Independent effects of temperature and precipitation on modeled runoff in the conterminous United States

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Received 3 March 2011; revised 5 October 2011; accepted 12 October 2011; published 22 November 2011.

[1] A water-balance model is used to simulate time series of water-year runoff for 4 km × 4 km grid cells for the conterminous United States during the 1900–2008 period. Model outputs are used to examine the separate effects of precipitation and temperature on runoff variability. Overall, water-year runoff has increased in the conterminous United States and precipitation has accounted for almost all of the variability in water-year runoff during the past century. In contrast, temperature effects on runoff have been small for most locations in the United States even during periods when temperatures for most of the United States increased significantly.

Citation: McCabe, G. J., and D. M. Wolock (2011), Independent effects of temperature and precipitation on modeled runoff in the conterminous United States, *Water Resour. Res.*, *47*, W11522, doi:10.1029/2011WR010630.

1. Introduction

[2] Concerns regarding adverse effects of global warming on water supplies in the United States have led to numerous studies of the hydrologic effects of climate change [*Gleick*, 2000; *Piao et al.*, 2007]. These studies have included examination of global warming effects on snow pack accumulations [*Mote*, 2003; *Stewart et al.*, 2004; *Mote et al.*, 2005; *McCabe and Wolock*, 2010], changes in the ratio of winter snow to winter precipitation [*Knowles*, 2006; *Barnett et al.*, 2008; *Bonfils et al.*, 2008; *Pierce et al.*, 2008], the occurrence and frequency of rain-on-snow events [*McCabe et al.*, 2007], lake ice-out dates [*Hodgkins et al.*, 2002], changes in streamflow timing [*Aguado et al.*, 1992; *Wahl*, 1992; *Pupacko* 1993; *Dettinger and Cayan*, 1995; *Rajagopalan and Lall*, 1995; *Cayan et al.*, 2001; *Hodgkins et al.*, 2003; *Regonda et al.*, 2005; *Stewart et al.*, 2004; *McCabe et al.*, 2005], and changes and trends in streamflow magnitude [*Wigley and Jones*, 1985; *Gleick*, 1986, 1987; *Karl and Riebsame*, 1989; *Lettenmaier et al.*, 1994; *Lins and Slack*, 1999; *McCabe and Wolock*, 2002].

[3] Effects of global warming on streamflow magnitude are of particular concern given that these effects directly alter water supplies. *Lettenmaier et al.* [1994] examined trends in water-year and monthly streamflow across the conterminous United States and found positive trends for a large proportion of the streams analyzed. *Lins and Slack* [1999] and *McCabe and Wolock* [2002] also analyzed streamflow in the conterminous United States and found statistically significant positive trends mostly in low and moderate streamflows; they found only a few positive trends in high streamflows. *Douglas et al.* [2000] also detected trends in low flows but not in floods. In contrast, *Groisman et al.* [2001] reported increases in high streamflow in the conterminous United States, particularly in the eastern United States

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[4] Previous studies of trends and variability of streamflow in the United States primarily have focused on the latter half of the 20th century because this is the period with the largest number of streamgauges with measured streamflow data. Temporal patterns during the latter half of the century, however, may not be representative of longer time periods. It would therefore be informative to evaluate temporal patterns in streamflow over the longest possible period. Toward this end, the objectives of this study are to (1) extend the analysis of streamflow to the beginning of the 20th century, and (2) determine the relative magnitude of the effects of temperature and precipitation on changes in streamflow. These objectives are accomplished through the use of long-term precipitation and temperature data, coupled with a water-balance model [*McCabe and Wolock*, 1999; *Wolock and McCabe*, 1999], as described below. This study focuses only on the effects of changes in precipitation and temperature on runoff. Other factors that may have important effects on runoff but were not considered in this analysis include the direct effects of atmospheric CO_2 on plants [*Gedney et al.*, 2006; *Piao et al.*, 2007], net radiation [*Gedney et al.*, 2006], changes in land cover and land use [*Piao et al.*, 2007], and changes in water use [*Gerten et al.*, 2008].

2. Data and Methods

[5] Monthly temperature and precipitation data provided on a 4 km × 4 km grid for the period January 1895 through December 2008 were obtained from the Parameter-elevation Regression on Independent Slopes Model (PRISM) data set (available at http:www.ocs.orst.edu/prism/). Temperature and precipitation data for all grid cells in the conterminous United States (481639 PRISM grid cells) were used as input to a monthly time step water-balance model to estimate monthly runoff, where runoff is defined as the flow per unit area delivered from each grid cell to streams and rivers in units of millimeters per month (mm month^{-1}). In the analysis presented here, runoff estimates for 1895 through 1899 were discarded to avoid effects of initial model conditions.

[6] The water-balance model uses an accounting procedure to compute the allocation of water among various

components of the hydrologic system [*McCabe and Wolock*, 1999; *Wolock and McCabe*, 1999; *McCabe and Markstrom*, 2007; *McCabe and Wolock*, 2008]. The water-balance model includes the concepts of climatic water supply and demand, seasonality in climatic water supply and demand, snow accumulation and melt, and soil-moisture storage [*Wolock and McCabe*, 1999; *McCabe and Markstrom*, 2007; *McCabe and Wolock*, 2008]. Similar water-balance models have been used in other studies [*McCabe and Ayers*, 1989; *Legates and Mather*, 1992; *Wolock and McCabe*, 1999; *Legates and McCabe*, 2005; *McCabe and Wolock*, 2008].

[7] Climate inputs to the water-balance model are monthly precipitation and potential evapotranspiration; the latter is calculated from latitude and monthly temperature using the Hamon equation [*Hamon*, 1961]. The Hamon potential evapotranspiration equation is simple and does not include the effects of humidity, wind speed, and land cover on potential evapotranspiration. However, because the Hamon equation only requires inputs of monthly temperature it can be widely applied in both time and space. Additionally, although conceptually simple, the Hamon potential evapotranspiration equation has been evaluated and compared with a number of other models and is considered to provide reliable monthly potential evapotranspiration estimates [*Lu et al.*, 2005; *Legates and McCabe*, 2005; *Federer et al.*, 1996; *Vörösmarty et al.*, 1998]. In a study of five potential evapotranspiration models for use with global water balance models, *Federer et al.* [1996] found that estimates of potential evapotranspiration from the Hamon model agreed with estimates from other models across a wide range of climates. In addition, *Vörösmarty et al.* [1998] compared 11 different potential evapotranspiration models for a wide range of climatic conditions across the conterminous United States and found that the Hamon model was comparable to more input-detailed models.

