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Characterizing Climate-Change Impacts on the 1.5-yr Flood Flow in Selected Basins across the United States: A Probabilistic Approach

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ABSTRACT: The U.S. Geological Survey Precipitation-Runoff Modeling System (PRMS) model was applied to basins in 14 different hydroclimatic regions to determine the sensitivity and variability of the freshwater resources of the United States in the face of current climate-change projections. Rather than attempting to choose a most likely scenario from the results of the Inter-governmental Panel on Climate Change, an ensemble of climate simulations from five models under three emissions scenarios each was used to drive the basin models.

Climate-change scenarios were generated for PRMS by modifying historical precipitation and temperature inputs; mean monthly climate change was derived by calculating changes in mean climates from current to various future

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decades in the ensemble of climate projections. Empirical orthogonal functions (EOFs) were fitted to the PRMS model output driven by the ensemble of climate projections and provided a basis for randomly (but representatively) generating realizations of hydrologic response to future climates. For each realization, the 1.5-yr flood was calculated to represent a flow important for sediment transport and channel geomorphology. The empirical probability density function (pdf) of the 1.5-yr flood was estimated using the results across the realizations for each basin. Of the 14 basins studied, 9 showed clear temporal shifts in the pdfs of the 1.5-yr flood projected into the twenty-first century. In the western United States, where the annual peak discharges are heavily influenced by snowmelt, three basins show at least a 10% increase in the 1.5-yr flood in the twenty-first century; the remaining two basins demonstrate increases in the 1.5-yr flood, but the temporal shifts in the pdfs and the percent changes are not as distinct. Four basins in the eastern Rockies/central United States show at least a 10% decrease in the 1.5-yr flood; the remaining two basins demonstrate decreases in the 1.5-yr flood, but the temporal shifts in the pdfs and the percent changes are not as distinct. Two basins in the eastern United States show at least a 10% decrease in the 1.5-yr flood; the remaining basin shows little or no change in the 1.5-yr flood.

KEYWORDS: Climate change; Hydrology; Probability density function; 1.5-yr flood

1. Introduction

General circulation model (GCM) simulations through 2099 project a wide range of possible future climate changes in response to increasing greenhouse-gas concentrations in the atmosphere (Solomon et al. 2007). To determine the sensitivity and potential impact of long-term climate change on the freshwater resources of the United States, the U.S. Geological Survey (USGS) global change study “An integrated watershed scale response to global change in selected basins across the United States” was undertaken in 2008 and 2009 (Markstrom et al. 2010). The long-term goal of this national study is to provide the foundation for hydrologically based climate-change studies across the nation.

Fourteen river basins for which Precipitation-Runoff Modeling System (PRMS; Markstrom et al. 2010) models previously had been calibrated and evaluated were selected as study sites (Figure 1; Table 1). PRMS is a process-based, distributed-parameter watershed model developed to evaluate the effects of various combinations of precipitation, temperature, and land use on streamflow and general basin hydrology. The PRMS models for this national study were developed, calibrated, and evaluated for previous or current hydrologic investigations. Outputs from five GCMs responding to three greenhouse-gas emission scenarios were input to PRMS models to simulate an ensemble of hydrologic responses to climate changes for each watershed. The hydrologic impact and sensitivity of the simulations to climate-change scenarios were determined by comparisons to PRMS simulations of baseline (historical) conditions (Hay et al. 2011).

One approach to analyzing results from numerous simulations is to compute mean or median statistics across the various GCMs and emissions scenarios. Although this may provide a picture of hydrologic response to climate change, it does not fully represent ranges and uncertainties regarding the future climate-change scenarios and associated hydrologic responses. As an alternative, we apply a

Table 1. General characteristics of each study basin.

Basin name	USGS gauge No.	Drainage area (km ²)	Elev range (m)
Western United States			
Feather River, CA	—	9324	325–2212
Flathead River, MT	12362500	4307	1045–2078
Naches River, WA	12494000	2437	562–1650
Sagehen Creek, CA	10343500	27	1941–2589
Sprague River, OR	11501000	4053	1316–2203
Eastern Rockies and central United States			
Black Earth Creek, WI	05406500	118	718–1551
Clear Creek, IA	05454300	254	205–261
East River, CO	09112500	748	2583–3796
Starkweather Coulee, ND	05056239	543	446–491
Trout River, WI	05357245	120	491–522
Yampa River, CO	09239500	1471	2124–3504
Eastern United States			
Cathance Stream, ME	01021230	85	46–174
Flint River, GA	02349500	7511	90–286
Pomperaug River, CT	01204000	194	63–332

methodology for estimating probability distributions of hydrologic responses by resampling the information contained in the ensemble of hydrologic predictions. The resulting distributions provide useful estimates of the probability that various magnitudes of hydrologic response will result (in the PRMS models) from any subset of the climate-change projection ensemble used here to force the watershed models (Dettinger 2006).

For this paper, the changing magnitude of estimates of flow magnitudes recurring with 1.5-yr return intervals was chosen to represent changes in flows important for sediment transport and channel geomorphology, with associated implications for stream habitat (Leopold et al. 1964; Dunne and Leopold 1978; Castro and Jackson 2001; Simon et al. 2004). Using the component resampling approach, empirical probability density functions (pdfs) of the 1.5-yr flood were determined for the 14 study watersheds at each of 3 decades spanning the twenty-first century. These pdfs provide temporally varying probabilistic characterization of climate-change impacts on flood flows at locations across the nation. Following these results, limitations of the analysis are described, and conclusions drawn from the exercise are presented.

