PROJECT DESCRIPTION

1. Introduction

The goal of this proposal is to contribute to the design of CUAHSI/CLEANER environmental field observatories by establishing a methodology to quantify flowpaths, fluxes, and stores of groundwater in urban areas. While certain aspects of interactions between the built environment and the hydrologic cycle have received a great deal of attention in an applied sense (stormwater management, sanitary engineering), there have been few efforts that have taken a comprehensive approach to evaluate how urban infrastructure affects groundwater on a watershed scale. Quantifying urban groundwater addresses both CUAHSI and CLEANER science goals because evaluation requires hydrologic analysis as well as knowledge of engineered water, wastewater, and stormwater systems. Urban infrastructure is not included in the current CUAHSI HIS (Hydrologic Information Systems) framework and this project will also identify relevant components needed to build this capability.

Example research questions that require an understanding of urban groundwater include:

- How does the built environment affect groundwater recharge and storage and how does this in turn affect groundwater discharge into streams?
- How does the subsurface infrastructure (i.e. sanitary sewers, municipal water supply, and storm sewers) affect flowpaths and fluxes of groundwater?
- How does quantification of urban groundwater fluxes and flowpaths improve our ability to estimate nutrient export from urban watersheds?
- How does an improved understanding of urban groundwater affect our ability to close the urban water budget at multiple scales?

From a broader impacts perspective,

- How can knowledge gained be utilized to improve planning for environmental restoration, e.g., stormwater management, sewer rehabilitation, and low impact development?

The objective of the current proposal is not to answer all of the relevant research questions; rather, we intend to develop a set of tools to address these questions that can be used by environmental observatories containing an urban component. It is to be expected that an iterative process will be required in solving the significant scientific and technical challenges posed by the interaction of groundwater with the built environment. This project will attempt to determine how close we can come to a satisfactory solution with existing resources, and our approach will be to identify key gaps in understanding, to target limited resources toward filling those gaps, and to identify what additional resources would be needed to resolve issues that cannot be handled within existing budget constraints.

We propose to use field sites in Baltimore as a test bed because extensive instrumentation is already in place that can be utilized for the proposed project. Baltimore is an ideal test site because it is already a part of LTER, NEON (planning), CLEANER (planning) and proposed CUAHSI field observatories; methodology developed from the proposed effort will be transferable to other urban areas both in the region and in other parts of the US and the world. Elements of the proposed work include synoptic field surveys, remote sensing, numerical modeling, data mining and visualization tools. We will: (1) compare base flow behavior from stream gauges in a nested set of watersheds at four different spatial scales from 0.8 to 170 km^2, with diverse patterns of impervious cover and urban infrastructure; (2) conduct a synoptic survey of well water levels to characterize the regional water table; (3) use airborne thermal infrared imagery to identify locations of groundwater seepage into streams across a range of urban development patterns; (4) use seepage transects and tracer tests to quantify the spatial pattern of groundwater fluxes to the drainage network in selected subwatersheds; (5) develop a mass balance for precipitation over a 170 km^2 area on a 1x1 km^2 grid using recording rain gages for bias correction of weather radar products; (5) calculate urban evapotranspiration using the Penman-Monteith method compared with results from an eddy correlation station; (7) use numerical groundwater model in a screening mode to estimate depth of groundwater contributing surface water flow; (8) mine data from public agency records of potable water and wastewater flows to estimate leakage rates and flowpaths in relation to streamflow and groundwater fluxes; and (9) evaluate the CUAHSI Hydrologic Information Systems data modeling tools for application to urban environments.

2. Background

2.1 The urban hydrologic cycle and hydrologic budget

Precipitation, evaporation, transpiration, infiltration, runoff, streamflow, and groundwater flow are the main components of the hydrologic cycle; discussion of the hydrologic cycle is typically illustrated by a sketch of the natural landscape showing cycles and subcycles of water flow. The importance of urban hydrology is generally acknowledged by showing how the percent impervious area affects the shape of the storm hydrograph, but the cumulative impact of infrastructure (buildings, roads, parking lots, culverts, storm drains, detention ponds, leaking water supply and wastewater pipe networks) on the hydrologic cycle is poorly understood. Among the components of the urban hydrologic cycle, groundwater is of key importance, yet it has received little attention from hydrologists in the U.S. in situations where groundwater is not used for water supply directly. Given that the majority of the nation’s and world’s population lives in urban areas and is dependent on the complete hydrologic cycle for water supply, understanding of the impacts of urbanization on the hydrologic cycle and on groundwater in particular should be better integrated into the study of this science. From the engineering perspective, urban water has been historically addressed in terms of designing facilities for water supply, wastewater treatment, and stormwater management, but the approach has focused on mitigation of specific engineering problems, not on understanding and planning for the integrated functioning of the natural and built environment.

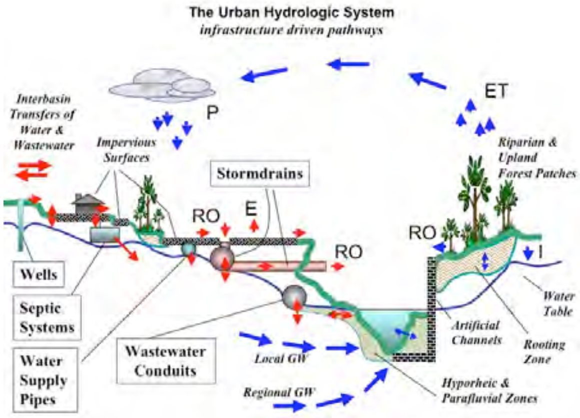

Figure 1. The urban hydrologic cycle.

Figure 1 depicts the elements of the urban water cycle. The blue arrows connect components of the natural system; red arrows indicate components that are added by the urban infrastructure and water management practices, including:

- water leaking from pressurized distribution pipes into the subsurface;
- infiltration and inflow into and exfiltration/overflows from both sanitary sewer lines and stormwater pipes;
- septic system discharge to groundwater;
- water routed through constructed stormwater ponds and basins;
- water supply importation from or export to neighboring basins;
- wastewater import from or export to neighboring basins
- point-source discharges to rivers from industrial operations;
- effects of impervious surfaces and hardened landscapes (turf, compacted soil, concrete stream channels) on runoff;
- influence of home gardening practices (lawn watering) on groundwater levels and base flow to streams in summer;
- influence of downcutting of urban stream channels on groundwater levels;
- interaction between urban vegetation and evapotranspiration processes; and
- groundwater withdrawals for water supply
- preferential flow paths created by subsurface infrastructure

The figure and the above list illustrate that many of the pathways associated with the built environment traverse the subsurface. Urban aquifers are therefore not only natural reservoirs but also media through which piped water flows. All pathways and exchanges that affect the mass balance on the watershed cannot be fully understood without baseline information on groundwater.