[8] In the water-balance model, monthly temperature also is used to determine the proportions of monthly precipitation that are rain and snow. Precipitation that is snow is accumulated in a snow pack and snow melt also is computed using a temperature threshold method; rainfall is used to compute direct runoff, evapotranspiration, soil-moisture storage recharge, and surplus, which eventually becomes runoff. When the sum of rainfall and snow melt for a month is less than potential evapotranspiration, actual evapotranspiration is equal to the sum of rainfall, snow melt, and the amount of moisture that can be removed from the soil. The fraction of soil-moisture storage that can be removed as actual evapotranspiration decreases linearly with decreasing soil-moisture storage; that is, water becomes more difficult to remove from the soil as the soil becomes drier and less moisture is available for actual evapotranspiration. When the sum of rainfall and snow melt exceeds potential evapotranspiration in a given month, actual evapotranspiration is equal to potential evapotranspiration; water in excess of potential evapotranspiration replenishes soil-moisture storage. When soil-moisture storage exceeds capacity during a given month, the excess water becomes surplus and eventually becomes runoff. For additional details of the water-balance model, see *McCabe and Markstrom* [2007].

[9] The water-balance model parameters used for this study mostly were taken from parameter sets developed in previous studies [*McCabe and Wolock*, 1999, 2010]. The parameter set includes: (1) a parameter that specifies the fraction of monthly precipitation that becomes direct runoff, (2) temperature thresholds that determine the proportions of monthly precipitation that are rain and/or snow, (3) a snow melt factor that controls the melt rate of the snow pack, and (4) a parameter that specifies how much surplus in a month becomes runoff. Each of the aforementioned parameters is assumed not to vary across space; that is, only a single value for each parameter is specified everywhere. The parameter values used are similar to those applied in other water-balance models with comparable simulated processes [e.g., *Tarboton et al.*, 1991; *Rango and Martinec*, 1995]. Only soil-moisture storage capacity varied spatially, and this parameter was computed using the available water-capacity values from the State Soil Geographic Data Base (STATSGO) data set and by assuming a one-meter rooting depth (available at http://soils.usda.gov/survey/geography/statsgo/). Figure 1 illustrates mean water-year runoff for 1900 through 2008 computed using the water-balance model and using the PRISM monthly temperature and precipitation data as inputs.

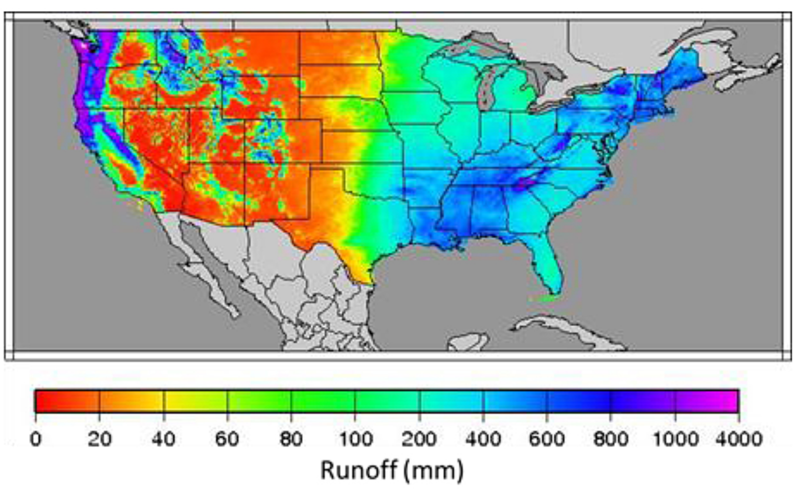

Figure 1. Mean water-year runoff in millimeters (mm) for the conterminous United States computed for the period 1900 through 2008.

[10] The water-balance model has been evaluated and verified in several previous studies [*McCabe and Wolock*, 1999, 2008; *Hay and McCabe*, 2010; *Gray and McCabe*, 2010; *McCabe and Wolock*, 2010]. To complement previous verifications of the water-balance model, the model was first evaluated in this study at 18 stream gauges located across the conterminous United States that have (1) minimal anthropogenic influences such as diversions and reservoirs in their basins; and (2) at least 90 years of data during 1902–2008 (available at http://waterdata.usgs.gov/nwis). The measured monthly streamflow data at the gauged test sites were converted to units of average monthly runoff (mm month^{-1}) by dividing the streamflow values by gauged drainage basin area for each site. The water-balance model estimated runoff values for all grid cells in each corresponding basin were averaged to compute estimated monthly runoff values for each basin.

[11] Measured and estimated runoff values for the 18 long-term sites were compared for two time periods: an early period (1902–1950) and a late period (1951–2008). The motivation for comparing the two time periods was concern that PRISM data in the early period may not be suitable for temporal analyses due to the sparseness of meteorological stations [*Gibson et al.*, 2002]. Correlation-coefficient values between measured and estimated water-year runoff (mm year^{-1}) ranged among the 18 long-term sites from 0.72 to 0.94 (mean = 0.86) for the early period and from 0.61 to 0.97 (mean = 0.92) for the late period. These results indicate that the water-balance model reliably simulates the overall temporal pattern in water-year runoff, regardless of the time period. Therefore, subsequent analyses presented in this study of the overall temporal variability in runoff will be based on the entire 20th century, not just the late period.

[12] Trend slope values (mm year^{-1}) for measured and estimated runoff values also were computed for the two time periods (early and late) for the 18 long-term sites. The correlation between the measured runoff trend-slope values and the water-balance model estimated runoff trend-slope values among the 18 long-term sites was 0.20 for the early period and 0.80 for the late period. The high correlation ($r = 0.80$) between measured and estimated trend slopes in the late period indicates that the model and PRISM climate data provide reasonably accurate trend estimates for this time period. In contrast, the low correlation ($r = 0.20$) between the measured and estimated trend slopes in the early period suggests that, as suggested by *Gibson et al.* [2002], the PRISM climate data prior to 1950 are not suitable for trend analysis. In the remainder of the paper, analyses of trends will be limited to just the late period.

