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ESTIMATES OF RUNOFF USING WATER-BALANCE AND ATMOSPHERIC GENERAL CIRCULATION MODELS[1]

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ABSTRACT: The effects of potential climate change on mean annual runoff in the conterminous United States (U.S.) are examined using a simple water-balance model and output from two atmospheric general circulation models (GCMs). The two GCMs are from the Canadian Centre for Climate Prediction and Analysis (CCC) and the Hadley Centre for Climate Prediction and Research (HAD). In general, the CCC GCM climate results in decreases in runoff for the conterminous U.S., and the HAD GCM climate produces increases in runoff. These estimated changes in runoff primarily are the result of estimated changes in precipitation. The changes in mean annual runoff, however, mostly are smaller than the decade-to-decade variability in GCM-based mean annual runoff and errors in GCM-based runoff. The differences in simulated runoff between the two GCMs, together with decade-to-decade variability and errors in GCM-based runoff, cause the estimates of changes in runoff to be uncertain and unreliable.
(KEY TERMS: climate change; runoff; surface water hydrology; meteorology/climatology.)

INTRODUCTION

The U.S. Global Change Research Program (USGCRP) is coordinating a national assessment of the potential consequences of climate variability and change for the United States (U.S.). This assessment, which was mandated by the Global Change Research Act of 1990 (Public Law 101- 606), is analyzing the effects of global climate change on various sectors of resources in the nation. These sectors include agriculture, water, human health, forest, and coastal areas and marine resources. The study presented in this paper is part of the water-sector assessment. In particular, this paper describes the effects of climate variability and change on mean annual runoff in the conterminous U.S.

Mean annual runoff is defined here as the average amount of water flowing through streams and rivers during a year expressed on a per-unit-area basis. For example, if a watershed with area A yields a volume of water V at its outlet during a year, then the annual runoff for the watershed is V/A; the average over a number of years is the mean annual runoff. Mean annual runoff is an important component of the national assessment because it represents the renewable supply of water. Mean annual runoff is sensitive to variability in climate (Wolock and McCabe, 1999) and, therefore, is a good indicator of how climate change may affect resources dependent on water.

In this paper, the effects of potential climate change on mean annual runoff in the conterminous U.S. are examined using a simple water-balance model and output from two atmospheric general circulation models (GCMs). The objectives of the study described herein are to: (1) compute estimates of future mean annual runoff for the conterminous U.S. given a set of climate-change scenarios and (2) determine the level of uncertainty in the estimated effects of climate change on mean annual runoff.

GENERAL APPROACH

The approach used in the study is based on guidelines prescribed by the national assessment. In this approach, mean annual runoff was estimated for historical baseline climate conditions (1961-1990) and for each of two future decades (2025-2034 and 2090-2099). The climate conditions (monthly temperature

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and precipitation) for the two future decades were taken from two general circulation models (GCMs) – the Canadian Centre for Climate Modeling and Analysis (CCC) model and the Hadley Centre for Climate Prediction and Research (HAD) model (Johns *et al.*, 1997). The climate conditions were used as inputs to a monthly time-step water-balance model to estimate mean annual runoff for each of the climate scenarios. The degree of uncertainty in the estimated changes in mean annual runoff then was evaluated.

Historical Measured Climate Data

Monthly temperature and precipitation data for the conterminous U.S. were obtained from the Vegetation/Ecosystem Modeling and Analysis Project (VEMAP). VEMAP has interpolated measured temperature and precipitation data for 1895-1993 to a 0.5-degree (deg) of latitude by 0.5-deg of longitude grid for the conterminous U.S. (Kittel *et al.*, 1995). The interpolated values account for topographic effects and are based on data from 8,000 observation stations.

The VEMAP-gridded monthly climate data for the 1961-1990 historical baseline were averaged within each of the U.S. Geological Survey's 2,100 water-resources cataloging units in the conterminous U.S. (Figure 1a). The water-balance model then was used with the climate data to estimate mean annual runoff for each cataloging unit. The cataloging-unit runoff values then were averaged within each of the Survey's 18 water-resources regions (Figure 1b) in the conterminous U.S. to provide mean annual runoff values for baseline climate conditions.

