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Impacts of Novel Stormwater Management on Groundwater Recharge
Proposal to National Science Foundation Earth Sciences Postdoctoral Fellowship
Project Summary

Overview

Novel forms of urban development aim to engineer systems that replicate natural hydrologic functioning. This includes preservation of near-natural groundwater recharge through infiltration of stormwater close to impervious surfaces where stormwater is generated. A small watershed in the Piedmont province of Maryland, USA is one of the first instrumented watersheds that was recently developed entirely with novel, distributed stormwater management techniques and is used as a case study for the proposed work.

This study seeks to understand how these alterations to the natural landscape impact subsurface flow systems and groundwater – surface water interactions. A network of field observations will be used, including measurements of streamflow, precipitation, hydraulic head, infiltration from and specifications of stormwater control measures, and hydraulic conductivity. The field data will inform the application of ParFlow, a three-dimensional, distributed hydrologic model, building on experience applying the same modeling system to other urban areas. Using a coupled surface-subsurface model, the interaction between stormwater management and groundwater can be explicitly studied. Data on the scale of individual stormwater control measures and watershed-scale modeling allows evaluation of the effect of site-scale decisions on watershed-level hydrologic functioning.

The specific objectives of the proposed work are to (1) estimate watershed-scale recharge due to distributed, infiltration-based stormwater control measures, (2) assess the effect of spatial pattern of stormwater infiltration on recharge volume at the watershed scale, and (3) estimate flowpaths of groundwater recharged in stormwater control measures. The Eastern Geographic Science Center at the US Geological Survey was chosen as the proposed host institution because of its existing project studying the effects of distributed stormwater management implemented during development, led by Dr. Dianna Hogan, the proposed scientific mentor.

Intellectual Merit

The proposed work will advance our understanding of how developed landscapes function. Modifications due to land use change result in altered hydrologic systems, and subsequent mitigation strategies, such as distributed stormwater management, may transform the water cycle in previously unseen ways. Distributed infiltration of stormwater may result in groundwater recharge above pre-development levels. This means that water that might have evaporated or been transpired by plants in a natural system, or generated stormflow in a conventionally developed urban system, is instead redirected to groundwater pathways. The implications of these potentially major water cycle alterations are as yet unknown but may include significant changes to riparian ecology and biogeochemical cycling in ways that are not well understood. Understanding the effectiveness of these mitigation strategies in replicating natural hydrologic functioning will provide a window into both the drivers of the natural hydrologic system and the landscape changes to which the natural system is most sensitive.

Broader Impacts

The proposed postdoctoral researcher will work with students who will assist with field deployment of sensors, monitoring and processing of data collected by sensors, and preparation of data for input into a hydrologic model. The project will also involve education outreach to high schools in the area of the developed watershed for hands-on presentations about earth science, hydrology, groundwater, and connections to this research project. Last, the proposed work will contribute to the scientific development, training, and mentoring of the postdoctoral researcher.

Impacts of Novel Stormwater Management on Groundwater Recharge

Introduction

Novel forms of urban development aim to engineer systems that replicate natural hydrologic functioning. This includes the preservation of near-natural groundwater recharge through infiltration of stormwater close to impervious surfaces where stormwater is generated. A small watershed in the Piedmont province of Maryland, USA is one of the first instrumented watersheds that was recently developed entirely with novel, distributed stormwater management techniques. Stream baseflow was observed to increase during development, while stormflow as well as stream baseflow of nearby watersheds exhibited no significant changes over the same time period [*Hogan et al.*, in press].

These results indicate the possibility that this infiltration-focused development form has increased groundwater recharge such that it has actually surpassed pre-development recharge. Water that might have evaporated or been transpired by plants in a natural system, or become stormflow in a conventionally developed urban system, may now instead be redirected to groundwater pathways. Recent stormwater management regulations have encouraged distributed stormwater infiltration without fully considering what happens to the resulting groundwater. The implications of these potentially major water cycle alterations are as yet unknown, but may include significant changes to riparian ecology and biogeochemical cycling in ways that are not well understood.

The proposed study seeks to understand how these novel modifications to the natural landscape impact subsurface flow systems and groundwater – surface water interactions. The previously discussed watershed, Tributary 104 in Clarksburg, Maryland, is used as a case study. A network of field observations, including those at the scale of individual stormwater control measures, will inform the application of a three-dimensional, distributed hydrologic model to the watershed. Using a coupled surface-subsurface flow model allows the interaction between stormwater and groundwater to be explicitly studied. The combination of data on the scale of individual stormwater control measures with larger scale modeling allows the evaluation of a development approach focused on small, distributed practices for watershed-level hydrologic functioning.

Background

Urban stormwater management put into place soon after World War II was designed to remove stormwater from developed areas as quickly as possible to prevent flooding. In the 1970s, peak flow reductions became standard using centralized infrastructure, such as detention ponds that delay stormwater discharge to area streams [*NRC*, 2009]. This “conventional stormwater management” however does not reduce stormwater volume or treat small storms, which make up the bulk of stormwater quantity and pollution [*Booth and Jackson*, 1997; *Emerson et al.*, 2005]. Since the aim of conventional stormwater management is peak flow reduction, other alterations of the natural flow regime due to urban development are not mitigated, and resulting impacts on stream quality, geomorphology, and ecology persist [*Poff et al.*, 1997; *Walsh et al.*, 2005]. The impacts of stormwater leading to the deterioration of urban streams, aquatic ecosystems, and downstream receiving water bodies has led regulators to demand new types of stormwater management that achieve more than just urban flood control. For example, cognizant of the EPA Total Maximum Daily Load (TMDL) requirements for drainage to the Chesapeake Bay, the State of Maryland has updated its regulations to require that urban development preserve the stormwater flow characteristics of “woods in good condition” to the maximum extent practicable [*MDE*, 2010] and has required counties to establish a fee to finance updated stormwater management [*Maryland House Bill 987*, 2012].

To address these fundamental concerns with conventional stormwater management, a new strategy for stormwater management aims to engineer a hydrologic system in urban areas that is functionally equivalent to a natural system. This approach may be referred to as Low Impact Development (LID) [*Prince George's County*, 1999], source-control stormwater management [*Hamel et al.*, 2013], Environmental Site Design [*MDE*, 2010], and distributed stormwater management [*Hogan and Loperfido*, 2012]. This strategy, which is referenced below as "distributed stormwater management," is intended to preserve or restore pre-development hydrologic conditions in an urban watershed by retaining and infiltrating stormwater close to its source. Distributing storage and infiltration throughout the watershed, similar to natural conditions, is expected to be more effective in promoting infiltration and avoiding saturation-excess overland flow than if drainage were concentrated in a few centralized stormwater ponds [*McCuen*, 2003]. Distributed stormwater management uses a mix of approaches including minimizing impervious surfaces, increasing time of concentration, reducing soil compaction and erosion during development, public education, as well as the use of stormwater control measures, also called best management practices (BMPs). BMPs used in this approach focus on greater stormwater infiltration (e.g., bioretention basins - also called rain gardens, porous pavement, grassy swales, dry wells), retention (e.g., rain barrels), evapotranspiration (e.g. green roofs), and treatment (e.g., filters, separators, and some of the previously mentioned BMPs).

