Investigation and Modeling of Winter Streamflow Timing and Magnitude under Changing Climate Conditions for the Catskill Mountain Region, New York, USA

MARK S. ZION[1], SONI M. PRADHANANG[2], DONALD C. PIERSON[1], AAVUDAI ANANDHI[2], DAVID G. LOUNSBURY[1], ADAO H. MATONSE[2]
AND ELLIOT M. SCHNEIDERMAN[1]

ABSTRACT:

Snowfall is an important part of the yearly water balance for the Catskill Mountains in New York State, the location of the West-of-Hudson water supply for New York City. Recent studies have shown that the effects of climate change on the hydrology of the Catskills will most likely create (1) a decrease in the proportion of precipitation falling as snow, (2) a shift in the timing of snowmelt that will cause snowmelt supplemented streamflow events to occur earlier in the fall and winter, and (3) a decrease in the magnitude of traditionally high streamflow period in April. Studies of streamflow, precipitation and temperature trends in the last 50 years have shown that this phenomenon is beginning to occur. This study investigates the use of watershed scale snowpack and snowmelt models that are incorporated in two existing watershed water quality models, GWLF-VSA and SWAT, to capture the potential effects of climate change on the timing and magnitude of streamflow during the late fall, winter and early spring for the Catskill Mountain Region. The GWLF-VSA model reasonably simulated the recent shifts in the winter streamflow timing. The SWAT model yielded similar results as the GWLF-VSA simulations for the winter streamflow shift. Forcing the watershed models with scenarios of potential climate change showed a similar shift in direction of winter streamflow, but at a larger magnitude than observed to date.

Keywords: Streamflow Timing, Trend Analysis, Watershed Modeling, Climate Change, SWAT, GWLF

INTRODUCTION

Current predictions of climate change in the northeastern United States (U.S.) suggest increased temperatures throughout the year, including the winter. Increased winter temperatures in northern latitudes and mountainous areas can have a profound effect on the accumulation of snow, the timing of snowmelt and, in turn, the magnitude and timing of winter and spring streamflow. Changes in the timing of winter streamflow can have many implications for the management of water supplies, flood control and water quality.

A number of studies have shown that temperatures in the northeastern U.S. have risen in the last 50 years (Trombulak and Wolfson, 2004; Burns *et al.*, 2007). These temperature increases have already created a shift in the winter streamflow patterns, with a movement of the traditional high spring runoff period due to snow melt to earlier in the year (Burns *et al.*, 2007; Hodgkins *et al.*, 2003; Hodgkins and Dudley, 2006; Zhang *et al.*, 2001; Burn, 2008). This phenomenon of shifting streamflow is more pronounced in more northern and more mountainous catchments (Hodgkins *et al.*, 2003; Hodgkins and Dudley, 2006; Burns *et al.*, 2007).

[1] New York City Department Of Environmental Protection, Kingston, New York
[2] Institute for Sustainable Cities, City University Of New York, New York, New York.

The Catskill Mountain Region of New York State supplies water for 9 million residents of New York City and surrounding areas. Winter precipitation (December-April) accounts for approximately 40% of the total yearly precipitation. Streamflow during the winter and early spring (January-May) which is highly dependent on the December-April precipitation accounts for 60% of the total annual flow. The majority of winter precipitation currently falls as snow, creating a snowpack that is useful for water storage in the winter and as a source of water throughout the spring.

In order to evaluate and plan for the potential impacts of climate change on the New York City Water Supply, the New York City Department of Environmental Protection (NYCDEP) has undertaken a Climate Change Integrated Modeling Project (CCIMP) to investigate the potential effects of climate change on the quantity and quality of the water supply (NYCDEP, 2008). Preliminary modeling efforts under this project have consistently shown a major shift in the timing of winter streamflow (NYCDEP, 2009). This shift in the streamflow has some potential effects on the patterns of the system's overall storage (Matonse *et al*., 2010) and on the timing and magnitude of nutrient and sediment loads to the reservoirs (NYCDEP, 2009).

As part of the CCIMP, existing watershed water quality models are being utilized to develop flows and constituent loads to the reservoir system. The models used within this program include the Generalized Watershed Loading Functions – Variable Source Area version (GWLF-VSA) (Haith and Shoemaker, 1987; Schneiderman *et al*., 2002; Schneiderman *et al*., 2007) and the Soil Water Assessment Tool (SWAT) (Neitsch *et al*., 2005), since these models incorporate the necessary water quality algorithms for CCIMP analyses.

Hydrological modeling of snow processes can span a wide range of spatial and temporal scales and the algorithms can also span a wide range of complexity from methods based only on temperature (e.g. GWLF-VSA, SWAT), to physically-based, data intensive energy balance approaches (Ferguson 1999; Marks *et al*. 1999; Walter *et al*., 1996). The models used in this study generally use the more simple temperature index approaches. Zhang *et al*. (2008) tested both an energy balance algorithm and the default temperature index algorithm in SWAT and found that the temperature index method when combined with the multiple elevation bands performed well for simulating monthly streamflow in gauged basins. As the GWLF and SWAT models are being used as part of the CCIMP, one goal of this study is to ascertain if the temperature index approaches embedded in these models is sufficient to simulate potential shifts in streamflow due to rising winter temperatures.

This study consists of three parts: (1) quantify recent trends in winter and early spring streamflow timing for the Catskill Mountain region; (2) investigate the ability of GWLF-VSA and SWAT models to capture any streamflow trends found in the above step; and (3) compare model estimates of streamflow in the context of potential future climate change.

METHODS AND DATA

Study Area

Four watersheds with long term historical streamflow measurements within the Catskill Mountain region of New York State are used for this study (figure 1). These four streams are also major tributaries to four separate water supply reservoirs for New York City. Each of the watersheds contains a streamflow gauge operated by the United States Geologic Survey (USGS). Table 1 lists the important features of each of the watersheds. Generally the watersheds are largely forested. There is some agriculture, mainly dairy, within the West Branch Delaware River (WBDR) watershed and, to a lesser extent, within the Schoharie Creek basin. Additionally WBDR and Schoharie watersheds also contain a number of small hamlets. The Rondout and Neversink watersheds contain little or no agriculture and only some scattered development. Elevation range for all the watersheds is about 270 to 1270 meters, with the higher elevations more dominant in the Rondout and Neversink watersheds. There has been little change in land development over the last fifty years, except for a slight decline in active agriculture n the WBDR basin. None of these watersheds contains any water diversions, transfers or flow regulation that significantly affect the inter- or intra-annual variability of the streamflow.

