Modeling Techniques to Assess Long-term Reliability of Environmental Flows in Basin Scale Planning

by

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One aspect of integrated water resources management is the sustainable management of river systems to preserve ecosystems. Historically, environmental flow (e-flow) requirements were specified as a minimum allowable flow, though recent research has suggested that all aspects of a flow regime are ecologically important. To better reflect the natural variability of the river system, e-flows now vary from year-to-year and include target baseflows and flood pulses. Many required e-flows are for reaches directly below reservoirs, where human abstractions have degraded the natural variability of the rivers but management can help sustain the river ecosystem through modifications to reservoir operations. In order to understand the reliability of meeting complex e-flow requirements in the future, e-flows need to be incorporated into a long-term planning model where the reliability can be analyzed. Since planning models operate at the monthly timescale and e-flows are stated in days the integration is not directly achievable.

This research aims to address the scale issues associated with integrating e-flow requirements into planning models. Since reservoir operations are required to meet e-flow targets, the focus is on incorporating complex sub-monthly reservoir operations into a planning model. This requires multiple facets: 1) The temporal scale issues that exist between daily e-flow requirements and the monthly operations of the reservoirs in the model must be resolved. 2) Reservoir releases rely on unregulated tributaries to sustain higher downstream e-flow targets, thus daily flows from the unregulated tributaries are also necessary. 3) Hydrologic year types guide reservoir operations to meet different e-flow targets, thus they must be incorporated into the model to capture reservoir operations. Finally, after addressing the integration of new reservoir operations into the planning model, flow alteration — the degree to which a river is departed from a baseline state — is presented as a metric for the reliability of meeting e-flows.

Through an example application on the Colorado River Basin, the techniques are demonstrated to have utility. The successful incorporation of daily reservoir requirements into a monthly model is a key result. Further results under multiple supply and demand scenarios are used to highlight the key components in the modeling framework and to demonstrate their use under a nonstationary climate.

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Chapter 1

Introduction

1.1 Motivation and Background

"Integrated water resources management is based on the perception of water as an integral part of the ecosystem, a natural resource and a social and economic good, whose quantity and quality determine the nature of its utilization" (*United Nations*, 1992).

One of the key principles in integrated water resources management (IWRM) is the sustainable management of the river to preserve ecosystems. Local, regional and national agencies in developed countries world-wide manage river systems in this way, while *United Nations* (1992) call for all rivers world-wide to be managed in this manner. The United States has taken steps to manage rivers in this way, e.g., the SECURE Water Act, but has not yet fully achieved this goal. To address ecosystem needs, scientists are working to establish (or have established) environmental flows (e-flows) within river basins. The e-flows typically state a minimum flow or flow regime (flow pattern resembling the natural hydrograph) which aims to maintain or promote ecosystem diversity. To determine the future reliability (ability to consistently meet e-flows in the future) of e-flows, there is a need to integrate e-flows into basin-wide, water resources management models; however, technical issues arise during the integration. Additionally, water resources are experiencing scarcities due to increasing demands and increasing populations which will be exasperated by climate change (*Vorosmarty et al.*, 2000), increasing conflicts between human and environmental uses of water (*Poff et al.*, 2003). This highlights the need for conscientious, long-term planning that is aware of the many competing demands on water resources.

1.1.1 State of E-Flows

Historically, the only consideration for environmental flows was in terms of a minimum flow value. However, research indicates that all aspects of a river's flow regime, including low flows, peak flows and inter and intra-annual variability are ecologically important (*Richter et al.*, 1996; *Poff et al.*, 1997; *Poff and Zimmerman*, 2010) and the closer the flows are to natural flows, the more pristine the ecosystem will remain (*Acreman and Dunbar*, 2004). However, with increasing populations and increasing demands on rivers, flows in rivers have been decreasing rapidly due to human influences. For this reason flow alteration is viewed as one of the most "pervasive and deleterious" factors degrading rivers today (*Kingsford*, 2011).

Throughout the previous several decades, a great deal of research has gone into determining how ecosystems respond to alterations in flow, developing tools to quantify the flow alterations and addressing how rivers can be managed to benefit ecosystems. *Poff and Zimmerman* (2010) reviewed 165 studies that related ecosystem responses to flow alterations. While the majority of the studies were based in North America, Europe, South America, Africa and Oceania were all represented in the studies. The studies reported the responses of macroinvertebrates, fishes, riparian vegetation, aquatic primary producers, birds and amphibians to changes in flow magnitude, duration, timing, frequency and rate of change (*Poff and Zimmerman*, 2010). One such method for quantifying flow alterations is the Indicators of Hydrologic Alteration (IHA) method which was introduced to determine the degree to which flows have been altered due to dams or other abstractions. The tool reports 32 parameters to indicate the degree that magnitude, duration, timing and frequency have been altered over timescales of days to years (*Richter et al.*, 1996). Once the ecosystem response has been determined and an acceptable degree of alteration found, actions can turn to managing the rivers to benefit the ecosystems. *Watts et al.* (2011) offers general methods for operating reservoirs to benefit the environment, while *Suen and Eheart* (2006) uses an example in Taiwan to demonstrate that it is possible to incorporate a maximum flow alteration requirement into reservoir operations while still meeting human needs. Specific flow targets can also be identified that will benefit the ecosystem for particular reaches, e.g., *Holden* (1999) and *Muth et al.* (2000). Reservoir operations can then be modified to meet the required e-flows (*Bureau of Reclamation*, 2005, 2006b). The requirements will usually vary from year-to-year in order to mimic the natural variability of the system.

When specific flows are identified to benefit ecosystems, they generally apply to only small reaches and are measured at a single gage, e.g., *Holden* (1999) and *Muth et al.* (2000), and they represent the culmination of a lengthy, site specific study. The required flows can be in lengths of hours to weeks and most times they are specified below reservoirs or other control structures where management actions can directly influence the flows; however, they can also be used to limit upstream diversions in order to maintain specified flows. In other cases, flow alteration is used to monitor or assess conditions over large spatial areas. *Döll et al.* (2009) applied the flow alteration metric world-wide to assess the global impacts of diversions and reservoirs to river flows. The flow alteration metric is meaningful at temporal scales from hours to years and in *Döll et al.* (2009) the metric was applied for monthly and annual deviations.

In addition to the impact of diversions and regulations on rivers, climate change is another factor expected to have an impact on river systems. Globally, there is projected to be anywhere from a 90% increase to a 90% decrease in discharge (*Palmer et al.*, 2008). As *Poff and Zimmerman* (2010) pointed out, both increases and decreases in flow negatively impact the ecosystem. In some individual basins, climate change is projected to increase flow alterations more than all other factors have up to present day (*Gibson et al.*, 2005; *Döll and Zhang*, 2010). In addition to increasing flow alterations, climate change can alter the frequency and durations at which floods and pulse flows occurred historically (*Booth et al.*, 2006). The change in flow regimes could impact the ecosystems ability to adapt to the changes in hydrologic variability. Since species evolved to live under these historical conditions, the rapid change in variability could negatively impact the species. Furthermore, in a nonstationary climate, the baseline for flow alterations is not clearly defined, since the 'natural' state is continuously changing.

Döll and Zhang (2010) performed a global analysis of relevant e-flow metrics under climate change conditions, though they were not able to incorporate a future projection of demands due to the large scale of the assessment. Additionally, again due to the scale of the study, reservoir operations were computed in a simplistic manner. Finer scale results are obtainable by focusing on individual basins where reservoir operations can be more accurately captured.

The historic flow regime that species are dependent on is impacted in many ways: changes in flow durations, magnitudes and timing due to dams, diversions and climate change. Furthermore, rivers on every continent are facing one or more of these degradations. While human actions can help alleviate certain negative impacts, changes in climatic conditions will further strain ecosystems. With all of the factors that can impact the ecosystem, there is a need to project future ecological conditions in order to assess the future reliability of meeting the e-flows under the influence of rising demands and changes in climate.

1.1.2 Use of Planning Models

Traditionally, long-term planning models, operating at a monthly timestep, have been used to evaluate system conditions over a large spatial scale for many years into the future. They can be used to identify potential conflicts between supply and demand or between competing demands. Decision makers also use planning study results to evaluate different operational policy choices. Planning models lend themselves well to scenario based analysis, where multiple scenarios are used to identify system trends due to changes in operational policy or to identify system responses due to hydrologic or demand based trends. Multiple supply scenarios will lead to an understanding of the risks associated with certain operations or demands in regards to variable hydrology. Multiple demand scenarios allow managers to understand the impacts of future demands or the impacts of 'business as usual' demand trends. Finally, using multiple policy scenarios can lead to more robust policies that can handle sustained drought or surplus conditions. For example, *Xu et al.* (2002) studied the sustainability of water supply on the Yellow River through 2030 using ten scenarios to simulate different increases in domestic and agricultural demands as well as different supply scenarios. *Bharati et al.* (2009) used a long-term planning model to evaluate how a proposed water transfer project in India would impact water shortages in both basins. Finally, *Bureau of Reclamation* (2007) used a basin-wide planning model of the Colorado River Basin to evaluate different policy options for handling shortage conditions. Recently, studies started using planning models to assess the impacts of climate change on water resources systems, e.g., *Payne et al.* (2004); *Brekke et al.* (2004). Due to the increased variability and general decreasing trends in total water availability, climate change is projected to strain water availability and the degree to which water managers can reliably meet demands, produce energy and maintain ecosystems.

E-flows are treated in a cursory manner, if it all, in many planning studies. *Payne et al.* (2004) and *VanRheenen et al.* (2004) included monthly flow targets, while *Jones and Page* (2001) used a minimum annual flow threshold as an environmental metric. Since planning models typically operate at the monthly timestep the monthly targets are the only e-flow targets that can be directly incorporated into a planning model.

1.1.3 Need for Integration of Planning Models and E-flows

Overall, there is a gap between site specific, local e-flow studies and global scale risk assessments. Regional and basin-wide studies have focused on system wide impacts due to water availability and have treated e-flows in a cursory manner, while only a few flow alteration studies have included climate change. In order to assess whether or not e-flows can be reliably met in the future, it is of paramount importance to incorporate e-flow related operations into planning studies. *Kingsford* (2011) further highlights the need for modeling tools that can incorporate hydrology and ecology over large areas and for many years into the future. As such, planning models provide this framework as long as ecologically relevant indicators are known and related to flow or if reservoir operations aim to directly incorporate environmental needs. The output of these models can help inform policy makers' decisions regarding future management of the system.

1.1.4 Colorado River Basin

The Colorado River Basin (CRB), which provides water to nearly 30 million people and 3.5 million acres of farmland (*Bureau of Reclamation*, 2007), is full of many of the topics discussed above. Climate change projections indicate decreasing water availability across the basin while diversions and dams have decreased the flows well beyond their natural state. However, several reservoirs are now being managed to meet e-flow requirements (*Bureau of Reclamation*, 2006a,c). Below both Flaming Gorge and Navajo dams, daily to weekly e-flow requirements exist to help sustain endangered fish populations.

Additionally, many basin-wide planning studies have been carried out to determine operational policies (*Bureau of Reclamation*, 2007) and to understand the impacts of climate change on the basin (*Christensen et al.*, 2004). Since the planning studies are performed in a monthly model, none of the planning studies up-to-date have been able to incorporate the daily operations for meeting e-flow requirements below Flaming Gorge and Navajo. For these reasons, the CRB is used as an example throughout the study. A further description of the basin and the analysis performed to identify e-flow requirements is included in Chapter II.

1.2 Proposed Research

The overarching goal of this thesis is to present a suite of techniques for incorporating e-flow metrics into a planning model in order to meaningfully assess the long-term reliability of e-flows. The spatial and temporal scale discrepancies between e-flow requirements and planning models are addressed, while the ambiguity of modeling e-flow requirements in a nonstationary climate is discussed. After a review of environmental requirements throughout the CRB it was deemed critical that modeled reservoir operations be updated to better capture actual reservoir operations that are required to meet downstream environmental flow requirements. In this review, several other items were highlighted which needed to be addressed in order to capture actual reservoir operations. The reservoirs generally combine their releases with downstream, unregulated rivers

(rivers with no significant reservoir activities) to meet higher e-flow targets. Additionally, the concept of hydrologic year types is introduced since it is used to vary e-flow targets from year-to-year by comparing the current hydrologic conditions in the basin to historical conditions. Figure 1.1 shows the areas addressed in the study and how they integrate with one another. The first area we address is the statistical generation of daily flows from an unregulated river (generally tributary flows). Next, the choice of hydrologic year typing schemes are discussed, specifically with regards to nonstationary hydrology. After addressing the first two areas, reservoir operations are then updated to reflect the e-flow based operations which use hydrologic year types to dictate operations, while supplementing the unregulated river releases downstream to meet e-flow targets. Finally, in order to determine the reliability of e-flows in the future, flow alteration metrics are introduced to monitor conditions basin wide. After the above techniques are presented, they are applied within a long-term planning model on the CRB in order to produce sample results. The following sections further introduce these areas of research.

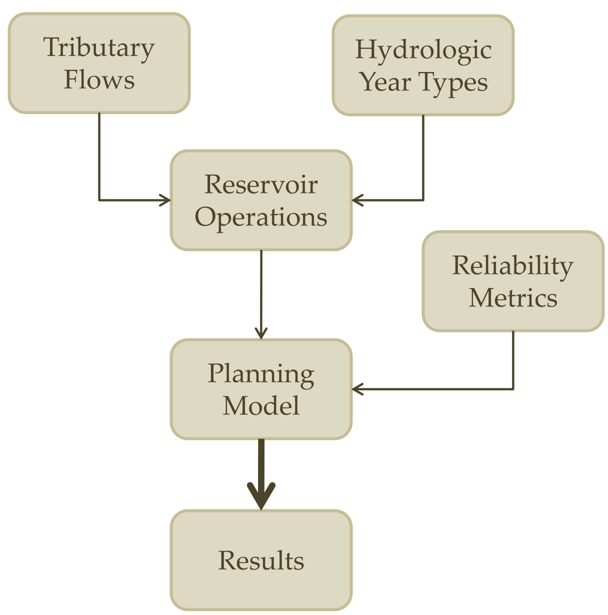


Figure 1.1: Flowchart of the study.

1.2.1 Daily Unregulated River Flows

Many e-flows rely on both unregulated rivers and reservoir releases to maintain the required flows. Since the Colorado River Basin planning model operates at a monthly timestep, the unregulated river flows also exist at the monthly level. In order to correctly assess whether the e-flows are met, the monthly flows need to be disaggregated into daily flows. In the model, both monthly natural flows and monthly demands are known. The planning model determines the monthly demands that can be met based on the monthly natural flows, resulting in monthly depleted flows. It is important to disaggregate to natural flows and then apply monthly demands in order to correctly capture the shape of the depleted hydrograph, which is an important characteristic that can affect whether or not the e-flow requirements are met. While many techniques exist for flow disaggregation, none entirely address the constraints of this problem: that monthly volumes are known and that daily values are required while maintaining continuity across months. Additionally, demands then need be applied so that the final result is daily, depleted flows. To address all of these needs, an existing nonparametric flow disaggregation method is modified and a framework is established for creating daily natural flows based on monthly natural flows and a record of historical gage data. This methodology is presented in Section 3.1.

1.2.2 Hydrologic Year Types

Hydrologic year types determine year-to-year reservoir operations depending on the annual hydrologic conditions in the basin. The year types determine which e-flow targets must be met, thus dictating how the reservoir will operate for the season/year. Year types are generally determined by comparing the annual hydrologic conditions to the historical conditions in the basin. Multiple methods exist for determining what the historical conditions are, and the computed year types are sensitive to the choice of the historical record. Additionally the year types are sensitive to the variability of the historical record, which can have especially significant impacts under climate change. The choice of the hydrologic record and sensitivities to the record are addressed in

Section 3.2.

1.2.3 Modeling Reservoir Operations

Since reservoir operations have recently been mandated to meet e-flow targets, the operations in planning models should reflect this. However, due to the temporal scale discrepancies between many e-flow requirements and a monthly planning model, this is not immediately achievable. To incorporate reservoir operations into a planning model, the daily requirements are translated to monthly releases. Additionally, the operations rely on both the hydrologic year types to determine operations, as well as the disaggregated flows from downstream tributaries to assist in meeting the e-flow requirements. Section 3.3 addresses the integration of daily flow targets into monthly reservoir operations.

1.2.4 Assessing Reliability of E-flows

Flow alteration is presented as a metric to assess the reliability of e-flows into the future. It is meaningful at the monthly timestep, so it can be directly incorporated into a monthly model and it can be applied uniformly over large spatial extents. However, flow alteration metrics rely on a baseline value for comparison. In many instances, the historical average natural flow is used as the baseline condition, though under climate change conditions the choice of the baseline condition is more complex for a number of reasons. The flow alteration metrics are presented in Section 3.4 with special consideration given to the choice of the baseline under climate change.

1.2.5 Applying Techniques

As a demonstration of the effectiveness and utility of the methods introduced in Chapter III, Chapter IV applies the techniques as an example on the CRB — Chapter II describes the CRB in detail. The new reservoir rules are incorporated and combined with disaggregated flows in order to meet downstream e-flow requirements. Additionally, flow alteration metrics are used to indicate ecological conditions basin-wide. In the chapter, four different scenarios are compared in order to highlight different areas of the results, including the impacts of climate change and how demands can impact ecological conditions.

Chapter 2

Description of the Colorado River Basin

2.1 Description of the Basin

The Colorado River Basin (CRB) encompasses seven states and two countries (Figure 2.1). The Colorado River begins at the Continental Divide in Colorado and flows down to the Sea of Cortez. Along the way it provides water to nearly 30 million people and 3.5 million acres of farmland (*Bureau of Reclamation*, 2007). Below Lake Powell, at a point one mile downstream of the confluence of the Colorado and Paria Rivers, the basin is divided into the Upper and Lower Basins at a point known as Lee Ferry. The Upper Basin consists of Colorado, Wyoming, Utah and parts of New Mexico and Arizona. California, Nevada and parts of Arizona and New Mexico make up the Lower Basin. The states are further divided by Division; Colorado, Wyoming, Utah and New Mexico compose the Upper Division States while the Lower Division includes Arizona, Nevada and California. Many state and federal laws and regulations, treaties, and contracts with the Secretary of the Interior make up what is collectively referred to as the *Law of the River*. Amongst many other purposes, the *Law of the River* dictates the allocation of water to each state and Mexico in normal, shortage and surplus conditions. The Colorado River Compact of 1922 allocates water for the Upper and Lower Basins and Mexico, while later laws further allocate the water between each of the states.

The CRB is a heavily litigated and studied basin. The studies encompass hydrologic studies (*Christensen et al.*, 2004; *Miller and Piechota*, 2008), management studies (*Christensen et al.*, 2004; *Christensen and Lettenmaier*, 2006; *Bureau of Reclamation*, 2007; *Rajagopalan et al.*, 2009) and envi-

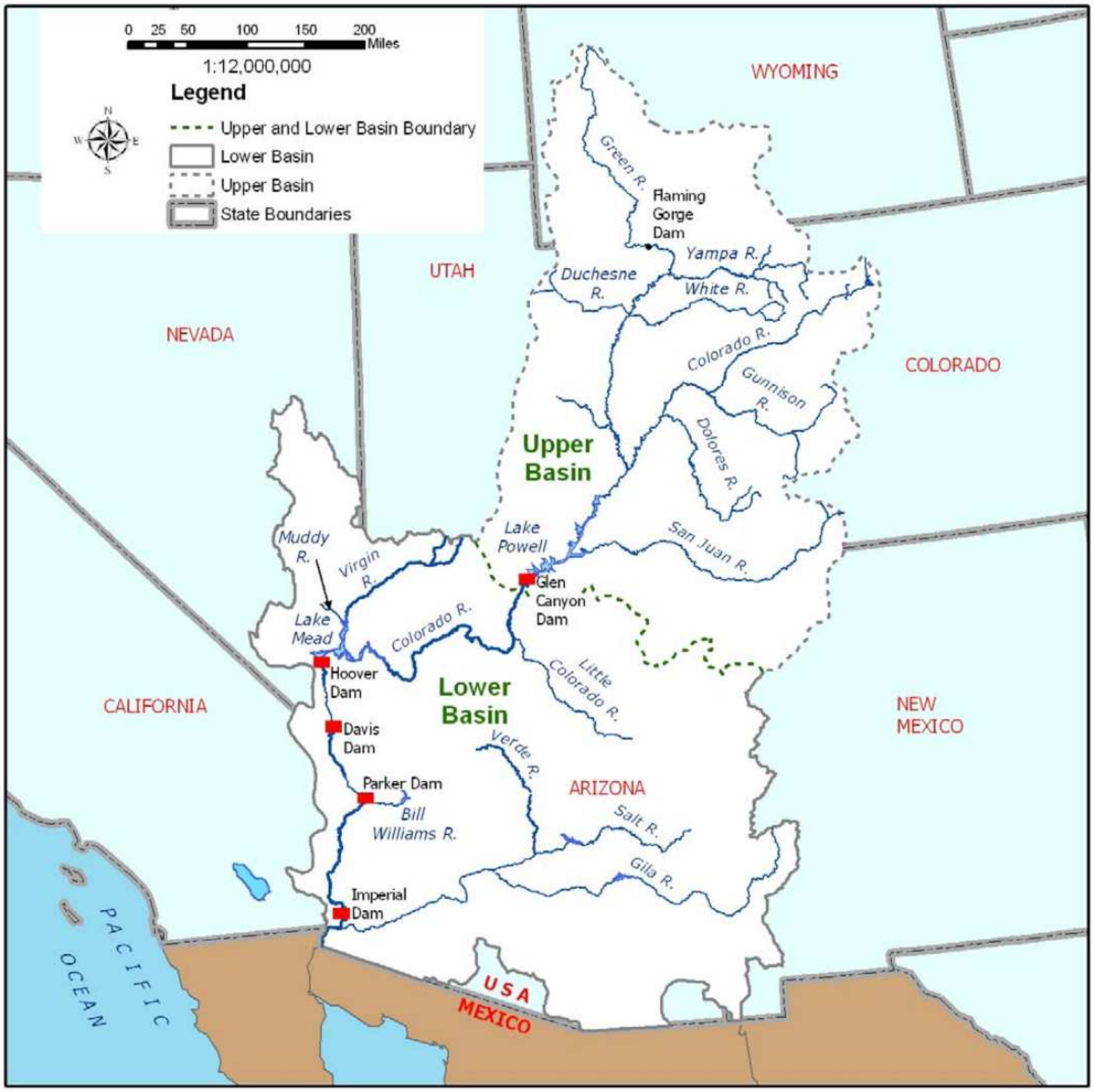


Figure 2.1: Map of the Colorado River Basin (*Bureau of Reclamation*, 2007).

ronmental studies (*Holden*, 1999; *Muth et al.*, 2000), to list only a fractional subset of the studies. These studies cover a wide variety of topics: determining the flow required to sustain endangered fish populations, understanding the historical variability of hydrology in the basin, projecting the future impacts of climate change on the basin, determining if management strategies can help cope with climate change impacts and determining robust operating policies. Furthermore, recent studies have led to new reservoir operations that have ecological benefits. Flaming Gorge and Navajo underwent flow studies and a NEPA based environmental impact review process to ensure the reservoirs are operated to help sustain endangered fish populations. Both reservoirs are now required to help meet daily downstream flow requirements.

2.1.1 Hydrology

The hydrology of the CRB is spatially non-uniform. The Upper Basin generates 90% of the annual stream flow, mostly through snowmelt in the spring, while rain (mostly) in the Lower Basin accounts for the remaining annual flow. Since it is a snow melt dominated basin, the natural hydrographs have low flows in the beginning of the calendar year with a sharp rise and peak flows in May – July (in typical years), with a return to low flows for the remainder of the year. Due to diversions and reservoir regulations, the depleted hydrographs do not always maintain this shape.

The hydrology of the CRB is highly variable with sustained periods of drought and surplus observed historically and through paleo reconstructed flows (*Woodhouse et al.*, 2006; *Meko et al.*, 2007). For 1906 - 2007 the annual natural flow at Lees Ferry ranges from 5.4 to 25.4 million acre-ft with a mean of about 15 million acre-ft, though the paleo reconstructions indicate the long-term mean could be lower. The historical period is used extensively in planning studies up to date, operating under the assumption that the past is a good representation of the future and that hydrology is stationary.

Climate change projections indicate that hydrology is likely nonstationary. Many studies incorporate climate change projections and indicate reduced streamflow for the CRB over the next 50

– 100 years (*Christensen et al.*, 2004; *Milly et al.*, 2005; *Christensen and Lettenmaier*, 2007; *McCabe and Wolock*, 2007; *Seager et al.*, 2007). In addition to a general decreasing trend in streamflow, the flows are projected to increase in variability. With both decreasing trends and increases in variability, developing robust operating policies is more important than ever before. As existing long-term policies are refined, consideration of e-flows is important, both since reservoirs are required to meet them and since IWRM includes a consideration of the environment.

2.2 State of CRB Modeling

Many agencies utilize modeling tools on the CRB. They range from stream flow forecasting models from the Colorado River Basin Forecast Center to long-term planning models used by the Bureau of Reclamation. Bureau of Reclamation also utilizes models for all timescales: from daily to two year operations models through long-term planning models that operate up to 90 years into the future. As the goal of this study pertains to planning models, the rest of this section focuses on the Bureau of Reclamation's long-term planning model the Colorado River Simulation System (CRSS).

2.2.1 CRSS Description

CRSS is a basin-wide, long-term planning model for the CRB implemented in RiverWare (*Zagona et al.*, 2001) that operates at the monthly timestep. It models nine Upper Basin reservoirs including Lake Powell and three Lower Basin reservoirs including Lake Mead. Model input includes demand data for users basin-wide, natural flow input at 29 nodes basin-wide and initial reservoir conditions. Figure 2.2 shows the CRB highlighting the natural flow nodes and basins. The model operates reservoirs using a 'policy ruleset' which logically expresses reservoir operations in priority based rules. With the exception of Lake Powell, the Upper Basin reservoirs are generally operated in a rule-curve approach — releases are set to meet a pre-determined end-of-month storage target. In certain cases the releases are increased to help supply downstream users with water. Similarly, with the exception of Lake Mead, the Lower Basin reservoirs are operated via rule-curves. Lake Powell and Lake Mead's operations include much more complex logic reflecting the coordinated operations of the two reservoirs as specified in *Bureau of Reclamation* (2007). Further details regarding CRSS can be found in *Bureau of Reclamation* (2007).

2.2.1.1 Natural Flow Data Sets

CRSS uses natural flow data at 29 nodes basin wide to 'drive' the model, or to simulate the hydrologic conditions across the basin. The natural flow data can be developed through a wide range of methods: direct natural flows, direct paleo natural flows and nonparametric paleo conditioned natural flows. Furthermore, the natural flows can be simulated using a basin-wide hydrologic model that is forced with climate change projections of temperature and precipitation in order to model possible hydrologic conditions due to climate change. This study uses the direct natural flows (DNF) and climate change projections, both of which are described more below.

The direct natural flows represent the observed natural flows in the basin from 1906 – 2007. The observed record does not extend through 1906 for all natural flow nodes; in these cases, the record is extended using statistical techniques. In order to produce a range of future hydrologic conditions based on the 102 year record, the direct natural flows use the Index Sequential Method (ISM; *Ouarda et al.* (1997)). The ISM technique uses an *n* year 'window' of the hydrologic record to create a single hydrologic trace. The next trace is created by shifting the window forward by one year and using this *n* year window for the second trace. The process is repeated up to the length of the hydrologic record, e.g., 102 times for a 102 year long record. Once the window extends past the last year of the record, it is looped around the beginning of the record, e.g., a 40 year window could include the years 1978 – 2007 followed by 1906 – 1915. For CRSS, the window is 51 years in order to simulate conditions in the system from 2010 – 2060.

The climate change natural flow data set was developed based on the projections from 16 Global Climate Models (GCM) for three future emission scenarios (with multiple initial conditions). The projections were downscaled, bias-corrected and moved through the Variable Infiltration Capacity (VIC) hydrologic model (*Liang et al.*, 1994) to produce 112 independent hydrologic

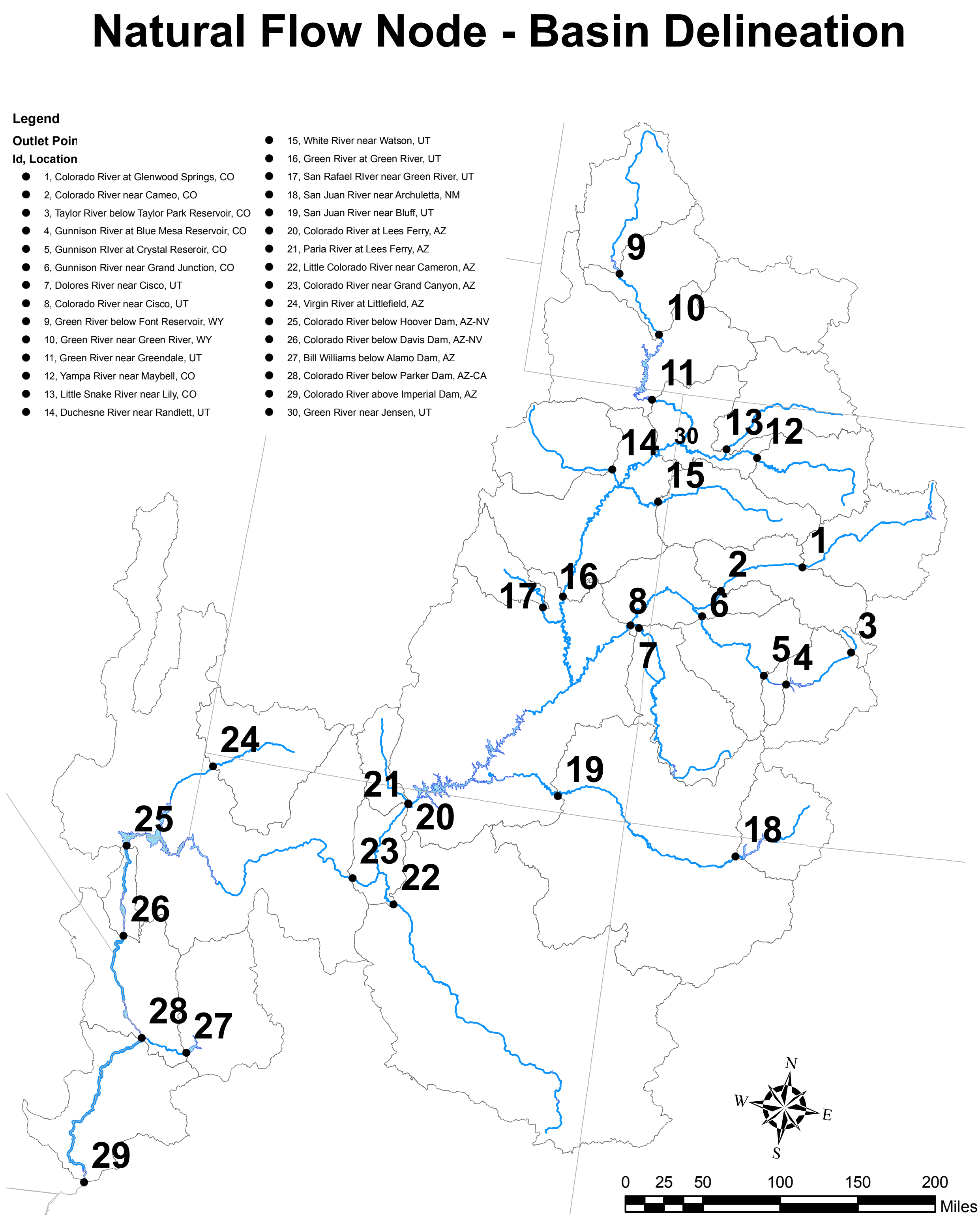


Figure 2.2: Colorado River Basin with natural flow nodes and basins.

inflow traces, which are transient through time. The climate change inflow traces are preliminary projections that have not undergone a secondary bias-correction, which may be required based on additional analysis that is presently underway.

2.3 Identification of E-flows and Modeling Needs

Since the CRB was chosen as an example case for incorporating e-flow related goals and metrics into a planning model, we performed a comprehensive inventory of the e-flows basin-wide. In the inventory, mandated e-flows (such as those required by a ROD below a reservoir) were cataloged, as were desired e-flows (those that studies indicated would benefit species but were not mandated by a ROD). In this phase of the project, there was no discrimination of the e-flows based on geography or temporal scale.

Once the inventory was completed, an assessment of CRSS was performed to determine which e-flows were directly compatible with the planning model, which could be incorporated with some work and those that were either impossible to incorporate or would take a disproportionate amount of time to incorporate. The technical issues associated with incorporating e-flow metrics into CRSS are summarized in *Butler and Zagona* (2010). Overall, two distinctions were made in the e-flow targets: those that are required based on reservoir operations and those that are monitoring metrics. Navajo and Flaming Gorge both have mandated operating procedures in order to meet downstream e-flow targets, though the current CRSS modeling does not incorporate these operations. The reservoir operations needed to be updated to include the new operating procedures to ensure that there was meaning to the modeled flows below the reservoirs, i.e., if the reservoirs were not operating to the new policies, then we could not make a meaningful assessment on the ability to meet the downstream flow targets. Including the new operating procedures would require that the temporal scale issues be addressed; the model operates at a monthly timestep, while the requirements are specified in terms of days to weeks. Additionally, the reservoirs 'piggy-back' their releases with downstream tributaries to meet higher downstream flow targets. In order to ensure the downstream metrics had meaning, the monthly tributary flows also needed to be known at the daily timestep.

The main issue associated with the monitoring metrics was that the gage at which the metric needed to be monitored, was not in the model. The natural flow gages are all inherently in the model (Figure 2.2), i.e., there is a point in the model that corresponds to the gage. Some additional gages can be placed in the model with ease, while others require significant amounts of work. In CRSS, the demands are aggregated over large spatial areas into one aggregate diversion object. If the gage in question is somewhere in the middle of the aggregated diversion objects, then it is very difficult to find a location which would be representative of the gage. Additionally, the natural flow inputs can represent the aggregation of multiple tributary flows. If the gage in question is on one of the tributaries or on the main stream between two of the confluences with the tributaries, then again, it is difficult to find a point which represents the gage. While it is possible to disaggregate the natural flows to a finer scale, it is a tedious process that is dependent on the gage records for the two tributaries. Finally, sometimes the gage in question is representative of the summation of two upstream natural flow gages, where there are no demands or additional inflows between the gages; these gages can be easily added to the model. *Butler and Zagona* (2010) comment on which gages are easy to add to the model and which would require the disaggregation of demands and/or natural flows.

After the assessment, it was determined that the reservoir rules would be updated for Flaming Gorge and Navajo in order to capture actual operations. As the reservoir releases are combined with tributary flows downstream, disaggregated tributary flows are also necessary for monitoring daily e-flow targets. Both of the areas are addressed in Sections 3.1 and 3.3. The additional gages that could be incorporated into the model without disaggregating natural flows or demands would also be included in the assessment of the reliability of environmental flows. To address these needs, the CRSS model needed to be modified; the modified version of CRSS is described in the next section.

2.4 The Research Model

The model used in this research project is based on CRSS, though it is modified to incorporate the techniques and metrics described in Chapter III. The operating rules for Flaming Gorge and Navajo were modified to better reflect their operations, so that the e-flow requirements could be assessed below these reservoirs. Several new gages, in addition to the natural flow gages, were incorporated into the model structure. Additionally, the capabilities to monitor other relevant e-flow metrics were added to the model, such as the flow alteration metrics (Section 3.4). Chapter IV includes modeling results derived from this model and throughout the thesis, results from the Research Model are compared with CRSS model results.

2.5 Summary

Overall the CRB provides a good example area to demonstrate the techniques developed for this thesis. There are existing supply and demand conflicts and operations that are required to provide water for e-flows. There is also ample existing data to rely on for ecological indicators and requirements from the numerous previous studies. The system is already a supply limited basin and supply is projected to decrease with climate change, so it offers the chance to monitor e-flow metrics under adverse conditions.

Chapter 3

Methodology

Assessing future reliability of environmental flows (e-flows) in a basin scale model requires addressing several modeling issues. In this study we have identified these issues and developed methods to address them. The most challenging modeling issue is that reservoir operating rules that are designed to meet daily e-flow targets must be executed at a monthly timestep. We have developed rule logic that addresses daily targets at the monthly timestep. The first three sections address the identified issues and are briefly described here:

(1) In meeting downstream e-flow targets, the reservoir rules need to coordinate releases with unregulated tributaries. In realtime operations, these flows are forecasted, but in a planning model they must be generated stochastically based on the natural flow ensembles. To address the daily targets, the monthly natural flows must be disaggregated. We have developed a new method for generating stochastic daily flows from monthly historic or climate change projected natural flows. This acts as a framework for developing daily natural flows from monthly natural flows and a daily record of historical gage data.

(2) Reservoir rules use hydrologic year typing to determine the e-flow targets each year of the planning study. Although this approach is widely used in defining and implementing e-flow targets, there are fundamental issues with the computation, especially in a non-stationary situation. We examine the method as it is typically implemented, analyze the problems, and propose a way forward (with caveats).

(3) We utilize methods in (1) and (2) to develop monthly planning model rules that are robust

with respect to daily requirements and uncertain and changing future hydrology. The rules incorporate required daily releases from the reservoir into monthly releases, while allowing the releases to be combined with unregulated tributary flows (downstream of the reservoir) from (1) to meet further downstream targets.

The above allow for future model simulations of the basin. Finally, we must develop metrics to asses the reliability of meeting e-flows in the future. In this final section we identify critical metrics and evaluate various methods of computing these metrics. Specific attention is given to these metrics under a nonstationary climate.

3.1 Unregulated Flow Disaggregation

This section describes the methodology developed to disaggregate monthly flows into daily flows. It represents an integration of a nonparametric, flow disaggregation method into a planning model, while providing a framework to obtain daily natural (flows with the effects of reservoir regulation and/or withdrawals removed) and depleted (flows that have had withdrawals from them) flows. In order to monitor daily e-flow metrics in a planning model, the monthly flow values need to be disaggregated to the daily level. The method generates daily natural flow from monthly natural flows. Next, monthly depletions are removed from the daily natural flow generating a daily depleted flow, which is the water that would be present in the stream for e-flows. As this method extends the methodology described in *Nowak et al.* (2010), the section begins with a review of the existing methodology. Next, the extension of the current methodology is described beginning with developing daily natural flow from historical gage data, ensuring the data is similar to natural flow and removing monthly depletions to arrive at simulated depleted flows. The terms gaged and depleted are somewhat analogous when describing flow — both refer to flows that have been affected by depletions and/or reservoir regulations. To help clarify the difference between historical gaged flows and the flow values we project in the model that are affected by depletions, gaged will be used when referring to historical gaged flows, while depleted flows will be used when referring to flows we generate that have demands taken out. The depleted flows in the model are a projection of future gage values though they are not part of a historical gage record. The section concludes with an application of the method on the Yampa River.

3.1.1 Review of Existing Methods

The disaggregation of stream flow, both spatially and temporally, is a classical issue in water resources. Many techniques have been proposed to accomplish the disaggregation from annual volumes to a monthly or daily flow sequence in parametric (*Stedinger and Vogel*, 1984; *Grygier and Stedinger*, 1988) and nonparametric implementations (*Sharma et al.*, 1997; *Tarboton et al.*, 1998; *Prairie et al.*, 2007; *Nowak et al.*, 2010). *Kumar et al.* (2000) provides a review of several existing methods. Typically, the methods disaggregate an annual volume to a monthly or daily flow sequence. In this case, the lag-1 correlation is preserved over consecutive days or months, though it is problematic to preserve the lag-1 correlation between the end of one year and the beginning of another year. If this is a low-flow period, it can be disregarded as a non-essential statistic to replicate (*Nowak et al.*, 2010). Additionally, when attempting to disaggregate from individual monthly flows to daily flows, the lag-1 correlation between the end of one month and the beginning of another is hard to capture. *Kumar et al.* (2000) casts the disaggregation problem as an optimization problem to help address this. By doing so, they constrain the disaggregation such that the daily values between two months do not fluctuate beyond a reasonable amount, thus preserving the lag-1 correlation.

In *Nowak et al.* (2010), the disaggregation from an annual (or seasonal) volume to daily flows is completed using a K-nearest neighbor (KNN) approach to select a historical year which has a similar annual volume. The pattern of the daily flows from the selected historical year is then used as a proportion vector, i.e., the proportion of the annual volume that occurs on each day. Multiplying the proportion vector by the annual volume to be disaggregated yields a daily flow record. This methodology produces a daily flow record which preserves many important statistics (mean daily flow, skew, maximum and minimum daily flow and lag-1 correlation within the disaggregation period), creates daily values that are not necessarily in the observed record and does not create negative flows which can occur in some nonparametric approaches (*Nowak et al.*, 2010). In this approach, the aggregate volume (annual or seasonal) is generally the only known volume; the method can disaggregate from the aggregate volume to monthly or daily flows in one step, but does not disaggregate in a step-wise fashion.

3.1.2 Proposed Disaggregation Method

The integration of a flow disaggregation method into a long-term planning model yields a slightly different problem than a typical annual to monthly/daily disaggregation. In the planning model, monthly natural flow values are input into the model, thus the monthly hydrograph is already known. Additionally, the planning model includes monthly demand as input and computes the monthly depletion based on demand and the available water. Since the daily, depleted streamflow is the desired product, there are two choices of how to proceed: 1) disaggregate from monthly, depleted streamflow to daily, depleted streamflow; 2) disaggregate from monthly, natural flow to daily, natural flow and then apply demands to get to daily, depleted flow. If using the *Nowak et al.* (2010) approach to disaggregate from monthly, depleted streamflow to daily, depleted streamflow, an implicit assumption would be that the future depleted hydrographs would have the same shape as the historical hydrographs. With demands that change both in magnitude and timing in the future, this assumption would not always be true. Thus, the remainder of this section describes the second option: disaggregating natural flows and applying demands to obtain depleted flows.

As mentioned above, the monthly natural flows are model inputs in the planning model. This provides additional information, and constrains the disaggregation problem to a degree. In *Nowak et al.* (2010), the disaggregation is completed directly from an annual (or seasonal) volume to daily flows. This effectively ignores the known monthly volumes if the index year is selected based solely on an annual (or seasonal) volume. When disaggregating the annual volume based on an index year's daily pattern, the monthly volumes would not necessarily be preserved, though the annual volume would be, i.e., the sum of the daily flows over one month would not equal the known monthly volume, though the sum of the daily flows over the year would equal the annual volume. This method ensures that the lag-1 correlation between months is preserved, though it does not incorporate the additional information the planning model provides.

In other disaggregation methods that perform a step-wise disaggregation (annual to monthly to daily), problematic discontinuities between periods, e.g., months, are created. *Kumar et al.* (2000) provides a methodology for disaggregating from monthly volumes to daily flows while preserving the lag-1 correlation between months. The method involves an optimization step which prescribes a maximum change between two days. While this method is powerful and would provide the necessary constraints to disaggregate from monthly volumes to daily flows, the introduction of an optimization step into the planning model could be tedious. Additionally, the nonparametric approach of *Nowak et al.* (2010) is preferred over determining several optimization parameters in *Kumar et al.* (2000). Thus, the method presented in this section extends *Nowak et al.* (2010) to incorporate the additional known information.

Nowak et al. (2010) and *Kumar et al.* (2000) present methods to disaggregate values both spatially and temporally. The focus of this section is on a temporal disaggregation of monthly to daily values at one site, though the method can be applied to a situation requiring spatial as well as temporal disaggregation. Additionally, for the purposes of evaluating daily e-flows, the disaggregation focuses on the runoff (April - July) season, as this is the season when the critical high flows are required. The method is employed over this period, though it could easily be extended to a longer season or the entire year.

The following sections detail the steps to disaggregate from monthly to daily natural flows and the application of demands to move from natural to depleted flows.

3.1.2.1 New Neighbor Selection

The disaggregation method in *Nowak et al.* (2010) depends on the selection of an index year out of K-nearest neighbors. In *Nowak et al.* (2010), the nearest neighbors are selected based on how close the historical years' aggregate volumes are to the aggregate volume in need of disaggregation, though there are numerous ways to select the nearest neighbors. Since the monthly natural flows are known in this application, the neighbor selection presented here aims to incorporate this information. Essentially, the monthly hydrograph shape for the spring period is specified based on inputs to the planning model. Selecting the neighbors based on an aggregate volume would not incorporate the knowledge of the shape of the hydrograph since the aggregate volume does not have a direct correlation to the shape of a hydrograph. To select the 'closest' neighbors, a distance vector D is created which represents how close each of the historical years are to the year in need of disaggregation (Z).

To account for the known monthly natural flow volumes, and to select years which have monthly hydrographs close to Z's, the distance is based on the ratio of each month's volume to the total spring volume. The distance vector is computed as

$$D_i = \sqrt{\sum_{m=4}^{7} \left(\frac{H_{i,m}}{S_i} - \frac{h_m}{s} \right)^2} \tag{3.1}$$

where i is an index into the historical record, m is the month (4 = April, 7 = July, etc.), H is the monthly volume in the historical record, S is the seasonal volume in the historical record ($\sum H_{i,m}$), h is the volume in month m of Z and s is the seasonal volume ($\sum h_m$) of Z. Computing the distance of the historical years from Z in this manner will select the neighbors that have roughly the same monthly hydrograph shape as Z. The ratio of the monthly volume to the seasonal volume ($H_{i,m}/S_i$ or h_m/s) gives the proportion of flow in each of the seasonal months, in this case April - July. Taking the Euclidean distance from all four months yields the distance (D_i) for each historical year.

Upon computing the distances for all historical years, the nearest neighbors are ordered and restricted to the K closest years. In this application, K is set to $\sqrt{n}$ where n is the number of historical years, i.e., the sample size (*Rajagopalan and Lall*, 1999). The index year is then randomly selected from the K-nearest neighbors (KNN) based on some weighting function that gives preference to the closest neighbors. The weighting function used in this application is

$$W(i) = \left(\frac{1}{i}\right) \Bigg/ \left(\sum_{i=1}^{K} \frac{1}{i}\right) \tag{3.2}$$

where K is the number of nearest neighbors and i is an index into the K-nearest neighbors (*Lall and Sharma*, 1996; *Nowak et al.*, 2010).

After the index year is selected, a proportion vector (P) is created based on the daily flow record of the index year. P is the daily volume of the index year over the seasonal volume of the index year. The daily flows for the year Z are created by multiplying s (the seasonal volume in Z) by P. This implementation does not entirely preserve the individual monthly volumes since the daily flows are created based on the seasonal sum of the monthly volumes; however, the selection of the index year aims to select an index year which has a monthly hydrograph shape close to the monthly distribution of Z. Even though the monthly volumes are not entirely preserved, they are close to the same.

3.1.2.2 Proving Data is 'Close' to Natural Flows

In order to progress through the steps described above (monthly natural to daily natural to daily depleted), the above neighbor selection is used to generate a daily natural flow series. In most situations a daily natural flow data set is not available, though daily depleted values are available in many locations through USGS (and other sources) gages. Additionally, monthly natural flows are available for several basins, e.g., the Columbia and Colorado River Basins. Since the disaggregation technique relies on historic daily data and gaged daily data is generally the only historical, daily data available, it is important to show that the historical gaged data is approximately natural. Since monthly data is available for both historical gaged and natural flows, we assume that the daily gaged flow is approximately natural if the monthly gaged flow is close to the monthly natural flow. The remainder of this section focuses on proving that the monthly gage data is 'close' to monthly natural flows.

The following sections present several different techniques to show that the monthly, historical, gaged flow is approximately natural. In any of the methods, it would be beneficial to trim the historical data set if it is known that a significant diversion or regulation came online, thus keeping the record to a period known to be fairly unaltered. Combining the various techniques will result in a well supported argument that the historical, monthly, gaged values are not statistically different from the historical, monthly, natural flows, thus the historical, daily, gaged flows are representative of daily natural flows.

3.1.2.2.1 Comparing Trends in the Data

The first proposed technique checks to see if there are conflicting trends between the gaged and natural flows. Generally, one can test for a trend in data using both parametric (t-test) and nonparametric tests (Mann-Kendall test). The Mann-Kendall (MK) test is widely applied in the hydrological sciences to detect trends in data (*Helsel and Hirsch*, 2002) since it makes no underlying assumption about the distribution of the data. However, *Yue and Pilon* (2004) showed that for normally distributed data, the t-test performs as well or better than the MK test. In either case, the trend testing will test the null hypothesis: that there is no trend.

If the test fails to reject the null hypothesis of both the gaged and natural flows, then one can conclude that depletions are at least remaining constant with respect to historical levels. The test does not reveal if the gaged flow is generally below the natural flow by a constant amount, however this does indicate that depletions or regulations are not changing with time. If the depletions and regulation on the river are known to be very low though, this does indicate that the gaged flow is approximately natural.

Additionally, this can be performed on different aggregation levels of the streamflow to reveal if there are any shifts in stream flow timing. For example, the test could be performed on annual flow, monthly flow and seasonal flow to understand more about the trends in the gaged and natural flows.

3.1.2.2.2 Comparing Means

The second technique uses another statistical test. This time, the mean streamflow of the gaged flow is compared to the mean stream flow of the natural flow. Using another t-test, a hypothesis test can be used to determine if the difference in means is equal to 0. The hypothesis test is:

$$H_0 : \mu_1 - \mu_2 = \Delta_0$$

$$H_1 : \mu_1 - \mu_2 \neq \Delta_0$$

where μ is the sample mean and $\Delta_0 = 0$. In this case, it is advantageous to assume that the variances are unknown and different. One of the assumptions in this test is that the two samples are normally distributed, thus it is important to verify this before performing the hypothesis tests. One option to verify such assumption is the Kolmogorov-Smirnov (KS) test, which can be used to see if the flow data is statistically different from a normal distribution.

If the hypothesis test fails to reject the null hypothesis, then the mean of the gaged flow is statistically non-distinguishable from the mean of the natural flow. This test indicates that the average gaged flow is approximately the same as the average natural flow, thus there is little difference in the gaged and natural flows. Again, this test can be performed at different aggregation periods to gain more insight into the similarities and differences between the natural and gaged flows.

3.1.2.2.3 Fit Model To Gaged Versus Natural Flow

The next technique fits a linear model to a scatter plot of gaged flow vs. natural flow. Using a t-test, one can determine if the slope (β_1) of the model is equal to 1 and the intercept (β_0) is equal to 0. In contrast to Section **3.1.2.2.1** which checks for a trend in the data, the t-test must be used here since we are testing for a slope equal to 1 rather than for a trend. Similarly, the t-test can be used to determine if β_0 is distinguishable from 0.

If both tests fail to reject the null hypothesis, then the gaged flow exhibits an approximate 1:1

relationship with natural flow at the user specified confidence level. As with the other methods, this can be performed at a variety of temporal aggregations. This test should not be used if there is not an apparent linear relationship between the natural and gaged data.

3.1.2.2.4 Deviation From Natural Flow

The final technique presented here computes the deviation from natural flow. By computing the deviation from natural flow as a percentage of natural flow for each year, one can see if there is a trend to the deviation or if the deviation ever exceeds a critical threshold. This technique is the least objective out of those presented, as it is left up to the user to prescribe the acceptable flow deviation percentage, e.g., a 10% deviation from natural flow is reasonably close to natural flow. Additionally, it can be helpful to look at the long-term average deviation from natural flow or a smoothed running average of the deviation. Since the percentage deviation from natural flow can change drastically from year-to-year, the smoothing helps identify time periods that are stable, while the long-term average can be compared with the critical threshold. It is important to note, that this can be deceiving in a low flow month, i.e., the percentage deviation could be very high, while the magnitude is small. As with the other methods, this method can be performed at various temporal aggregation levels to identify different shifts in the deviation from natural flow.

3.1.2.2.5 Summary of Techniques

Clearly, each technique has advantages and disadvantages. This section aims only to provide several techniques to compare gaged flow with natural flow. It does not prescribe the use of all the techniques or a specific subset of them. It is left up to the user to determine the seriousness of the 'passing' or 'failing' of one of the methods. Depending on the application and the user's knowledge of the system it is conceivable that failing one test while passing another would still result in a reasonable assumption that the gaged flow is approximately the natural flow.

3.1.2.3 Application of Demands

Keeping in mind that the goal of the disaggregation is to obtain depleted flows at a given point (gage) and that the method described up to this point generates a daily, natural flow data set, demands must be applied in order to obtain the depleted flows. This section details how the monthly demands are applied to the daily, natural flows.

Up to this point, the method produces daily, natural flows. In order to meaningfully assess the daily e-flow requirements, demands must be applied to the natural flows to generated depleted flows since depleted flows represent the water that will actually pass a certain gage and is available for environmental considerations. The demands are known at the monthly timestep, thus they cannot be directly applied to the daily natural flows. In the planning model, model inputs include monthly natural flow and monthly demand data. The demand data has two inputs: the diversion requested and the depletion requested. The actual diversion is computed as

$$Total\ Diversion = Min(Diversion\ Requested, Available\ Water) \tag{3.3}$$

where the available water is a function of the input natural flow and any upstream depletions. From the *Total Diversion*, the actual depletion is computed using the same ratio of depletion requested to diversion requested. Thus through these computations in the planning model, the actual monthly depletion is determined. The computations short the users if there is not adequate available water at the monthly level, so the application of demands to the daily natural flow uses the 'actual' depletion from the planning model. This indicates that the depletion should be able to be distributed through the daily flows without the creation of any additional shortages. Since there can be multiple demands in each reach, all computed monthly depletions on the reach are summed together before they are applied to the daily hydrograph.

Since the demands are input at the monthly level and shortages are computed at the monthly level as well, the monthly demand distribution is also known. With the absence of any additional insight or knowledge of the demand data, the assumption is made that the demands are distributed evenly within each month. For example, if from the planning model it is computed that the monthly depletion for April and May is 5,000 acre-ft/month (84 cfs) and 11,000 acre-ft/month (185 cfs), respectively, then the daily depletion for every day in April is 84 cfs while in May it is 185 cfs.

This assumption generally works well, though it can have issues during the ascending and descending limbs of the daily hydrograph. Depending on both the magnitude of the depletion and the magnitude of the base flow during the ascending/descending limb, subtracting the depletion from the daily natural flow can result in a negative value for flow. While this is clearly physically impossible, it is also problematic since it is known from the planning model that this depletion can be fulfilled in the given month at the monthly level. The occurrence of the negative flows is due to one of two things: 1) there is simply not a large enough volume of water (based on the sum of the disaggregated daily flows) in the given month to meet the computed depletion, or 2) there is enough total water to meet the demand, though the daily flow rate occasionally becomes negative since the disaggregated daily flows can be less than the monthly depletion rate. To remedy the latter issue, the daily demands are redistributed within the problematic month. This is described in the next section. To address the first issue, a secondary disaggregation procedure is proposed which is presented in Section 3.1.2.4.

3.1.2.3.1 Redistributing Demands Within a Month

The redistribution of demands within a month is a parametric, iterative procedure. The procedure hinges on one user-specified parameter for the minimum allowable flow; the choice of this parameter is discussed in the subsequent section. Denoting the minimum allowable flow as M, the procedure is as follows:

(1) Over the month, determine the total volume of water (V) necessary to ensure each daily flow is at least equal to M, i.e., if the daily flow is $< M$, what volume of water is necessary to make the daily flow equal to M?

(2) Set each daily flow that is less than M to M.

(3) Count the number of days that are greater than M (defined as C).

(4) Compute the daily adjustment: $A = V/C$.

(5) A is now an additional demand rate that should be applied to all days that are greater than M.

   (a) For each daily flow rate that is greater than M, subtract A from the daily flow rate.

(6) Subtracting A from each day above M can result in days that are now less than M, thus repeat the procedure starting from step 1; repeat until no days are less than M.

Repeating this procedure until all days are above M, results in a depleted hydrograph where the daily depletions have shifted towards the area within a month with enough available water to meet the demand. The strength of this procedure is that it ensures that the total monthly depletion remains the same as that specified in the planning model. The weakness is that it is dependent on a user specified value for M which can impact the results (described in the next section).

3.1.2.3.2 Choice of a Minimum Flow Parameter

The redistribution of demands within a month is governed by the choice of a minimum flow parameter. There are four immediately available choices for this value:

(1) An arbitrary value

(2) A value of 0

(3) The minimum recorded value from gage data in the months of interest

(4) A value from literature such as a biological opinion or environmental impact statement

Each of these choices deserves consideration depending on the application and goal of the disaggregation. An arbitrary value is the least appealing, though this could be empirically determined by iterating through the disaggregation and re-distribution of demands under many different values. This choice could result in the highest possible minimum flow value that ensures the demands can be redistributed. A value of 0 could be used to ensure the redistribution of demands can always occur (assuming there is enough total water in the month to meet the demands), though it would imply that it is acceptable to dry up the stream to meet demands. Choosing the minimum value from gage data is at least physically based. While the value has been observed historically, choosing this value would increase the frequency that it occurs as it would occur anytime the flow redistribution is necessary. Alternative to choosing the minimum recorded gaged value, one could analyze the gaged data to find a minimum flow that occurs often in the historical record. Finally, using a minimum flow value from literature would imply that there has been a suggested or required minimum flow on the river. If this is the case, it is important to ensure that the planning model is using this same minimum flow value.

The choice of the minimum flow parameter can impact the results. Though the actual choice impacts the low flows, the application of the demands to periods with higher flows will also decrease these flows. Since the results are dependent on this parameter it could be used as a tuning parameter or in a sensitivity analysis.

3.1.2.4 Secondary Disaggregation

As described in Section 3.1.2.3, the application of demands to the daily natural flows can result in negative flows. In many instances, redistributing the demands within the month will resolve this issue; however, in other cases there is simply not a large enough volume of water in the month to meet the specified demands. Recall that the neighbor selection selects a neighbor with a monthly hydrograph shape close to the year that is in need of disaggregation and that this selection does not entirely preserve the monthly volumes, though they are typically 'close' to the same. In certain years, they are not close enough. The planning model computes that the depletion can be met by the specified monthly input natural flow. The disaggregation procedure can select an index year with a minimally smaller monthly volume; however, reducing the total monthly volume by only a minimal percentage can result in a monthly natural flow volume that is less than the computed depletion. In these cases, redistributing the demands within the month does not remedy the issue, thus a secondary disaggregation step is described here. The secondary disaggregation step ensures the monthly volume remains identical after the disaggregation so that the monthly demands can always be fulfilled.