The effectiveness of distributed stormwater management for water quality and surface flow regimes has been evaluated by a number of researchers on the scale of individual BMPs [*Lindsey et al.*, 1992; *Davis*, 2008; *Wild and Davis*, 2009] and larger watershed or neighborhood scales [*Hogan et al.*, in press; *Holman-Dodds et al.*, 2003; *Perez-Pedini et al.*, 2005; *Williams and Wise*, 2006; *Hood et al.*, 2007; *Dietz and Clausen*, 2008; *Selbig and Bannerman*, 2008; *Bedan and Clausen*, 2009; *Gilroy and McCuen*, 2009]. On the other hand, evaluation of distributed stormwater management in maintaining groundwater recharge has been more limited [*NRC*, 2009].

The effect of distributed stormwater management on groundwater recharge and stream baseflow is important for understanding how to best design urban development to replicate aspects of natural hydrologic functioning. Furthermore, the promotion of infiltration can reduce stormflow quantity and prevent pollutants from discharging directly into streams and, for our study area, eventually the Chesapeake Bay. Infiltration of stormwater allows the filtration and biogeochemical processing of pollutants during subsurface residence time. Groundwater recharge can also maintain stream baseflow, which is important to the survival of aquatic species and connection of the stream with riparian vegetation, which in turn may promote denitrification. There may however be unintended consequences of novel remedies to the urban stream syndrome. Rising water tables could lead to deleterious effects on urban infrastructure such as structural property damage, flooding of underground structures (basements, tunnels, and parking structures), groundwater leakage into wastewater pipes, vegetation damage, and pollutant mobilization [*Göbel et al.*, 2004].

The effect of conventional or distributed stormwater infiltration on groundwater recharge depends on the magnitude of pre-development recharge. In arid areas where groundwater recharge is naturally small outside of mountain snowmelt, recharge can increase by as much as 40 times with distributed stormwater management [*Stephens et al.*, 2012]. Examining more humid areas, researchers have found minor increases in water levels in Boston [*Thomas and Vogel*, 2012] and a simulated increase of up to 5 feet in Long Island, NY [*Ku et al.*, 1992] with conventional stormwater infiltration, as well as no trend in water level with implementation of distributed treatment in a small German basin [*Keßler et al.*, 2012],.

Others have assessed the significance of groundwater mounding from distributed stormwater management, either through basin-scale modeling or using measurements of individual BMPs. *Göbel et al.* [2004] modeled the basin-scale effects of infiltrating all stormwater from impervious areas, and found that it resulted in greater recharge than would occur under natural conditions, and water tables up to 2.3 m higher. *Endreny and Collins* [2009] modeled the effect of spatial arrangement of bioretention basins on groundwater mounding for design storms. They found that the greatest groundwater mounding was related to more centralized spatial arrangements of total bioretention basin area, lower hydraulic conductivity, basins which were at topographic lows, and overlapping mounds. In contrast to the study of *Göbel et al.* [2004], *Endreny and Collins* [2009] found that the mounding was not significant enough (largely < 1 m) to have negative effects on subsurface infrastructure. *Machusick et al.* [2011] measured site-scale changes in water level due to focused runoff into a bioinfiltration basin and found that groundwater mounding was spatially constrained. Different conclusions about the magnitude of groundwater mounding are related to the quantity and spatial pattern of stormwater infiltrated as well as the hydraulic conductivity of the material beneath the BMP site [*Shuster et al.*, 2007; *Endreny and Collins*, 2009; *Carleton*, 2010].

Identification of knowledge gap

Although a primary goal of distributed stormwater management is to maintain near-natural groundwater recharge over the watershed [*Prince George's County*, 1999; *MDE*, 2010], there are no studies that have combined the site-scale approach of evaluating individual stormwater BMPs with the watershed-scale approach of quantifying aggregate effects on groundwater recharge. While the implementation of distributed stormwater management may be very local, the goals for this management approach target watershed-level hydrologic functioning. Therefore, the translation of knowledge about individual BMP infiltration to watershed-scale groundwater recharge is crucial to evaluating distributed stormwater management, but is currently not well understood [*Burns et al.*, 2012; *Hamel et al.*, 2013]. One of the reasons this has not yet been studied extensively is that few of the tools that are used to model BMPs include groundwater interactions [*Elliott and Trowsdale*, 2007; *NRC*, 2009], and with those that do, it is unclear how to translate infiltration as a result of an individual BMP to changes in recharge on a watershed scale [*Hamel et al.*, 2013]. Infiltration from single BMPs cannot simply be summed to derive infiltration at larger spatial scales. The spatial arrangement of BMPs is an important factor, and should be evaluated on longer time scales than it has been previously [*Endreny and Collins*, 2009].

One main motivation in maintaining groundwater recharge is to sustain stream baseflow. This is based on the assumption that infiltrated stormwater follows relatively short, shallow flowpaths, discharging as streamflow within the same watershed. However, this assumption has not been well tested. The relationship between the spatial distribution of infiltration over a watershed and the pathways that infiltrated water takes in entering longer or shorter flow paths is largely unknown [*Hamel et al.*, 2013].

Objectives

The increasing baseflow in Tributary 104 [*Hogan et al.*, in press] led to the hypothesis of this study, that greater recharge due to distributed, infiltration-based stormwater management compared to pre-development conditions has led to a rising water table and increased baseflow. This hypothesis will be tested to assess the effect of distributed stormwater management on watershed-scale recharge. Specific objectives include the following:

(1) Estimate watershed-scale recharge and baseflow due to the aggregated effect of distributed, infiltration-based stormwater Best Management Practices (BMPs) by contrasting with recharge in an urban watershed without stormwater BMPs.

(2) Assess how the difference between centralized and distributed spatial patterns of BMPs affects spatial patterns and total quantity of recharge and baseflow at the watershed scale.
(3) Estimate flowpaths of groundwater recharged in stormwater BMPs and the proportion of infiltrated stormwater contributing to local streamflow vs. regional inter-basin flow.

Study Area

The study focuses on Tributary 104, a 1.11 km^2 watershed northwest of Washington, DC, draining to the stream gage at Little Seneca Creek Tributary near Clarksburg, MD (USGS 01644371). Tributary 104 is a recently developed watershed that has increased in urban land cover from 11% in 1998 to 74% in 2010 [*Hogan et al.*, in press], and now contains 30% impervious surface cover [*J.V. Loperfido*, personal communication, 2013].

Tributary 104 falls within the Clarksburg Special Protection Area (CSPA; Figure 1). This is a designation used by Montgomery County, Maryland to protect high-quality waterways by applying more stringent stormwater management requirements than are mandatory elsewhere. Tributary 104 was entirely developed using distributed stormwater management because of these requirements and its status in a special protection area. As shown in Figure 2, all the stormwater BMPs in Tributary 104 are located in the upland area of the watershed, closer to the source of stormwater, not in or adjacent to the stream channels as is standard with conventional stormwater management [*J.V. Loperfido*, personal communication, 2013]. There are 73 infiltration-based BMPs in Tributary 104, comprised of 35 drywell recharge facilities, 18 storm drain recharge facilities, 13 dry swales, 5 bioretention facilities, and 2 recharge chambers.