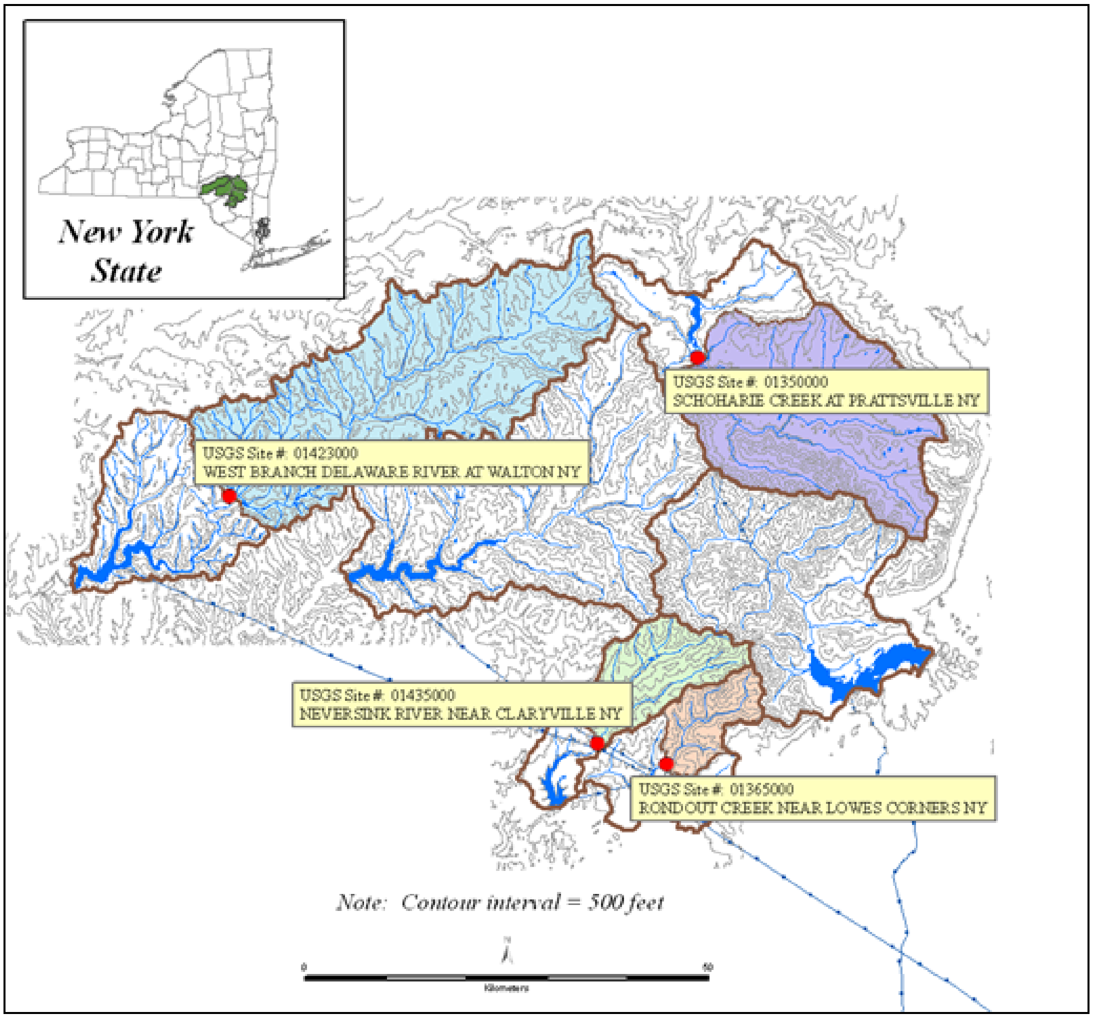


Figure 1. Location of study watersheds corresponding USGS gauges within Catskill Mountain region.

Table 1 Land use, drainage areas and other facts regarding study watersheds

Watershed	USGS Gauge No.	Watershed Area (ha)	Elevation Range and (Mean) (m)	Land Use % Forest / Undeveloped	Land Use % Agri-cultural	Land Use % Developed
West Branch Delaware River at Walton	01423000	85,925	370 – 1020 (590)	82	14	3
Schoharie Creek at Prattsville	01350000	61,250	360 – 1230 (650)	94	3	3
Neversink River near Claryville	01435000	17,248	470 – 1260 (770)	99	<1	1
Rondout Creek near Lowes Corners	01365000	9,949	270 – 1270 (630)	98	1	1

Streamflow Data

The streamflow data for the four watersheds is investigated over a 57 year period for water years 1952-2008. To gain a further understanding of the effects of shifts in snowpack development and melting two statistics are used throughout this study: (1) total winter-early spring flow volume and (2) the winter-early spring center of volume (WSCV) (Hodgkins *et al*., 2003). In this study the total winter-early spring flow is defined as the total volume of water in the streamflow for the months of January through May. This period is consistent with that used by Hodgkins *et al*. (2003) in a similar study of streamflow timing in New England and represents the time when the streamflow is most influenced by snow processes in the Catskill Region. In most years the snowpack in the Catskill Region is completely melted by early May. The WSCV is the Julian Day by which 50% the total winter-early spring flow volume has passed the flow gauge (Hodgkins *et al*., 2003). Court (1962) suggested that this type of half-flow date is more representative of shifts in the mass of streamflow as opposed to a seasonal maximum flow which may be more dependent on the finer details of an individual year's meteorology.

Trend Analyses

To test the trends in the streamflow time series, the Mann-Kendall test is used (Mann, 1945; Kendall, 1975). This non-parametric test is applicable for monotonic increasing or decreasing trends, detects either linear or non-linear trends and accounts for outliers. This test has been widely used to test trends in hydrologic time series (Burn and Hag Elnur, 2002; Zhang *et al*., 2001; Dery *et al*., 2009; Hodgkins *et al*., 2003; Hodgkins and Dudley, 2006; Burns *et al*., 2007). The results of the Mann-Kendall test were evaluated at a significance level of $p<0.1$. To calculate the slope of the trend, the Sen method (Sen, 1968) was used. The Sen slope is computed as the median of all possible pair-wise slopes for the data. The accuracy of the p-value of the Mann-Kendall test can be affected by any serial correlation in the data (Helsel and Hirsch, 1992). To check for serial correlation, the Durbin-Watson statistic (Helsel and Hirsch, 1992) was calculated from the residuals of the line based on the Sen slope. None of the trend analyses in this study exhibited any statistically significant serial correlation based on this analysis.

Modeling Analyses

The watershed hydrology and water quality models tested within this study include the GWLF-VSA (Haith and Shoemaker, 1987; Schneiderman *et al*., 2002; Schneiderman *et al*., 2007) and the SWAT 2005 (Neitsch *et al*., 2005). These models have been used in the past for analyzing the potential effects of land use and agricultural practices on water quality in the Catskill region (NYCDEP, 2006b; Easton *et al*., 2008; Rao *et al*., 2009; Gitau *et al*., 2004). Given their past history of use in the study area, these models are potential candidates for use in studies of climate change. Since one goal of this study is to better understand the differences in the winter and spring streamflows that are simulated by these two models, both models were used to simulate streamflow in the WBDR watershed. To further understand the patterns in the winter spring streamflow shifts, the GWLF-VSA model was also used for simulations in the other three study watersheds. The models were applied for the period 1952 – 2008 to understand if the models adequately translated the underlying forcing data into the winter streamflow timing shifts observed in the measured data.

The GWLF-VSA watershed loading model is a lumped-parameter model that simulates daily water, nutrients, and sediment loads from non-point and point sources. Model forcing inputs include daily minimum and maximum air temperatures, precipitation, incoming solar radiation, and daily average relative humidity. The original GWLF (Haith and Shoemaker, 1987) treats the watershed as a system of different land areas (Hydrologic Response units or HRUs) that produce surface runoff, and a single groundwater reservoir that supplies baseflow. GWLF-VSA incorporates a saturation-excess runoff on variable source areas, which is considered the primary runoff generation mechanism in Catskill watersheds. The GWLF-VSA model simulates runoff volumes using the SCS Curve Number (CN) Method, as in the original GWLF model, but spatially-distributes the runoff response according to a soil wetness index, based on the TOPMODEL soils-topographic index (Schneiderman *et al*., 2007). The spatial distribution of runoff by soil wetness index provides a more realistic identification of runoff generating areas in the NYC watersheds, with important consequences for simulation of pollutants that are typically transported by runoff.

The snowmelt algorithm in GWLF-VSA follows a temperature degree-day based methodology, with the daily updating of a single watershed-wide snowpack:

$$SNO_d = SNO_{d-1} + P_{snowd} - M_d \tag{1}$$

where SNO_d is the snowpack for day d, $SNO_{d\text{-}1}$ is the snowpack for day d-1, P_{snowd} is the snow fall for day d and M_d is snow melt for day d. The daily input precipitation falls as snow when the average daily temperature is less than 0^oC. When the average daily temperature exceeds 0^oC, melt of the snowpack proceeds as:

$$M = b_{melt} \cdot \left(\frac{T_{\min} + T_{\max}}{2} - 0^0\,\mathrm{C} \right) \tag{2}$$

where b_{melt} is a calibrated constant melt coefficient, T_{avg} is the average of the minimum and maximum daily air temperatures. The snowmelt is added to any precipitation that falls as rain ($T_{avg} > 0^oC$), with this total treated as precipitation available to be partitioned between direct runoff and infiltration. Direct runoff is added to streamflow with a short first order delay function to incorporate routing, while infiltrated water is stored in the groundwater zone and can be available for either evapotranspiration or slowly released as baseflow.

