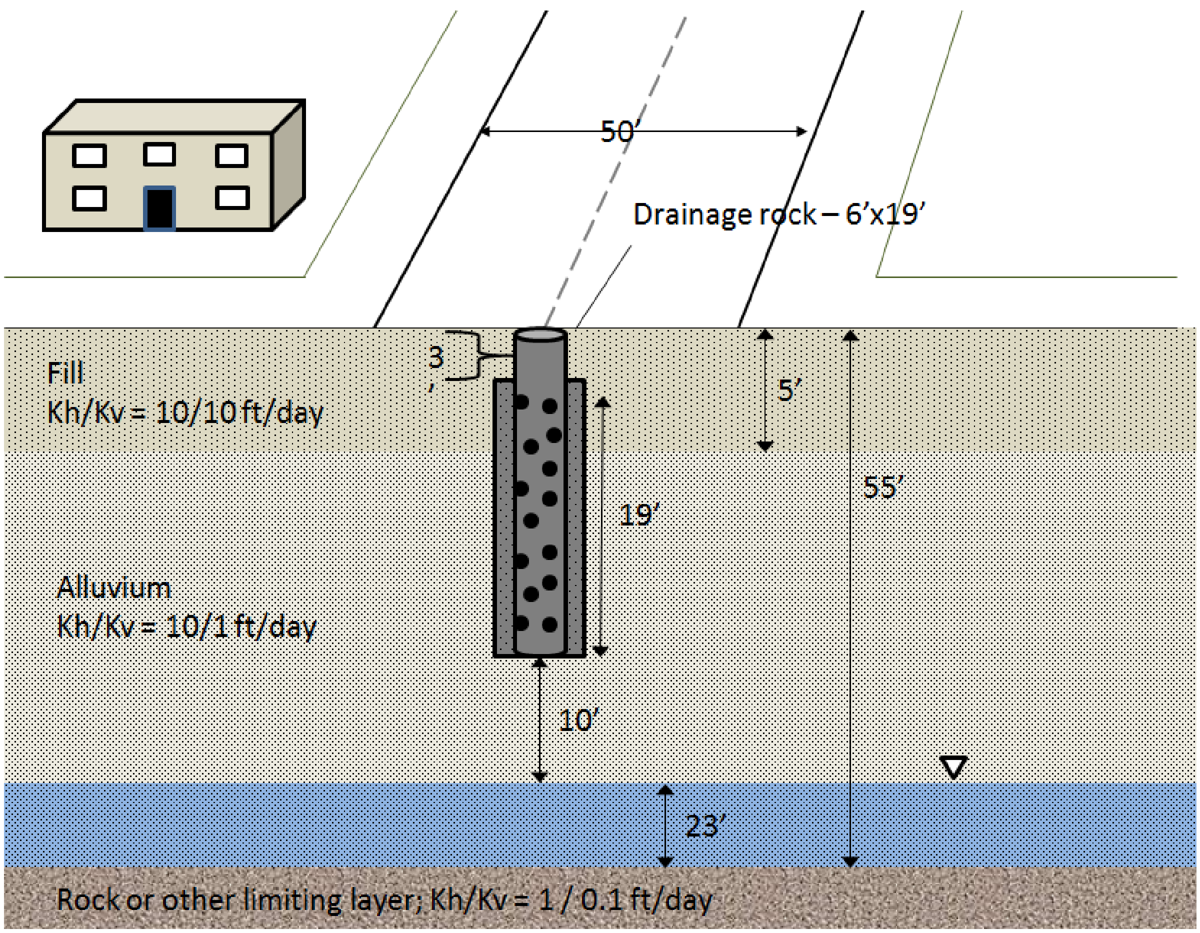

Figure 7 – Drainage Well Site Schematic (not to scale)

Figure 9 (a, b, c, and d) show the starting, 1-, 2-, and 3-day water contents, respectively, for the drainage well base case scenario. As the flux ceased at the end of the first day, **Figure 9** (c) and

(d) represent drainage only. Under this scenario, there is little to no impact on the vertical extent of the saturated zone (no mounding).