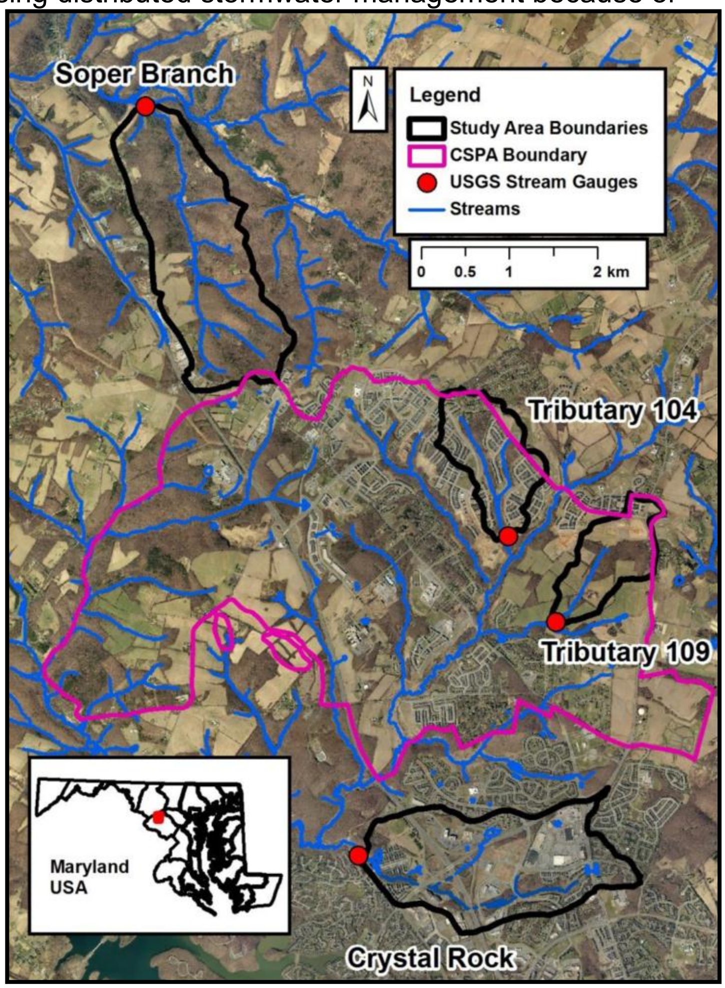


Figure 1. Clarksburg Special Protection Area, gaged watersheds, and stream gage locations in Clarksburg, Maryland. Figure from Hogan et al. [in press].

Tributary 104 is among the only instrumented watersheds in the US that have been completely developed with distributed stormwater management. This type of management is largely implemented elsewhere as piecemeal projects amongst existing conventional stormwater management infrastructure, making the effects on a watershed-scale difficult to evaluate [*Roy et al.*, 2008]. With stormwater management policies shifting towards requiring greater infiltration at the source of urban stormwater, more watersheds will be entirely developed or redeveloped using novel distributed stormwater management techniques. To understand the watershed-scale consequences of these policies, it is ideal to use a case study where contiguous, watershed-scale application of distributed stormwater management has taken place. Tributary 104 provides this unique opportunity. The watershed-scale changes in recharge can be used to inform management of stormwater within the Chesapeake Bay watershed.

Hogan et al. [in press] compared sediment export, water export, topographic change, and biotic health during the development of CSPA watersheds (Tributaries 104 and 109) with a rural watershed (Soper Branch at Hyattstown, MD) and an urban watershed with centralized stormwater management (Little Seneca Creek Tributary near Germantown, MD, also called Crystal Rock) (Figure 1). The Tributary 104 watershed completely converted from agriculture and forest to urban land use during the study period, and underwent profound topographic change with about 80 cm of earth moved for every square meter of watershed between 2004 and 2006 alone [*Hogan et al.*, in press]. *Hogan et al.* found that total streamflow and baseflow increased during development in Tributary 104, but that stormflow did not increase, nor were there significant changes in streamflow in the control watersheds over time (Figure 3). The ability to monitor new urban development as it occurs provides a rare opportunity to test hypotheses about urbanization, a process that is usually studied in hindsight.

