ABSTRACT: The potential effects of long-term urbanization and climate change on the freshwater resources of the Flint River basin were examined by using the Precipitation-Runoff Modeling System (PRMS). PRMS is a deterministic, distributed-parameter watershed model developed to evaluate the effects of various combinations of precipitation, temperature, and land cover on streamflow and multiple intermediate hydrologic states. Precipitation and temperature output from five general circulation models (GCMs) using one current and three future climate-change scenarios were statistically downscaled for input into PRMS. Projections of urbanization through 2050 derived for the Flint River basin by the Forecasting Scenarios of Future Land-Cover (FORE-SCE) land-cover change model were also used as input to PRMS. Comparison of the central tendency of streamflow simulated based on the three climate-change scenarios showed a slight decrease in overall streamflow relative
to simulations under current conditions, mostly caused by decreases in the surface-runoff and groundwater components. The addition of information about forecasted urbanization of land surfaces to the hydrologic simulation mitigated the decreases in streamflow, mainly by increasing surface runoff.

**KEYWORDS:** Hydrologic simulation; Urbanization; Land-cover change; Climate change; Surface depression storage; Effective imperviousness; Streamflow; Climate impacts; Human impacts; Modeling

1. **Introduction**

This article describes a study that is part of the climate-change project described in the overview article of this Integrated Watershed special collection (Hay et al. 2011). It is distinct from the other studies presented because it examines the hydrologic effect of changing land-cover patterns and the interaction of this effect with those created by climate change. In this study, a watershed model was run to simulate the hydrology of a basin through the year 2050 by using three different sets of inputs that describe 1) changes in urbanization as projected by a land-cover change model, 2) changes in climate as projected by general circulation models (GCMs), and 3) the combination of changes in urbanization and climate. The hydrologic effect of each set of inputs was determined by comparing the resultant simulations to those created by using the same hydrologic model run with inputs describing current land-cover and climate conditions.

The basin used in this study, the Flint River basin, Georgia, was originally modeled as part of the Upper Flint River Science Thrust of the U.S. Geological Survey (USGS), part of a federally funded program to address key national science priorities, including landslide and debris flows, fire science, integrated landscape monitoring, and water availability. The purpose of the Upper Flint River Science Thrust is to “advance the science needed to specify the hydrologic conditions necessary to support flowing-water ecosystems. This information is critical for management of water supplies” (Hughes et al. 2007, p. 1). Because the application of the watershed model, the Precipitation-Runoff Modeling System (PRMS; Leavesley et al. 1983) to the Flint River basin has already been documented in Viger et al. (Viger et al. 2010), this article will provide relatively brief descriptions of the setup, calibration, and results of the hydrologic model under historical land-cover and climate conditions.

The remainder of the article is organized into six sections: 1) a description of the study area; 2) a review of previous work related to urbanization and climate change in hydrological modeling; 3) a description of the PRMS model, including the data preparation and calibration approach used to simulate historical conditions; 4) the presentation of results of simulations based on urbanization and climate change; 5) discussion of these results; and 6) conclusions.

2. **Study area**

The Flint River basin at Montezuma, Georgia (USGS streamflow gauge 02349500; USGS 2009), has its headwaters in northern Georgia, emanating from a groundwater source: now through a concrete culvert that routes its flow underneath the Hartsfield-Jackson Atlanta International Airport (Morris 2009). This basin has
a drainage area of approximately 7510 km². The mean basin elevation is 233 m above the National Geodetic Vertical Datum of 1929. The basin is predominantly forested (≈73%), although there is notable recent urbanization in the northern headwaters. The most substantial urbanization near the river is the result of expansion of communities surrounding the Atlanta metropolitan area, although several smaller cities also are growing along downstream portions of the river. This is confirmed by comparison of the USGS National Land Cover Databases (NLCD) for 1992 and 2001 (Homer et al. 2007; Vogelmann et al. 2001) within the Flint River basin. The contributing area above the gauge terminates in the upper end of hydrologic unit 03130006 and includes the upstream hydrologic unit 03130005 (Seaber et al. 1994), as shown in Figure 1.

For the water years (a water year is defined as the period of 1 October–30 September, identified by the calendar year in which it ends) 1988–99, the highest mean monthly temperatures are seen in the month of July and the lowest are seen in December and January. Mean monthly precipitation is highly variable. Highest mean monthly values of streamflow are seen in March, with another peak in July because of the large precipitation events seen in that month for this period.

Figure 1. The Flint River basin includes hydrologic unit 03130006 and part of 03130005, above the USGS stream gauge, 02349500, shown as a blue triangle.
of record. The lowest mean monthly values of streamflow occur in September. See Figure 3 of Viger et al. (Viger et al. 2010) for more details. The gauge at the outlet of the basin has daily streamflow measurements from 1930 through February 2004.