In order to preserve the monthly natural flow volumes while staying in the nonparametric disaggregation framework, the proportion vector (P) used to disaggregate from the seasonal volume (s) is modified. Before, P was created by taking the daily volume from April 1 through July 31 and dividing by the seasonal volume, thus the hydrograph was continuous from April 1 - July 31 and all lag-1 correlations are preserved. The sum of P in this case is always 1. Now, n P vectors are defined, where n is the number of months and each P is redefined as the daily volume divided by the monthly volume. In this case, the sum of all Ps should equal the number of months (n) and the sum of each individual P will equal 1. The daily flows are generated by multiplying each monthly volume by the respective P:

$$d_m = P_m * h_m \tag{3.4}$$

where d are the daily flows in month m, P is the proportion vector for month m, and h is the monthly volume in the year that is being disaggregated.

While this method does exactly conserve the monthly volumes, it comes at a cost: the lag-1 correlation between the end of one month and the beginning of another is not replicated entirely accurately. However, this approach is viewed as acceptable for several reasons; most importantly it beats an error in the mass balance that would be created by leaving negative flows. Additionally, the other immediately apparent option was to continue the redistribution of demands into the next month or to apply a shortage to the depletion. This would imply that we did not 'trust' the depletions computed by the planning model and that we were willing to distort the information provided by the planning model. Since the depletion schedules are viewed as an acceptable representation of the future, it is important to preserve their view of the monthly distribution. Next, a slight discontinuity between two months will not adversely impact reservoir operations. Subsequently, the discontinuity could be eliminated by a more constrained selection of the nearest neighbors; perhaps by reducing K or by using a weighting function that gave even more weight to the first few neighbors. While this would help, it would reduce variability in the daily flow patterns that are selected as index years, which is viewed as a negative, and there would still be a small subset of years that the volume of water was not quite enough to fulfill the demand. Finally, since the secondary disaggregation will only be used when necessary, it will only adversely impact a small percentage of years. Since this framework is meant to be used in a probabilistic sense with many simulations, the small impact on a small subset of years is acceptable.

In application, the secondary disaggregation uses the same index year that was chosen by the initial KNN selection. After applying the secondary disaggregation step to the input natural flows, a new set of daily natural flows are generated. The demands are applied in the same manner as described previously. Similarly, the demands might need to be redistributed within a month to shift the demands away from the base flow periods in the leading and trailing months; however, it is now guaranteed that the demands can be redistributed within a month while conserving mass if the minimum flow threshold is properly chosen.

3.1.3 Application on the Yampa River

In this section, a demonstration of the disaggregation method is applied to the Yampa River at the Deerlodge Gage. This site was chosen as the Deerlodge gage is representative of the contribution of the Yampa River to the Green River. Downstream of the Yampa-Green confluence is the Jensen gage which is used to monitor e-flow requirements for the operations of Flaming Gorge (*Bureau of Reclamation*, 2006a). The e-flow requirements at the Green near Jensen rely on both releases from Flaming Gorge and the flow from the Yampa River. Since the requirements are in terms of days and weeks at a given flow, the disaggregation method is employed in a planning model to disaggregate the monthly natural flows on the Yampa River. The modeling of daily releases from Flaming Gorge is described in Section 3.3.

Since the Deerlodge gage has a sparse historical record, the aggregate of the Yampa River near Maybell and the Little Snake near Lily are used. Additionally, the natural flow for the Yampa near Maybell and the Little Snake near Lily are combined to create a natural flow record for the

Yampa near Deerlodge.

The following sections test all aspects of the disaggregation method: first, the new neighbor selection is tested to ensure it recreates historical statistics as the original method is shown to do in *Nowak et al.* (2010). Next, it is demonstrated that the historic record at Deerlodge is approximately natural, i.e., fairly unaltered by regulations and/or diversions. Finally, the disaggregation method is incorporated into a planning model to show the results of the daily disaggregation method when using several different input hydrologies.

3.1.3.1 Testing New Neighbor Selection

To ensure that selecting an index year using the method described above replicates historical statistics as well as *Nowak et al.* (2010), the same statistics were computed and are presented in the following section. Additionally, several new statistics were computed and are presented in the subsequent section. These are statistics that are essential to monitoring e-flow requirements and were not tested in *Nowak et al.* (2010). To compute the statistics, 250 simulations of April - July streamflow on the Yampa River at Deerlodge were generated using a KNN methodology to sample monthly values from the 88 years of historical gage data. Each simulation is a new sequence of 88 years worth of gage data realized by sampling the next months flow from K-neighbors.

3.1.3.1.1 Previously Checked Statistics

As in *Nowak et al.* (2010), the mean, variance, skew, maximum, minimum, and lag-1 correlations were computed for every day from April through July. For each day, the statistic was computed across all years in one simulation; the variability of the statistics over all simulations is shown as a box plot or as a grey band in the following figures. This section acts as proof that selecting the K-nearest neighbors based on the method described in Section 3.1.2.1 preserves the daily statistics. Figure 3.1 shows the statistics with the 5th and 95th percentiles of the 250 simulations shown as a grey region. In this figure, the mean, variance, skew, minimum, maximum and lag-1 correlation are shown for every day from April 1 through July 31. Additionally, Figure 3.2 shows the same

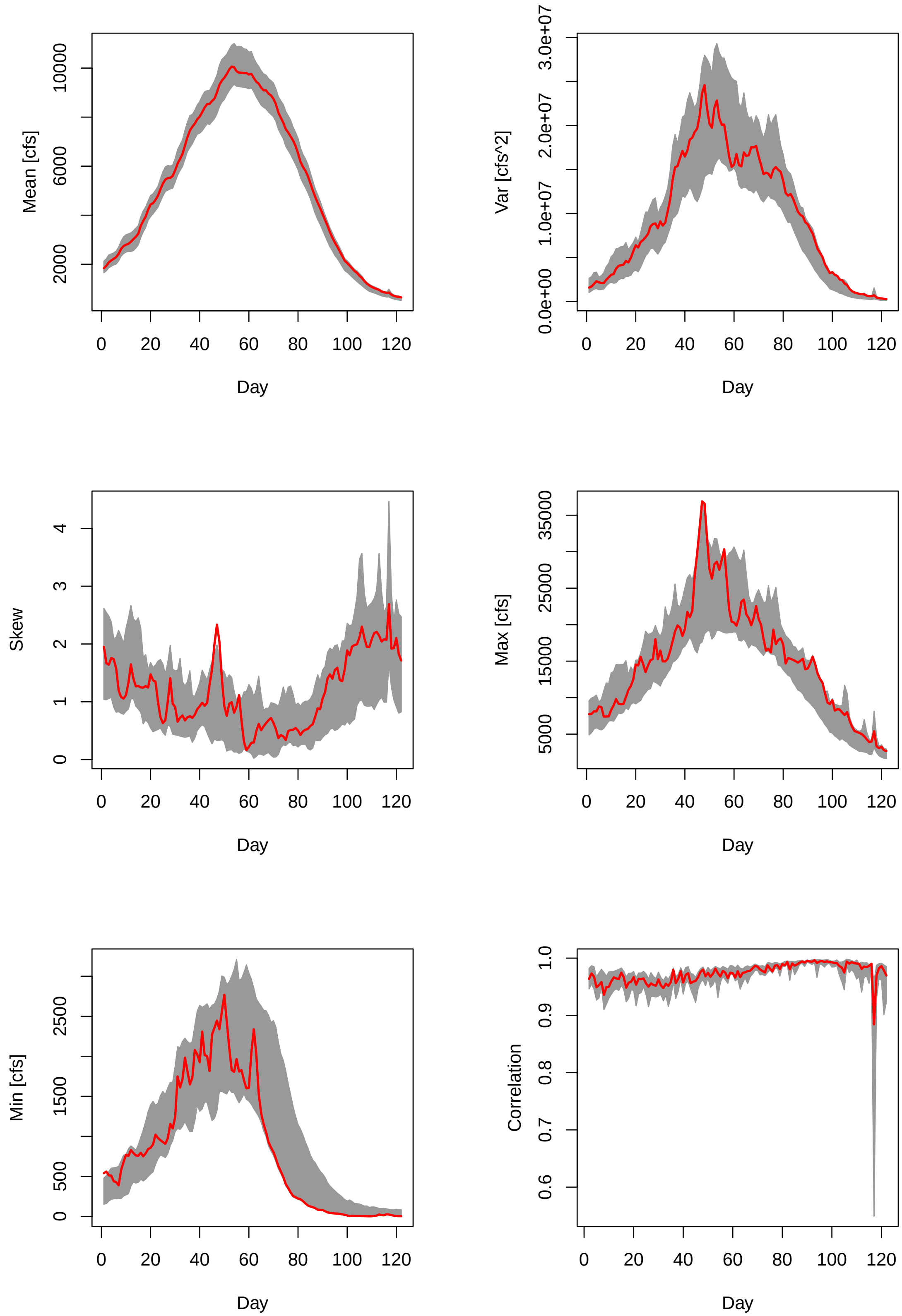


Figure 3.1: Daily statistics for 250 simulations of 88 years each of stream flow. The grey region shows the 5th and 95th percentiles from the 250 simulations. The historical value is shown as the red line. The days start at April 1 and go through July 31.

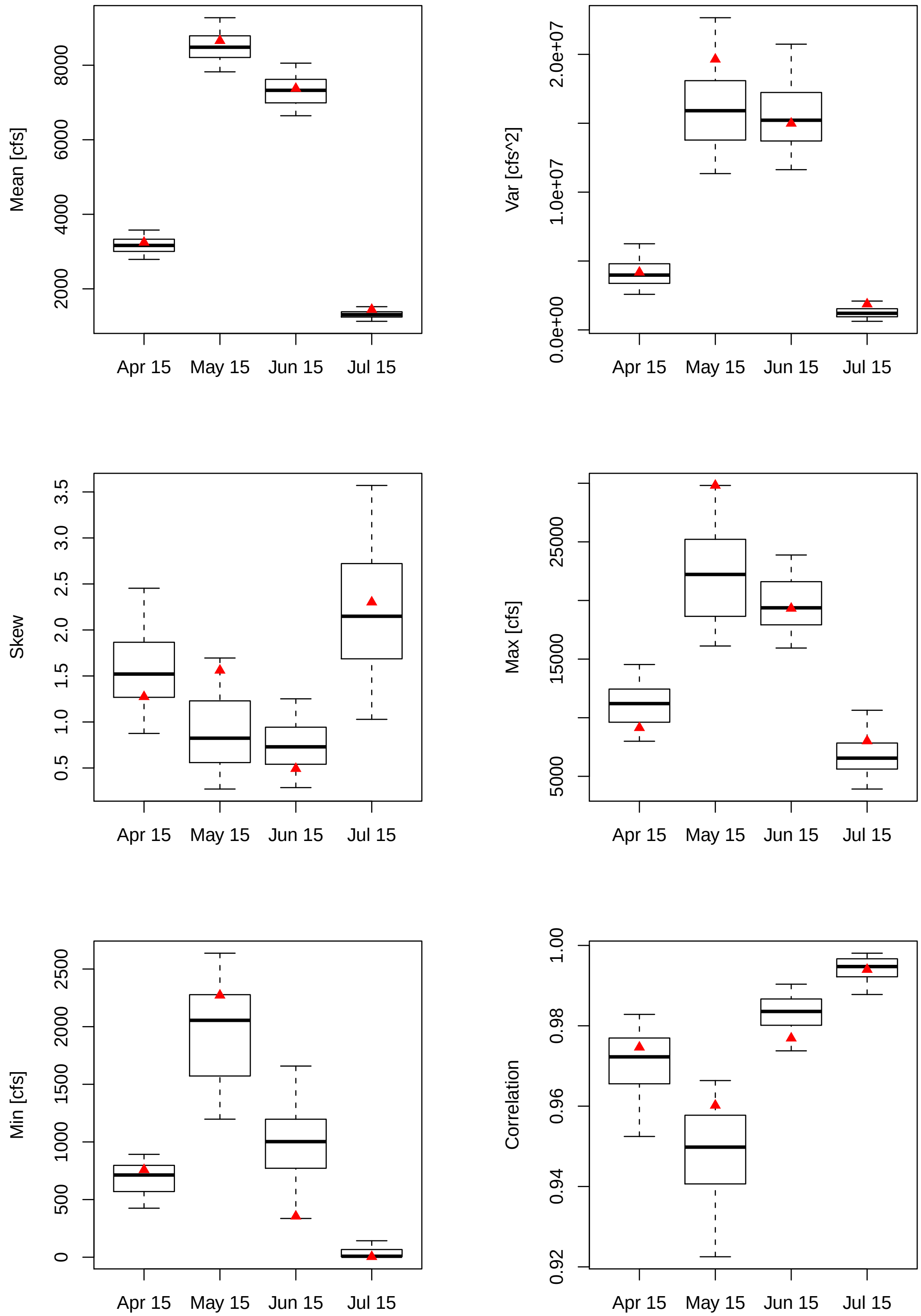


Figure 3.2: Daily statistics on the 15th of each month for 250 simulations of 88 years each of streamflow. The boxes extend to the 25th and 75th percentiles while the whiskers represent the 5th and 95th percentiles. The historical value is shown as the red triangle.

statistics for the 15th of each month; the values for the 250 simulations are shown as a box plot in this figure. Overall, the historical values are replicated well. The historical value always falls within the 5th and 95th percentiles of the simulations and typically falls within the 25th and 75th percentiles.

3.1.3.1.2 Threshold Statistics

In many e-flow requirements, the desired flows are stated as a certain number of days above a given threshold. Thus, to monitor the daily e-flow requirements, it is important to replicate these threshold statistics. This section tests the method's ability to replicate the distributional statistics of both spell lengths and spell volumes, where a spell is a given event over a threshold flow value. The following figures present the spell statistics for a threshold of 10,000 cfs. Appendix A presents the same figures for a threshold of 14,000 cfs. Both of these threshold were selected based on knowledge of the system, specifically the maximum release from Flaming Gorge and the targeted e-flows below the Yampa-Green confluence. The PDF of spell volumes and spell lengths are shown in Figures 3.3 and 3.4, respectively. A spell length was recorded for any number of days (1 - infinity) above 10,000 cfs. Once the flow fell below 10,000 cfs that spell was finished; though conceivably a new spell could begin the next day. To determine each spell volume, the daily flow was recorded for each day above 10,000 cfs. After, the spell concluded, the daily flows over the spell length were summed to a volume, thus the PDF shows the total volume of water over the duration of the spell length. Both the spell volumes and lengths were computed for every year in a simulation and an individual PDF was computed for that simulation. The ranges in the figures show the variability of the PDFs amongst the 250 simulations. The PDF of spell volume is well captured through a volume of 2,000 KAF though it is only shown through a volume of 1,000 KAF in Figure 3.3. Similarly, the PDF of spell length is well captured through a length of 60 days though it is only shown through a length of 30 days in Figure 3.4.

The final statistic that was computed is the maximum consecutive number of days above 10,000 cfs for each year. This results in a single value for each year in the historic record and in

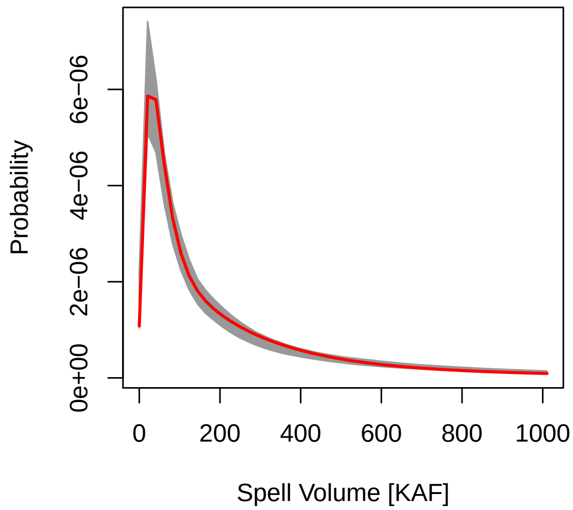


Figure 3.3: PDF of spell volumes above 10,000 cfs. The grey region represents the 5th and 95th percentiles of 250 simulations; the historical PDF is shown in red.

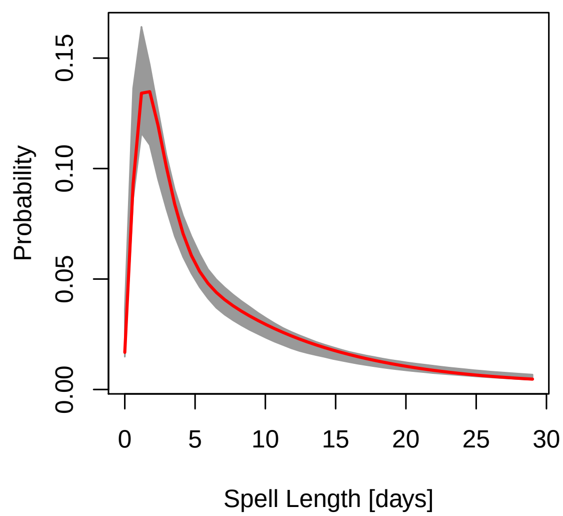


Figure 3.4: PDF of spell length in days above 10,000 cfs. The grey region represents the 5th and 95th percentiles of 250 simulations; the historical PDF is shown in red.

the 250 simulations. The results of the maximum consecutive days above 10,000 cfs are shown in Figure 3.5. The medians, 5th, 25th, 75th and 95th percentiles are all very similar between historic and simulated conditions, though the simulations produce longer extremes.

Overall, the spell length and volume statistics are well captured as are the maximum number of days above the threshold. So, in addition to capturing the historical mean, maximum and minimum daily flow statistics, the method also performs well at replicating historical spell lengths and volumes while also producing spell lengths not historically observed.

3.1.3.2 Proving Gage Data is Close to Natural Conditions

The methods described in Section 3.1.2.2 are implemented here to determine if the historical gage record for the Yampa near Deerlodge is approximately natural. In all cases three different time periods were tested: annual, April - July and September flow. The annual aggregation provides information as to the change in total basin yield over time. The April - July period was chosen as this is the same period that will be disaggregated in later sections, thus this is the most important period to examine. Finally, the month of September was arbitrarily chosen to demonstrate changes in a low flow month.

3.1.3.2.1 Comparing Trends in the Data

Before checking for a trend in the data a KS test was used to see if the gaged and natural flows for the different time periods were normally distributed. The p-values from the test are shown in Table 3.1. Based on the resulting p-values, both the annual and April - July periods are normally distributed at the 95 % confidence level, however the September data is not. Since the annual and April - July periods are normal distributions, the t statistic can be used to check for a linear trend in the data with strong results (*Yue and Pilon*, 2004). Though the Mann-Kendall test would be a better choice to check for a trend in the September data since it is not normally distributed (*Yue and Pilon*, 2004), the t-test is used here as a quick demonstration and since the September period is not the critical period in this application.

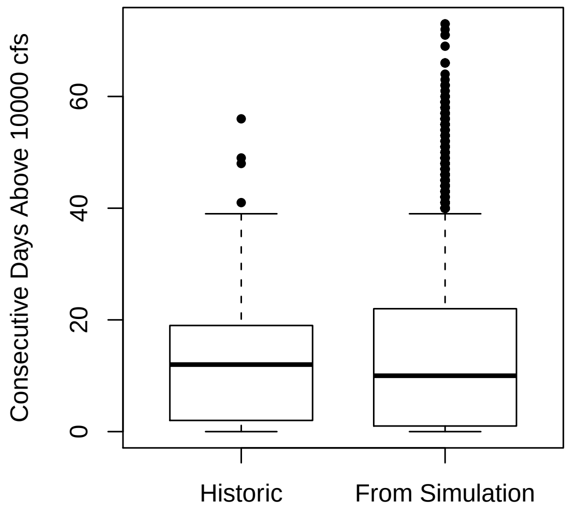


Figure 3.5: Box plot of the maximum consecutive days above 10,000 cfs in each year (historical and simulated).

Table 3.1: P-values from a KS test to determine if the flow data sets are normally distributed.

	Natural	Gaged
Annual	0.69	0.70
April – July	0.85	0.95
September	0.01	0.01

Table 3.2: Results of using a t-test to determine if the slopes of the models shown in Figure 3.6 are 0 at the 95% confidence level.

	t-theory	Natural Flow t	Natural Flow results	Gaged Flow t	Gaged Flow results
Annual	1.99	0.59	fail to reject	-0.42	fail to reject
April – July	1.99	1.07	fail to reject	-0.58	fail to reject
September	1.99	-3.79	reject	-0.28	fail to reject

Figure 3.6 shows the gaged and natural flow time series for the three time aggregations. Additionally, the linear fit to each of the time series is shown along with the mean of each time series.

Upon visual inspection of the linear models, with the exception of the natural flow in September, it is noticeable that the slopes of the models are very close to 0 if not 0. A t-test is used to determine if the slope of the model is different from 0 by using the following hypothesis test:

$$H_0 : \beta_1 = 0$$

$$H_1 : \beta_1 \neq 0$$

The t-value of each model is compared with the theoretical t-value; if the absolute value of the model t-value is greater than the theoretical t-value, then the null hypothesis is rejected. Table 3.2 shows the t-values for all of the models and the results of the hypothesis test. Except for the natural flow in September, all slopes are non-distinguishable from 0 at the 95% confidence level. The results of this test show that there is no decreasing linear trend in gaged flows while natural flows remain the same. It does not indicate that there is not some constant difference between the gaged and natural flows though.

3.1.3.2.2 Comparing Means

Next, the mean values of the gaged and natural flows are compared using another t-test to check that the differences in the means are equal to 0. When checking the difference in means using a t-

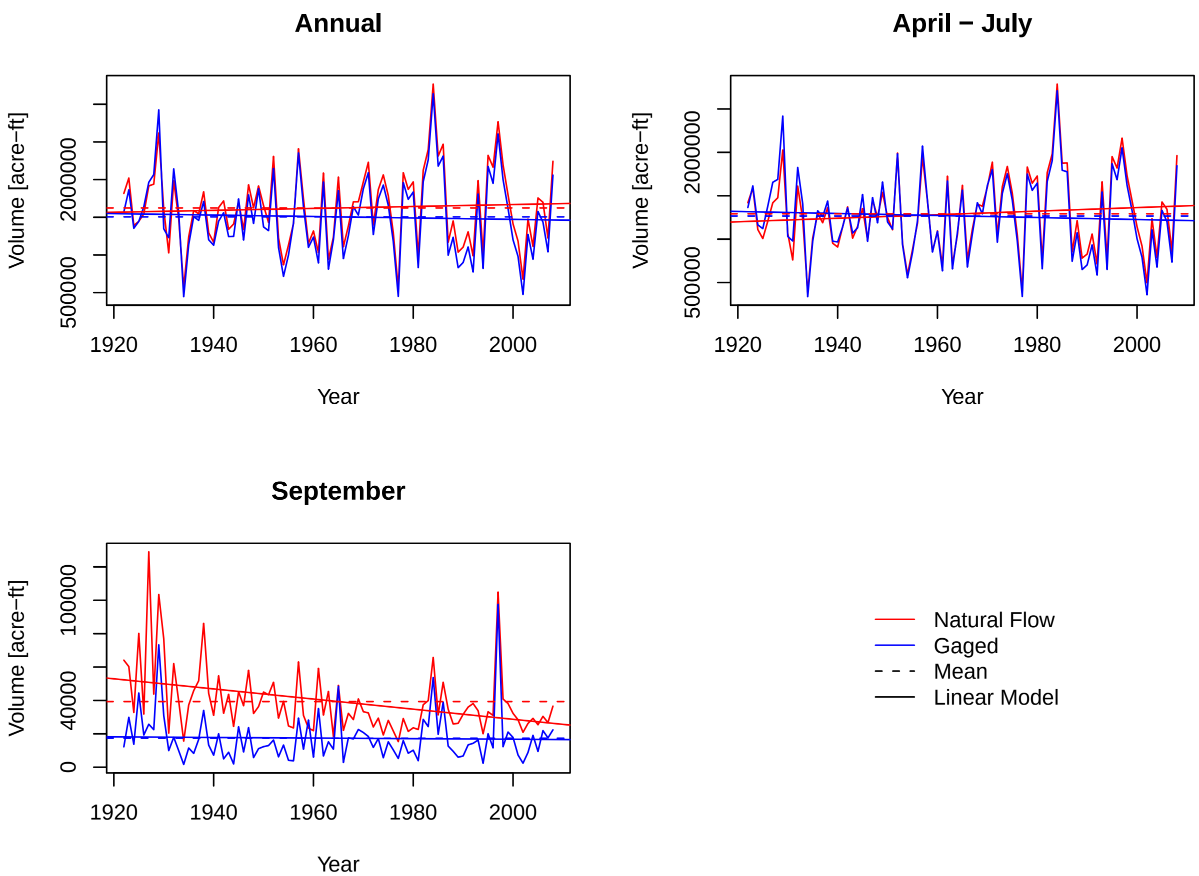


Figure 3.6: Time series of gaged and natural flow for the Yampa River near Deerlodge with linear models fit to the time series.

Table 3.3: Results of a t-test to determine if the mean of the natural flow equals the mean of the gaged flow at the 95% confidence level.

	t-theory	t	result
Annual	1.65	1.51	fail to reject
April – July	1.65	0.37	fail to reject

test, one of the assumptions is that the data is normally distributed. Based on the KS test described above, all data series except for the September period are normally distributed. In this section, the September flows are not tested since the normality assumption is not valid.

The following hypothesis test was used to compare the means of the gaged and natural flows for the annual and April - July periods:

$$H_0 : \mu_1 - \mu_2 = \Delta_0$$

$$H_1 : \mu_1 - \mu_2 \neq \Delta_0$$

where $\Delta_0 = 0$. Again, a t statistic was used to test the hypothesis and the null hypothesis is rejected if the absolute value of the test t-value is greater than the absolute value of the theoretical t-value. Table 3.3 lists the t-values and the results of the hypothesis test. The difference between the means is non-distinguishable at the 95% confidence level for both the annual and April - July periods. Thus, it is shown that the long-term average for the gaged flow is equal to the average natural flow, and the argument that the gaged flows at Deerlodge are close to natural is strengthened.

3.1.3.2.3 Fit Model to Gaged Versus Natural Flow

The next comparison of gaged and natural flows fits a linear model to a scatter plot of gaged vs. natural flow. If the slope of the model is 1, while the intercept is 0, it is shown that there is a 1:1 relationship between gaged and natural flow and thus there is no difference between the two. Figure 3.7 shows the scatter plots for each of the three time levels along with the linear model that was fit to the data. The figure shows there is little difference between the linear model and the

Table 3.4: Results of t-test to determine if the slopes of the models shown in Figure 3.7 are equal to 1 and the intercepts equal to 0 at the 95% confidence level.

		β_1		β_0	
	t-theory	t	result	t	result
Annual	1.99	0.81	fail to reject	-4.02	reject
April – July	1.99	0.64	fail to reject	-1.34	fail to reject
September	1.99	-8.46	reject	-1.63	fail to reject

1:1 line that is shown for the annual and April - July periods. There is a distinguishable difference between the two in September. To confirm the visual inspection, a hypothesis test is again used to test if the slope of the line is different from 1. The same procedure is used here as in Section **3.1.3.2.1** except that β_1 is compared to 1 instead of 0. Additionally, β_0 is compared to 0 to see if the intercept is different from 0.

Table 3.4 shows the t-values and the results of the hypothesis tests. From this, the slopes for the annual and April - July ranges are no different from 1 and the intercept for the April - July and September periods are no different from 0. This reveals several things including that the April - July time range has a 1:1 relationship between gaged and natural flow at the 95% confidence level. Additionally, it shows that there are some fairly constant depletions and/or regulations that show up on an annual level; the slope is 1, though the intercept is not 0. Additionally, it is more apparent that the low flow month of September is impacted more by depletions/regulations than the annual or spring periods.

3.1.3.2.4 Deviation from Natural Flow

The final comparison uses a technique further described in Section 3.4: the inspection of the percentage deviation from natural flow. Figure 3.8 shows the time series plots of the percentage deviation from natural flow, with an 11 year moving average, and the long-term average shown. Since this comparison is more qualitative than the previous three, the following discusses interesting features in the plots.

First, inspecting the long-term average can reveal if the stream is historically within a certain

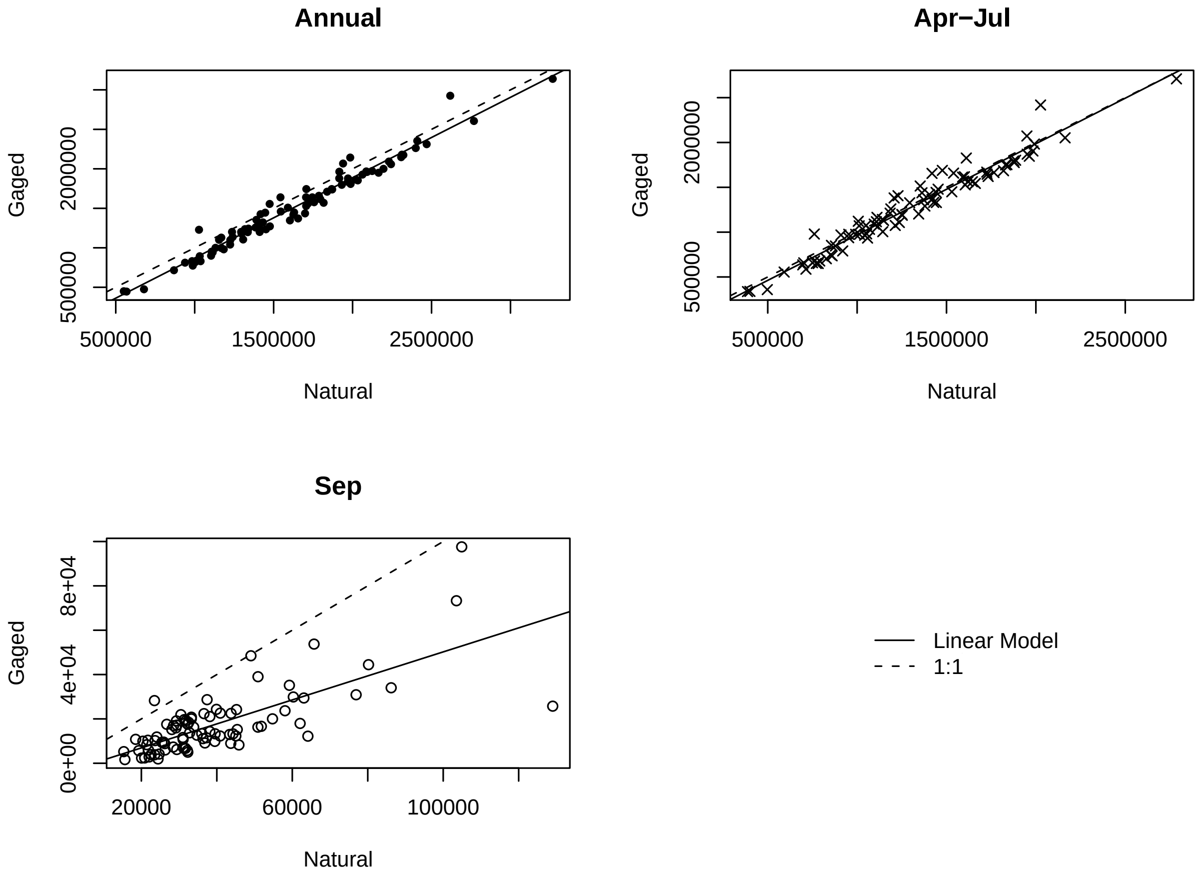


Figure 3.7: Scatter plots of gaged vs. natural flow with a linear model fit to the data.

percentage of natural flow. For example, the annual average percentage deviation is less than 10%, implying that historically close to 90% of the flow is unaltered above the Deerlodge gage. Looking at the 11 year moving average shows that there is a steady period followed by an increase in the deviation in recent years. Additionally, there is an apparent trend in the April-July range showing that the percentage deviation is getting larger over time. However, the 11 year average is never more than 10%, showing that the April - July flows are largely unaltered. Finally, the September plot shows that this month has a much larger portion of its flow altered than the other two periods. As shown in the previous section, September is impacted by regulations and/or depletions more than the other months, and it is a much larger portion of the monthly flow in September than in a high flow period.

3.1.3.2.5 Summary of Tests

From the previous four tests it is concluded that the historical flow at the Deerlodge gage is approximately natural flow. While most of the tests indicated that the flows in September are not close to natural flows, the important months of April - July are almost identical to natural flows. Since the disaggregation will take place in April - July it is more important that the gage is representative of natural flows in this period than in other periods. The model fit to gaged vs. natural flow shows a 1:1 relationship between the two indicating they are nearly the same. Additionally, the means are no different, and there are no noticeable trends in either the natural or gaged flows. The deviation from natural flow figures can act as a qualitative comparison of the two and could help identify time ranges that might be more or less impacted by depletions and/or regulation.

In practice, it is probably sufficient to use one or two of these methods, though this section demonstrated the application of all four.

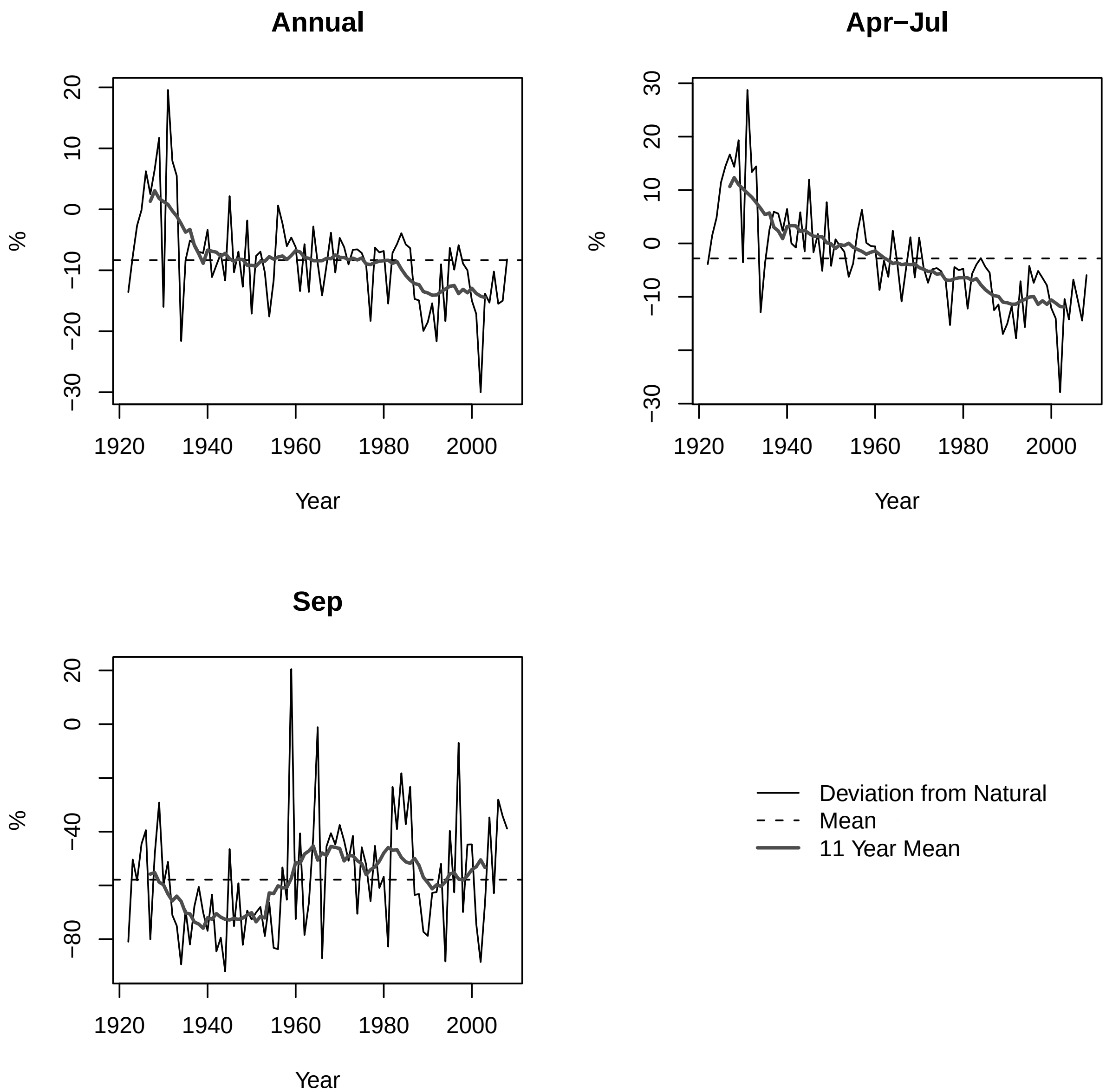


Figure 3.8: Deviation from natural flow at three time aggregations, with an 11 year moving average shown.

3.1.3.3 ISM Sample Model Results

In this section the results of the monthly to daily disaggregation are presented. The method was implemented in a planning model in RiverWare (*Zagona et al.*, 2001). The results in this section are generated from a 102 trace run of the direct natural flow using the Index Sequential Method (ISM; *Ouarda et al.* (1997)) from 2010 through 2060. The minimum allowable flow value was set to 2 cfs which is the lowest historical value observed in April - July at the Deerlodge gage. In the first section, probabilistic results are presented, where the 102 trace ensemble is used to generate the results. In the subsequent section, example daily hydrographs are shown for single years of individual traces.

3.1.3.3.1 Probabilistic Model Results

Figure 3.9 shows the lag-1 correlations for the model runs. On the left, the lag-1 correlations were computed as if no secondary disaggregation had occurred (without the secondary disaggregation there is a mass balance issue); on the right, the lag-1 correlations are computed with the secondary disaggregation occurring when necessary. This figure illustrates the impact that the secondary disaggregation has on the lag-1 correlations. While the correlations values are slightly lower, they are still very high (always above .9) and with the exception of July, the historical values are within the IQR. Since the secondary disaggregation occurs in only 11.6 % of years, it does not have a large detrimental impact on the lag-1 correlations. Additionally, Figure 3.10 shows the percentage difference between the input, monthly natural flows and the computed monthly natural flows (computed as the sum of the daily natural flows after disaggregation). It shows that in April - June, the median is near 0 which implies that the disaggregation does shift the monthly volumes around some, though it is often not a large amount.

In both Figures 3.9 and 3.10 the results are worse in July than in the other 3 months. One reason for this is that July is not always a high flow month. In some years, July is almost entirely a base flow month, while in others the flows remain high for the majority of the month. Thus, it is difficult to preserve the lag-1 corrlation and monthly volumes in this month consistently. In

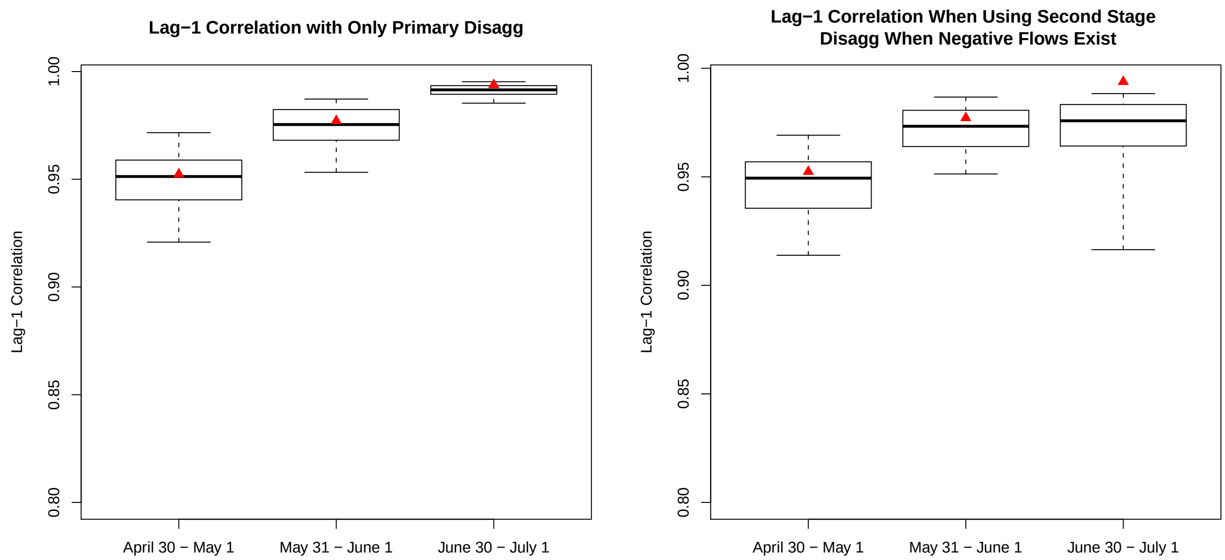


Figure 3.9: Lag-1 correlation between the end of a month and the beginning of the next month; showing results for solely the primary disaggregation and the actual results which use the secondary disaggregation when necessary. The historical values are shown as triangles. The whiskers extend to the 5th and 95th percentiles.

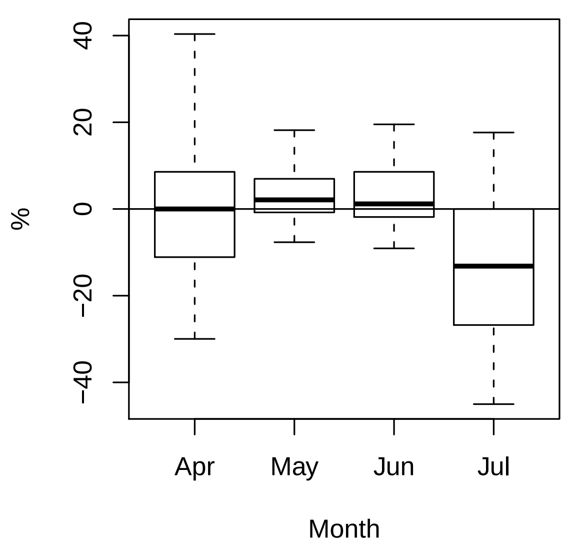


Figure 3.10: Boxplot of the percentage difference of the input monthly natural flow and the sum of the daily natural flows after the disaggregation for the ISM data. Whiskers extend to the 5th and 95th percentiles.

years where July has a majority of the month at base flow, the selection of an index year with even a slightly higher percentage of the total spring flow can have large percentage impacts. Additionally, when the secondary disaggregation is applied, the largest discontinuity is typically between June 30 and July 1.

3.1.3.3.2 Example Daily Hydrographs

The following two figures present example daily hydrographs that were generated within the planning model. Each figure aims to identify different disaggregation situations. In each figure, the disaggregated daily flow, the depleted flow and the index year's daily flows are shown. The inclusion of the index year's hydrograph helps illustrate the years that are selected; while they can vary in seasonal volume, their monthly proportions are similar to the year that is being disaggregated.

Figure 3.11 shows an example daily hydrograph in a dry year (total April - July volume had less than a 90 – 100% exceedance probability when compared with the historical record) which required no second-stage disaggregation. It shows that the selected index year (1998) was a year with higher magnitude flows though it was selected based on the monthly proportions and not the seasonal magnitude. There was no secondary disaggregation used, though the demands were redistributed in July: notice the low, constant depleted hydrograph after July 15. Figure 3.12 shows a moderately dry year (total April July volume had less than a 70 - 90% exceedance probability when compared with the historical record) which did need the secondary disaggregation to meet the specified depletions. Notice that when using the secondary disaggregation the general flow pattern of the index year (1954) is replicated, though certain features can be magnified or reduced. For example, in the month of July, the spikes in flow are magnified when the proportion vector is computed based only on the July flows and volume. This also creates a rather large discontinuity between June 30 and July 1 which illustrates some of the issues with July that were previously discussed.

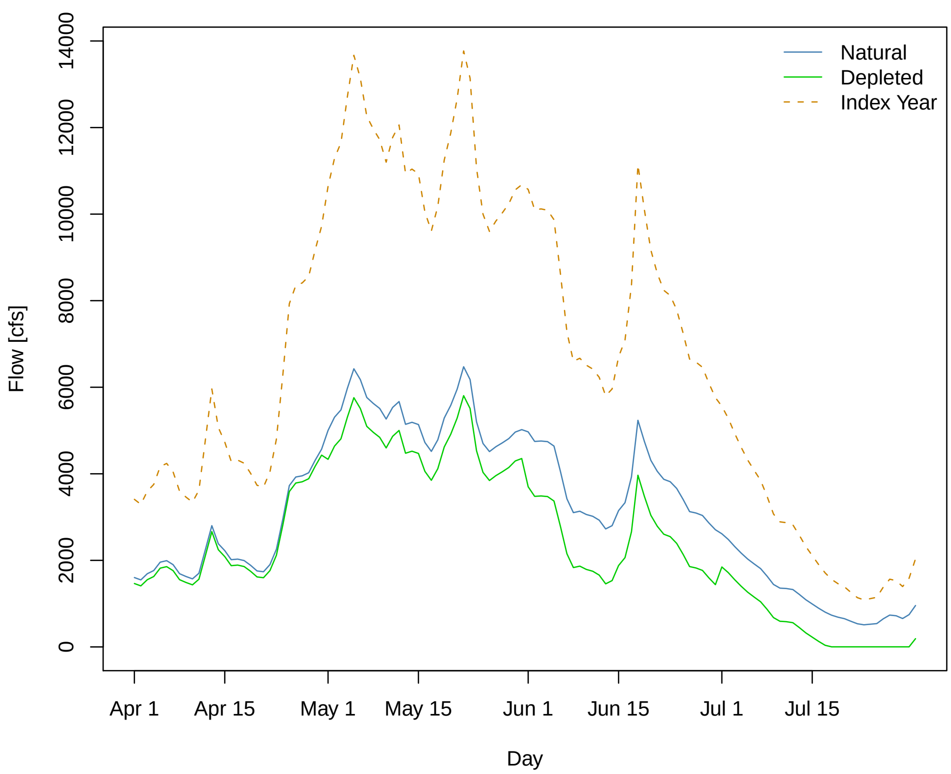


Figure 3.11: Example daily hydrograph from a dry year which required no second stage disaggregation. Index year was 1998.

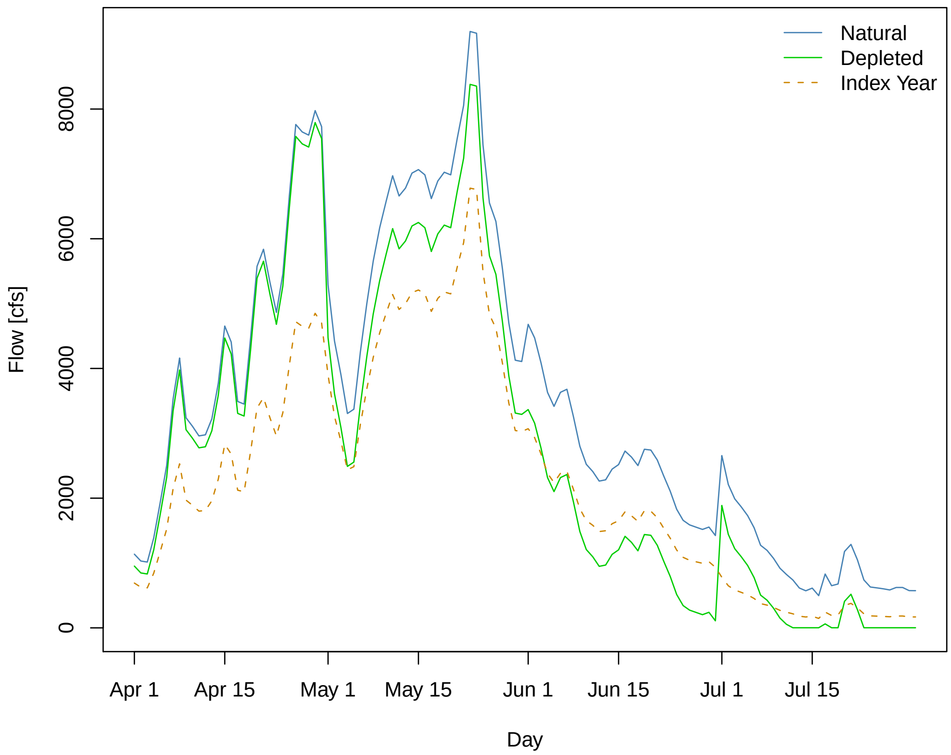


Figure 3.12: Example daily hydrograph from a moderately dry year which required the second stage disaggregation. Index year was 1954.

3.1.3.4 Climate Change Sample Model Results

In this section the results of the monthly to daily disaggregation are presented from a model run which used 112 projections of stream flow under climate change. The results in this section are generated from a 112 trace run of the simulated future flows from 2010 through 2060. The minimum flow value was set to 2 cfs which is the lowest historical value observed in April - July at the Deerlodge gage. In the first section, probabilistic results are presented, where the 112 trace ensemble is used to generate the results. In the subsequent section, example daily hydrographs are shown for single years of individual traces.

3.1.3.4.1 Probabilistic Model Results

Figure 3.13 shows the lag-1 correlation between months for the model run with the secondary disaggregation occurring when necessary. By comparing this to Figure 9 it is apparent that the medians drop slightly in the climate change run; however, the lag-1 correlations are still very high and with the exception of July, the historical value is encompassed in the IQR. In the climate change run, the secondary disaggregation is used 32.2 % of the time. This is approximately three times more often than in the run with historical natural flow, though the lag-1 correlations are still very high. Figure 3.14 shows the percentage difference from the input natural flows for the climate change data. In almost all cases, the median is close to 0 % indicating that the input monthly volumes are nearly the same as the sum of the daily flows. Compared to Figure 3.10, the median in July is much closer to 0 although there is a wider range. The closer median is probably a result of the increased number of times the secondary disaggregation is used.

3.1.3.4.2 Example Daily Hydrographs

The following two figures present example daily hydrographs that were generated within the planning model. Each figure presents a different combination of year type and implementation of the secondary disaggregation. In each figure, the disaggregated daily flow, the depleted flow and the index year’s daily flows are shown. The inclusion of the index year’s hydrograph helps

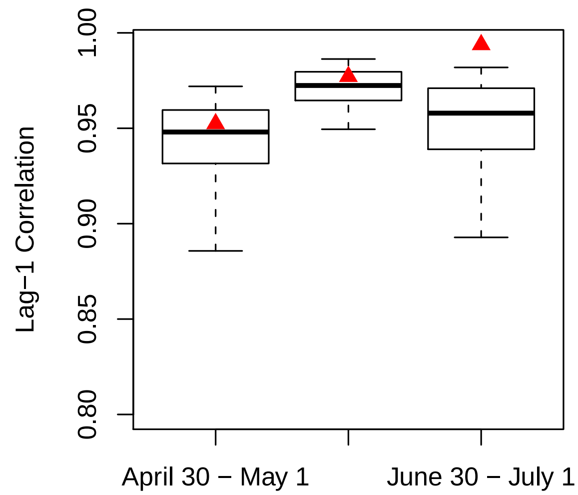


Figure 3.13: Lag-1 correlations between months from model run using climate change projections of streamflow.

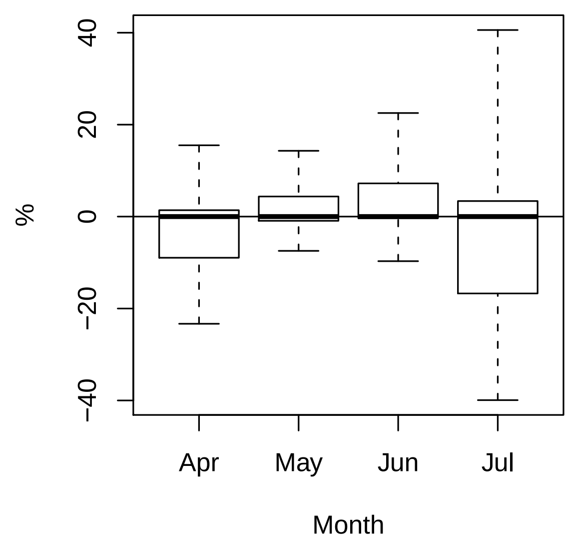


Figure 3.14: Boxplot of the percentage difference of the input monthly natural flow and the sum of the daily natural flows after the disaggregation for the climate change data. Whiskers extend to the 5th and 95th percentiles.

illustrate the years that are selected; while they can vary in seasonal volume, their monthly proportions are similar to the year that is being disaggregated.

Figure 3.15 shows an example daily hydrograph in an average year (total April - July volume had a 30 - 70% exceedance probability when compared with the historical record) which required no second stage disaggregation. It shows that the selected index year (1986) was a year with a very close seasonal volume. There was no secondary disaggregation used, and there were not even any redistribution of demands in this example. Figure 3.16 shows an example daily hydrograph in a wet year (total April July volume had a 0 - 10% exceedance probability when compared with the historical record) which required a second stage disaggregation. In this example, a very wet year needs the secondary disaggregation due to the extremely low flows in the month of July.

3.1.4 Conclusion

This section presented a methodology for generating daily flows in a planning model. An existing nonparametric disaggregation method (*Nowak et al.*, 2010) was modified to incorporate additional knowledge of monthly stream flows which are input into the planning model. The method disaggregates monthly natural flows to daily natural flows; depletions are then applied to generate daily depleted flows. Since the disaggregation technique uses historical gage data to generate the daily flow pattern, several methods are presented to compare historical gage data to historical natural flow data. The disaggregation method chooses a historical year (index year) to use the daily flow pattern for the disaggregation. The choice of the index year is based on selecting K neighbors, and then randomly selecting the index year based on a weighting function which gives preference to the closest neighbors. The 'distance' of the historical years to the year being disaggregated is based on the monthly hydrograph shape. The Euclidean distance of all monthly volume to season volume proportions is used to determine how close each historic year is to the year being disaggregated. The depletions, which are specified by the planning model, are applied to the daily natural flows first by assuming that they are uniformly distributed within each month. If the application of depletions results in any negative flows, then the depletions can

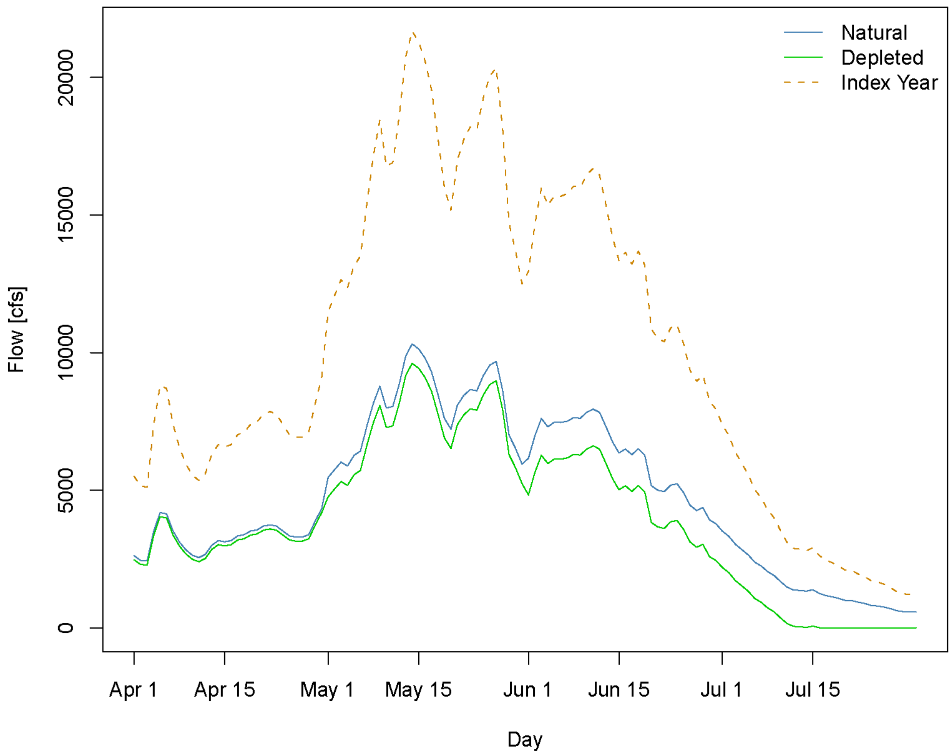


Figure 3.15: Example daily hydrograph from an average year which did not require the second stage disaggregation. Index year was 1986.

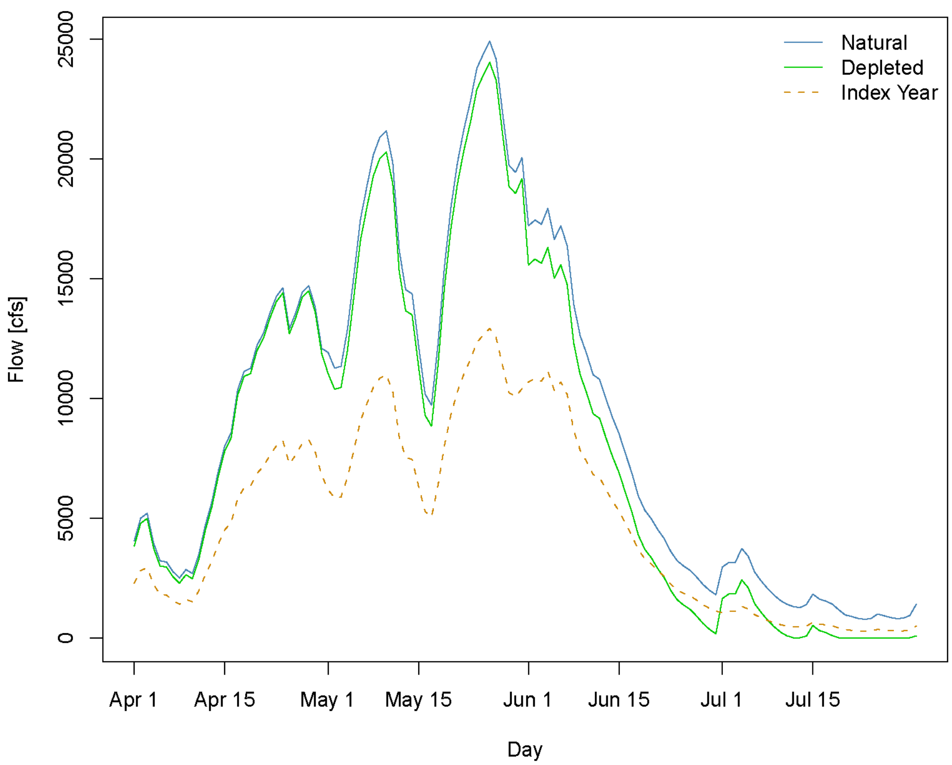


Figure 3.16: Example daily hydrograph from a wet year which required the second stage disaggregation. Index year was 1956.

be redistributed within the month if the total monthly volume of water is greater than the total monthly depletion. If this is not the case, then a secondary disaggregation is used to ensure the depletions can be applied as specified by the planning model in each month. The application presented here had the monthly depletions specified in the planning model. If used independently, other methods could be used to forecast the monthly depletions if depleted flow was the required final product.