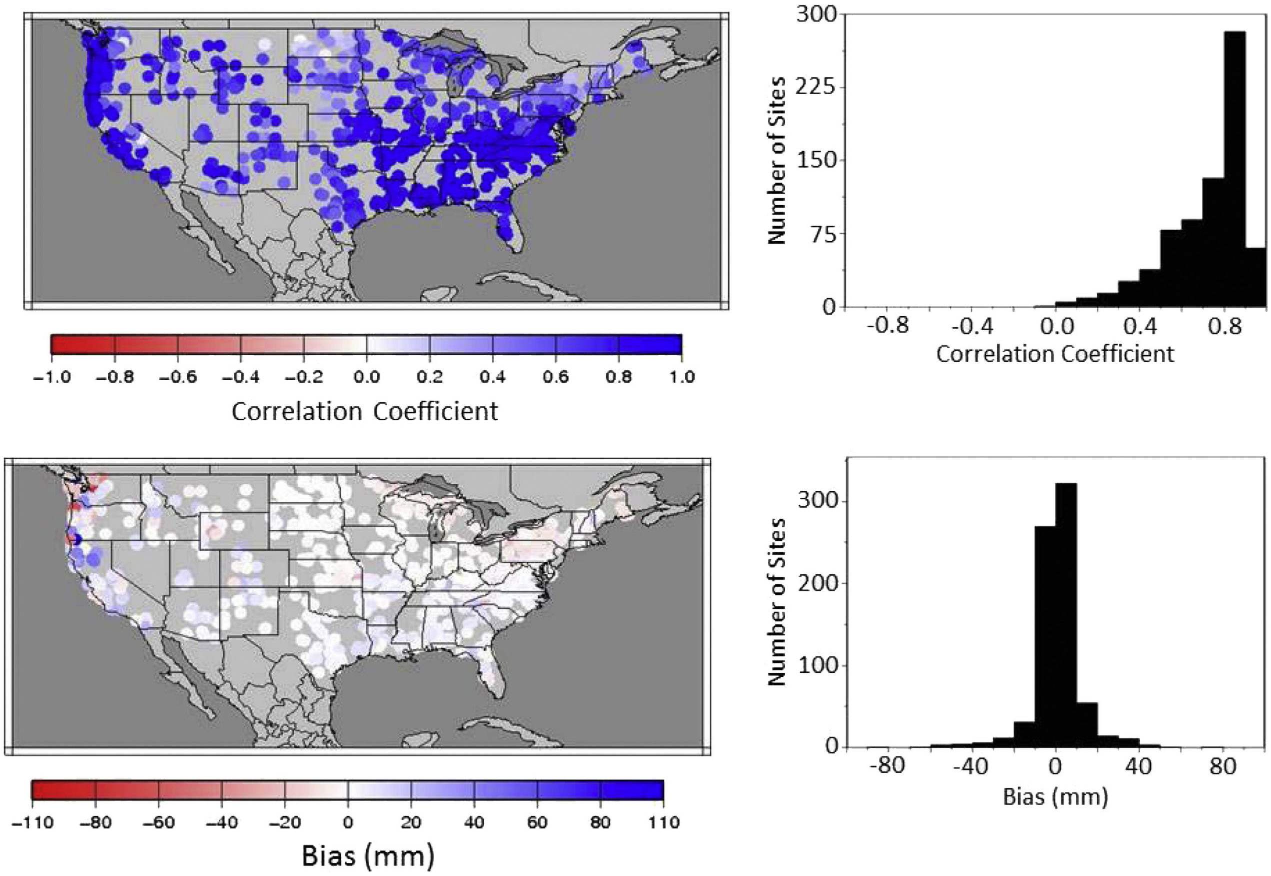

Figure 2. (top left) Map of correlations between measured and water-balance model estimated monthly runoff. (top right) Histogram of correlations between measured and water-balance model estimated monthly runoff. (bottom left) Map of biases (in millimeters) in water balance estimated mean monthly runoff computed as water balance estimated mean monthly runoff minus measured mean monthly runoff. (bottom right) Histogram of biases in mean monthly water balance estimated runoff. All statistics were computed for 735 stream gauges with at least 30 years of data during the 1951 through 2008 period.

[13] It may seem counter-intuitive that the water-balance model produces time series of estimated runoff that are highly correlated with measured runoff but inaccurate estimates of trend slopes during the early period. As will be shown below, this result occurs because the magnitude of the trend in runoff values is significantly less than the magnitude of other natural components of temporal variability in runoff. The early period PRISM climate data, coupled with the water-balance model, are sufficiently accurate to reproduce the considerable year-to-year variability in runoff. The sparseness of meteorological stations during the early period, however, results in PRISM data that are not accurate enough to discern small magnitude trends.

[14] Given the limited number of long-term sites, additional comparisons between water-balance model estimated runoff and measured runoff were made for a larger set of stream gauges (735) that have minimal human activities in their basins. For these sites, the period-of-record requirement was at least 30 years of streamflow data during 1951–2008. Comparison of the measured and estimated monthly runoff indicated that the water-balance model reliably simulates the temporal variability of monthly runoff for most of the stream gauges (Figure 2 (top)). The distribution of correlation values between water-balance estimated and measured monthly runoff for the 735 stream gauges has a median value of 0.78, with a 25th percentile value of 0.61 and a 75th percentile value of 0.87. Figure 2 (bottom) illustrates mean monthly biases computed as water-balance model estimated mean monthly runoff minus measured mean monthly runoff. For most stream gauges the biases are small (between −10 and 10 mm), except for the northwestern United States where measured monthly runoff values are large. The mean bias for the 735 stream gauges is 1 mm, with a 25th percentile of −3 mm and a 75th percentile of 5 mm. Biases between measured and water-balance model estimated runoff are likely due, in part, to hydrologic processes not included in the water-balance model, such as the effect of deep groundwater contributions to streamflow and in-stream water losses in channels located in arid areas. Other substantial biases occur in locations where runoff is generated by short-duration high-intensity precipitation events that are not resolved on a monthly time step. Additionally, uncertainties in the precipitation and temperature data used as inputs to the water-balance model may contribute to the biases.

