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Water Balances along an Urban-to-Rural Gradient of Metropolitan Baltimore, 2001–2009

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ABSTRACT

Urban water balances are generally unknown, yet they are necessary for assessing water availability in an urbanizing world and for understanding the effects of urbanization on the hydrologic cycle. We assess the spatial and temporal variability of water balances of 65 watersheds in the Baltimore, MD, metropolitan area during Water Years 2001–2009. Each water balance term is quantified independently and includes both natural (precipitation, evapotranspiration, streamflow) and piped (sewer infiltration and inflow [I&I], lawn irrigation, water supply pipe leakage) watershed inflows and outflows. The analysis also compares Gravity Recovery and Climate Experiment storage data with changes in storage calculated using the residual between watershed inflows and outflows. We find that when considering only natural water balance terms, the water balance residual (inflows minus outflows) increases with urbanization, largely as a result of the decrease in evapotranspiration as modeled by the land surface model Global Land Data Assimilation System/Noah. During wet years, the difference between urban and rural natural water balance residuals narrows because of increased urban streamflow. Excess water of the natural water balance in urban areas is largely exported by I&I into wastewater collection pipes; for some urban watersheds this excess is greater than gauged annual streamflow. I&I also outweighs piped inputs from lawn irrigation and water supply pipe leakage in the Baltimore area analysis. The net effect of piped flows on the urban water balance is a watershed export ranging between 300 and 465 mm/yr, underscoring the importance of interactions between engineered water and wastewater infrastructure and natural water balance components.

INTRODUCTION

Quantitative information on how urbanization changes water balances and corresponding water availability is generally unknown. Yet knowledge of water availability is needed to manage ecosystem impacts, maintain in-stream flow requirements for biota, and manage water supply for potable consumption and potential reuse. Urbanization affects all components of the hydrologic cycle. The most readily observed impact is the response of urban streams to rainfall inputs; urban streams are flashier, with higher peak flow rates and greater total runoff volumes, than their non-urban counterparts (e.g., Leopold, 1968). Other well-known effects associated with urbanization include reduced infiltration caused by increased impervious surface coverage; contributions to groundwater recharge from leaking water supply pipes; changes to evapotranspiration (ET) due to decreases in vegetative land cover and increases in lawn irrigation (Grimmond and Oke, 1999; Claessens et al., 2006); and increases in precipitation as a result of the urban heat island effect (Shepherd, 2005). These consequences can combine to alter the relative magnitudes of urban water balance components on a watershed basis, as compared to natural systems. The goal of this article is to quantify the effects of urbanization on catchment-scale water balances using Baltimore, MD, as a case study. The novel aspect of this article lies in the availability of spatially detailed hydrologic data in which water balance components are quantified along an urban-to-rural gradient of development.

Although often considered separately, engineered water and wastewater flows always interact with natural hydrologic flows. We refer to these engineered flows as piped flows. Piped flows include interbasin transfers of water and wastewater, leakage out of pressurized water supply pipes, and leakage into

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(infiltration) or out of (exfiltration) wastewater collection pipes. We define the water balance by setting the difference between inflows and outflows equal to the change in watershed storage, where the watershed defines lateral boundaries of a control volume. Our water balance equation for urban areas is given by

$$P + I + L - ET - Q - W - I\&I = \Delta S, \qquad (1)$$

where P is precipitation, I is lawn and garden irrigation using piped water supply, L is water supply pipe leakage, ET is evapotranspiration, Q is streamflow, W is reservoir withdrawal, I&I is inflow and infiltration into wastewater collection pipes, and ΔS is change in storage. Inflows are positive and outflows are negative components of the left side of Eq. 1. From I&I data available to us for the Baltimore region, we have evidence that although exfiltration from wastewater pipes occurs, on balance wastewater pipes act as a drain and as an additional watershed outflow. In other areas, however, wastewater pipes may predominantly act as sources of watershed inflow. In some cases, we group Q and W together and label the sum as Q*. All quantities are given in terms of average depth over a watershed per unit time. Changes in internal partitioning of water (e.g., increases in monthly storm runoff balanced by decreases in monthly baseflow that leave monthly streamflow volume unchanged) are not within the scope of this article.

Consideration of piped and natural flows together as part of integrated urban water management (e.g., Mitchell, 2006) is rare. Studies that have quantified natural water budget inflows and outflows, as well as piped water and wastewater inflows and outflows, have been conducted for a variety of purposes. These include prediction of future water supplies (e.g., Martinez et al., 2011), quantifying groundwater recharge (e.g., Birkle et al., 1998), and determination of stormwater and wastewater contaminant loads (e.g., Niemczynowicz, 1990). Previous studies provide comparisons of piped and natural flows in a variety of urban areas globally. Imported water is shown to exceed average precipitation in a few studies (Vizintin et al., 2009; Martinez et al., 2011). More commonly, imported water makes up less than half of the total watershed input, with the remainder being precipitation (Aston, 1977; Carlsson and Falk, 1977; Grimmond and Oke, 1986; Niemczynowicz, 1990; van de Ven, 1990; Stephenson, 1994; Binder et al., 1997; Birkle et al., 1998; Semádeni-Davies and Bengtsson, 1999; Eiswirth, 2001; Jia et al., 2002; and Mitchell et al., 2003). These catchment water balance studies contrast with water balance studies focusing on groundwater, in which researchers have more commonly found precipitation to be a smaller source of recharge than is leakage from water supply pipes (Kim et al., 2001; Garcia-Fresca, 2006).

There is no one form of outflow that is dominant across the spectrum of urban water balance studies. In some previous assessments, particularly in areas with combined sewer systems, the dominant outflow is wastewater (Niemczynowicz, 1990; van de Ven, 1990; Birkle et al., 1998; Jia et al., 2002; Vizintin et al., 2009; and Martinez et al., 2011). In others, streamflow or stormwater is the largest magnitude outflow (Aston, 1977; Grimmond and Oke, 1986; and Semádeni-Davies and Bengtsson, 1999). In still others, ET is dominant (Carlsson and Falk, 1977; Stephenson, 1994; Binder et al., 1997; Eiswirth, 2001; and Mitchell et al., 2003). Both large positive (e.g., Stephenson, 1994) and large negative (e.g., Niemczynowicz, 1990) changes in storage have been observed in urban water balance studies.

Only a few of the cited urban water balance studies compare natural and urban water balances to evaluate the differences between them. Stephenson (1994) and Grimmond and Oke (1986) both found that lawn irrigation led to greater or equal ET, compared to corresponding rural sites. In our study, we are able to compare urban and nearby undeveloped area water balances in the same climatic and hydrogeologic environment by evaluating a region with multiple watersheds ranging from urban to rural. This analysis of the spatial variability of urban to rural water budgets can also serve as a proxy for predicting the temporal evolution of water balances as an area becomes more urbanized.

Although yearly precipitation inputs exceed the volume of imported water for most previous studies, in some cases this is found to be dependent on annual climatic or seasonal variations. For example, Mitchell et al. (2003) evaluated multiple years in Canberra, Australia, and found that in the driest year imported water exceeded precipitation and exported wastewater exceeded streamflow, which was not the case in other years. To assess water availability impacts of urbanization, it is clear from the literature that a range of climatic conditions (multiple years) and seasonality should be considered.

