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Design of an environmental field observatory for quantifying the urban water budget

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Summary: Quantifying the water budget of urban areas presents special challenges, owing to the influence of subsurface infrastructure that can cause short-circuiting of natural flowpaths. In this paper we review some considerations for data collection and analysis in support of determining urban water budget components, with a particular emphasis on groundwater, using Baltimore as an example study area. We review selected data collection techniques and applications, including use of airborne thermal

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infrared imagery to determine locations of groundwater inputs to streams; use of seepage transects and tracer tests to quantify surface-subsurface exchange; estimating groundwater recharge rates; analysis of base flow behavior from stream gages; mining of public agency records of potable water and wastewater flows to estimate leakage rates and flowpaths in relation to streamflow and groundwater fluxes; and considerations for building a geodatabase that includes information relevant to urban hydrologic data.

INTRODUCTION

In this paper we outline design elements of an urban hydrologic observatory, using Baltimore as an example application area, with an emphasis on quantifying the influence of the components of the built environment that affect flowpaths, fluxes, and stores of groundwater. 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. Motivation for this effort stems from the recent emphasis by National Science Foundation to establish a national network of environmental observatories to address fundamental scientific water resource questions on a watershed scale, where data are collected in a coherent, coordinated fashion and the use of sensor networks and cyber-infrastructure are key system elements.

Precipitation, evaporation, transpiration, infiltration, runoff, streamflow, and groundwater flow are the main components of the hydrologic cycle; this is typically illustrated by a sketch of the natural landscape showing cycles and subcycles of water flow. The importance of the built environment is generally acknowledged by indicating 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 and aquatic ecosystem function is poorly understood. Among the components of the urban hydrologic cycle, groundwater is of key importance, yet it has received relatively little attention from hydrologists in the U.S. in situations where groundwater is not used for water supply directly. The majority of the world's population lives in urban areas and is dependent on the complete hydrologic cycle for water supply. Therefore, understanding 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 addressed historically in terms of designing facilities for water supply, wastewater treatment, and stormwater management. However, this work has focused on mitigation of specific engineering problems, not on understanding and planning for the integrated functioning of the natural and built environment.

Figure 6.1 depicts the elements of the urban water cycle. Arrows connect components of both the natural system (lower, upper and right portions of the figure) and of the urban infrastructure (left and center), including:

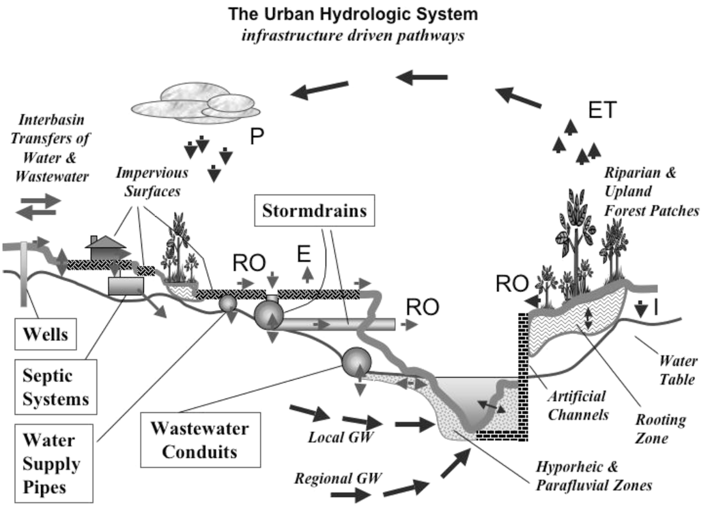

Figure 6.1. The urban hydrologic cycle.

- 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 import 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 residential and commercial irrigation practices (lawn watering) on groundwater levels and base flow to streams in summer;
- influence of incision of urban stream channels on groundwater levels;
- interaction between urban vegetation and evapotranspiration processes;
- groundwater withdrawals for water supply; and
- preferential flow paths created by subsurface infrastructure.

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, with multiple impervious barriers, hollow conduits, and sharp transitions in hydraulic conductivity associated with excavation and fill. All pathways and exchanges that affect the mass balance on the urban 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 of buildings to bedrock. An example water budget for such a control volume and annual period is given as

$$P + I + W - S - ET = \Delta S_G \tag{1}$$

where P = precipitation [L]; I = water imported to (+)/exported from (−) the basin via water distribution systems [L^3L^{-2}]; W = wastewater imported to (+)/exported from (−) the basin [L^3L^{-2}]; S = streamflow at the basin outlet [L^3L^{-2}]; S_G = 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. Closing the water budget would imply that all terms are measured 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.

