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COUPLING OF THE WATER CYCLE WITH PATTERNS OF URBAN GROWTH IN THE BALTIMORE METROPOLITAN REGION, UNITED STATES[1]

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ABSTRACT: Regional municipal water plans typically do not recognize complex coupling patterns or that increased withdrawals in one location can result in changes in water availability in others. We investigated the interaction between urban growth and water availability in the Baltimore metropolitan region where urban growth has occurred beyond the reaches of municipal water systems into areas that rely on wells in low-productivity Piedmont aquifers. We used the urban growth model SLEUTH and the hydrologic model ParFlow.CLM to evaluate this interaction with urban growth scenarios in 2007 and 2030. We found decreasing groundwater availability outside of the municipal water service area. Within the municipal service area we found zones of increasing storage resulting from increased urban growth, where reduced vegetation cover dominated the effect of urbanization on the hydrologic cycle. We also found areas of decreasing storage, where expanding impervious surfaces played a larger role. Although the magnitude of urban growth and change in water availability for the simulation period were generally small, there was considerable spatial heterogeneity of changes in subsurface storage. This suggests that there are locally concentrated areas of groundwater sensitivity to urban growth where water shortages could occur or where drying up of headwater streams would be more likely. The simulation approach presented here could be used to identify early warning indicators of future risk.

(KEY TERMS: urban areas; watersheds; simulation; hydrologic cycle; groundwater management; water supply; planning; urbanization.)

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INTRODUCTION

In 2006, Maryland Department of the Environment announced a moratorium on expanding exurban development northwest of Baltimore, Maryland, until new sources of water could be identified. The focus was on Westminster, Maryland, the seat of Carroll County, which at that time was actively seeking to build new housing to keep pace with its fast-growing population. Maryland Department of the Environment calculated that the city, whose water source is the fractured-rock aquifers of the Piedmont, could not meet existing water demand during even minor

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droughts. While Maryland may seem to be an unlikely place for water shortages owing to its temperate climate, proximity to the Chesapeake Bay, and the dense network of streams covering the state, continued pressures from urban growth emanating from the Baltimore-Washington metropolitan area have resulted in warnings about potential future water shortages.

In 2004, this region was the subject of two key studies, one focusing on patterns of urban growth, and one assessing impacts of population projections on future water supplies. Jantz *et al.* (2004) applied the urban growth model SLEUTH (Clarke *et al.*, 1997) to project the spatial distribution of urban growth patterns in the Baltimore-Washington area. This cellular automata model predicts patterns of "urban" *vs.* "nonurban" pixels, based on calibration to historical growth patterns. Since 1950, the pattern of urban expansion in the Baltimore region has been centrifugal with development occurring increasingly outside of the urban core; new development has not been coincident with existing water service infrastructure (Jantz *et al.*, 2014). This type of development pattern has implications for water availability as new private well installations place increased pressure on groundwater resources and alter spatial patterns and quantities of groundwater recharge and surface water flows.

A study by the State of Maryland (Wolman, 2004), prompted by the drought of 2002, made a rough prediction of water demands based on county-level population projections and crude estimates of water availability up to the year 2030. The study found that water use was projected to increase by 16.1% for the state, with a range of −2.1% (western Maryland) to +41% (southern Maryland), and concluded that predicting water supply and demand is a complex process requiring water use and population data, hydrologic data, and mathematical modeling. Interestingly, these two studies (Jantz *et al.*, 2004; Wolman, 2004) were carried out at about the same time for different purposes yet neither was used to inform the other.

This confluence of events motivated us to ask the following question, which we aim to address in this study: *What is the effect of the predicted pattern of urban growth on water availability?* We developed a fully integrated, three-dimensional groundwater-surface water-land surface model (ParFlow.CLM) coupled with the urban growth model SLEUTH, for the six-county Baltimore metropolitan region (Figure 1). The methodology can be applied to any urban area. Our conceptual model is that exurban development generated by the urban growth model can be incorporated into the integrated hydrologic model as additional water supply wells, changes in land cover, and changes in surface permeability (Figure 2).

METHODS

Study Area

We focused on the contiguous metropolitan Baltimore region (Baltimore City and the surrounding five counties of Anne Arundel, Howard, Carroll, Baltimore, and Harford) (Figure 1), with an estimated total population of 2.72 million (U.S. Census Bureau, 2014). The fall zone, where the Piedmont and Atlantic Coastal Plain physiographic provinces meet, crosses the study area (Figure 1). This region receives an average of 1,060 mm of annual precipitation and is classified as humid subtropical climate. The Baltimore water distribution system ("the Central System," Figure 3) is supplied by reservoirs on the North Branch Patapsco River and the Big Gunpowder Falls. Additional sources of public water supply in the region include groundwater, the Susquehanna River, several smaller rivers, and connections to the Washington, District of Columbia area water supply system (Figure 3).

Urban Growth Model

The SLEUTH urban growth model (Clarke *et al.*, 1997; Jantz *et al.*, 2010) serves as a platform to integrate urban land change, as observed at a fine scale by satellite, with other datasets that represent drivers of observed change. SLEUTH has been coupled with hydrologic models (*e.g.*, Arthur-Hartranft *et al.*, 2003; Goetz and Jantz, 2011; Ciavola *et al.*, 2014), climate models (*e.g.*, Civerolo *et al.*, 2007), and watershed land-use planning models (*e.g.*, Lin *et al.*, 2007).

We used the SLEUTH-3r model (Jantz *et al.*, 2010) to read and explore a series of historic snapshots that represent the geospatial distribution of nonurban and urban states in the Baltimore region. We derived our snapshots from the Chesapeake Bay Land Cover Data series (Irani and Claggett, 2010), which cover our study area and represent the spatial distribution of land cover states for the years 1984, 1992, 2001, and 2006 at a 30-m resolution. Because we had multiple historic data points available, we calibrated SLEUTH using the 1984-2001 time period and withheld the 2006 data for validation.

Both calibration and forecasting are informed by exclusion/attraction layers, required inputs to SLEUTH that describe areas more or less likely to become developed (Jantz *et al.*, 2004, 2014). The exclusion/attraction layers we developed for the Baltimore region incorporated population and employment changes as key drivers of urban land cover change (Jantz *et al.*, 2014). We relied on data from

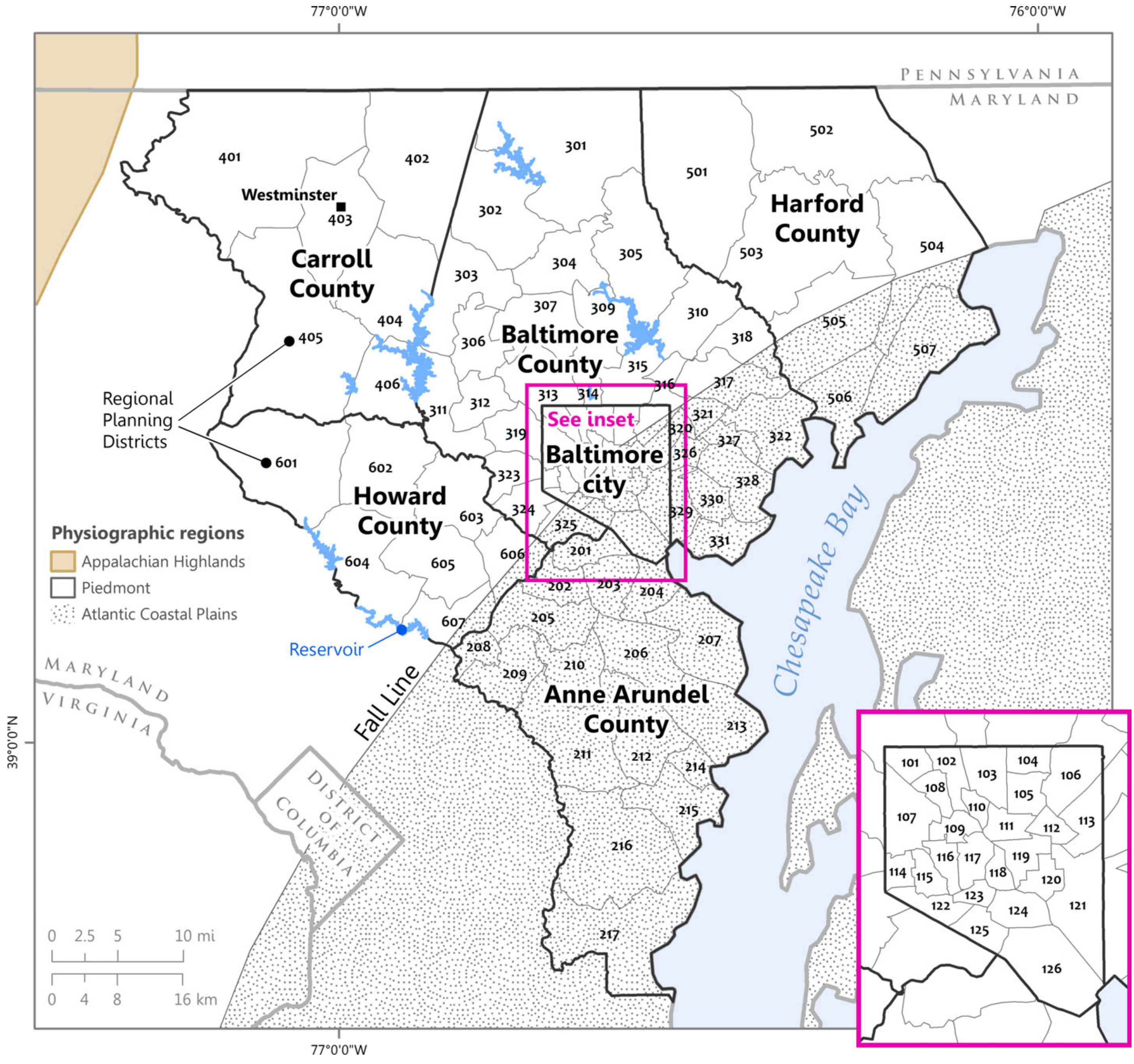

FIGURE 1. Map of Study Area Showing the Modeled Spatial Domain of the Baltimore Metropolitan Region. Locations of Westminster, Maryland, Baltimore water supply reservoirs, and Regional Planning District (numbered) boundaries are indicated.

