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Water Resource Modeling of the Colorado River: Present and Future Strategies

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An overview of the CRSS and its utility in analyzing alternative management paradigms concerning the future of the Colorado River

Executive Summary:

- The Colorado River Simulation System (CRSS) is a continuously evolving model that has been revised and modified during a 40-year period. The current model network (released January 2019) of 12 reservoirs, 29 headwater tributary and within-basin stream-flow gages, 520 water user objects, and 145 operating rules codify many aspects of a complex set of treaties, compacts, laws, decrees, Records of Decision, and other administrative rules that represent the modern administrative interpretation of the Law of the River.
- The CRSS is an influential water-policy planning tool that has been used by the Bureau of Reclamation and other stakeholders in numerous major efforts – such as negotiation of the 2007 Colorado River Interim Guidelines for Lower Basin Shortages and Coordinated Operations for Lake Powell and Lake Mead, the 2012 Colorado River Basin Water Supply and Demand Study, and the 2015 Glen Canyon Dam Long-Term Experimental and Management Plan.
- The primary focus of CRSS is simulating the operation of the major federal reservoirs of the mainstem Colorado River and its major headwater branches. The CRSS is configured to address water allocation of the lower Colorado River, simulate the management of stream flow through the Grand Canyon between Lake Powell and Lake Mead, and simulate the operations of Flaming Gorge Dam, the Aspinall Unit on the Gunnison River, and releases from Navajo Reservoir.
- The CRSS is imprecisely configured to address water supply and environmental management issues within many large tributaries of the headwater branches, including the Colorado River upstream from Glenwood Springs, the Yampa River upstream from Maybell, the Little Snake River upstream from Lily, the Dolores River, the Duchesne River watershed, the White River upstream from Watson, the Animas River, the Little Colorado River watershed, the Virgin River watershed, and other tributaries in the Lower Basin. Today, river management programs, endangered fish recovery programs, and some Native American tribes are focusing on these tributaries. It is important for stakeholders to understand that the CRSS is most appropriate for addressing basinwide issues but is not designed to address issues within these tributaries. Expanding the spatial resolution of the CRSS to do so will require significant effort, which Reclamation has not yet proposed doing.

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- The CRSS is not configured to simulate many modern environmental management issues that require finer temporal scales, such as those critical to river ecosystems. Using the CRSS to develop policies to enhance river ecosystems will require bridging the gap between the monthly time scale at which the CRSS operates and the daily or hourly time scales at which many river ecosystems respond to natural processes, reservoir releases, and water withdrawals.
- Interested stakeholders must invest significant resources to understand how the CRSS works and how to use it to meaningfully explore alternative paradigms to manage the Colorado River in ways that enhance water supply reliability, hydroelectricity production, and/or river ecosystem health. Expanding the pool of stakeholders who have sufficient expertise to use the CRSS is a significant challenge. To demonstrate the process and value of doing so, we describe the effort required to evaluate two publicly discussed alternative management paradigms: Fill Mead First and Fill Powell First.
- This white paper is the first of a series of papers by the Future of the Colorado River Project that seeks to explore alternative management strategies for the Colorado River which will benefit water supply users and river ecosystems and that empower more stakeholders to participate in planning the future of the river system.

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This publication is the second in a series of white papers from the Future of the Colorado River Project. Also included in the series:

White Paper 1: Fill Mead First – A Technical Assessment

Executive Summary • Full Paper

The Fill Mead First (FMF) plan would establish Lake Mead reservoir as the primary water storage facility of the main-stem Colorado River and would relegate Lake Powell reservoir to a secondary water storage facility to be used when Lake Mead is full. The objectives of the FMF plan are to re-expose some of Glen Canyon's sandstone walls that are now inundated, begin the process of re-creating a riverine ecosystem in Glen Canyon, restore a more natural stream-flow, temperature, and sediment-supply regime of the Colorado River in the Grand Canyon ecosystem, and reduce system-wide water losses caused by evaporation and movement of reservoir water into ground-water storage.

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Introduction

The Colorado River drains an area of about 247,000 mi^2, about 8% of the conterminous United States. The river provides water supply for 40 million people and maintains the economic vitality of large areas of irrigated agriculture and urban centers in the United States and Mexico (Reclamation, 2012). The water supply allocation, reservoirs, and diversions are operated under a complex array of treaties, laws, and administrative rules known as the Law of the River (MacDonnell et al, 1995). The large geographic scale of the watershed, the complexity of the Law of the River, and the need to evaluate alternative scenarios to manage the river served as impetus to develop a computer software platform useful in planning water system operations and evaluating different water supply management alternatives.

The first generation of large-scale water resource modeling software for the Colorado River system was developed in the 1970s (Fulp et al, 1999) and focused on the operation of federal dams authorized by the Colorado River Storage Project (CRSP) Act in the upper Colorado River basin and on dams on the mainstem Colorado River downstream from Glen Canyon Dam. Different models were developed for different purposes and operated at different time scales. Most of these models were initially written in the FORTRAN computer language and were considered sophisticated for that time period. However, these models were difficult to modify and could not be used to meet the expanding operational objectives and types of analyses that was increasingly required (Fulp et al, 1999).

In 1994, the Bureau of Reclamation initiated a research and development program to modernize and integrate these modeling systems so that planning policies and operation rules could be more flexibly evaluated. Reclamation and the University of Colorado's Center for Advanced Decision Support for Water and Environmental Systems (CADSWES) developed a generic modeling platform called RiverWare™ within which a river basin's network of dams and diversions could be represented and edited using a Graphical User Interface (Zagona et al 2001). Thereafter, the CRSS FORTRAN model was converted into a RiverWare™ model. RiverWare™ has become a widely used river and reservoir modeling platform, with applications ranging from long-term planning and management support such as the CRSS, the administration of water rights considered at daily time steps, and the optimization of the operations of multiple reservoirs on an hourly or even sub-hourly basis.

Today's CRSS model is maintained by Reclamation, and a key design attribute of RiverWare™ is the greater ease of access and transparency of the model. The power of a model like CRSS is to organize, systematize, and represent complex water systems. However, like most models used for supporting decision making, a significant challenge is to balance the degree of complexity required to accurately represent the river system with the simplicity and transparency that allows the model to be understood by stakeholders and used by decision makers (Wheeler et al, 2018). Various state governments, municipalities, and irrigation districts have invested in building in-house capacity to run the CRSS on their own. Nevertheless, the CRSS is a complicated modeling tool, and many watershed stakeholders such as water conservancy districts and municipalities typically contract with engineering consulting firms to run and interpret the results from CRSS. Non-government organizations and natural resource agencies of the Native American tribes of the watershed typically do not have sufficient expertise to run the CRSS and are dependent on analytical services provided by Reclamation or by consultants. The differing degrees of access and expertise to use the CRSS affects the number and types of alternative river operations and management paradigms that parties can formulate and use the model to test.

The purposes of this white paper are to:

- *Review the natural and human-constructed hydrography of the Colorado River and its tributaries;*
- *Describe the representation and operation of the CRSS;*
- *Compare the modern Colorado River system to the CRSS representation of the system;*
- *Describe the concept of alternative management paradigms, provide an illustration of these paradigms for the Grand Canyon segment of the river system; and,*
- *Describe the capability, challenges and limitations associated with using the CRSS to evaluate these strategies and approaches.*

The audience for this white paper is decision-makers and stakeholders involved in or concerned about planning a sustainable future for the Colorado River, and who use the results of CRSS modeling but are less familiar with the model's computational structure or operation. The following section reviews the modern Colorado River and its management, and subsequent sections describe the CRSS structure and solution sequence, representations of alternative management paradigms such as Fill Mead First and Fill Powell First, and the challenge to incorporate environmental considerations into the CRSS modeling. A final section presents next directions for the Colorado River Futures project.

The Modern Colorado River & Its Management

Physiography

The three headwater branches of the Colorado River – the upper Colorado River, the Green River, and the San Juan River – drain the middle and southern Rocky Mountains. These branches flow south and west across the Colorado Plateau. The upper Colorado River and the Green River join to form the Colorado River in Canyonlands National Park in southeast Utah (Fig. 1). The San Juan River drains the southern part of the San Juan Mountains and enters the Colorado River approximately 140 miles (hereafter, mi) downstream from the upper Colorado/Green confluence in what was once Glen Canyon and is now Lake Powell reservoir. No other large tributaries enter the mainstem Colorado River until the Gila River enters at the head of the Colorado River delta near Yuma. The Gila River's headwaters are in the Mexican Highlands of west-central New Mexico. The headwater branches of the Colorado River typically have gravel beds, flow clear, and transport relatively little suspended sediment. Further downstream, the Colorado River once transported a very large load of fine sediment whose source is the desert watersheds of the Colorado Plateau and Basin-and-Range Province.

The Colorado River watershed is administratively divided into two parts – the Upper Basin and the Lower Basin. The dividing point, Lee Ferry, is precisely defined as "a point in the main stream of the Colorado River one mile below the mouth of the Paria River" (Colorado River Compact, Article IIe). Lee Ferry is approximately 2 mi downstream from Lees Ferry, established in the late 1800s as a ferry crossing (Rusho and Crampton, 1992; Reilly, 1999), and today serves as the launch point for river trips through the Grand Canyon. The Lees Ferry gaging station (USGS gage 09380000) is located upstream from the Paria River confluence and has been operated by the US Geological Survey since 1921 (Topping et al, 2003).

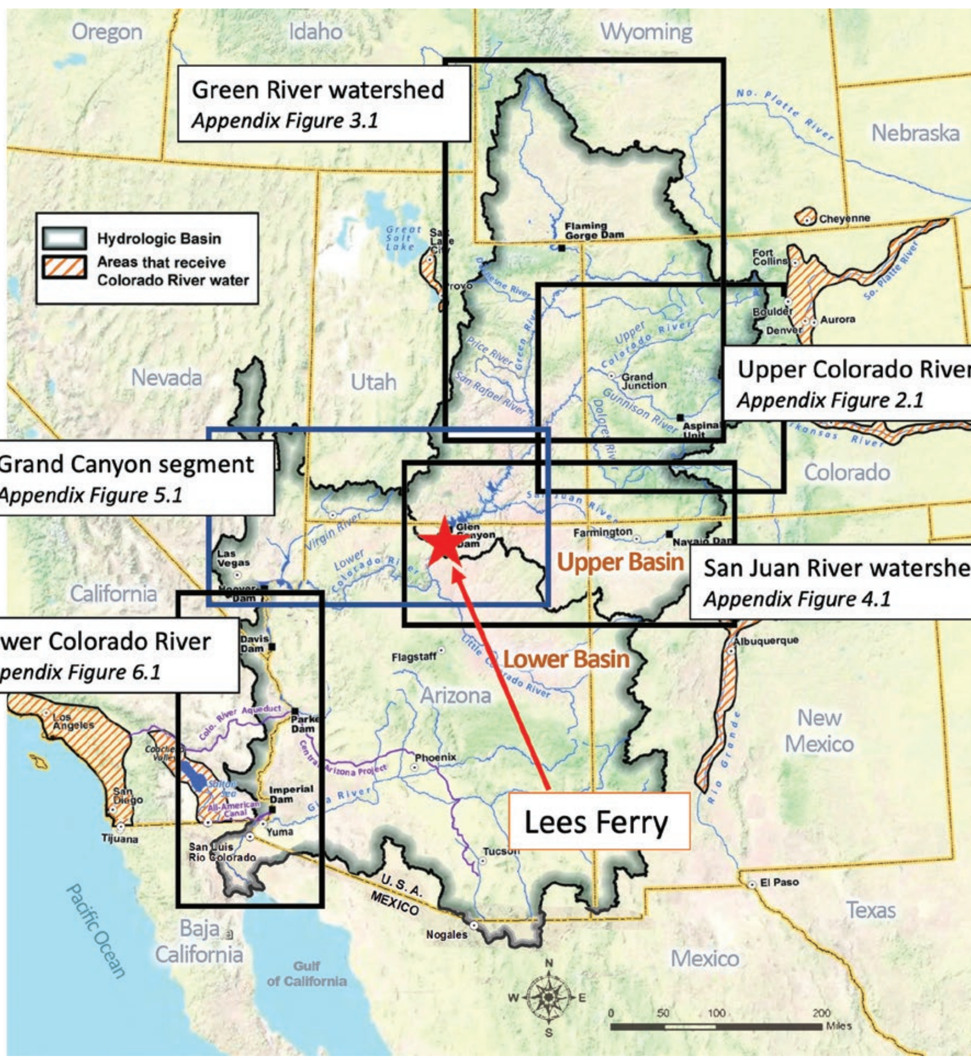


Figure 1. Map showing the Colorado River watershed. The areas of detailed maps are indicated and those figures are referenced. Based on map from Reclamation (2012).

Natural Hydrography

Runoff from the mountainous Upper Basin dominates the hydrology of the Colorado River. Most of the total annual flow in the Upper Basin occurs during the snowmelt season between April and July. The typical natural flow regime of the three headwater branches is illustrated in the hydrographs for the period between 1923 and 1935 before large dams were completed (Fig. 2A-2C). Further downstream, the mainstem Colorado's annual flood once reflected the combined contributions of the three headwater branches, as illustrated at Lees Ferry (Fig. 2D) and Yuma (Fig. 2E).

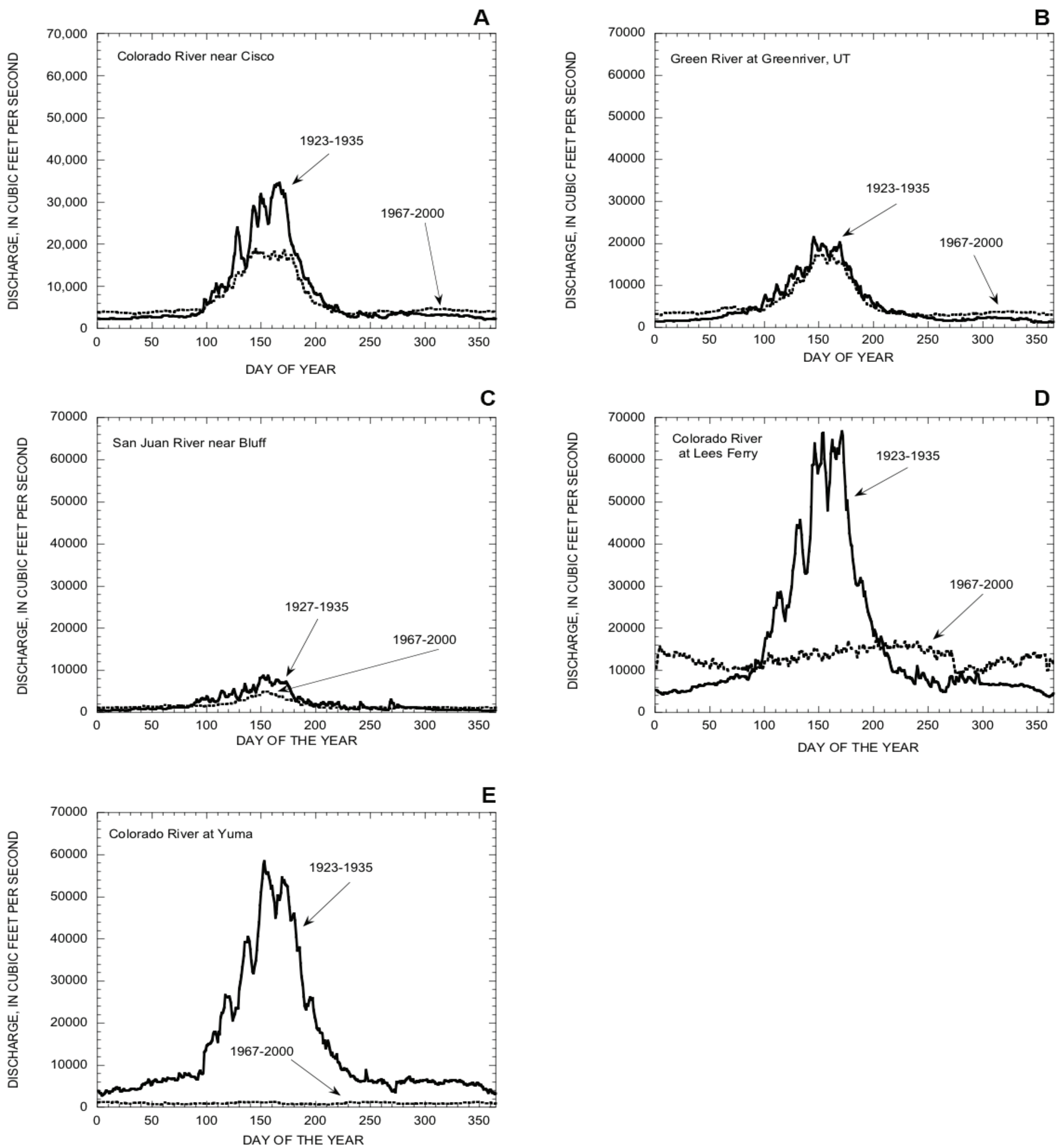


Figure 2. Hydrographs showing average conditions during representative pre-dam (1920s-1935) and post-dam (1967-2000) periods at gaging stations throughout the watershed (Fig. 1). Adapted from Schmidt (2007).

There is significant year-to-year variability in total annual flow, because the atmospheric flow of moisture from the Pacific Ocean may differ greatly from one winter to the next. Total annual natural stream flow at Lees Ferry estimated by Reclamation has varied by more than four-fold between the lowest and the highest years (Fig. 3). This record can be statistically divided into two periods. Between 1906 and 1929, the average annual estimated natural flow at Lees Ferry was 18 x 10^6 acre feet/year (hereafter, maf/yr), and the average flow was 14.0 maf/yr between 1930 and 2016. A similar shift from larger to smaller annual natural runoff occurred at about the same time on each of the upstream headwater branches. Estimates of the long-term mean annual natural flow of the Colorado River at Lees Ferry confirmed that the early 20th century was anomalously wet in relation to runoff of the previous many centuries, and these studies also showed that there have been many dry periods that were more intense and longer in duration than occurred in the last century. Estimates of the long-term mean annual natural flow are between 14.3 and 14.7 maf/yr and are similar to the estimated average conditions that have occurred since 1930 (Woodhouse et al., 2006; Meko et al, 2007).

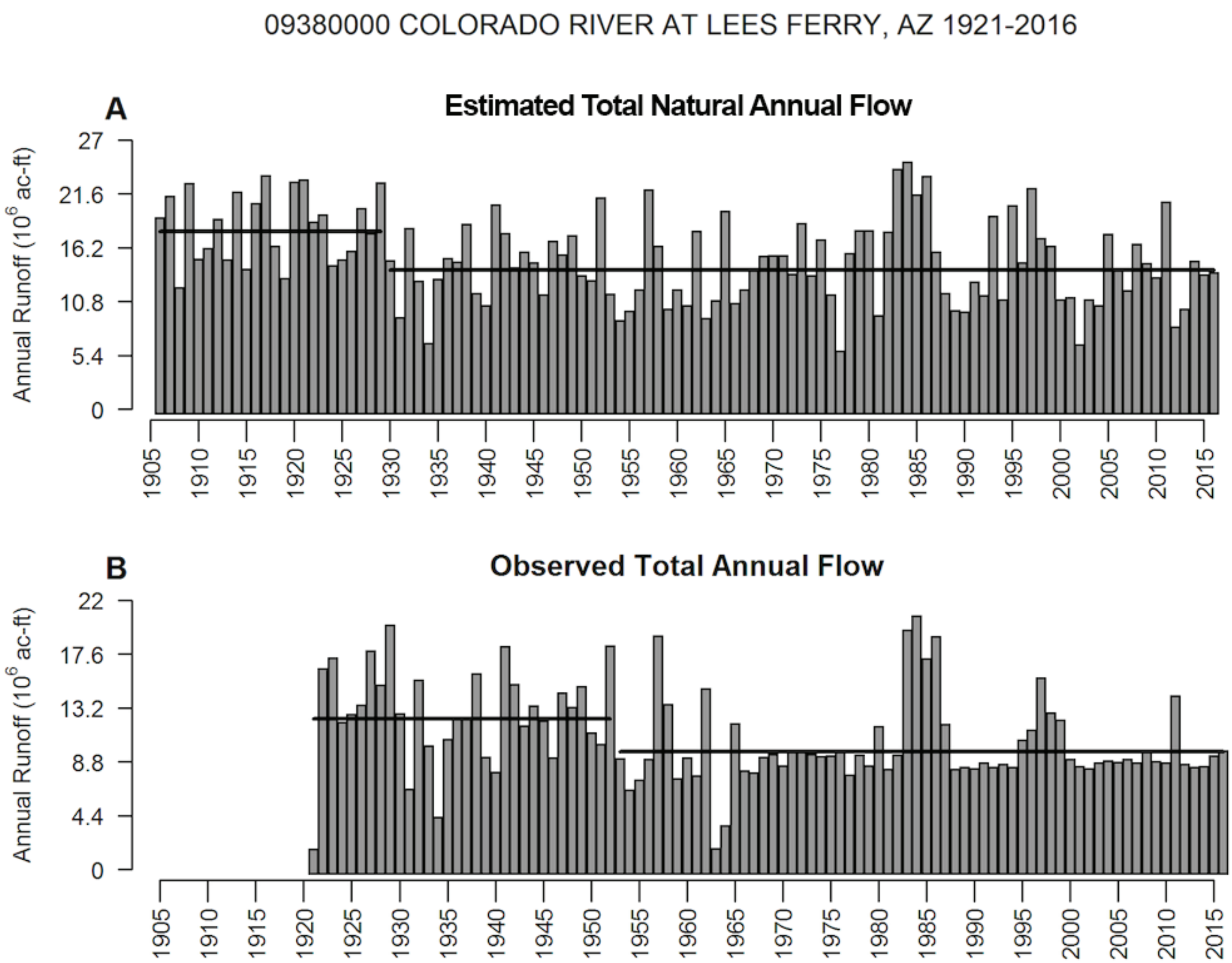


Figure 3. Graphs showing annual hydrology of the Colorado River at Lees Ferry. A. Estimated total annual natural flow (Reclamation, 2019, downloaded at https://www.usbr.gov/lc/region/g4000/NaturalFlow/current.html). B. Measured total annual flow. Horizontal solid lines in each graph indicate the average for the indicated period. The break points that distinguish each period were defined using the method of Blythe and Schmidt (2018).