A water budget can be calculated for any time increment Δt for a chosen control volume. If an annual water budget is computed beginning and ending in winter when the soil moisture is at field capacity, the change in soil moisture is zero and does not need to be included. A control volume of interest can be defined laterally by chosen watershed boundaries and vertically from the top elevation of buildings to bedrock. An example water budget for such a control volume and annual period is given as

$$P + I - S - G - W - ET = \Delta S \quad (1)$$

where P = precipitation [L]; I = net water imported to the basin by potable water distribution systems $[L^3/L^2]$; S = streamflow $[L^3/L^2]$; G = groundwater withdrawal from wells that is removed from the basin $[L^3/L^2]$; W = net wastewater export from the basin $[L^3/L^2]$; ΔS = change in groundwater storage [L]; and ET = evapotranspiration [L], where L^2 is the watershed area and the time period evaluated must be the same for all terms The annual change in groundwater storage is determined by multiplying the change in average well water levels over the year by specific yield. All terms can be measured except for ET which can be solved for as an unknown or modeled. Closing the water budget would imply that this would be a modeled term determined independently.

While closing the urban water budget provides estimates of total volumes or stores of water, this calculation does not address fluxes or flowpaths, which are both critical to understanding the exchanges of groundwater and associated contaminants with the atmosphere, streams, and piped flow.

2.2 Relation to ongoing work in Baltimore

Urban watersheds in the Baltimore area are some of the most densely instrumented in the world, stemming back to early work at Johns Hopkins University gaging storm sewers and quantifying water use (Lentz, 1963; Geyer and Lentz, 1966) and studies under the auspices of the EPA Nationwide Urban Runoff Program in the early 1980s (US EPA, 1983; Martin, 1986). More recent work includes stormwater and water resources investigations by local governments (e.g., Baltimore City DPW 1999, 2001; Baltimore County DEPRM, 2000), research in affiliation with the NSF-funded Baltimore Ecosystem Study (BES, http://www.beslter.org), and mandated monitoring under EPA consent decrees totaling almost 2 billion dollars with Baltimore City and County related to addressing sanitary sewer overflow problems. Field studies of hydrologic response in the Baltimore metropolitan region have been carried out as a contribution to BES.

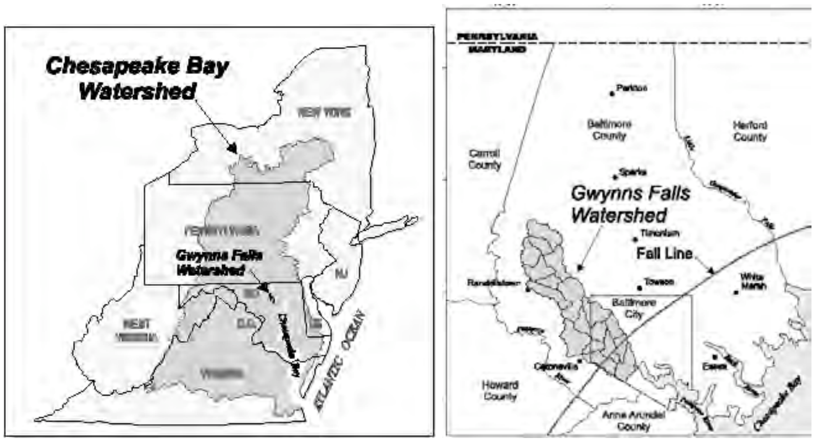

Figure 2. Location of the Gwynns Falls Watershed (Doheny,1999).

The primary are area of study is the Gwynns Falls watershed, a 171-sq km basin (Figures 2, 3) that lies within the Patapsco drainage to the Chesapeake Bay. The watershed was selected as an urban ecological study site because it is characterized by a gradient of urbanization stretching from downtown Baltimore to suburban development and a few small remnant agricultural areas at the headwaters. Baisman Run, a forested subwatershed (in the adjacent Gunpowder River drainage, which is the main water supply of the Baltimore Metropolitan region; see Figure 3) serves as a control. The field headquarters of the BES and affiliated USDA Forest Service personnel are housed on UMBC's campus, situated just outside the watershed boundary in Catonsville, MD. Additional NSF-funded field studies of urban flood response to storm events have been conducted by Miller and Smith in tributaries of Gwynns Falls during 2003-2005 (Nelson et al., 2005; Smith et al., 2005a, b).

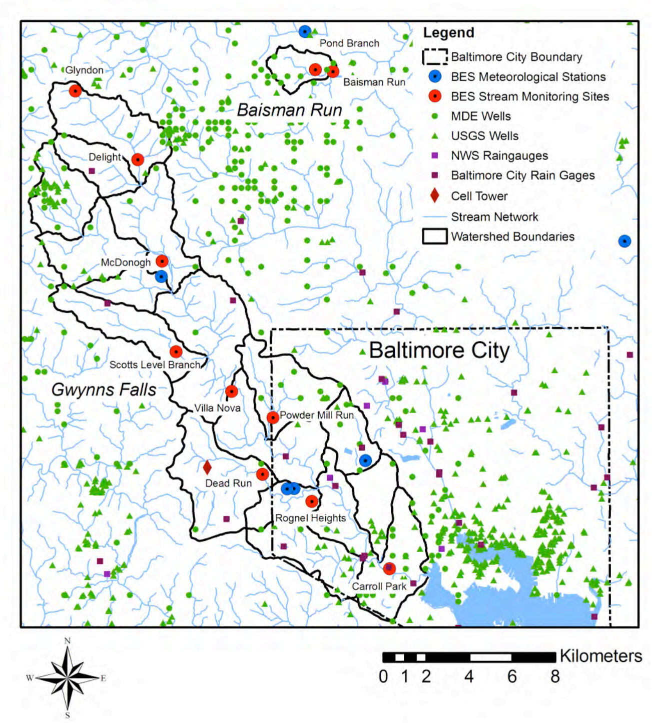

Figure 3. Streamflow, meteorological stations, and wells in the Gwynns Falls watershed. 30,000 additional Baltimore County wells are available in a data base that needs to be mined to determine additional well locations.