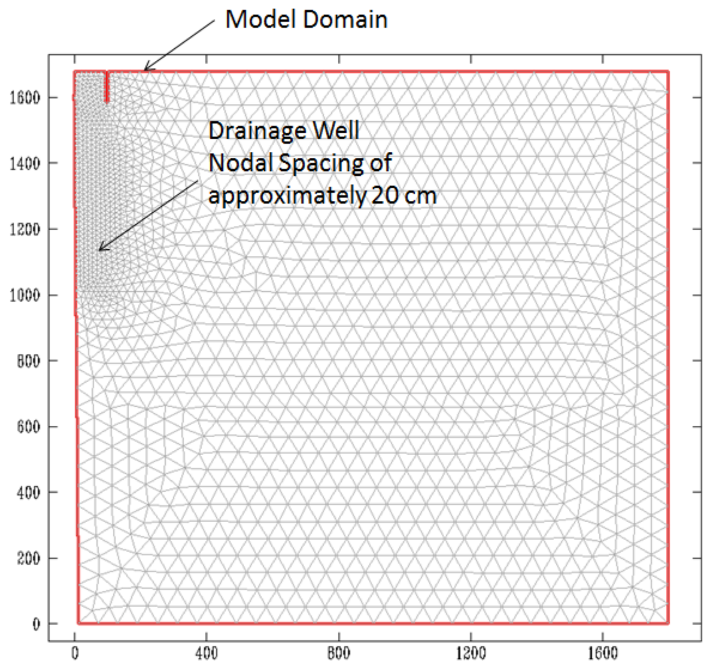

Figure 8 – Drainage Well Site Model Grid

Subsequent simulations were made varying the depth to bedrock and the depth to the water table to understand the potential mounding and post-infiltration mound recession that could be expected. **Figure 10** (a, b, c, and d) shows starting, 1-, 2-, and 3-day water contents for a variant with the water table situated just below the bottom of the drainage well and the bedrock less than 10 feet below the water table. In this instance mounding does occur (b), but after a one-day cessation of infiltration the saturated zone is of similar size and vertical extent to the starting conditions (c). The simulation indicates that mounding does not exceed 2 feet beyond a radial distance of approximately 17 feet from the center of the well at any point in time.

The same depth to bedrock and the water table were used to simulate the higher flow rates into the drainage well associated with a 15,000 square foot drainage area (approximately 1,500 ft^3/day). In this variant, mounding does not exceed 2 feet beyond a radial distance of approximately 22 feet from the center of the well at any point in time. A direct comparison of the 1-day (maximum) mounding for the 1,000 and 1,500 ft^3/day simulations is shown in **Figure 11**.

COMBO SITE SIMULATIONS

The third GSI site simulated was the axisymmetric representation of a drainage well combined with an unlined infiltration trench, as depicted schematically in **Figure 12**. The associated model grid is shown in **Figure 13**. In this scenario, a circular 5-foot deep infiltration trench with a 28-foot diameter is used. At the center of the trench is a 2-foot diameter drainage well screened from the bottom of the trench to five feet below the trench. Similar to the drainage well site simulations, the center of the well represents the vertical axis of symmetry and is located at zero on the x axis. Nodal spacing ranges from 10 cm in the drainage well and infiltration trench to 95 cm at the extremities. A flow rate of approximately 3,250 ft^3/day was applied constantly to the nodes located at the top of the drainage well for 12 hours. This flow rate represents infiltration of