2. Methods

A brief description of the development of climate-change emission scenarios and processing of the PRMS outputs is given here; a detailed description of the methods is given in Hay et al. (Hay et al. 2011). Given the uncertainty in climate modeling, it is desirable to use more than one GCM to explore a range of potential future climatic conditions. Monthly precipitation and temperature output from five GCMs constitute the climate-projection ensemble used here. The five GCMs were selected because they produced output needed for the PRMS model (daily precipitation and maximum and minimum daily temperature). The GCM output was

obtained from the World Climate Research Programme's Coupled Model Inter-comparison Project phase 3 multimodel dataset archive, which was referenced in the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report Special Report on Emission Scenarios (SRES; Solomon et al. 2007). For each GCM, one baseline and three future carbon emission scenarios were analyzed.

Climate-change emission scenarios were derived by calculating mean change in climate from baseline to future conditions in the simulations from each GCM. The IPCC historical simulation for water years 1988–99 was used to represent the baseline climatic conditions of each GCM. This 12-yr period of record was selected to match the period of overlap shared by the available historic records from the 14 basins included. Mean monthly climate-change estimates (percentage changes in precipitation and degree changes in temperature) were computed for 12-yr moving window periods (from 2001 to 2099) using the IPCC historical conditions (20C3M; 1988–99) and the SRES A2, B1, and A1B scenarios. Climate-change scenario files for input to PRMS were generated by applying these future (mean) changes uniformly to the daily PRMS precipitation and temperature inputs (1988–99), based on historical observations. The first year of each 12-yr simulation was used as PRMS initialization and is not included in the analysis, resulting in 11 years available for analysis. The analysis presented in this paper is for three specific periods, centered around the years 2030, 2060, and 2090 (2024–35, 2054–65, and 2084–95, respectively), with simulations based on each of the three future emissions scenarios and each of five GCMs, for a total of 45 scenarios analyzed in each river basin.

2.1. Component resampling approach

The component resampling approach used in this paper (Dettinger 2006) will be briefly described here. The PRMS model was run with the ensemble of 15 climate-change input files for each period of interest. This resulted in an ensemble of daily model outputs, which were harvested to determine the maximum daily discharge for each year in each simulation. For a particular simulation period, this results in an $m \times n$ matrix \mathbf{X} containing the ensemble of model forecasts, representing m years of annual maximum daily discharges (11 years) and n GCM–scenario combinations (15 members). A log transformation of the annual maximum discharges was used to ensure that discharges generated by the resampling approach would be nonnegative. Thus, the term $x_{i,j}$ represents the natural log of the maximum daily discharge for year i corresponding to model j . The ensemble of model forecasts is decomposed into an empirical orthogonal function (EOF) matrix \mathbf{E} and a coefficient matrix \mathbf{P} such that

$$\mathbf{X} = \mathbf{E}\mathbf{P}^T, \quad (1)$$

where the superscript T signifies the transpose operation. The EOF matrix \mathbf{E} is determined by a principal component analysis (PCA) of the correlation matrix $\mathbf{Z}\mathbf{Z}^T$, where \mathbf{Z} is a standardized zero-mean version of the matrix of model forecasts, with expectations taken across the ensemble of n model forecasts for each year in the ensemble,

$$z_{i,j} = \frac{(x_{i,j} - \mu_i)}{\sigma_i} \quad \text{for } i = 1, m \quad \text{and} \quad j = 1, n, \quad (2)$$

where

$$\mu_i = \frac{1}{n} \sum_{j=1}^n x_{i,j} \quad \text{and} \quad (3)$$

$$\sigma_i = \left[\frac{1}{n} \sum_{j=1}^n (x_{i,j} - \mu_i)^2 \right]^{1/2}. \quad (4)$$

The PCA on the correlation matrix \mathbf{ZZ}^T is performed, and all eigenvectors are retained as the EOF matrix. Because the correlation matrix is symmetric, the eigenvectors form an orthogonal set that can be used to decompose and recreate the original time series (Blyth and Robertson 2002). Retaining all of the eigenvectors allows for a complete recreation of the first two moments of the original ensemble matrix \mathbf{X} . The coefficient matrix \mathbf{P} is computed by projecting the standardized matrix \mathbf{Z} onto the EOFs; the k th vector \mathbf{p}^k is thus given as

$$\mathbf{p}^k = \mathbf{Z}^T \mathbf{e}^k, \quad (5)$$

where \mathbf{e}^k is the k th eigenvector from the PCA analysis. For a particular realization r , a column in the standardized forecast matrix \mathbf{Z} is given as

$$z_{i,r} = \sum_{k=1}^m e_i^k p_j^k. \quad (6)$$

In this expression, the index j is randomly drawn from 1 to n for each k in the summation. Because of the orthogonal nature of the eigenvectors, each eigenvector is independent of every other eigenvector; thus, the coefficient vectors are also independent of one another and hence can be selected at random without changing the first two moments of the original time series. This provides for a much larger set of random permutations and a more realistic representation of the pdf of an outcome calculated from the resampled time series. The results are then rescaled using the ensemble mean and standard deviations for each time step; thus,

$$x_{i,r} = \mu_i + \sigma_i z_{i,r}. \quad (7)$$

Each resampled discharge is then exponentiated to return the discharge to natural units.