the Baltimore Metropolitan Council's Cooperative Forecasting Group (BMC-CFG) for forecasts of population, households, and total employment for the Baltimore region. We opted to use this local dataset, as opposed to national forecasts such as the U.S. Environmental Protection Agency's Integrated Climate and Land-Use Scenarios data (Bierwagen *et al.*, 2010), because it includes forecasts of people, housing, and employment, all of which are required for different aspects of our modeling work and which are not consistently available through other sources. Using forecasts from BMC-CFG we assembled a complete time series for the period 1985-2030, at five-year intervals for subcounty Regional Planning Districts (RPDs) (Figure 1).

The amount and location of urban growth can be influenced by both patterns of population growth (new places of residence) and employment growth (new places of work) (Jantz *et al.*, 2014). Accordingly, we conceptualized urban growth in each RPD as the aggregate result of population growth and job growth. We estimated the expected amount of urban

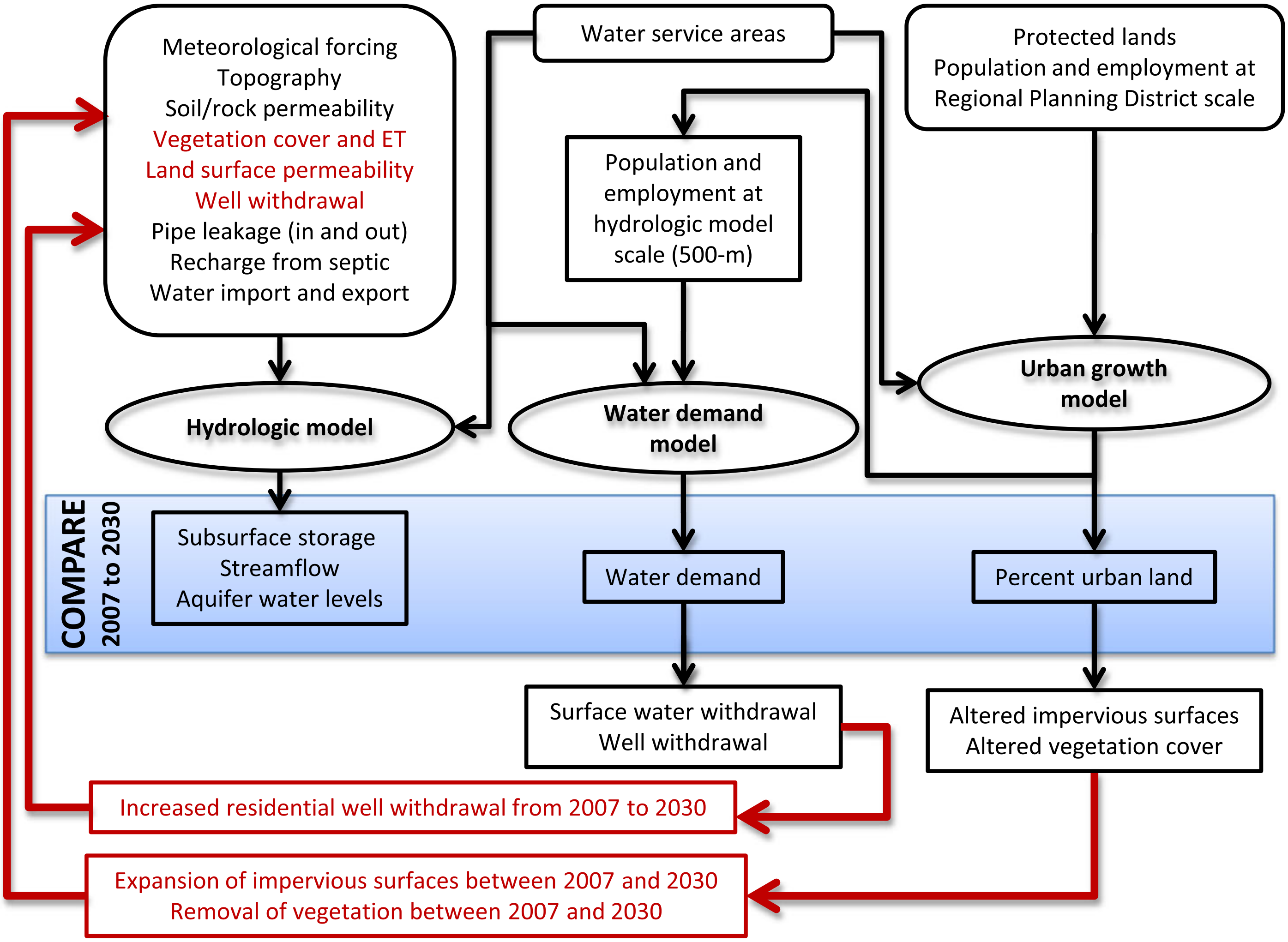

FIGURE 2. Conceptual Model of Coupling between Urban Growth Model and Integrated Hydrologic Model. Red boxes and associated arrows indicate coupling where three output datasets from the urban growth model affect input to the hydrologic model. The blue box shows model output (*e.g.*, percent urban land, water demand, and subsurface storage) evaluated as urban land was projected to grow between 2007 and 2030.

development at the regional scale given the population and job forecasts, under an accelerating rate scenario of land consumption, which resulted in a 7.8% increase in urban land cover over 2006 levels. We then identified RPDs that were expected to attract proportional or disproportional shares of total regional growth, and used this information to build exclusion/attraction layers to inform SLEUTH's subregional spatial allocation of growth (Jantz *et al.*, 2014) (Figure 4).

At this point in our land change modeling process, we had population and employment forecasts at the scale of RPDs; estimates of urban land change for 2030 derived from SLEUTH at the 30-m grid of the Chesapeake Bay Land Cover Data series; and the 500-m ParFlow.CLM grid (discussed below). We therefore developed a process that generates the required urban growth estimates at the 500-m grid for ParFlow.CLM using dasymetric mapping techniques.

Intelligent Dasymetric Mapping (Mennis, 2003; Mennis and Hultgren, 2006) is a GIS-based workflow that takes as input count data (in this case, population and employment forecasts) mapped to a set of source zones (in this case, RPDs) and a categorical ancillary dataset (in this case, SLEUTH predictions of urban and nonurban land covers), and redistributes the count data to a set of target zones (in this case, the 500-m grid used by ParFlow.CLM). To allocate the population and employment forecasts from the RPDs to the 500-m grid, we used the BMC-CFG's forecast data for transportation analysis zones