The VEMAP-gridded monthly climate data also were averaged for 1951-1980 within each of the water- resources cataloging units. These data were used as inputs to the water-balance model and the subsequent estimates of mean annual runoff were averaged within each of the 18 water-resources regions. The time period 1951-1980 was chosen so that the estimated runoff values could be compared with measured runoff data for the same period derived from the contour map produced by Gebert *et al.* (1987) (see section on *Estimation of Mean Annual Runoff*).

General Circulation Model Data

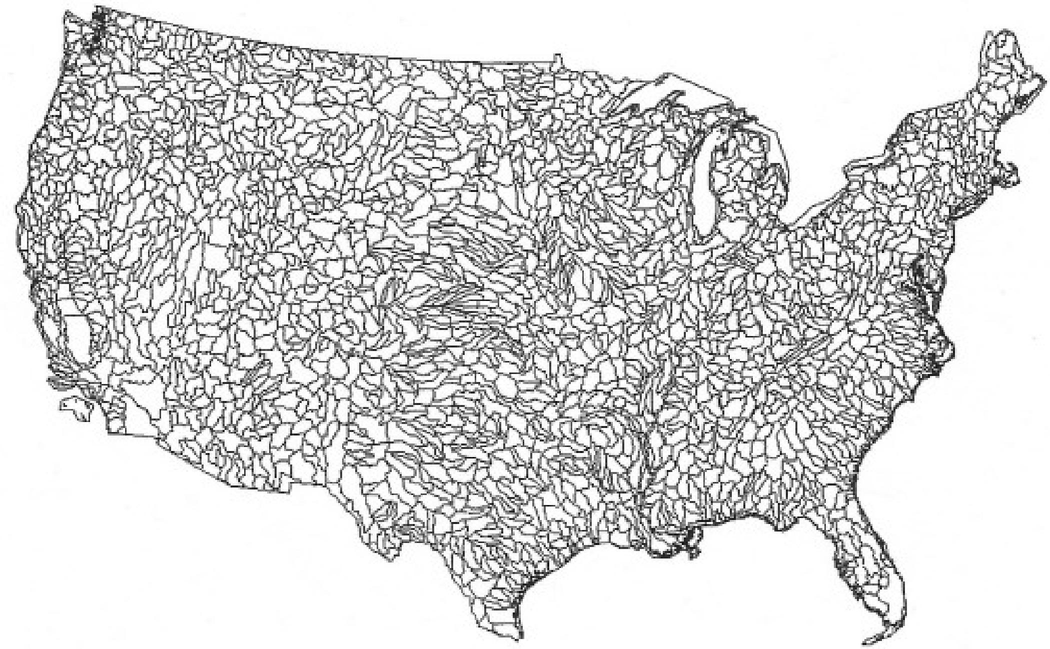
Simulations of changes in future temperature and precipitation from the CCC and HAD GCMs were used to represent future climate conditions in the conterminous US (Johns *et al.*, 1997). The CGCM1 version of the CCC model and the HADCM2 version of the HAD model were used. Both CGCM1 and HADCM2 are coupled ocean-atmosphere models. CGCM1 has a surface grid resolution of 3.75 by 3.75 deg (latitude by longitude) and 10 atmospheric levels; HADCM2 has a spatial resolution of 2.5 by 3.75 deg (latitude by longitude) and 19 atmospheric levels. The atmospheric forcing in these GCM simulations includes measured increases in CO_2 and sulfate concentrations from 1900-1993 and subsequent increases in atmospheric CO_2 and sulfate of 1 percent per year.

CCC and HAD GCM simulations of future climate were interpolated to the 0.5 by 0.5-deg VEMAP grid (Kittel *et al.*, 1995). The VEMAP-gridded monthly climate data for the periods 2025-2034 and 2090-2099 were averaged separately within each of the 2,100 water-resources cataloging units (Figure 1a). The water-balance model then was used with each climate data set to estimate mean annual runoff for each cataloging unit. The cataloging-unit runoff values then were averaged within each of the 18 water- resources regions in the conterminous U.S. to provide estimates of mean annual runoff for future climate conditions (Figure 1b).