A Monte Carlo experiment was designed to implement the component resampling approach described above. For each basin, three future periods were considered, centered around the years 2030, 2060, and 2090. The annual maximum discharge for each year was extracted from the PRMS output files for these three periods and the 15 GCM–emission scenario combinations. This resulted in three ensemble forecast matrices for each basin, which were standardized following

Table 2. Number of realizations resulting in high outliers identified by Bulletin 17B procedures based on 50 000 total realizations.

Basin	Realizations with high outliers		
	2030	2060	2090
Western United States			
Feather River, CA	9	6	14
Flathead River, MT	0	0	0
Naches River, WA	0	0	0
Sagehen Creek, CA	133	54	95
Sprague River, OR	0	0	0
Eastern Rockies/central United States			
Black Earth Creek, WI	4	0	42
Clear Creek, IA	0	6	13
East River, CO	0	4	2
Starkweather Coulee, ND	0	0	0
Trout River, WI	19	14	23
Yampa River, CO	1	1	5
Eastern United States			
Cathance Stream, ME	7	18	31
Flint River, GA	0	0	1
Pomperaug River, CT	3	10	2

Equations (2)–(4). A principal component analysis was performed, and the collection of eigenvectors was used to form each EOF matrix. The coefficient vector \mathbf{p} was then computed using Equation (5). The result for each basin was a set of three EOF (\mathbf{E}) and coefficient (\mathbf{P}) matrices.

For each set of EOF and coefficient matrices, a set of N_{real} realizations of possible future annual maximum flow series was formed by providing N_{real} sets of random j indices to Equation (6). Each annual maximum flow series was used to estimate the 1.5-yr flood following the procedures described in the next section. This resulted in N_{real} estimates of the 1.5-yr flood for each of the three future periods. To determine an appropriate number of realizations for estimating pdfs of 1.5-yr flood flows, N_{real} was increased until various statistics of the 1.5-yr flood approached asymptotic values. In the application here, $N_{\text{real}} = 50\,000$ realizations proved to be adequate.

2.2. Flood frequency analysis

For each realization, an estimate of the 1.5-yr flood was obtained by fitting the log-Pearson type-3 distribution (LP3) to the generated 11-yr series of annual maximum discharges using procedures outlined in Bulletin 17B (Interagency Advisory Committee on Water Data 1982). Station skewness was weighted with general skewness obtained from the map in Bulletin 17B using the procedure described in the report. Source code for the USGS software application PeakFQ was obtained (<http://water.usgs.gov/software/PeakFQ/>) and repackaged as a subroutine for the program executing the Monte Carlo experiment described in the previous section. A sequence of annual maximum discharges was generated using