None of the cited studies that address piped flows as well as natural flows have been carried out for cities in the northeastern United States. Since the effects of urbanization on water balances depend on regional climate, studies from other climates are not clearly applicable to this area. In addition, the age and leakiness of the water system may play a significant role in determining how water budgets change with development in different cities. Baltimore, with a relatively old water and sewer system, may provide an analogue city for population centers in the northeastern United States or elsewhere with similar climate and water system age.

For the above reasons, we undertook a spatial and temporal analysis of the water balance of the Baltimore metropolitan area for Water Years 2001–2009. In this article, we address the following questions:

1. The watersheds in our study area span a gradient from 0–60 percent impervious surface coverage. How does the water balance change along this gradient, both in the forms and relative amounts of watershed inflows and outflows?
2. How do the magnitudes of piped flows (water supply pipe leakage, wastewater infiltration and inflow, lawn irrigation, and reservoir withdrawals for water supply) compare to natural inflows (precipitation) and outflows (streamflow and ET)? Which piped flows are most significant?
3. How do urban and rural water balances vary as a function of time, both seasonally and annually (wet years versus dry years)?

STUDY AREA

The methodology used in this article is completely general and could be applied to a metropolitan region of any climate and infrastructure age. Baltimore was selected because of data availability in this region. The political jurisdictions that define the Baltimore metropolitan region include Baltimore City and Baltimore, Howard, Carroll, Harford, Anne Arundel, and Queen Anne's Counties (Figure 1). This study focuses on drainage from the counties on the western shore of the Chesapeake Bay and therefore excludes Queen Anne's County. The study area is approximately 4,500 km^2 in size and contains a population of about 2.5 million.

The political boundaries fall within five U.S. Geological Survey 8-digit cataloging units: the Gunpowder-Patapsco, Severn, Patuxent, Monacacy, and Lower Susquehanna watersheds. The study watersheds lie predominantly within the Piedmont and Atlantic Coastal Plain physiographic provinces. Land surface elevations range from 0 to 360 m above sea level, with an abrupt change at the Fall Line, the zone of transition between the Piedmont and Coastal Plain. The Piedmont is composed of fractured and folded igneous and metamorphosed igneous and sedimentary rocks. Bedrock near the land surface is weathered to saprolite, and valley floodplains typically are underlain by alluvium deposited by streams. The regolith (saprolite and alluvium) and fractured rock are viewed as two separate but interconnected flow systems based on differences in their storage properties (Heath, 1984). The Atlantic Coastal Plain is composed of semi-consolidated to unconsolidated sediments (overlying saprolite and bedrock) consisting of silt, clay, and sand, with some gravel and lignite, dipping toward the ocean. Coastal Plain sediments range in thickness from a few meters along the Fall Line to as much as 2,400 m along the Atlantic coast (Trapp and Horn, 1997).

The climate in Baltimore is characterized as humid subtropical, with average winter low and high temperatures of $-2^{\circ}C$ and $7^{\circ}C$, respectively, and average summer lows and highs of $23^{\circ}C$ and $33^{\circ}C$, respectively. The average annual precipitation is 1,110 mm and is distributed nearly evenly throughout the year. The storm-event hydrologic response of some Baltimore watersheds has been studied by previous researchers (e.g., Meierdiercks et al., 2010).

Three water filtration plants in Baltimore City supply water to the Baltimore central water distribution system. The Ashburton Water Filtration Plant draws raw water from Liberty Reservoir, located in the Patapsco River watershed. Montebello Nos. 1 and 2 Water Filtration Plants obtain raw water from the Loch Raven Reservoir, which is operated in conjunction with Prettyboy Reservoir, in the Gunpowder Falls watershed. The Baltimore system serves Baltimore City and portions of Baltimore, Howard, and Anne Arundel Counties. Wastewater from the Baltimore system is treated at two plants that discharge to the Back and Patapsco Rivers near their confluences with the Chesapeake Bay. The Washington Suburban Sanitary Commission, which serves the Maryland suburbs of the District of Columbia, provides some water to Howard County from the Patuxent Water Filtration Plant. The T. Howard Duckett and Triadelphia Reservoirs on the Patuxent River are operated together to serve as the raw water source for this plant. Municipal wastewater from the western part of the Howard County service area is treated at the Little Patuxent Water Reclamation Plant. Several smaller surface water systems supply portions of Harford and Carroll Counties. Municipal wells supply most of Anne Arundel County and portions of Harford and Carroll Counties. Outside of the service areas, private wells and septic systems are predominantly used for water supply and wastewater disposal.

METHODS

We collected and analyzed data sets from a wide variety of sources for use in this study. In this section we describe how each component of the water balance

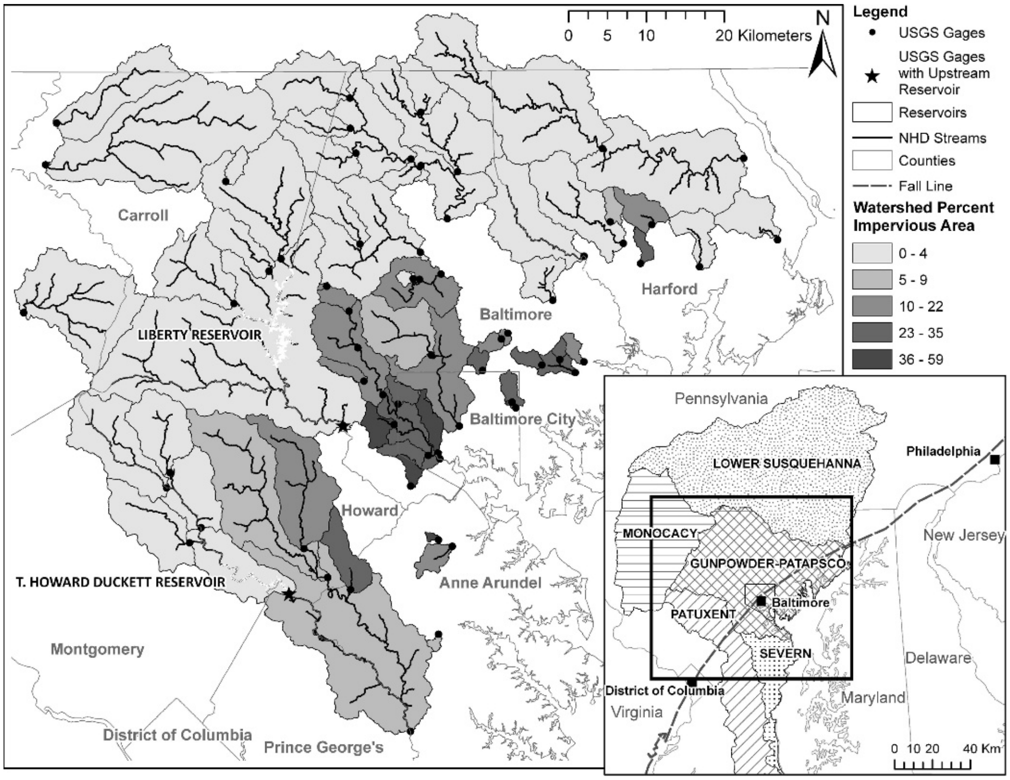

Figure 1. Locations of study watersheds relative to major river basins and political boundaries, with colors representing percentage watershed impervious area. Streams from the National Hydrography Dataset (NHD) are shown as solid black lines. U.S. Geological Survey (USGS) stream gauge locations are shown as black dots. Watersheds were delineated by USGS or by University of Maryland, Baltimore County, Center for Urban Environmental Research and Education (UMBC/CUERE). Percent impervious surface area is from the National Land Cover Dataset (NLCD) 2006. Stream gauges in reservoir-containing watersheds are designated by stars.