Modern Hydrology

The modern transformation of the Colorado River's natural flow regime is profound. The total volume of reservoir storage is now 92.8 maf, which is nearly seven times the estimated modern mean annual natural flow at Lees Ferry (Schmidt, 2007). Total basin consumptive uses and losses were ~17 maf/yr in the beginning of the 21st century (*see Appendix 1: Colorado River consumptive uses and losses in the 21st century*). Notably, this value is significantly larger than the modern estimated natural runoff at Lees Ferry. Thus, a delicate balance exists in the watershed wherein the entire natural flow of the river and its tributaries are entirely consumed, and effectively no stream flow reaches the Gulf of California.

The magnitude of human alteration of the Colorado River is least in the Upper Basin, and consumptive uses upstream from Lake Powell averaged only 3.9 maf/yr between 2000 and 2017. Evapotranspiration losses associated with irrigated agriculture in the Upper Basin accounted for 67% of the total consumptive uses, and 0.76 maf/yr was exported out of the watershed. Total export of water to the Colorado Front Range, Wasatch Front, Rio Grande Valley in central New Mexico, and Cheyenne area accounted for 19% of all consumption losses upstream from Lake Powell and was 6% of the estimated natural flow at Lees Ferry.

The Upper Colorado River

The upper Colorado River is the largest headwater branch, and most of the watershed is in the state of Colorado. Water yield from this headwater basin is measured near Cisco (USGS gage 09185000), and the average annual measured flow between 2000 and 2018 was 4.0 maf/yr. Reclamation estimated that the total consumptive uses and losses in the watershed were 1.8 maf/yr (see *Appendix 2: The upper Colorado River watershed*). Thus, the average annual undiverted natural flow of the upper Colorado during the first part of the 21st century was 5.8 maf/yr, and the total consumptive uses in the watershed comprised 31% of the natural flow. Today's peak flows near Cisco are somewhat less and base flows are somewhat higher than in the early 20th century (Fig. 2A).

As described in later sections of this paper, the CRSS coarsely represents the details of runoff and consumptive water use upstream from Glenwood Springs. Most of the stream flow of the upper Colorado River enters the river upstream from Glenwood Springs, which is the most upstream node of the CRSS. Approximately 55% of the total flow of the upper Colorado River measured near Cisco flows past the Glenwood Springs gage, and trans-basin diversions in Colorado, all of which occur upstream from CRSS nodes, accounted for 14% of the estimated natural flow near Cisco. Thus, the CRSS is not configured to address detailed water resource and riverine environmental issues associated with operations of these trans-basin diversions, headwater reservoirs, establishment of minimum flows, and future development.

In contrast, reservoirs and diversions in the Gunnison River watershed are relatively well articulated by the CRSS, as described later in this paper. The Gunnison River is the largest tributary of the upper Colorado River and had an annual mean flow of 1.5 maf/yr between 2000-2018. Trans-basin diversions in the headwaters of the Dolores River were among the earliest in the Colorado River basin and are represented in the CRSS as a transfer link into the San Juan Basin. These diversions transfer 70% of the Dolores River's flow (measured near Bedrock, upstream from the San Miguel River, USGS gage 09171100) to Montezuma Valley in the San Juan River watershed.

The Green River

The most distant source of runoff to the upper Green River is the western part of the Wind River Range, upstream from Fontenelle Reservoir. The magnitude of these inflows is derived in the CRSS from gaging below Fontenelle Dam (09211200 Green River Below Fontenelle Reservoir) and therefore these tributaries are not explicitly delineated. Water is used for flood irrigation in the Pinedale area and little inflow comes from the north slope of the Uinta Mountains, partly because some of the modern runoff is diverted for irrigated agriculture in southwest Wyoming. Water uses above Fontenelle Reservoir are spatially aggregated in CRSS, therefore the reservoirs in the foothills of the Wind River Range and spatial attributes of water management in these tributaries are not described.

Below the Fontenelle Dam, the upper Green River is stored and released through the Flaming Gorge Reservoir before joining the Yampa River at Echo Park in northwestern Colorado. The contributions from the Yampa generally exceed those of the upper Green River, thus the upper Green River and Yampa River can be considered coequal headwater branches. Between 2000 and 2018, the total annual flow released from Flaming Gorge Reservoir on the upper Green River averaged 1.24 maf/yr, and the total flow of the lower Yampa was 1.36 maf/yr (*see Appendix 3: The Green River watershed*).

The combined flow of the upper Green and Yampa Rivers accounts for ~80% of the total flow of the entire Green River at the confluence with the Colorado River. Flows from Yampa River account for 41% of the total flow of the Green River, while releases from Flaming Gorge Reservoir account for ~38%. Mean annual flow near Green River, UT, was 3.3 maf/yr between 2000 and 2018. Today's floods are somewhat smaller than before construction of Flaming Gorge and other dams, and base flows are now higher than they were in the past (Fig. 2B). The total consumptive uses and losses in the watershed between 2000 and 2017 were 1.4 maf/yr. Thus, the natural flow of the Green River in the first part of the 21st century was 4.7 maf/yr, 19% less than that of the upper Colorado River.

There is relatively little consumptive water use and few significant reservoirs in the Yampa River basin. Downstream from the confluence of the Green and Yampa Rivers, the only significant modern inflow comes from the White River, which contributed ~0.42 maf/yr to the Green River and whose flow is entirely controlled by releases from Taylor Draw reservoir. The Duchesne River also contributes to the Green River, but virtually all of Utah's trans-basin diversions to the Great Salt Lake watershed come from the Duchesne watershed, and therefore its contribution was only half the flow of the White between 2000 and 2018. Estimated consumptive water use by agriculture in the White and Yampa watersheds is far less than the estimated use in the Duchesne River watershed. The total trans-basin export of water in Utah between 2000 and 2018 was 0.14 maf/yr. As described in later sections of this paper, the CRSS represents these transfers as a single export, therefore none of the spatial details of the stream flow and consumptive water use in the Duchesne River watershed are explicitly simulated. The Price and San Rafael Rivers have been extensively developed for irrigated agriculture, and modern inflow to the Green River was only ~0/0.05 maf/yr from each between 2000 and 2018.

The San Juan River

The San Juan River is the smallest of the three headwater branches of the Colorado and flows directly into Lake Powell. The mean annual flow near Bluff was 0.98 maf/year between 2000-2018. Total consumptive uses and losses in the watershed were 0.70 maf/year (see *Appendix 4: The San Juan River watershed*). Thus, the natural flow of the San Juan River was 1.7 maf/year in the early 21st century, 71% smaller than the upper Colorado River.

More than 95% of the modern (2000-2018) San Juan annual flow entering Lake Powell comes from the upstream one-third of the watershed – either from the Animas River watershed or the uppermost San Juan River. At their confluence in Farmington, the modern total annual flow of each branch is approximately equal. Thus, releases from Navajo Reservoir only control about half of the total San Juan flow that enters Lake Powell (Fig. 2C).

Another part of the CRSP is the San Juan – Chama Project that collects stream flow from the Rio Blanco, Navajo, and Little Navajo Rivers and transfers that water through a trans-basin tunnel into the Rio Chama for subsequent distribution to central New Mexico. Between 2000 and 2018, 0.082 maf/yr was exported from the San Juan watershed by this system. During the same period, 0.22 maf/yr was imported into the San Juan watershed from McPhee Reservoir on the Dolores River. Virtually all of this water was consumed by agriculture in the Montezuma Valley north from Cortez.

Construction of the Animas – LaPlata project began in 2002, and the project was completed in 2013. This project involves diversion of the Animas River downstream from Durango to create an off-stream reservoir that stores ~0.12 maf of water. Diversions representing this project are included in the CRSS, however, the new reservoir is not depicted. The estimated present depletion from this reservoir is 0.06 maf/yr. In terms of stream flow, there are no significant tributaries downstream from Farmington. However, large amounts of fine sediment from the Chaco River, McElmo Creek, and Chinle Wash are delivered to the San Juan, especially during the summer/fall monsoon season.

The Grand Canyon Segment

Approximately half of the length of the Colorado River between the confluence of the upper Colorado and Green Rivers and Hoover Dam has been converted to reservoirs. Approximately 20 mi in Cataract Canyon upstream from Lake Powell remain as a river and are part of Canyonlands National Park. There are 255 mi of river between Glen Canyon Dam and Separation Rapid, the upstream limit of Lake Mead at full pool. The length of Lake Powell at full pool, measured along the old Colorado River channel, is approximately 180 mi and the similar length along Lake Mead is 70 mi.

Virtually the entire flow of the Colorado River in the Grand Canyon segment is determined by snowmelt from the distant Rocky Mountains and is regulated by storage and releases from Lake Powell (*see Appendix 5: The Grand Canyon segment*). Operations of Glen Canyon Dam have dramatically changed the monthly and daily flow regime. Changes in the monthly flow regime are illustrated (Fig. 2D), and there is no semblance of the former annual snowmelt flood. Today, the months of highest reservoir release coincide with the months of highest demand for hydroelectricity (Reclamation, 2016). The instantaneous pattern of stream flow reflects the greater demand for electricity in the daytime and on weekdays (*see Appendix 5: The Grand Canyon segment*). To date, the focus of Colorado River management has been on adjusting fine-scale attributes of the daily flows released from Lake Powell, because reservoir operations play the dominant role in creating the flow regime of the entire length of the Grand Canyon segment. Mitigation programs such as the High Flow Experiment Protocol and the Macroinvertebrate Production Flow Protocol involve fine-scale changes in releases and do not affect any aspect of the large-scale transfer of water supply from the Upper Basin to the Lower Basin.

There are no significant tributary inflows and no significant consumptive uses along the mainstem in the Grand Canyon segment. Between 2000 and 2018, the average annual inflow of the upper Colorado (near Cisco), the Green River (at

Greenriver, UT), and the San Juan River (near Bluff) was 8.3 maf/yr. Releases from Lake Powell, measured at the Lees Ferry gaging station (number 09380000) averaged 8.9 maf/yr for the same period. Schmidt (2016) demonstrated that Lake Powell's water storage volume is delicately balanced among inflows, evaporation, and outflows, and calculation of a precise and accurate water balance for Lake Powell is difficult. Although inflows of the large headwater branches and outflow at Lees Ferry are well measured, other components of the reservoir mass balance are poorly known (*see Appendix 5: The Grand Canyon segment*).

Downstream from Lake Powell, approximately 0.7 maf/yr flows into the Colorado River from the Paria and Little Colorado Rivers and from spring-fed tributaries within Grand Canyon. Some of these inflows occur upstream from the gage near Grand Canyon (USGS gage 09402500) which is a CRSS node. However, significant inflows also occur downstream from this gage and are measured near Peach Springs (USGS gage 09404200) where the total annual inflow to Lake Mead between 2000 and 2018 was 9.6 maf/yr.

The average rates of inflow, evaporation, and outflow from Lake Mead during the early 21st century can be approximately reconciled in a water budget. Lake Mead water storage declined by 15 maf (0.83 maf/yr) between January 1, 2000, and December 31, 2017, and average annual releases from Lake Mead were 9.5 maf/yr, approximately 0.1 maf/yr less than measured inflows at Peach Springs. Average annual diversion of water directly from Lake Mead by the Southern Nevada Water Authority was 0.27 maf/yr (*see Appendix 5: The Grand Canyon segment*).

The Lower River

Stream flow progressively increases throughout the Upper Basin watershed and through the Grand Canyon, as described above. Downstream from Hoover Dam, this pattern is reversed, and the river's flow is progressively depleted by diversions that transfer water to southern California and central and southern Arizona. Between 2000 and 2017, the average annual Lake Mead releases were 9.5 maf/yr, but only 1.7 maf/yr flowed across the international border to Mexico. The details of the systems of diversions, return flows, and formal accounting of water use in the lower basin is beyond the scope of this report and are described by Reclamation in its annual *Colorado River Accounting and Water Use Report: Arizona, California, and Nevada*. The hydrography of this system of diversions is depicted in the well known "Blue Dragon" diagram (*see Appendix 6: The Lower River*).

CRSS Structure and Representation of the Channel Network

The CRSS is a model that has been revised and modified throughout a 40-year period, incorporating representations of hydrologic conditions, water uses, and evolving water management practices of the Colorado River. The model was developed primarily to simulate operations of the major infrastructure of the mainstem Colorado River and the major federal facilities on the headwater branches. Historical runoff conditions serve as a proxy for the future, however, the CRSS can also incorporate future runoff conditions that change with ever improved predictive capabilities and knowledge of the Earth's changing climate, new findings arising from river science and environmental needs, and proposed changes to the management of major infrastructure such as dams and diversions. Management policies are embedded into the logic of the model, and as a result, the CRSS provides a platform to evaluate new or proposed operational policies, management methods and legal requirements that reflect the changing needs, interests or requirements of uses of the mainstem river. Alternative operation policies are typically evaluated by modifying logic that depicts a particular existing policy or the addition of new logic to reflect a new management proposal. The implications of changing hydrologic conditions or alternative water use projections can be evaluated concurrently when examining alternative management policies.

The CRSS is comprised of two major components: 1) a physical representation of the major elements of the river system and 2) a compilation of hierarchical logical statements that describe how water is managed in the system.

The Physical Representation

The network of reservoirs, river segments, and diversions of the Colorado River watershed is depicted as an object-oriented layout of the river basin (Fig. 1) and includes 12 reservoir objects that represent most of the major federal reservoirs of the mainstem river and its headwater branches. Reservoirs explicitly represented in the CRSS include many in the Gunnison River watershed (Taylor Park, Blue Mesa, Morrow Point, Crystal), mainstem reservoirs on the Green River (Fontenelle Reservoir and Flaming Gorge Reservoir), Navajo Reservoir on the San Juan River, Lake Powell, Lake Mead, Lake Mohave, and Lake Havasu. The reservoirs explicitly represented in the CRSS are the same ones included in the original FORTRAN model, and headwater parts of the basin are represented with variable spatial resolution. For example, the sequence of four reservoirs along the Gunnison River represented in the CRSS is contrasted with a single reservoir object referred to as ‘Starvation’ that represents the many storage reservoirs in the Duchesne River watershed including Strawberry and Upper Stillwater reservoirs (*see* *Appendix 3: The Green River watershed*). In the headwaters of the upper Colorado River, several minor reservoirs, including some managed by Reclamation (e.g. Granby Reservoir, Shadow Mountain Lake, Green Mountain) and some managed by other organizations (Dillon Reservoir managed by Denver Water, Wolford Mountain Reservoir managed by the Colorado River Water Conservation District), are not represented (*see* *Appendix 2: The upper Colorado River watershed*). McPhee Reservoir on the Dolores River is also not explicitly represented in the CRSS.

The river system is represented by interconnected network reach objects that link reservoirs and water users. Each reach object represents a river segment, from each of the headwater tributaries to the mainstem river and down to the Colorado River’s delta. Reach objects flow into and out from the headwater reservoirs and connect to, and between, each of the Lower Basin reservoirs. Reach objects also serve as diversion points for water users across the basin.

Hydrologic inflows into the modeled watersheds are represented as *natural inflows* to specific reach objects. These natural inflows are derived from a computational procedure that is external to the CRSS, which combines historic gaged flows, estimated consumptive uses and losses (i.e., *Upper Colorado River Basin Consumptive Uses and Losses Report* issued every 5 years), decree accounting (*Colorado River Accounting and Water Use Report: Arizona, California, and Nevada* issued every year), and historic reservoir operations. The product is Reclamation’s estimate of what *would have been* the flows absent upstream reservoir storage and upstream consumptive water uses (*see Fig. 4*). The *naturalization* method used to calculate these inputs, and data are described at https://www.usbr.gov/lc/region/g4000/NaturalFlow/.

The CRSS naturalization process starts with **gaged flow** -- the flow actually measured by a stream gage with historical reservoir operations and diversions (A). Next, the process numerically removes reservoirs and estimates the **unregulated flow** as the flow that would be observed at a stream gage absent upstream reservoir operations, evaporation, and bank storage (B). Finally, the process numerically removes water users and estimates **natural flow** as the flow that would be observed at a stream gage absent upstream reservoirs and diversions (C). The uses of natural flow inputs allows the CRSS to simulate a wider set of alternative reservoir operations and demand scenarios that typically affect river flows without having to preprocess flow inputs for each operational scenario. By using natural flow inputs, CRSS instead models and calculates these effects as simulation results.

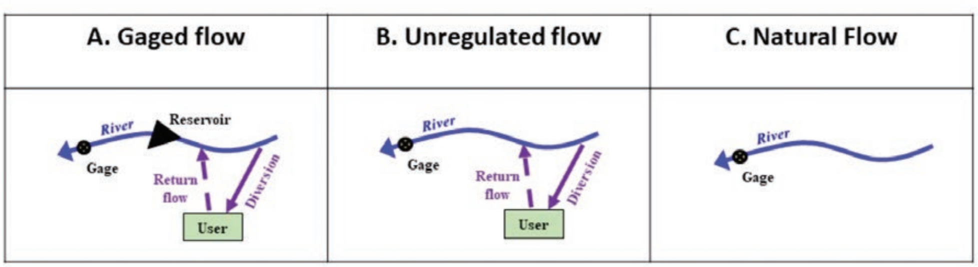


Figure 4. Naturalization Process to develop hydrologic inflows to CRSS

Natural inflows have been estimated at 29 locations in the watershed – 20 in the Upper Basin and 9 in the Lower Basin; each location is at or between USGS stream-flow gaging stations and thus represent headwater tributaries or tributary inflows that enter the system between each couplet of two gages. Values have been estimated for each month since 1906 (Fig. 3). Reclamation regularly updates these estimated inflows and occasionally revises the process used to develop them.

The CRSS can accommodate other estimates of monthly natural inflows, such as values generated synthetically from statistical methods or runoff derived from climate-informed physical models. In this way, the effects of decreasing runoff projected to occur in a warmer future climate (Udall and Overpeck, 2017) can be incorporated within the CRSS by simply changing the input hydrology and leaving all other assumptions of demands and management practices constant. In addition to the natural inflows derived from the historical record, Reclamation (2012) developed hydrologic inputs for CRSS based on reconstructions of paleo-hydrology and from the outputs of downscaled global climate models coupled with rainfall-runoff watershed models. These allow the evaluation of policy alternatives for the Colorado River under hydrologic scenarios outside of the limited historical record.

Consumptive and non-consumptive uses of Colorado River water are represented by water user objects in CRSS. Approximately 520 water user objects simulate diversion of water from reach objects across the modeled basin network. These water users represent the most significant uses of the Colorado River. When modeling future conditions, the CRSS seeks to meet *diversion requests* and *depletion requests* for each water user, with the difference representing return flows caused by agricultural runoff or municipal effluents. In the case of non consumptive uses, the depletion request is set to zero, so all diverted water immediately returns to the river. If the amount of water available at the point of diversion is not sufficient to meet a diversion request, then the total amount of depletion is reduced proportionately. While return flows are explicitly represented in some locations in the model, a technique representing time-lagged return flows by assigning negative diversion values to certain months was adopted from the original FORTRAN code and is used in much of the current model. Future water demands and irrigation efficiency values can be easily changed within the structure of the CRSS.