The Flint River system is important because it is one of only 40 rivers within the conterminous United States that flows unimpeded for more than 320 km (Morris 2009). It contains many water-storing surface depressions, including officially designated wetland areas such as the Great Swamp and the Chickasawatchee Swamp, and supports a diversity of plant and animal life. The Flint River is also important to human populations because it is a major water supply for the states of Georgia and Florida and because it has flooded several cities that lie along its path. Although early industry in the region was dominated by grist mills, irrigation-based agriculture is now important (Morris 2009). Crops include peanuts, soybeans, and vegetables. Dairy, cattle, and hogs are also important agricultural commodities for the area. General patterns of water use in the basin were not considered hydrologically significant for this study.

3. Previous work

Alley and Veenhuis (Alley and Veenhuis 1983, p. 313) state that “man-made impervious cover has long been known to significantly affect the hydrologic response of a watershed.” By 1968, study of this phenomenon was mature enough to support the publication of a guidebook on the subject (Leopold 1968). In addition to altering the ability of water to infiltrate into the soil and changing physical routing of water across the land surface, urbanization has been shown to affect heat budgets and evaporation (Dow and DeWalle 2000). The rate of conversion from rural to relatively impervious urban land within the United States is large (Alig et al. 2004; White et al. 2009). The effects of urbanization on the Peachtree Creek basin, which is near the Flint River basin, were evident as early as 1990 (Ferguson and Suckling 1990). Alig et al. (Alig et al. 2004) project that urbanization within the nation will continue for at least the next 25 years and that “developed area” will increase by as much as 79%, resulting in almost 10% of the U.S. land surface being converted to “developed” land cover.

As a result, experimental hydrologists focused on both urban (e.g., Alley and Veenhuis 1983; Leopold 1968) and more natural drainage systems (such as Harbor 1994; Booth 1991) have long sought to describe the dynamics of hydrologic response to urbanization. Applications of hydrological models that focus on the effect of urbanization on hydrology in the United States have been documented for a variety of geographic regions, such as the Piedmont (Hejazi and Moglen 2008), Midwest (Tang et al. 2005; Choi and Deal 2008), coastal New England (Schiff and Benoit 2007), Pacific Northwest (Cuo et al. 2008), and Southeast (Ferguson and Suckling 1990). Many of these have focused on water, habitat, and other ecological quality factors (e.g., Schueler et al. 2009; Brabec 2009; Walsh et al. 2009; Nelson et al. 2009).

GCM forecasts (e.g., Solomon et al. 2007) are increasingly available for use as input to hydrologic models. A sufficiently large number of methods for downscaling from GCM grid cells to the subcell-sized features used in hydrologic models have been presented, and there are a number of review papers available (Fowler et al. 2007; e.g., Xu 1999b; Xu 1999a). Although considerable research has gone into
evaluating and comparing downscaling methods, the present study described in this article applies a straightforward means of obtaining higher spatial resolution scenarios by downscaling coarse-scale GCM projections to an observed climate baseline of station points: the “change factor” method (Arnell 2003a; Arnell 2003b; Diaz-Nieto and Wilby 2005; Hay et al. 2000; Pilling and Jones 1999; Prudhomme et al. 2002; e.g., Arnell and Reynard 1996; Eckhardt and Ulbrich 2003). A number of studies (e.g., Markstrom and Hay 2009; Arnell 2003a) have attempted to examine the sensitivity of streamflow characteristics in a variety of basins to possible future climate scenarios.

A number of authors have attempted to evaluate the combined effects of urbanization and climate change. Hejazi and Moglen (Hejazi and Moglen 2008) drove a simplistic and statistically based hydrology model that is conceptually similar to PRMS with GCM climate forecasts. They modified the original version of the hydrologic model presented in McCuen and Snyder (McCuen and Snyder 1986) to allow the input of a time series of several parameters to reflect changing urbanization within a basin located in the Maryland Piedmont region. Franczyk and Chang (Franczyk and Chang 2009) also examined the joint hydrologic response of basins to changing land cover (mostly urbanization) and changing climate for a small urban basin in the vicinity of Portland, Oregon, by using a geographical information system (GIS)–based version of the Surface Water Assessment Tool (SWAT) model (Arnold and Fohrer 2005). Nelson et al. (Nelson et al. 2009) examined the effects of urbanization and climate change on fish populations by using PRMS. Rather than relying on land-cover change models to produce continuous evolution of land cover, the derivation of information about urbanization in these examples is relatively simplistic. The Hejazi and Moglen (Hejazi and Moglen 2008) study is based on an arbitrary, single increase in urban areas for all parts of the basin of interest over the simulation period. Franczyk and Chang (Franczyk and Chang 2009) rely on three heuristically created, single time step forecasts of land-cover development under different management scenarios, “compact,” “sprawl,” and “planned.” In the present study, a physically based model is used to simulate the hydrology of a larger, predominantly rural basin in the southeastern United States based on GCM forecasts of climate and detailed simulations of land-cover change.