was derived. We obtained the percentage of impervious land cover, shown in Figure 1, from the 30-m–resolution 2006 National Land Cover Dataset (NLCD) (Xian et al., 2009). For this and other gridded data sets evaluated, the zonal statistics tool in ESRI ArcGIS software was used to calculate areal means over each watershed. Nested watersheds were analyzed independently. Means of water balance components over the entire region were weighted by watershed area. To compare the hydrologic inflow-outflow behavior of urban and rural watersheds over this time period, we split the 65 study watersheds into two groups. The group referred to as rural includes watersheds characterized by less than 5 percent impervious land cover. The urban group is characterized by 5 percent impervious land cover or greater. Thirty-four watersheds comprised the rural group, and 31 made up the urban group.

We used Parameter-elevation Regression on Independent Slopes Model (PRISM) monthly precipitation grids (PRISM Climate Group, 2011) to estimate the precipitation component of water balances. PRISM uses point precipitation measurements and other climate and landscape parameters to generate monthly gridded precipitation at 2.5–arc minute resolution (~4 km). We obtained monthly streamflow data at U.S. Geological Survey gauges from the National Water Information System (NWIS) (U.S. Geological Survey, 2011). Only watersheds gauged by the U.S. Geological Survey for at least one Water Year during our study period were included. Streamflow and other volume-based water data were divided by watershed area so that all water balance components were comparable as units of depth.

We obtained ET estimates for the region from the Noah land surface model (Ek et al., 2003), forced by the Global Land Data Assimilation System (GLDAS) (Rodell et al., 2004b). The GLDAS/Noah model outputs are available in monthly and 0.25° (~22-km) resolutions globally at the Goddard Earth Sciences Data and Information Services Center (GES DISC, 2011). The finer-resolution NLDAS/Mosaic was not used in our analysis because of its high modeled ET values. Mueller et al. (2011) exhaustively compared global ET estimates and found that both GLDAS/Noah and NLDAS/Mosaic had higher ET globally than did a reference data set but that the GLDAS/Noah estimate was closer to the reference data set.

We used Gravity Recovery and Climate Experiment (GRACE) data to provide a regional estimate of water storage. GRACE is a twin satellite mission launched in 2002 by the National Aeronautics and Space Administration and the Deutsche Forschungsanstalt für Luft und Raumfahrt. The purpose of the mission is to map variations in the earth's gravitational field at approximately monthly and 400-km grid scales by making accurate measurements of the distance between two satellites using GPS and a microwave ranging system (Tapley, 2004). GRACE data have been used to estimate changes in water storage at regional and global scales (Rodell et al., 2004a). We used a Level-3 data product created by the Jet Propulsion Laboratory (GRACE Tellus POET, 2011) that consists of a monthly scaled time series of storage minus mean monthly storage calculated over the 2003–2007 period (Swenson and Wahr, 2006). The time series is a smoothed spatial average over the domain of interest, which overlaps with 4 pixels, each of 1° (~86-km) resolution. To compare our time series of monthly natural water balance changes in storage ($P-Q^*-ET$) to GRACE data, we summed monthly $P-Q^*-ET$ to get an estimate of total storage as a function of time, which we term "derived storage." We then subtracted the mean value of 2003–2007 derived storage from the entire derived storage time series to obtain derived storage normalized to 2003–2007.

When quantifying piped flows, we focused on areas served by imported water and exported wastewater. Because private well intakes, septic disposal systems, and stormwater drainage largely keep water within a watershed, these flows are not modifications to the overall water balance. Municipal groundwater is used in some jurisdictions (Harford and Anne Arundel Counties) and may cross watershed boundaries, but this was not investigated.

For reservoir-containing watersheds, which are shown as starred gauges in Figure 1, we calculated water withdrawals (W) in million gallons per day (MGD) and mm/mo. This amount was an additional monthly export for these two watersheds. The watershed containing Loch Raven Reservoir was not gauged downstream of the reservoir during our study time period; thus, the water balance for this basin could not be calculated. The source of information for water withdrawals consisted of records of raw water inputs to corresponding filtration plants. We obtained data on the combined volume of raw water inputs to all Baltimore water treatment plants from 2000 through 2009, as well as data on water inflows to only the Ashburton Water Filtration Plant from October 2003 through September 2004 (Charshee, 2010). We assumed that the proportion of raw water flowing to the Ashburton Water Filtration Plant of the total raw water flowing to all filtration plants was the same over the course of the decade as it was during the 2004 Water Year. The mean volume of water withdrawn from the Patapsco River between Water Years 2001 and 2009 was 86 MGD, or 157 mm/yr, when scaled by watershed area. For the Patuxent watershed, the reported average value withdrawn from the T. Howard Duckett Reservoir was 50 MGD, or 201 mm/yr (Prince George's County, 2008). This amount was used in our water balances throughout the study period.

Leakage from water supply pipes was calculated for the municipal water service areas of Baltimore City and Baltimore County to illustrate the effects of including pipe leakage on a subset of urban water balances. Leakage from the water distribution system of Baltimore is about 23 percent of flow (McCord, 2009). According to the City of Baltimore (2006), 204.7 MGD of finished water is supplied to Baltimore City and County. We obtained a GIS coverage of the water supply pipe layers, and since the distribution of pipe leaks and ages of pipes were unknown, we assumed the leakage rate to be distributed equally per unit-length of pipe within the service area. We calculated watershed inflows from supply pipe leakage for Baltimore City and County service areas, as well as for study watersheds within this area.

To estimate water inflows from lawn irrigation, we calculated lawn area using a 2007 land cover classification developed by the University of Vermont (UVM) Spatial Analysis Laboratory. UVM derived this 0.63-m land cover classification using LiDAR data, color infrared aerial imagery, building footprints, and road and water polygons for Baltimore City and Baltimore, Howard, and Anne Arundel Counties. The grass/shrub land cover class may overestimate lawns in areas where fields and shrubs are included in the class, and it may underestimate lawns in areas where tree canopy shades lawns and where lawns may therefore be classified as forest cover. We assumed that 25 percent of the area classified as grass/scrub is irrigated at a rate of 1 in. (25.4 mm) per week for 4 months of the year (Law et al., 2004; Milesi et al., 2005; and Claessens et al., 2006).