The SWAT model is significantly more complex than the lumped GWLF-VSA model. The model splits the watershed into sub-basins, with each sub-basin including HRUs defined by land use and soil combinations. Model forcing inputs include daily minimum and maximum air temperatures and precipitation for each sub-basin. Direct runoff, evapotranspiration and infiltration are calculated for each HRU and summed for the sub-basin. Sub-basin flows are routed through a stream network using a variable storage routing scheme. Infiltrated water is available for evapotranspiration or stored in groundwater for slow release as baseflow.

The SWAT snowmelt algorithm uses a temperature degree day methodology to calculate a daily snowpack for each sub-basin. The snowpack in each sub-basin can be further divided into a maximum of ten elevation bands. For this study the model was run twice: once with a single elevation band (SWAT – 1 Band) and a second time with three equal area elevation bands (SWAT – 3 Band) for each sub-basin. The input sub-basin temperatures are adjusted for each elevation band based on a lapse rate of $6.0^oC\cdot km^{-1}$ of elevation. For each elevation band within each sub-basin the daily snowpack is calculated by:

$$SNO_d = SNO_{d-1} + P_{snowd} - M_d - E_{subd} \tag{3}$$

where E_{subd} is the daily sublimation. The daily input precipitation falls as snow when the minimum daily temperature is less than 1^oC for this application). Melt of the snowpack proceeds as:

$$M = b_{melt} \cdot sno_{\mathrm{cov}} \left(\frac{T_{avg} + T_{\max}}{2} - T_{mlt} \right) \tag{4}$$

where b_{melt} is a calibrated melt coefficient, T_{max} is the maximum daily air temperature, T_{mlt} is a melt temperature parameter set to 0.5^oC for this application, and sno_{cov} is the fraction of the sub-basin with snow cover. Since no direct measurements of snow cover were available this parameter was set to one when the snow water equivalent of the snowpack is greater than 1 mm and is set to zero when the snow water equivalent was zero.

Model Input Data

Both the GWLF-VSA and SWAT models require daily forcing data, including temperature and precipitation. In addition the GWLF-VSA model uses input solar radiation data as part of a Priestley-Taylor evapotranspiration calculation. SWAT performs a similar calculation, but estimates the necessary solar radiation based on empirical relationships to daily temperature values. In addition to the daily forcing data, both models require information about the soils, land use/land cover and topographic information.

The required daily precipitation and daily minimum and maximum temperature data were from cooperator stations recognized by the National Climate Data Center and were obtained from the Northeast Regional Climate Center. For GWLF, the daily precipitation station data is averaged for the entire basin using a Thiessen polygon method (Burrough, 1987). A basin-wide estimate of daily minimum and maximum temperatures was calculated based on an inverse distance weighting to four cooperator stations (Cooperstown, Liberty, Slide Mountain, and Walton) and an environmental lapse rate of $6^oC\cdot km^{-1}$ was applied to adjust for the difference in station elevation versus basin average elevation. For SWAT a 5 km grid of both air temperature and precipitation data were derived from the cooperator station data using an inverse distance squared weighting scheme and again correcting temperature based on the same environmental lapse rate. The values for the closest grid point to each sub-basin were used as inputs to the SWAT model. Solar radiation data for GWLF was derived as the average of airport stations at Albany and Binghamton as supplied from the Northeast Regional Climate Center.

Land cover and land use (LC/LU) data for model input was derived from a combination of sources including a supervised LC/LU classification derived from LandSat imagery, information from the New York City Watershed Agricultural Program to refine total agricultural areas, and New York State Department of Transportation GIS road data (NYCDEP, 2006a) Sixteen land use classes are distinguished in the model classification – deciduous forest, coniferous forest, mixed forest, brushland, non-agricultural grass, cropland, permanent hayland, pasture, barnyard, rural roads, residential pervious and impervious, commercial/industrial pervious and impervious, wetland and water. Soils data is derived from the digital SSURGO database (NRCS, 2005) and topographic information was derived in the GIS from a 10-meter digital elevation model (USGS, 1998).

Model Calibration

Both the GWLF-VSA and the SWAT models were calibrated for the watersheds of application for the period of 1991-2000. For GWLF, the calibration optimized total streamflow and also the partitioning of streamflow into direct runoff and baseflow for all events during the calibration period. For purposes of calibration an event period is defined to begin on the first day of a rise in the hydrograph over a threshold value and continues until the beginning of the next event period. In this way an event period includes both the storm period with elevated flow and the inter-storm period following the storm flow. There are seven calibrated parameters for the hydrology portion of the GWLF-VSA model, each controlling a different facet of the hydrograph, including the long term water balance, partitioning of rain and melt into direct runoff and baseflow, the timing of direct runoff and baseflow at the watershed outlet, and, most importantly for this study, the melt coefficient, b_{melt}, which controls the rate at which the snowpack melts. Figure 2a shows the results for monthly streamflow for the calibration period and for a validation period from 2001-2007 for the WBDR watershed. Similar calibration and validation results are obtained for the other study watersheds.

The SWAT model was calibrated for daily streamflow for the WBDR watershed for the 1991-2000 calibration period as described in Pradhanang *et al*. (2010). Five model parameters are calibrated which control the baseflow recession, the partitioning of rainfall and snowmelt into direct runoff and infiltration, streamflow routing and the snowpack melting temperature, T_{melt}, which controls the rate at which the snowpack melts. Figures 2b and 2c show the results for monthly streamflow for the calibration period, as well as, for the period from 2001-2007 for the WBDR watershed.