4. Hydrologic model

This study uses PRMS, which is a physically based, distributed-parameter watershed model. Distributed-parameter capabilities are provided by partitioning a watershed into units, using characteristics such as slope, aspect, elevation, vegetation type, soil type, and precipitation distribution. These units are called hydrologic response units (HRUs) and are assumed to be homogeneous with respect to hydrologic response. A water balance and an energy balance are computed daily for each HRU and routed through the drainage network to control the travel time downstream.

The PRMS configuration from Viger et al. (Viger et al. 2010) was used as the foundation for this study. This model configuration accounts for large numbers of small water bodies and is valuable for applications in basins where surface depressions are too small or numerous to conveniently model as discrete spatial units.
but where the aggregated storage capacity of these units is large enough to have a substantial effect on streamflow. A brief overview of the model configuration is given in the next section. The reader is referred to Viger et al. (Viger et al. 2010) and Hay et al. (Hay et al. 2011) for further details on PRMS.

4.1. Model parameterization

In the Viger et al. (Viger et al. 2010) study, HRU delineation, characterization, and parameterization were done by using a GIS interface, the GIS Weasel (Viger and Leavesley 2007). Figure 2 shows the 128 HRUs delineated for the Flint River basin.

The GIS Weasel was used to derive model parameters describing HRU vegetation type and density, land cover, soils, and impervious area. The NLCD 2001 land-cover data (Homer et al. 2004; Homer et al. 2007) were used to derive the vegetation-type parameters for each HRU. Vegetation density was derived from
NLCD 2001 canopy density data (Huang et al. 2001). Estimates of impervious surface (an indicator of the level of urbanization in the basin) were derived by using the NLCD 2001 urban impervious layer (Yang et al. 2003).

PRMS was configured to use a Muskingum routing technique (Linsley et al. 1975, p. 275), as implemented by Mastin and Vaccaro (Mastin and Vaccaro 2002), to move outflow from each HRU through the drainage network to control the travel time downstream. Derivation of the Muskingum routing parameters is described in Viger et al. (Viger et al. 2010).

4.2. Model inputs

PRMS requires daily inputs of precipitation and maximum and minimum air temperature for each HRU. The USGS Downsizer (Ward-Garrison et al. 2009) was used to select, download, verify, and format the station-based time series data for direct input to PRMS. The Downsizer server provides access to daily streamflow data values from the USGS National Water Information System (available online at http://waterdata.usgs.gov/nwis) and daily minimum and maximum temperature and precipitation data values from the National Weather Service (NWS) Cooperative Observer Program (COOP; available online at http://www.nws.noaa.gov/om/coop). A three-dimensional multiple linear regression, based on longitude $x$, latitude $y$, and elevation $z$, is used to distribute temperature and precipitation station data to HRUs (Hay and Clark 2000; Hay and Clark 2003). For further information, see Viger et al. (Viger et al. 2010).

4.3. Model calibration

PRMS was calibrated by using Luca (Hay and Umemoto 2006; Hay et al. 2006), a multiple-objective, stepwise, automated procedure for hydrologic model calibration and the associated graphical user interface (GUI). The calibration procedure uses the Shuffled Complex Evolution global search algorithm (Duan et al. 1993; Duan et al. 1992; Duan et al. 1994) to calibrate PRMS. Viger et al. (Viger...
et al. 2010) used Luca to automate the sequential calibration of a model’s simulation of solar radiation (SR), potential evapotranspiration (PET), water balance, and daily runoff. The model was calibrated by using the water years 1990–99 and evaluated by using the water years 1980–89 and 2000–03. Figure 3 shows monthly means of daily minimum and maximum temperature and precipitation. Figure 4 shows a comparison of the measured and simulated basin mean monthly streamflow for the 1989–99 period of record (note that this is the chosen period of record for current climate in the present study). A detailed discussion of the calibration steps and associated calibration dataset(s), objective function(s), and model parameters, followed by an evaluation of model performance, can be found in Viger et al. (Viger et al. 2010).

5. Methods

The PRMS model developed by Viger et al. (Viger et al. 2010) was used to evaluate the effects of projections of future climate and urbanization in the Flint River basin. PRMS was run with two types of future conditions through the year 2050 for the Flint River basin: 1) changes in urbanization as projected by the Forecasting Scenarios of Future Land-Cover (FORE-SCE) model (Sohl et al. 2007) and 2) changes in climate as projected by GCMs. The following two subsections describe how these changes were processed for use in the PRMS simulations.

