RECLAMATION

Managing Water in the West

Long-Term Planning Hydrology based on Various Blends of Instrumental Records, Paleoclimate, and Projected Climate Information

U.S. Department of the Interior
Bureau of Reclamation

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Mission Statements

The mission of the Department of the Interior is to protect and provide access to our Nation's natural and cultural heritage and honor our trust responsibilities to Indian Tribes and our commitments to island communities.

The mission of the Bureau of Reclamation is to manage, develop, and protect water and related resources in an environmentally and economically sound manner in the interest of the American public.

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Executive Summary

This study tests alternative methods for developing planning hydrology that differ in terms of climate context, some of which may be useful for planning in the context of climate non-stationarity. The study relates planning hydrology to four different blends of climate information—a “null” or default alternative and three alternative methods of developing longer-term planning assumptions on water supply possibilities, termed “planning hydrology.” These information sets involve different blends of observations on precipitation and temperature (i.e., instrumental records), proxy data on paleoclimate prior to instrumental records (e.g., annual tree-ring chronologies), and information on projected climate during the 21st century. Any of these blends of climate information may provide an appropriate picture of water supply possibilities, depending on the planning issues being addressed.

This summary is for managers who may be interested in understanding the climate information options, key method differences in relating these options to water supply planning assumptions, and implications for portrayed water supply variability. The summary provides an overview of the research problem and question, alternative methods examined, results, and potential strategies for using these alternative methods.

Problem and Background

Reclamation’s longer-term planning studies generally involve evaluating the benefits and costs of implementing various proposed action-alternatives, relative to each other and to a future without any of the proposed actions. These planning studies range from specific local actions to broader, longer-range programs (e.g., system development, basin planning). The fundamental question to be answered in all of these studies is “is it worth it?” (i.e., do the benefits exceed the costs?). The answer to this question depends on look-ahead assumptions for water supply variability, water demands, and operating constraints. A climate information context is implicit in these planning assumptions. This study focuses on water supply planning assumptions and various climate information contexts that might underlie these assumptions.

Reclamation’s traditional methods for defining planning assumptions about plausible water supply variability have been based on the instrumental record, (i.e., weather station observations, stream gage data, information on historical flow impairments affecting stream gage data). Relying on the instrumental record implies that the historical water supply variability is a reasonable proxy for the variability that might be experienced during the planning look-ahead horizon—that “past results reflect future conditions.”

However, the instrumental record has a limited range of data and does not reflect the potential for events that may have occurred before historical observations. Moreover, assuming a future similar to the relatively short instrumental past is losing credibility for long-term planning. Longer-term planning evaluations of proposed actions might be conducted more robustly if water supply assumptions are based on more than observed climate information. For example, an expanded sense of possible climate variability (e.g., periods of drought or surplus) might be provided by blending paleoclimate proxy and observed climate information. Longer-term evaluations with look-ahead horizons that encompass many decades are relevant on a climate change time scale (i.e. multiple decades according to IPCC 2007). For these evaluations, incorporating climate projection information into the analysis might result in a more appropriate portrayal of future runoff conditions and water supply statistics (mean monthly, mean annual). The latter is motivated by evidence that regional climate in the western U.S. has been changing (CCSP 2008) and is expected to continue to change during the 21st century (IPCC 2007), and historically observed information does not shed light on these changes.

For longer-term evaluations meant to reflect future runoff conditions, choices are made on what to portray for runoff statistics (e.g., average, limits of variation) and frequency characteristics (i.e. drought and surplus possibilities). Climate projection information features information on both aspects of future runoff. However, while it is generally accepted that climate models are reasonably capable of projecting changes in future climate and runoff statistics, their ability to project changes in frequency aspects is questionable (Lau et al. 1996, Wood et al. 2004). Comparatively, frequency information from instrumental and/or paleoclimate information is rooted in physical evidence, which may be a more attractive basis for planning than the modeled frequencies in climate projections. This gives rise to interest in establishing future water supply assumptions that reflect the relative strengths of climate projection information (i.e. projected changes in hydroclimate statistics) and paleoclimate information (i.e. a long-retrospective period of evidence for drought and surplus possibilities).

At present, Reclamation has not established planning approaches that feature both a broadened sense of possible climate variability (paleoclimate information) and an expected future change in runoff statistics (climate projections). Reclamation has methods for individually accounting for these factors, but does not have a method for accounting for them jointly. This study, provides Reclamation with a methodology for incorporating the possibly more credible aspects of both paleoclimate information (i.e. frequency information on year-to-year variability) and projected climate information (i.e. change in runoff statistics).

Research Questions and Overview of Analysis

This research explores the following research questions:

1. How can paleoclimate and projected climate information be jointly and rationally represented in water supply planning assumptions (i.e., a planning hydrology)?

2. How would such a planning hydrology be similar to or different from a planning hydrology that represents paleoclimate or projected climate individually?

3. What implementation realities might influence choosing among climate information sets when defining water supply planning assumptions for Reclamation studies?

To address these questions, this study involved developing and comparing planning hydrology with respect to the following blends of climate information:

- Null Alternative– Instrumental Record only

- Alternative 1 – Instrumental Record, Paleoclimate Proxy

- Alternative 2 – Instrumental Record, Projected Climate

- Alternative 3 – Instrumental Record, Paleoclimate Proxy, Projected Climate.

For each alternative, planning hydrology was developed for two basins: the Missouri River above Toston (i.e., “Upper Missouri”) and the Gunnison River above its confluence with the Colorado River near Grand Junction (i.e., “Gunnison”). Reclamation operates several reservoirs in both basins.

Alternative 1 might be particularly appropriate for planning horizons up to 20 years (which are significant on drought time scales, but short relative to climate change time scale). Alternative 1 represents an expanded sense of possible climate variability (e.g., periods of drought or surplus) by blending paleoclimate proxy and observed climate information. Paleoclimate proxies offer a richer, longer-term history on potential hydrologic variability concerning how long spells of deficits and surpluses could last and how intense they could be. A key feature of Alternative 1 is a statistical modeling framework, where hydrologic sequences are generated in two stages. The first stage defines the hydrologic year-type, or “state”, and is derived from paleoclimate information. The second stage defines the runoff volume for the given year, or “magnitude”, and is derived from instrumental record information. This framework has been used to support a previous Reclamation planning effort (Reclamation (2007)).

Alternatives 2 or 3 may be more appropriate for planning horizons beyond 20 years, which are relevant on a climate change time scale (IPPC 2007). Alternative 2 represents expected future climate change and its expected effect on both statistical and frequency aspects of runoff and water supply. Alternative 2 planning hydrology is developed by using hydrologic simulation modeling that translates climate projections into runoff projections.

Alternative 3 still recognizes the desire to reflect expected climate change effects on runoff statistics, but it also reflects a desire to root the frequency aspects of drought and surplus in hard physical evidence (i.e., paleoclimate information) rather than climate modeling. This blend of paleoclimate and projected climate information in Alternative 3 was achieved by adopting the statistical modeling framework of Alternative 1 (i.e. first modeling state, then modeling magnitude). The framework application differs from that of Alternative 1 at the second stage. Rather than using the instrumental records as the basis for magnitudes (as in Alternative 1), the runoff projections of Alternative 2 are used as the “magnitudes source” (and from a specific projection period). In other words, to do the modeling for Alternative 3, Alternative 2 must be performed beforehand. Doing so permits establishing water supply assumptions that account for the change in runoff statistics associated with climate projections, but are not forced to exhibit the questionable frequency characteristics associated with climate projections (i.e. accepting the projections portrayal of drought and surplus spells). Rather, frequency characteristics from paleoclimate information are reflected in the water supply assumptions through the first stage modeling of state.

After developing each planning hydrology alternative, the resulting data were evaluated for changes in period-statistics (mean, variance, skewness, auto-correlation, others) and change in frequency characteristics (occurrence and accumulated volumes associated with drought and surplus spells). They were also qualitatively evaluated on issues associated with:

1. Disaggregating each planning hydrology to interior sub-basin locations and to a monthly time step

2. Establishing consistency between water supplies and other planning assumptions

3. Attaining stakeholder acceptance.

Issue (1) is relevant, recognizing that the hydrology data in this study were developed on an annual time step and for the basin-aggregate. While such aggregation is sufficient for addressing the research questions, the data disaggregation would be necessary to transfer these method alternatives into practice.

Results

Technical Development Issues

The research first asked: **”How can we jointly and rationally incorporate paleoclimate and projected climate information into a planning hydrology that represents assumptions about possible water supplies?”** This study demonstrated a modified application of a two-stage stochastic modeling approach previously used to blend paleoclimate information and instrumental records information (Alternative 1 in this study, Reclamation (2007) previously). In this modified application, the instrumental record information on runoff magnitudes possibility is replaced by projected climate and associated runoff information from a given projection period (Alternative 2 data). This leads to a planning hydrology (Alternative 3) that incorporates the relatively more credible state information from paleoclimate data (Gangopadhyay et al. 2009) rather than climate projections’ state information, and the relatively more credible magnitudes information from the climate and runoff projections during a future period of interest.

Research then asked: **“How would such a planning hydrology be similar to or different from planning hydrology developed to individually reflect paleoclimate or projected climate?”** Results illustrate that Alternative 3’s planning hydrology (a blend of instrumental record, paleoclimate, and projected climate information) can reflect change in runoff statistics (e.g., changes in monthly and annual mean and variance) while Alternative 1’s planning hydrology (from paleoclimate and instrument records) cannot. Further, Alternative 3 can incorporate historical information on frequency and avoid requiring trust in the frequency characteristics from climate models while Alternative 2 (projected climate, instrument records) cannot. However, if the paleoclimate basis used to provide frequency characteristics does not feature frequency aspects that substantially differ from those of climate projections (Alternative 2), there would be little to no benefit of relating water supply assumptions to a blend of paleoclimate and projected climate information (Alternative 3). *This is because development of the Alternative 2 data is a prerequisite for developing Alternative 3 data.* In other words, Alternative 3 may be an option worth considering, but only if the drought and surplus information in paleoclimate appears to be different than climate projections.

Case in point, the Gunnison basin results on drought frequency characteristics were similar in Alternatives 2 and 3 (although they differed in surplus frequency characteristics). The drought and surplus information of the paleoclimate overlapped with that of the climate projections and thus did not appear to provide additive information value for portraying drought in a planning hydrology. Thus, for the Gunnison, it might have been appropriate to proceed with only Alternative 2, assuming a planning emphasis on drought portrayal and a need to account for expected climate change effects on future runoff statistics. Proceeding with the further modeling required under Alternative 3 may not have been warranted because the results would not have shed any further light on possible hydrologic conditions.

In contrast to the Gunnison basin results, the Upper Missouri basin results for Alternative 2 and 3 showed different frequency characteristics for both droughts and surpluses. For the Upper Missouri basin, a choice point would be reached on whether to proceed with Alternative 2 data (accepting frequency portrayal in the climate projections) or Alternative 3 (replacing the climate projections frequency aspects with that of paleoclimate information). Alternative 3 thus would provide evidence of droughts and surpluses that were modeled in hard physical evidence such as tree-rings rather relying on the assumptions involved in developing climate projections. The choice for investing extra for Alternative 3 would depend on stakeholder preferences as outlined in the practical applications issues section below.

Practical Application Issues

Three issues were explored as they influenced the third research question: **"What implementation realities might influence choice among climate information sets when defining water supply planning assumptions for Reclamation studies?"**

1. **Detail of hydrology data.** Hydrology data developed in this study had an annual time step and reflected basin-aggregate runoff. These time and space resolutions are adequate for addressing the research questions posed, but are not appropriate for characterizing practical planning hydrology that can be used for Reclamation's planning purposes. Planning would require more detailed data, at least to a monthly time step and flows specified at various interior sub-basins locations (e.g., inflows at multiple reservoirs located on upstream tributaries relative to the basin-aggregate runoff location below these reservoirs). While methods to use more detailed

information are available for each alternative (Section 6), the amount of additional work required to perform such analyses may be a consideration for deciding which alternative approach to use to develop a planning hydrology.

2. **Consistency with other planning assumptions**. Questions will be encountered on how to reconcile the basis for assumptions for the planning hydrology with those regarding water demands and other operating constraints related to climate (e.g., flood control rules, environmental management). Methods for linking assumptions about water demands and operating constraints to these alternative climate contexts are not as evolved as those for linking supply assumptions to these contexts. Thus, studies would need to carefully explain the methodologies and assumptions to a lay audience.

3. **Stakeholder acceptance.** Stakeholder acceptance and/or understanding of a given climate information context and how it is translated into a planning hydrology may influence which alternative approach is preferred for a given planning process. Stakeholders and decision-makers are presumably familiar with the basis for water supply assumptions associated with the Null Alternative hydrology, where instrumental record information provides the climate context for both runoff statistics and frequencies. The practical ability to incorporate other sources of climate information (paleoclimate and climate projections) may be limited by the understanding and trust that prospective stakeholders and decision-makers have in the process of doing so. Some groups may be well informed on the nature of paleoclimate information and have experience with its application in water resources planning, including the use of stochastic modeling (e.g., Reclamation's Lower Colorado and Upper Colorado staff who participated in the development of Reclamation (2007)). Other groups may be well-oriented with projected climate information and have experience with its application in water resources planning (e.g., Reclamation's Mid-Pacific staff who participated in the development of Reclamation (2008)). Still other groups may be at more fundamental learning stages for both. In any case, introducing new climate contexts and application methods requires education and trust-building phases.

In summary, this research illustrates how instrumental records, paleoclimate and projected climate information might be incorporated into water supply planning assumptions, and how the statistical and frequency characteristics of these assumptions would vary relative to simpler climate context (e.g., instrumental records alone, or instrumental records blended individually with paleoclimate or projected climate). While it is technically possible to adopt any of these climate contexts for planning, the acceptability of any context choice may need to be vetted with stakeholders and decision-makers, and may vary depending on water resources planning decision being considered. For the time-being, even if the more evolved methods shown in the alternative approaches 1 – 3 are used to characterize supply assumptions (such as those featured in this study) and develop planning hydrology, it may be necessary to also use traditional methods for defining demand and operational constraint assumptions. The capacity of a planning process to support both traditional methods and these new information sources will determine how new methods are introduced in planning communities and at what pace.

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1.0 Introduction

1.1. Project Background

Reclamation has a great deal of experience conducting long-range planning studies involving proposed changes to its water and power systems, whether operational or infrastructural. Recently Reclamation's longer-range planning efforts have generally focused on evaluating modifications to existing systems. Sometimes the modifications involve proposed new criteria for how existing systems would be operated for a relatively long-term horizon (e.g., modified criteria that would apply for the next 20 years). Other times the modifications involve infrastructural changes, such as enlarged storage or conveyance facilities, that would be expected to provide decades of service life. In the future, Reclamation's longer-range planning efforts may broaden, focusing less often on modifying existing systems to more often focusing on system development or basin planning. In either case, the purpose of longer-term planning studies is to disclose the benefits and costs of implementing various project alternatives that might be proposed, relative to each other and relative to a "future without the project alternative." The fundamental question to be answered in such a study is "is it worth it" (i.e., do the benefits to the nation exceed the costs). The answer to this question depends on look-ahead assumptions for water supply variability, water demands, and operating constraints.

Water supply variability assumptions reflect the expected range and distribution of water supplies arriving during any time period (e.g., annually, monthly), and also the arrival sequence of these supplies (e.g., multiple year spells of relatively drier or wetter years). Traditionally, these assumptions have been based on historically observed information, or data from the instrumental record. Historical water supply information primarily comes from stream gauge data. Relying on such information implies that the historical water supply variability is a reasonable proxy for the variability that might be experienced during the planning look-ahead horizon. This implicitly assumes that the climate observed in the instrumental record is a reasonable proxy for the climate of the planning future.

Reclamation has recently questioned this assumption that historical observed climate and water supply variability are appropriate proxies for what would occur during the planning future. An alternative proposal is that planning might be conducted more robustly if water supply assumptions are based on more than observed climate information (i.e., by including paleoclimate information into the analysis). This proposal is made feasible by the recent advances in understanding how pre-instrumental climate variability can be inferred, and how recent paleoclimate studies suggest a broader envelope of western U.S. climate variability than what was observed during the 20th century (Woodhouse et al. 2006, Meko et al., 2007). Another alternative is to base water supply assumptions on projected climate information; motivated by evidence that regional climate in the western U.S. has been changing (CCSP 2008) and is expected to continue to change during the 21st century (IPCC 2007).

Reclamation has conducted planning studies where water supply assumptions are based on climate information of the instrumental record blended with either paleoclimate or projected climate information. One study used paleoclimate information to represent an expanded sense of possible hydrologic variability given stream gage data, complemented by annual streamflow reconstructions based on tree-ring chronologies (Reclamation 2007). That study also used stochastic modeling techniques to broaden the portrayal of water supply sequence possibilities that could be regarded as statistically consistent with sequences from the tree-rings and instrumental records (Prairie et al. 2008, Reclamation 2007). Another study used projected climate information, as water supply assumptions were cast as historical water supply variability adjusted to reflect how climate changes are projected to shift mean annual and mean monthly runoff conditions (Reclamation 2008). In contrast to Reclamation (2008), another method for relating climate projections to water supply assumptions involves developing water supply “projections” where runoff statistics evolve continuously through time, consistent with the evolving statistics of temperature and precipitation projections (e.g., Christensen and Lettenmaier 2007).

In summary, paleoclimate information offers a richer, longer-term history on potential hydrologic variability concerning how long spells of deficits and surpluses could last and how intense they could be. Projected climate information offers its own portrayal of future runoff frequencies, but there are questions in the ability of climate modeling to reliably simulate future frequencies (Lau et al. 1996, Wood et al. 2004). Thus, it is questioned whether it would be useful to relate planning assumptions for water supply possibilities to a blend of the possibly more credible aspects of paleoclimate information and projected climate information using:

- Frequency information from paleoclimate information on spell and intensity possibilities

- Statistical information from projected climate information on what runoff magnitudes could be in any given month or year.

1.2. Research Questions

While Reclamation has methods for individually relating paleoclimate or projected climate information to water supply assumptions, Reclamation does not have a method for jointly incorporating the possibly more credible aspects of both types of information. This research explores the need for blending these types of information, and in doing so poses several research questions:

(1) How can we jointly and rationally incorporate paleoclimate and projected climate information into a planning hydrology that represents assumptions about possible water supplies?

(2) How would such a blended planning hydrology be similar to or different from planning hydrology that represents paleoclimate or projected climate individually?

(3) What implementation realities might influence choosing among climate information sets when defining water supply planning assumptions for Reclamation studies?

The relevance of addressing questions (2) and (3) is that while it may be possible to develop a method to address question (1), it has not been demonstrated that the resultant planning hydrology would substantially differ from planning hydrology based on projected climate alone. To that end, to ultimately inform scoping questions about developing this blended planning hydrology, this research aims to develop an optional data-development method, demonstrate the method's application, and summarizes factors that might influence decisions on when to implement this blended planning hydrology developed from these alternative methods versus other available methods.

1.3. Report Purpose and Audience

The report is targeted to a technical audience that might be asked to implement some of the methods herein, or oversee their implementation by external parties. The report:

- Provides orientation on the types of data (Section 2), tools (Section 3) and methods (Section 4) used in each data-development alternative.

- Informs readers on how runoff characteristics may be expected to differ given the chosen climate information set underlying the planning hydrology (Section 5).

1.4. Audience Preliminaries

This report is developed for an audience that spans technical practitioners to managers. Sections 2.0 through 6.0 are aimed at a technical audience that is expected to have a basic familiarity with several concepts, which are outlined below. Managers may wish to focus on the summary of key findings in Section 7.0; discussion in Sections 5.3 and 6.0 may also be of value in helping to determine the significance of these findings.

In terms of data analysis, readers should be familiar with computation of descriptive statistics and estimation of probability distributions. Haan (1977) and Wilks (1995) provide useful primers on statistical methods and probability concepts in hydrology and atmospheric sciences, respectively. Readers should also be familiar with stochastic simulation concepts in hydrology, where hydrologic sequences are designed to vary randomly, but also in a way (by model design) such that resultant series exhibit the statistical and auto-correlation properties of a chosen "reference climate." Lall and Sharma (1996) provide a review of nonparametric stochastic modeling approaches, while Stedinger and Taylor (1982a, 1982b) offer a review of parametric approaches.

The audience should be familiar with physical concepts such as the process-based hydrologic models that are designed to simulate surface water balance distributed within a watershed and subsequent routing of runoff from basin sub-areas to downstream runoff locations. In each sub-area, the water balance calculation recognizes precipitation input, runoff output, evapotranspirative losses, and other intervening processes that affect water storage in the soil column or in snowpack (if present). DeVries and Hromadka (1993) provide an overview of process-based hydrologic simulation concepts.

Lastly, readers are expected to be familiar with basic climate system concepts. Some example concepts include the earth energy balance, the role of atmospheric greenhouse gases to regulate atmospheric temperatures and climate, the service that atmospheric and ocean circulation patterns provide to redistribute incoming solar energy from equatorial regions to polar regions (e.g., the tropical "Hadley Cell" atmospheric circulation pattern, the Gulf Stream ocean current), and how the poleward roll of the Hadley Cell (Hartmann 1994) affects the latitude position of middle-latitude storm tracks determining seasonal/regional climates in the western U.S..

1.5. Climate Information Alternatives and Approach Overview

As noted, planning hydrology assumptions might be developed relative to several types of climate information:

1. Instrumental records (e.g., weather station observations, stream gage data)

2. Paleoclimate proxies (e.g., tree-ring chronologies suggesting a sequence of annual hydroclimate conditions)

3. Projected climate information (i.e., historical to future temperature and precipitation simulated by global climate models given estimated historical climate forcings and scenario-future climate forcings).

This study defined four possible methods[1] to develop a planning hydrology: a Null Alternative method for developing a planning hydrology, which uses historical instrumental records only, plus three alternatives associated with different sets of climate information.

- Null Alternative – Instrumental Record only
- Alternative 1 – Instrumental Record, Paleoclimate Proxy
- Alternative 2 – Instrumental Record, Projected Climate
- Alternative 3 – Instrumental Record, Paleoclimate Proxy, Projected Climate. Note that Alternative 3 is a further analytic step from Alternative 2: Alternative 2 must be performed first in order to perform Alternative 3.

For each alternative, including the Null Alternative, planning hydrology data are surveyed at a single-aggregate runoff location for case study basins (Section 1.3.5) and on an annual time step. This report discusses addressing issues of disaggregating these data to interior sub-basin locations and to shorter time-steps. The choice of not disaggregating the hydrology for each alternative is appropriate given the research questions, which are primarily focused on how to develop Alternative 3, and how Alternative 3 hydrology compares to Alternative 2 and others. This is because the paleoclimate information used in this study is from tree-rings, which specify only annual climate variability. Also, the climate signals featured in each case study basin's tree-ring data are representative of regional, or basin-aggregate, climate variability (Woodhouse et al. 2006) rather than only local-area climate that proximate to the location of the tree-ring chronology. The following sections briefly introduce the Null Alternative and alternative planning hydrology.

1.5.1 Null Alternative– Instrumental Record only

This alternative considers only hydroclimate observations from the instrumental record period. Planning hydrology assumptions under this alternative were developed prior to this study and are described further in Section 2. Citations are provided in Section 2.1. These hydrology data are estimates of historical natural runoff volume and are based on evaluations of stream gauge observations and information on historical land and water management practices that impaired natural runoff patterns (e.g., historical stream diversions, return flows, or reservoir regulation effects). Note that the Null Alternative features the assumption that the "past is a reasonable proxy for the future." So while climate projection information may be available to suggest that hydroclimate conditions may

[1] Publications about this research have a color scheme to delineate alternatives: the Null Alternative is blue, Reconstructed is red , Alternative 1 is green, Alternative 2 is orange, and Alternative 3 is purple.

change, such information does not get factored into the Null Alternative's hydrology data.

1.5.2 Alternative 1 – Instrumental Record, Paleoclimate Proxy

For this study, paleoclimate information is provided by annual tree-ring chronologies, which suggest that the western U.S. experienced a broader envelope of climate variability than what was observed during the 20th century (Woodhouse et al. 2006, Meko et al., 2007). There have been recent advances in understanding how paleoclimate proxy data can be used to reconstruct runoff conditions prior to the period of instrumental record. Such runoff reconstructions can then be related to planning assumptions for water supplies using statistical techniques, as Reclamation has demonstrated (Reclamation 2007). The statistical technique demonstrated in Reclamation (2007) served Alternative 1 hydrology development in this study, and features the flexibility of choosing one source of climate information (e.g., tree-ring data) to define year-type variability (i.e. state), and another information source (e.g., instrumental record) to define any year's runoff volume possibility (i.e. magnitude).

In this alternative, climate information from both the instrumental record and paleoclimate proxy are represented in the planning hydrology. Data-development is described in Section 4.1 and involves building a stochastic runoff model that:

1. Reflects natural runoff magnitude (i.e., volume) possibilities from the instrumental records (i.e., the Null Alternative).

2. Runoff state and sequence possibilities consistent with the paleoclimate record, where climate state is a descriptor of a year's relative condition (e.g., "wet" versus "dry"). The stochastic model development is discussed further in Section 3.1.

Once built, the stochastic model is applied to generate a collection of annual runoff sequences or series, termed an "ensemble of runoff series." Within each series, the envelope of runoff variability is constrained to remain within the range of historically observed runoff. However, each series is permitted to feature a unique sequence of year-to-year climate states, consistent with frequency information from the paleoclimate record and possibly different than that of the instrumental record. Such information may be relevant if the planning study is concerned with portraying drought or surplus spell possibilities, and if such possibilities from the paleoclimate record would appear to pose greater challenge for water management than those from the instrumental record.

1.5.3 Alternative 2 – Instrumental Record, Projected Climate

In this alternative, both instrumental records and projected climate information are represented in the planning hydrology. For example, climate projection data featuring future warmer conditions would be input to hydrologic simulation analyses designed to reveal impacts to monthly runoff patterns (e.g., less winter snowfall, more winter rainfall, or less spring snowmelt). Precipitation trends in the climate projections would also be featured in the analysis, further affecting monthly runoff patterns.

This projected climate information originates from global climate simulations, forced by either estimated historical atmospheric conditions, or by scenario future (i.e. projected) atmospheric conditions. Such global climate simulation outputs are translated eventually into projected basin weather conditions, which are used to simulate projected runoff conditions using process-based hydrologic modeling. Such modeling reveals how changes in climate conditions through the projections translate into changes in runoff statistics with time. Water supply assumptions associated with a future milestone year might be developed by adjusting historical water supply variations to reflect such changes in runoff statistics consistent with the projected climate of the look-ahead horizon (Reclamation 2008). Or the time-varying runoff projections themselves might be directly input to the planning evaluation as time-varying water supply projections (e.g., Christensen and Lettenmaier 2007). The technique demonstrated in Christensen and Lettenmaier (2007) was reproduced here in Alternative 2 hydrology development.

Data development for this alternative involves calibrating a hydrologic simulation model to reproduce historical runoff when fed historical weather observations (Section 3.2). Such a model would then be applied to translate monthly temperature and precipitation information from a given climate projection into a corresponding runoff projection. Depending on the time period sampled in the climate projection, the period of runoff might span historical to future climate. For an historical period of the projection, the temperature and precipitation conditions are outputs from climate models simulating the past, that have been bias-corrected to be statistically consistent with past observations (Section 2.4). However, they have not been adjusted to be consistent in terms of frequency aspects like timing and duration of droughts or surplus periods.

Instrumental records on streamflow are used to calibrate the hydrologic simulation model. Instrumental records on weather observations factor into Alternative 2 data development in several ways. The first way occurs during hydrologic model calibration, where the model is parameterized to reproduce observed runoff when forced by observed weather during an historical period. The second way occurs during climate projection bias-correction (Section 2.4), where climate projection outputs are adjusted so that they statistically match the period-statistics of weather observations during a chosen historical period. The third way occurs during spatial downscaling of these bias-corrected climate projections (Section 2.4), where weather observations provide a representative spatial pattern of temperature and precipitation variability that is incorporated in the procedure that involves translating the coarser resolution outputs of global climate models to a finer spatial resolution required for hydrologic analysis. The fourth way involves using instrumental weather observations to guide the temporal disaggregation of monthly climate projections (that have been bias-corrected and spatially downscaled) into the sub-monthly weather series required as inputs to hydrologic simulation (as described in Section 4.2). The output of the simulation model is sub-monthly and can be aggregated to monthly or annual, as desired.

Alternative 2 involves considering an ensemble of climate projections from the climate model's simulated-historical to simulated-future conditions. For each climate projection in the ensemble, a separate hydrologic simulation is set up and conducted. Each simulation's results are surveyed for basin-aggregate runoff and are temporally aggregated into annual time step runoff.

For each series in the ensemble, the climate—and thus runoff sequences—are statistically non-stationary through time. In other words, climate statistics change through the projection, and that translates into changing runoff statistics through each climate projection in the ensemble. The series of a climate projection is time-developing and with evolving sub-period statistics through time (i.e. statistically non-stationary). In contrast, the runoff series in Alternatives 1 and 3 reflect a statistically stationary climate for the simulation periods considered (albeit, with climate statistics representing either that of the past as in Alternative 1, or of some future period as in Alternative 3). This means that the envelope of runoff variability of Alternative 2 hydrology will differ from that of the instrumental record. Just as climate statistics are non-stationary in Alternative 2, so are runoff statistics. The frequency characteristics of these sequences may also differ (e.g., varying by year or by decade) inasmuch that the climate projection's characteristics differ from instrumental records.

1.5.4 Alternative 3 – Instrumental Record, Paleoclimate Proxy, Projected Climate

This alternative involves blending climate information from instrumental records, paleoclimate proxy, and climate projections. Data development (Section 4.3) involves building a stochastic model similar to that featured in Alternative 1, and also completing all of the data-development under Alternative 2. Alternative 3 then involves applying the stochastic model to simulate annual state, just like Alternative 1. However, Alternative 3 differs from Alternative 1 in that it involves applying the stochastic model to simulate annual magnitudes with magnitude information coming from runoff projections developed under Alternative 2. Magnitude information is sampled during a desired projection period. For example, a pool of candidate annual runoff "magnitudes" is obtained from a period-window of projected runoff magnitudes (e.g., given 10 climate projections and a 2010-2039 period, the pool would contain 300 annual runoff magnitude possibilities). The choice of the future period-window is subjective in this demonstration, but in practice the future time period would be chosen to reflect a future period relevant to the given planning horizon (e.g., a planning evaluation concerned about operational performance during 2030 might select a period of 2026-2045).

As with Alternative 1, the stochastic model is applied to generate an ensemble of runoff series. Further, to foster comparison between Alternative 2 and 3 runoff statistics, periods are chosen for characteristics projected runoff characteristics in Alternative 2, and then used again as the sampling periods used in Alternative 3 data-development.

1.5.5 Case Study Basins

Two case study basins are targeted in this analysis (**Error! Reference source not found.**): the Missouri River above Toston (i.e., “Upper Missouri”) and the Gunnison River above its confluence with the Colorado River near Grand Junction (i.e., “Gunnison”). Reclamation operates several reservoirs in both basins (i.e., Clark Canyon Reservoir within the Upper Missouri; and Ridgeway, Silver Jack, Taylor Park, Paonia and the Aspinal Unit Reservoirs [Blue Mesa, Morrow Point, and Crystal) within the Gunnison]). Several factors drove basin selection: (1) they have climatic differences (e.g., .latitude position and proximity to middle-latitude storm track), (2) tree-ring chronologies were available in or near these basins, and (3) they exist in two of Reclamation’s five corporate regions, which invited study participation from these regions and allowed the study to involve a broader mix of Reclamation’s technical staff.

As noted, the focus in this evaluation is to develop a planning hydrology for each of these reservoirs tributary basins on an annual time step. In real planning studies for these basins, the hydrology would have to be disaggregated spatially to interior sub-basins and in time (e.g., monthly). Such disaggregation involves more expensive data development and does not offer additional insight on the research questions being posed here. Nevertheless, approaches for doing spatial and temporal disaggregation of Alternatives 1 through 3 are discussed in Section 6.1; Null Alternative planning hydrology was already developed in at a desired level of disaggregation and has been aggregated for considerations here.

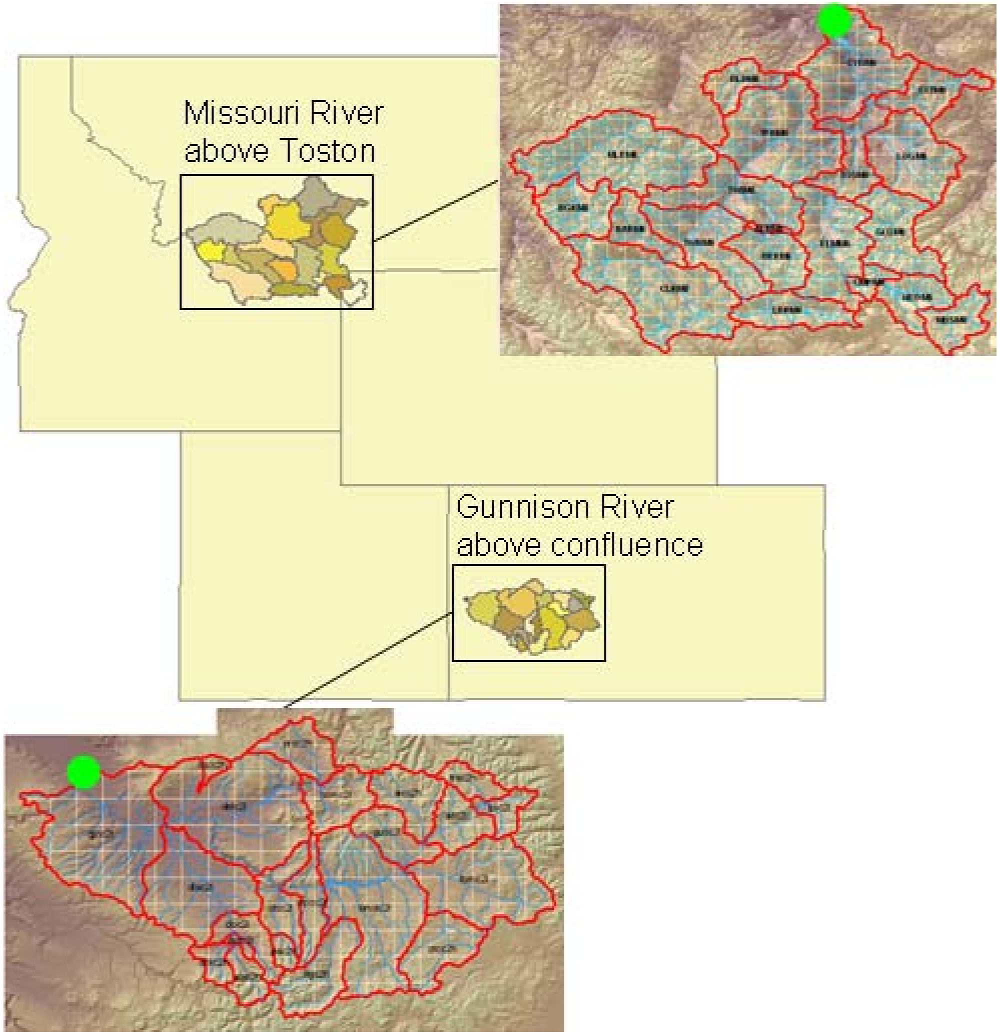

Figure 1 - Location of Case Study Basins.

Map shows locations of the case study basins. Inset boxes show basin outflow locations (green circles), basin topography (shaded relief), river channels (blue lines), sub-basin boundaries featured in the hydrologic simulation model (Section 3.2, red lines), and 1/8° spatial grid boundaries delineating downscaled climate projection information (Section 2.4, light yellow lines).

1.5.6 Evaluation of Results

As stated, differences in planning hydrology developed from these alternative methods will compared based on annual, basin-aggregate runoff properties. These differences will be characterized in several ways:

- Annual runoff statistics (i.e., long-term mean, standard deviation, skewness, backward lag 1-year auto-correlation, minimum, and maximum)

- Frequency characteristics describing surplus and deficit possibilities, with the latter being relevant to drought portrayal in planning.

- Qualitative issues associated with (1) disaggregating each planning hydrology to interior sub-basin locations and to a monthly time step, and (2) establishing consistency between water supplies and other planning assumptions, and (3) attaining stakeholder acceptance.

The stationarity of statistical characteristics varies between Null Alternative, Alternative 1, and Alternative 2. Based on reviews of the climate projection information considered, it is understood that statistics will not be stationary through the Alternative 2 sequences. By comparison, the Null Alternative features a single runoff sequence that may or may not be statistically stationary through the sequence. Nevertheless, the sequence, its distribution of magnitudes, and the magnitudes' frequency characteristics are collectively regarded to contain sufficient variability for planning purposes. Presence of stationarity in Alternative 1 is a bit more complex. The source of magnitudes' information is constant during stochastic sequence development, so the magnitudes' statistics might be thought of as stationary. However, as will be discussed in Section 3.1, the stochastic sequencing of annual state (i.e., wet or dry years), is designed to reflect the non-stationarity evident during the period of paleoclimate record.

2.0 Data

This section describes preliminary datasets that were used in this study's data-development efforts. The various preliminary datasets are indicated on Figure 2, four of which are described in more detail in Section 2.1 through 2.4:

(1) Estimated monthly volumes of natural runoff

(2) Observed daily streamflow and 6-hourly weather

(3) Reconstructed annual volumes of natural runoff based on tree-ring records

(4) Contemporary climate projection information

As Section 4 will explain, datasets (1) and (3) were used for developing Alternative 1 hydrology. Datasets (2) and (4) were used to develop Alternative 2 hydrology. Alternative 3 features a blended use of datasets (2), (3), and (4).

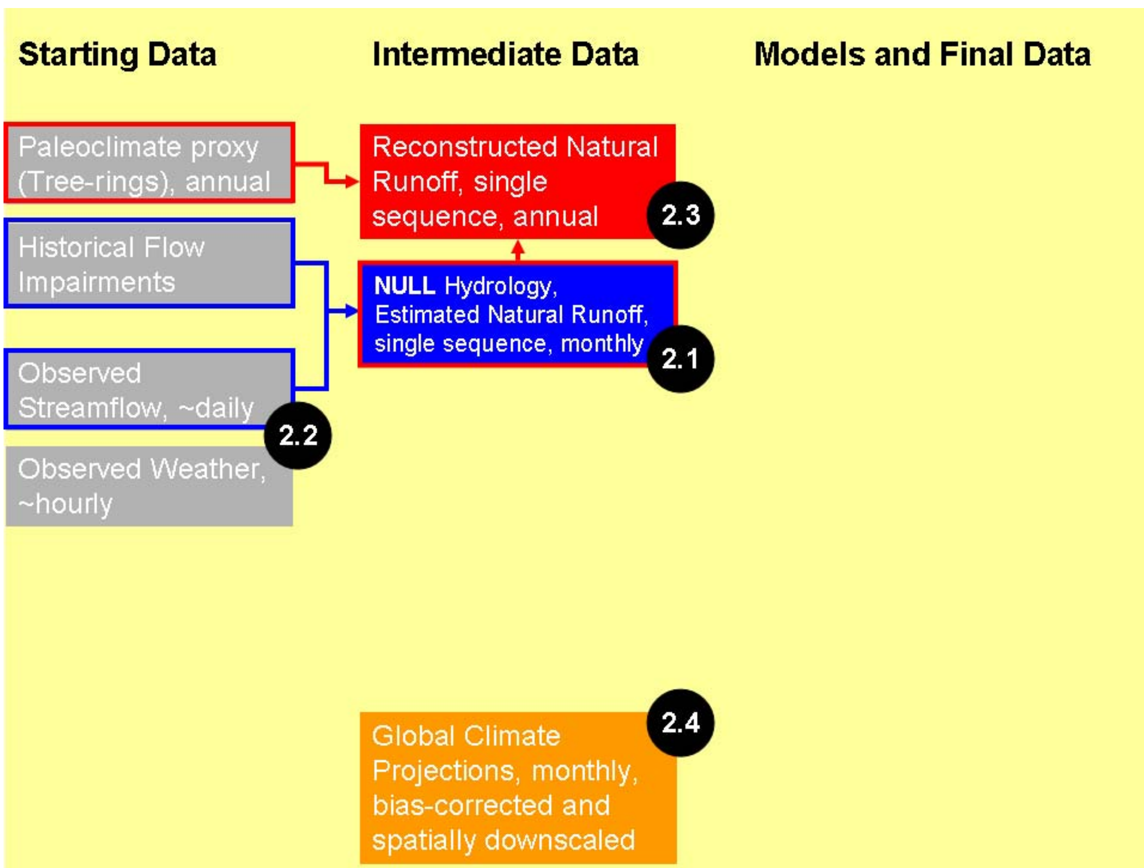

Figure 2 - Analysis Schematic – Preliminary Datasets.

