Simulating streamflow and the effects of projected climate change on the Savage River, Maryland, USA

Timothy W. Hawkins and Bradley J. Austin

ABSTRACT

The Savage River in western Maryland and its associated reservoir and watershed serves many purposes including recreation, drinking water supply, and auxiliary water supply for Washington DC. Streamflow on the Savage River was modeled using a simple hydrologic model and validated with historical streamflow observations. Future projected climate data were used to drive the model to assess the impact of temperature and precipitation changes on future streamflow. Winter streamflow is projected to increase, while spring, summer, and fall streamflow are projected to decrease. Annual streamflow totals show a slight negative trend over the coming century. Future changes in precipitation are more influencial on future streamflow during the winter while temperature may be more important during the summer and fall. On an annual basis, by the year 2098, the impacts of temperature and precipitation will essentially cancel each other out resulting in only a small negative trend in annual streamflow. Increased streamflow during the winter months may not be able to compensate for decreased flow during the remainder of the year which raises concerns about the ability of the reservoir to supply water during future droughts.

Key words | Chesapeake Bay, climate change, hydrologic model, Maryland, Savage River, streamflow

INTRODUCTION

The Savage River Reservoir (Figure 1), located in the Appalachian Plateau in western Maryland, USA, serves as a drinking water source for the nearby town of Westernport, MD. The reservoir also provides a source of flow augmentation for the Potomac River which serves as the primary drinking water source for the Washington, DC metropolitan area (WMA). Finally, the river, reservoir, and watershed are home to numerous recreational and environmental resources including state parks, hiking trails, camping facilities, trout fisheries, and an Olympic-caliber white-water kayaking course. The purpose of this study was to model and validate streamflow into the Savage River Reservoir using historical data and to use the model to assess the impact of projected future climate change on future streamflow. Given the wide range of uses served by the river, reservoir, and watershed, understanding how the hydrologic system may respond in the future is critical to the proper management of this resource.

The 276 km² Savage River watershed is located in Garret County, Maryland and consists primarily of steep, covered, mountain slopes with rocky soils and dense vegetation. Land use in the watershed is relatively homogeneous: 83% forested, 15% agriculture, and 2% urban (Figure 1) (MDE 2002). About 58% of the watershed is designated as either state forest or state park. Consequently, future changes in land use and the corresponding impact on streamflow is likely to be minimal.

The reservoir’s watershed is dominated by a Devonian and Carboniferous soft sandstone valley and bounded by harder Pottsville formation sandstone mountains to the west and east with only a few small faults and fractures (Eckel 1938). The water table near the reservoir site is...
relatively shallow, largely due to shallow, rocky, permeable soils overlaying impermeable bedrock. Some limestone exists near the edges of the valley, though the likelihood of large caverns is small (Eckel 1938). Additionally, aquifer storage in this region is typically limited because of the close relationship between ground and surface water (MCCC 2000), all suggesting that changes in streamflow are primarily driven by surface water processes.

The reservoir itself has a surface area of 1.5 km², a volume of 23.9 million m³, and a depth at the dam of 46 m. Average annual flow on the river feeding the reservoir is 3.05 m³/s. Average annual temperature is 8.4 °C with an average monthly high of 19.9 °C in July and an average monthly low of −3.8 °C in January. Average total annual precipitation is 1,066 mm with a maximum monthly average of 109 mm in May and July and a minimum monthly average of 72 mm in February.

As the drinking water supply for Westernport, MD (population ~2,000), the Upper Potomac River Commission (UPRC) and the US Army Corps of Engineers (USACE) maintain a minimum water elevation in the Savage River Reservoir ranging from 424 m above sea level (asl) in January to 436 m asl in June (ICPRB 2010). The height of the dam spillway is 448 m asl. Additionally, the Interstate Commission on the Potomac River Basin (ICPRB) may request releases from the reservoir during drought conditions for water quality control and flow augmentation of the North Branch Potomac River (Hagen et al. 2005). The Savage Reservoir is responsible for roughly 20% of these drought-time releases from the North Branch system which includes the Savage River Reservoir and the Jennings Randolph Reservoir (Hagen et al. 2005; ICPRB 2010). The Potomac River accounts for approximately 78% of the raw water supplied to the 4.3 million people in the WMA (ICPRB 2010).

