Flood Frequency in a Changing Climate, Projections Approach and Diagnostics

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Abstract:
The design and safety assessment of large dams in the western United States requires estimates of flood frequency. Flood frequency relates the magnitude of floods with their probabilities of occurrence. Often flood frequencies are described by return period. The return period concept, as often communicated in the community and practice, is that a 100-year flood is an event that should happen, on average, once every hundred years. A more strict interpretation of a flood frequency for a 100-year flood is that it is a flood that is believed to have a probability of being equaled or exceeded of 0.01 in any one year. While we do not wish to challenge the current paradigm of communication of flood hazard, it is reasonable to question the paradigm of what a return period means within a nonstationarity system (Sivapalan and Samuel, 2009). The nonstationarity concern and current paradigm are not mutually exclusive if it is acknowledged that a flood with a 100-year return period is not a constant value. Or, working within our preferred strict interpretation of the flood return period, a flood with an exceedance probability of 0.01 this year may have a different exceedance probability in the future.

This manuscript focuses on the use of climate projections to assess how current methods may be biased in a changing climate and the diagnostics of using climate projections to assess flood hazards. The analytical design includes three core elements: (1) a rationale for selecting climate projections with the objective of representing the breadth of climate projection information available; (2) generation of runoff projections consistent with climate projections, using a process-based hydrologic model and temporal disaggregation of monthly downscaled climate projections into sub-monthly weather forcings required by the hydrologic model; and (3) analysis of flood frequency distributions based on runoff projection results.

The hydrologic response within different climate states (Hot-Wet, Hot-Dry, Cool-Wet, and Cool-Dry) are then explored. This approach can be used to explore the basin response to different future climate states without relying on a GCM climate projection to perfectly describe flood risk.

Introduction:

Risk based decisions often use the probability of occurrence of a flood with a specified magnitude and the consequences of that event. If the consequences are deemed unacceptable, modifications of infrastructure or changes in operations may be necessary to alleviate the risk. In a changing climate, and given how flood risks are generated from the observed record of the past, it may be prudent to include information that not only describes the flood potential of the past but also of the future.

Flood frequency estimation within the United States government has as its fundamental doctrine, Bulletin 17-B published by the Interagency Advisory Committee on Water Data (IACWD 1982). Released in 1982, Bulletin 17-B provides guidance for observational data treatment and parameter estimation for flood frequency distributions (IACWD 1982). The general methodology of Bulletin 17-B is to gather a time series of annual maximum floods at the location that the user wishes to determine the flood magnitude versus frequency relationship. In additional to the gage information, any historical information about large floods that may pre-date the gage record is also used.

Fundamentally, Bulletin 17-B assumes that flood potential can be described by a three parameter log-Pearson distribution (log-Pearson III distribution).

That vast majority of research since the release of Bulletin 17-B has been focused on improved treatment of historical data from instrumental records and/or historical and paleoflood proxies. For brevity only a fraction of potential references are listed. There has been research focused on statistical properties of parameter selection (e.g., Lane and Cohn 1996, England 2003), uncertainty estimates (e.g., O'Connell et al. 2002) and incorporation of paleoflood information (e.g., Frances et al. 1994). Questions of stationarity assumptions (e.g., Milly et al. 2008) and questions about changes to extreme rainfall (e.g., IPCC, 2007a) has led to studies that use climate projections to assess flood potential (e.g., Cameron et al. 2000). From a statistical perspective, methods have been proposed to address how a changing climate might be related to flood frequency estimation (e.g., Griffis and Stedinger 2007).

While we do not wish to challenge the current paradigm of communication of flood hazard, it is reasonable to question the paradigm of what a return period means within a nonstationary system. To evaluate the physical response to a changing climate there remains limited guidance on how to incorporate climate projection data into a framework for flood hazard assessment. In this manuscript methods to address this gap in planning capabilities are introduced and diagnostically evaluated. The methods described are meant to identify whether climate change may influence risk assessments made using Bulletin 17-B (Raff et al. 2009). The methods are designed to reveal flood frequency consistent with climate projection information at a user-specified future period. Methods are demonstrated in a case study of the San Joaquin River above Friant Dam.