5.1. Changes in urbanization

Estimates of impervious surface by HRU were derived from the level of urbanization. Projections of future urbanization were derived from outputs of an
application of FORE-SCE to the southeastern United States (Sohl and Sayler 2008). The FORE-SCE application used process-based and statistical techniques to extrapolate future land cover by using USGS land-cover trends data (Loveland et al. 2002). The land-cover trends data are derived from an analysis of five sets of Landsat data: 1973, 1980, 1986, 1992, and 2000. Intermediate products of this modeling process are per-cover-type surfaces indicating probability of occurrence. Spatial modeling was then used with these data to allocate land-cover designations at future time increments in accordance with previous land-cover trend characteristics and development scenarios. Scenarios were developed as extrapolations of the USGS land-cover trends data. FORE-SCE was run continuously on an annual time step at a 250-m cell resolution. These data were used to set the PRMS parameter hru_percent_imperv by calculating the area of each HRU occupied by urban land-cover cells. The parameter hru_percent_imperv indicates the percentage of impervious surface area within a hydrologic response unit.

A comparison of the hru_percent_imperv parameter values derived from FORE-SCE output was made against the same parameter when derived from NLCD2001 urban imperviousness data (shown in Figure 5). Because the NLCD2001 dataset was based on imagery collected during the years 2000–02, the derivation of the parameter from the FORE-SCE output was also limited to these years. HRU impervious surface area derived from NLCD 2001 urban impervious layer were similar to the same statistic derived from the average of FORE-SCE output from the years 2000–02. Relative to the values derived from NLCD 2001, the hru_percent_imperv values derived from the FORE-SCE forecasts are underestimated for low levels of imperviousness and overestimated for high levels of imperviousness. This could be attributed to the differences in cell sizes used to represent the two datasets (FORE-SCE uses 250-m cells; NLCD 2001 uses 30-m cells). This difference could also be due to the distinction between all urban land surfaces (i.e., what the authors extracted from the FORE-SCE data) and those urban land surfaces that are impervious (which is what the NLCD 2001 urban impervious data are specifically engineered to describe). The solid black line is a fitted regression. The equation of this line and the \( R^2 \) goodness-of-fit statistic are reported in the inset box.

The FORE-SCE values from 2006 through 2050 were used to derive values of hru_percent_imperv from 2006 to 2050 for PRMS. This results in 45 forecasts of urbanization (one per year starting in 2006 and ending in 2050). Figure 6 shows annual values of the mean hru_percent_imperv parameter derived from FORE-SCE output through 2050. Note the steady increase in urbanization projected by the FORE-SCE model for the Flint River basin.

5.2. Changes in climate

GCM forecasts of climate were used in PRMS to simulate the changes in hydrologic response within the Flint River basin. Given the uncertainty in climate modeling, it is desirable to use more than one GCM to obtain a range of potential future climatic conditions. GCM forecasts were obtained from the World Climate Research Programme’s Coupled Model Intercomparison Project phase 3 multi-model dataset archive, which was referenced in the Intergovernmental Panel on
Climate Change (IPCC) Fourth Assessment Report Special Report on Emission Scenarios (SRES) (Solomon et al. 2007). The five GCMs used are specified in Table 1. Table 2 lists the four scenarios (one current and three future) under which the GCMs were run.

Climate-change factors were developed by Hay et al. (Hay et al. 2011) for each GCM scenario combination by comparing forecasted climate with baseline climate conditions. For a given GCM, baseline conditions were represented by the output of that GCM when run under the 20C3M scenario during the water years 1988–99. This 12-yr baseline period was chosen based on the overlap of the available historic records from the 14 basins included in the national study. For each GCM scenario combination, mean monthly climate-change factors (percentage changes in precipitation and degree changes in temperature) were computed for the 12-yr moving window periods for each year from 2001 to 2045. The first moving window period in the sequence was 2001–12, the second was 2002–13, and the last was 2045–56. This

Figure 5. Comparison of HRU impervious surface area derived from NLCD 2001 with FORE-SCE output (averaged) from the years 2000–02. The solid black line is a fitted regression.

Figure 6. Annual values of the mean hru_percent_imperv parameter derived from FORE-SCE output.
resulted in 675 sets of change factors (45 of the 12-yr moving window periods × 3 GCM scenarios × 5 GCMs).

Each set of change factors was used to modify a PRMS file of station-based observations for the 12-yr baseline period to create a new PRMS input file, each with 12 years of data. The only differences between the original and modified PRMS input files are in the mean, maximum, and minimum values. The temporal variability and sequencing remain unchanged, limiting this method to studies examining changes in mean climatic conditions. PRMS was then run 675 times, once for each modified input file.