The datasets numbered above are discussed in the following sections

2.1. Estimated Monthly Natural Runoff Volumes

Reclamation's Great Plains Region Office provided estimates of historical monthly natural flow for the Upper Missouri for water years 1930-2002 (Figure 3, bottom panel). The development procedures for these data are described in Reclamation (2005a). Reclamation's Upper Colorado Region Office provided the same type of data for the Gunnison during water years 1906-2005 (Figure 4, bottom panel). Procedures used to develop those data are described in Reclamation (2005b). For both basins, data development involved translating impaired historical streamflow data into natural streamflow data by accounting for estimated historical flow impairments related to water diversions, return flows, and reservoir regulation.

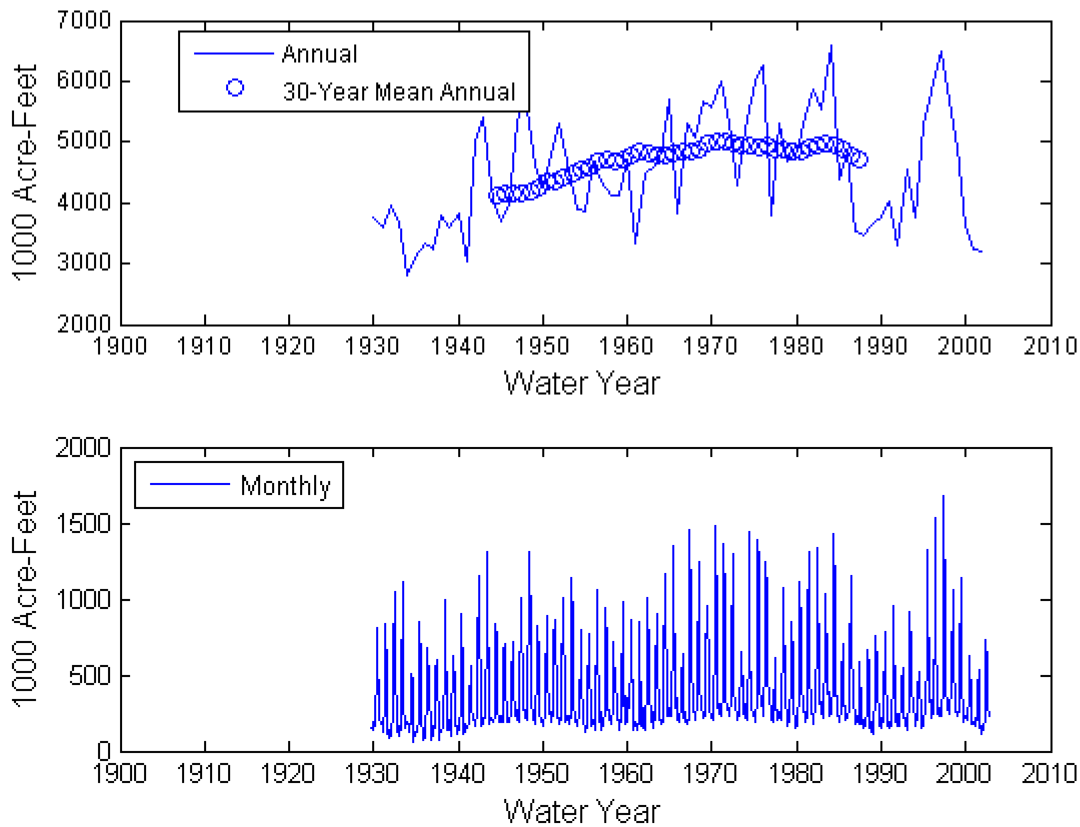

Figure 3 – Upper Missouri – Null Alternative – Estimated Annual Natural Runoff.

(Top panel) Circles show annually moving "30-year mean annual" runoff plotted at period-center.

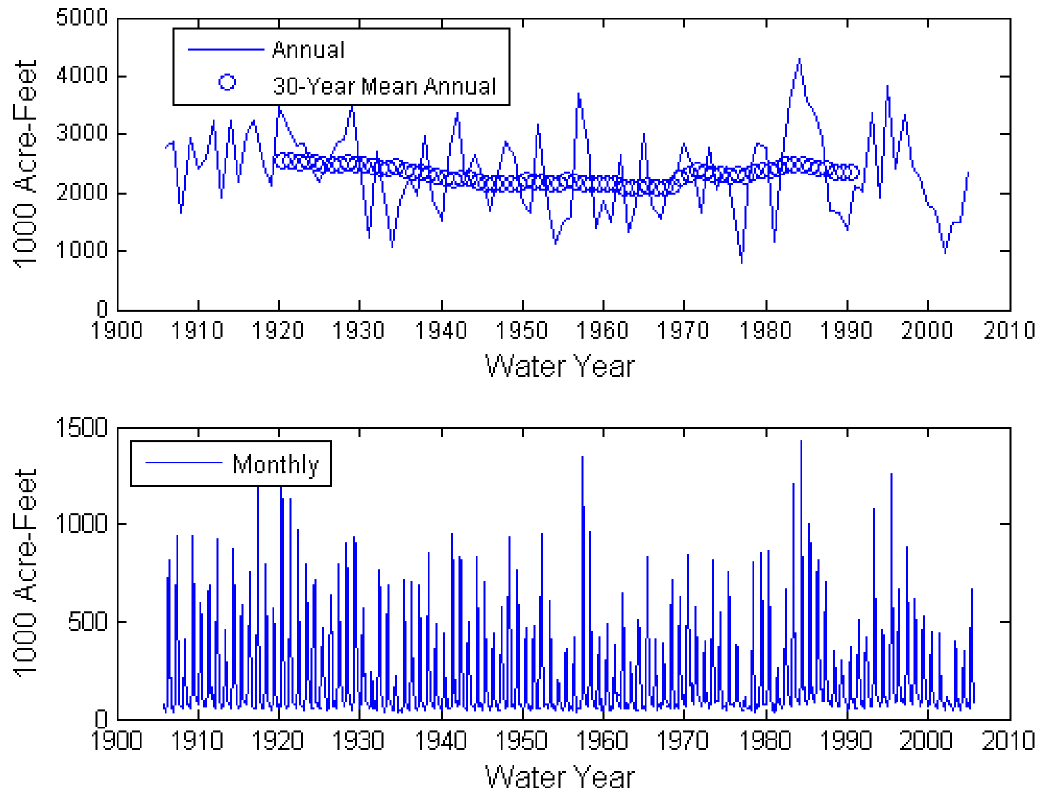

Figure 4 – Gunnison –Null Alternative – Estimated Annual Natural Runoff.

(Top panel) Circles show annually moving "30-year mean annual" runoff plotted at period-center.

In addition to showing monthly natural flow estimates, both Figure 3 and Figure 4 show time-aggregated series of annual runoff and annually moving "30-year mean annual" runoff. Relative to the monthly data, the latter series more clearly illustrate recent historical runoff variability on interannual to interdecadal scales (i.e., lower frequency variability).

2.2. Observed Runoff, Temperature, and Precipitation

As Sections 3 and 4 will explain, process-based hydrologic simulation models were used to develop hydrology data under Alternative 2 and Alternative 3. Such models simulate surface water mass balance over time within a watershed. This is usually accomplished with the mass balance computed in a disaggregated fashion for a network of watershed sub-areas, from which runoff is accounted for and routed to downstream locations. These models were developed and provided by the National Weather Service River Forecast Centers (RFCs) serving the Missouri Basin (MBRFC) and Colorado Basin (CBRFC). Discussion here is only meant to recognize that historical observations of streamflow and station weather (i.e., temperature and precipitation) were used in the calibration of these models. Prior to calibration, the station weather data were translated into mean-area temperature and precipitation for each hydrologic model's sub-areas for which mass balance is calculated (explained above)[2]. Besides their use in model calibration, these "mean-area" observed temperature and precipitation data are also used in the synthetic weather generation required in Alternative 2 (Section 4.2).

2.3. Reconstructed Natural Runoff based on Paleoclimate Proxy Data

Paleoclimate variability over each study basin was indicated by tree-ring chronologies collected within the basins or in nearby areas. These tree-ring chronologies show how annual ring-growth varied from year to year during the trees' life histories, thereby suggesting how climatic conditions varied annually. Tree-ring chronologies were developed by researchers from the University of Arizona, University of Colorado, and Wyoming State Climate Office (Appendix A).

Use of tree-ring chronologies in hydrologic assessments implies a confidence that the chronologies reliably reveal historical interannual patterns of climate stress on the trees. In that sense, such chronologies are useful in that they suggest the occurrence of surplus and drought spells during a pre-instrumental period. This may be particularly illuminating for planning assumptions of water supply variability if:

1. The concern is on multiple-year drought and surplus possibilities

2. The chronologies suggest spell possibilities exceeding those from the observed instrumental record.

For hydrologic data-development, the tree-ring chronologies can be translated into an annual series of reconstructed natural runoff. Woodhouse et al. (2006) provides an overview of several approaches for accomplishing this task, and highlights a general approach that involves:

1. Calibrating a multiple linear regression during the period of instrumental record that explains annual flow variability based on ring-growth variability

2. Applying that model retrospectively to the portion of the ring-growth chronologies preceding the period of instrumental record in order to "reconstruct" coincidental runoff.

[2] This station to "mean-area" translation was performed using NWS RFC procedures (*K. Werner, CBRFC, personal communication, February 2008*).

For the annual streamflow reconstructions used in this study (Figure 5 and Figure 6), the underlying tree-ring chronologies and reconstruction techniques are described in Appendix A. Briefly, that analysis featured several key outcomes and datasets serving data-development in this effort:

- The estimated natural flow data described in Section 2.1 were used to calibrate the reconstruction models for runoff. The reconstruction models were built to estimate "water year" natural runoff volume, where "water-year" means October through September.

- Multiple candidate reconstruction models were developed for each basin. Final model selections for runoff reconstruction were applied in the Upper Missouri to create a water year runoff series from 1569-1997 (Figure 5) and in the Gunnison to create a water year runoff series from 1576-1996 (Figure 6)[3].

- Tree-ring chronologies were also used to reconstruct annual water year precipitation. Comparing calibration statistics, the reconstruction models of annual runoff calibrated "better" (i.e., explained a greater proportion of calibration data variability during the calibration period) than the reconstruction models of annual precipitation.

It has been demonstrated that reconstructed flow magnitudes are sensitive to the sampling and statistical method employed (Hidalgo et al., 2000). As a result, their use has been met with some contention. Nevertheless, it is generally accepted that reconstructed flows are good indicators of annual hydrologic "state" (i.e., whether it was a wetter or drier water year in the chronology) (Woodhouse et. al., 2006). Further, it is generally accepted that reconstructed flows are more reliable indicators of state than of magnitude (i.e., runoff volume) during any given reconstructed year (Gangopadhyay et al. 2009).

Following that thought, and given a preferred classification system, the annual series of reconstructed volumes can be recast as an annual series of hydrologic state. For example, a two-state system might be delineated so that the two states are split at the median-annual reconstructed volume. Years having magnitudes greater than median-annual reconstructed runoff are deemed "wet" and the other years deemed "dry." This type of classification is shown on the bottom panels of Figure 5 and Figure 6, respectively. The state series still indicate spells of relatively wet or dry conditions. Comparing the annual runoff "state" series between the two basins, it appears that spells of roughly two to ten years long occurred with greater frequency in the Upper Missouri than in the Gunnison (i.e., lower-frequency climate persistence was more prominent in the Upper Missouri than in the Gunnison). As will be discussed in Section 4, these state series are

[3] The end-year of the reconstruction is limited by the chronology in the reconstruction model that is the least up-to-date.

used to represent paleoclimate interannual to lower-frequency climate variability in the hydrology development for Alternatives 1 and 3.

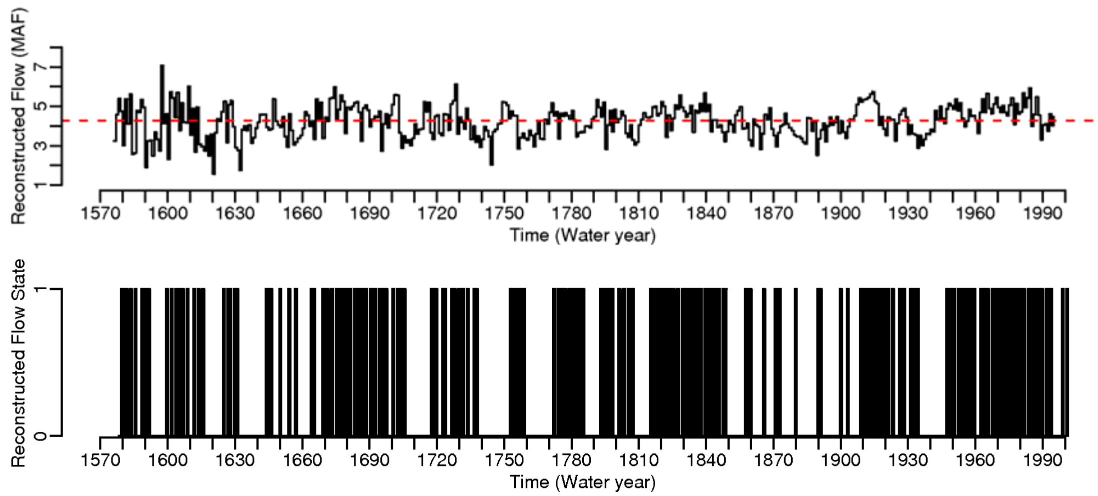

Figure 5 – Upper Missouri – Reconstructed Annual Natural Runoff.

(Top panel) time series of annual runoff “magnitudes” (black line) and full-period median-annual runoff (red line). (Bottom panel) time series of annual state defined as either categorically wetter than median-annual runoff (black) or drier (white).

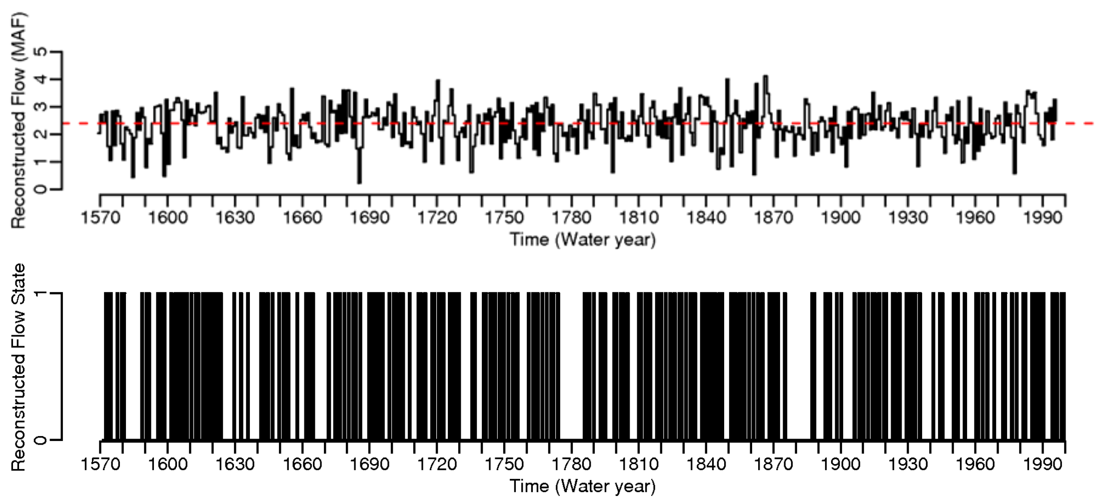

Figure 6 – Gunnison – Reconstructed Annual Natural Runoff.

Plot data are similar to those shown on Figure 5.

2.4. Global Climate Projections, Bias-Corrected and Downscaled

Another type of preliminary data used in this study is projections of future temperature and precipitation during the 21st century. The word “projections” arises from how these future data are developed. These future data are based on assumed future global human activities that affect atmospheric composition and climate. Because these human activity assumptions are cast as scenarios and not forecasts, the associated simulation of future climate under these scenarios are labeled projections rather than predictions or forecasts. This terminology is consistent with that used by the IPCC (2007).

2.4.1 Global Climate Projections

The regional climate projections used in this study were derived from global climate projections produced through the World Climate Research Programme (WCRP) Coupled Model Intercomparison Project (CMIP). The CMIP effort has advanced in three phases (CMIP1 [Meehl et al. 2000], CMIP2 [Covey et al. 2003], and CMIP3 [Meehl et al. 2007]). CMIP3 efforts were fundamental to the completion of the IPCC Fourth Assessment Report (AR4) (IPCC 2007) and involved the use of climate models that feature coupled global atmosphere and ocean circulation and a number of other climate-interactive components (e.g., atmospheric chemistry, sea ice, and atmospheric interactions with land surface hydrology and vegetation).

Many global climate projections were produced through CMIP3. Their differences stem from multiple:

1. Scenarios of future atmospheric greenhouse gases emissions (GHG) and resultant atmospheric composition, associated with possible human activity (IPCC 2000). Scenarios for future GHG emissions vary from lower to higher emission rates, and are associated with assumed global technological and economic conditions (IPCC 2000).

2. Ways to simulate the atmospheric, ocean and terrestrial processes that determine “climate.” It is evident that there is a multitude of ways for modeling climate based on the variety of model structures contributed by global modeling groups participating in CMIP3.

3. Flexibility in specifying the initial climate-system conditions that initialize any future climate simulation. For CMIP3 projections, initial condition estimates were generated for the start of 20th century climate simulations, and the end states of those simulations served as initial conditions for 21st century climate projections. Given our limited observation of the distributed climate system during the 20th century (e.g., ocean depths and

distributed heat content), multiple initial conditions can be defended. As a result, some CMIP3 modeling groups produced multiple projection "runs" for a given emissions path and model, where each "run" differs by the initial condition.

2.4.2 Regional Climate Projections

One issue not resolved with the CMIP3 dataset and global climate projections in general, is that the spatial scale of global climate model output is too coarse for regional studies on water resources response (Maurer et al. 2007). Addressing this issue, spatially downscaled translations of 112 CMIP3 projections have been made available[4], referred to as the "downscaled climate projections archive" (DCP archive).

A variety of methods can be used to produce downscaled translations of global climate projections (Wigley 2004, IPCC 2007, Fowler et al. 2007). The DCP archive data were produced using the Bias-Correction and Spatial Disaggregation (BCSD) approach of Wood et al. (2004).[5] The BCSD approach processes CMIP3 projections in two ways by:

- Using a process where CMIP3 projection data are "bias-corrected." This means that they have been adjusted to account for climate model tendencies to simulate conditions that are too warm, cool, wet, or dry. These tendencies are revealed when the model is used to simulate historical conditions and then compared to historical observations.

- "Spatially downscaling." This essentially involves mapping the bias-corrected CMIP3 data to a finer-scale spatial grid while also factoring in historical spatial climate patterns at the finer-scale grid.[6]

On the bias correction step, options for how to proceed depend on user preferences for what tendencies of the climate model to bias-correct. At the simplest level, the user might identify how the climate model's historical simulation period-mean differs from historical observed period-mean. This would be bias-identification "in the mean." This difference in simulated versus observed period-mean could then be applied as a correction factor to future simulated conditions, which would be bias-correction in the mean. Another more complex approach would recognize desire to correct for the climate model's unique tendencies during wetter years compared to drier years (e.g., underestimate wetter

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[4] "Statistically Downscaled WCRP CMIP3 Climate Projections" at <http://gdo-dcp.ucllnl.org/downscaled_cmip3_projections/ >

[5] See further discussion at: <http://gdo-dcp.ucllnl.org/downscaled_cmip3_projections/#Limitations >

[6] Techniques for accomplishing both steps are described at the DCP archive website <http://gdo-dcp.ucllnl.org/downscaled_cmip3_projections/> and were initially introduced by Wood et al 2002 and Wood et al. 2004.

years while overestimating drier years), or the model's unique tendencies during cooler years compared to warmer years. Likewise, these tendencies may vary during season or month of year. Such considerations feed into the bias-correction approach featured in BCSD (Wood et al. 2004), which is done on a month-by-month basis, and features bias-correction "in the distribution."

The BCSD bias-correction procedure first involves re-gridding CMIP3 projections to a common 2° grid from contributing CMIP3 model's native grid. Bias is then identified for a given projection's variable (temperature or precipitation), calendar month, and 2° grid location during a period of common overlap (i.e., 1950-1999), where cumulative distributions of variable conditions are produced for both observed and simulated (50 values each). Comparing these distributions reveals bias. Combined, the observed and simulated cumulative distributions can be called a "quantile map" (where values can be "mapped" along each cumulative probability quantile from the observed distribution to the simulated distribution). The quantile map is then used to correct any time-step value of a climate projection using a three-step process:

- Get uncorrected value for given location, and then get the quantile map for that location and for the climate model used to produce the given climate projection

- Identify the quantile-threshold of the uncorrected value in the simulated-historical distribution from the given climate model, and then look up the counterpart value in the observed-historical distribution at that same quantile-threshold

- Replace the uncorrected value with the counterpart value from the observed-historical distribution[6].

The BCSD method has been shown to provide downscaling capabilities comparable to other statistical and dynamical methods in the context of hydrologic impacts (Wood et al., 2002, Wood et al., 2004). However, dynamical downscaling has also been shown to identify some local climate effects and land-surface feedbacks that BCSD cannot readily identify (Fowler et al. 2007, Salathé et al. 2007). Another potential limitation of BCSD, like any statistical method, is the stationarity assumption where it is assumed that the relationship between larger- and finer-scale precipitation and temperature in the future will be the same as in the past. A second assumption is that any biases exhibited by a GCM for the historical period will also be exhibited in future simulations. Tests of these assumptions using historic data show that they appear to be reasonable, inasmuch as the BCSD method compares favorably to other downscaling methods (Wood et al, 2004).

Table 1 lists the menu of CMIP3 projections represented in the DCP archive. They were collectively produced by 16 different CMIP3 models, each applied to simulate 3 different emissions paths (e.g., B1 [low], A1b [middle], A2 [high]) from at least one initial condition (i.e., run). Each downscaled projection includes monthly simulated temperature and precipitation conditions from 1950-2099 at 1/8° spatial resolution (approximately 12km square) over the contiguous United States. The 1950-1999 period of each projection is simulated historical climate produced by the given climate CMIP3 model, where the simulation was based on estimated forcing of historical climate (e.g., solar input, volcanic episodes, atmospheric aerosol conditions) and an estimated initial condition for the climate system (i.e., conditions around 1900). Uncertainties in both lead to monthly and annual sequences during 1950-1999 that differ from observed conditions. However, the bias-correction procedure forces the simulated 1950-1999 period-statistics to match those of observed conditions.

The next series of figures characterize the body of climate projection information over the study region, from simulated 20th to projected 21st century. Figure 7 and Figure 8 show "median" changes in period-mean precipitation and temperature, as distributed across the DCP archive's 112 projections and spatially distributed by downscaling location. Specifically, the figures show median "period-mean change" in temperature and precipitation during four 30-year simulation periods (i.e., 1980-2009, 2010-2039, 2040-2069, and 2070-2099), each relative to simulated 1950-1979 period.

For precipitation (Figure 7), there appears to be a future tendency toward wetter conditions over the Upper Missouri (i.e., roughly 5 to 10% increase by 2070-2099 relative to 1950-1979). For the Gunnison, there appears to be a weak tendency toward drier mean-annual conditions in the late 21st century. However, it is interesting to note that the Gunnison basin is located close to the "dividing line" (i.e., color transition from red to blue on the maps) where roughly equal portions of projections trend wetter or drier. This should not be interpreted as implying that projected precipitation changes are less certain over the Gunnison than over the Upper Missouri. It only means that there is greater *consensus* about projected precipitation change north of the Gunnison (i.e., consensus being wetter) or southwest of the Gunnison (i.e., consensus being drier). For temperature (Figure 8), the projections suggest warming for both basins, and in similar amounts during future periods (e.g., roughly +6 to +7 °F for both basins by 2070-2099 relative to 1950-1979).

Table 1. Available Downscaled and Bias-Corrected Climate Projections Data.

Climate Modeling Group, Country	Climate Model (WCRP CMIP3 I.D.)	SRES "runs" [1]			Primary Reference
		A2	A1b	B1	
Bjerknes Centre for Climate Research	BCCR-BCM2.0	1	1	1	Furevik et al., 2003
Canadian Centre for Climate Modeling & Analysis	CGCM3.1 (T47)	1, 2, 3, 4, 5	1, 2, 3, 4, 5	1, 2, 3, 4, 5	Flato and Boer, 2001
Meteo-France / Centre National de Recherches Meteorologiques, France	CNRM-CM3	1	1	1	Salas-Melia et al., 2005
CSIRO Atmospheric Research, Australia	CSIRO-Mk3.0	1	1	1	Gordon et al., 2002
US Dept. of Commerce / NOAA / Geophysical Fluid Dynamics Laboratory, USA	GFDL-CM2.0	1	1	1	Delworth et al., 2005
US Dept. of Commerce / NOAA / Geophysical Fluid Dynamics Laboratory, USA	GFDL-CM2.1	1	1	1	Delworth et al., 2005
NASA / Goddard Institute for Space Studies, USA	GISS-ER	1	2, 4	1	Russell et al., 2000
Institute for Numerical Mathematics, Russia	INM-CM3.0	1	1	1	Diansky and Volodin, 2002
Institut Pierre Simon Laplace, France	IPSL-CM4	1	1	1	IPSL, 2005
Center for Climate System Research (The University of Tokyo), National Institute for Environmental Studies, and Frontier Research Center for Global Change (JAMSTEC), Japan	MIROC3.2 (medres)	1, 2, 3	1, 2, 3	1, 2, 3	K-1 model developers, 2004
Meteorological Institute of the University of Bonn, Meteorological Research Institute of KMA	ECHO-G	1, 2, 3	1, 2, 3	1, 2, 3	Legutke and Voss, 1999
Max Planck Institute for Meteorology, Germany	ECHAM5/ MPI-OM	1, 2, 3	1, 2, 3	1, 2, 3	Jungclaus et al., 2006
Meteorological Research Institute, Japan	MRI-CGCM2.3.2	1, 2, 3, 4, 5	1, 2, 3, 4, 5	1, 2, 3, 4, 5	Yukimoto et al., 2001
National Center for Atmospheric Research, USA	CCSM3	1, 2, 3, 4	1, 2, 3, 5, 6, 7	1, 2, 3, 4, 5, 6, 7	Collins et al., 2006
National Center for Atmospheric Research, USA	PCM	1, 2, 3, 4	1, 2, 3, 4	2, 3	Washington et al., 2000
Hadley Centre for Climate Prediction and Research / Met Office, UK	UKMO-HadCM3	1	1	1	Gordon et al., 2000

Notes:

1. These downscaled climate projections are from LLNL-Reclamation-SCU downscaled climate projections dataset, derived from World Climate Research Programme's (WCRP's) Coupled Model Intercomparison Project phase 3 (CMIP3) multi-model dataset, stored and served at the LLNL Green Data Oasis <http://gdo-dcp.ucllnl.org/downscaled_cmip3_projections/>.

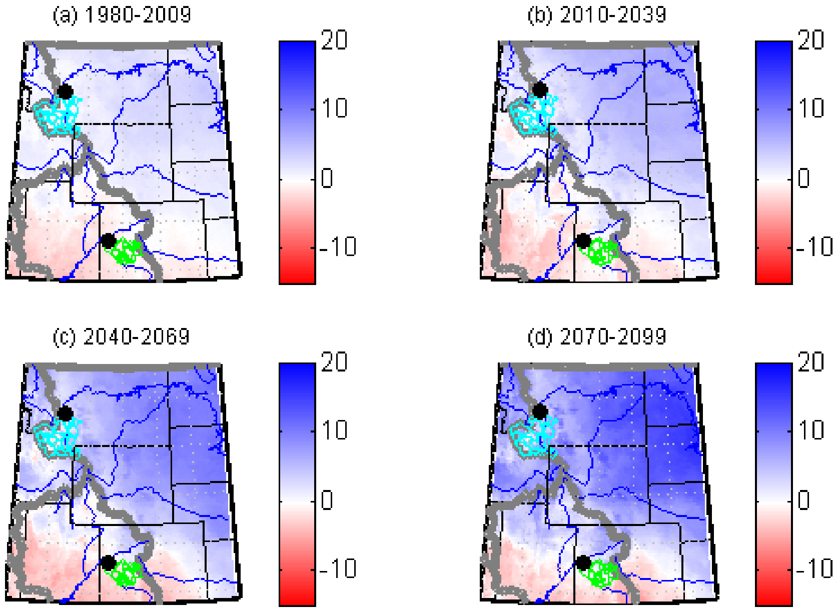


Figure 7 – Projected Change in Precipitation over the Study Regions.

Map data are shown as percentage change in 30-year Mean Annual relative to 1950-1979, computed at each downscaled location (Section 2.3) for periods: (a) 1980-2009, (b) 2010-2039, (c) 2040-2069, and (d) 2070-2099. Basin boundaries are highlighted (Upper Missouri as light blue, Gunnison as green); basin outflow locations are indicated by black circles.

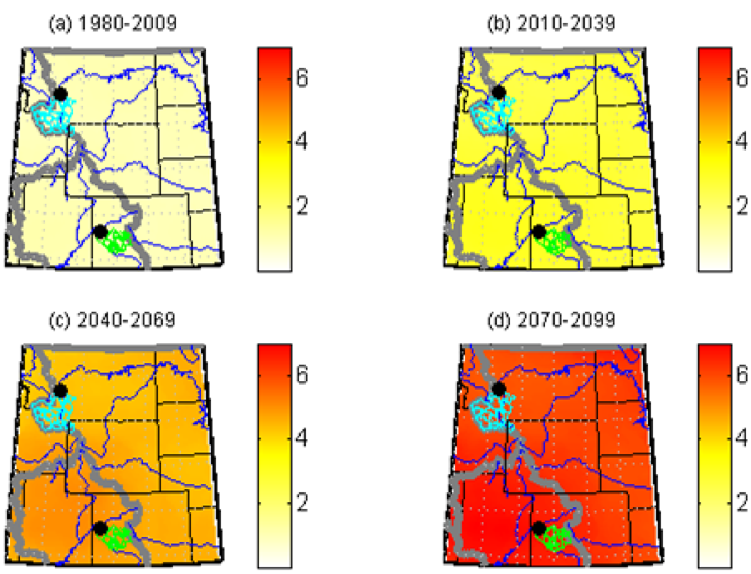


Figure 8 – Projected Change in Temperature over the Study Regions.

Map data are shown as incremental change (ºF) in 30-year Mean Annual from 1950-1979, computed at each downscaled location (Section 2.3) for periods: (a) 1980-2009, (b) 2010-2039, (c) 2040-2069, and (d) 2070-2099. Basin boundaries and outflow locations are shown similar to Figure 7.

Figure 7 and Figure 8 show change information representing all DCP archive projections. However, this study only focused on a subset of DCP archive projections: the 39 projections reflecting climate response to a simulated historical appended to the future “A1b” GHG scenario. Figure 9 through Figure 12 show change information from this projection subset.

Figure 9 and Figure 10 show how projection information over the Upper Missouri case study basin, representing information from the 39 A1b projections. Figure 11 and Figure 12 show the same type of projected climatologies for the Gunnison basin. Specifically, the figures show how either period-mean annual and monthly precipitation or temperature, distributed across the projection ensemble (i.e., boxplots), evolve during 30-year periods, moving from simulated 20th century through the projected 21st century. For any given period, the 30-year mean annual or mean monthly varies across the projection-ensemble. This is partially due to how the climate models provide different portrayals of natural climate variability, and how the projections did not start from a common estimated initial-condition for the climate system.

Focusing on the top panels of Figure 9 through Figure 12, and following the boxplot midlines through time provides a sense for trends in future precipitation and temperature. Specifically, a boxplot’s midline (i.e. horizontal line within the box of a boxplot) equals the ensemble-median period-mean condition for the period of that boxplot. Thus, following those midlines through time reveals a trend future precipitation and temperature as indicated by each variable’s ensemble-median period-mean condition. Trends from these figures and this projections subset are consistent with the trends shown on Figure 7 and Figure 8. For precipitation trends (Figure 9 and Figure 11), the boxplot medians through time suggest that wetter conditions would develop over the Upper Missouri while little change in precipitation would develop over the Gunnison. Focusing on the boxplot outliers through time offers the additional impression that 30-year mean precipitation conditions could get wetter through time for both basins. For the Gunnison, the dry side possibilities seem to decrease through time, but not so much for the Upper Missouri.

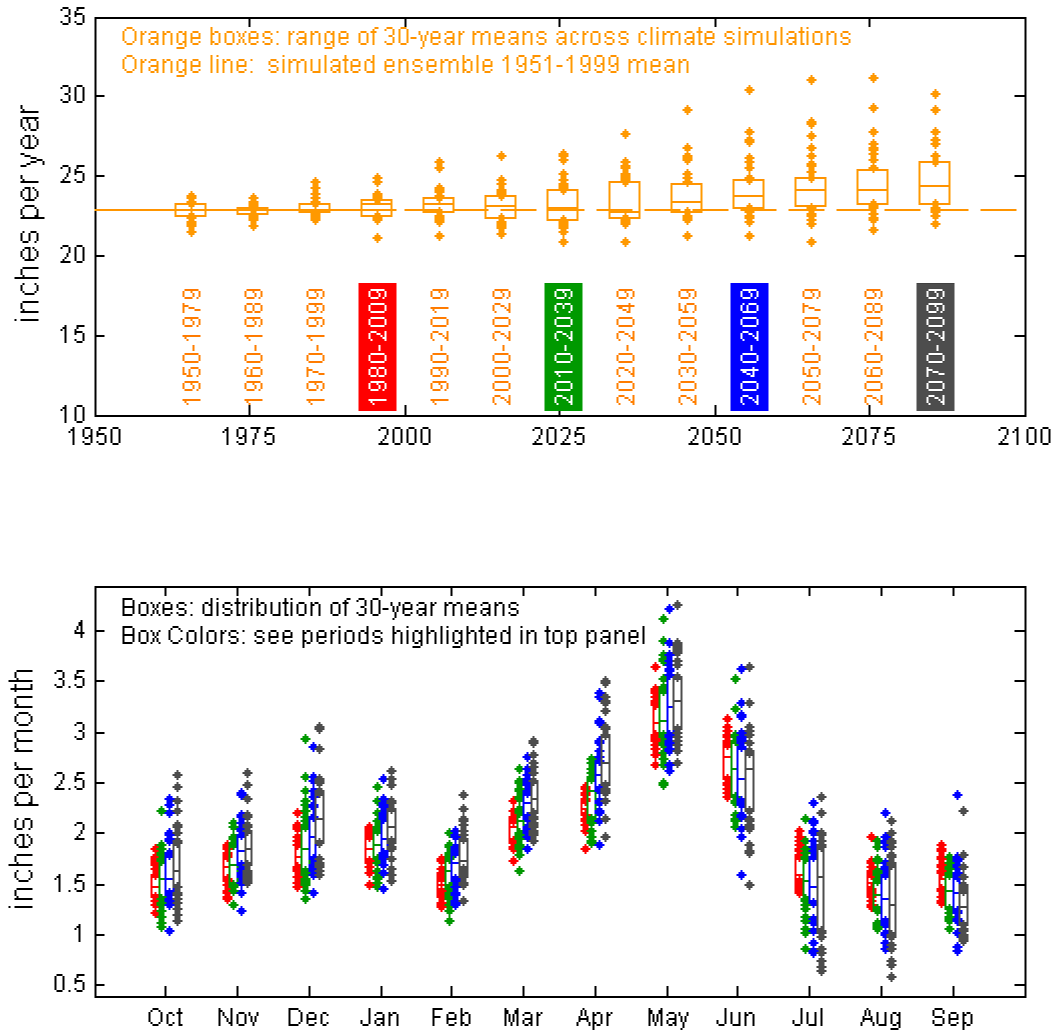
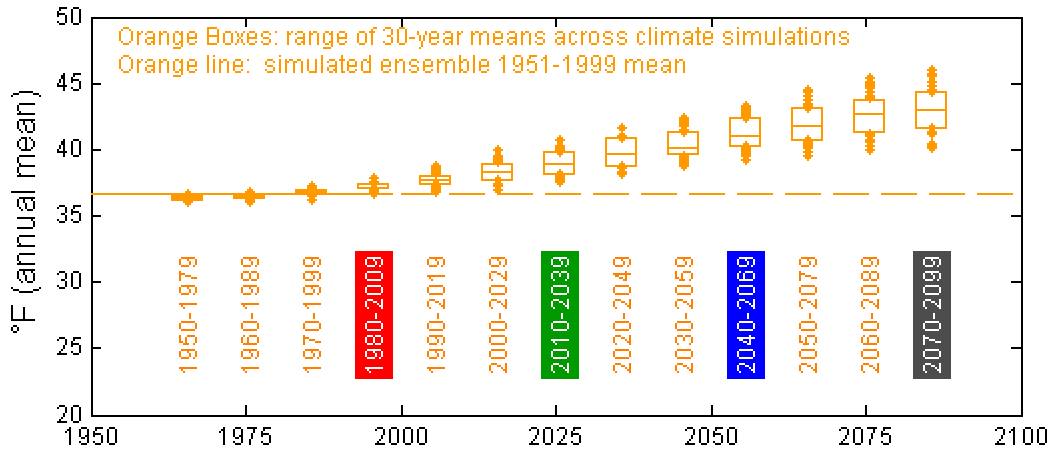


Figure 9 – Upper Missouri - Moving Projected Precipitation Climatologies.

Plot data show distribution of period-means (annual means in top panel, monthly means in bottom panel) across 39 climate projections sampled during the periods indicated.



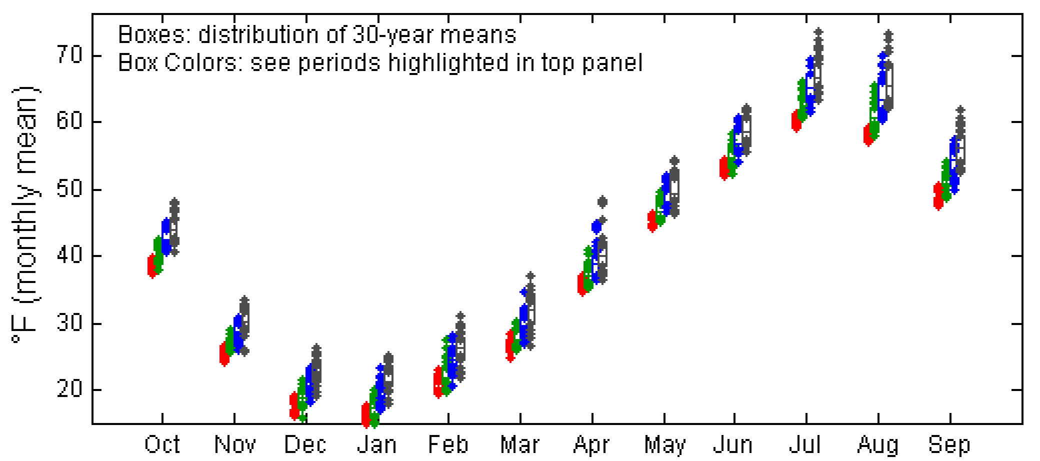


Figure 10 – Upper Missouri - Moving Projected Temperature Climatologies.