BACKGROUND

Urban water budget studies

Attempts at comprehensive long-term 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, "Assessing and Improving the Sustainability of Urban Water Resources and Systems" (AISUWRS, http://www.urbanwater.de), has 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) has described 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) have suggested 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, showing the highly variable nature of the water table under the city. These studies provide a foundation from which to build a comprehensive assessment of the urban water budget using state-of-the-art methodologies and frameworks.

Baltimore as a model study area

Baltimore's urban watersheds are some of the most studied and densely instrumented in the world, stemming back to early work at Johns Hopkins University gaging storm sewers and quantifying water use (Geyer and Lentz, 1966) and to studies under the EPA Nationwide Urban Runoff Program (US EPA, 1983). More recent work includes stormwater and water resources investigations by local governments (e.g., Baltimore City Department of Public Works, 1999, 2001; Baltimore County, 2000), research by the NSF-funded Long-Term Ecological Research (LTER) Baltimore Ecosystem Study (BES, http://www.beslter.org), and mandated monitoring under EPA consent decrees with Baltimore City and County to address sanitary sewer overflow problems. The many data collection efforts currently being conducted, which are similar to those found in many urban areas, can be utilized as starting point for determining components of the urban water budget.

A primary BES study area is the Gwynns Falls watershed, a 171-sq km basin (Figure 6.2) that lies within the Patapsco River drainage to the Chesapeake Bay. This watershed was selected as an urban ecological study site because it is characterized by a gradient of urbanization from downtown Baltimore to suburban and remnant agricultural areas at the headwaters. Baisman Run and Pond Branch, in the adjacent Gunpowder River drainage (the main water supply of the Baltimore Metropolitan region) serve as forested reference watersheds. As part of the BES ecological studies, nine stream gages have been installed in the study area (Figure 6.2) by USGS (Doheny, 1999), in a nested watershed design that spans different types of land use and land cover, with two new stations added to the official BES/USGS network in 2005. In the Dead Run subwatershed there are five additional sites with water-level recorders upstream of the USGS gage that were monitored during the summers of 2003 through 2005 as part of an NSF-funded study of urban flood dynamics conducted by Miller and Smith (Nelson et al., 2006; Smith et al., 2005).

A network of rain gages and meteorological stations is indicated in Figure 6.2. In addition, a number of spatial-data products from airborne surveys are available that capture landscape physical features at a very fine scale. LIDAR (Light Image Detection and Ranging) data of the landscape were obtained in 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. EMERGEâ airborne color-infrared imagery provides a high-resolution aerial photography record**.** Also available are 1-ft resolution ortho-imagery for the years 1996, 2000, 2002, 2004, and 2005 from Baltimore County and from Baltimore City 3-in resolution ortho-imagery from 2000 and 1-ft resolution ortho-imagery from

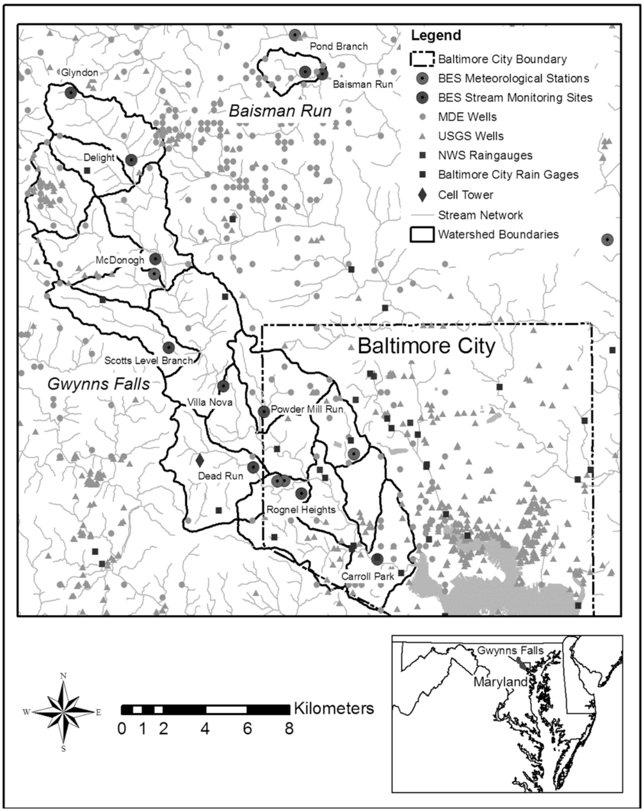

Figure 6.2. Stream monitoring sites (also USGS streamflow gages), and rain gage/meteorological stations, and wells in the Gwynns Falls watershed.