[15] It is worth noting that model bias, when expressed as a percentage of the mean-monthly runoff, can be very large in arid regions where runoff magnitudes are low (data not shown). The correlation (Figure 2 (top left)) between estimated and measured runoff in dry regions, however, is high.

[16] The model also was evaluated in terms of its accuracy in simulating trends in runoff by computing trend slopes (expressed in millimeters per year) in both estimated and measured water-year runoff for the 735 sites during the 1951 through 2008 period (Figure 3). Results indicate that the

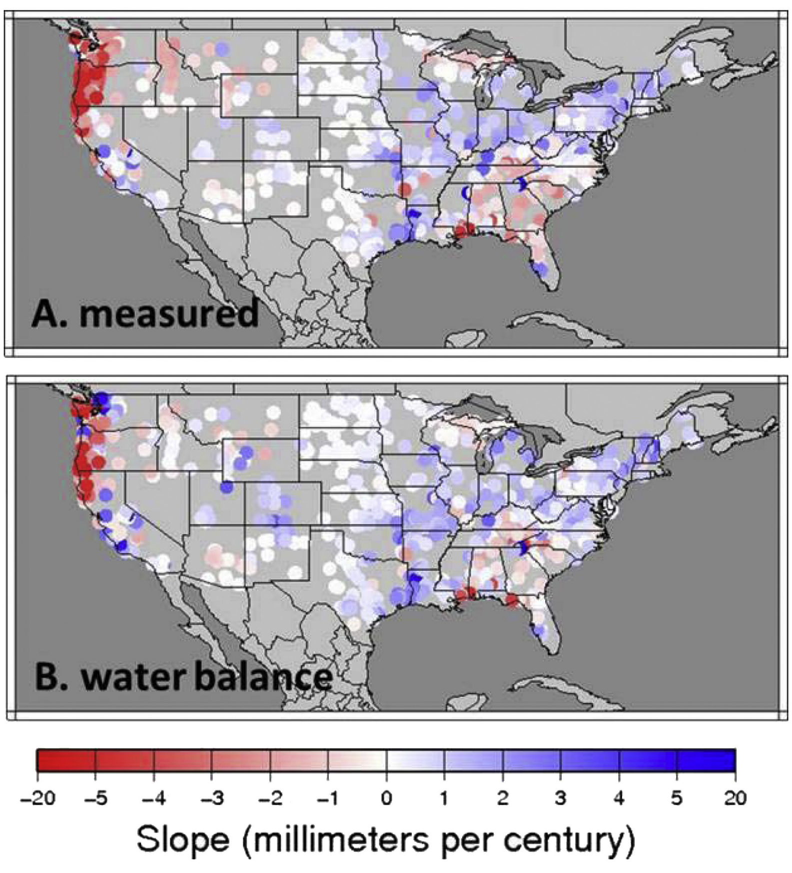

Figure 3. Trends in water-year (a) measured and (b) water balance estimated runoff (expressed as slopes in millimeters per year) for 735 stream gauges with at least 30 years of data during the 1951 through 2008 period.

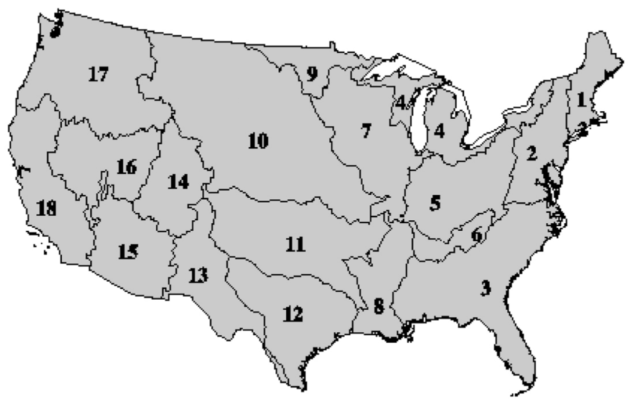

Figure 4. Map of water-resources regions.

trends in water-year runoff estimated using the water-balance model are similar to those of the measured data. The correlation between the spatial patterns of estimated and measured slopes illustrated in Figure 3 is 0.64 ($p < 0.01$).

[17] In addition to the original water-balance model simulations (the complete model), two other experiments were performed to separate the effects of temperature and precipitation on variability in mean water-year (October through September) United States runoff. For one experiment, the water-balance model was used to generate time series of water-year runoff using time series of measured monthly precipitation and long-term mean monthly temperature climatology (variable-precipitation model). In the variable-precipitation model, the same 12 values of long-term mean monthly temperature (computed for 1900 through 2008) are repeated each year; therefore, only inter-annual variability and long-term trends in precipitation can affect temporal variability of runoff. In the second experiment, the water balance is used to generate time series of water-year runoff using long-term mean monthly precipitation climatology (computed for 1900 through 2008) and time series of measured monthly temperature (variable-temperature model).

[18] The monthly runoff values were summed to compute time series of water-year runoff in each PRISM grid cell for each of the three models (complete, variable precipitation, and variable temperature). The time series of water-year runoff for all PRISM grid cells then were averaged to produce a time series of mean water-year runoff for the conterminous United States for each model. Additionally, to evaluate the effects of precipitation and temperature on water-year runoff for different regions of the conterminous United States, the time series of water-balance model estimated water-year runoff were averaged for each of the 18 water-resources regions of the conterminous United States (Figure 4).

3. Results and Discussion

[19] Results indicate that mean water-year runoff for the United States (computed using the complete model) varied significantly from year to year but experienced an apparent increase after about 1970 (Figure 5). This result is consistent with a step-like change in runoff around 1970 as suggested by *McCabe and Wolock* [2002]. The linear trend (correlation with time) in water-year runoff for the United States (computed using the complete model) is 0.22 (nonsignificant at $p = 0.05$) and explains about 5% of the total variance in runoff during the period 1951–2008. Thus, most of the temporal pattern in runoff is due to natural variability and is not related to a monotonic long-term trend or a step-like change.