Plot data show distribution of period-means (annual means in top panel, monthly means in bottom panel) across 39 climate projections sampled during the periods indicated.

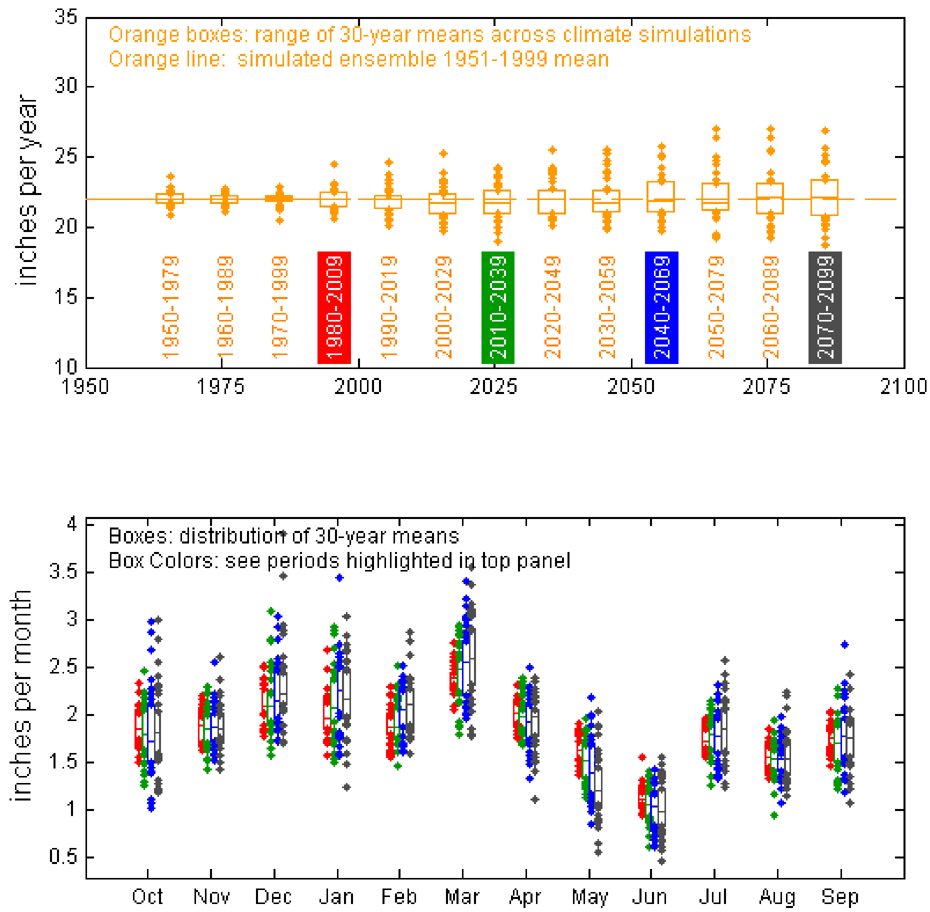


Figure 11 – Gunnison – Moving Projected Precipitation Climatologies.

Plot data are similar to those shown on Figure 9.

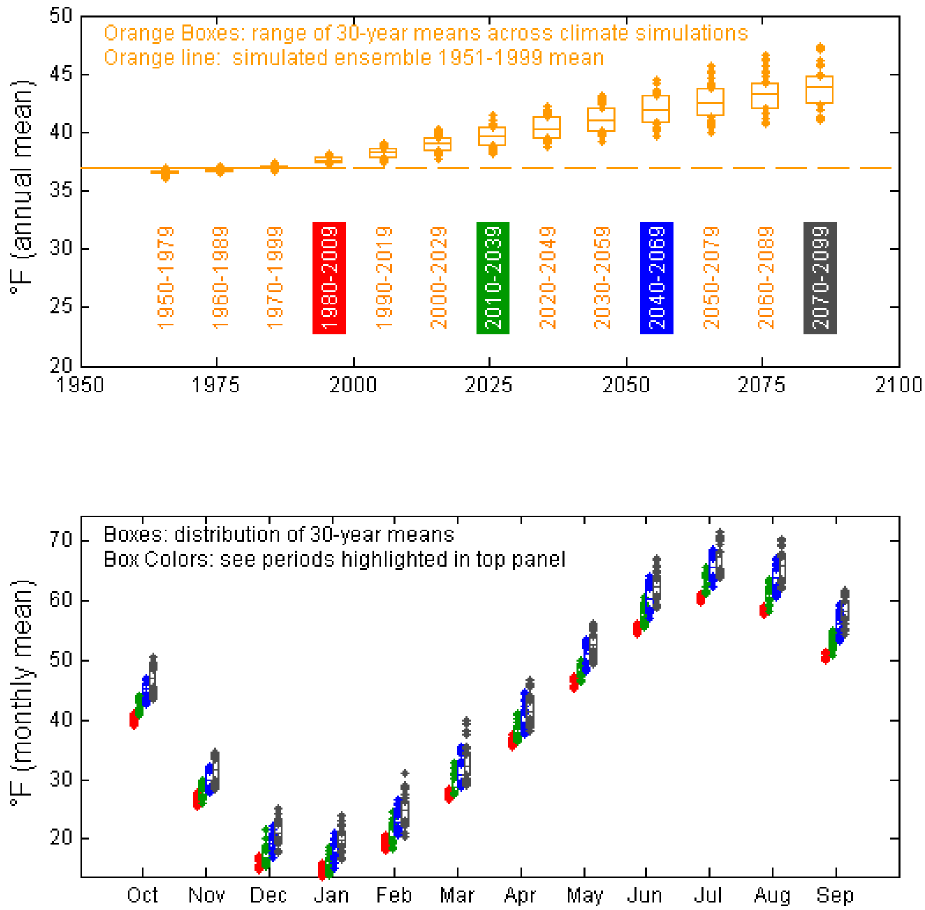


Figure 12 – Gunnison – Moving Projected Temperature Climatologies.

Plot data are similar to those shown on Figure 10.

3.0 Model Tools

Two types of hydrologic simulation models were used to develop hydrology data in this study (**Figure 13**):

1. The first type of model is used to develop hydrology data in Alternatives 1 and 3. It is based on stochastic concepts and computes plausible synthetic sequences of hydrology that are statistically consistent with a reference climate.

2. The second type of model is used to develop hydrology data in Alternative 2. These data are then used in Alternative 3, as explained in Section 4.3. It is a process-based simulation and computes a time-developing water balance in the basin given an input time series of temperature and precipitation and other basin characterizations (Section 3.2). This type of model can reveal runoff response to temperature and precipitation conditions that statistically change through time, like those associated with climate projections.

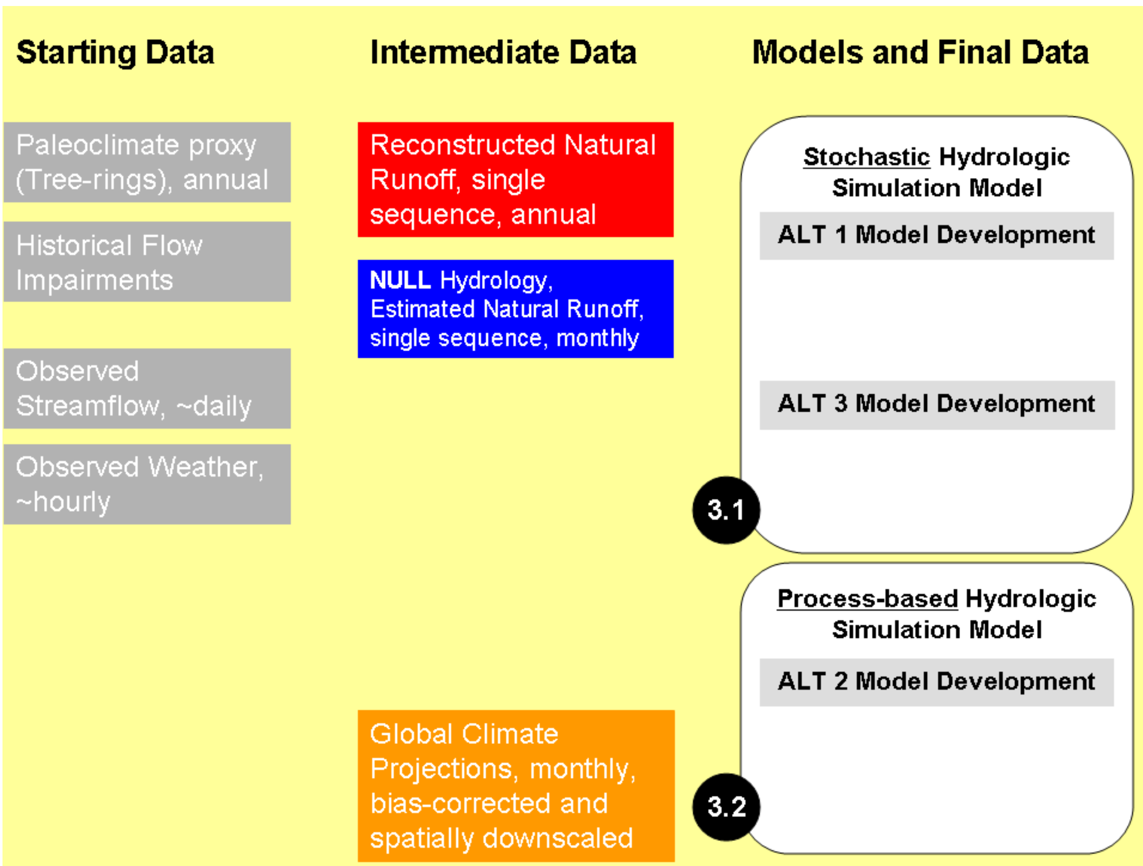


Figure 13 – Analysis Schematic –Hydrologic Models.

The two model types are discussed in the following sections, as numbered.

3.1. Stochastic Annual Runoff Model

For some water system planning studies (e.g., drought contingency planning, evaluating the vulnerability of reservoir operating criteria to severe and sustained drought), it is critical to understand how the system performance depends on water supply variability. In these particular water system planning situations, assessing water system performance under many variation situations (e.g., kinds of drought and surplus periods, characterized by spell and accumulation) is desirable because broader consideration of variation possibilities would produce a more robust vulnerability assessment with respect to drought. The instrumental record offers only a limited set of drought and surplus cases. One philosophical planning response is to enrich the set of possibilities through stochastic hydrologic modeling. In general, such modeling is based on the assumption that the statistics of a chosen climate and hydrologic period (i.e. reference hydroclimate period) are preserved for planning purposes, but that the possible sequencing of conditions within that reference period could have varied from observed conditions. Following that assumption, stochastic modeling is performed to develop a collection of synthetic runoff sequences that all represent the same reference hydroclimate.

Generally speaking, stochastic runoff modeling involves:

1. Choosing a reference climate period(s) having the runoff statistics that are to be preserved

2. Collecting data from the reference period(s)

3. Building a stochastic model (using parametric [e.g., Stedinger and Taylor 1982a] or nonparametric techniques [e.g., Lall and Sharma 1996])

4. Verifying that the model preserves desired reference runoff statistics and autocorrelation characteristics

5. Applying the model to generate synthetic runoff sequences for planning purposes. For this study, a nonparametric stochastic model framework was adopted and applied for data-development under Alternatives 1 and 3 (Section 4).

The modeling framework chosen for this study has been applied in previous Reclamation planning efforts (Reclamation 2007). It features a two-stage technique that allows separate reference climates to be used to first model annual hydrologic state (Section 2.3) and then hydrologic magnitude, or volume (Section 2.3). The choice to adopt a two-stage stochastic process in Reclamation (2007) was motivated by a desire to blend more reliable aspects of paleoclimate information from tree-rings (i.e., annual state information, Section 2.3) with the most reliable historical information on annual magnitude possibilities (i.e., instrumental records).

Mechanical details of this methodology and citations are outlined in Appendix B. Briefly, the two-stage methodology respectively features stage components labeled as a “Non-Homogenous Markov” state model and a “K Nearest Neighbor resampling technique” to associate magnitude to synthetically generated state. For discussion purposes here, only three key model-application decisions are highlighted, along with examples for illustration. The three decisions are:

1. Reference climates to define (a) annual state and (b) annual magnitude

2. Number of categorical states that will be modeled (e.g., two-state system like that shown on Figure 5 and Figure 6)

3. How much “n-year” auto-correlation to stochastically represent

The second and third decisions set up how many state-transition possibilities must be modeled. To illustrate, consider the following example decisions:

1. **Reference climates to define (a) annual state and (b) annual magnitude:** Use climate of the instrumental record to define both (i.e., for the case study basins, the reference runoff information would be the estimated natural flow records on Figure 3 and Figure 4).

2. **Number of categorical states that will be modeled:** Define two hydrologic states as “wet” and “dry”, specifically defined as being respectively wetter or drier than the period-median annual runoff from the reference state climate.

3. **How much “n-year” auto-correlation to stochastically represent:** Design model to represent lag 1-year auto-correlation tendencies in the reference climate. This means that 2-year state-transition sequences are probabilistically modeled. In other words, during any given stochastic year, the likelihood of state depends on the state of the previous year and four 2-year state-transition probabilities estimated from the reference climate: wet-wet (ww), wet-dry (wd), dry-wet (dw), and dry-dry (dd) (Appendix B).

Figure 14 and Figure 15 show how “wet” and “dry” year runoff magnitudes from the instrumental record vary depending on whether the “wet” or “dry” year is the leading or following a year of similar or different state[7]. For the Upper Missouri

[7] The distributions of Figure 15 and Figure 16 are based on the full-period of reference hydroclimate. These distributions would be sufficient for estimating static state-transition probabilities for *homogeneous* Markov modeling. However, as Appendix B notes, this implementation involves *non-homogeneous* Markov modeling, which means that state-transition

(Figure 14), the magnitude of a leading year (left panel) varies slightly with the following year state, which perhaps points to the tendency for two-year climatic persistence in the basin. Similar results were found in the Gunnison (Figure 15). Switching to the following year (right panel), the Upper Missouri magnitudes distributions for a following year's state varies depending on the preceding year's state, which might be a reflection of both climatic persistence and the characteristic effects of carryover soil moisture storage in the basin. Such dependence was not as apparent in the Gunnison's following year magnitudes (Figure 15).

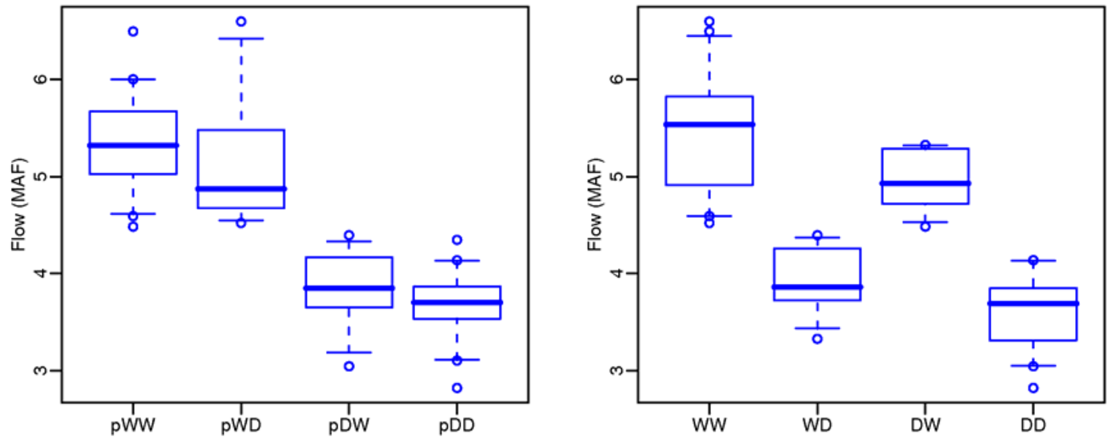


Figure 14 – Upper Missouri - Null Hydrology - Annual Runoff Distributions associated with possible Two-Year State Sequences.

(Left panel) Distribution of first-year volumes associated with four two-year sequence possibilities: wet preceding wet (pWW), wet preceding dry (pWD), dry preceding wet (pDW) and dry preceding dry (pDD). (Right panel) Distribution of second-year volumes associated with the same four two-year sequence possibilities.

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probabilities are estimated to change through time. Such time-varying probabilities come from assessing distributions like those shown on Figure 15 and Figure 16 in a sub-period "window," referred to as a bandwidth in Appendix B. Refer to Appendix B for more information.

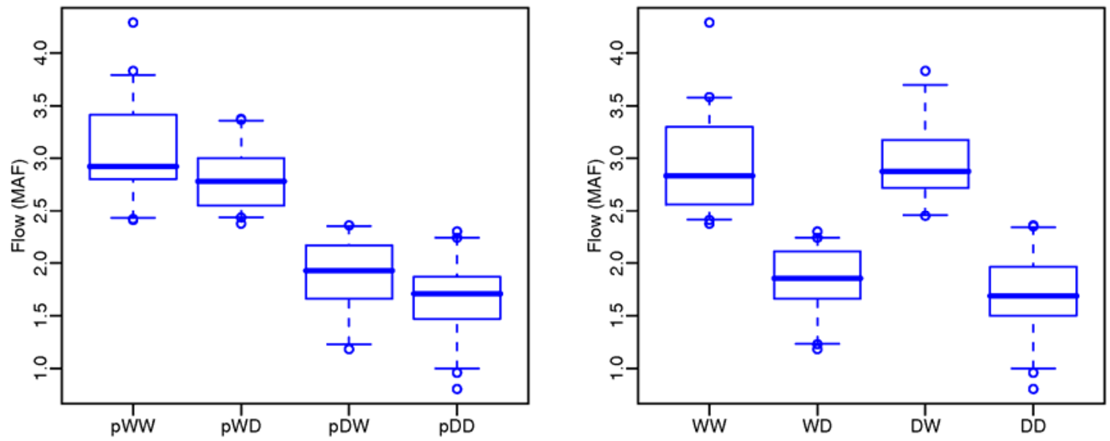

Figure 15 – Gunnison - Null Alternative Hydrology - Annual Runoff Distributions associated with possible Two-Year State Sequences.

Plot data are similar to those shown on Figure 14.

Using these decisions, stochastic annual runoff models were developed for both case study basins. The models were each applied to simulate 500 annual runoff sequences, each having a period-duration matching that of the reference climate, or period-duration of instrumental record (i.e., 73 years for the Upper Missouri sequences and 99 years for the Gunnison sequences). Sequences are not shown here. Rather, period-statistical summaries of these sequences are shown for each basin on Figure 16 and Figure 17, respectively. The models are expected to produce runoff sequences that have similar period-statistics as the instrumental record. It is possible for period-statistics of any single sequence to differ from those of the instrumental record. Thus, a model-check should focus on how the *median* of sequence-specific period-statistics compares to the period-statistics of the instrumental record (i.e., period-statistics of runoff from Figure 3 and Figure 4).

In summary, the models do a reasonable job of representing period-statistical characteristics of instrumental record runoff. Some statistical characteristics are reflected better than others. For the Upper Missouri (Figure 16), ensemble-median period-statistics are close to those of the instrumental record for mean, standard deviation, skew, maximum, and minimum, as indicated by comparing the median line of each statistic's boxplot distribution to the blue triangle representing the statistic from the instrumental record. The model tends to produce less auto-correlation than observed in the instrumental record (i.e., median sequence-specific auto-correlation being roughly 0.45 compared to roughly 0.55 in the instrumental record). For the Gunnison, similar model tendencies were found (Figure 17). It appears that the Upper Missouri application performed slightly better than the Gunnison application at simulating maximum magnitudes and positive skew. The Gunnison application generally underestimated lag-1 autocorrelation (i.e., sequence-median auto-correlation being roughly 0.1 compared roughly 0.25 in the reference climate).

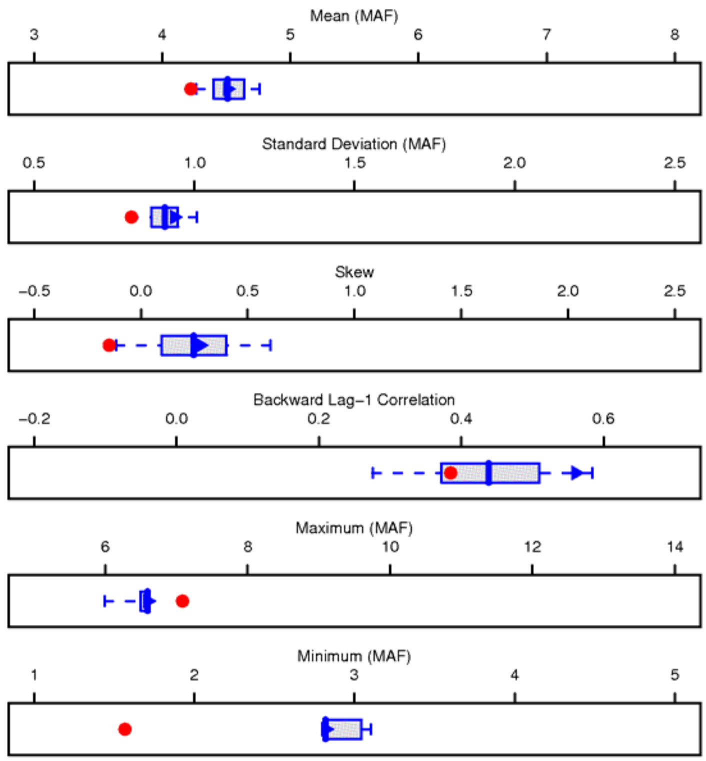

Figure 16 – Upper Missouri – Period Statistics on Stochastically modeled Annual Runoff reflecting statistics of the Null Alternative Hydrology.

Each panel corresponds to a given statistic, and shows: (a) distribution of how the statistic's value varies across an ensemble of 500 simulated 73-year sequences that are consistent with climate from the instrumental record (blue boxplots, where box equals interquartile range, box mid-line equals median, whisker limits equal 5 and 95 percentiles), (b) statistic from the instrumental record (blue triangle, data from Figure 3), (c) statistic from paleoclimate-based reconstructed runoff (red circle, data from Figure 5).

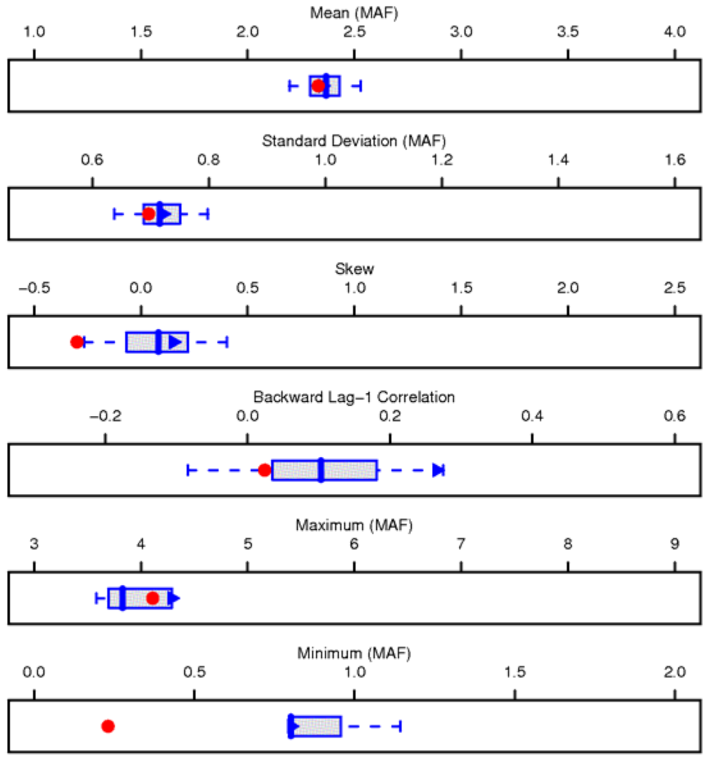

Figure 17 - Gunnison – Period Statistics on Stochastically modeled Annual Runoff reflecting statistics of the Null Alternative Hydrology.

Plot data are similar to those shown on Figure 16, except that distributions of statistic values are based on an ensemble of 500 simulated 99-year sequences.

3.2. Process-based Hydrologic Simulation Model

Under a changing climate, it is reasonable to expect that the relationship between basin precipitation, temperature, and runoff would change. For example, warmer air temperatures over a snowmelt-dominated basin would likely lead to proportionally more rainfall and less snowfall. This would likely increase rainfall-runoff volumes during winter. In addition, winter warming would likely reduce the areal extent and seasonal duration of snowpack, subsequently leading to reduced spring-summer snowmelt-runoff. Given changes in precipitation regime and runoff response, it might be expected that the proportional fate of precipitation over the basin, as runoff or evapotranspiration, would change over time (ignoring other fates, e.g., potential deep percolation). These changes would occur because the delay between precipitation input and output fate is affected by intervening hydrologic processes that manifest into basin soil moisture and snowpack conditions, and because warming is affecting these processes.

Process-based hydrologic simulation models have frequently been used to study climate change impacts on hydrology and water resources (Vicuna and Dracup

2007). Several types of process-based models have been applied in various western U.S. basins, for example:

- Variable Infiltration Capacity (VIC) model (Liang et al. 1994) applied to investigate impacts in California's Central Valley (Van Rheenan et al. 2004, Maurer 2007), Colorado River Basin (Christensen and Lettenmaier 2007), the Columbia-Snake Basin (Payne et al. 2004), and numerous others

- National Oceanic and Atmospheric Administration-National Weather Service (NOAA-NWS)' Sacramento Soil Moisture Accounting model (Burnash et al. 1973) coupled to the Snow17 snow accumulation and ablation model (i.e., SacSMA/Snow17) (Anderson et al. 1973) applied to investigate impacts in the California Sierra Nevada (Miller et al. 2003)

- The Water Evaluation And Planning System's hydrologic module (Yates et al. 2005) also applied to study California hydrologic impacts (Purkey et al. 2007)

- U.S. Geological Survey's Modular Modeling System (Leavesley et al. 1996) applied in Washington's Yakima River Basin (Mastin 2008) among other locations.

These process-model frameworks are similar in that they (1) are forced by an input time-series of weather, and (2) simulate the basin's surface water balance through time in response to the input weather. The input weather is characterized in space and time, which along with available information on basin characteristics, determines hydrologic model resolution for computing water balance in space and time. For this study, various types of process-based models were considered. Several criteria guided model selection:

1. The model type must represent surface water balance terms (i.e., precipitation, evapotranspiration, surface and subsurface runoff) and transient water storage (i.e., soil moisture and snowpack).

2. The model type must have already been applied and well-calibrated to the case study basins, thereby permitting this research demonstration to avoid the expense of hydrologic model calibration and verification.

Given these criteria, two sets of model-applications remained as candidates:

- The University of Washington applications of VIC in the Missouri and Colorado basins, which have served as seasonal water supply forecasting tools in an experimental western U.S. hydrologic forecasting system[8].

- NOAA National Weather Service MBRFC and CBRFC applications of SacSMA/Snow17 (Burnash and Ferral (1996) and Anderson 2006), which currently serve RFC operational hydrologic forecasting purposes in the case study basins.

As for structural similarity between these model types, VIC and SacSMA/Snow17 are consistent in that they each simulate surface water balance for a spatial distribution of sub-areas and then route runoff from these sub-areas to aggregate downstream locations. The two model types differ on several aspects, including (but not limited to) required meteorological variables, disaggregation of soil moisture zones, and treatment of potential evapotranspiration as an input or computed variable (Reclamation 2008).

As for the similarity between VIC and SacSMA/Snow17 model type applications in the two case study basins, both sets of model-applications were calibrated to reproduce historical streamflow conditions as observed. Both model-applications portray precipitation fate as only runoff or evapotranspiration with no deep percolation loss from the surface balance over time—water may reside in the basin as soil moisture but eventually it leaves the soil column as runoff or evapotranspiration. In conjunction, the local surface water balance is supplied only by precipitation and there are no simulated groundwater gains to the surface soil column. The applications are also similar in that they simulate basin runoff through a routed network of basin sub-areas. However, the applications differ in terms of time-step choice and how sub-areas are defined (see Figure 1, a grid showing VIC elements, red outlines showing SacSMA/Snow17 elements). The VIC applications simulate runoff on a daily time-step within a 1/8º spatial *grid* of sub-areas, requiring station weather observations to be translated into distributed weather time series on that grid (Maurer et al. 2002). In contrast, the MBRFC and CBRFC SacSMA/Snow17 applications simulate runoff on a 6-hourly time-step within a network of topographically and elevation-delineated sub-areas, requiring similar station weather observations to be translated into sub-area temperature and precipitation time series using NWS procedures (Werner (CBRFC), personal communication, October 2008).

Ultimately, a decision was made to use the MBRFC and CBRFC SacSMA/Snow17 applications in the process-based hydrologic simulation model. Three factors contributed to this decision:

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[8] Applications described at "University of Washington Westwide Streamflow Forecasting System" at: http://www.hydro.washington.edu/forecast/westwide/. Model described at "Variable Infiltration Capacity (VIC) Macroscale Model" at: http://www.hydro.washington.edu/Lettenmaier/Models/VIC/VIChome.html.

1. Previous Reclamation work has already suggested that the two model types produce comparable annual runoff results given common climate projections (Reclamation 2008).

2. The project team had greater familiarity with CBRFC and MBRFC SacSMA/Snow17 applications and their development.

3. There was confidence that the CBRFC and MBRFC model-applications had received ample calibration attention at the sub-basin scale considered in this study[9].

Figure 18 and Figure 19 provide information related to the calibration of the RFC models. Each figure shows a comparison of simulated runoff versus observed runoff (i.e., estimates from the instrumental record, Figure 3 and Figure 4, respectively). The simulated runoff is based on forcing the model with RFC-estimates of distributed historical weather observations over the basins. The figures suggest that both basin models generally do a reasonable job of reproducing observed variability in monthly and annual runoff. For the Upper Missouri application (Figure 18), monthly and annual comparisons are shown for water years 1979-2002. The correlation between observed and simulated annual volumes during this period is 0.97. The ratio of simulated to observed mean-annual runoff during this period (i.e., hydrologic model bias) was found to be 0.99. For the Gunnison application (Figure 19), comparisons are shown for water years 1976-2005. The correlation between observed and simulated annual volumes during this period is 0.98. The bias was found to be 0.93. The larger degree of bias for the Gunnison application may be partially related to how the model simulates unregulated flow rather than natural flow. Natural flow represents adjusted gage data to account for reservoir regulation effects, historical stream diversions, estimated return flows, and reservoir evaporation. By contrast, unregulated flow represents adjusted gauge data that accounts for only reservoir regulation effects.

[9] In retrospect, the second and third factors may have still led to use of the MBRFC and CBRFC model applications. However, the first factor may have been inappropriately linked to basins of this study, which are relatively arid compared to those of Reclamation 2008. This is based on recent work through the research project, "Reconciling Projections of Future Colorado River Streamflow" <http://wwa.colorado.edu/current_projects/rcn_strmflw_corvr.html> which suggests that runoff impacts modeling is sensitive to model characterizations of intervening processes, such as infiltration, soil moisture dynamics and potential evapotranspiration. VIC and SacSMA/Snow17 differ on these structural aspects. These processes could be affected by climate change (e.g., response of potential evapotranspiration due to warmer conditions). Different treatment of these processes by model type would mean different process responses to climate change by model type and thus different future impacts characterization. Thus, it may be incorrect to presume that the two model types would produce similar climate change impacts just because their applications show similar calibration and validation characteristics under historical climate conditions.

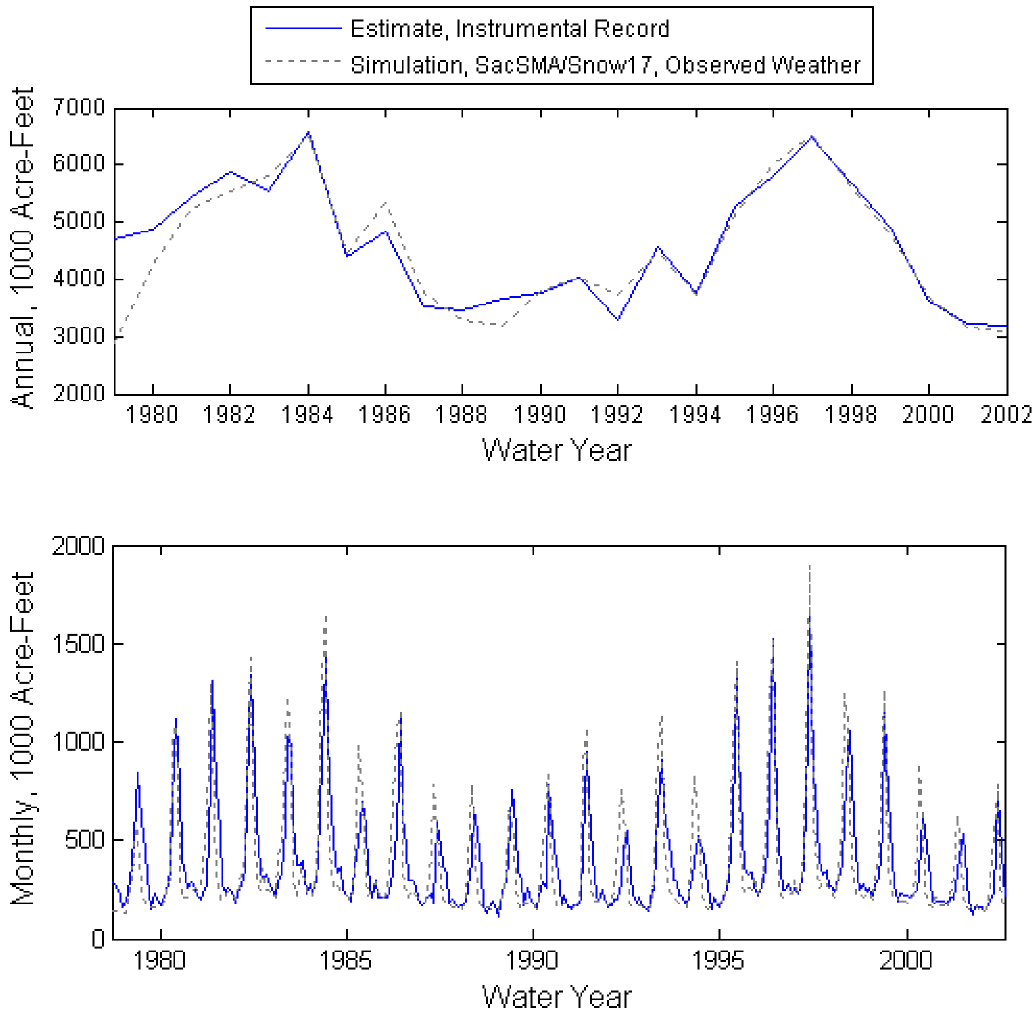

Figure 18 – Upper Missouri - Process-based Simulation of Historical Runoff given observed Weather.

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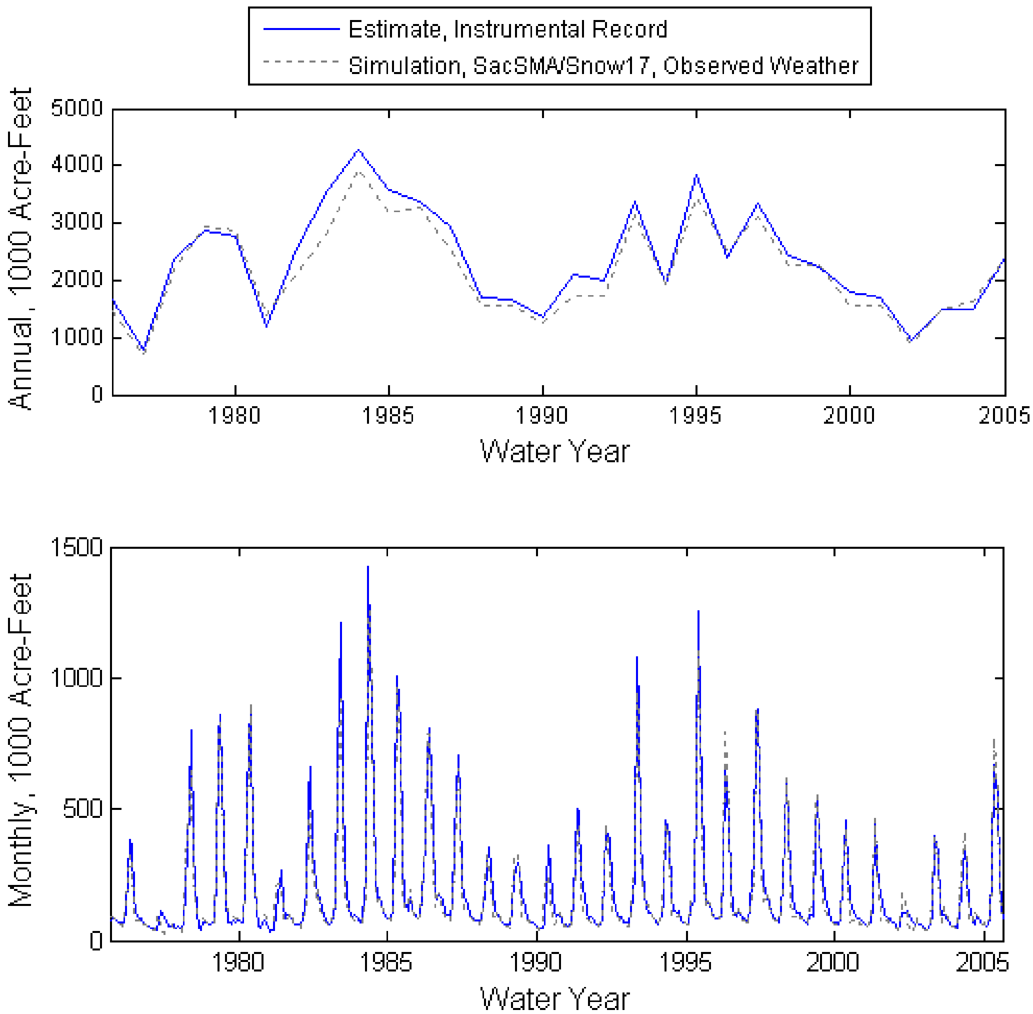

Figure 19 - Gunnison - Process-based Simulation of Historical Runoff given observed Weather.

4.0 Methods

Using the preliminary datasets described in Section 2, and the models described in Section 3, the Null Alternative hydrology dataset along with three alternative hydrology datasets were developed corresponding to the three alternative climate information sets described in Section 1.3:

- Alternative 1 – Instrumental Record, Paleoclimate Proxy
- Alternative 2 – Instrumental Record, Projected Climate
- Alternative 3 – Instrumental Record, Paleoclimate Proxy, Projected Climate.

4.1. Alternative 1 - Instrumental Record, Paleoclimate Proxy

As noted, it is generally accepted that reconstructed flows based on tree-rings are good indicators of annual hydrologic state (Woodhouse et. al. 2006), but less reliable indicators of annual magnitude. Using the two-stage stochastic modeling framework (Section 3.1), state information from reconstructed runoff is blended in Alternative 1 with magnitudes information from the Null Alternative hydrology (Figure 20).