The Maryland Commission on Climate Change (MCCC 2008) reported on the impacts of projected climate change on water resources as well as other environmental and socioeconomic sectors throughout the state. The following paragraphs summarize the findings relevant to this study. Maryland is projected to both warm and have increased precipitation over the next century. The clearest historic changes are shown in the temperature record where across Maryland the average monthly maximum temperature has been increasing faster than mean monthly temperature. This trend is expected to continue and result in a higher frequency and intensity of heat waves. Across the entire state, mean warming of 1.1 °C by 2025 is expected (regardless of emissions scenario) and 1.7 °C is expected in summer months by 2050 (regardless of emissions scenario). By 2100, temperatures are projected to increase by 2.7° to 5 °C in summer and 2.2° to 3.9 °C in winter, depending on the emissions scenario. High emissions correspond to Special Report: Emissions Scenarios (SRES) A2 (IPCC 2000) while low emissions correspond to SRES B1.

Temperature changes are expected to affect large-scale circulation patterns which in turn affect precipitation. Precipitation projections, though not as certain, do show marked changes. Winter rainfall is projected to increase 5% by 2025, 6.6–6.8% by 2050, and 10.4–12.6% by 2090, though increases of this magnitude do not reflect current inter-year variability. Given the projected warming, it is reasonable to presume that higher temperatures will result in less snowfall and/or more melting, which creates concern in western Maryland where winter activities such as skiing are common. Water available for runoff or groundwater recharge is projected to decrease by 2–7 mm per month in summer and increase by 6–7 mm per month in winter by 2100.

The average length of the growing season in the area is expected to increase, and therefore the dense forests of the Savage River watershed will bud leaves earlier and keep them longer. One line of reasoning suggests that
atmospheric demand for water may increase due to warmer temperatures, thereby increasing the amount of water lost through evapotranspiration and decreasing the amount of water available for groundwater recharge and runoff (MCCC 2008). This increase in temperature may also mean an increase in evaporation directly from the reservoir, which is one factor that is known to significantly decrease reservoir storage (Booker & O’Neill 2006). However, another line of reasoning suggests that the changes in wind, radiation, and humidity that accompany warming temperatures may actually serve to decrease evaporation rates (Hobbins et al. 2008).

In addition to the numerous studies that have examined the impact of projected climate change on future runoff levels throughout the USA (e.g. Frei et al. 2002; Fu et al. 2007; Ellis et al. 2008; Groves et al. 2008), several studies have examined the Mid-Atlantic region specifically. Najar et al. (2009) examined climate simulations for Mid-Atlantic watersheds including the Chesapeake Bay which includes the Savage River watershed. Projections are for the Chesapeake watershed to become warmer and wetter although there is greater confidence in temperature projections compared to precipitation projections. Additionally, the climate models assessed in the study that were deemed most accurate projected less warming and lower precipitation increases compared to the climate models that were assessed as less accurate. The implications are that precipitation projections need to be improved as well as the understanding of how temperature increases impact streamflow. Najar et al. (2010) elaborate that there will very likely be increases in precipitation on the Chesapeake Bay watershed, especially in the winter and spring, as well as increases in precipitation intensity. There is greater uncertainty but it is also likely that streamflow will increase during the winter and spring but overall, on an annual basis, perhaps decrease. The Chesapeake Bay Foundation (CBF 2008), in a review of literature relating to streamflow on the Chesapeake watershed, noted that most of the interannual variability in streamflow is driven by precipitation and not evapotranspiration. Trends in historical streamflow differ depending on the specific geographic region of the watershed examined and future streamflow projections vary widely. Again, this discrepancy is due to the quality of precipitation projections as well as the differing responses of hydrologic models to warming temperatures.

Most hydrologic/climate-change studies in the Mid-Atlantic have focused on large watersheds. This study examines a much smaller watershed as the issue of scale is important to consider in modeling the impacts of projected climate change. Wilbanks & Kates (1999) note that climate change affects people from the bottom-up, locally to globally, in various sectors and across various spatial and temporal scales. The Savage River Reservoir, while not a large supplier to the WMA on a regular basis, does still serve a vital role in the larger WMA water management process. Arguably more importantly however, the Savage River is the source of drinking water for a smaller, more rural population as well as the lifeblood of a vibrant ecosystem and its attendant attractions. Changes to watersheds of this size due to climate change are the types of changes that will be most obvious and perhaps most important to individuals. Thus, by modeling the projected changes to the Savage River and thinking about the consequences from a resource management perspective, this study serves as a template for assessing other watersheds of this size and importance.