As in many older cities in which the infrastructure is aging, the Baltimore wastewater collection system can be dominated by groundwater infiltration and rainwater inflow under high water table or wet weather conditions. Groundwater and rain water entering wastewater pipes through cracks or improper connections, such as stormwater draining to wastewater pipes, are commonly termed "inflow and infiltration" or "I&I." Between May 2006 and May

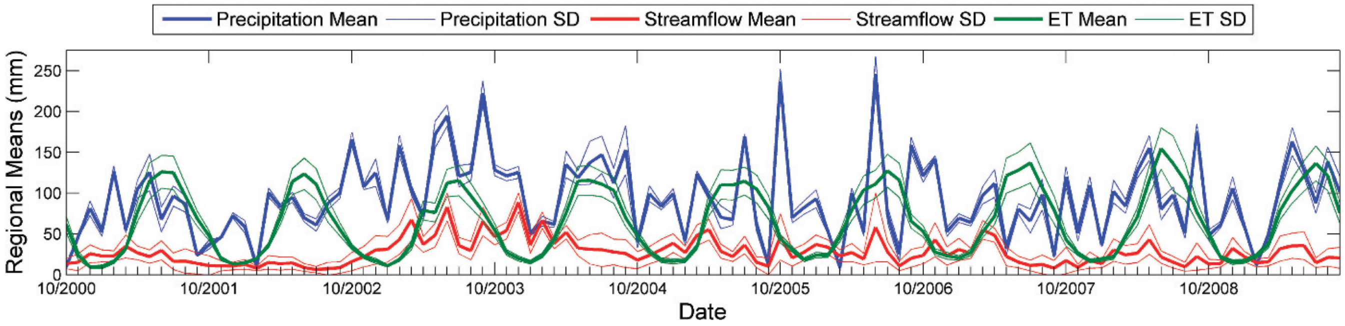

Figure 2. Monthly means and standard deviations (SDs) over all study watersheds of precipitation, streamflow, and evapotranspiration (ET).

2007 Baltimore City conducted a comprehensive wastewater monitoring program that involved metering wastewater flows and quantifying infiltration and inflow (Espinosa and Wyatt, 2007), delineated on a per sewer–basin basis (Espinosa, 2010). The Town of Hampstead in Carroll County conducted an I&I study of its sewer system from February to June 2009 (Carroll County, 2009). Howard County conducted a Sewer System Evaluation Survey of the Little Patuxent sewershed from March to July 2001 and March to June 2003 (Howard County, 2005). Other municipalities in the region have not conducted recent I&I surveys. Because of the difficulty associated with extrapolating from available I&I studies, we only considered I&I exports from Baltimore City sewersheds, Baltimore City as a whole, and study watersheds that fall within Baltimore City as case studies.

RESULTS

Figure 2 shows the mean and standard deviation over all study watersheds of the inflows and outflows of the natural hydrologic cycle—monthly precipitation, streamflow, and ET. The seasonal cycle of ET is evident, with peaks in summer months that sometimes exceeded monthly precipitation inflows. As expected, precipitation showed a high degree of variability from month to month, and streamflow peaks generally corresponded to precipitation but showed comparatively less variability. Monthly precipitation, streamflow, and ET were averaged by season over the 9-year record (Figure 3). For both urban and rural sites, ET was the dominant outflow except in the winter months. Precipitation was similar between urban and rural sites (92 mm/mo for urban; 94 mm/mo for rural), but streamflow was consistently higher in urban watersheds and ET was consistently lower, especially in the summer. In rural watersheds, average summer ET exceeded precipitation by 14 mm/mo. The ET peak in summer led to the well-known effect of decreased summertime streamflow.

To evaluate interannual variability, mean monthly inflows (P) and outflows (Q and ET) over rural and urban watersheds were each summed over water years and plotted in Figure 4. Precipitation averaged 1,118 mm/yr for the region, with an annual mean range of 820 to 1,635 mm/yr. Precipitation and streamflow both showed more interannual variability compared to ET. Mean annual ET was relatively constant, ranging from 695 to 848 mm/yr, and was generally greater than mean streamflow (128–531 mm/

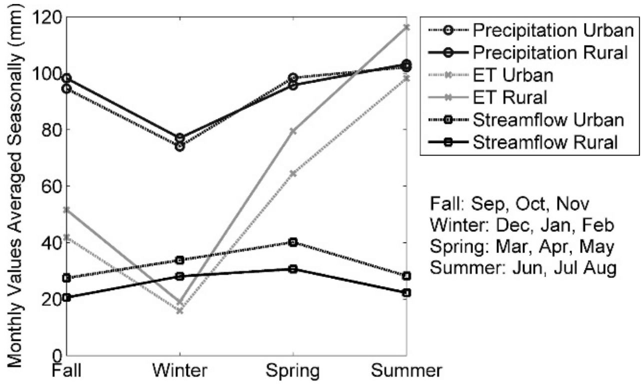

Figure 3. Monthly means over all study watersheds, averaged for each season. Urban watersheds are those with 5 percent impervious area or greater.

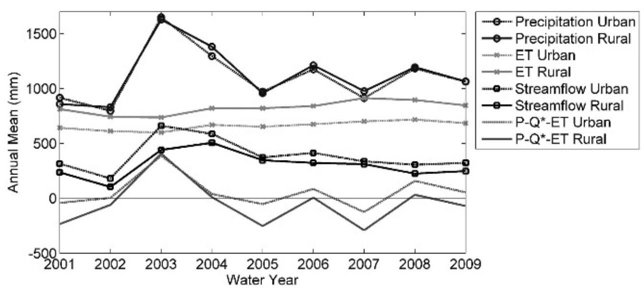

Figure 4. Regional annual means showing interannual variability, along with precipitation (P), streamflow (Q), evapotranspiration (ET), and water balance residual P−Q*−ET, where Q* indicates streamflow Q + reservoir withdrawals W for the two reservoir-containing watersheds.

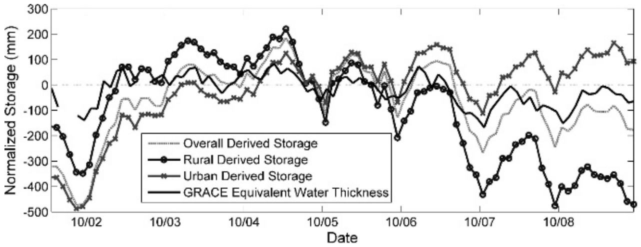

Figure 5. Gravity Recovery and Climate Experiment (GRACE) storage and derived storage both normalized by subtraction of their respective means over the 2003–2007 period and shown monthly for the time period during which the data sets overlap (April 2002–September 2009). Derived storage represents the sum of P−Q*−ET and is given for the average of all watersheds (overall) and the urban and rural subsets. Breaks in the GRACE time series in early months are due to unavailable data (GRACE Tellus POET, 2011).

yr). Mean ET in urban watersheds was 164 mm/yr less than rural ET, while mean urban streamflow was 64 mm/yr greater than rural streamflow. Again, there was little difference between urban and rural precipitation. Figure 4 also shows mean annual inflows minus outflows (P−Q*−ET) over the 9 years, where we included streamflow Q and reservoir withdrawals W together as Q* for the two reservoir-containing watersheds. Generally, the reduced ET in urban areas led to a greater residual P−Q*−ET value compared to the rural value. The difference between urban and rural streamflow increased during the wettest year (2003), which led to a convergence of the urban and rural P−Q*−ET values toward the same value. The annual difference between natural watershed inflows and outflows (P−Q*−ET) was on average negative for rural areas (−108 mm/yr) and positive for urban areas (19 mm/yr).