CCC and HAD GCM simulations of historical climate (not interpolated to the VEMAP grid) also were used in this study. GCM-based monthly temperature and precipitation were averaged within each of the 18 water-resources regions for each month in the period 1901-1990. The water-balance model then was used with each GCM historical climate data set to estimate mean annual runoff for each water-resources region for each decade in the period 1901-1990. Mean annual runoff results based on the historical GCM simulations were used to estimate uncertainty in the GCM simulations (see section on *Estimation of Uncertainty*).

Estimation of Mean Annual Runoff

The water-balance model used in this study includes the concepts of climatic water supply and demand, seasonality in climatic water supply and demand, and soil-moisture storage (Wolock and McCabe, 1999). Inputs to the model are monthly precipitation and potential evapotranspiration, which is calculated from monthly temperature using the Hamon equation (Hamon, 1961). In the water-balance model, when precipitation for a month is less than potential evapotranspiration, actual evapotranspiration is equal to precipitation plus the amount of moisture that can be removed from the soil. The fraction of soil-moisture storage that can be removed decreases linearly with decreasing soil-moisture storage; that is,



(a)

(b)

Figure 1. (a) Water-Resources Cataloging Units (eight-digit hydrologic units) and (b) Water-Resources Regions (two-digit hydrologic units).

water becomes more difficult to remove from the soil as the soil becomes drier and less moisture is available for actual evapotranspiration. When precipitation 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 reaches capacity during a given month, the excess water becomes surplus. In a given month, 50 percent of the total surplus becomes runoff; the remaining surplus is carried over to the following month. Soil-moisture-storage capacity was determined from the State Soil Geographic Data Base (STATSGO) data set (U.S. Department of Agriculture, 1993).

To evaluate the model's reliability to estimate mean annual runoff for the 18 water-resources regions in the conterminous U.S., VEMAP-gridded monthly climate data for 1951-1980 were used in conjunction with the water-balance model to estimate mean annual runoff. These estimated runoff data were compared with measured runoff data for the water-resources regions for the same period derived from the contour map produced by Gebert *et al.* (1987). Results of this analysis indicated that the water-balance model reasonably simulates measured mean annual runoff for most of the water-resources regions (Table 1, Figure 2). The correlation coefficient between the measured and estimated mean annual runoff among the regions was 0.98, and the root mean square error was 33 millimeters (12 percent of the mean annual runoff averaged for all 18 water-resources regions). Although the water-balance model reasonably estimates mean annual runoff across the conterminous U.S., the model underestimates measured runoff in 16 of the 18 water-resources regions. This bias is a significant percentage of the measured runoff in regions with low measured mean annual runoff, such as the Rio Grande and the Great Basin regions. The model bias may reflect some conceptual inadequacy, but it is more likely due to precipitation input data errors (Wolock and McCabe, 1999).

ESTIMATION OF UNCERTAINTY

Three sources of uncertainty in estimating the effects of climate change on mean annual runoff were quantified. These were (1) decade-to-decade variability in GCM-based mean annual runoff, (2) errors in GCM-based runoff, and (3) differences among the GCMs. These sources of uncertainty represent different measures against which the estimated changes in mean annual runoff can be compared. The sources of uncertainty are not necessarily independent of each other, nor can they be assumed to be additive.

TABLE 1. Measured and Estimated Mean Annual Runoff.

Water-Resources Region (Figure 1b)	1951-1980 Mean Annual Runoff (mm)	
	Measured	Estimated Using the Water-Balance Model
New England	629	564
Mid-Atlantic	490	401
South Atlantic-Gulf	423	365
Great Lakes	346	263
Ohio	448	414
Tennessee	642	657
Upper Mississippi	204	171
Lower Mississippi	478	460
Souris-Red-Rainy	69	33
Missouri	75	33
Arkansas-White-Red	139	111
Texas-Gulf	98	58
Rio Grande	21	3
Upper Colorado	92	39
Lower Colorado	16	1
Great Basin	35	19
Pacific Northwest	480	367
California	233	233