Methods:

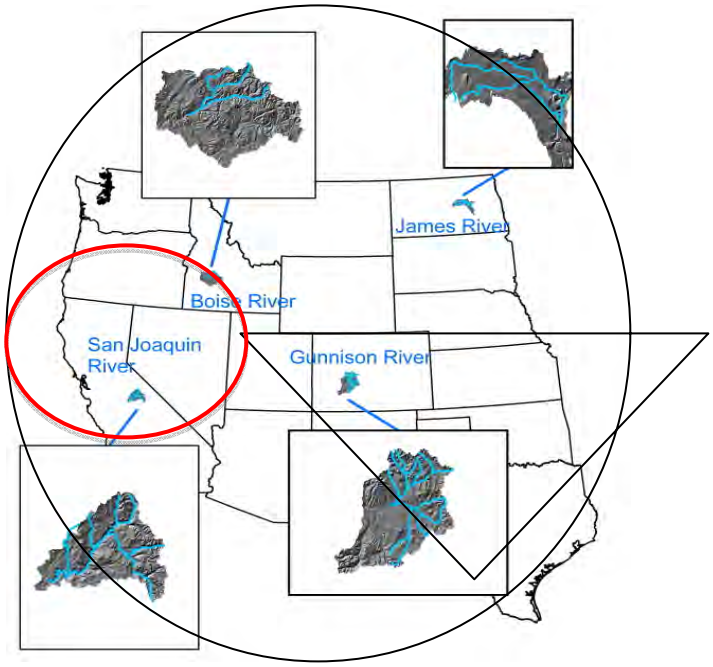
The general outline of methodology employed in this analysis was to (1) select a basin of interest, (2) identify a hydrologic tool to be used to take climate projection information and translate into floods, (3) Obtain and select climate projection information for evaluation, and (4) Analyze the floods within the context of a flood frequency analysis.

Basin Selection*:*

The effect of a changing climate may vary geographically. Therefore, to determine the suitability of the methods proposed it was desired to have a geographically diverse set of examples. Four geographically diverse reservoir watersheds were considered, each having dams that were either built by the Bureau of Reclamation (BOR) or significantly influence Reclamation operations. The four basins are the Boise River, above Lucky Peak Dam, the James River above Jamestown Dam, the Gunnison River above Blue Mesa Dam, and the San Joaquin River above Friant Dam (Figure 1). This manuscript presents the analysis for the San Joaquin River above Friant Dam, further information is available for the other three basins (Raff et al. 2009)

Friant Dam is located near 37° 00' N, 119° 42' W on the San Joaquin River about 19 miles from Fresno, California. The dam impounds Millerton Lake. The drainage area at Friant Dam is approximately 4120 km^2 (1,591 mi^2). Drainage is from the western slope of the Sierra Nevada range. Elevations in the basin range from 170 m at the dam to just under 4260 m along the crest of the Sierra Nevada range. The terrain in the basin may be described as rugged forest. Mean annual precipitation over the basin is approximately 900 mm which varies significantly by elevation.

Figure 1. Basin Selections are the Boise River above Lucky Peak Dam, the James River above Jamestown Dam, the San Joaquin River above Friant Dam, and the Gunnison River above Blue Mesa Dam.



Hydrologic Tool

The hydrologic model used in this study is the National Weather Service River Forecast System (NWSRFS) Sacramento Soil Moisture Accounting (SAC-SMA) Model (Burnash et al., 1971). The SAC-SMA Model is coupled to the Anderson Snow Model of snow accumulation and ablation (Anderson, 1973). This model was chosen because it is the operational model of the National Weather Service and calibrated models for all of the chosen basins were available. SAC-SMA consists of two upper and three lower soil moisture storage zones. The two upper zones are free and tension water storage and the three lower zones are a primary free, a supplemental free and a tension water storage zone (Burnash, 1995). The snow accumulation and ablation model computes a freezing height to distribute rain and snow by elevation. The NWSRFS SAC-SMA Model has a long history of operational use within the United States Federal Agencies. Despite the fact that this study looks at characterization of future climate, calibration sets based on an antecedent period were not altered for the future period.