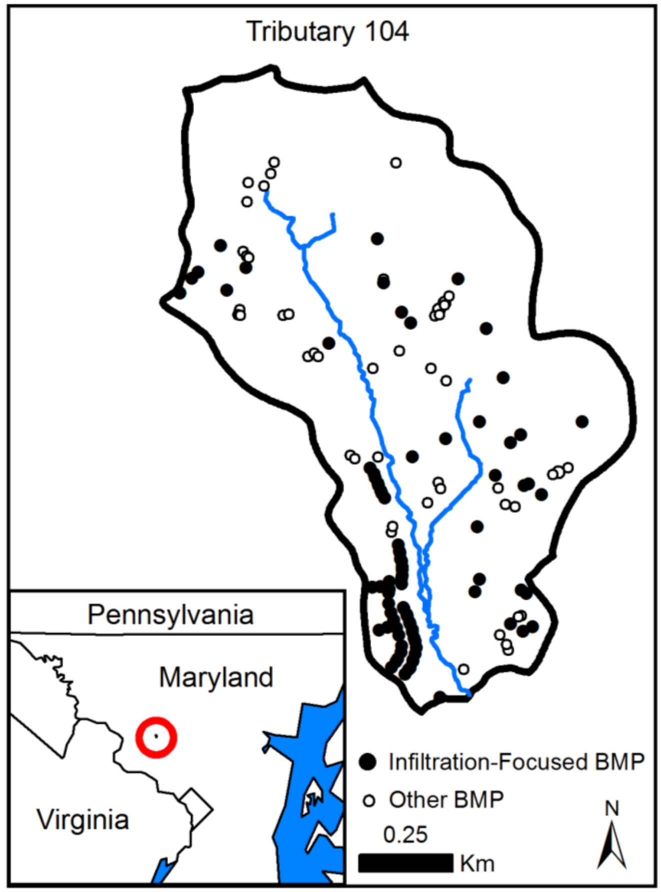
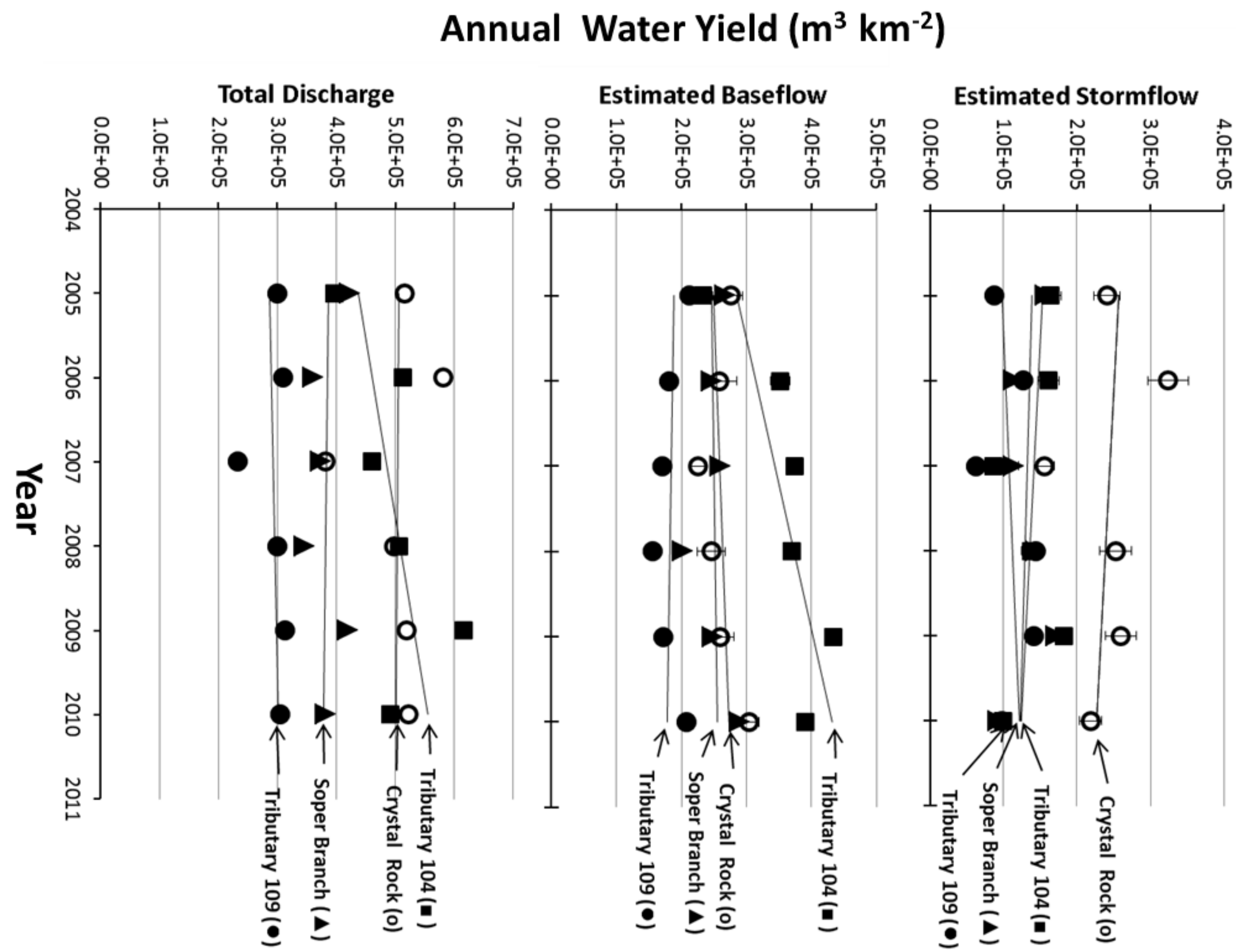


Figure 2. Infiltration-based stormwater BMPs and other stormwater BMPs (primarily retention or water quality focused) in Tributary 104. Figure from J.V. Loperfido [personal communication, 2013].

Through previous monitoring work in the CSPA watersheds, there are a number of existing datasets in or around Tributary 104 that are available for use in the present study. These include fine-scale land cover data, LiDAR topographic data, water quality monitoring data (e.g., nitrate, phosphorus, turbidity, specific conductance, pH), USGS streamflow data, and rain gage data. Partners at Montgomery County Department of Environmental Protection (DEP) have conducted annual benthic macroinvertebrate surveys and collected geomorphologic data. A wealth of data is available on stormwater BMPs in Tributary 104. This includes GIS (Geographic Information Systems) data on stormwater BMP locations, stormwater BMP connectivity and drainage areas, construction drawings, and as-builts. Selected BMP treatment train flow and quality monitoring in the Tributary 104 watershed was conducted in 2012. The extensive work in the CSPA study area has been carried out by a multi-agency partnership including the USGS Eastern Geographic Science Center, EPA, and Montgomery County DEP.



BMPs and instrumented with combined pressure transducers and temperature sensors (Figure 4). These instruments will provide information on water level response to storm events, which can be used to estimate recharge from discrete events [*Healy*, 2010], and hydraulic head for comparison with the model developed (discussed below). Temperature will be recorded and analyzed along with hydraulic head for a number of reasons. When rainfall falls on hot, impervious surfaces, the stormwater temperature can quickly increase [*Galli*, 1990; *Nelson and Palmer*, 2007; *Bhaskar et al.*, 2012b]. The presence of these temperature spikes beneath areas of stormwater infiltration can serve as indicators of recharge from storm events [*Foulquier et al.*, 2009]. Furthermore, vertical water flux can be estimated from propagation of temperature signals into the subsurface [*Anderson*, 2005; *Bhaskar et al.*, 2012b]. Previous researchers have also pointed out the importance of stormwater temperature on the infiltration of that water [*Machusick et al.*, 2011], as the viscosity change can lead to an almost doubling of hydraulic conductivity with warmer water [*Emerson and Traver*, 2008].

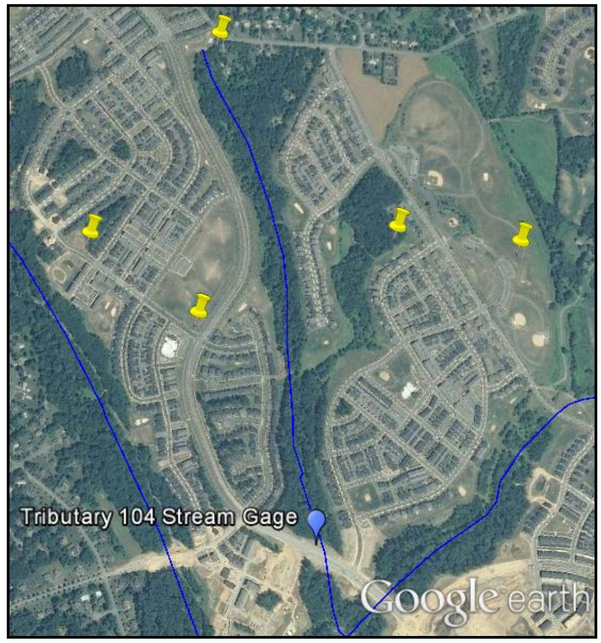


Figure 4. Tributary 104 stream network (dark blue) and proposed well locations in and near Tributary 104 (yellow).

A number of data sources will be used to estimate spatially- and depth-variable hydraulic conductivity. Multiple methods are used because hydraulic conductivity below BMPs is the main determinant for the amount of infiltration which will occur. Pressure transducers measuring inflows into and outflows from individual BMPs will be used to determine infiltration beneath these BMPs during specific rainfall events. *Emerson and Traver* [2008] found that infiltration-based BMPs became quickly saturated after the onset of a rain event. If this is the case in the study watershed, the infiltration rate soon after precipitation begins will be equal to, and can be used to determine, saturated hydraulic conductivity. For comparison with this source of data, infiltration tests with double-ring infiltrometers will be undertaken at BMPs which are at the land surface. Last, slug tests on wells will be used to estimate deeper hydraulic conductivity.