**DATA AND METHODS**

**Model description**

A simple climatic water budget model was developed to simulate the streamflow of the Savage River. This model is in part based on principles first developed by Thornthwaite (1948) and more recently modified by Frei et al. (2002), McCabe & Markstrom (2007), and Ellis et al. (2008). Figure 2 shows a conceptual schematic for the model. The model operates on a monthly time step using inputs of average temperature (T) and total precipitation (P). Input data are described in the next section.

Following McCabe & Markstrom (2007), precipitation was differentiated into rainfall and snowfall by setting monthly average temperature thresholds above which all precipitation is rain (Tₚ) and below which all precipitation is snow (Tₛ). Following McCabe & Wolock (1999), Tₚ was set to 3 °C and Tₛ was set to –10 °C. When the temperature
fell between the thresholds, snowfall was calculated as

\[ P_s = P \times \frac{T_r - T_s}{T_r - T_s} \quad (1) \]

and rainfall was calculated as

\[ P_r = P - P_s \quad (2) \]

Also following McCabe & Markstrom (2007), a snowmelt fraction (SMF) indicating the percentage of precipitation stored as snow that melted was calculated as

\[ \text{SMF} = \frac{T - T_s}{T_r - T_s} \quad (3) \]

SMF was constrained between 0 and 1. SMF was then multiplied by the sum of \( P_s \) and the snow stored from the previous month to produce a melt depth which was added to \( P_r \) to give a total water input to the soil (\( P_{\text{avail}} \)).

Potential evapotranspiration (PE), or the atmospheric demand for water, was calculated using the Hamon (1961) method as

\[ \text{PE} = 13.97dD^2 \left[ \frac{4.95e^{-0.062t}}{100} \right] \times CC \quad (4) \]

where \( d \) is the number of days in the month, \( D \) is the mean monthly hours of daylight in units of 12 h, and \( CC \) is a seasonal calibration coefficient used in similar studies to produce more accurate values of PE when compared with measurements (Federer & Lash 1985; Lu et al. 2005; Pyzoha et al. 2008). For this study, an average calibration coefficient of 1.3 was used.

IF \( P_{\text{avail}} - PE \) was positive, subsurface moisture (SM) was recharged up to a capacity of 125 mm. Capacity was determined using the methodology outlined in Ellis et al. (2008). If \( P_{\text{avail}} - PE \) was negative, subsurface moisture was calculated as

\[ \text{SM}_i = \text{SM}_{i-1} + \frac{(P_{\text{avail}} - PE) \text{SM}_{i-1}}{\text{cap}} \quad (5) \]

where \( i \) indicates the current month and cap is the subsurface moisture capacity of 125 mm.

IF \( P_{\text{avail}} \) is greater than PE, then actual evapotranspiration (AE) equals PE and excess water recharges SM. If \( P_{\text{avail}} \) is less than PE, then AE is the sum of \( P_{\text{avail}} \) and the change in SM from the previous month. In months where \( P_{\text{avail}} \) is greater than PE and SM is fully recharged surplus water is calculated as

\[ S = P_{\text{avail}} - PE - \Delta \text{SM} \quad (6) \]

Finally, following Mather (1978), runoff (RO) was calculated as 60% of the surplus. The remaining 40% of the surplus was held over to the next month where it was combined with the new month’s surplus. This methodology accounts for lag times between rainfall/snowmelt and runoff generation due to slower subsurface flow and distance from the edges of the watershed to the gage.

**Model input data**

Three different data sets of monthly average temperature and total precipitation were used as inputs into the model: observed data from the Parameter Regression on Independent Slopes Model (PRISM), simulated data from the World Climate Research Programme’s (WCRP) Coupled Model Intercomparison Project Phase 3 (CMIP3sim), and observed data corresponding to downscaled CMIP3 data.
The PRISM algorithm uses point meteorological data and a digital elevation model to generate monthly gridded values of temperature and precipitation for the United States that account for complex situations such as mountainous terrain, rain shadows, and temperature inversions (Daly et al. 1994). The resolution of the grid cells is approximately 4 km. Data from the 15 PRISM grid cells that were contained within the watershed were averaged.