Spatial and Temporal Resolution

With only 29 natural inflow locations in a basin exceeding 250,000 mi^2, the coarseness of the spatial resolution of the CRSS is significant. As described earlier, there are large watershed areas upstream from many headwater gages. Additionally, the CRSS does not represent the detailed physical processes by which headwater runoff reaches these upstream gages (*see* detailed discussion in *Appendix 2: The upper Colorado River* and *Appendix 3: The Green River*). Runoff from many small gaged or ungaged tributaries is estimated from the increase in the natural flows between gages. For example, the only tributaries in the Green River watershed for which natural flows are explicitly estimated are single gages on the Yampa, Little Snake, Duchesne, White, and San Rafael Rivers. All other tributaries are estimated from changes between the mainstem gages and are represented as lateral inflows that enter the system at discrete locations.

Although 520 water user objects are represented in the CRSS and their depletions are accounted for individually, many of these water users are spatially aggregated and assumed to withdraw water from combined locations. Similarly, multiple trans-basin diversions that transfer water outside of the physical watershed are not represented in the Upper Basin; instead, multiple transfers that originate from within a single upstream watershed are typically represented as a single aggregate upstream diversion point (*see Appendix 2: The upper Colorado River watershed*). Where water users do not consume the entire amount diverted, return flows are typically modeled to re-enter the river channel at the same point of diversion and during the same month. However, in certain cases where return flows are clearly not available to the next water user downstream, the CRSS models these flows to re-enter further downstream. The spatial and temporally diffuse nature of return flows makes it difficult to precisely simulate where and when these flows are modeled to be available to water uses downstream.

With the limited number of naturalized inflow locations, the aggregation of within-basin and trans-basin diversions, and absence of many headwater reservoirs, the course resolution of CRSS - as presently configured - is inappropriate for use in resolving water supply and environmental tradeoffs in many tributary watersheds such as the upper Colorado, Dolores, Yampa, Little Snake, Duchesne, White, San Rafael, Little Colorado, or Virgin River watersheds.

The temporal resolution of CRSS is also noteworthy and poses certain limitations on the salience of the model. As described above, the natural hydrology for the CRSS is derived using monthly consumptive uses and loss reports (Upper Basin) and decree accounting (Lower Basin). Future *Diversion Requests* and *Depletion Requests* are input as schedules of average monthly flow requirements. The solution of each component of the model is performed on a monthly basis, therefore, they do not represent what would happen at more precise time scales such as days or hours. Finer resolution historical inflows, such as those estimated by Blythe and Schmidt (2016) for the northern branch of the Rio Grande, have not been developed for the Colorado River.

Notwithstanding the challenges of spatial and temporal resolution of the CRSS, both the values of inflow to the network and the values of diversion requests can be changed and edited, allowing any number of water supply and demand scenarios to be evaluated.

Representation of Management

The second major component of the CRSS is the use of a 'rule set' that describes the operational logic of the human-controlled elements of the Colorado River system. The rule set describes how each reservoir is intended to operate, on a monthly basis, considering all of the multiple goals and objectives of reservoir operations. These goals generally include the goal to meet downstream municipal and agricultural demands, the goal to make releases that are consistent with environmental objectives described in various administrative rulings, the objective of providing flood control, and as a product of the reservoir releases, simulating hydroelectric power generation. Other rules implement administrative agreements such as those that address potential shortages of water, such as the *Colorado River Interim Guidelines for Lower Basin Shortages and the Coordinated Operations for Lake Powell and Lake Mead* that were adopted in 2007 (hereafter, 2007 Interim Guidelines). These rules describe the policies that are presently in place that govern water allocation among the various water users of the Colorado River, and these users can be considered individually or in aggregate, such as on a state-by-state basis. In this way, the CRSS is intended to represent the Law of the River.

CRSS Solution Sequence

The CRSS was initially designed to represent the complex interactions between the two largest reservoirs in the network and in the United States – Lake Powell and Lake Mead. The CRSS was also designed to represent the detailed configuration of diversions and dams on the lower Colorado River (*see Appendix 6: The Lower River*). To accurately simulate the inflows to Lake Powell, the CRSS also represented most of the large reservoirs in the Upper Basin built and managed by the Bureau of Reclamation, including all that are part of the CRSP.

The model has been refined over time to represent the detailed rules that govern these reservoirs, including rules concerning releases to achieve specific environmental objectives. The general sequence by which solutions in the CRSS proceeds from upstream to downstream. Computation begins in the upstream part of the watershed, based on the inflow hydrology and the operational rules of the upstream reservoirs. Each headwater reservoir is operated by a set of rules that produces monthly outflow values, which then allow computation of inflows for the downstream reach objects, water users that divert from these objects, and downstream reservoir objects. The set of rules that determine the releases from each reservoir depends on the complexity of the actual operational rules of the reservoirs.

The Green River Watershed

(Compare with [Appendix 3: The Green River Watershed](#).)

Here we describe the solution sequence for the Green River and its tributaries.

Figure 5. CRSS schematic for the upper and middle Green River and tributaries.

1. The headwaters of the Green River are represented by naturalized flows into the Fontenelle Reservoir, estimated for the gage below Fontenelle Dam (USGS gage 09211200). Users divert water upstream from the reservoir, and rules define the operation of Fontenelle Reservoir based on target elevations and required seasonal releases (Fig. 5). The results are monthly releases which provide inflows to Flaming Gorge Reservoir.

2. Flows in the Yampa and White Rivers derived from the Yampa River near Maybell (USGS gage 09251000), the Little Snake River near Lily (USGS gage 09260000) and the White River Near Watson (USGS 09306500). The spatial distribution of diversions and the operations of Stagecoach Reservoir and Taylor Flats Reservoir are not represented. The model is configured to calculate the flows that reach the Green River from these tributaries by subtracting out estimated consumptive uses. Due to the distance between the gages and the confluences of with the Green River, the CRSS can potentially be used to consider environmental flow issues of the Yampa River in Dinosaur National Monument and on the White River in the segment that is designated critical habitat for endangered fish.

3. The operation of Flaming Gorge Dam within the CRSS replicates the requirements described in the *Record of Decision for the Operation of Flaming Gorge Dam Final Environmental Impact Statement* issued in February 2006 (hereafter, the Flaming Gorge 2006 RoD). The outflows from Fontenelle Dam propagate as inflows to Flaming Gorge Reservoir, and releases from Flaming Gorge Dam are made to meet flood control requirements, satisfy downstream demands, and meet environmental objectives downstream from the dam, while considering the inflow from the Yampa River. Environmental objectives include achieving target flows in three river segments downstream from Flaming Gorge Dam, and those objectives include achieving target spring peak flows, a minimum duration of of those peak flows, and an acceptable range of summer-to-winter base flows. Flow values depend on the hydrologic classification for the year (dry, moderately dry, etc.) which depends on a flow exceedance criteria (Fig. 6).

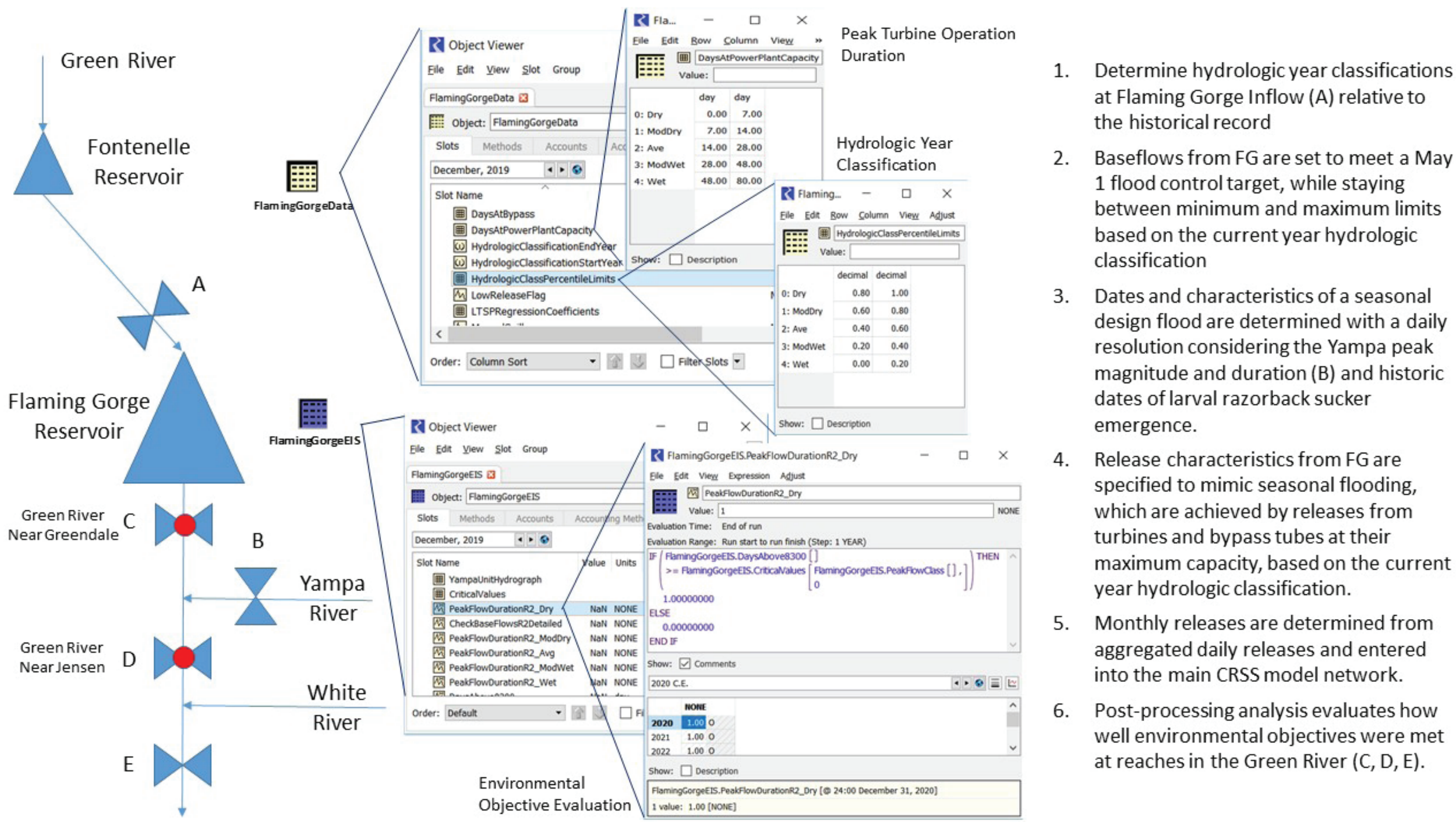


Figure 6. Schematic of the CRSS representation of the operating rules for Flaming Gorge Dam.

4. The Duchesne River flows into the Green River immediately upstream from the White River (*see Appendix 3: The Green River watershed*). The management of water in the Duchesne River Basin is represented by a single river reach above and below a single reservoir object labeled 'Starvation', which represents the combined managed storage of Strawberry Reservoir, Starvation Reservoir and other minor reservoirs (Fig. 7). The water available for users in the basin is calculated as the natural flows near Randlett (USGS gage 09302000) minus the magnitude of trans-basin diversions. These trans-basin diversions remove water from the headwaters upstream of the single reservoir even though the actual diversions occur from either Strawberry Reservoir or directly from the upper Duchesne River. This simplified reservoir object is operated to meet the demands of several downstream water users, which divert water from a single conceptual location. Evaporation from the combined reservoir is represented as a demand from a downstream water user, despite the fact that the Strawberry Reservoir is the second largest reservoir in the Green River watershed.

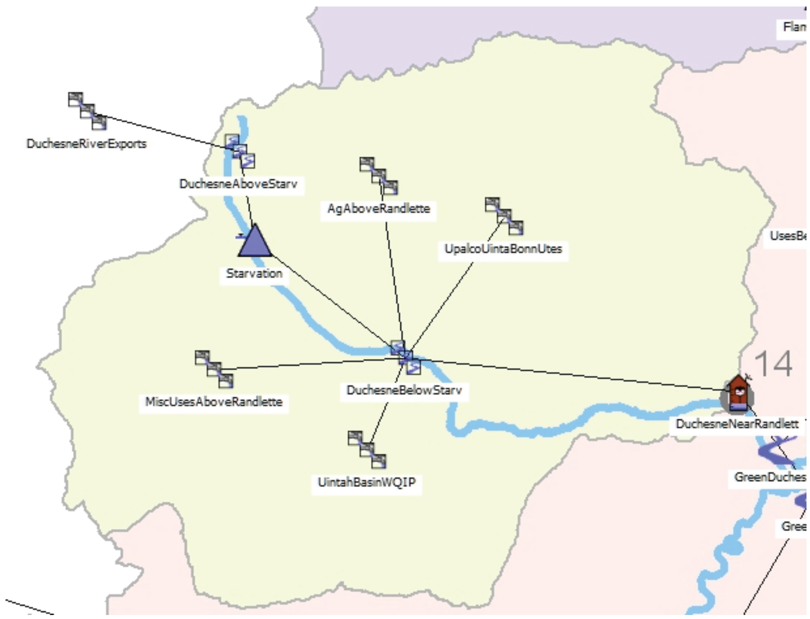


Figure 7. Schematic diagram of the CRSS representation of the Duschene River watershed.

Upper Colorado River watershed

(*Compare with Appendix 2: The upper Colorado River watershed*).

Steps 5 - 7 are provided to explain the modeling sequence for the upper Colorado River. This starts by determining the flows through the upper reaches of the Colorado River to the Gunnison River, then solves for flows along the Gunnison River itself, and then solves the inflows from the Dolores River.

5. Flows from the Colorado River upstream from the confluence with the Gunnison River are calculated beginning at the Glenwood Springs gage (USGS gage 09072500). Natural inflows entering at this node are reduced by trans-basin diversions and several in-basin consumptive uses, which are combined into two diversion points upstream from this node (Fig. 8). Inflows from tributaries downstream from Glenwood Springs are represented as the difference between the natural flows at Glenwood Springs and near Cameo (USGS gage 09095500). Eleven water users are assumed to withdraw water from a single location between these gage sites. Thus, the CRSS is too coarsely configured to address issues associated with the combined trans-basin diversions of approximately 0.5 maf/yr, the operations of headwater reservoirs, or the effect of water rights in this watershed.

6. The flows in the Gunnison River are determined starting from the upstream end of the river and operations of each reservoir are determined sequentially downstream. The natural flows in the headwaters of the Gunnison River basin are derived from a gage on the Taylor River below Taylor Park Reservoir (USGS gage 09109000). There are three other downstream sites where natural inflows are introduced to the river, estimated from increases in Gunnison River flows at gages above Blue Mesa Reservoir (USGS 09124700), Crystal Reservoir (USGS 09127800), and near Grand Junction (USGS 09152500). However, the first two of these gages are no longer operated and the measured flows at these points are actually the sum of

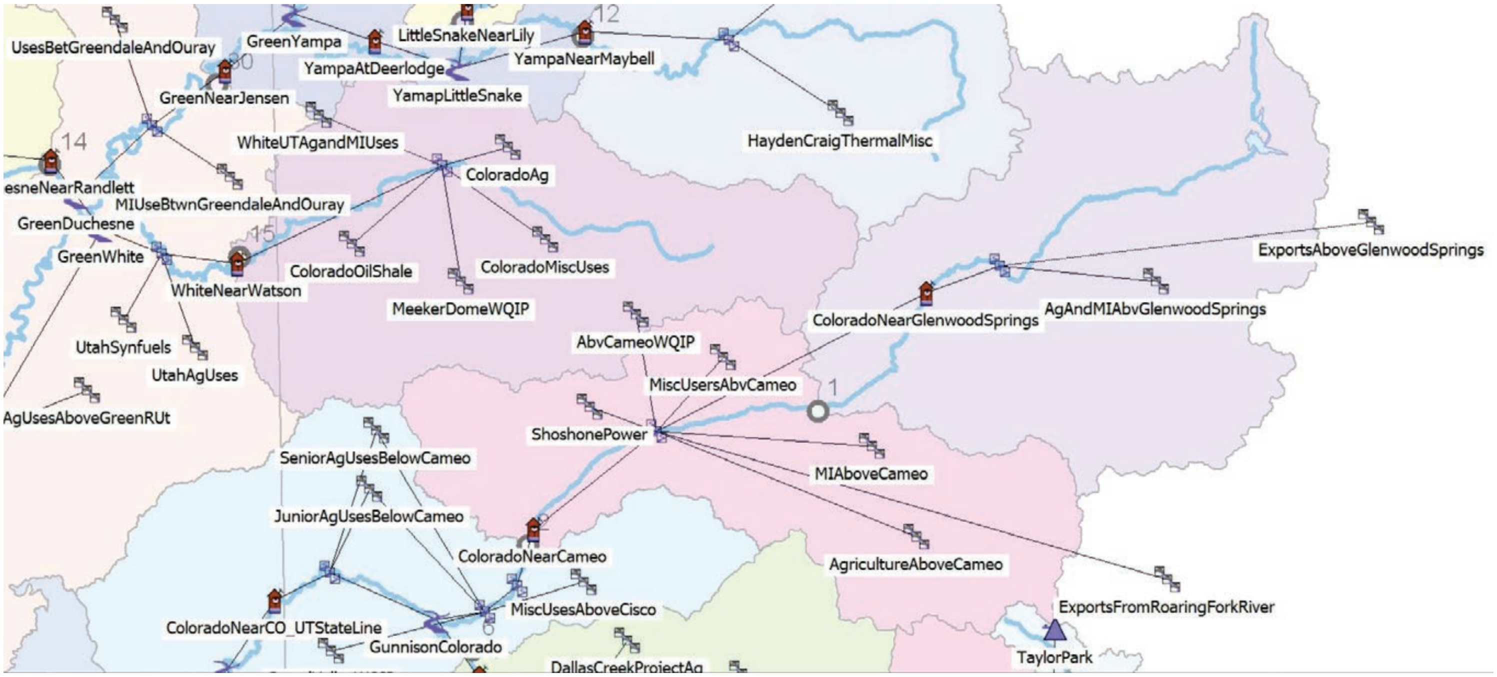


Figure 8. Schematic diagram of the CRSS representation of the upper Colorado River watershed.

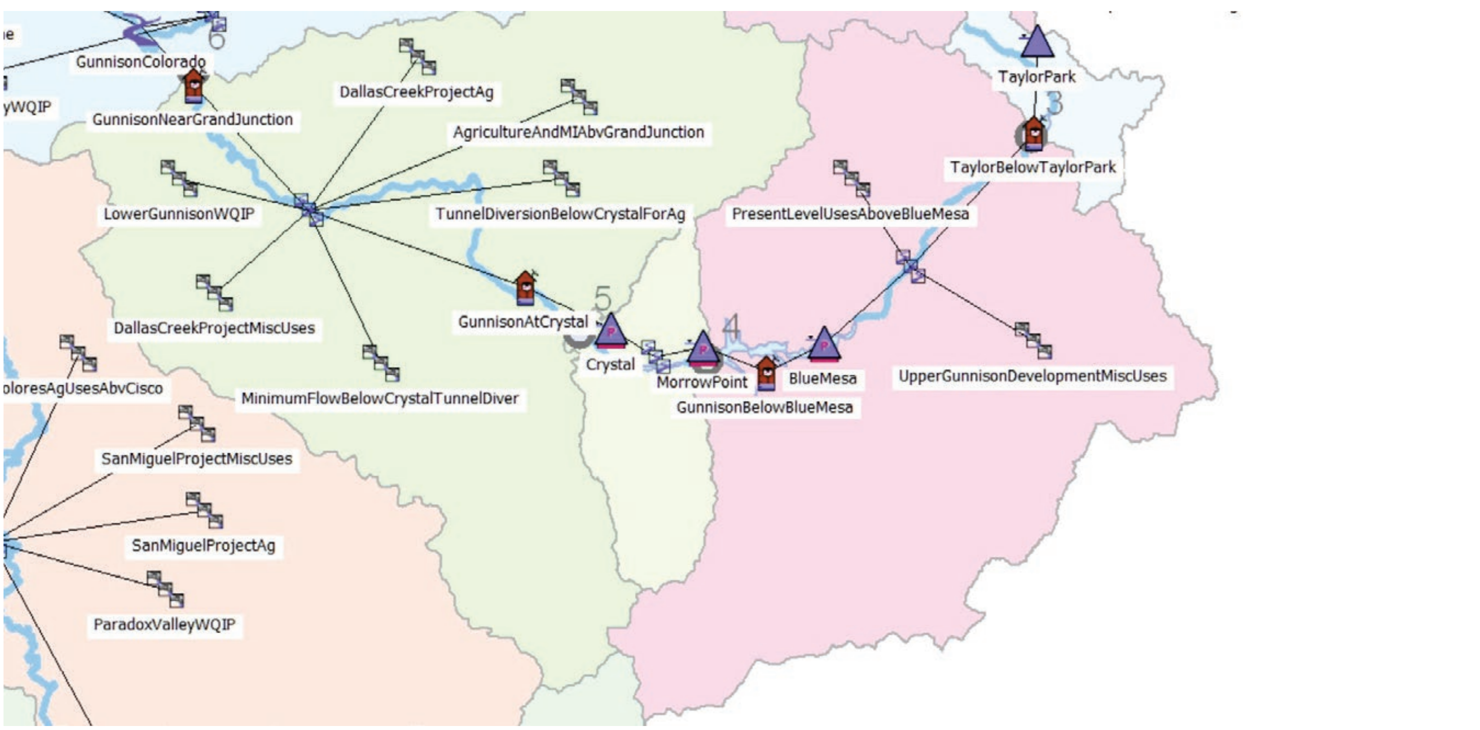


Figure 9. Schematic of the CRSS representation of the Gunnison River watershed.

other gages (see Appendix Fig. 2.1). The CRSS simulates operations of the Aspinall Unit series of reservoirs to meet downstream demands and in accordance with environmental objectives described in the *Record of Decision for the Aspinall Unit Operations Final Environmental Impact Statement* that was issued in April 2012 (hereafter the Aspinall 2012 RoD).

a. The simulated rules for operation of Taylor Park Reservoir are to meet monthly storage targets while meeting downstream consumptive demands between Taylor Park and Blue Mesa Reservoirs (Fig. 9).

b. Blue Mesa Reservoir, the largest in the Aspinall Unit, is operated to meet target flows at both the gage at the mouth (USGS gage 09152500, Gunnison River near Grand Junction, often referred to as the Whitewater gage) and in Black Canyon of the Gunnison National Park, while aiming to achieve storage targets in the reservoir. These flow targets vary depending on the hydrologic conditions, seeking to achieve specific magnitudes and duration of peak flows. More details of the operations are provided in Fig. 10.

c. Morrow Point and Crystal Reservoirs that are downstream from Blue Mesa but are part of the Aspinall Unit are operated to maintain target elevations of 7153.73 and 6753.04 feet above mean sea level (ft asl), respectively. This rule results in predicting that all releases from Blue Mesa Reservoir are passed downstream without alteration.