Conventional wisdom in urban hydrology suggests that increased impervious area leads to reductions in groundwater recharge and reduced base flow in streams (Paul and Meyer, 2001; McBride, 2001; Smakhtin, 2000; Barringer et al., 1994; Ferguson and Suckling, 1990; Simmons and Reynolds, 1982; Klein, 1979; Leopold, 1968). However observed patterns are sometimes more complex (Tripathy, 2005); there is reason to believe that leakage of imported water from public water mains, sanitary sewers and septic tanks may actually enhance groundwater recharge and increase baseflow in some urban watersheds (Lerner, 2003; Trowsdale and Lerner, 2003; Meyer, 2002; Paul and Meyer, 2001; Hirsch et al., 1990). Rose and Peters (2001) found in Atlanta that baseflow recession constants were 35-40% lower in an urban watershed than a non-urban one in summer, which was a possible indication that lower ET in the urban areas was resulting in less groundwater being removed from storage. On the other hand, there can be reaches where appreciable quantities of streamwater enter sewer interceptors, causing backwater and leakage upgradient. Multi-decade trends in summer base flow discharge in the Dead Run subwatershed of the Gwynns Falls (Figures 3 and 4) suggest a period of increasing base flow that may be attributable to leaking infrastructure (Nelson et al., 2005). Anecdotal observations of perennial dry-weather flow in some storm drains in Baltimore City may also be attributable to leaking infrastructure. Results from the City's dry weather outfall sampling program in 1994 (part of illicit discharge detection efforts) revealed that only 12 out of a total of 103 stormwater outfalls along city streams were without baseflow and that 25 % of these had flows in excess of 0.2 cfs (6 lps) (Baltimore City DPW 1995.) The median fecal coliform concentration for these flows was 1,100 org/100 ml (n = 85) and the mean concentration of fluoride was 0.52 mg/l (n = 84). Background fluoride levels were close to zero and a typical concentration for treated water (to which fluoride is added) was ca. 0.9 mg/l) indicating that contributions of potable water and/or wastewater were significant.

2.3 Relation to other work

Comprehensive field studies of the urban water budget are few. Grimmond et al (1986) and Grimmond and Oke (1986) focused on quantifying the relationship between lawn-watering practices and evapotranspiration in a 21-hectare area in Vancouver. The control volume selected did not include the saturated subsurface, nor did it attempt to address infrastructure leakage, and the study area was explicitly selected because it was devoid of streams. A major effort jointly sponsored by the European Union and Australia has recently been undertaken entitled "Assessing and Improving the Sustainability of Urban Water Resources and Systems" (AISUWRS, http://www.urbanwater.de). This effort has as a goal to develop fully coupled flow and transport models of the unsaturated and saturated subsurface and piped flow to track sources, sinks, flowpaths, and fluxes of contaminants.

As part of this effort, Mitchell et al. (2001) have set forth a water balance approach to account for inflows and outflows of all piped water (stormwater, wastewater, potable water) at the watershed scale to document the potential for harvesting stormwater and wastewater as a potential resource; in further development a contaminant tracking capability has been added to this model (Mitchell et al, 2005). Horn (2000) describes a methodology using publicly available data to develop a water budget including basin use and interbasin transfer of water and wastewater. Sharp et al. (2003) argue that the effects of urban infrastructure on the shallow subsurface are similar to the effects of karstification and provide detailed simulations of the movement of water around pipes modeled as preferred flow channels. Paulachok and Wood (1984) took advantage of the opportunity to open hundreds of old wells in Philadelphia to create a water table map; this shows the highly variable nature of the water table under the city.

2.4 Regional Setting

The Baltimore metropolitan region straddles the fall zone, where the Piedmont Plateau meets the Atlantic Coastal Plain. The Fall Zone is a region of locally steepened stream gradients marking the transition from the rolling upland of the Piedmont to the tidewater areas of the coastal plain and is aligned parallel to the Atlantic coast, across which major cities in the US were settled in colonial times to take advantage of abundant waterfalls for hydropower and milling operations at locations near the limits of navigation. Trenton NJ, Philadelphia, Baltimore, Washington DC, Richmond VA, Raleigh NC, and Augusta GA are examples of cities that were developed on sites traversing the Fall Zone. Insights from hydrogeological investigations of the Baltimore region are therefore transferable to other major east-coast urban environments.

The behavior of urban groundwater is generally not well documented, and this is certainly true for the Baltimore area. In the Piedmont and fall zone, groundwater flows through unconsolidated saprolite (weathered bedrock) and alluvium and fractured bedrock. The saprolite has a high porosity (20-30%); the porosity of the fractured rock is 0.01 - 2%. The unconsolidated and fractured formations can be considered separate but interconnected flow systems (Greene et al., 2004). Due to its high porosity and storage characteristics, the unconsolidated system is not very responsive to recharge. It feeds the underlying low-porosity fractured bedrock, which owing to its low porosity is extremely responsive to recharge, resulting in significant changes to water levels in wells. The thickness of the saprolite is highly variable and sometimes extends to depths on the order of 15-20 m; response of well levels and baseflow in streams to cycles of wetting and drying suggests that the saprolite may play an important role in buffering the response of the groundwater reservoir to these cycles, but that role is not well understood. Increases in impervious surfaces would be expected to reduce recharge in urban areas, which in turn would be expected to reduce base flow to streams, but the behavior of the saprolite in this regard has not been quantified. It may very well be that if the saprolite is not sensitive to recharge, the surficial groundwater reservoirs are also relatively insensitive to hydrologic extremes

The recent land use history of the Baltimore metropolitan region encompasses a wave of development progressing outward from the urban core in the period after World War II with the period of most rapid expansion beginning in the late 1950s and early 1960s. The axis along which development progressed is more or less parallel to the main stem of the Gwynns Falls. The period from the 1960s through the current decade witnessed several changes in regulatory policy governing urban infrastructure, particularly with regard to management of stormwater and construction and rehabilitation of sewers. Urban development up through the 1950s, 1960s and much of the 1970s proceeded by construction of a dense network of storm drains and storm sewers replacing many of the headwater tributaries, but with little else to control the rapid drainage of stormwater off the landscape and into the downstream drainage network. Following the 1972 passage of the federal Clean Water Act and particularly toward the end of the 1970s and the beginning of the 1980s, there were new regulatory measures in place requiring the construction of stormwater detention facilities. Over the subsequent two decades, design requirements and operating rules have gradually been modified to control runoff quality as well as quantity, to control the volume and release rate of runoff more effectively, to preserve natural channels flanked by riparian forest buffers, and most recently to encourage infiltration. The inner suburbs were built under the earlier regime, whereas the outer suburbs have been developed primarily since the 1980's. Within the Dead Run watershed (Figure 4) we also find many older suburban neighborhoods, juxtaposed with more recently developed commercial and industrial sites; different subwatersheds have differing percent impervious area, differing amounts of stormwater control by detention ponds, and differing runoff response which may also indicate differences in the pattern of groundwater recharge.


Figure 4. Dead Run drainage network. Blue represents surface drainage; orange represents the storm drain system

In Baltimore City and in parts of the surrounding metropolitan area, evidence suggests that at least in some locations the natural recharge of the system is being augmented by leakage both from public water-supply sources and from sanitary sewers. High levels of coliform bacteria, including pathogenic strains, are persistent in surface-water samples collected and processed for BES over a period of several years (Higgins et al., 2005), suggesting fairly chronic inputs from wastewater leakage. A set of water samples collected at several key locations and processed for caffeine (Chumble et al., 2004) offers the possibility that caffeine may be used as a tracer to determine the relative proportion of streamflow that is derived from leaking sanitary sewers. Similarly, fluoride levels vary widely in Baltimore City streams (Baltimore City DPW, 2003), probably because leakage from imported water mains and sewer lines.