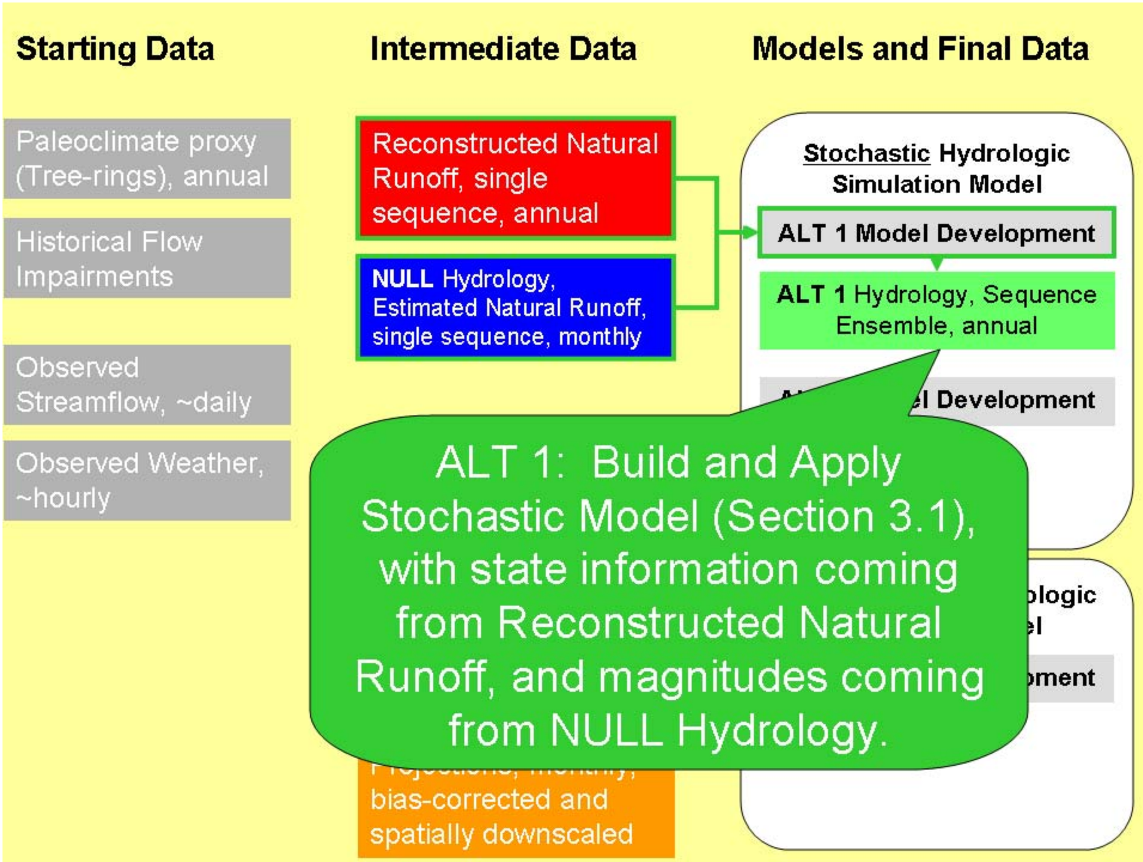

Figure 20 - Analysis Schematic –Alternative 1 Hydrology Development.

4.1.1 Stochastic Model Implementation Decisions

Referencing model implementation decisions outlined in Section 3.1, the following decisions were made for the Alternative 1 stochastic model:

1. **Reference climates to define (a) annual state and (b) annual magnitude:** Use the climate data in the reconstructed record to define state characteristics through time (i.e., the series of annual runoff states on Figure 5 and Figure 6), and the climate data of the instrumental record (which is equal to the Null Alternative) to define magnitude possibilities during any specific year (i.e., the annual runoff volumes shown on Figure 3 and Figure 4).

2. **Number of categorical states that will be modeled:** Define two hydrologic states as “wet” and “dry,” specifically defined as being

respectively wetter or drier than the period-median annual runoff during the complete reconstruction period[10].

3. **How much "n-year" auto-correlation to stochastically represent:** Design model to represent lag 1-year auto-correlation tendencies in the reference climate. This means that 2-year state-transition sequences are probabilistically modeled. In other words, during any given stochastic year, the likelihood of state depends on the state of the previous year and four two-year state-transition probabilities estimated from the reference climate: wet-wet, wet-dry, dry-wet, and dry-dry[11].

As with the model demonstration described in Section 3.1, the models developed under Alternative 1 were applied to simulate 500 annual runoff sequences, each having a period-duration matching that of the period of instrumental record (i.e., 73 years for the Upper Missouri sequences and 99 years for the Gunnison sequences). This duration was chosen so that statistical comparison of the Null Alternative's and Alternative 1's hydrologic sequences would not be affected by the respective datasets having different sample durations. (That said, Alternatives 2 and 3 planning hydrology feature hydrologic series of different durations, so this criterion was not universally applied in the study.)

Alternative 1 hydrology data were then summarized using period-statistics similar to those shown in the example discussed in Section 3.1 (and as shown on Figure 16 and Figure 17). The period-statistics vary across the ensemble of Alternative 1 sequences that were modeled. In addition to period-statistics, surplus and deficit spell and accumulation characteristics were also characterized; first by sequence, and then in a pooled sense across the ensemble of sequences. This latter view is relevant given that the ensemble of hydrologic sequences would presumably feed into an ensemble of operations simulations, the results of which would receive a pooled evaluation (e.g., Reclamation 2007).

4.2. Alternative 2 - Instrumental Record, Projected Climate

The purpose of Alternative 2 is to generate hydrology associated with climate projections that develop and evolve through time. This involves translating climate projections into runoff projections using the process-based hydrologic

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[10] For the second modeling stage when magnitude is associated with state, the candidate magnitudes from the Null Alternative are categorized according to similar "wet" and "dry" state. definitions, but defined relative to period-median annual runoff in the Null Alternative rather than reconstructed record. So, for example, when stage one simulates a "wet-wet" state based on transition information from the reconstructed record, a magnitude is sampled from the distribution of cases "wet-wet" cases characterized in the instrumental records.

[11] See information in Appendix B for how these transition probabilities are assumed to vary through time given information on lower frequency "state" variability in the reconstructed runoff record.

simulation model described in Section 3.2 and synthetic input weather scenarios consistent with the monthly climate projections described in Section 2 (**Figure 21**).

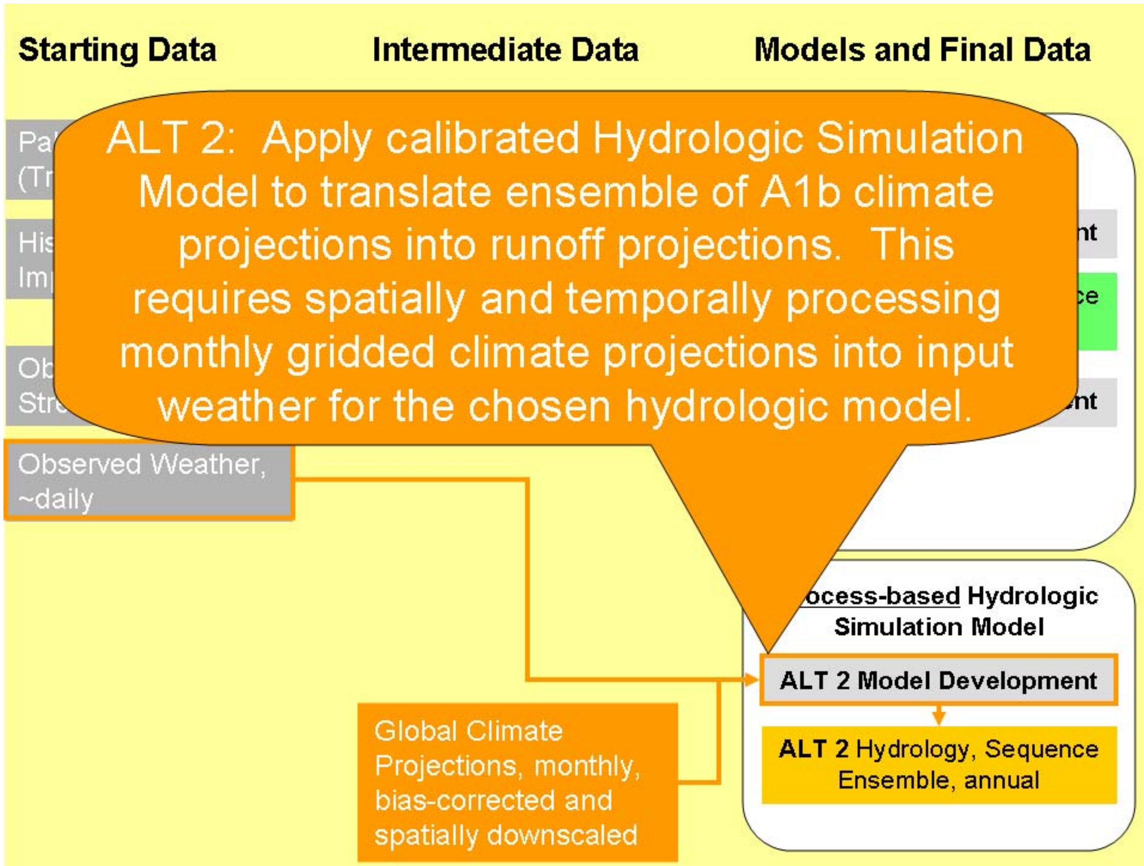

Figure 21 - Analysis Schematic – Alternative 2 Hydrology Development.

For this study, 39 A1b climate projections were considered, each illustrating how climate could evolve under the A1b GHG emissions scenario, but reflecting uncertainties of climate model choice and estimate of initial climate system condition. Each of the 39 projections includes a simulated-historical climate from 1950-1999 transitioning to a projected 21st century climate starting in year 2000 (and differing from historical 2000-2009). Each projection's monthly temperature and precipitation conditions during the sub-period of 1950-1999 are statistically consistent with observed monthly conditions during that period (Section 2.4, bias-correction discussion). This means that the simulated runoff statistics associated with these simulated-historical climate projections should be generally consistent with the observed runoff statistics from that period.

For each climate projection, an associated series of synthetic input weather had to be developed. Ideally, the SacSMA input series of potential evapotranspiration (PET) also would have been adjusted for projected changes in temperature.

However, this adjustment was not made, following the approach used in Reclamation (2008)[12].

Synthetic weather series had to satisfy two criteria:

- Be characterized in the time-step and spatial elements featured in the chosen calibrated hydrologic simulation models (i.e., use a 6-hourly time-step and be characterized as a mean-area condition during each time-step for the model's topographically defined sub-areas where water balances are computed).

- Be consistent with the time-step and spatial structure of the climate projection data (i.e., monthly time-step and regular 1/8º spatial grid as described in Section 2.4).

The following sections provide detail on how synthetic weather data were generated.

4.2.1 Synthetic Weather Generation - Spatial Processing

An area-weighted technique was used to compute mean-area time series of projected temperature and precipitation in each elevation-defined sub-area within each sub-basin area (i.e., sub-area). In the area-weighted technique, the climate projections' data grid (Figure 1, gray grid lines) was intersected with SacSMA/Snow17 sub-basins boundaries (Figure 1, red lines) and sub-areas within sub-basins (not shown on Figure 1). For a given sub-area, its fraction overlap with each projection grid-cell was computed. These fractions then served as weights in the aggregation of multiple grid-cell temperature and precipitation time series intersecting a given sub-area into mean sub-area time series.

4.2.2 Synthetic Weather Generation – Temporally Disaggregating Climate Projections

In summary, this section addresses how 6-hourly temperature and precipitation series are generated so that they aggregate to the same monthly series of an associated climate projection. The technique involves historical data resampling and scaling (or shifting) operated on the mean sub-area monthly time series (from

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[12] As alluded to in footnote 9, the choice to follow Reclamation (2008) and not adjust input PET for this study's SacSMA/Snow17 applications was probably a poor choice given that the basins of this study are relatively more arid (i.e., actual ET accounts for a greater share of precipitation fate). PET changes under warming could be significant in these basins. Hence, runoff projections developed under Alternative 2 and used under Alternative 3 likely feature overestimated mean-annual runoff conditions through the 21st century as climate warms. This interpretation issue will be revisited in Section 5. Even though the choice to not adjust PET with warming affects interpretation of Alternative 2 and Alternative 3 hydrology on their own, it should not affect comparative interpretation of these two alternatives.

Spatial Processing above. The technique is described in Wood et al. (2002) and Maurer (2007) and involves:

- Progressing through a given sub-area's simulated temperature and precipitation time series, 1950-2099, and associating a randomly selected historical observed month with every simulated month.

- Shifting the randomly selected historical observed month's 6-hourly series to match the month-aggregate value from the simulated month.

To illustrate, consider making synthetic 6-hourly weather for a single monthly climate projection. Each month's 6-hourly weather is generated using the above procedure, applying it independently for every month in the projection. Examine January 2031 in the projection. Consider a given sub-area's temperature and precipitation conditions. The chosen hydrologic simulation model needs these values disaggregated into plausible 6-hourly sequences of temperature and precipitation. The first step involves randomly sampling a historical month (e.g., January 1979), with some sampling constraints discussed later in this section. The purpose is for January 1979 to provide a realistic sequence of 6-hour weather variability, but shifted or scaled to be consistent with the simulated January 2031 month-aggregate condition. For temperature, the observed historical January 1979 6-hourly series is uniformly shifted by the difference in mean observed January 1979 and mean simulated January 2031. For precipitation, the observed historical January 1979 6-hourly series is uniformly scaled by the ratio of mean simulated January 2031 to mean observed January 1979.

There are some cautions when applying the temporal disaggregation scheme of Wood et al. 2002. The cautions primarily focus on precipitation scaling issues and, generally speaking, not wanting to sample "really dry" observed months for the purpose of generating a precipitation series associated with a "really wet" simulated month. There are also cautions about maintaining space-time coherence of weather patterns propagating across the basin during the month. To address these cautions, several resampling constraints were imposed.

- Sampling was coordinated by month, meaning that for a given simulated calendar month, only the pool of observed historical sequences for that calendar month were eligible for consideration (e.g., observed historical "January" sequences could be sampled for simulated January months, but not others).

- A wetness and warmth classification was applied. For each month, the observed-historical value was classified into four categories: wet-warm, wet-cool, dry-warm, dry-cool. This created an annual series of month-types for each month. This classification was conducted for each month and for each sub-area. Thus, when a relatively wet-warm projected January was encountered and needed to get a 6-hourly observed-historical

January, only the wet-warm historical Januaries were eligible to be sampled. From that limited pool of eligible Januaries, the sample was then random[13].

- To address the space-time coherence issue, the sampled observed-historical month had to apply to all model spatial sub-areas.

- A non-zero precipitation requirement was applied for eligible observed historical months, avoiding the possibility of infinite scaling ratios. This criterion combined with the previous bullet implies that if a sub-area's observed historical time series has a historical year-month with zero precipitation, then that historical year-month is automatically ineligible for consideration in other sub-areas.

The climate projection features a range of possible temperature and precipitation months that mostly overlaps with the range of historically observed conditions (following the bias-correction described in Section 2.4). It can be said that the scaling aspects of this weather generation technique do not (for the most part) generate an envelope of synthetic 6-hourly conditions that differ significantly from the observed envelop. Also, any exceptions to this are somewhat muted given that this study focuses on monthly to annual aggregate runoff from the simulation models. Sub-monthly runoff results would be more sensitive to the 6-hourly weather characterization.

4.2.3 Runoff Projections Ensemble and Evaluation Approach

Alternative 2 hydrology data were produced by applying the hydrologic simulation model to translate each of the 39 Alb climate projections into runoff projections, each forced by a uniquely generated 6-hourly synthetic weather series. Each projection has duration of 1950-2099, consistent with the climate projections' duration. The 6-hourly runoff was aggregated into monthly and annual runoff projections for evaluation purposes.

As with Alternative 1, the Alternative 2 hydrology data were first summarized using period-statistics for four projection periods: 1950-1999, 2010-2039, 2040-2069, and 2070-2099. These distributions indicate how Alternative 2 hydrologic statistics vary across the projections within a given period. In addition to period-statistics, surplus and deficit spell and accumulation characteristics were also characterized during each of the four projection periods. Comparison of period-statistics and spell/accumulation characteristics from period to period indicates how climate change is projected to affect hydrologic characteristics through time.

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[13] Although after identifying common year-type classifications, historical sampling was this classified year-type was random. Alternatively, a local-similarity technique might have been applied (e.g., k-Nearest Neighbor in temperature and precipitation space (Lall and Sharma 1996)).

4.3. Alternative 3 - Instrumental Record, Paleoclimate Proxy, Projected Climate

As discussed earlier, Alternative 3 development aims to produce a planning hydrology that blends the arguably more credible aspects of paleoclimate and projected climate information. Specifically, Alternative 3 blends state information from reconstructed annual runoff with runoff magnitudes associated with climate projections and a given future period (Figure 22). This produces a hydrology that represents interannual to interdecadal runoff variability from paleoclimate information, but also time-developing changes in monthly and annual runoff statistics associated with climate projections (e.g., early spring runoff in historically snowmelt-dominated basins, due to warming).

4.3.1 Stochastic Model Implementation Decisions

Stochastic model implementation of Alternative 3 is very similar to that of Alternative 1. The following model implementation decisions (outlined in Section 3.1) were made:

1. **Reference climates to define (a) annual state and (b) annual magnitude:** Use the climate of the reconstructed record to define state characteristics through time (i.e., the series of annual runoff state on **Figure 5** and **Figure 6**) as in Alternative 1, and climate projections (Alternative 2 runoff projections, and chosen projection period) to define magnitude possibilities during any specific year.

2. **Number of categorical states that will be modeled:** (Same as Alternative 1) Define two hydrologic states as “wet” and “dry,” specifically defined as being respectively wetter or drier than the period-median annual runoff during the complete reconstruction period[14].

3. **How much “n-year” auto-correlation to stochastically represent:** (Same as Alternative 1) Design model to represent lag 1-year auto-correlation tendencies in the reference climate. This means that two-year state-transition sequences are probabilistically modeled, as in Alternative 1.

[14] For the second modeling stage when magnitude is associated with state, the candidate magnitudes from the Null Alternative hydrology are categorized according to similar “wet” and “dry” state definitions, but defined relative to period-median annual runoff in the Null Alternative rather than reconstructed record. So, for example, when stage one simulates a “wet-wet” state based on transition information from the reconstructed record, a magnitude is sampled from the distribution of cases “wet-wet” cases characterized in the instrumental record.

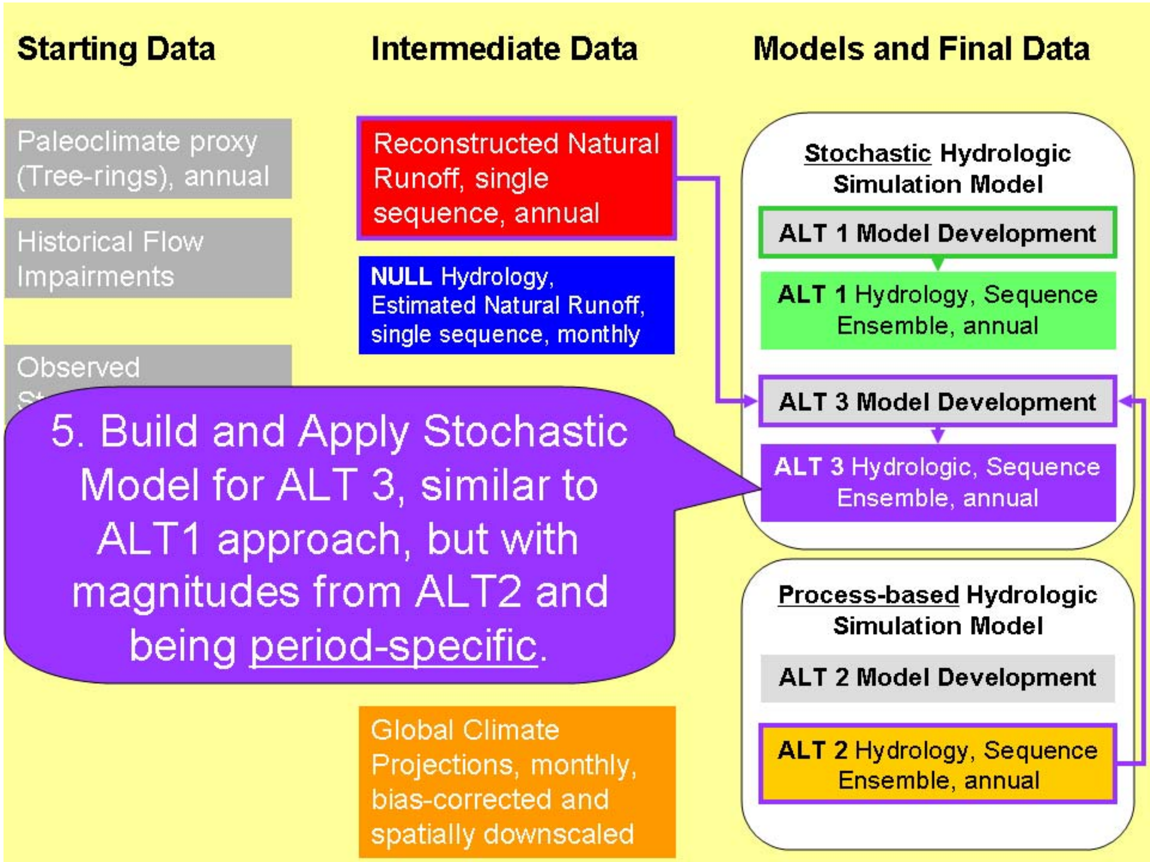

Figure 22 - Analysis Schematic – Alternative 3 Hydrology Development.

In summary, the Alternative 3 stochastic model primarily differs from that of Alternative 1 in its data source for specifying annual runoff magnitudes. The ensemble of projected annual runoff of a chosen projection period provides magnitude possibilities rather than the instrumental record runoff as used in Alternative 1.

Alternative 3 represents blending a stationary hydrology viewpoint (i.e., stochastic modeling and representing variability and statistics of a reference climate) with a non-stationary climate context (i.e., transient climate projections). This is accomplished by choosing multiple projection periods and applying the Alternative 3 stochastic model for each period's ensemble of runoff projection data (pooled across the ensemble) during the period. The same periods considered in Alternative 2 are considered in Alternative 3: 1950-1999, 2010-2039, 2040-2069, and 2070-2099. Note that these periods were chosen arbitrarily for evaluation purposes in this study. In application, the chosen projection period for magnitudes sampling would be influenced by the planning study's look-ahead horizon (e.g., if an infrastructure proposal is being evaluated and involves service life through 2060, then perhaps a projection period encapsulating 2060, like 2041-2070, might be chosen for sampling runoff projection information).

4.3.2 Runoff Sequences Ensemble and Evaluation Approach

As with Alternative 1, the models developed under Alternative 3 were applied to simulate 500 annual runoff sequences. However, unlike Alternative 1, the durations of these sequences matched that of the projection periods providing magnitudes information (i.e., either 50-year or 30-year projection periods). This duration was chosen so that statistical comparison of Alternative 2 and Alternative 3 hydrologic sequences would not be affected by the respective datasets having different sample durations (although comparisons with the Null Alternative's and Alternative 1's hydrologic sequences would be affected by such differences).

As with Alternative 2, the Alternative 3 hydrology data were first summarized using period-statistics, and for four projection periods: 1950-1999, 2010-2039, 2040-2069, and 2070-2099. These distributions indicate how Alternative 3 hydrologic statistics vary across the projections within a given period. In addition to period-statistics, surplus and deficit spell and accumulation characteristics were also characterized during each of the four projection periods. Comparing period-statistics and spell/accumulation characteristics from period to period indicates how climate change is projected to affect hydrologic characteristics through time.

5.0 Results

This section summarizes the planning hydrology developed for the three alternative climate information sets. Hydrology data are first summarized statistically and then evaluated for spell and accumulation characteristics for multiple year periods.

Table 2 provides a summary of annual period-statistics for each dataset and case study basin. For interpretation purposes, two notes are emphasized:

1. The Null Alternative’s hydrology data are statistically summarized for two different periods. The full period statistics are meant for comparison with Alternative 1’s statistics. The sub-period 1951-1999 statistics are meant for comparison with Alternative 2’s and Alternative 3’s statistics. The latter is based on the understanding that the simulated observed 1951-1999 statistics (i.e., for water years, starting October 1950 and ending September 1999) should be close to those of the climate projections given that the climate projections were bias-corrected relative to a 1950-1999 calendar-year period (i.e., January 1950 through December 1999).

The statistical information on Alternatives 1 through 3 hydrology data reflects an ensemble of runoff sequences and sequence-specific statistics. The number of sequences of each ensemble is indicated in the third column of Table 2.

Table 2. Period Statistics of Annual Runoff associated with Null Alternative and Alternative Climate Information Sets.

Alternative	Period	Ensemble Size	Mean (MAF[2])	Standard Deviation (MAF)	Skew	Lag 1-year Auto Correlation	Maximum (MAF)	Minimum (MAF)
Upper Missouri								
Null (Instrumental Record)	1929-2002	1	4.5	0.9	0.25	0.55	6.6	2.8
	1951-1999	1	4.8	0.8	0.1	0.44	6.6	3.3
Reconstructed (Paleo.)	1569-1997	1	4.2	0.8	-0.2	0.38	7.1	1.6
Alt. 1 (Instr., Paleo.)	73-year [1]	500	4.4 (4.1, 4.8) [3]	0.9 (0.8, 1.0)	0.3 (-0.25, 0.8)	0.48 (0.28, 0.68)	6.6 (6.0, 6.6)	2.8 (2.8, 3.1)
Alt. 2 (Instr., Projected)	1951-1999	39	4.6 (4.5, 4.7)	1.1 (0.8, 1.3)	0.7 (-0.2, 1.4)	0.44 (0.16, 0.59)	7.5 (6.5, 8.7)	2.8 (2.1, 3.1)
	2010-2039	39	4.6 (3.8, 6.0)	1.1 (0.7, 1.6)	0.5 (-0.1, 1.7)	0.33 (0.18, 0.60)	7.1 (5.4, 10.1)	2.9 (2.2, 3.7)
	2040-2069	39	5.0 (4.2, 6.9)	1.2 (0.8, 1.8)	0.7 (-0.3, 1.3)	0.28 (0.00, 0.58)	8.1 (6.4, 12.7)	3.1 (2.4, 4.3)
	2070-2099	39	5.6 (4.5, 7.2)	1.2 (0.8, 1.9)	0.3 (0.1, 1.2)	0.28 (-0.02, 0.52)	8.4 (6.8, 11.9)	3.5 (2.5, 4.3)
Alt. 3 (Instr., Paleo., Projected)	1951-1999	500	4.6 (4.1, 5.0)	1.0 (0.7, 1.2)	0.7 (0.0, 1.7)	0.33 (0.00, 0.55)	7.6 (6.2, 9.2)	2.8 (2.4, 3.3)
	2010-2039	500	4.6 (3.9, 5.3)	1.2 (0.7, 1.7)	0.8 (-0.1, 2.0)	0.34 (0.03, 0.63)	7.6 (5.7, 10.0)	2.7 (2.2, 3.4)
	2040-2069	500	5.1 (4.2, 6.1)	1.3 (0.8, 2.1)	0.8 (-0.1, 2.1)	0.33 (-0.02, 0.64)	8.6 (6.3, 12.9)	2.9 (2.3, 3.8)
	2070-2099	500	5.3 (4.6, 6.3)	1.4 (0.9, 1.9)	0.6 (-0.2, 1.7)	0.37 (-0.03, 0.67)	8.7 (6.6, 11.3)	3.2 (2.5, 3.9)
Gunnison								
Null (Instrumental Record)	1906-2005	1	2.3	0.72	0.2	0.27	4.3	0.8
	1951-1999	1	2.2	0.65	0.2	0.07	3.7	1.1
Reconstructed (Paleo.)	1576-1996	1	2.3	0.7	-0.3	0.03	4.1	0.2
Alt. 1 (Instr., Paleo.)	100-year [1]	500	2.3 (2.2, 2.5)	0.72 (0.64, 0.78)	0.2 (-0.2, 0.3)	0.05 (-0.10, 0.20)	4.3 (3.7, 4.3)	0.8 (0.8, 1.1)
Alt. 2 (Instr., Projected)	1951-1999	39	2.3 (2.3, 2.4)	0.82 (0.7, 0.97)	0.7 (0.2, 1.3)	0.22 (0.02, 0.36)	4.5 (4.0, 5.8)	1.1 (0.8, 1.3)
	2010-2039	39	2.3 (1.8, 2.9)	0.87 (0.58, 1.36)	0.9 (0.3, 2.4)	0.15 (-0.05, 0.41)	4.6 (3.3, 7.0)	1.2 (0.8, 1.4)
	2040-2069	39	2.3 (1.9, 3.3)	0.95 (0.65, 1.28)	0.8 (0.2, 1.8)	0.18 (0.00, 0.51)	4.9 (3.3, 6.5)	1.1 (0.8, 1.4)
	2070-2099	39	2.4 (1.8, 3.6)	0.88 (0.52, 1.34)	0.8 (0.2, 1.8)	0.18 (-0.07, 0.38)	4.9 (3.1, 6.8)	1.0 (0.7, 1.6)
Alt. 3 (Instr., Paleo., Projected)	1951-1999	500	2.3 (2.1, 2.6)	0.78 (0.62, 0.94)	0.7 (0.2, 1.5)	0.08 (-0.15, 0.30)	4.4 (3.7, 5.8)	1.0 (0.7, 1.3)
	2010-2039	500	2.3 (2.0, 2.7)	0.87 (0.66, 1.20)	0.9 (0.2, 2.2)	0.07 (-0.25, 0.41)	4.6 (3.6, 6.6)	1.1 (0.9, 1.3)
	2040-2069	500	2.4 (2.0, 2.8)	0.94 (0.68, 1.26)	1.0 (0.2, 1.8)	0.07 (-0.25, 0.38)	5.0 (3.7, 6.3)	1.1 (0.8, 6.3)
	2070-2099	500	2.5 (2.1, 2.9)	0.96 (0.68, 1.40)	0.8 (0.2, 2.0)	0.10 (-0.20, 0.40)	5.0 (3.8, 7.7)	1.0 (0.8, 1.4)

Notes:
[1] For comparison with Null statistics of the full period minus one year.
[2] MAF = Million Acre-Feet
[3] Values show how the period statistic varied across the different series in the ensemble (i.e. median (5th percentile, 95th percentile))

The variation of sequence-specific statistics is indicated in the columns that follow. A statistic's ensemble-median is listed first, followed by the minimum and maximum sequence-specific values listed in parentheses. For example, for the Upper Missouri, the 500-series ensemble of under Alternative 1 produced an ensemble-median mean annual runoff of 4.4 million acre-feet (MAF); sequences-specific values of "mean annual runoff" varied between 4.1 and 4.8 MAF.

Evaluation of Upper Missouri runoff period-statistics leads to the following observations when comparing hydrologic alternatives.

- **Mean:** The Null Alternative (i.e., instrumental record) and Alternative 1 runoff means are similar when the full period of the Null Alternative hydrology is considered. This is expected since Alternative 1 magnitudes were sampled from the Null Alternative hydrology. Reconstructed runoff mean is less than that of Null Alternative for both periods of Null Alternative hydrology considered. Alternatives 2 and 3 period-specific means, which reflect projected climate effects on annual runoff possibilities, both evolve during the 21st century to exceed the mean of the Null Alternative hydrology. Though, the latter may be an artifact of not adjusting potential evapotranspiration with warming[15]. Alternatives 2 and 3 have generally consistent period-specific means, which is expected since they reflect common periods of projected runoff.

- **Standard Deviation:** Results are similar for the Null Alternative hydrology, reconstructed runoff, and Alternative 1 (which features magnitudes possibilities from the Null Alternative hydrology). The envelope of variation broadens for Alternatives 2 and 3 (which reflects magnitudes possibility from projected climate).

- **Skew:** A weak positive skew exists in the Null Alternative hydrology and Alternative 1 This is expected because both feature magnitudes from the Null Alternative hydrology, which has a "wet" skew. A stronger positive skew exists in both Alternatives 2 and 3. A weak negative skew exists in the reconstructed record. This skew may exist because tree-ring chronologies are not able to accurately portray wetter year magnitudes.

- **Lag 1-Year Auto-Correlation:** The Null Alternative hydrology has more positive auto-correlation than the reconstructed runoff. Alternative 1 hydrology seems to have positive auto-correlation consistent with both the Null Alternatives magnitudes and reconstructed state information reflected

[15] Referencing footnote 9 and discussion in Section 3.2, the decision to not increase PET in response to projected temperature increases was likely a poor choice. As a result, mean-annual runoff estimates for Alternative 2 and Alternative 3 may be overestimated, and should be comparably overestimated given that Alternative 2 magnitudes are used in Alternative 3 (Section 4.3).

in the Alternative 1 stochastic model. The resultant Alternative 1 auto-correlation is in between that of the Null Alternative and reconstructed runoff, respectively. By comparison, Alternative 3 hydrology has positive auto-correlation consistent with both the Alternative 2 magnitudes and reconstructed state information reflected in the Alternative 3 stochastic model. Generally speaking, the resultant Alternative 3 auto-correlation is in between that of the Alternative 2 runoff (by period) and reconstructed runoff, respectively.

- **Maximum and Minimum:** The Alternative 1 and Null Alternative hydrology feature approximately the same range of magnitudes, which is expected since the Alternative 1 stochastic model sampled Null Alternative hydrology magnitudes. Alternative 2 and 3 maximum-annuals evolve similarly with time, increasing from the Null Alternative.

Evaluation of Gunnison hydrology period-statistics leads to the similar observations when comparing hydrologic alternatives, but with some differences as noted:

- **Mean:** Null Alternative hydrology (i.e., instrumental record) and Alternative 1 runoff means are similar when the full period of the Null Alternative hydrology is considered. This is expected since Alternative 1 magnitudes were sampled from the Null Alternative hydrology. Unlike the Upper Missouri, the Gunnison reconstructed runoff mean is approximately the same as that of Null Alternative during its full period. Alternatives 2 and 3 period-specific means, which reflect projected climate effects on annual runoff possibilities, both stay roughly similar to the Null Alternative until the mid-21st century, and then increase slightly toward the end of the 21st century. Though, as with the Upper Missouri, this result may be an artifact of not adjusting potential evapotranspiration with warming[15]. Alternative 2 and 3 have generally consistent period-specific means, as expected since they reflect common periods of projected runoff.

- **Standard Deviation:** As with the Upper Missouri, results are similar for the Null Alternative hydrology, reconstructed runoff, and Alternative 1. The envelope of variation broadens for Alternatives 2 and 3 (which reflects magnitudes possibility from projected climate).

- **Skew:** A weak positive skew exists in the Null Alternative hydrology and Alternative 1. This is expected because both feature magnitudes from the Null Alternative hydrology, which has a “wet” skew. A stronger positive skew exists in both Alternatives 2 and 3. A weak negative skew exists in the reconstructed record. This skew may exist because tree-ring chronologies are not able to accurately portray wetter year magnitudes.

- **Lag 1-Year Auto-Correlation:** The Null Alternative hydrology has more positive auto-correlation than the reconstructed runoff. Contrasting from Upper Missouri results, the Gunnison Alternative 1 hydrology's positive auto-correlation seems to be less consistent with the Null Alternative and more consistent with the reconstructed runoff's state information. The resultant Alternative 1 auto-correlation is closer to that of the reconstructed runoff. Likewise, Alternative 3 hydrology has positive auto-correlation consistent with both the Alternative 2 magnitudes and reconstructed runoff's state information, but resembles the latter more.

- **Maximum and Minimum:** The Alternative 1 and Null Alternative hydrology feature approximately the same range of magnitudes, which is expected since the Alternative 1 stochastic model sampled Null Alternative hydrology magnitudes. Alternative 2 and 3 maximum-annuals evolve similarly with time, increasing from the Null Alternative.

Sections 5.1 and 5.2 provide more detailed discussion and runoff graphics to compliment the statistical summaries in Table 2. Section 5.1 shows the Upper Missouri results and 5.2 shows the Gunnison results. Results are presented separately for each basin, focusing on: (i) period-statistics, (ii) and frequency (or spell and accumulation) characteristics.

5.1. Hydrologic Datasets for the Upper Missouri

5.1.1 Period Statistical Characteristics

5.1.1.1. Alternative 1

For Alternative 1 (i.e., instrumental record, paleoclimate), Figure 23 shows the ensemble of 500 stochastically modeled sequences of annual runoff (top panel). It also shows the ensemble translated into 500 sequence-specific probability density estimates (PDEs) of annual runoff (bottom panel); those PDEs have also been sampled by flow range (bottom panel, boxplots) for how density varied across the sequences at a given flow range. For comparison, the Null Alternative hydrology (instrumental record) sequence and PDE are shown. The reconstructed runoff PDE is also shown.

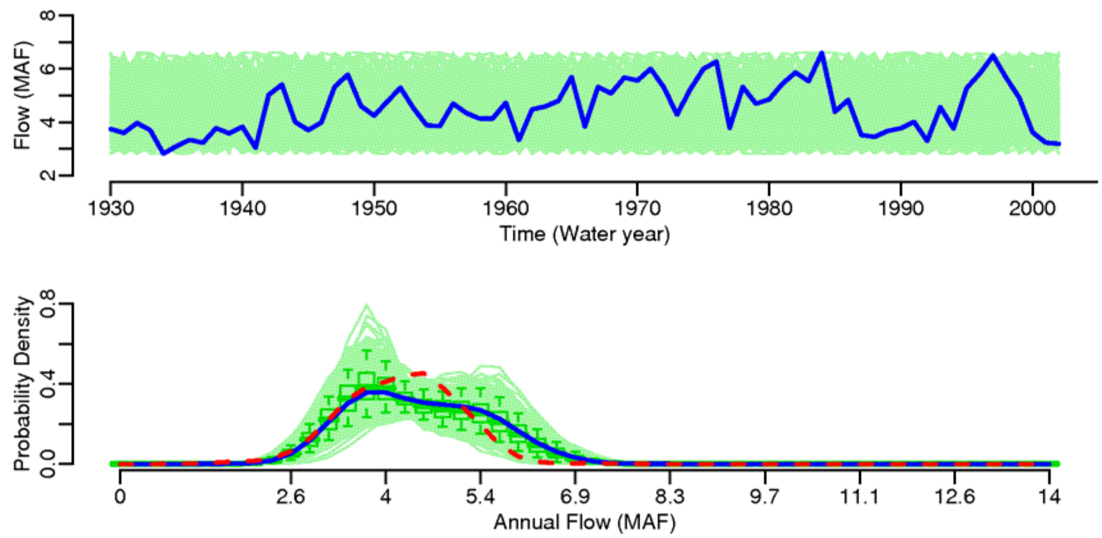

Figure 23 – Upper Missouri – Alternative 1 - Stochastically modeled Annual Runoff.

(*Top panel*) Ensemble of 500 stochastic annual flow series (light green lines) and instrumental record series (blue line, Figure). (*Bottom panel*) Ensemble of probability density estimates of annual flow (light green lines, associated with each flow series in the top panel. Dark green boxplots show how probability density estimate varied for the given flow range. Blue and red lines show probability density estimates for annual flow from the instrumental record (Figure 3) and reconstructed record (Figure 5), respectively.