7. Natural inflows to the Dolores River are aggregated based on the flows calculated near Cisco (USGS gage 09180000) at the mouth of the river (Fig. 11). Diversions in the Dolores River watershed are distinguished as 6 different users that meet demands of the Ute Mountain Ute Reservation, trans-basin export to the San Juan River watershed, non-tribal consumptive uses, and assumed evaporation from McPhee Reservoir. Trans-basin diversions from McPhee divert most of the natural flow of the upper Dolores River, but the affected river segment is not specifically delineated in the CRSS.

After steps 5 - 7 are implemented, the CRSS model solves for flows at the gage near Cisco (USGS gage 09180500), and there are no significant consumptive uses further downstream. However, there may be future in-stream environmental considerations proposed for Canyonlands National Park that could be incorporated into the CRSS.

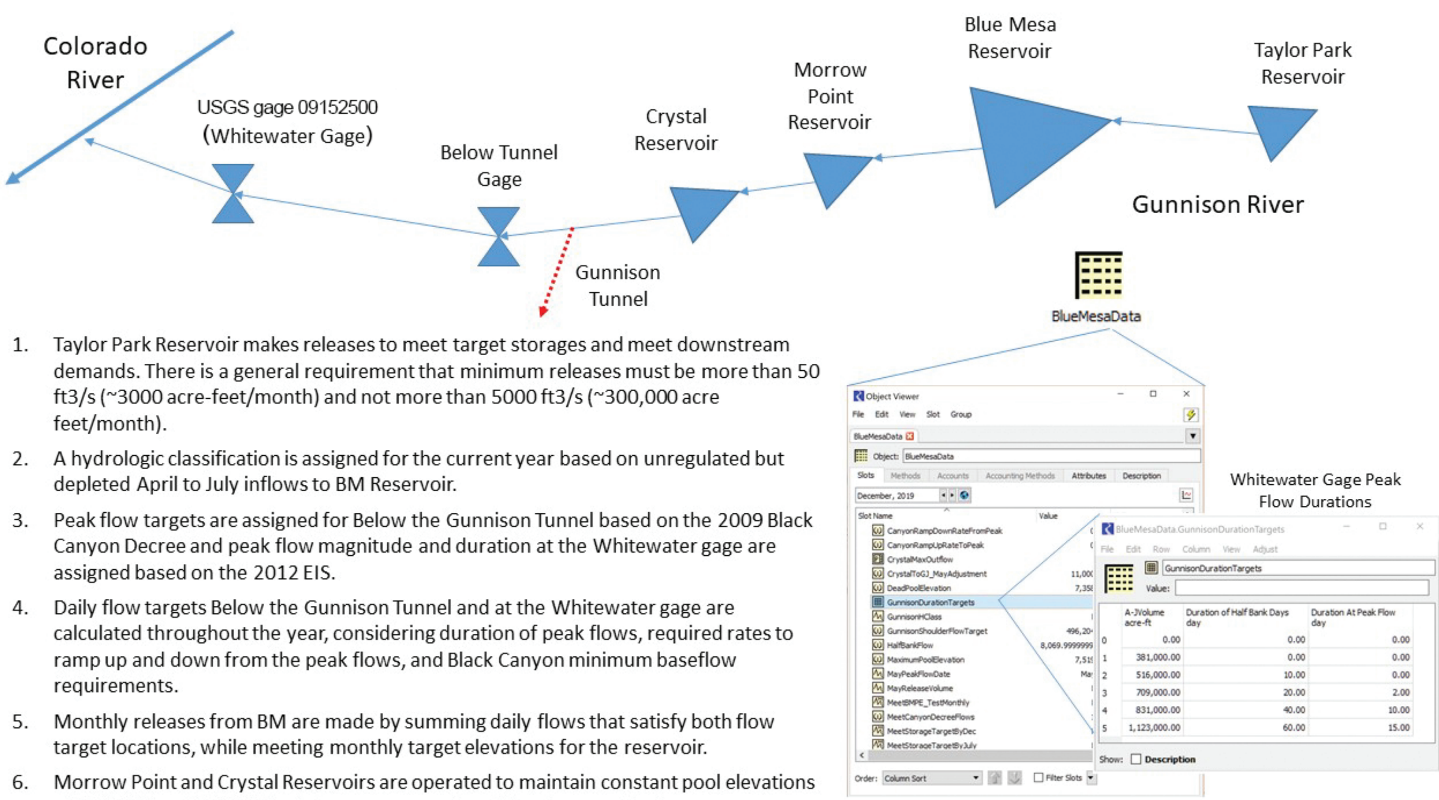


Figure 10. Schematic explanation of the rules governing operations of the Aspinall Unit

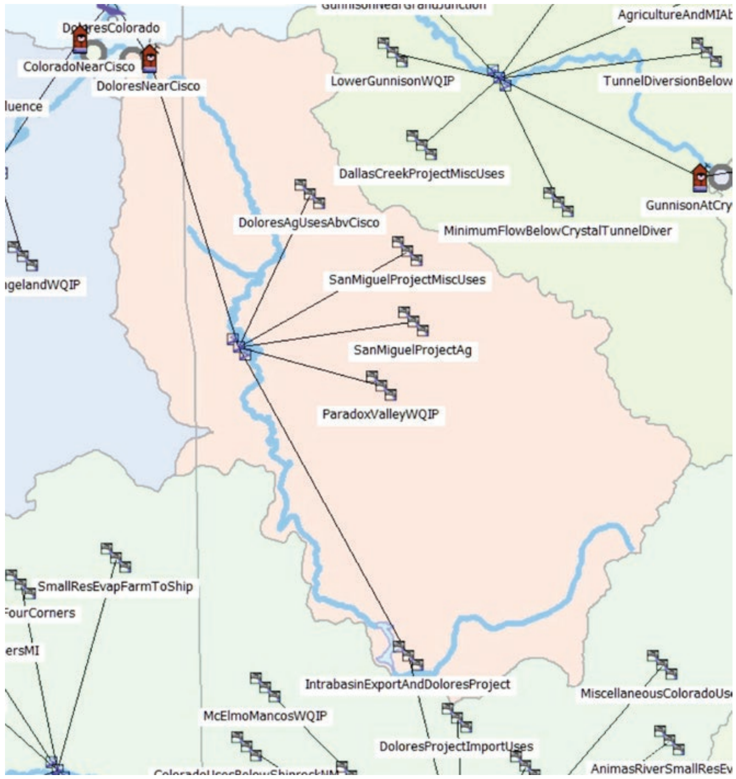


Figure 11. Schematic of the CRSS representation of the Dolores River watershed.

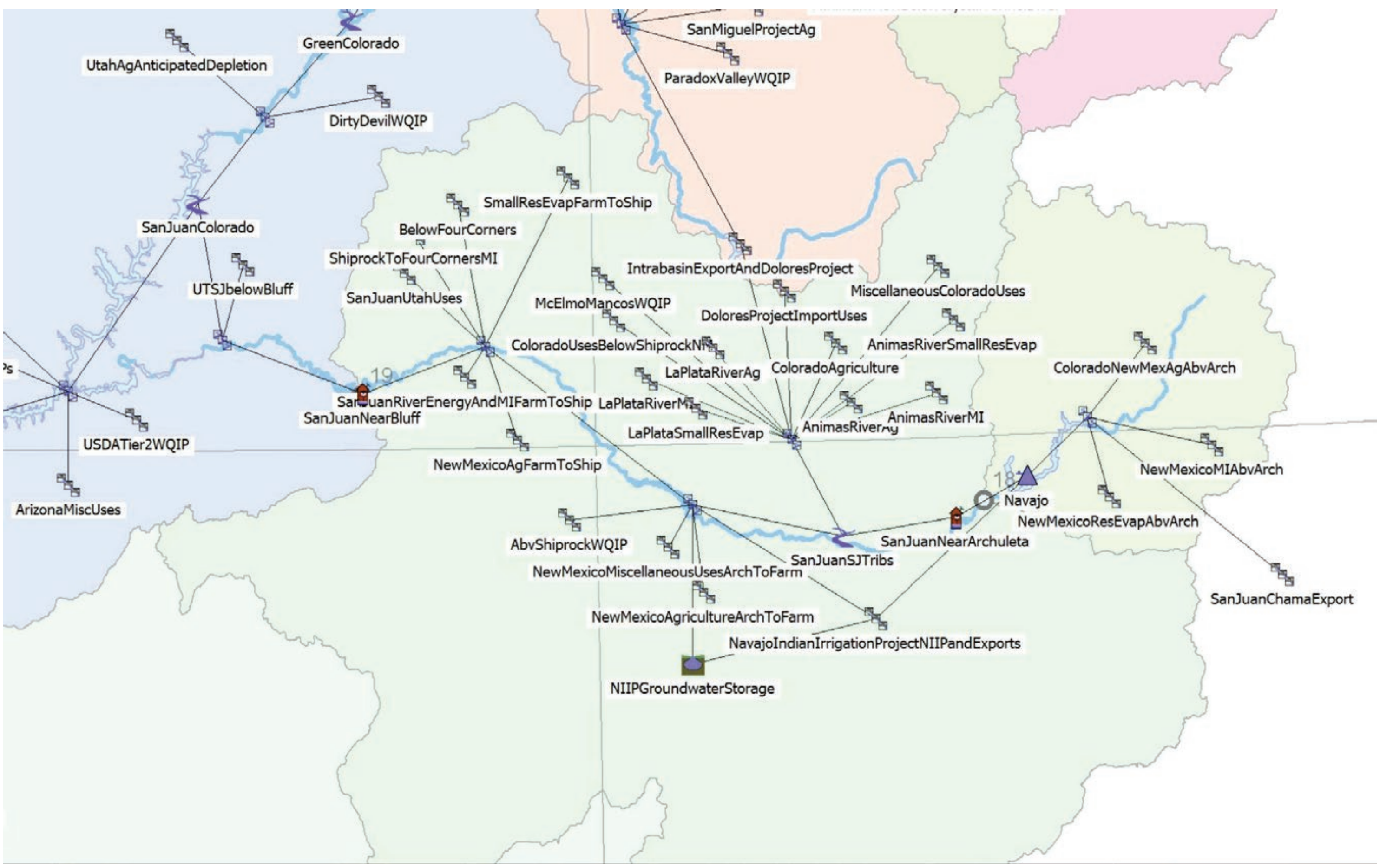


Figure 12. Schematic of the CRSS representation of the San Juan watershed.

San Juan River watershed

(*Compare with [Appendix 4: The San Juan River watershed]*)

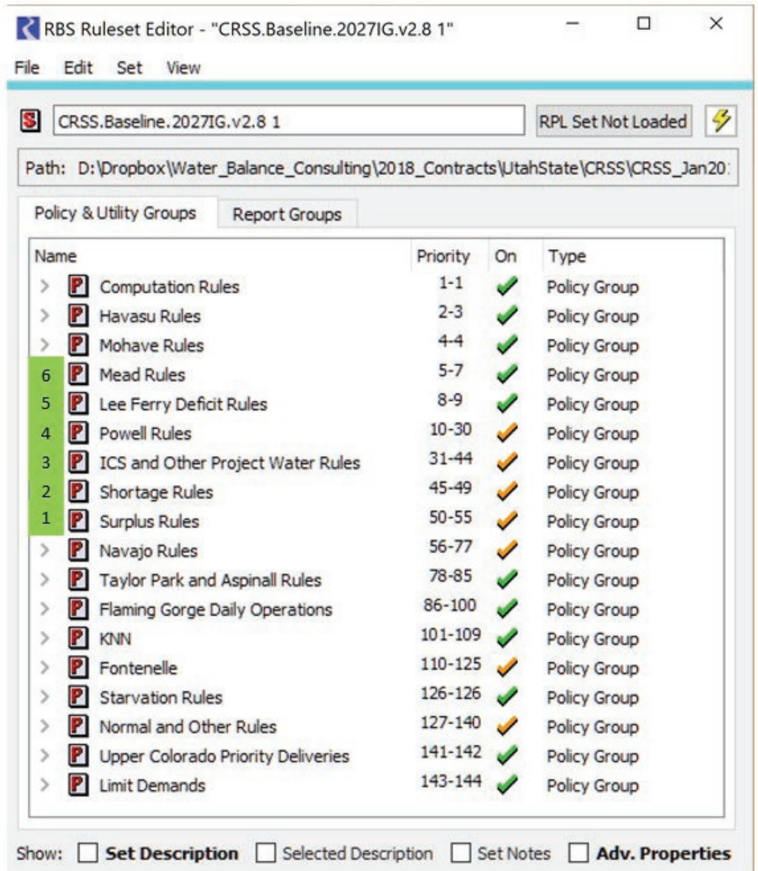
The San Juan River in the CRSS consists of 17 water users that divert water upstream from Navajo Reservoir and 39 users that divert water downstream from the reservoir, representing a wide variety of demands including agricultural, municipal, energy production, and tribal rights within the San Juan Basin (Fig. 12). Natural inflows in the headwaters upstream from the reservoir are estimated from the gage near Archuleta (USGS gage 09355500), and natural inflows from tributaries are derived from San Juan River near Bluff, UT (USGS 09379500). Tributaries to the San Juan River, such as the La Plata and Animas Rivers are combined into a single aggregated tributary in the CRSS. Imports of water from the Dolores Tunnel are also grouped into this aggregated tributary. Diversions from these tributaries, including diversions from the Animas-La Plata project are extracted from this CRSS tributary before flowing into the San Juan River.

8. Releases from Navajo Reservoir are made in accordance with the *Record of Decision for the Navajo Reservoir Operations, Navajo Unit-San Juan River New Mexico, Colorado, Utah, Final Environmental Impact Statement* (hereafter 2006 Navajo RoD) and with the objective to meet current and future downstream diversions while making releases between 250 and 5000 ft^3/s and achieving a target reservoir elevation by the end of September. Water shortage sharing agreements are also incorporated into the CRSS as 25 rules, and the goal of these agreements is to maintain Navajo Reservoir above 5990 ft asl.

Current Management Paradigm for Operations of Lake Powell, Lake Mead and the Lower Colorado River

(Lakes Powell and Mead, compare with [Appendix 5: The Grand Canyon segment] and Lower Colorado River, compare with [Appendix 6: The Lower Colorado River])

The operations of Lake Powell and Lake Mead are described as a prioritized series of rules that are derived from current interpretation of the Law of the River including interstate agreements, the bi-national treaty and subsequent minutes, the 2007 Interim Guidelines, flood operation policies, and the Long-term Experimental and Management Plan EIS for Glen Canyon (LTEMP). Here, we describe those rules to give the reader perspective on the large array of considerations associated with the management of Lake Powell and Lake Mead. The present rules evaluate current storage and forecasted hydrologic conditions for each year. Releases from Lake Powell and Lake Mead are determined to be consistent with those conditions and the various operational requirements and assumptions. Here, we describe these rules in the order CRSS processes rules from lowest priority (bottom in Fig. 13) to higher priorities (top of Fig. 13).



1. Determine Lower Basin Surplus conditions according to 2007 Interim Guidelines and Minute 323

2. Determine Lower Basin Shortage conditions according to 2007 Interim Guidelines and Minute 323

3. Determine ICS and ICMA account deposit, withdrawals, and balances

4. Operate Lake Powell according to 2007 Interim Guidelines

5. Evaluate compact delivery and optionally meet obligations

6. Operate Lake Mead to meet downstream demands according to 2007 Interim Guidelines

Figure 13. Rules set for CRSS showing priorities for operations of Lake Powell and Lake Mead.

Step 1: Determination of Lower Basin Surplus Conditions

Based on the 2007 Interim Guidelines, each year on January 1 the CRSS estimates any releases to be made from Lake Mead that exceed those required for compliance with the US- Mexico Water Treaty and compliance with deliveries to Arizona, California, and Nevada (hereafter, surplus releases). These surplus releases are made based on two criteria. First, a calculation is made to determine if there is a 70% probability that the monthly flood storage space in Lake Mead and Lake Powell will be maintained (hereafter, 70R Assurance Level), based on the inherent uncertainty of future runoff from that year's snowmelt flood. If Lake Powell releases must be increased to create sufficient flood storage space, then "Quantified Surplus" conditions are assumed and releases from Lake Mead are also increased to pass that water further downstream. The additional water allows higher rates of diversion for all downstream uses [i.e., the Metropolitan Water District (MWD), Central Arizona Project (CAP), Southern Nevada Water Authority (SNWA), and the Coachella and Imperial Irrigation Districts (IID)]. Alternatively, if the observed reservoir elevation of Lake Mead at the end of the previous December is above 1145 ft asl but the 70R assurance criteria is not expected to be reached, then a "Domestic Surplus" is declared and additional releases of water for MWD, SNWA, and CAP are allowed. Increased releases for Mexico are determined whenever Lake Mead is above 1145 ft asl according to agreements of Minute 323 of the bi-national water treaty.

Step 2: Determination of Lower Basin Shortage Conditions

Also defined by the 2007 Interim Guidelines, when runoff in the watershed is low and there is the potential that there is insufficient water available to meet all Lower Basin demands (hereafter, shortage), then releases from the Hoover Dam are reduced based on the elevation of Lake Mead (Fig. 14, dashed red line). If the pool elevation falls below thresholds at 1075, 1050, 1025 ft asl, the model reduces the diversion requests to each user including CAP, SNWA, and Mexico's aggregate diversion object, and most Arizona (Priority 4) water users. The Interim Guidelines only define delivery reductions down to a Mead level of 1,025 ft asl and require further consultation among states below that level. However, the CRSS rules assume the maximum level of delivery cutbacks specified in the guidelines are invoked until the reservoir reaches the dead pool elevation (895 ft asl).

In spring 2019, the Upper and Lower Basin states signed their respective Drought Contingency Plans (DCP; USBR 2019). In the Lower Basin, the primary changes included cutbacks almost twice as large as in the Interim Guidelines, cutbacks starting at a higher Mead level of 1,090 ft asl (Fig. 13, solid blue line), with California and its users participating in the cutbacks. The USBR is currently adding DCP operations to the CRSS rules and our analysis for this white paper excludes the DCP.