Modeling

The field data collected will be used to inform the development of a hydrologic model of the area surrounding Tributary 104. This study will use ParFlow, and build on experience applying this model to urban watersheds at a variety of scales [*Barnes et al.*, 2012; *Bhaskar et al.*, 2012a]. ParFlow is a three-dimensional, finite-difference, variably-saturated flow model that has been coupled with overland flow [*Ashby and Falgout*, 1996; *Jones and Woodward*, 2001; *Kollet and Maxwell*, 2006; *Maxwell et al.*, 2010]. Unlike previous models that have been used to investigate the effect of stormwater infiltration on groundwater recharge, ParFlow couples surface and subsurface flow by coupling the Richards and kinematic wave equations so that pressure head can be solved throughout the model domain. This makes the model well-suited for the current application in which the interaction between surface and subsurface flow is critical. ParFlow is highly efficient for parallel computing applications [*Kollet et al.*, 2010], allowing for finely gridded models with large numbers of grid cells to be feasibly run.

The model will be initialized using a spin-up procedure in which an initially arbitrarily placed water table is allowed to equilibrate through meteorological and topographic forcing. Meteorological forcing (precipitation and evapotranspiration) from a land surface model will be used, and surface topography based on LiDAR data will be averaged to the model grid resolution. Other properties will remain homogeneous during model initialization. The model will be run using a ten minute time step for a period of two years after initialization. The model will be discretized with a grid resolution of 5 m in the horizontal dimension and 1 m in the vertical dimension, resulting in over 1 million grid cells. Models of this size have been successfully run using parallel computing resources, such as those on XSEDE (Extreme Science and Engineering Discovery Environment). Water levels measured within the study area will be used to define lateral model boundary conditions. Regional flow gradients can be represented in the model with constant flux or constant head boundary conditions.

Following the initialization procedure, hydrogeologic and urban input data will be incorporated, following procedures similar to those outlined in *Bhaskar and Welty* [in review]. Information from field data collection, local and national soil databases, and published literature will be used to define soil, saprolite, and bedrock hydraulic conductivity. Since development in the watershed is largely less than 10 years old, infiltration and inflow of groundwater and stormwater into wastewater pipes and water supply pipe leakage will be assumed to be small. Impervious surfaces will be represented as low hydraulic conductivity values at surface cells.

Topography alone does not define surface flow paths in urban watersheds, as stormwater pipes modify the natural drainage patterns. Stormwater pipes will be represented in the model domain as streams in the surface slope network, since flow in storm drains is not pressurized. This will be done by merging the stream and stormwater pipe GIS layers, and enforcing the locations of this combined drainage network in the slope input dataset [*Barnes et al.*, 2013; *Cole et al.*, 2013]. This method is not intended to physically represent the hydraulics of flow through pipes. Rather, the intent is to represent the flow to stormwater BMPs as the combined input of natural topographic drainage and contributions from the storm drain network.

Infiltration-based stormwater BMPs will be represented as single-cell pits or sinks in the overland flow domain. A sink is a cell which according to its surface slopes has no downstream flow path, so water that enters the cell does not exit. This will allow stormwater entering the BMP to quickly saturate the grid cell, and infiltrate over time (including after the storm has ended) based on the hydraulic conductivity of the soil and underlying materials. All infiltration-based BMPs will be defined in this way. Although the physical expression of infiltration basins and drywells are different, they both are operating with the same fundamental behavior. Namely, they are infiltrating incoming stormwater according to the quantity and rate of input and the quantity and rate of infiltration (which depends primarily on saturation and hydraulic conductivity). The method of including drywells as wells in ParFlow would not be effective because the recharge rate over time would need to be specified before the simulation, whereas in reality recharge is temporally-variable depending on precipitation and hydraulic head conditions. By representing all BMPs as model sinks, drywells are more effectively represented and are included in a similar way to all other BMPs. The last step in model development will be to calibrate Mannings n, as there is no physical analogy to this model parameter which applies to streams as wide as the model gridding (5 m). Measured and modeled water level and streamflow will be compared to evaluate model behavior.

Methods for objective (1): Estimate watershed-scale recharge and baseflow due to the aggregated effect of distributed, infiltration-based stormwater BMPs by contrasting with recharge in an urban watershed without stormwater management BMPs.

To assess the effect of stormwater BMPs on recharge and baseflow, two scenarios will be compared. The first scenario is described above, which includes the infiltration-based stormwater BMPs as sinks in the surface flow domain, allowing no downstream surface flow and just infiltration or surface ponding. Recharge will be calculated in this scenario by water flux moving from above to below the water table at each time step. The recharge and baseflow from this scenario will be compared to the recharge and baseflow from a scenario in which these stormwater BMPs are removed, but all other aspects of urban development are kept intact. This will be achieved by raising the elevation of the stormwater BMP grid cells so that they are no longer sinks in the surface domain. The water that enters these cells as surface flow will then be routed to downhill neighboring cells based on topographic slope. Water that would have entered the stormwater BMPs in the first scenario would now either continue as overland flow or infiltrate (based on saturation and hydraulic conductivity). This would approximate the conditions in a watershed that had directly connected storm drains to streams without features that retain or infiltrate this stormwater. The hypothesis will be tested by comparing the increase in baseflow during development in Tributary 104 with the modeled change in baseflow between the two scenarios due to distributed stormwater management.

Note that in addition to stormwater infiltration, there are many other aspects of urban development that have different and sometimes opposing effects on groundwater recharge and stream baseflow, such as decreased evapotranspiration, leaking water mains, and lawn irrigation [*Bhaskar and Welty*, 2012]. These other features of urban areas that could contribute to increased watershed baseflow are not proposed to be directly investigated here.

Methods for objective (2): Assess how the difference between centralized and distributed spatial patterns of BMPs affects spatial patterns and total quantity of recharge and baseflow at the watershed scale.

The existing distributed spatial arrangement of BMPs in the study watershed will be compared to a hypothetical more centralized arrangement in order to evaluate changes in recharge. To modify the distributed scenario to generate a centralized arrangement, BMPs will be moved along their current surface flow path such that they are all adjacent to the stream. Since the BMPs are now in a more down gradient location, they will be receiving drainage from larger areas. Therefore the number of BMPs will be reduced so that the centralized arrangement has the same amount of impervious surface cover in the area draining to BMPs as the distributed arrangement. This will allow comparison of recharge with an approach that has more concentrated, down gradient, and centralized BMP structures.

Methods for objective (3): Estimate flowpaths of groundwater recharged in stormwater BMPs, and the proportion of infiltrated stormwater contributing to local streamflow vs. regional inter-basin flow.