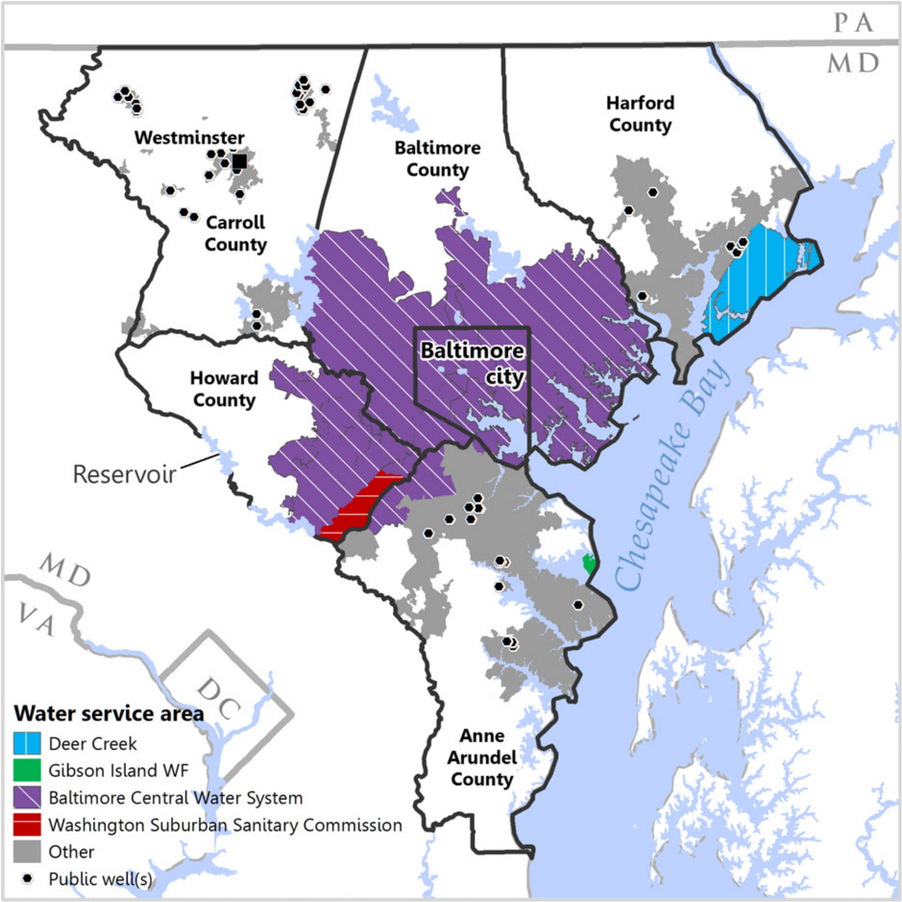

FIGURE 3. Water Service Areas in the Baltimore Metropolitan Region. The four service areas highlighted in this figure (Deer Creek, Gibson Island Well Field, Baltimore Central Water System, and the Washington Suburban Sanitary Commission) are also shown in Figure 8. Gray indicates other municipal water service systems, whereas white areas indicate areas without municipal systems where residents use private wells.

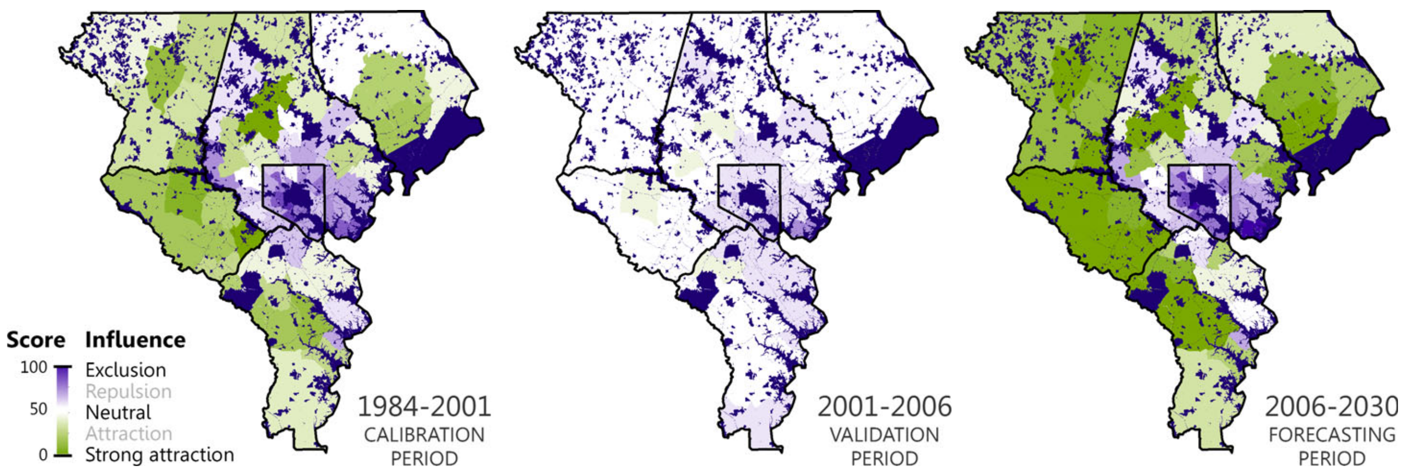

FIGURE 4. Maps of the 30-m Exclusion/Attraction Layers Used in Calibration, Validation, and Forecasting of the SLEUTH Urban Growth Model.

(TAZ), small spatial units nested within RPDs as an intermediary spatial unit. We identified TAZs that were completely contained within urban or nonurban areas and assigned the population counts to the respective class. The population value in a TAZ that overlapped more than one class was assigned to either the urban class or the nonurban class, whichever covered the largest portion of the TAZ. Next, we summed TAZ population counts and TAZ polygon areas by class and by RPD, from which we estimated the population intensity value of each class in each RPD. Then, using the same workflow just described, we used the TAZ-level BMC-CFG employment forecasts to help us estimate the relative employment intensities, by class, within each RPD. At this point, we had all the information needed to use the Intelligent Dasymetric Mapping technique to integrate the annual time series of SLEUTH predictions and the annual time series of BMC-CFG forecasts, and to organize the results in the 500-m grid to be used by the water use analysis and hydrologic model ParFlow.CLM (Figure 5).

Water Use

Based on the SLEUTH output and BMC forecasts, we estimated yearly residential and worker population in each model grid cell (Figure 5). By assuming that residential water use was 300 L (80 gallons) per person per day (Kenny *et al.*, 2009) and commercial water use was 80 L (20 gallons) per person per day (W. Qadri, Baltimore City Public Works, February 15, 2011, personal communication), the projected residential and commercial water use values were calculated for each grid cell, and summed to obtain total annual water use. The source of residential water in each grid cell was then designated as being either public or private. Within the public area, designated sources included water supply reservoirs, well fields, or rivers (Figure 3). The urban growth in the metropolitan area according to SLEUTH was then apportioned to the appropriate water source.

Hydrologic Model

ParFlow is a three-dimensional, finite-difference, parallel hydrologic model that couples variably saturated subsurface flow with overland flow (Ashby and Falgout, 1996; Jones and Woodward, 2001; Kollet and Maxwell, 2006, 2008). ParFlow.CLM further integrates ParFlow with the land surface model Common Land Model (CLM), allowing for two-way coupling between soil moisture and evapotranspiration processes (Maxwell and Miller, 2005). We use ParFlow.CLM to represent the surface and subsurface hydrologic systems in an integrated way and to allow for parallel processing to simulate a regional hydrologic system.

The model domain for our application of ParFlow.CLM included an area of 13,216 km^2 (Figure 1). Model grid resolution was 500 m by 500 m (horizontal) by 5 m (vertical), with a maximum vertical thickness of 1,080 m, resulting in a total of 2,869,549 model grid cells (Bhaskar *et al.*, 2015). Even with a coarser grid resolution as compared to the SLEUTH model, efficient execution of a hydrologic model with this number of grid cells required parallel processing. ParFlow was built for efficient parallelization, and was chosen in part for this purpose. The simulations presented here were run on 324 parallel processors on the National Institute of Computational Sciences Kraken supercomputer system; a test of model performance required 1 h of wall-clock time for 24 h of simulated time.

Inputs to the ParFlow model included topographic data to derive surface drainage direction, and hydraulic conductivity and porosity for fractured bedrock, saprolite, soil, and Atlantic Coastal Plain aquifers and confining units. Data were derived from state well records, SSURGO (http://soildatamart.

FIGURE 5. Maps of Employment, Population, and Impervious Surfaces at the 500-m Grid Scale Used as Input to ParFlow.

nrcs.usda.gov/USDGSM.aspx), and literature sources (see Bhaskar *et al.*, 2015, for details). Input datasets for CLM included meteorological forcing data (derived from the North American Land Data Assimilation System Phase 2 (NLDAS-2), http://mirador.gsfc.nasa.gov) as well as land cover, which affects evapotranspiration through properties such as leaf area index. For urban areas, we included fluxes of estimated lawn watering rates, water supply pipe leakage, infiltration and inflow of groundwater and rainwater into wastewater pipes, residential and municipal well pumping, and reservoir withdrawals (Bhaskar *et al.*, 2015).

We initialized the hourly model with a water table 10 m below land surface, and allowed meteorological forcing between model dates October 1, 2000 and December 31, 2006 to fill up subsurface storage such that the water table reached a dynamic equilibrium. We performed calibration of the roughness parameter Manning's n by comparing modeled streamflow to observed records at 78 U.S. Geological Survey stream gages in the region, such that cumulative mean modeled streamflow was ~100% of cumulative mean observed streamflow (Bhaskar *et al.*, 2015).

Previous work examining differences between urban and rural water balances in the Baltimore region highlighted the importance of reduced evapotranspiration in urban areas and the infiltration of groundwater into the wastewater system (Bhaskar and Welty, 2012). Bhaskar *et al.* (2015) used scenarios to isolate the effects of these urban processes and impervious surfaces on subsurface storage, finding that impervious surfaces play a relatively minor role in decreasing subsurface storage compared to loss of groundwater to the wastewater system. We used the final output from the simulation in which all urban processes were represented, referred to as the "base case" in Bhaskar *et al.* (2015), as the initial condition for ParFlow.CLM simulations presented here.