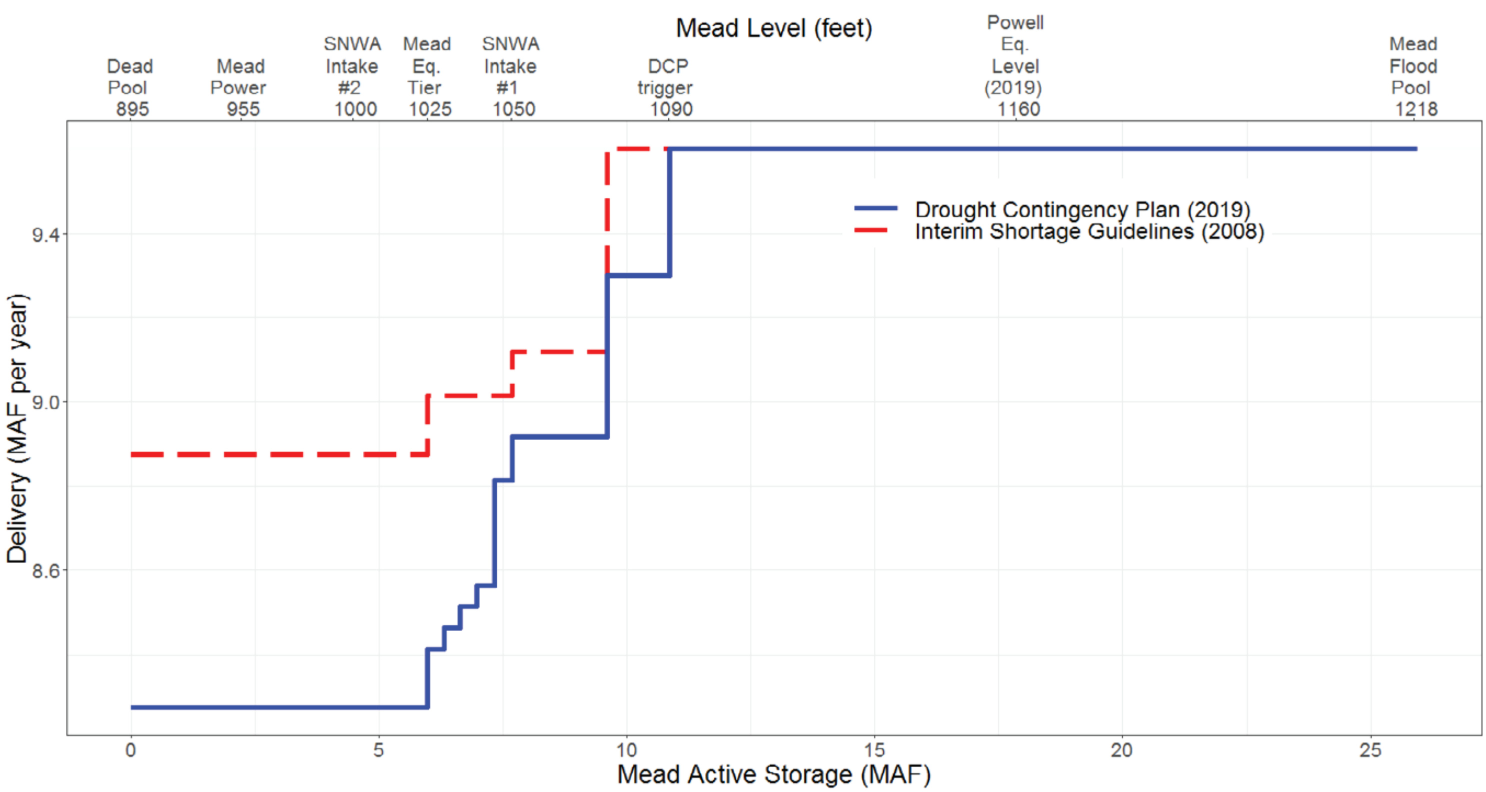


Figure 14. Schedules of total delivery reductions are functions of Lake Mead level for the new Lower Basin drought contingency plan (DCP) and interim shortage guidelines.

Step 3: Intentionally Created Surplus and Intentionally Created Mexico Allocation

The bi-national treaty and the 2007 Interim Guidelines have also defined two additional conditions that allow multi-year water storage accounts to be created within Lake Mead: Intentionally Created Surplus (ICS) and Intentionally Created Mexico Allocation (ICMA). Definitions and operations consistent with these conditions also affect how water is distributed among the Lower Basin states and Mexico, and include consideration of Colorado River tributaries in Nevada, Brock Reservoir along the All-American Canal, SNWP, IID, MWD, and CAP. Use of these accounts are optional and allow users to decrease some releases, store the water in Lake Mead, and withdraw that water at a later time if Mead level is below a threshold.

Step 4: Operations of Lake Powell

Along with a number of operational requirements regarding spring releases for dam safety purposes, releases from Lake Powell are primarily determined by criteria set forth in the 2007 Interim Guidelines to coordinate storage volumes between Lakes Powell and Mead. The active pools in the two reservoirs are divided into operational tiers from which fixed releases or ranges of Lake Powell releases are defined to better balance or equalize reservoir contents (Fig. 15).

- The guidelines establish an equalization elevation level in Lake Powell that defines a condition when water is to be transferred from Lake Powell to Lake Mead to make the storage content in the two reservoirs effectively equal. This level increases from 3655 in 2019 to 3666 in 2026

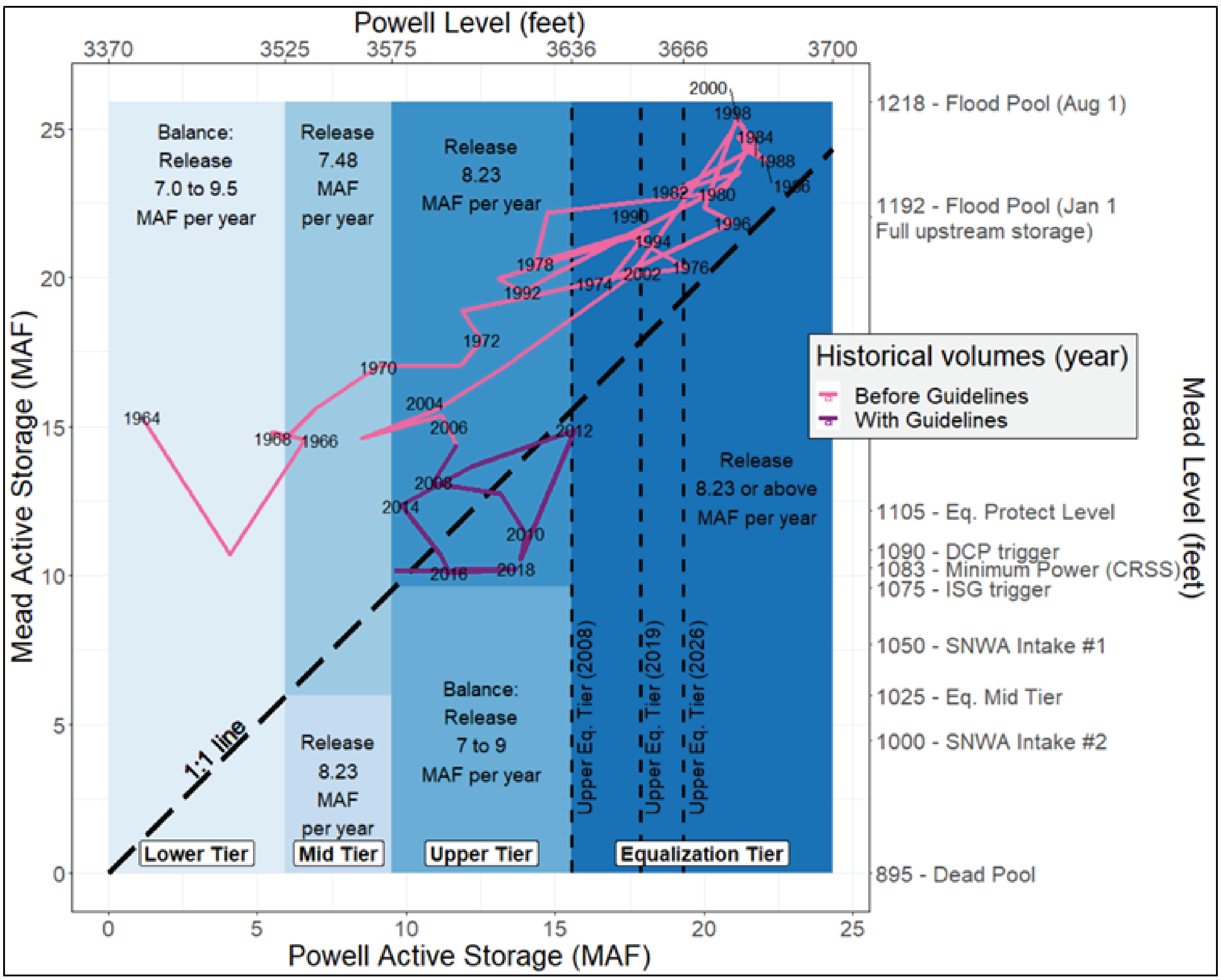


Figure 15. Diagram depicting the Lake Powell-Lake Mead Coordination rules. Annual Powell release (black text in blue rectangles) is a function of Powell active storage (Tier) and Mead active storage. The Powell active storage volume separating the Upper and Equalization Tiers increases year-to-year (short dashed black lines). Overplotted thick solid lines with year labels show observed January 1 Lake Mead-Lake Powell storage volumes before (pink) and with (purple) Equalization Guidelines in place.

when the 2007 Interim Guidelines expire. When the Powell elevation is above the equalization level (Equalization Tier), Powell releases at least 8.23 maf/yr to increase the elevation of Lake Mead and thereby equalize the two reservoir storage contents and avoid spills from either reservoir. During a year of equalization releases, if Powell reaches the equalization level and the September 30 projected Lake Mead is below the protection elevation of 1105 ft asl, Powell can make a larger release until (i) the reservoirs fully equalize; (ii) Lake Mead reaches elevation 1,105 feet; or (iii) Lake Powell reaches 20 ft below the equalization level for the year.

- If Lake Powell is above 3575 ft asl but below the equalization elevation on January 1, the system is considered in the "Upper Elevation Balancing Tier" (Upper Tier in Fig. 14). If the elevation of Lake Mead is below 1075 ft asl, then releases are made to balance the contents of the two reservoirs, with a maximum annual release of 9.0 million acre feet/year and a minimum annual release of 7.0 maf/yr. The term *balance* is used instead of *equalization* in this case due to the minimum and maximum allowable releases.
- If Lake Powell is between 3525 and 3575 ft asl on January 1, the system is considered in the "Middle Elevation Release Tier" (Middle Tier in Fig. 14). If the elevation of Lake Mead from the previous end of year is greater than 1025 ft asl, then releases from Powell are set to equal 7.48 maf during that year. Otherwise the release from Lake Powell is set to 8.23 maf.
- If Lake Powell is below 3525 ft asl on January 1, the system is considered in the "Lower Elevation Balancing Tier" (Lower Tier in Fig. 14) and releases are made to balance the contents of the two reservoirs, with a maximum annual release of 9.5 maf and a minimum annual release of 7.0 maf.

The release values are reconsidered beginning in April based on the forecasted end of water year storage values, allowing equalization to begin if Lake Powell is projected to exceed the equalization threshold or the projections allow a switch from the minimum objective release of 8.23 maf to balancing the reservoirs with a maximum and minimum values stated above.

Superseding these guidelines however, releases from Lake Powell are made to evacuate space in the reservoir to absorb forecasted incoming flood flows, creating 0.5 maf by the end of July and 2.4 maf of space by the end of the calendar year. Furthermore, additional releases from Lake Powell can be declared during years of large projected runoff if 1) the unregulated inflow forecast from January until July exceeds 13 maf, 2) the outflows resulting from flood control (spillway) releases during any month between February and July exceeds 1.5 maf, or the projected monthly average spring outflow from Lake Powell exceeds 1.5 maf. In these cases, an additional bypass volume of 0.2 maf is added to the otherwise planned releases from Glen Canyon Dam to create the necessary storage space.

The release patterns from Lake Powell are further complicated by several conditions. We describe these conditions here to illustrate the complicated constraints on the operations of Lake Powell:

- If the storage in July is > 23 maf and the outflow is less than 1 maf/mth, then the reservoir release is increased to 1 maf/mth.
- From July until December, if the outflow is greater than 25,000 ft^3/s and the storage that would result from an outflow of 25,000 ft^3/s is less than 23.822 maf then the outflow is restricted to 25,000 ft^3/s.
- The CRSS also limits releases based on the capacity of the river outlets and spillway.

Step 5: Lee Ferry Deficit

The predicted stream flow at Lee Ferry is calculated and accumulated during a period of 10 years to evaluate the potential deficit of Upper Basin deliveries to the Lower Basin. Due to the multiple interpretations of compact obligations, the default setting of the CRSS does not automatically compensate for compact deficits, however the model user has the option to 'create' compensatory water upstream of the compact point, thus allowing the Lower Basin water supplies to be evaluated appropriately. In this case, no specific reductions of upper basin uses are identified, however the total depletions of the Upper Basin are reported after the deduction of any created water.

Step 6: Operations of Lake Mead

Releases from Lake Mead are set to meet the sum of all requested demands specified after the rules described above have been executed, with the additional requirement to compensate for estimated evaporation losses at Lake Havasu and Lake Mohave, and allow these reservoirs to meet target elevations. These releases reflect the requirements for all Lower Basin users including Mexico, and also seek to account for evapotranspiration losses caused by riparian vegetation, even though the magnitude of these losses is poorly known. Adjustments are also made for ICS and ICMA. Furthermore, since adjustments for any shortage or surplus conditions to Lower Basin users including Mexico are already incorporated, any shortages imposed by this stage are considered 'structural,' or planned. If there is not enough water in the system to meet the downstream requirements, these are considered 'hydrologic' shortages in the parlance of Reclamation.

The outflows from Lake Mead are also modified as needed with flood control algorithms defined by the U.S. Army Corps of Engineers. From January until July, a selection of release steps are made (0, 19,000, 28,000, 35,000, 40,000, 73,000 ft^3/s) while assuring that all downstream surplus demands are met and a sufficient outflow is maintained to keep the reservoir from overflowing. From August until December, releases are made that assure that an increasing flood control space is created for the subsequent runoff period. Many complexities exist in this algorithm.

The most downstream reservoirs in the CRSS are Lake Mohave and Lake Havasu, formed by the Davis Dam and the Parker Dam, respectively. Releases from these two dams are based on simple monthly rules to reach target reservoir levels and allow for the withdrawal of water for the Colorado River Aqueduct and the Central Arizona Project (*see Appendix 6: The Lower Colorado River*).

CRSS Management and Updating

The CRSS model has been a cornerstone of Colorado River planning and management for more than 40 years. The CRSS was primarily developed and is managed by Reclamation, and the model is made available through a Stakeholder Modeling Workgroup. Reclamation releases an 'official' version of CRSS several times during each calendar year with updates and modifications. Initial conditions of reservoir storage levels are updated with the results from Reclamation's Mid-term Operation Model (MTOM), and the hydrologic inputs are updated with the naturalized flows derived from gage measurements collected during the most recent years. Assumptions regarding projected water usage are provided to Reclamation by the Upper Colorado River Commission and the states, which are updated periodically. Current balances, projected uses, and projected withdrawals of ICS and ICMA accounts are also updated with each model release.

The staff at Reclamation frequently modifies the logic of the ruleset to better reflect reservoir operations. New logic is periodically introduced to represent changing policies or management practices. As with most models, assumptions are embedded in the logic, some of which are clearly derived from operational guidelines while others are derived from interpretations of policies. This is particularly relevant when policies are not precisely defined. The scientific assumptions that underpin the representation of the physical characteristics of the river basin are also updated periodically. This can include items such as revisions of the historical naturalized hydrologic dataset, modification of evaporation coefficients from the reservoirs, and changes to the hydropower-generation characteristics. The process of changing the assumptions or logic used in the model is typically verified by multiple Reclamation staff and presented in webinars to the Stakeholder Modeling Workgroup. While Reclamation attempts to maintain a version of CRSS that best reflects the operation of the Colorado River, it must also be emphasized that modeling is an imperfect process and changes to the model often lag behind the development of management policy, actual operations, or scientific advances. Historical algorithms are often embedded into the logic, and a cautious approach is followed by Reclamation when making modifications, often seeking to avoid large differences in the outputs between model versions.

Many stakeholders have also invested their own resources in building in-house capacity to operate the CRSS to increase their own understanding of the physical system and management of the river. In addition, these investments allow stakeholders the ability to explore alternative approaches independently of Reclamation, using hydrologic conditions, future demand scenarios, and reservoir operations that differ from those assumed in the officially released version of the CRSS. Encouraging this active use of the CRSS by knowledgeable stakeholders not only allows these groups and individuals to examine and question the assumptions used, but it also increases the level of trust through a common understanding of how the model is being used by Reclamation. The dissemination of the CRSS promotes a common understanding of the implications of proposed policy changes, and the increased use of the model throughout the Basin by stakeholders helps to ensure its continued use and development. However, significant expertise is needed to operate the CRSS and many stakeholder groups do not have access to this expertise.

The Challenge of Incorporating Environmental Considerations into the CRSS Modeling

The detailed description of the present configuration and implementation of the CRSS highlights the capability of the model to simulate reservoir operations for water supply and flood damage reduction purposes in some parts of the channel network. However, it remains a challenge to incorporate river ecosystem objectives into the structure of the CRSS. One attribute of the CRSS that limits the effort to bring together water supply and river ecosystem objectives is the monthly time step resolution of the model, because many environmental release rules are typically specified on a daily basis. For example, the required magnitude and duration of peak flows described in the Aspinall 2012 RoD, Flaming Gorge 2006 RoD, and Navajo 2006 RoD identify spring peak releases that typically begin in the middle of months and last for a few days to a few weeks. Because the CRSS is a monthly time-step model, calculations estimating the timing of these peaks within the CRSS platform must be made outside of the core monthly model rule structure and calculated as daily values in RiverWare 'data objects' that are not connected to the rest of the model structure. Daily values at discrete locations, including reservoir outflows and certain locations specified in various RoDs, are estimated and then aggregated to average monthly flows to be integrated into the basin-wide model network.

Other sub-monthly operations of the Colorado River are not explicitly implemented in the CRSS, such as the controlled flood releases from the Glen Canyon Dam (i.e., High Flow Experiments) that have durations of 3 to 7 days and typically occur in fall. Each fall's controlled flood is planned based on whether or not there have been significant flash floods in the Paria River watershed that delivered significant amounts of sand during the late summer and fall. Implementation of the *High Flow Experiment Protocol*, adopted in 2012, requires coordination and adaptability between the objectives of large-scale water supply planning conducted at a monthly time step and precise planning of the magnitude and duration of controlled floods at a daily and hourly time step. The RoD of the 2012 LTEMP EIS also includes adoption of Trout Management Flows and Macroinvertebrate Production Flows (i.e., Bug Flows) whose implementation requires daily and hourly time step resolution. The discordance among monthly, daily, and hourly time steps in water supply and river ecosystem management remains a persistent challenge in modeling future river management alternatives.

While the CRSS simulates water flows and volumes for water supply objectives, it does not consider water constituents such as sediment and temperature that affect key endangered and introduced fish species survival. RiverWare™ has modules to calculate monthly average temperatures in reservoirs and reaches, however these modules are not currently used in the CRSS. Finer temperature resolution metrics such as daily degree-days, daily minimums, daily maximums, or ranges may still be needed to resolve fish survivability or species competition.

Alexander and Olson (2013) similarly describe the omission of important species and physical variables, incompleted temporal and spatial representation, and lack of specificity in their review of the use of CRSS in the Basin Study to manage for fish species in the Yampa-Little Snake, Green, White, and Virgin Rivers. They recommend including additional simplified metrics and locations, developing daily resolution RiverWare models for select river segments, and developing new models and coupling them with the CRSS.

The CRSS also imperfectly represents several issues of importance to Native American tribes such as full use of tribal water rights, water infrastructure that tribes currently operate or plan to build, salinity and nutrients as potential contaminants of some ground- and surface- water sources, and management for fish as discussed above. Additionally, tribal visions to protect the Colorado River that include passing on

traditions and cultural connections to future generations and holistically manage the River, the land, and all resources are not currently reflected in the CRSS model outputs and performance metrics (Department of Interior, 2018).

The monthly time step of the CRSS likewise poses a challenge for the representation of hydropeaking, load following, turbine scheduling, and other hydropower operations that occur at daily and finer time scales. This challenge thus makes it difficult to use the CRSS to explore interactions between hydropower operations and river ecosystem objectives. While the CRSS can be used to assess a general sense of positive vs. negative effects of release policies on hydropower generation or revenues, CRSS results of monthly reservoir release volumes can provide the inputs for shorter duration, finer time resolution (e.g., hourly) hydropower scheduling models the Western Area Power Administration and others use to determine hydropower operations.