Climate Projection Data

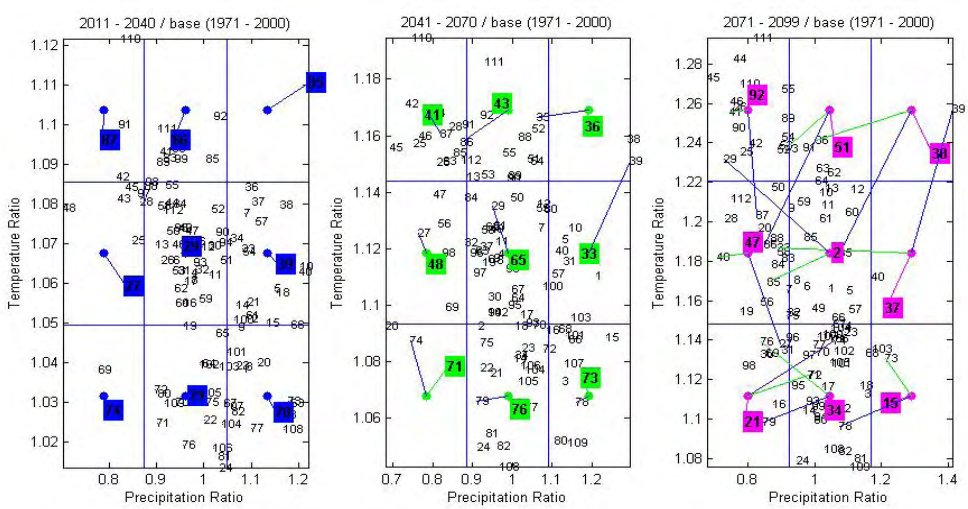
For this study, the focus was having access to a large set of consistently downscaled climate projections over each of the case study basins. Using these criteria, a decision was made to use data from the "Bias Corrected and Statistically Downscaled WCRP CMIP3 Climate Projections" archive (http://gdo-dcp.ucllnl.org/downscaled_cmip3_projections/) (Maurer et al. 2007). These data were developed using a statistical downscaling technique called bias-correction spatial disaggregation (e.g., Wood et al. 2002) that has been used to support numerous investigations on projected hydrologic impacts under climate change (e.g., Brekke et al. 2009). The data archive includes downscaled projections of 112 CMIP3 projections of simulated monthly climate from 1950-2099 and at 1/8° spatial resolution.

All 112 projections were obtained for the latitude longitude coordinate of the dam for the purposes of projection selection. Here a method was chosen that chose a subset of 9 GCM model projections that

encapsulate the variability of precipitation and temperature. This information, as opposed to attempting to identify a specific risk can be used to show the range of risk that may exist. The selected nine projections are allowed to vary by lookahead period. Three lookahead periods were considered, 2011 – 2040, 2041 – 2070, and 2071 – 2099. These periods represent three different decision time frames in which one might change operations or physical infrastructure. A tercile grid is constructed based upon the projected temperature and precipitation relative to the simulated historical antecedent period (1971 – 2000) (Figure 2). The tercile grid is generated through a Cartesian sectioning between the maximum and minimum changes in precipitation and temperature at the lookahead period relative to the antecedent period. The GCM projections that were geometrically calculated to be closest to the nine vertices encompassing the array of projected temperature and precipitation shifts were chosen. Projections have internal climate dynamics and just as there is observed interdecadal variability in the observed and historical past, the climate models have interdecadal variability in their projected future. The interdecadal variability are not necessarily synchronous with each other and also do not necessarily share the same dynamics or initial conditions and have other differences. Projections, therefore, depending when in the future they are examined, may display different relative precipitation and temperature. The relative precipitation and temperature of the 9 selected GCM projections are hence different by lookahead period. In Figure 2 the blue lines in the second and third panel represent the location of projection from the 2011 – 2040 lookahead in the 2041 – 2070 and 2071 – 2099 lookahead, respectively.

The bias corrected spatially downscaled projections in the archive describe time series of temperature and precipitation conditions on a monthly time step. The SAC-SMA model, as applied in the case study basins, operates on 6-hr values of temperature and precipitation. Therefore, a method is necessary to equate monthly average temperature and precipitation values to 6-hourly values to force each basin SAC-SMA model. The general approach was to scale a monthly set of observed 6-hourly values by the ratio of projected temperature and precipitation to the observed monthly average temperature and precipitation within the scaled month (e.g., Maurer 2007).

Figure 2. Projection Selection by lookahead period and basin. Numbers represent spread of individual climate projections. Panels moving from left to right are the three lookahead periods with colored numbers representing selected projections. Colored lines show where previously selected projection are with respect to spread at future lookahead periods.