CMIP3sim data were compiled from hundreds of climate model simulations into a single archive for use in multimodel projections and impacts assessments (Meehl et al. 2007). CMIP3sim data are of a grid-scale that is generally not useful for finer-scale analyses. Bias-corrected and spatially downscaled climate projections derived from CMIP3sim data (http://gdo-dec.ucllnl.org/downscaled_cmip3_projections/) were therefore used. See Wood et al. (2004) and Maurer (2007) for descriptions of the methodology for downscaling the CMIP3sim data. Data are available at 1/8° resolution for 112 different climate projections. Data from the six cells contained in the watershed were averaged. The 112 projections are the result of 16 different CMIP3sim models using three different emission scenarios. Information regarding the 112 projections is available at the previously listed website. Depending on the model/emission scenario combination, a number of different runs were available featuring unique initial conditions. The three different emission scenarios as defined by IPCC (2000) and available through the dataset were A2 (higher emissions path, 36 projections), A1B (middle emissions path, 39 projections) and B1 (lower emissions path, 37 projections). Initial analysis of the hydrologic data resulting from the 112 individual climate projections as well as the average of the projections for the high, middle, and low emission scenarios indicated that there was not a significant difference between the projected hydrology based on the emission scenario. To facilitate presentation of the results in the most understandable manner, all 112 climate projections were averaged and run through the hydrologic model. Possible causes of the lack of difference between the climate projections include the relatively small spatial area of the study compared with the climate model domains as well as the possible offsetting influences of temperature and precipitation changes (discussed later). CMIP3sim projections encompass the period from 1950 to 2098. Also associated with the downscaled dataset are observed station data from 1950 to 1999 that have been rasterized to the same grid (CMIP3obs). PRISM and CMIP3obs data were used to drive the hydrologic model from 1950 to 1999 while CMIP3sim data drove the model from 1950–1999 as well as from 2000–2098.

Correlations over the 1950–1999 time period between the three datasets (PRISM, CMIP3sim, and CMIP3obs) indicated that temperatures between the three datasets were highly correlated (not shown). Precipitation between PRISM and CMIP3obs was highly correlated but precipitation between CMIP3sim and the other two datasets was not highly correlated (not shown) and resulted in poor streamflow simulations (discussed in results). As the goal of this study was to assess future runoff based on climate simulations, it was important to ensure that the climate simulation data were as accurate as possible. To this end, a synthetic precipitation time series was developed (CMIP3sim w/Psyn).

Average monthly precipitation values for CMIP3sim and CMIP3obs were nearly identical for each of the 12 months. The variance however, for CMIP3obs was much larger. Therefore, for each of the 12 months, the 50 years of data from 1950–1999 for both datasets were ranked by the difference from the mean for that month. The ranked CMIP3obs difference data were substituted for the ranked CMIP3sim difference data with minor alterations made to ensure that differences of a certain sign always matched up with data of the same sign.

For example, January 1981 was the most below average January CMIP3obs value (59.3 mm below average) while January 1985 was the most below average January CMIP3sim value (12.9 mm below average). January 1996 was the most above average January CMIP3obs value (106.3 mm above average) while January 1970 was the most above average January CMIP3sim value (15.1 mm above average). The low observed value (59.3 mm below average) replaced the low simulated value (12.9 mm below average) and the high observed value (106.3 mm above average) replaced the high simulated value (15.1 mm above average). This same
process was repeated for all January data points between the high and low values illustrated here as well as for the other months. The substituted differences were then used to calculate actual precipitation by adding or subtracting the difference to the monthly mean based on the sign of the difference. These values were then resorted chronologically into a time series. This methodology essentially increased the variance of the CMIP3_sim data to more realistic values based on the observed data.

A similar technique was applied for the CMIP3_sim data from 2000–2098. Instead of the monthly average being used to calculate monthly differences however, the trend line was used to account for the clear increasing trend in simulated precipitation. Ranked differences were matched up with ranked CMIP3_obs differences, the CMIP3_obs differences were substituted, new values of precipitation were calculated based on the trend line, and the data were resorted into chronological order. The 2000–2098 synthetic precipitation data retained the trends and timing of the climate simulations but added the more realistic variation evident in the observed data.