[20] The linear trend (correlation with time) in water-year runoff computed using the variable-precipitation model (Figure 5) is 0.26 ($p < 0.05$) during the period 1951–2008. This trend is similar in sign and magnitude to the trend in runoff computed for the same period using the

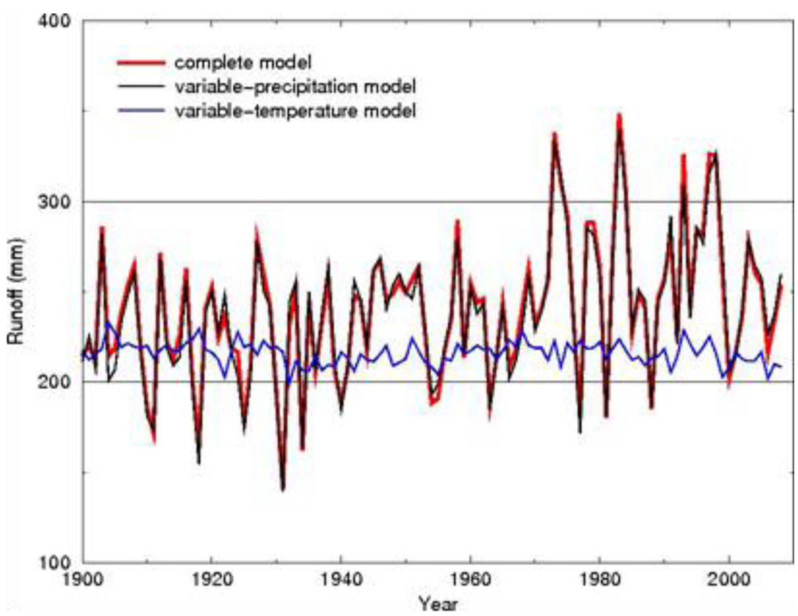

Figure 5. Time series of mean water-year runoff in millimeters (mm) for the conterminous United States for 1900 through 2008 computed using the complete model (red line), variable-precipitation model (black line), and variable-temperature model (blue line).

complete model. In contrast, the 1951–2008 trend in water-year runoff computed using the variable-temperature model (Figure 5) is -0.23 (nonsignificant at $p = 0.05$). This trend value has a small magnitude and opposite sign of the trend in runoff computed using the complete model. However, the negative trend in runoff during 1951–2008 computed using the variable-temperature model is consistent with warming temperatures and increased potential evapotranspiration for the United States during the past century.

[21] A comparison of the time series of long-term runoff computed using the three models (Figure 5) indicates that precipitation accounts for almost all of the variability (98%) in mean water-year United States runoff. In addition, the time series computed using the variable-temperature model has low variability compared to the complete model. This suggests temperature has had a minor effect on runoff variability for the United States as a whole. Similar results also are apparent for all of the individual water-resources regions (Figure 6).

[22] The Nash-Sutcliffe statistic (coefficient of efficiency (E); Nash and Sutcliffe, 1970) was calculated to compare the time series computed using the variable-precipitation and variable-temperature models with the time series computed using the complete model. The coefficient of efficiency has been widely used to evaluate the performance of hydrologic models [*Legates and McCabe*, 1999]. *Nash and Sutcliffe* [1970] defined E as,

$$E = 1 - \frac{\sum_{i=1}^{N}(M_i - P_i)^2}{\sum_{i=1}^{N}(M_i - \bar{M})^2}$$

where N is the number of observations, M_i is the measured value for year i, P_i is the model-estimated value for year i, and $\bar{M}$ is the long-term mean of the measurements. The coefficient of efficiency ranges from minus infinity to 1, with a value of 1 indicating perfect agreement between measured and model-estimated values. A value of 0 indicates that the measured mean is as good a predictor as the model, whereas negative values indicate that the measured mean is a better predictor than the model. The coefficient of efficiency represents an improvement over the coefficient of determination (r^2) for model evaluation