When applied, the disaggregation method preserves historical statistics such as minimum, mean, and maximum daily flow, daily flow variance, and lag-1 correlation as well as spell lengths and volumes. The secondary disaggregation negatively impacts the lag-1 correlation, though it still remains very high (greater than .9) with historical natural flows used in the planning model. Additionally, the disaggregation method preserves spell statistics that are especially important in monitoring e-flows.

The method can also be applied with simulated future monthly natural flows that have not been observed in the historical period. The method will produce daily flow sequences based on the historical flow patterns, but new high and low flows can be generated based on the magnitude of the seasonal volume. When used with future climate change data, the number of instances the secondary disaggregation is necessary nearly triples; however, the lag-1 correlation is generally above .9.

In the application described here, the disaggregation is applied to the high flow period of April - July since this is when the critical environmental flows must be met. The method can be extended to generate flows in any and all months as desired. Additionally, it could be spatially extended to disaggregate for multiple nodes with some additional work.

3.2 Hydrologic Year Types

In this section, we describe how hydrologic year typing is used in environmental flow metrics, methods of computing the metrics and issues that arise with nonstationary hydrology. First, the background on hydrologic year typing is presented followed by some examples demonstrating how the choice of year typing can impact the distribution of year types and how the distributions differ under climate change projections. Finally, conclusions and recommendations are drawn.

3.2.1 Background

Hydrologic year typing is a widely used approach to classify current hydrologic conditions in a river basin. Reservoir operations (*Muth et al.*, 2000), required flows (*McAda*, 2003) and water availability (*Department of the Environment, Water, Heritage and the Arts*, 2009) may be modified to help meet environmental flow requirements based on hydrologic conditions. The targeted environmental flow requirements typically vary with hydrologic condition, e.g., (*Muth et al.*, 2000), in order to maintain the natural inter and intra-annual variability in a system (*Poff et al.*, 1997).

Hydrologic year types have been applied or suggested for a number of different river systems and regions, for example: the Sacramento and San Joaquin Rivers in California (*State Water Resources Control Board*, 1995), the Colorado River Basin (*Muth et al.*, 2000; *McAda*, 2003), the Poudre River in Colorado (*Milhous*, 2010), the Snake River in Idaho (*Jager et al.*, 2000), the Patuca River in Honduras (*The Nature Conservancy*, 2007) and Australia (*Department of the Environment, Water, Heritage and the Arts*, 2009). In each case, the application of the year types differs slightly as does the determination of the year type, though the general process is the same: compare the current year's conditions to historical conditions to determine the year type, then meet the corresponding year type's goals. Generally, the goals are analogous in the various applications: if the year is a 'wetter' year then meet higher flow requirements; if it is dryer, meet lower flow requirements. The goals can vary within the year types as well to ensure intra-annual variability, e.g., minimum flow values for several months followed by a specified peak flow for a minimum number of days before returning to another minimum flow value for the remainder of the year in order to resemble a natural hydrograph shape in a snow-melt dominated basin. In application, year types can dictate reservoir operations or diversions. Along with each year type are varying flow targets, where the wetter the year type, the higher the flow targets. The reservoir operations would release more to try and meet high flow targets in wet years and would be allowed to hold back more water in dry years; conversely, diversions would be controlled more in drought years than in wet years. The purpose of having different targets for different year types is to resemble natural, inter-annual variability.

While the goals of all the applications are similar, the comparison to historical conditions varies. In the Sacramento and San Joaquin rivers, the California River Index is computed based on the current year's forecasted and observed inflow volumes combined with the previous year's observed spring inflow volume. The value of the index determines the hydrologic year type, (*State Water Resources Control Board*, 1995). For the Patuca River, the annual flow is compared to the mean historic annual flow. If it is more (less) than one standard deviation above (below) the mean annual flow, then it is considered a 'wet' ('dry') year, otherwise it is a 'normal' year (*The Nature Conservancy*, 2007). Similarly, on the Colorado and Gunnison Rivers, the spring volume at a particular gage is compared to the average spring volume. The current year's percent of average determines the year type, e.g., between 118 and 163% of average is a 'moderately wet' year, while less than 43% of average is a 'dry' year. All in all, on this system there are six hydrologic year types. The percentage of average that corresponds to each of the year types were determined by computing the 10, 30, 50, 70 and 90 % exceedance values based on the hydrologic record of 1937 – 1997 (1958 – 1997) on the Gunnison (Colorado) River (*McAda*, 2003). Finally, on the Green River, the flow targets are based on the current spring volume's exceedance percentage. For this river, the year types have been split into five hydrologic year types based on the 10th, 30th, 70th and 90th exceedance percentiles. In this example, the exceedance values are computed based on the 'hydrologic record'; however, the record is not explicitly defined (*Muth et al.*, 2000).

Based on a review of these studies, the hydrologic record used to compare the current years value to historical values can vary from 1 to n years in length. n can be static, e.g., 1959 – 2000, or always increasing, to include the updated hydrologic record every year (1959 – present). We refer to these as either a static or moving year type threshold. The static year type thresholds are based on a set period and implicitly assume that the selected period adequately represents the hydrologic variability. The moving year type thresholds are modified each year. Since they are based on the hydrologic record up through the present, the exceedance values can change every year as the most recent year's observed values are added to the historic record. This implicitly assumes that more data is useful to continually update the characterization of the hydrologic variability.

Nonstationary climatic conditions can undermine assumption of the hydrologic year typing framework. In the recommendations for the Green River, it is assumed that the hydrology on the Green River will remain largely unaltered in the future (*Muth et al.*, 2000). In the draft environmental impact statement on the Gunnison River (*Bureau of Reclamation*, 2009), which takes into consideration the previously discussed recommendations (*McAda*, 2003), climate change is briefly addressed, though no definitive actions are suggested. It acknowledges that the frequency of some of the year types could increase. *VanRheenen et al.* (2004) show that climate change hydrology would shift the mode of hydrologic year types on the Sacramento - San Joaquin River Basin.

In previous flow recommendation studies, nonstationarity has either not been considered or only briefly acknowledged; in all cases nonstationarity violates the assumptions of the recommendations. To inform future studies that will apply hydrologic year typing schemes, we present here an example of the sensitivities of the distribution of hydrologic year types to the choice of a static or moving year type threshold and how the distributions are affected by a nonstationary climate.

3.2.2 Year Typing Sensitivities to the Historical Record

The main objective of this section is to show that different distributions in year types are achieved by using a moving or static year type threshold. Furthermore, the differences in distributions are much more significant when using climate change projections instead of historical hydrology. To demonstrate these impacts, model results from the wettest and driest traces of both the direct natural flow (DNF) and climate change data sets are presented side-by-side. In the first section the differences between a moving and static year type threshold are shown. The thresholds are the values that break two different hydrologic year types, e.g., what value separates a 'dry' year from a 'moderately dry' year. After presenting the differences in distributions, the overall impacts of the choices are discussed.

The year type for the Green River above Flaming Gorge is used as an example. The year type of the Green River guides Flaming Gorge's operations. The year type is based on the April – July unregulated inflow (no reservoir regulations) into Flaming Gorge Reservoir. In practice operations dependent on the year type begin in mid to late May, thus the year type is based on the forecasted May – July inflows along with the observed April unregulated inflow. In the examples presented, the year types were determined with perfect knowledge of the April – July inflows. The classification is divided into five different hydrologic year types, thus there are four thresholds. The examples compare the year types using the DNF and climate change natural flow data sets.

3.2.2.1 Examples of Differences in Hydrologic Year Type Distributions

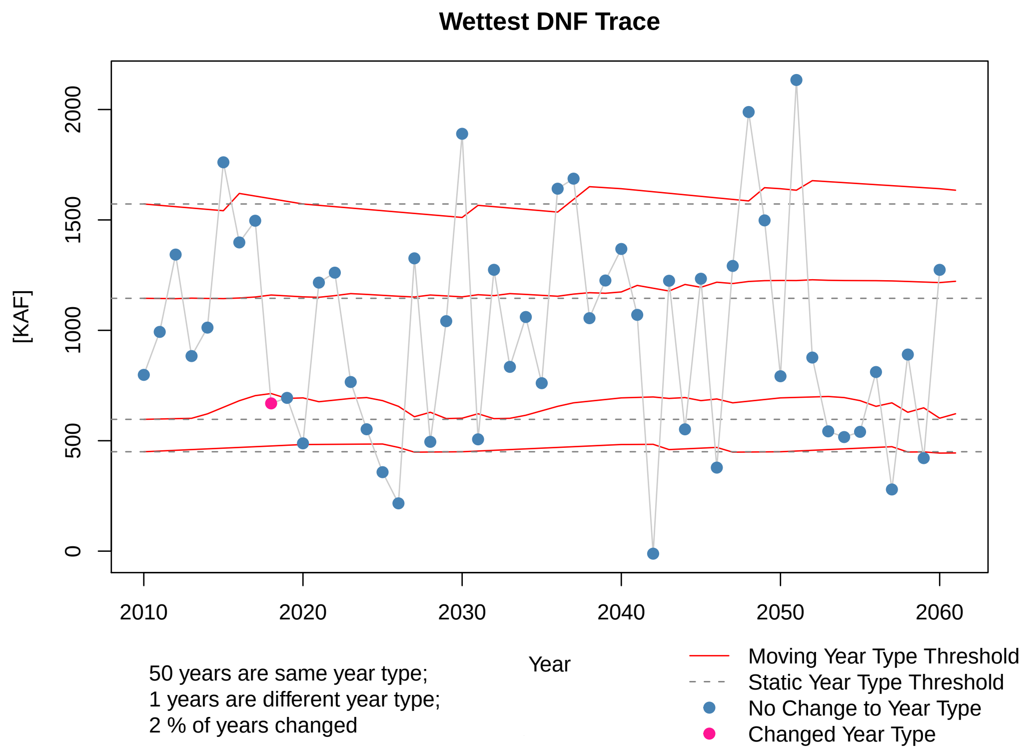
As discussed above, there are two comparisons in the example case. The first shows the difference between a static and moving year type threshold. The second shows the difference between the DNF and climate change flows. To demonstrate these, the "wettest" and "driest" individual traces from the DNF and climate change flows are used. The "wettest" and "driest" traces were identified as the traces with lowest and highest mean annual April – July unregulated inflow through the modeled period. The April – July unregulated inflow was used since it is the value the year types in the example are based on.

Figure 3.17 shows how the four different year type thresholds evolve through time for the wettest DNF and climate change traces. The unregulated inflow for each modeled year is shown and years that have a different year type if a moving threshold is used instead of a static threshold are indicated by a pink circle while those that stay the same are marked by blue circles. The first thing to note in these results is that only one out of the 51 years (2%) from the DNF trace changes year types if a moving threshold is used compared to 12 years (23.5%) in the climate change projected flows. Additionally, while the thresholds do move around in the DNF example, they do not deviate from the static thresholds nearly as much as the moving threshold in the climate change example. This is exemplified by Figure 3.18 which shows the thresholds of both the DNF and climate change cases on the same graph.

Figure 3.19 shows the same evolution of thresholds and the individual years that change classification for the driest trace of the DNF and climate change flows. Again, there are more years that change year type in the climate change example (16 or 31.4%) than in the DNF example (6 or 11.8%). Similarly, the year type thresholds deviate much farther from the static year type thresholds for the climate change example than they do in the DNF example. This is again further highlighted in Figure 3.20.

Finally, Figure 3.21 demonstrates the percentage of years that change year type in each trace for the DNF and climate change flows. It shows that there are typically many more years that change year type in the climate change traces than in the DNF traces. The median percentage of years that change year type when using a moving threshold instead of a static threshold over all traces is nearly three times higher in the climate change flows (17.8%) than in the DNF data (5.9%).

Figure 3.21 shows an interesting feature in the case of the DNF example which warrants further explanation. Notice that the years with the lowest percentage change of year types are clustered in the middle traces: approximately from trace 20 to trace 70. Since the index sequential method (*Ouarda et al.*, 1997)(ISM) is used to create the DNF data, the hydrologic record from 1907 through 2007 is trimmed to contain only 51 years. Once there are less than 51 years the record is repeated or wrapped around to produce a 51 year long trace, e.g., the natural flows from 1957 through 2007 would represent one trace while the natural flows from 1958 through 2007 followed by the natural flow from 1907 would make up the next trace. Since the historic record used to compute static year type thresholds is 1969 through 2009, the middle traces are the traces which contain the least number of years outside of this window. When the thresholds are updated with volumes they have observed before, or values very close to those previously observed, the values of the thresholds do not change as much. For example, the first trace consists of natural flows from years 1908 through 1958, none of which was used to compute the static thresholds. So, each



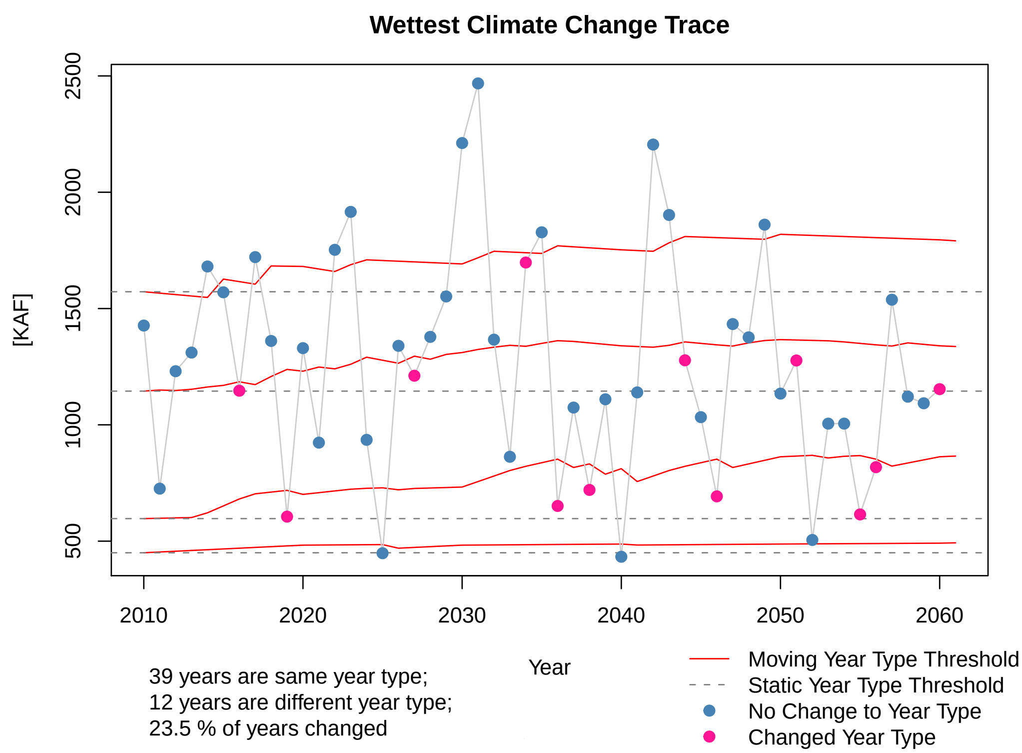


Figure 3.17: The maximum average April - July natural flow trace from the DNF and climate change flows. The moving and static thresholds between year type are shown along with a time series of the modeled April - July unregulated inflow into Flaming Gorge; symbols denote whether the particular year changed classifications based on the moving year type thresholds.

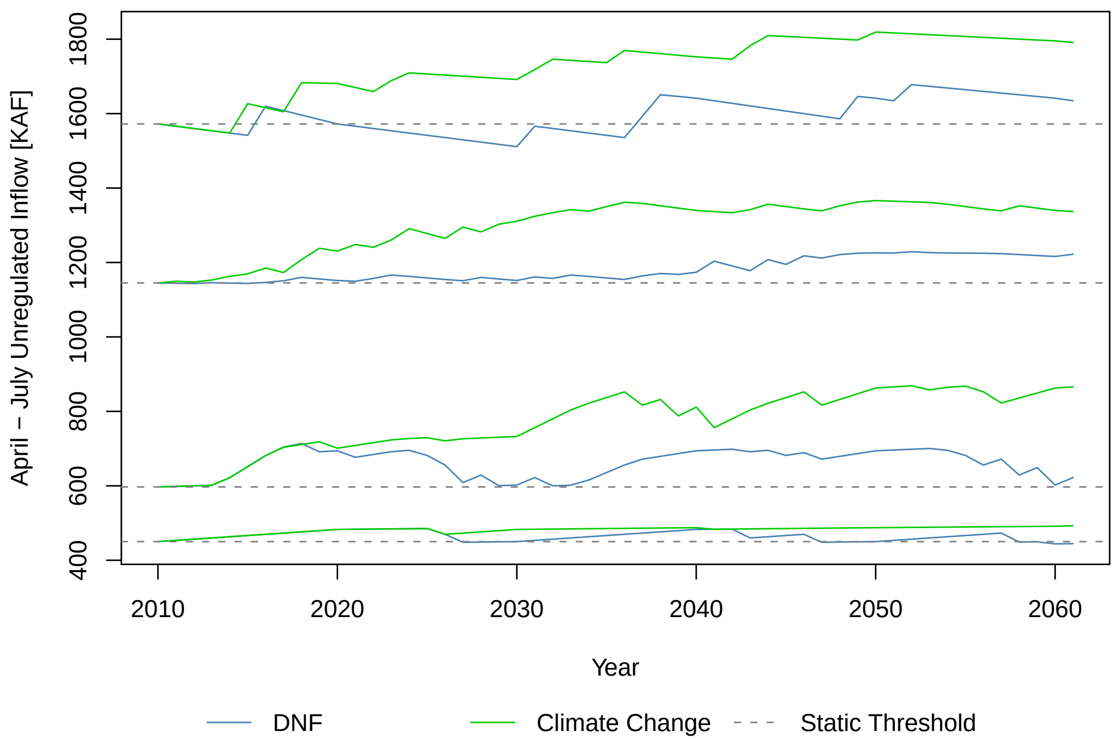
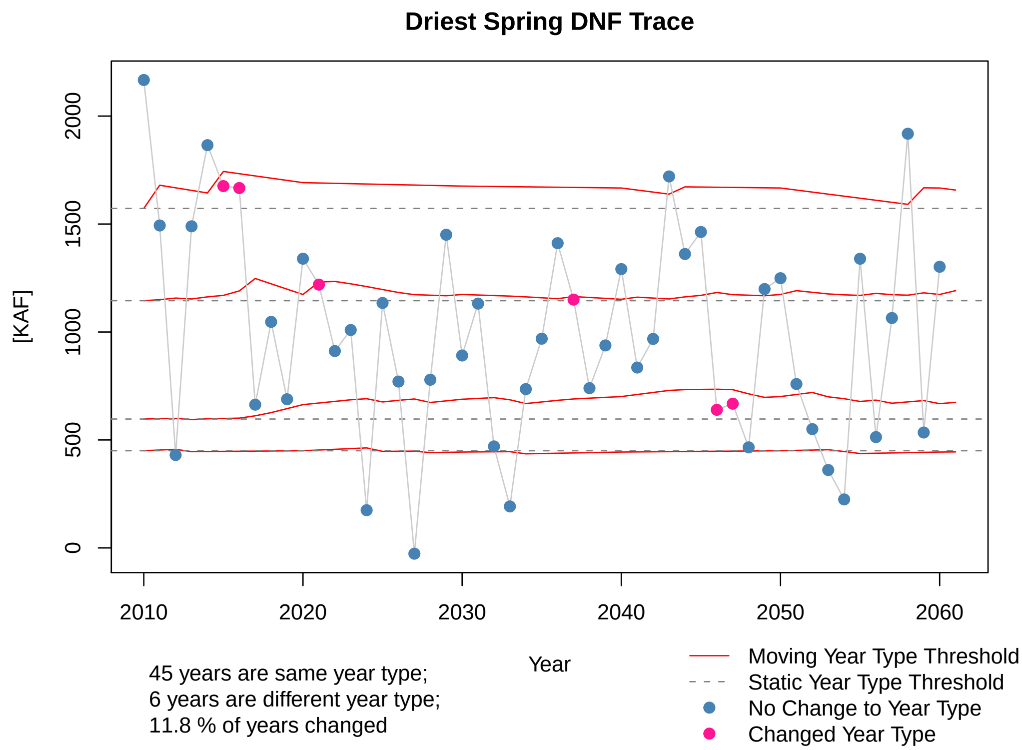


Figure 3.18: The time varying year type thresholds for the wettest trace in the climate change and DNF model runs compared to the static threshold.



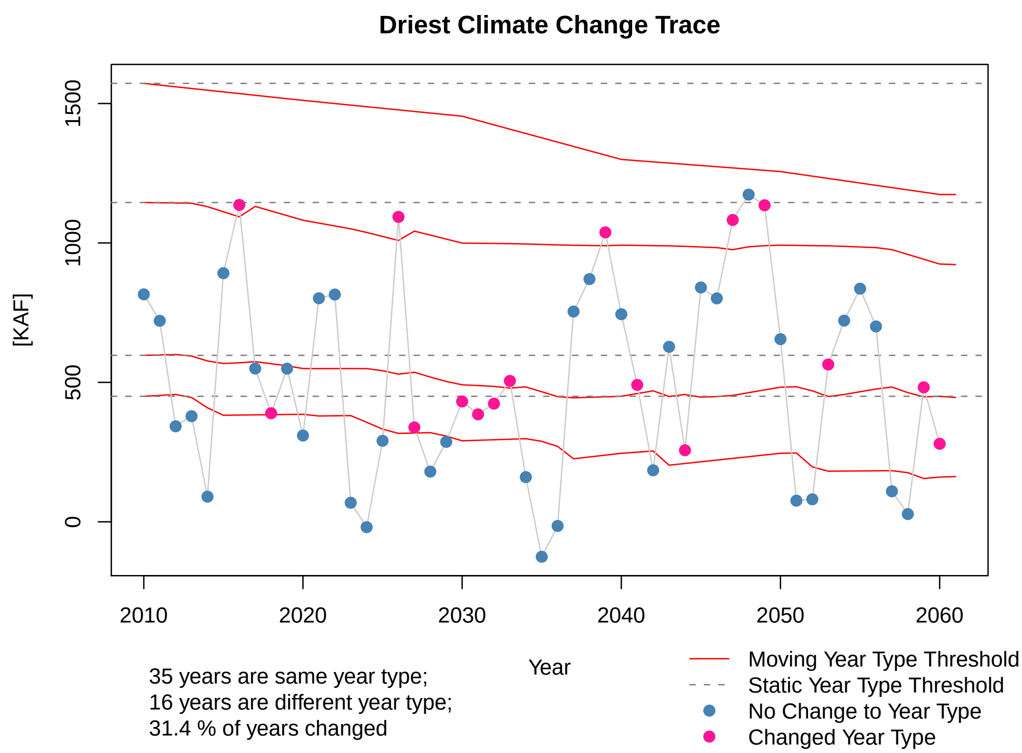


Figure 3.19: The maximum average April - July natural flow trace from the DNF and climate change flows. The moving and static thresholds between year type are shown along with a time series of the modeled April - July unregulated inflow into Flaming Gorge; symbols denote whether the particular year changed classifications based on the moving year type thresholds.

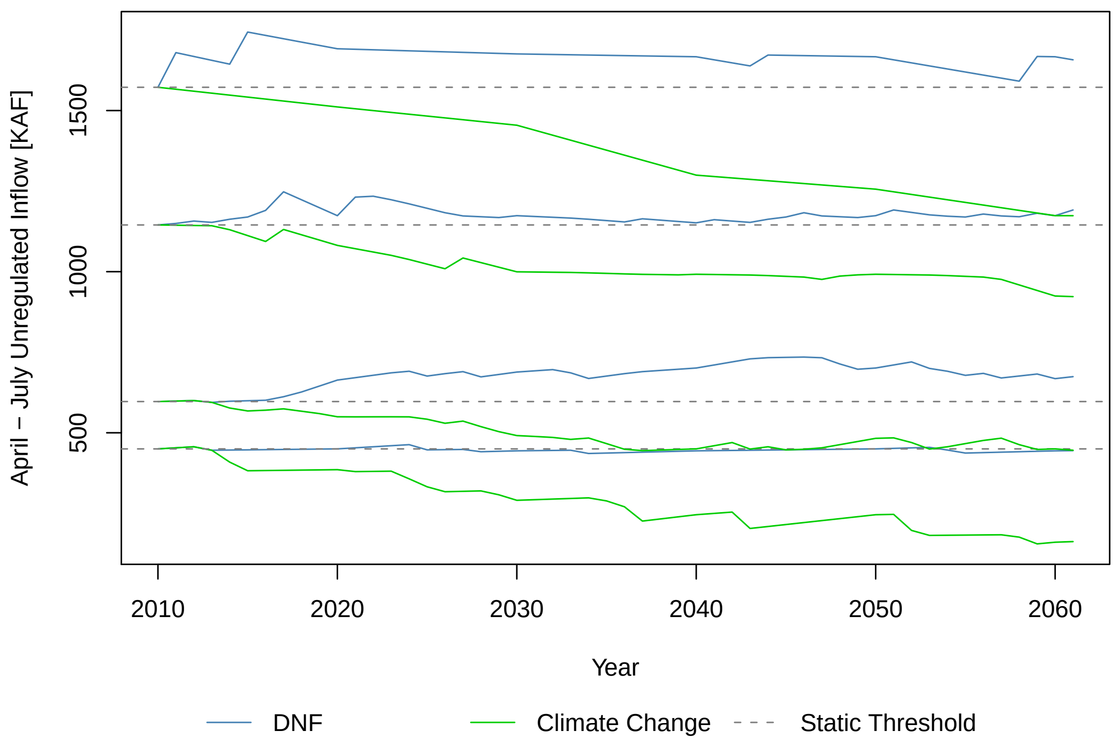


Figure 3.20: The time varying year type thresholds for the driest trace in the climate change and DNF model runs compared to the static threshold.

time the record is updated, it is updated with a value that is potentially higher or lower than any observed value. Thus when a range of unobserved values are consecutively seen, they will shift the distribution (and the thresholds) more than a string of values that are close to the observed values.

This is similar to the explanation of why the thresholds shift more in the climate change example than in the DNF example. Since many of the climate change flows have not been observed before and their values are higher/lower than any observed, they can shift the distribution more, especially when the unobserved values are consecutive. Additionally, the year typing thresholds are more sensitive to a projection with a lower variance than to one with a higher variance. If the projection is on average wetter than the historical period but has a lower variance, it will pull the thresholds up more than if the projection is wetter but has a high variance. This particular example is demonstrated in Figure 3.22 which shows that the trace with the lower variance shifts the year type thresholds more than the trace with the higher variance. For this example, two traces were selected that had very similar median spring volumes, but that had a large difference in variance. The selected traces were within the wettest 15% of traces, so it is expected that the thresholds are pulled up; however, the difference in variance helps explain why some of the thresholds are pulled up more by one trace than the other. In particular, the threshold between dry and moderately dry years stays nearly the same as the static threshold for the high variability trace while it is pulled up for the low variability trace. Since the high variability trace still has some year types with low spring volumes, this threshold stays lower. This demonstrates that the year typing thresholds are particularly sensitive to a hydrology with a low variance and an average volume greater or less than the historical average value.

In addition to examining the number of years that change year type, it is also important to examine the distribution of the year types since years can change year types in such a way that the overall distribution of year types is not significantly affected. The exceedance values for this system are defined in such a way that the year types have the following probabilities of occurring:

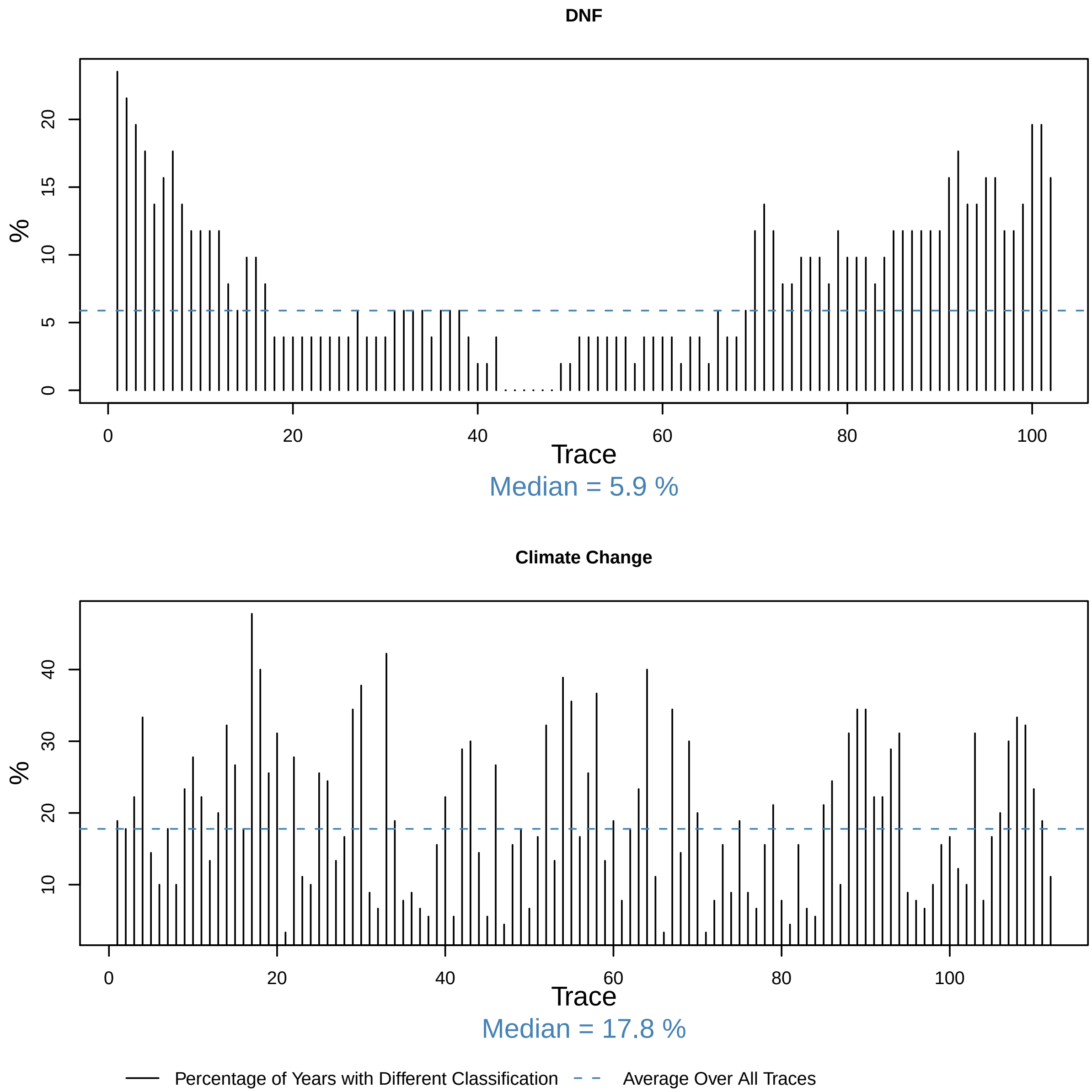


Figure 3.21: The percentage of years in each trace that changed year types if a moving year type threshold was used instead of a static year type threshold shown for the DNF and climate change runs.

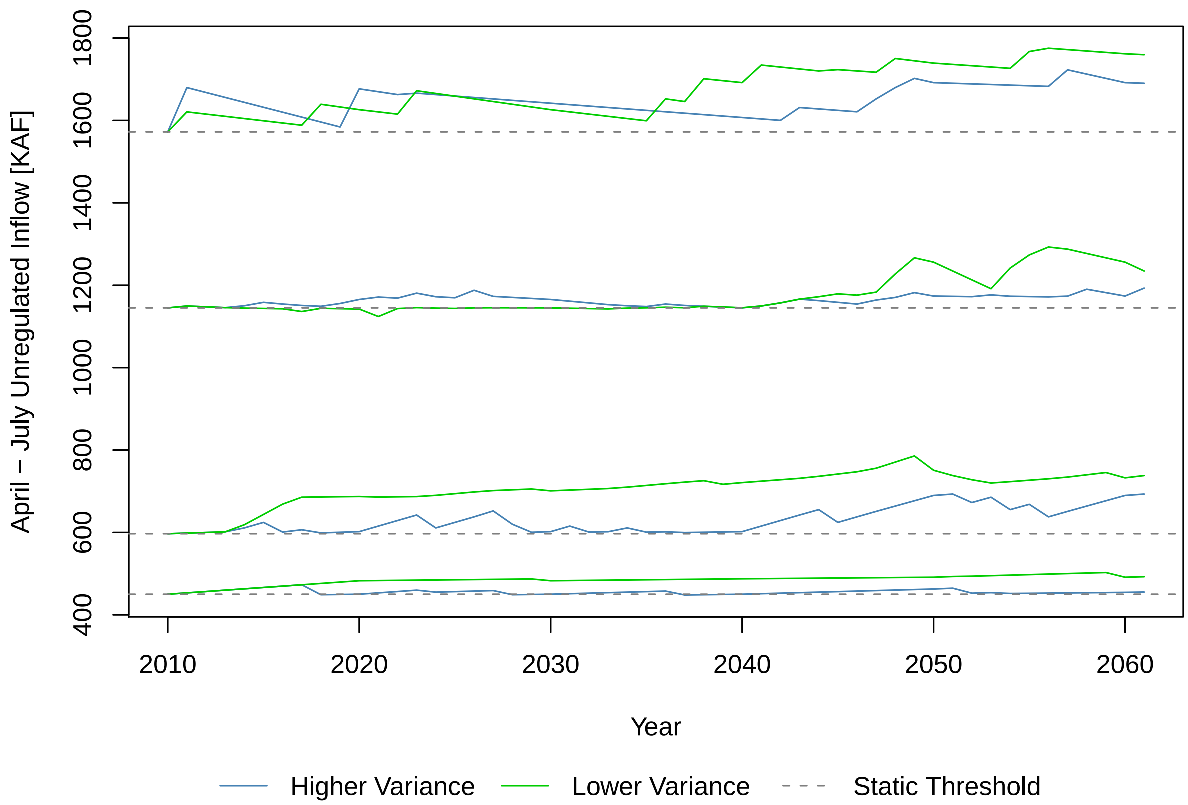
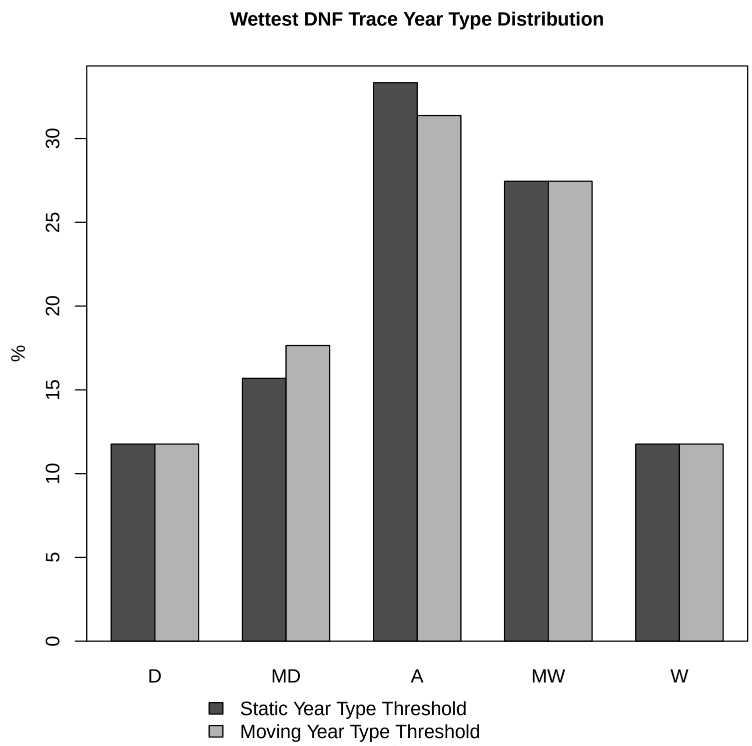


Figure 3.22: Comparison of year type thresholds for two traces with similar median spring volumes but with different variances in spring volumes.

Year Type	Exceedance Probability [%]	Probability of Occurring [%]
Dry	90 - 100	10
Moderately Dry	70 - 90	20
Average	30 - 70	40
Moderately Wet	10 - 40	20
Wet	0 - 10	10

Figure 3.23 shows the distribution of year types with static and moving year type thresholds for the wettest trace of both the DNF and climate change examples. Again, we can see that in the DNF case, there is not a large difference; as described above only one year changed year types, so the distributions for the static and moving year type thresholds are similar. This is not the case for the climate change trace. Since this example uses the wettest trace found in the climate change flow projections, the figure shows that when using a static year type threshold, there are very few dry and moderately dry years. There are, however, a very large number of moderately wet and wet years. When using a moving year type threshold, the figure shows that there are an increased number of moderately dry years, while the number of average, moderately wet and wet years decreases. This shows that the moving year type threshold tries to shift the distribution to be similar to the expected occurrence probabilities, i.e., 10% dry years, 20% moderately dry years, 40% average years etc. That is, the moving threshold tries to reduce the number of wet and moderately wet years since there is a disproportional number, and increase the moderately dry and dry years. Even with the threshold between moderately dry and dry years increasing, years with very low flows do not occur, which is why the number of dry years does not change between the static and moving thresholds.

The shift works similarly for the driest trace from both data sets, as shown in Figure 3.24. Again, in the DNF trace, there is little difference in the distribution of year types from the static and moving year type thresholds. Even though 6 years actually changed year types, the distribution remains largely the same. When the static threshold is used for the driest climate change trace,



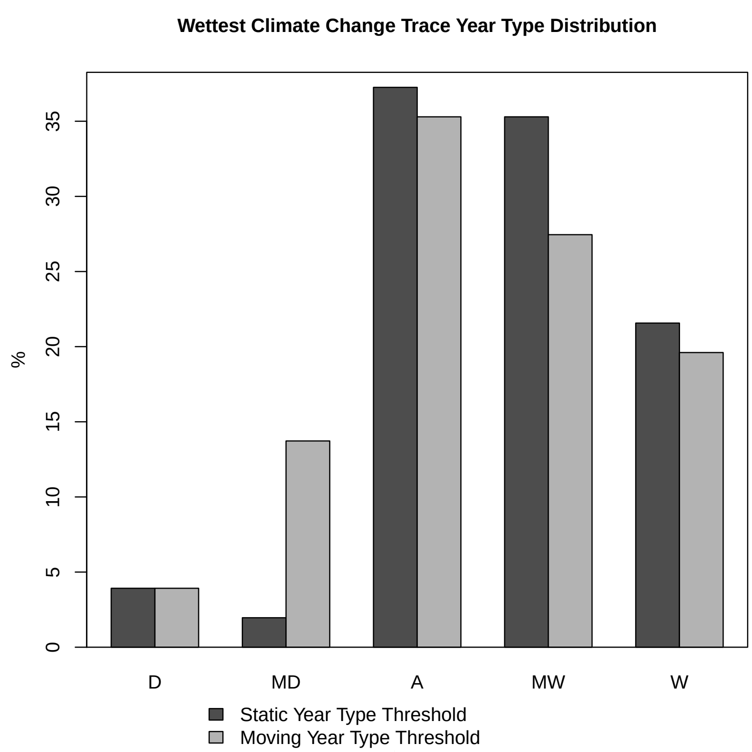


Figure 3.23: Distribution of hydrologic year types for the maximum average April - July natural flow trace from the DNF and climate change flows with a static vs. moving year type threshold where D, MD, A, MW and W correspond to dry, moderately dry, average, moderately wet and wet year types.

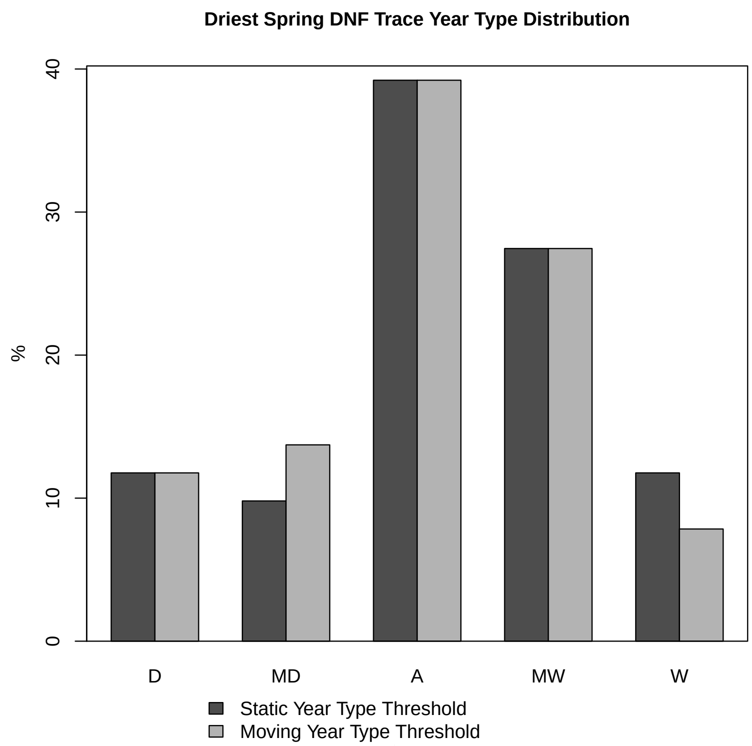
there is a very skewed distribution, in which the majority of years are dry years and no wet years occur. The use of the moving year type threshold does not help produce any wet year types, though the number of moderately wet years is greatly increased and the number of dry years is decreased substantially.

3.2.2.2 Implications of Threshold Choices

The examples above show that the distributions of year types can be noticeably different depending on whether a moving threshold or static threshold is used to determine hydrologic year types, especially in the case of climate change projected flows. In many cases the targeted e-flows are dependent on the year type classification, thus a change in the year type distributions would impact flow in the river. It is clear that a change in the year type distributions would impact the inter-annual variability of the e-flow targets. Presumably, the different distributions would have an ecological impact, though it is less clear what type of impact it would have. While research has concluded that there are typically negative ecological impacts when flows are departed from the natural flows in the system, there is no explicit quantitative equation that can predict the ecological implications (*Poff and Zimmerman*, 2010). The underlying assumption when requiring that flows occur with historical variability is that the ecosystems have adapted to the historical conditions and thus the variability should be observed in the future (*Booth et al.*, 2006); however, in the presence of climate change and nonstationary flows, the mean flow is changing and there is increased variability. Since the health of the ecosystem is tied to the unaltered historical flows, the measure of ecological health is undefined for the future with a nonstationary climate.

The impacts on the target flows are also dependent on what future is realized. The examples presented here were the driest and wettest traces from the DNF and climate change projected flows. In the case of the climate change projections, these are each one plausible future scenario and do not have an associated probability of occurrence. The choice of moving or static thresholds would have different impacts if the wettest trace was realized than if the driest trace was realized.

While the exact impacts to the ecosystem are not known, the choice of a moving or static



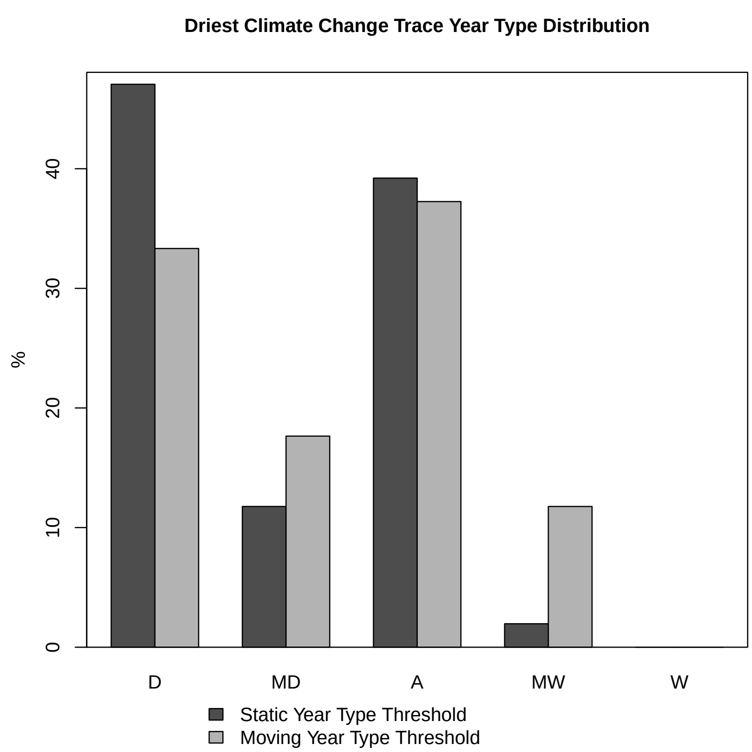


Figure 3.24: Distribution of hydrologic year types for the minimum average April - July natural flow trace from the DNF and climate change flows with a static vs. moving year type threshold where D, MD, A, MW and W correspond to dry, moderately dry, average, moderately wet and wet year types.

year type threshold can impact reservoir storages and thus water availability. Figure 3.25 shows the end-of-July pool elevation for the reservoir used to meet the e-flow requirements in this example. In it, we can see that the 90th percentile elevations are nearly the same and there are small differences ($\approx$ 1 foot) in the median elevations. However, the differences in the 10th percentile elevations are much more significant ($\approx$ 5-10 feet). This is probably due to the drier traces that use the moving year type threshold. When the moving threshold is used, it pulls down the thresholds for a wetter year type, so the wetter year types occurs more often. Since the traces are drier, the storage of the reservoir is used to help meet the wetter year targets.

The example does not take into consideration the ability to actually meet the year type flow requirements which is an entire different issue. Take for example the driest climate change trace from above. When using the moving year type threshold, the number of moderately wet years was drastically increased. Even though the year is classified as a moderately wet year, it could be impossible to meet the moderately wet flow targets depending on the conditions in the system.

3.2.3 Year Types with a Nonstationary Climate

Overall, this example demonstrates that there are some issues with hydrologic year typing, especially with a nonstationary climate. While the overall goal of year typing is to replicate historical, natural variability it is uncertain if the variability should be replicated in the future under nonstationary climatic conditions. While it is acknowledged that the distributions could shift in the future due to climate change (*VanRheenen et al.*, 2004; *Booth et al.*, 2006; *Bureau of Reclamation*, 2009), no conclusions are made as to how to address this. *Bureau of Reclamation* (2009) uses the distributions to sustain endangered fish species and concludes that if the shift in distributions would negatively impact the goals of the EIS, then Reclamation should reconsult with the Fish and Wildlife Service. Regardless, the demonstrated shifts in year types raise several questions. Are a disproportionate number of wet years and no dry years beneficial or should the system be operated to force the dry year conditions if the climatic conditions are overall much wetter than historical conditions? Similarly, should the system be forced to meet high flow targets based on

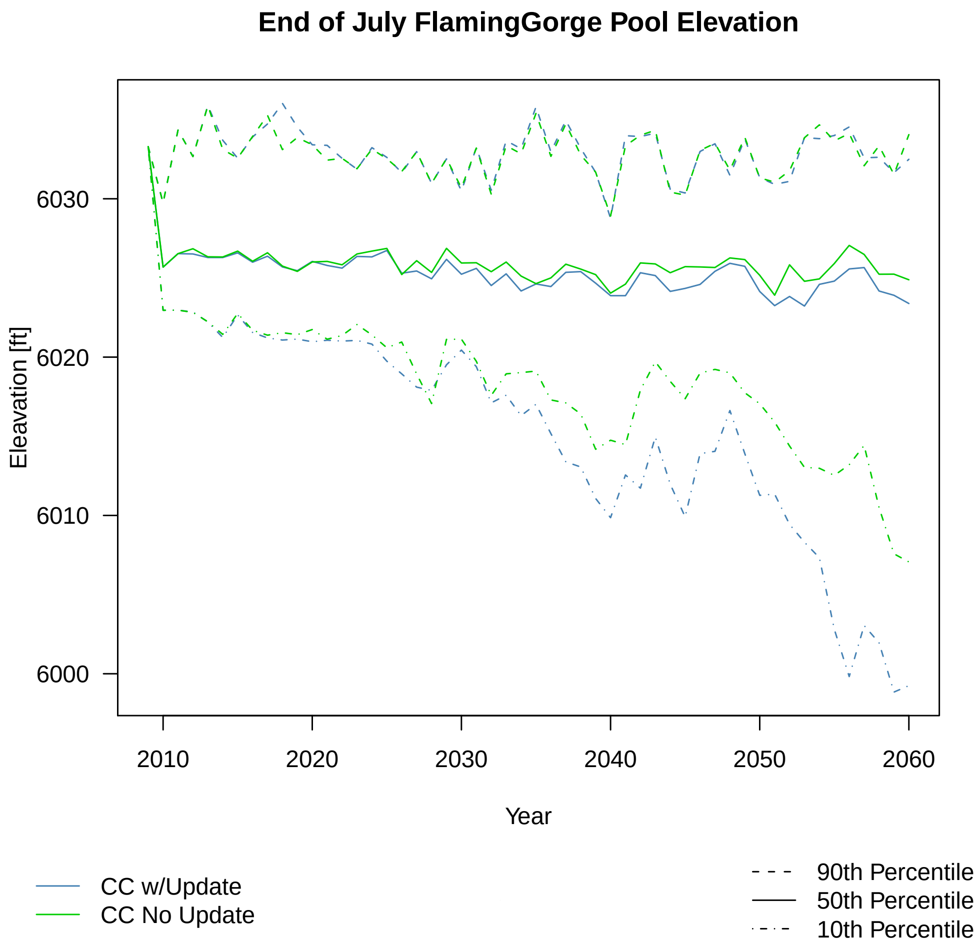


Figure 3.25: The 10th, 50th and 90th percentiles for the end of July pool elevation at Flaming Gorge comparing the impacts of using a moving or static year type threshold.

historical conditions, if the climatic conditions are such that these historical high flows would not be met even without human impacts on the system? While the example raises more questions than it answers, it points to specific questions that need to be addressed in future ecological research. It also illustrates that future environmental flow specifications should carefully consider the choice of using a moving or static year type threshold.

3.2.4 Conclusion

The examples presented demonstrate two important sensitivities of hydrologic year typing: 1) The distributions of year types are different with climate change flow projections than with historical flows; 2) Using a static or a moving year type threshold can make a significant difference in the distributions of year types, especially under climate change flow projections. Since e-flow targets are dependent on the year type classification, the distribution of year types directly impacts the storage of a reservoir used to meet the flow requirements. However, it is unclear to what degree, if any, the shift in distributions would have on the ecological health of the river.

Furthermore, the year type thresholds are more sensitive to lower variability than to higher variability. Since high variability traces encompass a wider variety of flows, the year type thresholds are more likely to remain close to the static year type thresholds. The year type thresholds change the most in traces with low variability and a mean annual volume that differs greatly from the historical mean.

In this study, the moving year type threshold is used. This does not indicate that we think the choice of a moving threshold is necessarily better or worse than the static year type threshold. In cases where the use of a static threshold is used, it is specifically indicated.

3.3 Reservoir Releases

Another important area to address in the process of modeling environmental flow requirements is reservoir releases for e-flow requirements. In some cases these can be adequately represented at the monthly timestep, while in others they must be addressed at sub-monthly time scales. This section discusses the process of incorporating sub-monthly requirements into a monthly model. First, a review of the existing methods and introduction to the system is presented. The implementation is then summarized and finally, results are presented.

3.3.1 Introduction

Most reservoirs are operated to meet multiple objectives such as flood control, recreation, hydropower, and agricultural and municipal water supply. Operations are thus constrained and can be very complex. Furthermore, environmental flow requirements are becoming more common in recent years and place another constraint on operations. As such, reservoir operating rules now need to include environmental flow requirements and constraints. Initially, most environmental flow requirements were specified as a static minimum flow that had to be met. Now, many environmental constraints are more complex: they specify time-varying requirements which include minimum flows and flood pulses with magnitudes and durations to resemble a more natural hydrograph (*Arthington et al.*, 2006). In these cases, they are specified at the daily to weekly time-scale and in some cases even extend to hourly fluctuations.

Numerous previous studies use optimization to determine optimal reservoir operations, mainly in regards to hydropower. *Jager and Smith* (2008) reviewed 47 of these studies and found that 29 considered environmental flow requirements in the optimization problem. Of the 29, 14 used only a minimum flow requirement as the environmental constraint. Additionally, these studies generally focus on optimizing daily reservoir operations, rather than on addressing long-term impacts. The models operated at the daily timestep, which allows most e-flow requirements to be directly incorporated into the model. E-flow requirements were included in several studies using long-term planning models, though they were included only as a minimum monthly flow requirement (*Payne et al.*, 2004) and as critical, minimum annual volume (*Jones and Page*, 2001). As environmental constraints are often times more complex than a minimum flow requirement and in order to model them in a long-term planning model, this section describes the process of incorporating sub-monthly specified reservoir operations into a monthly planning model.

3.3.1.1 Navajo and Flaming Gorge Operations

Within the past several decades, a process was undertaken to address reservoir operations on several Colorado River Storage Project reservoirs in order to help endangered fish populations in compliance with the Endangered Species Act (ESA). The general process is described here, as it was applied to Navajo and Flaming Gorge reservoirs.

Initially, for both the Green River and the San Juan River, flow recommendation studies were published which specified certain flows that would help the endangered fish species on the rivers (*Holden*, 1999; *Muth et al.*, 2000). These documents were the conclusions of biological studies on the respective rivers. In them, the specific needs of the fish are discussed and certain base and peak flows were identified which would help sustain and develop the fish populations. This was followed in each of the basins by a NEPA Environmental Impact Statement (EIS) process that studied several alternatives for implementing flow recommendations into the reservoir operations while still meeting the designated purposes of the reservoirs. Additionally, the EIS process included public review and stake-holder input in order to try to find a solution that was acceptable to all parties involved. The Final EISs were published by Reclamation (*Bureau of Reclamation*, 2005, 2006b) with a designated preferred alternative. After further review and public comment, Reclamation accepted the preferred alternatives for both Flaming Gorge and Navajo, and made these the official operating procedures in Records of Decision (ROD) (*Bureau of Reclamation*, 2006a,c). By signing the RODs, Reclamation agreed to operate the reservoirs to meet certain in-stream flow (or e-flow) requirements.

The Navajo ROD (*Bureau of Reclamation*, 2006c), dictates that Navajo operate to meet two general requirements: the peak flow requirements and the base flow requirements. The peak flow requirements are measured at the USGS gage on the San Juan River near Bluff, Utah (Figure 3.26). The peak flows are expressed in terms of the number of days that a certain flow should be maintained, and how often the requirement should be met. Since Navajo's peak release is 5,000 cfs and two of the four peak release requirements are for flows greater than 5,000 cfs, the requirements rely on tributary flows from the Animas, La Plata and Mancos Rivers to help meet the peak requirements. The operations of Navajo utilize four standard peak release patterns, each with a different number of days at 5,000 cfs, to help meet the requirements at Bluff. The peak release pattern is selected based on which peak release pattern will result in a September storage closest to the desired storage target. The ROD states that the mean weekly baseflow must be within 500 to 1,000 cfs using an average of three of the four downstream gages. Below the San Juan and Animas confluence there are four gages (in upstream to downstream order): the San Juan near Farmington, Shiprock, the Four Corners and Bluff, Utah (see Figure 3.26). To monitor the baseflow requirement a seven day average flow rate is computed for the three most upstream and the three most downstream gages; the lower of the two averages is compared to the 500 – 1,000 cfs range to determine if the requirement is met.

The Flaming Gorge ROD (*Bureau of Reclamation*, 2006a) also specifies that Flaming Gorge operate to meet both baseflow and peak flow requirements at several downstream locations. Hydrologic year types (Section 3.2) are used to classify the hydrologic conditions in the basin. Depending on the hydrologic conditions, different downstream flows are required, thus the operations of Flaming Gorge are different depending on the year type. Downstream flow requirements are specified for gages at the Green River near Greendale, Jensen and Green River, Utah. The Greendale gage is directly downstream of Flaming Gorge reservoir, the Jensen gage is downstream of the Green River and Yampa River confluence (both shown in Figure 3.27) and the Green River, Utah gage is downstream of the Duchesne and Green and White and Green confluences. The requirements are assumed to be met at Green River, Utah if they are met at Jensen, so the Green River, Utah gage is not considered in this study. The releases from Flaming Gorge are supplemented with the Yampa River flows to help meet the requirements at Jensen. The hydrologic year types on the Green and Yampa Rivers determine Flaming Gorge operations. The target requirements are based on the Green River year type; however, the conditions on the Yampa River are used to fine tune Flaming Gorge operations, i.e., the number of days days at peak or bypass release. The base releases are set after the spring peak period for the remainder of the year and the beginning

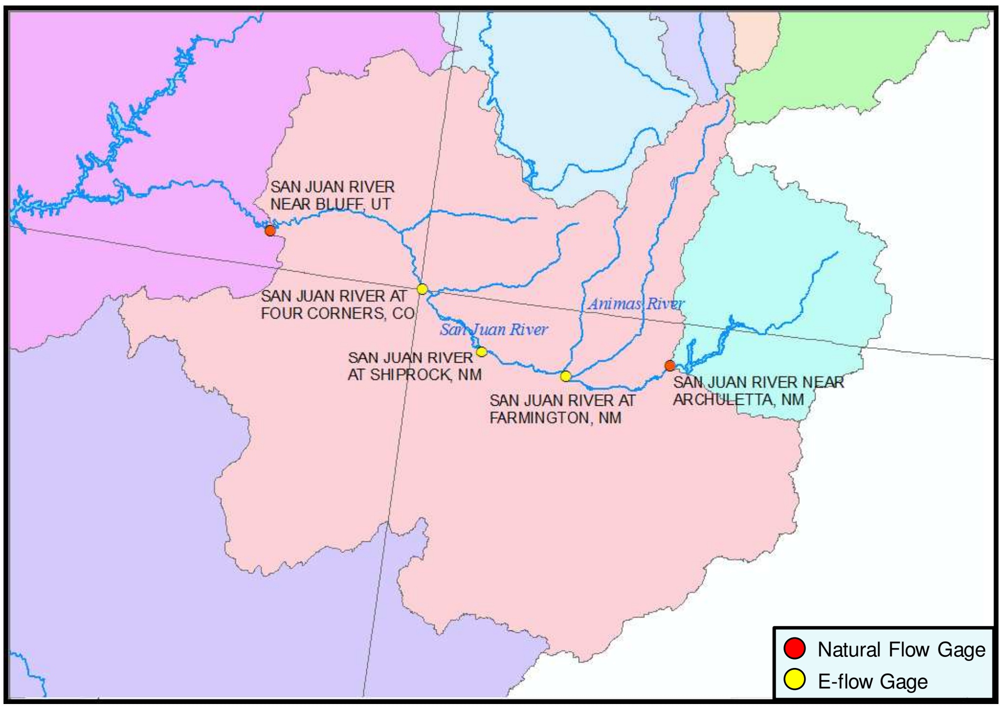


Figure 3.26: Map of the San Juan Basin with natural flow nodes and basins shown, as well as all gages relevant to monitoring e-flows.

of the next year, e.g., August – December and January – February. Each hydrologic year type has an acceptable range of base releases from Flaming Gorge. The magnitude of the releases within the range is determined based on a May 1 target storage. The constant base release for August – February that results in Flaming Gorge having a storage closest to the storage target is used, though it cannot be higher or lower than the allowable range. The releases in March and April can vary to ensure the May 1 target storage is met as long as the releases are not less than 800 cfs.