The top panel of Figure 23 shows how the Alternative 1 stochastic model produced a range of annual runoff magnitudes that didn't depart from the Null Alternative hydrology range. This was by model design (Section 3.1). The bottom panel of Figure 23 shows that the stochastic model generally produced synthetic sequences that had annual runoff PDE consistent with the PDE of the magnitudes source (i.e., Null Alternative hydrology). This is evident by noticing that the PDEs in the Null Alternative hydrology's bi-modal nature is generally encapsulated and mimicked by the PDEs in Alternative 1's ensemble. However, as with any stochastic modeling exercise, a specific Alternative 1 sequence might be modeled in such a way that its PDE is fairly different from that of the reference climate (i.e., the Null Alternative PDE in this case). Figure 24 shows period-statistics from the Alternative 1 sequences, Null Alternative hydrology sequence. Alternative 1's ensemble-median statistics compare well with those of the Null Alternative. This is expected due to stochastic model design as the Null Alternative served as the magnitudes reference, and should influence statistics on mean, standard deviation, skew, maximum, and minimum.

Lag 1-year auto-correlation is influenced by both the state's climate source and the magnitudes' climate source, based on stochastic model design (Appendix B). Thus, the auto-correlation of the reconstructed runoff would be expected to be reflected in the Alternative 1 first-stage modeling of state, but then the auto-correlation of the Null Alternative hydrology would be introduced during the second-stage modeling of magnitudes. The latter is because the modeled "current year" magnitude is a sampled magnitude from the Null Alternative hydrology, where eligible magnitudes were weighted to reflect previous-to-current year state transition that was just modeled (Appendix B). Figure 24 shows that lag 1-year auto-correlation for the Upper Missouri River basin during the full-period instrumental record is roughly 0.55 whereas it is roughly 0.38 for the reconstruction period. The ensemble-median auto-correlation among Alternative 1 sequences was 0.48, or in between these two values. It remains a subject of further study to understand whether, under this model design, the resultant ensemble-median auto-correlation should be closer to state's or magnitudes' reference. Results on this matter vary for Alternative 3 of the Upper Missouri and for Alternatives 1 and 3 for the Gunnison.

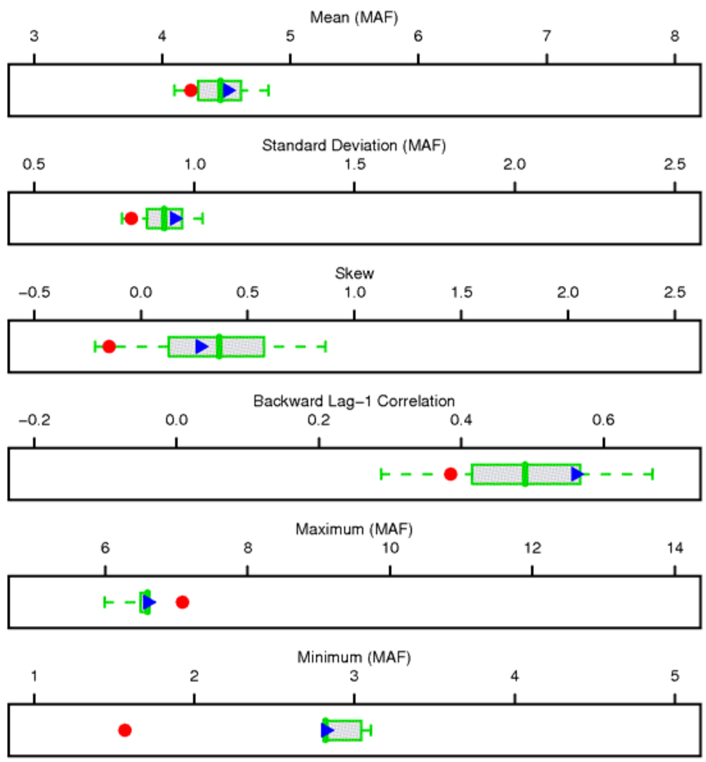

Figure 24 – Upper Missouri – Alternative 1 - Period Statistics of Annual Runoff.

Each panel corresponds to a given statistic, and shows: (a) distribution of statistic values across the Alternative 1 ensemble of 500 simulated 73-year sequences (boxplots, where box equals interquartile range, box mid-line equals median, whisker limits equal 5 and 95 percentiles), (b) the statistic's value from the instrumental record sequence (blue symbols, data from Figure 3), (c) statistic from paleoclimate-based reconstructed sequence (red symbols, data from Figure 5).

5.1.1.2. Alternative 2

Alternative 2's hydrology reflects a blend of instrumental record and projected climate information. Figure 25 shows an ensemble of annual runoff projections from 1950-2099 (top panel)[16]. This 150-year period is consistent with the period for the climate projection information. Figure 25 also shows how "30-year mean annual runoff" varies by projection and through time (i.e., the boxplots, top panel). The annual Null Alternative hydrology from Figure 3 is shown, along with the range of 30-year mean runoff within the full period of the Null Alternative hydrology. Lastly, the bottom panel shows projection distributions of mean monthly runoff for four non-overlapping periods.

Figure 25 shows the envelope of projected annual runoff possibilities from simulated history to simulated future. In the simulated history, a broader range of annual runoff possibility is evident when comparing simulated runoff series to that of the Null Alternative. This is the case even though the simulated temperature and precipitation series underlying the runoff simulations had been bias-corrected (Section 2.4) to be period-statistically consistent with observations from calendar years 1950-1999. However, the simulated runoff ensemble seems largely consistent with the Null Alternative hydrology when viewing historical period-statistics rather than historical single-year possibilities. This judgment is based on comparing the distributions of 30-year mean runoff during the three overlapping 30-year periods during 1951-1999 (i.e., first three boxplot distributions starting from the left in the top panel) with the range of 30-year mean possibilities from the Null Alternative (e.g., blue area).

Progressing into the 21st century, the envelope of annual runoff possibilities gradually broadens and drifts towards conditions that are wetter than historical. This is consistent with precipitation projections over the Upper Missouri that gradually become wetter into the 21st century (Figure 9). However, these results are also based on the simulation choice not to increase potential evapotranspiration in the hydrologic simulation in response to warming air temperature in the climate projections. It seems likely that annual runoff possibilities are overestimated in the 21st century given this simulation choice[15]; but this should not affect research questions involving comparison of Alternatives 2 and 3, as these alternatives will have the same bias in results.

Considering mean monthly runoff through time (Figure 25, bottom panel, four periods), the results show increasing runoff during August through May and decreasing runoff during June and July. For the summer decrease, warming would seem to be a significant factor, given that Winter-Spring warming would tend to reduce snow accumulation and subsequent snowmelt volume during

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[16] These runoff projections which were scaled to account for the hydrologic model bias for the Upper Missouri identified as a simulated-to-observed ratio of 0.99 in Section 3.2.

Spring-Summer. Precipitation is also projected to decrease during June-July (Figure 9), which would also contribute to runoff decreases during those months.

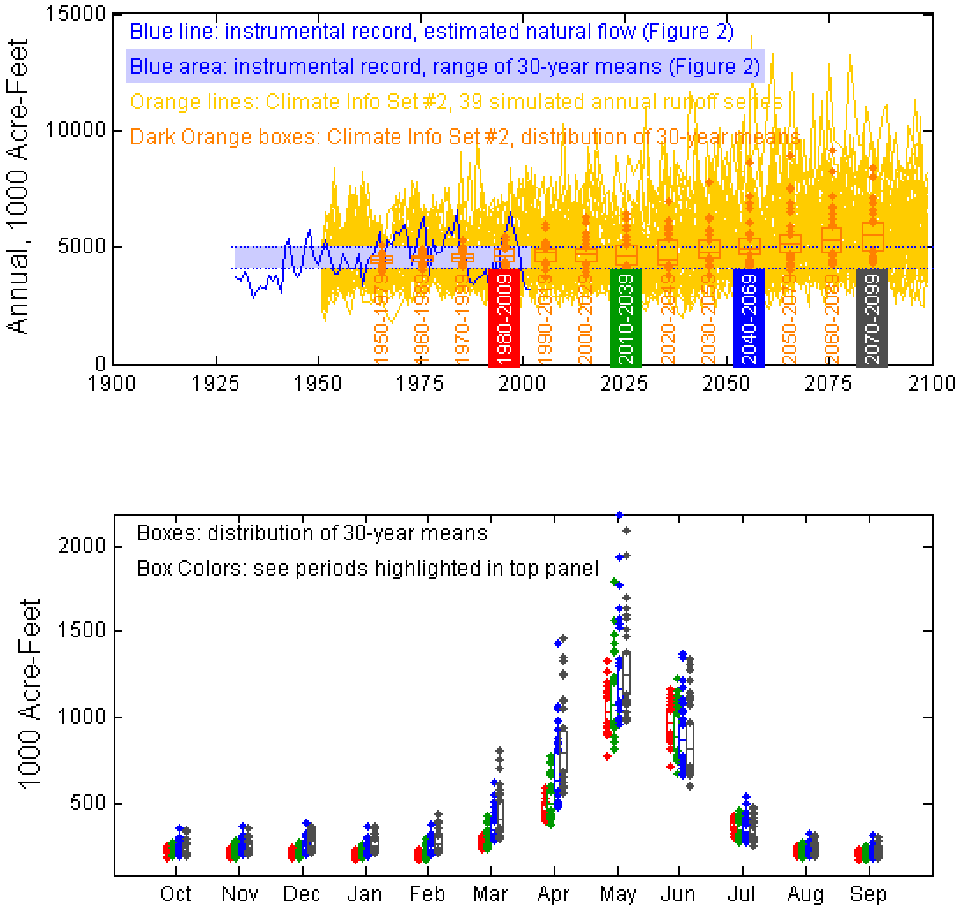


Figure 25 - Upper Missouri – Alternative 2 – Simulated Runoff Projections.

(*Top Panel*) Blue line is Null Alternative hydrology. Blue shaded area reflects range of moving 30-year mean runoff values from Null Alternative hydrology. Orange lines are simulated annual runoff projections consistent with the 39 climate projections considered in Alternative 2, corrected for hydrologic model bias (see footnote 16). Orange boxplots show how 30-year mean-annual runoff varies across the 39 runoff projections during periods indicated. (*Bottom Panel*) Focusing on the four periods color-highlighted in the top panel, boxplots show how 30-year mean-monthly runoff varies across the 39 runoff projections.

August through May's runoff increase is undoubtedly related to the simulation choice of not increasing potential evapotranspiration in response to warming. Aside from that, other factors would seem to be influential, including warmer temperatures (year-round) and increased precipitation during October through May (Figure 9). Ignoring the effect of precipitation increase, warming by itself would lead to proportionally greater fraction of annual runoff during Fall-Winter when precipitation would occur in greater fraction as rainfall rather than snowfall.

This would generate proportionally more rainfall-runoff during those months and less snowpack accumulation.

Figure 26 shows period-statistics for the ensemble of Alternative 2 runoff projections, the Null Alternative hydrology and reconstructed runoff. For Alternative 2, statistics are computed for four sub-periods in the projections, as listed in Section 4.2: 1951-1999, 2010-2039, 2040-2069, and 2070-2099., Comparing how Alternative 2's ensemble-median statistics change from historical to future shows that there was a gradual increase in the mean, standard deviation, maximum and minimum annual runoff. By contrast, there was little trend in skew through the periods, and the lag 1-year auto-correlation decreased toward the later future periods. During the overlapping historical period (1951-1999), the ensemble-median of Alternative 2 lag 1-year auto-correlations was close to that of the Null Alternative hydrology (blue symbol).

It might be noticed that the Alternative 2 ensemble generally exhibits a 1951-1999 mean-annual runoff close to 4.5 MAF, which is less than that of the observed 1951-1999 period (~4.8 MAF, based on Figure 3 data). A likely factor behind this result relates to how historical meteorology used to calibrate these hydrologic models (Section 4.2) differed from the historical meteorology used to bias-correct climate projections (Section 2.4). At issue are the procedures can be used to translate station weather observations into basin-distributed weather. The procedure used by the MBRFC to generate historical 6-hourly weather forcings (i.e., RFC distributed weather) in each model sub-area (Section 4.2) differs from the procedure used to generate historical gridded weather observations that were used to bias-correct climate projections during calendar years 1950-1999 (i.e., distributed weather from Maurer et al. 2002). As a result, the mean-area temperature and precipitation for the case study basins differ slightly between the two datasets. This is significant because the hydrologic model is calibrated to correctly relate RFC distributed weather to observed historical streamflow. When RFC distributed weather is replaced by some other distributed historical weather dataset (e.g., Maurer et al. 2002), the simulated runoff can statistically differ from that of the calibrated historical runoff.

Lastly, attention switches to Alternative 3, which features a blend of instrumental record, paleoclimate, and projected climate information. Recall that Alternative 3 involves period-specific stochastic modeling, where magnitudes modeling vary by period and originate from periods in the Alternative 2 runoff projections. Figure 27 shows period-specific ensembles of annual runoff PDE results (shown as ensemble densities binned by flow range). Figure 27 also shows annual runoff PDEs from the Null Alternative hydrology of water years 1951-1999, and from the full period of reconstructed runoff. Focusing on how the Alternative 3 ensemble of PDEs change from historical to future, results show that there is a tendency toward wetter skew, and an increase in median runoff (for the later future periods). This is consistent with the Alternative 2 tendencies in annual runoff mean and skewness (**Figure 26**).

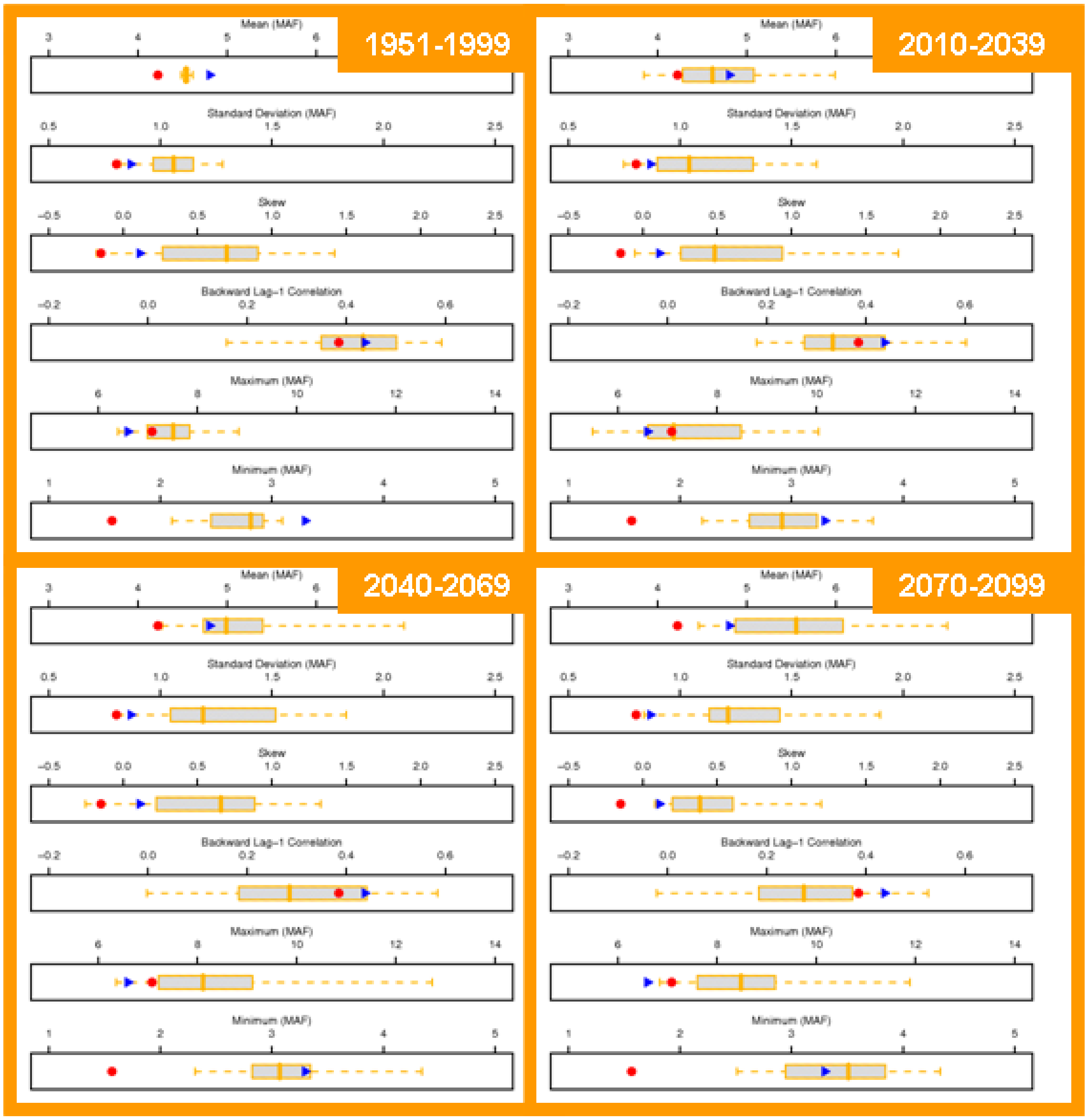


Figure 26 – Upper Missouri – Alternative 2 – Period Statistics of Annual Runoff.

Similar to Figure 24, but showing how the statistical information varies with four periods: one simulated-historical climate period and three projected future climate periods. Each panel shows: (a) distribution of statistic values across ensemble of 39 runoff projections (Figure 25) during period indicated (boxplots, where box equals interquartile range, box mid-line equals median, whisker limits equal 5 and 95 percentiles), (b) the statistic's value from the instrumental record sequence (blue symbols, data from Figure 3), (c) statistic from paleoclimate-based reconstructed sequence (red symbols, data from Figure 5).

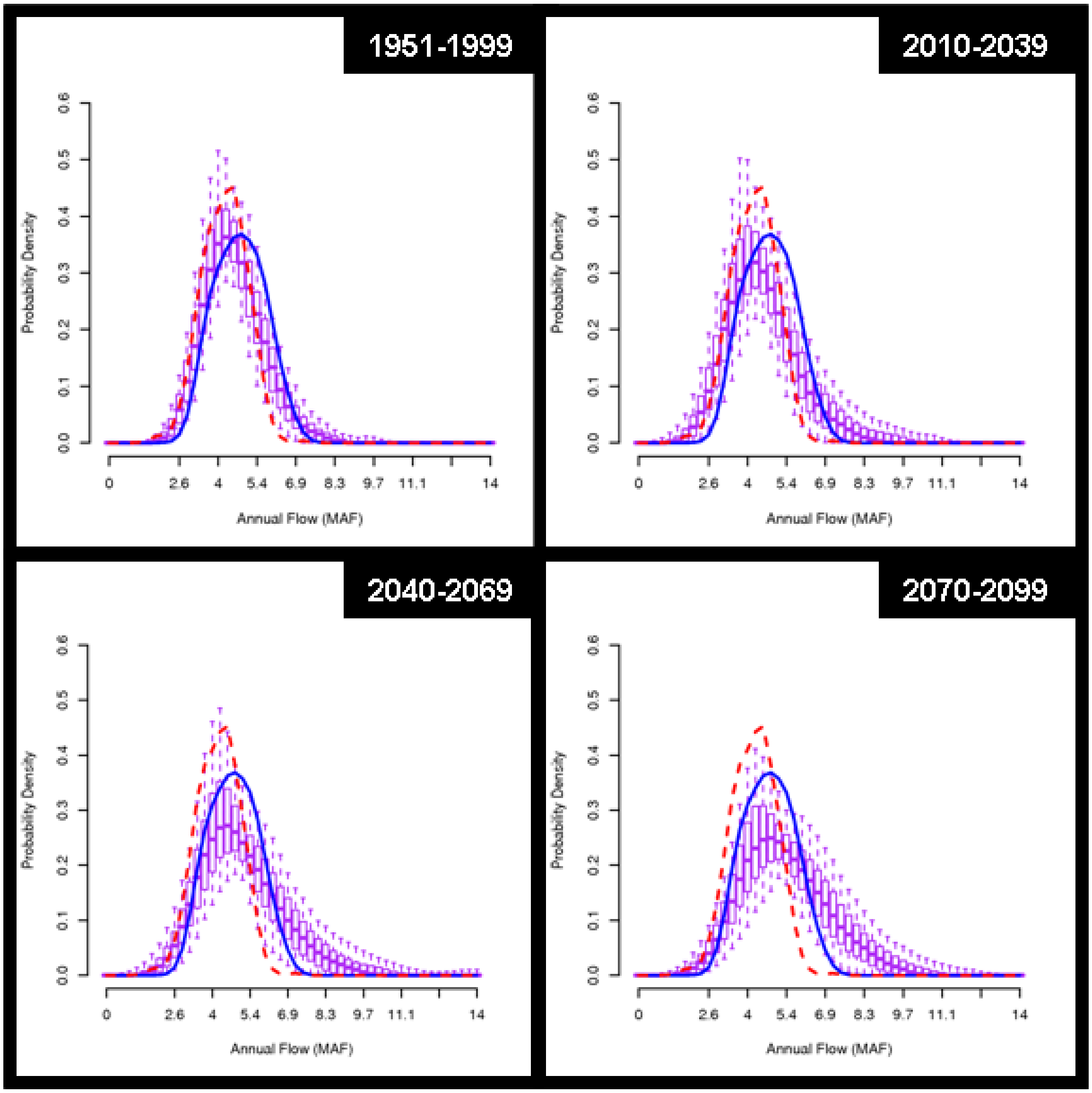


Figure 27 - Upper Missouri – Alternative 3 – Stochastically modeled Annual Runoff.

Similar to bottom panel of Figure 23, each panel shows how probability density varies at given flow ranges (purple boxplots) across a 500-member ensemble of 73-year stochastically modeled runoff series, each having duration equal to the panel's period duration. Also shown are the probability density estimates for annual flows from the instrumental record (blue line) and reconstructed record (red line).

Figure 28 shows period statistics for the ensemble of Alternative 3 sequences, repeated for each period, as well as those of the Null Alternative hydrology and reconstructed runoff. By design of the stochastic model, the Alternative 3 ensemble-median statistics should be close to the ensemble-median statistics of Alternative 2 for mean, standard deviation, skewness, maximum, and minimum.

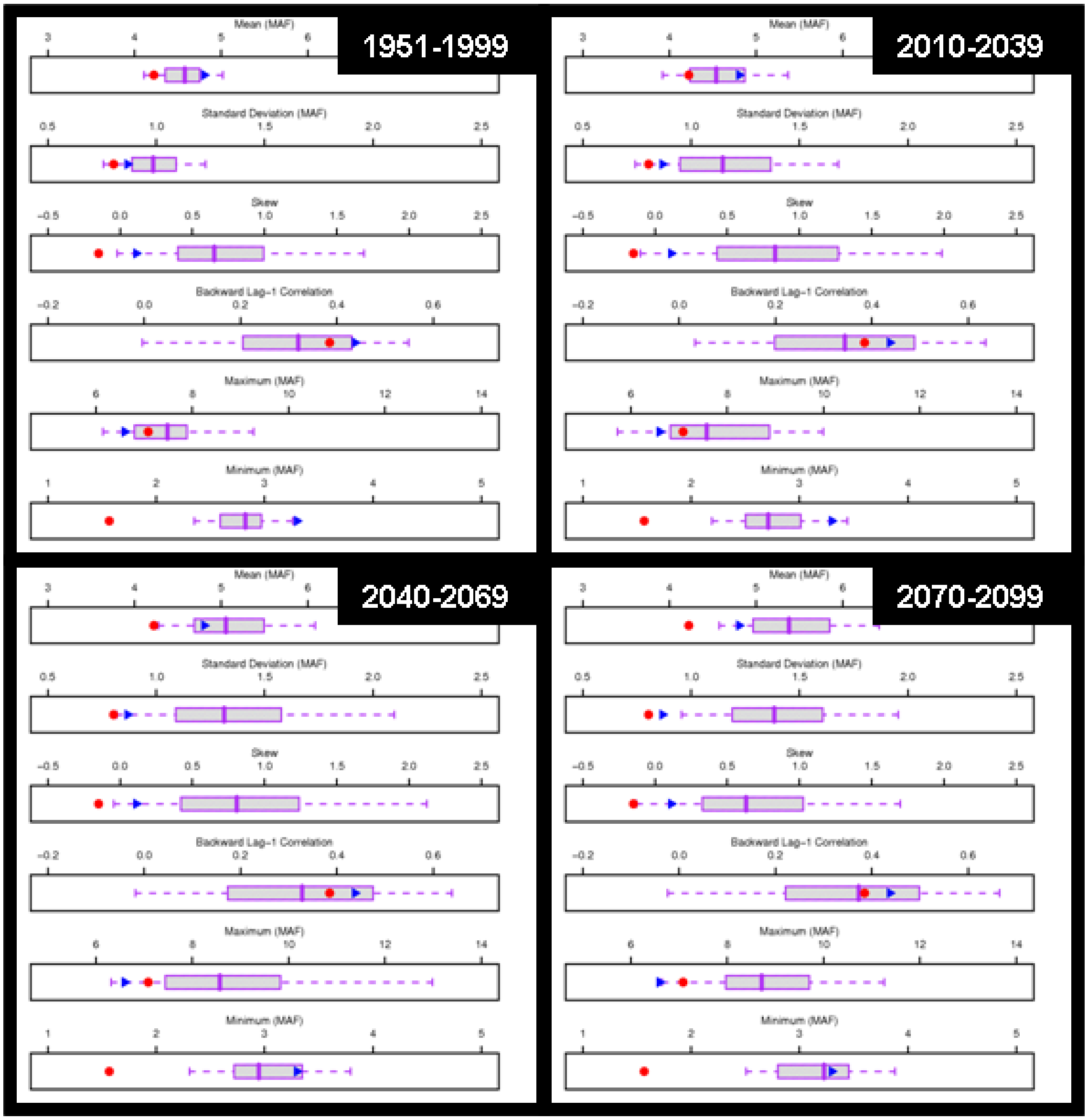


Figure 28 - Upper Missouri – Alternative 3 - Period Statistics of Annual Runoff.

Similar to Figure 26, but showing how the statistical information varies with four periods: 1 simulated-historical climate period and 3 projected future climate periods. Each panel shows: (a) distribution of statistic values across a 500-member ensemble of stochastically modeled annual flow series, each having duration equal to the panel's period of duration (boxplots, where box equals interquartile range, box mid-line equals median, whisker limits equal 5 and 95 percentiles), (b) the statistic's value from the instrumental record sequence (blue symbols, data from Figure 3), (c) statistic from paleoclimate-based reconstructed sequence (red symbols, data from Figure 5).

Results show that this is generally the case for each period (Table 2). Taki**ng** auto-correlation and Alternative 1's results into consideration, any period-specific ensemble of Alternative 3 sequences will be expected to have a median auto-correlation resembling a blend of auto-correlation from the state reference (reconstructed runoff) and from the magnitudes reference (period-specific magnitudes from Alternative 2). Results showed that this was generally the case. The ensemble-median auto-correlation varied by period, ranging between 0.33 to 0.37, which was close to the auto-correlation of reconstructed runoff (0.38) and range of period-specific ensemble-median auto-correlations from Alternative 2 (0.28 to 0.44).

5.1.2 Frequency Characteristics (Drought and Surplus Variability)

Results in Table 2 and discussion in Section 5.1.1 focus on period-statistical aspects of results. Such information does not describe frequency characteristics in the hydrologic data. Frequency characteristics are of great interest in water resources planning, as they define expectations for drought and surplus spell possibilities, and the intensities of both.

Frequency characteristics were compared between four hydrology datasets[17]:

- Instrumental record, 1951-1999, 1 series
- Reconstructed record, 1569-1997, 1 series[18]
- Alternative 2, given future period, results pooled from the period's 39 projections
- Alternative 3, given future period, results pooled from the period's 500 series

The Alternative 2 and 3's hydrology were evaluated only during their three future periods (2010-2039, 2040-2069, and 2070-2099). Drought and surplus possibilities were first grouped by n-year spell, where n = 1 or more years. Two evaluations followed:

- Assessment of accumulated volume possibilities by n-year case
- Count of n-year spell instances by n-year case

[17] Appendix A describes how well reconstructed runoff matches that of the instrumental record, but during the full instrumental record period rather than the water years 1951-1999 sub-period. The 1951-1999 sub-period was chosen for to permit comparison in this case of instrumental record runoff and Alternative 2 "simulated historical" runoff (reflecting the climate models' frequency characteristics) during a period of common overlap; and, the data for Alternative 2 were not generated before 1950.

[18] The periods of tree-ring chronologies limit the periods of reconstructed runoff; the chronologies end in 1997.

For each, the definition of drought and surplus is relative, as each are defined relative to the period-median annual runoff of the given hydrology[19]. For Alternatives 2 and 3, this meant computing a period-median annual for each series in their ensembles and then defining droughts and surpluses specific to each series. Alternative 1 is not considered here because the study's interest is in determining the significance of choosing Alternative 2 or Alternative 3 (each involving projected climate information) when scoping a planning study meant to account for expected climate change.

Figure 29 through Figure 31 show results on accumulated volume possibilities (and also spell occurrence, but not count of occurrences). The figures vary according to which period of results from Alternative 2 and Alternative 3 is being evaluated. Deficit spells and accumulations are shown on top panels. Surplus counterparts are shown on bottom panels. When a boxplot is shown for n = "N-year" spells, this means that (1) there were multiple instances of the N-year spell in the given hydrology, and (2) that accumulated volume varied across the instances as indicated by the boxplot variation. Single instances are indicated by a single plot point (horizontal dash). To guide interpretation of Figure 29 through Figure 31, consider the example of runoff deficits in the Null Alternative hydrology during 1951-1999 (i.e., instrumental record, Figure 3) and defining deficits relative to the Null Alternative's 1951-1999 period-median annual runoff. This yields one 8-year deficit, another 11-year deficit, and multiple 1-year deficits. Figure 29 shows a blue boxplot for the 1-year spell case, indicating a distribution of 1-year accumulation volumes across the 1-year instances. In contrast, the plot shows a single blue dash for the 8-year and 11-year cases to indicate the accumulated volumes for each singular instance, respectively. Doing the same analysis on the reconstructed runoff series (Figure 4) reveals multiple instances of 1- to 8-year and 12-year spells, which correspond to distributions of accumulated volumes for each spell case (red boxplots).

Review of deficits results from Figure 29 through Figure 31 reveals several differences in drought expression among the alternative planning hydrology:

- The Null Alternative hydrology during 1951-1999 exhibits fewer instances of droughts than the other alternatives. This is not surprising given that the shorter-period and single-series offered by the dataset.

- Reconstructed runoff and Alternative 3 datasets generally exhibit a similar trend in median accumulation volume (across instances) with n-year spell case (i.e. following boxplot midlines from 1-year to 14-year spell cases). This is not surprising given that Alternative 3 is based on stochastic modeling that is supposed to reflect some of the interannual persistence expressed in the reconstructed record.

[19] Thought was given toward defining drought relative to period-mean, but given that there may be a skew in the distribution of annual runoff magnitudes, the period-median was chosen to categorizing equal-sized pools of surplus versus deficit runoff years.

- The Null Alternative hydrology's two instances of longer-term deficit (i.e., 8- and 11-year spells) had volumes generally consistent with the volumes during spells of eight years or greater from the reconstructed runoff and Alternative 3 hydrology.

- Alternatives 2 and 3 show different tendencies in possible spell duration. Alternative 2 (as sampled) had spells primarily of 1- to 9-years duration while Alternative 3 (as sampled) had spells of 1- to 14-years duration.

- Alternatives 2 and 3 show different tendencies in accumulated volume by n-year spell. Results from the overlap of common spell-duration occurrence (roughly 1-year to 9-year spells), and the ways that the median accumulated volume trends as spell duration increases (i.e., following trend in boxplot midlines through spell durations) show that Alternative 2 trends toward greater accumulated volumes than Alternative 3. This suggests more intense drought possibilities in Alternative 2 than in Alternative 3 for the given spell durations. (However, this does not necessarily mean that Alternative 2 hydrology would be a more "conservative" hydrology for planning purposes as Alternative 3 hydrology has longer, if less intense, deficit spells.)

Similar comparisons are evident when examining surpluses results from Figure 29 through Figure 31 (bottom panels), Differences in accumulated volume possibilities for Alternatives 2 and 3 are somewhat more striking, especially for the two later periods.

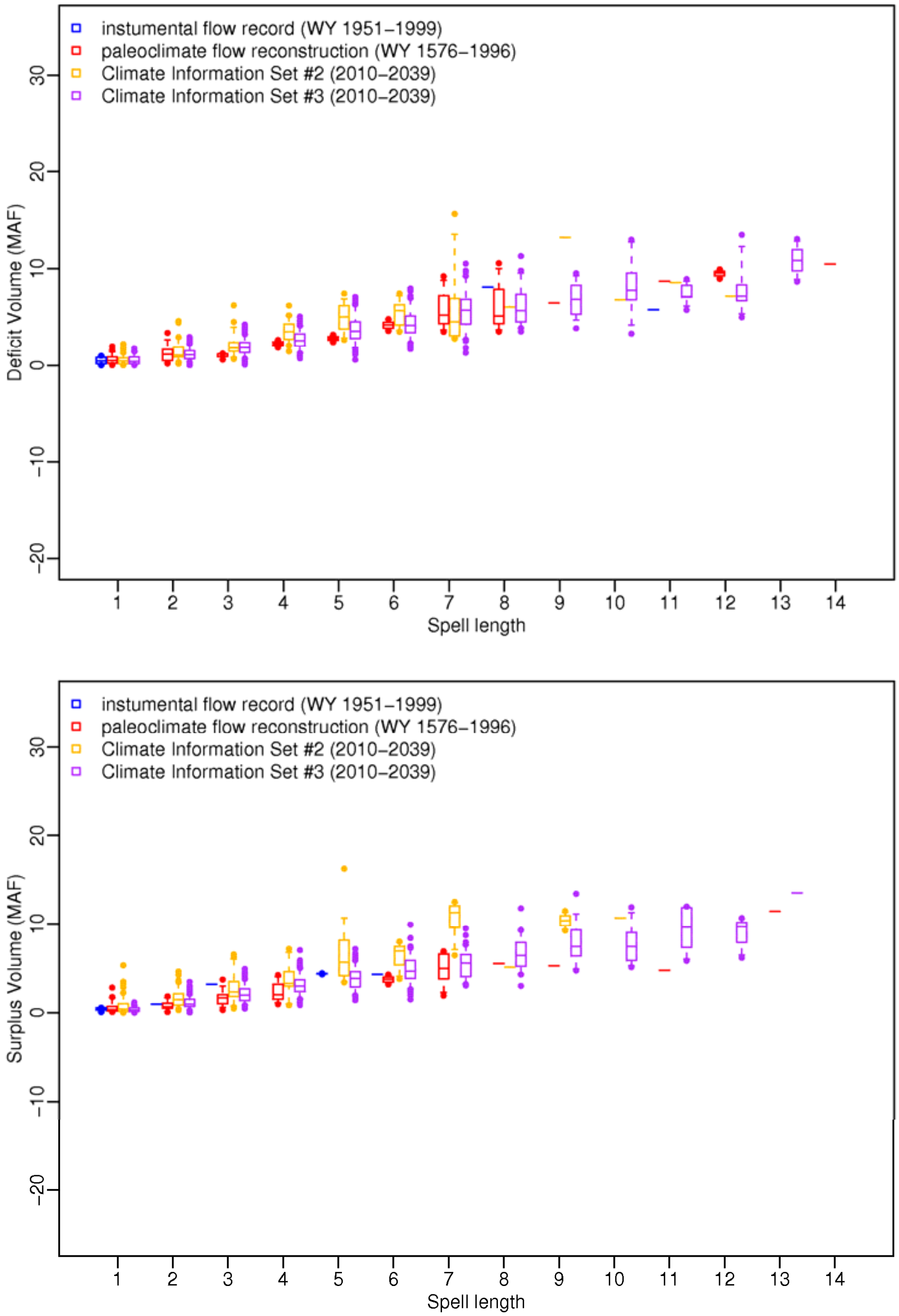
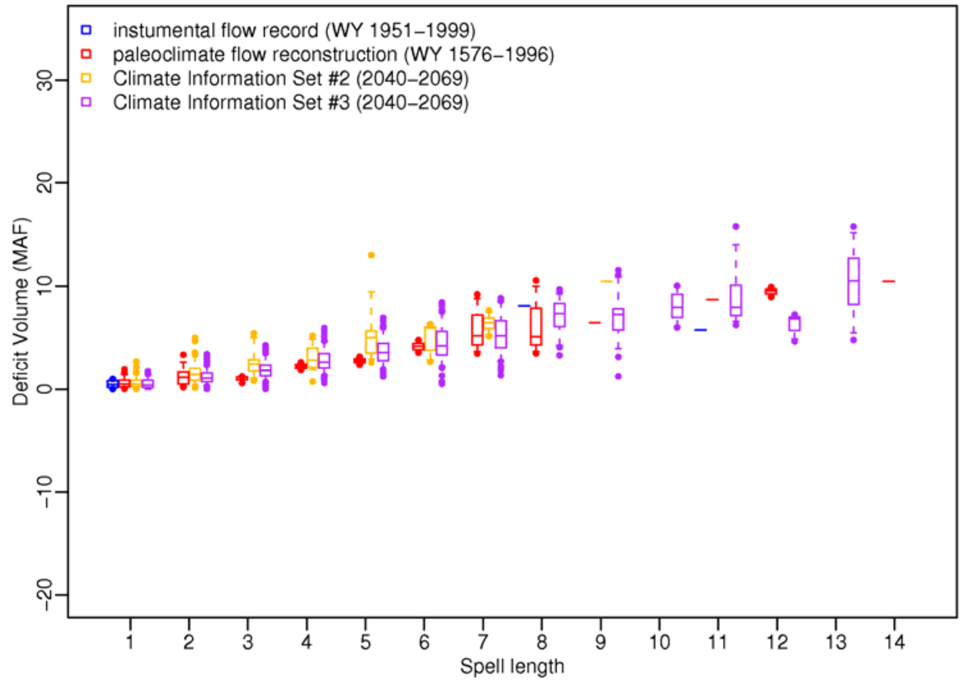


Figure 29 – Upper Missouri – Frequency Characteristics – Accumulated Volumes in the Hydrology Alternatives – 2010-2039 period for Alternatives 2 and 3.

(Top Panel) For the given hydrology alternative (see legend), boxplots show how accumulated deficit volume (y-axis) varied across their spell occurrences for a given spell duration (x-axis, years). (Bottom Panel) Same as top panel, but for accumulated surplus volume.