Loose Coupling of SLEUTH and ParFlow.CLM Models

We simulated two urban growth extents with ParFlow.CLM, defined by SLEUTH simulations of 2007 and 2030, to examine two end points having the greatest differences in land cover. Given the computational intensity of ParFlow, we did not model the entire period from 2007 to 2030. Simulations incorporating urban growth scenarios for 2007 and 2030 both used the same meteorological forcing data (January 1, 2007-December 31, 2007) as input, to isolate hydrologic changes resulting from urbanization as distinct from hydrologic changes resulting from differences in meteorology. Although climate change can also affect water availability, we did not consider changes to climate between 2007 and 2030, as our goal was to isolate effects of land cover change. The 2007 forcing used in both cases had a precipitation total of 888 mm, which is in the 20th percentile of annual precipitation based on the long-term precipitation record at Baltimore-Washington International Airport.

Figure 2 depicts the coupling between the urban growth and hydrologic models. Two-way coupling entails feedbacks of water availability affecting urban growth patterns, but was not carried out due to computational barriers. Instead, we carried out one-way coupling where urban growth patterns affected water availability. The three urban processes represented in the ParFlow.CLM model that expanded with urban development between the 2007 and 2030 SLEUTH scenarios are (1) the extent of impervious surfaces, (2) the extent of urban land cover used for land surface modeling, and (3) groundwater withdrawals by private wells in residential areas outside of the municipal water service area.

Impervious Surfaces. We classified surface grid cells as being impervious where impervious surface coverage was calculated as being greater than 50%. Impervious surfaces were represented in the ParFlow.CLM model by specifying lower hydraulic conductivity grid cells than vegetated areas, with a value of 1×10^{-7} m/s based on road infiltration tests (Wiles and Sharp, 2008). SLEUTH provided estimates of "urban land cover" and did not directly predict impervious surface cover. Therefore, we compared the 2007 SLEUTH model output and National Land Cover Dataset 2006 to derive a relationship between SLEUTH urban land cover and impervious surface cover (Figure 6). Areas with a high percentage of SLEUTH urban land may be characterized by a range of impervious percentages because urban land can be developed as high, medium, or low density. A curve was fit using Shape Language Modeling (D'Errico, J., MATLAB File Exchange SLM Shape Language Modeling, Last Updated April 29, 2014, http://www.mathworks.com/matlabcentral/fileexchange/24443-slm-shape-language-modeling) where the ends of the curve fit were constrained by 0% urban land corresponding to 0% impervious cover and 100% urban land corresponding to 100% impervious cover, to best represent the range of urban land using imperviousness in the hydrologic model.

Urban Land Cover for Land Surface Modeling. Land surface modeling in CLM uses a categorical land-use classification scheme, such as the IGBP (International Geosphere-Biosphere Programme) global vegetation classification scheme (https://lpdaac.

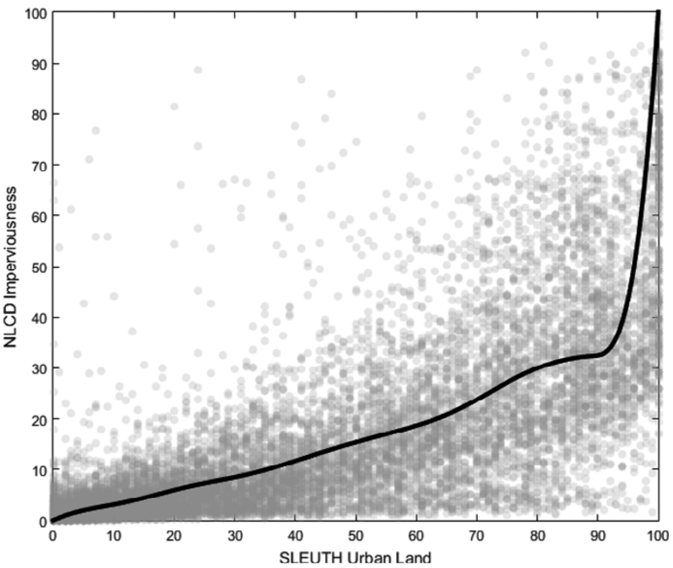

FIGURE 6. SLEUTH Percentage of Urban Land Compared with National Land Cover Dataset (NLCD) 2006 Percent Impervious Cover in the Same 500-m by 500-m Pixel (gray dots). Black curve indicates fit that was used to estimate NLCD percent impervious from SLEUTH percent urban land (R^2 = 0.58).

usgs.gov/dataset_discovery/modis/modis_products_table/mcd12q1). For ParFlow.CLM model initialization, MODIS 2007 Land Cover Type 1 (http://webmap.ornl.gov/wcsdown/wcsdown.jsp?dg_id=10004_31) was used.

One of the 17 classes within the IGBP classification is urban land, whereas SLEUTH produces continuous land cover data, describing the percentage of urban land cover within a model grid cell. Therefore, to use changes in urban land cover over time simulated by SLEUTH in CLM, a relationship between the categorical and continuous data representing urban land was developed. We found that SLEUTH urban land above 70% most closely corresponded to the categorical representation of urban land in the MODIS IGBP data (Figure 7). This cutoff value was used to translate the continuous percentages of urban land from SLEUTH to the urban land cover category used in CLM, where urban land cover results in less transpiration.

Expansion of Private Wells. Water use within the municipal water service area (Figure 3) was assumed to remain within the system capacity and the extent of the service areas was assumed to remain constant throughout the study time period (2007-2030). The City of Baltimore projects adequate water supply in the surface water reservoir system (City of Baltimore, 2006; Koterba *et al.*, 2011) and we did not have information on unused capacity in the municipal well systems to allow projection of future changes. Therefore, the municipal water withdrawals were held constant in ParFlow.CLM throughout the study period, although our previously discussed water demand analysis using the SLEUTH output did examine changes in water use throughout the region. Our focus with the hydrologic model was on water use changes outside of the municipal water service area where private wells are used for water supply. In areas served by private wells, consumptive use was taken to be 18% of the total water use (DeSimone, 2004) as we assumed the remainder of the water was returned to the same aquifer via septic disposal. Therefore, the amount of groundwater withdrawn in each grid cell outside of the water service area was estimated to be 18% of the residential water use per person (18% of 300 L) (Kenny *et al.*, 2009) multiplied by the residential population in 2007 or 2030 SLEUTH simulation for each grid cell. The groundwater withdrawal from each ParFlow.CLM grid cell increased or remained constant from 2007 to 2030 as the population of exurban areas increased.

RESULTS

Water Use

Eighty-four percent of the Baltimore regional water demand is currently served by public water systems and 16% is served by private wells. We calculated an 11.8% increase in the total regional water demand between 2007 and 2030. Based on the locations of increased growth forecast by SLEUTH and the water serving these areas of population growth, well use was predicted to increase faster (17%) than public water use (an 11% increase), so that the percentage of regional demand served by public systems decreased by 1%. Within the publicly served area, growth in water demand varied by about 10-fold among different sources of water (Figure 8). The largest increases in water demand between 2007 and 2030 were in areas served by the Washington Suburban Sanitary Commission and the Susquehanna River. The smallest increases were found in the Gibson Island well field in Anne Arundel County and the part of the Baltimore central water system that is 75% served by Loch Raven Reservoir and 25% by Liberty Reservoir. In the area served by Deer Creek, there was a decrease in population from 2007 to 2010, which then increased in later years, leading to the drop in water demand seen in 2010 (Figure 8). This change in population in the area served by Deer Creek was part of a pattern of a decreasing residential population in combination with increasing employment, which led to an