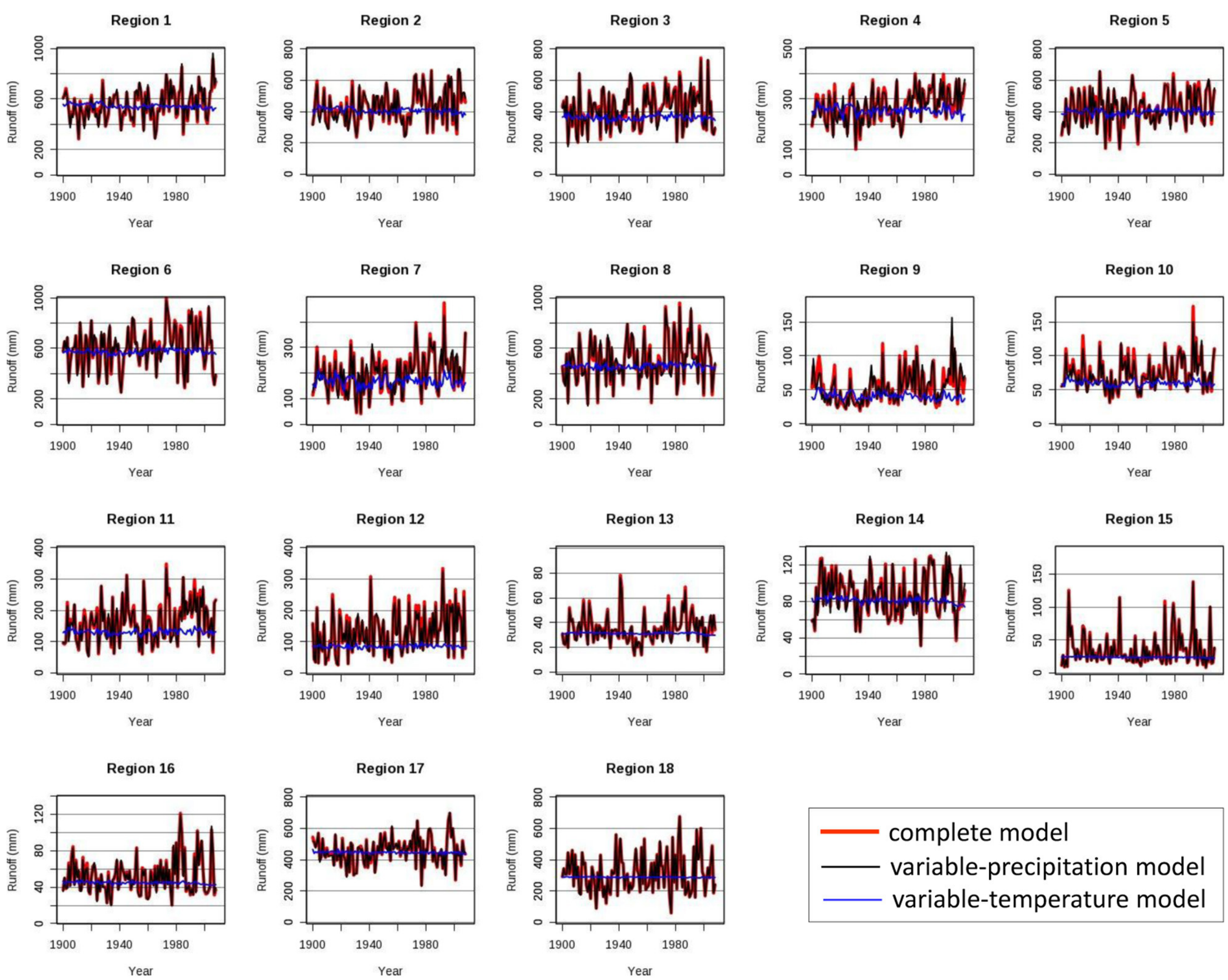

Figure 6. Time series of water-year runoff in millimeters (mm) for each water-resources region computed using the complete model (red), the variable-precipitation model (black line), and the variable-temperature model (blue line).

Table 1. Nash-Sutcliffe Coefficient of Efficiency for Comparisons of Water-Year Runoff for Each of the Water Resource Regions Computed Using the Compete Model With Water-Year Runoff Computed Using the Variable-Precipitation and Variable-Temperature Models[a]

Region	Variable-Precipitation Model	Variable-Temperature Model
1	0.98	−0.10
2	0.98	−0.11
3	0.99	−0.20
4	0.95	−0.05
5	0.98	−0.04
6	0.99	−0.02
7	0.96	−0.04
8	0.99	−0.07
9	0.89	−0.23
10	0.95	−0.26
11	0.99	−0.25
12	0.99	−0.46
13	0.99	−0.09
14	0.99	−0.06
15	1.00	−0.20
16	0.99	−0.16
17	0.99	−0.04
18	1.00	−0.04

[a]The Nash-Sutcliffe coefficient of efficiency ranges from minus infinity to 1, with a value of 1 indicating perfect agreement between measured and model-estimated values. Negative values indicate that the measured mean is a better predictor than the model.

purposes in that it is sensitive to differences in the measured and model means and variances [*Legates and McCabe*, 1999].

[23] The *E* values are near 1.0 for all of the water-resources regions (Table 1) for the comparisons of the time series computed using the variable-precipitation model with the time series computed using the complete model. These results indicate that the variability in precipitation provides the climate information necessary to explain variability in water-year runoff. In contrast, for the comparisons of water-year runoff computed using the variable-temperature model with time series from the complete model, the *E* values are negative for all water-resources regions (Table 1). Thus, variability in temperature does not provide the information needed to reliably estimate water-year runoff. In fact, the long-term mean water-year runoff for each water-resources region provides a better estimate of water-year runoff than does the variable-temperature model.

[24] Because of observed global warming during the 20th century, there is interest in determining if increases in temperature are causing trends in hydroclimatic variables such as runoff [*Lins and Slack*, 1999; *Groisman et al.*, 2001; *McCabe and Wolock*, 2002; *Gedney et al.*, 2006; *Barnett et al.*, 2008]. Analyses of 1951 through 2008 trends in water-year runoff (expressed as linear correlations with time) computed using the complete and variable-precipitation models indicate positive trend values for almost all water-resources regions. The only exception is a slightly negative trend in water-year runoff computed using the complete model for region 17 (the Pacific Northwest). The positive trends are statistically significant ($p < 0.05$) in the eastern half of the United States (Figures 7a and 7b). The positive trends in runoff, which occur primarily in the eastern United States, are consistent with previous studies [*Lins and Slack*, 1999; *McCabe and Wolock*, 2002; *Milly et al.*, 2005; *Andreadis and Lettenmaier*, 2006; *Dai and Trenberth*, 2009].

[25] The positive trends in water-year runoff for the conterminous United States and several of the eastern United States regions (computed using the complete and variable-precipitation models) appear to be related to an increase in runoff near 1970 (Figures 5 and 6) [also see *McCabe and Wolock*, 2002]. The increase in runoff (and precipitation) across most of the eastern United States near 1970 may be due to a shift in the North Atlantic Oscillation (NAO). Precipitation in the eastern United States is positively correlated with the NAO [*Hurrell*, 1995], and around 1970 the NAO shifted from a primarily negative phase to a primarily positive phase [*Milly and Dunne*, 2001]. The NAO is a primary mode of Northern Hemisphere fall/winter atmospheric circulation. When the NAO is in a positive phase, southerly winds over the eastern United States are strengthened and enhance the transport of moisture from the Gulf of Mexico into the eastern United States The enhanced transport of atmospheric moisture across the eastern United States results in increased in precipitation and runoff [*Milly and Dunne*, 2001].

[26] Trends (expressed as linear correlations with time for the period 1951–2008) in water-year runoff computed using the variable-temperature model are negative for most water-resources regions (Figure 7c), except for region 11 (Arkansas-White-Red) where temperatures have decreased. In addition, for some of the water-resources regions, the trends in water-year runoff computed using the variable-temperature model are larger than any of the trends in water-year runoff computed using the complete and variable-precipitation models.

[27] The large trends in water-year runoff computed using the variable-temperature model do not indicate that temperature has had a large effect on water-year runoff. The slope values of the trends in water-year runoff (expressed as millimeters year^{-1}) indicate that changes in water-year runoff computed using the variable-temperature model are small compared with the changes in water-year runoff computed using the complete and variable-precipitation models (Figure 7). The slopes of the trends in water-year runoff computed using the variable-temperature model range from -0.30 to 0.03 mm yr^{-1} with an average value of -0.10 mm yr^{-1}, whereas the slopes in the trends in water-year runoff calculated for the complete model range from -0.60 to 1.52 mm yr^{-1} with an average of 0.61 mm yr^{-1}. Additionally, the variability and trends in water-year runoff due to variability in temperature are dwarfed by the magnitude of variability in water-year runoff due to precipitation variability.