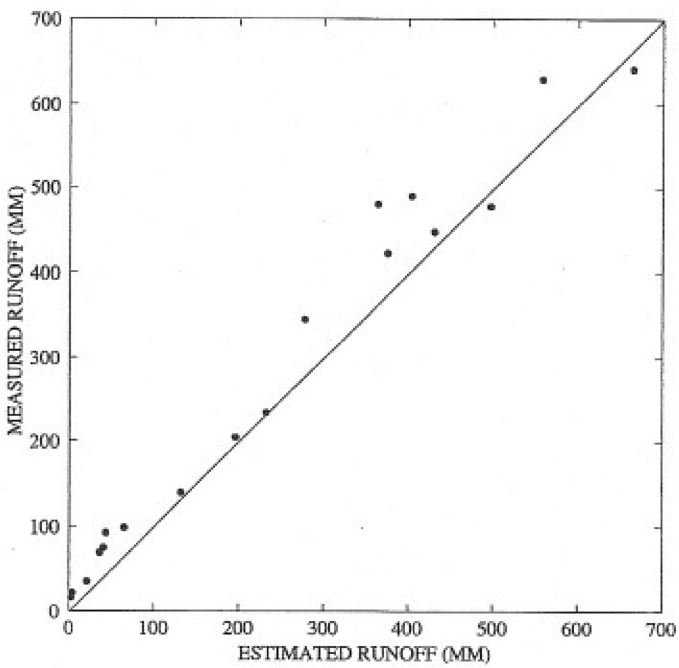


Figure 2. Measured and Estimated Mean Annual Runoff for the 18 Water-Resources Regions in the Conterminous United States for 1951-1980.

Uncertainty Due to Decade-to-Decade Variability in GCM-Based Mean Annual Runoff

Following the USGCRP national assessment protocol, mean annual runoff estimated for two future decades (2025-2034 and 2090-2099) was compared to mean annual runoff for historical baseline conditions (1961-1990). Mean annual runoff estimated on the basis of GCM-simulated climate, however, would be expected to vary from decade to decade due to variability in GCM-simulated climate even in the absence of climate change. Decade-to-decade variability in GCM-based mean annual runoff during a period in which trends in climate are minimal, therefore, constitutes a "background" level of variability against which changes in runoff from baseline conditions to future conditions can be compared. The statistical significance of the change in runoff estimated for a future decade can be calculated using the decade-to-decade variability in GCM-based mean annual runoff.

Variability in GCM-based mean annual runoff was estimated by first computing mean annual runoff for each decade during 1901-1990 using the CCC and HAD GCM estimates of historical monthly temperature and precipitation for each of the water-resources regions. (There was no trend in GCM-based mean annual runoff for either GCM during 1901-1990.) The variability in GCM-based mean annual runoff then was computed as the standard deviation of mean annual runoff estimated for each of the nine decades during 1901-1990 (Table 2). Variability in GCM-based mean annual runoff for the CCC model was lowest for the Lower Colorado, California, Arkansas-White-Red, and Souris-Red-Rainy water-resources regions and highest for the Tennessee, South Atlantic-Gulf, Mid-Atlantic, Ohio, and Lower Mississippi regions. Variability in GCM-based mean annual runoff for the HAD model was lowest in the Lower Colorado, Upper Colorado, Souris-Red-Rainy, and Arkansas-White-Red water-resources regions and highest in the Tennessee, Ohio, California, and South Atlantic-Gulf water-resources regions.

The differences in decade-to-decade runoff variability among water-resources regions and between the GCMs reflect differences in variability in precipitation. Precipitation is the primary factor that determines estimated runoff (see the section on *Estimated Changes in Runoff*). Therefore, differences in precipitation variability will cause differences in runoff variability.

The variability in GCM-based mean annual runoff was used to determine the statistical significance (at $\alpha = 0.05$) of the GCM-simulated changes in mean annual runoff estimated for future periods (2025-2034 or 2090-2099) using a two-tailed t-test. The test statistic was computed as:

$$t = \frac{\Delta}{\sqrt{4/3} \cdot s},$$

where t is the test statistic, Δ is the change in mean annual runoff from the baseline climate (1961-1990) to one of the climate-change decades (2025-2034 or 2090-2099), and s is the standard deviation of mean annual runoff estimated for 1901-1990. The term $\sqrt{4/3}$ is required in the denominator because a one-decade period (2025-2034 or 2090-2099) is compared to a three-decade period (1961-1990). The test statistic (t) and Δ are estimated for each combination of GCM (CCC or HAD) and climate-change decade (2025-34 or 2090-99), and s is estimated for each GCM. Changes in GCM-simulated mean annual runoff not significant at $\alpha = 0.05$ were considered uncertain (or at least smaller than GCM-based decade-to-decade runoff variability).

