POTENTIAL IMPACTS OF EXTENSIVE STORMWATER INFILTRATION IN PHILADELPHIA

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ABSTRACT

There is an emerging trend in urban stormwater management, as more and more major U.S. cities are considering green stormwater infrastructure to reduce stormwater impacts to their separate and combined sewers. "Green stormwater infrastructure" (GSI) is a term used to refer to a number of strategies for handling storm precipitation at its source, rather than after it has entered a sewer system. It often relies heavily on systems designed to infiltrate stormwater. The Philadelphia Water Department's (PWD) proposed Long Term Control Plan Update for Combined Sewer Overflow control calls for "greening" more than 40 percent of the city's impervious cover in the coming 25 years. This is the most ambitious use of GSI being proposed to date by a major U.S. city. Although GSI is being widely tested and implemented, urban applications at the scale at which Philadelphia proposes is unprecedented. One of the key concerns associated with urban GSI is the long-term impact of enhanced recharge on the groundwater table. PWD has examined rising groundwater table concerns using groundwater models. Models have been developed on the local level nearby proposed infiltration structures to assess groundwater mounding, as well as on a city-wide scale to assess the long-term impacts of the GSI program. Modeling shows that the water table could mound beneath the trench up to about 1 m following significant rain events; however, the mounding drops off quickly at distances of several meters from the infiltration facility and dissipates over several days. Keeping infiltration facilities more than 3 meters from nearby structures should avoid any problems with basement flooding. At full implementation of PWD's program, the groundwater table could eventually stabilize up to 1.5 meters higher than its current level in some areas of the city, but this would occur in areas where the groundwater table is more than 3 meters deep.

INTRODUCTION

Major U.S. cities are considering green stormwater infrastructure to reduce stormwater impacts to their separate and combined sewers (Civic Federation 2007). "Green stormwater infrastructure" (GSI) is a term used to refer to a number of strategies for handling storm precipitation before it has entered a sewer system. It employs natural systems, such as vegetation, wetlands, and open space to handle stormwater in populated areas. It can also involve manufactured solutions, such as rain barrels or permeable pavement. The Philadelphia Water Department's (PWD) proposed Long Term Control Plan Update for Combined Sewer Overflow (CSO) control calls for "greening" more than 40 percent of the city's impervious cover in the coming 25 years. This is the most ambitious use of GSI being proposed to date by a major U.S. city (Civic Federation 2007). The concept of greening an acre of impervious cover in the city means that at least the first inch of runoff from every storm must be managed by the green stormwater infrastructure. Managing can be infiltrating stormwater into the ground, using trees and plants to enhance evapotranspiration of captured stormwater, or retention and slow release of captured stormwater back into the sewer system to prevent overflows. The exact balance between these mechanisms will depend on the mix of GSI projects implemented and the designs applied to these projects.

Although GSI is being widely tested and implemented, urban applications at the scale at which Philadelphia proposes to implement its GSI program are unprecedented. One of the key concerns associated with urban GSI is the long-term impact of enhanced recharge on the groundwater table. In particular, the concern is that higher groundwater levels may intersect existing basements, causing flooding, or even contributing to foundation instability where rubble masonry foundations are common. Although this appears to be an obvious concern related to intensive urban infiltration (Coldewey and Meber 1997), a literature search on the subject turned up only two studies that addressed this potential problem (Goebel et al. 2002, 2004; and Endreny & Collins, 2009). Goebel (2004) found that infiltration facilities could restore or even exceed natural recharge rates, and potential problems with groundwater mounding are possible and

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must be investigated prior to large scale infiltration programs. Endreny & Collins (2009) modeled an eight hectare site in a residential area of Syracuse, New York, analyzing the impacts of multiple basins on groundwater mounding. Their findings were that for a 2-year storm, mounding of 0.2 to 0.7 m could occur, depending on the arrangement of the basins and the hydraulic conductivity of the soils.

PWD is planning a much larger implementation of infiltration facilities within the city, and needs to address rising groundwater table concerns on two levels: on the city block level nearby each of the proposed infiltration structures (groundwater mounding), as well as on a city-wide scale to address the long-term impacts of the GSI program.

TRANSIENT CALCULATIONS OF GROUNDWATER MOUNDING

There has been significant progress in developing analytical solutions to the groundwater mounding problem (Bouwer 1962; Amoozegar et al. 1965; Bittinger and Trelease 1965; Ghavami 1970; Rao and Sarma 1981a,b; Rao and Sarma 1983; Musiake and Herath 1987; Griffen and Warrington 1988; Finnemore 1995; Swamee and Ojha 1997; Bouwer et al. 1999; Bouwer 2002; Dewberry 2002; Zomorodi 2005). Groundwater mounding is a transient process, however, and steady-state analytical solutions are likely to overestimate the height of the groundwater mound and cannot be used to test the range of conditions in Philadelphia. Transient analytical solutions exist, but are limited in their applicability (Hantuch 1967; Marino 1974a,b; Ortiz et al. 1978a,b; Ortiz et al. 1979; Latinopoulos 1984, 1986; Morel-Seytous et al. 1989, 1990; Guo 1991; Zomorodi 1991; Rai and Singh 1995). The importance of using a transient modeling approach is indicated in a number of prior studies (Guo 1998; Bouwer 1999). Carleton (2010), Nimmer et al. (2009, 2010), and Machusick (2011) are recent, transient modeling and monitoring studies of mounding effects of individual basins; however, they are only partially applicable to the more urban GSI proposed in Philadelphia because they deal with larger, single recharge basins in a suburban setting.

To be able to investigate groundwater mounding as a result of proposed street infiltration in Philadelphia, a simplified city block scale groundwater model was developed using the groundwater flow code DYNFLOW. The DYNFLOW code is a 3-dimensional finite element groundwater modeling code, and has been evaluated and accepted for use for a wide variety of applications (IGWMC 1985).