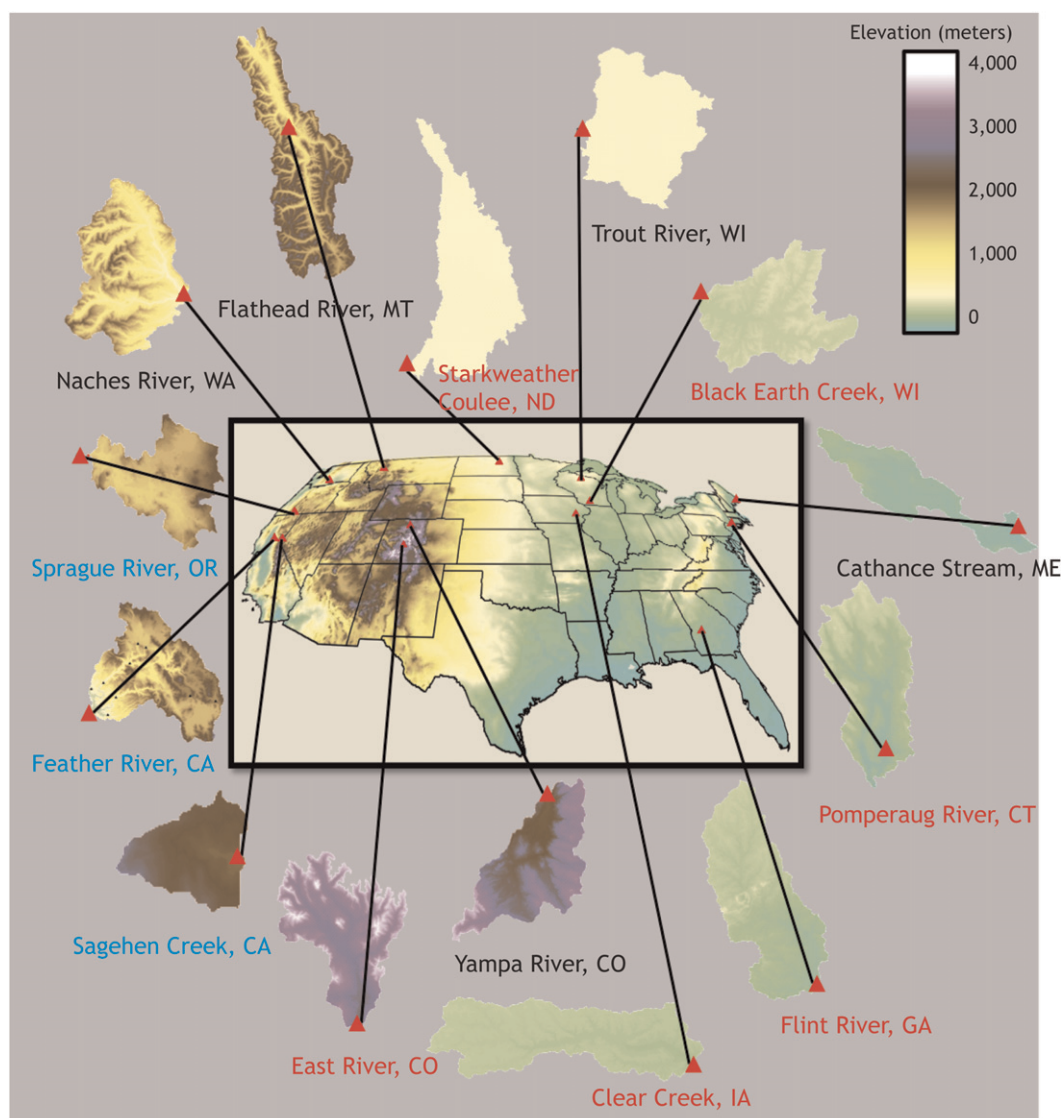


Figure 1. Location of study basins in the United States with shaded topography indicating relief across the basins. Site name colors indicate the degree of change in the 1.5-yr flood resulting from climate change: black indicates relatively little change (less than 10% difference between current conditions and the 2090 projection), red indicates decreasing 1.5-yr floods, and blue indicates increasing 1.5-yr floods. Note that basins are not to scale.

the component resampling approach described in the previous section, and a particular sequence was discarded if the application of Bulletin 17B procedures identified one or more low outliers. Because the Bulletin 17B procedure drops the data corresponding to low outliers, it was felt that reducing the sample size below 11 years would result in an unreasonable estimate of the 1.5-yr flood. For cases

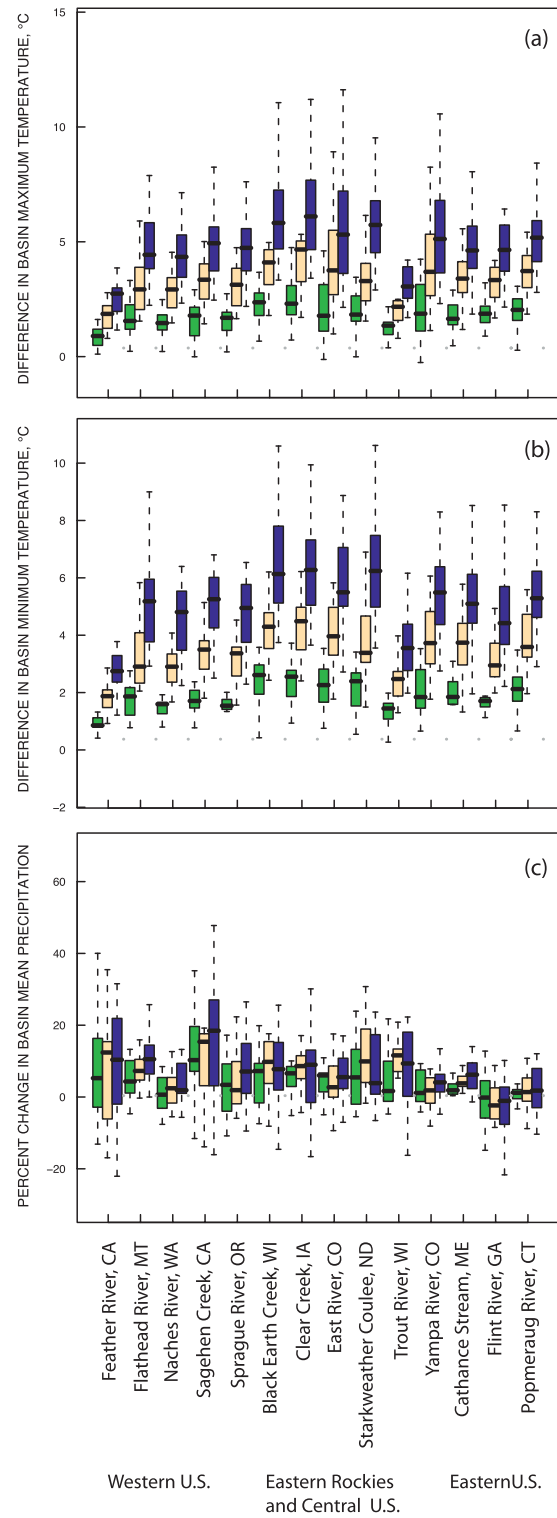


Figure 2. Change in (a) maximum and (b) minimum temperature and (c) percent change in mean daily precipitation (for the five GCMs and three emissions scenarios for the three periods examined in this paper (2030 in green; 2060 in tan; 2090 in blue).

where high outliers were identified, they were included in the analysis, and a count of the percent of realizations resulting in high outliers was tabulated (Table 2). For all basins, less than 0.5% of the realizations resulted in high outliers, which was considered to a reasonable percentage of high outliers that were included in the analyses. With the exception of Sagehen Creek, the percentages of high outliers generated were extremely small. It is unclear why the EOF for the Sagehen Creek basin results in a larger number of high outliers. However, because the number of outliers does not exhibit a trend as the climate-change scenarios progress through time, the conclusions concerning the change in the distribution of the 1.5-yr flood over time should still be valid.

2.3. Empirical probability density function

Each of the N_{real} resampled flow-series realizations results in its own 1.5-yr flood flow estimate. To estimate the probability density function of the 1.5-yr flood, we used a procedure based on a kernel estimate (Parzen 1962),

$$\hat{f}_h(x) = \frac{1}{hN_{\text{real}}} \sum_{i=1}^{N_{\text{real}}} K\left(\frac{x - x_i}{h}\right), \quad (8)$$

where N_{real} is the number of discrete values comprising the empirical pdf, h is the width of the kernel window, $K(\cdot)$ is the kernel, and $\hat{f}_h(x)$ is the resulting empirical pdf for a particular value of x .