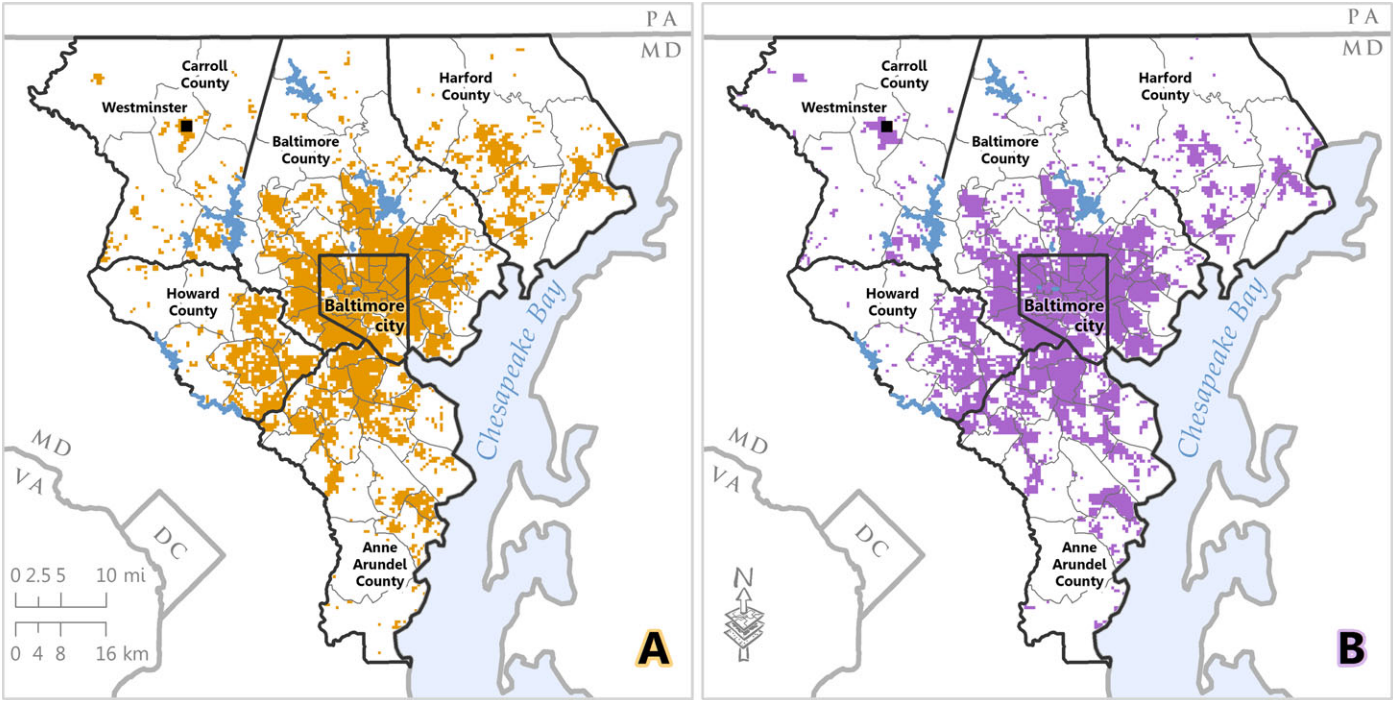

FIGURE 7. Urban Land Area Rasters Derived from: (A) the SLEUTH Output for Year 2007 (>70%) (dark orange); and (B) the MODIS IGBP Land Cover Classification for Year 2007 (purple).

overall increasing trend in population except between 2007 and 2010.

Urban Growth Driving Changes in Hydrologic Model Inputs

For locations where the SLEUTH model forecasted an increase in urban land between 2007 and 2030, we assumed that addition of impervious surfaces would lead to a decrease in land surface hydraulic conductivity. Figure 9 shows the land surface hydraulic conductivity in 2007 and the change between 2007 and 2030. The ParFlow.CLM grid cells that became more than 50% impervious between 2007 and 2030 covered an area of 11.25 km^2; these cells are mostly located near the edges of the 2007 impervious areas. The decreases in hydraulic conductivity between 2007 and 2030 for these model grid cells were greatest where the original hydraulic conductivity was highest, *e.g.*, in the Atlantic Coastal Plain.

Land cover and conversion into urban land between 2007 and 2030, forecasted by SLEUTH using the cutoff described in Figure 7, is shown in Figure 10. The number of ParFlow.CLM model grid cells that became urban between 2007 and 2030 was 193, corresponding to an area of 48.25 km^2. As the urban core was already designated as urban land cover in the IGBP classification, the areas that became urban between 2007 and 2030 were outside of the urban core (Figure 10).

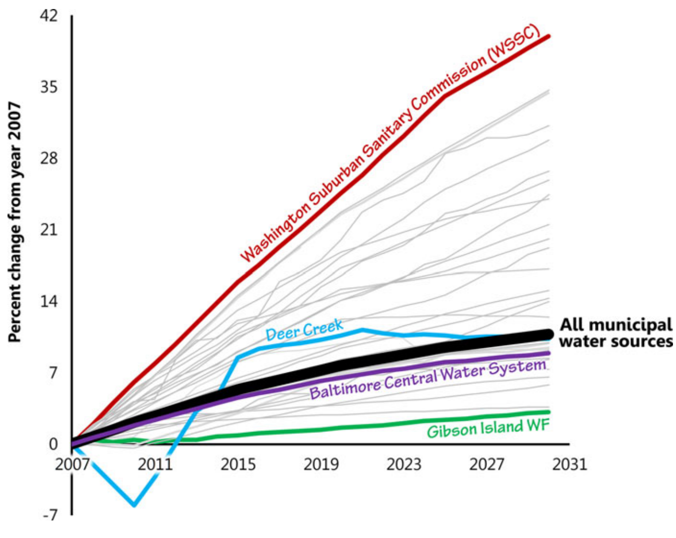

FIGURE 8. Percent Change in Water Demand from 2007 for All Sources of Municipally-Supplied Water with Colored Line Colors Corresponding to Highlighted Areas Shown in Figure 3. WF indicates a public well field.

Private residential consumptive water use in 2007 is shown in Figure 11, along with the change in residential well withdrawals between 2007 and 2030. The residential well withdrawals were directly

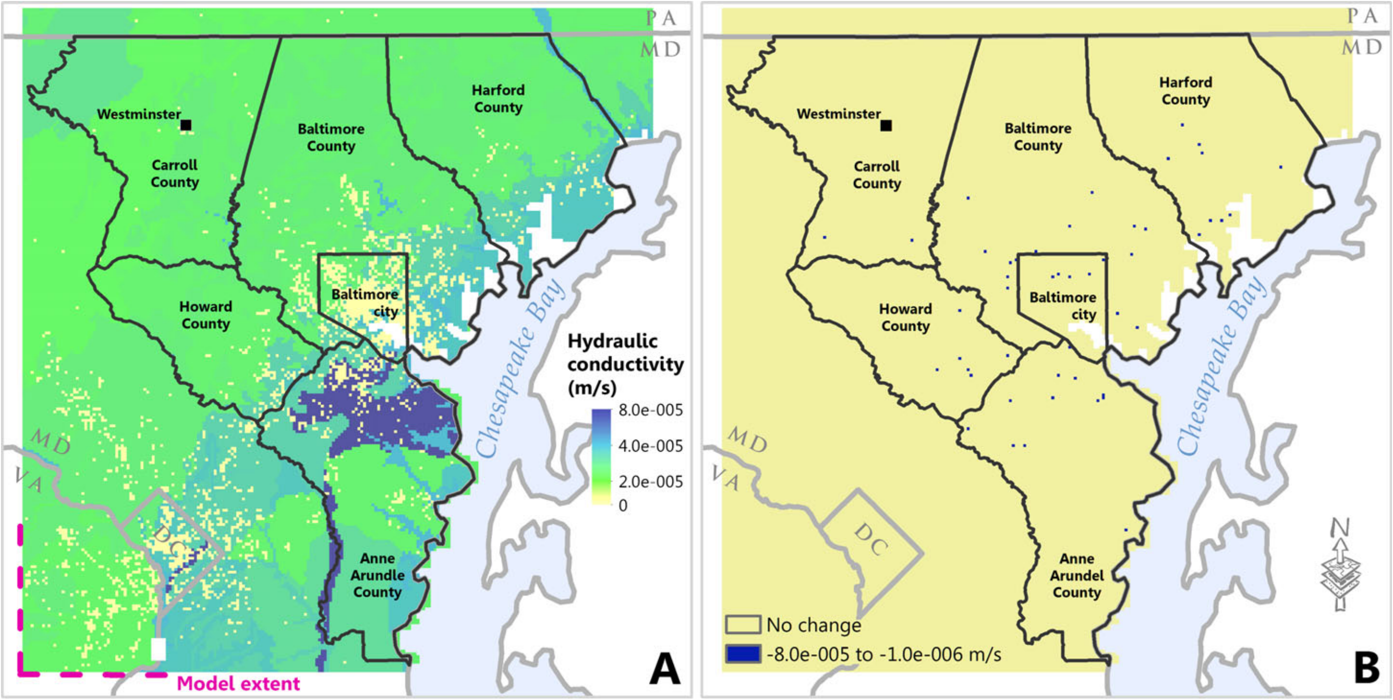

FIGURE 9. (A) Land Surface Hydraulic Conductivity in m/s in 2007, Where Light Yellow Indicates the Low Hydraulic Conductivity of Impervious Surfaces. (B) Change in hydraulic conductivity between 2030 and 2007.