We evaluated our calculated storage changes by comparison to GRACE data. GRACE data over our study region showed that mean storage changed little between 2002 and 2009 (Figure 5). The GRACE storage and P−Q*−ET derived storage curves showed annual cycles that were similar in timing. Storage in both curves peaked during spring months, declined with high ET during summer, and started increasing again in the fall. Following the increase in storage with the wet year of 2003, however, the rural P−Q*−ET storage curve exhibited a negative trend for the remainder of the study period, whereas the GRACE curve showed little trend. Urban-derived storage had the opposite trend: it increased over time compared to GRACE storage. Monthly changes in GRACE storage were calculated by subtracting the previous month's storage value from the current month's storage. Over the same time period (April 2002 to September 2009), the mean change in storage from GRACE was 0.84 mm/mo. The change in

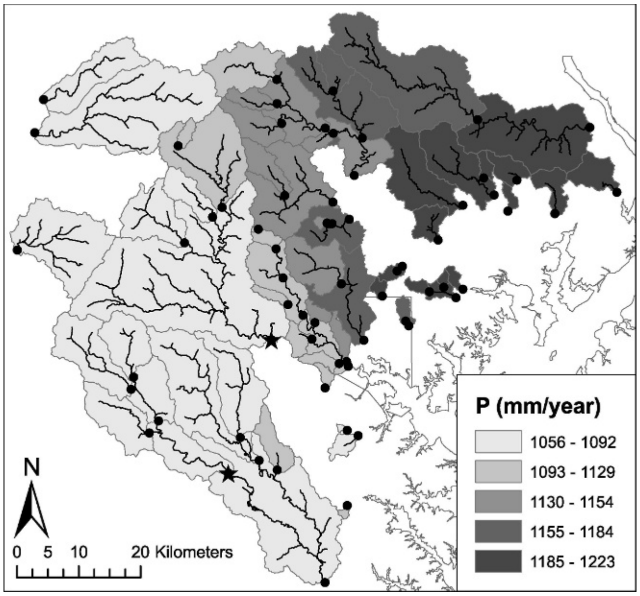

Figure 6. Mean annual precipitation, 2000–2009, from Parameter-elevation Regression on Independent Slopes Model (PRISM) monthly precipitation grids (PRISM Climate Group, 2011).

storage from the normalized derived storage for rural areas (−2.8 mm/mo) was less than the GRACE change in storage, while the corresponding urban value (5.5 mm/mo) was greater.

Figure 6 shows the spatial pattern of mean annual PRISM precipitation by watershed. There is a clear spatial pattern in precipitation over the Baltimore region. The northeastern-most watersheds received over 100 mm/yr more precipitation than did the western watersheds. Mean annual streamflow + withdrawals (Q*) is shown in Figure 7. Urban watersheds were characterized by greater runoff (427 mm/yr) compared to rural watersheds (363 mm/yr). There was also greater streamflow in the northeast part of the study region, which appears to correspond to the high-precipitation region. The range in streamflow was much greater than that of precipitation. Figure 8 shows the mean annual ET where urban watersheds generally had lower ET.

The mean annual P−Q*−ET (mm) is shown in Figure 9. P−Q*−ET is plotted versus percent impervious area in Figure 10, where the size of the marker is proportional to watershed area. The logarithm of percent impervious area was used because many of the watersheds have close to zero percent impervious area. Figure 10 shows generally that watersheds with the lowest values of percent impervious area are associated with negative values of P−Q*−ET. As the percent impervious area increases, there is a larger spread in P−Q*−ET values, with most urban watersheds characterized by an increase in P−Q*−ET compared to the rural baseline.

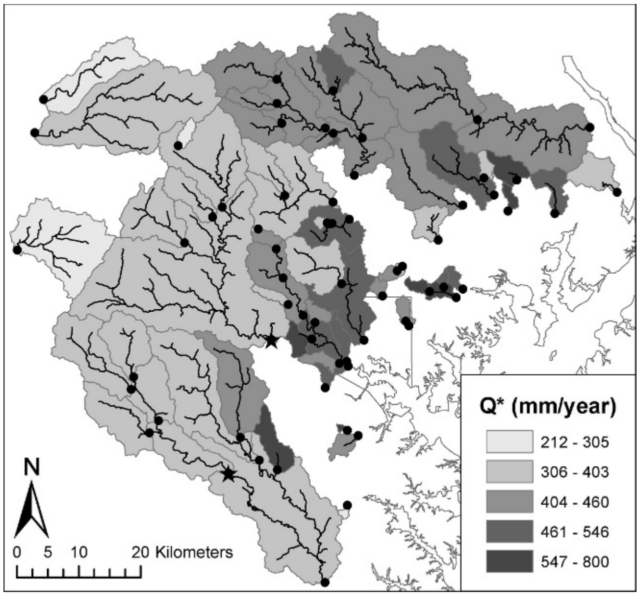

Figure 7. Mean annual streamflow Q + reservoir withdrawals W, where Q* = Q + W. Mean annual streamflow 2000–2009 is from the U.S. Geological Survey (USGS) National Water Information System (NWIS) (U.S. Geological Survey, 2011). Reservoir withdrawals were estimated for Liberty Reservoir (Charshee, 2010) and T. Howard Duckett Reservoir (Prince George's County, 2008).

The three piped water balance terms we considered were lawn irrigation, supply pipe leakage, and I&I. The supply of treated water to Baltimore City in fiscal year (FY) 2005 was 107.25 MGD, or 707 mm/yr (City of Baltimore, 2006). The metered water in FY 2010 was 90.6 MGD (598 mm/yr) (Espinosa, 2010). We proportionally allocated wastewater between Baltimore County and Baltimore City by population served, which resulted in an estimated wastewater demand of 101 MGD for Baltimore City in FY 2000 (669 mm/yr) (City of Baltimore, 2006). Instead of presenting overall numbers for watershed potable water imports and wastewater exports, we believe it is more relevant to water budget calculations to quantify the interactions between piped and natural systems.

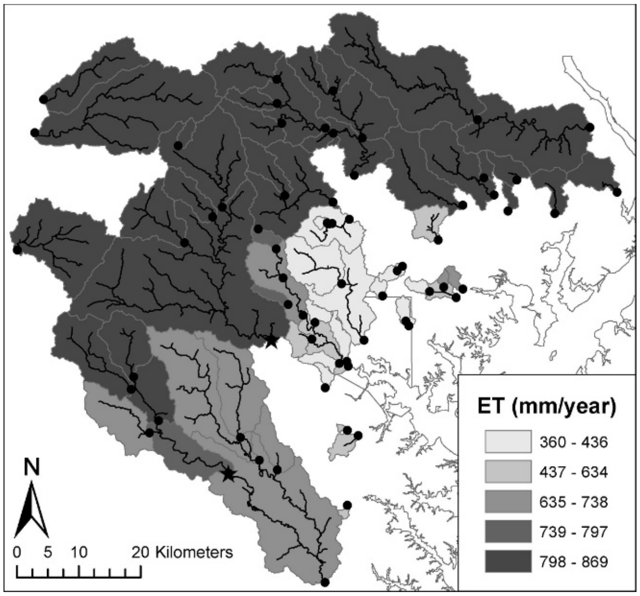

Figure 8. Mean annual evapotranspiration (ET) from Global Land Data Assimilation System (GLDAS)/Noah, available at the Goddard Earth Sciences Data and Information Services Center (GES DISC, 2011).