The Epanechnikov kernel was used,

$$K(u) = \frac{3}{4\sqrt{5}} \left(1 - \frac{u^2}{5}\right) \quad \text{for } |u| \leq \sqrt{5}. \quad (9)$$

The following kernel window produced reasonably smooth pdfs:

$$h = \frac{1.06s_x}{n^{1/5}}, \quad (10)$$

where s_x is the sample standard deviation of the N_{real} 1.5-yr flood predictions.

Empirical pdf values were thusly estimated for 1000 values of flow, distributed uniformly between the minimum and maximum 1.5-yr flood from the N_{real} scenarios.

3. Results

A detailed description of the temporal changes in the inputs to the PRMS model (temperature and precipitation) for the five GCMs and three emission scenarios is given in Hay et al. (Hay et al. 2011). A summary of the changes in maximum and minimum daily temperature and percent change in precipitation across the 14 basins is given in Figure 2 for reference. In general, the central tendencies of the three emissions scenarios indicate a 2°–6°C increase in maximum and minimum temperature, with a positive trend through time. The most extreme increases in

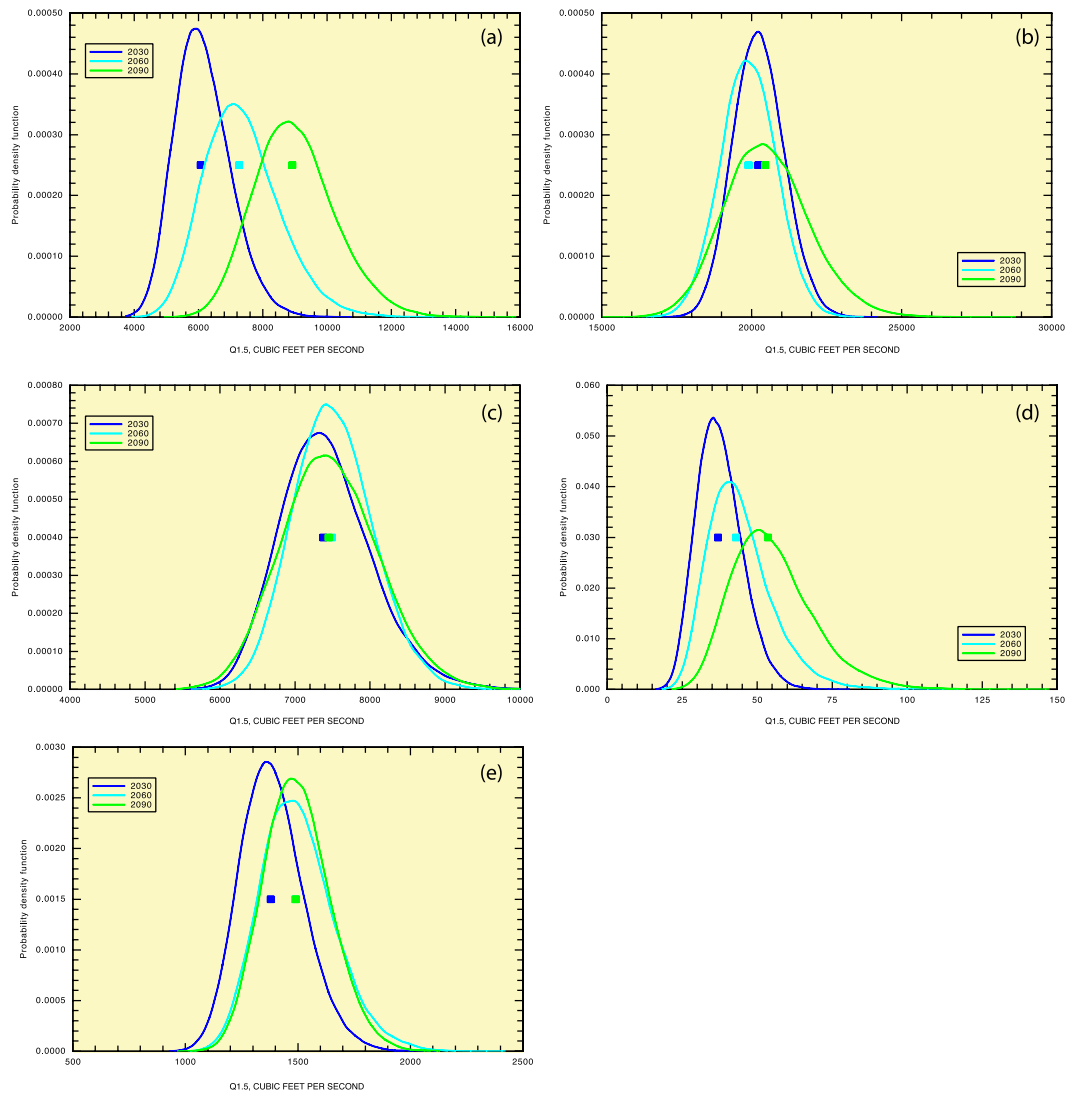


Figure 3. Estimated probability density functions for the 1.5-yr flood for basins in the western United States: (a) Feather River, California; (b) Flathead River, Montana; (c) Naches River, Washington; (d) Sagehen Creek, California; and (e) Sprague River, Oregon. Squares represent the median value.

temperature are somewhat higher for maximum temperature compared to minimum temperature. Further, the variability of the changes in temperature increases as the simulations progress through time. The percent changes in precipitation show less distinct patterns, with central tendencies ranging from a decrease of less than 5% to an increase on the order of 20%. In general, most of the basins show an increase in precipitation around 5%, with one basin showing a decrease and two basins showing increases between 10% and 15%. For some basins, there is a slight positive trend with time, but for the most part precipitation is roughly stationary across the three future periods. As with temperature, the variability of the changes

in precipitation increase somewhat with time, although it is less pronounced than the increased variability in temperature.