3.3.1.2 Official CRSS Operations

As of this date, the official version of CRSS reflects the operations of Flaming Gorge and Navajo before the RODs changed the operating rules. In the model, the reservoirs' releases are generally set by a rule curve, i.e., set to meet pre-determined storage levels depending on the month. Additionally, both reservoirs increase releases to help meet several downstream demands when necessary. While this representation does include a minimum release from the reservoir, it does not accurately represent the new operating procedure of the reservoirs. So, in order to assess the long-term reliability of e-flows, first, the operations of the reservoirs in the model needed to be updated. This process includes determining how to represent sub-monthly requirements, e.g., 7 days at 18,600 cfs, in a monthly timestep model.

In the remainder of this section, the process of modeling the new ROD operations of the two reservoirs is described. The main assumptions going into the new operations are discussed and modeled daily flows are compared to actual daily flows. Then, the rules are further validated by comparing the monthly releases with historic monthly releases. Finally, the new monthly releases are compared to the previous operating procedure's monthly releases from CRSS.

3.3.2 Implementation

In this section, the overall process of updating the model to reflect the RODs (*Bureau of Reclamation*, 2006a,c) is described. Since the model is implemented in RiverWare (*Zagona et al.*, 2001), the reservoir operations are specified by a ruleset which dictates how the reservoir should oper-

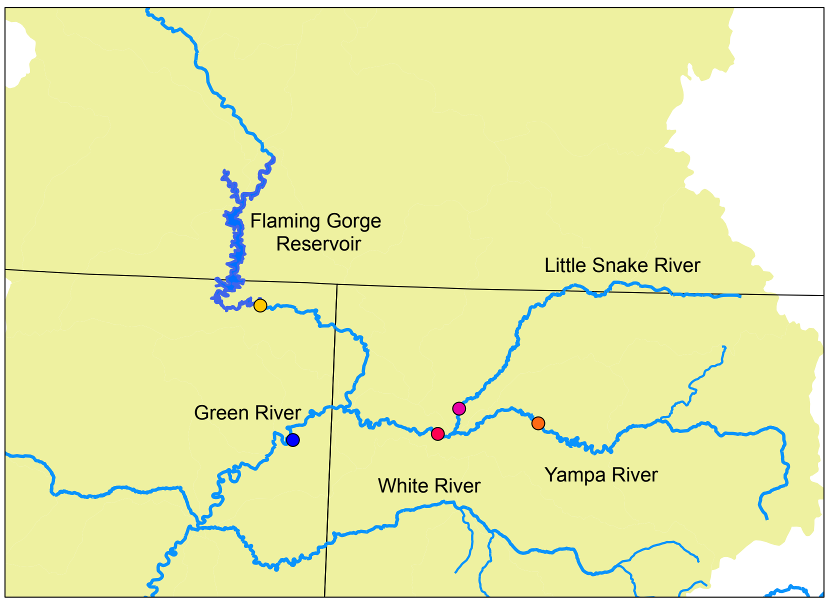


Figure 3.27: Map of the Yampa and Green Rivers, gages are represented by colored circles as follows: yellow = Green near Greendale; blue = Green near Jensen; orange = Yampa near Maybell; purple = Little Snake near Lily; red = Yampa near Deerlodge.

ate based on user specified logic, constraints and parameters. In this process, it is the rulesets of Flaming Gorge and Navajo that were updated to move away from the rule curve based operations and towards a policy which reflects the respective ROD. While specifics in operations differ, the process was similar for both Flaming Gorge and Navajo. First a general description of the process is presented; some of the differences between the Navajo and Flaming Gorge implementations are addressed in the end. The process described below was undertaken jointly with Cameron Bracken under the development of Reclamation's new Midterm Probabilistic Operations Model as part of a Cooperative Agreement between the University of Colorado - CADSWES and the Bureau of Reclamation. The approaches taken by Bracken on Flaming Gorge's rules was similar to the approach developed as part of this research on Navajo's rules, with most differences relating to operational differences between the reservoirs.

For both reservoirs, the operations specified by the RODs can generally be broken up into two periods: the baseflow period and the spring peak flow operations. During the baseflow period, a minimum flow threshold or window of steady flow values is specified, e.g., minimum flow of 250 cfs or steady base flow over 6 months between 1,000 and 1,150 cfs. During the peak flow period the specifications are more complicated. They generally prescribe a certain number of days at or above a threshold, e.g., 7 days above 5,000 cfs. In conjunction with the specified number of days at the threshold, they also include a ramp-up (ramp-down) period from (to) the baseflow to (from) the peak flow which can have restrictions on the daily rate of change. The baseflow periods can be reasonably represented in a monthly timestep model by setting the outflow of the reservoir, which represents the average monthly release, to the required baseflow. It is assumed that if the average monthly release is 250 cfs, then the average flow requirement of 250 cfs is met over that month. Therefore, the remainder of the section focuses on the peak flow period, since this is the area which has obvious temporal scale issues.

In addition to the assumption that the average monthly release represents the baseflow, an additional assumption was necessary for the San Juan requirements. The San Juan baseflows are supposed to be measured using four downstream gages (discussed in Section 3.3.1.1). In the

Research Model, only the Bluff gage is a natural flow node and thus inherently present in the model (see Figure 2.2). The natural flows above Bluff contain the tributary flows of the Animas, La Plata and Mancos rivers, as well as several more intermittent streams. In order to monitor flows at any of the gages besides the Bluff gage, it would be necessary to separate the natural flows above Bluff into the different tributary flows, which is time consuming and difficult. Additionally, several users represent aggregated demands for the entire area below Navajo, thus the demands would also need to be separated for the individual tributaries and reaches on the San Juan between the gages. Rather than separate the natural flows and demands above Bluff, it was assumed that since in the model Bluff would have the lowest flow value since it is the farthest downstream gage, the baseflow requirement could be adequately monitored at Bluff, i.e., if the baseflow is above the minimum flow requirement at the farthest downstream gage, it is presumably higher at the three upstream gages.

The aim of incorporating the sub-monthly requirements into a monthly planning model is to model the 'typical' operations. The rules must realistically represent operations at the monthly timestep, as well as the sub-monthly requirements. The new rules leave out the exceptions and special circumstances with which operators deal, e.g., pulse flow requests and adaptive management decisions, though procedures for such things as dam protection releases and drought year operations are still included.

In order to understand exactly how the reservoirs are operated, the process involved direct contact with the respective operators. Through many discussions with the operators, outlines of the operating rules were formed which represent a priority based set of rules that prescribe how the reservoirs are operated in practice. The rule outlines for Flaming Gorge and Navajo are presented in Appendix B and C, respectively. The outlines were used as a basis for the new rules and details were added to them as they were implemented.

In order to represent daily release requirements, including ramp-up and ramp-down periods, we sum up the daily releases over one month, and use this as the monthly release volume. The operations were split up into different periods (shown in Figure 3.28), e.g., ramp-up, peak

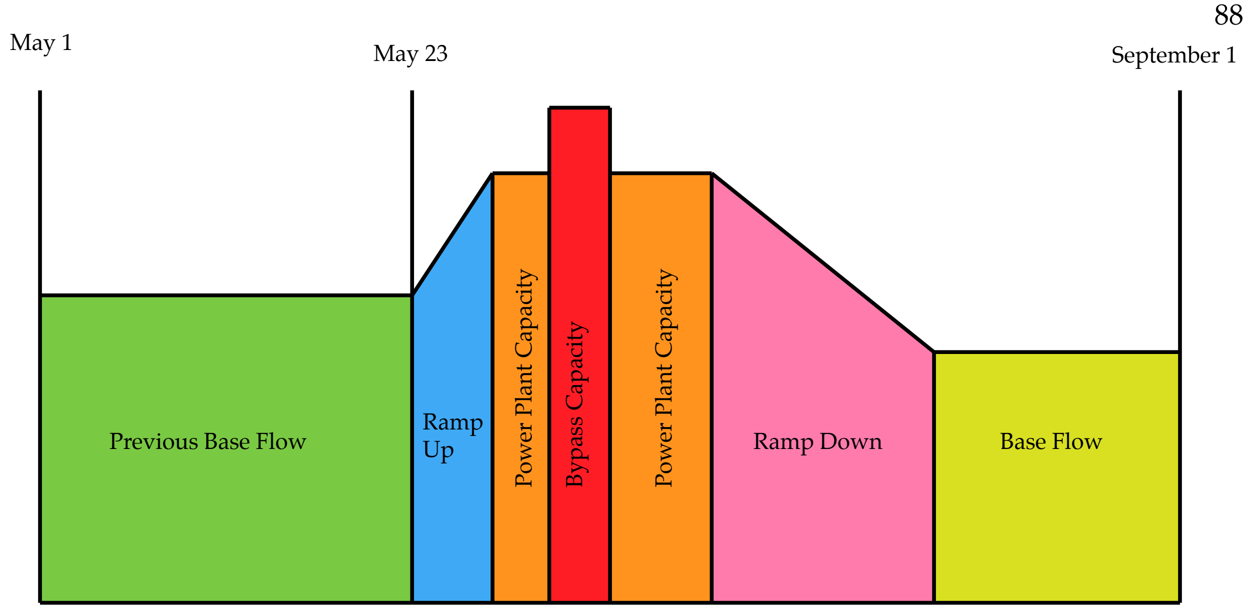


Figure 3.28: Example of how reservoir releases were split into different categories.

release, baseflow, etc. While the idea is simple enough, many issues were addressed in the implementation. For example, the ramp-up/down periods are not constrained to be within one month, the number of days at peak flow are not always the same and in the case of Flaming Gorge, there are certain cases when a bypass release is needed in addition to the peak release.

One major assumption that had to be made was in regards to the timing of the peak releases. For Flaming Gorge, the peak releases are specified to occur at the same time as the peak flows in the Yampa River (*Bureau of Reclamation*, 2005) — a tributary to the Green River below Flaming Gorge — and for Navajo the peak releases are supposed to be within five days of May 31 (*Bureau of Reclamation*, 2006b). Both of these specifications allow for some variations in when the peak flows begin and end. Rather than allowing for the peak dates to change from year-to-year, assumptions were made for each reservoir on when operations would begin ramping up to peak release levels. Flaming Gorge was assumed to begin ramping up in late May to correspond with the historical average peak date. Navajo was assumed to always use a 'standard' release schedule; a further explanation of the standard release schedules is provided below. The flexibility in the timing of the peak releases is used to help match the reservoir's peak release with a downstream tributary's peak flow period. Rather than vary the peak release period from the reservoir which would complicate the rules, the disaggregated daily flows from the downstream tributary are shifted to peak at the expected time of the reservoir peak release. The disaggregation technique is used as described in Section 3.1. Then the disaggregated daily flows are shifted so the peak release from the reservoir corresponds with the peak daily disaggregated flows. Essentially, this assumes that the operators will be able to match the peak releases from the tributaries. This allows for slightly less complex rules though the monthly release patterns from the reservoir can be slightly impacted.

Navajo has four standard peak release patterns which act as starting points for each year's peak release level. Each pattern stays at the peak release for a different number of days; the choice of which pattern to use is made based on which pattern will result in the reservoir being closest to the end-of-September storage target for the reservoir. In a given year, the release patterns are modified to avoid changing release values during weekends and holidays and the timing can shift within five days of May 31 as allowed by the ROD. In the model rules, Navajo uses one of the standard peak release patterns in most cases, thus the ramp-up date is fixed as are the number of days at the peak release. This allows for a fairly simple rule that sums up the standard peak release patterns for the majority of years. However, there are some exceptions which complicate matters. The greatest flexibility in the peak release patterns is in extremely wet years; the pattern which releases the most water can have its duration lengthened both earlier and later in the year to release more water. The number of days that the pattern can be extended either earlier or later is not defined a priori; depending on the reservoir conditions, the number of days the peak release is extended is computed in order to meet the September storage target. Additionally, the release that is extended is not always the peak release. If the releases are extended earlier into the year, any release from 2,000 cfs to the peak release in increments of 500 cfs can be extended earlier into the year. As such, the ramp-up date can change and in this case can be any time from March to May. The rules that were developed are flexible enough to account for the shifting in ramp-up and ramp-down dates and consider the additional days at higher releases. So, while in most years the computation of the monthly releases is fairly straight forward, it quickly becomes complex in wet years.

While the daily components are summed together to produce the monthly releases which are set in the model by the rules, an analogous procedure is used to get a daily time series from the monthly release volumes. It is necessary to obtain daily values in order to monitor daily e-flow metrics. When the daily to monthly procedure is carried out in the model, variables are used to store important information: peak release pattern, days the peak is extended, days a lower flow rate is extended and the lower flow rate that is extended. An alternative to storing this information would be to write out (or save) the daily time series; then this monthly to daily step would not be necessary. By knowing the assumptions we made in going to the monthly values from daily requirements and the value of these variables, the monthly releases can be reconstructed back to a daily time series. The daily time series can then be used to check e-flow requirements or combined with a disaggregated daily time series for another tributary (Section 3.1) to check further downstream e-flow requirements.

One difference between the Flaming Gorge implementation and Navajo implementation is in terminology. Flaming Gorge's rules were written with the concept of monthly proportions, e.g., the proportion of the month spent ramping-up, at peak release level or at baseflow. In Navajo's case, the rules were written in terms of days at each release level, which essentially translates to a monthly proportion. Additionally, the Flaming Gorge days at peak release is computed in each modeled year, whereas the Navajo values are known as long as it is a standard release. This demonstrates that in general the daily flows can be represented by summing daily releases to monthly release volumes; however, the implementation will differ at each reservoir due to the subtleties of that reservoir's operations.

3.3.2.1 Daily Output Comparison

This section presents several example daily time series from the model and compares them with the actual daily time series for the same years. Figure 3.29 shows the modeled and observed daily flows from Navajo for 2005 – 2007. In 2005, the model computed that the maximum release pattern was necessary with an extended ramp-up bench of 2,000 cfs for most of the month of April in order to achieve the September target storage. It appears as though the actual operations also used the maximum release pattern, though it did not extend the 2,000 cfs bench through April. Since this extension step is only performed when there is a fair degree of certainty that more water is expected later in the summer it is not surprising that it did not occur in actual operations. Since the model has perfect foresight of the future flows, the extension was made, though in actual operations there was not enough information in the forecasted future flows to be certain of high future inflows. Additionally, both the modeled and observed release stopped at several 'benches' during the ramp-up. The number of days at the peak release is similar as is the ramp-down process. The 2006 daily flows match almost identically indicating 2006 was an ideal year with no special circumstances. There are only slight differences in the ramp-up and ramp-downs as the actual operations appear to remain idle for several days before continuing the ramping operations. It is known that the operators avoid changing flow rates during weekends, which is presumably why there are several days with no change in release. Finally, the base release in July is slightly higher in actual operations. This indicates that Navajo was releasing extra to help maintain the baseflow downstream. Since the flows are reduced due to users' demands, this indicates more of an issue with the modeled demands than with the reservoir operations. Finally, 2007 has the largest differences between actual operations and modeled operations. As discussed in Section 3.3.3, the model computed that a large spring peak was necessary to meet the September storage target. Actual operations missed the September storage target since the late summer inflows were not forecasted. Finally, the peak period was shifted much earlier into May in actual operations. The reason for this is unknown, and the rules do not have logic for shifting the peak to earlier in the month, thus this is presumably an exception to the normal operating procedures.

Figure 3.30 shows the modeled and actual daily releases from Flaming Gorge for 2005 and 2007. In 2005, the observed and modeled releases are similar. Both determined that bypass releases (releases greater than 4,600 cfs) were necessary. The actual operations performed this in two sepa-

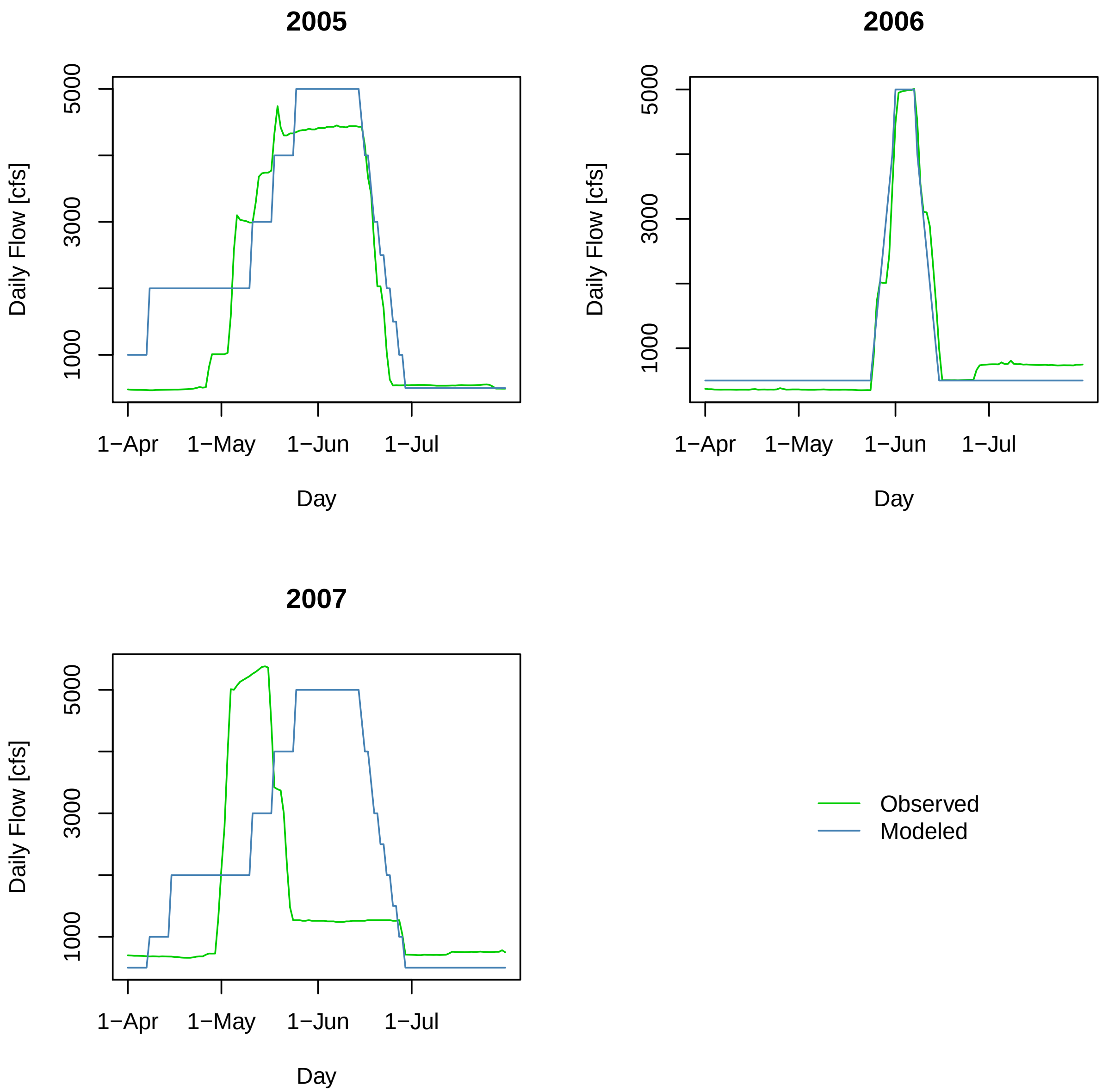


Figure 3.29: Example of the modeled daily releases from Navajo in 2005-2007

rate spikes that did not go to full bypass capacity, whereas the model performed a longer duration bypass release at full bypass capacity. This difference is expected because the rules assume that when bypass releases are necessary they will occur all at once and at full bypass capacity. Additionally, the peak date was slightly later in the model than it actual was, though the total number of days at peak release is nearly the same. Again, the rules assume a fixed ramp-up date rather than varying it to meet the Yampa River's peak. The historical peak release started earlier to try and meet the Yampa River's peak. Finally, there is a slight difference in the base flow during the end of June and beginning of July. Since the model sets only one base release in July it does not have the capability of switching baseflows during one month. Additionally, the base releases are computed based on the projections of the next May's pool elevation. The model computed the base release based on perfect knowledge of all inflows into the system (past and future), while the actual operations do not have this luxury. If the actual observed April – June inflows into Flaming Gorge were slightly different then the forecasted April – June inflows, which is not an unlikely scenario, then a change in baseflow in July would have been necessary. In 2007, the overall shape is again quite close. The total number of days at peak release are nearly the same as are the beginning and ending baseflows. The timing is not identical for the reasons discussed above and the June baseflow is also different, again for the same reasons discussed above.

Overall the modeled daily releases are similar to the actual daily releases. In most cases, the differences are not surprising as assumptions made in the rule development process aimed to capture typical operations and not every detail, such as the shifting of the peak date for Flaming Gorge. In most cases discussed above, there are likely not large impacts to the required e-flow metrics since the number of days at peak release were usually close.

3.3.3 Monthly Timestep Validation

In order to ensure the new rules generally capture actual operations, a validation was performed in which historical values, such as observed inflow, starting reservoir storage and historical demands were used to run the model. The new rules were used at Flaming Gorge and Navajo

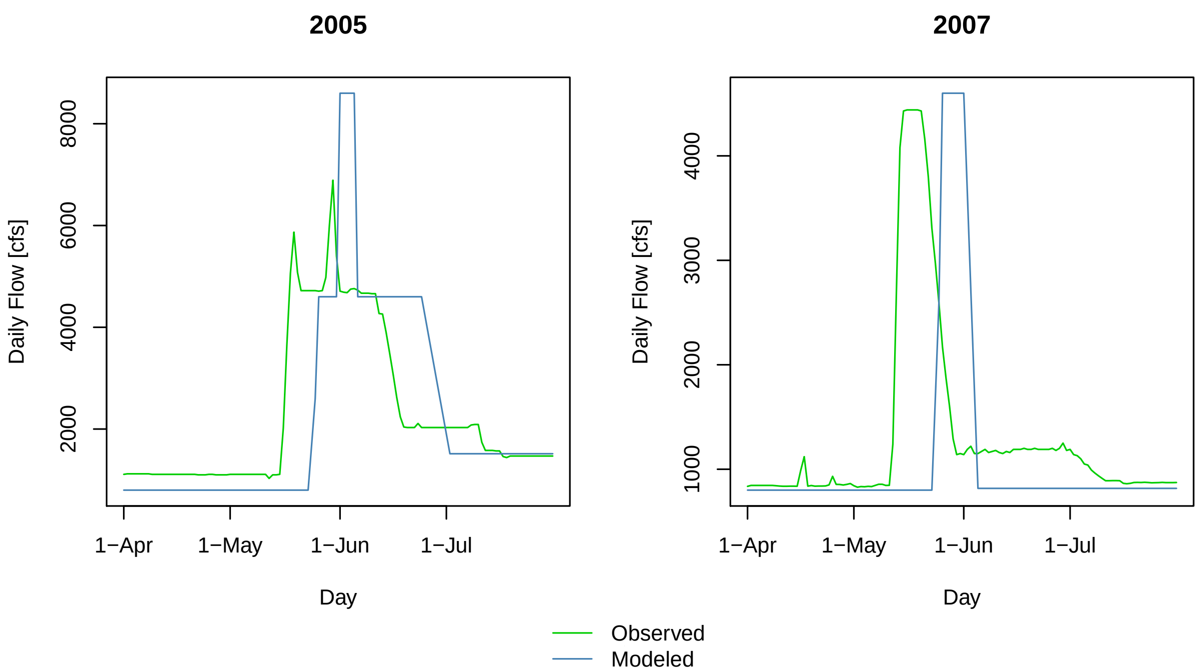


Figure 3.30: Example of the modeled daily releases from Flaming Gorge for 2005 and 2007

and model results were compared to historical values. In general, the rules captured operations fairly well in *typical* years, though in several abnormal years the modeled operations were not as close to historical operations. Below is a discussion of several example validation figures for both Navajo and Flaming Gorge.

Figure 3.31 compares modeled and historical values of Navajo's pool elevation and releases for two different years. For 2005, the releases are pretty close although the peak monthly volume was modeled in June when it historically occurred in May. The pool elevations are very similar in trend although the magnitudes are slightly off. One of the main contributing factors in the differences of the pool elevation and releases is the end-of-September storage target. The targeted storage corresponds to a pool elevation of about 6,065 ft. In the figure it is apparent that the model forced Navajo to be much closer to that elevation in September. Since the model operates with perfect knowledge of the future inflows into Navajo reservoir, it will be closer to the storage target in most cases as it will compute the peak release which gets it closest to the storage target. In actual operations, the peak releases are set based on forecasted inflows into the system, thus it is not abnormal to miss the storage target as the actual inflows will not be identical to the forecasted inflows. The storage target is also the main reason that the modeled values from 2007 (Figure 3.31) seem to be quite different from the actual values. Notice that the modeled pool elevation is almost exactly 6,065 ft in September; to reach this target, the model computed that a much larger spring release volume was necessary. The release in June was much larger in the model than it actually was and this is the month that the pool elevation curves noticeably deviate from one another. We can hypothesize that there might have been an unusually large and unexpected late summer inflow. This would have caused the operator to choose a lower peak release to meet the target as the forecast did not foresee the late inflow, so with the unexpected inflow the storage remained much higher than originally forecasted. Since the model was aware of the late inflows and chose a peak release pattern which released more water in expectation of the late inflows, the September pool elevation was very close to 6,065 ft. Depending on the conditions in the downstream tributaries, the increased release from Navajo could help meet a higher flow target at the downstream gages.

The results here also demonstrate an issue with 'hard' storage targets. Since the model is aware of all future inflows into the reservoir, it can compute nearly exactly what the release should be to obtain the storage target, and will essentially force operations to meet that target. In actuality, the inflows are based on a forecast which has an associated error. This is one factor which can cause the storage target to be missed in actual operations.

Figure 3.32 shows Flaming Gorge monthly releases and pool elevations for modeled and historical values in 2005 and 2007. In 2005, it is apparent that the pool elevations were replicated very well, though the releases are slightly different. Due to the assumed ramp-up date in the model, Flaming Gorge's peak release month will almost always be June. In this case, the model started the ramp-up in late May and peaked in June. Historically, the ramp-up started in May and also peaked in June, however the relative differences between the monthly releases in May and June indicate that more of the peak occurred in May historically than we modeled. Historically, the peak was shifted earlier to help meet the peak on the Yampa River, whereas the model assumes a static ramp-up date. Since the pool elevations match well, the total volume released during the peak period was nearly the same, though the monthly distributions differed slightly between the modeled and actual values. In the model and actual operations, the 2007 peak monthly release was in May since it was a dryer year. The ramp-up began in May, and the days at peak release were completed or nearly completed by the end-of-May. Since the observed May release is larger, we can assume more of the peak release occurred in May and that there could have been more days at the peak release. With the exception of the early baseflows and the difference in the May volume, the modeled and observed releases match well.

Overall, this qualitative verification shows that the new rules performed fairly well. Comparisons were made for 10 other years for Navajo and 3 other years for Flaming Gorge which all performed similarly. In general, some relatively minor differences, like those discussed here, are acceptable in a planning model. Since the goal is to model the typical operations over the long-term, small differences from one year to another will not significantly impact the results. Additionally, if one year the modeled release is too high, it is likely that in a different year the modeled release will be too low, so over the long-term the trends in operations are still apparent. The five years that have operated to the RODs do not offer a wide range of cases against which to verify the model. As more data is collected in the future, the rules can be updated to better reflect operations and there will be more opportunities for verification of the rules.

Additionally, the reservoirs are adaptively managed; the operations are specified by the ROD, though there is a degree of flexibility. The adaptive management working group along with Reclamation can decided that for a given year a specific target might be more important than another, or that one certain goal (a storage target) might be relaxed in order to achieve a different goal (a peak flow). Although it is not possible to model the exact operations that result from the adaptive management process, the new rules adequately capture the general operating procedures. The verification figures were presented to and discussed with the operators of the reservoirs. In both cases, the operators indicated that the monthly operations seemed adequately represented by the new rules. Additionally, the years that were not well captured were viewed as 'abnormal' years by the operators. While we did consult the operators, the rules have not been approved nor verified by Reclamation.

3.3.4 Comparison to CRSS

In this section, the monthly releases and pool elevations resulting from the new operating rules (denoted 'Updated Rules' in the figures) for Navajo and Flaming Gorge based on their respective RODs (*Bureau of Reclamation*, 2006a,c) are compared with the rules that are in the current version of CRSS (denoted 'CRSS Rules' in the figures). As described in the introduction, the previous rules for Flaming Gorge and Navajo operated to meet rule curve based storage targets or to meet downstream demands. The new rules reflect the operations specified in the RODs and have two general periods: the baseflow period and the spring peak periods.

Figure 3.33 shows a boxplot of the monthly storage levels and monthly releases for Navajo along with a time series of the 10, 50 and 90th percentiles of the annual release volume. From these figures it is apparent that the old rules did not have a spring peak period release policy; the

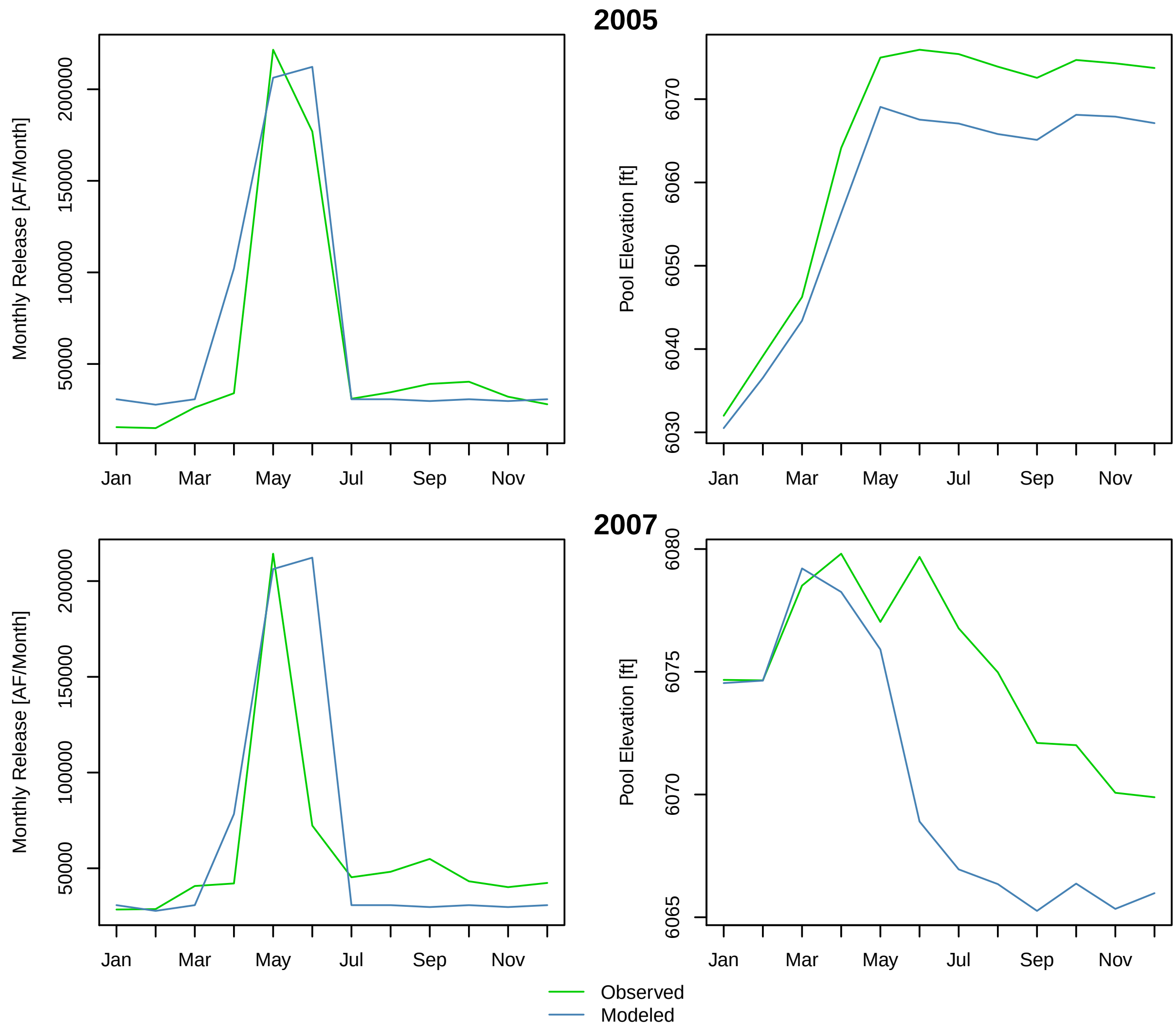


Figure 3.31: Comparison between modeled results and observed historical values for Navajo's release and end-of-month pool elevation. The top two figures are for 2005, while the bottom figures are for 2007.

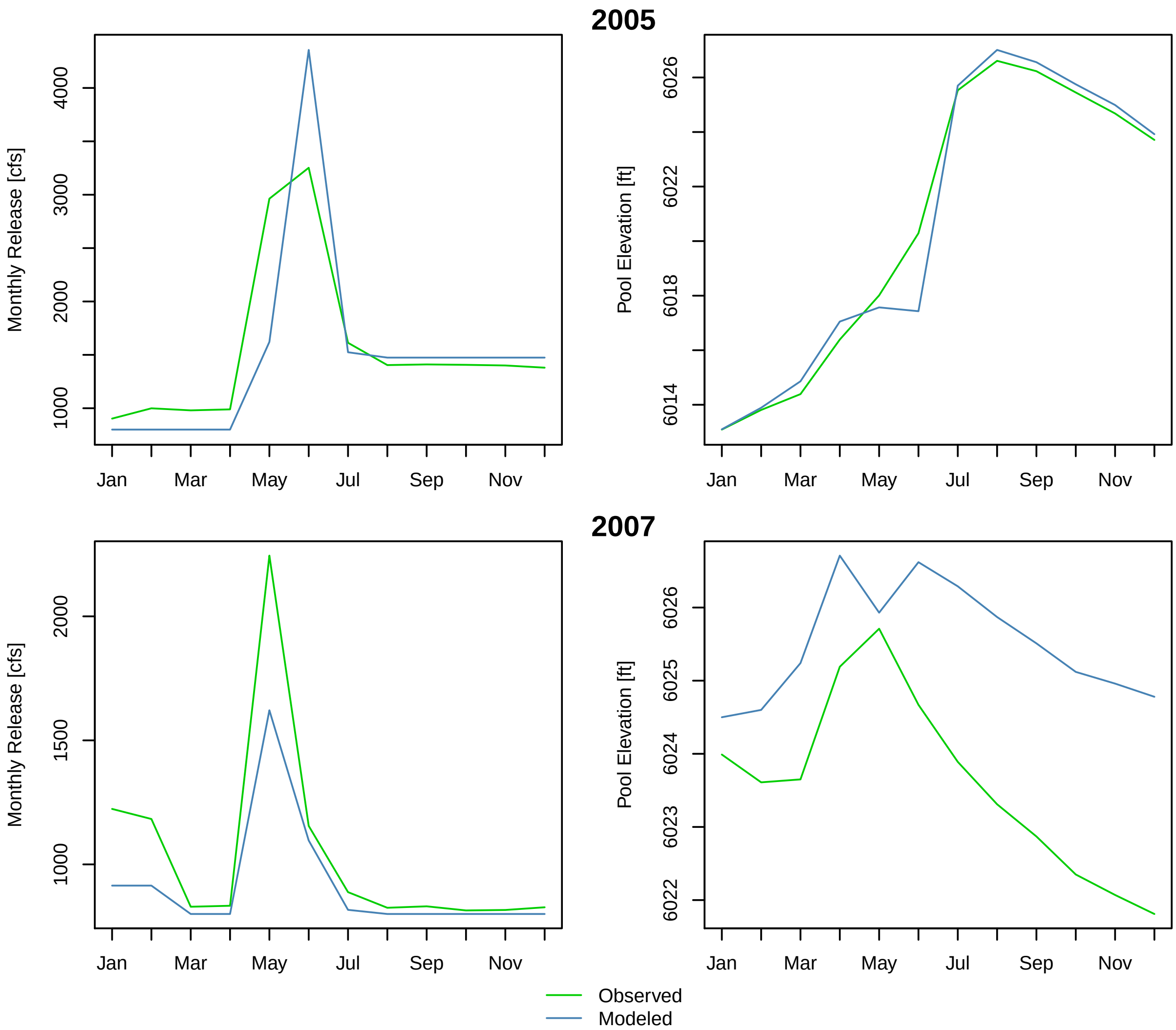


Figure 3.32: Comparison between modeled results and observed historical values for Flaming Gorge's release and end-of-month pool elevation. The top two figures are for 2005, while the bottom figures are for 2007.

monthly releases in May through July were some of the lowest releases. The new rules have larger releases in April through July, mimicking the natural runoff hydrograph, while the rest of the months are almost always at the baseflow value. The variability and magnitude were reduced for January through March and August through December in the new rules. The reservoir is typically fuller in the new rules and the variability in storage is reduced. The new rules also have a larger median annual release by about 100,000 AF.

A larger median release is not consistent with higher storage values; however, there is a diversion directly from Navajo that has a lower diversion requested in the new rules. The reduction in diversion is greater than the increase in releases, thus the new rules can release more water and still maintain higher storage levels.

Figure 3.34 shows the same boxplots for Flaming Gorge along with the annual release volume. In this figure, we again see that the old rules had some of the lowest releases in May through July, while under the new rules these months have the largest releases. It also shows that the new rules have baseflow values that are much larger in August through October and much lower in January through April. The larger January through April releases, in the old rules, were probably to draw down the reservoir in expectation of the runoff period; the storages are also lower in the old rules for the months of March and April. The new rules show reduced storages in June through December, which is due to the much larger releases in May through July. In August through October, the previous rules resulted in a very skewed distribution compared to the more normally distributed range of flows from the new rules, e.g., the old rules result in release in June and July where 75% of the releases are nearly identical. The Flaming Gorge ROD (*Bureau of Reclamation*, 2006a) allows for a wide range of baseflows depending on the year type, while the rule curve based rules seem not have to release much water in August through October to meet the storage targets for those months. This also shows up in the storages as they are also highly skewed in October through December. In the plot of the 10, 50 and 90th percentiles of the annual release volume, the median annual release is about 75,000 AF/year higher in the new rules than in the old rules. However, it has a lower annual release at the 10th and 90th percentiles. Since the monthly

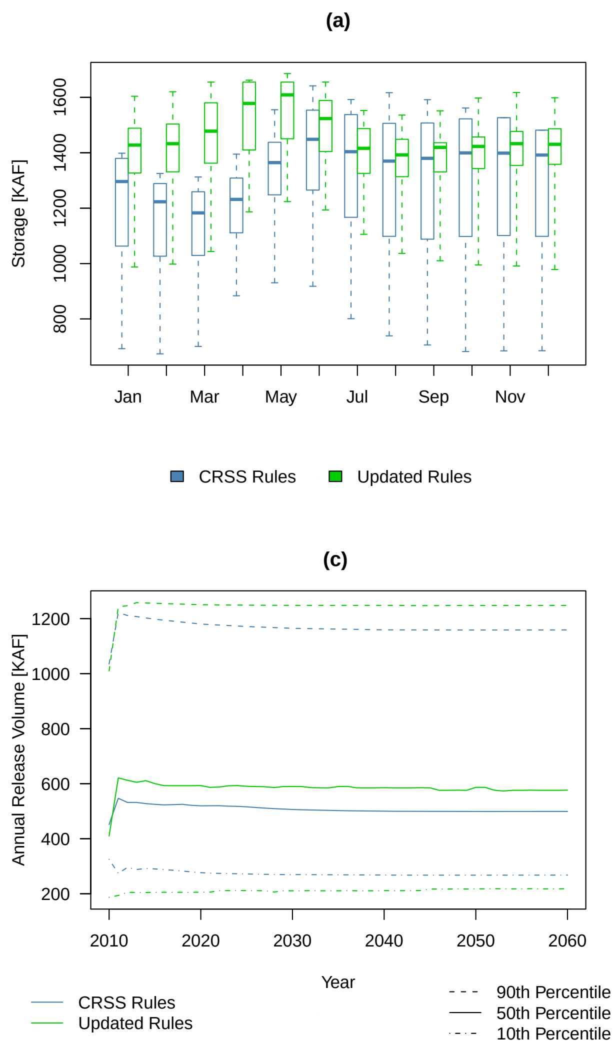


Figure 3.33: Comparison of the Navajo end-of-month pool elevation (a), monthly releases (b) and annual release volumes (c) between the CRSS rules and the newly implemented rules.

boxplots of pool elevations show lower elevations during the majority of the year it follows that this would correspond to a generally higher annual release volume. The lower annual release at the 10th percentile also corresponds to the monthly boxplots: the old rules have a lower minimum pool elevation, thus with a lower annual release volume, the pool elevation should be slightly higher in the dryer years. Similarly, since the storages are lower on average in the new rules, there would be less total water stored so the large releases in the wet years would be lower to return the reservoir to the same levels. This shows up in the lower 90th percentile annual release volume.

Overall, the most noticeable feature is that the new rules show a pronounced baseflow to peak release to base flow shape, whereas the old rules were almost completely opposite — the lowest releases were in the summer months. The releases are can be more or less skewed depending on the reservoir. Since Flaming Gorge is allowed a wide range of baseflows the new rules result in a less skewed release distribution. Oppositely, Navajo's base releases are generally at one minimum release value, thus the releases are more skewed than the old rules. In both cases, the median annual release is higher in the new rules. By representing the RODs in the new rules, the intra-annual variability was modified and storage levels changed slightly.

3.3.5 Summary

We have demonstrated that sub-monthly flow specifications can be adequately represented in a monthly model. After working with the reservoir operators to outline the rules, a method was used to sum up the daily releases and set monthly average releases so that the reservoirs still operated at the monthly level. Then, to monitor daily flow requirements, the monthly releases are used to reconstruct daily flow values. The monthly releases and pool elevations were compared to several historical years where they were able to match historical values fairly well. The new rules also changed the intra-annual operations of the reservoirs in the model when compared to the old rules. While the values do not match historical values exactly, they are representative of the typical operations and are adequate for a planning model. Additionally, we cannot expect to match historical values exactly as there are many factors which go into actual reservoir operations

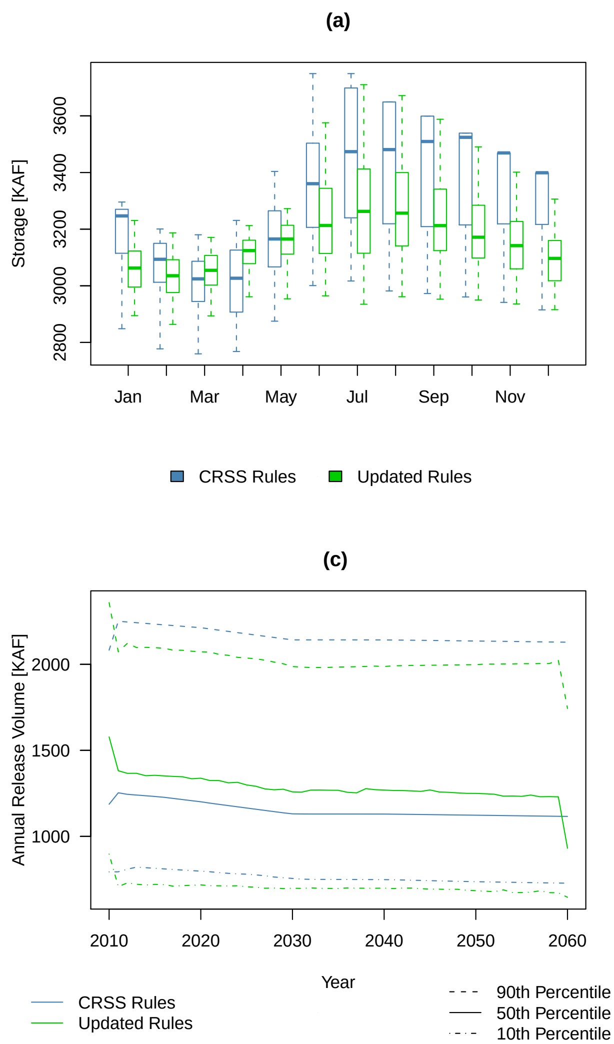


Figure 3.34: Comparison of the Flaming Gorge end-of-month pool elevation (a), monthly releases (b) and annual release volumes (c) between the CRSS rules and the newly implemented rules.

that we cannot perfectly model.

3.4 Flow Deviation Metrics

3.4.1 Background

Flow alteration is a widely used environmental flow metric used to quantify how far a river's flow deviates from a baseline condition. *Poff and Zimmerman* (2010) reviewed 165 papers that used flow alteration of some sort to quantify ecological response. Ninety-nine of the 165 reviewed papers focused on using the magnitude of flow alteration as the metric to relate to ecological response. While no prescribed formula has been found to relate flow deviation to degree of ecological alteration, evidence suggests that the higher the degree of flow alteration, the worse the ecological alteration (*Poff and Zimmerman*, 2010). Additionally, flow alteration is one of the most "pervasive and deleterious" factors degrading rivers today (*Kingsford*, 2011). Thus, flow alteration is a reasonable metric for determining the future degree of reliability of environmental flows. While certain quantitative, site-specific relationships have been found, e.g., (*Wilding and Sanderson*, 2010), the approach can be broadly applied over large spatial extents to get some idea of the ecological conditions at large scales, e.g., (*Döll and Zhang*, 2010).

Flow deviation is used as an e-flow metric in many studies (*Richter et al.*, 1996; *Taylor et al.*, 2003; *Gibson et al.*, 2005; *Mathews and Richter*, 2007; *Döll et al.*, 2009; *Belmar et al.*, 2010; *Döll and Zhang*, 2010; *Poff et al.*, 2010). Often the 'natural' flow is the baseline for computing the flow deviation (*Gibson et al.*, 2005; *Belmar et al.*, 2010; *Poff et al.*, 2010), though the current conditions or conditions after dam regulation are also used as the baseline (*Gibson et al.*, 2005; *Döll and Zhang*, 2010).

The Indicators of Hydrologic Alteration (IHA) method has been widely applied for assessing flow alterations, e.g., *Taylor et al.* (2003); *Gibson et al.* (2005); *Mathews and Richter* (2007), and is estimated to have been applied to at least 30 ecological studies world-wide (*Tharme*, 2003). In the IHA method, the flow data is split into a pre-impact and post-impact period. Thirty-two different parameters' values are then computed for both periods at a daily to monthly timestep. The post-impact departure from pre-impact conditions is reported as a percentage of the pre-impact value. The parameters indicate different aspects of both inter and intra-annual variability (*Richter et al.*, 1996). In a monthly model, many of the daily to weekly parameters cannot be meaningfully represented, though there are several ecologically important parameters at a monthly timestep (*Döll et al.*, 2009), one of which is mean monthly flow.

When assessing the impacts of climate change on flow deviations, the baseline condition is not well-defined because conditions are constantly changing. *Gibson et al.* (2005) compares observed historical flows to future climate change flows with future demand; however flow deviation is not explicitly computed. *Döll and Zhang* (2010) compare the future altered flows due to climate change to the historical altered flows (altered by diversions and regulation) and compare historical altered flows to naturalized conditions. In this case, the comparison is made to show that climate change will impact flows more than all diversions and regulations up to present day.

Future flow values in climate change conditions could be compared with pre-dam and diversion conditions, i.e., historical natural conditions, or with current conditions (present day altered flows) or with the projected natural conditions. We present a variety of metrics for evaluating the climate change conditions, each of which uses a different baseline condition. The discussion focuses on the strengths and weaknesses of each metric since each baseline choice can provide different insights.

The following sections present a suite of flow alteration metrics in the context of deviation from a baseline flow. First the metrics are discussed in the context of stationary hydrology; then consideration is given to deviation metrics in a nonstationary climate. In all cases the flow alteration metrics provide some insight into the inter-annual variability at the chosen location. Finally, a monthly hydrograph boxplot is presented which provides information regarding the intra-annual variability. Examples of all deviation metrics are presented alongside the descriptions. Two nodes on the Colorado River Basin are selected as examples: the Yampa River near Deerlodge and the Green River near Greendale. The Deerlodge node is an example of an unregulated reach while the Greendale node is an example of a node with a reservoir directly above it. The importance of the distinction between an unregulated and regulated reach is addressed in the metric sections. The model runs from 2010 through 2060 though the first and last year of the model run are trimmed off of the results to eliminate the boundary effects from the model.

3.4.2 Deviation from Natural Flow

One common choice for the baseline flow is the historical natural flow: the flow that would have occurred if there were no depletions or regulations by dams. The historical natural flow is used in numerous previous studies (*Gibson et al.*, 2005; *Belmar et al.*, 2010; *Poff et al.*, 2010) and can be computed at the daily, monthly or annual timestep (*Mathews and Richter*, 2007) as well as aggregated across multiple timesteps to get seasonal or annual deviations.

In the Research Model, or as a post-processing computation, the deviation from natural flow calculation is computed at each timestep (every month in a monthly model) at each natural flow node in the basin as

$$D^{nat}_{i,j,k} = \frac{G_{i,j,k} - \overline{N}_i}{\overline{N}_i} * 100\% \tag{3.5}$$

where G is the modeled (altered) flow in month i, year j, and trace k. $\overline{N}_i$ is the average, historical, natural flow at the gage in month i. D^{nat} can be computed for a single month, e.g., the deviation of this year's July flow from the average July historical natural flows, or for aggregations of months. In this study we compute the natural flow deviation for three different aggregations: sum of annual flows, sum of the three highest flow months and the single, fall, low flow month. The computation for the annual time aggregations is

$$D^{nat}_{annual,j,k} = \frac{\sum_{i=1}^{12}(G_{i,j,k} - \overline{N}_i)}{\sum_{i=1}^{12}(\overline{N}_i)} * 100\% \tag{3.6}$$

For the three high flow months it is

$$D^{nat}_{high,j,k} = \frac{\sum_{i=a}^{a+2}(G_{i,j,k} - \overline{N}_i)}{\sum_{i=a}^{a+2}(\overline{N}_i)} * 100\% \tag{3.7}$$

where a is an index to the start month of the maximum three month volume of the natural flows in year j and trace k of the computation. The computation for the fall, low flow month is

$$D^{nat}_{low,j,k} = \frac{G_{c,j,k} - \overline{N}_c}{\overline{N}_c} * 100\% \tag{3.8}$$

where c is the index (8 or 9 for August or September), whichever is the minimum low flow month, e.g., $Min(N_{8,j,k}, N_{9,j,k})$.

The three high flow months represent the 90-day max as in *Wilding and Sanderson* (2010) and *Richter et al.* (1996). The fall low flow month was chosen somewhat arbitrarily but was selected to show the deviation in a base-flow or low-flow month. The annual aggregation provides insights into how the total annual flow is impacted by diversions and regulations. Examining all three of these aggregations provides an overall view of seasons as well as years that are impacted. Additionally, it can indicate the 'reversal' of the annual hydrograph if the low-flow month's deviations are positive while the high flow month's deviations are negative.

After computing the deviations for each year of each trace, the median deviation over all traces ($Median(D^{nat}_{high,j,k=1:n})$, where n is the number of traces) can be plotted through time to reveal any trends in the deviations at any of the time aggregations. While the mean is used to compute the baseline values from the historical natural flow, the median is a more robust statistic when comparing across multiple traces. The historical natural flows generally fit close to a normal distribution; thus, there is little difference between the mean and median. However, the modeled flows are generally not normally distributed, especially below a regulation point such as a reservoir. Minimum release rules result in a skewed distribution. The median over all traces is the value that is most likely to occur whereas the average value is influenced by outliers. Additionally, upon comparing the mean and median deviations for multiple nodes, the mean is generally higher than the median, though the trends they reveal are similar. The mean is higher because it is heavily influenced by several years with particularly high flows (outliers).

When simulating with historical natural flows traces generated by the Index Sequential

Method (ISM) (*Ouarda et al.*, 1997), referred to here as the direct natural flows (DNF; described in Section 2.2.1.1), the resulting median deviation from historical natural flow shows how the demands and river regulation impact the altered flow. Figure 3.35 demonstrates the median deviation from the average historical natural flow at the Deerlodge gage for the three time aggregations. The trends shown in Figure 3.35 show how demands impact the flows when the model is run with DNFs. By comparing Figure 3.35 (c) with Figure 3.36, which shows the annual requested depletions for all users above the Deerlodge gage, one can see that the trend in flow deviations is similar to the trend in annual depletions; as the depletions increase, the flows become more departed from natural conditions. Additionally, Figure 3.37 shows the same deviations from the average historical natural flow for the Greendale gage. In this case, both the demands above Greendale and the regulation of Flaming Gorge Dam are reflected in the deviations which is why Figure 3.37 shows more variability than Figure 3.35. With a full set of ISM-generated traces, each future modeled year sees each year of historical flows one time, hence the average projected natural flow is the same for every future modeled year and only changing depletions or reservoir regulations will cause the deviation values to change with time.

3.4.3 Deviation from Current Conditions

Another deviation metric uses current (altered) conditions as the baseline value with which to compute the deviations. *Döll and Zhang* (2010) compare conditions in the future to the flow alterations that had occurred by 2002. In this study the following options exist for defining 'current conditions': 1) the average historical gage data (from USGS records). Since each gage that is modeled in the Research Model has a different period of record, comparisons would not be valid. Additionally, in situations where demands are increasing, the average historical flow is higher than the expected 'current' flow. 2) One recent, single year of USGS gage data that represents current conditions. This could lead to skewed results if the selected year has particularly high or low flows. 3) The first modeled year's median value over all traces. This would represent current conditions as the long-term median natural flow minus the median depletions and regulations in

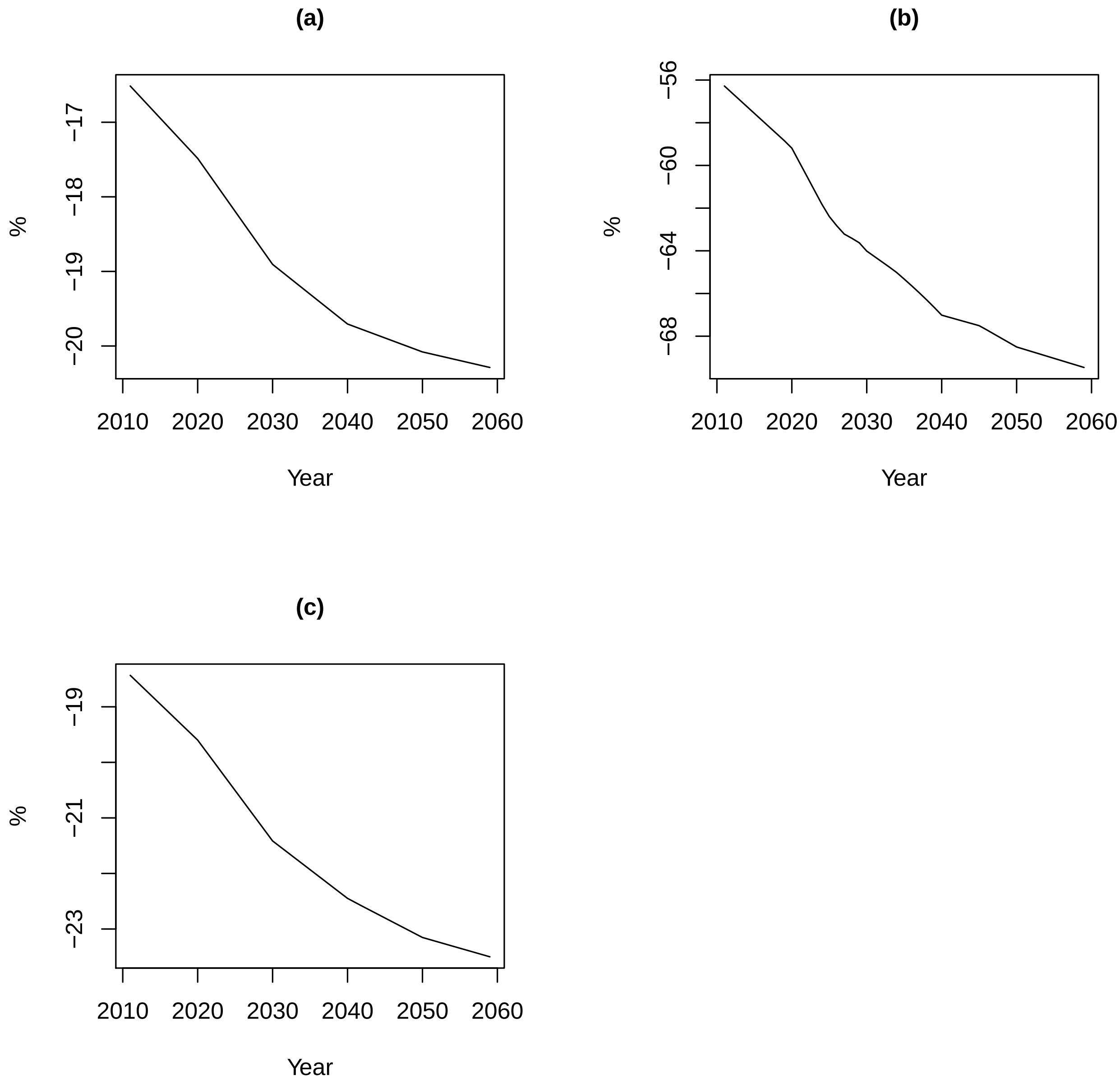


Figure 3.35: Median deviations from historical average natural flow from DNF run on the Yampa River at Deerlodge for (a) the three high flow months (b) the single low flow fall month (c) the annual flow.

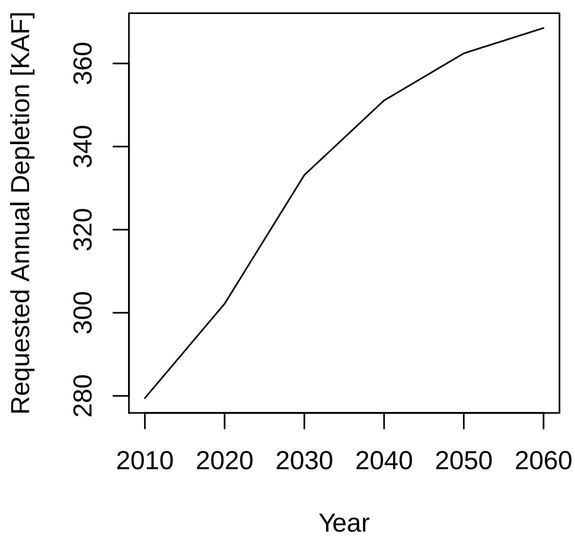


Figure 3.36: Annual requested depletion above Deerlodge.