The city block model is designed to simulate various types of soils and street and sidewalk infiltration facilities likely to be tried under the GSI program. Philadelphia intends to develop a standard street design that features tree trenches that act as stormwater control structures as one of the primary means of reducing stormwater flows to the combined sewers. Figure 1 (USEPA 2009) shows a typical tree trench layout similar to the designs being developed for a Philadelphia street. Tree trenches were used as the primary infiltration facility example in the modeling study, but most of the planned GSI facilities act in a similar fashion, infiltrating water at rates related to the size of the facility and the soil properties. Thus the study results are applicable to a wide variety of concentrated infiltrating facilities such as rain gardens, tree pits, planters, and infiltration trenches. To model street tree trenches, a model grid was developed centered along a standard city street and block of 500 foot length, with each hypothetical block containing up to 12 tree trench infiltration beds, each trench 30-feet long, 5-feet wide, and 3-feet deep. Each simulated trench is separated by 5 feet (see Figure 2). The intent was to simulate transient recharge into multiple basins along the block, and to see if there

Figure 1
Typical Tree Trench Layout (USEPA 2009)

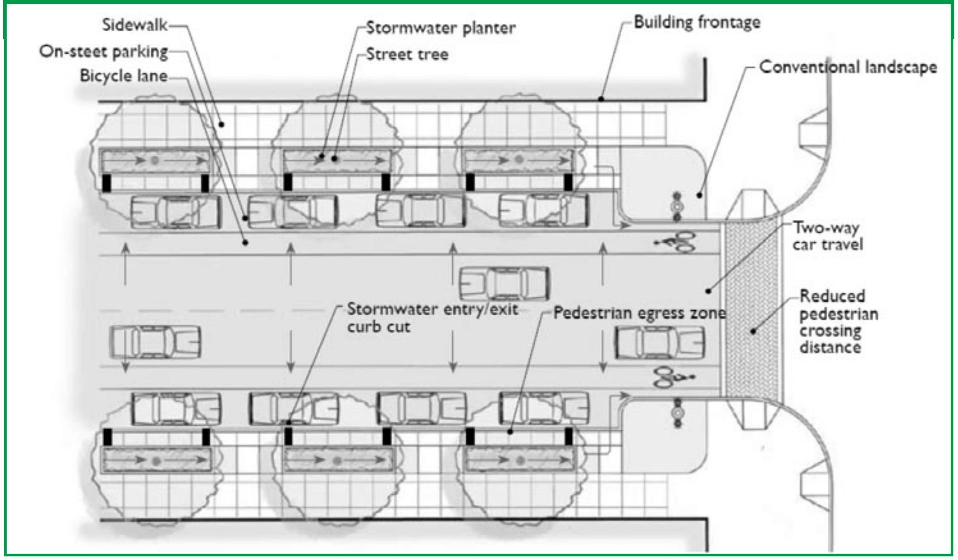
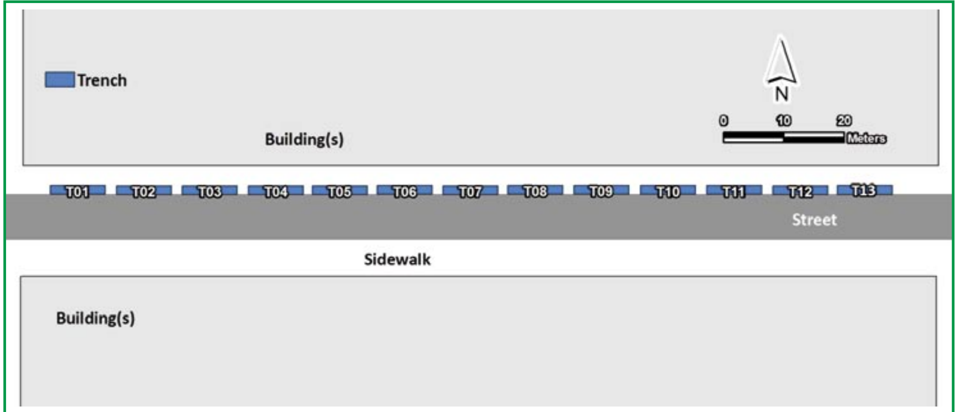


Figure 2
Hypothetical trench design for site scale model simulations.



are appreciable differences for trenches in the middle of the block versus trenches at the end of the block. The model is also designed to simulate a variety of depths to bedrock, aquifer thicknesses, and the presence or absence of clay layers. The city block model contains 12 layers, which can be flexibly used to simulate aquifers and aquitards. The model boundaries include two no flow boundaries, and two fixed head boundaries that created a slight east to west gradient of 0.0007 and flow consistent with Philadelphia coastal plain conditions. No area-wide recharge was added to the model to isolate the impacts of recharge from the tree trenches.

The primary use of the numeric city block model was to simulate transient conditions that are reasonably realistic and representative of the way tree trenches would actually function in the city. To do this, the model needed to have a time series of infiltration through the tree trenches to carry out transient infiltration simulations. A spreadsheet model was developed to estimate the expected infiltration in each tree trench based on the following factors:

- Impervious area draining to the infiltration trench
- Area of infiltration trench
- Rainfall depth during 15-minute time step
- Soil vertical hydraulic conductivity

The infiltrating water for each trench was calculated for a 15-minute rainfall time series from the year 2005 (used by PWD as a “standard rainfall year”). The spreadsheet was designed to calculate the runoff from the total impervious area connected to the tree trench, and track the volume of water stored in the tree trench, the volume of water infiltrated, and the volume of water that spilled back to the sewer. Water entering the tree trench first fills the available volume in the soil to capacity, then slowly releases to the sewer as well as infiltrates into the groundwater. Water in excess of the available capacity of the trench is routed into the sewer directly without entering the tree trench. Because the infiltration trench receives stormwater from an area much larger than the area of the trench, a simplifying assumption was made that antecedent moisture conditions and storage in the unsaturated zone are relatively small compared to total recharge. This implies the conservative assumption that all stormwater flows directed to the infiltration trench become groundwater recharge. The calculations assume fully saturated conditions and saturated conductivity with a unit vertical gradient. The area of downward vertical flow is assumed to equal the area of the infiltration trench.

For these simulations, the effects of evapo-transpiration in the tree trenches were ignored. The infiltration volumes per 15 minutes were taken from the spreadsheet model and input into the numerical groundwater model at each of the 12 tree trench locations along the block for a 1-year, transient simulation.

For this study, simulations were run for a variety of soil conditions underlying the hypothetical tree trenches, as well as for various designs that increased or decreased the area of impervious cover draining to the tree trenches. Presenting all the results of these sensitivity simulations goes beyond the scope of this paper, and only some of the conclusions from the simulations are presented.

There are a number of factors that influence the height of the mound, how fast it rises and falls, and the distance from the trench where water table mounding occurs.

- *Storage volume of the trench:* a greater volume of storage will increase the duration and height of the mound because it will allow more water to infiltrate.
- *Area ratio:* a greater area ratio (area of impervious cover connected to the trench divided by the infiltration area of the trench itself) will create more runoff and fill the trench more frequently and faster. Whether this results in a significant increase in the mound height will depend on the trench storage volume, the soil conditions, and the frequency and duration of the storms. Often higher area ratios result in more overflow to the sewers, and thus a lower efficiency of the system.
- *Vertical hydraulic conductivity (Kv):* a lower vertical conductivity will have two, contrasting effects. It will create a higher mound for the same amount of water infiltrated. It will, however, limit the rate of infiltration, thus decreasing the height of the mound at the same time. The factor that is dominant depends on the specific combination of factors applied and cannot be easily predicted.
- *Horizontal hydraulic conductivity (Kh):* a lower hydraulic conductivity will increase the height of the mound.
- *Rainfall intensity:* a greater intensity will fill the trench faster, but since infiltration is controlled by the soil properties, will not always have much of an influence on the height or extent of the groundwater mound once the trench has been filled.
- *Rainfall duration:* the duration will affect whether the trench fills completely, and how long it remains filled. Thus, it will affect the mound height by creating a longer period of infiltration before the trench is emptied and the mound starts to recede.