The estimated pdfs for the western United States, eastern Rockies/central United States, and the eastern United States are presented in Figures 3–5, respectively. The median values for the 2090 future period along with the simulated values for the historic period (1988–99) are presented in Table 3. Of the 14 basins studied, 9 showed clear temporal shifts in the pdfs of the 1.5-yr flood in response to the ensemble projections of climate change (Figure 1, red and blue basin names). Three basins in the western United States show an increase of at least 10% in the 1.5-yr flood, four basins in the eastern Rockies/central United States show a decrease of at least 10% in the 1.5-yr flood, and two basins in the eastern United States show a decrease of at least 10% in the 1.5-yr flood (Table 3). For the remaining five basins without clear temporal shifts in the pdfs, three show a slight increase in the 1.5-yr flood and two show a slight decrease in the 1.5-yr flood. For most of the pdfs presented in Figures 3–5, the mode of the distribution changes and the variability increases as the simulations progress through time (2030–90), indicating that the ensemble range of 1.5-yr flood estimates increases with time. This increasing ensemble range reflects increasing differences among the three emission scenarios and between the various GCMs as time progresses, but it may also reflect some increased year-to-year variability later in the projections. Exceptions to this tendency for increasing variability could likely be due to interactions between precipitation and temperature effects on the simulation of peak discharge at those sites.

In the western United States, three basins show clear temporal shifts in the pdfs trending toward an increase in the 1.5-yr floods throughout the simulation period (Figures 3a,d,e). For these basins, the largest annual peak discharge occurs during unusual rainfall events in December and January; in years where there is not a winter storm, the annual maximum discharge typically occurs during snowmelt in the spring. Because the smaller annual peak discharges would more strongly impact the lower-frequency floods such as the 1.5-yr flood, changes in the snowmelt peaks and the frequency of winter storms would likely impact estimates of the 1.5-yr flood. From the projected changes in hydrologic budget components, for these basins surface runoff increases and the snowmelt peak occurs earlier (Markstrom et al. 2010), which is likely resulting in higher annual maximum discharges during these years. For the two basins without clear temporal shifts in the pdfs (Figures 3b,c), snowmelt dominates the annual discharge hydrograph, and the 1.5-yr floods under climate-change conditions are slightly larger than the corresponding baseline (1988–99; Table 3). This is consistent with the finding for the other basins in this region.

In the eastern Rockies/central United States, five basins show clear temporal shifts in the pdfs trending toward a decrease in the 1.5-yr floods throughout the simulation period (Figures 4a–d,f). For all of these basins, the projected changes in hydrologic budget components indicate an increase in infiltration and evapotranspiration with a corresponding decrease in soil moisture and a decrease in surface runoff (Markstrom et al. 2010), which is consistent with a decrease in the annual maximum discharge. The projected changes in hydrologic budget components also indicate a decrease in snowmelt runoff, which would also contribute to decreasing annual peak discharges. For the basin without a clear temporal shift in the pdfs (Figure 4e), the trends in the hydrologic budget components are generally weaker compared to other basins (Markstrom et al. 2010); however, this basin