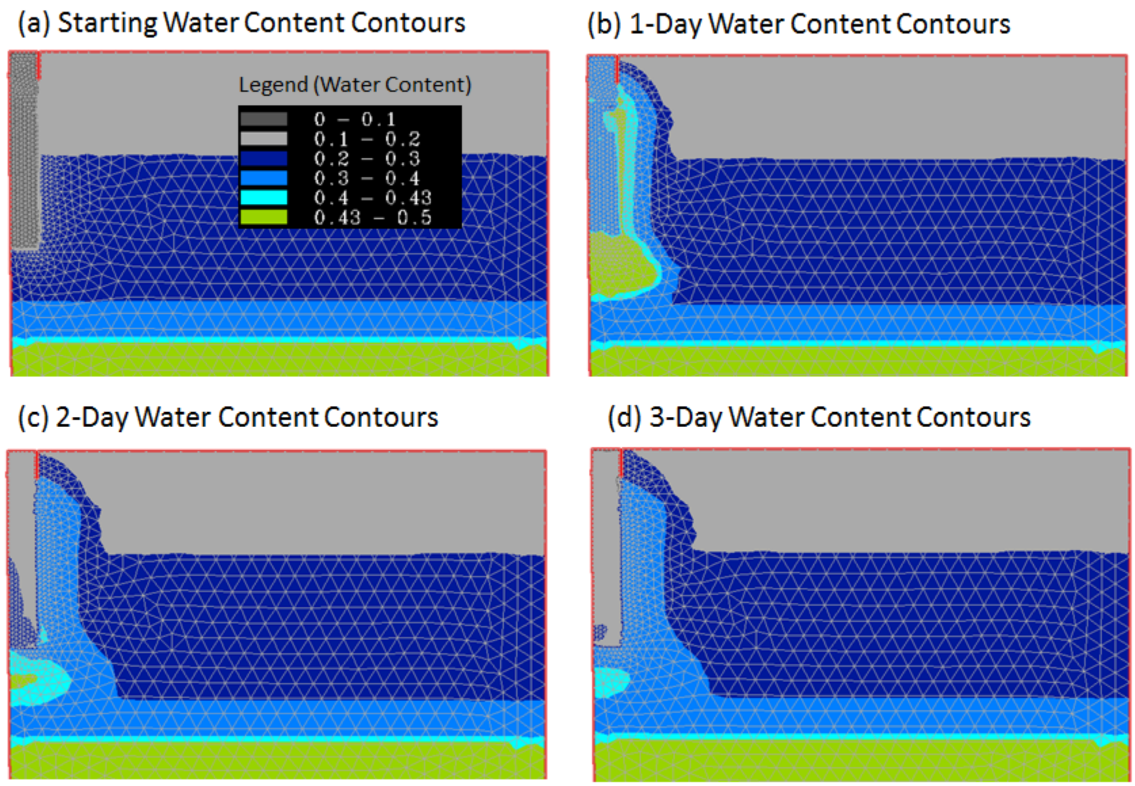

Figure 9 – Simulated Water Content Contours, Drainage Well Site, 1,000 ft^3/day for 1 Day