Because each of these factors affects the groundwater response in different ways, it is impossible to predict exactly which set of conditions will create a higher or lower groundwater mound without simulating a time series. Several example simulations are shown below to provide insight into the response of the groundwater mound to varying soil properties and loading ratios.

Soils underlying Philadelphia streets can vary from silt to coarse sand, as well as areas of the city which are underlain by fill material. The model was used to assess the impact of soil properties ranging from silt to course sand on the groundwater mound height. Because the current tree trench designs generally have area ratios of 15:1 or less, these soil sensitivity simulations were made using an area ratio of 15:1.

Figure 3 shows the transient nature of the simulated groundwater mound beneath tree trench 7 at the center of the block (see Figure 2) in response to rainfall in 2005, with infiltration simulated at the same time at the other trenches within the model. These results are for a silty sandy soil, with a vertical hydraulic conductivity and maximum infiltration rate of 3.5 x 10^{-6} m/s (1 ft/d), and a horizontal hydraulic

Figure 3
2005 transient response of groundwater to infiltration trenches with area ratio of 15 in fine sand

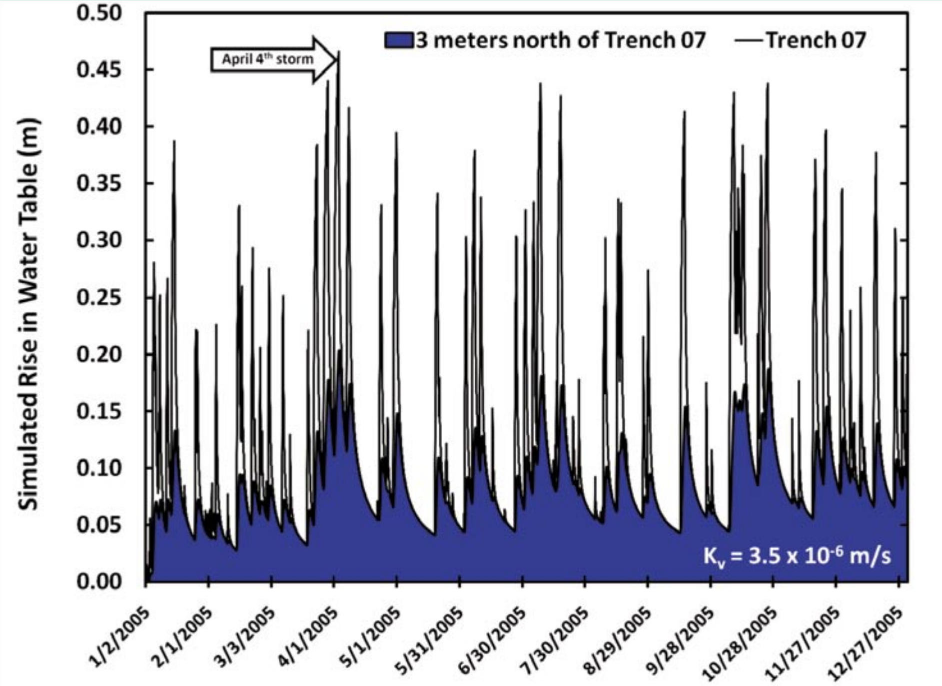
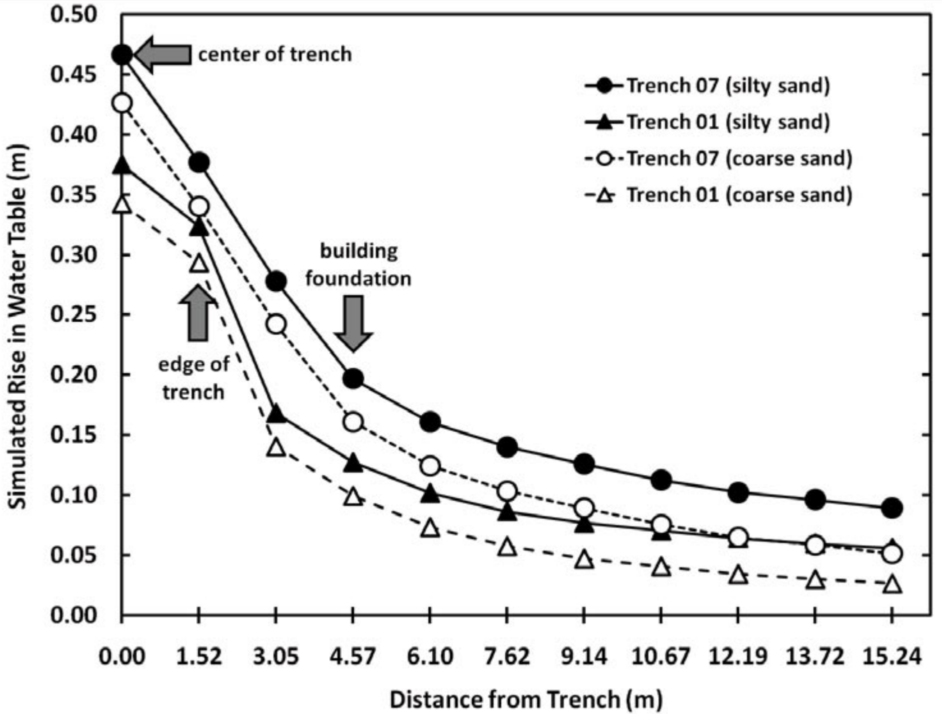


Figure 4
Cross section from center of trench - groundwater mounding from April 4, 2005 storm showing silty sand and coarse sand



conductivity of 3.5×10^{-5} m/s (10 ft/d). Philadelphia's stormwater regulations require storage of the 1st inch of rainfall if infiltration testing indicates infiltration rates of less than 3.5×10^{-6} m/s (1 ft/d). The simulated groundwater mound directly beneath the trench seems to hover around 5 to 7 cm, increasing occasionally to almost 0.46 m (1.5 ft) for the worst storms. At a distance of 3 m (10 ft), an assumed adjacent building, the peaks of the groundwater mound in response to storms are damped, with maximum increases of only about 15 to 20 cm (6 to 8 in).