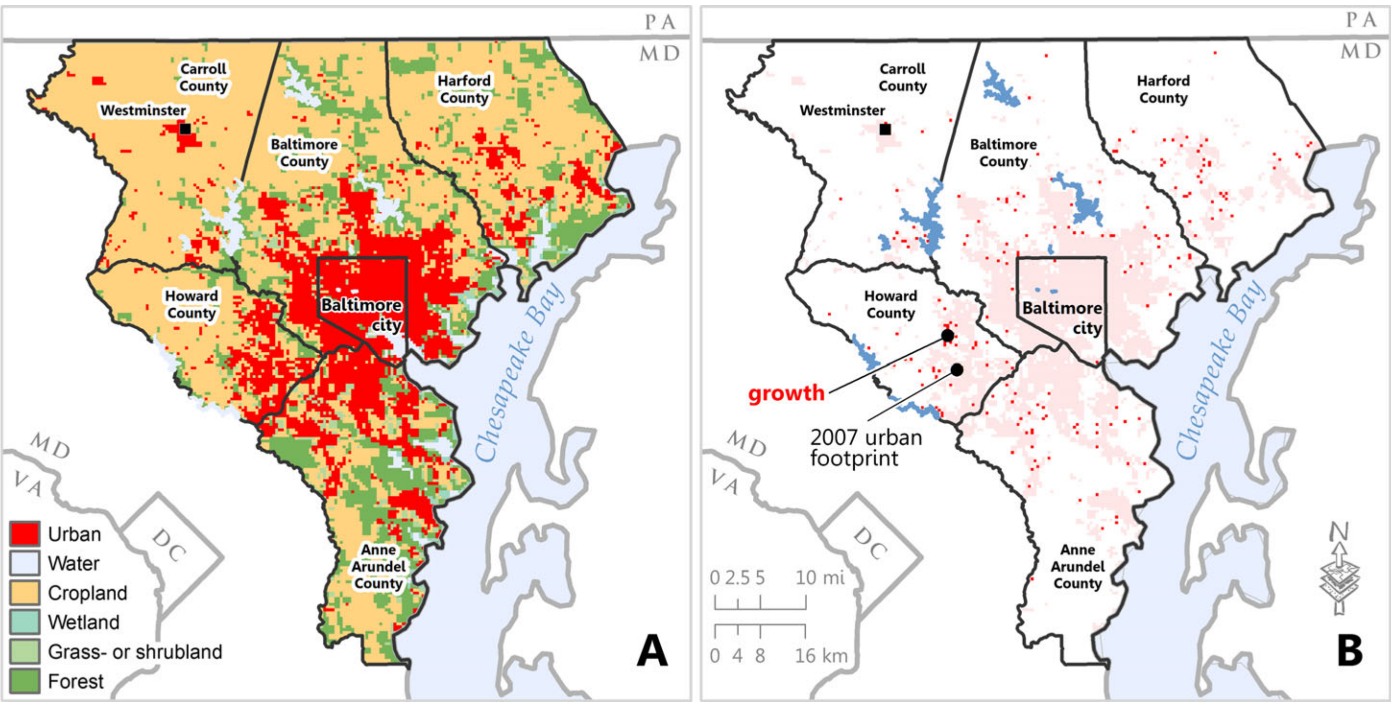

FIGURE 10. (A) Land Cover Represented in Common Land Model (CLM) in 2007 and (B) Urban Growth between 2007 and 2030 (bright red).

proportional to the distribution of residential population outside of municipal water service areas. The population estimates used by SLEUTH were on the RPD scale (Figure 1). RPDs are in part separated by county boundaries, so they can reflect the influence of county governments and policies on growth

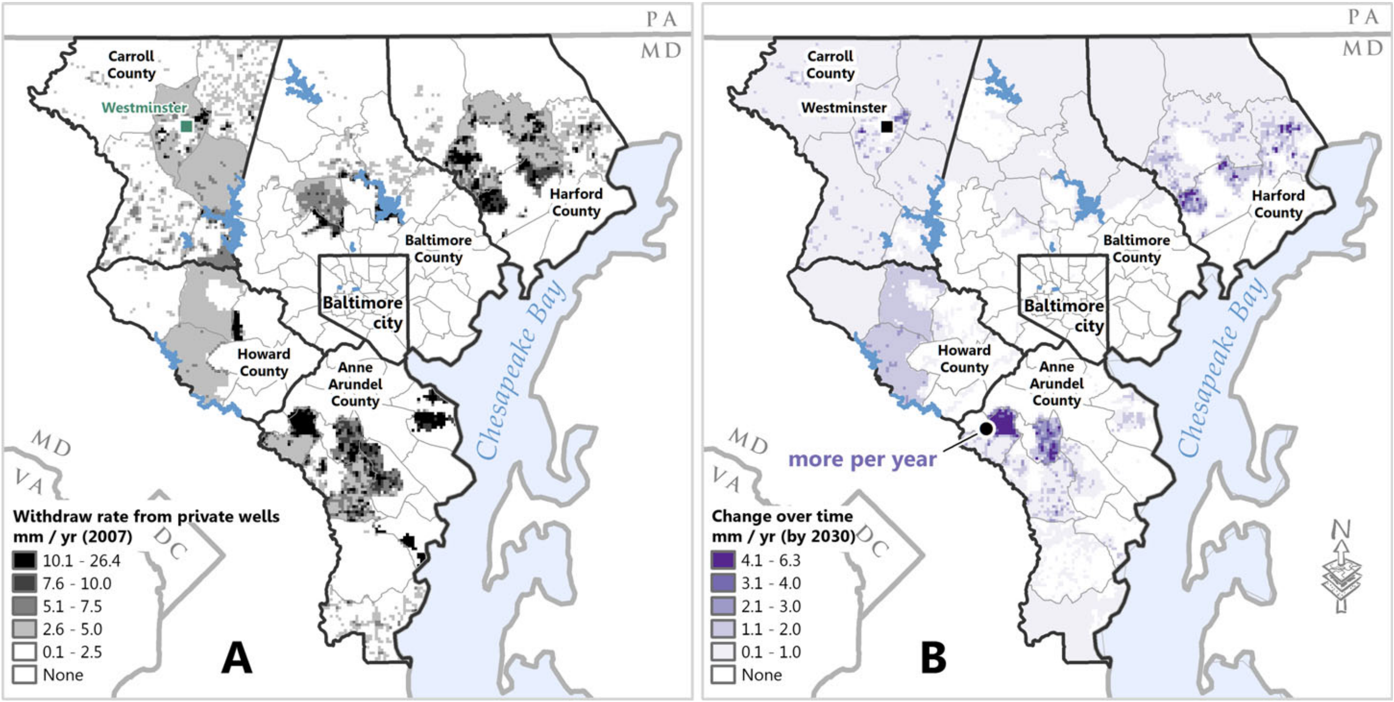

FIGURE 11. (A) Private Residential Well Withdrawals (mm/year, where volumetric withdrawals are normalized by grid cell size of 0.25 km^2) in 2007. (B) Difference in withdrawal rates from private wells, 2030 minus 2007.

projections for RPDs. Therefore, county boundaries are clearly visible in residential well use in Figure 11. For example, northern Baltimore County has lower private water use than either Carroll County to the west or Harford County to the east because of county policies and county growth forecasts. The largest increases in well withdrawals are in Howard County, northern Anne Arundel County, Carroll County, and southern Harford County.

Hydrologic Modeling Results

The previous section showed the changes to hydrologic model input data from urban growth-driven changes (Figures 9, 10, and 11). We can also examine changes in hydrologic model output between 2007 and 2030, two years for which the same climate forcing was used but for which different land cover forcing based on the urban growth forecasted by SLEUTH was incorporated. To illustrate how the hydrologic model output changed between 2007 and 2030, we evaluated changes in subsurface storage in a spatial subset of our domain.

We focus on the area surrounding Westminster, Maryland, in central Carroll County (Figure 12). Westminster hosts a population of 18,590 and is served by a municipal water system. This area is shown in white in Figure 12 because private well withdrawals are zero within the municipally served area. The surrounding area uses private wells, where consumptive water use is forecasted to increase between 2007 and 2030 (Figure 12). The subsurface storage for the surrounding area is given in Figure 13. Figure 13A shows cyclic and seasonal variation, with the greatest subsurface storage occurring in spring and lowest in fall. The subsurface storage in 2007 and 2030 is indistinguishable relative to the annual cycle in subsurface storage, and therefore in Figure 13B the difference between 2030 and 2007 is plotted. In this area of urban growth with more residential wells withdrawing water at a constant rate in 2030 *vs*. 2007, subsurface storage in 2030 decreases relative to subsurface storage in 2007 at an approximately linear rate over the modeled year. The difference shown in Figure 13B represents the difference in subsurface storage between the amount withdrawn in model year 2007 *vs*. 2030, and does not account for total change in subsurface storage over the entire time interval of 2007 through 2030, as the model run did not include the years in between. The change in subsurface storage of −0.63 mm (Figure 13B) is large (74%) compared to the average increase in well withdrawals around Westminster (Figure 12C; 0.85 mm).