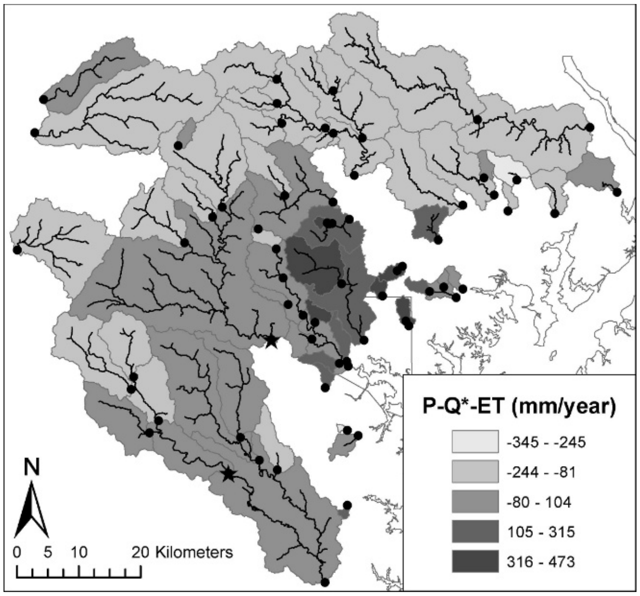

Figure 9. Mean annual P−Q*−ET, where the sources of P, Q*, and ET are as indicated in Figures 6 through 8.

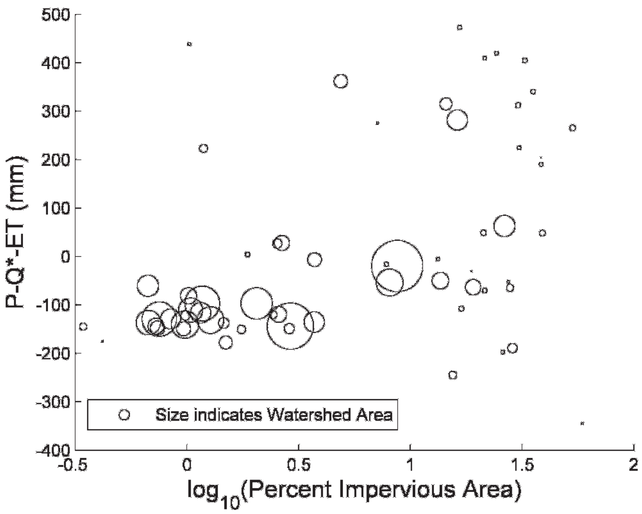

Figure 10. Logarithm of impervious area versus P−Q*−ET (mm), where the size of the marker is proportional to watershed area. The division between urban and rural at 5 percent impervious is at 0.7 on the log-scale of the horizontal axis.

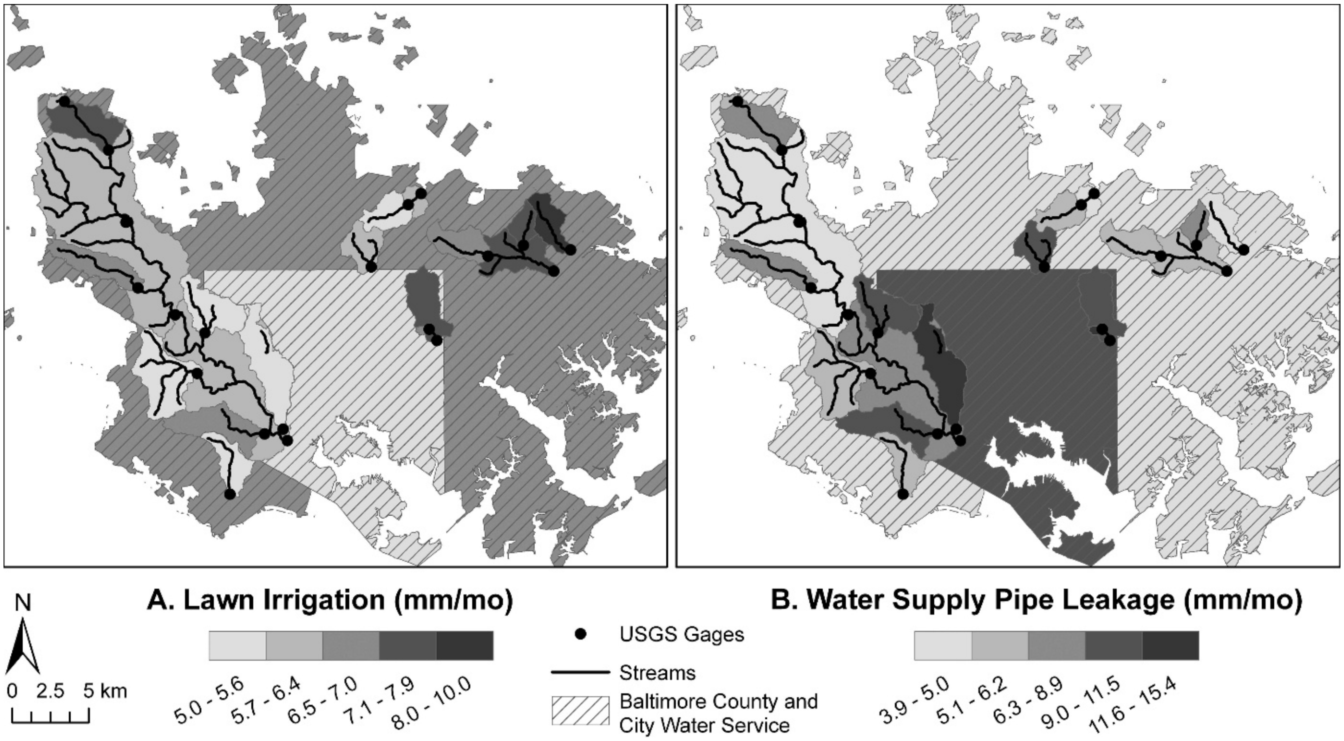

Figure 11. Contributions of lawn irrigation (A) and water supply pipe leakage (B) (in mm/mo) over Baltimore City, the served area of Baltimore County and the watersheds contained in these areas.

We found water was served to Baltimore City and County through a total length of 6.5×10^6 m of water supply pipes. We assumed that leakage was 23 percent of water supply flow (McCord, 2009), and this 47 MGD of leakage was equally distributed per pipe length. This was calculated to be 7 gallons/day of leakage per meter of pipe. Watersheds within the served area of Baltimore City and County ranged between 20 percent and 80 percent grass/shrub. Overall, Baltimore City and served Baltimore County were characterized by 21 percent and 26 percent of land area in the grass/shrub class, respectively. Estimates of the spatial distribution of supply pipe leakage and lawn irrigation are provided in Figures 11A and B. Only watersheds within service areas of Baltimore City and County are shown, along with overall estimates for the city and county served areas. Pipe leakage was related to density of water supply pipes. Thus, leakage generally increased with impervious surface coverage, as they are both estimators of degree of urbanization. Lawn irrigation was correlated to lawn area, which was inversely correlated with impervious surface cover within the service area. The sum of supply pipe leakage and lawn irrigation ranged between 11 and 20 mm/mo, or assuming that leakage occurred for 12 mo/yr and lawn irrigation for 4 mo/yr, between 84 and 203 mm/yr. Over Baltimore City, the sum was 160 mm/yr.