6. Results

In this study, PRMS was configured to run with two types of future conditions (through 2050) for the Flint River basin, 1) changes in urbanization as projected by the FORE-SCE model and 2) changes in climate as projected by GCMs. In the following sections, the PRMS simulation results are presented for each of the following configurations: 1) changes in urbanization (with constant climate); 2) changes in climate (with constant urbanization); and 3) changes in urbanization and climate.

6.1. Changes in urbanization

Changes in urbanization were generated for PRMS by modifying the hru_percent-imperv parameter values with the annual values of urbanization projected by FORE-SCE, resulting in 45 PRMS parameter files. PRMS was run with the station-based

Table 1. GCM outputs used in this study.

<table>
<thead>
<tr>
<th>GCM</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>BCM2.0</td>
<td>Bjerknes Centre for Climate Research model, version 2.0, Norway</td>
</tr>
<tr>
<td>CSIRO-Mk3.0</td>
<td>Commonwealth Scientific and Industrial Research Organisation Mark</td>
</tr>
<tr>
<td></td>
<td>version 3.0, Australia</td>
</tr>
<tr>
<td>CSIRO-Mk3.5</td>
<td>Commonwealth Scientific and Industrial Research Organisation Mark</td>
</tr>
<tr>
<td></td>
<td>version 3.5, Australia</td>
</tr>
<tr>
<td>INM-CM3.0</td>
<td>Institute of Numerical Mathematics Coupled Model, version 3.0, Russia</td>
</tr>
<tr>
<td>MIROC3.2</td>
<td>Model for Interdisciplinary Research on Climate 3.2, National Institute</td>
</tr>
<tr>
<td></td>
<td>for Environmental Studies, Japan</td>
</tr>
</tbody>
</table>

Table 2. Climate-change scenarios used by GCMs in this study.

<table>
<thead>
<tr>
<th>IPCC scenario</th>
<th>Description/assumptions</th>
</tr>
</thead>
<tbody>
<tr>
<td>20C3M</td>
<td>Twentieth-century climate</td>
</tr>
<tr>
<td>SRESB1</td>
<td>Convergent world, with the same global population as scenario SRESA1 but with</td>
</tr>
<tr>
<td></td>
<td>more rapid changes in economic structures toward a service and information economy</td>
</tr>
<tr>
<td>SRESA1B</td>
<td>Very rapid economic growth, a global population that peaks in midcentury, and rapid</td>
</tr>
<tr>
<td></td>
<td>introduction of new and more efficient technologies</td>
</tr>
<tr>
<td>SRESA2</td>
<td>Very heterogeneous world with high population growth, slow economic development,</td>
</tr>
<tr>
<td></td>
<td>and slow technological change</td>
</tr>
</tbody>
</table>
observations for the 12-yr baseline window, 1988–99, once for each level of urbanization. This had the effect of holding the climate conditions constant across all levels of urbanization. For each level of urbanization, PRMS produced a 12-yr simulated streamflow record. In the subsequent analysis of simulated streamflow, the first year of streamflow was ignored to avoid effects of PRMS initialization. The remaining 11 years were averaged, resulting in an 11-yr mean value for each simulated state for each level of urbanization.

Figure 7 shows the results from the PRMS simulations using the projections of FORE-SCE urbanization. Each year on the \( x \) axis corresponds with a FORE-SCE forecast of urbanization. In Figure 7a, the mean values of streamflow and components of flow (surface runoff, subsurface flow, and groundwater flow) are shown. PRMS simulated streamflow increases in direct response to increasing percentage of impervious area within HRUs. The increase in streamflow is driven by increasing surface runoff and decreasing evapotranspiration (Figure 7b). Both subsurface and groundwater flows decrease with increasing percentage of impervious area, although the magnitude of these changes is less than that of the increase in surface runoff.

Table 3 shows the slope of the trend line of projected change in annual values for various hydrologic states simulated by PRMS. The trend line (also referred to here and in the figures as central tendency) was calculated as a mean annual value using the last 11 years of each 12-yr window (the first year was reserved for PRMS model initialization) from all five GCMs under a given scenario.

The last column in Table 3, labeled “land-use-change only,” shows similar information to that depicted in Figure 7. It indicates not only that there are increases in streamflow again driven by increasing runoff and decreasing evapotranspiration and slightly decreasing subsurface and groundwater flows but that all of these changes are statistically significant. No slope values are presented for the precipitation and temperature variables in this column because the historical data from the baseline period were used and no change was applied.