Soil with hydraulic properties of medium to coarse sand (vertical hydraulic conductivity and maximum infiltration rate of 1.8×10^{-5} m/s or 5 ft/d, horizontal hydraulic conductivity of 1.8×10^{-4} m/s or 50 ft/d) allows greater infiltration rates but can also more effectively convey groundwater away from the trench area. Results were remarkably similar to those shown in Figure 3. The groundwater mound was only slightly lower, stabilizing around 5 cm (2 inches) directly below the trench. Short-term spikes of up to 0.42 m (1.4 ft) were also simulated, very similar to results for silty sandy soil shown in Figure 3. Figure 4 shows a cross-section drawn perpendicular to the trench from the center of the tree trench towards an adjacent building. The results are for April 4, 2005 when the simulated groundwater mound was at its highest point. Both the mid-block (trench 7) and end-of-block trench (trench 1) are shown for both silty sand and medium to coarse sand. Note that the mound drops steeply off from its highest point beneath the trench within the first 3 m (10 ft), and then gradually dissipates over a distance of about 15m (50 ft) from the trench. The cross-section suggests that if the trench edge is more than 3 m (10 ft) from a building foundation, even using the conservative estimate for the silty sand, the groundwater rise at the building foundation is likely to be less than 25 cm (0.83 ft).

Sensitivity simulations were also made to test the response of the groundwater mound to a range of area ratios. The assumptions used to evaluate infiltration for a variety of area ratios were a silty sand [$Kh = 3.5 \times 10^{-5}$ m/s (10 ft/d), $Kv = 3.5 \times 10^{-6}$ m/s (1 ft/d)], and recharge based on 2005 annual precipitation (15-minute time steps). Figure 5 summarizes the area ratio simulations for the trench at the center of the block for the groundwater mound beneath the trench and at the nearest building 3 m away for the worst case storm of April 4, 2005.

The results suggest that the groundwater mound does increase with increasing area ratio, from a maximum of 18 cm (0.6 ft) at the nearest building for an area ratio of 10, to about 30 cm (1 ft) for an area ratio of 25. The response is not linear to increasing area ratio because the rate of infiltration is limited by the vertical hydraulic conductivity in the trench. Thus, as the area ratio increases, more water is either held in storage for longer periods and slowly infiltrated, or is spilled through overflow to the sewers with no effect on the mound.

To get a better sense of the system response to individual storms, with the trench filling, then slowly draining down, a one-month simulation using January 2005 rainfall was conducted. Results for a variety of soil conditions using a relatively high area ratio of 20 are shown in Figure 6. At the top of the figure, the 15-minute rainfall amounts (right vertical axis) are also shown. Note how a large storm may create a rising groundwater mound for 2 to 3 days after the storm, as the trenches slowly drain down. Once drained, it can take almost a week for the mound to dissipate, and never completely returns to the initial level before another storm occurs.

Figure 5
Increase in height of groundwater mound in fine sand with increase in area ratio for trench in the middle of the block

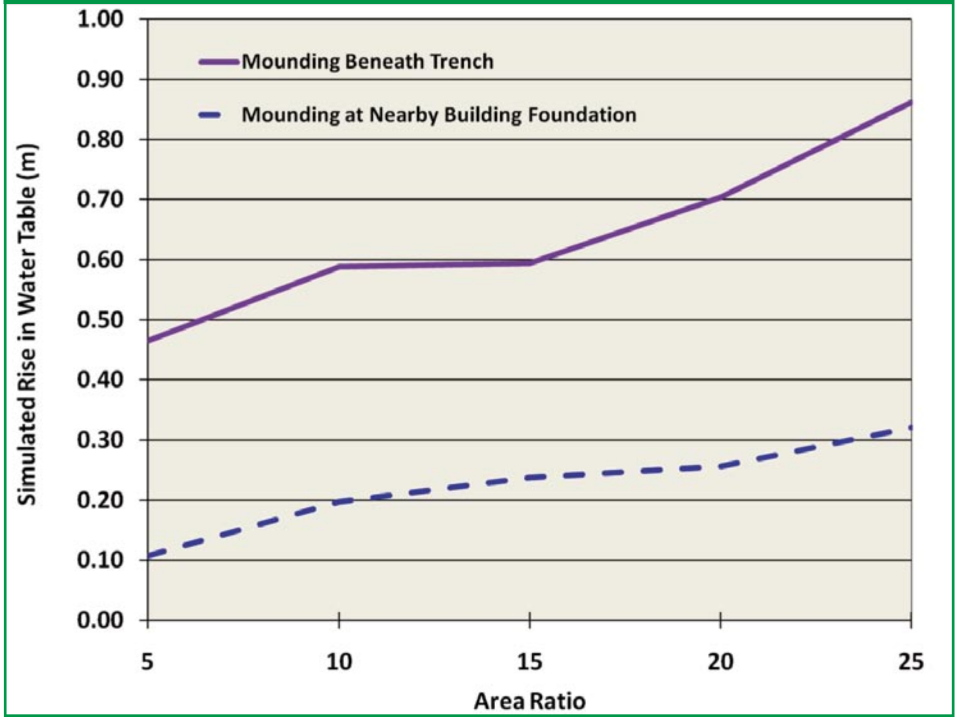
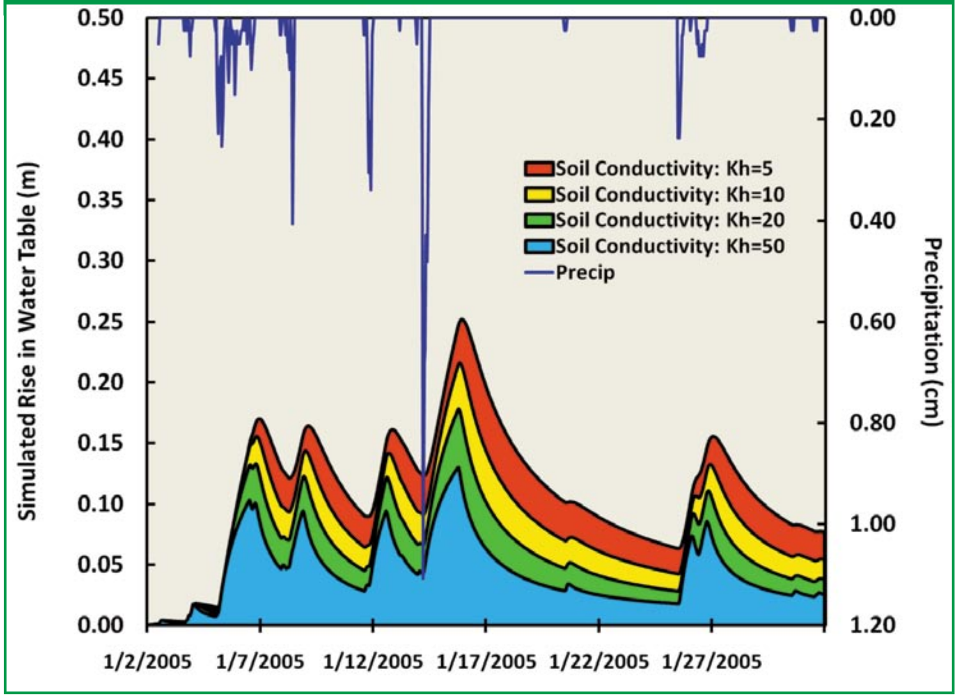


Figure 6
One month transient response of groundwater to trench 07 with area ratio of 20 at nearest building for various soil conditions (Soil Conductivity in ft/day).