Uncertainty Due to Errors in GCM-Based Runoff

Another measure of uncertainty in GCM-based estimates of mean annual runoff is prediction error. Prediction error is defined here as the difference between mean annual runoff estimated using measured historical climate data and mean annual runoff estimated using GCM-based historical climate data. Mean annual runoff was estimated using the water-balance model and 1961-90 GCM-simulated climate data averaged for each of the water-resources regions. The GCM-based mean runoff values then were compared to mean annual runoff estimated using measured historical 1961-1990 climate data (obtained from the VEMAP grid and averaged for each water-resources region). The error in the CCC-based runoff was computed as the CCC climate-based mean annual runoff minus the measured historical climate-based runoff; the error in the HAD-based runoff was computed as the HAD climate-based mean annual runoff minus the historical climate-based runoff.

The CCC and HAD GCMs produced similar spatial patterns of error in GCM-based runoff (Table 2). In general, both models underestimate mean annual runoff in the Lower Mississippi and Tennessee water-resources regions and overestimate runoff in the Pacific Northwest, Great Basin, Upper Colorado, California, Mid-Atlantic, and Missouri water-resources regions. In absolute terms, the errors in CCC- based runoff mostly were larger than the errors in HAD-based runoff.

TABLE 2. Estimates of Uncertainty in GCM-Based Mean Annual Runoff.

Water-Resources Region (Figure 1b)	Variability* in GCM-Based Runoff (mm)		Error** in GCM-Based Runoff (mm)	
	CCC	HAD	CCC	HAD
New England	48	45	-53	-33
Mid Atlantic	68	39	111	102
South Atlantic-Gulf	75	53	78	0
Great Lakes	40	21	48	108
Ohio	66	55	-70	35
Tennessee	87	76	-291	-199
Upper Mississippi	20	34	-13	34
Lower Mississippi	60	28	-323	-249
Souris-Red-Rainy	16	15	231	73
Missouri	25	21	248	123
Arkansas-White-Red	15	16	-35	-10
Texas-Gulf	34	29	-10	0
Rio Grande	27	10	63	54
Upper Colorado	42	17	180	148
Lower Colorado	4	15	90	71
Great Basin	24	30	299	279
Pacific Northwest	52	29	218	177
California	12	55	90	123

*Variability in GCM-based runoff is computed as the standard deviation of mean annual runoff estimated for the nine decades in the period 1901-1990.

**Error in GCM-based runoff is estimated as the runoff computed using the 1961-90 GCM-based climate minus the runoff computed using the 1961-1990 historical baseline climate.

The spatial patterns of error in CCC- and HAD-based runoff are caused by errors in GCM-based precipitation estimated for 1961-1990 (data not shown). The GCMs underestimate (or overestimate) measured mean annual runoff in regions where they underestimate (or overestimate) measured mean annual precipitation. These biases in GCM-estimated precipitation are consistent with wet and dry biases reported by Doherty and Mearns (1999).

Uncertainty Due to Differences Among the GCMs

A final measure of GCM uncertainty is indicated by differences in the GCM estimates of future mean annual runoff. The direction of change (increase or decrease) in mean annual runoff caused by climate change was used as an indicator of differences among the GCMs. If the CCC and HAD GCMs indicated different directions of change for a given water-resources region, then the change in mean annual runoff for that water-resources region was considered uncertain. However, it should be noted that when the GCMs indicate the same direction of change, one cannot conclude that the GCM estimates are correct or certain because both models can be wrong. When the GCM-simulated changes are different, the uncertainty simply is more apparent.

ESTIMATED CHANGES IN RUNOFF

In most water-resources regions, the CCC-estimated climate changes caused decreases in runoff during the 2025-2034 and 2090-2099 decades (Table 3). The changes were greatest in the South Atlantic-Gulf, Tennessee, and Lower Mississippi water-resources regions. In California, however, the CCC-estimated climate changes caused an increase in mean annual runoff. The HAD-estimated climate changes caused small increases in runoff for the 2025-2034 decade and larger increases in runoff for the 2090-2099 decade. The HAD-based increases in runoff were greatest in the water-resources regions in the eastern half of the U.S. and in California.