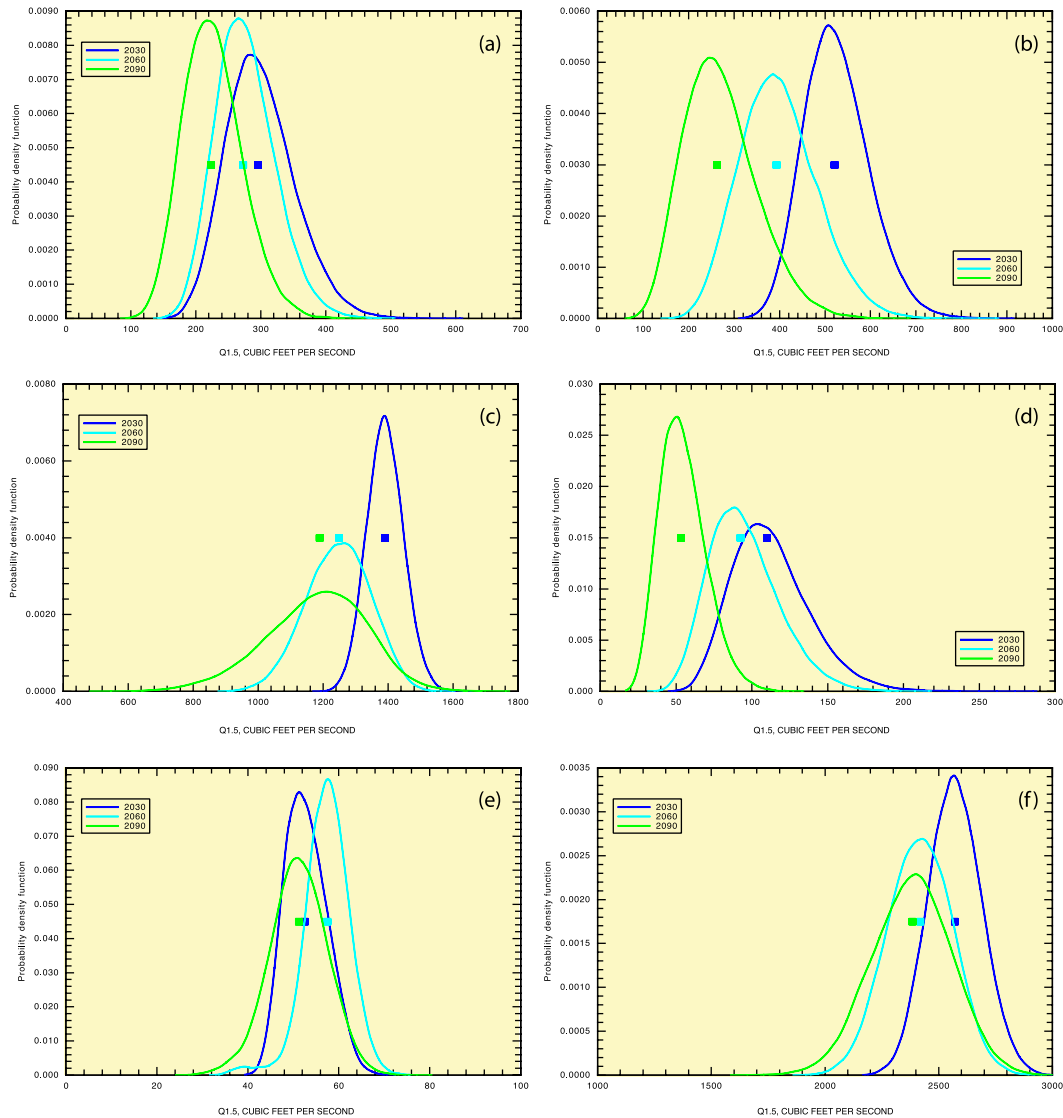


Figure 4. Estimated probability density functions for the 1.5-yr flood for basins in the eastern Rockies/central United States: (a) Black Earth Creek, Wisconsin; (b) Clear Creek, Iowa; (c) East River, Colorado; (d) Starkweather Coulee, North Dakota; (e) Trout River, Wisconsin; and (f) Yampa River, Colorado. Squares represent the median value.

exhibits a slight decrease in the 1.5-yr flood compared to the corresponding baseline (1988–99; Table 3), which is consistent with the other basins in this region.

In the eastern United States, one basin shows a clear temporal shift in the pdfs trending toward a decrease in the 1.5-yr floods throughout the simulation period (Figure 5b). For this basin, the projected changes in hydrologic budget components indicate an increase in infiltration and evapotranspiration with a corresponding decrease in soil moisture and a decrease in surface runoff (Markstrom et al. 2010),

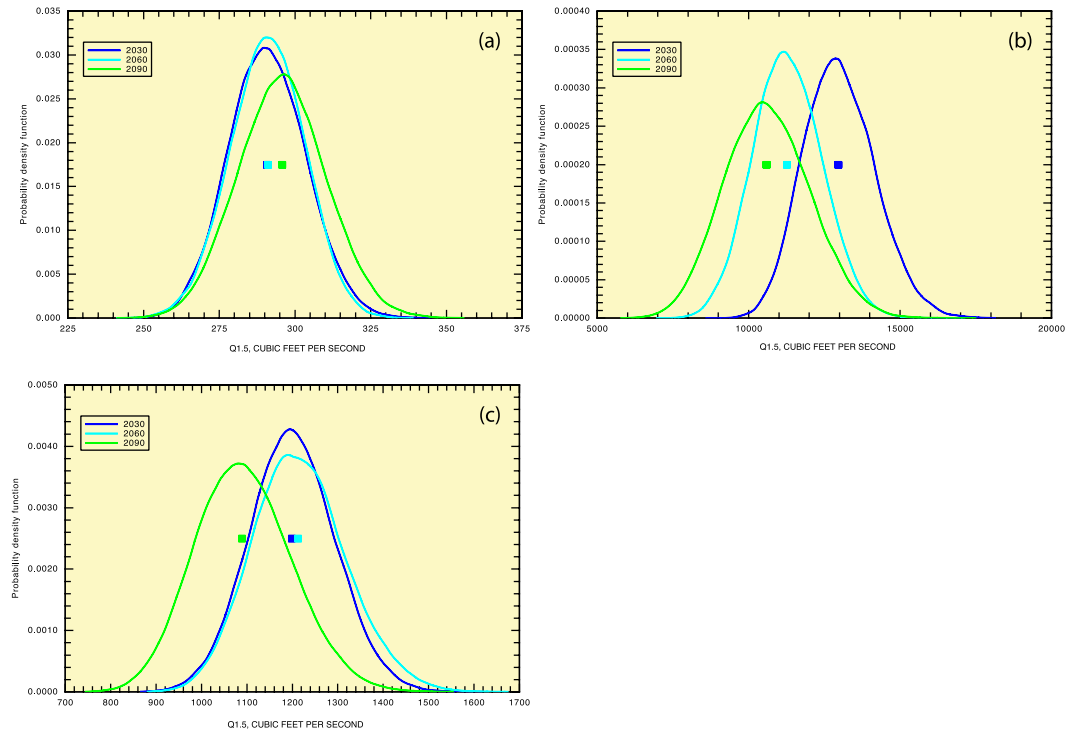


Figure 5. Estimated probability density functions for the 1.5-yr flood for basins in the eastern United States: (a) Cathance Stream, Maine; (b) Flint River, Georgia; and (c) Pomperaug River, Connecticut. Squares represent the median value.