2.5 Instrumentation/records already in place and available to us

In support of the BES ecological studies, nine stream gauges have been installed in the study area (red dots in Figure 3) by USGS in a nested watershed design to span different types of land use and land cover. Two new stations have been added to the official USGS network in 2005, and there are five additional sites with water-level recorders in the Dead Run watershed upstream of the USGS gage that have been monitored during the summers of 2003 through 2005 as part of an NSF-funded study of urban flood dynamics. A network of meteorological stations is indicated by the blue symbols in Figure 3. In addition, a number of spatial-data products from airborne surveys are available that capture landscape physical features at a very fine scale. We have previously purchased LIDAR (Light Image Detection and Ranging) data of the landscape from 2002 that quantify the urban/suburban topography on a 1-m horizontal and 10-cm vertical resolution. Baltimore County has recently acquired a new set of LIDAR data flown in 2005 that will be made available within the next several months. EMERGE® airborne color-infrared imagery is available that provides a high-resolution aerial photography record**.** We also have available to us 1-ft resolution orthoimagery for the years 1996, 2000, 2002, 2004, and 2005 from Baltimore County and from Baltimore City 3-in. resolution orthoimagery from 2000 and 1-ft. resolution orthoimagery from 2004. 4-m. multi-spectral/1-m. panchromatic IKONOS imagery for Baltimore captured in 2000 is also available. GIS coverage of potable water, sewer, storm sewer and septic system location for Baltimore County and Baltimore City are also available, as well as meter records for potable water and sewerage flows.

Large monitoring programs in both Baltimore City and County, related to the identification of problems and rehabilitation of sanitary sewers will be getting underway in 2006 as a result of mandates under consent decrees from EPA. City officials have agreed to work with university researchers to integrate our efforts with the City work (including modifications of their design to suite our objectives.) The City effort will be comprehensive in nature, with deployment of rainfall, groundwater and wastewater flow sensors. These will include up to 150 monitoring stations operating simultaneously in pipes with diameters ranging in size from 8 inches to 12 feet, over a period of 18 months. This network includes about 30 groundwater wells that will aid our efforts greatly. Three contracts are being awarded now for $5.5 to $6.5 million each to do this work. The work will include pump station flow measurements and wireless telemetry for real time collection of data. The objectives of this "city wide" flow monitoring program are to 1) obtain good rainfall and sewer flow records, 2) create baseline flow data for future sewer rehabilitation work, 3) provide information to develop a field inspection program for dry/wet weather flow characterization, and 4) support the development of a calibrated hydraulic model of dry and wet weather sewer flows.

Baltimore County efforts are more focused than the City's approach (fewer older sewers). They will be installing 45 new rain gauges and new flow gauges throughout the Gwynns Falls with an open time period for monitoring that will end when they have enough data to evaluate infiltration and inflow problems there and to suggest areas where sewers need to be rehabilitated, repaired or replaced. They plan on monitoring sewage flows in the Dead Run watershed late next year; we anticipate extensive interactions with their personnel and monitoring plans to integrate our own efforts. The county's long-term efforts (over the next 14 yrs) include extensive cooperation with Baltimore City (many streams/sewers are similar to those in the Gwynns Falls and traverse both jurisdictions).

Although the original purpose of installation of the USGS gauges in the BES was to provide data for ecological studies, presence of this rich resource has spawned interest in hydrologic analysis utilizing the data sets. Most notably, the detailed computations of Miller and Smith in Moores Run and Dead Run have led to very fine-scale characterization of precipitation fields and the surface drainage systems in efforts to model rainfall-runoff processes. A recent GIS representation of the drainage system for Dead Run, completed by Meierdiercks et al. (2004) for input to a stormwater hydraulic model, is shown in Figure 4. This figure shows surface drainage in blue and the major storm drains in orange. The smallest drainage pipes and the gutter and curb portions of the drainage system are not shown. A characteristic that is not widely recognized regarding these kinds of urban drainage systems that is well illustrated by this figure is that the drainage density is actually *increased* compared to a natural system, owing to the fine scale at which the drainage structure is imposed onto the landscape**.** **(**Turner-Gillespie et al., 2003)

3. Methodology

Our methodology is intended to characterize groundwater systems within the Gwynns Falls watershed across a range of scales (drainage areas) and across a range of spatial patterns of impervious cover and urban infrastructure. The work plan includes a synoptic survey of the regional water table from a large group of existing wells documented in federal, state and local databases, and uses a nested watershed design with four spatial scales (0.8-2.0, 4-6, 10-15 and 80-170 km^2) for investigation of surface flow patterns that may be used to derive information about groundwater stores, fluxes and flowpaths. A numerical groundwater model of the regional water table will be calibrated using information derived from wells, streamflow records and data from field studies described below and will be used in exploratory mode to test inferences about aquifer characteristics and to identify significant gaps and inconsistencies that need to be addressed. Rainfall fields covering the entire Gwynns Falls watershed at a 1 km^2 grid scale will be constructed based on NEXRAD weather radar products using the local rain gage network for bias correction; the mass balance derived from the precipitation database is essential for comparison with other components of the water budget and can be derived for any specified area within the larger domain. Evapotranspiration will be estimated for intensive study subwatersheds using the Penman-Monteith method and compared with results from an eddy correlation station that will be deployed on a cell phone tower. Field campaigns in our intensive study subwatersheds will be conducted twice annually under base flow conditions at times of maximum (mid-March) and minimum (mid-September) water-table elevation, allowing us to assess annual and seasonal changes in groundwater storage and flux rates to stream channels and to see how drainage areas with different patterns of urban development respond to these annual and seasonal cycles.

Within the Gwynns Falls watershed there are four USGS stream gages on the mainstem, with drainage areas of 0.8, 11.0, 84.4 and 171 km^2. The first two of these are within the Upper Gwynns Falls, one of our two intensive study watersheds. Our other intensive study watershed, Dead Run, has a USGS gage at a drainage area of 14.3 km^2, and we have installed gages for a previous NSF-funded study on two tributaries (DR3 and DR4) with drainage areas of 4.9 and 6.1 km^2 respectively. We also have installed three additional gages nested within these two tributaries (DR1, DR2 and DR5) at drainage areas between 1.3 and 1.9 km^2 (see Figure 5 for gage locations and watershed boundaries). Additional information to help characterize varying patterns of base flow and runoff ratio within the Gwynns Falls watershed will be available from two new USGS gages on additional tributaries (Scott's Level Branch and Powder Mill Run) with drainage areas of about 6-9 km^2 that will become operational within the next several months, as well as a three-year record (Water Years 2002-2004) from a tributary draining part of the inner city (Gwynns Run, drainage area 6.5 km2) that is a "sewershed" with no surface drainage. These give us a broad range of urban development patterns with varying percentages of impervious cover and types and ages of infrastructure; comparative analysis of streamflow records from this diverse set of gages can help us to draw inferences about varying conditions affecting groundwater fluxes.