2004. Four-m. multi-spectral/1-m panchromatic IKONOS imagery for Baltimore captured in 2000 is also available. GIS coverages of potable water, sewer, storm sewer and septic system locations for Baltimore County and Baltimore City are also available, as well as continuous flow records for potable water and sewerage flows at a great many locations.

Extensive monitoring programs in both Baltimore City and County, related to the identification of problems and rehabilitation of sanitary sewers, are being implemented as a result of mandates under consent decrees from EPA. The City effort is comprehensive in nature, with deployment of rainfall, groundwater and wastewater flow sensors. These 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. 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's efforts are more geographically focused on isolated "trouble spots" than the City's approach (the City network has many more older sewers). The County is installing 45 new rain gages and new flow gages throughout the Gwynns Falls with an open time period for monitoring that will end when enough data have been obtained to evaluate infiltration and inflow problems and to suggest areas where sewers need to be rehabilitated, repaired or replaced. The County plans on monitoring sewage flows in the Dead Run watershed in 2007 and long-term plans include extensive cooperation with Baltimore City, as many streams/sewers traverse jurisdictions.

Although the original purpose of installation of the USGS gages in the BES was to provide data for hydro-ecological studies, this rich data resource has spawned additional hydrologic analyses. 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 6.3. This figure shows surface drainage and the major storm drains. 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

Figure 6.3. Dead Run drainage network. Dark grey lines represent open channel drainage; lighter grey lines represent the larger components of the buried storm drain system (Meierdierks et al., 2004).

at which the drainage structure is imposed onto the landscape (Turner-Gillespie et al., 2003). The dissection of the urban landscape by dense networks of pipes may exert great influences on urban water budgets that go beyond simple consideration of surface runoff volumes.

Considerations of regional hydrogeology

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 a number of major cities in the US (Trenton NJ, Philadelphia, Baltimore, Washington DC, Richmond VA, Raleigh NC, and Augusta GA) have been settled to take advantage of abundant waterfalls for hydropower and milling operations at locations near the limits of navigation. Insights from hydrogeological investigations of the Baltimore region are therefore transferable to other major east-coast urban environments.

In the Piedmont and fall zone, groundwater flows through unconsolidated saprolite (weathered bedrock) and alluvium, and fractured bedrock that may play an important role in the urban water budget. The saprolite has a high porosity (20-30%); the porosity of the fractured rock is only 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 fracture-bedrock wells. The thickness of the saprolite is highly variable and can extend 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 would be expected to reduce base flow to streams, but the behavior of the saprolite in this regard has not been quantified. If the saprolite is not sensitive to recharge, the surficial groundwater reservoirs may also be relatively insensitive to hydrologic extremes. Understanding the behavior of the saprolite is therefore essential for determining the water budget in Baltimore and in similar hydrogeologic environments.

QUANTIFICATION OF URBAN WATER BUDGET COMPONENTS

Base flow comparative studies

A high density of streamflow gages allows comparison of base flow characteristics and runoff ratios covering a broad range of urban development patterns.

Studies in 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. Streamflow records can be examined from the large network of gages identified above, focusing on the frequency distribution of dry-weather flows and on recession curves following storm events. Comparison of unit discharge at base flow for different seasons and antecedent moisture conditions can allow preliminary inferences to be made about differences in groundwater fluxes among watersheds, and comparative analysis of seasonal baseflow trends can yield some insight into seasonal trends in groundwater storage. Using available information compiled in GIS databases allows comparison of 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 can be included in the comparison. Statistical tools can be applied to determine whether there are identifiable correlations between patterns of urban infrastructure and trends in baseflow response. Using the nested watershed design (Figure 6.4) also allows examination of 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 can be addressed using information from leak detection studies while surveys of baseflows in stormdrains provide insight with respect to how networks of these pipes facilitate the removal of shallow groundwater to streams.

Regional groundwater characterization and modeling

The geologic framework in urban environments is often not well documented due to lack of exposed bedrock and outcrops for geologic mapping. However, there is a plethora of underutilized data in many locations, including Baltimore, 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 any time a road, bridge, waterline, or sewer is constructed. This information can be used to determine the depth of overburden and also as a record of the depth to water table at the time the core was taken and to provide geologic context for urban groundwater studies.