The changes in runoff that are based on the GCM-estimated climate changes mostly were associated with GCM-estimated changes in precipitation (Figure 3). The differences in estimated changes in mean annual runoff between the GCMs and the differences in estimated changes among the water-resources regions primarily are related to differences in estimated changes in precipitation. The Pearson correlation coefficient for the relation between changes in runoff and changes in precipitation was 0.87. Changes in temperature, which are reflected by changes in potential evapotranspiration, had a less important effect on changes in mean annual runoff (correlation coefficient = -0.26).

The CCC and HAD GCMs predict different changes in precipitation because they are different mathematical representations of the hydrologic cycle. The two models differ in their spatial and conceptual complexity, and they are parameterized differently (Felzer and Heard, in review). The HAD model is more complex than the CCC model, but this does not necessarily imply that the HAD model estimates of future climate are more correct.

For the 2025-2034 decade, the absolute magnitudes of the simulated changes in runoff were greater than variability in GCM-based mean annual runoff in only 3 of the 18 water-resources regions for the CCC model and in none of the water-resources regions for the HAD model (Table 4). Thus, most of the CCC- estimated changes in runoff and all of the HAD-based

TABLE 3. Estimated Mean Annual Runoff and Changes in Runoff.

Water-Resources Region (Figure 1b)	Runoff and Changes* (Δ) in Runoff Estimated Using the Water-Balance Model (mm)				
	Historical 1961-1990	Δ CCC 2025-2034	Δ CCC 2090-2099	Δ HAD 2025-2034	Δ HAD 2090-2099
New England	557	-40	-104	48	151
Mid-Atlantic	403	-52	-100	39	132
South Atlantic-Gulf	375	-226	-272	2	118
Great Lakes	277	-31	-26	54	153
Ohio	430	-69	-77	31	185
Tennessee	665	-216	-243	26	263
Upper Mississippi	195	-42	0	42	133
Lower Mississippi	496	-315	-284	-47	89
Souris-Red-Rainy	35	-8	-29	-6	28
Missouri	40	-9	19	7	18
Arkansas-White-Red	131	-51	7	-1	57
Texas-Gulf	65	-56	-21	-6	-5
Rio Grande	3	-2	-2	0	2
Upper Colorado	43	-15	2	3	28
Lower Colorado	2	-1	0	6	33
Great Basin	21	-1	16	4	29
Pacific Northwest	363	-6	69	55	48
California	232	60	320	63	273

*The change in runoff is computed as the future decade value minus the 1961-1990 historical baseline value.

changes in runoff for 2025-2034 were within the background "noise" level of decade-to-decade variability in mean annual runoff.

In addition, the 2025-2034 decade changes in runoff were greater than the error in the GCM-based mean annual runoff in only four of the 18 water-resources regions for the CCC model and in only four regions when the HAD model was used (Table 4). These results show that the GCM-based changes in mean annual runoff are less than the expected error in the simulations for the majority of the water-resources regions for both GCMs.

The 2025-2034 decade changes in mean annual runoff were in the same direction for five water-resources regions (Table 4). When all three sources of uncertainty are considered (variability in GCM-based mean annual runoff, error in the GCM-based mean annual runoff, and disagreement in direction of change between the two GCMs), then the changes in mean annual runoff for all the water-resources regions would be considered uncertain.

For the 2090-2099 decade, the absolute magnitude of the simulated changes in runoff was greater than variability in GCM-based mean annual runoff in only four of the 18 water-resources regions for the CCC model and in eight of the water-resources regions for the HAD model (Table 5). The 2090-2099 decade changes in runoff were greater than the error in the GCM-based mean annual runoff for five of the 18 water-resources regions for the CCC model and for 10 of the water-resources regions for the HAD model (Table 5).