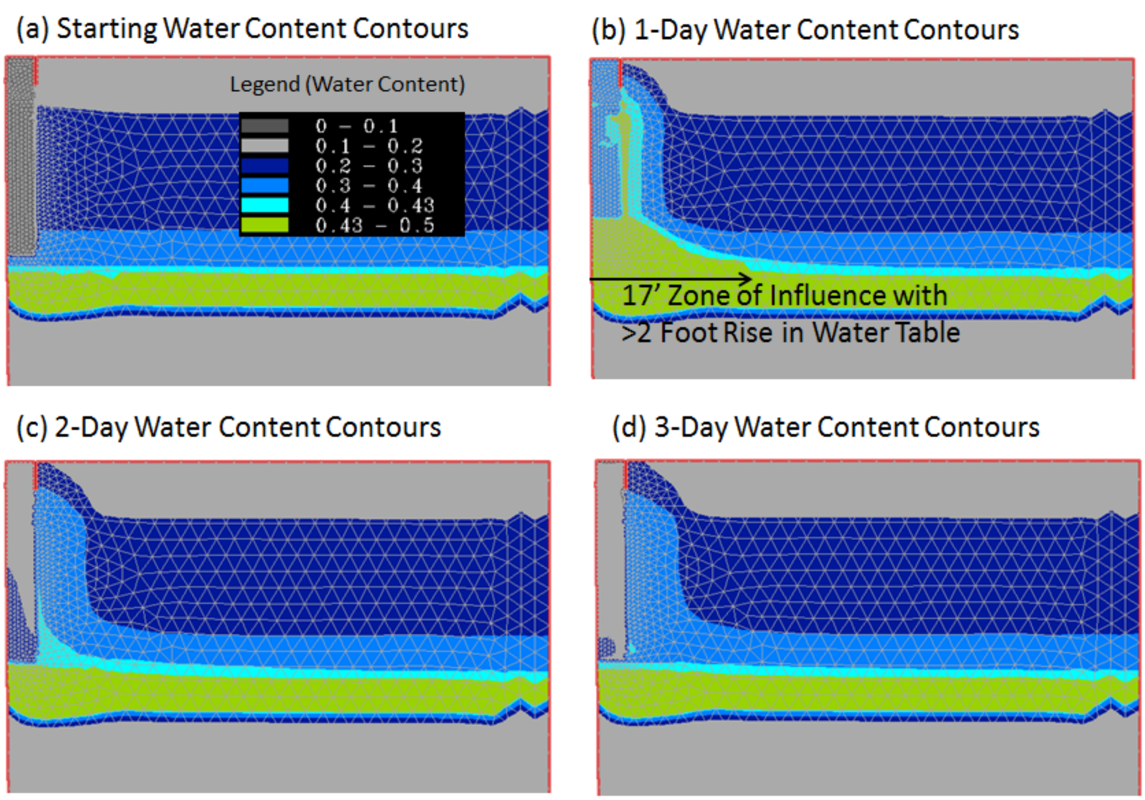

Figure 10 – Simulated Water Content Contours, Drainage Well Site, Higher Water Table Variant

1.5 inches of rainfall from a drainage area of 13,000 square feet, which is the median drainage

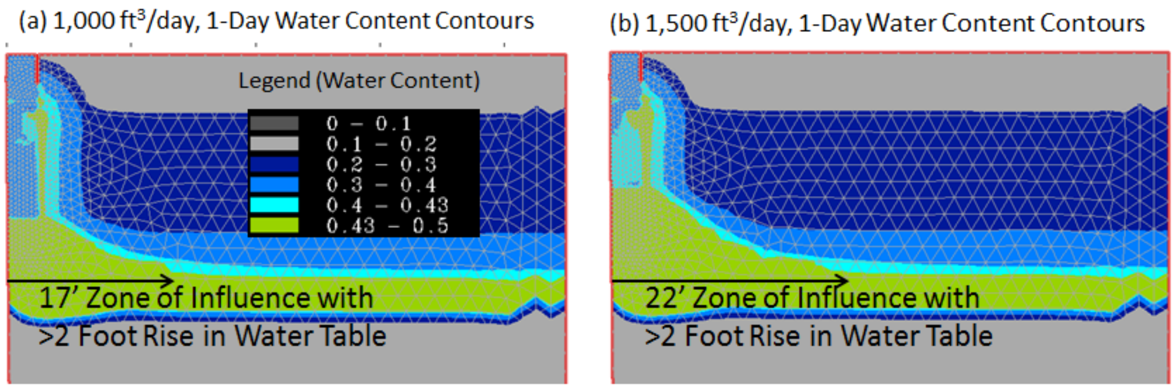

Figure 11 – Comparison of 1-Day Water Content Contours at the Drainage Well Site for 1,000 and 1,500 ft³/day inflow rates

area for Philadelphia Water tree trenches, and a loading ratio of 20:1.