CITY-WIDE EFFECT ON GROUNDWATER LEVELS

The initial transient simulations suggest that, although the water table will rise and fall with the filling and emptying of the tree trenches, there does appear to be some local permanent groundwater mounding around each infiltration trench, due to the fairly frequent storms that occur throughout the year in Philadelphia. If stormwater infiltration is applied to whole sections of roads or urban districts as planned, the result may be a general rise in the groundwater surface over entire portions of the city.

To assess the long-term impact of Philadelphia's proposed GSI Program on the groundwater table, a groundwater flow model of the combined sewer areas of the city was developed. The model grid was chosen to provide reasonable hydrologic boundary conditions, with a focus on capturing the two primary hydrogeologic areas within the city's borders: the Piedmont and the Coastal Plain. Horizontally, the Philadelphia model includes the area between the Delaware and Schuylkill Rivers, with a northern boundary set to represent a no flow boundary based on 1980 groundwater contours (Paulachok and Wood 1984). The finite element grid contains 7,253 nodes and 14,290 elements for each model layer/level. Node spacing ranges from approximately 75 to 300 m (250 to 1000 feet).

The model contains 11 layers (Table 1) and covers both the Coastal Plain and Piedmont physiographic provinces within the city boundaries. The Fall Line separating the two physiographic provinces runs through the middle of the model, creat-

Table 1
Hydraulic Properties assigned to each stratigraphic unit in the model

Stratigraphic Unit	Model Layers	Model Kh, Kv (m/day)	Published Values[1]
Overburden (Piedmont)	4 - 11	3.05, 0.30	None identified
Fill/Sand	11	3.05, 0.30	None identified
Alluvium	11	3.05, 0.30	1.68/1.68
Trenton Gravel	10	44.19, 4.42	43.28
Upper Clay	9	0.30, 0.03	<<< 0.10 to 0.11
Upper Sand	8	30.48, 3.05	10.67 to 43.28
Middle Clay	7	0.30, 0.03	<<< 0.10 to 0.11
Middle Sand	6	38.10, 3.81	29.87 to 46.33
Lower Clay	5	0.30, 0.03	<<< 0.10 to 0.11
Lower Sand	4	60.96, 6.10	26.21 to 63.09
Saprolite	3	0.76, 0.76	None identified
Bedrock	1, 2	0.76, 0.76	Highly variable

1. Sources: USGS (1988, 1991, 2001)

Table 2
Tabulation of stratigraphic units in the Piedmont and Coastal Plain areas of Philadelphia (descriptions summarized from Paulachok, 1991).

Piedmont			Coastal Plain			
Stratigraphic Unit	**Description**	**Thickness in Model (m)**	**Stratigraphic Unit**	**Description**	**Thickness in Model (m)**	
Overburden (sand, silt)	Sand, gravel, silt, fill	0 to 21	Alluvium / Fill	Fine sand and silt, some gravel	0 to 17	
			Trenton Gravel/ Bridgeton Formation (combined in model)	Sand and gravel	0 to 17	
			Upper Clay	Multi-colored clay, sandy in places	0 to 16	Potomac-Raritan-Magothy Aquifer System
			Upper Sand	Medium to coarse sand. Coarser at base of unit (gravel common)	0 to 12	
			Middle Clay	Red and white clay, sandy in places	0 to 21	
			Middle Sand	Fine to coarse sand	0 to 45	
			Lower Clay	Generally a red caly, sandy in places	0 – 27	
			Lower Sand	Coarse sand and fine gravel, fines upward to fine to medium sand with silt and clay	0 to 29	
Bedrock	Primarily Wissahickon Formation (Schist)		Bedrock	Primarily Wissahickon Formation (Schist)		

ing two distinct stratigraphies. Table 2 illustrates the contrasting stratigraphies associated with the two primary physiographic provinces, the Piedmont and the Coastal Plain beneath Philadelphia (Paulachok 1991, U.S.G.S 2000). The stratigraphy in the coastal plain consists of a sequence of sands, gravels and clays, reaching a thickness of more than 60 m (200 ft) near the Delaware River. Beneath these aquifers and aquitards is the bedrock formation. The sequence of layers is much simpler in the Piedmont, with a relatively thin layer of sand and fill material overlying bedrock.

Aquifer properties were assigned to model layers to represent the hydraulic characteristics of the sediments in different stratigraphic layers. For each material type, a range of reasonable hydraulic property values (vertical and horizontal hydraulic conductivities) was determined based on previous modeling studies and literature values (Sloto 1988). These estimates were used to guide the hydraulic property assignments in the Philadelphia model, and were adjusted so that model simulated heads provided a reasonable visual match to the 1980 published contours of groundwater head (Paulachok and Wood 1984). No numeric calibration statistics were possible due to a lack of data. It is the intent that, as the groundwater monitoring program in Philadelphia is re-established, model calibration will be revisited. Table 1 includes the hydraulic conductivity properties that best fit the limited data available and that created the best match of simulated water table elevations with the only available groundwater contours.

BOUNDARY CONDITIONS

The boundary conditions of the Philadelphia groundwater flow model were selected to provide a reasonably realistic representation of the flow system. The boundary conditions are listed below.

- The bottom of the modeled aquifer system was assigned a no-flow boundary condition, assuming that the deeper bedrock is relatively impermeable compared to the overlying sediments.
- Inland, the top level of the model was assigned a rising water boundary condition, whereby if the water level is simulated to rise to the elevation of the ground surface, it is held fixed at that elevation and the discharge or flux (such as stream base flow) is calculated. Ground-

water flow to local streams and drainage channels was represented in this way.

- A specified head boundary condition, set at the mean river stage of the Schuylkill and Delaware rivers, was assigned to the eastern, western and southern edges of the model in the top model level. This simulates the connection between the groundwater system and the two main rivers in Philadelphia. Below the top level of the model, the lower model levels were no flow boundaries reflecting the tendency of groundwater to discharge to the major rivers.
- One exception was made along the southern half of the Delaware River. Along the southern half of the Delaware River, within the model domain, the deeper levels are influenced by pumping in New Jersey, and heads were specified based on recent published values (Sloto 1988; U.S.G.S 1997, Schreffler 2001). This boundary condition causes the model to represent the flow beneath Philadelphia in the deeper aquifers toward the pumping centers in New Jersey.