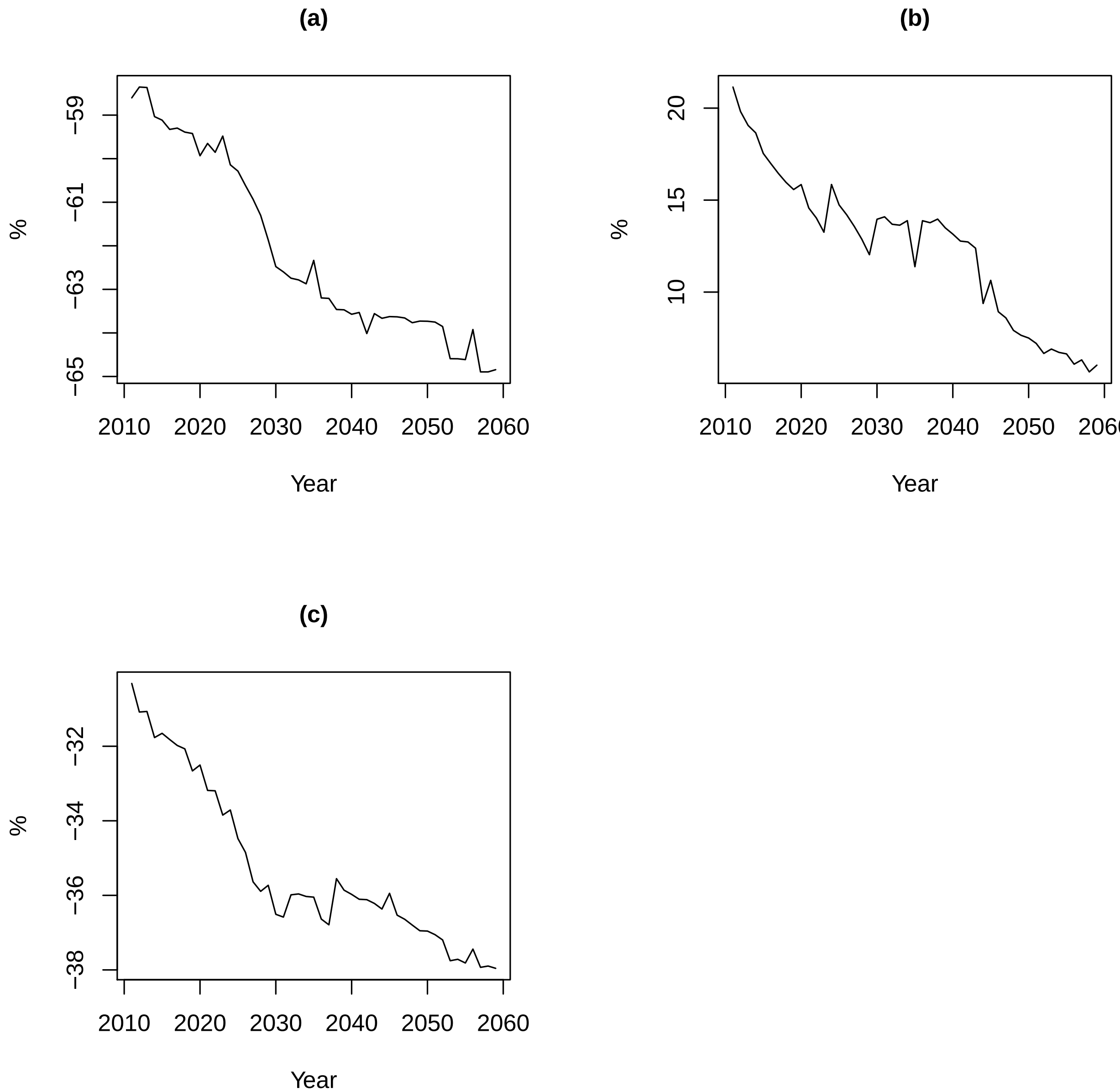


Figure 3.37: Median deviations from historical average natural flow from DNF run on the Green River at Greendale for (a) the three high flow months (b) the single low flow fall month (c) the annual flow.

the first modeled year (2010 in this study). This is the representation of current conditions chosen for this study to compute the deviation from current conditions for the DNF model runs.

As with the deviation from natural flows, the following computation is made during every month to compute the deviation from current conditions:

$$D^{cur}_{i,j,k} = \frac{G_{i,j,k} - \widetilde{G}_{i,j=1}}{\widetilde{G}_{i,j=1}} * 100\% \tag{3.9}$$

where $G_{i,j,k}$ is the modeled flow in month i, year j and trace k. $\widetilde{G}_{i,j=1} = Median(G_{i,j,k=1:n})$ is the median modeled flow (across all traces where n is the number of traces) in month i of the first year ($j = 1$) of the model run. Again, this computation can be aggregated over multiple months to provide seasonal or other information into how the deviations are changing through time. The aggregation over multiple months is analogous to Equations 3.6 – 3.8.

Figures 3.38 and 3.39 show the median deviation ($Median(D^{cur}_{i,j,k=1:n})$) from current conditions for the Deerlodge and Greendale nodes, respectively. Since the first modeled year (2010) is impacted by initial conditions, mainly below reservoirs, 2011 is considered representative of average current conditions — Equation 3.9 is thus computed from $\widetilde{G}_{i,j=2}$. Computing and showing the deviations in this manner does help explicitly show how much worse the conditions are in the future than they are now. However, if there is a relationship between the flow deviations from natural conditions and a certain species health, as in *Wilding and Sanderson* (2010), then using the deviations from current conditions is not as relevant as using the deviations from historical natural flows. The deviations from current conditions metrics shifts the baseline from average historical natural flows such that the first modeled year is at 0% deviation.

Overall, showing the deviations with respect to a baseline of either historical natural flow or current conditions qualitatively shows whether or not there is a trend in future flow deviations. For example, for the high flow months at Greendale, the deviations become 15% farther from natural conditions over the 50 year simulation in both the deviation from natural and deviation from current conditions. Depending on the situation, one metric could be more suitable than

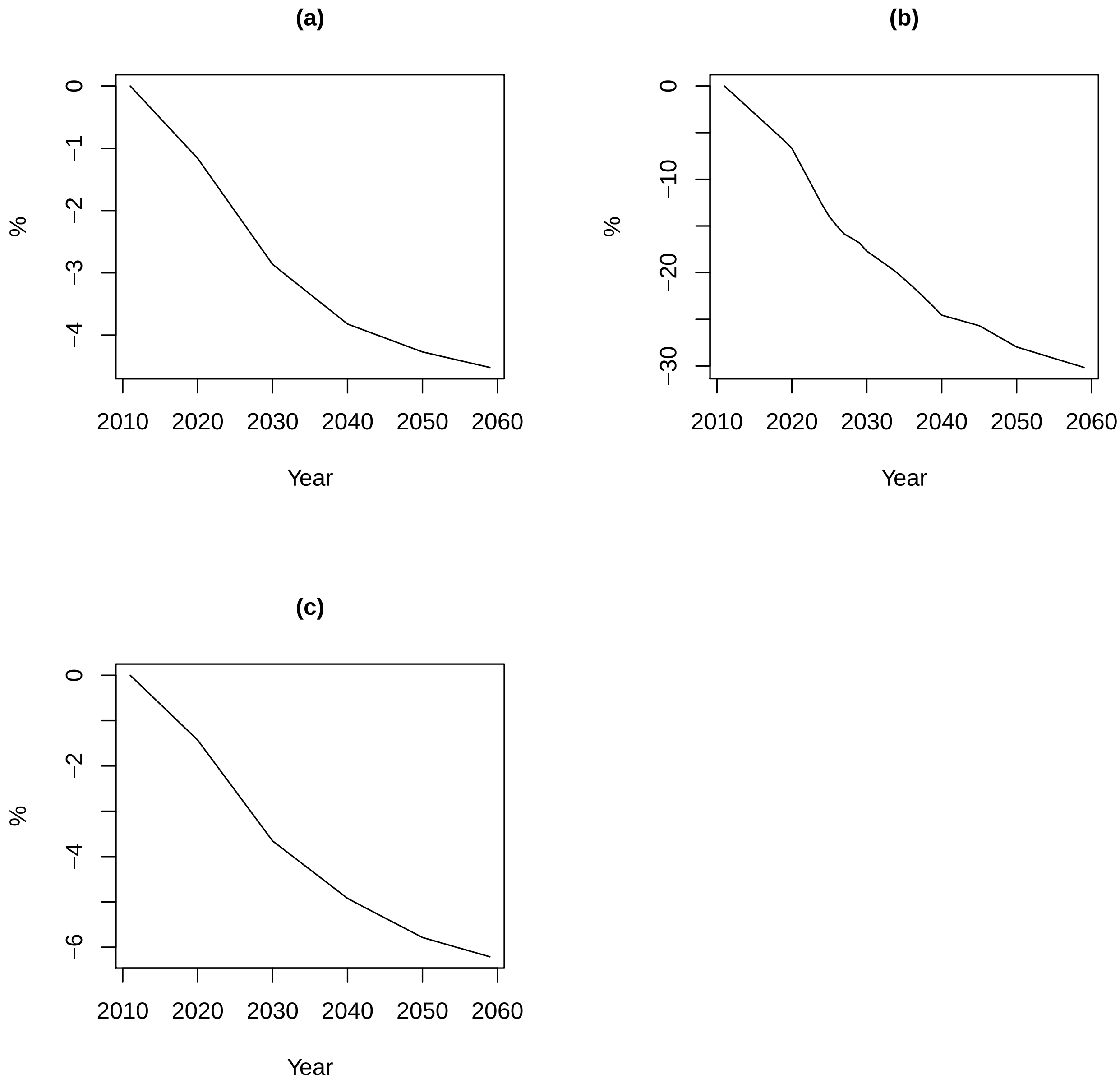


Figure 3.38: Median deviations from current conditions from DNF run on the Yampa River at Deerlodge for (a) the three high flow months (b) the single low flow fall month (c) the annual flow.

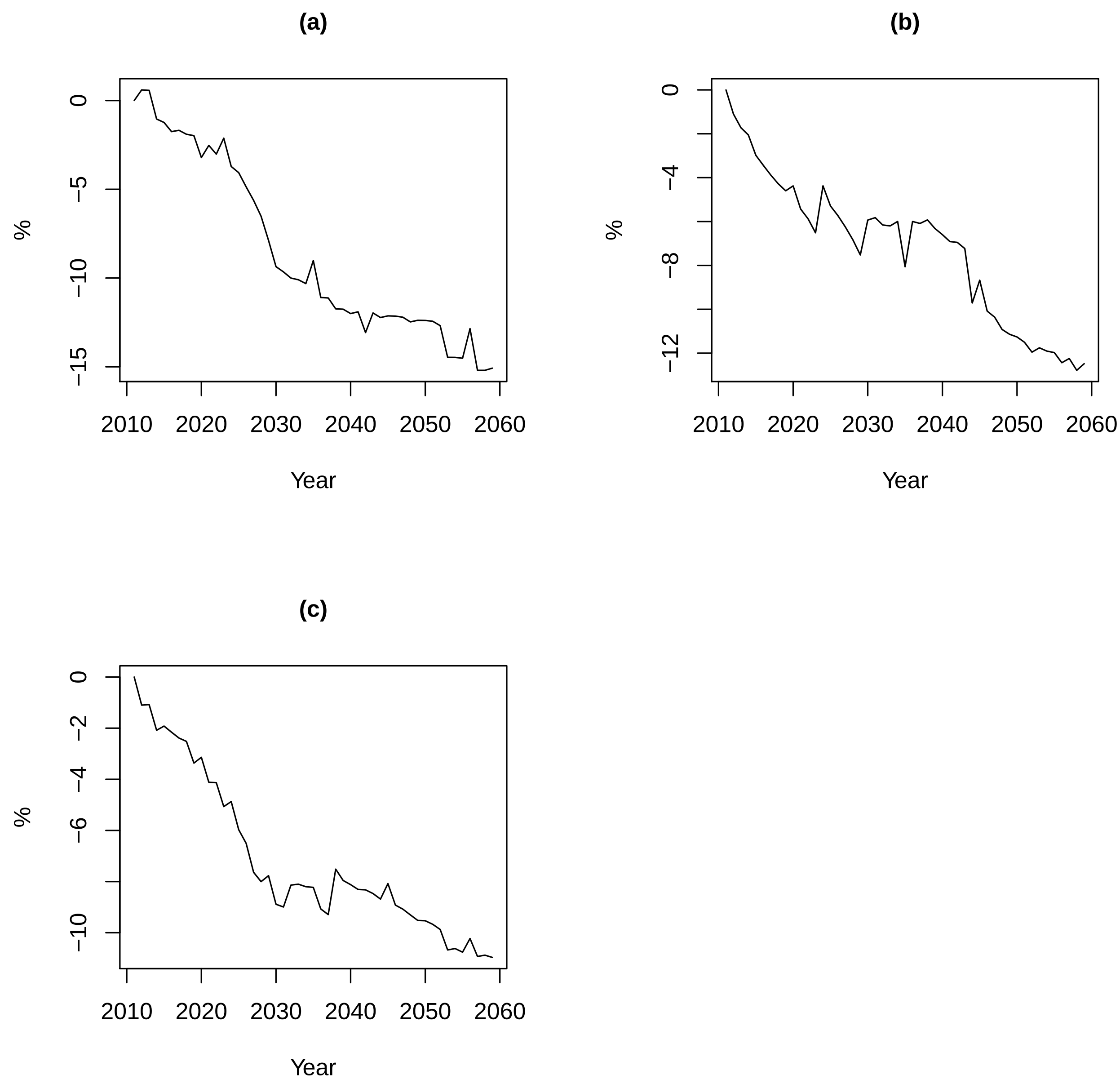


Figure 3.39: Median deviations from current conditions from DNF run on the Green River at Greendale for (a) the three high flow months (b) the single low flow fall month (c) the annual flow.

the other; if species to flow deviation relationships have been found at a particular site, then the deviation from current conditions does not provide the necessary information as the flow deviation relationships are developed with natural conditions as the reference baseline.

3.4.4 Change in Deviations Over Time

As discussed in *Mathews and Richter* (2007), a trend analysis can determine if the deviations are changing over time. Assuming stationary climate, a trend would be due to a trend in depletions, in regulation, or both. Due to the nature of ISM and the demand schedules, trend tests are not valid for the deviations from historical natural flows or the deviations from current conditions. Since the deviations are a result of the demand schedules and regulations, the residuals from fitting a linear model to the data would not be normally distributed nor would they be randomly distributed with respect to the independent variable. Figure 3.40 shows the deviations from historical average natural flow for the Deerlodge high flow months and the Greendale annual deviations. In Figure 3.40, a linear model is shown that has been fit to the data and residuals from the model are shown for both nodes. Both residual plots indicate that a linear model used for a trend test is inadequate — there is a pattern to the residuals. A linear model is an inadequate model because the trends are a reflection of the demand trends and the demands are determined on a decadal basis with linear interpolation between decades. This results in a piecewise demand schedule, thus a single linear model cannot capture the trend. While there is no single linear trend to the data, it is visually apparent in Figure 3.40 that the deviations are regularly changing and there is a trend from the beginning of the model run to the end of the model run.

3.4.5 Flow Deviations in a Nonstationary Climate

In a nonstationary climate, the aforementioned techniques can be used but with some qualifications/restrictions. As mentioned in the Background Section, the choice of the pre-impact period if the period does not exhibit stationarity is ambiguous. Further, the value of the natural (unaltered) flow as the ideal condition against which to compare future altered states is called into

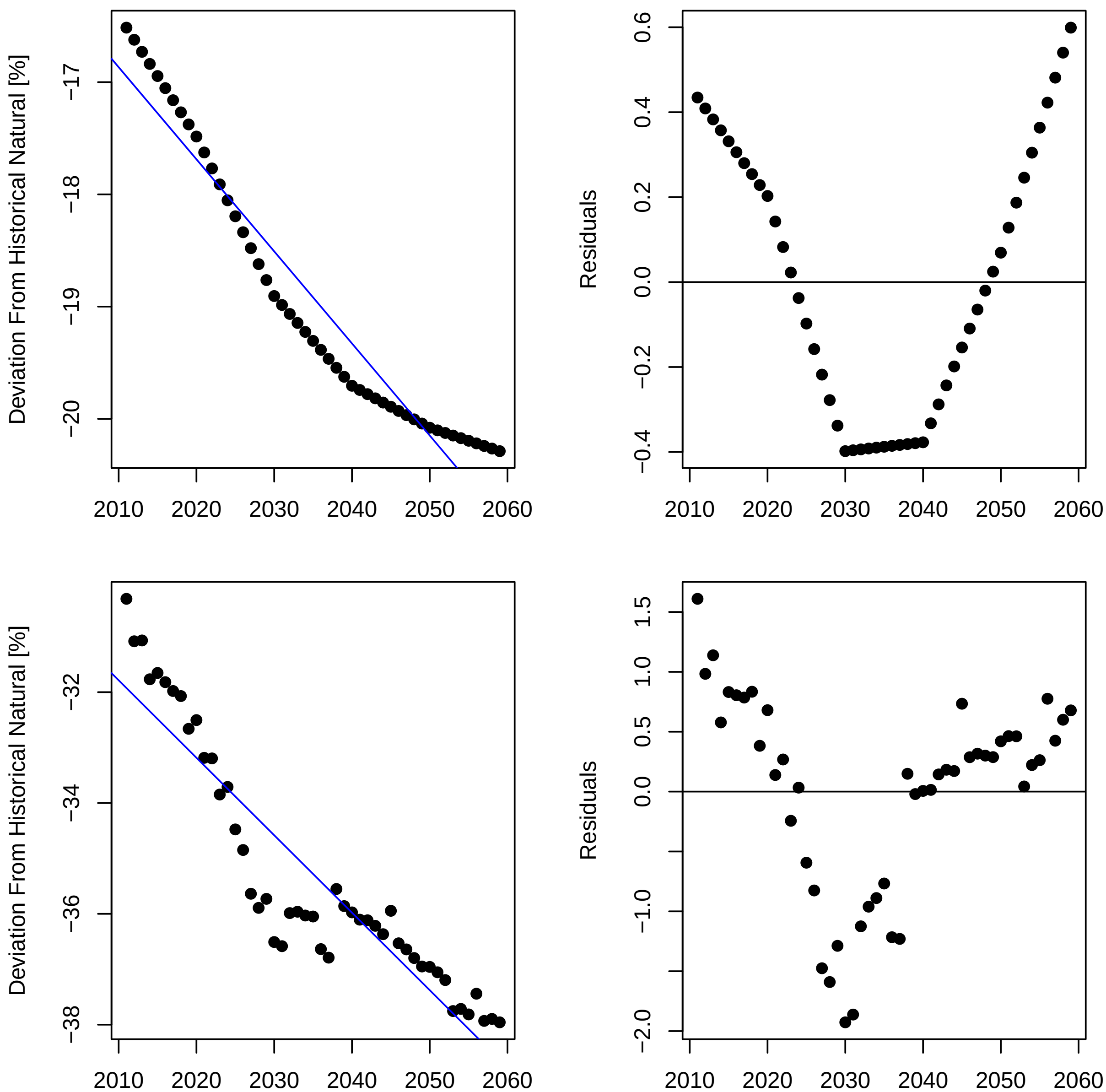


Figure 3.40: Deviation percentages with a linear model (blue line) fit to the data and residual plots from the model for the deviations from historical average natural flows for the Deerlodge high flow months (top) and for Greendale annual aggregation (bottom).

question if the natural state itself is changing.

To begin, the deviations from the average, historical, natural flow can be computed (Equation 3.5). The examples shown in this section were generated by running the research model with an ensemble of hydrologic traces from climate change projections. Figures 3.41 and 3.42 show the deviations of future altered flows under climate change hydrology from historical, average, natural flow for the Deerlodge and Greendale nodes, respectively. Again, this comparison might not be the most relevant comparison, since in the climate change projections the natural conditions are no longer stationary. The deviations are much more variable than those observed from the DNF run (Figures 3.35 and 3.37). The low flow month at Deerlodge shows a much higher degree of alteration than the annual or high flow months. Comparing Figure 3.42 and 3.37 shows that the flow variability with climate change affects the alteration more than just the regulation of the upstream reservoir.

An alternative to computing the deviation from the historical average natural flow, is to compute the deviation from the projected natural flow. The computation performed is

$$D_{i,j,k}^{Proj} = \frac{G_{i,j,k} - N_{i,j,k}}{N_{i,j,k}} * 100\% \tag{3.10}$$

where $G_{i,j,k}$ is the modeled flow in month i, year j and trace k of the model run. $N_{i,j,k}$ is the natural flow at the location the deviation is being computed at in month i, year j and trace k. Once again, the metric can be aggregated to different time periods as in Equations 3.6 – 3.8.

The deviations from the projected natural flows for the climate change run are shown in Figures 3.43 and 3.45. In this case, the comparison mainly shows the influence of demands on future flow alterations as in the deviations from historical natural flow in the DNF run (Figures 3.35 and 3.37); however, the variability of the flows with climate change hydrology dominates the trends and variability due to changing demands and regulation. The information in Figures 3.43 and 3.45 is similar to the deviations from historical natural flow for the DNF run shown in Figures 3.35 and 3.37. This is further highlighted in Figure 3.44, which shows the deviation from

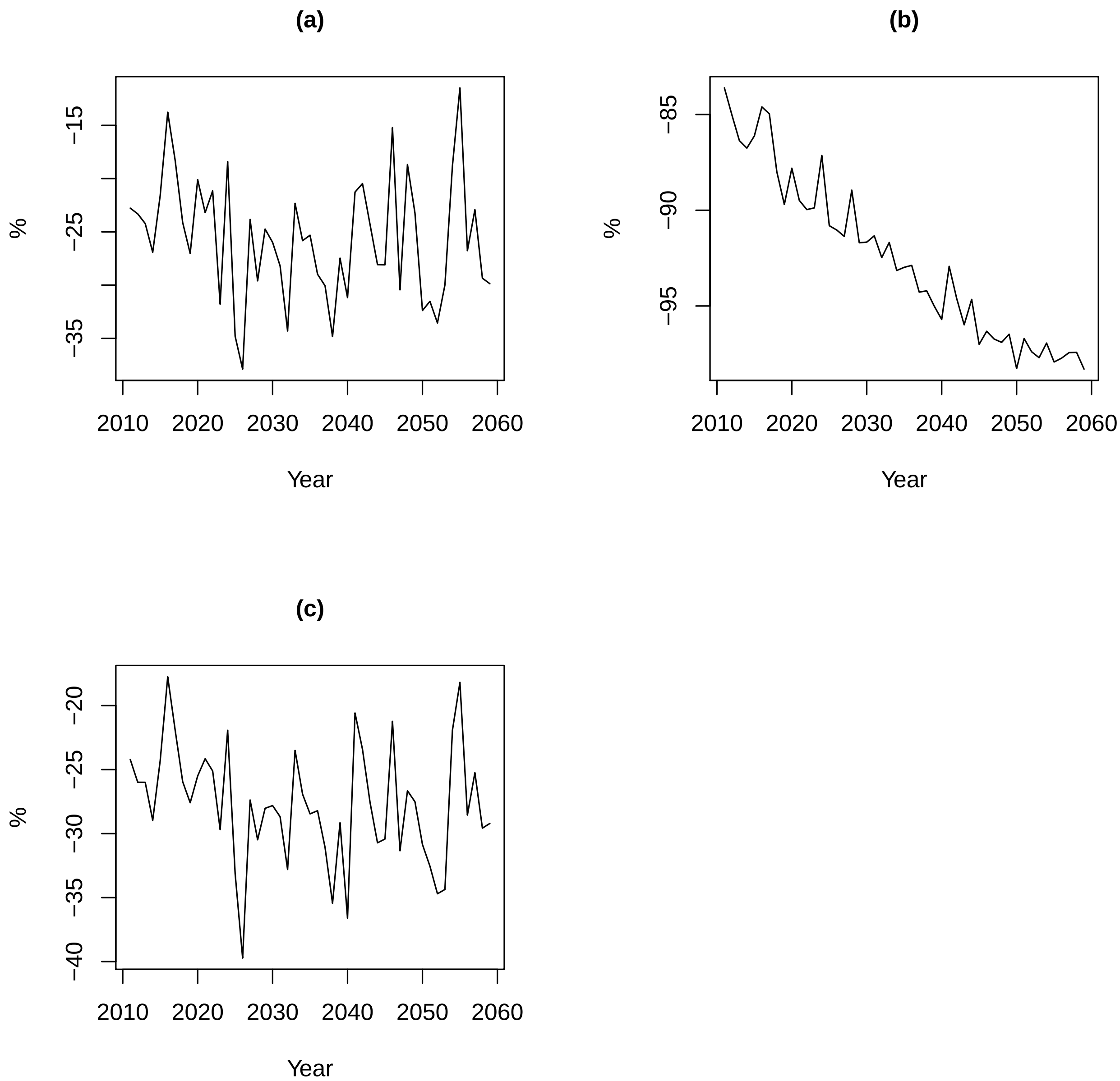


Figure 3.41: Median deviations from historical average natural flow from climate change run on the Yampa River at Deerlodge for (a) the three high flow months (b) the single low flow fall month (c) the annual flow.

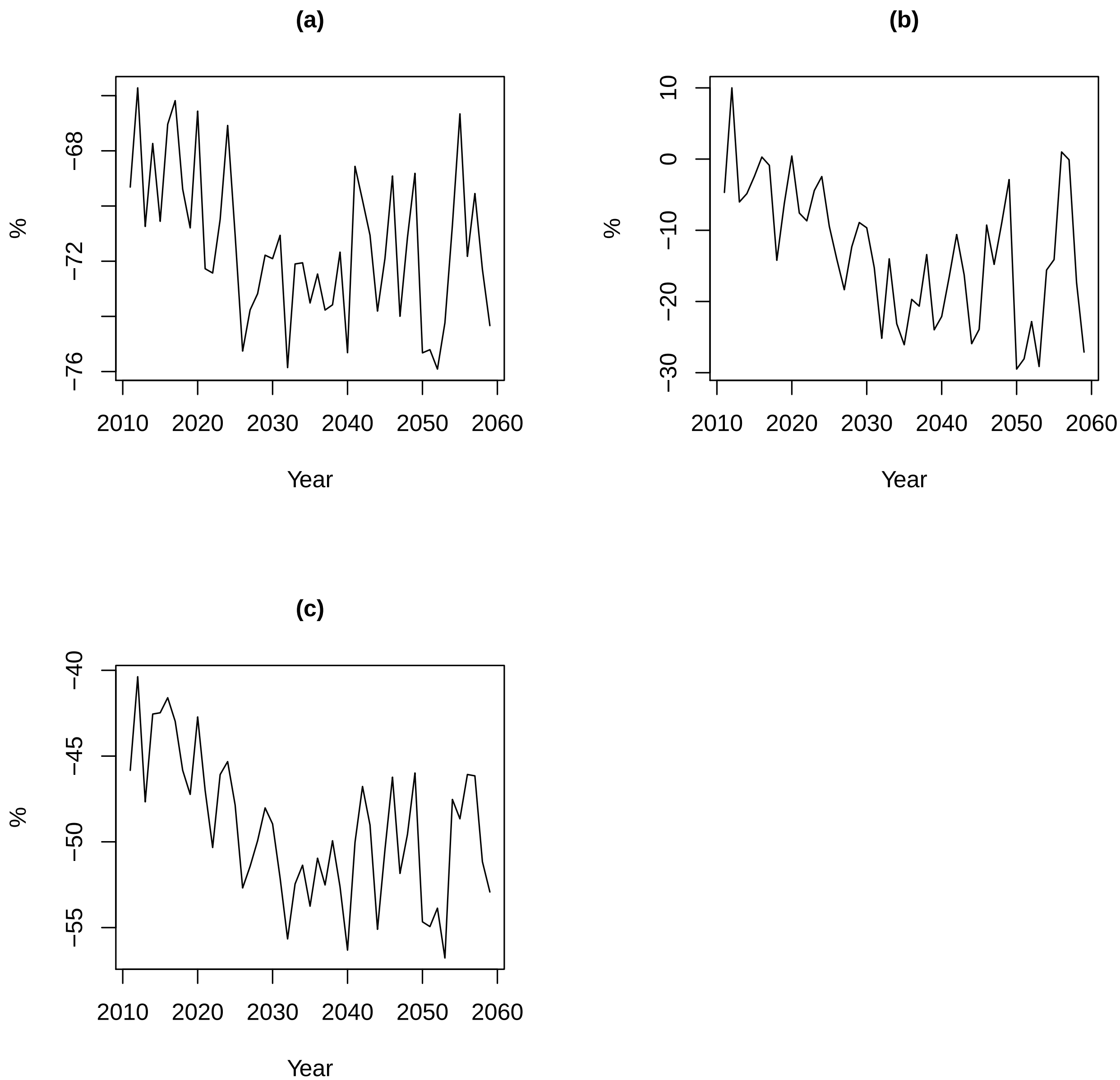


Figure 3.42: Median deviations from historical average natural flow from climate change run on the Green River at Greendale for (a) the three high flow months (b) the single low flow fall month (c) the annual flow.

historical natural flow for the DNF run with the deviation from projected natural flows for the climate change run. While the magnitudes differ slightly, and the climate change case shows the variability of the projected future independent flows, the changes in deviation over time do appear similar: both show about a 4 % decrease overtime. This shows that the demands impact the flows to about the same degree in both the DNF and climate change runs; thus we can assume that for this node, the median climate change flows are slightly higher than the median historical flows.

Additionally, the deviations can be computed with respect to current conditions based on the beginning of the model run as in *Döll and Zhang* (2010). The computation would be the same as Equation 3.9, where $\widetilde{G}_{i,j=1}$ is the median modeled flow in the DNF model and $G_{i,j,k}$ is the altered flow in the model run with climate change data. The future deviations from current conditions for the climate change run were computed based on the 2011 value from the DNF run as the view of current conditions. Choosing the same baseline value for both model runs allows for a direct comparison of the deviations from current conditions from the DNF run verses the climate change run. Figures 3.46 and 3.47 show the deviations from current conditions for Deerlodge and Greendale. Since the 2011 DNF value was used as the baseline condition, the 2011 deviations in these figures are not necessarily zero as in the DNF deviation from current conditions (Figures 3.38 and 3.39) — the 2011 climate change flows are 5 to 55 % below the 2011 value from the DNF run. With nonstationary (climate change) data this result shows how flow alterations are impacted by both future depletions and by climate change induced flows. Therefor, any trends in the data could be from demands, hydrology, or both.

Another flow deviation metric for non-tationary future flows is similar to that in *Gibson et al.* (2005). This metric compares current hydrologic conditions and future demands (the DNF flows with projected future demands) with future nonstationary flows and future demands (the climate change induced flows with projected future demands) in order to provide information indicating how hydrology is changing independent of demands. This flow deviation metric is computed as

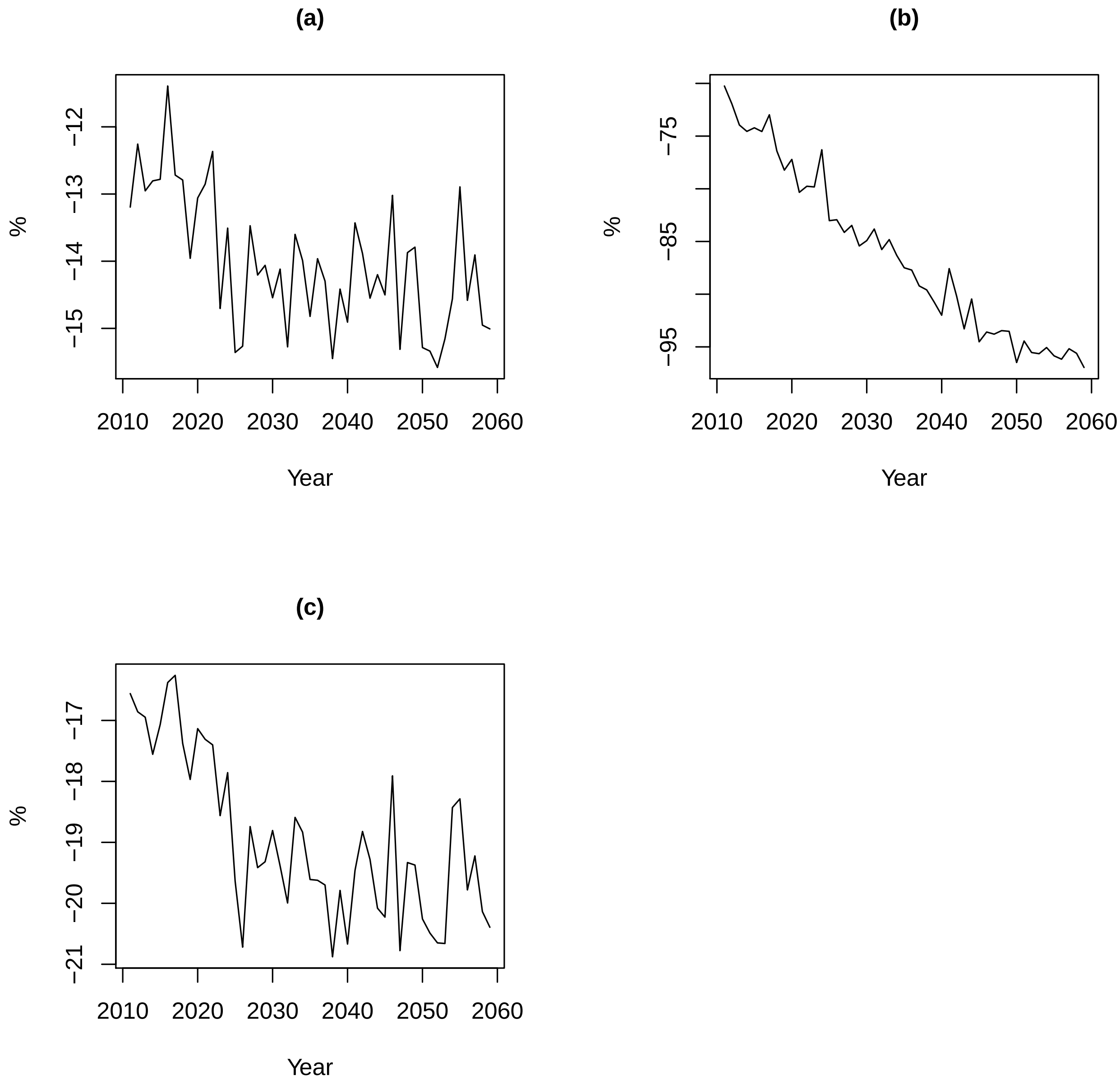


Figure 3.43: Median deviations from projected natural flows from climate change run on the Yampa River at Deerlodge for (a) the three high flow months (b) the single low flow fall month (c) the annual flow

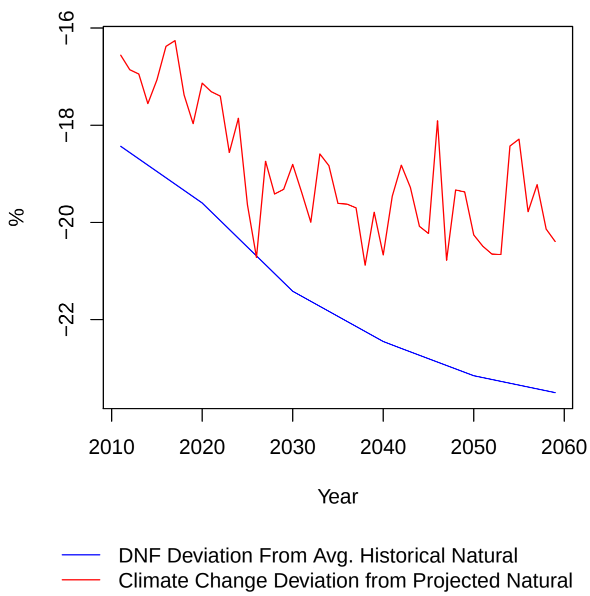


Figure 3.44: The deviation from average historical natural flow from a DNF model run and the deviation from projected natural flows from a climate change model run for the annual flows at Deerlodge.

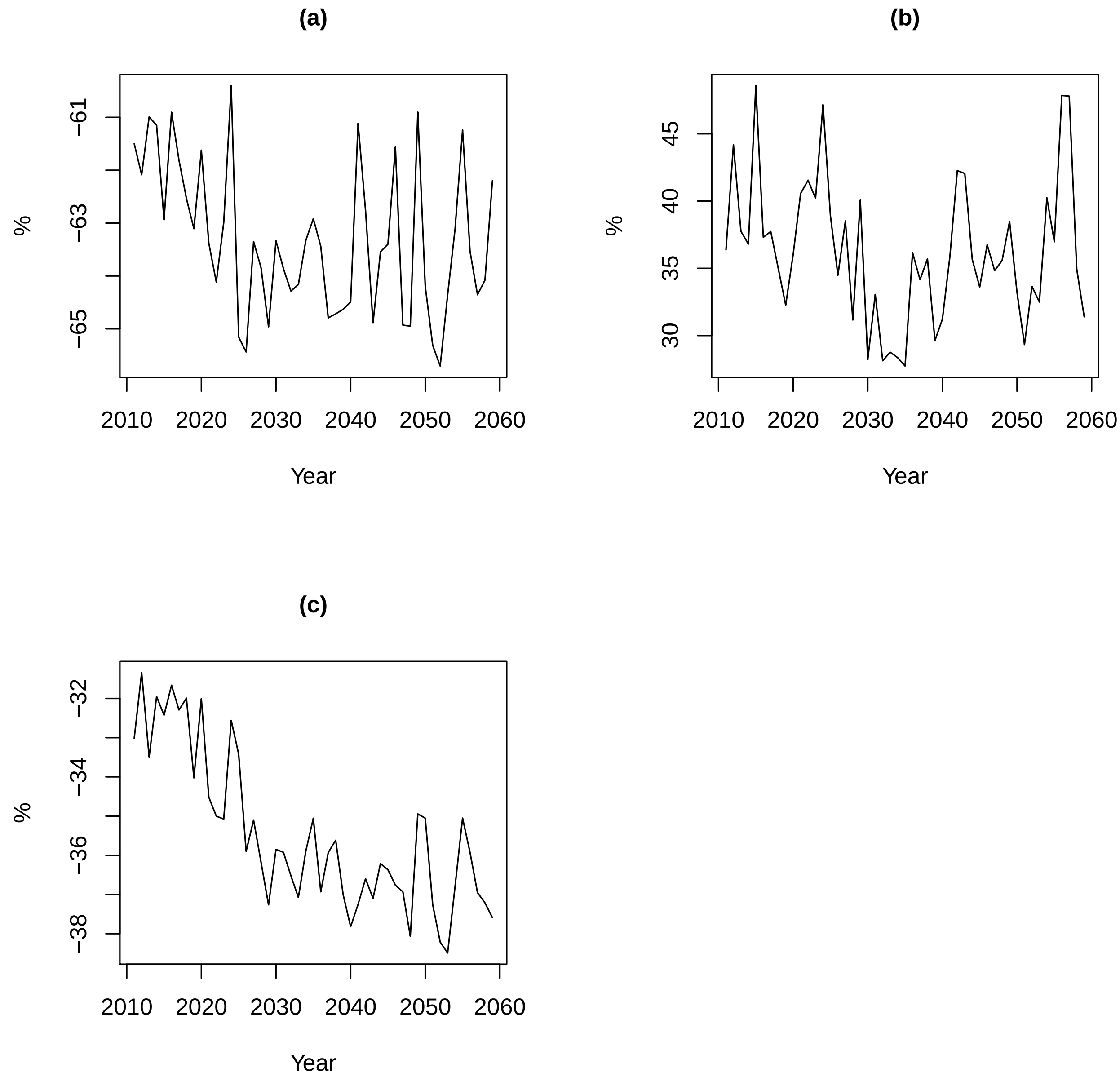


Figure 3.45: Median deviations from projected natural flows from climate change run on the Green River at Greendale for (a) the three high flow months (b) the single low flow fall month (c) the annual flow.

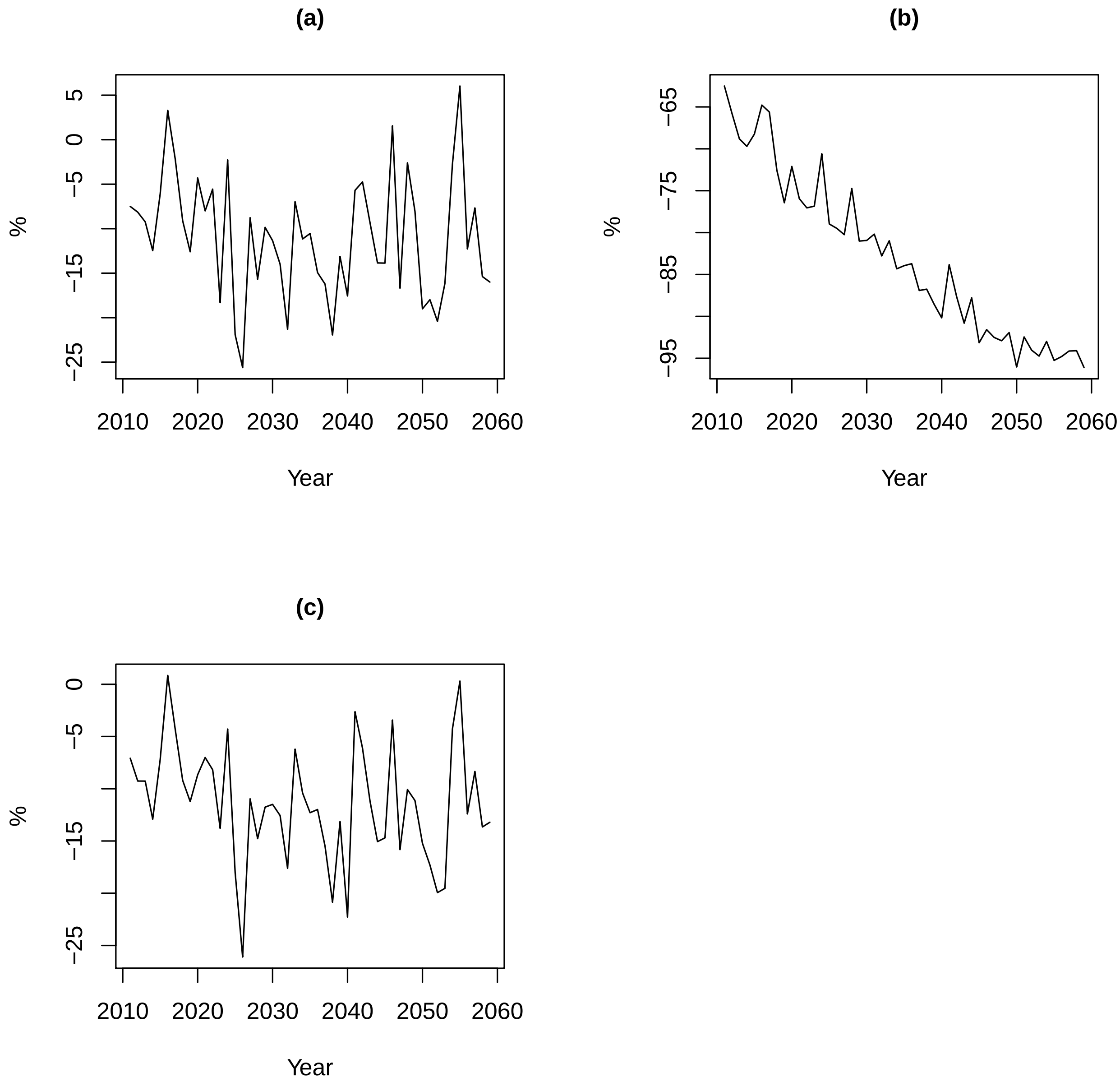


Figure 3.46: Median deviations from current conditions from climate change run on the Yampa River at Deerlodge for (a) the three high flow months (b) the single low flow fall month (c) the annual flow.

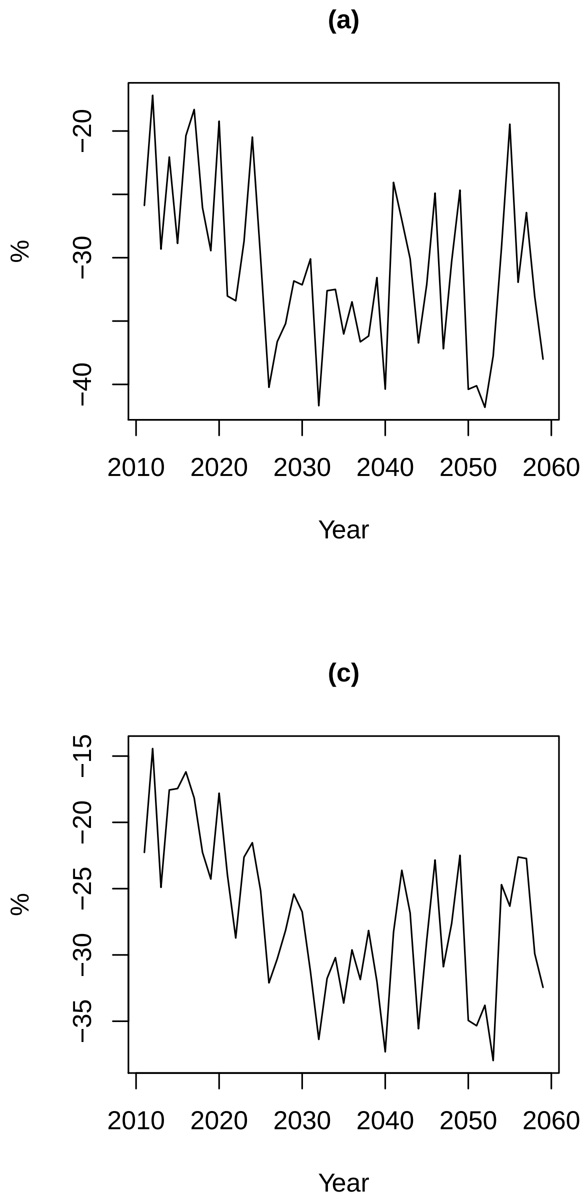


Figure 3.47: Median deviations from current conditions from climate change run on the Green River at Greendale for (a) the three high flow months (b) the single low flow fall month (c) the annual flow.

$$D_{i,j,k}^{mod} = \frac{G_{i,j,k} - \widetilde{G}_{i,j}^{BaseMod}}{\widetilde{G}_{i,j}^{BaseMod}} * 100\% \tag{3.11}$$

where $G_{i,j,k}$ is the modeled flow in month i, year j and trace k of the model run. $\widetilde{G}_{i,j}^{BaseMod}$ is the median modeled flow, over all traces, at month i and year j from a base model — in this case the DNF model run. In general, the base model could be the modeled results from any hydrologic, demand combination. Dividing by $\widetilde{G}_{i,j}^{BaseMod}$ results in a percentage deviation from the DNF run, so the result will show how much better or worse the conditions are with climate change relative to the conditions from historical hydrology repeating itself.

While Figures 3.46 and 3.47 show the deviations of future altered flows under climate change hydrology from current conditions (2011 value from DNF run), Figures 3.48 and 3.49 show the climate change deviations from DNF projected values using Equation 3.11. The results shown are for $\widetilde{G}_{i,j}^{BaseMod}$ from the DNF model run and $G_{i,j,k}$ from the model with climate change flows. This gives a view of how the hydrology is impacting the system independent of depletions, whereas the deviation from current conditions shows how the combination of depletions and hydrology is changing the system. It offers a view of how much better or worse the deviations are in the future with climate change hydrology compared to the case in which future hydrology is similar to historical hydrology. Figures 3.48 and 3.49 are similar to Figures 3.46 and 3.47 in shape though in years farther from 2011, the magnitudes differ more since the flows are compared to the same year in the DNF run in Figures 3.48 and 3.49. Since Figures 3.48 and 3.49 are similar to Figures 3.46 and 3.47 we can conclude that the deviations are more dependent on hydrology than demand, at these nodes.

3.4.5.1 Testing for Trends in Nonstationary Results

The climate change flow deviations are highly variable and in some cases a trend may not be obvious. A Mann-Kendall (MK) test can quantitatively identify if a trend exists in the data. The MK test is a nonparametric test that tests for monotonic change with time (*Helsel and Hirsch*, 2002).

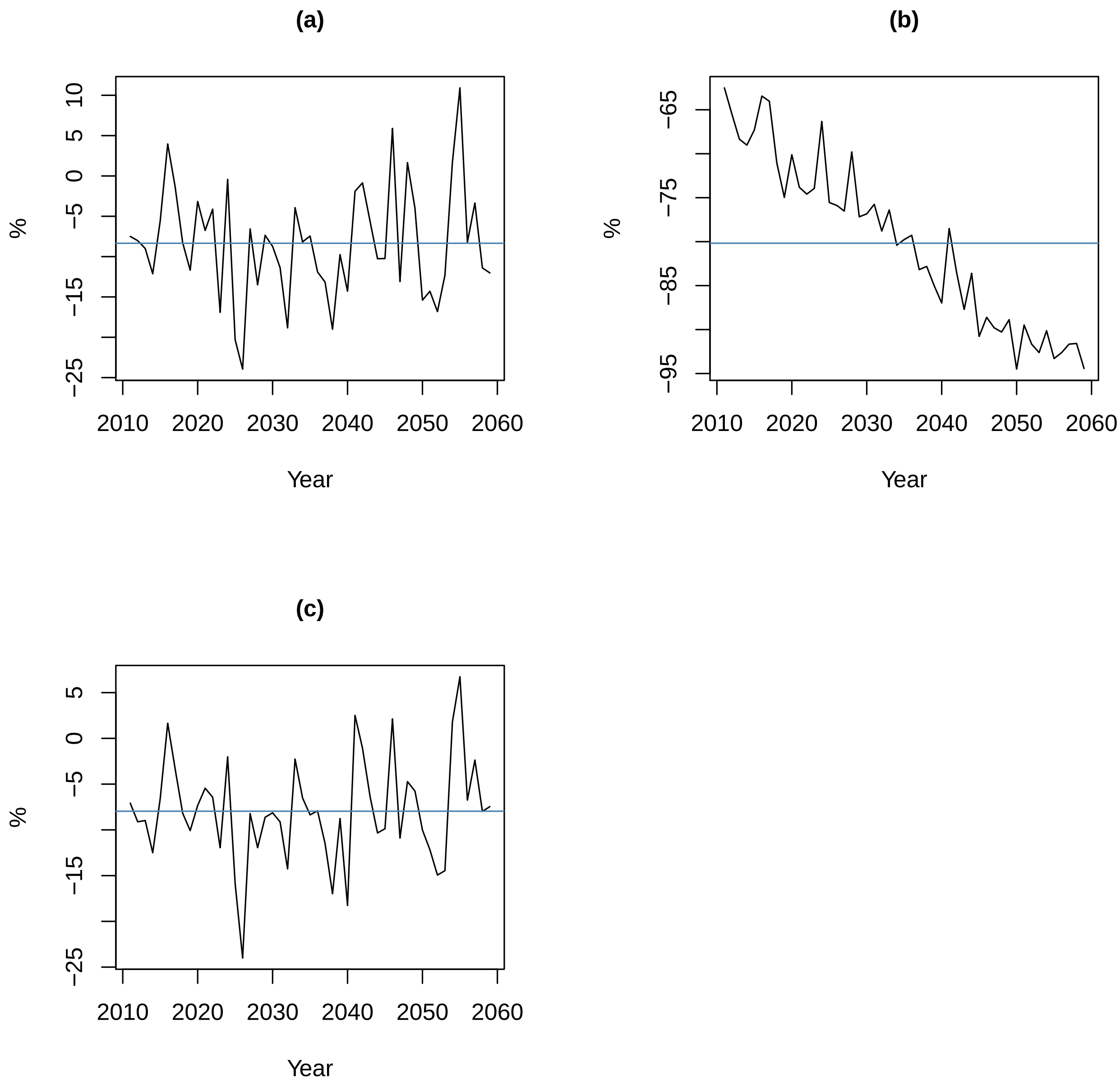


Figure 3.48: Median climate change deviations from DNF run on the Yampa River at Deerlodge with the median over all years shown in blue for (a) the three high flow months (b) the single low flow fall month (c) the annual flow.

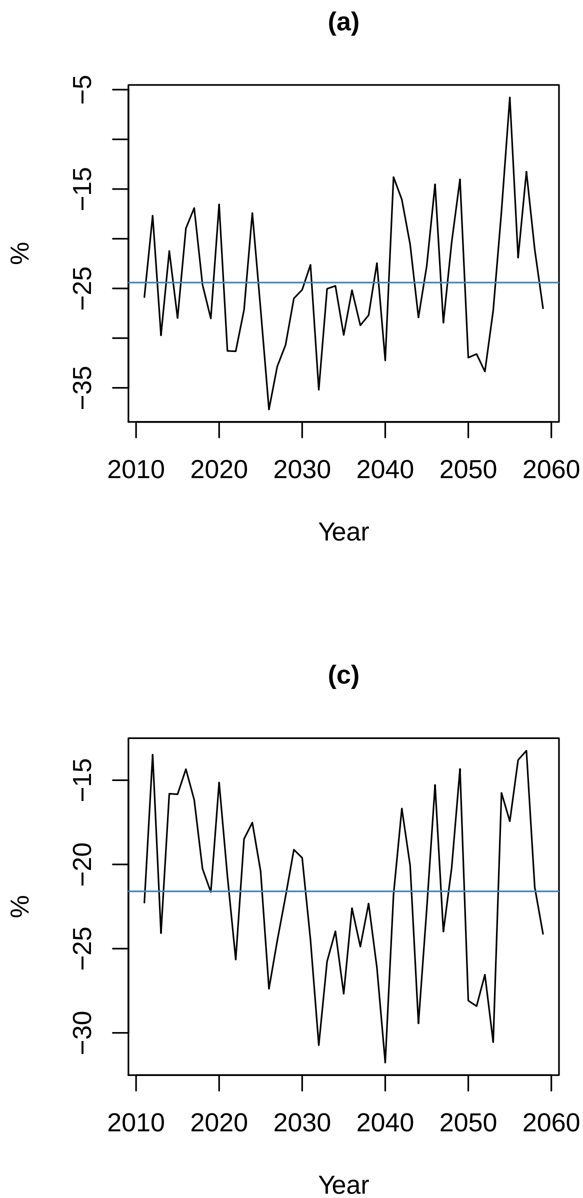


Figure 3.49: Median climate change deviations from DNF run on the Green River at Greendale with the median over all years shown in blue for (a) the three high flow months (b) the single low flow fall month (c) the annual flow.

Tables 3.5 and 3.6 show the results of testing each of the climate change deviation metrics for each time period for Deerlodge and Greendale, respectively. The tables report the p-values for the MK test for trends and the maximum confidence level that would results in a conclusion that there is a trend in the data. The p-values indicate the confidence in rejecting the hypothesis that there is no trend in the data. If the p-value is less than .05, then there is a statistically significant trend in the data at the 95% confidence level, though if the p-value is .9 there is only a trend in the data at the 10% confidence level. The maximum confidence level reports the highest confidence level that would results in identifying a trend in the data. For example, the Yampa River, high flow aggregation, deviation from projected natural flows has a trend in it at the 99% confidence level. Conversely, the Yampa River, high flow aggregation, deviation from DNF metric only has a trend in the data at the 20% confidence level. Based on these two test results we can be fairly certain there is a trend in the deviation from projected natural flows, though there is likely not a significant trend in the deviation from DNFs. By comparing the medians from the deviation from the DNF run results (blue line in Figures 3.48 and 3.49) to the trend test results, several generalizations can be made: 1) conditions can be worse than DNF conditions (negative median) but not changing through time (low confidence level in trend identification), e.g., Greendale high and annual deviations. 2) Conditions an be worse than DNF conditions while getting worse through time (high confidence level in trend identification), e.g., Deerlodge low flow deviations. 3) Conditions can be about the same and not changing through time, e.g., Deerlodge high flow deviations.

While many climate change projections indicate decreasing trends over the entire CRB, this is not necessarily the case for every sub-basin. In the climate change deviations from DNF, for the high flow months on the Yampa River, Table 3.5 shows the maximum confidence level for a trend is 20%. Since this metric shows how hydrology is changing in reference the the DNF hydrology independent of demands, this indicates that there is likely no trend in the climate change projections at this node. An analysis of the actual natural flows at this node reveals the same thing, that there is no statistically significant trend in the projected flows on the Yampa River basin. The annual flows for the Yampa River also indicate no significant trend, whereas there is a strong trend in the low flow (99% confidence level). Thus, while the low flow months are experiencing reductions in flow, the annual flows are not projected to decrease through time due to the high flow months remaining largely the same. Conversely, at Greendale (Table 3.6) the climate change deviations from DNF indicate a stronger likelihood that there is a trend in the hydrology — 75% for the high flows, 97% for the low flows and 82% for the annual flows. The lower confidence that there is a trend in the annual flows could be due to an oscillatory characteristic in the data which is discussed more below.

Even with the MK test, visual inspection of the data is still important. While the MK test can identify monotonic changes, it cannot identify other trends or oscillatory characteristics. If there are oscillatory characteristics and a monotonic trend in the data, the MK test can identify a trend given there is enough data. This is exemplified in Figure 3.50. The MK test concluded that there was a trend at the 82% confidence level for the annual climate change deviation from DNF at Greendale. However, visually a non-linear trend — or low frequency oscillation — is apparent in the data, which is highlighted by using a smoothed local polynomial function (the blue curve in Figure 3.50). Due to the short length of the data set, it is unclear if this is a non-linear (quadratic) trend or a low frequency oscillation. In either case, the visual inspection reveals what the MK test cannot. While we are concerned with trends in the data, to help predict if conditions will be better or worse in the future, the oscillatory characteristics can also provide useful knowledge, e.g., that conditions might degrade before improving again.