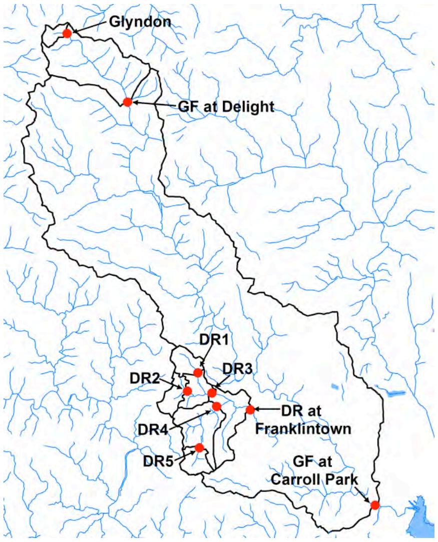

Figure 5. Gauge locations and watershed boundaries.

Dead Run is highly urbanized (43.2% impervious area) and represents a mixture of older residential development, circa 1950s construction, together with more recent commercial and institutional development (including a major shopping mall complex and the national headquarters of the federal Social Security Administration) ranging in age from the 1970s to the present. Two interstate highways (I-695 and I-70) and several major transportation arteries form transects along the main axes of the watershed. Although the older subdivisions have no stormwater control, the most recently developed subwatersheds have stormwater facilities downstream of the majority of their drainage area.

The upper Gwynns Falls at Delight is a relatively new suburban area, with development occurring in the 1980s through present time; percent impervious area for 1997 is estimated to be 26.7%, nearly double the amount estimated for 1985. The USGS gage on Gwynns Falls at Glyndon is nested within the area draining to the Delight gage and the Glyndon subwatershed has been the site of numerous BES investigations conducted (Groffman et al., 2002, 2003, 2004, 2005) characterizing nutrient budgets as well as relationships between soil moisture, shallow subsurface flow and streamflow.

The set of tasks listed below lays out in more detail the specific plans associated with the numbered list in section 1 of this proposal.

3.1 Base flow comparative studies

The high density of streamflow gages in the study area will allow us to compare base flow characteristics and runoff ratios covering a broad range of urban development patterns. Previous studies in the Dead Run watershed (Smith et al., 2005) indicate that there are significant seasonal patterns in the storm-event water balance that can be related in part to antecedent moisture and (presumably) groundwater storage. There are also significant differences between runoff ratios in adjacent subwatersheds that may be related to impervious cover and to differing patterns of development. Rose and Peters (2001) found that a highly urbanized Atlanta watershed had lower baseflow discharge, shorter storm recession periods, higher 2-day recession constants and lower seasonal baseflow recession constants than in other less-urbanized watersheds. We will examine streamflow records from the various gages identified above, focusing on the frequency distribution of dry-weather flows and on recession curves following storm events. We anticipate that comparison of unit discharge at base flow for different seasons will allow us to make preliminary inferences about differences in groundwater fluxes among watersheds, and that comparative analysis of seasonal baseflow trends will yield some insight into seasonal trends in groundwater storage. Storm-event hydrographs cannot be used to identify actual water sources (this would require isotopic analyses that are beyond the current scope of the project), but we posit that the slope, time base and final discharge value of the recession curve may provide some insight about the dominant subsurface flowpaths operating in watersheds of similar scale. Using available information compiled in GIS databases we can compare amount and spatial arrangement of impervious cover among watersheds, “natural” drainage density and the additional elements of drainage density associated with storm-drain networks and roads, percent of drainage area captured by stormwater retention facilities, and spatial extent of sanitary sewers in the riparian zone; information on differences in soil type is also available and will be included in the comparison. We will apply statistical tools to determine whether there are identifiable correlations between patterns of urban infrastructure and trends in baseflow response. Because we have several levels of nested watersheds we can also examine whether baseflow characteristics and recession curves follow trends with increasing drainage area that are consistent with simple scaling assumptions, or whether there are changes in baseflow response with increasing watershed scale that require alternative explanations. The potentially confounding effect of baseflow augmentation from leaking infrastructure will be incorporated in the analysis based on findings from investigations described in section 3.8 below.

3.2 Regional groundwater characterization and modeling

As is often the case, the geologic framework in urban environments is not well known due to lack of exposed bedrock and outcrops for geologic mapping. However, there is a plethora of underutilized data that is collected as a matter of routine by highway departments in the form of plan and profile drawings and borings removed for geotechnical analysis anytime a road, bridge, waterline, or sewer is constructed. This can be used to determine the depth of overburden and also as a record of the depth to watertable at the time the core was taken. We will mine this information from the MD State Highway Administration, Baltimore City and County Departments of Public Works, and the City Bureau of Highways and document how this can be used to fill in the geologic framework in an urban area.

Information on the urban groundwater flow system is also often lacking, as is the case in Baltimore, owing to the low spatial density of wells in this urban area that relies on surface water distribution for potable water supply. Nonetheless, locations of existing wells have been obtained from USGS and MDE data bases (Figure 3), and we know of an additional 30,000 wells in the Baltimore County data base that we need to mine to determine any locations within the study area. USGS personnel will open approximately 100 (total) of these wells within and outside of the Gwynns Falls boundary to obtain a snapshot of the deep and shallow potentiometric surface elevations under wet (late winter/early spring) and dry (late summer) conditions. These measurements will be used to contour heads for shallow (e.g., 50 ft) and deep (e.g., 300 ft) well elevations. Comparison of the two potentiometric surfaces will provide an indication of regions of downward vs upward flow exchange from the deep bedrock to the overlying saprolite and alluvium. An approximate indication of shallow lateral flow directions can be determined from the potentiometric head map derived from the shallow wells. The regional depiction of hydraulic head is expected to be too coarse to be very meaningful at the small subwatershed scale; additional methods can be employed to refine the groundwater flow field as needed. Drilling of any additional deep well locations will be recommended based on the water table map derived, but actual drilling of the wells would be beyond the budget of this study.

The extent to which deep groundwater is contributing to stream base flow can be determined through model calibration to measured heads and stream-groundwater flux rates (see section below) plus any available information on hydraulic conductivity from aquifer pumping tests. We will use a three-dimensional model numerical groundwater model (MODFLOW) in a screening mode where we will adjust the fluxes to the streams to match those measured with seepage tests to determine the possible range of groundwater depths and the range of average aquifer hydraulic conductivities that will yield fluxes of the appropriate order of magnitude.

In addition to describing the regional groundwater system, we wish to begin to explore methods for determining local recharge rates; this information can also be incorporated into the groundwater model. Opportunities for infiltration of precipitation in urban areas are severely reduced by the presence of impervious surfaces, hardened soils, and even turfgrass in some cases. Even in the event that infiltration does occur, this may not be directly correlated to the amount of water that reaches the saturated zone as recharge. Infiltrating groundwater is subject to high evaporation rates in areas lacking canopy vegetation, and to shortcuts and shortcircuiting through and around buried pipes that can serve as infiltration galleries and subsurface preferential flowpaths.