Model assessment

Modeled streamflow data were compared with observed streamflow data derived from Army Corps of Engineers estimates for total inflow to the reservoir. These estimates were based in part on a gage located just upstream of the Savage Reservoir (Figure 1) and were provided by the ICPRB. Comparisons were made for monthly averages and water year totals of runoff. Because impacts to future runoff are examined in decadal time steps, model assessment of water year runoff totals employed a 10-year running average.

Analysis of streamflow projections

Trends in water year streamflow projections were analyzed through 2098. The annual cycle of streamflow and other components of the hydrologic model that help to explain streamflow patterns were averaged for three future periods: 2025–2035, 2055–2065, and 2085–2095. These future periods were compared to the baseline period of 1950–1999. Changes in reservoir inputs, calculated as the sum of runoff and precipitation minus evaporation, were also calculated for the three future periods relative to the baseline period.

To test which input parameter (temperature or precipitation) has more influence on future streamflow, following McCabe & Wolock (2010), the model was rerun holding temperature constant at 1950–99 monthly averages and allowing precipitation to fluctuate using the synthetic precipitation time series. This model run is referred to as ‘T constant’. This technique was repeated holding precipitation constant at monthly average values from 1950–1999 and allowing temperature to fluctuate using the CMIP3_sim values. This model run is referred to as ‘P constant’. Average monthly streamflow values for each of the three future periods for both the T constant and P constant model runs were compared to the model run where both T and P were allowed to vary (T and P vary). Differences between the model runs were compared for the T constant and P constant runs to assess the relative importance of temperature and precipitation on streamflow.

RESULTS

Model assessment

Figures 3 and 4 show modeled and observed monthly average and water year total streamflow respectively. Average monthly modeled streamflow (Figure 3) using PRISM, CMIP3_obs, and CMIP3_sim w/Psyn, all agree well with observations. Average monthly modeled streamflow using CMIP3_sim compare well from December to April but underestimate streamflow from May to November. In fact in October, average modeled streamflow is zero. Year-to-year variability (Figure 4) is not modeled as well but again modeled streamflow using PRISM, CMIP3_obs, and CMIP3_sim w/Psyn are markedly better than modeled values using CMIP3_sim. The poor performance of CMIP3_sim in Figures 3 and 4 was the impetus for creating the synthetic precipitation time series. The decreased variability in streamflow that results from the unrealistic lack of variability in CMIP3_sim precipitation values is clearly evident in Figure 4. Because the water year values in Figure 4 are based on 12 months of data where the monthly average values in Figure 3 are based on 50 years of data, simulations generally
appear more accurate in Figure 3. Examination of the results from Figure 4 that have not been subjected to the 10-year smoothing show that PRISM and CMIP3$_{obs}$ streamflow values compare very well with observations while CMIP3$_{sim}$ w/P$_{syn}$ perform less well but much better than CMIP3$_{sim}$. This all indicates that precipitation associated with
CMIP3_{sim} is the limiting factor in this study as well as numerous other studies that have attempted to use simulated values of future precipitation (IPCC 2007). The synthetic precipitation time series is an attempt to minimize the impact of the relatively poor quality of the simulated precipitation data.

### Analysis of streamflow projections

Figure 5 shows future projections of streamflow, subsurface moisture, precipitation, snowfall, PE, and AE for three future time periods while Figure 6 shows the water year total runoff out to the year 2098. Streamflow (Figure 5(a)) is projected to increase in January and February, remain nearly constant during the peak month of March, and generally decrease between April and November. For December, runoff increases for the 2025–35 and 2055–65 periods but decreases for the 2085–95 period. For nearly all months, the 2085–2095 period has the largest runoff values (i.e. it shows the largest increases from the 1950–99 period or the smallest decreases). Annual runoff is highly variable (Figure 6) but still shows a decreasing trend of 19 mm/century. Note that when CMIP3_{sim} precipitation data were used in the hydrologic model (not shown), the decreasing trend was 45 mm/century and highly significant. CMIP3_{sim} precipitation data indicate a decrease in precipitation in the future. The more realistic variability in precipitation added in the synthetic precipitation time series diminishes the decreased runoff trend.

The increased variability in synthetic precipitation can be seen in Figure 5(c). No clear precipitation pattern exists for any given month or for any time period suggesting that precipitation will be variable in the future and therefore its impacts not consistent. Because temperature is projected to consistently increase (not shown), snowfall and snow cover are projected to further decrease with each future time period (Figure 5(d)). Conversion of snowfall to rainfall in December through February explains the increase in runoff during these months while the lack of snow cover and therefore snowmelt during the spring explains the decreased streamflow during the spring and summer.