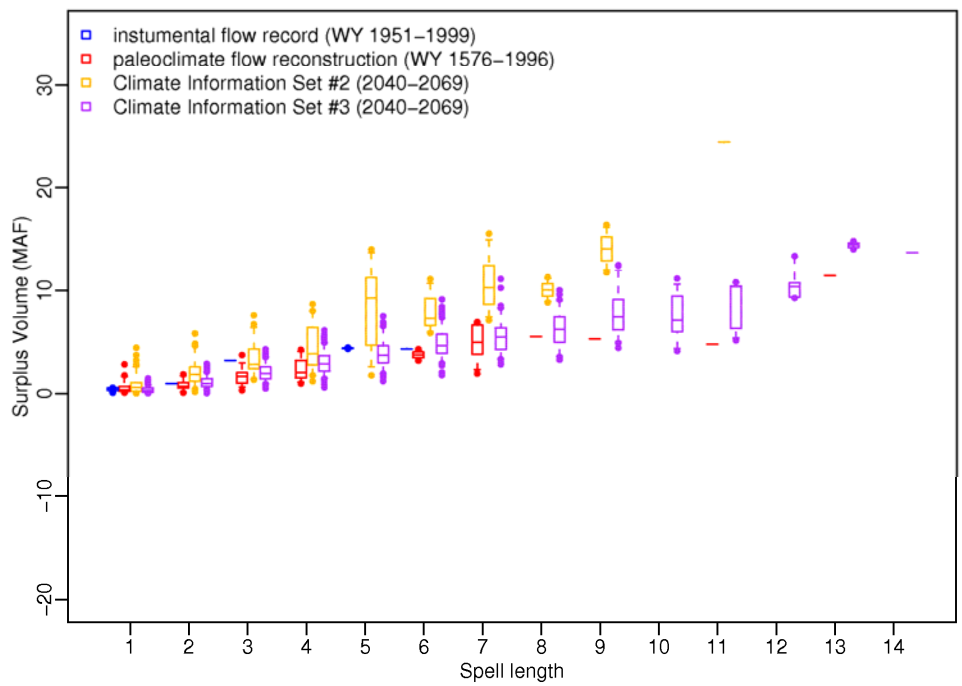
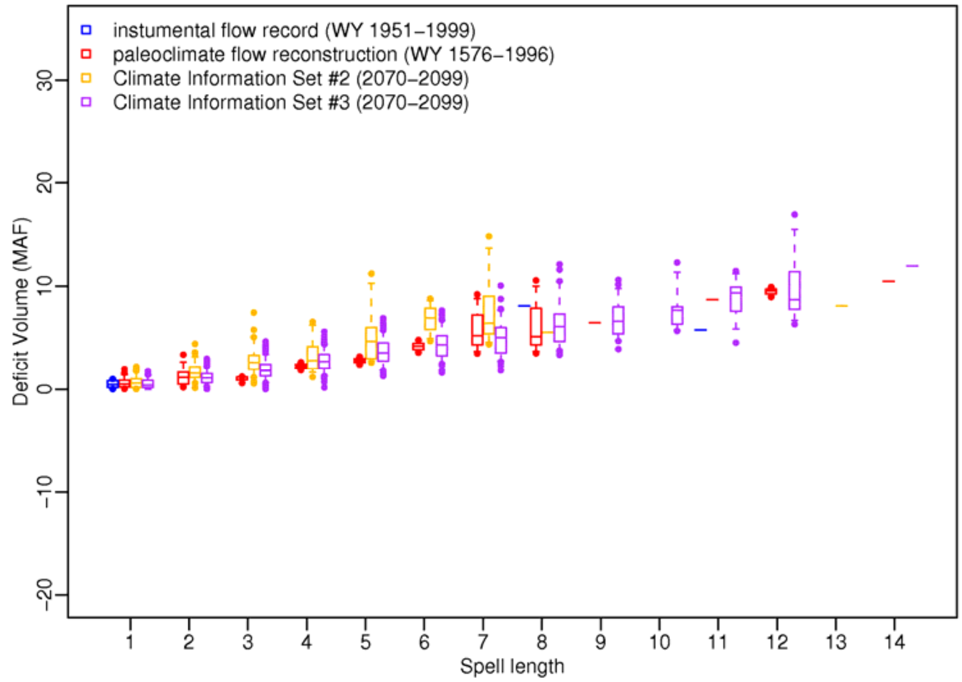


Figure 30 - Upper Missouri – Frequency Characteristics – Accumulated Volumes in the Hydrology Alternatives – 2040-2069 period for Alternatives 2 and 3.

For description of presentation, see Figure 29.



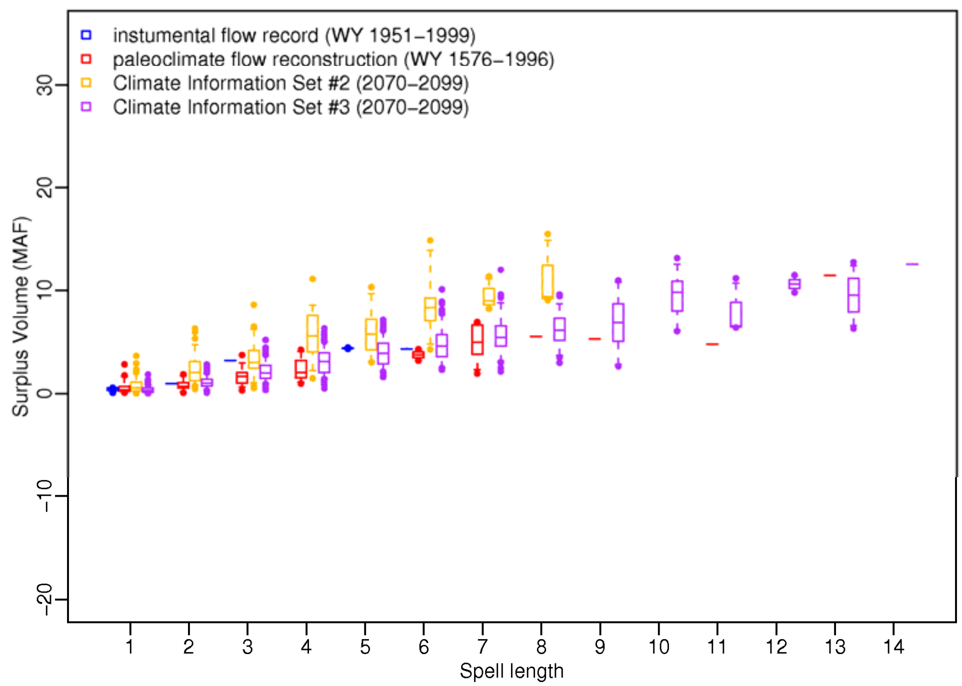


Figure 31 - Upper Missouri – Frequency Characteristics – Accumulated Volumes in the Hydrology Alternatives – 2070-2099 period for Alternatives 2 and 3.

For description of presentation, see Figure 29.

The other evaluation considered how the counts of spells were proportionally distributed across n-year spell. In other words, does a given hydrology give proportionally shorter spells or provide a greater frequency of longer-term spells. The frequency evaluation proceeded by constructing frequency histograms (i.e., count of spell occurrences by spell duration). The histograms were then rescaled so that they integrated to 1. This permitted easier comparison of “count distribution shape” between the alternatives.

Example results are shown on Figure 32, focusing on deficit counts for the Null Alternative hydrology, reconstructed record, and Alternative 2 only. Figure 32 offers some results similar to those offered by Figure 29 through Figure 31. For example, the Null Alternative hydrology has a relatively short period of record and only one hydrologic sequence. This limits the types and frequency of spells that can be featured. By contrast, the reconstructed record, which still only offers a single sequence but features a much longer period of record, offers a richer portrayal spell duration possibility and frequency of occurrence. Also, the results on Figure 32 similarly show that Alternative 2 hydrology exhibits spells up to roughly 9years duration, which is shorter than the possibilities in the reconstructed record. However, the shape of the histograms on Figure 32 shows greater frequencies of mid-range spells (e.g., 3- to 6-year duration) in the Alternative 2 hydrology than in the reconstructed runoff.

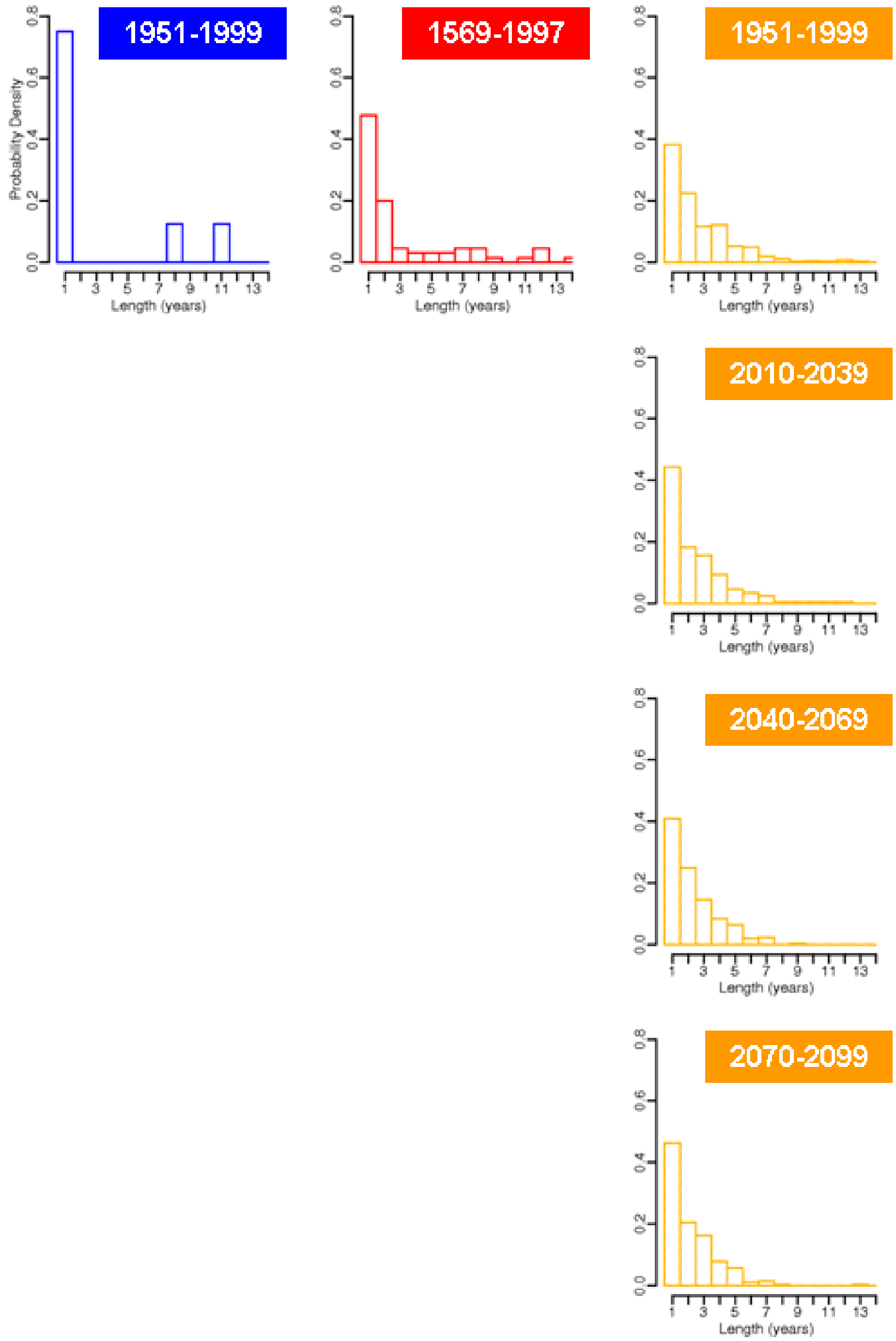


Figure 32 - Upper Missouri – Frequency Characteristics –Deficit Counts proportionally distributed by Spell Duration.

Plot shows histograms of spell counts rescaled so that they integrate to 1 across all spell durations. (Row 1) Historical results are shown for the Null Alternative hydrology (blue), reconstructed runoff (red), projected (orange), and Alternative 2 (Figure 25). (Rows 2-4) Results are shown for Alternative 2 during the future periods indicated.

5.2. Case Study Basin #2: Gunnison

5.2.1 Period Statistical Characteristics

5.2.1.1. Alternative 1

For Alternative 1 (i.e., instrumental record, paleoclimate), Figure 33 shows the ensemble of 500 stochastically modeled sequences of annual runoff (top panel). It also shows the ensemble translated into 500 sequence-specific (PDEs of annual runoff (bottom panel); those PDEs have also been sampled by flow range (bottom panel, boxplots) for how density varied across the sequences at a given flow range. For comparison, the Null Alternative hydrology (instrumental record) sequence and PDE are shown. The reconstructed runoff PDE is also shown.

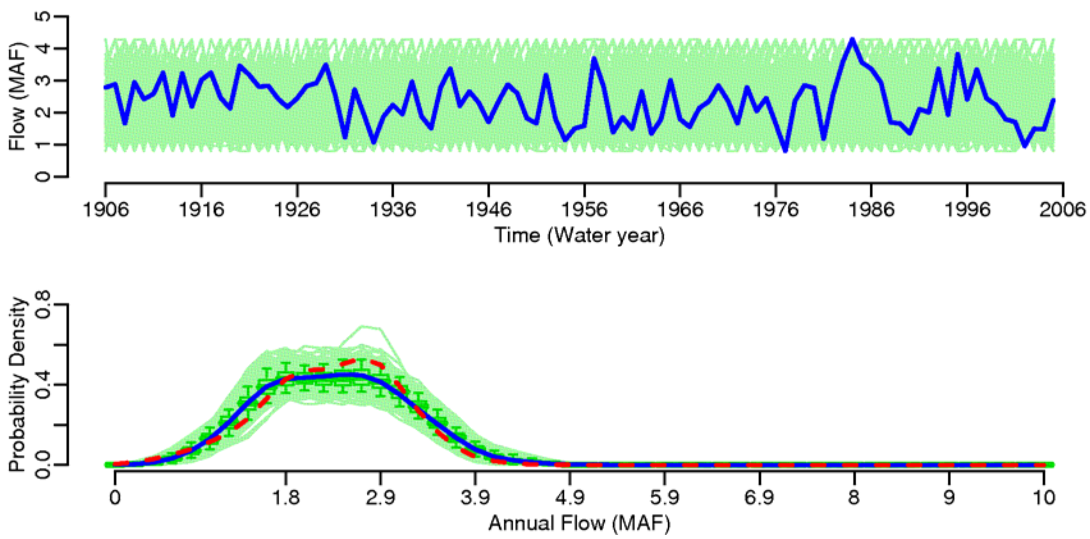


Figure 33 - Gunnison – Alternative 1 - Stochastically modeled Annual Runoff.

For description of presentation, see **Figure 23**.

The top panel of Figure 33 shows how the Alternative 1 stochastic model produced a range of annual runoff magnitudes that didn't depart from the Null Alternative hydrology range. This was by model design (Section 3.1). The bottom panel of Figure 33 shows that the stochastic model generally produced synthetic sequences that had annual runoff PDE consistent with the PDE of the magnitudes source (i.e., Null Alternative hydrology). This is evident by noticing that the Null Alternative's PDE has a bi-modal nature that is generally encapsulated and mimicked by the ensemble Alternative 1's PDEs. However, as with any stochastic modeling exercise, a specific Alternative 1 sequence might be modeled such that its PDE is fairly different from that of the reference climate (i.e., the Null Alternative PDE in this case). Figure 34 shows period-statistics from the Alternative 1 sequences, Null Alternative hydrology. Alternative 1's ensemble-median statistics compare well with those of the Null Alternative. This is expected due to stochastic model design as the Null Alternative served as the magnitudes' reference, and should influence statistics on mean, standard deviation, skew, maximum, and minimum.

Lag 1-year auto-correlation is influence by both the state climate source and magnitudes' climate source, based on stochastic model design (Appendix B). Thus, the auto-correlation of the reconstructed runoff would be expected to be reflected in the Alternative 1 first-stage modeling of state, but then the auto-correlation of the Null Alternative hydrology would be introduced during the second-stage modeling of magnitudes. The latter is because modeled "current year" magnitude is a sampled magnitude from the Null Alternative hydrology, where eligible magnitudes were weighted to reflect previous-to-current year state transition that was just modeled (Appendix B). Figure 34 shows that lag 1-year auto-correlation for the Gunnison basin during the full-period instrumental record is roughly 0.27 whereas it is roughly 0.03 for the reconstruction period. The ensemble-median auto-correlation among Alternative 1 sequences was 0.05, or in between these two values. As noted in discussing similar results for the Upper Missouri (Section 5.1.1), it remains a subject of further study to understand whether, under this model design, the resultant ensemble-median auto-correlation should be closer to the state's or magnitudes' reference.

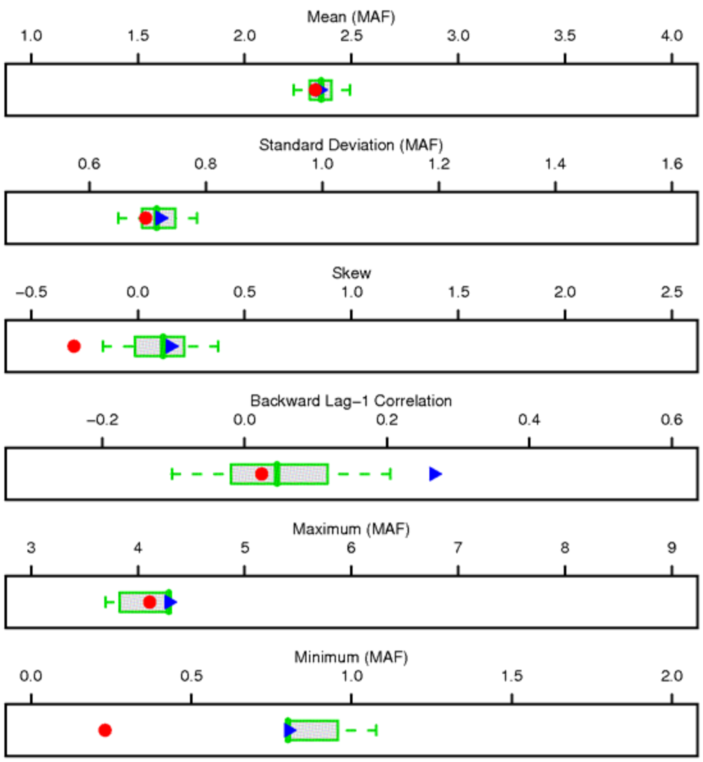


Figure 34 - Gunnison – Alternative 1 - Period Statistics of Annual Runoff.

For description of presentation, see Figure 24.

5.2.1.2. Alternative 2

Alternative 2's hydrology reflects a blend of instrumental record and projected climate information. Figure 35 shows an ensemble of annual runoff projections from 1950-2099 (top panel)[20]. This 150-year period is consistent with that of the climate projection information. Figure 35 also shows how 30-year mean annual runoff varies by projection and through time (i.e., the boxplots, top panel). The annual Null Alternative hydrology from Figure 3 is shown, along with the range of 30-year mean runoff within the full period of the Null Alternative hydrology. The middle panel is the same information, but rescaled (explained later in this section). The bottom panel shows projection distributions of mean monthly runoff for four non-overlapping periods.

To interpret middle panel results of Figure 35, first recognize that the top panel shows the ensemble of runoff projections that have already been scaled once to account for the Gunnison's hydrologic model bias[20]. But the top panel indicates that this does not completely remove bias in the simulated runoff period mean during historical periods (i.e. Compare the three simulated historical boxplots of 30-year period means versus the Null Alternative hydrology range of historical 30-year means.). To remove this bias and permit better comparison of Alternative 2 hydrology to Null Alternative hydrology, the simulated runoff projections were scaled a second time. The second scaling was done dividing each simulated runoff series by the ratio of the dataset "ensemble mean-annual simulated runoff during 1951-1999" to the dataset "mean-annual Null Alternative hydrology runoff during 1951-1999". This ratio equaled 0.80. It is suspected that some of this bias stems from differences in historical meteorology used to calibrate the hydrologic model and historical meteorology used to bias-correct the climate projections, corresponding to discussion in Section 5.1.1 on RFC distributed weather versus distributed weather from Maurer et al. (2002). For the Gunnison, the distributed weather of Maurer et al. (2002), when spatially averaged over the basin, had period-mean temperature and precipitation biases of +0.6 ºF and -3 percent during water years 1961-1999, both of which would promote the lower period mean when forcing the hydrologic simulation model by simulated historical weather that is consistent with Maurer et al. (2002).

Figure 35 shows the envelope of projected annual runoff possibilities from simulated historical to simulated future based on the middle panel results from the historical viewpoint, a broader range of annual runoff possibility is evident when comparing simulated runoff series of Alternative 2 to that of the Null Alternative. This is the case even though the simulated temperature and precipitation series underlying the runoff simulations had been bias-corrected (Section 2.4) to be period-statistically consistent with observations from calendar years 1950-1999. However, when viewing the historical period statistics as a whole rather than the possibilities in a single year, the simulated runoff ensemble seems largely

[20] These runoff projections were scaled to account for the hydrologic model bias for the Gunnison and are identified as a simulated-to-observed ratio of 0.93 in Section 3.2

consistent with the Null Alternative hydrology. This judgment is based on comparing the distributions of the 30-year mean runoff from Alternative 2 during the three overlapping 30-year periods between 1951-1999 (i.e., first three boxplot distributions starting from the left in the top panel) with the range of 30-year mean possibilities from the Null Alternative (e.g., blue area).

The envelope of annual runoff possibilities from the historical period gradually broadens as the projections progress into the 21st century. The period-mean annual runoff stays roughly consistent from the historical period through the 21st century. This is consistent with how precipitation projections over the Gunnison also appear to trend along “no change” from historical through the late 21st century (Figure 11). However, this result is also based on how potential evapotranspiration in the hydrologic simulation model was not increased in response to warmer air temperature. It seems likely that annual runoff possibilities are overestimated in the 21st century given this simulation choice[15]; but this should not affect research questions involved in comparing Alternatives 2 and 3, which will both have the same overestimations as they have the same bias in results.

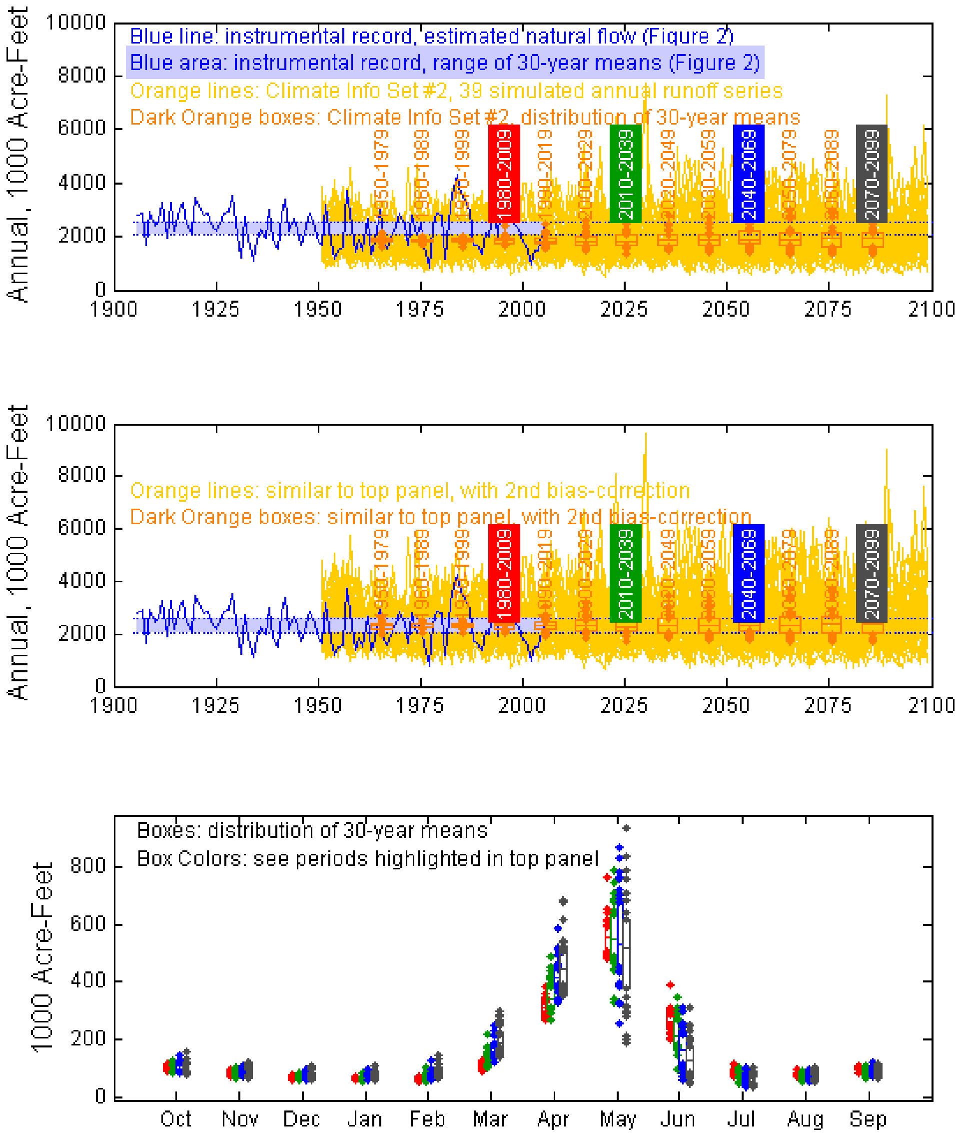


Figure 35 - Gunnison – Alternative 2 – Simulated Runoff Projections.

(Top and bottom panels) For description of presentation, see Figure 25. (Middle panel) Same as top panel, but with simulated runoff scaled a second time, as discussed in the text.

Changes in mean monthly runoff through time are shown on Figure 35, bottom panel, through four non-overlapping periods. Results show increases during October through April, decreases during May through July, and little change during August through September. For the Spring-Summer decrease, warming during Fall-Spring (Figure 12) would seem to be a significant factor, as discussed to explain similar decreases in the Upper Missouri (Section 5.1.1). Precipitation is also projected to decrease during May and June (Figure 11), which would also contribute to runoff decreases during those months. In October through April, the runoff increase is undoubtedly related to the simulation choice of not increasing potential evapotranspiration in response to warming. Aside from that, other factors would seem to be influential, including warmer temperatures (year-round) and increased precipitation during October through April (Figure 11), which leads to similar runoff response as discussed for the Upper Missouri results (Section 5.1.1)[21].

Figure 36 shows period-statistics for the ensemble of Alternative 2 runoff projections, the Null Alternative hydrology, and reconstructed runoff. For Alternative 2, statistics are computed for four sub-periods in the projections, as listed in Section 4.2: 1951-1999, 2010-2039, 2040-2069, and 2070-2099.

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[21] Projected trends in monthly runoff for the Upper Missouri and Gunnison basins, are generally consistent, except that the spell of monthly runoff increase seems to be slightly longer for the Upper Missouri (August-May) than for the Gunnison (October-April). This may relate to the two basins' geographic proximity to two regional circulation effects that are thought to be set up by future global warming (IPCC 2007 and Seager et al. 2007).

The first effect might be labeled "wetter storms." Atmospheric moisture-holding capacity increases with warmer air temperature. This means that Winter-Spring storms advecting into the western U.S. from the North Pacific may be laced with additional moisture, and thereby providing more precipitation over locations where precipitation is going to occur.

The second effect might be labeled "Hadley Expansion and broader Subsidence Zones." Some theorize that warmer air temperatures over the equatorial latitudes could invigorate the atmospheric Hadley Circulation (Hartmann 1994), which would result in a greater flux of falling air over sub-tropical latitudes. This would broaden the latitudinal sub-tropical zones of atmospheric subsidence (Seager et al. 2007) and further suppress precipitation in and near these areas of subsidence, which generally coincide with large desert regions (e.g., American Southwest, Sahara, etc). As a related phenomenon, an invigorated poleward roll of the Hadley Cell could also result in a poleward displacement of middle-latitude storm tracks.

Depending on the location of a basin relative to the second effect, the combination of the two effects could promote runoff increase if the wetter storm track is placed over the basin more frequently. It could also promote runoff decrease if the wetter storm track is displaced away from the basin relative to historical conditions. The Upper Missouri is located further from the sub-tropics, and therefore might be influenced more by "wetter storms" effect. In contrast, the Gunnison is located closer to the sub-tropics, perhaps receiving proportionally more influence from the second effect and less from the first. This may help explain projected annual precipitation increase for the Upper Missouri and roughly no change for the Gunnison. Competition between these two effects could also vary by season. Middle-latitude storm track influence may drift more southerly during Winter and early Spring (thereby affecting both basins), whereas a sub-tropical subsidence zone broadening may be more influential during Spring and Summer and have precipitation-suppression effects on both basins, but more so in the more southerly-located Gunnison. In any case, these are only conceptual explanations at this time. More research is required to understand and anticipate how global warming should translate into regional precipitation changes for western U.S. basins.

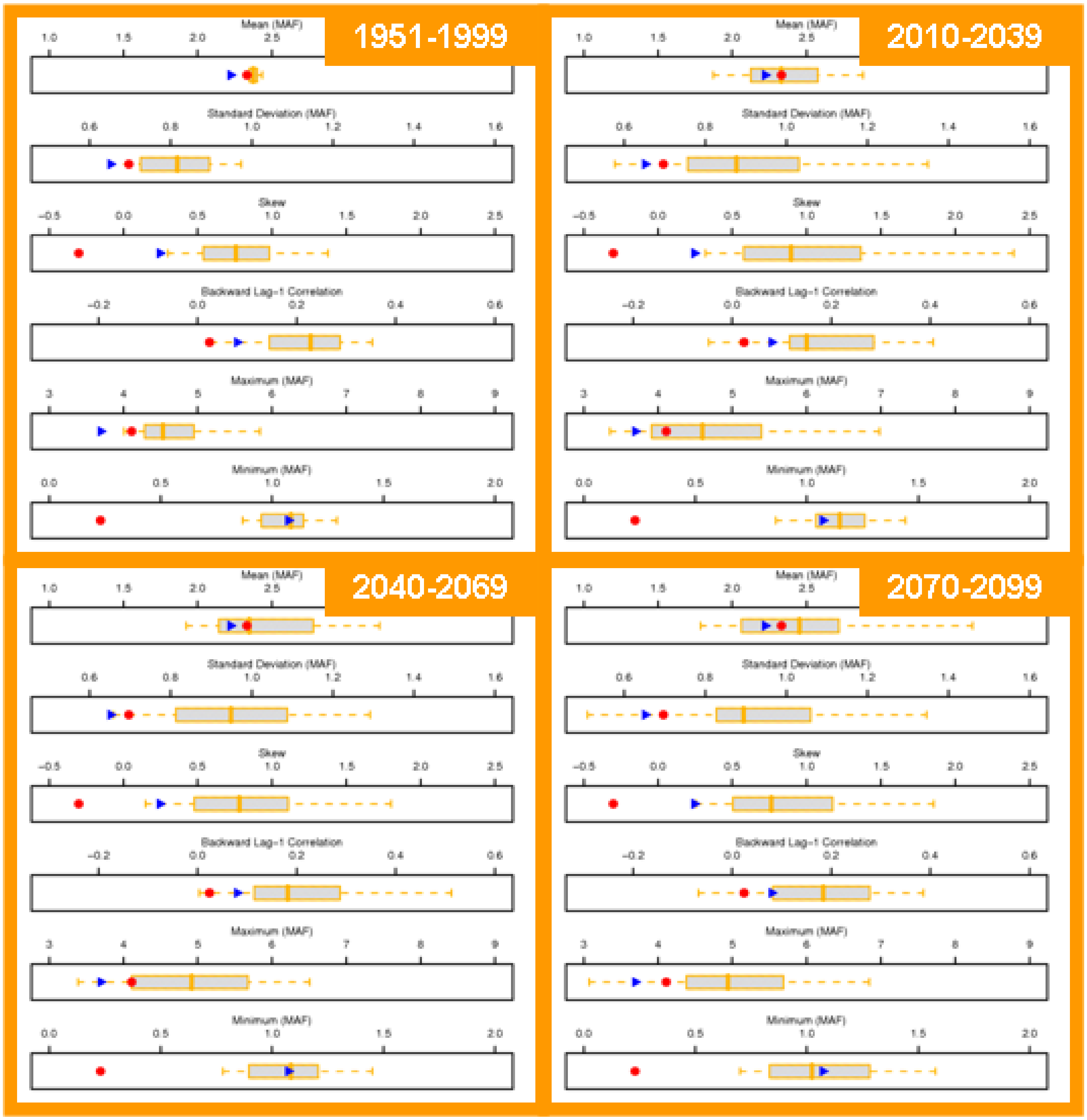


Figure 36 - Gunnison – Alternative 2 - Period Statistics of Annual Runoff.

For description of presentation, see Figure 26.

Comparing Alternative 2's ensemble-median statistics of Alternative 2 from historical to future shows a slight increase in the mean and maximum annual runoff near the end of the century, with simulation caveats noted[15]. By contrast, there was little trend standard deviation, skew, auto-correlation, and minimum annual flow through the periods.

5.2.1.3. Alternative 3

Alternative 3 features a blend of instrumental record, paleoclimate, and projected climate information. Alternative 3 involves period-specific stochastic modeling, where magnitudes' modeling varies by period and originates from periods in the Alternative 2 runoff projections. Figure 37 shows period-specific ensembles of annual runoff PDE results (shown as ensemble densities binned by flow range). Figure 37 also shows annual runoff PDEs from the Null Alternative hydrology of water years 1951-1999, and from the full period of reconstructed runoff. Comparing Alternative 3's historical and future ensemble of PDEs shows a tendency toward wetter skew starting early in the 21st century and an increase in median runoff later in the century. This is consistent with the Alternative 2's tendencies in annual runoff mean and skewness (Figure 36, middle panel).

Figure 38 shows period statistics for the ensemble of Alternative 3 sequences, repeated for each period, as well as those of the Null Alternative hydrology and reconstructed runoff. By the stochastic model's design, the Alternative 3 ensemble-median statistics should be close to the ensemble-median statistics of Alternative 2 for mean, standard deviation, skewness, maximum, and minimum. Results show that this is generally the case for each period (Table 2). Taking autocorrelation and Alternative 1's result into consideration, any period-specific ensemble of Alternative 3 sequences would be expected to have a median auto-correlation resembling a blend of auto-correlation from the state reference (reconstructed runoff) and from the magnitudes' reference (period-specific magnitudes from Alternative 2). Results showed that this was generally the case. The ensemble-median auto-correlation varied by period, ranging from 0.08 to 0.10, which was close to the auto-correlation of reconstructed runoff (0.03) and range of period-specific ensemble-median auto-correlations from Alternative 2 (0.18 to 0.22).

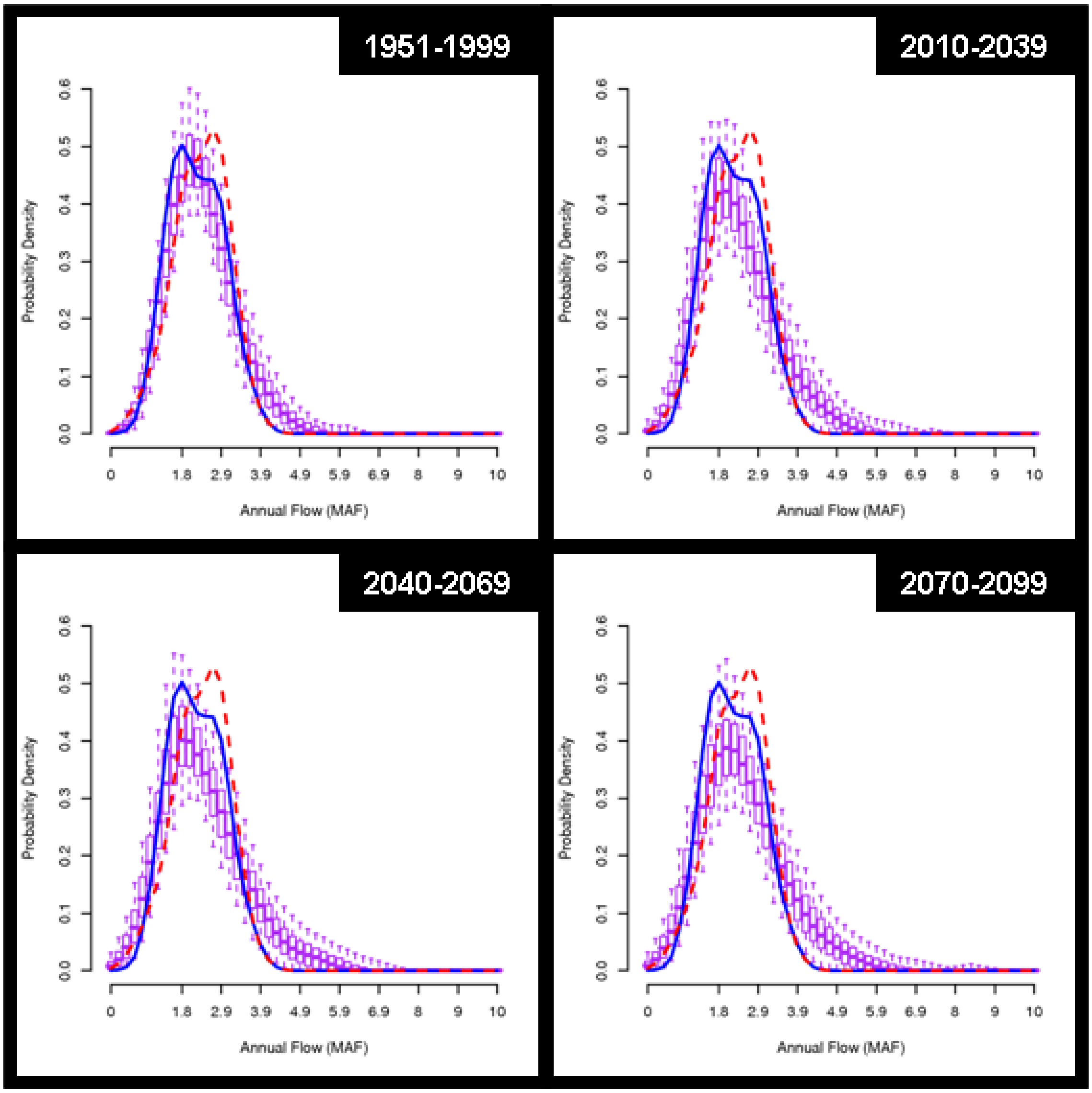


Figure 37 - Gunnison – Alternative 3 – Stochastically modeled Annual Runoff.

Similar to presentation of results for Upper Missouri on Figure 23.

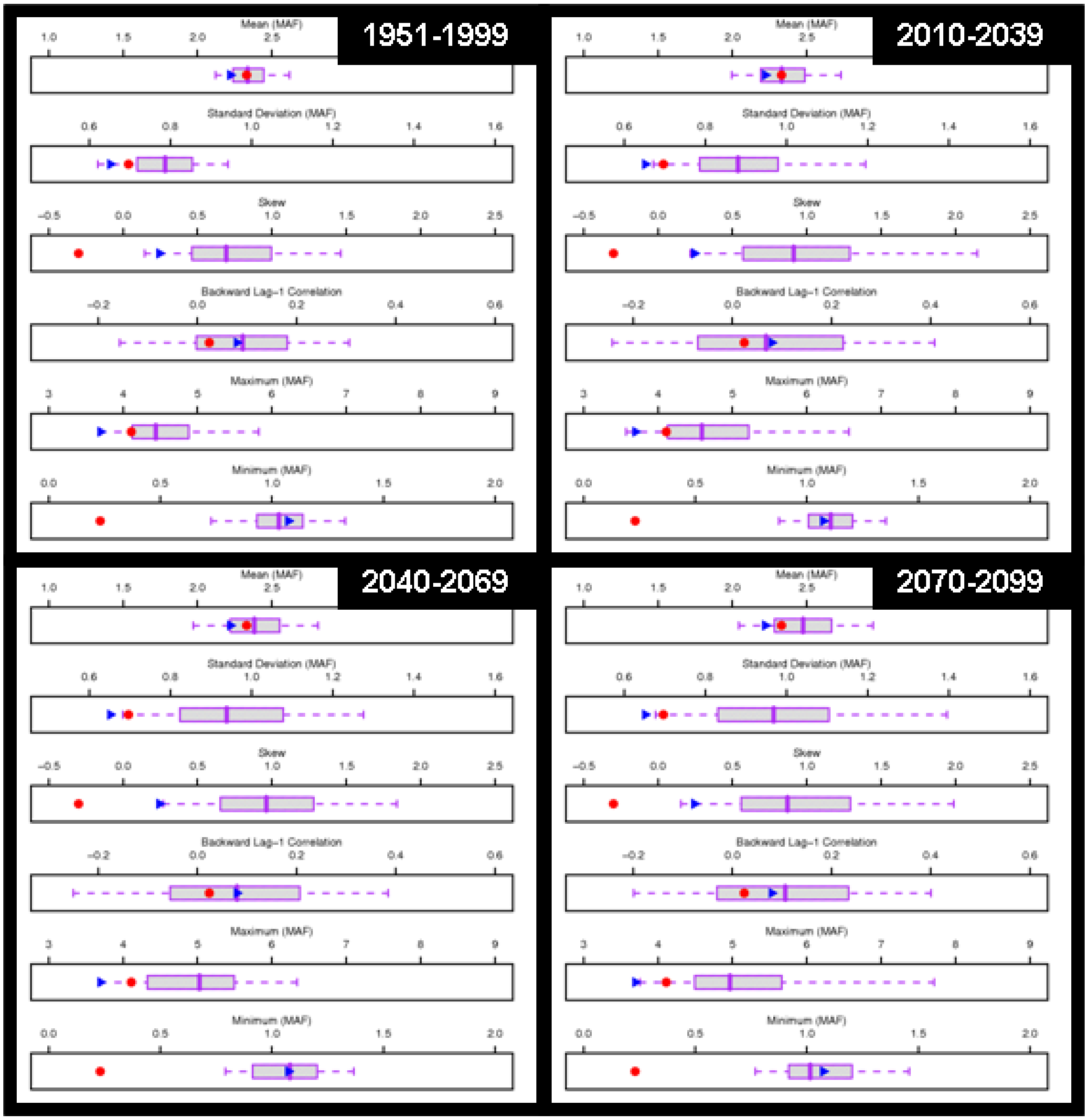


Figure 38 - Gunnison – Alternative 3 – Period Statistics of Annual Runoff.