Conceptually this scenario would be applied at locations where infiltration trenches are installed into relatively low permeable material overlying higher permeable material located at a depth below the bottom of the trench. The inclusion of the drainage well is intended to provide a pathway for infiltrated water to flow directly into the lower, more permeable material and subsequently lower the risk of basement infiltration and loss of infiltration capacity in the trench.

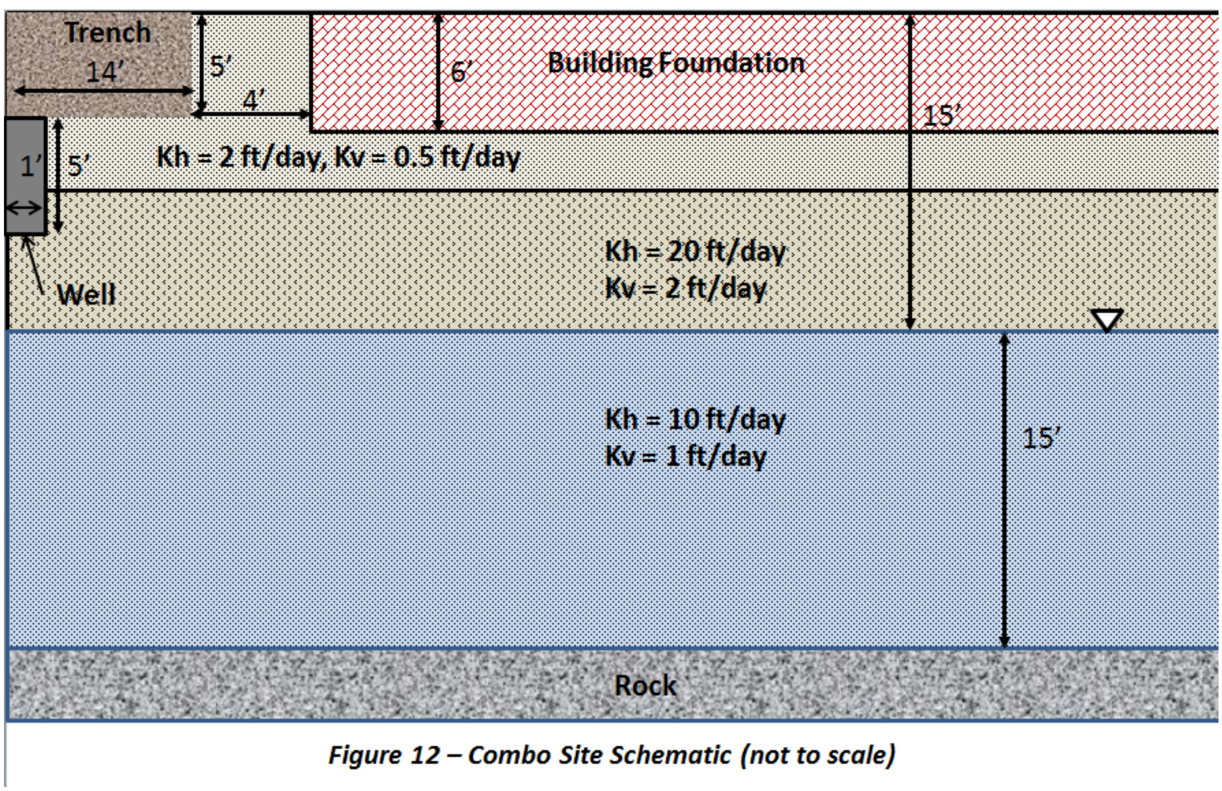

Figure 12 – Combo Site Schematic (not to scale)

Figure 14 (a, b, c, and d) shows the starting, 12-hour, 1-day and 3-day water contents, respectively, for the Combo Site base case scenario. As the flux ceased at the end of the 12th hour, **Figure 14** (c) and (d) represent drainage only. In this scenario, a portion of the water infiltrates slowly through the low permeability upper zone, with the remainder draining through the well. The zone of influence to the water table extends approximately 6 feet radially from the center of the site under these conditions. Due to the slow nature of the infiltration through the low permeability upper zone, the impact to the water table is muted.