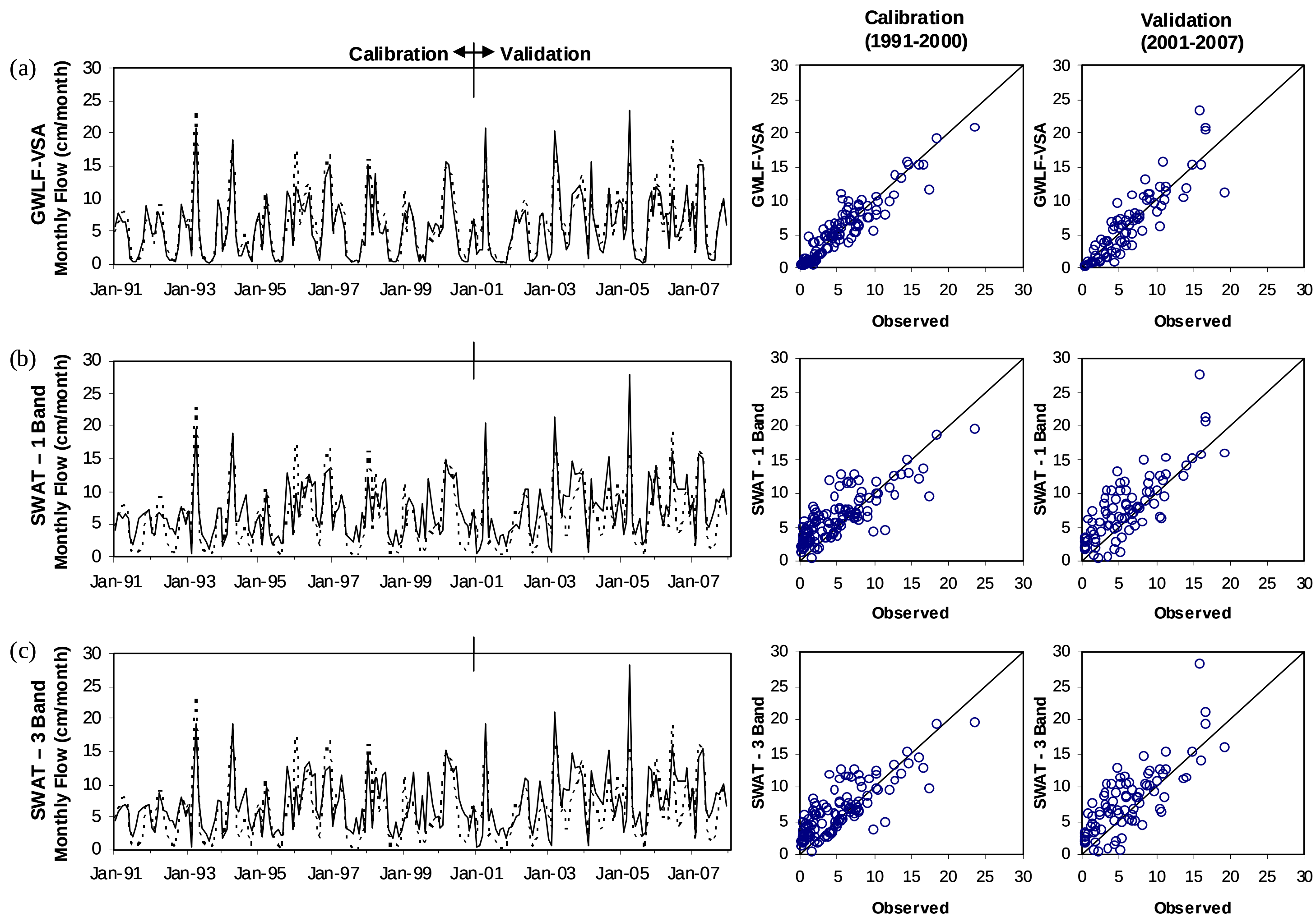


Figure 2. Calibration (1991-2000) and validation (2001-2007) results for monthly streamflow for the WBDR watershed using the (a) GWLF , (b) SWAT-1Band and (c) SWAT-3Band watershed models. All flow values are in cm/month representing the total monthly flow volume divided by the watershed area. The panels on the left show a time series of simulated (solid lines) and observed (dotted lines) monthly streamflow. The scatterplots show the monthly versus the observed monthly flows for calibration and validation periods. The lines on the scatterplots show the 1:1 relationship.

Climate Change Analysis Inputs

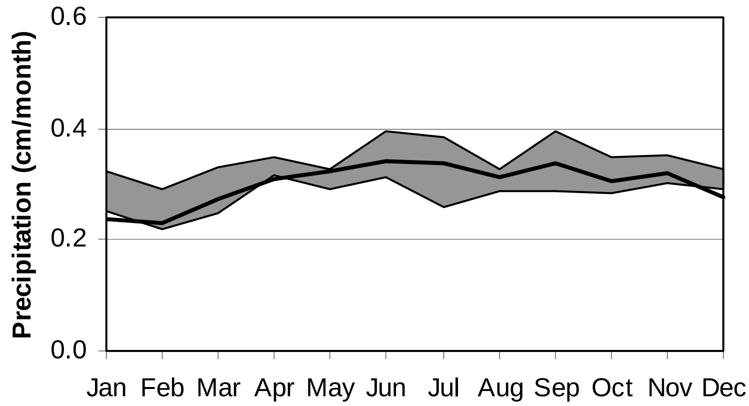
To place the results of the trends into the context of potential climate change, the models for WBDR were further run with input precipitation and temperature forcing scenarios based on Global Climate Model (GCM) simulations of future climate.

The future climate forcing scenarios are defined by the combination of the GCM, an emission scenario based on the projected greenhouse gas emissions, and a time slice which defines the time period over which the prediction applies. Precipitation and average temperatures at the land surface were obtained from GCM simulations archived in the World Climate Research Programme's (WCRP's) Coupled Model Intercomparison Project phase 3 (CMIP3) multi-model dataset. The GCM results from the region surrounding the study region are extracted and interpolated to a common 2.5º grid using bilinear interpolation. Two GCMs were used for this study, GFDL 2.0 and IPSL, as both of these GCM showed good results using the winter precipitation and temperature forcings to simulate snowpack using current conditions (Anandhi *et al*., 2010a). The emission scenarios used include the A2 and B1 scenarios. These two scenarios represent opposite ends of the spectrum of possible greenhouse gas emissions with the A1 representing a higher greenhouse gas emissions and the B1 representing lower emissions. To represent the future climate the GCM results for the 2080-2100 time slice are used. In total, four future climate forcing scenarios (2 GCM x 2 emission scenarios x 1 time slice) are generated.

A monthly change factor method (also referred as delta change factor methodology) (Anandhi *et al*., 2010b) was used to downscale the GCM results and generate the four future climate forcing scenarios. For the change factor calculations baseline (20CM3) scenario data were also downloaded for each GCM model. Additive monthly change factors for adjusting air temperature were calculated as the average monthly difference between the GCM results for the future time slice and the 20CM3 scenario. These monthly change factors were then added to the temperature forcings for that month for the entire observed WDBR dataset from 1952-2008. Similarly, for precipitation, the monthly change factors were calculated as the ratio of the monthly mean precipitation values derived from the future and the 20CM3 GCM data sets. To produce future climate scenarios the historical WDBR precipitation data were multiplied by the calculated monthly change factors. In this way the climate forcing scenarios follow the patterns of the historical data with the magnitudes changed on a monthly basis throughout the simulation time period. Similar methods have been used in other climate change studies (e.g. Semadeni-Davies et. al., 2008; Schneiderman et. al. 2009). Other more complicated statistical or dynamic downscaling techniques are possible, but, given the preliminary nature of this study, this method was used to obtain a “first-cut” of the potential effects of climate change on the shift in streamflow timing.

Figure 3 shows the range of the four future climate forcing scenarios showing average monthly temperatures and precipitation. For temperature, there is a consistent increase of about 2-8 ^{o}C throughout the year with greater increases in winter than in summer. For precipitation, there tends to be an increase in most months for most GCM/emission scenario combinations, but the results vary widely across the scenarios.

(a)



(b)

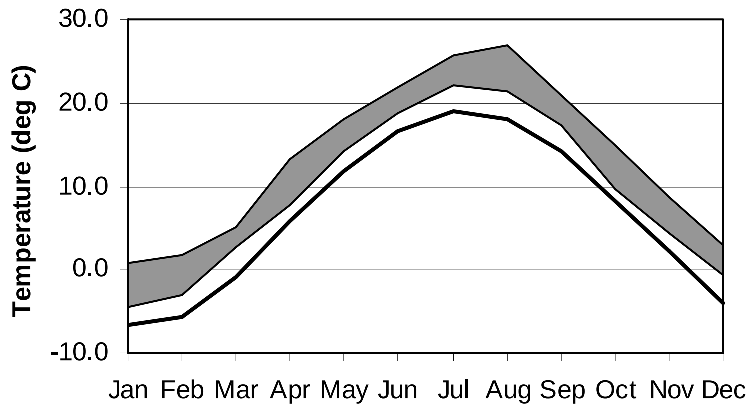


Figure 3. Range of climate change forcing scenarios for (a) precipitation and (b) temperature shown on a monthly basis for the WBDR watershed. The solid line represents the monthly average current observed conditions (1952-2008), and the grey shaded region displays the range of the four climate change forcing scenarios.

RESULTS AND DISCUSSION

Trends in Winter-Spring Streamflow

The first step in the process of investigating if current watershed water quality models are able to successfully simulate trends in streamflow timing is to better understand the streamflow trends that are actually occurring. Burns, *et al*. (2007) found that there were fairly significant trends of increasing temperature (0.5-2.0^{o}C/50 years) and increasing precipitation (8-26 cm/50years) at about half sampling stations in the region. The increased temperature, especially in the winter generally shifted the timing of the spring runoff period to earlier in the year. The streamflow shift was more pronounced in the more mountainous catchments of the study (Burns, *et al*., 2007).

This study investigates many of the same watersheds as in Burns *et al*. (2007), and reanalyzes these basins for a slightly longer time period through 2008. Figure 4 shows the winter early spring flow volume for 1952-2008 for each of the study streamflow gauges along with the trends and the Sen slope for each of the time series. Although the slopes of the trend lines are slightly positive, the Mann-Kendall significance p-values are much greater than 0.1 suggesting that the trends in increasing temperature and precipitation are not having a significant effect on the total winter streamflow.