### 6.2. Changes in climate

PRMS was run with each 12-yr moving window PRMS input file. Results (Figures 8–11) are summarized as mean daily streamflow for each 11-yr window for all the GCMs in a scenario. The first year of simulation for each 12-yr moving window was used as PRMS initialization and is not included in the calculation of mean values. Current conditions are shown as a dashed black line (1989–99). The three solid colored lines differentiate the mean values (\( x \)-axis position indicates center of the 11-yr window) for the three scenarios. The yellow-, blue-, and red-shaded regions represent the range of conditions for the SRESB1, SRESA1B, and SRESA2 climate-change scenarios, respectively.

Figures 8a,b show a summary of the annual basin mean values of minimum and maximum temperature. Both maximum and minimum temperatures show the smallest projected changes for the SRESB1 scenario (yellow). All GCM simulations project an overall increase in temperature, with uncertainty increasing with time. Figure 8c shows a summary of the annual basin mean values of precipitation. Projected annual changes in precipitation for the Flint River basin are
Figure 7. Annual values of basin mean daily (a) streamflow, surface runoff, subsurface, and groundwater flow and (b) evapotranspiration resulting from PRMS simulations that use the FORE-SCE urbanization changes during the period 1992–2050.
Table 3. Projected change by year (slope) based on the central tendencies of the five GCMs for the three emission scenarios.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Climate change only</th>
<th>Climate and land-use change</th>
<th>Land-use-change only</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>SRESB1</td>
<td>SRESA1B</td>
<td>SRESA2</td>
</tr>
<tr>
<td>Precipitation</td>
<td>0.0011</td>
<td>-0.0006</td>
<td>-0.0047</td>
</tr>
<tr>
<td>Temperature, max</td>
<td>0.016*</td>
<td>0.031*</td>
<td>0.033*</td>
</tr>
<tr>
<td>Temperature, min</td>
<td>0.015*</td>
<td>0.031*</td>
<td>0.029*</td>
</tr>
<tr>
<td>Evapotranspiration</td>
<td>0.0012*</td>
<td>0.0023*</td>
<td>0.0010</td>
</tr>
<tr>
<td>Streamflow</td>
<td>-0.0048</td>
<td>-0.2296*</td>
<td>-0.4490*</td>
</tr>
<tr>
<td>Surface runoff</td>
<td>-0.00112</td>
<td>-0.054 04*</td>
<td>-0.118 74*</td>
</tr>
<tr>
<td>Subsurface flow</td>
<td>0.005 06</td>
<td>-0.048 09*</td>
<td>-0.100 71</td>
</tr>
<tr>
<td>Groundwater flow</td>
<td>-0.0892</td>
<td>-0.127 71*</td>
<td>-0.229 51*</td>
</tr>
</tbody>
</table>

* Indicates a significant trend (p < 0.05) accounting for lag-1 autocorrelation.
highly variable. The large range in the precipitation projections indicates a large amount of uncertainty. These visual interpretations are supported by the analysis of rates of change in these variables presented in the precipitation, maximum temperature, and minimum temperature rows of Table 3, which show that the increases in both forms of temperature is statistically significant and that change in precipitation varies in both the positive and negative directions but not to a statistically significant degree.

Figure 9 shows a summary of the mean daily value for each 12-yr window for streamflow and flow components (surface runoff, subsurface flow, and groundwater flow). The central tendencies of the PRMS simulations using the GCM scenarios project a decrease in mean annual streamflow and corresponding flow over time, though the uncertainties associated with these projections are quite large. Although evapotranspiration and streamflow are sensitive to increases in temperature, the
Figure 9. Change in 11-yr moving mean daily values of (a) streamflow and the corresponding flow components (b) surface runoff, (c) subsurface, and (d) groundwater for the five GCMs by climate-change scenario.
Figure 10. Change in 11-yr moving mean daily values of (a) streamflow and the corresponding flow components (b) surface runoff, (c) subsurface, and (d) groundwater, using the urbanization forecasts, for the five GCMs by climate-change scenario.
simulation results show that streamflow is highly sensitive to changes in forecasted precipitation, whose uncertainty is large.

The climate-change-only columns of Table 3 present data that are consistent with the visual interpretation made above. Streamflow increases under all scenarios, although this change is not significant in the SRESB1 ("best case") scenario. The rate of decrease in streamflow is larger with the SRESA2 ("worst case") scenario. All the fluxes, except evapotranspiration, show a negative trend that gets larger and becomes statistically significant as the carbon-emission level increases (i.e., from SRESB1 to SRESA1B to SRESA2).