Other Models of the Colorado River Basin

A variety of other models have been developed and applied to analyze the Colorado River. Reclamation's mid-term planning model has been converted to RiverWare™ and continues to be the primary tool used to generate the 24-month study. This deterministic model is run using discrete forecasts from the Colorado Basin River Forecast Center (CBRFC) including a single 'most-probable' hydrologic trace, along with traces representing minimum and maximum probable conditions. The results of the most probable hydrologic condition are incorporated into Reclamation's Annual Operating Plan for the Colorado River System. The physical domain of the 24-month study model includes the reservoirs of the Upper Basin, but most Upper Basin consumptive uses are implicitly incorporated into the inflow forecasts. Approved and operational water orders are used as Lower Basin demands, subject to adaptations for shortage and surplus conditions. Similar to the 24-month study model, Reclamation's Mid-term Operation Model (MTOM) uses an ensemble of 35 hydrologic traces from the CBRFC to project a range of system conditions for a 5-year period. While the 24-month study model is a relatively simplistic simulation of the system that requires the user to input all reservoir operations, the MTOM has a significant overlap in rule-based logic with the CRSS. The results from the MTOM are used to develop initial reservoir conditions for the CRSS.

Individual states also develop and maintain their own models for use within their state boundaries. One of the most sophisticated examples in the Upper Basin is the Upper Colorado River Model for the Colorado River Decision Support System (CRDSS). Written in the FORTRAN-based StateMod program, this model simulates water rights distribution for at least 75% of the decreed water rights in the upper Colorado River basin. To manage the large number of water users, the prioritization logic is well established and allows limited flexibility to deviate from built-in operating rules. The goal of the CRDSS is to be integrated into a state-wide modeling platform, and integrated with a database of hydrologic information. The detailed accounting focus of StateMod in a limited geographic area is in stark contrast to the CRSS model, which covers a large geographic area but with significantly less detailed spatial resolution.

Alternative Management Paradigms

We define alternative management paradigms (AMPs) as new ways to manage Colorado River water that might achieve societal objectives for water supply and hydroelectricity production, yet also better meet environmental objectives. The CRSS can be used to assess the implications of AMPs on the basin-wide water management system, however the current configuration of the CRSS has numerous operational details which pose challenges when changes to operations are proposed. These details must be considered when deciding how to operationalize an AMP, and whether the CRSS is the appropriate tool to evaluate AMPs. One advantage of using the CRSS to evaluate AMPs is the need to refine broad ideas into precisely constructed rules. Refinement and modeling can be a benefit to provide specificity or it can reveal shortcomings of the ideas. The axiom of "the devil is in the details" applies when new ideas must be reconciled with or replace existing management logic. Large-scale AMPs potentially require detailed legal, administrative, or structural changes that may require numerous changes throughout the CRSS input data and rules. Changes can inevitably have a cascade of smaller scale implications that the model can help identify.

In future work, we will use the CRSS model to test two alternative management paradigms that represent bookends on a continuum of potential operations to jointly manage Lake Powell and Lake Mead for water supply, river ecosystem, and other objectives. One bookend of this continuum is what is sometimes called the Fill Mead First (FMF) Phase I proposal wherein Colorado River water is preferentially stored in and used to keep Lake Mead full, and water is only secondarily stored in Lake Powell. This paradigm has been widely discussed in popular media and some technical issues associated with its adoption have been analyzed (Schmidt, 2016). The other bookend of the joint management continuum is Fill Powell First (FPF) wherein Colorado River water is preferentially stored in and used to keep Lake Powell full before storing water in Lake Mead. The FPF paradigm has not been widely evaluated but has occasionally been proposed. The existing Lake Powell-Lake Mead equalization operations specified by the 2007 Interim Guidelines and currently coded in the CRSS represent an intermediate point on the continuum of potential joint reservoir operations. Additional specifics of the Fill Mead First and Fill Powell First alternative management paradigms and their implementation in CRSS are described in *Appendix 7: Explanation of the Fill Mead First and Fill Powell First Alternative Management Paradigms*.

After evaluating the FMF and FPF paradigms as bookends of the continuum of joint Lake Mead-Lake Powell operations, perturbations of these two scenarios will be developed as additional AMPs. The FMF paradigm could be adapted to retain any extreme flows in Lake Powell that might cause unacceptable fine sediment evacuation from the Grand Canyon, and re-allocate those flows that have the potential to maximize ecological benefits. Similarly, the FPF paradigm could relax its retention rules to satisfy similar environmental requirements in the Grand Canyon. The additional alternative paradigms we explore will depend on the identified strengths and drawbacks of the FMF and FPF paradigms. Another part of the Future of the Colorado River Project concerns the effort to predict reservoir release temperatures associated with different reservoir water storage conditions; we also seek to predict the implications of different river temperatures on downstream ecosystem function.

Performance Metrics

To evaluate the AMPs, we will use performance metrics that quantify water supply, river ecosystem, and other key management objectives. These metrics operate at annual or monthly time scales and are similar to performance metrics used in the Colorado River Basin Water Supply and Demand Study (Reclamation, 2012) and decision analysis to support development of the Glen Canyon Dam LTEMP (Runge et al, 2015), except that we use metrics that are more coarsely aggregated in space. We will evaluate metrics described in Table 1.

Table 1: Metrics for consideration in Evaluation of Alternative Management Paradigms

Metric	Time Spacing	CRSS Slots
Reliability of deliveries to Upper Basin States	Annual	UBShort.{AnnualColoradoShort, AnnualNewMexicoShort, AnnualUtahShort, AnnualWyomingShort}
Reliability of deliveries to Lower Basin States and Mexico	Annual	LBShortHydrologicShortage.{CAAnnualShortage, NV.AnnulaShortage, AZAnnualShortage}
Reliability of deliveries to Mexico	Annual	LBShortHydrologicShortage.{MXAnnualShortage}
Powell Storage	Monthly	Powell.Storage
Mead Storage	Monthly	Mead.Storage
Total Storage	Monthly	Powell.Storage + Mead.Storage
Powell Release - an indicator for sediment, sand, boating, and other ecosystem objectives	Monthly	Powell.Outflow
Reservoir Evaporation	Annual	Powell.Evaporation, Mead.Evaporation
Reservoir Power Generation	Monthly	Powell.Power, Mead.Power
Reservoir Energy Generation	Annual	AnnualEnergy.Powell AnnualEnergy.Mead

Conclusions and Summary

Like many modeling tools, the CRSS has had a large impact on Colorado River management but is inherently imperfect. This paper presents the first step in unpacking both the utility and imperfections of this tool for a wider audience.

In explaining the structure, logic, advantages, and limitations of the CRSS, we show the complexity embedded in the model. We also show how improvements can be made to meet the growing calls for analyses that considers objectives at a finer spatial and temporal resolution than the current configuration and monthly time step allows. We emphasize the potential to use the CRSS to explore alternative management paradigms that are not currently being considered by existing model users. Some of these alternative management paradigms include strategies to coordinate the management of the main reservoirs, Lakes Powell and Mead, for water supply reliability and river ecosystems. While these strategies may be simulated in the CRSS or other modeling platforms, these alternative paradigms may face additional economic, social, and political obstacles to implement. Our goal is to demonstrate that significant changes to Colorado River management can be examined with the existing tools and to show that whether or not these changes might benefit water supply for users and river ecosystems. We will model these and other changes as part of the Colorado River Futures project.

Data Availability

Data and code used to generate Figures 13 and 14 are available at Rosenberg (2019).

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Colorado River consumptive uses and losses in the 21st century

2000 was the last year that Lakes Powell and Lake Mead were relatively full. In January 2000, the combined active storage contents of the two reservoirs was 84% (Reclamation, *Compilation of Records in Accordance with Article V of the Decree of the Supreme Court of the United States in Arizona v. California Dated March 9, 1964, Calendar Year 2000*), and reservoir storage in these two reservoirs decreased greatly thereafter. In December 2017, the combined reservoir contents were 48% (Reclamation, *Colorado River Accounting and Water Use Report: Arizona, California, and Nevada Calendar Year 2017*). What was the magnitude of water use and consumptive water loss during this critical period when reservoir storage plummeted? Comprehensive data are available between 2000 and 2017, summarized in two data series. One of those data series are referred to as the Water Accounting Report series (available at https://www.usbr.gov/lc/region/g4000/wtracct.html). Data about Upper Basin uses and losses are described in a five-year summary *Upper Colorado River Basin Consumptive Uses and Losses Report* (hereafter, referred to as Upper Basin water accounting reports), and these reports are available at https://www.usbr.gov/uc/envdocs/plans.html.

The total consumptive uses and losses include those by agriculture, municipalities and industry (M&I), water exported from the watershed in trans-basin tunnels and canals, water evaporated from reservoirs, and "channel transmission losses" that are accounted along the Lower River downstream from Hoover Dam. Consumptive uses and losses on tributaries of the Colorado River in the Lower Basin – the Virgin River and its tributaries in Utah and Nevada, the Gila River and its tributaries in New Mexico and Arizona, and smaller tributaries in Arizona – are accounted for separately, because those uses are not part of the allocation agreements of the Colorado River Compact. Nevertheless, these Lower Basin tributary uses and losses once would have been part of the Colorado River's natural stream flow that entered the delta in Mexico. Reclamation summarized Lower Basin tributary consumptive uses, losses and evaporation from Lake Mead and evaporation and losses from reservoirs further downstream until 2005 in the *Colorado River Basin Consumptive Uses and Losses Report*, but more recent estimates have not been made.

Total average annual consumptive uses and losses in the Upper and Lower Basin between 2000 and 2017 were 11.4 maf/year, and 1.7 maf/year flowed across the international border and was used or lost in Mexico (Appendix Table 1.1). Reclamation estimated that evaporation losses from the CRSP reservoirs (Powell, Flaming Gorge, and Aspinall Unit) averaged 0.49 maf/year between 2000 and 2017, and Reclamation estimated that there was 1.2 maf/yr of evaporation and channel losses from Lake Mead and downstream to Yuma between 2000 and 2005. However, published estimates of Lake Powell are for net evaporation and are not the estimated total evaporation from the reservoir surface, as explained in *Appendix 5: The Grand Canyon segment*. Total evaporation from Lake Powell averaged 0.6 maf/yr between 2000 and 2018. Schmidt (2016) showed that estimated that evaporation from Lake Mead between 2010 and 2014 averaged 0.6 maf/yr, using the data of Moreo (2015). The total estimated average annual consumptive uses and losses during the 21st century, including those that occur in Mexico, was 17 maf/year, although there is obvious uncertainty in combining estimates made between 2000 and 2017 with the estimates made only between 2000 and 2005.

The largest amount of mainstem consumptive uses and losses occurred in California – 4.5 maf/yr – but the total annual consumptive uses and losses of mainstem and tributary stream flow occurred in Arizona – 4.7 maf/yr – of which 2.7 maf/yr came from the Colorado River itself. The largest uses and losses in the Upper Basin occurred in Colorado where 2.2 maf/yr was consumed. Thus, 56% of the total consumptive uses and losses in the Upper Basin occurred in Colorado. Agriculture accounted for 67% of the total Upper Basin consumptive uses and losses, and trans-basin diversions accounted for 19% of the Upper Basin uses.

Mean annual measured inflow to Lake Powell from the upper Colorado, Green, and San Juan Rivers between 2000 and 2018 was 8.3 maf/yr. Thus, the natural inflow to Lake Powell from the three large headwater branches during this period was 12 maf/yr, which is the sum of the measured inflows plus the estimated Upper Basin consumptive uses and losses. Reclamation (2019, https://www.usbr.gov/lc/region/g4000/NaturalFlow/current.html) estimated that the natural flow of the Colorado River at Lees Ferry was 12.7 maf/yr, and this estimate includes inflows from smaller streams that are downstream from the gages on the three headwater branches. Measured releases from Lake Powell during this period were 8.9 maf/year and exceeded measured inflows from the three headwater branches.

Appendix Table 1.1. Average annual consumptive uses and losses in the Colorado River basin, 2000-2017, and average stream flow at Lees Ferry

	Average annual consumptive uses and losses, in acre feet per year
Entire Colorado River Basin	
Total	17,000,000
Total Mexico delivery (2000-2017)	1,700,000
Total Lower Basin mainstem (within USA) (2000-2017)	7,500,000
Total Lower Basin tributary (2000-2005)	2,300,000
Total Upper Basin, including state reservoirs (2000-2017)	3,900,000
Total Lower Basin mainstem reservoir evaporation and channel losses (2000-2005)	1,200,000
Total Upper Basin CRSP reservoir evaporation (2000-2017) (includes gross Lake Powell evaporation)	690,000
Total Lower Basin (by state and water source)	
Arizona (mainstem) (2000-2017)	2,700,000
Arizona (tributaries) (2000-2005)	2,000,000
California (2000-2017)	4,500,000
Nevada (mainstem) (2000-2017)	270,000
Nevada (tributaries) (2000-2005)	110,000
New Mexico (tributaries) (2000-2005)	28,000
Utah (tributaries) (2000-2005)	120,000
Mainstem reservoir evaporation and losses (2000-2005)	1,200,000
Mexico (2000-2017)	1,700,000
Total Upper Basin (by state) (2000-2017)	
Arizona	35,000
Colorado	2,200,000
New Mexico	390,000
Utah	870,000
Wyoming	400,000
Upper Basin (by use) (2000-2017)	
Total agriculture	2,600,000
Total trans-basin exports	760,000
Total M&I	260,000
Total reservoir evaporation (state and CRSP)	930,000
Annual measured inflow to Lake Powell from upper Colorado, Green, and San Juan Rivers) (2000-2018)	8,300,000
Mean annual natural inflow to Lake Powell (measured inflow plus upstream consumptive uses)	12,000,000
Mean annual natural inflow to Lake Powell, estimated by Reclamation, at Lees Ferry gage	13,000,000
Mean annual release from Lake Powell (2000-2018)	8,900,000

The Upper Colorado River Watershed

Once called the Grand River, the watershed has a long history of water development that includes large diversions to support West Slope agriculture and trans-basin diversions to support irrigated agriculture and urban uses in East Slope Colorado. Alteration of the natural flow regime has been significant for more than a century, and there is substantial work underway by the state of Colorado, farmers and ranchers, and NGOs to balance water supply and environmental objectives in the watershed, especially in the headwaters.

Agriculture in Colorado accounts for the greatest consumptive uses and losses in the watershed – 0.95 maf/yr between 2000 and 2017. Diversion of water to support large agricultural areas in western Colorado began before negotiation of the Colorado River Compact (Sibley, 2012), and these very senior water rights significantly affect modern management of the upper Colorado River. Diversions to support these large agricultural areas are delineated in the CRSS.

The Grand Valley Canal, near Grand Junction, was completed in 1886 and originally served 45,000 acres. Reclamation began construction of the Grand Valley Project's Government Highline Canal in 1910, one of the agency's first projects. This canal has a capacity of 1620 ft^3/s and eventually served 4 irrigation districts. In present times, the "Cameo Call" is sometimes implemented during the summer base flow season to ensure that the full water rights of the Grand Valley Irrigation Company and the Grand Valley Project are fulfilled. Between 2000-2018, 0.65 maf/yr was diverted into the Government Highline Canal, located at the confluence of the upper Colorado River with Plateau Creek.

Another significant attribute of modern upper Colorado River management is the very senior water rights of the Shoshone Powerplant, located 8 mi downstream from Dotsero (USGS gage 09070500). Water is diverted throughout the year, and the original water right for this diversion has a priority date of 1902, which is senior to most trans-basin diversions and most agricultural diversions. In low water years when the flow of the river is less than 1250 ft^3/s, operations of trans-basin diversions and associated reservoirs are significantly affected by the need to maintain minimum flows at this powerplant (Colorado Water Conservation Board and the Colorado Division of Water Resources, 2007).

The earliest trans-basin diversions also date to the late 1800s. In 1890, the Grand Ditch began intercepting runoff from the Never Summer Range and transporting that water across Poudre Pass to the Cache la Poudre River that flows eastward to agricultural areas near Fort Collins and Greeley. As the key element of the Twin Lakes Project, construction of a tunnel to transfer water from the headwaters of the Fryingpan River to the Arkansas River began in the mid-1920s. In 1931, the Colorado state engineer issued a report describing a system of tunnels and canals capable of transferring nearly 0.50 maf/yr eastward to rectify what many referred to as "Colorado's natural inadequacy" (Sibley, 2012). These projects included three to transfer water to the Denver area from the Fraser, Blue, and Williams Fork Rivers.

Between 2000 and 2017, 29 tunnels and canals transferred 0.52 maf/yr to East Slope Colorado. The largest of these transfer systems are the Colorado-Big Thompson Project (to northern and eastern Colorado), the Moffat Tunnel system (to Denver), the Roberts Tunnel system (to Denver), the Fryingpan-Arkansas Project (to southeastern Colorado), the Independence Pass system (to the Arkansas River watershed), and the Homestake system (to Colorado Springs) (Colorado Water Conservation Board and the Colorado Division of Water Resources, 2007).

As described below in this report, detailed operations of the trans-basin diversions are not delineated in the CRSS, and the most upstream node of the model is the gage downstream from Glenwood Springs (USGS gage 09085100), just downstream from the Roaring Fork River. The mean annual measured flow past this gage between 2000 and 2018 was 2.2 maf/yr, which was approximately 55% of the total flow of the entire river measured near Cisco. Significant tributaries, all of which are partly diverted to the East Slope, include the Roaring Fork River (0.75 maf/yr), Eagle River (0.39 maf/yr), Blue River (0.29 maf/yr), and Williams Fork (0.10 maf/yr) (measured mean annual flows 2000-2018 for each river). Within the watershed upstream from the Cameo gage, there are 16 reservoirs and 3 aggregations of small reservoirs on Grand Mesa that have capacities of at least 0.004 maf.

In contrast, reservoirs and diversions are well articulated in the Gunnison River watershed. The Gunnison River is the largest tributary of the upper Colorado River and had an annual mean flow of 1.5 maf/yr between 2000-2018. Thus, ~38% of the total flow measured near Cisco came from the Gunnison River watershed. Most of the headwater tributaries of the Gunnison River have smaller natural runoff than do the headwater tributaries of the most upstream parts of the Colorado River. The largest headwater tributaries of the

Gunnison River are the Taylor River, East River, Lake Fork, and Uncompahgre River.

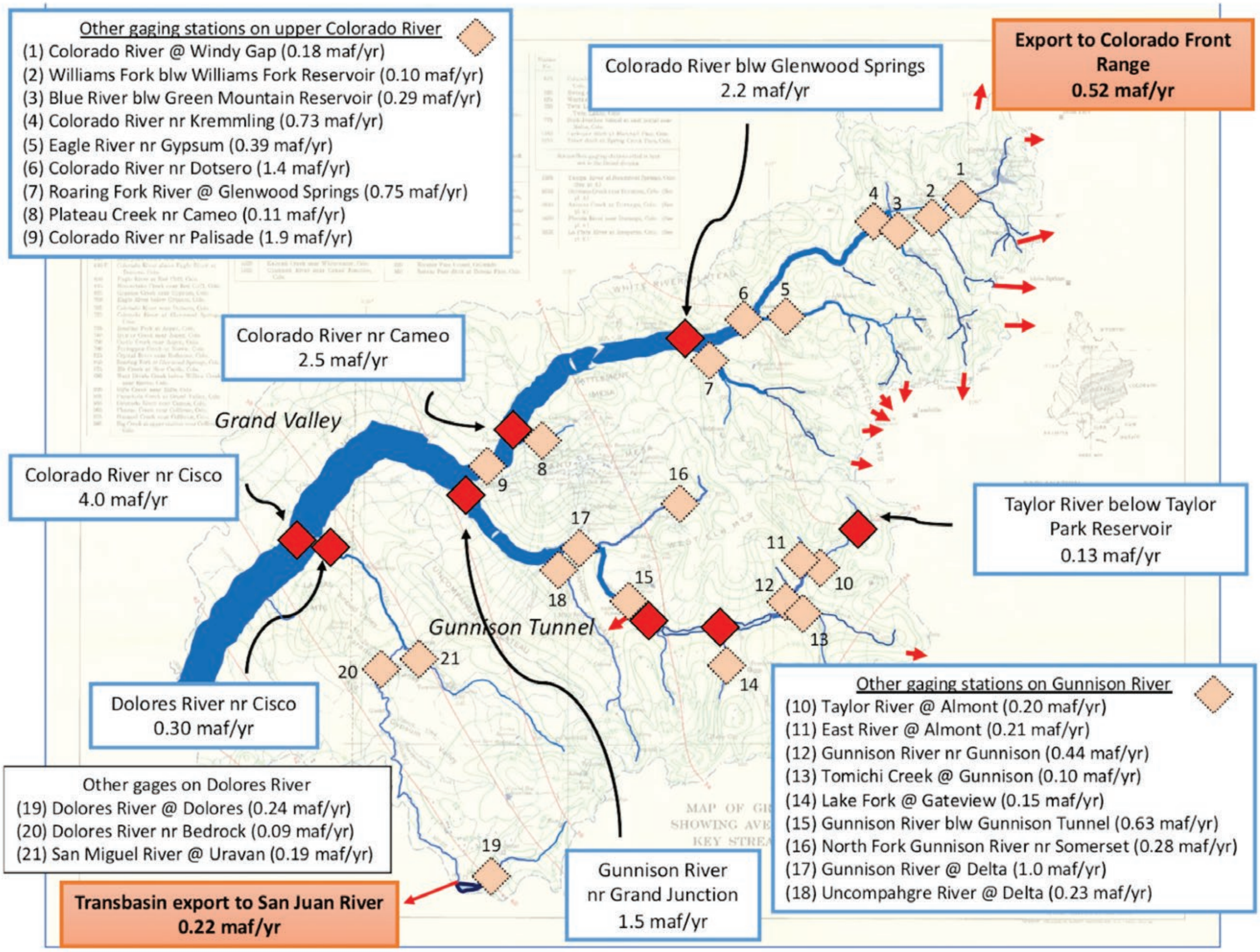
Reclamation completed the Gunnison Tunnel in 1909. At the time of its completion, this 5-mi long tunnel was the longest irrigation-supply tunnel in the world and transferred water from the narrow Black Canyon of the Gunnison to the adjacent, broad valley of the Uncompahgre River. In 1956, the CRSP Act authorized construction of the Blue Mesa, Morrow Point, and Crystal Dams on the Gunnison, upstream from the Tunnel. These Reclamation dams play a significant role in providing base flows for modern management of endangered endemic fish, and rules for operating these reservoirs are represented in the CRSS.