The 2090-2099 decade changes in mean annual runoff were in the same direction for both GCMs in seven water-resources regions (Table 5). When all three sources of uncertainty are considered (variability in GCM-based mean annual runoff, error in the GCM-based mean annual runoff, and disagreement in direction of change between the two GCMs), then the changes in mean annual runoff would be considered uncertain in all but one (California) water-resources region. It cannot be concluded, however, that a future increase in mean annual runoff for the California water-resources region is a certain outcome. Analysis of future climate conditions predicted by other GCMs could yield very different results.

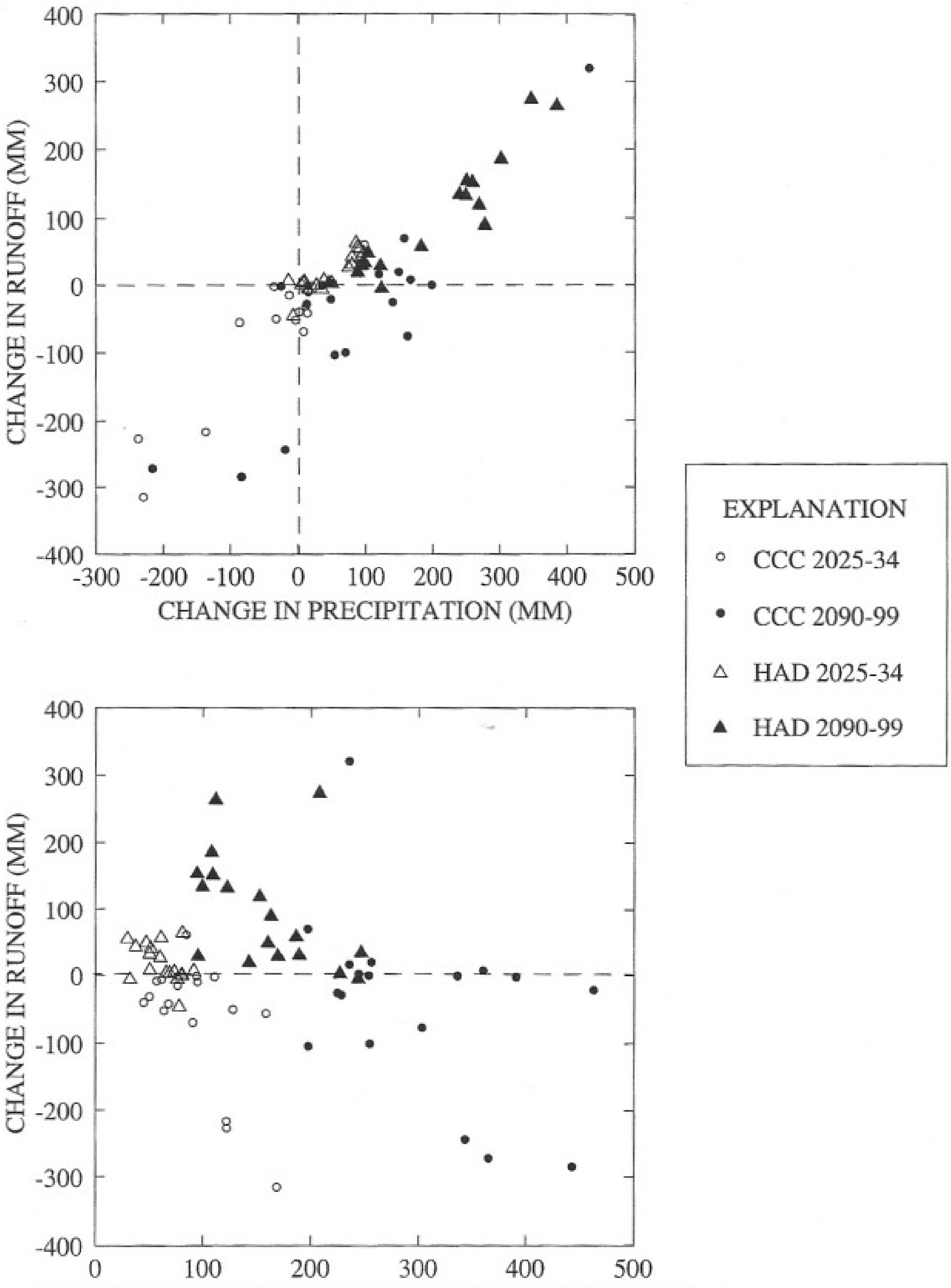


Figure 3. Changes in Mean Annual Runoff, Mean Annual Precipitation, and Mean Annual Potential Evapotranspiration from Historical Baseline (1961-90) to Future GCM-Simulated Climate Conditions. The results are for GCMs from the Canadian Centre for Climate Prediction and Research (CCC) and Hadley Centre for Climate Prediction and Research (HAD).