6.3. Changes in urbanization and climate

Climate and urbanization change scenarios were made by combining the 675 climate-change scenarios with the 45 annual urbanization projections. For each 12-yr window of a GCM scenario combination, PRMS was run with that 12-yr window’s modified input file of climate data and the parameter file reflecting the
projected level of urbanization at the midpoint of that 12-yr window. As with the PRMS runs that only used climate change, 12 years of PRMS simulations resulted from each 12-yr window’s modified input file of climate data. Mean values were derived for the modeled states for the last 11 years of simulation. The mean of GCM-specific mean values within a scenario was then derived.

Figure 10a shows the mean annual value (mean of all the annual values over the 11 years of each window) of basin streamflow. Each of the solid-colored lines indicates the mean value derived by PRMS when using one of the corresponding three climate-change scenarios (central tendency of the five GCMs for each scenario) with the urbanization projection. The yellow-, blue-, and red-shaded regions represent the SRESB1, SRESA1B, and SRESA2 climate-change scenarios with projected urbanization, respectively. The shaded areas shown for each scenario indicate the range of potential future climatic conditions simulated by the five GCMs and associated urbanization projections.

Figures 10b–d show a summary of the annual basin mean values of the components of streamflow (surface runoff, subsurface flow, and groundwater flow). The central tendency of mean annual streamflow simulated using the GCM scenarios decreases, with a corresponding decrease in subsurface and groundwater flow, though the uncertainties associated with these projections are quite large. Figure 10b indicates a projected increase in surface runoff. This is a direct result of the urbanization changes, which increase streamflow (see Figure 7a).

The climate and land-use-change columns in Table 3 show that, although there are statistically significant changes in surface runoff (and that those rates of change are noticeably larger for the corresponding climate-change-only columns), the net impact on streamflow is less clear. Reductions in streamflow are lower than under the climate-change-only columns and are never statistically significant. This appears to be due to the relatively large increases in runoff offsetting reductions in subsurface and groundwater flow.

Figure 11 shows a more direct visual comparison of the projected streamflow under climate-change conditions with and without the changes in urbanization (Figures 9a, 10a, respectively). In Figure 11, the central tendency of streamflow that resulted from climate-change-only simulation (lines outlined in black) and climate change with urbanization simulation (solid lines) are expressed as a percentage change from the first 12-yr window for the same scenario. The downward trend in the central tendency of streamflow that was seen when only climate change was simulated with PRMS is reduced over time by the corresponding changes in urbanization that lead to increases in surface runoff and the corresponding changes in total streamflow.

7. Discussion

The large degree of uncertainty about forecasted precipitation is a major issue in interpreting the results of this study, as is the case for other studies in this special collection (Hay et al. 2011). The Flint River streamflow is extremely sensitive to precipitation, clearly more so than to increases in impervious surfaces. Reducing, understanding, and properly handling the uncertainty in future precipitation forecasts are the most important factors for improving understanding about future streamflow conditions.
As described in greater detail above, trends in hydrologic response under increasing daily temperature and precipitation were consistent with the authors’ expectations in that streamflow and all components of flow decreased, with the most significant reductions occurring in the groundwater flows. This is understood to be, in large part, the result of reduced water availability caused by an increase in evapotranspiration. The increased temperatures promote evaporation as well as the bioactivity of the plant biomass.

The impact of changing land use, specifically increases in the proportion of impervious surfaces, through time was to increase surface runoff. This was consistent with expectations because no storage was ascribed to the newly impervious land surface and any incident precipitation would be immediately converted into surface runoff and routed directly to the stream network by PRMS. This increased runoff had the effect of moderating the reduction in streamflow. The increase in impervious surfaces also resulted in a reduction of subsurface and groundwater fluxes. This is conceptually consistent with the idea that, by reducing acreage of exposed, permeable soil within the watershed, infiltration of moisture into the soil would be reduced and thereby limit the water available to the subsurface and groundwater systems. Increases in imperviousness also resulted in significant reductions in evapotranspiration. This was expected as the result of reduced soil moisture (because more precipitation was directly transferred into surface runoff, reducing infiltration) and because the increases in impervious areas resulted in a reduction of vegetation biomass and therefore transpiration.

When simulated in conjunction with climate change, increases in imperviousness changed the negative trends in surface runoff seen under climate-change conditions alone to positive ones, demonstrating that land use can be an important moderator of this form of hydrologic response to climate change. The decreasing trends in subsurface and groundwater flow seen with climate change were strengthened when land-use change was integrated. The trend in evapotranspiration when simulated with both climate and land-use change was negative, although not as strongly under the simulation driven only by land-use change. This reflects the impact increases to daily temperatures caused by climate change.

There are several issues regarding the handling of climate by the FORE-SCE application data used in the Flint River basin study. The FORE-SCE application characterized historical climate conditions by deriving statistics of DAYMET station observations. These data were used as driving variables for the land-cover extrapolation process. The data (DAYMET station observations plus at least six other themes of data; T. Sohl, ASRC Research and Technology Solutions, 2009, personal communication) and methodology (including error checking and resolution, statistical summary of the data, and extrapolation trends into the future) used to derive these characteristics are potentially very different than those that were used in the development of the historical PRMS model.