Also based on the consistent temperature increases, PE correspondingly increases with the largest increases seen in the warmer summer months and during the most future time period (Figure 5(e)). Corresponding to increased PE, AE also increases (Figure 5(f)). For all periods, a deficit (when AE cannot meet PE) first appears in June. These deficits grow increasingly larger in the future as the temperature warms. The increased PE demand cannot be met by precipitation that is highly variable (Figure 5(c)) and subsurface moisture that is increasingly utilized in the warmer months (Figure 5(b)). Subsurface moisture is a representative integrator of water inputs and outputs and therefore the potential to generate runoff. Subsurface moisture is maintained at or near capacity in the future for December through May. SM shows increased utilization from June to October. For the 2085–95 period, recharge takes nearly a month longer compared to the other three previous periods. Future SM values at capacity also explain the increased or constant future streamflow values in the winter and early spring while increased SM utilization in the late spring and summer explain the decreased streamflow during this time.

Figure 7 shows the monthly and annual change in net reservoir input (runoff + precipitation – evaporation) for the three future periods compared to the 1950–1999 period. As net inflow is primarily dominated by runoff (208 times more volume on an annual basis), the pattern of net inflow is similar to runoff (Figure 5(a)). In January and February, future inputs increase relative to 1950–1999. In March and April, future inputs increased for the 2085–2095 period yet decreased for the 2025–2035 and 2055–2065 periods. From May to November, future inputs decreased for all time periods with the largest decreases in November. December had increased inputs for the first two time periods but decreased inputs for the 2085–2095 period. On an annual basis, reservoir inputs decreased for the 2025–2035 and 2055–2065 periods and slightly increased for the 2085–2095 period. The increase during the most future period is due to the few relatively high streamflow years during this period (Figure 6) that result from the highly variable precipitation. Sliding the averaging window slightly forward or backward in time would result in decreased reservoir inflows for the most future period as well.

Figure 8 shows monthly average modeled streamflow for the three future periods for the $T$ constant and $P$ constant scenarios. For reference, streamflow is also
shown for when both $T$ and $P$ vary. Figure 9 shows water year annual values for the $T$ constant and $P$ constant scenarios. With the exception of January for the 2025–2035 and 2055–2065 time periods, allowing $P$ to vary while holding $T$ constant at average conditions caused streamflow to increase for all months and for all three
future periods. The increase in streamflow is generally greater for the most future period although there are exceptions due to the variable nature of future precipitation. The result is that on an annual basis runoff under the $T$ constant scenario increases and these increases are larger into the future.

Because future temperatures are projected to increase in a more consistent manner compared with precipitation,
the pattern of streamflow changes in the $P$ constant scenario is more consistent. Holding precipitation at average values while allowing temperature to vary results in decreased streamflow for all months (Figure 8). These decreases are greatest for the most future time period. The model does not allow streamflow to ever reach zero but values approach zero in August and do not increase until December. Low streamflow values are lower and
last longer compared with the scenario where $T$ and $P$ vary. By holding the variable precipitation values to average conditions, annual streamflow totals using the $P$ constant scenario shows steadily decreasing values (Figure 9) due to the warming temperatures and increased evapotranspiration.

Figure 10 shows the relative importance of precipitation and temperature in modeling streamflow on a monthly basis. The three bars for each month represent the three future periods. Grey bars indicate that precipitation was more important and white bars indicate that temperature was more important. The impact of precipitation is generally most important from November to February. In May and June, precipitation is generally more important but to a lesser degree. For March and April, temperature is generally more important although during the 2085–2095 time period there is no difference for March and precipitation is more important for April. From August to November, temperature is more important to modeling streamflow although these results are misleading. Because streamflow cannot go below zero, the streamflow values have a lower bounding limit and thus comparing relative changes is misleading. If streamflow could become negative, Figure 8 suggests that in fact precipitation may actually be more important.