One other issue with boundaries was identified during the modeling simulations. It is known that the older, brick lined combined sewers in Philadelphia tend to leak, and often take in groundwater at the seams and joints. In some areas of the city, it appears from the shape of the water table contours that the combined sewers actually control the water level. This was also suggested by Paulachok (1991). In those areas of the city where combined sewers are clearly influencing the groundwater table, they were simulated as head-dependent fluxes in the model. Thus, as the water table rises above the invert of the sewer, the model allows water to enter the sewer and be discharged to the rivers. The greater the difference in head between the water table and the sewer invert elevation, the more water the model allows to flow into the sewers and leave the groundwater system. Sewer exfiltration when the water table is below the water table was implicitly modeled as part of the baseline urban infiltration rate. Figure 7 shows the areas of the city within the model area where head-dependent fluxes were assigned to represent the brick sewers.

Figure 7
Location of brick sewers where inflow is simulated. Figure on the left shows the 1980 water table map and where brick sewers are currently installed. Figure on the right shows representation of brick sewers with model nodes.

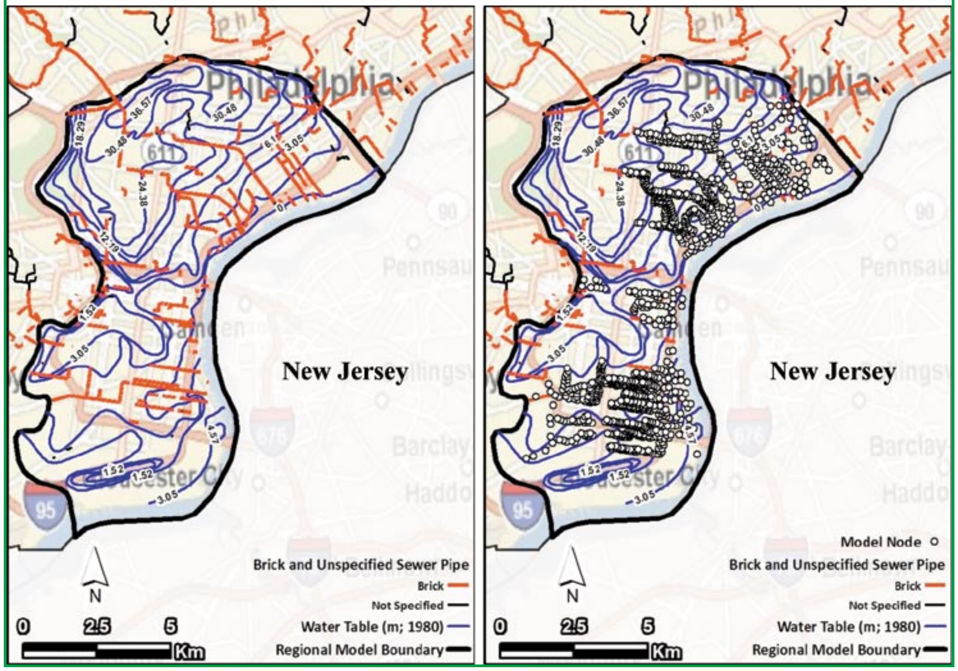
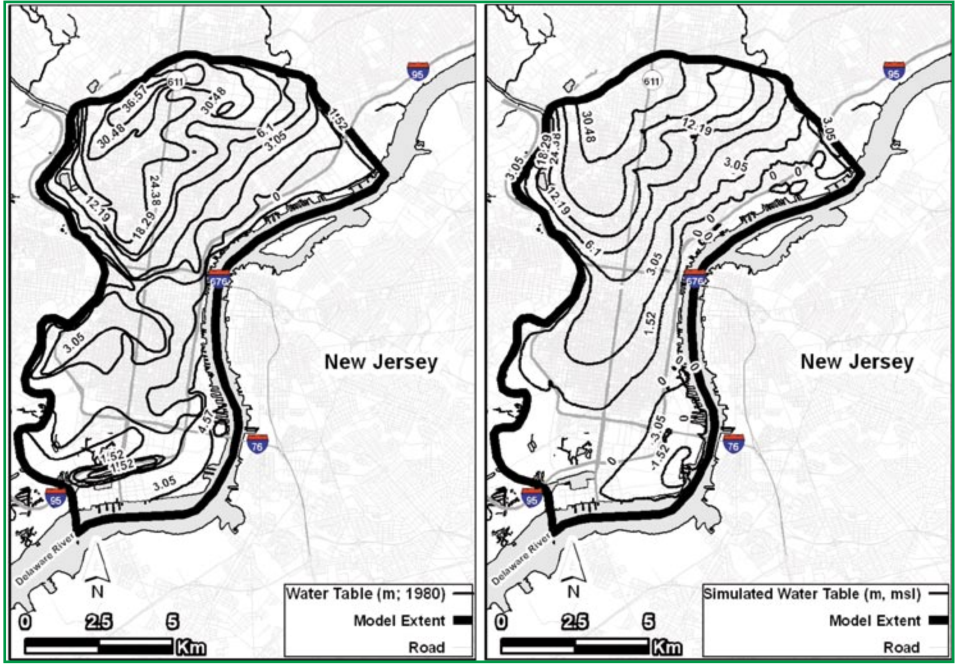
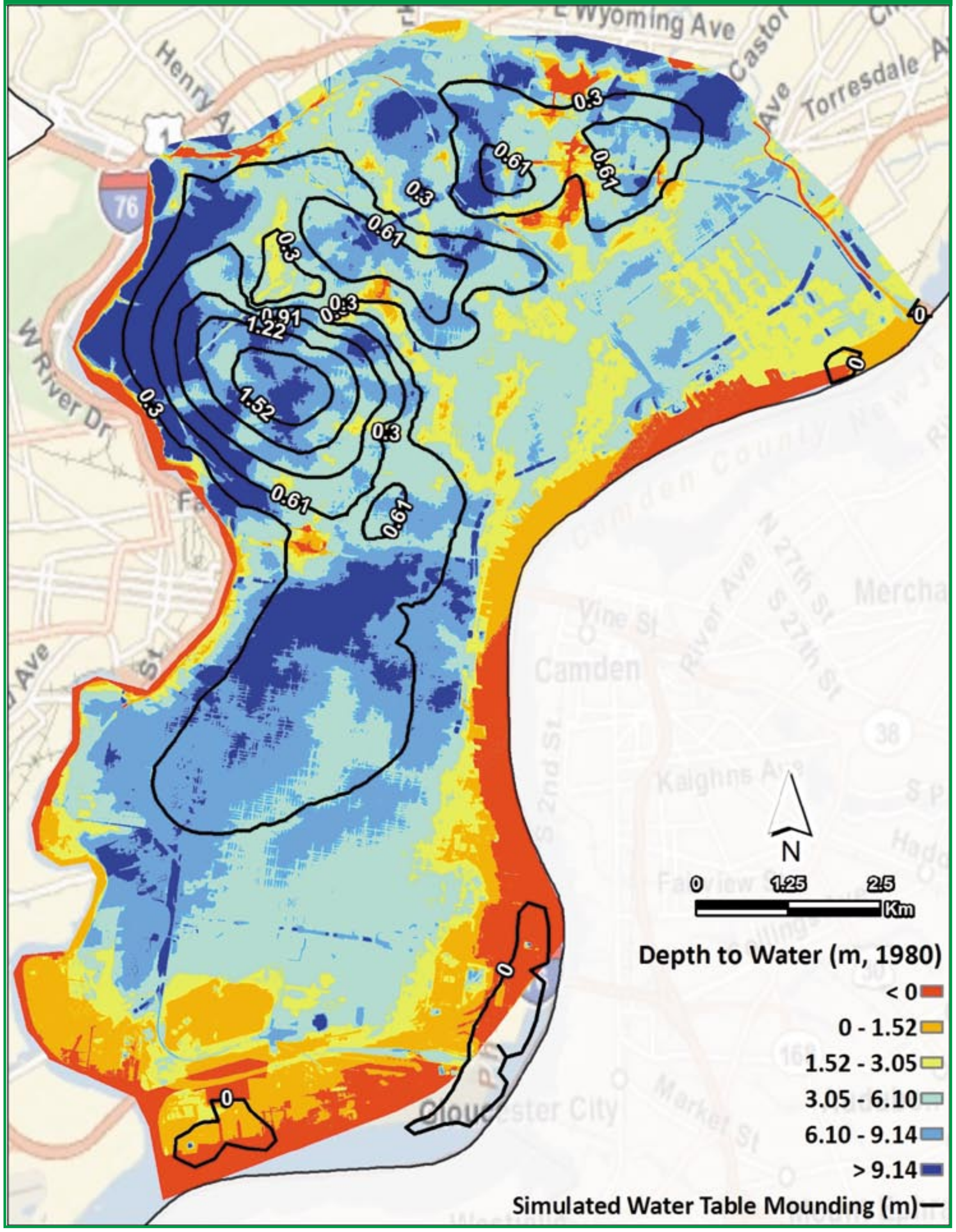