For description of presentation, see Figure 28.

5.2.2 Frequency Characteristics (Drought and Surplus Variability)

Results in Table 2 and discussion in Section 5.1.1 focus on period-statistical aspects of results. Such information does not describe frequency characteristics in the hydrologic data. Frequency characteristics are of great interest in water resources planning, as they define expectations for drought and surplus spell possibilities, and the intensities of both.

Frequency characteristics were compared between four hydrology datasets in the Gunnison, using the same approach as discussed for the Upper Missouri results (Section 5.1.1, comparison of Null Alternative hydrology, reconstructed runoff, and period-specific hydrology from Alternatives 2 and 3). Evaluations were conducted on:

- Assessment of accumulated volume possibilities by n-year case
- Count of n-year spell instances by n-year case

As with the Upper Missouri evaluations, definition of drought and surplus in the Gunnison basin is relative to the period-median annual runoff of the given hydrology. Also as with the Upper Missouri evaluation, Alternative 1 is not considered here because the study focuses on determining the significance of choosing Alternative 2 or Alternative 3, as these alternatives involve projected climate information and would be used when scoping a planning study meant to account for both expected climate change.

Figure 39 through Figure 41 show results on accumulated volume possibilities (and also spell occurrences, but not count of occurrences). See introductory discussion in Section 5.1.2 on Figure 29 through Figure 31 to guide interpretation of Figure 39 through Figure 41.

Review of deficits results from Figure 39 through Figure 41 shows several differences in drought expression among the alternative planning hydrology:

- The Null Alternative hydrology during 1951-1999 exhibits fewer types of droughts than the other alternatives. This is not surprising given that the shorter-period and single-series offered by the dataset.
- Reconstructed runoff and Alternative 3 datasets generally exhibit a similar trend in median accumulation volume (across instances) with n-year spell case (i.e., following boxplot midlines from 1-year to 14-year spell cases). This is similar to results found for the Upper Missouri (Figure 29 through Figure 31).
- Alternative 2 and Alternative 3 show similar tendencies in possible spell duration. The upper limit is roughly 8 years in each alternative (albeit with perhaps greater spell duration in Alternative 3 during the 2070-2099 period). This contrasts with the Upper Missouri results where Alternative 3 featured longer spell durations than Alternative 2.
- Alternative 2 and Alternative 3 show similar tendencies in accumulated volume by n-year spell. Alternatives 2 and 3 have similar accumulated volume possibilities as shown by comparisons of median accumulated volume trends as spell duration increases (i.e., following trend in boxplot

midlines through spell durations). This suggests that drought portrayals in Alternatives 2 and 3 would be similar at given spell durations.

Review of surpluses results from Figure 39 through Figure 41 (bottom panels) show differences between surplus possibilities in Alternatives 2 and 3 for the Gunnison. These differences are similar to found in the Upper Missouri results.

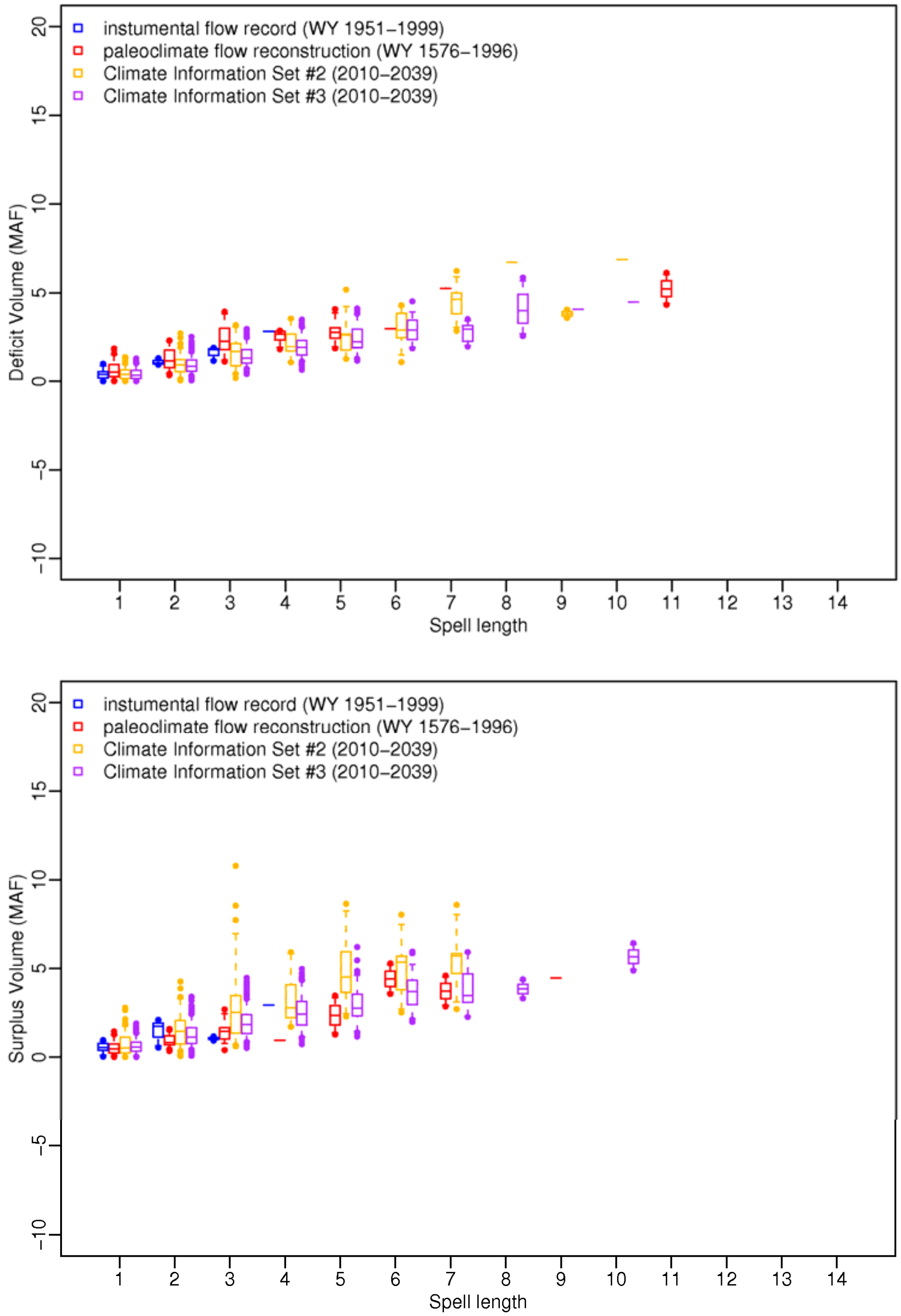
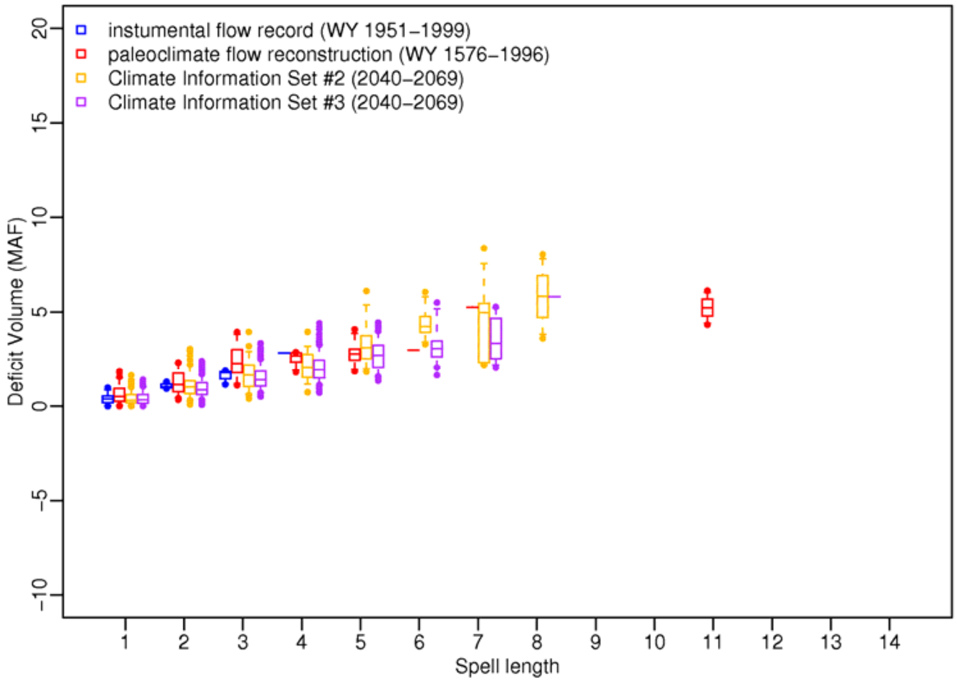


Figure 39 - Gunnison – Frequency Characteristics – Accumulated Volumes in the Hydrology Alternatives – 2010-2039 period for Alternatives 2 and 3.

For description of presentation, see Figure 29.



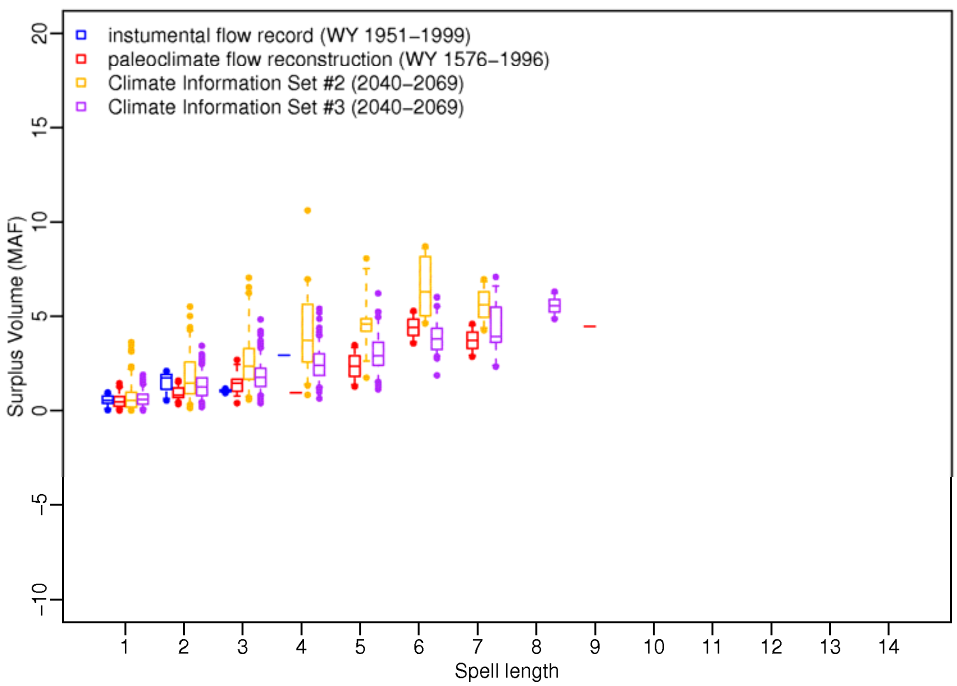


Figure 40 - Gunnison – Frequency Characteristics – Accumulated Volumes in the Hydrology Alternatives – 2040-2069 period for Alternatives 2 and 3.

For description of presentation, see Figure 30.

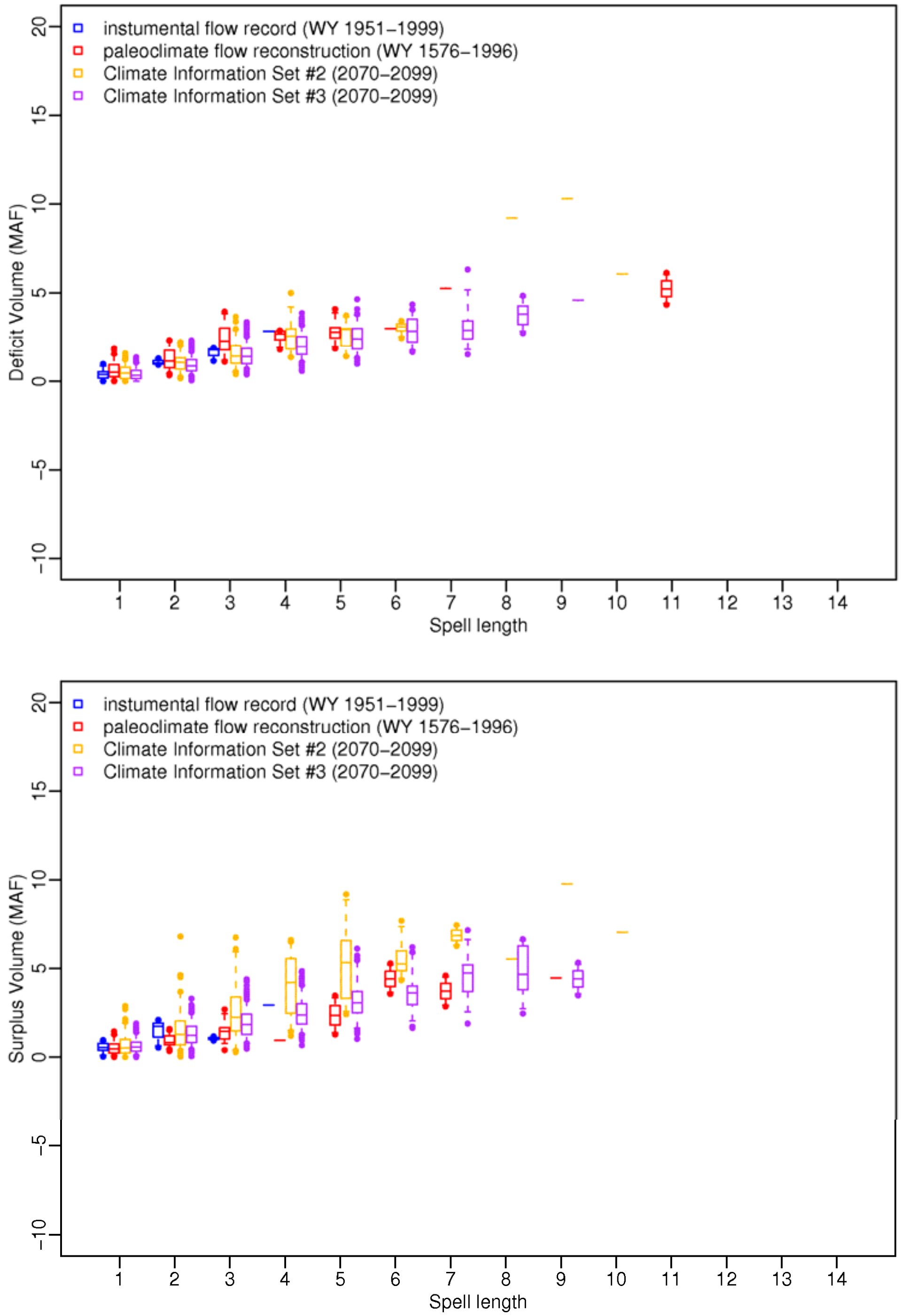


Figure 41 - Gunnison – Frequency Characteristics – Accumulated Volumes in the Hydrology Alternatives – 2070-2099 period for Alternatives 2 and 3.

For description of presentation, see Figure 31.

The other frequency evaluation considered how the counts of spells were proportionally distributed across n-year spell. In other words, does a given hydrology provide proportionally shorter spells or a greater frequency of longer-term spells? The evaluation proceeded by constructing frequency histograms (i.e., count of spell occurrences by spell duration). The histograms were then rescaled so that they integrated to 1. This permitted easier comparison of “count distribution shape” between the alternatives.

Example results are shown on Figure 42, focusing on deficit counts for the Null Alternative hydrology, reconstructed record, and Alternative 2 only. Figure 42 offers some impressions similar to those offered by Figure 39 through Figure 41. For example, the Null Alternative hydrology has a relatively short duration and only one hydrologic sequence. This limits the types and frequency of spells that can be featured. By contrast, the reconstructed record, which still only offers a single sequence but featuring a much longer period of record, offers a richer portrayal spell duration possibilities and frequency of occurrence. Also, the results on Figure 42 similarly show that Alternative 2 hydrology exhibits spells up to roughly 9-year duration, which is shorter than the possibilities in the reconstructed record. The shape of the histograms on Figure 42 shows that the frequency of mid-range spells (e.g., 3- to 6-year duration) is similar in the Alternative 2 hydrology and reconstructed runoff, which contrasts with Upper Missouri results where there were proportionally greater counts of mid-range spells in the Alternative 2 hydrology.

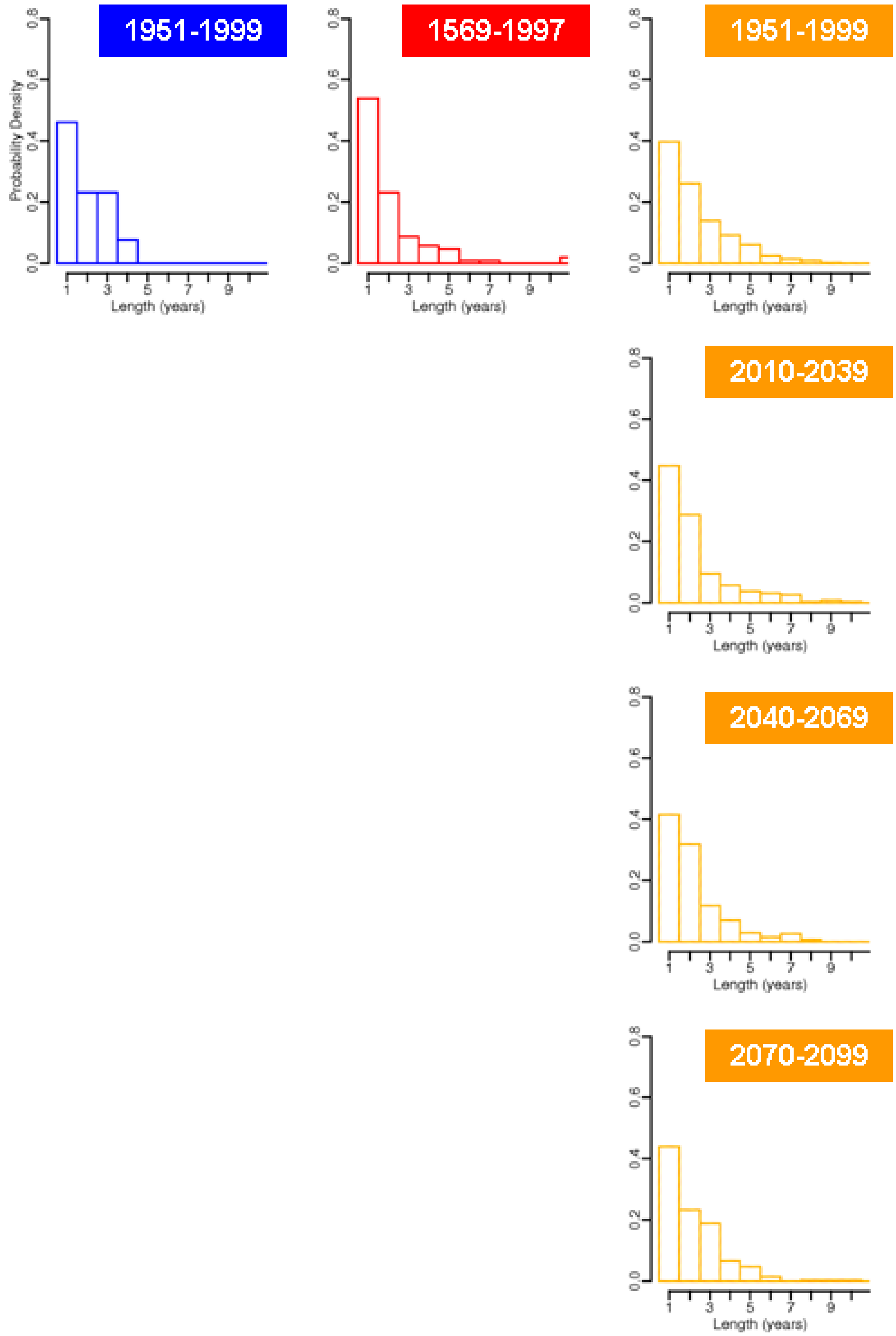


Figure 42 - Comparison of how Gunnison N-Year Spell Counts are proportionally distributed across Spell lengths (N) within the Null Alternative, Reconstructed and Alternative 2 hydrology.

Data are shown in similar fashion as shown for Upper Missouri (Figure 32).

5.3. Data-development Uncertainties

This section discusses data-development uncertainties associated with the hydrology of Alternatives 1 through 3. The uncertainties of developing the Null Alternative hydrology data are not discussed. Interested readers might refer to Null Alternative hydrology documentation in Reclamation 2005a and Reclamation 2005b.

Alternative 1's hydrologic data reflects climate of instrumental record and paleoclimate. Uncertainties of these hydrologic data stem from several sources, including:

- **Chronology development:** Chronologies are developed from a series of trees at a given location. Choosing appropriate location and tree species for developing chronologies is both a science and an art. To build chronologies that exhibit strong correlation with moisture availability, the proper tree species for a region must but found and their ring widths characterized to generate a given chronology. A properly developed chronology will reliably translate moisture availability in their ring-widths providing a view into past soil moisture availability and indirectly past runoff characteristics. There is inherit uncertainty in this process, and the reliability of one chronology versus another varies. Chronologies are not only influenced by available moisture but also by biological factors, including the trees growth over time. Statistical time series techniques are typically used to reduce or eliminate the impact of factors unrelated to moisture availability. However, this reduction can also reduce how much runoff variance a chronology can explain and thereby contributes to the uncertainty in streamflow reconstruction.

- **Interpretation of reconstructed runoff magnitudes and state:** Various statistical techniques can be used to relate ring-width to streamflow magnitude and state. The multiple linear regression technique is often used to accommodate multiple tree-ring sites. Principle component analysis (Haan 1977) might also be used prior to regression analysis to consolidate ring-width information from multiple chronologies to more easily develop and/or produce better quality regression models (Hidalgo 2000). Additional sources of uncertainty arise from the choice of whether and how to detrend the chronology prior to regression modeling, given understanding that tree-ring series typically show a declining trend with age. The decision of whether or not to remove this trend from the chronology can impact the statistical properties of the reconstructed streamflow.

- **Choice of stochastic modeling framework**: This study employed a nonparametric stochastic modeling framework. Nonparametric methods have the advantage of not requiring knowledge of the underlying statistical distribution of reference data, which the stochastic model would then mimic. Choices of which specific techniques to employ still exist within a nonparametric framework. The outlined framework couples a nonhomogeneous Markov model to simulate state and a K-Nearest Neighbor resampling (KNN) technique to associate magnitude with modeled state (Appendix B). Other techniques (e.g., kernel density method) could have been used instead of KNN to allow the stochastic model to generate magnitudes beyond those seen in the reference magnitudes source. However, that choice would have come with a downside of including more complicated model development and implementation, in addition to the generation of magnitude values that some might regard as difficult to justify. During the selection of a framework, such choices need to be considered and their advantages and disadvantages assessed for a given project.

Alternative 2 hydrologic data reflect climate of instrumental record and projected climate information. Uncertainties of these hydrologic data stem from several sources, including:

- **Global climate forcing:** This study considered only a limited set of available climate projections (Section 2.4) representing a single green house gases (GHG) emissions scenario (A1b). Other GHG scenarios and associated projections are available, and it has been shown that climate projection results in the latter part of the 21st century are path-dependent (IPCC 2007). Thus, for application purposes with planning horizons beyond roughly mid-21st century, it is advised that Alternative 2 data be redeveloped to represent a range of GHG emissions paths rather than just the single path considered in this study. As for the GHG path scenarios themselves, they also possess uncertainties about:

    1. Technological and economic developments, globally and regionally

    2. How those assumptions translate into global energy use involving GHG emissions

    3. Biogeochemical analysis to determine the fate of GHG emissions in the oceans, lands, and atmosphere

    Also, not all of the uncertainties associated with climate forcing are associated with GHG assumptions. Considerable uncertainty remains associated with natural forcings, with the cooling influence of aerosols being regarded as the most uncertain on a global scale (e.g., Figure SPM-2 in IPCC 2007).

- **Global climate simulation:** While this study considers climate projections produced by state-of-the-art coupled ocean-atmosphere climate models, and these models have shown an ability to simulate the influence of increasing GHG emissions on global climate (IPCC 2007), there are still uncertainties about our understanding of physical processes that affect climate, and how to represent such processes in climate models (e.g., atmospheric circulation, clouds, ocean circulation, deep ocean heat update, ice sheet dynamics, sea level, land cover effects from water cycles, and vegetative other biological changes). There are also uncertainties introduced when making "modeling simplifications" designed to permit simulation of such processes in a mathematically efficient manner given computational limitations.

- **Climate projection bias-correction:** This study is designed on the philosophy that climate model simulation biases toward wet, dry, warm, or cool conditions should be identified and corrected before relating projection information to runoff impacts. Such projections are labeled "bias-corrected" climate projections (Section 2.4). The decision on whether and how to bias-correct climate projections data can affect portrayal of associated runoff projections. For example, the technique featured in this report corrects for period-statistics bias, but does not force correction of period-frequencies bias. In other words, all projections will have the same monthly period statistics during their simulated historical period of 1950-1999, but some may feature shorter duration spells of droughts and surpluses, while others may feature longer duration spells. Further, the technique in this report corrects for bias in period-monthly statistics, but does not force correction of bias in period-seasonal or period-annual statistics.

- **Climate projection spatial downscaling:** This study uses the empirical BCSD technique (Section 2.4), which features spatial disaggregation of the climate projections data from climate model resolution to more local resolution on a monthly time-step. Although this technique has been used to support numerous water resources impacts studies in California (e.g., Van Rheenan et al. 2004, Maurer and Duffy 2005, Maurer 2007, and Anderson et al. 2008, Reclamation 2008, Brekke et al. 2009a), uncertainties remain about the limitations of empirical downscaling methodologies. One potential limitation relates to how empirical methodologies require use of historical reference information on spatial climatic patterns at the downscaled spatial resolution. These finer-grid patterns are implicitly related to historical large-scale atmospheric circulation patterns, which would presumably change with global climate change. Applying the historical finer-grid spatial patterns to guide downscaling of future climate projections implies an assumption that the historical relationship between finer-grid surface climate patterns and large-scale atmospheric circulation is still valid under the future climate.

In other words, the relationship is assumed to have stationarity. In actuality, it is possible that such stationarity will not hold at various space and time scales, over various locations, and for various climate variables. However, the significance of potential non-stationarity in empirical downscaling methods and the need to use alternative downscaling methodologies remains to be established. Dynamical downscaling, which involves finer-resolution atmospheric simulation forced at it's boundaries by GCM output, holds potential for revealing the significance of stationarity assumptions featured in empirical downscaling.

- **Climate projections temporal disaggregation from monthly to 6-hourly (synthetic weather generation):** This study uses a historical resampling and scaling technique to generate 6-hourly weather sequences consistent with the monthly downscaled climate projections (Wood et al. 2002). This technique has been used to support numerous water resources impacts studies (e.g., Van Rheenan et al. 2004, Maurer and Duffy 2005, Maurer 2007, and Anderson et al. 2008, Reclamation 2008). However, other techniques might have been considered. Preference among available techniques remains to be established.

- **Natural systems response:** This study features use of SacSMA/Snow17 models (Section 3.2) to analyze natural runoff response to changes in precipitation and temperature while holding other watershed features constant. Other watershed features might be expected to change as climate changes and affect runoff (e.g., potential evapotranspiration given temperature changes, vegetation affecting evapotranspiration and infiltration, etc.). In the SacSMA/Snow17 model-applications, potential evapotranspiration estimates are inputs and were not adjusted. In retrospect, this was likely a poor simulation setup choice[9], and probably led to overestimated future annual runoff possibilities in Alternatives 2 and 3[15]. However, this simulation choice would not seem to impair our ability to compare results from Alternatives 2 and 3 since they would feature the same bias in future annual runoff possibilities from not changing PET It is uncertain how to account for the possibilities of land cover response to climate changes in hydrologic simulation modeling. This is because such models are calibrated to reproduce historical runoff given historical weather and basin-characterizations (e.g., land cover, soils) that also reflect history. Thus, the historical relationship between weather and runoff is mediated by historical land cover. Adjustment to watershed land cover as a result of climate change would theoretically affect this relationship. How such a change should translate into a different model parameterization is a question of further research. That said, it is also not a given that such a change would significantly affect model parameterization.

Alternative 3 inherits the uncertainties of Alternative 2 hydrologic data development, as the latter provides the magnitudes information used in the stochastic modeling of Alternative 3. In addition, Alternative 3 is confounded by the non-stationary nature of climate projections. Alternative 3 was implemented in this application for four separate 30-year periods in the Alternative 2 climate projections. Questions remain about suitable period-duration for Alternative 3 implementation relative to the non-stationary characteristics of Alternative 2 climate projections (e.g., lower frequency variability, trends).

6.0 Other Issues Affecting Use of Alternatives

This section discusses other issues that could affect decisions on which of these alternatives to use for planning purposes. The discussion is outlined by hydrology disaggregation, consistency with other planning assumptions, and stakeholder considerations.

6.1. Hydrology Disaggregation

The results discussion in Section 5 summarize how statistical and frequency characteristics of a planning hydrology might vary among Alternatives 1 through 3, and how each of these alternatives might vary relative to the Null Alternative hydrology. However, such results were discussed with an annual time scale and a basin-wide approach. The planning reality is that hydrology must be specified at monthly time scale or shorter, and for a number of interior sub-basin locations. This section describes disaggregation approaches that would have to be applied to Alternative 1 through 3 datasets. Varying levels of effort would be required by alternative, and varying levels of uncertainty would be introduced by alternative when performing disaggregation. Note that the Null Alternative datasets already feature such disaggregation (Reclamation 2005a, 2005b) even though this study only focused on their annual, single-location aggregates (Figure 3 and Figure 4). For discussion purposes in the following sections, assume a goal of specifying hydrology for interior sub-basin outflow locations and on a monthly basis.

6.1.1 Alternative 1 (instrumental record, paleoclimate)

The stochastically modeled annual runoff series at the downstream basin outlet are the starting points for this disaggregation. Translation to a monthly runoff at interior sub-basin locations would involve an empirical approach that ensures temporal consistency (i.e., preserving annual-to-monthly runoff relationships at each interior location) and spatial consistency (i.e., preserving aggregate-to-subbasin runoff relationships). Defining these relationships would likely be based on evaluating the Null Alternative hydrology, given that the Null Alternative hydrology was used as the magnitudes' reference and understanding that it has already been characterized on a monthly basis and at the targeted interior sub-basin locations.

An approach to disaggregating in a temporally and spatially consistent manner (Prairie et al. 2007) was applied to disaggregate annual runoff at Lees Ferry on the Colorado River to monthly runoff at multiple interior sub-basin locations. That approach was later applied to support an environmental compliance study within the Colorado River basin, completed jointly by Reclamation's Upper Colorado and Lower Colorado Regions (Reclamation 2007).

6.1.2 Alternative 2 (instrumental record, projected climate)

Translation of these data involves two steps:

1. **Configure the output reporting of the hydrologic simulation model.** The model simulations would be set up to compute routed runoff at each the interior sub-basin locations of interest. The output would be the time-step of simulation (e.g., 6-hourly for the models used in this study) and would have to be aggregated to the time step of interest (i.e., monthly in this discussion).

2. **Account for hydrologic simulation model bias.** The hydrologic simulation model's results during the simulated historical period of the runoff projection should be evaluated for bias relative to observed runoff during the common historical period. The ratio or period-means might be used to correct the modeled runoff bias, as was discussed for the Gunnison results in Section 5.2.1. Monthly runoff biases should first be corrected first at a given location. Then, the remaining annual runoff basis should be identified. If the model simulation decision is to ensure the basin-aggregate runoff is correct at the expense of some residual bias at specific sub-basins, then the remaining annual runoff bias would be corrected.

6.1.3 Alternative 3 (instrumental record, paleoclimate and projected climate):

The disaggregation procedure for Alternative 3 first involves completing the disaggregation procedure for Alternative 2. Then, as stochastic modeling of Alternative 3 proceeds, the sequencing of basin-aggregate annual runoff (looking up annual magnitudes from Alternative 2 data) would coincidentally trigger the sequencing of basin-disaggregated monthly runoff (grabbing associated multi-location monthly runoff associated with the basin-aggregate annual runoff sampled). So in other words, as the basin-aggregate annual runoff is sampled, that simulated year's monthly runoff volumes at upstream sub-basin locations are also sampled. Further, these upstream monthly runoff volumes reflect the climate projection effect on seasonality and reflect the bias-corrections performed under Alternative 2 disaggregation.

6.2. Consistency between Planning Assumptions for Water Supply, Water Demands, and Operating Constraints

Other planning assumptions about water demands and operational constraints must be established, and in a manner that is consistent with assumptions underlying the assumed hydrology, and water supply possibilities. Reclamation's planning assumptions for water demands and operating constraints are typically scenario-based. For example, water demands relate to a "current" or "scenario future" level of land use. "Scenario" sets of values are also reflected in assumed flood control rules, instream flow requirements, etc.

The Null Alternative, Alternative 1, and Alternative 3 hydrology offer a period-stationary view of hydrologic possibility (historical for the Null Alternative and Alternative 1, and historical or future for Alternative 3). A period-stationary view is consistent with scenario-view of demands and constraints. The assumptions for scenario demands may be based on scenario land use associated with the assumed hydrologic period. In this case, the scenario demands and assumed hydrology originate from a common period context and are both meant to be regarded as plausible and appropriate for the given planning look-ahead period. Whether they are appropriate is a matter of judgment. Applying the Null Alternative and Alternative 1 in a context where climate has been and is projected to be non-stationary leads to questions about this judgment.

The Alternative 2 and Alternative 3 datasets are both predicated on the notion that projected climate could change and should be reflected in hydrologic assumptions. This raises a question on whether assumed demands and operating constraints should also be adjusted for climate change. Further, Alternative 2 is a non-stationary portrayal of hydrology, as it is a runoff projection that has time-varying statistics. Likewise, characterizing demands and constraints in a projection sense would be consistent. However, data and methods supporting the development of such demand and constraint projections remain to be developed. As a result, for the time being, demand and constraint assumptions will likely have to remain scenario-based and period-stationary for the planning analysis, even though hydrology would be characterized as a nonstationary projection.

Such incompatibility raises questions about the direct, near-term implementation of Alternative 2 as it was portrayed here. As a compromise, the range of period-specific runoff changes might be sampled from Alternative 2 information and used to scaled period-stationary water supply assumptions (similar to approach in Reclamation 2008). However, selecting the range of results sampled is easy to do—but not straight-forward—given the challenge of interpreting such sample changes in simulated runoff means as being due to climate change and/or low-frequency variability (Brekke et al. 2009b). Nevertheless, such an approach has been featured in many operations impacts studies, including Anderson et al. 2008, Reclamation 2008, Brekke et al. 2009a, and Vano et al. 2009.

6.3. Stakeholder Acceptance

The methods required to generate these hydrology alternatives significantly depart from those traditionally used to develop Null Alternative hydrology. Stakeholders and decision-makers are well-oriented with the latter. The Null Alternative datasets serving both basins in this analysis have been reviewed by planning stakeholders in each given basin. That review process, in conjunction with data development documentation (Reclamation 2005a and 2005b), has served to build stakeholder trust in the veracity of these data and their appropriateness for defining plausible water supply variability assumptions for long-range planning questions. However, their appropriateness still resides in the paradigm that the "past is a proxy for the future."

Stakeholder and decision-maker orientation on the methods of Alternatives 1 through 3 may be limited. This could then limit their acceptance of using these alternative methods to support longer-term planning, at least until an education and trust-building process has occurred. For example, stakeholders and decision-makers may already be challenged with understanding the processes that define the Null Alternative hydrologic data. Explaining the arguably more complex data-development procedures of Alternatives 1 through 3 to non-technical stakeholders would likely be an even greater challenge, particularly when it involves stakeholders who have grown accustomed to focusing on how the planning study depicts operating performance during historical hydrologic events, sequenced as they were experienced, which is what the Null Alternative hydrology features.

To secure stakeholder orientation on any of Alternatives 1 through 3, it would seem necessary to have a well-reviewed standard description of how the data are processed so that Reclamation's technical liaisons are able to explain it to the stakeholders. Such descriptions would likely follow a rigorous application and documentation process to start the process of building stakeholder familiarity and trust. Such a process was executed in the development of Appendix N for Reclamation (2007). However, even with thorough data-development documentation, it may be a case where stakeholders are able to follow underlying concepts, but not able to track the details of data-development. To secure stakeholder trust in these cases, it may also be necessary to subject such datasets and documentation to external peer review.

In addition to building stakeholder trust in the alternative datasets, it may also be necessary to spend time conversing with stakeholders on how planning analysis output and supported decisions are affected by choice of alternative hydrologic dataset. For example, traditional use of the Null Alternative hydrologic dataset invites the stakeholders and decision-makers to consider planning results based on:

1. A scenario defining a proposed system change

2. Scenario demands and constraints

3. Assumed water supply variability under the paradigm that "observed past is proxy for the future"

This approach produces a single operations simulation given scenario (1-3). The simulation output is then summarized statistically (e.g., full-period statistics, statistics by hydrologic year-type, or statistics during historic drought periods).

In contrast, using any of the alternative hydrologic datasets would introduce a more complex (but perhaps more appropriate) portrayal of operations possibilities because each planning scenario would be analyzed under an ensemble of hydrologic series. This means that stakeholder groups would be asked to analyze operations statistics in two ways:

1. At a given time stage, statistics on operated system state across the hydrologic-ensemble (recognizing that such statistics reflect the ensemble's multiple histories of hydrology leading up to the given time stage)

2. Across time periods to illustrate how the envelope of operated-state possibilities evolves through the simulation time stages.

This hydrologic-ensemble perspective for planning analyses is already used in some Reclamation basins (e.g., Colorado River Basin studies, such as the recently completed Reclamation 2007). However, for regions where ensembles are not yet used, introducing such a perspective would be a significant and challenging departure from current practice. This perspective may require considerable effort in building stakeholder and decision-maker understanding. However, the benefits of gaining such understanding could provide for a more robust context for planning under transient basin conditions, (e.g., climate, demographic, or land cover changes).