In order to investigate potential changes in the timing of the winter-spring streamflow, the WSCV is used as an indicator. Figure 5 shows the WSCV for 1952-2008 for each of the study watersheds. In this case the Sen slopes of the trend lines show a fairly high negative slope, indicating a shift in the WSCV day ranging from 5.6 to 10 days earlier over a 50 year period. This trend is statistically significant ($p<0.10$) in two cases, the Rondout and Neversink watersheds and not statistically significant in the Schoharie and WBDR watersheds. This result is consistent with the findings of Burns, *et al*. (2007) as the Rondout and Neversink watersheds are more mountainous and contain the highest elevations in the Catskill Region and the winter temperature increases have been greatest in these high elevation zones.

The shift in winter streamflow is further illustrated in figure 6 which shows boxplots of annual fraction of the winter-spring flow that occurs in each month. The white boxes show the fractions of winter-spring flow during each month in the years 1952-1966 and the grey boxes show the same values for the years 1994-2008. For Rondout and Neversink watersheds, about 35-45% of the winter-spring flow occurred in April for a majority of the years in the earlier 15 year period, while in the later 15 year period the similar value ranged from about 20-30%. The fraction of winter-spring flow in April seems to shift somewhat to January. This shift is due to the increased temperatures during the winter creating a combination of more precipitation falling as rain during the winter and more melt of the snowpack prior to the traditional late March-April snowmelt period. These boxplots also illustrate the much stronger response to the temperature changes in the higher elevation watersheds (Rondout and Neversink) versus the other two study watersheds.

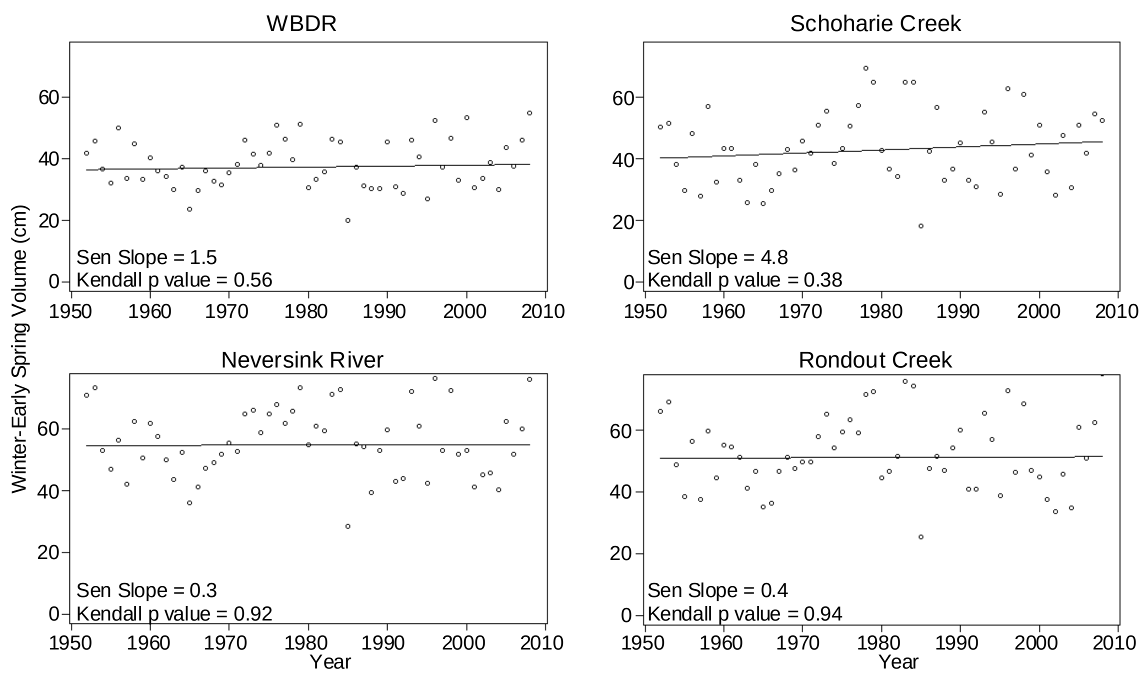


Figure 4. Plot of annual winter-early spring streamflow volume in unit depth (volume divided by watershed area). Points show annual data. Sen slopes are in cm per 50 years.

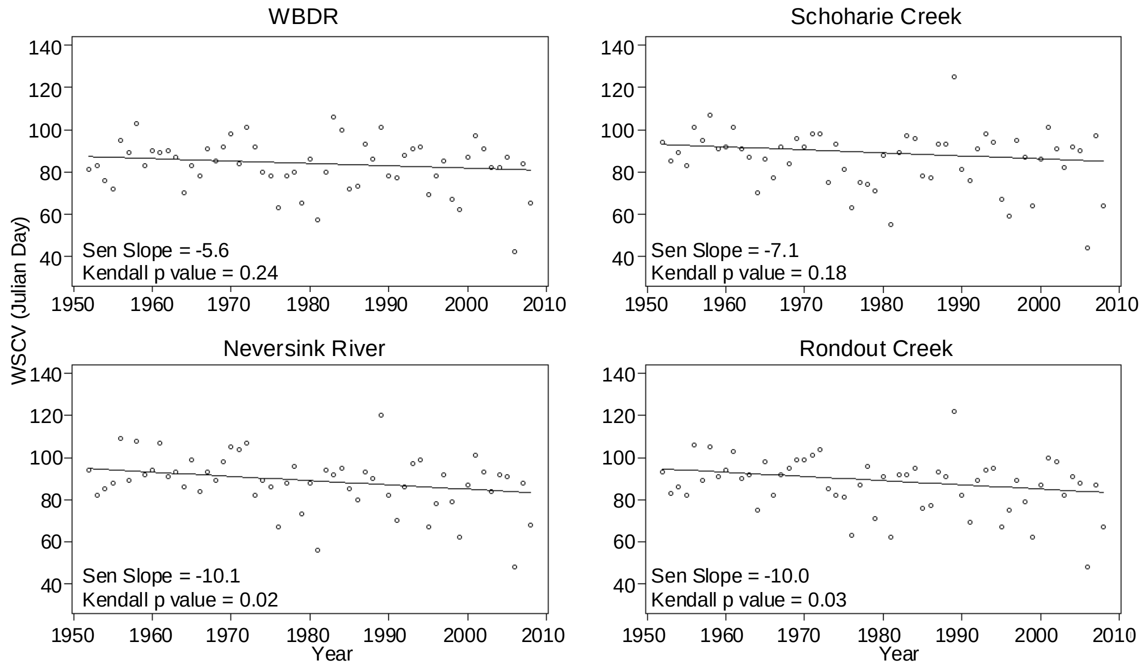


Figure 5. Plot of WSCV in Julian Day for each study watershed. Points show annual WSCV. Sen slopes are in days per 50 years.