The watershed model will be used along with forward particle-tracking to determine flowpaths of water infiltrated through stormwater BMPs. The steps that will be used are (1) flow field generation, (2) trace advective streamlines, and (3) calculate residence times, similar to *Atchley et al.* [2013]. Flow field generation is performed using the ParFlow model as described above. A transient flow field during a recession period will then be used by the transport model SLIM-FAST to trace advective streamlines. SLIM-FAST is a variably-saturated subsurface code that uses a random walk method to move solutes represented by particles [*Maxwell*, 2010]. Within the model, conservative, non-reactive particles will be placed at the surface-subsurface interface of the BMP location and forward particle-tracking will be used to define streamlines after a storm. The flux through streamlines that eventually discharges into streams within the gaged watershed will be compared to that through longer, deeper streamlines that intersect the lateral subsurface boundary condition, and exit the basin through inter-basin groundwater flow. Last, estimates of the times that infiltrated stormwater takes to travel these streamlines will be determined using SLIM-FAST [*A. Atchley*, personal communication, 2013; *Kollet and Maxwell*, 2008].

The methods used for the three objectives show three different ways that this surface-subsurface hydrologic model can be used to examine the impact of novel stormwater management on groundwater – surface water interactions. The model could be further used to examine other questions, such as the effect of stormwater management at every parcel, the influence of above- vs. below-ground stormwater management on evapotranspirative losses, or coupling with reactive transport to examine interactions between nutrient inputs to stormwater infrastructure, groundwater travel times, and biogeochemical processing. Advances in these areas will provide insight into the functioning of both natural and altered hydrologic systems and will facilitate more informed protection of our waterways.

Justification for choice of host

The Eastern Geographic Science Center at the US Geological Survey was chosen because of its existing project studying the effects of distributed stormwater management implemented during development in the CSPA. These efforts are led by Dr. Dianna Hogan, the proposed scientific mentor. The current project at the host institution includes analyses of topographic change during development, nutrient concentrations and water quality impacts, economic valuation of distributed vs. centralized stormwater BMPs, and biotic effects of using distributed stormwater management. Evaluation of the efficacy of stormwater BMPs in mitigating the effects of urban development are presented to decision makers in the area. This project has the capability to directly inform development regulation and land use decision making in other nearby watersheds proposed for development (such as Ten Mile Creek near Boyds, MD). Collaborating scientists are J.V. Loperfido (USGS), J. LaBaugh (USGS), B.J. Fleming (USGS), D.K. Jones (USGS), G. Noe (USGS), K. Van Ness (Montgomery County DEP), and S.T. Jarnagin (USEPA).

Broadening participation activities

The USGS research group actively works with high school, undergraduate, and graduate level interns interested in scientific research. Mentoring these students is important for maintaining their interest in science, and helps create pathways that will enable them to move into careers in science. I will continue this effort by working with students who will, for example, assist with field deployment of sensors, monitor and process data collected by sensors, analyze field data, and prepare data for input into a hydrologic model. This will build on my work at UMBC mentoring undergraduate students working on research projects, as well as my involvement with groups on campus which seek to broaden participation of underrepresented groups in STEM fields. My activities working with students will be extended to the Clarksburg area, where I will reach out to Clarksburg High School and other area schools for hands-on classroom presentations about earth science, hydrology, groundwater, and connections to the research project described here.

Plan of work

The activities discussed will be achieved over a period of 24 months as outlined below.

Activity	**Q1**	**Q2**	**Q3**	**Q4**	**Q5**	**Q6**	**Q7**	**Q8**
Field data collection and analysis	■	■	■	■	■	■	■	
Model development		■	■	■	■			
Objective 1					■	■		
Objective 2					■	■		
Objective 3						■	■	
Project write-up and presentation							■	■
Broadening participation activities	■	■	■	■	■	■	■	■

References Cited

Anderson, M. P. (2005), Heat as a Ground Water Tracer, *Ground Water*, *43*(6), 951–968, doi:10.1111/j.1745-6584.2005.00052.x.

Ashby, S. F., and R. D. Falgout (1996), A Parallel Multigrid Preconditioned Conjugate Gradient Algorithm for Groundwater Flow Simulations, *Nuclear Science and Engineering*, *124*, 145–159.

Atchley, A. L., R. M. Maxwell, and A. K. Navarre-Sitchler (2013), Using streamlines to simulate stochastic reactive transport in heterogeneous aquifers: Kinetic metal release and transport in CO2 impacted drinking water aquifers, *Advances in Water Resources*, *52*, 93–106, doi:10.1016/j.advwatres.2012.09.005.

Barnes, M., J. Cole, A. J. Miller, and C. Welty (2013), Effects of incorporating the urban stormwater drainage system in an integrated groundwater-surface water model, 2013 CUAHSI Conference on Hydroinformatics and Modeling, July 17-19, 2013, Logan UT.

Barnes, M. C., C. Welty, and A. J. Miller (2012), Distributed Modeling with Parflow using High Resolution LIDAR Data, in *Abstract H51J-1489. Fall 2012 Meeting of the American Geophysical Union, December 3-7, 2012, San Francisco, CA.*

Bedan, E. S., and J. C. Clausen (2009), Stormwater Runoff Quality and Quantity From Traditional and Low Impact Development Watersheds, *Journal of the American Water Resources Association*, *45*(4), 998–1008, doi:10.1111/j.1752-1688.2009.00342.x.

Bhaskar, A. S., and C. Welty (in review), Synthesis of disparate data sets for distributed modeling of urban groundwater systems, *Hydrogeology Journal*, *submitted 1 May 2013*.

Bhaskar, A. S., and C. Welty (2012), Water Balances Along an Urban-to-Rural Gradient of Metropolitan Baltimore, 2001–2009, *Environmental & Engineering Geoscience*, *18*(1), 37–50, doi:10.2113/gseegeosci.18.1.37.

Bhaskar, A. S., C. Welty, and R. M. Maxwell (2012a), Integration of Urban Features into a Coupled Groundwater-Surface Water Model, in *Abstract H54F-03. Fall 2012 Meeting of the American Geophysical Union, December 3-7, 2012, San Francisco, CA.*

Bhaskar, A. S., J. W. Harvey, and E. J. Henry (2012b), Resolving hyporheic and groundwater components of streambed water flux using heat as a tracer, *Water Resources Research*, *48*(8), doi:10.1029/2011WR011784.

Booth, D. B., and C. R. Jackson (1997), Urbanization of Aquatic Systems: Degradation Thresholds, Stormwater Detection, and the Limits of Mitigation, *JAWRA Journal of the American Water Resources Association*, *33*(5), 1077–1090, doi:10.1111/j.1752-1688.1997.tb04126.x.

Burns, M. J., T. D. Fletcher, C. J. Walsh, A. R. Ladson, and B. E. Hatt (2012), Hydrologic shortcomings of conventional urban stormwater management and opportunities for reform, *Landscape and Urban Planning*, *105*(3), 230–240, doi:10.1016/j.landurbplan.2011.12.012.

Carleton, G. B. (2010), *Simulation of Groundwater Mounding Beneath Hypothetical Stormwater Infiltration Basins*, U.S. Geological Survey Scientific Investigations Report 2010-5102.