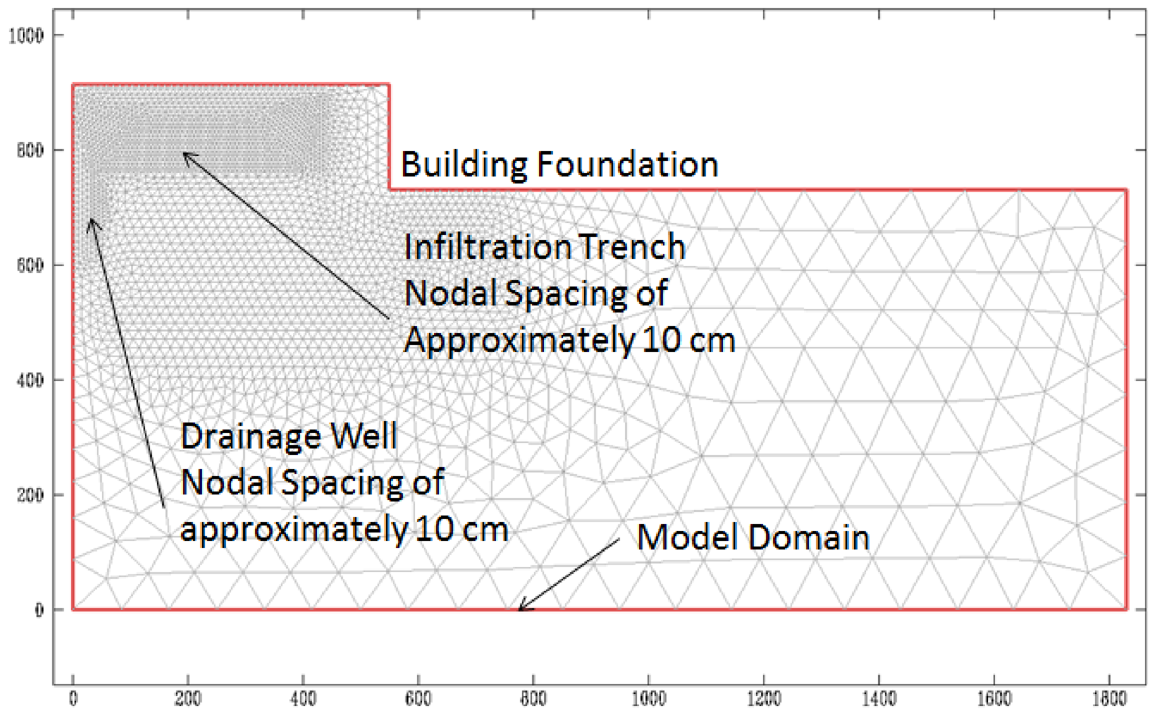

Figure 13 – Combo Site Model Grid

To provide a more complete understanding of the benefits of utilizing a combined trench and well system, two additional variants were run with the 12-hour water content contours for each variant shown alongside the base case scenario in **Figure 15** (a, b, and c). In the first variant, the drainage well is removed from the model, eliminating the direct pathway from the trench to the

higher permeability zone. A comparison of Figures 15 (a) and (b) indicates that without this direct pathway, infiltration to the saturated zone is inhibited. The trench-only variant also retains more water in the trench after 12 hours with full saturation over 70% of the trench area for the variant, as compared to only 40% in the base case. This comparison illustrates the benefits of the inclusion of a drainage well under certain geologic conditions.