3.4.6 Monthly Hydrograph Boxplot

While the previous techniques compare inter-annual variability, creating boxplots of the monthly flow values allows one to compare the intra-annual variability by showing each months' flow as a boxplot. The IHA tool provides median monthly flow results along with specific parameters that report on monthly variability (*Mathews and Richter*, 2007). Figures 3.51 and 3.52 show the DNF model results for each month along with climate change results in the beginning and ending five years of the model run. The modeled flows are shown as box and whiskers to show the full

Table 3.5: P-values from a Mann-Kendall test for trends for the multiple climate change flow deviation metrics at the Yampa River near Deerlodge for all three time aggregations.

	p-value	Maximum Conficence Level For Trend Identification
High Flow - Deviation From Historical Natural	2.0513E-01	79 %
High Flow - Deviation From Current Conditions	1.5495E-01	85 %
High Flow - Deviation From Projected Natural	1.7511E-04	99 %
High Flow - Deviation From DNF	8.0261E-01	20 %
Low Flow - Deviation From Historical Natural	1.9570E-19	99 %
Low Flow - Deviation From Current Conditions	1.1643E-18	99 %
Low Flow - Deviation From Projected Natural	9.5841E-21	99 %
Low Flow - Deviation From DNF	1.1336E-17	99 %
Annual Flow - Deviation From Historical Natural	9.7533E-02	90 %
Annual Flow - Deviation From Current Conditions	6.1414E-02	94 %
Annual Flow - Deviation From Projected Natural	1.8435E-07	99 %
Annual Flow - Deviation From DNF	6.8538E-01	31 %

Table 3.6: P-values from a Mann-Kendall test for trends for the multiple climate change flow deviation metrics at the Green River near Greendale for all three time aggregations.

	p-value	Maximum Conficence Level For Trend Identification
High Flow - Deviation From Historical Natural	6.4647E-04	99 %
High Flow - Deviation From Current Conditions	3.8814E-03	99 %
High Flow - Deviation From Projected Natural	1.6248E-03	99 %
High Flow - Deviation From DNF	2.5161E-01	75 %
Low Flow - Deviation From Historical Natural	1.6716E-05	99 %
Low Flow - Deviation From Current Conditions	7.0752E-05	99 %
Low Flow - Deviation From Projected Natural	1.0779E-01	89 %
Low Flow - Deviation From DNF	3.3246E-02	97 %
Annual Flow - Deviation From Historical Natural	2.7765E-05	99 %
Annual Flow - Deviation From Current Conditions	3.0418E-04	99 %
Annual Flow - Deviation From Projected Natural	6.0499E-10	99 %
Annual Flow - Deviation From DNF	1.8152E-01	82 %

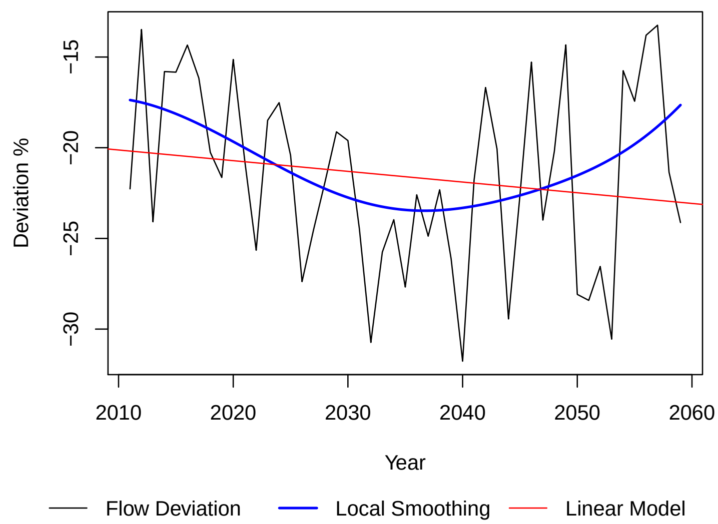


Figure 3.50: Annual climate change deviation from DNF at Greendale with a local polynomial and linear trend fit to the deviations.

range of variability into the future. The boxes show the inner quartile range, while the whiskers extend to the 5th and 95th percentiles; the horizontal, bold line reports the median flow value. A shaded back drop shows the 5th and 95th percentiles of historical natural flows to demonstrate the historical variability; the median historical natural flow is shown as a black line. The model runs are split into a beginning and ending five year periods to show changes in flow through time. A single year is not used since the climate change data is highly variable from one year to the next, thus a range of years produces a more thorough picture of beginning and ending conditions. Additionally, showing multiple model runs allows one to compare important results in a qualitative manner. For example, Figure 3.51 shows that the ending decade climate change flows are more variable than historic flows in most months and more variable than the DNF results. Additionally it shows a decrease in the median June flow with an increase in the median April flow, indicating there is a shift in the seasonal runoff. The figure also reveals that the median 2011 DNF values are generally less than the historic median and that for May through September, the median 2011 climate change values are all much less than the historic medians. The figure also demonstrates that climate change impacts the flows more than increased demands do at this node: the difference between the 2059 and 2011 medians is much greater for the climate change values than for the DNF values. Since Greeendale is directly below a reservoir, Figure 3.52 shows less variability in the high and low flows (5th and 95th percentiles of the modeled flows), though there are shifts in the median values.

In the case of the node below a reservoir (Figure 3.52), the figure visually depicts how the reservoir operates during the year and how hydrology and demands impact the operations. In Figure 3.52, the boxplots in June highlight several interesting features. In the DNF hydrology from the beginning to end of the run, there is a decrease in median and 25th percentile release, though the 5th, 75th and 95th percentile flows stay the same. This indicates that demands alone decrease the typical release, though the high flow releases are made about the same amount of time. In the Climate Change hydrology, the releases do not change as much from the beginning to end, however even in the beginning of the run, the median release is already much lower than the

DNF median release. Here, the results show that climate change hydrology reduces the releases more than all increasing demands do.

Table 3.6 indicates there is a trend at the 75, 97 and 82 % confidence levels in the climate change deviations from DNF in the high, low and annual aggregations, respectively. Figure 3.52 visually confirms that there is a decrease in the values in the climate change results compared to the DNF results, during most every month. Conversely, Table 3.5 reports there is likely no trend in the high flow months climate change deviations from DNF at Deerlodge (trend identified at the 20% confidence level). Figure 3.51 shows decreases in monthly flows in May and June, though there are increases in March and April. Since the statistic is computed for the three high flow months, the increases in March and April must balance out the decreases in May and June, which results in no change in the three high flow months from the DNF to climate change results.

The boxplot provides comparisons of most of the metrics described in the previous sections: the comparison to current conditions (the DNF 2011 value), the comparison to historical natural (median and 5th to 95th percentile range) and climate change to DNF comparison and how they change through time. The monthly data shows, how each month is impacted by climate change and whether there is a shift in the month of the annual peak flow month. Additionally, the range of variability is shown and can provide valuable information, including how variability is changing through time (by comparing the beginning and ending boxplots of a single scenario) or how variability is changing across scenarios (by comparing boxplots of two different scenarios during the same time period).

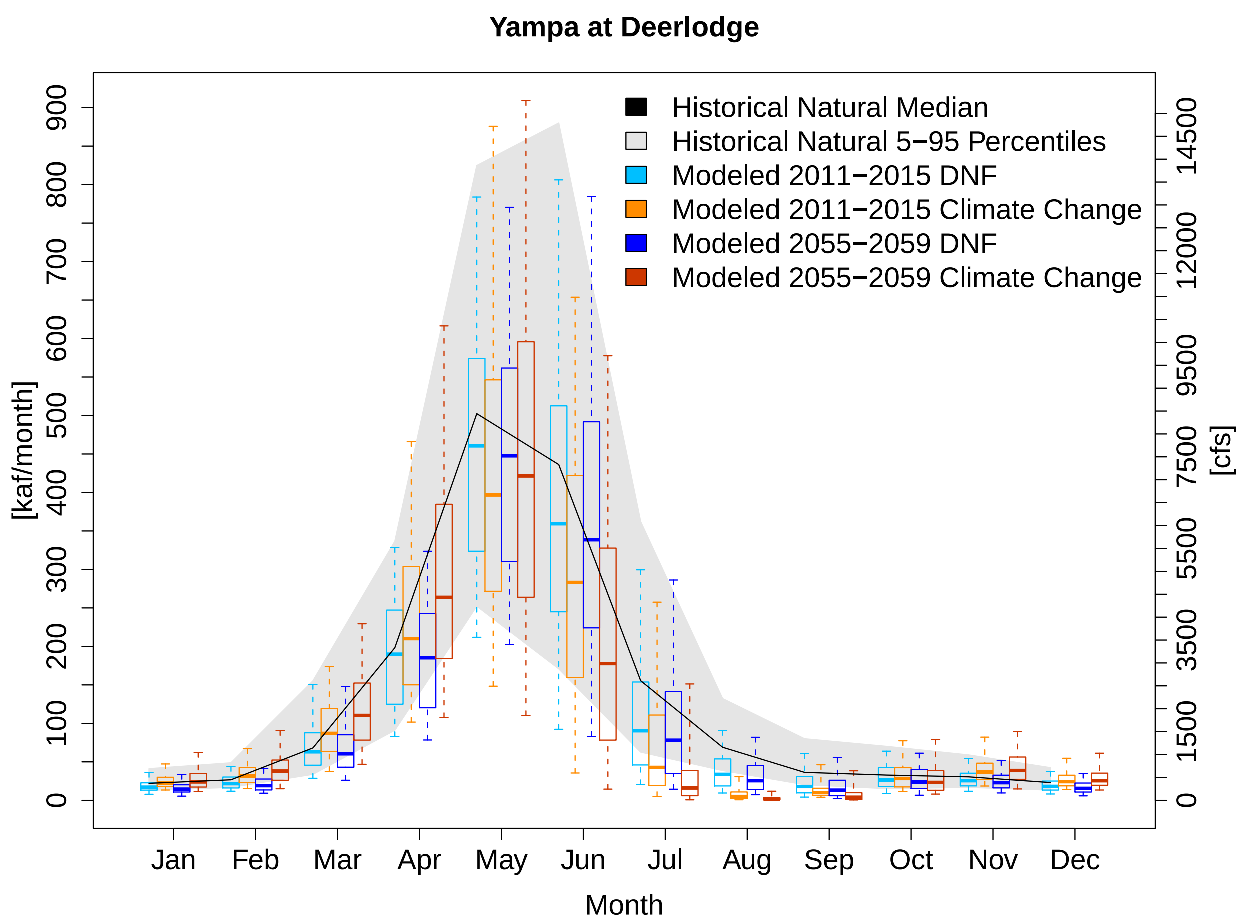


Figure 3.51: Monthly modeled flows on the Yampa River at Deerlodge for the DNF and Climate Change model runs.

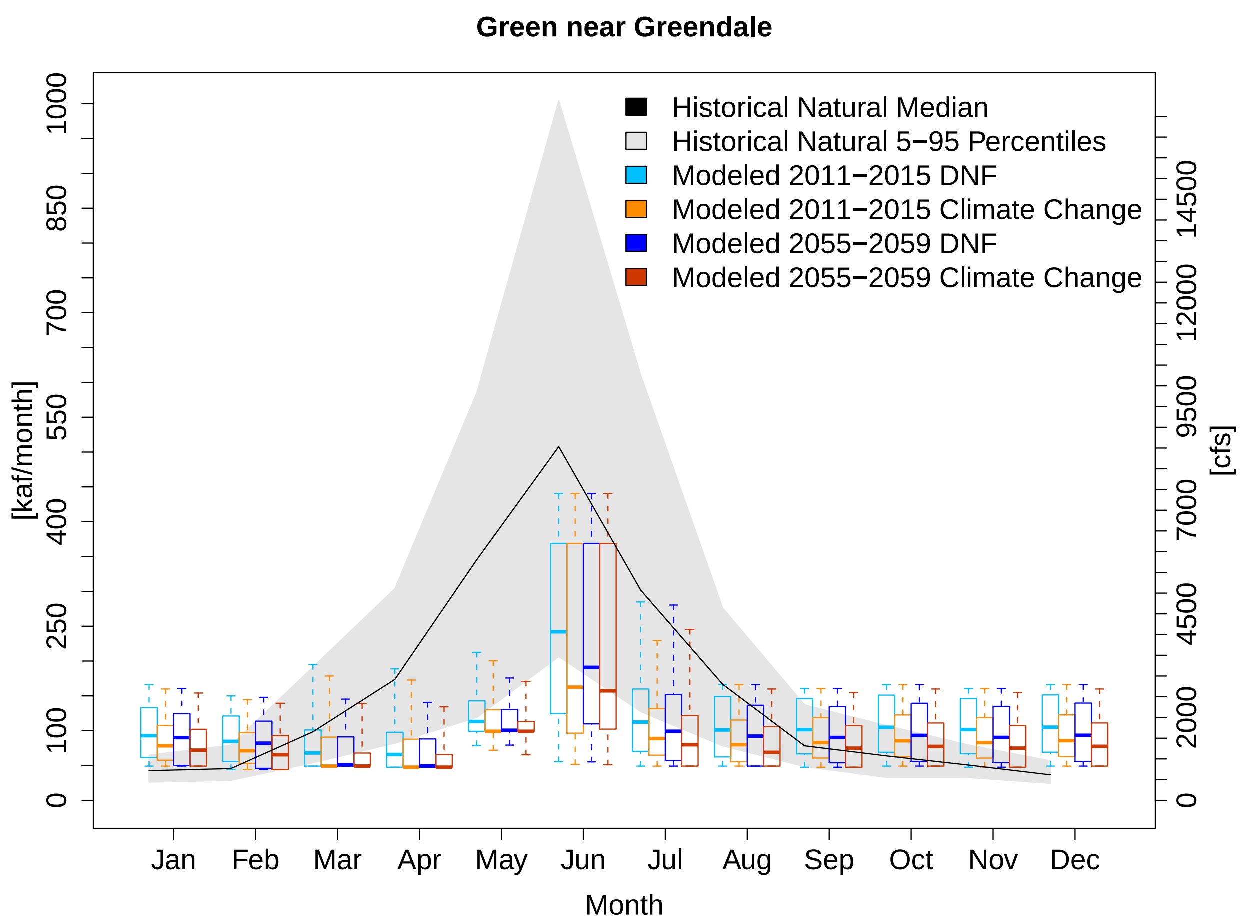


Figure 3.52: Monthly modeled flows on the Green River at Greendale for the DNF and Climate Change model runs.

Chapter 4

Example Applications

This Chapter applies the techniques described in Chapter II to the Colorado River Basin and presents example results. The application is used to demonstrate how the methods and metrics described in the previous chapter can be integrated to provide basin wide information about the future reliability of environmental flows. The data and projections do not represent anticipated conditions nor do they suggest the future ecological health of the basin; rather they demonstrate the kinds of results and comparisons that can be made while offering explanations of the underlying mechanisms driving the results. We suggest that these techniques could be applied in the future to scenarios and data that are used in realistic more realistic projections.

First we briefly describe the Research Model the model of the Colorado River system that incorporates the techniques developed in this research. The Research Model is a modification of Reclamation's Colorado River Simulation System (CRSS) model, the agency's official planning model for the Basin. The official CRSS is described and the Research model compared to it. Four scenarios are described which are the application examples for the Research Model. The first scenario, the Baseline, is compared to the official version of CRSS to demonstrate the impacts of detailed modeling of e-flow requirements in reservoir operations. Next, results comparing the four scenarios are presented and discussed. A summary of the techniques and results concludes the chapter.

4.1 The Research Model

The modeling techniques and metrics developed in this research were integrated into a model of the Colorado River system (Research Model). The Research Model is based on the official version of Reclamation's Colorado River Simulation System (CRSS). The Official version of CRSS is described in detail in *Bureau of Reclamation* (2007), particularly in Appendix A. The Official version simulates Upper Basin reservoir operations by using a rule-curve based approach while the coordinated operations of Lake Powell and Lake Mead are explicitly represented. The model input includes user demand basin-wide and natural flow at 29 nodes basin-wide. The 2007 Upper Colorado River Commission (UCRC) schedule is used for the Upper Basin demands while the Lower Basin demands are the same as those in *Bureau of Reclamation* (2007). This schedule increases demands in the Upper Basin until 2060, though certain demands may peak before 2060. The model results of the Official version presented here were simulated using the direct natural flow data with ISM to create 102 traces of natural flow input. The version was updated to start with reservoir conditions from December 2009 to simulate a model horizon of 2010 through 2060. Rather than revert to the no-action alternative after 2026, the ROD specifications for shortage and surplus conditions as well as the coordinated operations of Powell and Mead are extended through 2060. The timeframes specified by the ROD for intentionally created surplus (ICS) were applied, i.e., ICS creation through 2026 and delivery through 2036 (*Bureau of Reclamation*, 2007).

The Research Model was developed by modifying CRSS with the methods and metrics described in Chapter 3. The operating rules for Flaming Gorge and Navajo were updated to capture the ROD required reservoir operations to meet daily e-flow requirements as described in the previous chapter. While the new rules were compared to actual operations (see Section 3.3), they have not been verified or accepted by Reclamation. Additionally, Fontenelle reservoir's operating rules were updated and the rule execution order was reversed to allow for a more intuitive representation of the new Flaming Gorge and Navajo rules. Several small modifications were made to the rule order, though they have no major impact on simulation results. The Resarch Model also differs cosmetically from the Official CRSS in several ways, e.g., stream gages were added throughout the basin, though these differences have no impacts on model results.

4.2 Scenario Descriptions

The Research Model was applied to the following cases, or scenarios. Each scenario represents a variation on the input hydrological sequences or the Upper Basin demands.

4.2.1 Baseline Scenario

The Baseline Scenario reflects hydrology and demands are identical to those in CRSS. Direct natural flow using ISM drives the model and the Upper Basin demands are identical to the currently projected UCRC demand projection.

4.2.2 Frozen Demands Scenario

The Frozen Demands (Freeze) Scenario represents a modification to future Upper Basin demands. For the entire Upper Basin, all users demand schedules were 'frozen' at their 2010 demand levels. For most users this represents a reduction in projected use over the model horizon and at the state level it is a reduction in the projected use for all Upper Basin states. The Lower Basin demands were not modified, as all Lower Basin states are already at their full allocation.

4.2.3 Climate Change Hydrology Scenario

The Climate Change Hydrology (Climate Change) Scenario represents an alternative hydrological future which differs from historical hydrology. The Climate Change Scenario is identical to the Baseline Scenario except that the direct natural flow used for the future inflows are replaced by simulated natural flows derived from climate projections. The projections from 16 Global Climate Models (GCM) for three future emission scenarios (with multiple initial conditions) were downscaled, bias-corrected and moved through the Variable Infiltration Capacity (VIC) hydrologic model (*Liang et al.*, 1994) to produce 112 independent hydrologic inflow traces which are transient through time. The climate change inflow traces are preliminary projections that have not undergone a secondary bias-correction. Each trace represents one plausible future scenario with no explicit probability of occurring.

Although the model can be successfully run through December 2099 with the climate change flow input, the Climate Change Scenario runs were limited to 2060 to be comparable with the other scenarios.

4.2.4 Frozen Demands with Climate Change Hydrology Scenario

The Frozen Demands with Climate Change Hydrology (Freeze with Climate Change, sometimes abbreviated Freeze w/ C.C.) is a combination of the Freeze and Climate Change Scenarios. The Upper Basin demands are frozen at their 2010 levels, and the direct natural flows are replaced by the climate change projections.

4.3 Model Results

This section first compares the baseline scenario to the official CRSS results, then compares results of the Baseline, Freeze, Climate Change and Freeze with Climate Change scenarios. We compare the four scenarios to one another for required e-flow metrics below Navajo and Flaming Gorge, flow alteration metrics and system variables, e.g., Powell releases and Mead storage levels.

4.3.1 Comparison to CRSS

This section presents and analyzes the differences between the Research Model Baseline Scenario and CRSS results. The analysis does not include the flow alteration metrics or any daily flow metrics since CRSS does not have the capabilities to compute these metrics. The monthly baseflow metrics below Flaming Gorge and Navajo, the monthly storage levels and monthly releases, the annual energy generated and the overall system conditions indicated by Powell and Mead illustrate the differences between the Baseline Scenario and the Official CRSS results.

The baseflow requirements are specified at the Greendale and Jensen gages for the Green River, while the Bluff gage monitors the baseflow requirements on the San Juan River. See Section 3.3.2 for a full discussion on the use of solely the Bluff gage to monitor the San Juan e-flows. Figure 4.1 shows a boxplot of the flow conditions at Greendale, Jensen and Bluff for the baseflow months. The red lines indicate the acceptable range of baseflows as specified by the respective RODs (*Bureau of Reclamation*, 2006a,c). For the Green River, the Greendale gage represents the releases from Flaming Gorge, while the Jensen gage is a sum of the releases from Flaming Gorge and the tributary flows from the Yampa River. For the Greendale gage, Figure 4.1 shows that the official model does not constrain the releases within a certain range, particularly in January and February. However, the Baseline Scenario constrains Flaming Gorge's releases to be entirely within the acceptable range (the whiskers stop exactly at the acceptable range which is why the horizontal tick does not show up for the Baseline Scenario). The monthly flows are also more normally distributed for the Baseline Scenario than for CRSS. The median values for August through October are at the minimum release of 800 cfs for CRSS with only 50 percent of the values having higher releases than 800 cfs.

While the Baseline Scenario flows are entirely within the range at Greendale, this is not always the case at Jensen. Since both the Flaming Gorge releases and Yampa River flows impact the Jensen gage, the flows are sometimes outside the prescribed range. While Flaming Gorge is always releasing within its constraints, the Yampa River provides additional variability, e.g., the Jensen gage could be above its maximum constraint even with Flaming Gorge releasing at its minimum constraint if the Yampa River was experiencing abnormally high flows. The figure does show that the majority of the time, the flows are within the acceptable range for the Baseline Scenario.

The Bluff results are comparable to the Jensen results in that the flows are composed of Navajo releases, tributary flows and return flows from a water user that diverts directly from Navajo reservoir. In the Baseline Scenario, the median values are within the range for all of the baseflow months except for August and September. This shows a noticeable reduction of flows

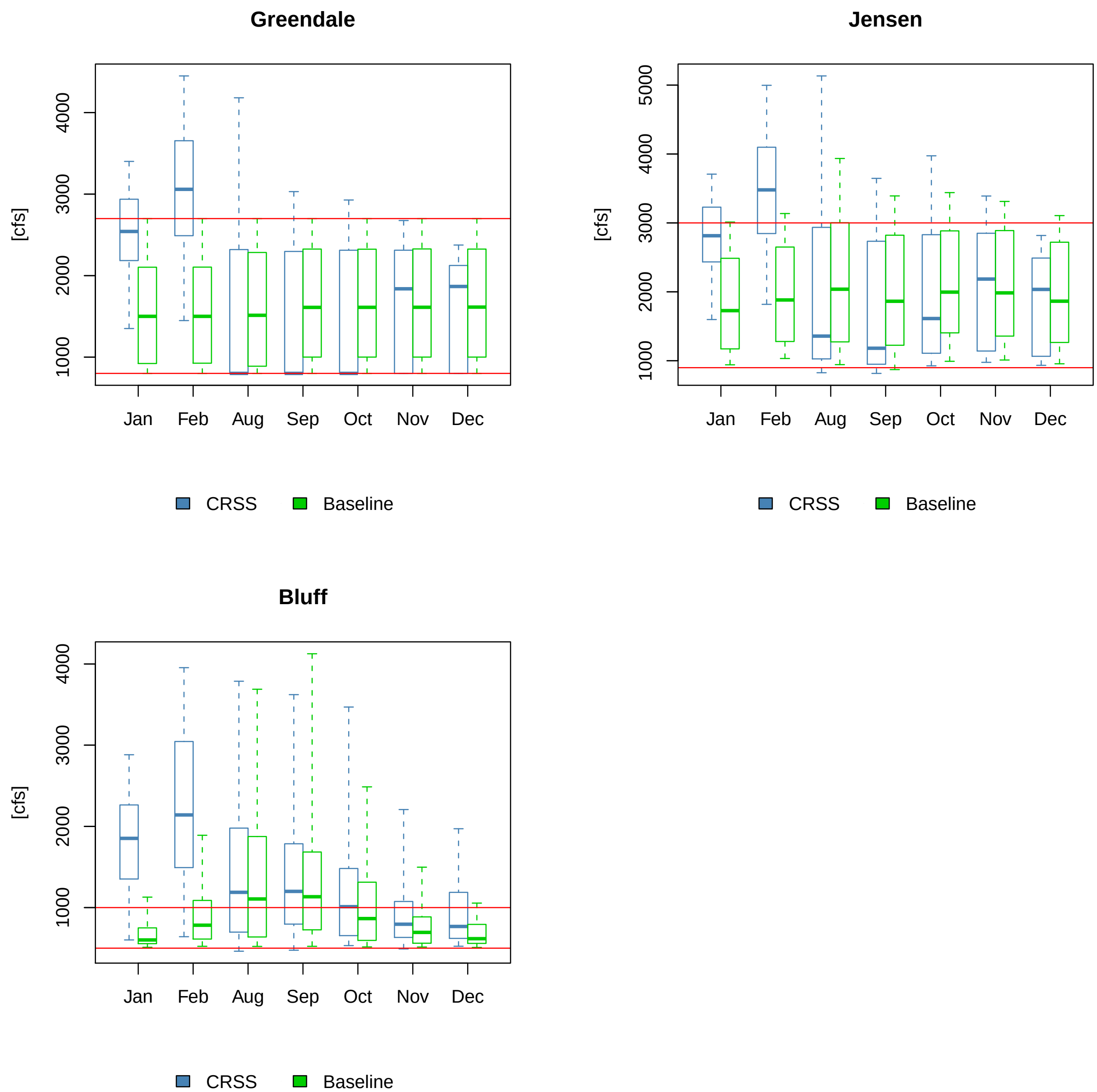


Figure 4.1: Baseflow months shown for the Green River at Greendale and Jensen and the San Juan River at Bluff for the Baseline and Offical Scenarios. Red lines indicate range of baseflows as prescribed by the respective RODs.

from the CRSS results, particularly in January and February. The minimum flow threshold of 500 cfs is never violated for the Baseline Scenario, though it rarely is in the CRSS results. Navajo will increase its release in order to meet the minimum flow of 500 cfs, though it will not reduce its release below 250 cfs. Thus, the maximum constraint is more easily violated due to tributary flows. Overall, the Baseline rules ensure that the reservoir releases are not too high in baseflow months, though the variability in the tributary flows cannot be controlled.

The pool elevations and releases for Flaming Gorge and Navajo are impacted by the new rules and thus differ from the CRSS model. Section 3.3.4 presents these impacts and comments on the differences. In summary, Navajo releases more water and also has higher median storage levels. The higher releases are a result of meeting the e-flow requirements, though the increased storage level is a result of a changing diversion, not a result of e-flow requirements. Conversely, Flaming Gorge releases more and has lower median storage levels, though both reservoirs have monthly release patterns that are more 'naturally' shaped. Figure 4.2 shows the 10th, 50th and 90th percentiles of the annual energy production at Flaming Gorge. The median generation is higher for the Baseline Scenario than for the CRSS results, though both the 10th and 90th percentiles are lower. This directly maps to the annual releases from Flaming Gorge which are discussed in Section 3.3.4.

Even though there are larger annual releases at both reservoirs, there are also higher annual shortages in the basins. Figure 4.3 shows the average annual shortages for the CRSS results and the Baseline Scenario for the Green and San Juan Rivers as a percentage of the scheduled depletions. The shortages were computed by subtracting the user's actual depletion from the requested depletion for each month and summed to obtain the annual shortage. The shortages for the Green River represent all users on the Green and Yampa Rivers upstream of Green River, Utah. Both the White and Duchesne Rivers flow into the Green River above Green River, Utah, though the users on these rivers are not used in the shortage computation since they are not impacted by different Flaming Gorge operations. The shortages for the San Juan River represent shortages to all users in the San Juan Basin upstream of Bluff, Utah. In both cases, the average annual shortages increased

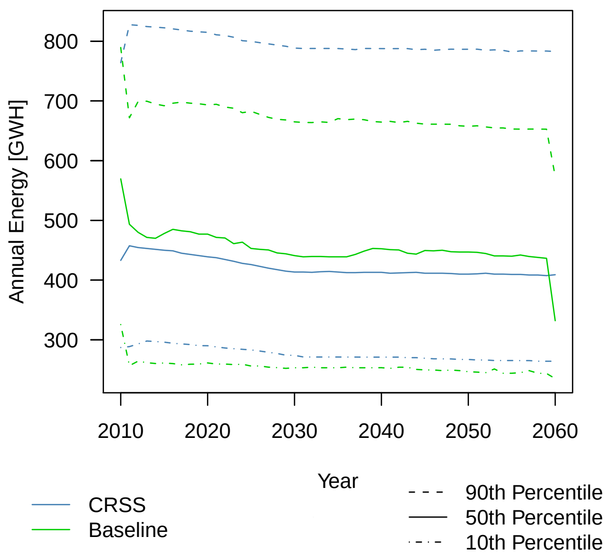


Figure 4.2: Annual energy produced at Flaming Gorge for the Official and Baseline Scenarios.

in the Baseline Scenario, though the annual shortages are quite low in both cases: less than 5 % on the Green River and less than 1.2 % on the San Juan River.

Figures 4.4 and 4.5 demonstrate how the changes in operations at Flaming Gorge and Navajo impact the system as a whole. Figure 4.4 shows very little difference in the probability that Powell's release is greater than 8.23 MAF and virtually no differences in the annual energy production at Powell. The 10th percentile of energy production is actually higher toward the end of the model run in the Baseline Scenario than it is in the CRSS results. This is likely a result of the increased releases from Navajo and Flaming Gorge. Figure 4.5 also shows there are only small differences in the end-of-year pool elevation (storage) of Mead.

The Baseline Scenario includes new operating rules for Navajo and Flaming Gorge that better represent their relatively new operating procedures that aim to meet downstream e-flow requirements. In doing this, the annual releases at these reservoirs increase though shortages also increase. The increases in annual release were due to increased spring peak releases in the months of April through July. Typically, the tributaries peak in this period too, thus there is usually adequate available water for users. The reservoirs then have lower base flow releases during the remainder of the year and do not typically increase their releases to ensure the users can divert their entire requested diversion. Thus, while the spring peak releases contribute to an overall larger annual release, the lower base releases lead to overall greater shortages to users. With the larger annual releases, the energy produced at Flaming Gorge is also higher. Finally, while there are differences at Navajo and Flaming Gorge between the Baseline and CRSS results, there are only small differences at Powell and Mead.

4.3.2 Scenario Comparisons

This section compares values of the flow alteration metrics, required e-flow metrics and system operations for the Baseline, Freeze, Climate Change and Freeze with Climate Change Scenarios. Each metric is presented and discussed for all scenarios in the respective section.

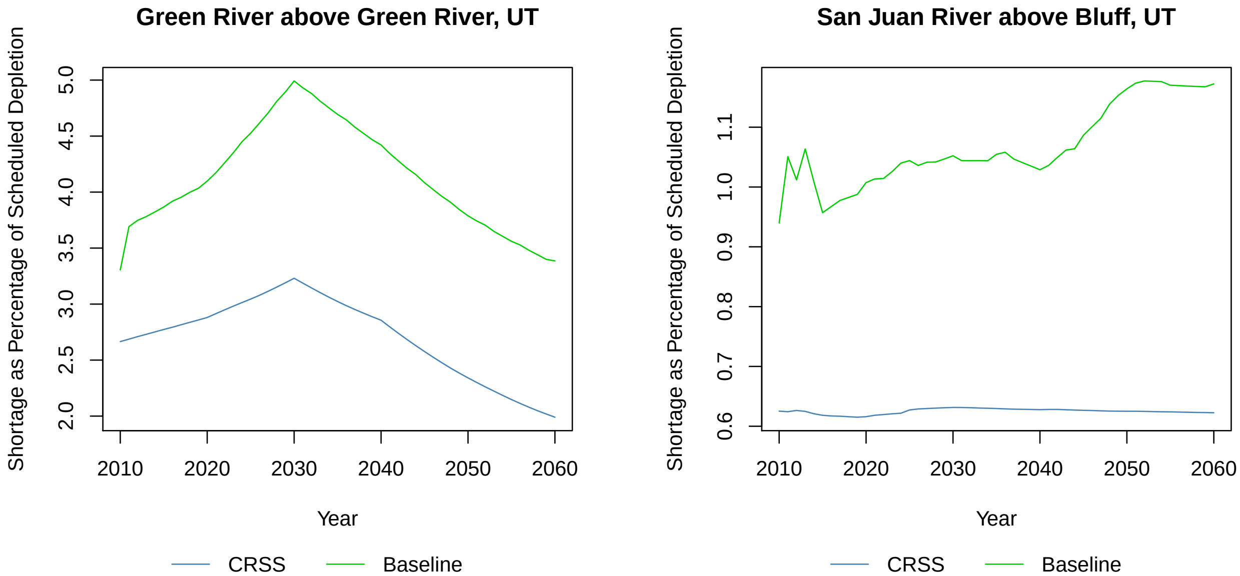


Figure 4.3: Average annual shortages above nodes on the Green and San Juan Rivers for the Official and Baseline Scenarios.

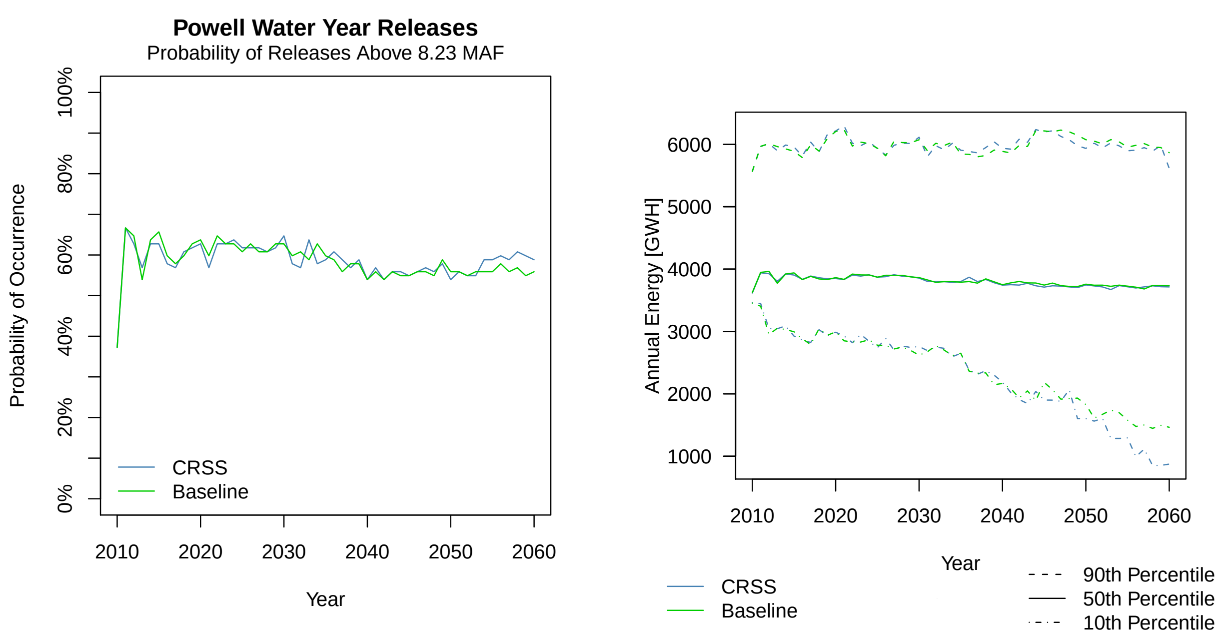


Figure 4.4: Probability that Powell's water year release is greater than 8.23 MAF and annual energy production at Powell for the Baseline and Official Scenarios.

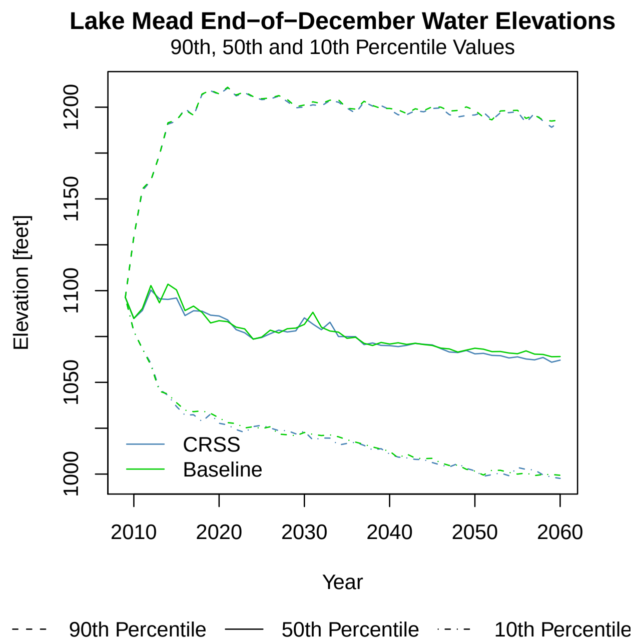


Figure 4.5: 10, 50 and 90th percentiles of end-of-December pool elevation at Powell for the Baseline and Official Scenarios.

4.3.2.1 E-flow Requirements

This section presents ROD specified e-flow requirements below Flaming Gorge and Navajo, focusing on the peak flow and base flow requirements. Even though the reservoirs' storage levels and releases are not e-flow requirements, they are presented alongside the e-flow metrics since they are directly impacted as a result of operating to meet the e-flow requirements.

To evaluate the required e-flow metrics at Jensen, downstream of Flaming Gorge, the daily Flaming Gorge releases (Section 3.3) were combined with daily disaggregated flows from the Yampa River (Section 3.1). The target flows below Flaming Gorge change with the hydrologic year type on the Green River, which is computed based on the April – July unregulated inflow into Flaming Gorge reservoir. Figures 4.6 and 4.7 show two example e-flow requirements at Jensen. Figure 4.6 presents the percentage of years that meet the single day peak flow target of 20,300 cfs for all four scenarios. The red horizontal line represents the long-term, expected number of years that will meet this requirement; this particular target is required in all moderately wet years and is satisfied in wet years since in wet years the single day target is greater than 20,300 cfs. Since wet years are expected to occur 10% of the time and moderately wet years are expected to occur in 20% of years, the long-term target for this requirement is that 30% of years should meet or exceed the single day peak of 20,300 cfs. The number of years that meet the year target are broken up into decades, with the final group showing the percentage of years over the entire model run that meet the target. The separation of results into decades is somewhat arbitrary but was meant to illustrate how the target percentages and the number of years meeting the target can vary with time. Since the hydrologic year types that actually occur in the model do not necessarily occur with the expected distribution described above, the red crosses represent the target number of years that should meet the requirement for each decade and scenario. For example, in the Baseline Scenario about 40% of all years were classified as moderately wet or wet years throughout the entire model run, instead of the expected 30%. This particular target is met in all cases, i.e., all decades and scenarios have greater than the required number of years meeting the requirement. Based on the decadal target percentages, the results show that there are less moderately wet and wet years in the climate change scenarios than in the scenarios driven by DNF. Additionally, the static demand levels (the freeze scenarios) slightly increase the number of moderately wet and wet years while also increasing the number of times the target is met. This result is intuitive since lower demands on the Yampa River will lead to higher peak daily flow rates.

Figure 4.7 shows the number of years that meet the two weeks at 18,600 cfs requirement. Two weeks at 18,600 cfs is required for all moderately wet years, one in four average years and will be met in all wet years since wet years are required to have 4 weeks at 18,600 cfs, thus the long-term target is that the requirement be met in 40% of years. Again, the long-term target is computed based on the expected year type distributions: 10% wet years, 20% moderately wet years and 40% average years (only have to meet the target in one-fourth of the average years). While this requirement is never met, some of the same trends that were described above are present. The number of average through wet years decreased in the climate change scenarios and the static demands slightly increased the number of years that meet the target. In both cases, the decadal targets for the climate change scenarios are closer to the the long-term target than the decadal targets for the Baseline and Freeze Scenarios. This is an artifact of the hydrologic year typing computation. As shown in Section 3.2, when using a moving threshold for the year type threshold, the distributions tend to shift more towards the expected distribution. The shift in distributions of year types is more pronounced in the variable climate change hydrology than in the DNFs. For example, the percentage of wet year types will be closer to 10% in the climate change runs than in the DNF runs.

Figure 4.8 presents the baseflow requirements at the Greendale and Jensen gages below Flaming Gorge. The flows over each of the baseflow months are depicted as boxplots with the allowable range of baseflows shown as red lines. The Climate Change Scenario has a reduced median flow and the 25th percentile has collapsed to the minimum allowable base flow indicating that 25% of the time, the releases from Flaming Gorge are at the minimum allowable release. The Freeze with Climate Change Scenario does increase the median flows and shift the 25th percentile

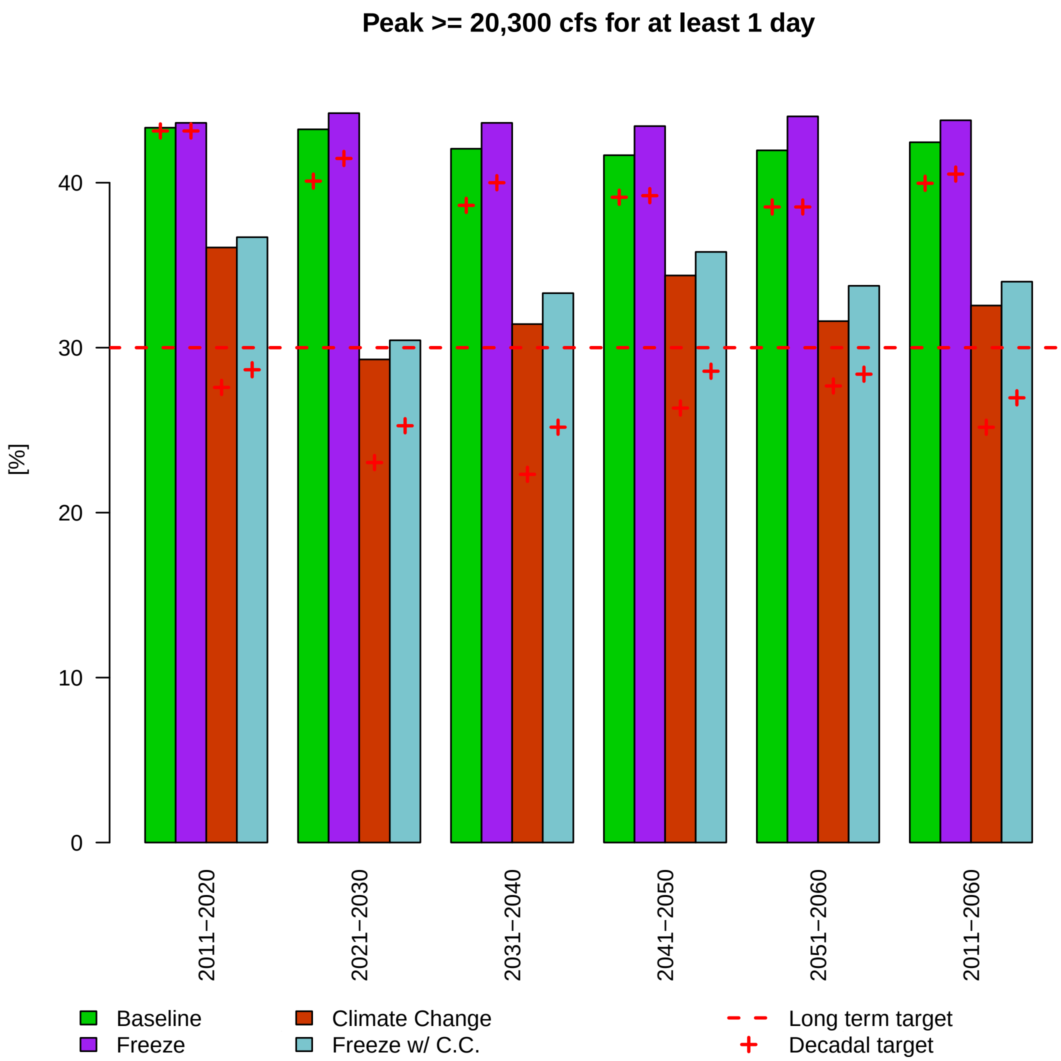


Figure 4.6: Comparison of the percentage of years which met the single day peak of 20,300 cfs target at Jensen for all scenarios.

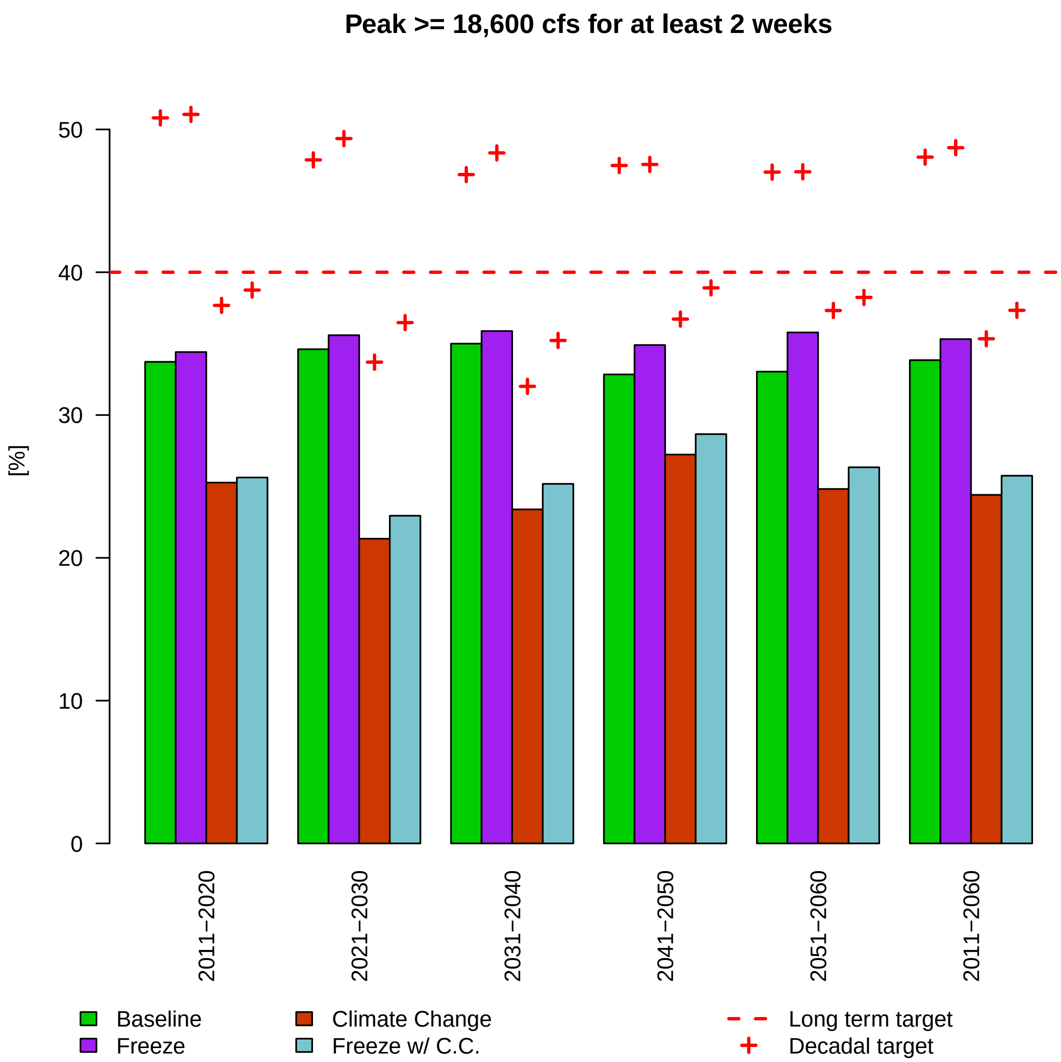


Figure 4.7: Comparison of the percentage of years which met the two weeks at 18,600 cfs target at Jensen for all scenarios.

up from the minimum slightly. Again, the benefit of the static demands is not as great as the reduction due to climate change. The same trends show up at Jensen, though the variability is increased due to the Yampa River. For the Climate Change Scenario, in August and September, there are some years which are below the minimum threshold. Since Flaming Gorge is always releasing at least the minimum requirement, the Yampa River must be especially low. The reductions in median flow are greatest in August – October, indicating that the Yampa River reductions are greatest in these months, since the reductions in Flaming Gorge's releases were equivalent in all months.

One reason the baseflows are reduced in the Climate Change Scenario is that the storages are lower after the spring peak releases than they are in the Baseline Scenario. Since the baseflows are set to meet a May first storage target, the releases can be lower to meet the same storage target. Figure 4.9 shows that the median storage in July through November is lower in the Climate Change Scenario than in the Baseline Scenario. Since the storage is lower in July, the baseflow releases are set lower to meet the same May first target. The Climate Change Scenario also has higher variability in the storages. Additionally, the variance is similar in the June releases, though the median is lower. This indicates that the higher release targets are still made in the Climate Change Scenario, but less often than they are in the Baseline Scenario.

The Navajo peak flow requirements also represent a combination of the reservoir releases and tributary flows. In this case, the tributary flows were generated using an average daily hydrograph rather than the disaggregation method presented in this thesis. It is unclear what impacts the daily disaggregation method would have on the peak flow metrics below Navajo, though this is one item that should be addressed in any future work. Navajo is not operated based on hydrologic year types and the required flows and durations are expressed in terms of how often they should occur along with the maximum interval between occurrences, e.g., a flow of 2,500 cfs for 10 days should occur in 80% of years with a maximum interval between occurrences of three years. Due to the nature of the requirements, the results are presented for each trace. For each trace, the percentage of years the requirement occurs is computed as is the maximum interval between oc-

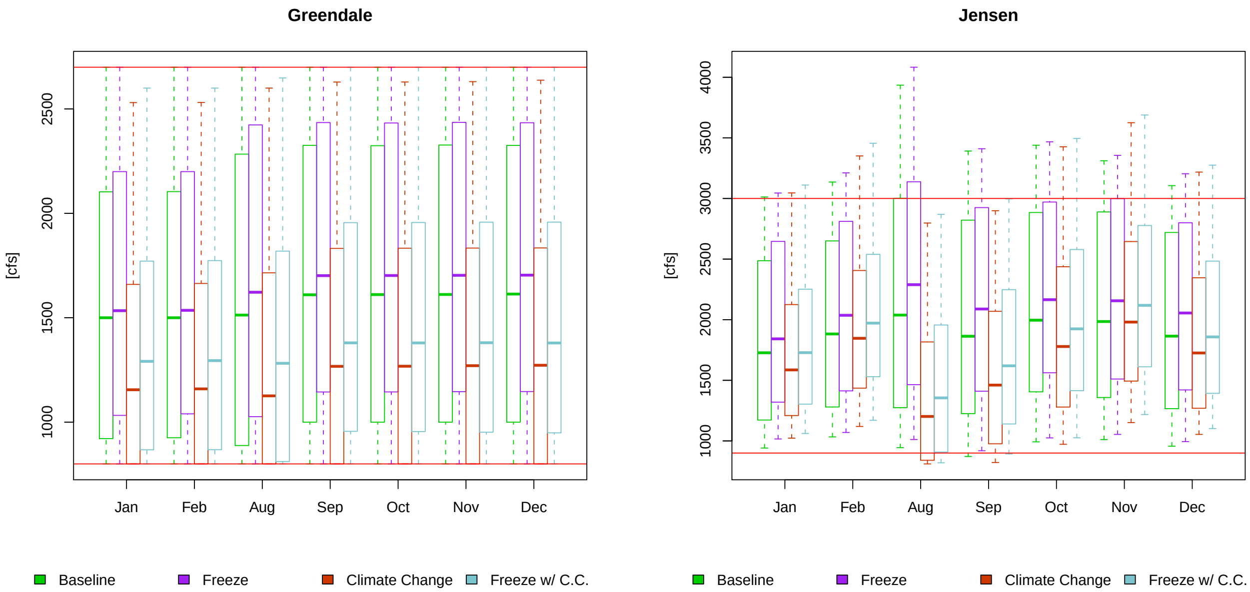


Figure 4.8: Boxplots of baseflow months on the Green River for all scenarios.

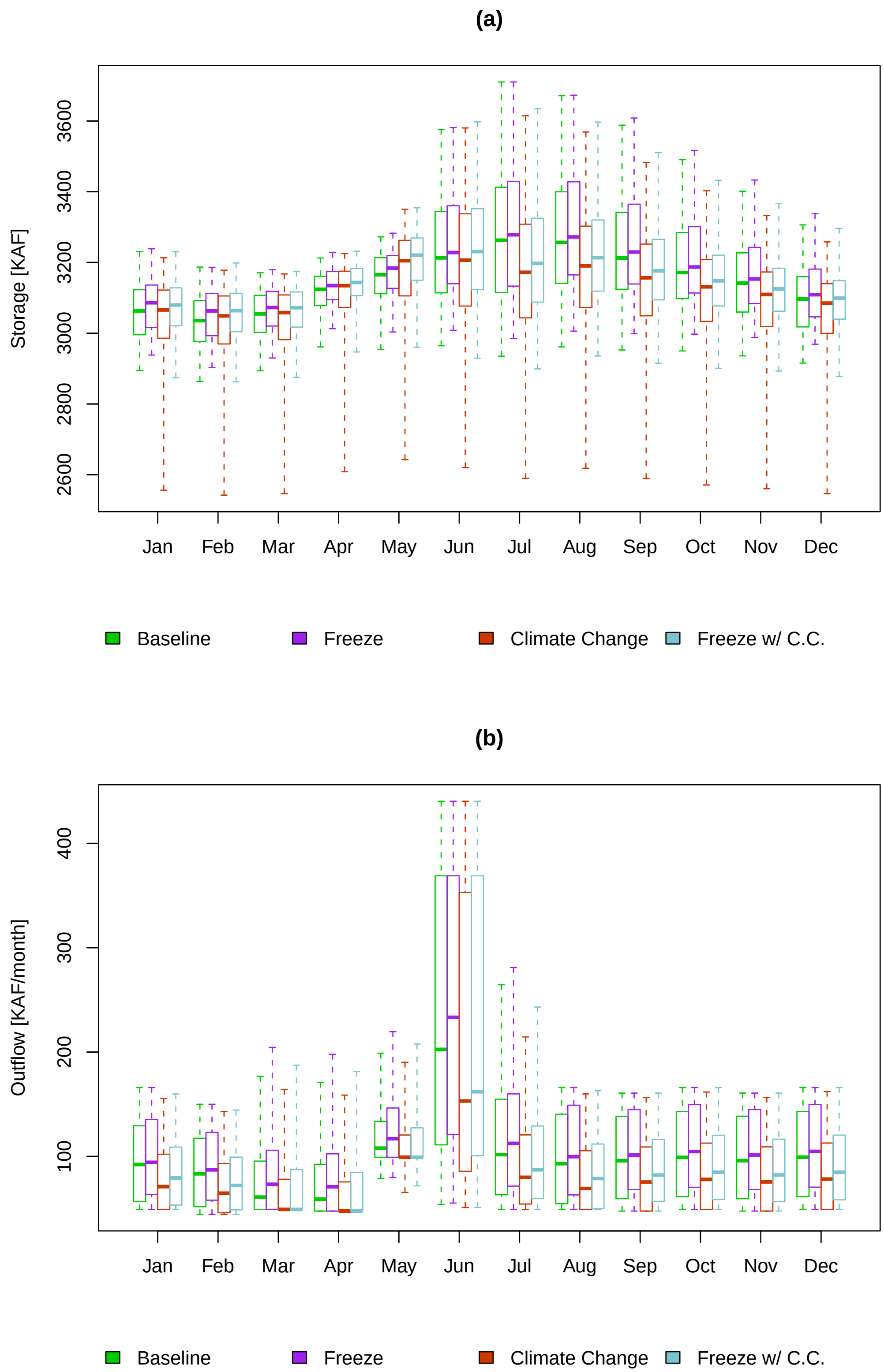
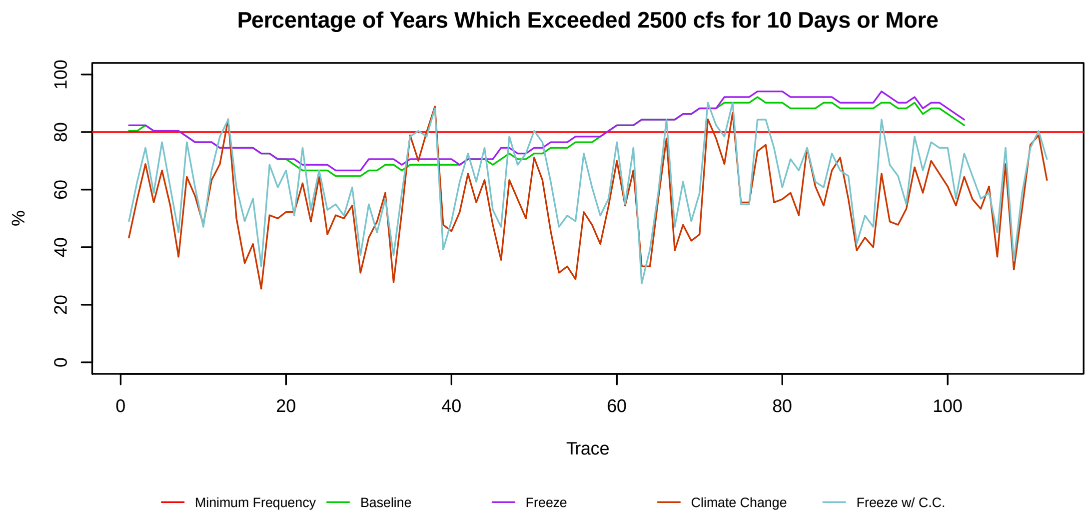


Figure 4.9: Monthly boxplots of Flaming Gorge's storage and release for all scenarios.

currences. Figure 4.10 presents the results for the 10 days at 2,500 cfs target. The target percentage is met when the scenario is above the horizontal red line while the maximum interval is met when the scenario is at or below the horizontal red line. The minimum percentage of occurrences are met for about half of the Baseline and Freeze Scenario traces while it is only rarely met for the Climate Change and Freeze with Climate Change Scenarios. Similarly, the maximum interval is exceeded in almost all of the climate change scenarios while it is exceeded in about half of the Baseline and Freeze Scenarios. In both cases, the frozen demands slightly benefit the flow requirements, i.e., the percentage of years the target is met increases while the interval between occurrences decreases. The Climate Change and Freeze with Climate Change Scenarios' results extend further since there are 112 traces compared to the 102 traces in the Baseline and Freeze Scenarios.

Figure 4.11 presents the results for the 10,000 cfs for 5 days flow requirement. The Baseline and Freeze Scenarios always meet both the minimum occurrence percentage and the maximum interval between occurrences. However, the Climate Change and Freeze with Climate Change Scenarios do not meet the minimum occurrence percentage often and rarely satisfy the maximum interval between occurrences. Again, the frozen demands provide a slight benefit to the Baseline and Climate Change Scenarios. Both figures show that the climate change traces are independent while the DNF traces are not. The results from the climate change scenarios are highly variable from one trace to the next since there is no connection between traces. In the Baseline and Freeze Scenarios, the transition between traces is smoother since only one year of hydrology changes between each trace.