TABLE 4. Uncertainty Tests for the 2025-2034 Changes in Runoff (— indicates a significant decrease, and + indicates a significant increase in mean annual runoff).

Water-Resources Region (Figure 1b)	Significantly Greater Than Variability* in GCM-Based Runoff		Greater Than Error** in GCM-Based Runoff		CCC and HAD Change Same Direction	Significant Result in All Categories
	CCC	HAD	CCC	HAD		
New England				+		
Mid-Atlantic						
South Atlantic-Gulf			—	+		
Great Lakes						
Ohio						
Tennessee						
Upper Mississippi			—	+		
Lower Mississippi	—				—	
Souris-Red-Rainy					—	
Missouri						
Arkansas-White-Red	—		—		—	
Texas-Gulf			—	—	—	
Rio Grande						
Upper Colorado						
Lower Colorado						
Great Basin						
Pacific Northwest						
California	+				+	

*Variability in GCM-based runoff is computed as the standard deviation of mean annual runoff estimated for the nine decades during 1901-1990.

**Error in GCM-based runoff is estimated as the runoff computed using the 1961-1990 GCM-based climate minus the runoff computed using the 1961-1990 historical baseline climate.

CONCLUSIONS AND IMPLICATIONS

The USGCRP national assessment protocol for determining the effects of climate change and variability on mean annual runoff yields highly uncertain results. The GCMs selected for the national assessment simulate climate changes that result in opposite changes in mean annual runoff – decreases in runoff on the basis of the CCC model and increases in runoff on the basis of the HAD model. The two GCMs predict different changes in mean annual runoff because they estimate different changes in precipitation for future decades. Thus, despite the simulated warming predicted by the CCC and HAD models, future mean annual runoff is determined by the estimated changes in precipitation. The results also are uncertain because they are mostly within the range of GCM decade-to-decade runoff variability and GCM-prediction error.

The effects of climate change on mean annual runoff cannot be estimated reliably because of uncertainty related to GCMs. Most atmospheric scientists believe that GCMs will become more reliable as their spatial and conceptual complexity continue to improve. The level of adequate detail and the time when that will be achieved, however, are unresolved issues. Until the large uncertainty associated with GCM-simulations of future climate can be resolved, a useful path for future research is sensitivity analyses using a range of changes in temperature and precipitation. Such analyses can be used to understand the response of annual runoff (and water resources systems) to climate and to identify important vulnerabities.

TABLE 5. Uncertainty Tests for the 2090-2099 Changes in Runoff (— indicates a significant decrease, and + indicates a significant increase in mean annual runoff).

Water-Resources Region (Figure 1b)	Significantly Greater Than Variability* in GCM-Based Runoff		Greater Than Error** in GCM-Based Runoff		CCC and HAD Change Same Direction	Significant Result in All Categories
	CCC	HAD	CCC	HAD		
New England		+	—	+		
Mid-Atlantic		+		+		
South Atlantic-Gulf	—		—	+		
Great Lakes		+		+		
Ohio		+	—	+		
Tennessee	—	+		+		
Upper Mississippi		+		+		
Lower Mississippi	—					
Souris-Red-Rainy						
Missouri					+	
Arkansas-White-Red		+		+	+	
Texas-Gulf			—	—	—	
Rio Grande						
Upper Colorado					+	
Lower Colorado						
Great Basin					+	
Pacific Northwest					+	
California	+	+	+	+	+	+

*Variability in GCM-based runoff is computed as the standard deviation of mean annual runoff estimated for the nine decades during 1901-1990.

**Error in GCM-based runoff is estimated as the runoff computed using the 1961-1990 GCM-based climate minus the runoff computed using the 1961-1990 historical baseline climate.

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