Hydrologic Hazard Assessment

To put information into a context that is used throughout flood hazard assessment and management the information developed from the simulation model are used to create flood frequency curves. Two different approaches are employed. The first, called the "expanding retrospective" approach is the current paradigm for hazard assessment and the second called the "moving window" approach is an alternative.

The "expanding retrospective" approach is how most flood frequencies are calculated in that all information at a location of interest is considered equally when developing a flood frequency curve. Every year there is a new observation of an annual maximum discharge added to an expanding record of floods at that location. For example, using expanding retrospective analysis for a basin that has a period of record from 1950 - 1990 those forty occurrences of annual maxima would be treated as independent samples from a general population and used to fit a distribution to (i.e. Log-Pearson III from Bulletin 17B). If time then proceeds to 2020 there would be 30 additional independent samples (i.e., 1950 – 2020). This approach relies heavily on the stationarity assumption in that all 70 years are assumed to independent samples from the same distribution. The expanding retrospective flood frequencies were calculated as follows. For the 2011-2040 future periods, a total of 60 samples were used to fit the log-Pearson III distribution. These 60 samples comprised 30 random samples taken from between the 5th and 95th quantiles from the length of record of the calibration set for that particular basin and 30 samples taken from the 5th and 95th quantiles between the 2011 - 2040 simulations. The result is 60 total samples which were then fit to a log-Pearson III distribution as described in Bulletin 17B without any regional skew adjustment. Because of the random selection of 30 simulations from the 4,5000 possibilities for the retrospective period and the 30 random samples from the 2,700 possibilities for the 2011 - 2040 period, the procedure was performed 100 times to account for some of the variability. The procedure was repeated for the 2041 – 2070 and 2071 – 2099 lookahead periods.

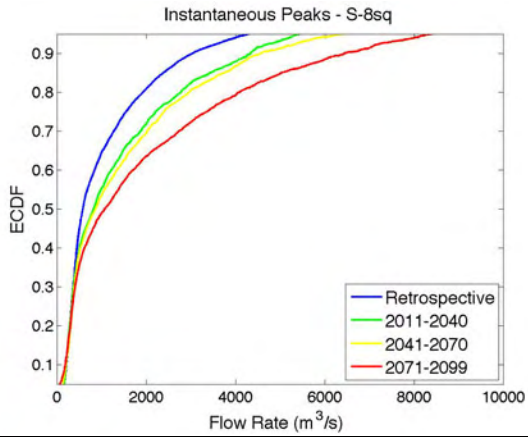
The "moving window" differs from this approach in that it will consider only a limited set of floods to estimate a flood frequency curve. This approach is used to somewhat account for non-stationarity. The implicit statement is that floods are representative of a given climate state and samples from a different climate state should not be considered. For example, for a location that has a period of record from 1950 – 2020 as before only the period of 1990 - 2020 is used to compute the flood frequency. Although the period of 1990 – 2020 is considered to be stationary when fitting a distribution it assumes that the period of 1950 – 1990 does not come from this same distribution. The lookahead flood frequencies were calculated as follows. For the 2011-2040 lookahead period 30 random samples were taken from between the 5th and 95th quantiles from the 30 years by 9 GCM projections by 10 simulations between 2011 and 2040. The difference between this set and the expanding retrospective set is that for this set there is an absence of the retrospective period. The sample size from which a distribution is being fit is smaller. This is a total of 30 samples which were then fit to a log-Pearson III distribution as described in Bulletin 17B without any regional skew adjustment. This was repeated 100 times. For the 2041 – 2070 lookahead period 30 random samples were taken from between the 5th and 95th quantiles from the 30 years by 9 GCM projections by 10 simulations between 2041 and 2070. Again, this is a total of 30 samples which were then fit to a log-Pearson III distribution. The procedure for the 2071 – 2099 lookahead was similar. For each of the three lookahead periods using the lookahead flood frequency approach there are 30 years of data from which to fit the log-Pearson III distribution. For the 2071 - 2099 lookahead period the difference between the lookahead approach (30 years data) and the expanding retrospective approach (120 years data) is 90 years of data. The implications of reducing the sample size in an attempt to better characterize the population from which the floods are being observed are examined later in the document.