Although Alternatives 1 through 3 feature hydrologic ensembles that introduce more complexity in planning results, such results might form a more robust context for planning that involves investments that are made in the near term, at a specific (and largely fixed) scale. Alternatives 1 through 3 would produce a richer set of results, and specifically Alternatives 2 and 3 would portray a richer set of assumed futures that represent expected climate change and climate variability (with paleoclimate information informing the latter under Alternative 3). Decision-making must take into account the variability and uncertainty in project outputs and analysts must be able to provide estimates of that variability and uncertainty in an understandable, meaningful fashion. This is where risk and uncertainty enter into the decision-making process. Effective display of such uncertainty information to decision-makers remains a matter to be jointly explored by technical staff, decision-makers and stakeholders.

7.0 Summary

This study considers alternative climate contexts for water supply assumptions used in Reclamation's longer term planning studies. Reclamation has traditionally assumed that water supply variability reflects climate of the instrumental record. However, Reclamation has recently featured alternative climate contexts, either by incorporating a blend of paleoclimate and instrumental records information to offer a broader portrayal for possible hydrologic variability, or by incorporating projected climate information to reflect future changes in climate and runoff statistics.

This study is motivated by an interest in being able to establish water supply assumptions based on the possibly more credible aspects of paleoclimate information (i.e., year to year variability, or "frequency" characteristics) and projected climate information (i.e., change in climate and runoff statistics, but not necessarily frequency characteristics). Given such a methodology, there is also interest to know whether such a climate context is warranted relative to the simpler context of blended paleoclimate and instrumental records information, or blended projected climate and instrumental records.

Given these interests, three research questions were posed:

(1) How can paleoclimate and projected climate information be jointly and rationally represented in water supply planning assumptions?

(2) How would such a planning hydrology be similar to or different from planning hydrology that represents paleoclimate or projected climate individually?

(3) What implementation realities might influence choice among climate information sets when defining water supply planning assumptions for Reclamation studies?

To address these questions, the study involved developing hydrology data under three alternative climate contexts (summarized below) for two case study basins: Missouri River above Toston, Gunnison River above confluence. Data characteristics were then compared amongst climate information alternatives. Briefly, hydrology and climate context alternatives are:

- **Null Alternative – Instrumental Records.** Hydrology is based on historical observations and implicitly the climate of the instrumental record period (e.g., streamflow gages, flow impairment information). Both statistical and frequency characteristics of hydrology are defined by historical observations. Only the single observed historical sequence is used for planning purposes.

- **Alternative 1 – Instrumental Record, Paleoclimate Proxy.** Statistical and frequency characteristics come from separate climate references in this alternative. Runoff statistics (i.e., magnitude possibilities in any given year or month) come from the Instrumental Record period. Frequency characteristics defining possible deficit and surplus spells and accumulations (i.e., state information on hydrologic year-type, and state-transition tendencies) come from variability information in paleoclimate data (i.e., annual tree-ring chronologies). Stochastic modeling is done where state is modeled first based on paleoclimate information, and then magnitude is modeled for the given simulated state based on Instrumental 0Records information. The stochastic model is applied to generate a collection, or ensemble, of hydrologic sequences for planning purposes.

- **Alternative 2 – Instrumental Record, Projected Climate.** Statistical and frequency characteristics come from the projected climate information, which evolve in a fashion where statistics change with time, meaning they are nonstationary. However, instrumental record is used to bias-correct projected climate information during a historical period of common overlap. Instrumental records are also used to calibrate the hydrologic simulation model defining precipitation-temperature-runoff relationships in the case study basins. As a result, the climate context for this alternative is viewed as a blend of instrumental records and projected climate. Hydrologic simulation modeling is done to translate the nonstationary projections of temperature and precipitation into associated runoff projections. An ensemble of climate projections is considered because individual projections have unique frequency characteristics. Further, they may be in different phases because the climate projections do not feature a common estimate of initial climate-system condition for 20th century simulations or 21st century projections.

- **Alternative 3 – Instrumental Record, Paleoclimate Proxy, Projected Climate.** Statistical and frequency characteristics come from separate climate references, like Alternative 1. Frequency characteristics about hydrologic state and state-transition tendencies still come from paleoclimate records, as in Alternative 1. Runoff statistics on magnitude possibilities come from runoff projections developed under Alternative 2 and from a specific future period in those projections consistent with the planning look-ahead interests. Stochastic modeling is then done where state is modeled based on paleoclimate information, and then magnitude is modeled given the period-specific runoff projection information. The stochastic model is then applied to generate an ensemble of hydrologic sequences for planning purposes.

Several preliminary datasets supported the development of the hydrology (Section 2), including: estimated monthly volumes of natural runoff for each basin, observed daily streamflow and 6-hourly weather, reconstructed annual volumes of natural runoff based on tree-ring records, and contemporary climate projection information that has been bias-corrected for global climate model tendencies and then spatially downscaled from "climate model" resolution to "basin relevant" resolution for hydrologic analysis. Two types of hydrologic simulation models were used in this study (Section 3): one featuring stochastic concepts where different hydrologic sequences are generated that exhibit statistical and frequency characteristics of reference climate information; and, a process-based simulation model that computes hydrologic response to any time-series forcing scenario of temperature and precipitation. Methods used to apply preliminary datasets and model tools for each climate alternative are discussed in Section 4.

Each alternative's planning hydrology was evaluated for statistical and frequency characteristics (Section 5). Table 2 summarizes sequence durations and number of ensemble members, by alternative. For Alternative 3, four ensembles were generated for each basin, each corresponding to a sub-period of Alterative 2 runoff information: 1951-1999, 2010-2039, 2040-2069, and 2070-2099.

- The statistical characteristics of the alternatives offer a range of runoff portrayals. Alternative 1 offers the same range of annual runoff possibility as the Null Alternative, but has a broader set of deficit and surplus spell possibilities due to the nature of paleoclimate information used. Alternative 2 offers a broader range of annual runoff possibility than the Null Alternative when focusing on a period of common historical overlap with the Null Alternative, even though runoff statistics are generally consistent. The reason that range is broader during the historical period is related to both climate modeling uncertainty and natural variability in the climate system as reflected by climate models. Beyond the historical period, Alternative 2 portrays statistical and frequency characteristics that change with time. Lastly, Alternative 3 features a range of runoff possibilities constrained by what's developed under Alternative 2, but with frequency characteristics reflecting the paleoclimate information used.

- The study focused on frequency characteristics and understanding the merit of blending paleoclimate information with projected climate information (Alternative 3) versus using only an ensemble of climate projections (Alternative 2). In other words, does frequency portrayal differ between the two? If yes, then a choice point is reached on which to dataset to use, informed by these differences. If no, then it would seem appropriate to proceed with Alternative 2 and avoid the extra data-development work associated with Alternative 3.

  Results for the Upper Missouri suggest that a choice point would exist, as Alternative 3 data exhibited greater deficit and surplus spell-duration possibilities than Alternative 2. For spell durations common to both alternatives, accumulation tendencies would be more intense under Alternative 2 than Alternative 3.

For the Gunnison, a weaker choice point exists. Spell-duration possibilities were generally comparable in these two alternatives. Only surplus accumulation possibilities differed significantly, with more intense possibilities occurring in Alternative 2 relative to Alternative 3 during common projection periods.

Preliminary impressions on Alternative 2 versus Alternative 3 frequency characteristics might have been drawn before going through the stochastic modeling exercise in Alternative 3. Such an impression could be based on comparison of the frequency characteristics of Alternative 2 runoff projections and the reconstructed runoff series. In Alternative 3, completing this comparison before performing stochastic modeling is recommended to avoid unnecessary hydrology data-development. Decisions to proceed would be based on reviews of this preliminary evaluation and impressions offered by stakeholders and decision-makers (e.g., risk attitudes on what water supply aspects are most important for the given planning situation).

Revisiting the first two research questions posed in this study, the following conclusions are offered:

1) "*How can we jointly and rationally incorporate paleoclimate and projected climate information into a planning hydrology that represents assumptions about possible water supplies?*" The two-stage stochastic modeling approach used in this study (Alternative 3) illustrates one such framework, incorporating the more credible state information from paleoclimate data and the projected runoff statistics associated with climate projections during a future period of interest.

2) "*How would such a planning hydrology be similar to or different from planning hydrology developed to individually reflect paleoclimate or projected climate?*" The planning hydrology in question features a blend of instrumental record, paleoclimate, and projected climate information (Alternative 3). Alternative 3 can reflect climate change effects on runoff statistics (e.g., changes in monthly and annual mean and variance) while Alternative 1 (paleoclimate, instrument records) cannot. Further, Alternative 3 can incorporate historical information on frequency and avoid requiring trust in the frequency characteristics from climate models while Alternative 2 (projected climate, instrument records) cannot. However, if the paleoclimate basis used to provide frequency characteristics does not feature frequencies substantially different than those from climate projections, there would be little to no benefit of

relating water supply assumptions to a blend of paleoclimate and projected climate information (Alternative 3).

Three issues influence the third research question of "*What implementation realities might influence choice among climate information sets when defining water supply planning assumptions for Reclamation studies?*"

1) **Hydrologic data-disaggregation.** Hydrology data developed in this study are sufficient for addressing the research questions posed, but insufficient for planning purposes as they are aggregated temporally to annual time step and spatially at a downstream runoff location. Planning would require disaggregated data, at least to a monthly time step and specified at various interior sub-basins locations. The amount of additional work required to perform such disaggregation may be a consideration for deciding which alternative to use. However, methods to perform this disaggregation are available for each alternative (Section 6).

4. **Establishing consistency with other planning assumptions**. Questions will be encountered on how to reconcile the basis for assumptions on water supply possibilities with those regarding water demands and other operating constraints related to climate (e.g., flood control rules, environmental management). Methods for linking assumptions about operating constraints to these alternative climate contexts are not as evolved as those for linking supply assumptions to these contexts.

5. **Stakeholder acceptance.** Stakeholder acceptance and/or understanding of a given climate information context and how it is translated into water supply may influence which alternative is preferred for a given planning process. For the Null Alternative, stakeholders and decision-makers are presumably familiar with the basis for water supply assumptions, including underlying data and methods. For the alternatives, the ability to proceed may be limited by the orientation and trust levels exhibited by prospective stakeholders and decision-makers. Some groups may be well oriented on the nature of paleoclimate information and have experience with its application in water resources planning, including using stochastic modeling (e.g., staff in Reclamation's Lower Colorado and Upper Colorado who contributed to technical analyses in Reclamation 2007). Other groups may be well-oriented with projected climate information and have experience with its application in water resources planning (e.g., Reclamation's Mid-Pacific and Pacific Northwest regions). Still other groups may be at more fundamental learning stages for both. In any case, introduction of new climate contexts and application methods necessitates education and trust-building phases.

For the time-being, even if more evolved methods are used to characterize supply assumptions (such as those featured in this study), it may be necessary to proceed with traditional methods for defining demand and operational constraint assumptions. The acceptability of such an approach may need to be vetted with stakeholders and decision-makers. The capacity of a planning process to support both phases will determine how new methods are introduced in planning communities and at what pace.

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Appendix A. Tree-Ring Based Reconstructions of Water Year Streamflow and Precipitation for the Upper Missouri and Gunnison Basins

Prepared by: Connie A. Woodhouse[1] with collaborators Steve Gray[2], Jeff Lukas[3], Greg Pederson[4], and Erika Wise[1] (*edited by L. Brekke*)

This document provides information on streamflow and precipitation reconstructions discussed in the main report[5] for the two basins: the Missouri River above Toston and the Gunnison River basin above its confluence with the Colorado River (hereafter referred to as the Upper Missouri and Gunnison basins). Information in this appendix includes: description of data supporting reconstruction model development (i.e. streamflow data, tree-ring chronologies), model development approach, summary of model development results, and comparison of reconstruction climate variability with that from climate projections described in the main report[6].

A.1 Data

A.1.1 Instrumental Records Streamflow

Estimates of natural water year (WY) streamflow volumes (acre-feet) were obtained for the Gunnsion (1906-1995) and the Upper Missouri (1929-2002) from the Bureau of Reclamation[7]. These two basins are hereafter referred to as the Upper Missouri and Gunnison, respectively. Estimates for basin mean-area total WY precipitation were obtained from both: (a) historical gridded precipitation from 1951-1999[8] and, (b) historical gridded meteorology from 1896-1999 developed using a different technique[9]. For each gridded precipitation data source, basin mean-area time series were produced by spatially intersecting the gridded data with basin boundary shapefiles[10].

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[2] University of Wyoming, Wyoming State Climate Office
[3] University of Colorado, INSTAAR
[4] University of Arizona School of Natural Resources
[5] Section 2.2
[6] Section 2.4
[7] Reclamation's Upper Colorado Region Office provided natural flow estimates for the Gunnison River at confluence. Reclamation's Great Plains Region Office provided similar data fro the Missouri River at Toston.
[8] Data from Maurer et al. 2002, and accessible at: http://www.engr.scu.edu/~emaurer/data.shtml.
[9] PRISM = Parameter-elevation Regressions on Independent Slopes Model, with data available at: http://www.prism.oregonstate.edu/
[10] Provided by National Weather Service Colorado Basin and Missouri Basin River Forecast Centers

A.1.2 Tree-ring Chronologies

The International Tree-Ring Data Bank (ITRDB) at the NCDC Paleoclimatology Branch[11] was surveyed to identify available tree-ring chronologies for species that were: (a) known to be sensitive to variations in moisture, and (b) in the two case study basins or in nearby and similar climate regions. In addition, the survey for the Upper Missouri also considered several unpublished data sets jointly collected by the Wyoming State Climate Office and University of Arizona School of Natural Resources. Species include those known to be sensitive to moisture variability: *Pinus ponderosa*, *Pinus edulis*, *Pinus flexilus*, and *Pseudotsuga menziesii*.

Chronologies were screened for a common end date, using a cutoff of at least 1997 (1999) for Gunnison flow (precipitation), and at least 1996 (1998) for Upper Missouri flow (precipitation). Next, the chronologies were evaluated to determine which of them should be considered as candidate predictors in reconstruction model development. In this evaluation, each annual chronology was separately correlated with basin WY streamflow and precipitation time series during their period of common historical overlap. For the hydrologic series, correlations were checked over the first and second halves of the common years to assess the significance of the correlation during two time periods. For precipitation, correlations were checked relative to both instrumental records data source, where the 2nd data source (based on PRISM data[9]) permitted the correlation to also be checked during early 20th century. Chronologies with correlations that were not significant at $p<0.05$ for the full period or either of the split periods were deleted from the candidate pool of predictors for reconstruction model development. Applying this criterion resulted in separate sets of candidate chronologies for reconstructing two hydroclimate variables (flow and precipitation) in two basins (Figures A.1 and A2 for the Upper Missouri and Gunnison, respectively).

Since water year precipitation and streamflow are correlated, there was quite a bit of overlap in these candidate sets of chronology variables. Comparing the chronology sets between basins, there is one fundamental difference in their inclusion of low order persistence (e.g., multi-decadal climate variability). The chronologies used for Gunnison reconstruction modeling were “prewhitened” with low order persistence removed (Woodhouse et al. 2006) because analysis of Gunnison streamflow and precipitation from instrumental records did not reveal a significant amount of low order persistence. In contrast, a significant amount of 20th century low order persistence seems present in the Upper Missouri. Consequently, the chronologies for the Upper Missouri reconstructions were not prewhitened.

[11] http://www.ncdc.noaa.gov/paleo/treering.html

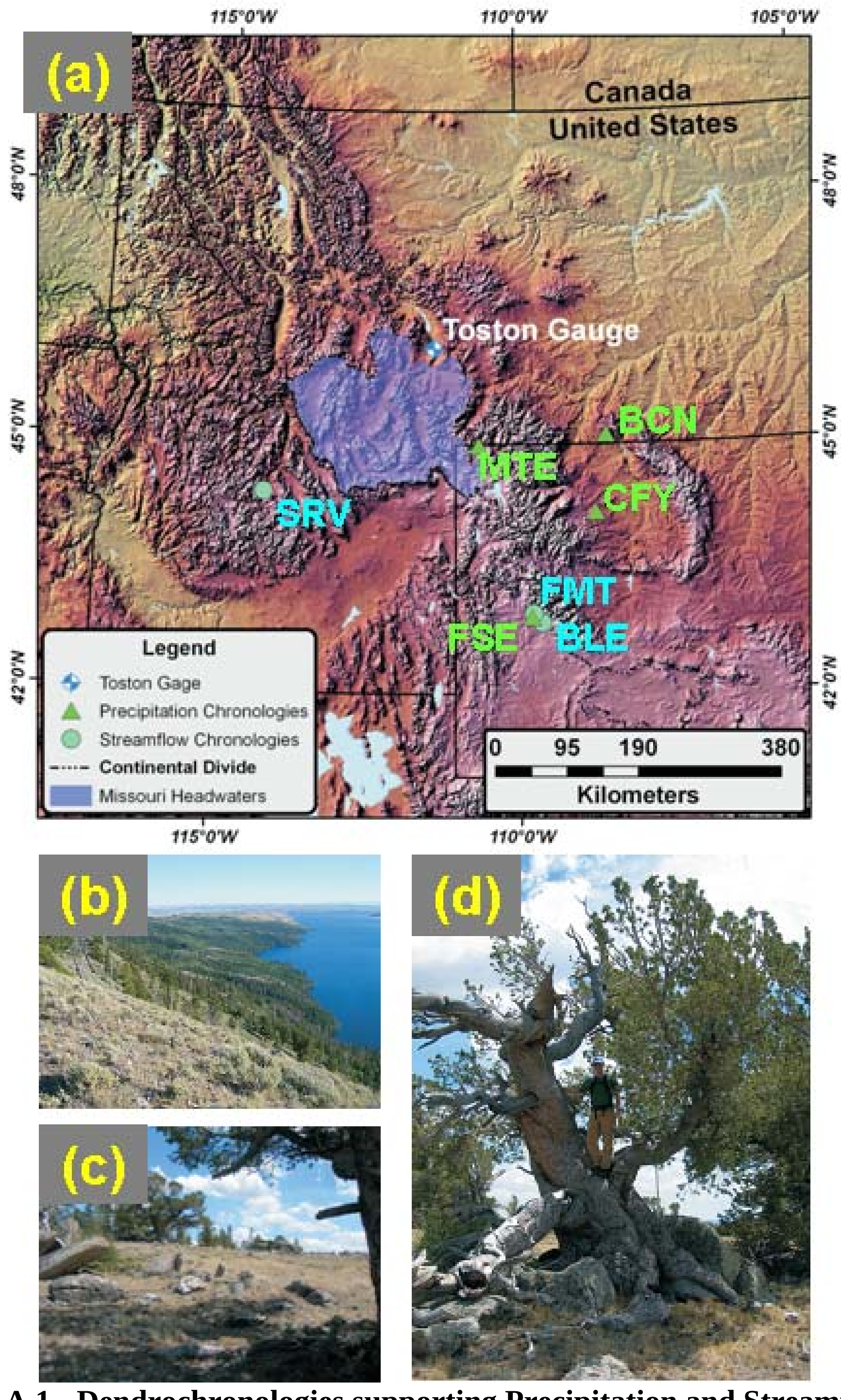

Figure A.1 - Dendrochronologies supporting Precipitation and Streamflow Reconstructions for the Upper Missouri. (a) Location of chronologies used in reconstructions of water year runoff, and water year total precipitation over the basin. Photos show Freemont site labeled FMT (b) and representative trees for the region (c, d).

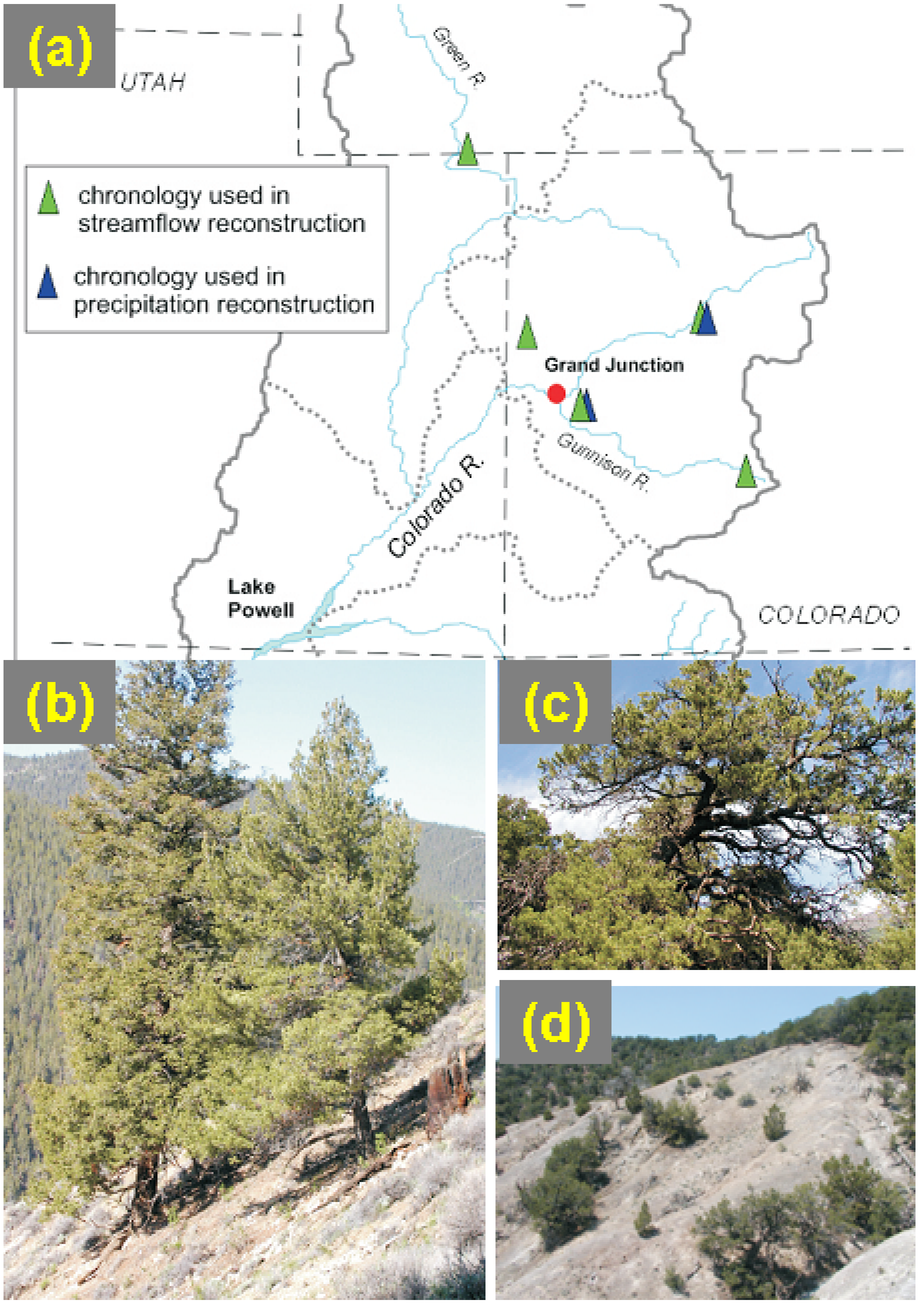

Figure A.2 Dendrochronologies supporting Precipitation and Streamflow Reconstructions for the Gunnison. (a) Location of chronologies used in reconstructions of water year runoff and water year total precipitation. Photos show Douglas Fir at Sargeants Site (a), Pinyon Pine at Wild Rose site (b), Pinyon Pine at Trail Gulch site (c).

A.2 Model Development

Reconstruction models were developed using multiple linear regression to calibrate tree-ring data with instrumental series. Methods are described in Woodhouse et al. 2006. Forward stepwise regression was the main approach used, but alternative model development approaches were applied to both basins (i.e., PCA regression, Woodhouse et al. 2006). Several alternative models were developed using subpools of longer chronologies for the Gunnison precipitation. All methods yielded similar results. In the case of the Gunnison water year precipitation reconstructions, two models are presented, one extending to 1491 and one to 1120. Regression assumptions were assessed graphically and statistically (all models met assumptions). Model cross validation was performed and the validation root mean squared error (RMSE) and the reduction of error (RE) were evaluated. The RE assessment tests the model skill compared to a model based on no knowledge (the mean of the calibration series in this case). The highest RE value obtainable is 1.0, and there is no limit to the lowest; any positive value is considered an indication of some skill (Fritts 1976).

A.3 Results

The selected reconstruction models for water year (WY) streamflow and precipitation are summarized in Table A.1 and defined in equations A.1 – A.4. The 3-letter codes are the chronology site names, which are listed in Table A.2. For the Gunnison above confluence, WY precipitation reconstruction models were applied for two historical periods: 1120-2002 and 1491-2002.

Table A.1 Reconstruction model results from the final stepwise models.

Reconstruction	Calibration Period	Reconstruction Period	Explained variance(1)	RMSE(2)	RE
Gunnison at confluence, WY streamflow	1906-1997	1569-1997	77%	370	0.73
Gunnison above confluence, WY precipitation	1951-1999	1491-2002	69%	2.6	0.61
		1120-2002	57%	2.8	0.52
Missouri at Toston, WY streamflow	1930-1996	1576-1996	58%	610	0.54
Missouri above Toston, WY precipitation	1951-1998	1657-1998	44%	2.9	0.31

Notes:

(1) during Calibration Period

(2) units are KAF for flow, inches for precipitation

The resultant model equations are listed below:

(Eq. A.1) Gunnison at confluence WY streamflow = - 368 + WIL*872 + TRG*765 + DJM*703 + DOU*564 + SAR*363

(Eq. A.2a) Gunnison above confluence WY precipitation (1120-2002) = 13.99 + WIL*6.20 + TRG*2.61

(Eq. A.2b) Gunnison above confluence WY precipitation (1491-2002) =11.17+ WIL*3.51 + MTR*5.25 + CCC*3.25

(Eq. A.3) Missouri at Toston WY streamflow = 1872 – BLE*1424 + FMT*2837 + SRV*1032

(Eq. A.4) Missouri above Toston WY precipitation = 7.61 + CFY*3.36 + MTE*3.51 + FSE*2.05 + BCN*2.87

Table A.2. Chronologies used in Model Equations A.1-A.4.

Site code	Site name	Metadata in Woodhouse et al 2006(1)	Archived in the ITRDB with metadata(2)	Unpublished; for metadata, see S. Gray or G. Pederson
BCN	Bear Canyon			X
BLE	Boulder Lake, WY			X
CCC	Chokecherry	X		
CFY	Canyon		X	
DJM	Clarks Fork,	X		
DOU	Yellowstone	X		
FMT	Dutch John			X
FSE	Douglas Pass			X
MTE	Fremont Lake, WY		X	
MTR	Fremont South East	X		
SAR	Mount Everts	X		
SRV	Montrose			X
TRG	Sargents	X		
WIL	Salmon River	X		
	Valley			
	Trail Gulch			
	Wild Rose			

Notes:

(1) see http://www.ncdc.noaa.gov/paleo/pubs/woodhouse2006/woodhouse2006.html

(2) see http://hurricane.ncdc.noaa.gov/pls/paleo/fm_createpages.treering

Time series comparisons of reconstructed and instrumental record streamflow and “categorical wet or dry” year-type are shown on Figures A.3 and A.4 for the Upper Missouri and Gunnison, respectively. Both figures also show time series categorical “state” (i.e. wet or dry relative to full-period median) for both reconstructed series. The categorical state series indicates occurrence of relatively wet or dry spells during the reconstruction period.

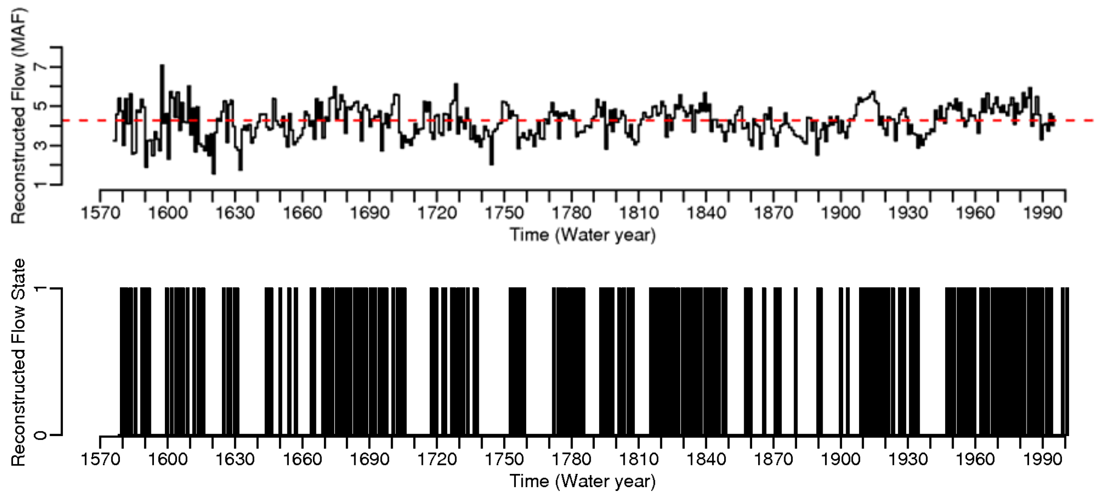

Figure A.3 Runoff Reconstruction, Upper Missouri: (a) time series of magnitudes, (b) time series of binary-state.

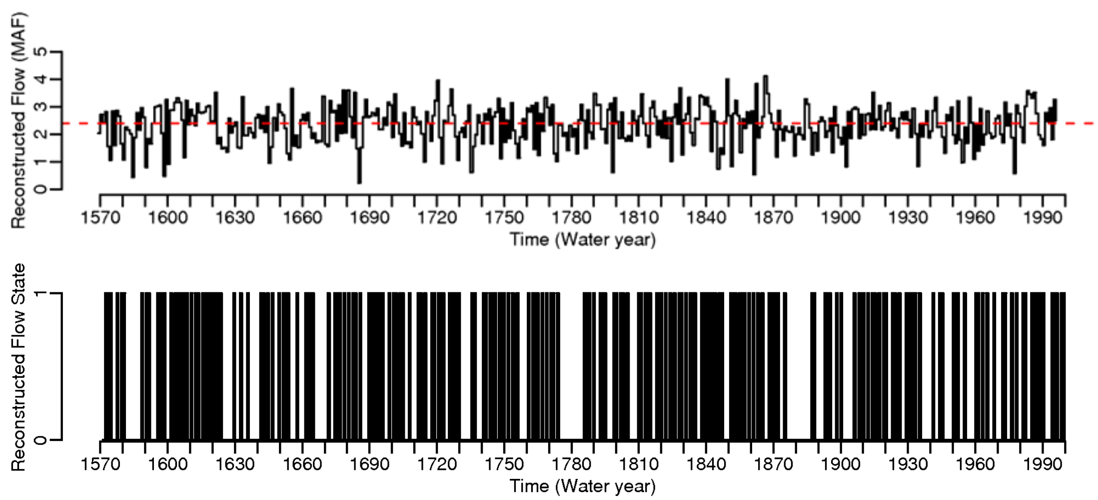

Figure A.4 Runoff Reconstruction, Gunnison: (a) time series of magnitudes, (b) time series of binary-state.

A.4 References

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Appendix B. Development of Stochastic Flow Sequences based on separate Reference Datasets for Hydrologic State and Magnitude

Prepared by: Ken Nowak[1] and Jim Prairie[2] (*edited by L. Brekke*)

This document provides information on the stochastic modeling approach used to simulate synthetic annual runoff sequences, as discussed in the main report, for the two case study basins: Missouri River above Toston and Gunnison River above confluence. The approach involves a two-stage modeling approach where hydrologic state information (e.g., categorically wet or dry) is derived from one reference climate (e.g., paleo-reconstructed runoff) and hydrologic magnitudes information (i.e. runoff volume) is permitted to be derived from the same or other reference climate (e.g., instrumental record, or projected climate).

In the case study of the main report, all applications of this approach involved two-state models where state is defined as wetter than or drier than median annual runoff volume from the reference runoff series. This means that the reference runoff series is converted to a binary state series. A decision is also made to focus on lag 1-year auto-correlation in the state series. Given these implementation choices, a non-homogeneous Markov model (Rajagopalan, et al., 1996) is used to generate synthetic state sequences of any specified duration. In the second stage, flow magnitudes are assigned by sampling flow volumes from the magnitudes' reference climate (e.g., annual volumes from the instrumental record, or annual volumes from a given climate projection period). A k-nearest neighbor (KNN) data resampling technique is used to perform this second stage.

In the sections that follow, both the non-homogeneous Markov model and KNN data-resampling technique are described in detail.

B.1 Non-Homogeneous Markov (NM) Model

A Markov model provides a framework to model discrete-valued process. Examples of discrete-valued processes include rainfall and extreme events (i.e., drought or flooding). These are processes that take on an integral value such a 0 and 1 to represent no rain or rain event. A homogeneous Markov model would feature constant state-transition probabilities within the sequence begin simulated. By contrast, a non-homogeneous model permits transition probabilities that vary during a pass through a given sequence (or source hydroclimate series). The choice to compute transition probabilities for each year in the reconstructed runoff series permits the non-homogeneous nature of the data to be incorporated into the

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generated synthetic flow sequences. The remainder of this section explains the NM approach. Interested readers are also referred to Prairie et al. (2007), Rajagopalan, et al. (1996) and Rajagopalan, et al. (1997).

Consider a NM model simulating hydrologic state based on information contained within a 300-year paleo-reconstructed runoff series and the following implementation decisions:

- two states (wetter or drier than reconstructed median annual runoff), and
- intent on preserving lag 1-year auto-correlation

This implies that four state transitions are relevant for model development: wet-wet, wet-dry, dry-wet, and dry-dry.

The next step is to estimate the four possible transitions respective probabilities local to each year *t*. This can be determined from the probabilities of transitioning from a dry to wet state (P_{dw}) and a wet to dry state (P_{wd}). The probability of transitioning from a dry to dry state is found as $P_{dd} = 1 - P_{dw}$ and the probability of transitioning from a wet to wet state is found as $P_{ww} = 1 - P_{wd}$.

In this technique, transition probabilities are calculated based on years in the range [$t - h_0$ to $t + h_0$] as:

$$P_{dw}(t) = \frac{\sum_{i=2}^{n} K\left(\frac{t - t_i}{h_{dw}}\right) S_t [1 - S_{t-1}]}{\sum_{i=2}^{n} K\left(\frac{t - t_i}{h_{dw}}\right) S_t} \qquad (1)$$

$$P_{wd}(t) = \frac{\sum_{i=2}^{n} K\left(\frac{t - t_i}{h_{wd}}\right) [1 - S_t] S_{t-1}}{\sum_{i=2}^{n} K\left(\frac{t - t_i}{h_{wd}}\right) [1 - S_t]} \qquad (2)$$

where:

- $K(\,)$ = the kernel function
- h_0 is kernel bandwidth for the transition of interest (*dw* or *wd*)
- $S_t =$ system hydrologic state (1 = wet, 0 = dry) at time t
- $S_{t-1} =$ system hydrologic state at time $t-1$
- t = year of interest; and

- $n =$ the number of values in the window $t - h_{()}$ to $t + h_{()}$.

The discrete kernel function *K* used for this study (Rajagopalan and Lall, 1995) is defined as:

$$K(x) = \frac{3h}{(4h^2 - 1)}\left(1 - x^2\right) \qquad (3)$$

where:

- $x = \left(\frac{t - t_0}{h}\right)$
- $|x| \leq 1$
- t is the year of interest, and
- t_0 is the transition of interest.

The bandwidth is a time-window overlaying the current year, during which the transition probabilities are calculated. Part of model development involves determining a value for *h*, which in this study was optimized for years transitioning from wet and then again for years transitioning from dry using a Least Squares Cross Validation (LSCV) (Scott, 1992) method defined as:

$$\text{LSCV}(h) = \frac{1}{n}\sum_{i=1}^{n}[1 - \hat{P}_{-t_i}(t_i)]^2 \qquad (4)$$

where:

- n = the number of *dw* or *wd* transitions within the window [$t - h_0$ to $t + h_0$]
- $\hat{P}_{-t_i}(t_i)$ = the estimate of the transition probability ($\hat{P}_{dw}$ or $\hat{P}_{wd}$) at year t without including the information from year t.

The LSCV is calculated for a suite of *h* values. The *h* ultimately selected results in the smallest LSCV value. Once *h* values have been selected for transitions from both wet and dry years, transition probabilities can be calculated for each year.

This process results in a matrix of sequential transition probabilities from which a block (i.e., a group of sequential years) are randomly selected (bootstrapped) in *N* year block lengths, where *N* is typically the length of the simulation horizon. In order to generate the new binary sequence, the first year is randomly selected as wet or dry. Once a hydrologic state has been assigned to the first year, the state of the second year is determined based on the set of bootstrapped transition probabilities, which reflect the previous year's state. This process is repeated until the binary sequence has been completed.

B.2 "K Nearest Neighbor" (KNN) Magnitude Resampling Technique

After generating the desired number of synthetic state traces, flow magnitudes are then associated with each state sequence by resampling annual volumes from the magnitudes' reference climate data. The technique used in this study is referred to as a "K Nearest Neighbor (KNN)" framework. Concepts of K, neighbors, and nearness are explained in the following paragraphs. However, in a general sense and for annual stochastic runoff modeling, the technique can be viewed as assigning a magnitude runoff to a "current year" in the synthetic sequence based on current and previous state information and previous year runoff magnitude.

This model can be described as the conditional probability density function (PDF):

$$f(x_t | S_t, S_{t-1}, x_{t-1}) \qquad (5)$$

where the flow at the current time $t = x_t$, and is conditioned on the current system state = S_t, previous system state = S_{t-1}, and previous flow = x_{t-1}.

Magnitudes reference data are first grouped based on hydrologic state (i.e., wet or dry) and then their transition category (i.e., a wet year proceeded by dry falls into the category of dry-wet transition). Magnitude assignment the proceeds as follows:

1. Randomly select a magnitude from the magnitudes reference data having the same hydrologic state as the first year in the synthetic state sequence. Let this selected magnitude be the year-1 magnitude in the synthetic runoff sequence.

2. Identify the state of the second year and the associated transition from first to second year (i.e., if the first year was wet and the second dry, the transition category for year 2 would be wet-dry).

3. Assign a runoff magnitude to year 2 using a lag-1 KNN approach (Lall and Sharma, 1996). The approach focuses on the differing similarity between the previous-year's synthetic magnitude and all of the eligible reference magnitudes (i.e. those from years having a common state as the previous synthetic year's state, and being part of the state-transition in questions, wet-dry in this example). Each of the eligible reference magnitudes are considered "neighbors" and the "nearness" of each neighbor is measured as the difference between the eligible reference "previous-year" magnitude and synthetic "previous-year" magnitude. Subjectively, an arbitrary amount of "nearest" neighbors are chosen to offer candidate transitions, and thereby candidate current year magnitudes.

The amount of neighbors, K, is equal to the pool of years assigned to each respective transition category in this study.

4. Choice among the K nearest neighbors is determined by a weighted random resampling approach. The K neighbors are weighted such that the closet neighbor has the greatest weight and the farthest the least. Then one of the weighted neighbors is randomly resampled. The magnitude of the year following the selected neighbor becomes the flow for the second (current) year in the binary trace.

This process repeats until all years in the synthetic state sequence have received a magnitude runoff value. Upon completion of magnitudes assignment to the first sequence, the process begins again with the next sequence, continuing until flow magnitudes have been assigned to all synthetic state sequences.

B.3 References

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