I&I for Baltimore City (Figure 12) was estimated to be 92 MGD (606 mm/yr) and was dominated by groundwater-derived infiltration during dry weather conditions. I&I was approximately 90 percent of the wastewater demand, which is high but not unheard of in the region. In the Howard County I&I study, the percentage of metered sewer flow from I&I in different sewersheds ranged from 41 percent to 94 percent. Within the town of Hampstead in Carroll County, 49 percent of dry-day wastewater flow was from groundwater infiltration alone. I&I export from Baltimore City was greater than average streamflow for gauged urban watersheds (427 mm/yr).

We used two watersheds within Baltimore City as case studies for comparison of I&I and other water balance components. These watersheds, Gwynns Run and Moores Run (shown in Figure 12), had spatially averaged I&I values of 670 mm/yr and 460 mm/yr, respectively. In Figure 13, we present the average of the water balances for these two watersheds, including all piped and natural components, along with the mean rural water balance. The urban water balance exhibits less ET, more streamflow, and much more outflow in the form of I&I as compared to the rural water balance. Urban pipe leakage and lawn irrigation are minor compared to inflows by precipitation. The components shown in this figure were estimated separately (not by subtraction), and therefore inflows

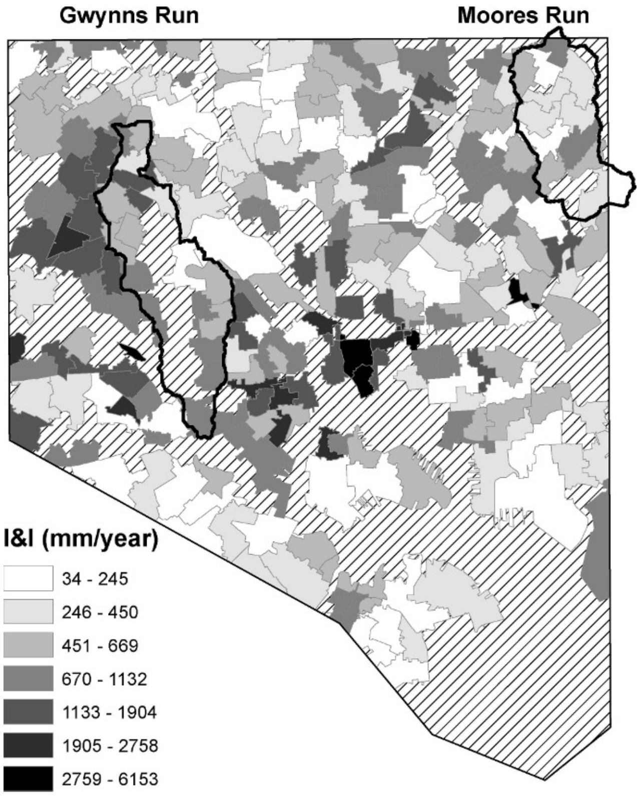

Figure 12. Infiltration and inflow (in mm/yr) per sewershed from the Baltimore City Comprehensive Wastewater Monitoring Program (Espinosa and Wyatt, 2007; Espinosa, 2010). The hatched areas are those for which infiltration and inflow (I&I) estimates are not available. Gwynns Run and Moores Run watersheds are indicated by heavy black boundaries.

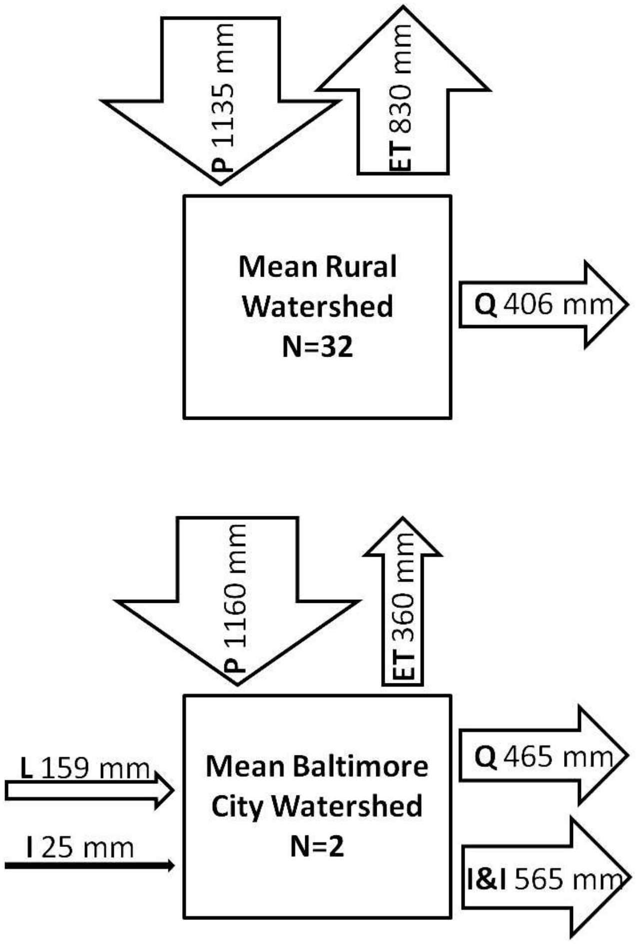

Figure 13. Comparison of the annual water balance components between the mean of 32 rural (impervious area <5 percent and without reservoirs) and two urban watersheds in Baltimore City (Gwynns Run and Moores Run). The width of the arrows corresponds to the magnitude of the flows (in mm/yr). Components were estimated separately (not by subtraction), so inflows do not necessarily equal outflows.

do not necessarily equal outflows. In the case of average of rural watersheds (excluding the two reservoir-containing watersheds), the value for inflows minus outflows was −101 mm/yr, whereas for urban watersheds the inflows minus outflows value was −46 mm/yr.

DISCUSSION

In comparing GRACE data and the residual between natural water balance terms (P−Q*−ET), we expected that we would need to include piped components for urban areas but that we would have well-characterized rural inflows and outflows. If we had accurately estimated flows in rural areas, and if there was no annual change in storage, we would predict the difference between inflows and outflows (P−Q*−ET) to be zero. Instead, we found that the P−Q*−ET value in rural watersheds was negative. On the other hand, GRACE data, which offer an evaluation of an integrated signal of water storage over the region, did not show declining storage. The monthly change in GRACE storage was greater than that found using rural P−Q*−ET. This leads to a decreasing derived P−Q*−ET storage curve over time for rural watersheds as compared to the GRACE data.