In addition to evaluating change in subsurface storage within one spatial subset, as in Figures 12 and 13, we can also examine the variation throughout the entire model domain. Figure 14 shows the differences in subsurface storage between two one-

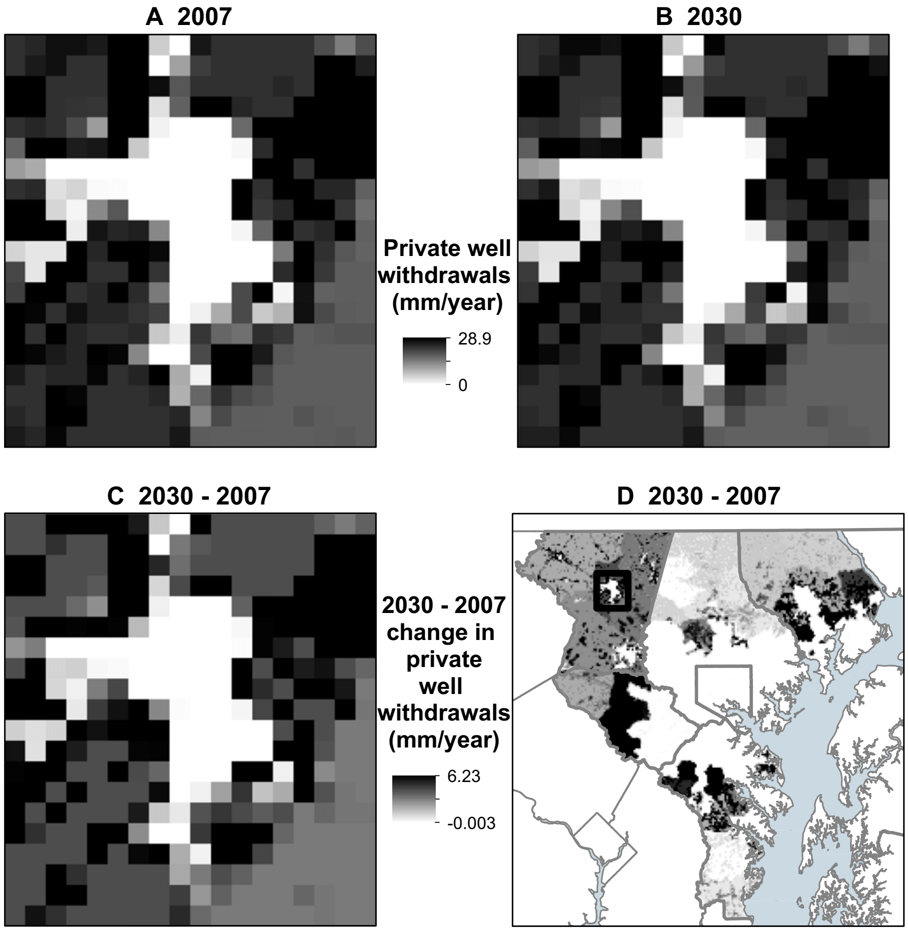

FIGURE 12. Private Well Pumping (mm/year, where volumetric withdrawals are normalized by grid cell size of 0.25 km^2) in (A) 2007, (B) 2030, (C) 2030 minus 2007, within the Spatial Subset Shown in Black around Westminster, Maryland (D).

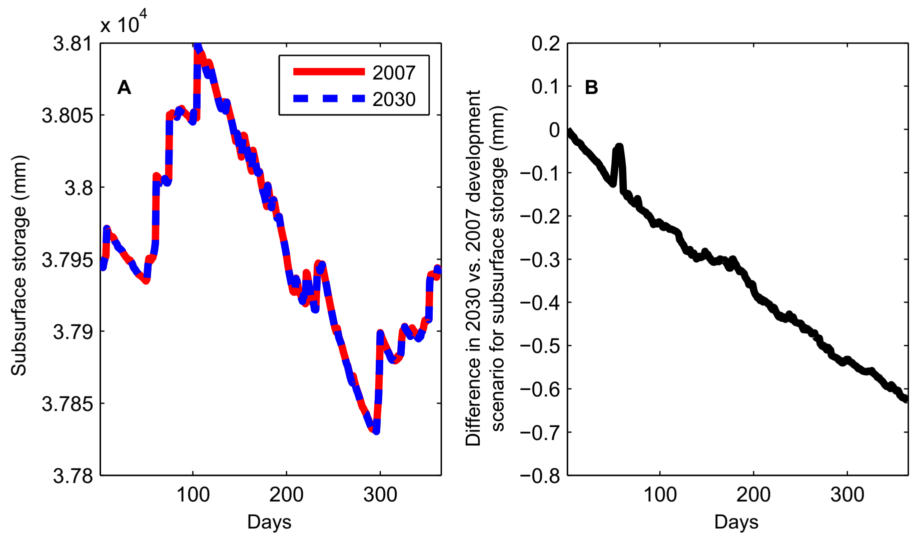

FIGURE 13. Subsurface Storage (mm) in Spatial Subset (Figure 12D) in (A) 2007 and (B) Difference in 2030 *vs.* 2007 Development Scenarios.

year simulations of 2007 and 2030, normalized by the surface area of each grid cell. The red areas indicate decreased subsurface storage from 2007 to 2030. The majority of cells fall in the −1.9 to 2 mm category, which appears as white. Areas that show decreased subsurface storage are generally further

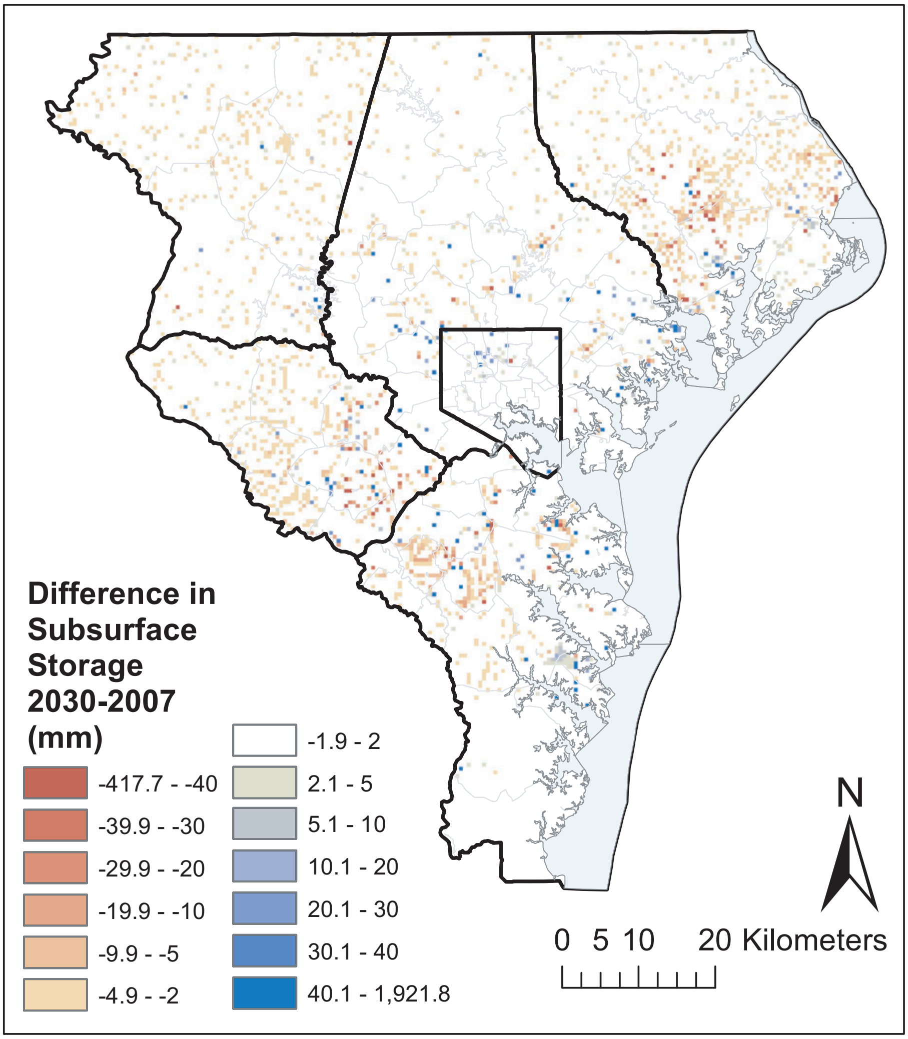

FIGURE 14. Heterogeneous Differences in Subsurface Storage between Two One-Year Simulations under Identical Meteorological Forcing. Red areas had smaller subsurface storage in 2030 as compared to 2007, whereas blue areas had greater subsurface storage in 2030 compared to 2007.

from the urban core, and include exurban areas where increased private well withdrawals over time led to reduced total storage (as in Figure 13). The areas that had decreased subsurface storage are less prevalent in Baltimore County than in other counties; this is related to the lower exurban growth predictions for northern Baltimore County (Figure 4). Closer to the urban core, and within the area served by municipal water systems, the changes in subsurface storage are more varied; some areas increase, some decrease, many stay approximately constant. Areas served by municipal water systems did not have changes in private well withdrawals, but they did have reductions in vegetative cover, which may lead to decreased evapotranspiration, as well as decreases in hydraulic conductivity with a greater extent of impervious surfaces.

DISCUSSION AND CONCLUSIONS

We have presented one approach for coupling a land-use change model and an integrated hydrologic model. A two-way coupling approach would allow for coevolution of the sociohydrological system (Troy *et al.*, 2015) where limits on water availability could affect future incremental changes in urban development, as well as potential changes to the urban growth pattern. The decision to focus on one-way rather than two-way coupling for the simulations carried out reflects our judgment that the magnitude of change in urban cover for this particular modeling domain was small enough that the hydrologic response was unlikely to trigger policy changes affecting subsequent growth. In situations where larger changes in hydrologic response are likely, two-way coupling would be a productive avenue for future research.

Using the SLEUTH predictions and water sources for municipal water systems throughout the region, we predicted demand for each source of municipal water. We found that areas outside the public water systems had a larger percentage increase in water demand compared to the municipal systems, although they served a much smaller portion of the region.