Results:

For each lookahead period there are nine projections with 10 simulations each for a total of 90 simulated projections. Each simulated projection is a thirty-year time period for a total of 2,700 simulated years per lookahead. All 2,700 simulated annual maximum values were pooled to create a single empirical distribution function for each of three lookahead periods. Figure 5 shows the empirical distribution functions for each of the four basins included in this study for each lookahead period as well as the retrospective period (1951 - 1997). For the San Joaquin basin, the cumulative distributions show no major

deviations from historical floods for floods with non-exceedance probabilities (NEP) less than 0.4. For floods with NEP greater than 0.4 the magnitude of the simulated floods show a monotonic increase in magnitude with time. The floods in this probability range from 2011 – 2040 are greater than those from the historical record and likewise the floods from the 2041 – 2070 range are greater than those. The floods from the 2071 – 2099 range are greater than all previous periods.

Figure 5: Cumulative distributions of annual maximum discharge based on ensemble hydrologic simulation for the periods and basins shown. Retrospective period is defined as 1951 - 1997 for all basins. CDFs based on SacSMA simulation of GCM simulated historic climate.



Hydrologic Hazard Assessment

As described previously the most common method to estimate flood risk is to use an expanding retrospective analysis. A second method ("moving window") was also described that only considers the most recent time period to evaluate flood risk. Figure 6 shows the "expanding retrospective" vs. "moving window" approach to flood frequency for each of the lookahead periods. The solid blue lines in each of the plots represent the median flood frequency curve from the 100 flood frequency curves using the methods described previously. The dashed blue lines represent the flood frequency curves that had 10 and 90th quantile 100-year return period values from the random selections. The colored solid and dashed lines have corresponding meanings for the "moving window" flood frequency approach. From Figure 6 there are clear differences in the flood frequency estimates depending on whether the expanding retrospective approach or the lookahead approach was employed. The implications for the 100-year flood are now discussed.

For all locations and all lookahead periods the expanding retrospective approach results in a lower estimate of the 100-year flood than the lookahead approach (Table 1). The percent differences in the 100-year estimates vary by lookahead period and by basin. For the 2011 0 2040 lookahead period the smallest percent difference is 4% in the Boise River Basin and the largest percent difference is 17% in the San Joaquin and Jamestown River Basins. For the 2041 - 2070 lookahead periods the percent differences range from 8% to 28% in the Boise River Basin and the James River Basin, respectively. The smallest percent difference in the 2071 - 2099 is 8% for the Boise River Basin and the largest percent difference is 32% for the James River Basin. The implication of this result is that to characterize the flood frequency given current methods of fitting log-Pearson III distributions may result in a biased underestimate of the true flood potential. This is an intuitive result given that the empirical distribution functions for each of the locations show an increased trend to bigger floods. The expanding retrospective approach to characterizing the floods continues to give equal weight to floods that occurred during an entirely different climatology. Perhaps a more important implication is in the context of designing for some lookahead period. Consider if we were to make a flood frequency estimate in 2041 for a structure with a life span until 2099 for each of the four basins analyzed in this manuscript. The current methodology would be the expanding

retrospective approach over the retrospective period 1951 - 2041. If the flood potential is increasing through time however at the end of the life span, 2099, of the structure than the flood potential at that time may be very different than the 1951 - 2041. So consider a comparison of the expanding retrospective approach for the 2011 - 2041 lookahead period as described in Table 2 and the lookahead approach for 2071 - 2099. The differences for the four basins are 11%, 52%, 23%, and 45% for the Gunnison, San Joaquin, Boise, and James River Basins, respectively. Therefore, the design would be underestimating the flood with a given risk by between 11% and 52%, depending on the basin, over the life span of the project.

Figure 6: Flood Frequency Curves for the locations and lookahead periods as specified. Blue lines represent the Expanding retrospective approach and colored lines represent lookahead approach.