[28] Additional analyses were performed to examine the effects of temperature and precipitation on runoff time series for each calendar month separately. Comparisons of monthly runoff computed using the complete model with monthly runoff computed using the variable-precipitation and variable-temperature models indicate that the variable-precipitation model explains most of the variability in runoff for most months and most water resources regions (Figure 8). Comparisons of runoff computed using the complete model with runoff computed using the variable-precipitation model (Figure 8a) indicate Nash-Sutcliffe statistics above 0.7 for most months and water-resources

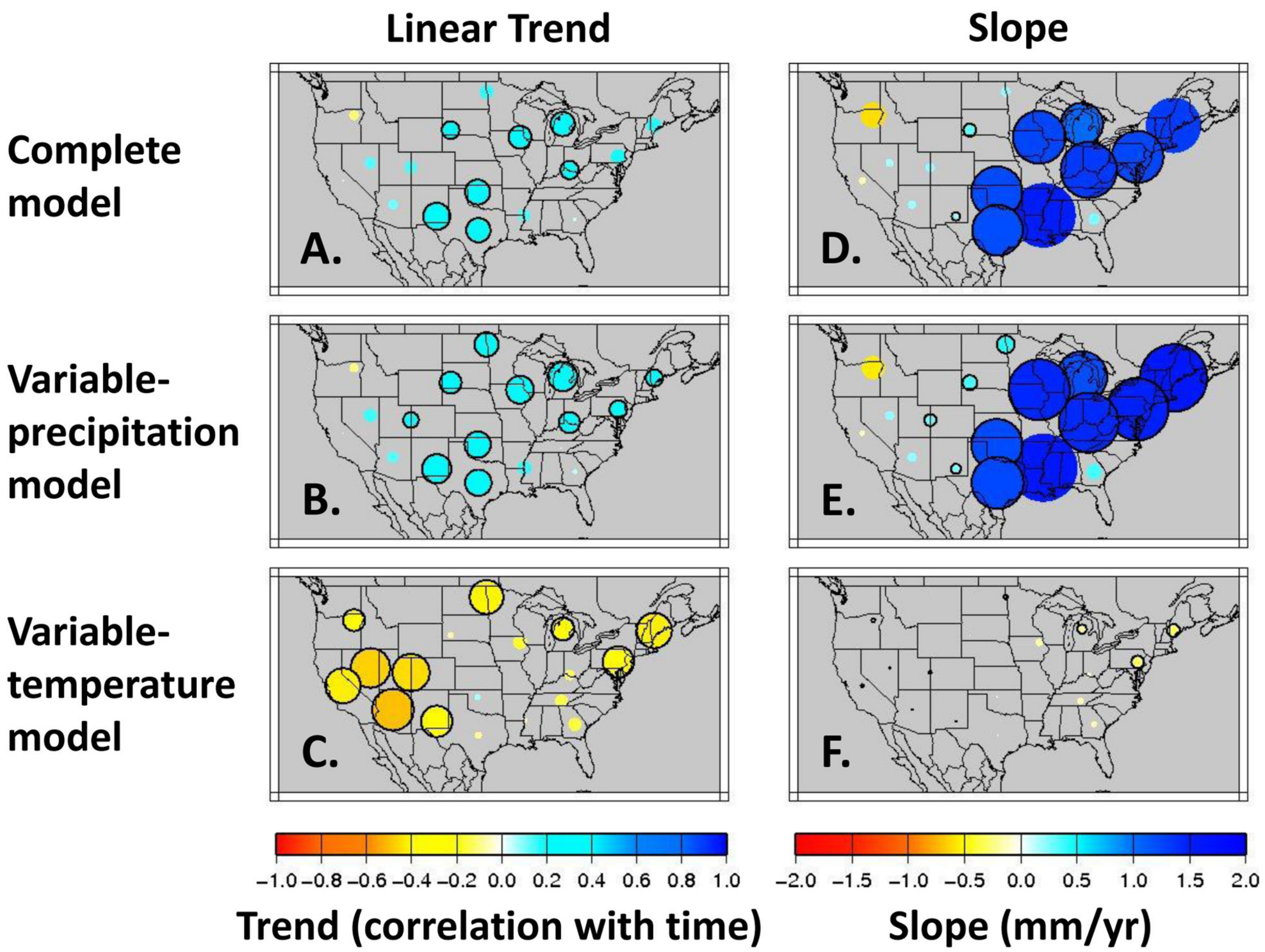

Figure 7. Trends (expressed as linear correlations with time) and slopes (in millimeters per year (mm yr^{-1})) in water-year runoff during 1951 through 2008 for each of the water-resources regions computed using the complete model, variable-precipitation model, and variable-temperature model. The diameter of the circles indicates the relative magnitude of the trends. Circles outlined in black indicate trends that are statistically significant at a 95% confidence level.

regions. In contrast, the Nash-Sutcliffe statistics for the comparisons of runoff computed using the complete model and runoff computed using the variable-temperature model are mostly near zero or below zero, except for the winter and early spring months in the northeastern and north-central United States and in regions 16 (the Great Basin) and 17 (the Pacific Northwest) in the western United States These results indicate that temperature has had an important effect on runoff during these months and in these water-resources regions. These results may be indicative of the effects of temperature on the occurrence of rain rather than snow during winter and/or the effects of temperature on snow melt runoff.

[29] Analyses of linear trends in monthly runoff (slopes expressed as mm month^{-1}) indicate positive trends in runoff for the fall and winter months for most water-resources regions using the complete and variable-precipitation models (Figure 9). Additionally, the slopes in monthly runoff for most water-resources regions are similar for the complete and variable-precipitation model (Figures 9a and 9b). The positive slopes (trends) for the fall and early winter months are similar to results reported by *Karl and Knight* [1998] who reported that precipitation increases in the conterminous United States have been greater during the fall season than during other seasons.