Figure 4.12 shows the baseflows at Bluff during the baseflow months. The climate change scenarios show an increased median flow in January, February, November and December, while the medians decrease in August – October. The variability is also reduced in February and August – October. These results are indicative of a shift in the tributary flows above Bluff. The flows in January, February, November and December all increased some, while the flows decreased substantially in August and September. A decrease in August and September flows is also impacted by the agricultural demands; since it is still the irrigation season, the demands can reduce the



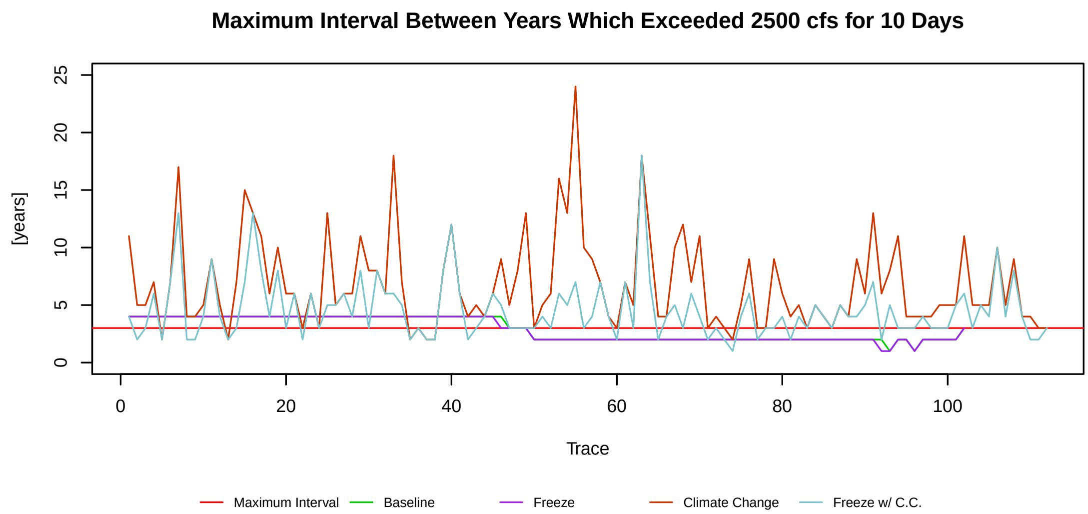
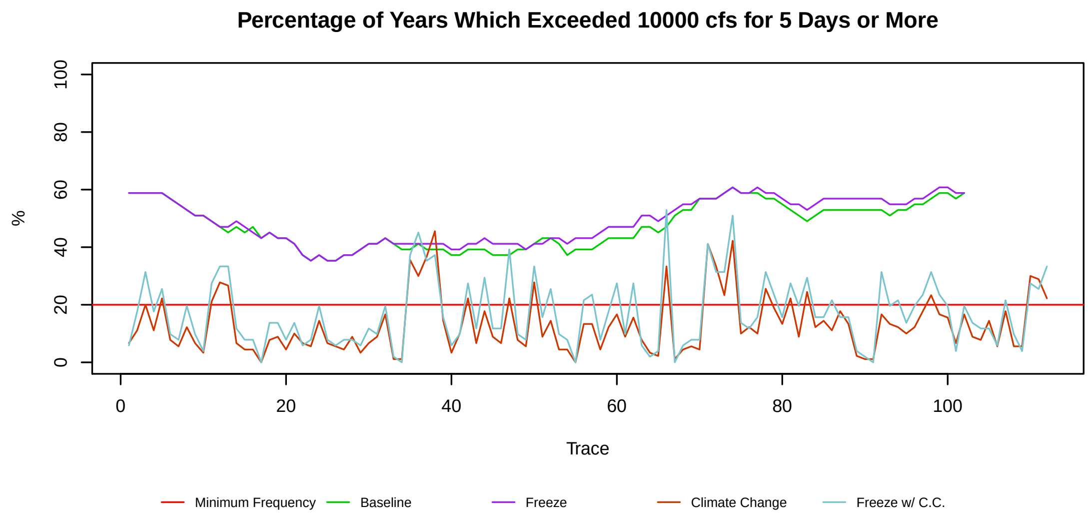


Figure 4.10: Results for the 2,500 cfs flow requirement below Navajo for all scenarios.



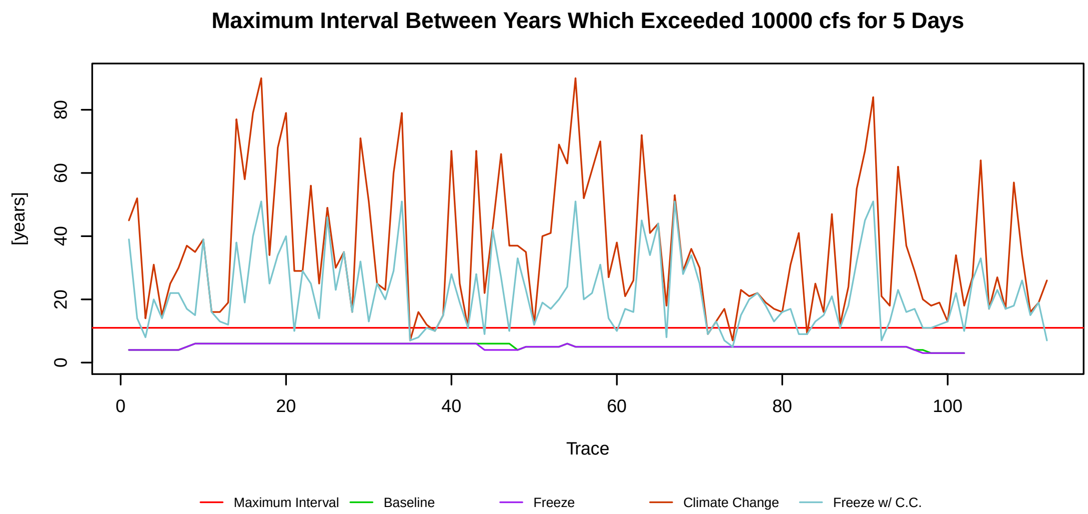


Figure 4.11: Results for the 10,000 cfs flow requirement below Navajo for all scenarios.

tributary flows to near zero leaving only Navajo's release in the stream. This explains some of the reduced variability; with less water available on average, there is less of a spread of water left in the stream after supplying all of the diversions. To fully understand the impacts of the climate change projections, the trends in monthly flow from the projections need to be analyzed for shifts in peak month and changes in the mean flow, which is beyond the scope of this project.

Figure 4.13 presents the storage levels and monthly releases for Navajo. The median storages are lower for the climate change scenarios than for the Baseline and Freeze Scenarios. There is also little difference when the demands are frozen since there are only limited demands above Navajo. The peak releases are affected by climate change as well. While there are some years with high releases, the median releases are essentially at the base release level. The peak release pattern is selected based on which pattern results in the September storage closest to the target storage. Since the storages are low to begin with, often no peak release is necessary to meet the storage target. The median releases are slightly higher in July through September for the climate change scenarios which indicates that Navajo is increasing its release to help meet some demands while maintaining the minimum baseflow at Bluff. With less tributary flows, Navajo supplements the baseflows to ensure the minimum flow requirement is met at Bluff.

4.3.2.2 Flow Alteration Metrics

The flow alteration metrics presented in this section are for the three high flow months in each year. It was an arbitrary choice to present the three high flow months rather than the annual deviations, the low flow month or another season's deviation. The three high flow month deviations act as an example of the comparisons that can be made for any temporal aggregation. The investigation of additional temporal aggregations can provide a more complete understanding of how flow alterations are changing inter-annually.

To begin, Table 4.1 presents the deviation from natural flow for the Baseline Scenario for all of the natural flow nodes basin-wide. Presenting the deviations in this form helps show the overall basin conditions. Since the deviations in the Baseline Scenario are smooth or linear through time,

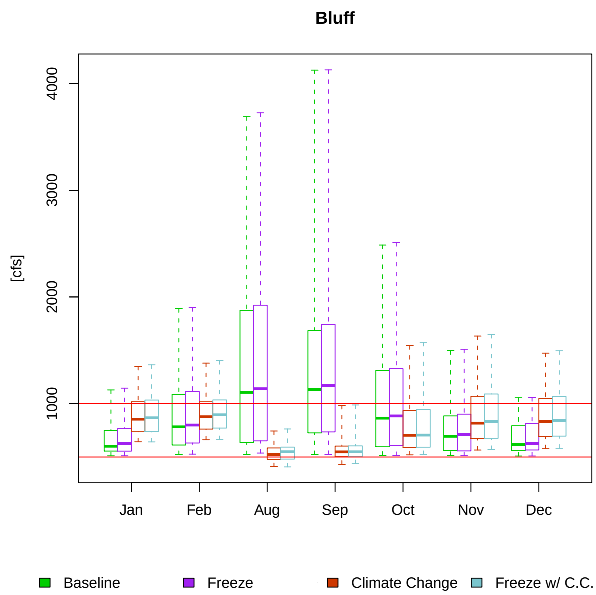


Figure 4.12: Boxplots of baseflow months on the San Juan River near Bluff, UT for all scenarios.

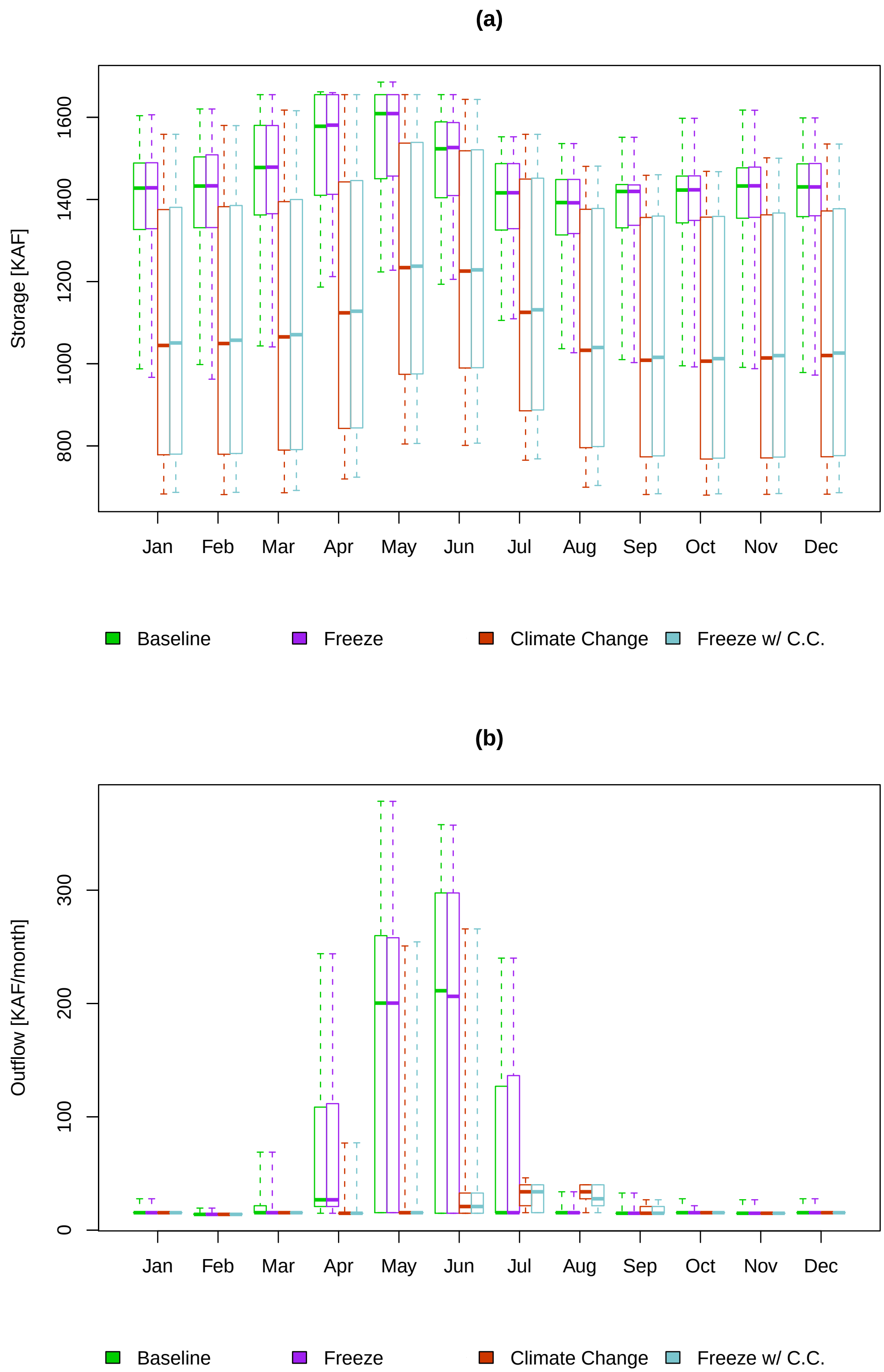


Figure 4.13: Monthly boxplots of Navajo's storage and release for all scenarios.

the values in 2011 and 2059 are reported, while the change in deviations are computed based on these values. In the table Column A is the historical average natural flow. Column B (D) is the median modeled high flow over all traces in 2011 (2059). Columns C and E represent the deviation from natural flow while columns F and G report how the flow and deviations change through time. Columns C, E, F and G are computed as follows:

$$C = \frac{B - A}{A} * 100\% \tag{4.1}$$

$$E = \frac{D - A}{A} * 100\% \tag{4.2}$$

$$F = \frac{D - B}{B} * 100\% \tag{4.3}$$

$$G = E - C \tag{4.4}$$

Using the risk classes for cottonwood abundance based on flow alteration from *Wilding and Sanderson* (2010) as an example only, the table can help identify areas of low to very high risk in both 2011 and 2059 and whether or not the risk category changes over time. For example, both the Yampa near Maybell and the White near Watson are in the low risk class (0 to -15% deviation) in 2011 and 2059 while the Colorado near Glenwood Springs is in the very high risk class (-50 to -100% deviation) in 2011 and 2059. Additionally, the Little Snake near Lily is in the moderate risk class (-15 to -30% deviation) in 2011 and the high risk class (-30 to -50% deviation) in 2059. Columns F and G highlight this change in deviation over time. For example, the Colorado near Cisco is highly altered in 2011 but is in essentially the same state in 2059 where as the Little Snake near Lily experiences a large change in deviations over time.

Table 4.2 presents the same information basin wide for the deviations from current conditions. This zeros Column C and makes Columns E – G the same as they now all show the change from 2011 to 2059 values. Additionally, Columns E – G in the deviation from current conditions

Table 4.1: Deviation from historical average natural flow for the Baseline Scenario.

		2011		2059			
	A Average Historical High Flow [acre-ft]	B Median Modeled High Flow [acre-ft]	C Deviation from Natural Percentage	D Median Modeled High Flow [acre-ft]	E Deviation from Natural Percentage	F Change in Median Flow Volume	G Difference in Deviation from Natural Flow
Colorado near Glenwood Springs	1,417,289	454,469	-67.9 %	453,844	-68.0 %	-0.1 %	-0.0 %
Colorado near Cameo	2,359,590	1,057,184	-55.2 %	1,009,504	-57.2 %	-4.5 %	-2.0 %
Gunnison below BlueMesa	710,423	244,058	-65.6 %	246,394	-65.3 %	1.0 %	0.3 %
Gunnison near Grand Junction	1,471,308	603,412	-59.0 %	585,500	-60.2 %	-3.0 %	-1.2 %
Colorado near UT/CO State Line	3,853,840	1,528,310	-60.3 %	1,455,046	-62.2 %	-4.8 %	-1.9 %
Dolores near Cisco	562,560	214,189	-61.9 %	262,649	-53.3 %	22.6 %	8.6 %
Colorado near Cisco	4,352,812	1,727,578	-60.3 %	1,728,099	-60.3 %	0.0 %	0.0 %
Green below Fontenelle	835,787	423,733	-49.3 %	432,903	-48.2 %	2.2 %	1.1 %
Green at Green River WY	875,284	417,592	-52.3 %	419,123	-52.1 %	0.4 %	0.2 %
Green near Greendale	1,204,894	498,787	-58.6 %	423,596	-64.8 %	-15.1 %	-6.2 %
Yampa near Maybell	923,391	818,662	-11.3 %	815,961	-11.6 %	-0.3 %	-0.3 %
Little Snake near Lily	300,858	225,157	-25.2 %	184,243	-38.8 %	-18.2 %	-13.6 %
Yampa at Deerlodge	1,205,382	1,006,322	-16.5 %	960,833	-20.3 %	-4.5 %	-3.8 %
Green at Jensen	2,376,125	1,456,486	-38.7 %	1,390,892	-41.5 %	-4.5 %	-2.8 %
Duchesne near Randlett	472,023	120,370	-74.5 %	123,200	-73.9 %	2.4 %	0.6 %
White near Watson	303,101	266,620	-12.0 %	265,331	-12.5 %	-0.5 %	-0.4 %
Green at Green River UT	3,342,948	1,947,619	-41.7 %	1,792,522	-46.4 %	-8.0 %	-4.6 %
San Rafael near Green River UT	123,232	66,040	-46.4 %	66,869	-45.7 %	1.3 %	0.7 %
San Juan near Archuletta	737,704	460,608	-37.6 %	432,397	-41.4 %	-6.1 %	-3.8 %
San Juan near Bluff	1,233,423	962,205	-22.0 %	846,926	-31.3 %	-12.0 %	-9.3 %
Colorado at Lees Ferry	9,242,350	2,475,000	-73.2 %	2,100,000	-77.3 %	-15.2 %	-4.1 %
Colorado below Hoover	9,454,298	2,546,112	-73.1 %	2,598,353	-72.5 %	2.1 %	0.6 %
Colorado below Davis	9,524,716	2,584,061	-72.9 %	2,631,530	-72.4 %	1.8 %	0.5 %
Colorado below Parker	9,584,107	1,954,965	-79.6 %	1,960,456	-79.5 %	0.3 %	0.1 %
Colorado above Imperial	9,613,953	1,586,764	-83.5 %	1,536,856	-84.0 %	-3.1 %	-0.5 %

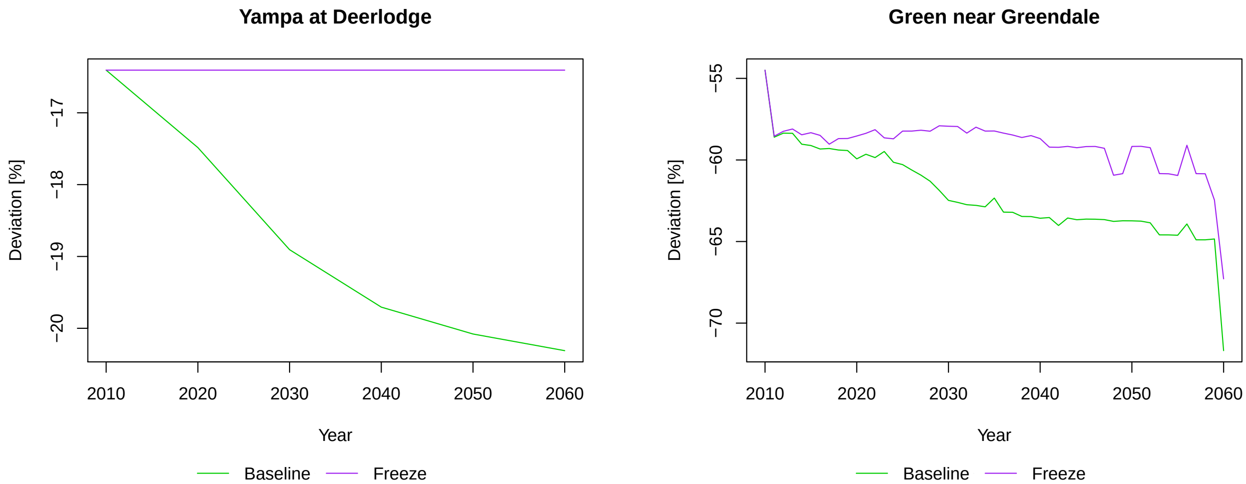


Figure 4.14: Deviation from historical average natural flow at two nodes for the Baseline and Freeze Scenarios.

are the same as Column F in the deviation from natural flow table, so Table 4.1 depicts both the deviation from natural flow in columns C and E and the deviation from current conditions in Column F. The deviations from current conditions show how the deviations are changing overtime using the first modeled year, 2011, as the baseline condition. In this case, the risk classes from *Wilding and Sanderson* (2010) cannot be used in conjunction with the table since the deviations are from current conditions rather than from natural conditions.

Since the Baseline and Freeze Scenarios use direct natural flows (DNF) with the index sequential method (ISM), the deviation from natural flow essentially depicts how the changes in demands are affecting river flows. Figure 4.14 shows the deviation from natural flow for two nodes for the Baseline and Freeze Scenarios. Since the Yampa at Deerlodge is an unregulated stream, the deviations change with demands in the Baseline Scenario while the deviations remain constant in the Freeze Scenario due to the static demands. For the Green near Greendale (also Figure 4.14), there is slightly more variability since it is directly below a reservoir. Even in the case of the Freeze scenario, the deviations are not entirely constant through time due to some regulations from the upstream reservoir.

Table 4.2: Deviation from current conditions for the Baseline Scenario.

		2011		2059			
	A Median High Flow Current Contions [acre-ft]	B Median Modeled High Flow [acre-ft]	C Deviation from Current Contions	D Median Modeled High Flow [acre-ft]	E Deviation from Current Contions	F Change in Median Flow Volume	G Difference in Deviation from Current Contions
Colorado near Glenwood Springs	454,469	454,469	0.0 %	453,844	-0.1 %	-0.1 %	-0.1 %
Colorado near Cameo	1,057,184	1,057,184	0.0 %	1,009,504	-4.5 %	-4.5 %	-4.5 %
Gunnison below BlueMesa	244,058	244,058	0.0 %	246,394	1.0 %	1.0 %	1.0 %
Gunnison near Grand Junction	603,412	603,412	0.0 %	585,500	-3.0 %	-3.0 %	-3.0 %
Colorado near UT/CO State Line	1,528,310	1,528,310	0.0 %	1,455,046	-4.8 %	-4.8 %	-4.8 %
Dolores near Cisco	214,189	214,189	0.0 %	262,649	22.6 %	22.6 %	22.6 %
Colorado near Cisco	1,727,578	1,727,578	0.0 %	1,728,099	0.0 %	0.0 %	0.0 %
Green below Fontenelle	423,733	423,733	0.0 %	432,903	2.2 %	2.2 %	2.2 %
Green at Green River WY	417,592	417,592	0.0 %	419,123	0.4 %	0.4 %	0.4 %
Green near Greendale	498,787	498,787	0.0 %	423,596	-15.1 %	-15.1 %	-15.1 %
Yampa near Maybell	818,662	818,662	0.0 %	815,961	-0.3 %	-0.3 %	-0.3 %
Little Snake near Lily	225,157	225,157	0.0 %	184,243	-18.2 %	-18.2 %	-18.2 %
Yampa at Deerlodge	1,006,322	1,006,322	0.0 %	960,833	-4.5 %	-4.5 %	-4.5 %
Green at Jensen	1,456,486	1,456,486	0.0 %	1,390,892	-4.5 %	-4.5 %	-4.5 %
Duchesne near Randlett	120,370	120,370	0.0 %	123,200	2.4 %	2.4 %	2.4 %
White near Watson	266,620	266,620	0.0 %	265,331	-0.5 %	-0.5 %	-0.5 %
Green at Green River UT	1,947,619	1,947,619	0.0 %	1,792,522	-8.0 %	-8.0 %	-8.0 %
San Rafael near Green River UT	66,040	66,040	0.0 %	66,869	1.3 %	1.3 %	1.3 %
San Juan near Archuletta	460,608	460,608	0.0 %	432,397	-6.1 %	-6.1 %	-6.1 %
San Juan near Bluff	962,205	962,205	0.0 %	846,926	-12.0 %	-12.0 %	-12.0 %
Colorado at Lees Ferry	2,475,000	2,475,000	0.0 %	2,100,000	-15.2 %	-15.2 %	-15.2 %
Colorado below Hoover	2,546,112	2,546,112	0.0 %	2,598,353	2.1 %	2.1 %	2.1 %
Colorado below Davis	2,584,061	2,584,061	0.0 %	2,631,530	1.8 %	1.8 %	1.8 %
Colorado below Parker	1,954,965	1,954,965	0.0 %	1,960,456	0.3 %	0.3 %	0.3 %
Colorado above Imperial	1,586,764	1,586,764	0.0 %	1,536,856	-3.1 %	-3.1 %	-3.1 %

The flow alteration metric presented for the Climate Change Scenario is the deviation from DNF (or the deviation from the Baseline Scenario). Similar to the approaches taken by *Gibson et al.* (2005) and *Döll and Zhang* (2010) when computing deviation metrics for climate change data, this offers a view of the deviations from 'current' conditions. However, this metric takes into account changing future demands. Presenting a snapshot of 2011 and 2059, as done for the Baseline Scenario, is not an adequate representation of the conditions due to the year-to-year variability in the flows. Instead, the deviations from DNF are shown for four different nodes in Figure 4.15 and a trend test indicates whether there is a statistically significant trend in the deviations. This figure shows that the change in deviations over time could vary if they were computed based on 'snapshots' of individual years. Since the climate change projections are independent, the results are more variable than the results from DNF with ISM. The figures help visually confirm what the trend test reveals: that both the Dolores near Cisco and the Green at Jensen do not have a trend, that the San Juan near Bluff has a decreasing trend and that the Colorado near Glenwood Springs has an increasing trend. The deviations are normalized by the Baseline values, so it does not show alterations as a percentage of natural flows, rather it shows how the flows are changing compared to the Baseline conditions.

Table 4.3 reports the trend test results for all natural flow nodes basin-wide for the Climate Change deviations from Baseline conditions. Since the trend test does not indicate the magnitudes, the table also reports the median deviation. Using the table, the overall conditions at any node are well represented. For example, at the Colorado near Glenwood Springs, there is an increasing trend while the median deviation is 22.1%. This indicates that the flows at Glenwood Springs due to climate change projections are closer to natural flows than they are for the Baseline Scenario and they are getting closer to natural conditions through time. Oppositely, at the San Juan near Bluff, there is a decreasing trend with a median deviation of -53.9% indicating that the climate change projections are further from natural conditions and are getting worse through time. Finally, at nodes such as the Dolores near Cisco, there is no trend though conditions are worse than Baseline conditions (median deviation of -80.6%).

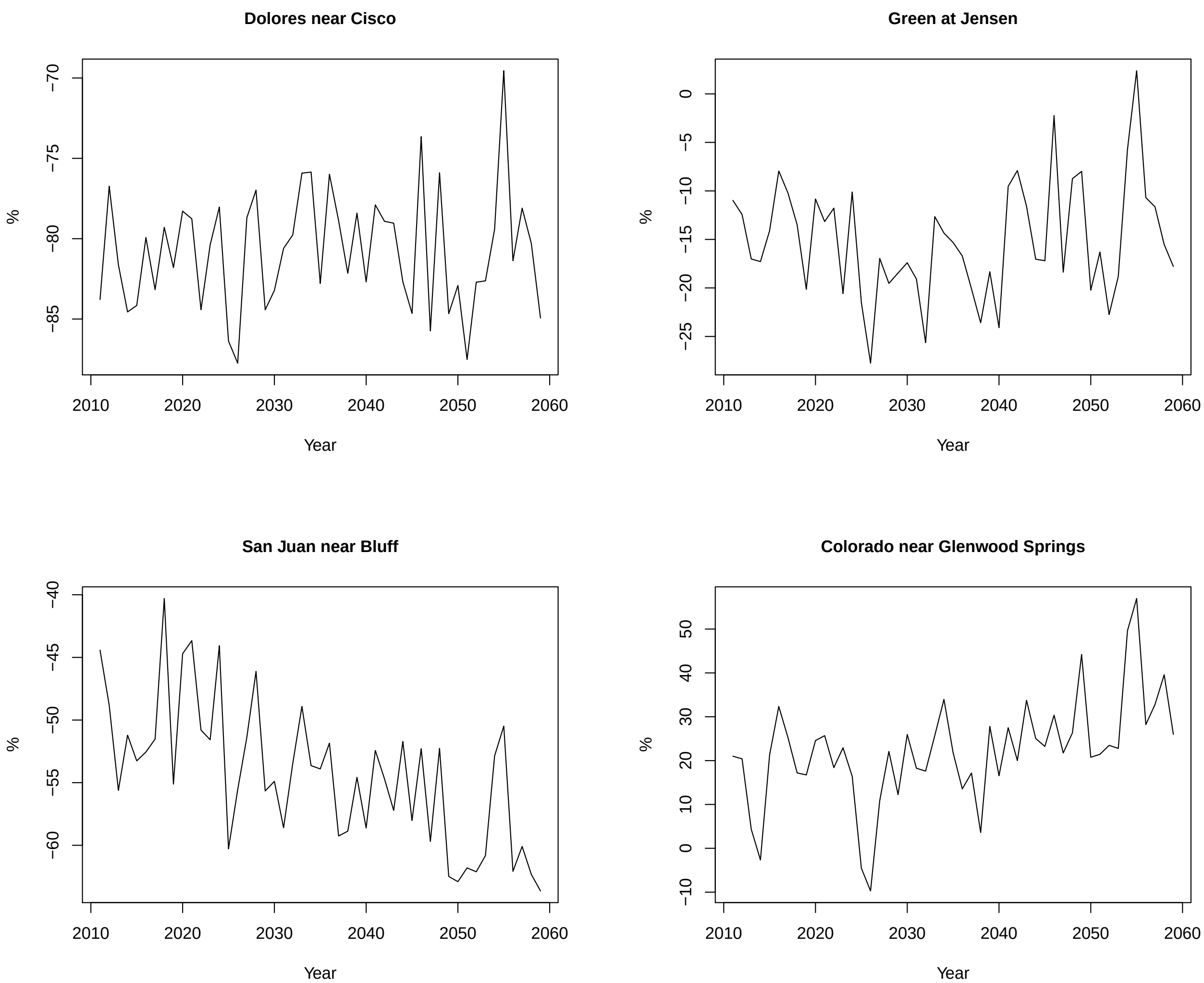


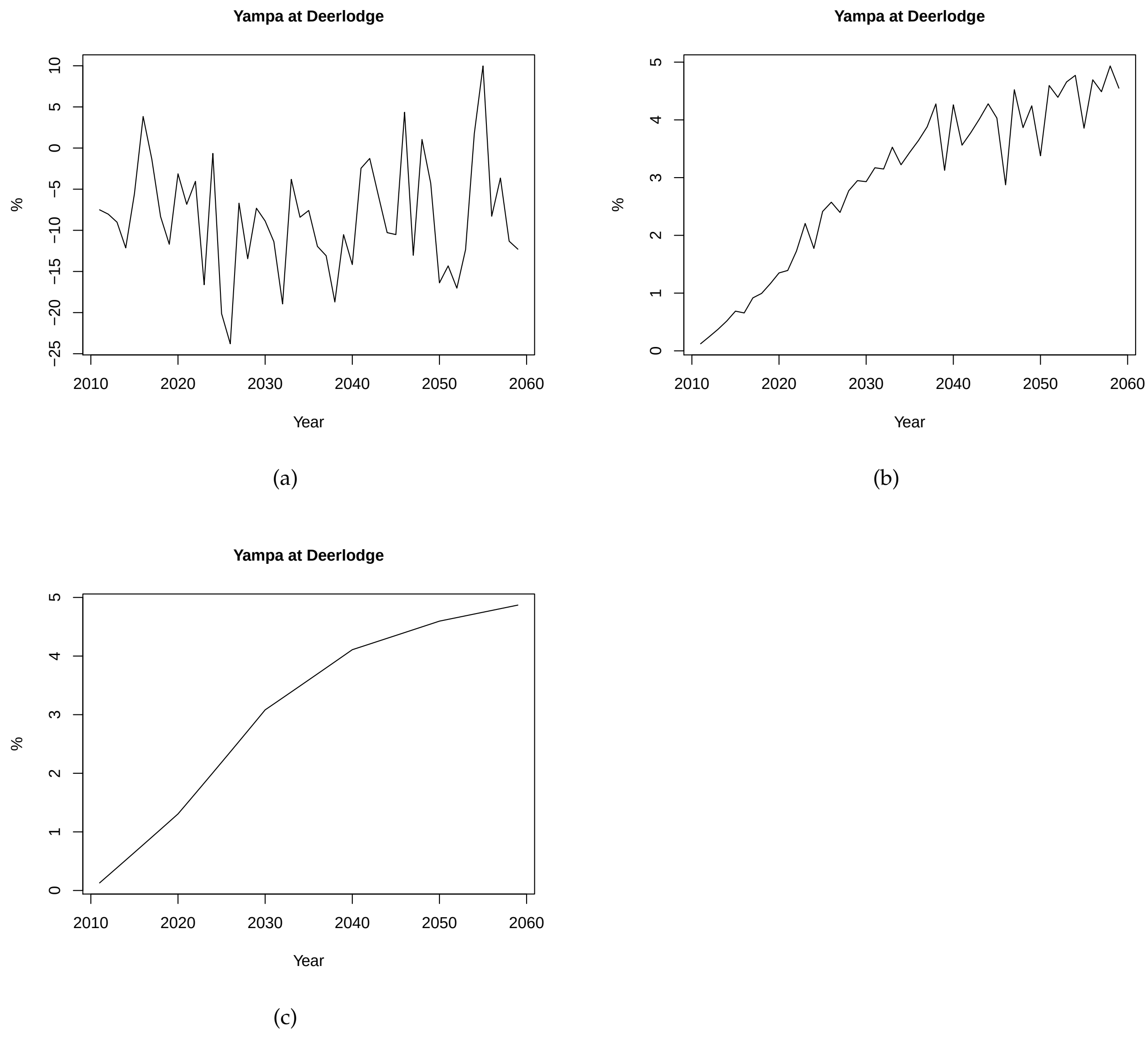
Figure 4.15: Climate Change deviations from DNF at four nodes showing different trends.

Table 4.3: Results of MK test for trends in the Climate Change deviations from DNF basin wide.

	p-value	Confidence Level w/Trend	Trend	Median Deviation
Colorado near Glenwood Springs	3.9597E-04	99 %	Increasing	22.1 %
Colorado near Cameo	3.1846E-02	97 %	Increasing	2.3 %
Gunnison below BlueMesa	5.6863E-05	99 %	Decreasing	25.7 %
Gunnison near Grand Junction	8.0148E-02	92 %	Decreasing	-29.3 %
Colorado near UT/CO State Line	7.6289E-01	24 %	Increasing	-4.9 %
Dolores near Cisco	7.2378E-01	28 %	Increasing	-80.6 %
Colorado near Cisco	4.6375E-01	54 %	Decreasing	-14.7 %
Green below Fontenelle	9.9567E-03	99 %	Increasing	-36.2 %
Green at Green River WY	6.2858E-03	99 %	Increasing	-32.9 %
Green near Greendale	2.5161E-01	75 %	Increasing	-25.2 %
Yampa near Maybell	9.6562E-01	3 %	Increasing	-24.3 %
Little Snake near Lily	5.3659E-03	99 %	Increasing	45.0 %
Yampa at Deerlodge	8.0261E-01	20 %	Decreasing	-8.3 %
Green at Jensen	7.4978E-01	25 %	Increasing	-16.3 %
Duchesne near Randlett	3.0811E-03	99 %	Decreasing	0.0 %
White near Watson	5.0874E-03	99 %	Decreasing	1.1 %
Green at Green River UT	6.3544E-01	36 %	Increasing	-11.8 %
San Rafael near Green River UT	1.5428E-02	98 %	Decreasing	52.6 %
San Juan near Archuletta	6.5377E-05	99 %	Increasing	-87.0 %
San Juan near Bluff	5.1180E-06	99 %	Decreasing	-53.9 %
Colorado at Lees Ferry	2.0388E-02	98 %	Increasing	-11.9 %
Colorado below Hoover	1.1466E-05	99 %	Decreasing	4.1 %
Colorado below Davis	5.3588E-09	99 %	Decreasing	1.3 %
Colorado below Parker	2.6945E-05	99 %	Decreasing	-1.3 %
Colorado above Imperial	1.2305E-06	99 %	Decreasing	1.7 %

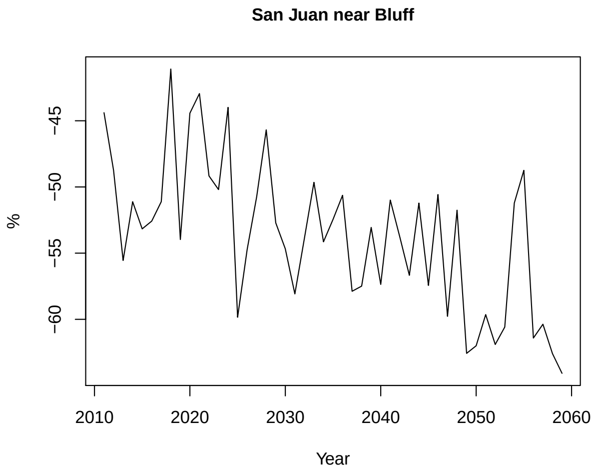
For the Freeze with Climate Change Scenario, two different flow deviation metrics are shown in Figures 4.16 and 4.17 for two different nodes. The deviation from the Freeze Scenario and the Deviation from the Climate Change Scenario were computed at each node. For comparison, the Freeze Scenario's deviation from the Baseline Scenario is also shown as it is analogous to the Freeze with Climate Change's deviation from the Climate Change Scenario. The Freeze with Climate Change deviations from the Freeze Scenario is similar to the Climate Change's deviation from Baseline indicating that the hydrology impacts the deviations from the Baseline more than the demands do. Additionally, there are modest gains (flows closer to natural flows) in having no demand growth as shown in the deviations from the Climate Change Scenario. Finally, in the unregulated reach (Yampa at Deerlodge — Figure 4.16), the gains made by freezing demands are similar for the DNF (Freeze Scenario's deviation from Baseline conditions) and climate change flows (Freeze w/ C.C. Scenario's deviation from Climate Change conditions). However, the gains are more substantial at Bluff for the Freeze with Climate Change than they are for just the Freeze: there is about a 12% increase over time in the Freeze with Climate Change deviations from Climate Change conditions compared to about a 6% increase in the Freeze deviations from Baseline conditions.

Figures 4.18 and 4.19 show the monthly hydrograph boxplots for all scenarios at Jensen and Glenwood Springs, respectively, to provide insights into the changes in inter-annual variability. At Jensen, the median flow is slightly increased in the Freeze Scenario when compared to the Baseline Scenario. Otherwise, there is not a huge difference between the flows in the two scenarios. There are much more drastic differences between the Climate Change and Baseline Scenarios. The decrease in the median June flow from 2011 to 2059 is much larger in the Climate Change Scenario; there is also an increase in the median April flow indicating that the peak flow is likely shifting earlier into the year. Historically, the peak flow was in June whereas by 2059 with climate change impacts, the peak flow is generally in May, though the variability is much larger. Finally, by comparing the Freeze with Climate Change to the Climate Change Scenario, it is apparent that the static demands provide modest benefits with slightly higher median flows in 2059; however,

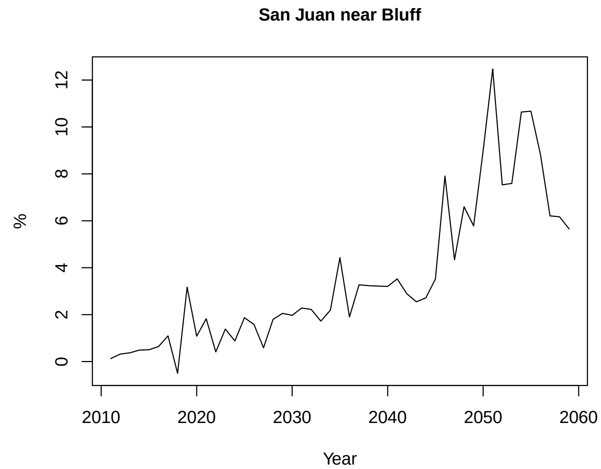


(a) (b) (c)

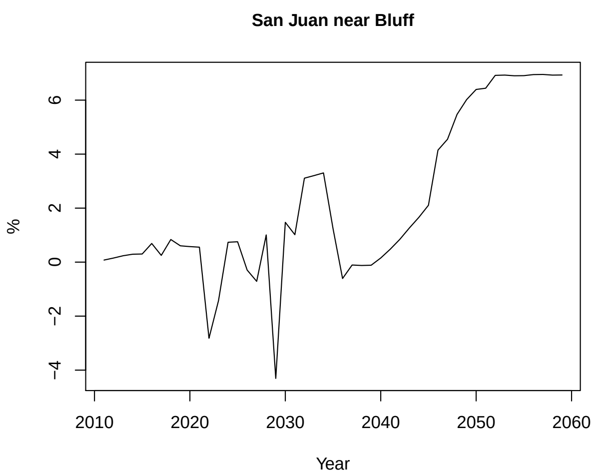
Figure 4.16: The Freeze with Climate Change deviations from (a) the Freeze Scenario (b) the Climate Change Scenario and (c) the Freeze Scenario's deviation from Baseline Scenario for the Yampa at Deerlodge.



(a)



(b)



(c)

Figure 4.17: The Freeze with Climate Change deviations from (a) the Freeze Scenario (b) the Climate Change Scenario and (c) the Freeze Scenario's deviation from Baseline Scenario for the San Juan near Bluff.

the increases in flow due to static demands are not as large as the decreases in flow due to climate change.

For Glenwood Springs, Figure 4.19 shows that the static demands have almost no impact on flow since the users above Glenwood are generally already at their full allocation. However, the flow from climate change does have an impact. The flows in April and May increase while the flow in June decreases. In June – August at the end of the run, the flows are reduced virtually to 0 almost 50% of the time with climate change. Additionally, the variability in many months, particularly April and May, increases with climate change. Again, since there are no increasing demands above Glenwood, the static demands do not provide any benefits at Glenwood in the Freeze with Climate Change Scenario. Though the deviations from the Baseline for the three high flow months shows an increase with Climate Change (Figure 4.15), there are several months where the flow is decreased substantially, thus the increase in May outweighs the decrease in June. This also indicates that the three high flow months shifted from April – June in the Baseline to March – May in the Climate Change Scenario.

4.3.2.3 System Results

The final results compare the scenarios for overall system impacts. Figure 4.20 shows the energy generated at Flaming Gorge for all four scenarios. The results are intuitive as the Freeze Scenario produces the most annual energy, followed by the Baseline, Freeze with Climate Change and Climate Change Scenarios at the 10th and 50th percentiles. At the 90th percentile, the climate change scenarios can sometimes produce more power than the Baseline Scenario. Since the climate change projections are more variable, it is to be expected that there will be higher highs, which results in more energy production.

Figure 4.21 displays the average annual shortages on the Green and San Juan Rivers. Again, the results are expected: the shortages are higher in the climate change scenarios than the scenarios using DNFs and on the Green River, the shortages are lower with static demands. The freeze scenarios show minimal differences from the non-freeze scenarios on the San Juan, similar to the

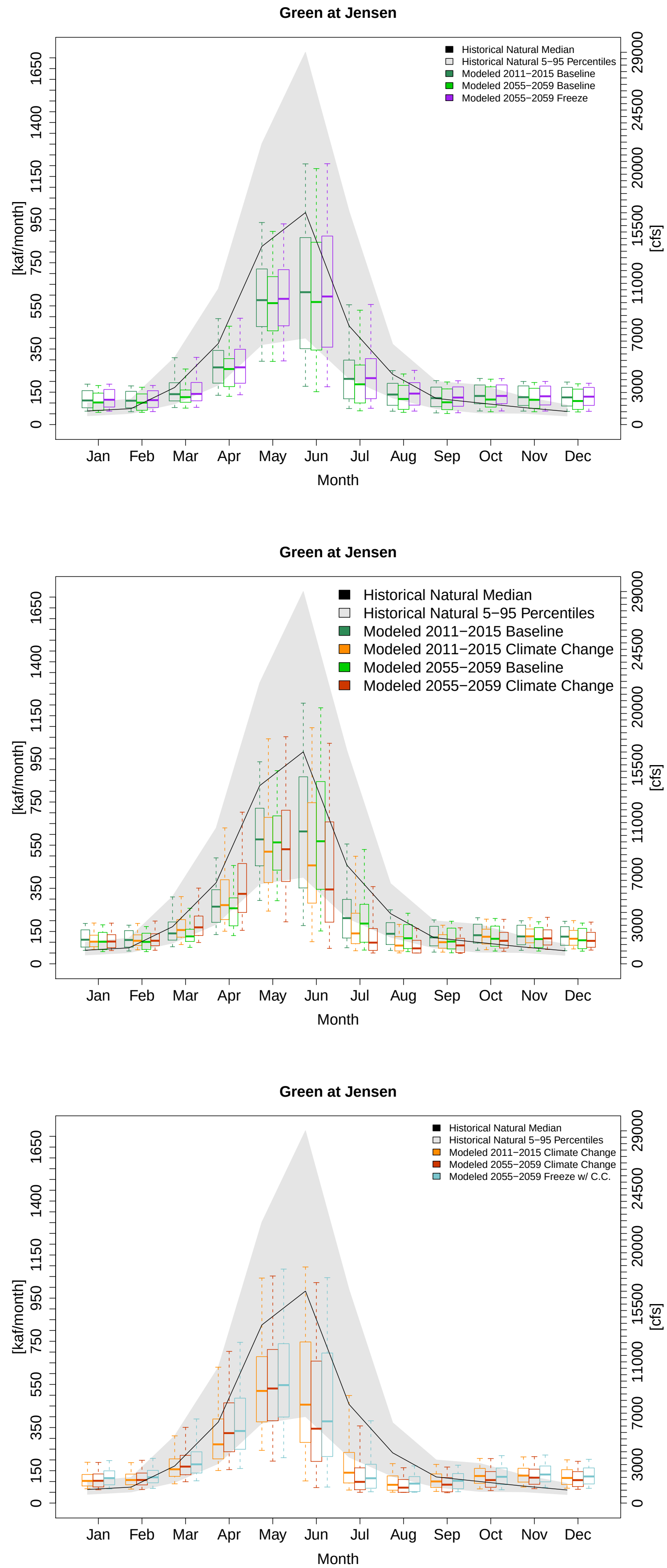
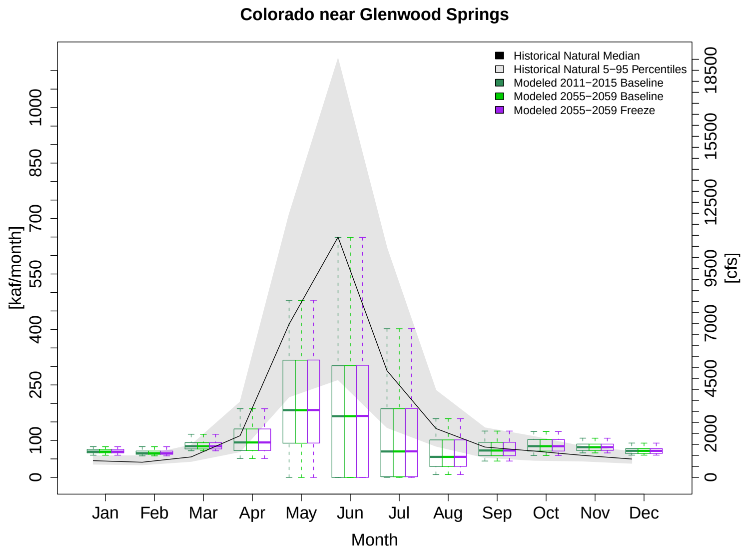
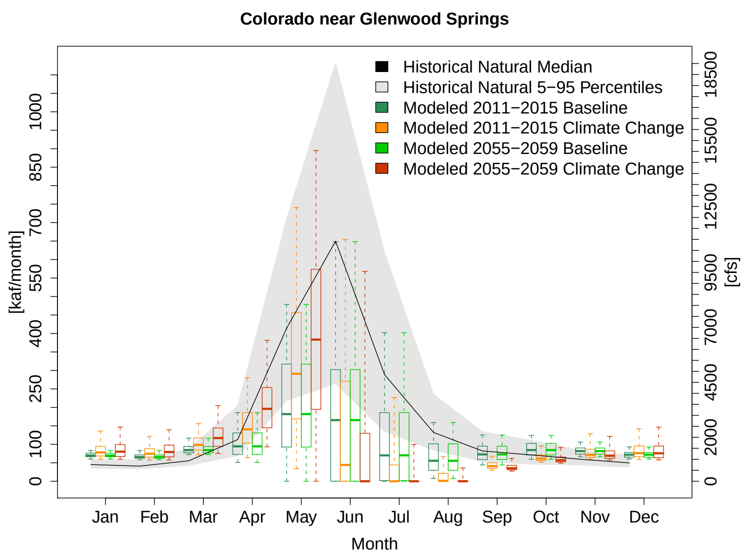


Figure 4.18: Monthly hydrograph boxplots for the Green River near Jensen for all scenarios.





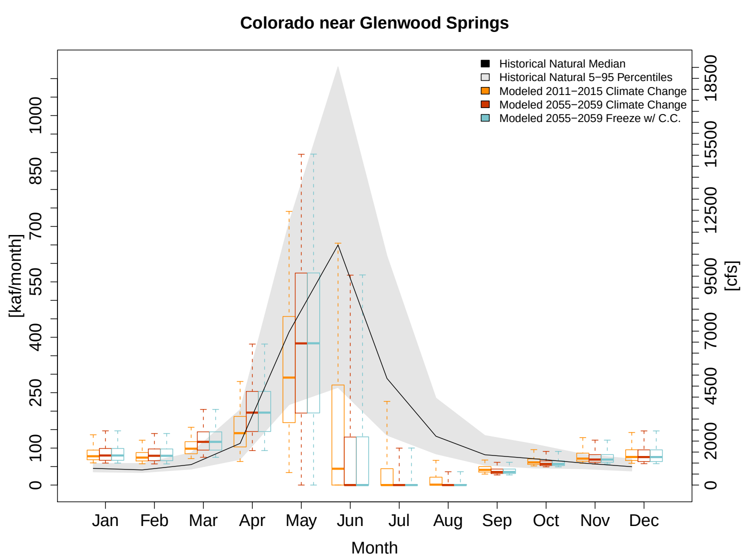


Figure 4.19: Monthly hydrograph boxplots for the Colorado River near Glenwood Springs for all scenarios.

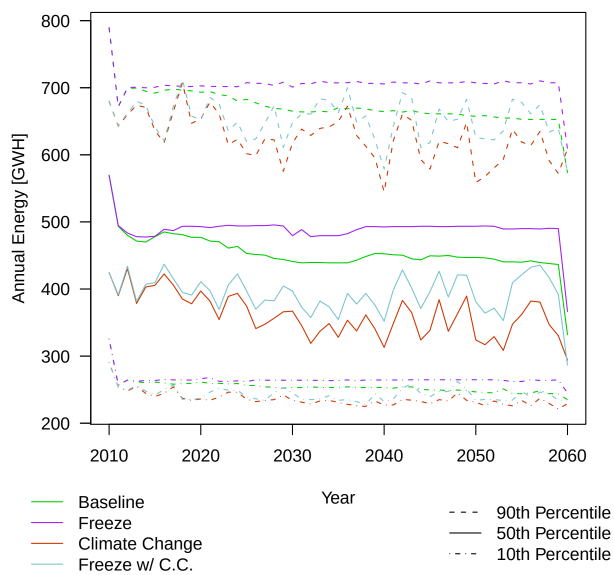


Figure 4.20: Annual engergy production at Flaming Gorge for the Baseline and Climate Change Scenarios.

other metrics on the San Juan.

Figure 4.22 shows the probability that Powell's release is greater than 8.23 MAF each water year along with the annual energy production at Powell. Once again, we see that the climate change scenarios impact the results more than the frozen demands do. In the case of the water year releases, the freeze scenarios increase the probability of a release greater than 8.23 MAF by about 5 – 10% each year; however, there is about a 20% decrease from the Baseline to the Climate Change Scenario. For Powell's annual energy production, the Freeze Scenario provides a greater increase from the Baseline at the low end (10th percentile) than at the median or 90th percentile. For both climate change scenarios the 10th percentile energy production is zero, since in the driest of years Powell is below the minimum power pool elevation. Finally, Figure 4.23 shows the end-of-year pool elevation at Mead. Once again, the pool elevations respond similarly to all previous results; the highest median elevations are from the Freeze Scenario, with the lowest occurring in the Climate Change Scenario.

4.4 Summary

This chapter uses the Colorado River Basin as an example of incorporating multiple environmental flow metrics into a long-term, basin planning model. Four scenarios — Baseline, Freeze, Climate Change and Freeze with Climate Change — are compared to illustrate the differences in results due to changing demands and changing hydrology. While the results here are not indicative of the basin conditions or do they aim to present the ecological health of the system, they do offer a framework for incorporating them into a planning model while highlighting some of the interesting differences between scenarios.

When comparing the Baseline Scenario to the official CRSS results, it is apparent that the new representation of Flaming Gorge and Navajo rules helps to better capture e-flow requirements below the projects at the expense of slightly higher shortages to users. Even though the annual releases from the reservoirs increase, the shortages increase as a result of the temporal distribution of demands and reservoir releases. Since the annual releases are higher, so too is the

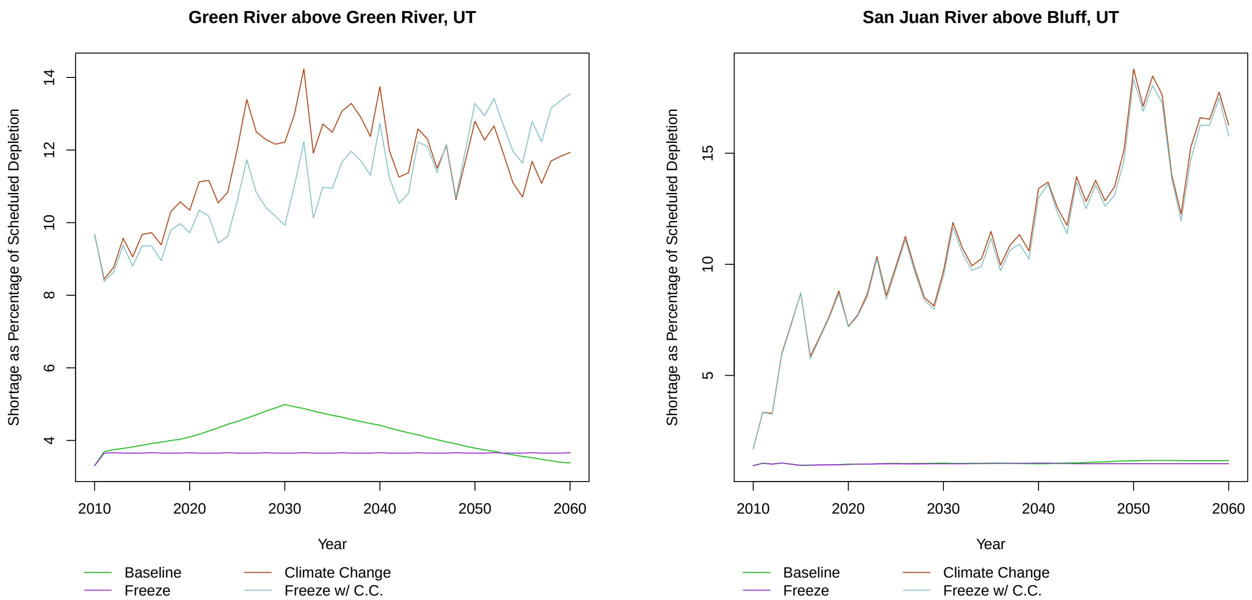


Figure 4.21: Average annual shortages above nodes on the Green and San Juan Rivers for all Scenarios.

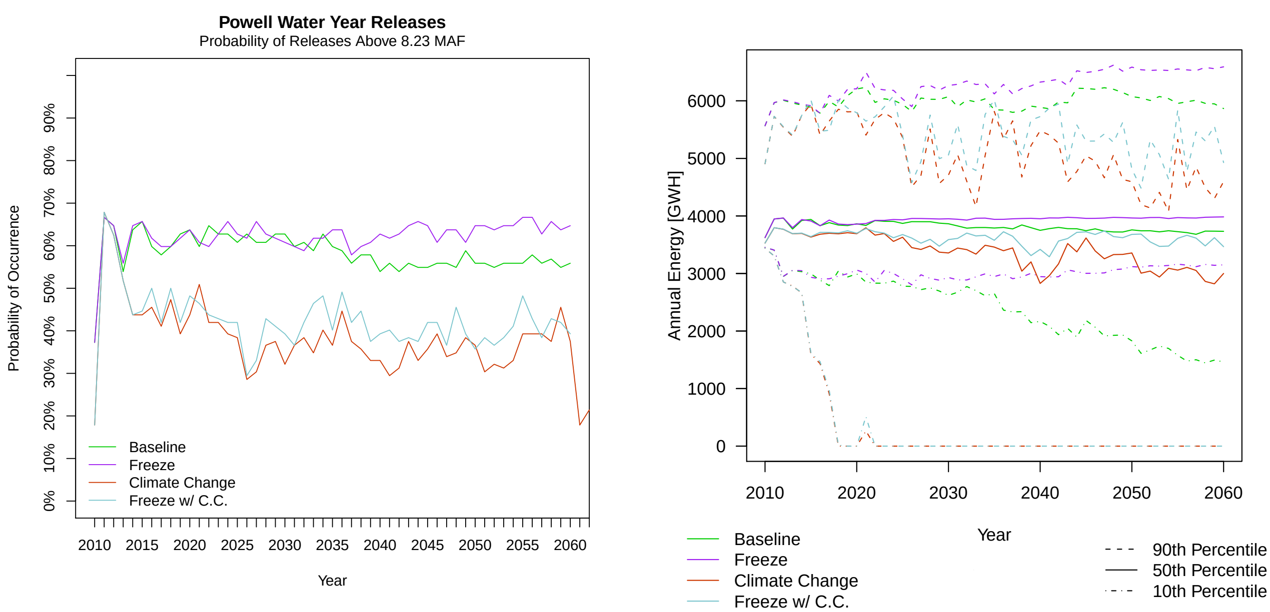


Figure 4.22: The probability that Powell's release is greater than 8.23 MAF and the annual energy generated at Powell for all scenarios.