We suspect that the negative monthly rural change in storage (P−Q*−ET) is due to bias in one or more of the water balance components. For example, if ET, the most uncertain natural water balance term, is regionally overestimated by the land surface model, undeveloped P−Q*−ET would be negative. This would lead to an apparent declining storage trend, when actual storage is relatively stable. For urban watersheds, our calculated mean monthly change in storage is greater than the GRACE change in storage. If GLDAS/Noah overestimated ET throughout the region, then P−Q*−ET for urban areas would be even more positive. Lawn irrigation in water service areas is not included in the forcing of GLDAS/Noah, however, so actual urban ET might be higher than the ET modeled by GLDAS/Noah. When considering only natural water balance components, urban excess water can be explained by including piped components. For Baltimore City, the net watershed export due to piped components (I&I − L − I) was found to be 446 mm/yr (606 mm/yr of I&I − 160 mm/yr of I + L). Correspondingly, for Gwynns Run and Moores Run, the net watershed exports due to piped components were 466 and 297 mm/yr, all of which are greater than the discrepancy between urban and rural water balances. The high levels of I&I measured by Baltimore City occurred before planned upgrades were made to the wastewater system, and therefore the water balance of the Baltimore region will change as cracked pipes are repaired.

Although the mean P−Q*−ET value was greater for urban compared to rural watersheds, there is a larger spread in P−Q*−ET for urban watersheds (Figure 10). This may be related to, among other things, the spatial variability in piped water balance terms. The net contribution of piped components may change dramatically over small distances. For example, I&I per sewershed ranged from 0 mm/yr to 6,150 mm/yr, with the highest I&I values located in downtown Baltimore (Figure 12). This range means that for an individual sewershed, the net effect of piped components (I&I − L − I) on the water balance may be positive or negative regardless of the mean for Baltimore City. Lawn irrigation and pipe leakage might also have similar spatial heterogeneities, although we do not have the data to quantify these components. Pipe leakage is likely not distributed equally per pipe length, but rather is highly concentrated among a few water main leaks. Similarly, homeowners of some watersheds could be irrigating their lawns well above landscaping industry recommendations, which would lead to higher lawn irrigation inputs than we have assumed in some areas. Depending on the relative rates of I&I, pipe leakage, and lawn irrigation, urban watersheds may have a range of positive or negative net contributions to the water balance from piped components, which can lead to the spread among urban watersheds shown in Figure 10.

Since each component of the water balance in Figure 13 is estimated separately (not by subtraction), neither of the example watersheds is balanced in terms of inflows and outflows. The rural watersheds have negative values for inflows minus outflows. The average of two Baltimore City watersheds shown in Figure 13 has a small negative value of inflows minus outflows. We do not have strong evidence to indicate that the apparent imbalance between inflows and outflows is caused by a progressive cumulative change in annual storage for either rural or urban watersheds. The regionally flat trend of GRACE data and the heterogeneous distribution of net water balance values for individual watersheds, all of which are characterized by uncertainty, indicate that these apparent discrepancies may be caused by errors in one or more of the components of the water balance.

Some of the challenges for this study included obtaining accurate ET estimates as well as resolving the spatial mismatch of data sets. We used land surface models to obtain ET estimates. This procedure is less than ideal for urban areas because (1) the resolution of land surface model output is far too coarse to precisely describe ET in cities and (2) the forcing data set, which includes gridded precipitation used to drive the land surface models, does not properly reflect urban water inflows from irrigation and supply leakage. One alternative would be use of a finer-resolution satellite product, such as the newly released MODIS ET product (MOD16) (Mu et al., 2011). This product does not, however, include urban areas because of the lack of good satellite estimates of leaf area index (Mu, 2010). Flux towers can provide good point estimates of ET in urban areas, but a sparse network may not be reasonably extrapolated to entire cities. Modeling approaches (e.g., Bou-Zeid et al., 2009) can be used to calculate urban ET, but they require distributed meteorological inputs that are not commonly available. Accurate, fine-scale, spatially variable estimates of ET over cities are currently lacking but are crucial to water budget closure. This is an important area of future work for those interested in understanding the quantity and distribution of water for both natural and engineered urban systems.

As is often the case for urban areas, it is a complex task to integrate the spatial boundaries required, such as watersheds, counties, and water and wastewater service areas. For example, streamflow was measured for watersheds, pipe leakage was estimated over water service areas, and sewer infiltration was measured over sewersheds within one of the area municipalities. This leads to limitations in the comparison of piped and natural water balance components for all of the developed watersheds. Data from municipalities, necessary for quantifying piped components of the water balance, are often scarce compared to the availability of natural component data.

CONCLUSIONS

1. Our analysis has shown that in the Baltimore region, natural inflows minus outflows (P−Q* −ET) increase along a rural-to-urban gradient. When we solely considered natural water balance components, we found excess water in many urban

watersheds due to decreased ET, compared to rural sites. We did not have evidence to indicate that the magnitudes of total inflows and outflows were different between urban and rural watersheds or that there were systematic increases or decreases in storage over time. Nevertheless, the forms of inflows and outflows were certainly different, since urbanization introduces a number of additional water balance components, including leakage from supply pipes, lawn irrigation, and infiltration and inflow into wastewater collection pipes. There was a much greater proportion of water exiting urban watersheds by wastewater pipes or streamflow as compared to ET-dominated rural watersheds. Precipitation was still the largest inflow to urban watersheds, although lawn irrigation and water supply pipe leakage both contributed additional water.

2. Using estimates of piped components, we compared their magnitudes to natural water balance components. We found that I&I for two Baltimore City watersheds were 131 percent and 110 percent of watershed mean annual streamflow. Within the Baltimore City and County water service areas, lawn irrigation and water supply pipe leakage together accounted for 11–21 percent of monthly precipitation inputs. Annually, for the average of two Baltimore City watersheds, lawn irrigation and pipe leakage were 14 percent of total watershed inflows, and I&I was 41 percent of total watershed outflows. Reservoir withdrawals upstream of gauges were 64 percent (Liberty Reservoir) and 100 percent (T. Howard Duckett Reservoir) of annual streamflow in reservoir-containing watersheds. On average, the most significant piped flows were I&I, but piped components were extremely spatially heterogeneous. The net effect of pipe leakage can change within relatively small distances and led to an observed broad range of natural inflows minus outflows in urban areas.
3. We observed that $P-Q^{*}-ET$ in urban areas was greater than in rural areas for dry years (e.g., 2001, 2002, 2005, 2007), whereas the urban and rural $P-Q^{*}-ET$ values converged in the wet year of 2003. The wet-year behavior could be attributed to urban streamflow increases relative to rural streamflow, while the ET difference stayed about the same compared to other years. Rural areas showed more seasonal variability in ET than did urban areas. On average, there were some modest variations in precipitation and streamflow by season, but ET was by far the largest control of seasonal variations in the water balance, leading to corresponding seasonal storage cycles.
4. Our understanding of water balances would benefit from expanded data collection by municipalities as well as continued development of gridded national and global data products, such as those provided by precipitation models, land surface models, and remote sensing. On regional scales, gridded data products would help close the water budget for even data-sparse areas. For understanding of urban areas, however, finer-scale data are needed, particularly for ET, to constrain water budgets. Municipalities could collect data to help increase the accuracy of urban water balance components. For example, municipalities could estimate I&I by improving communication and data sharing between water and wastewater agencies and comparison of volumes between their systems. Assessments of temporal (e.g., seasonal) changes in I&I could be used to determine times of concentrated groundwater infiltration. Municipalities could also document water supply and wastewater collection pipe leakage through existing meter records in many cases. Improved knowledge of the significant components of urban water balances can be used for a variety of purposes, including the development of urban hydrologic surface and subsurface models.

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