which is consistent with a decrease in the annual maximum discharge. For the remaining basins without a clear temporal shift in the pdfs (Figures 5a,c), the trends in the hydrologic budget components are generally weaker compared to other basins (Markstrom et al. 2010). For these basins, one showed a slight increase (Figure 5a) and one showed a decrease (Figure 5c) in the 1.5-yr flood compared to the corresponding baseline (1988–99; Table 3). This is likely due to the balance between slightly increased precipitation and reduced soil moisture and surface runoff for these basins (Markstrom et al. 2010).

4. Limitations

The flood frequency analysis described in Bulletin 17B is normally applied to the record of annual maximum instantaneous discharge. For many streams, the annual maximum instantaneous peak is considerably larger than the daily maximum discharge for a particular year. Because the PRMS models used in this study are based on daily data, the peaks used in the analysis were based on the largest daily discharge for each year. The differences between instantaneous and daily discharges are generally small for large streams, which typically have flood hydrographs that span many days. However, for small streams the differences between the maximum instantaneous and daily peaks can be considerable. For the 14 study

Table 3. Comparison of median values for the 11-yr period centered around 2090 relative to 1988–99 conditions for the study basins.

Basin	Modeled value for the 1.5-yr flood ($\text{ft}^3 \text{s}^{-1}$)	
	1988–99	2090 median
Western United States		
Feather River, CA	4400	8900
Flathead River, MT	19 000	20 000
Naches River, WA	7100	7500
Sagehen Creek, CA	29	54
Sprague River, OR	1200	1500
Eastern Rockies/central United States		
Black Earth Creek, WI	260	160
Clear Creek, IA	520	260
East River, CO	1500	1200
Starkweather Coulee, ND	130	53
Trout River, WI	53	51
Yampa River, CO	2600	2400
Eastern United States		
Cathance Stream, ME	290	300
Flint River, GA	13 000	11 000
Pomperaug River, CT	1300	1100

basins listed in Table 1, the difference between instantaneous and maximum daily flows for the 1988–99 period was less than 10% for the 7 basins with an area greater than 700 km^2 and for the groundwater-dominated Trout River basin. The difference between instantaneous and maximum daily flows for the two basins with areas between 200 and 700 km^2 and Sagehen Creek was less than 50%. For the remaining three basins, the difference between instantaneous and maximum daily flows was greater than 50%.

Based on the downscaling procedure used, the future climate records represent climate averaged over a 12-yr window; the temporal patterns of precipitation are essentially the same as the patterns contained in the historic period (1988–99). Hydrologic predictions from this average climate will result in reasonable estimates of annual and monthly average discharges. For floods, the annual peaks are typically generated by extreme conditions that are not represented by the down-scaled data. It should be noted that the component resampling methods set forth in this paper would be valid for alternative downscaled climate projections and results from other hydrologic models. Further, the additional information provided by estimating the pdf of a given hydrologic model response enhances the utility of the future projections for resource managers.

Finally, the ensemble of climate-change scenarios used to drive the PRMS models represents a relatively small sampling of variations and uncertainties regarding how the five GCMs respond to emissions scenarios, differences among the three emissions scenarios used to drive each of the GCMs, the downscaling approach used, and variations due to the whole range of simulated climate processes from less-than-hourly to century scales. The ensemble is limited, however, and does not span the full range of possible future climates (including long-term natural influences), the full range of possible GCM configurations and errors, or the full

range of possible emissions. The ensemble also is not weighted according to which models might be more accurate (however, see Pierce et al. 2009) or according to which emissions trajectories might be more likely. Thus, as noted previously, the pdfs of 1.5-yr flows developed here represent the variations and uncertainties as captured by the ensemble of climate-change scenarios used to force the PRMS models; they do not represent completely all of the uncertainties surrounding future climate changes. Thus, the results presented herein can be considered a heuristic exercise examining the potential impacts of climate change on the 1.5-yr flood.

5. Conclusions

Of the 14 basins studied, 9 showed distinct temporal shifts in the pdfs of the 1.5-yr flood projected into the future using results from five GCM projections for three emissions scenarios. Three snowmelt-dominated basins in the western United States show at least a 10% increase in the 1.5-yr flood in the twenty-first century. The other two snowmelt-dominated basins in the western United States also indicate increases in the 1.5-yr floods, but the temporal shifts in the pdfs and the percent changes are not as distinct. Four basins in the eastern Rockies/central United States show at least a 10% decrease in the 1.5-yr flood. Two basins in the eastern Rockies/central United States indicate a decrease in the 1.5-yr flood, but the temporal shifts in the pdfs and the percent changes are not as distinct. Two basins in the eastern United States show at least a 10% decrease in the 1.5-yr flood. For other basins in the eastern United States, the 1.5-yr flood shows little or no change in the twenty-first century.

The results presented in this paper demonstrate a technique for estimating the probability density function of hydrologic change resulting from climate change. The estimated pdf provides resource managers with vital information on the variability of future projections. Because of limitations imposed by the use of previously developed hydrologic models and the downscaling technique used, the results presented here should be considered a heuristic exercise, showing potential results and techniques that can be used to provide valuable information to resource managers struggling to plan for the future in the face of climate change.

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