Cole, J., M. Barnes, C. Welty, and A. J. Miller (2013), A data preparation technique for integrating stormwater pipes into DEMs for use in hydrologic models. 2013 CUAHSI Conference on Hydroinformatics and Modeling, 2013 CUAHSI Conference on Hydroinformatics and Modeling, July 17-19, 2013, Logan UT.

Davis, A. (2008), Field Performance of Bioretention: Hydrology Impacts, *Journal of Hydrologic Engineering*, *13*(2), 90–95, doi:10.1061/(ASCE)1084-0699(2008)13:2(90).

Dietz, M. E., and J. C. Clausen (2008), Stormwater runoff and export changes with development in a traditional and low impact subdivision, *Journal of Environmental Management*, *87*(4), 560–566, doi:10.1016/j.jenvman.2007.03.026.

Elliott, A. H., and S. A. Trowsdale (2007), A review of models for low impact urban stormwater drainage, *Environmental Modelling & Software*, *22*(3), 394–405, doi:10.1016/j.envsoft.2005.12.005.

Emerson, C. H., and R. G. Traver (2008), Multiyear and Seasonal Variation of Infiltration from Storm-Water Best Management Practices, *Journal of Irrigation and Drainage Engineering*, *134*(5), 598–605, doi:10.1061/(ASCE)0733-9437(2008)134:5(598).

Emerson, C. H., C. Welty, and R. G. Traver (2005), Watershed-Scale Evaluation of a System of Storm Water Detention Basins, *J. Hydrologic Engrg.*, *10*(3), 237, doi:10.1061/(ASCE)1084-0699(2005)10:3(237).

Endreny, T., and V. Collins (2009), Implications of bioretention basin spatial arrangements on stormwater recharge and groundwater mounding, *Ecological Engineering*, *35*(5), 670–677, doi:10.1016/j.ecoleng.2008.10.017.

Foulquier, A., F. Malard, S. Barraud, and J. Gibert (2009), Thermal influence of urban groundwater recharge from stormwater infiltration basins, *Hydrol. Process.*, *23*(12), 1701–1713, doi:10.1002/hyp.7305.

Galli, J. (1990), *Thermal Impacts Associated With Urbanization and Stormwater Management Best Management Practices*, Metropolitan Washington Council of Governments for the Sediment and Stormwater Administration of the Maryland Department of the Environment, Washington D.C.

Gilroy, K. L., and R. H. McCuen (2009), Spatio-temporal effects of low impact development practices, *Journal of Hydrology*, *367*(3–4), 228–236, doi:10.1016/j.jhydrol.2009.01.008.

Göbel, P. et al. (2004), Near-natural stormwater management and its effects on the water budget and groundwater surface in urban areas taking account of the hydrogeological conditions, *Journal of Hydrology*, *299*(3-4), 267–283.

Hamel, P., E. Daly, and T. D. Fletcher (2013), Source-control stormwater management for mitigating the impacts of urbanisation on baseflow: A review, *Journal of Hydrology*, *485*, 201–211, doi:10.1016/j.jhydrol.2013.01.001.

Healy, R. W. (2010), *Estimating Groundwater Recharge*, 1st ed., Cambridge University Press.

Hogan, D., T. Jarnagin, J. Loperfido, and K. Van Ness (in press), Mitigating the Effects of Landscape Development on Streams in Urbanizing Watersheds, *Journal of the American Water Resources Association*.

Hogan, D. M., and J. V. Loperfido (2012), *Effects of Urban Stormwater-Management Strategies on Stream-Water Quantity and Quality*, U.S. Geological Survey Fact Sheet 2012-3079.

Holman-Dodds, J. K., A. A. Bradley, and K. W. Potter (2003), Evaluation of Hydrologic Benefits of Infiltration Based Urban Storm Water Management, *Journal of the American Water Resources Association*, *39*(1), 205–215, doi:10.1111/j.1752-1688.2003.tb01572.x.

Hood, M. J., J. C. Clausen, and G. S. Warner (2007), Comparison of Stormwater Lag Times for Low Impact and Traditional Residential Development, *Journal of the American Water Resources Association*, *43*(4), 1036–1046, doi:10.1111/j.1752-1688.2007.00085.x.

Jones, J. E., and C. S. Woodward (2001), Newton-Krylov-multigrid solvers for large-scale, highly heterogeneous, variably saturated flow problems, *Advances in Water Resources*, *24*(7), 763–774, doi:16/S0309-1708(00)00075-0.

Keßler, S., B. Meyer, S. Seeling, E. Tressel, and A. Krein (2012), Influence of Near-to-Nature Stormwater Management on the Local Water Balance Using the Example of an Urban Development Area, *Water Environment Research*, *84*(5), 441–451, doi:10.2175/106143012X13347678384729.

Kollet, S. J., and R. M. Maxwell (2006), Integrated surface-groundwater flow modeling: A free-surface overland flow boundary condition in a parallel groundwater flow model, *Advances in Water Resources*, *29*(7), 945–958, doi:16/j.advwatres.2005.08.006.

Kollet, S. J., and R. M. Maxwell (2008), Demonstrating fractal scaling of baseflow residence time distributions using a fully- coupled groundwater and land surface model, *Geophysical Research Letters*, *35*(7), L07402.

Kollet, S. J., R. M. Maxwell, C. S. Woodward, S. Smith, J. Vanderborght, H. Vereecken, and C. Simmer (2010), Proof of concept of regional scale hydrologic simulations at hydrologic resolution utilizing massively parallel computer resources, *Water Resources Research*, *46*(4), doi:10.1029/2009WR008730.

Ku, H. F. H., N. W. Hagelin, and H. T. Buxton (1992), Effects of Urban Storm-Runoff Control on Ground-Water Recharge in Nassau County, New York, *Ground Water*, *30*(4), 507–514, doi:10.1111/j.1745-6584.1992.tb01526.x.

Lindsey, G., L. Roberts, and W. Page (1992), Inspection and maintenance of infiltration facilities, *Journal of Soil and Water Conservation*, *47*(6), 481–486.

Machusick, M., A. Welker, and R. Traver (2011), Groundwater Mounding at a Storm-Water Infiltration BMP, *Journal of Irrigation and Drainage Engineering*, *137*(3), 154–160, doi:10.1061/(ASCE)IR.1943-4774.0000184.

Maxwell, R. M. (2010), *SLIM-FAST: A User's Manual V.4*, International Groundwater Modeling Center GWMI 2010-01.

Maxwell, R. M., S. J. Kollet, S. G. Smith, C. S. Woodward, R. D. Falgout, I. M. Ferguson, C. Baldwin, W. J. Bosl, R. Hornung, and S. Ashby (2010), *ParFlow User's Manual*, International Ground Water Modeling Center Report, GWMI 2010-01.

McCuen, R. (2003), Smart Growth: Hydrologic Perspective, *Journal of Professional Issues in Engineering Education and Practice*, *129*(3), 151–154, doi:10.1061/(ASCE)1052-3928(2003)129:3(151).