In the second variant, distinctions between soil properties outside of the trench and well system are removed and horizontal and vertical hydraulic conductivities of 20 and 2 feet/day, respectively, are applied uniformly. A comparison of the water content contour plots in Figure 15 (a) and (c) indicates that the inclusion of a drainage well under these conditions provides little benefit in terms of infiltration rates or trench capacity and is largely unnecessary.

DISCUSSION

These simulations, coupled with the saturated zone/groundwater flow modeling completed to date for Philadelphia Water, help to provide a clearer understanding of the subsurface response to infiltration through GSI. In general, the results of the unsaturated zone simulations are consistent with those of the saturated flow models with respect to groundwater table mounding. Specifically, all analyses indicate that appreciable groundwater table mounding is generally

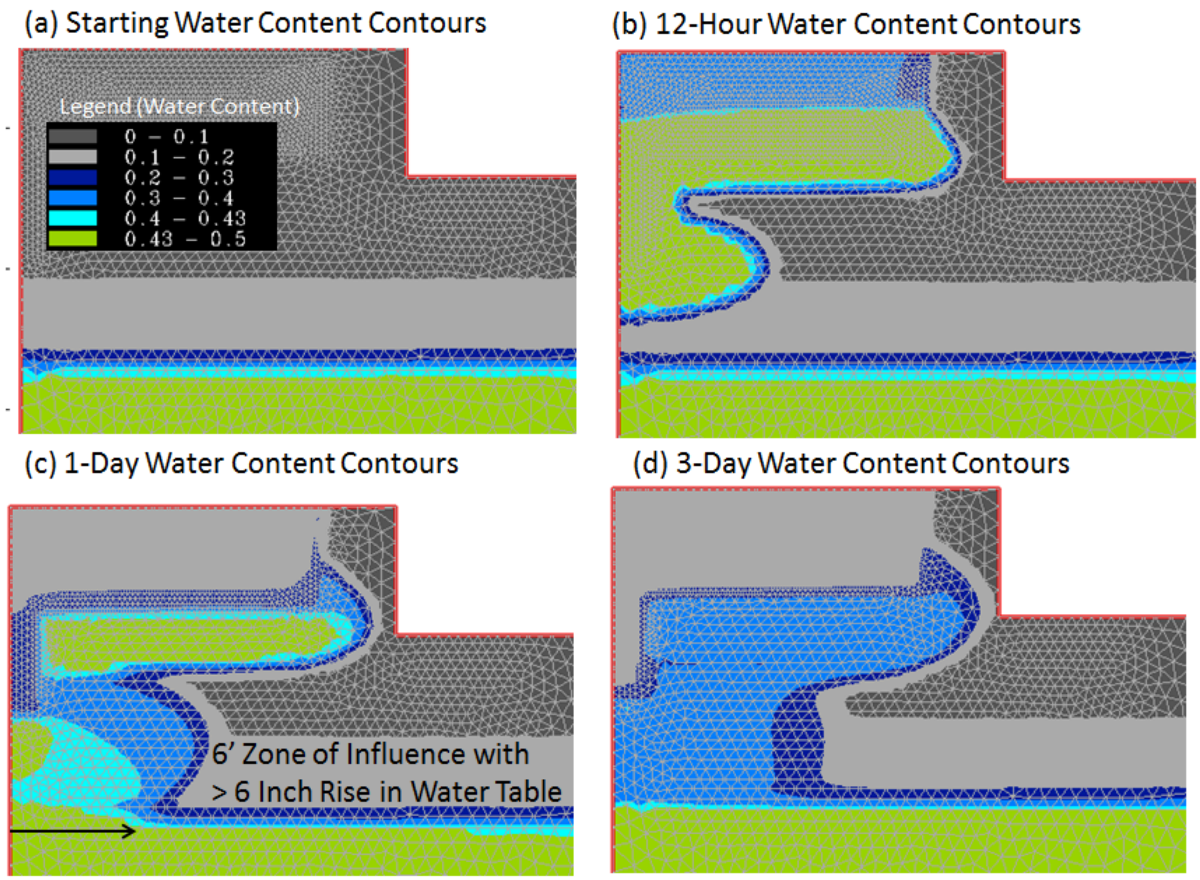

Figure 14 – Simulated Water Content Contours, Combo Site, 3,250 ft³/day Over 12 Hours

limited to the area within the immediate vicinity of the GSI. With respect to the questions posed in Section 1, the following is noted:

- GSI liners are effective at limiting the potential for lateral flow and should be installed in all trenches located in right-of-ways within 5 feet of building foundations. Liners may also be needed in trenches located 5 to 8 feet from building foundations depending on site conditions.

- The presence of shallow bedrock (or other relatively impermeable material) can be problematic and could increase the potential for lateral flow and basement infiltration, particularly if the rock is not significantly fractured to allow water to drain vertically into the formation. The potential for basement infiltration is highest when the distance between the bottom of the building foundation and the top of bedrock is small. GSI siting protocol should be updated accordingly.

- Drainage wells can be effective GSI alternatives. Simulation results were used to determine the radial distances from a drainage well to which limited groundwater table mounding would be expected under a range of infiltration and hydrogeologic conditions. The drainage well model can be updated to suit field conditions at proposed drainage well sites and to provide guidance with respect to depth, infiltration rates, level of control, and minimum distance from structures.

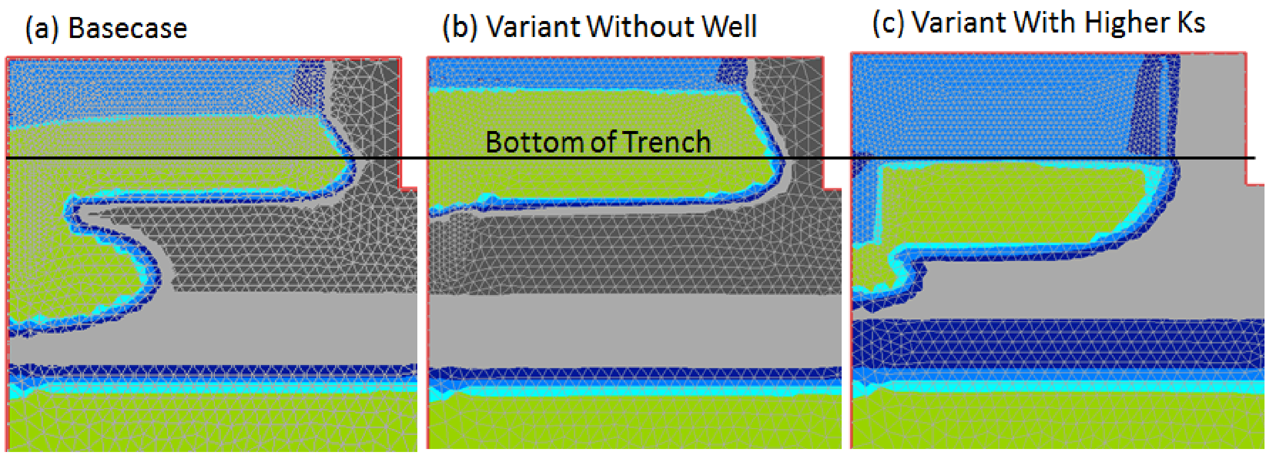

Figure 15 – Simulated Water Content Contours, Comparison of Basecase to Two Variants at 12 Hours

- The coupling of drainage wells and GSI can enhance vertical infiltration and lessen the potential for undesirable outcomes such as basement infiltration and surcharging of the GSI at locations where the underlying soils have relatively low permeability. Site assessments should be coupled with model simulations to determine the need for drainage wells on a case by case basis.

ACKNOWLEDGEMENTS

The authors gratefully acknowledge the cooperation and input from Philadelphia Water staff toward the execution of this innovative approach to GSI planning and analysis.

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