Trans-basin diversions in the headwaters of the Dolores River were among the earliest in the Colorado River basin and are described in the CRSS. The headwaters of the Dolores River drain the southwest part of the San Juan Mountains. After leaving the mountains, the Dolores makes a 90° turn to the north and flows for ~150 mi through deep canyons north to the Colorado River. To the south and west of the big bend in the Dolores River is the large and relatively flat Montezuma Valley that drains to the San Juan River. Efforts began in 1878 to divert water from the Dolores River Canyon to the Montezuma Valley, and a 1-mi long tunnel and the "Great Cut" of an open canal were part of a 100-mi system of distribution canals that began to supply Dolores River water to the Montezuma Valley and Cortez by 1890. Farmers continued to advocate for water storage on the Dolores that would allow expanded trans-basin diversion, and Reclamation began construction of the Dolores Project in 1979. McPhee Dam was completed in 1986, and the project became fully operational in 1999.

Because most of the Dolores' flow is diverted south, the modern San Miguel River is much larger than the Dolores River. At the confluence with the San Miguel River, the mean annual total flow of the Dolores was only 0.090 maf/yr between 2000 and 2018, whereas 0.22 maf/yr was diverted from McPhee Reservoir to the Montezuma Valley. During this same period, the San Miguel River has an average annual total flow of 0.19 maf/yr.

Appendix Table 2.1. Consumptive uses and losses in the upper Colorado River watershed in the 21st century

Upper Mainstem	Consumptive uses or losses, in acre feet per year, 2000-2017
Colorado	
Reservoir evaporation	71,000
Agriculture	950,000
M&I	38,000
Trans-basin export	520,000
Export to San Juan River watershed	220,000
Utah	
Reservoir evaporation	1,500
Agriculture	16,000
M&I	2,200
Aspinal Unit evaporation	8,800
Total consumptive uses and losses	1,800,000
Annual stream flow	
Colorado River near Cisco	4,000,000 (measured)
	5,800,000 (natural)



Appendix Figure 2.1. Map showing the upper Colorado River watershed, with mean annual measured stream flow (2000-2018) and mean trans-basin exports (2000-2017) for the 21st century. The widths of all streamlines are proportional to the measured flow. Red diamonds indicate approximate locations of the natural flow inflow locations (nodes) represented in the CRSS. Other gaging stations with mean annual flow >0.10 maf/yr are indicated, except in some headwater tributaries where only the gage at the tributary mouth is shown.

Appendix Three

The Green River Watershed

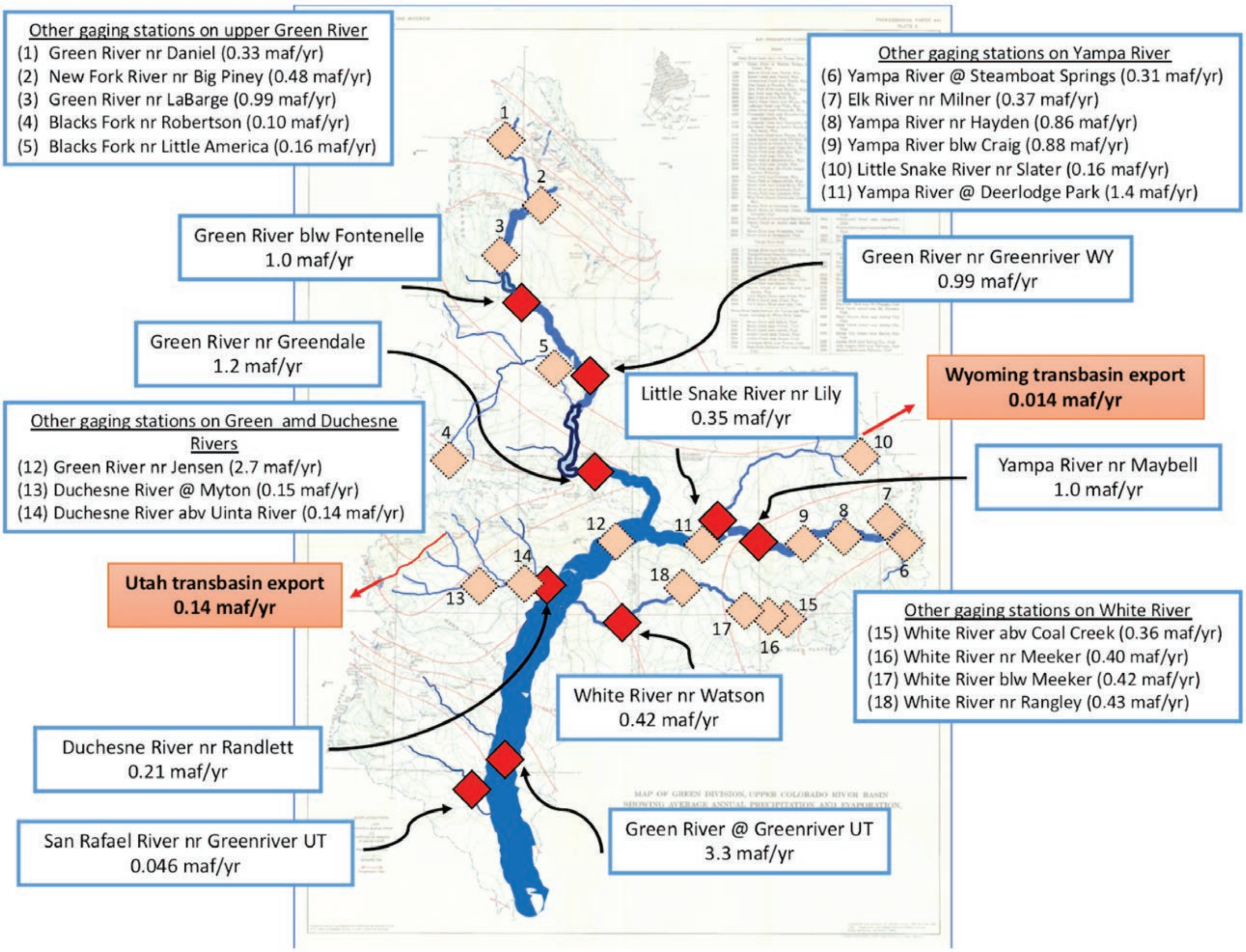
The largest consumptive uses and losses in the Green River watershed are evapotranspiration and seepage associated with irrigated agriculture in Utah (0.50 maf/yr), Wyoming (0.30 maf/yr), and Colorado (0.18 maf/yr) (Appendix Table 3.1). Approximately 0.14 maf/yr is diverted from the headwaters of the Duchesne River to the Great Salt Lake watershed where most of Utah's population lives.

Several tributaries draining the south side of the Uinta Mountains provide runoff to the Duchesne River (Appendix Fig. 3.1). The details of this hydrography and the details of trans-basin diversions are not described in the CRSS.

Trans-basin diversions from the Duchesne watershed began in 1915 by the Strawberry Project through the Strawberry Tunnel, and the Uintah Indian Irrigation Project in the Uinta Basin was completed in 1920. The efficiency of stream-flow regulation and the magnitude of trans-basin diversions was expanded in the 1970s and 1980s with enlargement of Strawberry Reservoir and trans-basin diversion system, construction of Starvation and Stillwater Reservoirs, and completion of an extensive system of aqueducts that intercept the flow of many streams that drain the western Uinta Mountains (Gaeuman et al, 2005).

Appendix Table 3.1. Consumptive uses and losses in the Green River watershed in the 21st century

	Consumptive uses or losses, in acre feet per year, 2000-2017
Colorado	
Reservoir evaporation	7,900
Agriculture	180,000
M&I	21,000
Export (inside)	2,600
Utah	
Reservoir evaporation	69,000
Agriculture	500,000
M&I	49,000
Export (outside)	140,000
Wyoming	
Reservoir evaporation	36,000
Agriculture	300,000
M&I	45,000
Export (outside)	14,000
Flaming Gorge evaporation	76,000
total consumptive uses and losses	1,400,000
Annual stream flow	
Green River @ Green River, UT	3,300,000 (measured)
	4,700,000 (natural)



Appendix Figure 3.1. Map showing the Green River watershed, with mean annual measured stream flow (2000-2018) and trans-basin diversions (2000-2017) for the 21st century. The widths of all streamlines are proportional to the measured flow. Red diamonds indicate approximate locations of the natural flow inflow locations (nodes) represented in the CRSS. Other gaging stations with mean annual flow >0.10 maf/yr are indicated.

Appendix Four

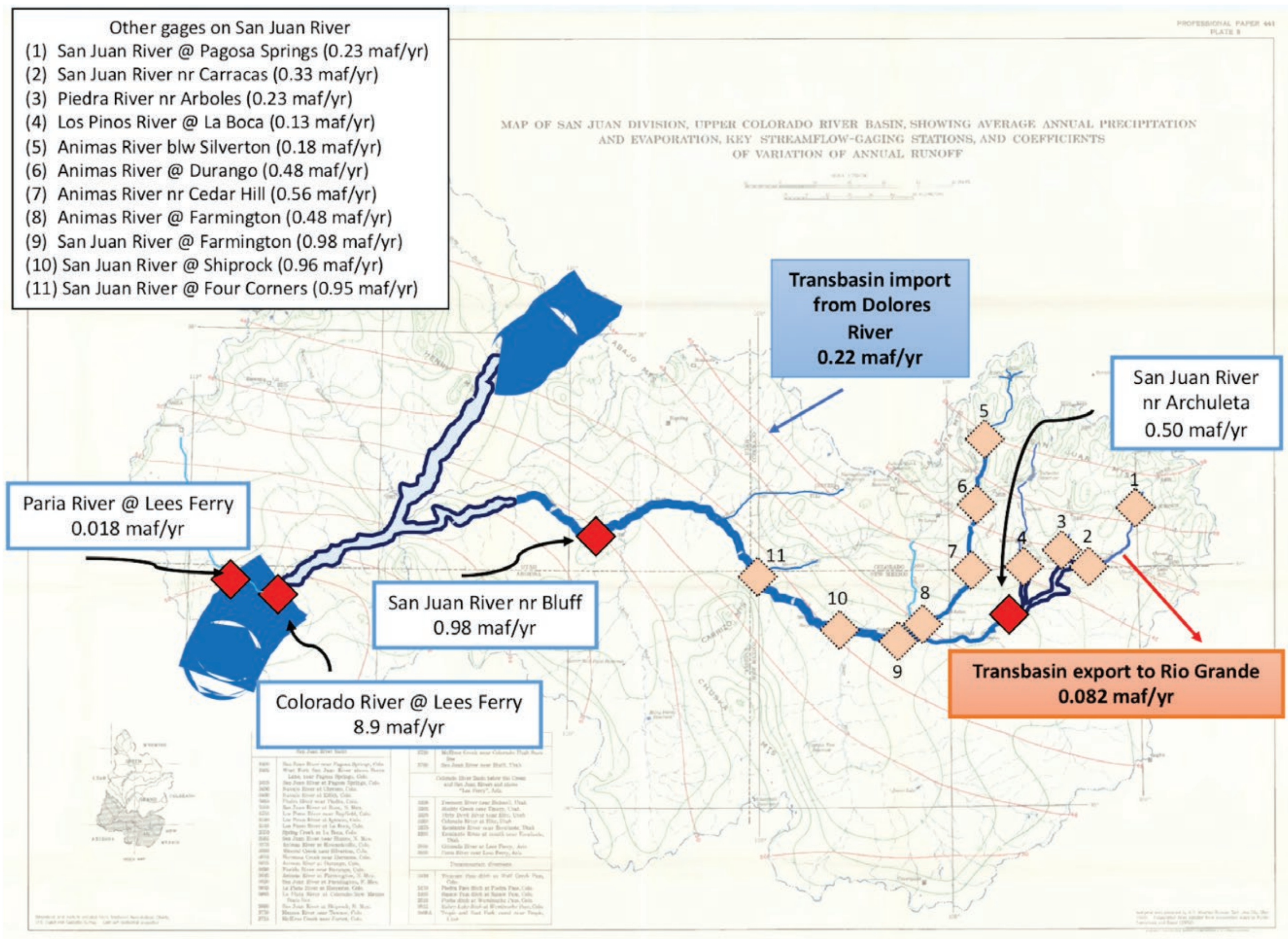
The San Juan River Watershed

Consumptive uses and losses between 2000 and 2017 are summarized in Table 4.1 and compared to measured stream flow in Appendix Fig. 4.1.

Appendix Table 4.1. Consumptive uses and losses in the San Juan River watershed in the 21st century

Sidebar Table 4.1. Consumptive uses and losses in the San Juan River watershed in the 21st century

	Consumptive use or loss, in acre feet per year, 2000-2017
Arizona	
Reservoir evaporation	3,700
Agriculture	2,000
M&I	30,000
Colorado	
Reservoir evaporation	11,000
Agriculture	360,000
M&I	6,700
Export (outside)	2,000
Export (inside)	(220,000)
New Mexico	
Reservoir evaporation	27,000
Agriculture	220,000
M&I	62,000
Export (outside)	88,000
Utah	
Reservoir evaporation	6,600
Agriculture	95,000
M&I	6,200
Export (outside)	(5,000)
Total consumptive uses and losses	700,000
Average annual stream flow	980,000 (measured)
San Juan River near Bluff	
	1,700,000 (natural)

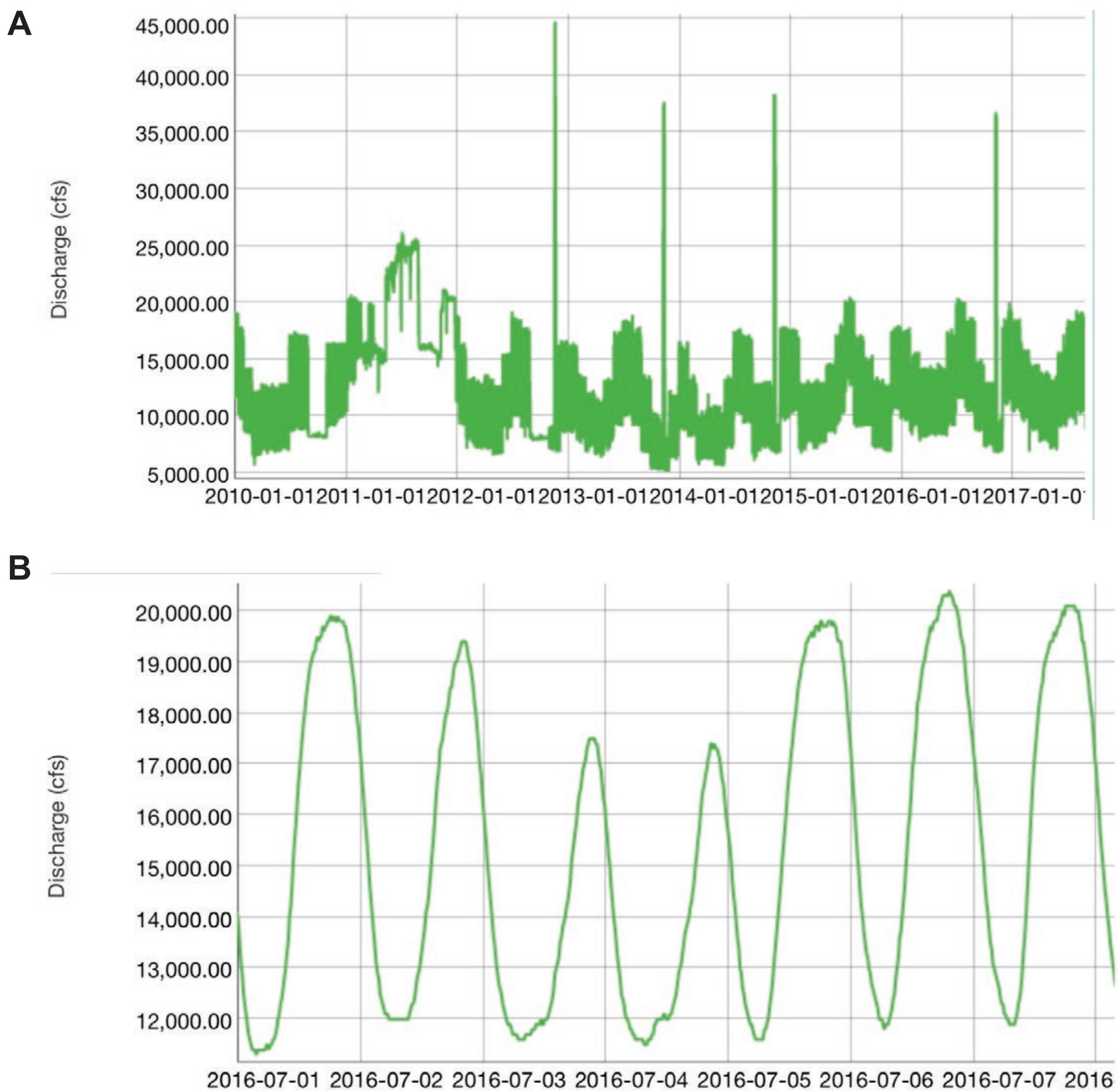


Appendix Figure 4.1. Map showing the San Juan River watershed, with mean annual measured stream flow (2000-2018) and trans-basin diversions (2000-2017) for the 21st century. The widths of all streamlines are proportional to the measured flow. Red diamonds indicate approximate locations of the natural flow inflow locations (nodes) represented in the CRSS. Other gaging stations with mean annual flow >0.10 maf/yr are indicated.

Appendix Five

The Grand Canyon Segment

The instantaneous hydrograph of the Colorado River in Grand Canyon strongly reflects the pattern of releases from Glen Canyon Dam. Large-scale water supply agreements determine the annual volume of flow released from the dam. Monthly, weekly, and daily patterns of reservoir release primarily reflect load-following operations to meet regional electricity demands, These patterns are illustrated in the instantaneous hydrograph for the Colorado River at Lees Ferry between 2010 and 2017 (Appendix Fig. 5.1A). In this figure, what appears as a wide swath is actually the daily range of daytime and nighttime releases (Appendix Fig. 5.1B). The four discrete short duration periods of high flow are each a controlled flood (administratively termed High Flow Experiments), and these floods had durations of 3 to 5 days. The period of 2010 and 2011 when the range of daily fluctuation was less and the average daily flow was relatively high was a period when an unusually large amount of water was transferred to Lake Mead to equalize the contents of the two reservoirs. The rules governing these “equalization” releases are described in the next section of this report.



Appendix Figure 5.1. A. Instantaneous hydrograph of the Colorado River between 2010 and 2017. B. Instantaneous hydrograph of one week of typical reservoir releases from Glen Canyon Dam in July 2016.