Information on the urban groundwater flow system is also often lacking, owing to the low spatial density of wells in this urban area that relies on surface water

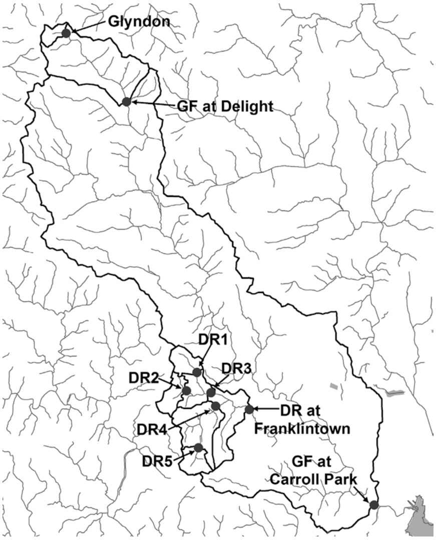

Figure 6.4. Stream gauge locations and subwatershed boundaries of nested study sites in older suburban (Dead Run – DR) and newer suburban (Glydon and Gwynns Falls at Delight) development.

distribution for potable water supply. Nonetheless, locations of existing wells can be obtained from USGS and state data bases (Figure 6.2), as well as from other sources (e.g., county-level data). Selected existing wells can be opened 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 can be used to contour heads for shallow (e.g., 15 m) and deep (e.g., 100 m) well elevations. Comparison of the two potentiometric surfaces can 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.

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. A three-dimensional numerical groundwater model can be used in a screening mode where the flux rates are adjusted to match stream discharges measured with seepage tests. This makes it possible to determine the range of groundwater depths and the range of average aquifer hydraulic conductivities that will yield fluxes of the appropriate order of magnitude.

Groundwater recharge

In addition to describing the regional groundwater system, quantification of local recharge rates is desirable; this information can also be incorporated into a groundwater model. Opportunities for infiltration of precipitation in urban areas are reduced by the presence of impervious surfaces, hardened soils, and even turfgrass in some cases. Even where infiltration does occur, this may not be directly correlated to the amount of water reaching 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 several square meters 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 causes 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. Soil moisture characteristic curves based on soil texture (percent of sand, silt, and clay) can be determined from databases 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 can 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 one example of the fundamental challenges in working with urban systems as opposed to natural systems; approximation procedures must be derived as needed.) Automatic water level recorders can be placed in selected shallow wells identified in the groundwater synoptic survey to record temporal changes in water levels. Recharge rates can be determined in these limited locations based on the above-described method. Locations where additional shallow wells should be drilled to fill information gaps can be identified.

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 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 in 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; Loheide and Gorelick, 2006).

Airborne and ground level surveys of streamwater temperatures can be undertaken to identify concentrated points 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 can be done using a hand held IR instrument and both continuously recording and instantaneous temperature sensors. A TIR imaging device can be used to detect groundwater inputs to streams using methods described by Torgeson et al. (2001). 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.

Seepage transects and tracer tests

For selected stream reaches, groundwater contributions to streamflow can 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 gross inflow and outflow components for a stream reach. A tracer such as a solution of sodium bromide can be released at the upper end of a reach for the dilution-gaging method. Velocity measurements can be made using one of a variety of velocity meters. Groundwater fluxes to the stream calculated by this method can be compared to the crude approximation using Darcy's law applied to estimated hydraulic gradients from the shallow regional potentiometric surface map combined with published hydraulic conductivity data for the area.

A survey of dry weather flow rates in storm drain systems can be undertaken to further delineate the general extent of groundwater-streamflow interactions. This can include measurement of discharge at storm drain outfalls as well as at selected points in the upstream network (via access through manholes). Discharge measurements can 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) can 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 can be combined with the seepage studies to address how much groundwater discharge to streams occurs in riparian vs. engineered settings.

Precipitation data analysis

Given the rapid and efficient delivery of runoff from urban watersheds, it is imperative to have accurate estimates of precipitation inputs. Daily rainfall fields at a spatial scale of 1 km^2 can be estimated from rain gage and radar reflectivity observations. For the Baltimore site, analyses are based on National Weather Service rain gages supplemented by rain gage networks maintained by Baltimore City, Baltimore County and BES (Figure 6.2), and with radar reflectivity observations from the Sterling, Virginia WSR-88D radar. "Volume scan" reflectivity data from the Sterling WSR-88D radar at a 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 can be computed at 5-minute time intervals 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. The "convective" Z-R relationship (for which $a = 0.0174$ and $b = 0.71$) 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).