This notion is corroborated by Figure 11 which shows annual differences in streamflow values for the $T$ constant and $P$ constant scenarios compared with the scenario where $T$ and $P$ vary. The $T$ constant differences show relatively little variation because the $T$ constant scenario is so similar to the $T$ and $P$ vary scenario (Figure 9). The opposite is true for the $P$ constant differences. To allow comparisons between the $T$ constant and $P$ constant differences, trend lines were calculated. The effect of holding temperature constant is to produce an overall increase in streamflow that gets greater with time corresponding to the increasing trend in precipitation. The exact opposite is true for $P$ constant as streamflow decreases with time due to warming temperatures and increased evapotranspiration. Comparing the predicted differences associated with the trend lines indicates that precipitation is nearly twice as important on an annual basis as temperature in modeling streamflow in 2000 but is nearly equal in importance to temperature by 2098. The impact of temperature and precipitation essentially cancel each other out in the future. These results are
in line with those presented in Figure 6 that indicates only a slight impact in streamflow over the next century.

**DISCUSSION**

Previous studies have suggested that future streamflow in the Chesapeake Bay watershed is likely to increase in the winter and spring months and decrease during the summer months (CBF 2008; MCCC 2008; Najar et al. 2009, 2010). Streamflow studies have also been hindered by the relatively poor quality of projected precipitation data. In general, this study confirms and elaborates upon these results.

For the Savage River watershed, streamflow is projected to increase during the winter months, reach approximately the same peak in March, and then decrease in spring, summer, and fall. The cumulative effect is a slight decrease in annual streamflow. The nature of projected streamflow change raises questions about the Savage River Reservoir’s ability to perform its main functions: to provide drinking water to Westernport, MD and to provide releases to the Potomac River to improve water quality and augment flow as a service to the WMA. These concerns are more pressing given that precipitation is projected to become more variable (IPCC 2007; MCCC 2008), drought occurrence is projected to increase (IPCC 2007; MCCC 2008), and the population and consumption of the WMA are projected to increase (ICPRB 2010). Given that UPRC and the USACE operate the Savage River Reservoir to maintain a minimum level to supply Westernport, it is possible that the reservoir may not be able to assist the WMA as it has in the past. Furthermore, increased winter flow does not guarantee that the reservoir will maintain an adequate supply because of the finite volume of the reservoir. Additional winter runoff may need to be released downstream to avoid a dam breach and will not be available to compensate for the decreased flow throughout the rest of the year. These issues may necessitate a rethinking of the Savage River Reservoir’s management plan.

This study provides an example of the impact of projected climate change on a smaller watershed. The majority of studies related to streamflow in this region examine large watersheds (e.g. Potomac or Chesapeake Bay), but relatively few focus on the smaller subwatersheds as this study does. From a water resources perspective, it is critical to understand how subwatersheds that have specific purposes in the overall management plan will respond. The
Savage River watershed serves a vital role for the WMA during times of drought. The results of this study clearly suggest that at the very least, the regulations regarding that role may need to be re-examined in the future. In a worst case, the reservoir may not be able to perform its role at all. These types of insights are not apparent when examining the issue at the larger watershed scale.

As with other previous studies, this study is limited by the quality of the projected precipitation data. A technique was presented that improved the quality of the data by increasing the variation to more realistic levels but the quality could still be improved further. This technique is similar to methodology presented by Wood et al. (2004) (incorporated into the downscaled data used in this study) and Sun et al. (2011). Sun et al. (2011) found that historic and model-simulated precipitation in the Murray-Darling Basin in Australia did not differ significantly from a random distribution. This result held for both uncorrected and bias-corrected time series. The significance of this finding is that it provides a baseline from which to assess precipitation projections as different models produce dramatically different variances in precipitation time series and therefore assessing the ‘best’ one for a region is problematic. Similar to Sun et al. (2011), this study was able to use the variance in the historical and projected time series to assess the quality of the individual model runs and reach one of the same conclusions that the projections could be averaged together as the results did not differ significantly from using individual model runs. Furthermore, precipitation projections must consider the variance of the time series in interpreting the results of future projections. The synthetic precipitation time series employed in this study accomplished that goal.

At this point, precipitation data are limited by the capabilities of the climate models that produce them. Given these data issues, streamflow results based on these data must be viewed cautiously. The raw data from the CMIP3 project show a clear small but increasing annual trend in precipitation for the Savage River watershed. This trend is minimized but still present in the synthetic time series created for this study. Given the projected temperature changes as well, the projected streamflow results make physical sense and are certainly in line with previous research as discussed earlier. The concern comes from the high degree of interannual variability that is present in the historical precipitation record and that will likely be more dramatic in the future. While not the focus of this study, it stands to reason that managers of the Savage River Reservoir, as well other reservoirs, may need to prepare for more climate variability in their decision making and reliance on historical data may not be sufficient.