One method of estimating recharge on a scale of order m^2 that does not rely on quantifying processes in the unsaturated zone but rather that focuses on mass reaching the water table, is the water-table fluctuation method (Healy and Cook, 2002). This simple method evaluates short-term changes in water levels in shallow wells, assuming that a short-term intense storm event is reflected by a change in water table elevation. The water level change is multiplied by specific yield to calculate recharge. Determination of a field value of specific yield to utilize in the calculation at the appropriate scale is not straightforward, but Healy and Cook recommend a simple procedure that will be used here. Soil moisture characteristic curves based on soil texture (percent of sand, silt, and clay) can be determined from data bases of soil properties (e.g., Leij et al., 1996). Specific yield is then taken as the difference between specific retention and total porosity. SSURGO 1:24,000 soils coverages (http://www.ncgc.nrcs.usda.gov/products/datasets/ssurgo/) are available in digital form for the Baltimore area; these will be utilized to determine spatially variable soil texture to the extent possible. (It should be noted that disturbed urban soils are often not well represented by these maps, i.e., soils are designated as “urban complex”. This issue is but one example of the fundamental challenges in working with urban systems as opposed to natural systems; approximation procedures will have to be derived as needed.) Automatic water level recorders will be placed in selected shallow wells identified in the groundwater synoptic survey to record temporal changes in water levels. Recharge rates will be determined in these limited locations based on the above-described method. Locations where we recommend additional shallow wells to be drilled to fill in information gaps will be identified.

3.3 Airborne thermal infrared imagery

Infrared imagery techniques, such as aerial infrared thermography and color infrared photography are increasingly being used by regulatory and natural resources agencies to detect sewage and septic system discharges to streams. These technologies are included in a recent guidance manual produced by USEPA/CWP (Brown et al 2004) supporting efforts under the federally mandated NPDES stormwater permit program, which requires municipalities to conduct illicit discharge detection and elimination (IDDE) programs to find sewage and septic leaks in their storm drainage networks and streams. Thermal infrared imagery has also been used to determine concentrated locations of groundwater inputs into surface water systems based on temperature differences. The technique has proven to be useful slow-moving shallow waters such as lakes (Anderson et al., 1995), estuaries (Portnoy et al, 1998), and wetlands (Olsen 2003, pp 3-4); the technology has also been shown to work in fast moving waters (Torgerson et al., 2001).

Airborne and ground level surveys of streamwater temperatures will be undertaken primarily to identify hotspots of groundwater discharge to streams and location of hillside seeps/springs, but at the same time sewage discharges may be incidentally located. Small-scale investigations will be done using a hand held IR instrument (owned by the US Forest Service) and both continuously recording and instantaneous temperature sensors. UMBC owns a TIR imaging device through its NASA-supported Joint Center for Earth Systems Technology (JCET) and has access to aircraft and helicopter time through other ventures. We will fly the TIR instrument to detect groundwater inputs to streams using methods described by Torgeson et al. (2001) along with a UMBC-owned hyperspectral instrument simultaneously to get information about types and condition of the vegetative cover. This is of interest to NASA-supported personnel for related projects. The TIR data can be used as a guide to determine where significant fluxes of groundwater are entering the stream and where the optimal location would be to conduct seepage transects and tracer tests as described below. Also, this can be used as a guide for determining locations to deploy temperature probes, which can be used to record the dynamic signal of groundwater temperature inputs, whereas the TIR only provides a snapshot in time. The TIR work will be supervised by Dr. Juying Warner of UMBC/JCET.

3.4 Seepage transects and tracer tests

For selected stream reaches, groundwater contributions to streamflow will be evaluated by utilizing the velocity gaging method (Rantz et al., 1982) in combination with the dilution-gaging method (Kilpatrick and Cobb, 1985) as described by Harvey and Wagner (2000). The combination of these methods allows determination of the net inflow (inflow minus outflow) as well as the inflow and outflow components for a stream reach. Sodium bromide will be released at the upper end of a reach as the tracer for the dilution-gaging method. Velocity measurements will be made using a Sontek Flowtracker acoustic Doppler velocimeter available at UMBC. Groundwater fluxes to the stream measured by this method can be compared to the crude approximation using Darcy's law applied to estimated hydraulic gradients from the shallow regional piezometric surface map and published hydraulic conductivity data for the area.

A survey of dry weather flow rates in storm drain systems will be undertaken to further delineate the general extent of groundwater-streamflow interactions. This will include measurement of discharge at storm drain outfalls as well as at selected points in the upstream network (via access through manholes). Discharge measurements will be undertaken through measurement of velocities and areas (or by measures of volumes directly.) A limited suite of water quality constituents (e.g., fluoride, specific conductivity, temperature, and turbidity) will be determined at these points to enable flux calculations and to facilitate the determination of sources (e.g., Pitt 1993; Brown et al, 2004). These data will be combined with the seepage studies to address how much groundwater discharge to streams occurs in riparian vs. engineered settings.

3.5 Precipitation data analysis

Daily rainfall fields will be estimated from rain gage and radar reflectivity observations for the 2 year duration of the project. The objective will be to obtain daily rainfall fields at a spatial scale of 1 km^2 for the Gwynns Falls watershed, with special focus on Dead Run and Gwynns Falls above Glyndon. Analyses will be based on official National Weather Service rain gages supplemented by rain gage networks maintained by Baltimore City, Baltimore County and BES (Figure 3), with radar reflectivity observations from the Sterling, Virginia WSR-88D radar. Baltimore County anticipates adding approximately 45 new rain gages to the existing network under the terms of the consent decree with EPA and these will also be used when the data become available.

"Volume scan" reflectivity data from the Sterling WSR-88D at time resolution of 5-6 minutes and spatial resolution of 1 km in range by 1 degree in azimuth are archived on a routine basis at Princeton University. Rainfall estimates will be computed at 5-minute time interval using algorithms that combine gage and radar observations (Baeck and Smith [1998]) and then aggregated to longer durations (15 minute, hourly and daily). The gage-radar rainfall estimation algorithm has been used for a range of applications, including storm-event water balance analyses in the Gwynns Falls watershed (Smith et al. [2005]).

Radar rainfall estimates are computed using a Z-R relationship of the form, $R = a Z^b$, where R is rainfall rate (mm h^{-1}), Z is radar reflectivity factor ($mm^6\ m^{-3}$) and the Z-R parameters, a and b, are empirical coefficients. We will use the "convective" Z-R relationship (for which $a = 0.0174$ and $b = 0.71$), which is used for operational rainfall estimation by the National Weather Service (Fulton et al. (1998]). Rain gage observations are incorporated into the analyses through a local multiplicative bias correction (Smith et al. [1996]). The rainfall estimation algorithms have been used extensively at Princeton and rainfall analyses in this project will draw on existing software and observational resources at Princeton.