In terms of subsurface storage, we found that changes were not regional in scale but instead concentrated where development occurred. In our simulations, three urban processes—expansion of urban land cover, decrease in surface hydraulic conductivity, and increasing private well water use—occurred simultaneously with urban development between 2007 and 2030, although their spatial distributions had quite different patterns (Figures 9-11). These urban features have variable effects on subsurface storage as demonstrated in Bhaskar *et al.* (2015). We found that in exurban areas relying on private wells (*e.g.*, Figure 13), comparison of subsurface storage for one-year simulations of 2007 *vs*. 2030 showed modest declines. Areas characterized by increased impervious surface area and decreased vegetative cover were generally concentrated in inner suburbs. These areas had a more varied hydrologic response because these two types of changes had effects that tended to cancel each other out.

In contrast with urban development seen in previous decades in the Baltimore region, the extent of new development forecasted between 2007 and 2030 is relatively modest, representing an increase of only 7.8% (Jantz *et al.*, 2014). Our coupled modeling efforts show relatively modest changes in water availability for the simulated scenario. This does not mean, however, that the changes are uniform or trivial. In particular, we observed high spatial heterogeneity in our simulated changes in water availability (Figure 14). This spatial heterogeneity in water availability and simulated decrease in subsurface water storage of some areas (Figure 14) could have significant implications during drier periods or for larger changes in development over a longer period of time, and warrants finer-scale further study related to future growth.

A water shortage in any reservoir system will generally affect the entire region serviced by municipal systems. In contrast, water supply limitations in areas using wells are likely to be felt locally. The areas most affected by increased groundwater pumping are northern Anne Arundel County, western Howard County, and parts of Harford County (Figure 11), the latter two of which are using private wells in low-productivity Piedmont aquifers.

The moratorium on construction in Westminster due to concerns about water supply was one motivation for carrying out this work. Although simulated changes in storage were modest, local heterogeneity as represented by 500-m grid cells was dramatic. Most grid cells had negligible change in subsurface storage, but a few cells had changes in storage of up to two orders in magnitude greater. Observed spatial heterogeneity of changes in water availability with urban development would be more pronounced if we were to examine 500-m subgrid heterogeneity. For example, localized effects on headwater streams affected by increased groundwater pumping would likely include larger changes with steeper hydraulic gradients over finer spatial scales than are modeled here. If we were to extrapolate these changes to cumulative change in storage over multiple decades rather than a comparison between two model years, and consider the larger heterogeneity in local storage changes that might be observed at the scale of a headwater stream with grid cells of 10 m or less, it is apparent that even modest changes in land cover may be sufficient to trigger significant problems in water availability. The simulation approach presented here could be used to identify early warning indicators of future risk associated with urban development.

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LITERATURE CITED

Arthur-Hartranft, S.T., T.N. Carlson, and K.C. Clarke, 2003. Satellite and Ground-Based Microclimate and Hydrologic Analyses Coupled with a Regional Urban Growth Model. Remote Sensing of Environment 86:385-400.

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

Bhaskar, A.S. and C. Welty, 2012. Water Balances along an Urban-to-Rural Gradient of Metropolitan Baltimore, 2001-2009. Environmental & Engineering Geoscience 18:37-50.

Bhaskar, A.S., C. Welty, R.M. Maxwell, and A.J. Miller, 2015. Untangling the Effects of Urban Development on Subsurface Storage in Baltimore. Water Resources Research 51(2):1158-1181, DOI: 10.1002/2014WR016039.

Bierwagen, B.G., D.M. Theobald, C.R. Pyke, A. Choate, P. Groth, J.V. Thomas, and P. Morefield, 2010. National Housing and Impervious Surface Scenarios for Integrated Climate Impact Assessments. Proceedings of the National Academy of Sciences 107:20887-20892.

Ciavola, S.J., C.A. Jantz, J. Reilly, and G.E. Moglen, 2014. Forecast Changes in Runoff Quality and Quantity from Urbanization in the DelMarVa Peninsula. Journal of Hydrologic Engineering 19:1-9.

City of Baltimore, 2006. Comprehensive Water and Wastewater Plan. Department of Public Works, Baltimore, Maryland.

Civerolo, K., C. Hogrefe, B. Lynn, J. Rosenthal, J.-Y. Ku, W. Solecki, J. Cox, C. Small, C. Rosenzweig, R. Goldberg, K. Knowlton, and P. Kinney, 2007. Estimating the Effects of Increased Urbanization on Surface Meteorology and Ozone Concentrations in the New York City Metropolitan Region. Atmospheric Environment 41:1803-1818.

Clarke, K.C., S. Hoppen, and L. Gaydos, 1997. A Self-Modifying Cellular Automaton Model of Historical Urbanization in the San Francisco Bay Area. Environment and Planning B: Planning and Design 24:247-261.

DeSimone, L.A., 2004. Simulation of Ground-Water Flow and Evaluation of Water-Management Alternatives in the Assabet River Basin, Eastern Massachusetts. U.S. Geological Survey SIR 2004-5114.

Goetz, S.J. and C.A. Jantz, 2011. Forecasting Future Land Use and Hydrology: A Case Study of the Upper Delaware Watershed. Watershed Science Bulletin Fall 2011:18-26.

Irani, F.M. and P.R. Claggett, 2010. Chesapeake Bay Watershed Land Cover Data Series. USGS Numbered Series, U.S. Geological Survey, Reston, Virginia.

Jantz, C., S. Drzyzga, and M. Maret, 2014. Calibrating and Validating a Simulation Model to Identify Drivers of Urban Land Cover Change in the Baltimore, MD Metropolitan Region. Land 3:1158-1179.

Jantz, C.A., S.J. Goetz, D. Donato, and P. Claggett, 2010. Designing and Implementing a Regional Urban Modeling System Using the SLEUTH Cellular Urban Model. Computers, Environment and Urban Systems 34:1-16.

Jantz, C.A., S.J. Goetz, and M.K. Shelley, 2004. Using the SLEUTH Urban Growth Model to Simulate the Impacts of Future Policy Scenarios on Urban Land Use in the Baltimore—Washington Metropolitan Area. Environment and Planning B: Planning and Design 31:251-271.

Jones, J.E. and C.S. Woodward, 2001. Newton-Krylov-Multigrid Solvers for Large-Scale, Highly Heterogeneous, Variably Saturated Flow Problems. Advances in Water Resources 24:763-774.

Kenny, J.F., N.L. Barber, S.S. Hutson, K.S. Linsey, J.K. Lovelace, and M.A. Maupin, 2009. Estimated Use of Water in the United States in 2005. http://pubs.usgs.gov/circ/1344/.

Kollet, S.J. and R.M. Maxwell, 2006. Integrated Surface-Groundwater Flow Modeling: A Free-Surface Overland Flow Boundary Condition in a Parallel Groundwater Flow Model. Advances in Water Resources 29:945-958.

Kollet, S.J. and R.M. Maxwell, 2008. Capturing the Influence of Groundwater Dynamics on Land Surface Processes Using an Integrated, Distributed Watershed Model. Water Resources Research 44:W02402, DOI: 10.1029/2007WR006004.

Koterba, M.T., M.C. Waldron, and T.E.C. Kraus, 2011. The Water-Quality Monitoring Program for the Baltimore Reservoir System, 1981–2007—Description, Review and Evaluation, and Framework Integration for Enhanced Monitoring. U.S. Geological Survey Scientific Investigations Report 2011–5101.

Lin, Y.-P., N.-M. Hong, P.-J. Wu, and C.-J. Lin, 2007. Modeling and Assessing Land-Use and Hydrological Processes to Future Land-Use and Climate Change Scenarios in Watershed Land-Use Planning. Environmental Geology 53:623-634.

Maxwell, R.M. and N.L. Miller, 2005. Development of a Coupled Land Surface and Groundwater Model. Journal of Hydrometeorology 6:233-247.

Mennis, J., 2003. Generating Surface Models of Population Using Dasymetric Mapping. The Professional Geographer 55:31-42.

Mennis, J. and T. Hultgren, 2006. Intelligent Dasymetric Mapping and Its Application to Areal Interpolation. Cartography and Geographic Information Science 33:179-194.

Troy, T.J., M. Pavao-Zuckerman, and T.P. Evans, 2015. Debates—Perspectives on Socio-Hydrology: Socio-Hydrologic Modeling: Tradeoffs, Hypothesis Testing, and Validation. Water Resources Research 51:4806-4814.

U.S. Census Bureau, 2014. American FactFinder Population Estimate. http://factfinder.census.gov/faces/tableservices/jsf/pages/productview.xhtml?pid=ACS_13_5YR_B01003&prodType=table, *accessed* October 2016.

Wiles, T.J. and J.M. Sharp, 2008. The Secondary Permeability of Impervious Cover. Environmental & Engineering Geoscience 14:251-265.

Wolman, M.G., 2004. Advisory Committee on the Management and Protection of the State's Water Resources. State of Maryland, Baltimore, Maryland.