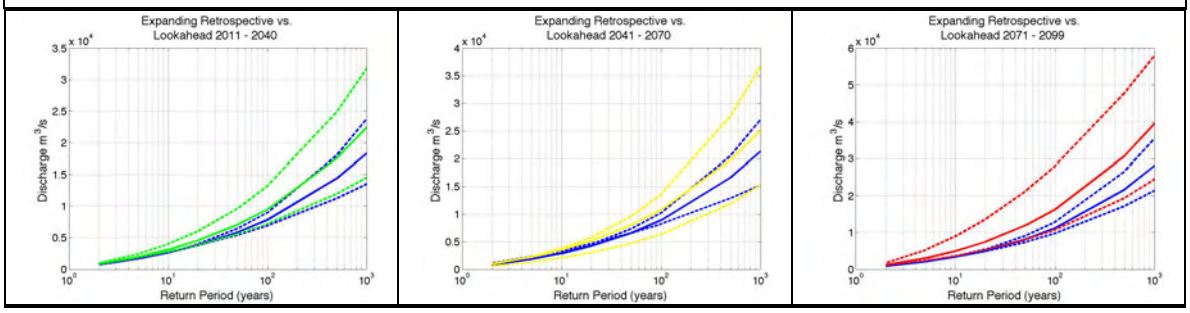


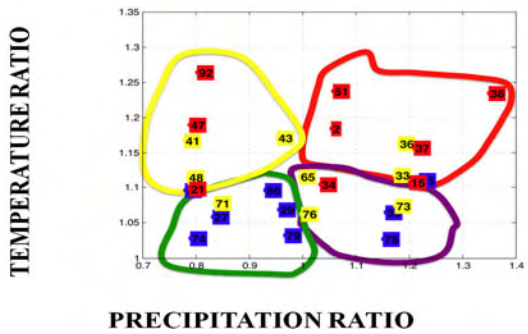
Table 1: Relative change of 100-year discharge by lookahead period for the San Joaquin basin using "expanding retrospective" and "moving window" approach to flood frequency estimation.

		2011 – 2040	**2041 – 2070**	**2071 - 2099**
San Joaquin River Basin	Expanding Retrospective	7850	8870	11180
	Lookahead	9490	10740	16230
	Percent Difference	17%	17%	31%

Diagnostics*:*

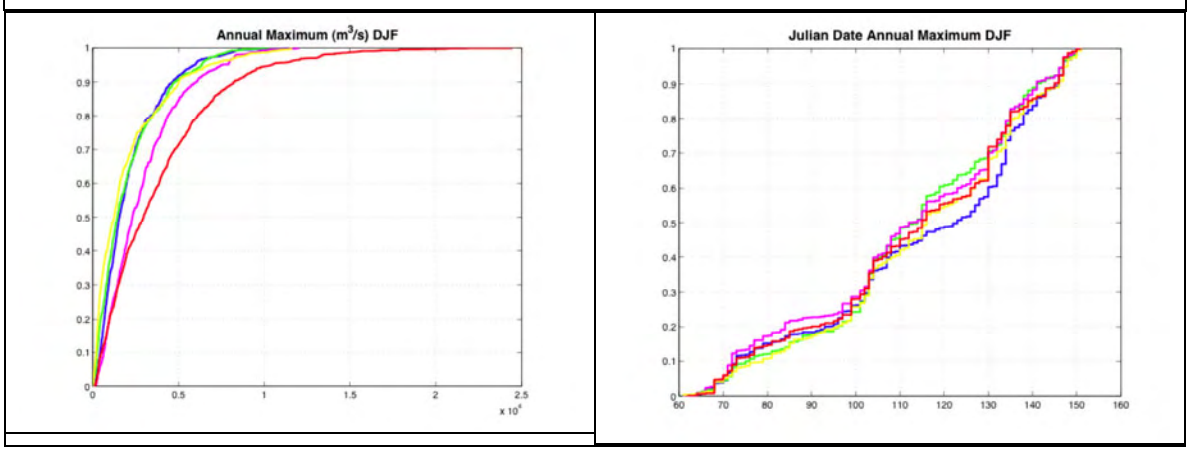
A diagnostic evaluation was performed to explore the sensitivity of flood frequency assessment to different types of climate change and attempt to attribute frequency changes to physical conditions associated with each climate change type. For the diagnostic evaluation the climate projections were regrouped to represent three distinct climate regimes in order to evaluate the changes in flood response relative to climate state. The four climate states are represented by Hot-Wet, Hot-Dry, Cool-Wet, and Cool-Dry as shown in Figure 7. The color scheme for the remainder of the figures are relative to the four climate states as opposed to look ahead periods. This is done in order to be able to ask the questions of how does the basin respond, in terms of climate state without relying on how well the GCMs represent the future periods.

Figure 7: Climate Projections regrouped to evaluate diagnostic response relative to climate state.