Rainfall fields can also be developed for the 2003-2005 water years using the same techniques described above, with the caveat that the density of the rain gage network and therefore the accuracy of the bias correction for those additional years of record may be somewhat less.

3.6 Evapotranspiration

Evapotranspiration can be explicitly calculated using any of several equations. We have chosen the Penman-Monteith equation (see e.g., Maidment, 1996; Drexler et al. 2004), because our meteorological stations are already collecting data needed as input to this model – i.e. net all-wave radiation, wind speed, vapor pressure, air temperature, and surficial heat flux. We have access to the required leaf-area index data and reference vegetation data from local USDA Forest Service personnel. However the inherent spatial heterogeneity of the urban environment places constraints on the accuracy of Penman-Monteith estimates developed for larger areas because of factors that influence canopy conductance (e.g. vapor pressure deficit, root zone soil moisture). Other factors might also affect local ET rates, such as the drainage efficiency of the urban infrastructure in controlling the amount of standing water on the surface. Presumably the aerodynamic conductance is high, so surface fluxes would be expected to be highly coupled with the atmospheric properties. In order to address these sources of uncertainty we will compare Penman-Monteith estimates with direct calculations of ET using an eddy correlation station (Licor H2O/CO2 open path analyzer and 3-d sonic anemometer, both available from the University of Virginia, and a CR23X data logger to be purchased with project funds) that will be mounted on a cell phone tower located in the Dead Run watershed during the project period.

3.7 Pipe flows

GIS coverages of sewers, storm sewers, septic systems, and potable water supply are available and will be obtained for the project. Meter records for water and wastewater flows at a variety of scales will also be obtained and examined. In cases where water is missing from the system, locations of potential leaks will be noted.

The extent to which sewers are leaking into groundwater and subsequently to streams can be evaluated by analyzing stream water samples for a suite of tracers mentioned in the previous section. In locations where we determine that the sewer is running parallel to the streams and where sewage leaks have been reported, we will take samples to determine the flux of sewerage to the stream using this method.

The presence of fluoride in streamwater can be used as an indicator that potable water is leaking into the surface water system. An ion-specific fluoride probe will be used to make this determination in stream water samples in the field. Locations for analysis will be selected where metering data suggests that potable water is being lost from the system.

The consideration of importing potable water from another watershed (or export) as well as sewage import or export are also important components of the urban water budget. In the case of the watersheds under consideration, potable water is imported, no well water is used, and wastewater is exported from the watersheds. Records of the import/export volumes, extensive water quality data for dry weather flows in streams and numerous infiltration and inflow studies are available from Baltimore Dept. of Public Works.

3.8 A Data Model for Hydrologic Information Systems in Urban Areas

The ArcHydro data model, as developed by David Maidment at UT Austin, has been widely adopted to represent hydrologic features in a spatial database (Maidment, 2002). More recently, the ArcHydro data model has been extended by the Consortium of Universities for the Advancement of Hydrologic Science, Inc, (CUAHSI http://www.cuahsi.org) Hydrologic Information Systems (HIS) group to represent a digital watershed. The digital watershed concept combines data sources (geospatial data, hydrologic observations, weather and climate data, and remote sensing data) along with hydrologic flux, flow, and storage (Maidment, 2005). We will use the digital watershed concept developed by the CUAHSI HIS group as the foundation for a prototype urban digital watershed.

The digital watershed spatial data model is based on the geodatabase model used in ESRI ArcGIS® and consists of geodatabases for surface water, ground water, and atmospheric water. Each geodatabase consists of feature datasets and raster layers to represent physical hydrologic features and measurement features. Also included is a time series component for hydrologic observations. Thus far, the digital watershed model has not been developed for urban environments. Therefore, we intend to extend the model by including urban infrastructure features in the appropriate geodatabases. For example, we will add paved surfaces, buildings, artificial channels, and retention ponds to the surface water geodatabase and wells and septic systems to the groundwater geodatabase. To account for the complexity of the water supply, wastewater, and stormwater infrastructure and its interaction with the subsurface, we will create a new geodatabase to include a network of stormwater pipes, wastewater conduits, and water supply pipes. We will use high resolution GIS data from local jurisdictions, as well as derivative products from remote sensing products such as LiDAR and high resolution airborne and satellite imagery, as the base datasets for the representation of urban features.

We will build further on the digital watershed concept by representing measurements of urban hydrologic fluxes, flowpaths, and storage. The hydrologic flux coupler component of the digital watershed model allows for the calculation of fluxes and flowpaths of water based on measurement and modeling in surface, subsurface and atmospheric water (Maidment, 2005). The current implementation of the hydrologic flux coupler accounts for fluxes such as precipitation, evaporation, and subsurface recharge, and flow based on USGS stream flow measurements. We will investigate adding fluxes, flow paths, and storage mechanisms that are unique to the urban environment. We will use Figure 1 and discussion in section 2.1 as a framework for including urban fluxes such as stormwater discharge, wastewater discharge, and imported water; urban flow paths such as runoff, stormwater drainage, wastewater transport, pipe infiltration and exfiltration, septic disposal, irrigation, and leakage; and urban storage such as impervious surface storage, pervious soil, infiltration basins, and urban groundwater. We will then calibrate the fluxes, flow paths, and storage with field measurements and finally connect them to the spatial data model.

4. Timeline and management plan

Overall project management and coordination will be carried out by Dr. Claire Welty, Director of the UMBC Center for Environmental Research and Education (CUERE) and Professor of Civil and Environmental Engineering. Dr. Welty is committed to having CUERE staff provide GIS support, equipment procurement, office and conference space, and lab facilities as needed for this project. Dr. Welty will ensure that project goals are carried out and annual and final reports are written and submitted to NSF in a timely fashion. The budgeted 1/2-time post-doctoral associate will report to Dr. Welty and coordinate the day-to-day activities of the undergraduate and graduate students and field technician. A field technician is included in the budget because care of the deployed equipment must be carried out year-round and under all weather conditions; students are expected to be tied up with classes at times when some field work during the academic year is needed. Monthly conference calls and quarterly meetings will be held among the project team co-PIs to ensure that the project is on track. In addition, we anticipate frequent contact among PIs, students and other staff in carrying out field investigations. All project personnel will maintain field/lab notebooks and all notebooks and electronic files will be exchanged once per quarter with other team members. A web site will be set up at UMBC to foster information exchange and provide visibility for the project. We will disseminate results through the web site, presentations at national and regional conferences, and submission of papers to journals. Description of responsibilities among personnel is further detailed in the budget justification.