Evapotranspiration

Evapotranspiration can be explicitly calculated using any of several equations. The Penman-Monteith equation (see e.g., Maidment, 1996; Drexler et al. 2004) is popular because most standard meteorological stations collect data needed as input to this model – i.e. net all-wave radiation, wind speed, vapor pressure, air temperature, and surficial heat flux. Required leaf-area index data and reference vegetation data for Baltimore are available 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 are expected to be highly coupled with the atmospheric properties. In order to address these sources of uncertainty, direct calculations of ET can be made using an eddy correlation station (Beringer and Tapper, 1996).

Pipe flows

GIS coverages of sanitary sewers, storm drains, septic systems, and potable water supply networks are available for many urban areas, including Baltimore; however the data are typically not compiled in one database and often lack key attributes needed for hydraulic modeling. Municipal water and wastewater records for a variety of scales are a rich but normally underutilized source of data for hydrologists. For example, water distribution system records are long-term and typically feature water meters at the household level, pumping and storage data for many points in the landscape, and gaging stations for key networks. Notably, these kinds of records are often indispensable for urban work, since "engineered" water can dominate the urban water budget. For example in the Baltimore watersheds, potable water is imported, no well water is used, and wastewater is exported from the watersheds but there are extensive exchanges with ground and surface waters. Records of the import/export volumes, extensive water quality data for dry weather and storm flows in streams and numerous infiltration and inflow studies are available from the Dept. of Public Works.

A data model for hydrologic information systems in urban areas

Modeling hydrologic processes in urban areas requires input data from numerous sources that are collected and archived at various temporal and spatial scales and in a variety of units and formats. There is a national movement to bring disparate data sources together for the purpose of facilitating analysis and visualization and an increased focus on data management techniques that allow researchers to focus their time on analysis rather than searching for data and using ad-hoc methods for converting data sets to units and formats required for a chosen model. Examples include CUAHSI (Consortium for the Advancement of Hydrologic Science, Inc., http://www.cuahsi.org); SEEK (Science Environment for Ecological Knowledge, http://seek.ecoinformatics.org); and KNB (The Knowledge Network for Biocomplexity, http://knb.ecoinformatics.org)). The emphasis in water-related fields has been on bringing together standard large-scale spatial data sets such as National Hydrography Data (NHD), National Elevation Data (NED), National Land Cover Data (NLCD), and temporal data such as those provided by USGS streamflow gages, NOAA weather stations, and Ameriflux towers. While great strides have been made for applications to natural landscapes, special requirements for urban areas have been virtually unaddressed. For example, in one recent application, Tenenbaum et al. (2006) used high resolution LIDAR elevation data with sampled soil moisture to determine that suburban catchments required order of magnitude finer resolution to adequately resolve topographic influence on water redistribution. In addition, the NHD does not account for piped flow, and the NLCD and NED datasets are available at too coarse a scale to capture the fine-grain spatial features of urban landscapes. Detailed data sets of the type required for water resources management in urban areas are available (LIDAR, high resolution aerial photography, GIS coverages of pipe networks, 5- or 15-minute streamflow data) for some locations, but these have not been systematically incorporated into organized national databases.

Related to this is the explosion in development and deployment of wireless sensors and sensor networks to deliver real-time data for environmental monitoring (e.g., Arzberger et al., 2005). One goal is ultimately to interface real-time data with mathematical models to provide dynamic predictions of water and contaminant movement through the terrestrial environment. Also, new developments in data warehouse and online analytical processing (OLAP) systems allow users to explore data across a large number of dimensions. Spatial OLAP, the integration of geographic information systems (GIS) and OLAP, can improve knowledge discovery from spatial distributions and relationships by allowing users to explore multidimensional data through spatial visualization. The application of SOLAP can prove to be a very powerful tool in exploring relationships between spatially and temporally dynamic environmental systems.

RECOMMENDATIONS AND FUTURE RESEARCH

Given the significance of the interaction between urban infrastructure and the water cycle, in this paper we aimed to review some relevant considerations in data collection and analysis, with an emphasis on the groundwater component. Future work will include implementation in Baltimore of many of the methods discussed. One important application is quantifying delivery of nutrients and contaminants from groundwater beneath cities to surface waters, and in the case of Baltimore, to the Chesapeake Bay. To aid in evaluating urban water resources problems, the national effort for developing a unified geodatabase can be built on by developing a prototype system for collecting, transmitting, storing, mining, manipulating, communicating, and visualizing hydrologic data sets pertaining to urban areas. This will involve fusing data streams from on-ground sensor networks including meteorological stations and USGS gages; fine-grid spatial data sets (LIDAR, EMERGE imagery, SSURGO soils, geology); city and county storm sewer and sanitary sewer systems; and census, health, and tax-parcel data.

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