MDE (2010), *Stormwater Management Guidelines for State & Federal Projects*, Maryland Department of the Environment, Baltimore, MD. [online] Available from: http://www.mde.state.md.us/assets/document/State%20and%20Federal%20SWM%20Guidelines%20final.pdf

Nelson, K. C., and M. A. Palmer (2007), Stream Temperature Surges Under Urbanization and Climate Change: Data, Models, and Responses, *Journal of the American Water Resources Association*, *43*(2), 440–452.

NRC (2009), *Urban Stormwater Management in the United States*, Committee on Reducing Stormwater Discharge Contributions to Water Pollution, National Research Council, The National Academies Press, Washington, D.C.

Perez-Pedini, C., J. Limbrunner, and R. Vogel (2005), Optimal Location of Infiltration-Based Best Management Practices for Storm Water Management, *Journal of Water Resources Planning and Management*, *131*(6), 441–448, doi:10.1061/(ASCE)0733-9496(2005)131:6(441).

Poff, N. L., J. D. Allan, M. B. Bain, J. R. Karr, K. L. Prestegaard, B. D. Richter, R. E. Sparks, and J. C. Stromberg (1997), The Natural Flow Regime, *BioScience*, *47*(11), 769–784, doi:10.2307/1313099.

Prince George's County (1999), *Low-Impact Development Hydrologic Analysis*. [online] Available from: http://water.epa.gov/polwaste/green/upload/lidnatl.pdf

Roy, A. H., S. J. Wenger, T. D. Fletcher, C. J. Walsh, A. R. Ladson, W. D. Shuster, H. W. Thurston, and R. R. Brown (2008), Impediments and Solutions to Sustainable, Watershed-Scale Urban Stormwater Management: Lessons from Australia and the United States, *Environmental Management*, *42*(2), 344–359, doi:10.1007/s00267-008-9119-1.

Selbig, W. R., and R. T. Bannerman (2008), *A Comparison of Runoff Quantity and Quality from Two Small Basins Undergoing Implementation of Conventional and Low-Impact-Development (LID) Strategies: Cross Plains, Wisconsin, Water Years 1999-2005*, U.S. Geological Survey Scientific Investigations Report 2008-5008.

Shuster, W. D., R. Gehring, and J. Gerken (2007), Prospects for enhanced groundwater recharge via infltration of urban storm water runoff: A case study, *Journal of Soil and Water Conservation*, *62*(3), 129–137.

Stephens, D. B., M. Miller, S. J. Moore, T. Umstot, and D. J. Salvato (2012), Decentralized Groundwater Recharge Systems Using Roofwater and Stormwater Runoff, *Journal of the American Water Resources Association*, *48*(1), 134–144, doi:10.1111/j.1752-1688.2011.00600.x.

Thomas, B. F., and R. M. Vogel (2012), Impact of Storm Water Recharge Practices on Boston Groundwater Elevations, *Journal of Hydrologic Engineering*, *17*(8), 923–932, doi:10.1061/(ASCE)HE.1943-5584.0000534.

Walsh, C. J., A. H. Roy, J. W. Feminella, P. D. Cottingham, P. M. Groffman, and R. P. Morgan II (2005), The urban stream syndrome: current knowledge and the search for a cure, *Journal of the North American Benthological Society*, *24*(3), 706–723.

Wild, T., and A. Davis (2009), Simulation of the Performance of a Storm-Water BMP, *Journal of Environmental Engineering*, *135*(12), 1257–1267, doi:10.1061/(ASCE)EE.1943-7870.0000106.

Williams, E. S., and W. R. Wise (2006), Hydrologic Impacts of Alternative Approaches to Storm Water Management and Land Development, *Journal of the American Water Resources Association*, *42*(2), 443–455, doi:10.1111/j.1752-1688.2006.tb03849.x.

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(i) Professional Preparation

Brown University; Environmental Geology-Physics/Math; Sc.B. 2008

Senior thesis title: *Land Cover Variability and Water Resources in Spring Valley, Nevada*

UMBC; Environmental Engineering; Ph.D. expected December 2013

Proposed dissertation title: *Effects of Urbanization on Groundwater Flow Systems and Streamflow Generation*

(ii) Appointments

2008 - present	Graduate Research Assistant, Department of Chemical, Biochemical, and Environmental Engineering, University of Maryland, Baltimore County
2008 - 2010	Integrative Graduate Education and Research Traineeship (NSF IGERT) Fellow at UMBC in the Water in the Urban Environment program, Center for Urban Environmental Research and Education
2010 - 2010	Summer Intern, S.S. Papadopulos and Associates, Water Resource and Environmental Consultants, Bethesda, MD
2006 - 2006	Summer Researcher in Research Experience for Undergraduates (REU) Environmental Fluids Program, Department of Civil, Environmental and Architectural Engineering, University of Colorado-Boulder
2005 - 2005	Summer Researcher in Research Experience for Undergraduates (REU) Carnegie Institution of Washington, Department of Terrestrial Magnetism

(iii) Products

(a) Five Related Products

1. Bhaskar, A.S. and C. Welty. 2012. Water Balances Along an Urban-to-Rural Gradient of Metropolitan Baltimore, 2001–2009, Environmental & Engineering Geoscience, 18(1), doi:10.2113/gseegeosci.18.1.37.
2. Bhaskar, A.S. and C. Welty. Submitted on 1 May 2013. Synthesis of disparate data sets for distributed modeling of urban groundwater systems, Hydrogeology Journal.
3. Bhaskar, A.S., J.W. Harvey, and E.J. Henry. 2012. Resolving hyporheic and groundwater components of streambed water flux using heat as a tracer, Water Resources Research, 48, W08524, doi: 10.1029/2011WR011784.
4. Bhaskar, A.S. 2010. Getting Started with ParFlow: Dead Run, Baltimore, Maryland Example. UMBC/CUERE Technical Report 2010/002. University of Maryland Baltimore

County, Center for Urban Environmental Research and Education, Baltimore, MD, http://www.umbc.edu/cuere/BaltimoreWTB/modeling.html.

5. Neupauer, R. M., J. L. Wilson, and A.S. Bhaskar. 2009. Forward and backward temporal probability distributions of sorbing solutes in groundwater, Water Resources Research, 45, W01420, doi:10.1029/2008WR007058.

(iv) Synergistic Activities

1. UMBC Graduate students in Environmental Engineering (GEE), President and Founder, 2010 – 2012.
2. Guest scientist lecturer to high school and middle school science teachers, Baltimore Ecosystem Study Math-Science Partnership, 2012.
3. UMBC Women in Science and Engineering Graduate Association (WISE), Secretary and Webmaster, 2009 – 2011.
4. Reviewer for Hydrological Processes and National Science Foundation Hydrologic Sciences.
5. Membership in American Geophysical Union, Geological Society of America, and the Association of Environmental Engineering and Science Professors.

(v) Collaborators and Other Affiliations

(a) Collaborators within the Past 48 Months

Barnes ML (UMBC); Harvey, JW (USGS); Henry, EJ (UNC Wilmington); Maxwell, RM (Colorado School of Mines)

(b) Graduate and Post-Doctoral Advisors

Ph.D. – Welty C (UMBC)

(c)Thesis Advisor and Postgraduate-Scholar Sponsor

None

(vi) Other required information

Citizenship: USA.