Task description↓ Quarter →	1	2	3	4	5	6	7	8
Groundwater well synoptics		▨		▨				
Groundwater modeling				▨	▨	▨	▨	
Recharge analysis		▨	▨	▨	▨	▨	▨	
Precipitation analysis	▨	▨	▨	▨	▨	▨	▨	▨
ET measurement	▨	▨	▨	▨	▨	▨	▨	▨
Seepage transects and tracer tests		▨		▨				
Data mining of governmental data bases	▨	▨	▨	▨	▨	▨	▨	
Analysis of pipe flows		▨	▨	▨	▨	▨	▨	
HIS development	▨	▨	▨	▨	▨	▨	▨	
Write final report/journal articles								▨

5. Broader impacts

The grant will contribute to the education of graduate and undergraduate students, thereby contributing to the NSF mission of supporting education at the university level. Graduate students from UMBC, UNC, UVa, and Princeton will participate as research assistants during the summer field season, as coordinated through CUERE and via communication among the co-PIs. We will emphasize recruitment of undergraduate student assistants from UMBC's Meyerhoff Scholars program, which has a national reputation for training of talented minority students committed to graduate education in science and engineering and which has recently approved the Environmental Science B.S. degree as an option for students in the program.

Through the BES/LTER, an extensive outreach educational program managed by the BES educational coordinator is already in place with inner city Baltimore schools, which includes a hydrologic science module within the environmental science curriculum. Results from the proposed work can contribute to/enhance this ongoing curriculum development effort.

This project will provide results that are of interest to regulatory agencies concerned with urban impacts on water quality, riparian ecology and delivery of nutrients to receiving waters. We are working in close collaboration with Baltimore County Department of Environmental Protection and Management, which maintains an inventory of stormwater detention ponds and other urban infrastructure and which plans and funds detention-pond upgrades and stream restoration for management purposes. DEPRM is interested in using our results to provide supporting evidence for management decisions at other locations. We expect that our results will also be of interest to state regulatory agencies and to EPA, who are both increasingly concerned with the downstream impacts of nutrient loads contributed by tributaries to Chesapeake Bay.

A recent examination of water quality trends in surface waters in urban and suburban areas in the northeastern US concluded that many surface waters will not be potable for human consumption and will be toxic to freshwater life in the next century if salinization rates continue on their upward trend (Kaushal et al., 2005). The authors suggest that increased salinity is directly correlated with impervious surface and the use of road deicing salts in winter, which infiltrate into groundwater and are subsequently discharged as stream base flow over long periods of time. Understanding the dynamics of urban groundwater in terms of quality and quantity is required to address this kind of potentially very significant societal problem.

6. Prior support from NSF

Human Settlements as Ecosystems: Metropolitan Baltimore from 1797 - 2100, DEB-9714835; 11/1/97 – 10/30/04; $4.2M; Phase II -- DEB-0423476; 11/1/04 -10/31/10; $4.2 M.
PI: S. Pickett; co-PIs: P. Groffman, A. Berkowitz, L. Band, G. Heisler, G. Fisher, J. Smith, A.J. Miller, C. Welty, K. Belt, R. Pouyat, and others. Research on the Baltimore urban LTER is governed by three questions: (1) What are the fluxes of energy and matter in urban ecosystems, and how do they change over the long term? (2) How does the spatial structure of ecological, physical, and socio-economic factors in the metropolis affect ecosystem function? (3) How can urban residents develop and use an understanding of the metropolis as an ecological system to improve the quality of their environment and their daily lives? The project is focused on the Gwynns Falls

drainage. The work has centered on long-term stream and watershed monitoring, riparian processing of nutrients and carbon, and stream restoration. BES education programs engage youth, educators, and young scientists in investigations of the urban environment. 82 journal articles, 37 book chapters, 7 books, and 6 theses/dissertations have been published from this work to date. The publications database can be queried at http://beslter.org.

Collaborative Research on Hydrology, Hydraulics and Hydrometeorology of Flood Response in Urbanizing Drainage Basins, EAR-0208225/0208669, 8/1/02–7/31/05, $300,000, UMBC PI: A. J. Miller, Princeton PI: J. A. Smith. This research focuses on evaluating: (1) how scale-dependent flood response of urban drainage basins depends on the space-time structure of rainfall for warm-season systems of thunderstorms; (2) how flood response varies with land-surface properties including impervious cover and structure of the urban drainage network; and (3) the relative role of changing channel/floodplain morphology due to urbanization, as compared with geologic controls of channel floodplain morphology, in determining the transmission and attenuation of flood waves in an urbanizing drainage basin. Efforts focus in watersheds in the Baltimore area with varying patterns of urban development, infrastructure and geologic controls. Field activities have included collection of rainfall data to calibrate weather-radar rainfall fields with 1-km^2, 5-minute resolution. High-resolution (1 m horizontal, 15-20 cm vertical) topographic data derived from LIDAR and field survey have been used to characterize channels/riparian zones for hydraulic modeling purposes. Resulting publications are marked with a (^{1}) in the reference list.

An Acre an Hour: Documenting the Effects of Urban Sprawl on a Model Watershed near Philadelphia, Pennsylvania, NSF/EPA/USDA Water and Watersheds Competition, EAR 0001884; 4/1/00 - 3/31/04; $705,000 + $8500. PI: C. Welty; Co-PIs: S. Kilham, A.I. Packman, and R. J. Brulle. Biotic community structure was analyzed using species composition, stable isotopes and C:N:P ratios. Nitrogen isotope levels were found to be indicative of inputs of anthropogenic N sources to the stream attributed to leaking septic systems. Diversity of fish species at each of 15 stream sampling stations showed a response to land use parameters including percent impervious surface coverage, but was also correlated to groundwater inputs at measured spring locations along the stream. Dominating controls on spring water quality (anthropogenic versus geologic) of 110 springs were shown to be correlated to patterns of land use and geology. Measured anthropogenic perturbations to stream water quality/quantity were used to determine stream-aquifer exchange parameters by model calibration to measured flow and transport. Bromide tracer tests were used to examine the temporal effect of streambed clogging due to sediment washoff from construction sites both at the local (reach) scale and watershed scale. Hydrologic modeling of 82 stormwater detention basins showed the basins have little effect on controlling flooding of a typical storm and can actually exacerbate flooding due to the additive nature of peak flows and the lack of watershed-wide considerations in design of stormwater management facilities. 5 theses/dissertations and over 50 presentations/publications resulted from this work.

Collaborative Research (CLEANER): Cyberinfrastructure Needs for a Model Environmental Field Facility as Part of an Engineering Analysis Network, BES 0414206, 8/1/04 – 7/31/06; $34,980 per institution. UMBC: C. Welty, PI; M.P. McGuire co-PI; Drexel University: M. Piasecki, PI. This is one of 12 planning grants to assist the NSF Engineering Directorate in developing a Collaborative Large-Scale Engineering Analysis Network for Environmental Research (CL*EAN*ER). The PI team is evaluating the Baltimore Ecosystem Study as a prototype environmental field facility (EFF) to determine the cyberinfrastructure needs for this site to become a functional component of an Engineering Analysis Network. In addition, the team is evaluating existing available information on other environmental observatories and field sites of interest for use by environmental engineers that would assist NSF in forming a CL*EAN*ER network. One journal publication to date from this work is in press.