Some components of the water budget for Lake Powell are imprecise and reflect the inherent uncertainty in managing large water storage facilities in remote locations. A water budget for Lake Powell is

$$\Delta S_{LP} = CR_C + GR_{GR} + SJR_B + \sum tribs_{ungaged} + P - E - G_{seepage} - G_{storage:long} \pm G_{storage:short} - CR_{LF}$$

where the left side of the equation is the change in water storage in the reservoir, CR_C, GR_{GR}, SJR_B, and *tribs* are the gaged and ungaged inflows to the reservoir, CR_{LF} is the reservoir release measured at Lees Ferry, *P* is precipitation, *E* is evaporation, and *G* is long and short-term exchange of reservoir water with the regional ground-water system. The left side of this equation is precisely known, because the elevation of Lake Powell is precisely measured, and there is a well-defined relation between reservoir elevation and reservoir water storage (Reclamation, 2007, Table Att. B-1). Although stream flow of the upper Colorado, Green San Juan, and a few other smaller tributaries, inflow from a watershed area of 20,000 mi^2 is ungaged (Schmidt, 2016). Precipitation onto the reservoir surface is poorly measured, and exchange of water with the regional ground-water system is poorly understood (Schmidt, 2016).

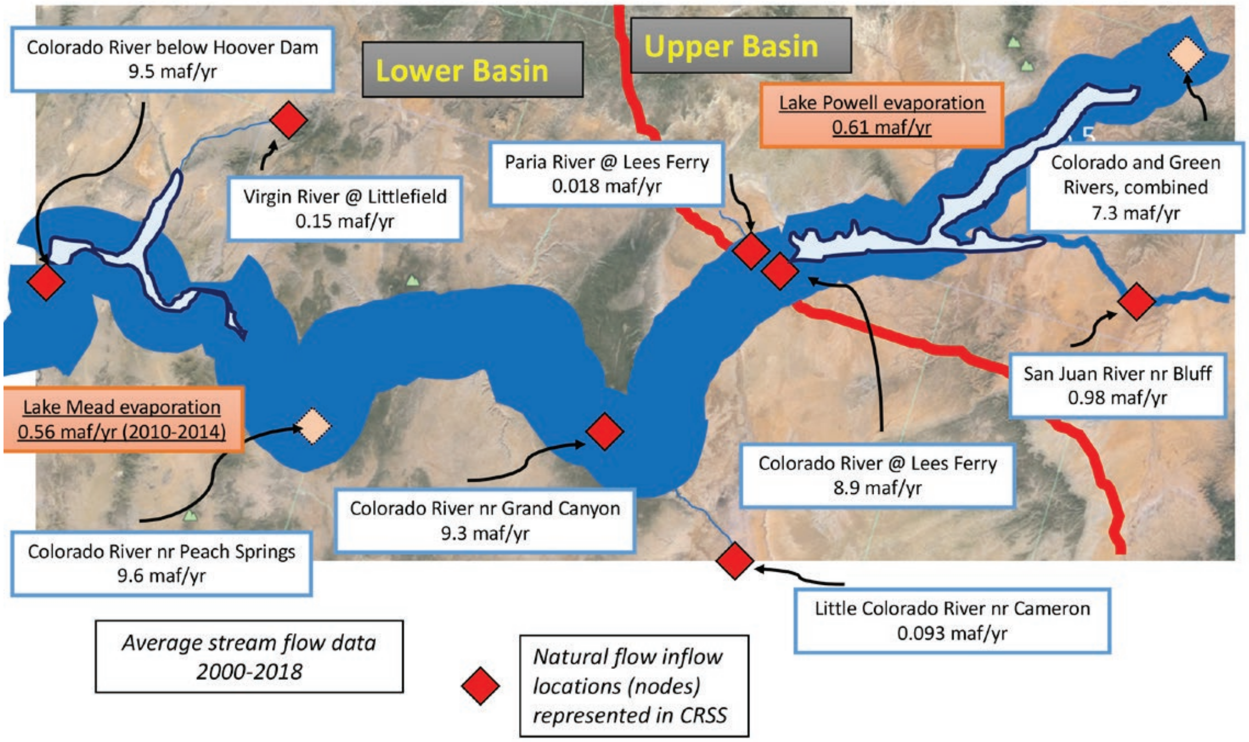
Reclamation estimated that 0.41 maf/yr evaporated from Lake Powell between 2000 and 2017, as summarized in the Upper Colorado River Basin water accounting reports. However, these data are for net evaporation, which is the difference between actual evaporation from the reservoir and the estimated evapo-transpiration that occurred in the Colorado River valley in Glen Canyon (Schmidt, 2016). The average annual total reservoir evaporation from Lake Powell between 2000 and 2018 was 0.61 maf/yr, based on the estimated reservoir evaporation rate estimated by Jacoby et al (1977) multiplied by the reservoir surface area.

Casual inspection of the water budget for Lake Powell demonstrates the large uncertainty in this water budget (Table 5.1). The measured inflows and the estimated precipitation are nearly 1 maf/yr less than the sum of the well-measured reservoir releases and the poorly understood evaporation rate. During the 2000-2018 period, Lake Powell declined in storage at an average rate of 0.63 maf/yr. Thus, an additional annual decrease of 0.4 maf/yr is unaccounted in this budget, either because inflows are underestimated or evaporation is over estimated. It is beyond the scope of this report to evaluate this discrepancy, but it is clear that there is large uncertainty in developing a water budget for Lake Powell and an even greater uncertainty in predicting future conditions in Lake Powell.

Appendix Table 5.1. Water balance for Lake Powell in the 21st century.

	Average, in million acre feet per year
Total Inflow to Lake Powell (water years 2000-2018)	
Colorado River near Cisco	3.99
Green River at Greenriver	3.30
San Rafael River nr Greenriver	0.05
San Juan River nr Bluff	0.98
Dirty Devil River nr Hanksville	0.07
Escalante River nr Escalante	0.01
Ungaged inflows to Lake Powell	unknown
Precipitation onto Lake Powell surface (assumed 0.57 ft/yr)	0.06
Outflow from Lake Powell (water years 2000-2018)	
Evaporation from Lake Powell (based on Jacoby et al, 1977, evaporation rate of 5.75 ft/yr)	0.61
Colorado River at Lees Ferry	8.88
Measured change in reservoir storage (water years 2000-2018)	- 0.63

Approximately 0.7 maf/yr enters the Colorado River between Glen Canyon Dam and Lake Mead (Appendix Fig. 5.2), and approximately 40% of this inflow occurs downstream from the gage near Grand Canyon that is a CRSS node.



Appendix Figure 5.2. Map showing the Grand Canyon segment, with mean annual measured stream flow for the indicated period of the 21st century. The widths of all streamlines are proportional to the measured flow. Note that there are no significant consumptive losses in this segment except for evaporation from the two reservoirs. Evaporation rates for Lake Powell and Lake Mead are discussed in the text.

Between 2000 and 2017, Lake Mead water storage declined by 14.5 maf, which is an annual rate of 0.81 maf/yr (Appendix Table 5.2). This decline occurred despite an average inflow rate of 9.64 maf/yr, measured near Peach Springs (USGS gage 09404200), that was primarily caused by releases from Lake Powell that were 7% greater than the legally required delivery of water from the Upper Basin to the Lower Basin. Additionally, withdrawals of water by the Southern Nevada Water Authority were 0.27 maf/yr during this period which is less than Nevada's full allocation of 0.3 maf/yr. Thus, the water storage in Lake Mead during this period could not be maintained despite larger than required releases from Lake Powell and less than legally allowed withdrawals by the state of Nevada.

Appendix Table 5.2. Water balance for Lake Mead in the 21st century.

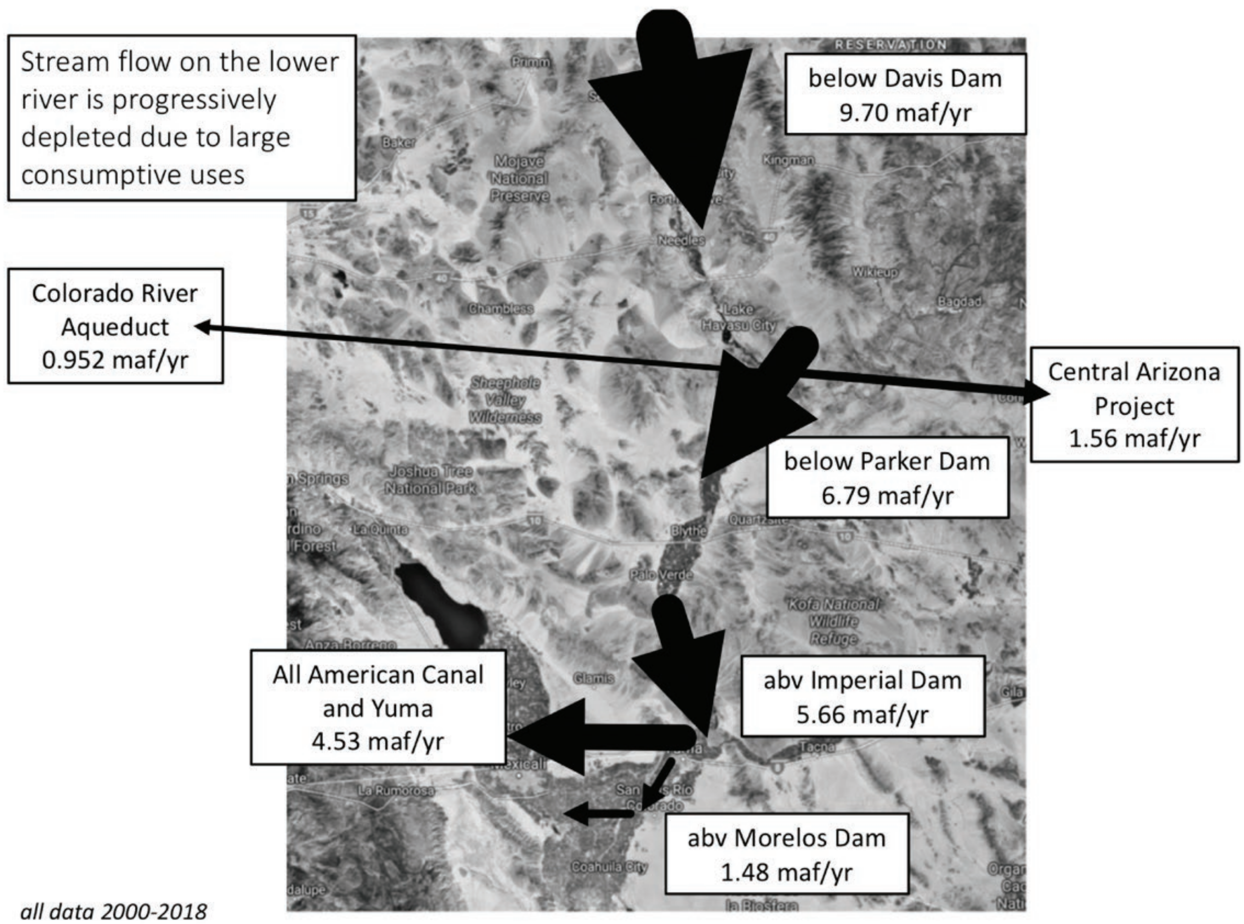
	Average, in million acre feet per year
Total Inflow to Lake Mead	
Colorado River nr Peach Springs (2000-2017)	9.64
Virgin River @ Littlefield	0.15
Outflow from Lake Powell	
Evaporation from Lake Mead (2010-2014; based on Moreo, 2015)	0.56
southern Nevada diversion (2000-2017)	0.27
Colorado River below Hoover Dam (2000-2017)	9.5
Measured change in reservoir storage	- 0.81

The Lower River

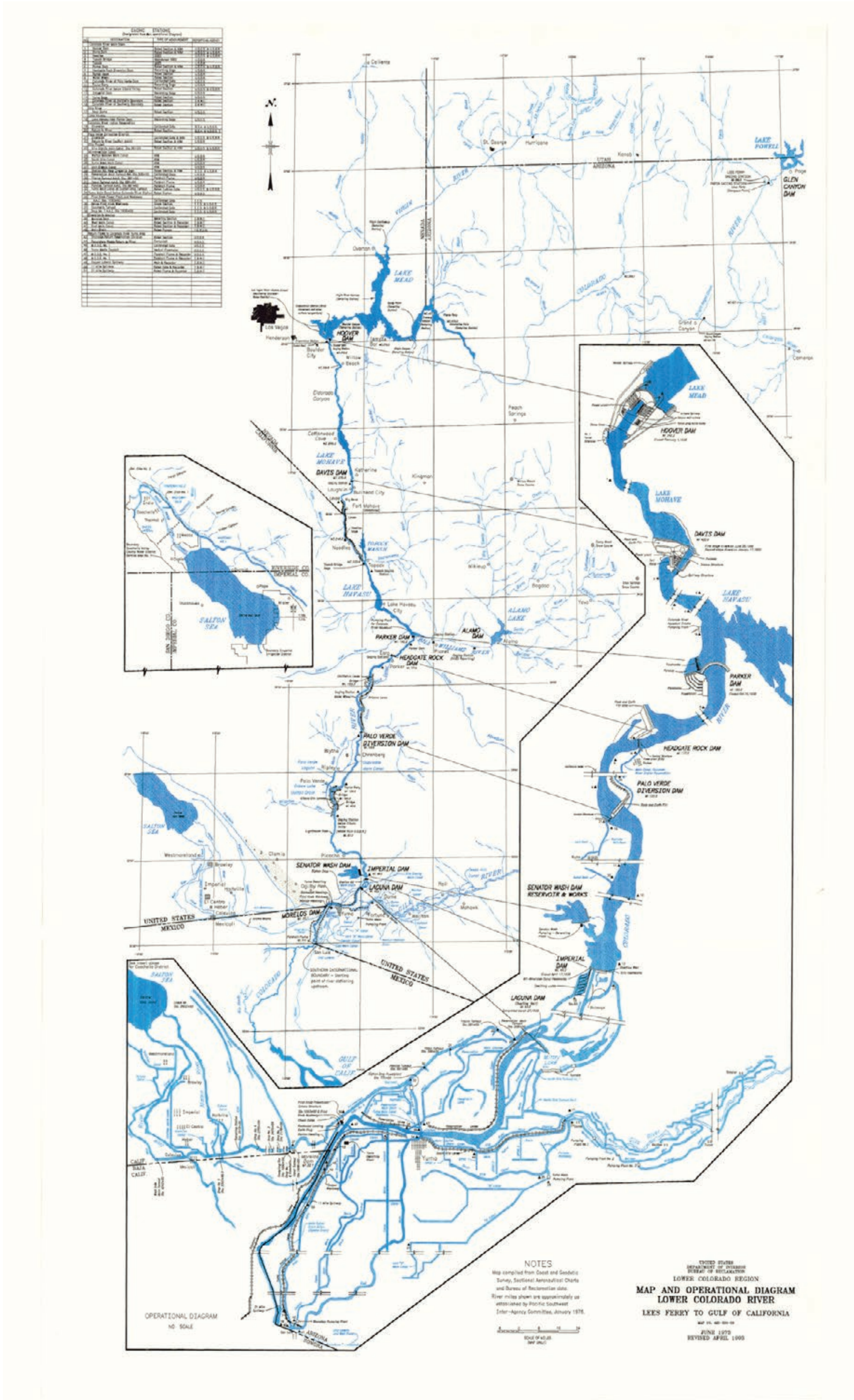
The transformation of the lower Colorado River -- America's Nile -- is profound, supporting the growth of Yuma and the Imperial Valley, southern coastal California, and central and southern Arizona, and transforming the natural river environment (Mueller and Marsh, 2002). It is beyond the scope of this report to fully describe the storage and distribution of water of the Lower Colorado River, and the literature describing the history of river development is immense. Today, environmental issues are addressed by the Lower Colorado River Multi-Species Conservation Program.

This complex distribution system is well represented in the CRSS and is described in detail in the Lower Colorado River water accounting annual reports. These reports demonstrate that 7.5 maf/yr of mainstem Colorado River water is consumptively used in Arizona, California, and Nevada (Appendix Table 1.1). Additionally, 1.7 maf/yr flowed across the international border to Mexico between 2000 and 2017. These uses were sustained by the annual release of 9.5 maf/yr from Lake Mead.

The hydrography of this part of the river is generalized in Appendix Fig. 6.1 that illustrates the progressive downstream depletion of stream flow. There are significant depletions of approximately 2.5 maf/yr from Lake Havasu, formed by Parker Dam. Nearly twice this amount is diverted from the river into the All American Canal, and most of this water is transferred to the Imperial Valley. The distribution system near Yuma is very complex (Appendix Fig. 2.2) and some of these diversions are also returned to Mexico at the international border.



Appendix Figure 6.1 Stream flow and diversions of the lower Colorado River in the early 21st century. All data are from USGS gages of the Colorado River or of major diversions.



Appendix Figure 6.2. The Blue Dragon diagram showing the water distribution system of the Lower Colorado River (available at https://www.doi.gov/water/owdi.cr.drought/en/).

Explanation of the Fill Mead First (Phase I) and Fill Powell First Alternative Management Paradigms

Fill Mead First - Phase I

The FMF paradigm represents a significant alteration to the operation of the reservoirs, both in practice and in the CRSS. Since both reservoirs are used to store water, changes to the model schematic are not required. All modifications to the model will be made in the rule set, describing the operations of Lakes Powell and Mead.

Operation of Lakes Powell and Mead

The operation of Lake Powell in this paradigm would nominally require releasing the majority of reservoir inflows, in addition to any storage that has been retained in Lake Powell whenever there is space available to receive this water in Lake Mead. This would result in a highly variable flow through the hydropower penstocks of Glen Canyon Dam and possibly the river outlets, however, reservoir releases would always be limited to the physical capacity of the reservoir outlets themselves. Use of the spillways would only occur in emergencies and never as a regular operational method. The total release rate required from Lake Powell to reach a minimum operational threshold (e.g. a minimum power generation elevation) will be determined given the inflows from the Upper Basin, capacities of outlets available at the current reservoir level, flow through the Grand Canyon, necessary releases from Lake Mead to meet all downstream demands, and Lake Mead pool elevation staying below the maximum level allowed for flood operations. Whenever the pool elevation of Lake Mead is below its maximum operational threshold, Powell would be modeled to remain at its minimum threshold.

A significant consideration in the Fill Mead First - Phase I paradigm is how to operate Lake Mead to meet the downstream demands under all hydrologic circumstances. Currently, releases are made to meet the combined needs of Arizona, California, and Mexico, and include demands that are adjusted for any surplus, shortage, or flood control conditions for MWD, CAP, Coachella, IID, Mexico, and a variety of Arizona users. Lake Mead releases under the surplus and shortage rules are tied to specific Lake Mead levels and assumptions about flows from Lake Powell to Lake Mead. We will explore alternative surplus and shortage rules that consider the combined storage of Lakes Mead and Powell. These levels can be set to achieve the equivalent probability of shortages and surplus conditions as projected under current operations with or without the drought contingency plan (DCP) in place. Similarly, surplus and shortage rules for Mexico will also reflect the combined storage of the two major reservoirs, with probabilities and magnitudes of shortage commensurate with current probabilities.

The evaluation of this AMP using the CRSS requires designing, writing, and testing new operational rules for both Lakes Powell and Mead. A significant number of the existing rules must be disabled or eliminated from the modified the CRSS rule set. Flood control operations will be minimally altered as the existing flood rules consider Lakes Powell and Mead a joint system. We will also evaluate how releases from Lake Powell would affect river ecosystem conditions in the Grand Canyon, including the effects of water temperature and sediment mass balance.

Fill Powell First

The Fill Powell First paradigm also represents a significant modification to the operation of the Colorado River system and the CRSS. The logic behind this paradigm is to keep the water level in Lake Powell as high as possible, while still meeting the demands in both the Lower Basin and the deliveries to Mexico with at least as much regularity as is currently the case. Similar to the FMF paradigm, no changes to the CRSS object workspace would be required. However the rules that operate the reservoirs would need to be significantly changed.

The proposed logic will initially assume that releases from Lake Powell are made only to meet the immediate environmental and recreational needs of the Grand Canyon. Additional releases will be made to not allow Lake Powell to exceed a high operational threshold. Lake Mead would attempt to make a release to meet all downstream demands, but not fall below its own low operational threshold that allows hydropower production. If additional water is required to meet the Lower Basin demands, an additional release is made from Lake Powell to precisely meet this need. This will allow Lake Mead to also increase its releases, but maintain its own low operational threshold. Outflows from Lake Powell will be limited by the capacity of the turbines, river outlets, and spillway. The timing of these flows, however, will not necessarily synchronize with natural flows, but will align with the anthropogenic demands.

Similar to the Fill Mead First paradigm, the declaration of surpluses and shortages to the Lower Basin will need to be reconsidered. These declarations will again be redesigned to consider the combined storage volumes in Lake Mead and Powell.

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