Although annual maximum floods can occur during any month of the year, the presentation of information within this manuscript focuses on the winter season of December, January, and February (DJF). This selection of season is somewhat consistent with the season of historic maximum values and represents the larger of simulated floods both for the historic and future periods when the year is broken up into four seasons. The diagnostic evaluation of the climate states show that for the Hot-Wet climate state the floods are largest in magnitude for almost all NEPs, the Cool-Wet climate suggests some increase in flood potential and the Cool-Wet and Cool-Dry climate states showing only marginal differences from the historical period (Figure 8). The timing with respect to the DJF period shows only marginal differences amongst the four climate states and the historic period although for NEPs between approximately 0.4 and 0.6 there is a small shift towards earlier in the season. This timing shift would be of more importance for water supply and flood control evaluations during the seasons of MAM, which, although not shown here, show a more dramatic shift towards earlier timing of floods.

Figure 8. Diagnostic evaluation of the magnitude and timing of annual maximum floods for the four climate states (Hot-Wet [red], Hot-Dry [yellow], Cool-Wet [purple], Cool-Dry [green], and the historic period [blue]).



For each of the annual maximum floods evaluated by climate state (total of 10 simulations by 6 or 7 climate models, by 30 years) segregated by season (DJF) hydrologic variables were selected corresponding to the two days prior to the annual maximum values. The hydrologic variables selected were the rainfall input, the rain and snowmelt contribution to the flood, the snow cover, and the snow water equivalent in the

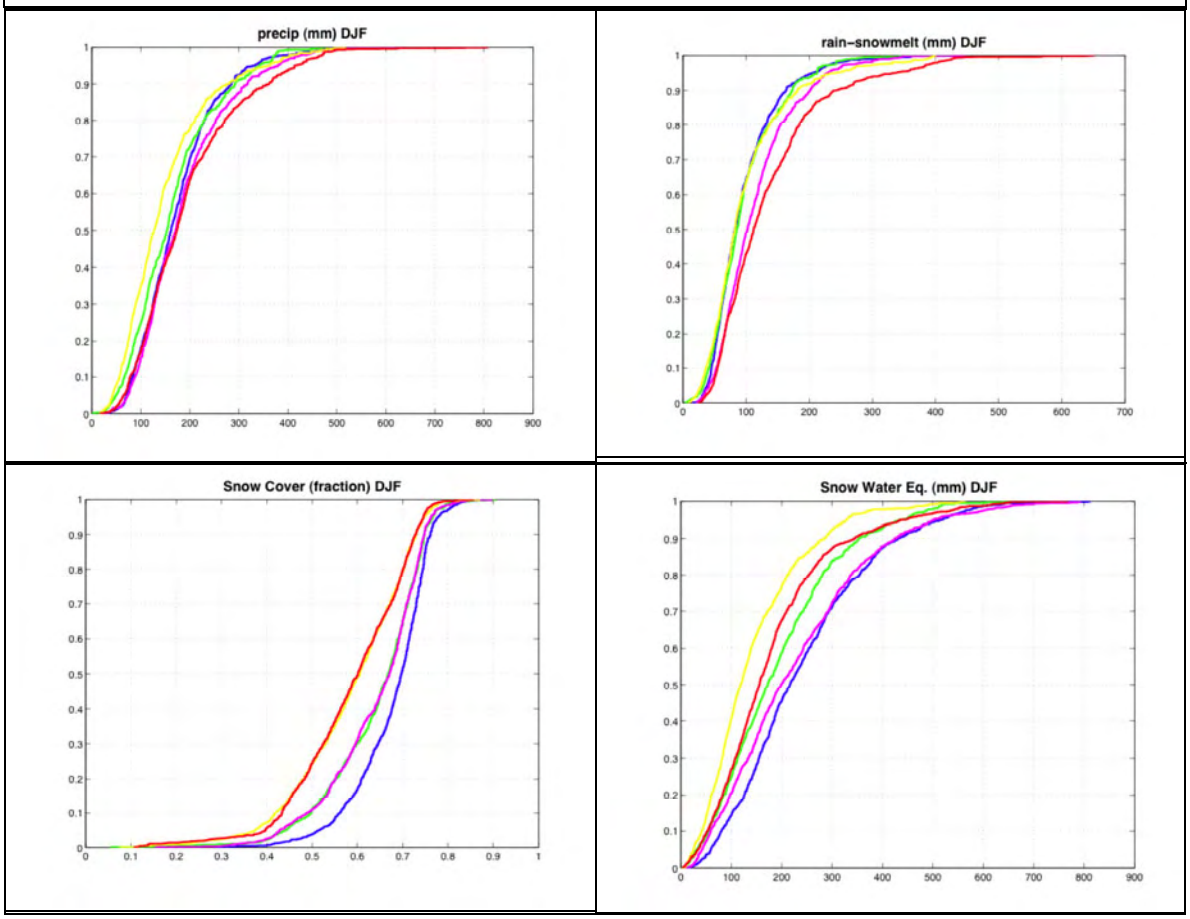
basin. The precipitation amounts are a basin average value expressed as millimeters of rainfall. The rain-snowmelt is a total amount also expressed as millimeters. The snow cover is a fraction of the total basin area, and the snow water equivalent is a basin average amount expressed in millimeters.