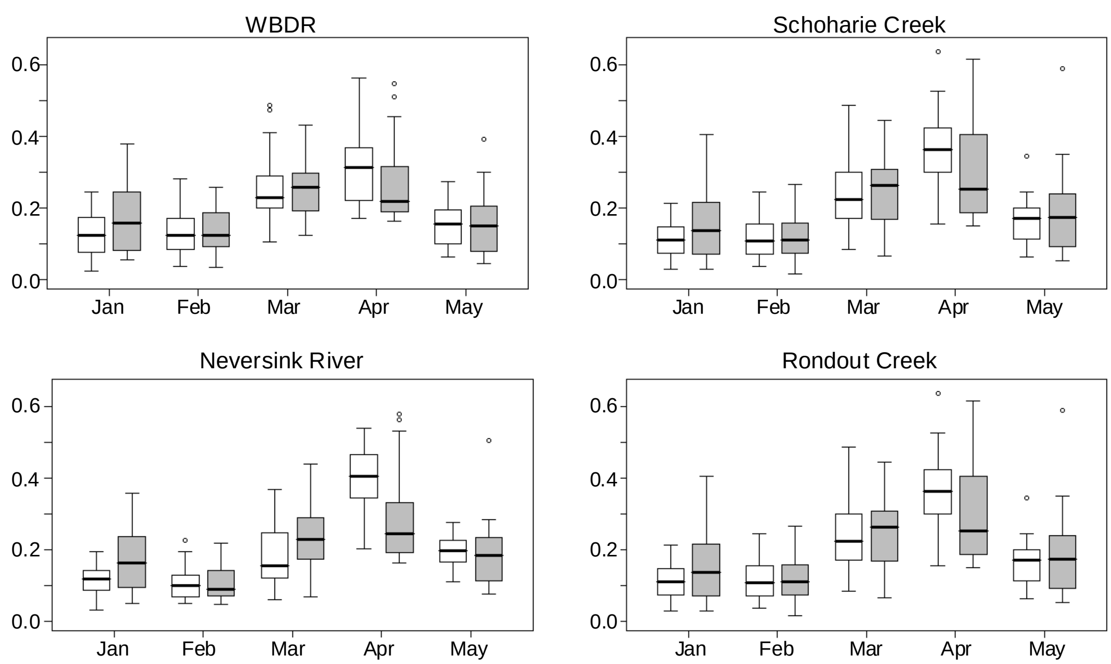


Figure 6. Boxplot of fraction of winter-early spring flow volume occurring in each month. The white boxes include data for years 1952-1966 and the grey boxes are for years 1994-2008.

Modeling of Streamflow Trends

The GWLF-VSA model was run for each of the study watersheds for the period of 1952-2008 to further ascertain how well the model could simulate the trends in the changes in timing of winter streamflow. Figure 7 shows the time series of the yearly modeled and observed WSCV for each of the study watersheds. For all the basins, if the trend in the data was strong, then the model also simulated a similarly strong trend. In cases where the trend in the data was not particularly strong, the model also indicated a weak trend. The data from the Rondout and the Neversink watersheds showed some of the strongest and most significant trends in earlier WSCV, with the WSCV moving back at a rate of approximately 10 days per 50 years. The models also showed statistically significant trends ($p<0.10$) in these two watersheds, with slopes that showed a slightly higher rate of reduction (12 - 15 days per 50 years) than the observed values. For the Schoharie watershed the trend in the model was almost exactly the same as that for the data (a reduction of about 7 days per 50 years), even though the p-value indicates a statistically non-significance of the trend for both the data and the model result. Finally for Cannonsville, where the observed slope of the trend is the least and the trend test is least significant, the model slope of the trend was somewhat less than that of the data (negative 1.8 days per 50 years for the model versus 5.6 days per 50 years for the data) and the p-value indicates statistical non-significance for the trend.

The SWAT model, using both a single elevation band and three elevation bands, was also run for the WBDR watershed to test if the less significant trend in this basin is able to be better simulated using the slightly more complex snow processes included in this model. Figure 8 shows the results of the SWAT model for the simulated WSCV trends versus the observed trends. Both SWAT model tests produced trend results similar to the GWLF-VSA runs. The trends were underestimated with the SWAT – 1 Band model producing a shift in WSCV of -2.8 days per 50 years the SWAT – 3 Band model producing a shift of -1.4 days per 50 years. These values are compared to the -5.6 days per 50 years shift in the data. For the WBDR basin, where the trends are not strong or statistically significant in the data, model simulations yielded similar results for the shift in WSCV when using either GWLF-VSA or SWAT model applications.

Overall, the GWLF-VSA model captured the shift in timing of the winter streamflow well, especially for the basins with the strongest and most significant trends. For the WBDR basin, where the trends are not strong or significant in the data, similar results were simulated for the shift in WSCV in both the GWLF-VSA and the two SWAT models.

Climate Change and Streamflow

The climate change scenarios are modeled in the WDBR watershed to compare the already occurring shift in winter streamflow to the changes projected to occur under future climate conditions. Figure 9 shows the monthly average streamflow for the current conditions and the range of streamflows for the four climate change scenarios using the GWLF, SWAT – 1 Band and SWAT – 3 band models. Each of the models consistently shifts the streamflow from the spring to the early winter, with the traditional April peak becoming less and the flows during the early winter becoming greater. This is consistent with the direction of shifts observed in the most recent data (figure 6). As expected the magnitude of the shift is much greater in the climate change runs, as the climate change scenario temperature shifts are much greater than any observed to date.

Figure 10 shows a similar result when looking at the winter-early spring flow volume and the WSCV. The climate change runs show little change from the current conditions for total winter-early spring volume. In the future climate scenarios the WSCV seems to shift consistently in all the models with the median WSCV shifting about 15-20 days earlier from mid-March to late February. This result is fairly consistent between the three models. The predicted shift is also reasonably consistent with the current trend for this watershed (figure 5), of about 5.6 days per 50 years. When extrapolated forward this trend would yield about a 12 day shift over about 100 years into the future.

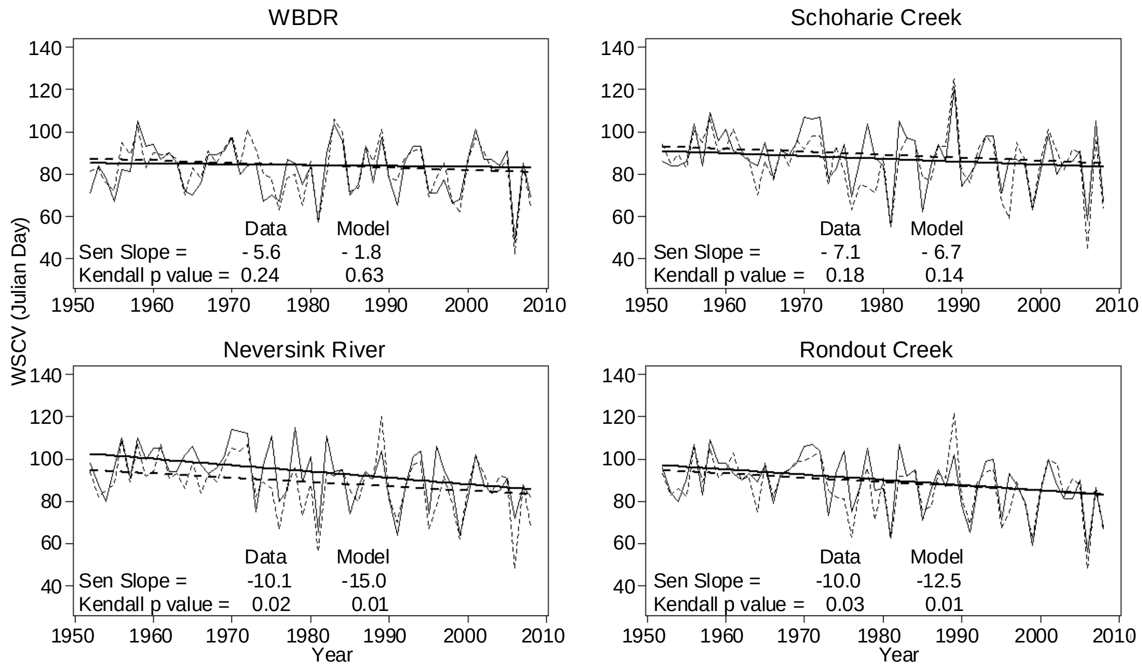


Figure 7. Plot of the annual WSCV and the corresponding Sen slope in Julian Day for each study watershed for data (dashed lines) and for the GWLF-VSA model simulation (solid lines). Sen slopes are in days per 50 years.