[30] For runoff computed using the variable-temperature model, there are negative slopes during the summer months in several of the water-resources regions (e.g., regions 1–9 and region 17; Figure 9c). These likely indicate a shift in runoff to earlier months in the year related to earlier snow melt and/or increased winter runoff due to decreases in the fraction of winter precipitation that occurs as snow. These results are consistent with the results of other studies that have indicated decreases in snow accumulation in parts of the United States [*Hodgkins et al.*, 2003; *Mote*, 2003; *Stewart et al.*, 2004; *Mote et al.*, 2005; *McCabe and Wolock*, 2010], decreases in the ratio of winter snow to winter precipitation [*Knowles et al.*, 2006; *Barnett et al.*, 2008; *Bonfils et al.*, 2008; *Pierce et al.*, 2008], and a shift to earlier snow melt in many parts of the United States [*Aguado et al.*, 1992; *Wahl*, 1992; *Pupacko*, 1993; *Dettinger and Cayan*, 1995; *Rajagopalan and Lall*, 1995;

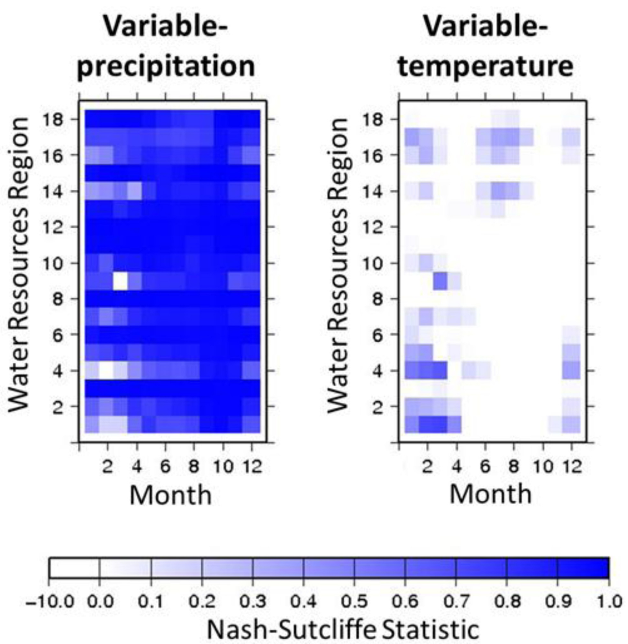

Figure 8. Nash-Sutcliffe statistics comparing monthly runoff computed using the complete model with monthly runoff computed using the variable-precipitation and variable-temperature models for the water-resources regions during 1900–2008.

Cayan et al., 2001; *Regonda et al.*, 2005; *Stewart et al.*, 2004; *McCabe and Clark*, 2005].

[31] The independent effects of temperature and precipitation identified in these analyses are consistent with those reported by *Karl and Riebsame* [1989]. Karl and Riebsame examined the effects of temperature and precipitation on runoff during the period 1930 to 1980 for 82 river basins in the conterminous United States that had negligible human disturbance. Karl and Riebsame reported that the effects of temperature on runoff were minimal, but that the effects of even small changes in precipitation on runoff were amplified by a factor of two or more. They further suggested that because precipitation variability controls runoff variability, little confidence can be placed in climate-model estimates of future runoff without reliable estimates of precipitation. Our study has expanded on this previous work by extending the analysis throughout the entire conterminous United States and over a much longer time period. Our results confirm previous findings and show that the overwhelming effects of precipitation on streamflow are consistent over the entire century across a large range of climatic and physiographic regions.

[32] Although the temperature effects on runoff have been small during the 20th century, it should be noted that for some locations, especially those where the consumptive use of water is equal to or greater than the natural supply of water, small increases in temperature and associated increases in evapotranspiration can drive water supplies below critical thresholds or "tipping points." For example, recent studies have shown that small increases in temperature (e.g., ~1°C to 2°C) in the Colorado River basin, with no compensating increase in precipitation, can result in substantial decreases in runoff (e.g., ~10% to 20% decrease) and an increase in the risk (~15% to 35% increase) of failing to meet the delivery obligations of the Colorado Compact [*Christensen et al.*, 2004; *Christensen and Lettenmaier*, 2006; *Hoerling and Eischeid*, 2007; *McCabe and Wolock*, 2007].

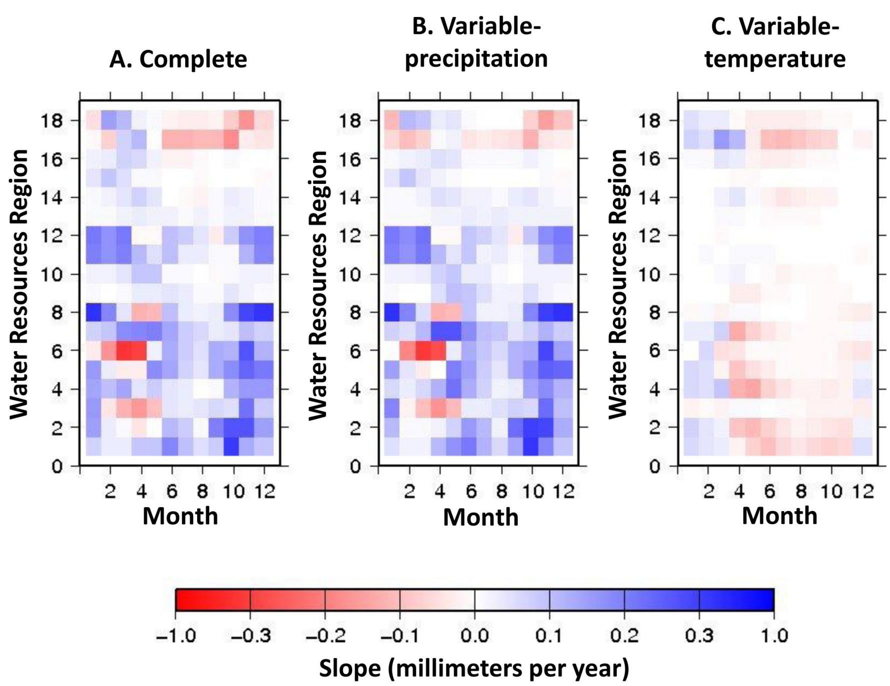

Figure 9. Slopes (in millimeters year^{-1}) in monthly runoff by water-resources region, 1900 through 2008.

4. Conclusions

[33] Simulations of water-year runoff for the conterminous United States indicate that precipitation variability during the past century has accounted for nearly all of the variability in runoff for almost all of the conterminous United States. Although temperatures have increased during the past century for most of the United States, the effects of increased temperature on runoff have been small compared with the effects of precipitation on runoff. If temperatures continue to increase, as projected by climate models, the effects of temperature on runoff may become more apparent.

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