Exploring Figure 9:

- Precipitation patterns show that for NEPs less than approximately 0.7 all precipitation events corresponding to the annual maximum floods are consistent across the climate regimes. For NEPs greater than 0.7. The two wetter climate regimes show greater amounts of precipitation inputs to the annual maxima. The two drier climate regimes show virtually no change from the historical period.
- Rain on Snowmelt patterns track virtually the annual maximum cumulative distribution functions displayed in Figure 8. This, of course, makes intuitive sense given that it is the majority (non-base flow) portion of these annual maxima that is comprised of the rain-snowmelt. The two drier climate states show only marginal changes from the historic period. The two wetter climates show increased in flood potential with the majority of difference occurring at NEPs greater than 0.3 – 0.4.
- Snow Cover Fractions show a marketable difference from the historic period for all cases. The two hotter climate states have a significantly reduced fraction of the watershed covered by snow at the start of the annual maximum floods. The two cooler climates also show significant reductions in area covered by snow although not as much of a reduction as the hotter climates.
- The snow water equivalent shows that there is a very small decrease in snow water equivalent between the historical and the Cool-Wet climate state. The cool-dry climate state shows a marketable decrease in SWE, which is relatively similar to the Hot-Wet climate state. The Hot-Dry climate state shows the most significant reduction in SWE.

The meaning of the differences in hydrologic variables and flood response is just beginning to be explored. A couple of general comments can be made from these analyses however. First, for the two drier climate states that shows no major changes in overall cumulative distributions of annual maxima. Both climates show a reduced area of snow pack, it is therefore reasonable to assume that the snow line is moving up in elevation in these basins and despite even a reduction in precipitation totals the rainfall is falling on more bare ground which will result in a different basin response to these events in time and magnitude. For the two wetter climates there appears to be more rain falling on, again, a smaller snowpack leading to increased runoff from the exposed ground.

Figure 9: Diagnostic evaluation of hydrologic variables corresponding to the annual maximum floods (precip, rain + snowmelt, snow cover, and snow water equivalent). Four climate states are represented by Hot-Wet [red], Hot-Dry [yellow], Cool-Wet [purple], Cool-Dry [green], and the historic period [blue].



Conclusions:

A set of methods have been developed and presented that allow for the estimation of flood potential given a set of climate projections. These methods are intended to provide an envelope of expected variability of the climate through an equally weighted tercile selection of candidate projections of temperature and precipitation. Through the use of a weather generation scheme and a rainfall runoff tool simulated annual maximum discharges are derived for look ahead periods of 2011 -2040, 2041 - 2070, and 2071 - 2099. These annual maximum discharges are then put into the context of flood frequency analysis. Results indicate that for the four basins analyzed in this study the climate projections result in an increased simulated annual maximum flood potential through time. An expanding retrospective approach to characterizing flood hazard may increasingly underestimate the flood potential as time progresses. Decisions based upon the expanding retrospective approach to characterizing flood frequency could be based upon underestimates of future flood potential. Additional work is required to understand the differences in basin response with the climate forcings, but current results indicate that more consideration should be given to non-stationarity assumptions when estimating flood risk.

The reliability of the methods employed is then explored through an analysis of the physical processes by which different climate states may alter flood behavior. The same projections utilized for the look ahead

period analysis were re-oriented into four climate states (Hot-Wet, Hot-Dry, Cool-Wet, and Cool-Dry). The analysis of these four climate states shows significant differences in hydrologic responses in generation of the annual maxima. This information could provide useful as we gather more information about which climate state we expect for this and other geographic regions.

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