Figure 8
Comparison of simulated (right) water table with USGS 1980 estimated water table (left). Water table is shown in meters above mean sea level.



Recharge is the primary source of water to the model, and drives the movement of water toward the rivers. Recharge in an urban environment is particularly difficult to assess because much of the land surface is impervious, sewers can either leak or drain groundwater, and leaking water lines can significantly affect the total amount of recharge applied. To estimate recharge in an urban environment, the best approach is to have a calibrated surface runoff model that can provide both average and time series breakdowns of rainfall into runoff, evapo-transpiration (ET) and infiltration.

Figure 9
Estimated increase in water table after implementation of GSI program



An EPA-based SWM model (James and James 2000) of the area exists, and provided most of the information needed to estimate total recharge under both baseline and future conditions associated with the GSI Program. The SWM model provided a time series of recharge estimates for an average rainfall year, 2005, accounting for spatial variation in soils and impervious cover. Infiltration time series were created for today's conditions and for the projected conditions once the proposed GSI program is fully implemented (Myers et al. 2004).

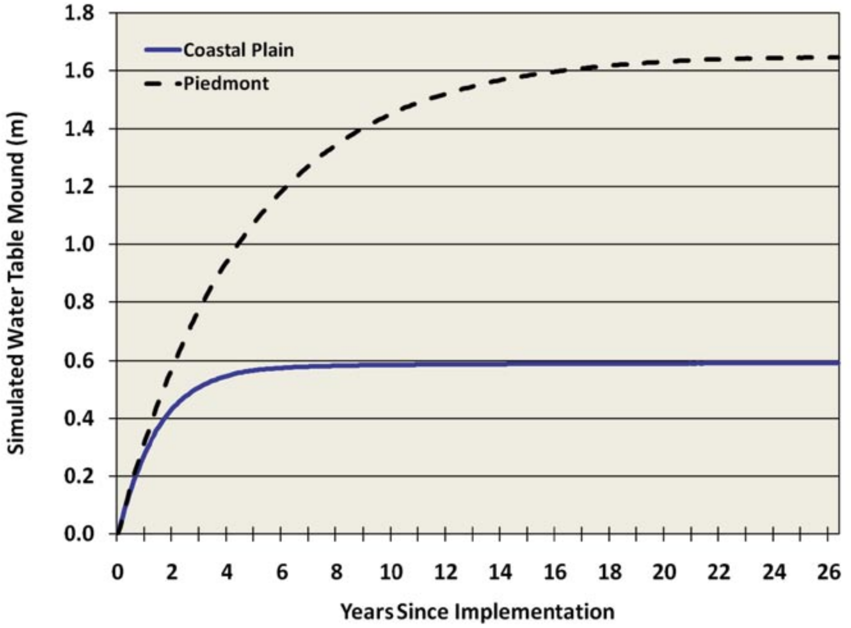
For the baseline, steady-state groundwater model, recharge was uniformly assigned to the model at the surface. The recharge for an average year of precipitation estimated by the SWM model was applied at a rate of 45 cm per year (17.6 in/year). The annual average rate of 45 cm per year is the amount of recharge from the 114 cm per year (45 in/year) of average annual rainfall that falls on Philadelphia after runoff and ET are accounted for. This rate takes into account the impacts of current impervious cover, but does not include potential leakage from water mains, much of which is reported to be collected in the underlying sewers.

The SWM model was also used to estimate the amount of stormwater runoff and recharge plus evapo-transpiration that will occur once the city is "greened." The GSI Program assumed that 2,115 ha (5,227 ac) of impervious cover within the model area was outfitted with stormwater infiltration measures such as tree trenches, infiltration trenches, or rain gardens to capture the first inch of runoff from each rain event, as required by the city's stormwater regulations. In areas of the model not affected by GSI, infiltration still averaged 45 cm per year (17.6 in/year). In areas that have been "greened," the calculation had to account for the effects of stormwater infrastructure that can detain and release, as well as infiltrate stormwater. The transient mounding model described above used an input series from a spreadsheet model that tracked infiltration, storage, and overflow in tree trenches. The spreadsheet model showed that a significant portion of the captured stormwater might not make it to the groundwater, depending on soil conditions, the trench design, and the frequency of storm events. This implies that only a portion of the 1 inch captured by the GSI would actually infiltrate, the rest either evaporating or releasing through a controlled orifice back to the combined sewer. The balance between these three pathways for the stormwater will depend on the mix of designs implemented. Because this is not yet known, a range of infiltration assumptions were tested. Space limitations allow results for only one set of simulations to be presented in this paper. Results are shown using the assumption that the mix of tree trenches, porous pavement, and rain gardens in the Philadelphia CSO control program will infiltrate 70 percent of the 1 inch of stormwater runoff captured by the GSI. Under this assumption, 63 cm per year (24.8 in/ year) is assumed to infiltrate into the ground through the installed infiltration devices in areas of the city that have green stormwater infrastructure in place. This is an increase of 40 % compared to the non-greened areas.