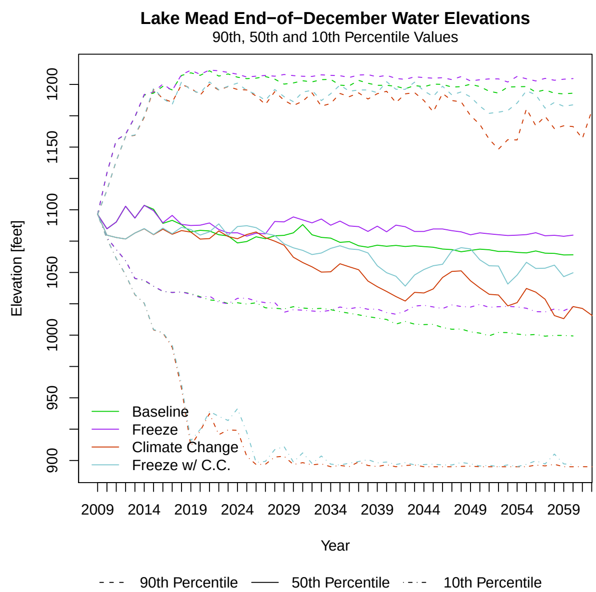


Figure 4.23: Mead's end-of-December pool elevations for all scenarios.

annual energy production. *Watts et al.* (2011) noted that dams can be reoperated to help meet environmental needs without negatively affecting other sectors. In this comparison, we found similar results; the dams operations were changed to meet e-flow requirements with only minimal additional shortages to users. While the new rules do impact the reservoirs and basins they were implemented at, there are only small impacts to the system's operations as a whole.

Flow alteration metrics were used to compare the different scenarios, revealing similarities to previous studies. First, most nodes basin wide have already experienced a 12 to 70 % reduction in the three high flow month's flows. Second, as *Döll and Zhang* (2010) concluded, many nodes will experience greater reduction in flows due to climate change than they have from all development up to the present day. For example, the San Juan near Bluff is experiencing about a 22% reduction in high flows presently. The climate change projections indicate that the flows will be reduced a further 53% on average over the next 50 years. Next, the frozen demands had a greater positive impact on regulated nodes in the climate change scenarios than in the scenarios using DNFs. Finally, changes in timing and the form of precipitation contribute to a shift in peak flow months and higher variability in many months' flows, as shown by the monthly hydrograph boxplots. Additionally, the flow alteration metrics can indicate higher peak flows over the three months, though individual months are experiencing reductions in flow. This demonstrates the importance of investigating multiple metrics at each node.

At the system level, the results are generally the same with regards to energy production, shortages or reservoir storages. The Freeze Scenario had the highest storages and energy production and lowest shortages while the lowest storages and energy production occurred in the Climate Change Scenarios. These results also indicated the system is more sensitive to the changing hydrology than to the increasing demands in the future. That is, the negative impacts due to climate change were larger than the positive impacts due to freezing all demands at their 2010 levels. Since the basin is already highly developed, freezing the demands at 2010 levels probably does not constitute a high percentage change from current conditions. However, the projected changes in future hydrology, from the Climate Change Scenario, are more different from current hydrological conditions than the projected 2060 demands are from the 2010 demands, which produces larger differences in the results.

Chapter 5

Conclusions and Recommendations

5.1 Summary and Conclusions

Historically, e-flows were stated as a minimum flow in the river; however, research suggests that the entire flow regime — baseflows, floods, inter and intra-annual variability — are ecologically important. Newer, more complex e-flows, to reflect the entire flow regime, are stated at the daily timescale and as such are not easily represented in a planning model. Incorporating e-flows into basin planning models provides the utility of being able to use the planning model framework to assess multiple different hydrologic and demand scenarios' impacts on e-flows. *Poff et al.* (2010) states that there is a need for a model that can help assess e-flow targets at multiple nodes while taking into consideration how all water uses affect the e-flows and have the capability to incorporate climate change projections. This study developed a suite of techniques for incorporating e-flow requirements into a planning model, to help address this need, and in doing so provides a framework for the incorporation of fine scale requirements into coarser scale decision models.

As many e-flow targets are below reservoirs and other control structures, where human management decisions can help sustain the river ecosystem, research focused on incorporating sub-monthly targets into monthly reservoir operations. Additionally, since the impacts due to climate change are an issue being addressed by water managers world-wide, care was taken to ensure all techniques were applicable under a nonstationary climate. E-flow targets downstream of reservoirs typically rely on both reservoir releases and unregulated tributaries to meet the flow targets, thus the scale issues were addressed at both the reservoirs and the tributaries. A disaggregation technique was used to obtain daily flows for tributaries, while daily requirements were incorporated into the monthly reservoir releases. As the flow targets vary from year-to-year depending on the hydrologic year type, hydrologic year typing schemes were analyzed, particularly under nonstationary conditions. Flow metrics were introduced to assess the long-term reliability of e-flows, and all methods were implemented on the Colorado River Basin to demonstrate their utility.

5.1.1 Daily Disaggregation

The daily disaggregation technique incorporates an existing nonparametric flow disaggregation technique into a planning model and modifies it to incorporate additional constraints that are provided by the planning mode, such as known monthly flow volumes and monthly demands. The technique modifies an existing nonparametric disaggregation method (*Nowak et al.*, 2010) to obtain daily natural flow values by selecting neighbors that have similar monthly hydrograph shapes. This incorporates our knowledge of the monthly natural flow volumes provided by the planning model. Results indicate that the new neighbor selection preserves the daily statistics tested in *Nowak et al.* (2010), such as mean, variance and daily maximums and minimums, while also capturing flow threshold statistics. The flow threshold statistics are important characteristics to capture for e-flow monitoring, since many e-flow targets are stated as a desired number of days above a flow threshold. After disaggregating to daily, natural flows, monthly demands that are input to the planning model are applied to the disaggregated time series resulting in a depleted, daily time series. Since the monthly demands must be able to be met in each month, as this is determined by the planning model, the demands may need to be redistributed in each month or a second-stage flow disaggregation could be necessary. The second-stage disaggregation ensures that the monthly volume of water can fulfill the monthly demand. Flow continuity between months was addressed because it is an issue in the second-stage disaggregation. The disaggregation technique also provides a framework for obtaining daily natural flows from monthly natural flows and a historical, daily gage record.

5.1.2 Hydrologic Year Types

Hydrologic year types guide reservoir operations by varying flow targets in response to the hydrologic conditions in the basin. In wet years, flow targets are higher so reservoirs will increases their releases to meet the targets, whereas in dry years, reservoirs can hold back more water since they are allowed to meet lower flow targets. This application of year typing aims to benefit the ecosystems by recreating the natural inter-annual variability of the rivers. The current year type is dependent on the conditions in the basin compared to the historical conditions. Thus, the hydrologic year type is sensitive to the choice of the historical record. The historical record can be static, assuming that a given period (1959–2005) is representative of natural variability, or it can be updated every year (1959–present), which assumes that more information is useful in characterizing the hydrologic variability of the system. The occurrences of each year type can change depending on whether a static or moving year type threshold is used. Results demonstrated that the occurrence of year types are particularly sensitive to low-variability conditions with a mean substantially different than the historic mean. Additionally, climate change violates the assumptions made in developing year types. Thus under climate change conditions, the year type occurrences can be different than the sought after occurrences, which could have negative ecological impacts.

5.1.3 Reservoir Rules

Reservoir operations are guided by hydrologic year types and help sustain downstream tributary flows to meet higher flow targets. Since operations to meet e-flow targets are daily and planning models typically operate at the monthly timestep, the direct incorporation of the two is not possible. This temporal scale issue was addressed by summing daily releases to a monthly flow release using RiverWare rules to implement the reservoir operations. The daily operations can vary from year-to-year, including different ramp-up dates and a different number of days at peak release; the rules are flexible enough to capture this. By comparing modeled reservoir operations to historical operations at the daily and monthly timesteps, the effectiveness of the modeled operations was demonstrated. The operations do included a number of assumptions that can cause minor differences between modeled and actual operations, though they adequately represent the typical operations of the reservoirs.

5.1.4 Flow Metrics

Flow alteration metrics, which compare the flows in a river to a baseline condition, are widely used to assess ecological conditions in a river. In many applications, the baseline condition is the unaltered, natural flows. However, under nonstationary conditions, it is unclear what the baseline condition should be. The issues of comparing climate change induced conditions to the historical conditions were addressed with several baseline conditions considered. With the careful selection of the baseline conditions, the flow alteration metrics can provide insight into how conditions are changing over time. The metric is applicable at the daily to annual timescale, so the metric can be directly incorporated into a monthly planning model and it can be aggregated across months to provide seasonal or annual information.

5.1.5 Long-term Planning Results

The utility of the above techniques was demonstrated through an example on the Colorado River Basin. All of the techniques were incorporated into a research version of the Bureau of Reclamation's Colorado River Simulation System. Reservoir operations, reflecting mandated operations for e-flow targets, were updated at two reservoirs, and the downstream flow targets were assessed using both the new reservoir rules and disaggregated tributary flows. Basin wide conditions were assessed using flow alteration metrics, and the results were compared under multiple supply and demand scenarios. The results indicate that many metrics are more dependent on future hydrology than future demands, possibly due to the already large demands on the system. The demonstration acts as a framework for assessing the reliability of e-flows basin-wide, similar to the tool *Poff et al.* (2010) call for.

5.2 Future Work

This research has led to many more questions and ideas for future research and applications. Some are specific technical issues while others are more broad in concept.

(1) When selecting the neighbors in the flow disaggregation, the weight of each month (April – July) is the same. The weights of each month could be optimized which could lead to less need for the second-stage disaggregation, thus improving the month-to-month correlations.

(2) The second-stage disaggregation is dependent on a user specified parameter for the minimum allowable flow. While several ideas for obtaining this value were presented, more work could reveal a more satisfactory method. By casting this stage of the disaggregation method as an optimization problem, the minimum flow could be determined dynamically, without the need for the user to specify it.

(3) The hydrologic year types were shown to change the most under climate change conditions. Since many projections indicate an earlier spring peak, the impacts of the earlier spring peak should be analyzed in regards to the year type determination. Since the current determination is based on the April – July volume, if the peak shifted significantly, this could result in an overall lower (or higher) April – July volume, which could bias the year type classifications.

(4) While the possible shift in year type distributions due to climate change is acknowledged, no solution has been proposed. The determination of how the year types should be distributed relative to historical conditions or current conditions (under climate change), can be philosophical in nature. It is unclear if historical natural conditions should be replicated if natural conditions are changing. However, if the changes in natural conditions are anthropogenic, do humans have a responsibility to maintain the historical conditions, if possible?

(5) The monthly hydrograph boxplots show a disconnect between the modeled conditions

from DNFs and climate change flows in the beginning of the model runs (2011-2015). Since the natural flows are not declining to that degree, that rapidly this is concerning. The results would be more meaningful if the climate change projections were more indicative of the current conditions during this time period. This highlights the importance of the ongoing efforts to perform a secondary bias correction of the climate change projected flows.

(6) The reservoir operations were shown to capture operations adequately; however, there will always be room for improvement in the rules. An obvious improvement would be to update the rules to shift the peak release to match the downstream tributary peak. Additionally, there are many technical issues that could be addressed in the rules to improve model performance.

(7) The framework of the basin wide modeling tool could be applied to assess many more possible scenarios. By combining it with tools such as the Demand Input Tool (*Hickman and Wilson*, 2010) many scenarios could be compared to weigh the ecological benefit of changes in demands across the basin.

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Appendix A

Statistics for 14,000 cfs Flow Threshold

Appendix A includes statistics similar to those presented in Section **3.1.3.1.2** for a threshold of 14,000 cfs. Figure A.1 shows the simulated and historical spell length PDFs while Figure A.1 shows the simulated and historical spell volume PDFs. Both the spell volume and spell length PDFs are well captured as they were for the threshold of 10,000 cfs. This comparison provides further proof that the disaggregation method captures spell lengths and volumes well.

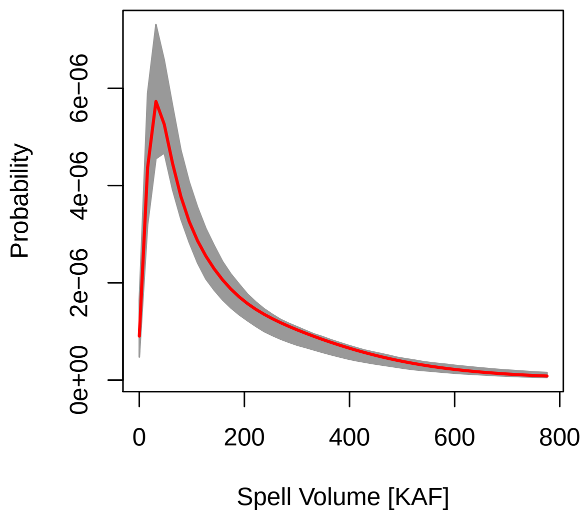

Figure A.1: PDF of spell volumes above 14,000 cfs. The grey region represents the 5th and 95th percentiles of 250 simulations; the historical PDF is shown in red.

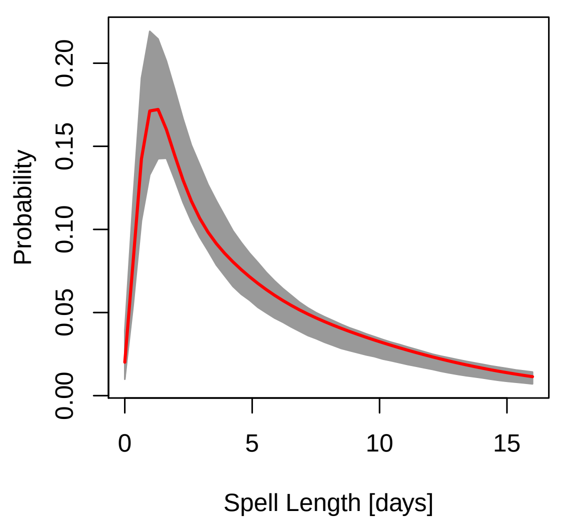

Figure A.2: PDF of spell length in days above 14,000 cfs. The grey region represents the 5th and 95th percentiles of 250 simulations; the historical PDF is shown in red.

Appendix B

Flaming Gorge Rule Outline

Appendix B includes an outline of the Flaming Gorge rules that were developed to incorporate daily requirements into the monthly model.

Flaming Gorge Rule Outline for E-flows Model

This document outlines the Flaming Gorge rules in the E-flows model. The rules are revised from the version under development for the Mid-term Probabilistic Operations Model, mostly to adapt the logic for a planning model rather than operational forecasting mode.

Version 1: June 7, 2010; Alan Butler
Version 2: January 25, 2011; Alan Butler

Data

Data Object

FlamingGorgeData

- 1963 - Present historic Data for definitions of hydrologic classification
- HydrologicClassPercentileLimits: Look up tables for Hydrologic Classification Wet, Moderately Wet, Average, Moderately Dry, Dry (based on quantile of obs or fc)

Table 2-4.—Percentage Exceedances and Hydrologic Classifications

Hydrologic Classification	Percentage Exceedance Range
Wet	<10
Moderately Wet	30 to 10.1
Average	70 to 30.1
Moderately Dry	90 to 70.1
Dry	>90

- May1TargetElevation:

Table 2-3.—Upper Limit Drawdown Levels for Flaming Gorge Reservoir

Unregulated Inflow Forecast Percentage Exceedance Range	May 1 Upper Limit Drawdown Elevation Level
1 to 10	6023
10.1 to 30	6024
30.1 to 40	6025
40.1 to 59.9	6027

- BaseFlowMagnitudeLimits: Base flow limits and ramp down rates for each classification

- Manual input Feb-May flows and usage flag indicating special case year
- DaysAtPowerPlantCapacity: Required days at Power Plant Capacity
  - Dry: 0 – 7
  - Moderately Dry: 7 - 14
  - Average: 14 - 28
  - Mod Wet: 28 – 42
  - Wet: 42 +
- Slots for All proportions, remaining days at ppc
  - PreviousMonthProportion
  - RampUpProportion
  - PPCProportion
  - RampDownProportion
  - RemainingProportion
- RampUpRate: Spring Ramp up rate, 2000 cfs
- PowerPlantCapacity: 4600 cfs
- BypassRelease: 8600 cfs

Other Data

- YampaNearMaybelle: Yampa Forecast
- GreenNearGreenRiverWy: Local inflows for corresponding natural flow node
- GreenNearGreedaleUT: Local inflows for corresponding natural flow node
- Uses above FG

Required User Data Input

- Reach Intervening Flows for entire run length
- Initial Reservoir Storage
- If the model is starting in a spring flow month, the previous flow proportions and remaining days at power plant capacity
- Initial Hydrologic classification for spring or base flow period
- TBD: Projected Demands

Rules

Any references to 'depending on start month' are not applicable to the E-flows Model. The operations model will have a rule which handles adaptive management. The following rules are in order of highest to lowest priority, though the model will execute them in lowest to highest order.

1. Spill for PE Control

Execution Constraint: None

Description: This is a dam safety rule. If Flaming Gorge's pool elevation is > 6,039' then bypass enough water to return the pool elevation to 6,039'.

Slots Set: FlamingGorgeData.ManualSpill, FlamingGorge.Outflow, FlamingGorge.Bypass

2. Min Flow in Extremely Dry Years with Low Storage

Execution Constraint: Not May, June or July

Description: If Flaming Gorge pool elevation is below 5948' then the outflow can be reduced to 400 cfs to protect the remaining water in storage. In May, the base flow period (before May 23) will be set to 400 cfs is this rule sets the April release to 400 cfs (See Spring Flow Operations Rule).

Slots Set: FlamingGorge.Outflow, FlamingGorgeData.LowReleaseFlag

3. Spring Flow Operations

Execution Constraint: May - July (depending on classification)

Description: Sets the spring release to meet power plant capacity and control flooding. August is not included because it will always be handled by the base flow operations rule. Any of the components of the monthly flow, when splitting (ppc, downramping and baseflow), may be zero, e.g., downramping and baseflow are zero when the whole month is at ppc.

```
PreviousProportion * PreviousBaseFlowRelease +
RampUpProportion * AverageRampUpRelease +
PPCProportion * PowerplantCapacity +
RampDownProportion * AverageRampDownRelease +
RemainingProportion * BaseFlowMagnitude +
BypassProportion * BypassReleaseRate
```

- Get base flow release from previous timestep
- Get Average ramp up release knowing proportion (i.e. number of days to reach peak and then average)
- Power Plant Capacity = 4,600 cfs
- Get Ramp Down release by similar calculation in ramp up.
- Get Base flow magnitude from hydrologic classification and lookup table
- Proportions are calculated by proportion rules
- Checking if total volume in month is enough to meet peak flow requirement.

Slots Set: FlamingGorge.Outflow

Flow Recommendations:

Hydrologic Category	Frequency	Reach	Spring Peak Magnitude	Spring Peak Duration
Dry	10%	1	≥ 4,600 cfs	Achieve Reach 2 target
Dry	10%	2	≥ 8,300 cfs	≥ 2 days except in extreme years
Moderately Dry	20%	1	≥ 4,600 cfs	Achieve Reach 2 target
Moderately Dry	20%	2	≥ 8,300 cfs	≥ 7 days
Average	40%	1	≥ 4,600 cfs	Achieve Reach 2 target
Average	40%	2	≥ 8,300 cfs	≥ 7 days in 50% of average years
Average	40%	2	≥ 18,600 cfs	One day in 50% of average years
Average	40%	2	≥ 18,600 cfs	≥ 14 days in 25% of average years
Moderately Wet	20%	1	≥ 4,600 cfs	Achieve Reach 2 target
Moderately Wet	20%	2	≥ 18,600 cfs	≥ 14 days
Moderately Wet	20%	2	≥ 20,300 cfs	One day in moderately wet years
Wet	10%	1	≥ 8,600 cfs	Achieve 2 target
Wet	10%	2	≥ 18,600 cfs	≥ 28 days
Wet	10%	2	≥ 22,700 cfs	≥ 14 days
Wet	10%	2	≥ 26,400 cfs	One day in wet years

4. *Release to Meet ULDE*

Execution Constraint: March, April

Description: Release at whatever rate is necessary to meet the May 1 upper limit draw-down elevation (ULDE) from the EIS. Note that if the reservoir is already below the ULDE, then the outflow will be constrained to the minimum base flow for the current year type.

Slots Set: FlamingGorge.Outflow

5. *Base flow Operations*

Execution Constraint: June - April

Description: Depending on the model start month, set the base flow operations based on the hydrologic classification. The value of the base flow within the allowable range is calculated based on meeting the May 1 upper limit draw down elevation (ULDE). Only set June, July if down ramping has completely finished in the previous month.

- Overlap with spring flow rule since ramp down month is variable
- Relies on previous proportions being set.
- If model is starting in June, July or August, check if base flow operations have started and either continue base flow or start it

Slots Set: FlamingGorge.Outflow

Flow Recommendations:

Hydrologic Category	Frequency	Reach	Downramp Rate	Base Flow Period	Base Flow Magnitude
Dry	10%	1	350 cfs/day	About 15 June to 1 March	800 to 1,000 cfs
Dry	10%	2			900 to 1,100 cfs
Moderately Dry	20%	1	350 cfs/day	About 1 July to 1 March	800 to 1,300 cfs
Moderately Dry	20%	2			1,100 to 1,500 cfs
Average	40%	1	500 cfs/day	About 15 July to 1 March	800 to 2,200 cfs
Average	40%	2			1,500 to 2,400 cfs
Moderately Wet	20%	1	1,000 cfs/day	About 1 August to 1 March	1,500 to 2,600 cfs
Moderately Wet	20%	2			2,400 to 2,800 cfs
Wet	10%	1	1,000 cfs/day	About 15 August to 1 March	1,800 to 2,700 cfs
Wet	10%	2			2,800 to 3,000 cfs

6. *Set Remaining Proportion*

Execution Constraint: May - July

Description: In a given spring flow month, if ramping down has finished before the end of the month the remaining portion of the month must be base flow.

- 1 - ∑(All other proportions)

Slot Set: FlamingGorgeData.RemainingProportion

7. Set Ramp Down Proportion

Execution Constraint: May - July

Description: In a given spring flow month, if no more days remain at power plant capacity, then compute the time necessary to ramp down to base flow.

Slots Set: FlamingGorgeData.RampDownProportion

8. Set Power Plant Capacity Proportion

Execution Constraint: May - July

Description: In a given spring flow month, if no more days remain at power plant capacity, then compute the time necessary to ramp down to base flow. Power plant capacity is a surrogate for explicitly setting peak flows.

- In May 3 cases:
  1. No ppc because ramping takes all 7 days (Only applies to extreme cases)
     - PPCProportion = 0
  2. PPC for the rest of the month after ramp up or
     - PPCProportion = Remaining time in May after ramping up occurs
  3. PPC completely finishes (Only in extreme dry years)
     - PPCProportion = Only the portion of the month that will deplete the PPCDays

- In June:
  1. Start PPC and finish (if ramping took all of May)
     - PPCProportion = portion of the month that will deplete the PPCDays
     - Reduce RemainingPPCDays to zero
  2. Start/Continue PPC and do not finish
     - PPCProportion = 1
     - Reduce RemainingPPCDays by number of days in June
  3. Start/Continue PPC and finish
     - PPCProportion = portion of month that will deplete ppc days
     - Reduce RemainingPPCDays to zero
  5. PPC Previously finished (Extreme Low flow years)
     - PPCProportion = 0

- In July:
  1. Continue PPC and finish with no time left (extreme wet years)
     - PPCProportion = all of month less the time to downramp
     - Reduce RemainingPPCDays to zero

  - Increase outflow above PPC (bypass) for the amount of time necessary to meet ULDE
2. Continue PPC and finish with time to spare
  - PPCProportion = portion of the month that will deplete the PPCDays
  - Reduce RemainingPPCDays to zero
3. PPC previously finished
  - PPCProportion = 0

9. Set Bypass Proportion

Execution Constraint: June

Description: In wet years Flaming Gorge will always bypass. In dry years Flaming Gorge will never bypass. In the other three year types, Flaming Gorge will bypass if conditions on the Yampa River warrant bypassing water to try and meet the "wetter" targets at Jensen. The number of days that the Yampa River is above 14,000 cfs is the decision variable which determines if Flaming Gorge will bypass water. The following empirical relationship was determined to compute the number of days above 14,000 cfs on the Yampa from the April – July gaged volume at Deerlodge.

$$D = \begin{cases} 0\,;\, V < 860\ KAF \\ 0.03 * V - 25.81\,;\, V \geq 860\ KAF \end{cases}$$

Where D = the days above 14,000 cfs and V is the April – July gaged volume at Deerlodge in thousands of acre-ft (KAF).

D must be greater than or equal to the following values for Flaming Gorge to bypass water:

Year Type	Days
Moderately Dry	12
Average	10
Moderately Wet	8

If D is greater than the values listed above then the following table is used to determine the number of days at bypass. This is a function of both the year type on the Yampa and the year type on the Green as determined by the `Compute Percent Exceedance' rule. Note that in all wet years Flaming Gorge bypasses, so it is not dependent on D.

	Yampa Dry	Yampa Mod Dry	Yampa Average	Yampa Mod Wet	Yampa Wet
Green Dry	0	0	0	0	0
Green Mod Dry	0	0	8	10	10
Green	0	7	10	12	12

Average					
Green Mod Wet	0	7	12	14	21
Green Wet	10	10	21	21	21

Slots Set: FlaminGorgeData.BypassProportion

10.Set Ramp Up Proportion

Execution Constraint: May

Description: Determine the amount of time to ramp up from base flow to power plant capacity.
Assume May 23 ramp up date, 2000 cfs/day (partition volume across months if necessary)

- In May: RampUpProportion = DaysToRampUp() / NumDaysInMay
- Otherwise : RampUpProportion = 0

Slots Set: FlamingGorgeData.RampUpProportion

11.Set Previous Proportion

Execution Constraint: May

Description: This is fixed at 23/30 for May only

Slots Set: FlamingGorgeData.PreviousProportion

12.Set Days at Power Plant Capacity

Execution Constraint: March - July

Description: Sets the number of days at power plant capacity given the spring hydrologic classification. Each hydrologic classification has a range for the days at power plant capacity (see DaysAtPowerPlantCapacity in the Data section). The number of days is determined by interpolation based on the particular year's exceedance percentage from the Yampa River. ie: an average year with exactly a 50% exceedance percentage would result in 21 days at power plant capacity.

Also initializes the remaining days at power plant capacity to be the same as the total days.

Slots Set: FlamingGorgeData.PPCDays, FlamingGorgeData.RemainingPPCDays

13.Spring Flow Hydrologic Classification

Execution Constraint: January - July

Description: Use forecast of April-July volume (unregulated Flaming Gorge inflow) to determine the hydrologic classification for the given month

- In any particular month, classify based on following season forecasted April - July unregulated inflow.
- When running from different start dates, the hydrologic classification may change from month to month but will not change during a single run

Slots Set: FlamingGorgeData.SpringHClass

14.Base Flow Hydrologic Classification

Execution Constraint: June - February

Description: Use observed April-July volume (unregulated Flaming Gorge inflow) to determine hydrologic classification.

- Classification will not change from spring classification during a single run
- Between runs with start dates August-December, classification will not change
- In June and July treat the forecast as the observed in order to get an estimate of volume and set classification
- May vary between runs with start dates Jan - July since incomplete or no observations are available

Slots Set: Sets FGData.BaseFlowHClass

15.Calc Percent Exceedance

Execution Constraint: None

Description: By comparing the current year's April - July volume to the historic record, the percent exceedance is determined – this dictates the hydrologic year type (see the attached figure for the percent exceedance ranges that correspond to each year type). The current year's April – July volume is set by the `Calc April July Volume Monthly' rule. If HistoricData.UpdateHistoricRecord is set to 1, then the true historic record plus the modeled volumes up to the previous model year are used for computing the year's percent exceedance. If HistoricData.UpdateHistoricRecord is set to 0, then only the true historic record is used to compute the year's percent exceedance.

Slots Set: FlamingGorgeData.AprJulPercentExceedanceSpringFlow, FlamingGorgeData.AprJulPercentExceedanceBaseFlow, FlamingGorgeData.YampaAprJulVol

16.Initialize Proportions

Execution Constraint: None

Description: Initializes all proportion slots to 0.

Slots Set: FlamingGorgeData.PreviousMonthProportion, FlamingGorgeData.RampUpProportion, FlamingGorgeData.BypassProportion, FlamingGorgeData.PPCProportion, FlamingGorgeData.RampDownProportion, FlamingGorgeData.RemainingProportion, FlamingGorgeData.ManualSpill

17. Calc April July Volume Monthly

Execution Constraint: None

Description: Compute the current year's April - July Flaming Gorge unregulated inflow volume and the April – July gaged volume at Deerlodge for the Yampa River at Deerlodge. These volumes will determine the current year's hydrologic year type when compared to the historic record.

Slots Set: FlamingGorgeData.AprJulVolSpringFlow, FlamingGorgeData.AprJulyVolBaseFlow, FlamingGorgeData.YampaAprJulVol

18. Update Historic Record

Execution Constraint: Execute every August if HistoricData.UpdateHistoricRecord is equal to 1

Description: This rule adds on modeled spring volumes (unregulated for Flaming Gorge and gaged for the Yampa) to the historic record. The slots which are set by `Calculate April to July Volume Annual Slot' are updated so that the previously modeled spring volumes will be used to compute the next year's hydroglogic year type thresholds. **Though this rule reflects the procedure currently implemented by the operator, it can be viewed as an interpretation of the ROD.** To use a static period (1969-2009 for the unregulated inflow into Flaming Gorge in the current model), set HistoricData.UpdateHistoricRecord to 0 to effectively shut this rule off.

Slots Set: FlamingGorgeData.YampaAprJulVolAnnual, FlamingGorgeData.AprJulVolAnnual

19. Calculate April to July Volume Annual Slot

Execution Constraint: Beginning of run

Description: Using the historic monthly flows (found in the HistoricData data object) for the unregulated inflow into Flaming Gorge and for the Yampa at Deerlodge, sum April – July to come up with a spring volume and store in the appropriate slot. Note that the Yampa at Deerlodge is the summation of the Yampa at Maybell and the Little Snake at Lily and not the actual Deerlodge gage values. The values stored in these slots are used to compute the year type thresholds.

Slots Set: FlamingGorgeData.AprJulVolAnnual[1969 - 2009], FlamingGorgeData.YampaAprJulVolAnnual[1922 - 2009]

Flow recommendations from EIS included for reference.

Table 2-1.—Recommended Magnitudes and Duration of Maximum Spring Peak and Summer-to-Winter Base Flows and Temperatures for Endangered Fishes in the Green River Downstream From Flaming Gorge Dam as Identified in the 2000 Flow and Temperature Recommendations

Location	Flow and Temperature Characteristics	Hydrologic Conditions and 2000 Flow and Temperature Recommendations[1]				
		Wet[2] (0–10% Exceedance)	Moderately Wet[3] (10–30% Exceedance)	Average[4] (30–70% Exceedance)	Moderately Dry[5] (70–90% Exceedance)	Dry[6] (90–100% Exceedance)
Reach 1 Flaming Gorge Dam to Yampa River	Maximum Spring Peak Flow	• 8,600 cfs (244 cubic meters per second [m^3/s])	• 4,600 cfs (130 m^3/s)	• 4,600 cfs (130 m^3/s)	• 4,600 cfs (130 m^3/s)	• 4,600 cfs (130 m^3/s)
	Peak flow duration is dependent upon the amount of unregulated inflows into the Green River and the flows needed to achieve the recommended flows in Reaches 2 and 3.					
	Summer-to-Winter Base Flow	1,800–2,700 cfs (50–60 m^3/s)	1,500–2,600 cfs (42–72 m^3/s)	800–2,200 cfs (23–62 m^3/s)	800–1,300 cfs (23–37 m^3/s)	800–1,000 cfs (23–28 m^3/s)
Above Yampa River Confluence	Water Temperature Target	• 64 degrees Fahrenheit (°F) (18 degrees Celsius [°C]) for 3-5 weeks from mid-August to March 1	• 64 °F (18 °C) for 3-5 weeks from mid-August to March 1	• 64 °F (18 °C) for 3-5 weeks from mid-July to March 1	• 64 °F (18 °C) for 3-5 weeks from June to March 1	• 64 °F (18 °C) for 3-5 weeks from mid-June to March 1
Reach 2 Yampa River to White River	Maximum Spring Peak Flow	• 26,400 cfs (748 m^3/s)	• 20,300 cfs (575 m^3/s)	• 18,600 cfs[7] (527 m^3/s) • 8,300 cfs[8] (235 m^3/s)	• 8,300 cfs (235 m^3/s)	• 8,300 cfs (235 m^3/s)
	Peak Flow Duration	Flows greater than 22,700 cfs (643 m^3/s) should be maintained for 2 weeks or more, and flows 18,600 cfs (527 m^3/s) for 4 weeks or more.	Flows greater than 18,600 cfs (527 m^3/s) should be maintained for 2 weeks or more.	Flows greater than 18,600 cfs (527 m^3/s) should be maintained for 2 weeks in at least 1 of 4 average years.	Flows greater than 8,300 cfs (235 m^3/s) should be maintained for at least 1 week.	Flows greater than 8,300 cfs (235 m^3/s) should be maintained for 2 days or more except in extremely dry years (98% exceedance)
	Summer-to-Winter Base Flow	2,800–3,000 cfs (79–85 m^3/s)	2,400–2,800 cfs (69–79 m^3/s)	1,500–2,400 cfs (43–67 m^3/s)	1,100–1,500 cfs (31–43 m^3/s)	900–1,100 cfs (26–31 m^3/s)
Below Yampa River Confluence	Water Temperature Target	Green River should be no more than 9 °F (5 °C) colder than Yampa River during summer base flow period.	Green River should be no more than 9 °F (5 °C) colder than Yampa River during summer base flow period.	Green River should be no more than 9 °F (5 °C) colder than Yampa River during summer base flow period.	Green River should be no more than 9 °F (5 °C) colder than Yampa River during summer base flow period.	Green River should be no more than 9 °F (5 °C) colder than Yampa River during summer base flow period.
Reach 3 White River to Colorado River	Maximum Spring Peak Flow	• 39,000 cfs (1,104 m^3/s)	• 24,000 cfs (680 m^3/s)	• 22,000 cfs[9] (623 m^3/s)	• 8,300 cfs (235 m^3/s)	• 8,300 cfs (235 m^3/s)
	Peak Flow Duration	Flows greater than 24,000 cfs (680 m^3/s) should be maintained for 2 weeks or more, and flows 22,000 cfs (623 m^3/s) for 4 weeks or more.	Flows greater than 22,000 cfs (623 m^3/s) should be maintained for 2 weeks or more.	Flows greater than 22,000 cfs (623 m^3/s) should be maintained for 2 weeks in at least 1 of 4 average years.	Flows greater than 8,300 cfs (235 m^3/s) should be maintained for at least 1 week.	Flows greater than 8,300 cfs (235 m^3/s) should be maintained for 2 days or more except in extremely dry years (98% exceedance)
	Summer-to-Winter Base Flow	3,200–4,700 cfs (92–133 m^3/s)	2,700–4,700 cfs (76–133 m^3/s)	1,800–4,200 cfs (52–119 m^3/s)	1,500–3,400 cfs (42–95 m^3/s)	1,300-2,600 cfs (32–72 m^3/s)

[1] Recommended flows as measured at the United States Geological Survey gauge located near Greendale, Utah, for Reach 1; Jensen, Utah, for Reach 2; and Green River, Utah, for Reach 3.

[2] **Wet** (0% exceedance): A year in which the forecasted runoff volume is larger than almost all of the historic runoff volumes. This hydrologic condition has a 10% probability of occurrence.

[3] **Moderately Wet** (10–30% exceedance): A year in which the forecasted runoff volume is larger than most of the historic runoff volumes. This hydrologic condition has a 20% probability of occurrence.

[4] **Average** (30–70% exceedance): A year in which the forecasted runoff volume is comparable to the long-term historical average runoff volumes.

[5] **Moderately Dry** (70–90% exceedance): A year in which the forecasted runoff volume is less than almost all of the historic runoff volumes. This hydrologic condition has a 20% probability of occurrence.

[6] **Dry** (90–100% exceedance): A year in which the forecasted runoff volume is less than almost all of the historic runoff volumes. This hydrologic condition has a 10% probability of occurrence.

[7] Recommended flows • 18,600 cfs (527 m^3/s) in 1 of 2 average years.

[8] Recommended flows • 8,300 cfs (235 m^3/s) in other average years.

[9] Recommended flows • 22,000 cfs (623 m^3/s) in 1 of 2 average years.

Appendix C

Navajo Rule Outline

Appendix C includes an outline of the Navajo rules that were developed to incorporate daily requirements into the monthly model.

Navajo Operations
Rule Outline for E-flows Model

Revisions:

Version 1: March 29, 2010; Alan Butler
Version 2: April 8, 2010; Alan Butler
Version 3: April 19, 2010; Alan Butler
Version 4: April 22, 2010; Alan Butler
Version 5: May 3, 2010; Alan Butler
Version 6: May 14, 2010; Alan Butler
Version 7: June 7, 2010; Alan Butler
Version 8: June 29, 2010; Alan Butler
Version 9: July 6, 2010; Alan Butler

Data

SanJuanNewMexicoDiversionSchedules

Includes the diversion and depletion schedules for the following aggregate diversion objects:

1. NewMexicoAgriculture
    a. NewMexicoAgricultureTribUse and NewMexicoAgricultureSJUse are calculated from this total schedule
2. NewMexicoMiscellaneousUses
3. SanJuanRiverEnergyAndMI
4. NewMexicoUsesBelowShiprockNM
5. NavajoIndianIrrigationProjectNIIP
6. SanJuanChamaExport

NavajoData

Scalar: BaseRelease = 250 cfs
Scalar: MinTargetBaseflow = 500 cfs
Series: ForecastedInflow
Scalar: EOWYTargetPE = 6,065’
Table: SpringPeakReleaseData

- VolumeAbove Base Release:
    - 0-days = 0 AF- No days above 250 cfs
    - 1-week = 128,430 AF Above 250 cfs release
    - 2-week = 184,959 AF Above 250 cfs release
    - 3-week = 260,331 AF Above 250 cfs release
    - Max = 387,273 AF Above 250 cfs release
- Days at Peak Operations
- April Vol Above Base Release
- May Vol Above Base Release

June Vol Above Base Release
Scalar: SpringPeakRelease = 5,000 cfs
Scalar: maxPE = 6,085'
Scalar: PostDamProtectionPE = 6,082'
Scalar: SupplementalReleaseIncrement = 100 cfs
Scalar: MaxDesiredPE = 6,082'
Scalar: PostFloodControlPE = 6,075'
Table: ExtendedMaxHydrographData
Table: SpringPeakJuneJulyExtData
Table: Level1To3RampDown
Table: Level4RampDown

NavajoResults

Series: CurrentTargetBaseflow
Series: PeakReleaseLevel
Series: SupplementalRelease
Series: DamProtectionFlag
Series: VolumeReleasedForDamProtection
Series: ExtremeDroughtFlag
Series: ProjectedEOWYPE
Series: FloodControlFlag
Series: TotalSpringPeakExtensionDays
Series: ExtendedSpringFlow
Series: ExtendedSpringFlowIndex
Series: ProjectedPE
Series: WSAShortage
Series: WSAPercentageReduction

SanJuanNMWaterSharing

Series: NewMexicoAgSJAnnualDepletion = 37,000 acre-ft/year 2010-2060
Scalar: ProtectedPE = 5,990'
Series: MinFarmingtonDiversion:
 2010 = 14,500 acre-ft
 2011 = 15,000 acre-ft
 2012 – 2060 = 15,500 acre-ft
Series: EnergyVoluntaryReduction = 3199.25 acre-ft/year 2010-2060
Scalar: BaseflowReductionStorage = 1,000,000 acre-ft
Scalar: ReducedTargetBaseflow = 400 cfs
Scalar: MinReducedBaseflow = 300 cfs

General Notes:
The term 'Water Sharing Agreement' (WSA) throughout this document refers to the *Recommendations for San Juan River Operations and Administration for 2009 – 2012* dated January 29, 2009.

Rules

In order of highest to lowest priority

1. Extreme Drought per Water Sharing Agreement

- If PE <= 5,990' then
  - outflow = inflow
  - ExtremeDroughtFlag = 1
  - Set all diversions/depletions in Shortage Sharing Agreement Subbasin to 0

Slots Set by Rule:
Navajo.Outflow, NavajoResults.ExtremeDroughtFlag

Notes:
This rule stems from the Water Sharing Agreement and is meant to protect NIIP's canal invert. In CRSS this rule should not fire as long as it is operating with perfect knowledge if the Protect Elevation 5,990' rule is operating correctly. However, in the Midterm Probabilistic or if a forecast is implemented in CRSS it is conceivable that this rule is needed.

2. Dam Protection Flood Control

- If PE >= 6,085', then release enough water to so that PE goes to 6,082' (NavajoData.PostDamProtectionPE)
- Set Outflow to needed release
  - Monthly spill calc will then determine the amount of unregulated release which is anything over the maximum of 5000 cfs

Slots Set by Rule:
Navajo.Outflow, NavajoResults.DamProtectionFlag, NavajoResults.VolumeReleasedForDamProtection

3. Flow Recommendation Covered Flood Control

Execute in September - December

- If PE > 6,082' then enter flood operations
- Release up to 5000 cfs
  - Duration will be as short as possible to ensure PE < 6,075' and will then return to baseflow
- Increase release by volume above baseflow

Slots Set by Rule:
Navajo.Outflow, NavajoResults.FloodControlFlag, NavajoResults.FloodControlVolume

Notes:
During model verification, check to ensure that there are not several months in a row of spike releases, as it is likely that they would try and have only one fall spike flow.

4. Makeup for Shorted Diversion per Water Sharing Agreement

Execute in November and December

- If Navajo is releasing base release of 250 cfs and the base flow at Bluff (See Notes of rule 13-Set Base Release) is above 500 cfs, then the following users can divert water in excess of any shorted diversion from the current year as long as the minimum base flow is maintained at Bluff without increasing Navajo's release
    - San Juan Generating Station, the Four Corners Power Plant, the City of Farmington and the minor Jicarilla Apache Nation subcontractors
- Will assume that the total amount of water available above the base flow is distributed proportionally to the above users
- The above users are assumed to be embedded in the SanJuanRiverEnergyAndMI and NewMexicoMiscellaneousUses diversion objects
    - These objects belong to the "WSA Energy Farmington Jicarilla" subbasin for this rule

Slots Set by Rule:
Total Depletion Requested and Total Diversion Requested for all aggregate diversion objects in the "WSA Energy Farmington Jicarilla" subbasin

Notes:
For modeling purposes we will assume that through 2060, any shortages would be handled similarly to the current agreement as described in the Water Sharing Agreement. The Total Depletion Requested and Total Diversion Requested slots are set to the correct values, however the individual water users in the aggregate diversion object are not modified.

5. Reduce Minimum Target Base Flow per Water Sharing Agreement

Execute in March - October

- If the Minimum Probable Inflow Forecast projects the July 31, Navajo Reservoir content to be below 1,000,000 acre-feet **and** there is not a water shortage for the year then the target minimum base flow at Bluff is reduced to 400 cfs through October of that year
    - Check the NavajoDataObject.ProjectedPoolElevation[@July] and NavajoDataObject.ShortageSharingFlag

Slots Set by Rule:
NavajoResults.CurrentTargetBaseFlow

Notes:
For modeling purposes we will assume that through 2060, any shortages would be handled similarly to the current agreement as described in the Water Sharing Agreement.In CRSS, rather than using the

minimum probable forecast, the NavajoDataObject.ForecastedInflow slotwill be used to make the calculation. Currently, this slot represents perfect knowledge of the future inflows into Navajo.

6. Protect Elevation 5,990 per Water Sharing Agreement

Execute in March – October

Determination of Shortage:

- Using the NavajoDataObject.ProjectedPoolElevation slot determine if Navajo's PE will fall below 5,990' anytime from March – October
  - If the PE is ever < 5,990' then determine the total volume of water which would ensure PE > 5,990' for the current water year

Application of Shortage:

- Proportionally distributed this amount of water (found above) to all users in the "Water Sharing Agreement Users" subbasin with the following caveats:
  - City of Farmington:
    The city of Farmington will not be reduced below the following diversion amounts; in the absence of official numbers beyond 2012, the 2012 protection level was extended through 2060 (SanJuanNMWaterSharing.MinFarmingtonDiversion)
    - 14,500 acre-ft in 2010
    - 15,000 acre-ft in 2011
    - 15,500 acre-ft in 2012 – 2060
  - Power plants:
    San Juan Generating Station and Four Corners Power Plant diversions will be voluntarily reduced by 5% before the shortage amount is calculated (SanJuanNMWaterSharing.EnergyVoluntaryReduction)
  - Agricultural users:
    Agricultural users will have the irrigation season shortened to meet their percentage reduction. Other users will have their percentage reduction distributed over the year based on their percentage use in each month.
    - If irrigation season has not begun, then the beginning of the irrigation season will be shortened by taking water from the first month the object has a non zero depletion requested slot
    - If irrigation season has already begun, then the end of the irrigation season will be shortened by taking water from the last month the object has a non zero depletion requested slot
    - In either case, if the first/last month does not have enough water to meet the needed reduction, water will be taken from the next month and so on until the reduction volume has been met
    - The percentage reduction will be taken off of a 37,000 acre-ft annual volume (SanJuanNMWaterSharing.NewMexicoAgSJAnnualDepletion) which represents the aggregate depletion of Citizens Ditch, the Hammond Irrigation Project, the Farmers Mutual Ditch, the Fruitland Irrigation Project, the Jewett Valley Ditch, and the Hogback Irrigation Project

- San Juan Chama Project:
  Limit San Juan Chama Project to 107,500 minus percentage reduction

Effects on Flow Recommendations:

- The instantaneous e-flow is shorted the same percentage as all other users from March 1 – October 31 of the shortage year
  - WSA states: "after shortage, base flow (at Bluff- see note of rule 13) shall not be below 350 cfs for more than 50 days of which no more than 40 days may be below 300 cfs, with a minimum flow of 250 cfs"
  - The above will be simplified in the model to a minimum of 300 cfs in the model since it is a monthly model

Slots Set by Rule:
NavajoResults.CurrentTargetBaseFlow, Total Depletion Requested and Total Diversion Requested of aggregate diversion objects in the "Water Sharing Agreement Users" subbasin

Notes:
For modeling purposes we will assume that through 2060, any shortages would be handled similarly to the current agreement as described in the Water Sharing Agreement.

In reality, shortage sharing is implemented based on the PE expected from the minimum probable forecast starting in March and extending through October. For CRSS, it will be based on the actual inflow into Navajo. This assumes that not accounting for the uncertainty of the forecast will not affect Navajo's operations beyond the current year.

The shortage sharing agreements states that instead of a forecast, the monthly inflow can be estimated by the 90% exceedance inflow to the reservoir determined from the hydrologic record.

The Total Depletion Requested and Total Diversion Requested slots are set to the correct values, however the individual water users in the aggregate diversion object are not modified.

7. Determine Water Sharing Agreement Percentage Reduction

Based on the total shortage computed in rule #8 determine the percentage shortage applied to all users in the "Water Sharing Agreement Users" subbasin .

- Compute the percentage reduction as the total shortage divided by total annual use of users
  - Total annual use of users is the 37,000 acre-ft annual depletion of agricultural users, the total NIIP diversion, the total annual depletion of SanJuanRiverEnergyAndMI and NewMexicoMiscellaneousUses minus the voluntary reduction and the protected Farmington Diversion, and the total supplemental release volumes that would be necessary to maintain 500 cfs at Bluff
- The percentage reduction is rounded up to the nearest percent

Slots Set by Rule:
NavajoResults.WSAPercentageReduction

8. Determine Water Sharing Agreement Shortage

Execute in March – October when NavajoResults.WSAShortage is NaN

If the current PE or any future projected PE (now through October) is less than 5,990' then compute the total shortage which needs to be applied to all users in the "Water Sharing Agreement Users" subbasin in rule #6. If no elevation is below 5,990' then set Shortage to 0 acre-ft.

- Calculate Shortage as the storage at 5,990' minus the storage at the minimum elevation (now or future projected)

Slots Set by Rule:
NavajoResults.WSAShortage

9. Project Elevations for the Water Sharing Agreement

Execute in March – September
This rule will be used to project the elevation of Navajo from the current month through October of the current year. It will set a slot on a data object which the Determine Water Sharing Agreement Shortage rule can check to determine whether a shortage is necessary. Note that in March the rule will set the slot for April – October (don't need to project the elevation of the month we're in since it has already been determined from normal operations), then when the rule executes in April it will overwrite the values for May – October and so on.

- Using the remaining inflow into Navajo (NavjoData.ForecastedInflow[@t]), reservoir evaporation estimated on projected elevations for each month, anticipated releases, and NIIP's anticipated diversions to calculate the PE for all remaining months

Slots Set by Rule:
NavajoResults.ProjectedPE[@t through @October]

Notes:
For modeling purposes we will assume that through 2060, any shortages would be handled similarly to the current agreement as described in the Water Sharing Agreement.

10. Extend Spring Peak Release for PE Control

Execute if NavajoResults.TotalSpringPeakExtensionDays has a valid number of days

<u>In March – May</u>

Based on the number of days in PeakExtensionDays, add the applicable volume to Navajo's release. The volume includes a new/different ramp-up volume, the base/supplemental volume, the volume at the extended rate, and the volume above the extended rate (in May).

- The earliest start date depends on the bench that is currently being extended because ramp up will start from base release and ramp up at most 1,000 cfs/day
  - So from the base release 3 days ramp-up are needed to get to 2,500/ 3,000 cfs or 4 days to get to 3,500/4,000 cfs
- The ramp up could be split between March and April or April and May- the logic checks for this and properly splits the ramp-up volume between the proper months

In June-July

Based on the number of days in PeakExtensionDays, add the applicable volume to Navajo's release.

- The ramp-down could be split over June and July- the logic checks for this and properly accounts for it
- The total number of days available is the same for peak release level 1-3 and less for level 4 based on the number of days needed to ramp-down to base release
- In July, check to see if the number of needed extension days was satisfied in June- if not then continue the extension in July

Slots Set by Rule:

Navajo.Outflow

Notes:

This rule does not officially represent the flow recommendations, but it does take advantage of the increased peak flows in wet years by extending them to ensure that the September PE is at an acceptable level.

This rule covers the case of a forecast increasing and thus needing to release more water. For a dramatically decreasing forecast, the Set Peak Release Level and Spring Peak Release rules will drop down to a lower release pattern.

While the CRSS version has perfect knowledge in the spring and can thus increase March's flow leaving a low chance of needing July, the Midterm Probabilistic version will have a greater need for it in max release years. Because the spring peak release pattern could already be under way, when it is decided that September PE will be > 6,065', the release can be increased in June/July. For this an elevation greater than 6,073' on June 30th would suggest increasing releases in June/July.

11. Determine if Spring Peak Extension is Required

Execute in March-July

In March:

- If Max Standard Release results in a September 30th PE > 6,065’ then extend peak release backwards starting in May through the current month
    - First, extend 2,000 cfs release backwards, having it begin as early as March 1 or the beginning of the current month
    - If the PE is still greater than 6,065’ then extend 2,500 cfs release backwards in same manner as above
        - Keep iterating in 500 cfs increments up to 5,000 cfs to obtain PE <= 6,065’
- Set the number of days and spring flow which meet the desired September PE; the index is for ease of use in the rule #10 where 0 corresponds to 2,000 cfs, 1 to 2,500 cfs, etc.
- Rounds the calculated number of days necessary down to the nearest whole number of days

<u>In April/May:</u>
Copy the TotalSpringPeakExtensionDays, ExtendedSpringFlow and ExtendedSpringFlowIndex which were computed in March

<u>In June:</u>
- For any release pattern (NavajoDataObject.PeakReleaseLevel > 0)
- If the forecasted September 30th PE > 6,065’ then extend days at 5,000 cfs forward through June and into July if necessary to meet the 6,065
- Rounds the calculated number of days necessary down to the nearest whole number of days

<u>In July:</u>
Copy the TotalSpringPeakExtensionDays and ExtendedSpringFlow that were computed in June

Slots Set by Rule:
NavajoResults.TotalSpringPeakExtensionDays, NavajoResults.ExtendedSrpingFlow, NavajoResults.ExtendedSpringFlowIndex

12. Spring Peak Release for Flow Recommendations

Execute in April – June
<u>General Operations:</u>
- Check the NavajoResults.PeakReleaseLevel slot and distribute the corresponding volume over April, May and June centered on June 4th
    - Since the Supplemental Base Release rule has already executed, the base release during the month should already be met, and increasing the volume released should cover the peak release
- Increase release in appropriate month by days at peak flow and ramp up volume
    - Note that if the base release has been supplemented, then the supplemented amount should be subtracted off the period of ramp up/peak so that additional volume is in addition to 250 cfs base release only

<u>Exceptions:</u>
- In May or June and PeakReleaseLevel[@”t-1”] == 4 and PeakReleaseLevel[@”t”] < 4

    - Maintain last month's release, but decrease duration at 5,000 cfs or ramp up benches to meet new peak release pattern
    - Return to base release for first part of May, then begin ramp-up according to new PeakReleaseLevel
- In June and PeakReleaseLevel[@"t-1"] > PeakReleaseLevel[@"t"]
    - Decrease duration at 5,000 cfs to meet new peak release pattern
    - The peak release will no longer be centered around June 4th

Slots Set by Rule:
Navajo.Outflow

Notes:
CRSS version will use standard release volumes (determined by the Determine Peak Release rule) while Midterm Probabilistic will accept user input for first year when difference in release volume due to maintenance and weekend ramp up avoidance has been determined.

13. Set Projected EOWY Pool Elevation

Execute in January – June when the ProjectedEOWYPE is NaN

Calls ProjectedNavajoPE(peak release level, September 30, Current Year) to set the ProjectedEOWYPE slot which is used by several other rules. See Functions section for detailed explanation of function.

Slots Set by Rule:
NavajoResults. ProjectedEOWYPE

14. Set Peak Release Level

Execute in January – June AND IsNaN(NavajoResults.PeakReleaseLevel[])
<u>In January - May</u>

- Using current PE, current month – September "forecasted" inflow, and current month – September projected releases:
    - Determine release volume that will result in September 30th PE closest to 6,065'
        - This will be determined as the absolute closest value
- Call DeterminePeakRelease() and set Peak Release Level flag:
    - = 0; No spring peak
    - = 1; 1 week peak release
    - = 2; 2 week peak release
    - = 3; 3 week peak release
    - = 4; max peak release

<u>In June</u>

- Call DeterminePeakRelease()
    - If DeterminePeakRelease() is < Peak Release Level Flag[@"t-1"] and > 0 then set Peak Release Level Flag to new value

    - The Spring Peak Release for Flow Recommendations rule will now have to recalculate the monthly release volumes based on the new peak release pattern

Slots Set by Rule:
NavajoResults.PeakReleaseLevel

Notes:
With the addition of Vallecito, this causes Vallecito to solve for an entire year/water year before Navajo can solve if perfect knowledge is desired for Navajo's inflow. This rule allows the release pattern to decrease if necessary based on a crashing forecast. Since the release will have already started in May, it will no longer be centered on June 4^{th}.

15. Compute Forecasted Inflow

Execute in January - October

- Computes and sets the forecasted inflow for current month through end of water year
- Currently sets the forecasted inflow to the actual inflow Navajo will receive

Slots Set by Rule:
NavajoData.ForecastedInflow[@t through @October]

Notes:
This rule could compute the forecasted inflow based on linear regression or some other method. At this time forecasted inflow is set to the actual inflow that will occur in the future. This rule is implemented so that in the future, a forecasting error could be applied to future inflows if desired. It will also provide consistency in other rules between CRSS and the midterm probabilistic model as they will all use the forecasted inflow slot to determine future operations.

16. Supplement Base Release

- Check flow at Bluff to determine if Navajo's release should be increased above BaseRelease to meet minimum target base flow at Bluff (see *Notes* section of Set Base Release rule for explanation of checking only Bluff)
- If supplemental release is necessary, increase Navajo's release in 100 cfs increments
- Set NavajoResults.SupplementalRelease to the additional release from Navajo or zero if no supplemental release is necessary
- Additionally, Navajo's release can be supplemented if the users which depend on Navajo water are being shorted- in certain cases, the base flow at Bluff is maintained, but an upstream diverter is not receiving its entire diversion. In this case supplement Navajo's release enough to ensure all diverters are receiving their entire diversion. If a user is supposed to be shorted, then the Total Diversion/Depletion Requested will be reduced by another rule
- Set NavajoResults.SupplementalReleaseFlag to 1 if the flow was increased to meet the minimum baseflow at Bluff, to 2 if the flow was increased to satisfy diversions, or to 0 if it was not increased.

Slots Set by Rule:
Navajo.Outflow, NavajoResults.SupplementalRelease, NavajoResults. SupplementalReleaseFlag

17. Set Base Release

This aims to meet the target baseflow of 500-1000 cfs at the downstream gages from the flow recommendations by setting Navajo's release to 250 cfs

Slots Set by Rule:
Navajo.Outflow, NavajoResults.CurrentTargetBaseflow

Notes:
The flow recommendations state that an average of the Farmington, Shiprock and Four Corners gages and an average of the Shiprock, Four Corners, and Bluff gages should be taken and the lower of the two averages will be used to monitor the base flow. As the Bluff gage is the only gage out of these four inherently in CRSS and it is the farthest downstream gage, we will only look at it, since it will have the lowest flow in CRSS.

18. Set Normal Depletion Schedules

Execute at beginning of run
This rule initialized the normal depletion schedules of any user that might have its depletion modified via rules. Additionally, it zeros out all flags.

- Set depletion and diversion requested on nodes in Shortage Sharing Agreement subbasin and the SanJuanChamaExport object to their normal depletion schedules
- Extreme Drought Flag = 0
- Dam Protection Flag = 0
- Flood Control Flag = 0
- SupplementalReleaseFlag = 0
- CurrentTargetBaseflow = 500 cfs
- VolumeReleasedForDamProtection = 0 acre-ft
- FloodControlVolume = 0 acre-ft

Functions

NUMERIC DeterminePeakRelease ( )

- Determines spring peak release level that will result in September 30th PE closest to 6,065'
- Returns:
  - 0; No spring peak
  - 1; 1 week peak release

  - 2; 2 week peak release
  - 3; 3 week peak release
  - 4; max peak release
- Indirectly calls ProjectedEOWYNavajoPE with each peak release level and chooses the level which results in a September 30th PE closest to 6,065'

NUMERIC ProjectedNavajoPE(NUMERIC springPeakRelease, DATETIME date)

- Determines the projected September PE as follows:
  - Current Navajo Storage + Anticipated Inflow – Anticipated Navajo release – NIIP's Anticipated Diversion – Estimated Evaporation
- Anticipated Inflow =
  - Forecasted Inflow[@t+1 through September]
- Anticipated releases =
  - Baseflow releases[@t+1 through September] + Supplemental Baseflow releases [@t+1 through September] + Spring Peak Release according to springPeakRelease number – Already Released Spring Volume
- NIIP's Anticipated Diversion =
  - NIIP.Diversion Requested[@t+1 through September]