Another limit to this study is the availability of meteorological data to calculate evapotranspiration. The Hamon method used here to calculate PE is driven primarily by air temperature. As temperature warms, clearly PE will increase as well. Depending on the amount of precipitation and subsurface moisture, AE will change correspondingly. Hobbins et al. (2008) suggest that the increase in AE associated with temperature-based calculations of PE is not often supported by estimates or measurements of evapotranspiration from more physically based methods or from evaporation pans due to changes in radiation, humidity, and wind that are not accounted for in temperature-based PE formulations such as the Hamon method. Ideally, a method such as the Penman–Monteith formulation that incorporates wind, humidity, and radiation into the calculation of evapotranspiration would have been used in this study, but as noted by Hobbins et al. (2008) the data to use this methodology often do not exist. This is true for the Savage River watershed.

Also noted by Hobbins et al. (2008), temperature-based calculations of PE are most problematic in ‘energy limited’ locations where precipitation is able to meet evaporative demand and evapotranspiration is therefore limited by the amount of energy input into the hydrologic system. The Savage River watershed represents an ‘energy limited’ environment on average from December to April when PE and AE are low. However, the watershed represents a ‘water limited’ environment from May to November when evaporation is a much more influential component of the hydrologic system. ‘Water limited’ environments are not able to meet evaporative demand through precipitation and therefore evaporation is much more influenced by precipitation. Hobbins et al. (2008) show that temperature-based PE formulations work well in ‘water limited’ environments. Because the Savage River watershed is ‘water limited’ during the time of highest evapotranspiration, the use of the Hamon PE method, while not ideal, likely does
not have a major influence on the results. This notion is corroborated by results that indicate the relative importance of precipitation compared to temperature in calculating streamflow.

**CONCLUSION**

A hydrologic model was developed to simulate streamflow on the Savage River watershed and was validated using historical streamflow observations. Future climate projections were then used to drive the model to assess the response of future streamflow to climate changes. The results can be summarized as follows:

- Climate model-simulated temperature data match up well with observed data while simulated and observed precipitation data do not match up well. A synthetic precipitation time series improves upon the original precipitation data and helps account for spatial variability when downscaling coarse-scale climate model projections to smaller watersheds.

- Winter streamflow is projected to increase, the March peak is projected to remain nearly constant, and spring, summer, and fall streamflow are projected to decrease. Annual streamflow totals show a slight negative trend over the coming century.

- Future changes in precipitation are more influential on future streamflow during the winter while temperature may be more important during the summer and fall. On an annual basis, by the year 2098, the impacts of temperature and precipitation will essentially cancel each other out resulting in only a small negative trend in annual streamflow.

- Increased streamflow during the winter months may not be able to compensate for decreased flow during the remainder of the year when considering the Savage River Reservoir’s role in the WMA water supply system.

The Savage River Reservoir is a unique resource given its size and its role in the WMA water supply system. It is critical for water resource managers to appreciate the various roles that specific watersheds play within a larger system and that the responses of these individual watersheds to a changing climate necessitate unique analysis and decisions. Ultimately, the Savage River Reservoir’s ability to supply water to the WMA in times of drought relies on the operating rules in place and continual re-evaluation of these rules as data quality and availability increase.

**ACKNOWLEDGEMENTS**

The authors thank Sarah Ahmed and Cherie Schultz at ICPRB for providing data and answering questions relating to the data as well as two anonymous reviewers whose comments improved the quality of this manuscript.

**REFERENCES**


Maurer, E. P. 2007 Uncertainty in hydrologic impacts of climate change in the Sierra Nevada, California under two emissions scenarios. Climatic Change 82, 9180–9189.


MDE. 2002 Total Maximum Daily Load of Mercury for Savage River Reservoir Garrett County, Maryland. Maryland Department of the Environment, Baltimore, Maryland.


Najar, R., Patterson, L. & Graham, S. 2009 Climate simulations of major estuarine watersheds in the Mid-Atlantic region of the US. Climatic Change 95, 159–168.


First received 17 March 2011; accepted in revised form 14 July 2011.