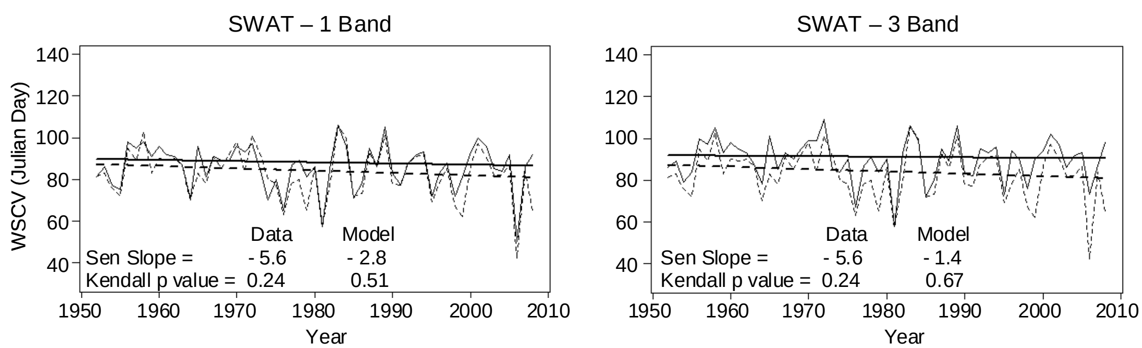
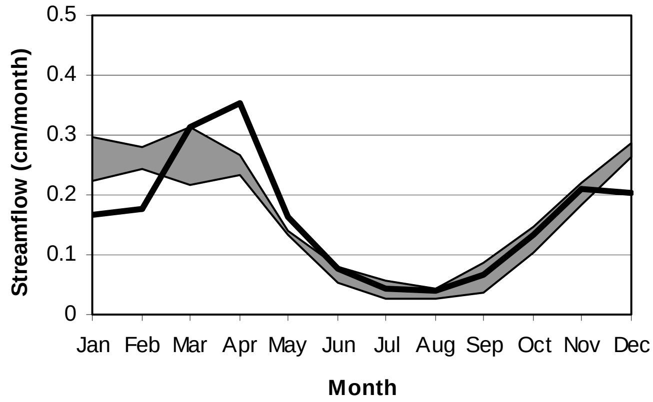
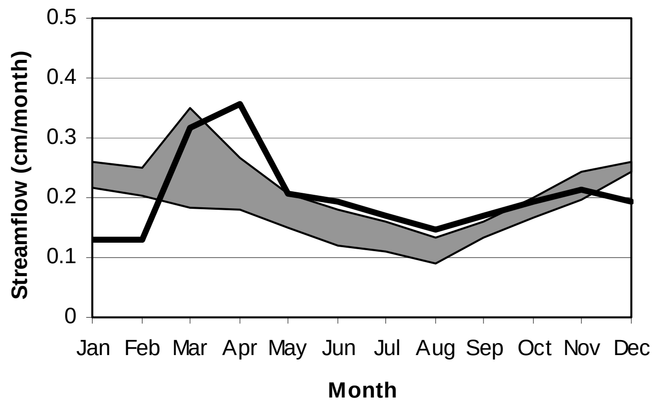


Figure 8. Plot of the annual WSCV and the corresponding Sen slope in Julian Day for WBDR watershed for data (dashed lines) and for the GWLF-VSA model simulation (solid lines). Sen slopes are in days per 50 years.

(a) GWLF-VSA:



(b) SWAT – 1 Band:



(c) SWAT – 3 Band:

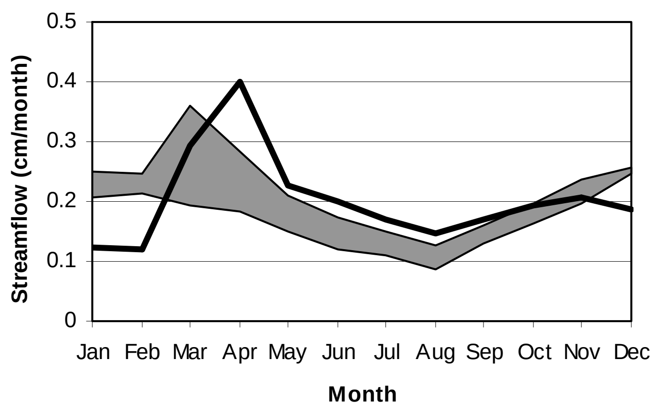


Figure 9. Monthly average streamflow results for climate change simulations in WBDR watershed using (a) GWLF-VSA, (b) SWAT – 1 Band and (c) SWAT – 3 Band models. Solid line shows the baseline (current conditions) simulation and the shaded area shows the range of the four climate change scenarios.

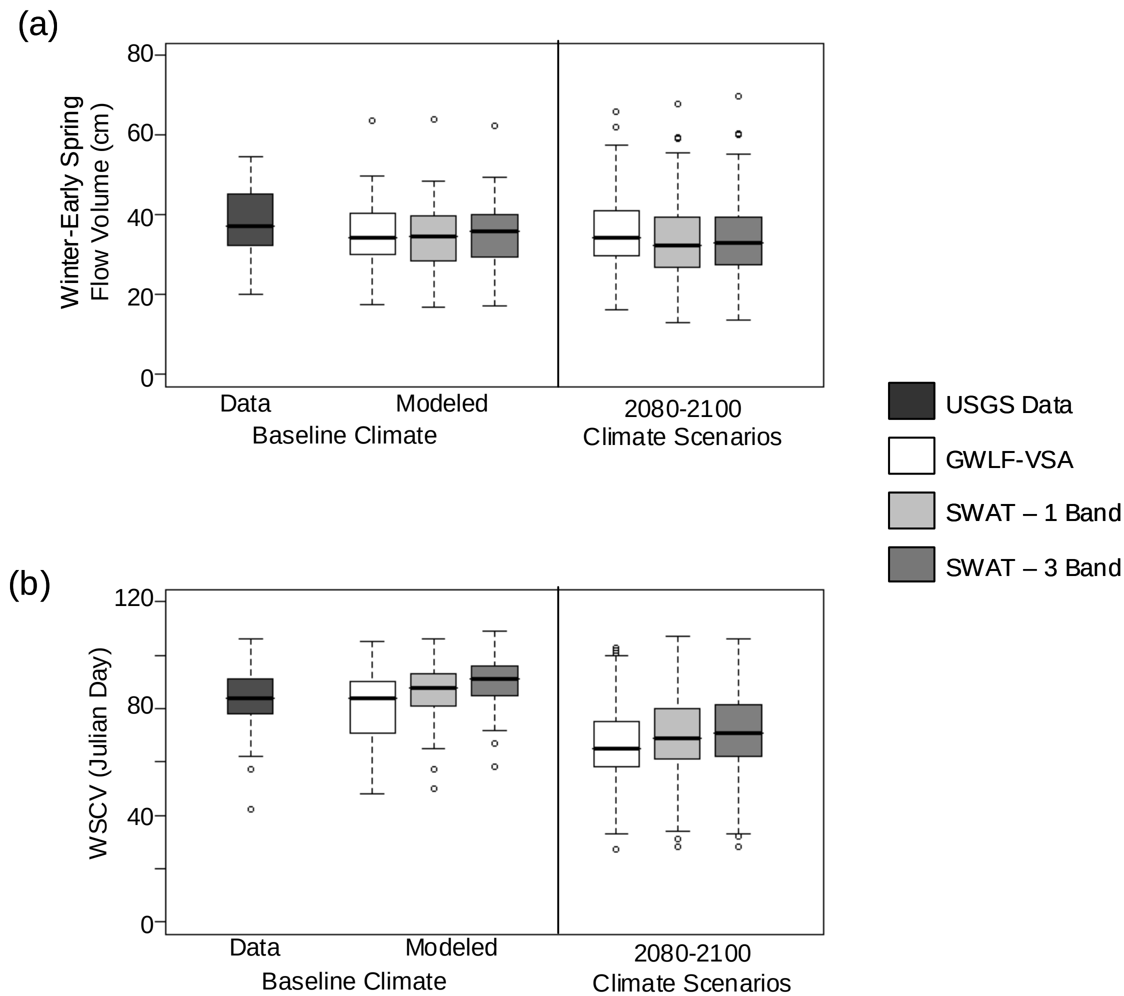


Figure 10. Boxplots showing range of WBDR baseline and future climate scenarios obtained from data and different watershed model simulations for (a) winter-early spring flow volume in unit depth (flow volume/watershed area) and (b) WSCV in Julian Day.