BASELINE MODEL RESULTS

A steady-state, baseline simulation was made to test the model's ability to simulate groundwater table elevations using the estimated current rates of recharge. Although no formal calibration was pos-

Figure 10
Response time of the aquifer to enhanced recharge in the Coastal Plain and Piedmont



sible due to a lack of data, the properties of the aquifers were adjusted until the simulated water table generally resembled the estimated 1980 water table elevations from a USGS study (Paulachok 1991). Figure 8 shows that the model simulates the estimated water table in 1980 with reasonable accuracy.

The ability of the model to capture the flow patterns and depth to groundwater suggests that by modeling a range of recharge rates, the model should provide a reasonable range of groundwater level responses that will help to identify potential areas in the city where the regional rise in groundwater due to enhanced infiltration might eventually lead to problems associated with a high groundwater table.

SIMULATING THE GSI PROGRAM

The Philadelphia GSI Program is being implemented with a variety of green stormwater infrastructure measures that combine stormwater infiltration with slow release and evapo-transpiration to reduce the volume of combined sewers overflows. The GSI Program simulation results presented here assume that up to 34 percent of the impervious cover will be "greened." The initial use of the groundwater model was to address the issue of potential long-term impacts of infiltration on the water table. This addressed the concern that over time, the water table would reach a new, higher equilibrium position that might cause basement flooding or other problems associated with a high groundwater table. The model was used to compare the steady-state water table elevation under today's conditions of recharge with the estimated increase in the water table, once the GSI Program is substantially completed and the aquifer system has reached a new state of equilibrium in response to increased recharge. The estimated increase in the water table due to the enhanced infiltration was compared to the estimated depth to water under current conditions to highlight areas where the simulated water table is less than 3 m (10 ft) below ground surface.

Figure 9 shows the maximum expected water table elevation increase. The maximum rise in the water table is shown to occur in the Piedmont, and is projected to be about 1.8 m (6 ft) in a limited area of the Piedmont. In the coastal plain, the water table increase is limited to less than about 0.5 m (less than 2 ft). Figure 9 also includes an estimate of depth to groundwater. Note that the areas of greatest increase in groundwater levels are located in areas where the depth to groundwater is currently estimated to be more than 9 m (30 ft). Thus, even the maximum rise of 1.8 m is not likely to cause any problems with basement flooding.

SENSITIVITY TO ASSUMED HYDROGEOLOGIC PROPERTIES

As noted above, the model appears to simulate water table contours with reasonable accuracy when compared to USGS-estimated contours from 1980; however, the model has not been calibrated to contrasting steady-state conditions or to a transient response to changes in recharge due to a lack of data. This means that the properties of the aquifer near the surface are not well known beyond the use of literature values that match the soil descriptions of the many borings available. To test the sensitivity of the results to the assumed aquifer properties, the horizontal (Kh) and vertical (Kv) hydraulic conductivity values of the overburden and alluvium in the surface model layer were varied within ranges that did not cause significant deviation of the water table contours when compared to the 1980 measured contours. Kh was varied between 1.76×10^{-5} cm/sec and 7.1×10^{-5} cm/sec (5 and 20 ft/d), and Kv was varied between 3.5×10^{-6} cm/sec and 7.0×10^{-6} cm/sec (1 and 2 ft/d) in both the Piedmont and Coastal Plain and the difference in the water table response to the implementation of the GSI program was noted. The results of the sensitivity analysis suggest that the aquifer system responds primarily to the change in recharge once equilibrium is reached, and that the expected variety of hydraulic properties of the surficial soils is not likely to cause large differences in the equilibrium response.

Finally, the model was run in a transient mode using the baseline hydraulic properties shown in Table 1. The purpose of the simulation was to estimate the time it would take, once the GSI Program was fully implemented, to achieve the full impacts on the water table. Figure 10 indicates that the response in the Coastal Plain portion of Philadelphia is likely to achieve equilibrium within about 16 years, with most of the impacts occurring in the first 5 years. For the Piedmont, equilibrium conditions are not expected to occur for up to 22 years, with most of the impacts occurring within the first 10 years.

CONCLUSIONS

Urban infiltration through GSI is a growing trend in stormwater, as concepts of sustainability are applied to the urban hydrologic cycle. The concept of using green stormwater infrastructure to control stormwater at the source, rather than using sewers to discharge it as rapidly as possible to surface water bodies, will require considerably more investigation of potential impacts than is currently occurring. This is particularly true for cities considering more ambitious programs, such as Philadelphia's target of greening more than 40 percent of all impervious cover to control combined sewer overflows.

In modeling urban groundwater systems, stormwater infiltration rates, soil properties, and the design parameters of green stormwater infrastructure interact in complex ways, and transient mounding effects near infiltration facilities are impossible to predict without using numerical models with transient capabilities. Based on the initial modeling results for Philadelphia, a number of results are of importance for PWD:

- Even for a wide variety of soils, local transient water table mounds dissipate with distance from the infiltration facility, and keeping infiltration facilities more than 3 m (10 ft) from building foundations should avoid most problems.
- The water table is usually lowered by impervious cover in cities as recharge is reduced. Green stormwater infrastructure can reverse this, and create enhanced recharge in highly urban settings that can surpass recharge rates found in grassy or wooded open space.
- City-wide effects of enhanced recharge do occur over time, as the groundwater system seeks a new equilibrium. An ambitious program such as Philadelphia's can result in water table rises of up to 2 m (6 ft) in some areas.
- The modeling of GSI in Philadelphia shows that a significant percentage of the infiltrated stormwater is likely to re-enter the sewers, but at a steadier, more controlled rate. For cities facing requirements to reduce CSOs, this can also be considered a beneficial effect of GSI infiltration.
- Groundwater mounding on a localized scale is very dependent on trench layout and design, and overlapping mounds from adjacent infiltration facilities can increase the mound height relative to a single infiltration facility.

Groundwater models need to be developed and applied at both local and city-wide scales to assess potential impacts of GSI on basement flooding, foundations, and on local streams and wetlands. The initial modeling results for the city of Philadelphia suggest that long-term increases in the groundwater elevation can be managed by avoiding infiltration in areas of shallow groundwater, and by keeping infiltration trenches more than 3 m from nearby buildings.

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