The study might be improved by driving FORE-SCE using the same GCM scenarios used to drive PRMS. FORE-SCE relied on a set of climate characteristics derived from historical observations and therefore did not recognize any climate-change scenarios. Although climate change clearly can influence changes between vegetative land-cover types (e.g., from forest to desert or shrub or from agriculture to shrub or prairie), it was assumed that urban land cover, the most hydrologically important type of land cover and urban development within the modeled region and
time frame, were controlled by other exogenous factors, such as economic development, population growth, and migration, that would continue for the duration of the study simulation period. In future work, the effect of climate change on land-cover development could be tested by rerunning the FORE-SCE simulations with the same information derived from the GCM scenarios as used in the hydrological modeling and comparing these new results with the current FORE-SCE output.

The study results also might be improved by more appropriate transformation of FORE-SCE output into the parameter used in PRMS, which is referred to as “effective imperviousness.” To do this, the hydrological connectedness of impervious surfaces forecast by FORE-SCE to the drainage network could be analyzed at each future time increment and used to adjust the hru_percent_imperv parameter values. Viger et al. (Viger et al. 2010), among other authors (e.g., Lee and Heaney 2003; Alley and Veenhuis 1983; Olivera and DeFee 2007; Schueler et al. 2009; Wissmar et al. 2004), have demonstrated that the presence of surface depressions such as farm ponds can detain runoff from impervious surfaces, reducing peaks in streamflow response that might otherwise be expected to accompany an increase in the acreage of impervious surfaces in a basin. The analysis presented in this article assumes that no such detention of surface runoff from impervious surfaces occurs. It would be informative to assess the level of urbanization beyond which the buffering of runoff by these surface depressions was overwhelmed. Further, it would be a valuable planning tool to be able to evaluate the number, size, and geographic positioning of new surface depressions needed to control the runoff anticipated from future urbanization. A problem with carrying out this analysis would be developing a method to forecast the maps of surface depressions and other features that serve to disconnect surface runoff from impervious surfaces from the stream network.

The interpretation of FORE-SCE designated urban areas as 100% impervious could be improved upon. Green spaces, such as parks and lawns, on which infiltration occurs within urban areas are not recognized in the current study. Including a more detailed interpretation of the FORE-SCE output could reveal that the increases in surface runoff (shown in Figure 7a) and decreases in evapotranspiration (shown in Figure 7b) are too steep because the hru_percent_imperv parameter was consistently overestimated.

Although the study integrated output from FORE-SCE into PRMS input parameters, there are a number of additional parameters that also could be updated. For example, the PRMS parameter values describing type and density of vegetation could be updated based on the annual levels forecast by FORE-SCE. The study used temporally constant values for vegetation type, vegetation density, interception, and radiation transmissivity for each HRU.

8. Conclusions

The potential effects of long-term climate change and urbanization on the freshwater resources of the Flint River basin were examined by using the Precipitation-Runoff Modeling System (PRMS). PRMS is a deterministic, distributed-parameter watershed model developed to evaluate the effects of various combinations of precipitation, temperature, and land cover on streamflow and general basin hydrology. Precipitation and temperature output from five general circulation models (GCMs) using one current and three future climate-change scenarios were statistically downscaled
for input into PRMS. Projected effects of urbanization for the Flint River basin were derived by using output from the FORE-SCE model through 2050. The hydrologic effects and sensitivity of the Flint River basin to climate and urbanization change were evaluated by comparison of the PRMS simulations for current climate conditions to the ensemble of results produced by using the GCM climate and FORE-SCE urbanization projections.

All future GCM scenarios project a steady increase in maximum and minimum temperature. Unlike temperature, projected changes in precipitation show both increases and decreases, indicating a high degree of uncertainty associated with future precipitation projections in the Flint River basin. PRMS simulates spatially distributed estimates of streamflow, components of flow (surface runoff, subsurface flow, and groundwater flow), and multiple intermediate states of interest. The central tendency of streamflow simulated based on the three climate-change scenarios showed a slight decrease in overall streamflow, mostly caused by decreases in the surface runoff and groundwater components. The addition of information about forecasted urbanization of land surfaces to the hydrologic simulation mitigated the decreases in streamflow, mainly by increasing surface runoff.

REFERENCES


Vogelmann, J. E., S. M. Howard, L. M. Yang, C. R. Larson, B. K. Wylie, and N. Van Driel, 2001: Completion of the 1990s national land cover data set for the conterminous United States from