In recent years, the traditionally strong April snowmelt influenced streamflow peak has lessened in the Catskill Mountain region with a greater proportion of flow now occurring during the earlier winter months. This phenomenon is mostly due to increased temperatures creating earlier snow melt and more winter precipitation falling as rain instead of snow. This streamflow timing shift seems to be strongest in the more mountainous catchments of the region. A test of the GWLF-VSA has shown that a relatively simple temperature index method for predicting snow accumulation and melt is able to capture this seasonal shift in streamflow. Tests of the SWAT model, using either a single elevation band or three elevation bands in each simulated sub-basin yielded similar results to GWLF-VSA in detecting the streamflow timing trends. Finally, a preliminary investigation of potential climate change using both the GWLF-VSA and the SWAT models predicted a similar 15-20 day shift in winter streamflow (WSCV) for 100 years into the future.

REFERENCES

Anandhi A, Pradhanang S, Zion M, Pierson D, Frei A, Schneiderman E, Mukundan R, Matonse A. 2010a. AR4 climate model performance in simulating snow water equivalent over Catskill Mountain watersheds, New York, USA. *Proceedings of the the 67th Annual Eastern Snow Conference*, Hancock, MA, June 8-10, 2010.

Anandhi A, Frei A, Pierson DC, Schneiderman EM, Zion MS, Lounsbury D, Matonse AH. 2010b. Examination of change factor methodologies for climate change impact assessment. *Water Resources Research*, submitted.

Burn DH. 2008. Climatic influences on streamflow timing in the headwaters of the Mackenzie River Basin. *Journal of Hydrology* **352**: 225-238.

Burn DH, Hag Elnur MA. 2002. Detection of hydrologic trends and variability. *Journal of Hydrology* **255**: 107-122.

Burns DA, Klaus J, McHale MR. 2007. Recent climate trends and implications for water resources in the Catskill Mountain region, New York, USA. *Journal of Hydrology* **336**: 155-170.

Burrough PA. 1987. *Principles of Geographical Information Systems for Land Resources Assessment*. Clarendon Press: Oxford, England; 186p.

Court A. 1962. Measures of streamflow timing. *Journal of Geophysical Research* **67**(11): 4335-4339.

Dery SJ, Stahl K, Moore RD, Whitfield PH, Menounos B, Burford JE. 2009. Detection of runoff timing changes in pluvial, nival and glacial rivers of western Canada. *Water Resources Research* **45**: W04426.

Easton ZM, Walter MT, Steenhuis TS. 2008. Combined monitoring and modeling indicate the most effective agricultural best management practices. *Journal of Environmental Quality* **37**: 1798-1809.

Gitau MW, Veith TL, Gburek WJ. 2004. Farm-Level optimization of BMP placement for cost-effective pollution reduction. *Transactions of the ASABE* **47**(6): 1923-1931.

Haith DA, Shoemaker LL. 1987. Generalized watershed loading functions for stream flow nutrients. *Water Resources Bulletin* **23**(3): 471-478

Helsel DR, Hirsch RM. 1992. *Statistical Methods in Water Resources*. Elsevier: Amsterdam; 510p.

Hodgkins GA, Dudley RW. 2006. Changes in the timing of winter-spring streamflows in eastern North America. *Geophysical Research Letters* **33**: L06402.

Hodgkins GA, Dudley RW, Huntington TG. 2003. Changes in the timing of high river flows in New England over the 20th Century. *Journal of Hydrology* **278**: 244-252.

Ferguson RI. 1999. Snowmelt runoff models. *Progress in Physical Geography* **23**(2): 205-227.

Kendall MG, 1975. *Rank Correlation Methods*. Charles Griffin: London.

Mann HB. 1945. Non-parametric tests against trend. *Econometrica* **13**: 245-259.

Marks D, Domingo J, Susong D, Link T, Garen D. 1999. A spatially distributed energy balance snowmelt model for application in mountain basins. *Hydrological Processes* **13**: 1935-1959.

Matonse A., Pierson D, Frei A, Zion M, Schneiderman E, Anandhi A, Pradhanang S, Mukundan R. 2010. Effects of changes in snow and timing of runoff on NYC water supply. *Proceedings of the the 67th Annual Eastern Snow Conference,* Hancock, MA, June 8-10, 2010.

Natural Resources Conservation Service (NRCS), United States Department of Agriculture, 2005. Soil Survey Geographic (SSURGO) Database. Available URL: http://soildatamart.nrcs.usda.gov.

Neitsch SL, Arnold JG, Kiniry JR, Srinivasan R, Williams JR. 2005. *Soil and water assessment tool : Theoretical documentation, Version 2005*. Agricultural Research Service, Temple, Texas, 476p.

New York City Department of Environmental Protection (NYCDEP), 2009. *Multi Tiered Water Quality Modeling Program Annual Status Report*. Valhalla, NY. October 2009.

New York City Department of Environmental Protection (NYCDEP), 2008. *Climate Change Program: Assessment and Action Plan*. New York, NY. May 2008.

New York City Department of Environmental Protection (NYCDEP), 2006a. *Multi Tiered Water Quality Modeling Program Semi-Annual Status Report.* Valhalla, NY. January 2006.

New York City Department of Environmental Protection (NYCDEP), 2006b. *2006 Watershed Protection Program and Assessment.* Valhalla, NY. March 2006.

Pradhanang SM, Anandhi A, Mukundan R, Zion MS, Pierson DC, Schneiderman EM, Matonse A, Frei AP. 2010. Using SWAT model and snow survey data to assess spatial variability of snowpack in the Cannonsville watershed, New York, USA. *Proceedings of the the 67th Annual Eastern Snow Conference,* Hancock, MA, June 8-10, 2010.

Rao, NS, Easton ZM, Schneiderman EM, Zion MS, Lee DR, Steenhuis TM. 2009. Modeling watershed-scale effectiveness of agricultural best management practices to reduce phosphorus loading. *Journal of Environmental Management* **90**: 1385-1395.

Schneiderman EM, Järvinen M, Jennings E, May L, Moore K, Naden P, Pierson D. 2009. Modeling the effects of climate change on catchment hydrology with the GWLF model, Chapter 3. In *The Impact of Climate Change on European Lakes*, George G (ed.). Springer: Dordrecht; 507p.

Schneiderman EM, Steenhuis TS, Thongs DJ, Easton ZM, Zion MS, Neal AL, Mendoza GF, Walter MT. 2007. Incorporating variable source area hydrology into the curve number based Generalized Watershed Loading Function model. *Hydrological Processes* **21**: 3420-3430.

Schneiderman EM, Pierson DC, Lounsbury DG, Zion MS. 2002. Modeling the Hydrochemistry of the Cannonsville Watershed with Generalized Watershed Loading Functions (GWLF). *Journal of the American Water Resources Association* **38**(5):1323-1347.

Semadeni-Davies A, Hernebring C, Svensson G, Gustafsson LG. 2008. The impacts of climate change and urbanization on drainage in Helsingborg, Sweden: Combined sewer system. *Journal of Hydrology* **350**(1-2): 100-113.

Trombulak SC, Wolfson R. 2004. Twentieth-century climate change in New England and New York, USA. *Geophysical Research Letters* **31**: L19202.

United States Geological Survey (USGS), 1998. Digital Elevation Models (DEM) - New York State.Available URL: http://www.dec.ny.gov/geodata/ptk.

Walter MT, Brooks ES, McCool DK, King LG, Molnau M, Boll J. 2005. Process-based snowmelt modeling: does it require more input data than temperature-index modeling? *Journal of Hydrology* **300**: 65-75.

Zhang X, Srinivasan R, Debele B, Hao F. 2008. Runoff simulation of the headwaters of the Yellow River using the SWAT model with three snowmelt algorithms. *Journal of the American Water Resources Association* **44**(1): 48-61.

Zhang, X, Harvey KD, Hogg WD and Yuzyk TR. 2001. Trends in Canadian streamflow. *Water Resources Research* **37**(4): 987-998.